5

Assets

Physical and Intellectual Infrastructure

COMPLETE TABLE OF CONTENTS

This chapter gives an overview of the resources available at TRIUMF with an emphasis on changes and enhancements over the past five years. It is not intended to be a comprehensive description of everything at TRIUMF, but it will give the reader a good sense of the laboratory's capabilities and capacities.

5.1 INTRODUCTION

TRIUMF brings a lot to Canada's national research agenda: experimental facilities; a network of accelerators, detectors, production targets, and beam lines; supporting infrastructure and systems; highly trained personnel with unique knowledge, skills, and abilities; a set of practices and procedures for conducting business in a safe, efficient, and reliable manner; and a portfolio of intellectual property and industrial partnerships. The combined physical and intellectual capital, accumulated over more than four decades, can be valued at approximately 1 billion dollars.

While the most valuable assets at TRIUMF are its human people: the talented and dedicated staff who are responsible for TRIUMF's success (see Sections 5.2 and 5.7), the laboratory also has substantial intellectual property in terms of patents, know-how, and established collaborative relationships with the private sector (see Section 5.10). For example, TRIUMF received a provisional patent to develop cyclotron production of the world's most popular medical isotope, technetium-99m.

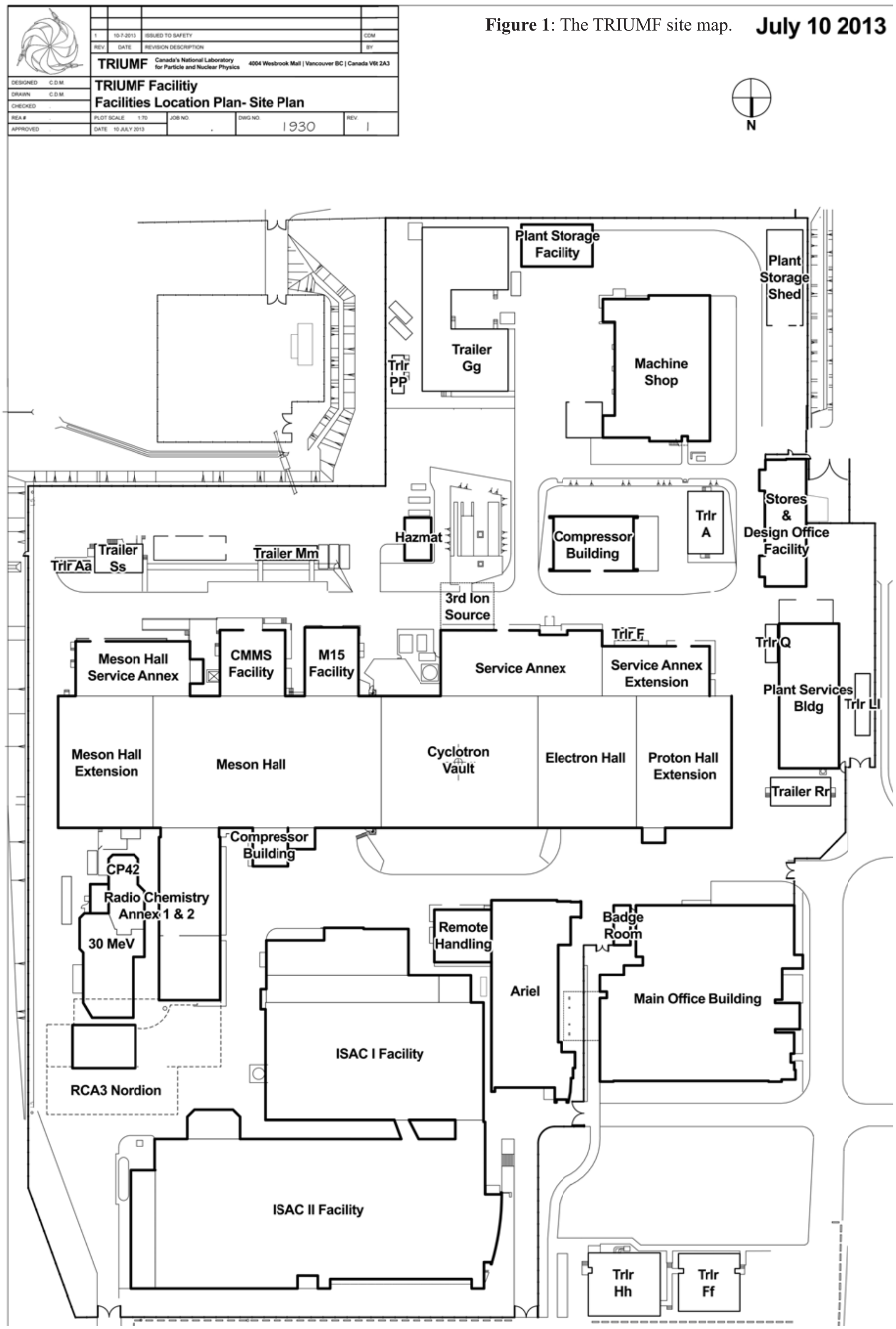
TRIUMF is located on a 12-hectare site on the south end of the University of British Columbia's Vancouver campus. The land is leased from UBC on a 99-year contract. It has three large building complexes, a number of stand-alone buildings and temporary structures. Three buildings are new in the present five-year plan. Housed within the buildings are an array of accelerators, experimental halls, support facilities, and offices.

At the center of site (see Figure 1) is the main accelerator building, which houses the cyclotron vault for the main cyclotron, the electron hall for the new e-linac accelerator, the meson hall for muon physics and the ultra-cold neutron facility, and a number of annexes and extensions. North of the main cyclotron building are the ISAC and ARIEL buildings used for the rare-isotope program. These two building are both connected to the main cyclotron building by tunnels that contain the proton and electron beam lines. ISAC consists of an isotope-production complex mostly located underground and two experimental halls (ISAC-I and ISAC-II) that contain a suite of detector facilities for studying isotopes. To the south of the main cyclotron building are the machine shop and the new stores and compressor buildings.

TRIUMF has an array of particle accelerators: the main 520 MeV cyclotron, a TR-13 cyclotron, a number of low-energy medical cyclotrons (three are owned by Nordion, Inc.), various rare-isotope beam accelerators, and the e-linac. The accelerators in turn feed the many experimental facilities on site. The experimental facilities are mainly in the ISAC-I and ISAC-II experiment halls, the meson hall and its annexes (see Sections 5.3–5.6 for a description of the accelerators and experimental facilities). The main cyclotron has been recognized as a feat of modern engineering; in 2010, it received the IEEE Engineering Milestone Award (one of only 11 in Canada),[1] and in 2012, on the occasion of its 125th anniversary, the Engineering Institute of Canada named TRIUMF an honourary member as one of Canada's six "Great Engineering Achievements."

Support facilities are located throughout the site but special attention should be drawn to the Machine Shop on the south part of the site, the Design Office located in the top floor of the Stores Building, and the ATLAS Tier-1 Data Centre (see Section 5.8.1) located on the upper floor of the ISAC-II building. Although the Machine Shop is not described in this chapter, it contains some of the industry's most advanced equipment for forming, shaping, and assembling materials. The Machine Shop is a unique resource in Canada because it provides advanced, one-of-a-kind, fabrication and assembly services to TRIUMF and the Canadian research community. The Machine Shop maintained a complement of

Figure 1: The TRIUMF site map.



16-18 FTEs over the past five years and performed an average of 550 “jobs” each year. The Design Office provides mechanical and engineering design services to TRIUMF and the Canadian community with a team of 10-11 FTEs, completing an average of 60 complex design jobs each year.

Tying this all together are the TRIUMF administrative and business offices, including safety and licensing, procurement, human resources, and project- and quality-management systems. The management structure has undergone some changes in the last five years and the current structure is described in Section 5.9.

5.2 EXPERT PERSONNEL

TRIUMF, over the 45 years of its existence, has assembled a core staff of approximately 350 people with a strong and diverse skill set. The staff can be divided into five categories: senior management, scientific staff, engineering staff, technical staff, and administrative staff. Senior management runs the laboratory and sets the tone for its efficient operation. The scientific staff in collaboration with university-faculty colleagues define the scientific goals and manage the laboratory’s many research activities. The engineering and technical staff provides the essential skills needed to undertake the complex and challenging technical and mechanical tasks that allow Canada to achieve its goals and meet its challenges. The administrative staff provide effective support in areas ranging from safety and quality management to communications and financial accounting. Both collectively and on their own, these groups deserve a closer look.

5.2.1 SENIOR MANAGEMENT

The Senior Management team is made up of key leaders from all Divisions and the Office of the Director. The Senior Management team meets weekly to stay current with TRIUMF news and ongoing projects, to ensure effective coordination of operations, and to regularly share information. It acts coherently to help the laboratory reach the objectives established by the larger community and approved by TRIUMF’s Board of Management. Senior management personnel have a wide variety of skills, including:

- Environment, Health and Safety
- Financial Strategy in a Research Environment
- Management, Administrative Management, and Human Resources
- Project Planning and Management
- Quality Assurance and Quality Management
- Scientific and Engineering Leadership
- Strategic Communications

Retirements over the last five years have resulted in a renewed senior management team with new division heads for all divisions and a new Chief Financial Officer. Most of these individuals have come to TRIUMF from abroad or from industry.

5.2.2 SCIENTIFIC STAFF

TRIUMF scientific personnel are primarily qualified at the Ph.D. level and represent about 17% of the laboratory’s core staff. About one-fifth of the scientific staff is resident at Canadian universities, strengthening both TRIUMF’s and the universities’ intellectual and scientific abilities. Scientists from Canadian universities and laboratories, as well as from international institutions, visit TRIUMF for periods ranging from a few days to weeks or a year. These visitors add to TRIUMF’s intellectual and

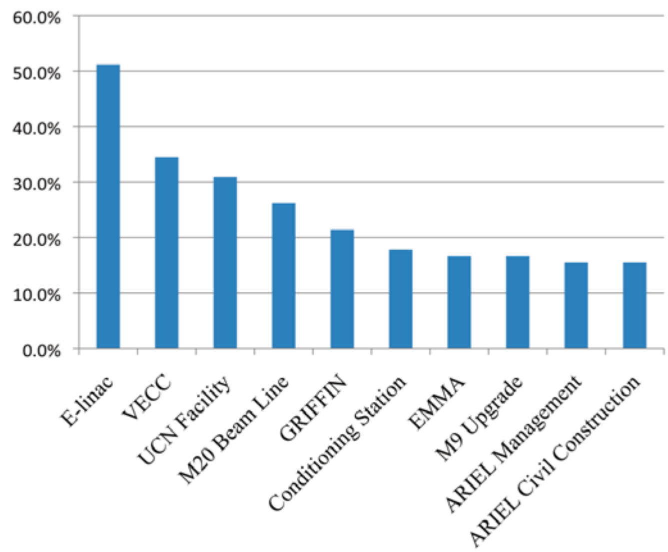


Figure 1: Fraction of the organization chart groups used by the larger projects in 2012.

scientific strength and diversity. The list below illustrates the skills of the scientific staff. These skills match the core research areas of the laboratory as well as provide a key resource for technology transfer to Canadian industry.

- Accelerator Physics
- Chemistry and Radiochemistry
- Experimental Subatomic Physics
- Nuclear Medicine
- Molecular and Materials Science
- Theoretical Subatomic Physics

5.2.3 ENGINEERING STAFF

TRIUMF's engineering personnel are primarily qualified at the B.Sc. and B. Eng. level and have a diverse skill set that ranges from high-power radio frequency engineers to specialists with unique skills in magnet design, cryogenics, digital electronics, or civil construction. One of the engineering staff is resident at a Canadian university. The engineering staff fall into the following categories.

- Accelerator Engineers
- Civil Engineers
- Computing Engineers
- Electrical Engineers
- Mechanical Engineers
- Nuclear Engineers
- Project Engineers

5.2.4 TECHNICAL STAFF

Technical personnel represent 65% of TRIUMF's core staff. Many of them hold M.Sc. or technical degrees and more than 15% of them have a diploma from local technical colleges or institutes such as Camosun, Kwantlen, the British Columbia Institute of Technology, and Okanagan College. Many are provincially registered with professional associations such as the Applied Science Technicians and Technologists of BC.

TRIUMF technicians perform the extremely complex technical tasks required to achieve the scientific goals of the laboratory. Our technicians maintain, operate, and upgrade TRIUMF's infrastructure. They are also responsible for the smooth and safe operation of the cyclotrons that produce medical isotopes for

Nordion, Inc. TRIUMF technicians are integral to the job of providing isotopes to the BC Cancer Agency and to the TRIUMF/UBC PET Centre. The machine shop has specialized equipment and machinists with the talent to fabricate the specialized apparatus technicians and technologists need in an advanced science facility.

In addition to maintaining and operating existing facilities, the technical staff are essential in developing new capabilities such as mechanical components and the increasingly complex electronics, controls, and data acquisition systems.

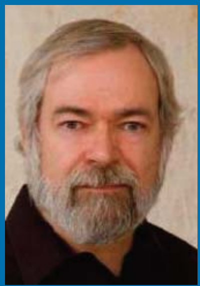
The list below illustrates just some of the unique skills of TRIUMF's technical staff.

- Accelerator Operations
- Beam Lines
- Chemistry
- Controls Electronics and Software
- Data Acquisition Systems
- High Current Power Supplies
- High Power RF
- Ion Source Technology
- Lasers
- Magnets
- Nuclear Engineering and Accelerator Technology
- Positron Emission Tomography (PET)
- Radiation Detectors
- Remote Nuclear Handling
- Radiation, Nuclear, and Industrial Safety and Hazards Reduction
- Scientific Computing
- Specialized Electronics
- Specialized Mechanical Design
- Superconducting RF

5.2.5 ADMINISTRATIVE STAFF

TRIUMF's small but effective administrative staff, which makes up 19% of the total staff, provides and maintains the administrative infrastructure necessary for the efficient operation of the laboratory. These staff have a wide variety of skills which covers several different areas, including:

- Accounting
- Business and Office Administration
- Human Resources
- Logistics
- Procurement
- Treasury
- Safety: Environmental Management; Occupational Health; Radiation Protection and Shielding; Radiation Monitoring and Safety Systems.



GERALD OAKHAM HONOURED AS ONE OF OTTAWA'S TOP 50 PEOPLE

12 September 2008

Gerald Oakham, a TRIUMF research scientist, was recently selected as one of the "Top 50 People in the Capital," an annual feature produced by Ottawa Life magazine. In addition to his position at TRIUMF, Oakham is a physics professor at Carleton University, one of TRIUMF's member universities. He is also the principal investigator and team leader for the Carleton University group contributing to the ATLAS project at CERN.

Before joining TRIUMF to work on ATLAS, Oakham participated in both the Omni-Purpose Apparatus at LEP (OPAL) and the European Muon Collaboration (EMC) projects at CERN. Since then, Oakham has returned to the university from which he earned his Ph.D. in 1981, this time as a professor in particle physics.

From 2002 to 2005, Oakham served as the director of the Ottawa Carleton Institute for Physics. He became Graduate Chair of the physics department at Carleton University in 2008. Additionally, Oakham is a member of the SNO Institute Board of Management and Chair of the SNOLAB Scientific and Technical Committee.

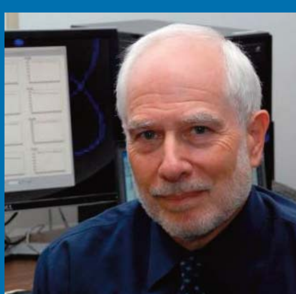
COMBINING SKILLS

TRIUMF's real strength is its ability to bring a variety of skills to any given project. Its matrixed organizational structure allows expertise from across the laboratory to be used on any project as needed (see Figure 1 again). Some groups, such as the machine shop and the design office, work on almost all projects while others have a more specialized role.

The e-linac (part of the ARIEL project) drew resources from about half of the organization-chart groups, and even more modest projects like GRIFFIN (a gamma-ray spectrometer) drew resources from one fifth of the groups. For other projects, a specific skill set is more important than a range of resources. For example, TRIUMF was able, with support from the University of Calgary, to build a cryostat for the ALPHA project at CERN because it had the required welding and cryogenic engineering expertise.

In addition to projects, TRIUMF staff is also responsible for the day-to-day operations of the laboratory. Just over 50% of the staff, primarily accelerator operators and administrative staff, has only operational duties while about 35% of the staff, mostly engineers and technicians, make significant contributions (more than 15% of their time) to both operational and project activities.

The TRIUMF technical and engineering staff have also contributed their unique skills and talents to international collaborations; for example, at CERN in Switzerland and J-PARC in Japan. These contributions from the TRIUMF are highly valued by the international community and facilitate the participation of Canadian scientists in international experiments.



TRIUMF'S DOUG BRYMAN SHARES PANOFSKY PRIZE

03 May 2011

Doug Bryman (UBC and TRIUMF), Laurie Littenberg (Brookhaven National Laboratory), and Stew Smith (Princeton University) have been awarded the 2011 American Physical Society's W.K.H. Panofsky Prize in Experimental Particle Physics, which recognizes outstanding achievements in experimental particle physics. The prestigious prize was awarded for the joint work on Experiment 787 at Brookhaven National Laboratory, a project analyzing billions of particle decays looking for an unusual decay pattern of a kaon particle involving two neutrinos.

The physicists were cited for discovering and measuring a very rare decay of a positively charged subatomic particle called a kaon, or K meson — a feat first reported in 1997 by a team of 50 collaborators from around the world after ten years of searching through the remains of the decays of 1.5 trillion particles.

Bryman's research has focused on flavor physics through the study of rare decays of muons, pions, and kaons. He has also been involved in detector instrumentation development for which he has received several patents. His current research involves measurements of rare pion decays, positron emission tomography, and cosmic ray muon geotomography.

AWARDS

The talent and dedication of TRIUMF's staff have been recognized with a number of awards over the previous five years (see Section 7.3 for more detailed accounting):

- Young Professionals Committee Award for Best Science, Society for Nuclear Medicine (U.S.)
- Tom Fairley Prize for Editorial Excellence, Editors' Association of Canada
- Fellow, American Physical Society (U.S.)
- Bunka Korosha Prize (Japan)
- Michael J. Welch Award of the Radiopharmaceutical Sciences Council (U.S.)
- W.K.H. Panofsky Prize in Experimental Particle Physics of U.S. American Physical Society
- U.S. DOE Early Career Research Award
- Yamazaki Award of the International MuSR Society (International)
- Special Fundamental Physics Prize of the Milner Foundation (shared) (International)
- Scientist of the Year, Radio Canada
- Business in Vancouver "Top 40 Under 40"
- CAP-TRIUMF Vogt Prize for Outstanding Contributions to Subatomic Physics (Canada)
- John Dawson Award for Excellence in Plasma Physics Research, American Physics Society (U.S.)

5.3 ARIEL

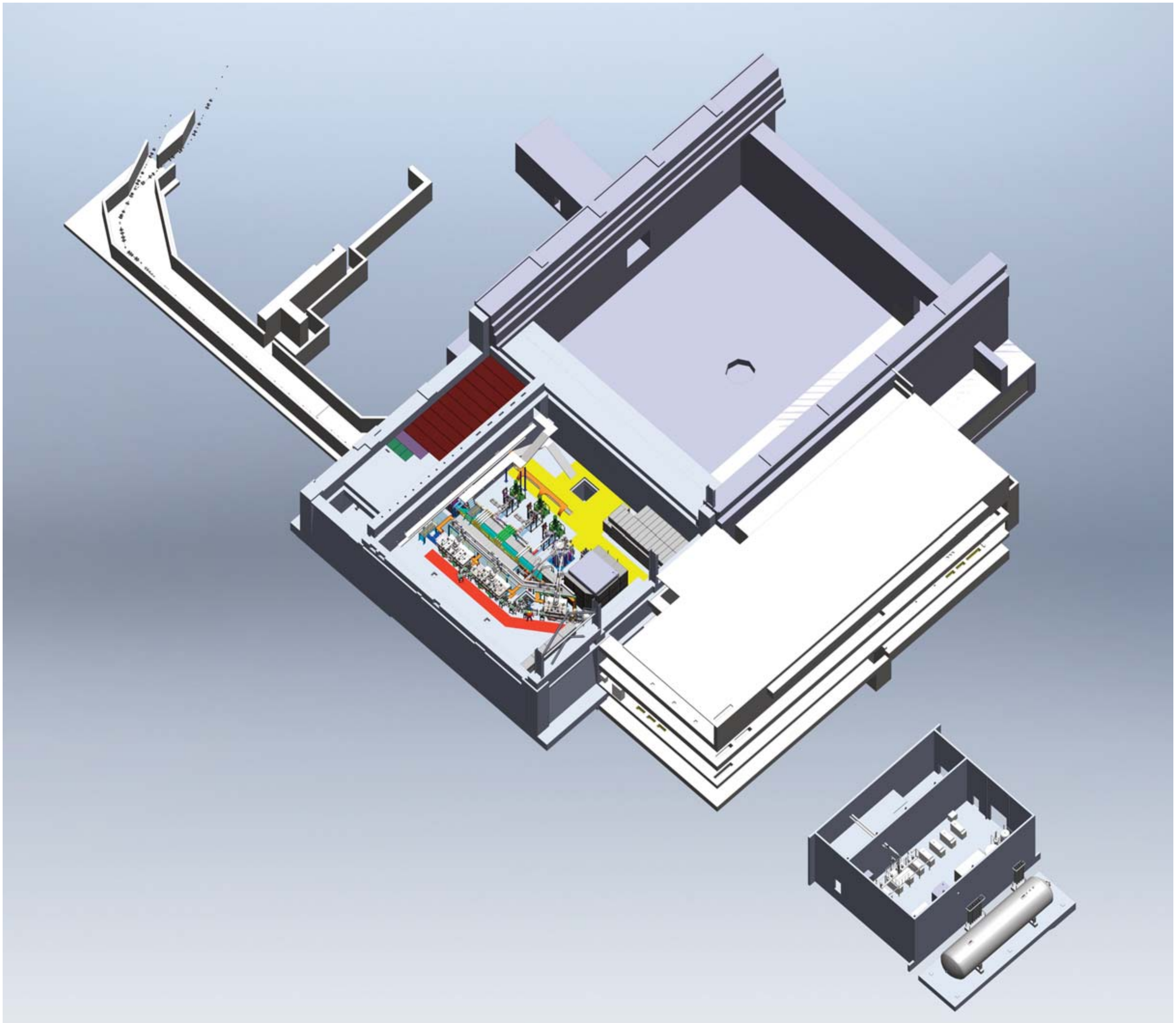
Construction of the Advanced Rare IsotopE Laboratory (ARIEL) at TRIUMF began in 2011 after funding for Phase I was secured in mid-2010. The flagship project is led by the University of Victoria in collaboration with the federal and provincial governments and multiple agencies. The project consists of a civil construction and conventional facilities element (i.e. the buildings and infrastructure) that will be completed in mid-2013; the electron linear accelerator will be subsequently installed and will begin commissioning in 2014.

The primary mission of ARIEL is to deliver unprecedented intensities of rare, short-lived exotic isotopes, in particular those with extreme neutron excess, to simultaneous and multiple experiments, at the existing and world-leading ISAC accelerator complex. A secondary mission of ARIEL is to anticipate future uses of e-linac technologies such as free electron lasers, and including commercial uses such as the production of medical isotopes by photo-fission.

When fully installed and commissioned, ARIEL will increase TRIUMF's annual scientific productivity by up to three times its current level: ARIEL will provide two additional beams of rare isotopes to augment the existing single beam line.

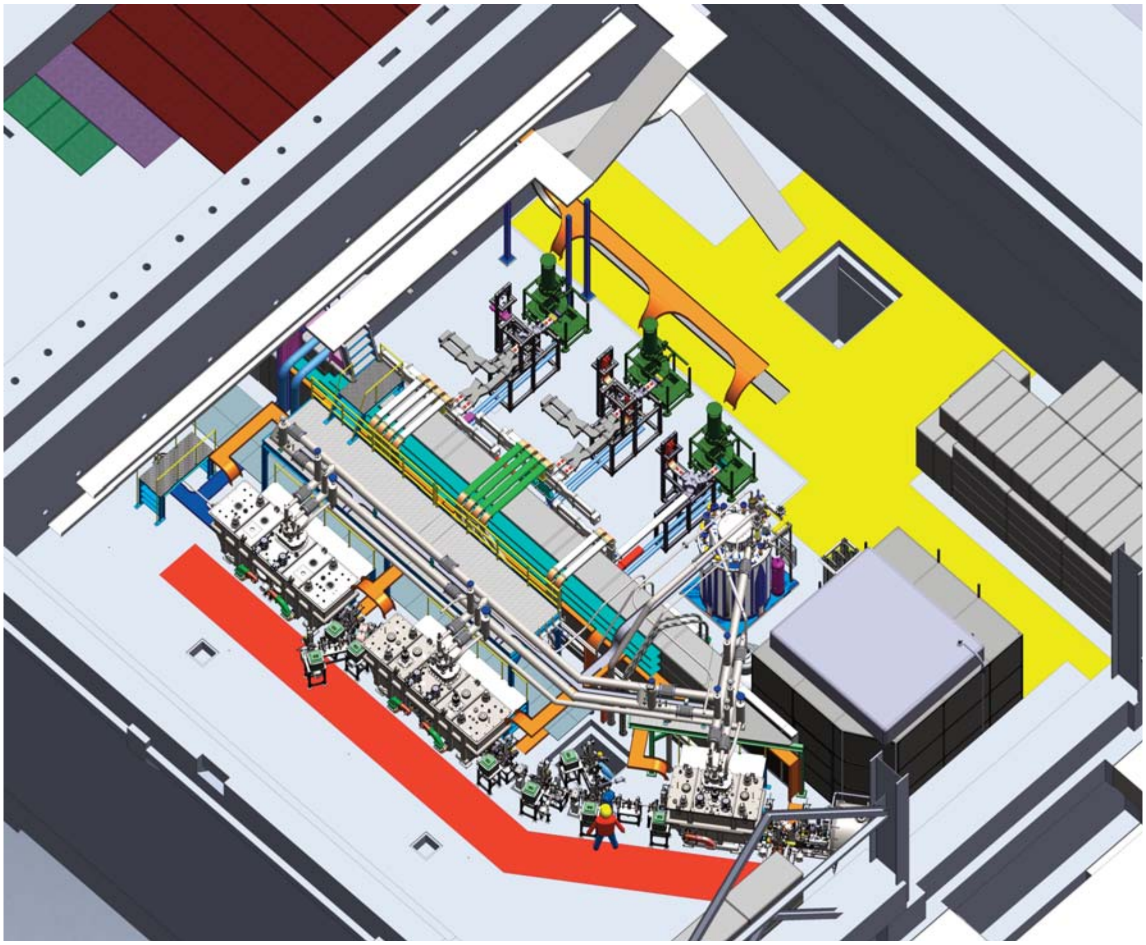
The project brings together accelerator technology expertise from British Columbia, as well as India, to develop an electron accelerator capable of using less electricity by roughly a factor of five, as compared to conventional technology. Once complete, the laboratory will have profound impacts on isotopes for science, isotopes for medicine, and next-generation accelerator technologies.

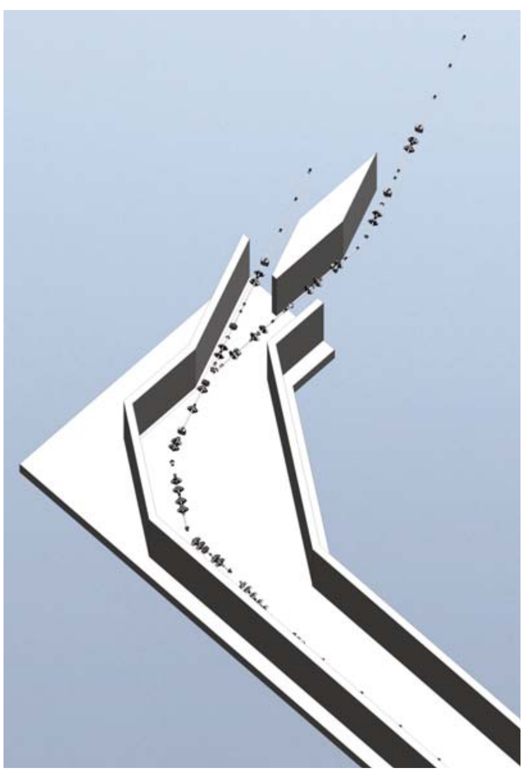
ARIEL construction is now effectively complete. Technical infrastructure is being installed in the Electron Hall, an existing vault adjacent to the main cyclotron repurposed to house the e-linac. The new ARIEL building, which houses the target hall, rooms for the beam delivery and remote handling infrastructure as well as laboratories for target preparation, has been completed and is connected to the Electron Hall via a new underground beam line tunnel. Support facilities including the cryogenic compressor building and a new building for the displaced stores facility have been completed as well.

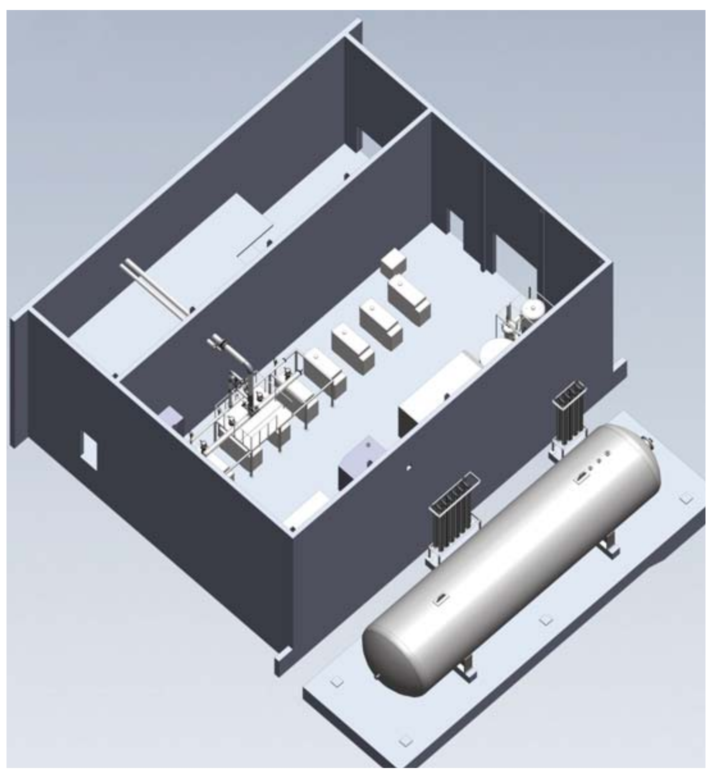


Shown here are the chief elements of the ARIEL facility that have been funded for completion by the end of 2014. The helium compressors and storage are located in detached building at the south end. The e-linac is shown in the Electron Hall and the underground tunnel connecting it to the isotope-production areas extends to the north.

Not shown is the ARIEL RIB building that will house the the targets, mass separator complex, and laser room.







In parallel to the construction of the physical buildings, much work has been done on the accelerator technology. The 4 K cryogenic plant is being assembled and tested, a 300 kW c.w. klystron and the first two 1.3 GHz niobium 9-cell cavities from PAVAC Industries, a local Canadian supplier, have arrived on site and are being prepared for installation. Procurements were received in mid-2013 for the klystron's 600 kW HV power supply and all quadrupole magnets for the electron beam. The 300 keV thermionic gun has been installed and is undergoing testing and the 10 MeV injector cryomodule is being assembled for first tests in fall 2013. The 25 MeV Accelerator Cryomodule will follow in 2014.

5.3.1 CIVIL CONSTRUCTION

In June 2010, the Province of British Columbia provided the University of Victoria with $30.7M through the British Columbia Knowledge Development Fund for design and construction of conventional infrastructure to house the Advanced Rare IsotopE Laboratory (ARIEL) at TRIUMF. The conventional infrastructure consisted of five facilities: Stores/Design Office Building, Badge Room, Compressor Building, Electron Hall, and the Main ARIEL Building.

Functional programming began immediately upon award of the funding, as did preparation of the Request for Proposal (RFP) for Architectural and Engineering Services for design and inspection of the facilities. The RFP was issued through BC Bid in late July 2010, and proposals were received a month later from five teams. Following analysis of the proposals and interviews of the proponents, the Selection Committee consisting of University of Victoria and TRIUMF representatives selected the design team lead by Chernoff Thompson Architects: Structural Engineer—Bush Bohlman and Partners; Mechanical Engineer—Stantec Engineering; Electrical Engineer—Applied Engineering Solutions/Lex Engineering; Building Code Consultant—LMDG; Landscape Architect—Durante Kreuk; Civil Engineer—HY Engineering; Envelope Consultant—Read Jones Christoffersen; Acoustics/Vibration—BKL; and Elevator Consultant—John W. Gunn Consultants.

Competitive selection processes were also held for supporting consultants and testing agencies including: Cost Estimating—Hanscomb Limited; Geotechnical—Thurber Engineering; Surveying—Murray Associates; Concrete Testing—Metro Testing and Exova; Commissioning Services—KD Engineering; and Steel erection Inspection—Elander Inspections.

Design work began in October 2010 with the issuance of construction documents for the Stores/Design Office Building in December 2010, the ARIEL Schematic Design Report in March 2011, the ARIEL Design Development Report in July 2011, construction documents for ARIEL Excavation in September

WORK BEGINS ON THE ARIEL RESEARCH TUNNEL

31 October 2011

Today, the first of 300 BC workers began building a tunnel and lab that will be used to demonstrate new ways to solve medical isotope shortages, keep BC and Canada leading in particle and nuclear physics, and create 160 permanent jobs.

The $62.9-million project is underway at TRIUMF with $30.7 million provided by the provincial government. By 2015, ARIEL is expected to demonstrate a new way to produce medical isotopes, which are used to diagnose and treat cancer, heart disease, Parkinson's and Alzheimer's.

ARIEL, which stands for Advanced Rare IsotopE Laboratory, features an underground beam tunnel surrounding a next-generation linear accelerator, or e-linac. The e-linac is being designed and built by a 13-university consortium led by the University of Victoria. The team is also collaborating with researchers in India, Germany, the U.S., and the U.K.

Figure 1: Newly constructed Compression Building.

Figure 2: A view towards the north of the completed Electron Hall interior.

Figure 3: The ARIEL building, as of July 2013; the south elevation (a) and the north elevation (b).

Figure 4: South elevation of ARIEL building, with the Badge Room (right corner).

2011, and construction documents for the Compressor Building, Electron Hall, and the Main ARIEL Building in December 2011.

The construction was implemented in four packages: (1) Stores/Design Office Building; (2) Badge Building; (3) Demolition of existing facilities and excavation for the Main ARIEL Building; and (4) Compressor Building, Electron Hall, and Main ARIEL Building (see Figures 5.3-1 through-4).

The first construction contract was awarded in February 2011 to Scott Construction Group for construction of the replacement Stores and Shipping/Receiving Building. Construction began after an official groundbreaking ceremony on March 28, 2011. This building was completed September 2011 for move-in, enabling demolition of the old stores building to make way for site construction for ARIEL.

A second construction contract was awarded to Scott Construction in July 2011 for construction of the replacement Badge Building. This building is the controlled access portal to the TRIUMF site, replacing the function demolished with the old Stores building. A temporary badge room was erected until construction of the new building was complete. The new building opened in December 2011. Final cost of the two construction contracts awarded to Scott Construction was $2,618,000.

A third construction contract was awarded to EllisDon in September 2011 for the demolition, excavation, and shoring of the site for the ARIEL building. An official groundbreaking ceremony was held on November 1, 2011. Excavation was completed at the end of March 2012. Final cost of this contract was $2,025,000.

The fourth and final construction contract was awarded in February 2012 to EllisDon. This contract included construction of the ARIEL Building, the Compressor Building and the Electron Hall. The Compressor Building and the Electron Hall were completed in early 2013 with the Main ARIEL Building being completed in the summer of 2013. Final cost of this contract was $21,244,000.

In conjunction with the construction work, significant scientific equipment, electrical services, and shielding concrete was removed from the Proton Hall in the Main Accelerator Building to allow conversion into the Electron Hall to house the electron linear accelerator (e-linac).

The design and construction of the ARIEL Project entailed: 44,000 architectural, engineering, and project Management person hours; 300,000 construction worker hours; over 1,000 tandem dump truck loads to remove the 14,500 cubic metres of excavation; and over 600 concrete trucks loads to deliver 6,100 cubic meters of concrete.

The photographs on page 210 and 211 document the major milestones of the construction.

5.3.2 E-LINAC AND BEAM LINE

TRIUMF's 2010–2015 Five-Year Plan outlined a strategy to at least double the rare-isotope beam (RIB) program, which targets nuclear structure, nuclear astrophysics, and fundamental symmetries studies; and quadruple the time available for β-NMR, which targets materials science. A centrepiece of the ARIEL project is an electron linear accelerator (e-linac) that will serve as a driver for production of RIBs via photo-fission of actinide targets and a parallel source of Li-8 produced by photo-reactions on Be-9. The e-linac ultimate 0.5 megawatt (MW) beam parameters (50 MeV, 10 mA) derive from the requirement of in-target fission rates up to 10^{14}/sec, and the production efficiency versus energy which falls steeply below 20 MeV and starts to saturate above 60 MeV; after that it is a better investment to increase the electron flux. Continuous wave (c.w.) operation increases integrated yield and avoids thermal cycling of the targets, which can be damaging. Due to funding limitations, the ARIEL project is phased: the e-linac first stage is limited to 30 MeV, and Beam Line 4 North (BL4N) proton beam line is delayed until after 2015.

E-Linac Baseline Design

Three goals shaped the design of the e-linac: (1) high average power c.w. operation; (2) the utilization of existing technology wherever possible; and (3) flexibility towards operation and reconfiguration. Superconducting radio-frequency (SRF) technology has been chosen for the e-linac because the dramatically reduced power consumption makes feasible c.w. operation. The selection of elliptical cavities has two collateral benefits: (1) it prepares Canada for SRF projects worldwide (such as the future Linear Collider); and (2) it qualifies a Canadian commercial partner (PAVAC) to build niobium (Nb) elliptical RF cavities operable at 1.3 GHz and 2 K.

Major components of the e-linac are a 300 keV 10 mA electron gun, a 1.3 GHz NC bunching cavity, a 10 MeV injector cryomodule (ICM), followed by a 10 to 50 MeV main linac composed of two 20 MeV accelerator cryomodule (ACM) sections. Due to heavy beam loading, five 9-cell cavities at 100kW/cavity are required to reach the 0.5 MW beam power. The ICM has one 9-cell cavity, and the two ACMs will each contain two 9-cell Nb elliptical cavities. Initially there will be only the ICM and one ACM.

Downstream of the linac are 75 MeV capable electron beam lines to the ARIEL target stations and a tuning dump in the in the Electron Hall (e-hall). Division of the linac into a low-energy injector and high-energy accelerator section allows the facility to be reconfigured for multi-pass operation by the installation of a return arc.

Project Timeline

In October 2008 the University of Victoria other collaborating university partners applied to the Canadian Foundation for Innovation (CFI), the federal agency for science infrastructure projects, to fund the e-linac project in the context of the Advanced Rare IsotopE Laboratory (ARIEL). In July 2009 the application was approved, contingent on matching funds for the civil construction from the British Columbia provincial government. In June 2010 the ARIEL became a funded project: the Government of British Columbia funded the construction of a new target building, connecting tunnel, and ancillary buildings were awarded, and the CFI funds were released for the construction of the electron linear accelerator and rehabilitation of an existing vault to house the machine.

In 2008, TRIUMF entered into a collaborative agreement with the Variable Energy Cyclotron Centre (VECC) in Kolkata, India, for development of a 10 MeV injector for e-linac leading to a systems integration test at ISAC-II. The collaborators completed the Injector Cryomodule detailed design and constructed a 100 keV electron source test stand and low-energy beam transport. Beam testing of diagnostic equipment prototypes was conducted at the ISAC/VECC test stand throughout 2012.

Subsequent to the full funding, in 2010 June, TRIUMF embarked on three parallel activities: (1) definition and construction of the ARIEL buildings; (2) specification, design, and procurement of the e-linac infrastructure (cryoplant, high-power RF sources, beam lines) starting with the long lead items; and (iii) development of the RF cavities and elaboration of the cryomodules designs leading toward construction of the first 20 MeV ACM in 2014. TRIUMF started construction of a 300 keV thermionic gun and 10 MeV injector cryomodule (ICM) in 2012, leading to completion in 2013 June and October, respectively.

TRIUMF has now signed contracts for most of the major equipment purchases: the 4 K cryogenic plant, 4 K liquid He distribution system, and four 2 K sub-atmospheric pumps, a 290 kW c.w. klystron and 600 kW high-voltage power supply, the entire facility quadrupole magnets, ICM tank and lid, and four 1.3 GHz niobium 9-cell cavities from PAVAC, a local Canadian supplier. All items, except the HV power supply and two SRF cavities, have been received. The He cryoplant and klystron RF system will be commissioned in 2013. The Electron Hall beam lines will be installed 2013 to spring 2014, and the ARIEL tunnel beam lines installed in 2014. A second klystron RF system will be procured in fiscal year 2013.

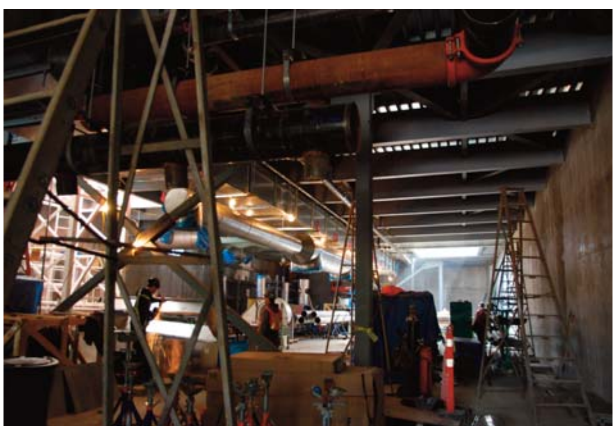
Conventional Infrastructure

The conventional infrastructure consists of four contracts: the main ARIEL construction, demolition and excavation, and replacement of the Stores and Badge Building, which is necessitated by site congestion. The new He Compressor Building forms part of the ARIEL package. In addition, major renovations have transformed the former Proton Hall to the Electron Hall (e-hall).

Chernoff-Thompson Architects led a successful bid for the overall architecture and engineering contract, awarded in October 2010. The Stores and Badge building construction was completed in September 2011 and occupancy was taken in December 2011.

The demolition and excavation work started October 2011, and completed April 2012. The ARIEL main construction package was awarded February 2012 and at time, there has been substantial completion of all the building components: the tunnel, actinide target preparation lab space, target hall and Rare Isotope Beams annexe; occupancy was allowed in August 2013. Occupancy of the compressor building was taken December 2012, and the He compressors were delivered to this space in February 2013.


VOLVO



AIR LIQUIDE BRINGS WORLD-CLASS TECHNOLOGY

22 December 2011

TRIUMF has just signed a major contract with Air Liquide Advanced Technologies (AL-AT) to provide major components of the cryogenic system for the new ARIEL laboratory. The deal will provide ARIEL with the world-class engineering and infrastructure for maintaining the ultra-cold temperatures required for the flagship e-linac accelerator. Air Liquide will have the opportunity to showcase its technology at a major scientific laboratory in North America.

The cryogenic technology from AL-AT is critical to the ARIEL facility and its associated electron accelerator (e-linac). The facility will feature a next-generation superconducting accelerator, which will require supercool temperatures - just two degrees above absolute zero - in order to operate at its peak performance. The equipment to be delivered by Air Liquide will be a major component of realizing the ultra-low temperatures required for operating the ARIEL e-linac. Air Liquide will design, manufacture and deliver custom cryogenic equipment, and provide its expertise for installation and inspection of the system.

The e-linac will be housed in the e-hall and linked to the ARIEL target halls by an 80 m beam line in a new tunnel. The hall is divided into three areas: (1) linac; (2) equipment (klystrons and 4 K coldbox); and, (3) BL4N p-beam line. Klystron HV and magnet DC power supplies, along with controls and beam diagnostic electronics racks, will be located above the linac on concrete roof beams at ground level. Installation of the racks is 30% complete at the date of this report. A 10-ton full-coverage crane at the underside of the roof beams will allow easy transport of cryomodules and other large equipment in an otherwise congested area.

The e-hall was emptied of legacy proton spectrometers in March 2012. The e-hall shielding, south wall upgrade and new north wall, which will protect the e-hall from the future BL4N proton beam, are complete. The 10-ton crane, NE egress stairway, new floor covering and lighting system are all installed. The concrete roof beams are sealed and are now the base for the rack farm and the 12.5 kV supply. Occupancy of the e-hall was taken November 2012. Communication between the Meson Hall space and the e-hall is via a 3×6 m^2 concrete shielded hatchway; the hatch blocks were completed 2013 February.

To accommodate the power requirements of ARIEL systems, a new 12.5 kV 5 MW switchgear is installed atop the e-hall roof beams. The gear will be close to the klystron power supplies and other local loads, including a 0.5 MW emergency power bus. Furthermore, the gear will feed north to the ARIEL building (2 MW) and south to the compressor building (1 MW) that houses the He compressors and sub-atmospheric pumps. The 12.5kV was connected to the TRIUMF grid and energized in December 2012. An uninterruptable power supply (UPS) system to support emergency operation of critical systems in the event of a power outage was installed in March 2012.

The e-linac power supplies, klystrons, and beam dumps present a significant heat load that must be removed, predominantly by cooling water. This task is accomplished by tying into the existing raw water cooling circuit via a 2 MW heat exchanger installed at the B3 service annex. The contract for this work was awarded in February 2013, and the tie-ins are complete. The next step is to bring this cooling water to manifolds in the e-hall.

Electron Gun

A thermionic gridded gun was chosen as the electron source based on low cost, simplicity, and ease of maintenance. Pre-bunching the beam at the gun obviates the need for a chopper and beam dump in the low-energy beam transport (ELBT). The beam is modulated by applying a radio frequency (RF) field between the cathode and the grid. To explore the operating parameters of such a source, construction of a gun test stand was begun in 2009.

A 100 keV DC gun was acquired from Jefferson Laboratory for the purpose of emittance characterization and the implementation of a 650-MHz modulation scheme similar to that developed for the FELIX accelerator. The gun was modified from diode to triode operation by the addition of a gridded cathode. To minimise RF reflection and to ensure stable operation, an RF network was designed to impedance match the 50 Ω transmission line to the cathode-grid structure. Modulation was successfully demonstrated in April 2011. The inferred conductance angle ±16° at 650 MHz and 16 pC per bunch meets the e-linac spec. The same source confirmed that the beam intensity can be varied from 99.9% down to 0.1% by applying a macro pulse structure with variable duty factor; the lowest value is essential for intercepting profile monitors.

In 2010, it was realized that the complicated SRF capture cavity scheme contemplated in the Conceptual Design Report (CDR) could be eliminated if the gun voltage was raised to 300 keV. At this energy, the longitudinal acceptance of the first cell of the 9-cell cavity becomes sufficient; moreover, some of the space-charge effect and phase-dependent RF focusing at entrance to the cavity are ameliorated. 300 keV enables efficient matching to a ß=v/c = 1 TESLA style cavity, but is not so demanding as to risk voltage breakdown and unreliable operation of the gun.

The main components of the 300 keV electron source are a gridded gun in a 2 bar (gauge) SF6 filled vessel, and in-air HV power supply. The pressurized SF6 insulating gas reduced the required length of the ceramic to stand off 300kV. The gun bias and heater power are applied through an isolation transformer. The gun ceramic, anode-tube internal steering coil, gun solenoid, isolation transformer, conditioning resistors and 350kV Glassman HV power supply have all been delivered.

The gun has two unique features. To minimize dark current, the design has an inverted electrode profile compared to the classical electron gun design. This reduces the surface area of the high-voltage electrode, reducing the likelihood of field emission. The second feature is the transmission of RF modulation via a dielectric (ceramic) waveguide and chokes through the SF6. The latter obviates the need for a HV platform inside the SF6 vessel to carry the RF transmitter, and results in a significantly smaller/simpler vessel. The modulation is applied to a CPI Y-845 gridded dispenser cathode via a stepped coaxial line impedance matching section from the RF-collecting choke. The ceramic waveguide was subject to bench testing on scale models and extensive simulation and optimization with HFSS. The ceramic was received from Kyocera 2012 September and subsequently installed at the 100 kV test stand where it operates with the expected performance.

The gun electrodes, the vessel internal corona domes and shroud, were subject to extensive 3D electrostatic modelling and optimization. The electrodes are fabricated and polished. Detailing of all HV cage and SF6 vessel components is complete. Fabrication of the gun HV cage, SF6 vessel, HV shroud and gun support struts are all near completion. Components assembly and integration will take place June 2013, and gun conditioning follows thereafter.

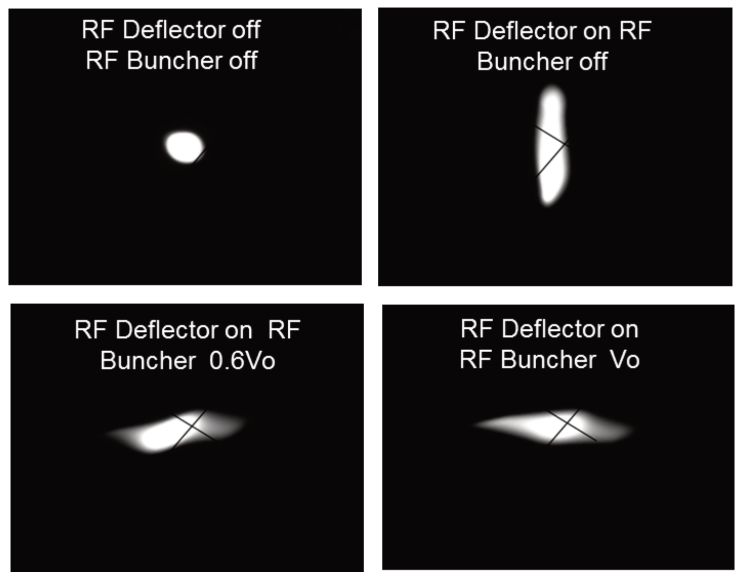
Injector Test Facility

The test facility at ISAC-II, under collaboration between TRIUMF and VECC of Kolkata, India, provides an ideal proving ground for e-linac design and operation strategies. It prototypes the injector from gun through ELBT and up to the exit of the cryomodule, with enhanced diagnostic capability for benchmarking the performance of the gun, various diagnostic devices and procedures, and demonstrating the sustained operation at the design parameters.

The extant part of the ELBT comprises the sequence: box DB1A after first solenoid; DB1B after buncher cavity, DB3 after third solenoid, all in the mainline; and MB0 dipole, RF deflector cavity, DB0 in the analyzer stub. Button BPMs are installed between the first and second solenoids. View screens VS1A, VS1B, VS3 are installed and tested at each of the diagnostic boxes. An Allison type emittance scanner, a wideband capacitive pickup (a.k.a non-intercepting monitor, NIM), and fast Faraday cup (FC) are moveable. A crane was installed for shielding block lifts and moves, and the complete downstream section comprising ICM and transport and beam dump is, at time of writing, in fabrication or being installed.

To date there have been three rounds of beam tests: phase (1) to ELBT:DB1B; (2) transport along the straight to ELBD:DB0; and (3) along the analyzing leg to ELBD:DB1.

The outcomes of the phase-one test were: (1) the solenoid and correctors successfully controlled beam trajectory and shape as designed; (2) the low-level control of the 1.3 GHz buncher cavity and phase lock to the 650 MHz gun grid were demonstrated; (3) the beam horizontal emittance was measured directly with the Allison scanner, and indirectly with scintillator screen and solenoid scan. Both methods confirmed the Gaussian distribution from the gun; and, (4) BPM, Faraday cups, slit scanner, chromox and YAG scintillator screens, capacitive pickup, photo-multiplier tube-based loss monitor, were tested, and areas for improvement identified. The time structure of the electron source was measured with the NIM. The measured bunch length of 200 ps agrees with beam dynamics simulations.



For the phase-two test, two solenoids and diagnostic boxes were added; and the Allison rig and FC reinstalled after DB3. This set-up enabled comprehensive beam-based characterization of 6-dimensional transport and phase space properties of the beam as functions of intensity. The analyzer magnet MB0 and RF deflecting cavity are now installed for measurement of longitudinal parameters.

The e-gun, buncher, and deflector LLRF have all been synchronized and their operation has been demonstrated with beam at the phase-three test. The 1.3 GHz deflecting cavity utilizes the TM110 mode to generate a time-dependent vertical kick to the beam. The bunch length can be measured with high resolution by noting the vertical spread of the deflected beam at a downstream screen. Figure 1 shows a series of screen images from ELBD:VS1 downstream of the deflector. In (a) the final solenoid focuses the beam on the screen; in (b) the deflector is turned on to disperse the beam vertically; in (c) and (d) the buncher is then turned on at $0.6V_0$ and V_0 to rotate the longitudinal phase space to create a time focus. In the screen image, the momentum dispersion from the magnet has transformed energy spread into horizontal width.

Beam Dynamics

The primary objective of e-linac is to deliver 50 MeV electrons to RIB and Li-8 production targets as efficiently as possible by a single-pass through linac and beam lines. Nevertheless, with recirculation arcs introduced between the exit and entrance, the linac could be reconfigured either: (1) as a recirculated linear accelerator (RLA) producing a 75 MeV beam for RIB production, or (2) an energy-recovery linac (ERL) for the production of photon beams. For example, configured as a 70 MeV ERL and coupled to a high-Q cavity Free Electron Laser (FEL), the e-linac could produce hundreds-watts-level infrared radiation in the range 2–200 μm.

This range of applications motivated a beam dynamics study with three objectives: (1) ensuring the baseline layout is compatible with a future recirculation ring configured either as RLA or ERL, (2) ensuring the cavity design is compatible with two-passes and impervious to beam break up (BBU) instability, and (3) ensuring the injector and accelerator are compatible with a high-brilliance beam (100 pC bunch charge) for FEL operation in addition to the low brightness beam (16 pC bunch charge) for the photo-fission RIB application. This study resulted in the current machine geometry and criterion for the cavity High Order Mode (HOM) spectrum. All studies completed, the primary focus returned to a detailed beam optical design of the e-linac and its beam lines for RIB production. Several detailed design notes were issued on the beam line optical and diagnostic elements, and form the basis for the engineering design. In addition, impedance and wakes of beam line in-vacuum elements, such as gate valves and bellows and diagnostic boxes, were evaluated for their contribution to emittance growth, and an impedance budget was established for the machine.

Beam Lines

Beam lines transport the electron beam between accelerator components and then on to the RIB targets. The e-gun and cryomodules are linked by short beam line sections. The electron low-energy beam transport (ELBT) operates at 300 keV and contains three solenoids in-line to the injector cryomodule, a variety of diagnostics, and a spectrometer stub (ELBD). The injector is followed by a 10 MeV merger section (EMBT) consisting of small angle dipole magnets and quadrupole optics. The merger presages the recirculation ring and is achromatic. The merger optics provides the opportunity for clipping momentum tails, emanating from the gun, and could be equipped with collimation jaws. Transport between the accelerator cryomodules is by quadrupoles, and the first such transport (EABT) at 30 MeV is equipped with a spectrometer stub (EABD).

At the 50 MeV exit of the second accelerator cryomodule, the Electron High-energy Beam Transport (EHBT) leads northward to the target stations 80 metres distant. This line begins with a matching section, a dogleg that bends in horizontal and vertical planes, and a quadrupole matching system to the following periodic lattice. The dogleg implements a change in beam line height between the linac vault and tunnel that accommodates the future necessity of running the electron beam below the 500 MeV proton beam line magnets. At the end of the tunnel, a vertical dogleg brings the e-beam into the plane of the targets. Thus far, the transport is achromatic. Finally, the line divides in two branches with bends and matching quadrupoles and a rastering system before each target. The EHBT is the “main line”, but there is a branch (EHDT) inside the linac vault leading to a 100 kW capable beam tuning dump. To date, a “requirements” document and a preliminary design note for the dump have been issued.

To summarize, the beam line sections are: ELBT, the 300 keV transport; EMBT 10 MeV transfer between ICM and first ACM, EABT 30 MeV transfer to future second ACM; EHAT 30–50 MeV transport downstream of the cryomodules to a switching magnet; EHDT leading to a 100 kW beam dump; and EHBT 25–75 MeV transport to the photo-fission targets. The EHBT, in the tunnel, consists mainly of a periodic section consisting of six 90^o FODO cells, each 4m in length. The EMBT contains a 36^o bend section, the EHDT, a 90° section formed of four bends, and the EHBT two doglegs and bend sections to the west and east targets. All insertions are achromatic.

Presently, the beam line is being designed in detail with all components (diagnostic, vacuum, magnets, etc.) integrated prior to issuing engineering drawings for support stands, flanges, beam tubes, and vacuum boxes, etc.

Quadrupoles

From the injector linac onward, the most convenient focusing device is the magnetic quadrupole; however, at the lowest envisioned beam energy of 5 MeV, the focal power required is rather small. This forces us to shortest possible quadrupoles, or else the fields are too low compared with expected remnant field of low-carbon steel. A theoretical study was made to derive the optimal pole shape for short quadrupoles whose lengths are comparable to, or smaller than, the aperture. Conventional 2D treatment and fabrication practice, assuming sufficiently large pole length, break down in such cases. A new 3D shape was derived analytically, and demonstrated yields with smaller aberrations. For short quads it is well approximated by a simple spherical pole, provided the sphere radius is 1.65 times the quadrupole aperture radius.

The beam lines in the e-hall adopt weak and medium quadrupoles, with integrated strengths up to 0.2 T and 0.7 T respectively. This is easily achieved with the short quadrupoles of aspect ratio 1 and cylindrical poles with spherical faces. The weak quads are also used for the periodic section in the tunnel. At the highest envisioned energy of 75 MeV, the shortest required focal length is 0.24 m in the EHBT dogleg sections. The required integrated gradient is 1.05 T; this will be achieved with a more conventional strong quadrupole design with rectangular cross-section poles and hyperbolic faces. The strong quads will be water-cooled, the weaker ones air-cooled, and the medium ones indirectly cooled. All have aperture diameters equal to 52.0 mm. In total, there are 89 quadrupoles; the contract for their manufacture was awarded to Buckley Systems Ltd., New Zealand, August 2012 with delivery March to June 2013.

Dipoles

The different beam lines contain a total of fifteen dipoles, which have been divided into four groups, depending on their required integrated field and field quality, for the purpose of design and procurement. Longitudinal space constraints in the beam line layout, particularly in “merger” and doglegs, lead the team to design the magnets as small as possible. Thus, many of these dipoles are short compared with their aperture leading to low strength because the field does not “plateau” inside the magnet. Proximity of other magnets implies the use of field clamps to contain the field fall-off. These features combine to make it essential that their modeling be done with a 3D finite element code such as OPERA. Moreover, one must ensure that the second order aberrations (sextapole) will cause negligible emittance growth (<0.01% per dipole). To study the non-linear optical properties of our models, we used the differential algebra and particle tracking code COSY INFINITY, with field maps imported from OPERA. Satisfactory pole, field clamp and yoke geometries were obtained and are being used as the basis for a series of tenders. The first dipole, the EMBT momentum analyzer, was received from Alpha Magnetic Inc. in January 2013 January, and the design of EMBT merger dipoles was conducted with the vendor in March 2013 and the contract for seven 34° bends for the EHBT was awarded that same month.

Vacuum

The electron beams are transported in vacuum. Vacuum also provides thermal isolation in the cryostats. ARIEL e-linac has 13 vacuum volumes with requirements ranging from 10^{-9} in the gun and ELBT, 10^{-8} in EMBT and EABT, to 10^{-7} in EHAT, EHDT and EHBT when the beam is present. The limits arising from residual gas (Rutherford) scattering and ion neutralization are an order of magnitude relaxed compared with these values. The beam pipes inside the cryomodules will naturally cryopump to 10^{-11}Torr, and the issue there is of cleanliness and particulates free. The cryomodule insulating and coupler vacuums are 10^{-6} Torr. The beam line volumes, from the e-gun to exit of the second cryomodule will be separated by RF-screened, all-metal electro-pneumatic gate valves. A large pumping capacity NEG pump will protect the cryomodules from volatile hydrocarbons in the manner of a “cold finger”. The remaining beam lines leading to the ARIEL target stations and 100kW beam tuning dump will be separated by all-metal electro-pneumatic valves. The vacuum volumes will be evacuated from atmospheric pressure to high vacuum level with turbo-molecular pumps, which are also used during the *in-situ* bake-out. After the bake-out is completed, the turbo-pumps are isolated via gate valves, and the pressure lowered further by ion pumps. The ion gauges are used only during the initial evacuation and bake-out. Once the ion pumps are turned on, the ion gauges are turned off, and the pressure is observed on the ion-pumps’ controllers.

The master e-linac vacuum system design note was released March 2013. This document constitutes the primary reference for vacuum components procurement and installation and is the basis for the EPICS-controlled vacuum system interlocks. As of 2013 March, 60% of all e-linac vacuum components were received from vendors and available for installation into the beam line. A clean area for assembling high vacuum components has been identified and will soon be modified for e-linac assembly needs.

Beam Diagnostics

Initial electron beam threading at e-linac and its beam lines will be with view screens, followed by orbit correction with 4-button type beam position monitors (BPMs), each measuring in two planes H and V. Beam stops will be used as temporary *termini* during this procedure.

Four complete view screen systems were built and installed at ISAC/VECC; the camera data acquisition and processing was built by the University of Victoria. Remaining parts for 16 view screen monitors at e-linac have been built and assembled. All button electrodes (224 in total) for the BPMs have been ordered from Kyocera. Sixty buttons were delivered, inspected, and verified to be within tolerance of 0.05 mm. The position sensitivity is 1.4dB/mm between opposite pick-ups. The signal power of -27dBm was measured at ISAC/VECC with the beam current of 10 mA (peak), and agrees well with the expected value of -30dBm.

The BPM electronics design is complete; a prototype unit has been successfully tested in the laboratory. This consists of a commercially available Bergoz analog front-end (AFE) customized for 650 MHz and a TRIUMF-developed intermediate frequency (IF) processing unit based on a 125 MHz 14-bit ADC and Spartan-6 FPGA. The output bandwidth is around 1 MHz. Most of the BPM electronics components have been procured. The University of Victoria has designed 75 MeV-capable, 100 W beam stops and a prototype is under fabrication. An off-the-shelf diagnostic box prototype was made and is being tested.

A Bergoz DC current transformer for absolute current measurement is housed in a magnetic and vibration shielded and temperature stabilized enclosure. Initial bench tests reveal a drift of ~ 40 uA over 48 hours; the cause is being investigated.

A fast wire scanner prototype, for the measurement of beam profiles at high beam power, has been assembled. Preliminary tests demonstrated that speeds of 0.5m/s are achievable. Further tests are required with a goal of 3 m/s. The vacuum test stand for this scanner has also been designed and is under construction. The prototype of a strip line BPM is being manufactured for testing at the VECC Test Facility in ISAC-II.

Cryomodules and Cavities

A cryomodule is essentially a vacuum-insulated cryostat that isolates the 2 K cavity volume from room temperature. The injector cryomodule contains a single 9-cell cavity and has been designed and constructed in collaboration with VECC. The accelerator cryomodules each house two 9-cell SRF cavities. Because of the c.w. requirement, the cryomodule design was driven by the large dynamic heat load on the input couplers and 9-cell niobium cavities; a situation very different from the 1% duty factor TESLA, ILC or XFEL where the static heat loads dominate; the 4 K thermal shield is not needed and the suspension heat load can be larger. At an early stage, the Cornell/CPI 50 kW couplers were adopted over the TESLA design. The cavity heat load was dealt with by adopting a 90 mm ID chimney for thermal transport across the L-He to the 2-phase pipe.

The cryomodule design utilizes a box vessel with a top-loading cold mass. The cold mass cavity string and 2-phase He pipe is supported from a strong back which, in turn, is held by 2-point and 3-point suspension rods from the lid. The tuner actuating motors are warm and also mounted on the lid. Adopting this configuration allows e-linac to benefit from the crane and clean room infrastructure at ISAC-II. In contrast to ISAC, the e-linac cryomodule must be made compatible with 2 K (rather than 4 K), elliptical cavities, high beam loading (10 mA average current), the fixed location of horizontally mounted input couplers, and separate beam line and isolation vacuums. The comparatively long suspension rods provide the interior headroom to install within each module a 4 K/2 K cryo-insert to produce 2 K liquid right where it is needed.

The cold mass is suspended from the lid with mounting posts, struts, and, a strong back, and is surrounded by a LN2-cooled copper box for thermal isolation. A 1 mm warm mu-metal shield is fastened to the inside of the vacuum vessel to exclude magnetic field from the SRF cavities. The cold mass consists of the cavity hermetic unit, a cold mu metal layer and the tuner. The hermetic unit includes the cavity(ies), power coupler, RF pick-up(s), the warm-cold transition) with HOM damping material and warm isolation valves. A carbon fibre-reinforced silicon carbide material, CESIC, was chosen for the damping material, with measured conductance at 1.3 GHz and 80 K of 2200 Si/m.

The cavity operates in the heavily beam loaded regime leading to comparatively low loaded Q, obviating the need for fast Piezo control. The very small number of cavities makes the linac vulnerable to ceasing of the tuner actuator. For these reasons, the tuner cold part is the Jefferson Lab–styled scissor type, which is and is followed by a long actuator and warm ISAC-II-style rotary servomotor mounted on the lid.

The 4 K/2 K cryoinsert was built and tested as a separate package. It includes a 4 K phase separator, 4 K/2 K heat exchanger, Joule-Thomson expansion valve, and a 4 K cool down valve plus siphon circuit for intercept cooling. The prototype heat exchanger is from DATE, France, with an estimated capacity of 2.5 gm/sec. A cold test of the cryoinsert was completed in November 2012 to verify performance. The tests included a LN2 thermal shock test, a static load test of the 4 K and 2 K volumes, a 2 K liquid production efficiency test for various heat loads, and a test of the thermal intercept siphon circuits. The measured static load of the 2 K and 4 K volumes were 1.6 and 0.4W respectively. The 2 K production efficiency is 66% at 0.6 gm/sec mass flow. This efficiency is expected to increase towards the design goal of 80% as the He mass flow increases to the design value. Further tests are planned for 2013.

The fabrication of the lid, tank, support posts, strong back, and cavity support for the injector cryomodule are all complete. Assembly of the LN2 (77K) thermal shield is also complete. The cryomodule tank has been assembled with outer (warm) layer of mu metal awaiting the top assembly.

SRF Cavities

The cavities support RF electrical fields that accelerate the electron beam. Our nine-cell 1.3 GHz elliptical cavity borrows the TESLA/ILC-type inner-cell geometry but uses modified end groups to accommodate the large power couplers and to mitigate HOMs. A multi-pass beam break up (BBU) criterion establishes an impedance limit of $R_d/Q*Q_L < 10^7$ Ohm; and Rd/Q*QL < 2×10^6 Ohm has been achieved. End group beam tubes with inner radius 48 mm and 39mm, respectively, are used for the power coupler and RF pick-up end. Consistent with the high beam load, the nominal cavity gradient E = 10 MV/m is modest – as can be achieved with buffered chemical each alone. Nevertheless, the Q_0 of 10^{10} to manage the c.w. heat load is challenging and will require cavity baking at 650 ^{o}C.

The first of four niobium cavities is presently being fabricated at PAVAC Industries, Inc. of Richmond, BC. A seven-cell cavity in copper was completed February 2012 to test all fabrication procedures and manufacturing jigs; lessons learned are now being applied to the Nb cavity production to improve quality assurance.

Processes have been developed at PAVAC that will expedite the fabrication of future cells and cavities in terms of reproducibility, true to shape and frequency. A main study was on forming. The original dies produced cells too short at the equator—causing material stress and some multipacting. PAVAC developed a forming tool with male die against a plastic that becomes almost fluid at high pressure and "hydroforms"—all cells formed since then are exceptionally reproducible. Next the fixturing during welding of half-cells became an issue. Our equator weld set-up initially was a butt weld of two identical half-cells. During forming and machining, and due to grain structure, the niobium (Nb) half-cells can go slightly out of a true circle. The question became how to hold them nicely true to a circle while not touching the newly etched weld zone. A self-fixturing solution is adopted: an interleaving feature is machined into the equator of unique male and female half-cells so they fit together and "self-fixture" during welding. Multiple Nb cells have been prepared in this way, and frequency is very repeatable. Success at the equator suggested that we prepare the iris in the same way to control the weld better and reduce centroid drift over multi-cell length. All cell parts are coming out very true and the self-fixturing is better suited for production.

TRIUMF has prepared significant equipment to develop and test the e-linac multi-cell cavities. These include a single cell 1.3GHz cryostat, a warm tuning station for plastic deformation of the nine-cell cavity for frequency tuning and field flattening, a high-pressure water rinse station for cavity cleaning, a BCP etching station, fixtures for chemical polishing, and a multi-cell cryostat for cavity cold testing prior to final assembly in the cryomodule.

Cryogenic Equipment

The cryogenic equipment is the infrastructure needed to provide a 2 K environment for the SRF activities. The system supplies three cryogens: (1) liquid helium at 4 K - in a closed liquefaction and refrigeration loop; (2) liquid He at 2 K - produced in the cryomodules and returned to the close loop; and (3) liquid nitrogen, LN2, at 77 K - delivered from an external supply and exhausted to the atmosphere. The 4 K He is produced by expansion of pressurized gaseous He delivered to the cold box at near room temperature. The 4 K LHe is distributed to individual cryomodules by vacuum–jacketed trunking. The 2 K He is produced by Joule-Thomson expansion into 30 millibars maintained by sub-atmospheric (SA) pumping. The LN2 is used to pre-cool the cold box and to cool the 77 K thermal shield and intercepts. The cold-box, with 1,000-litre liquid helium storage Dewar, are positioned in the immediate vicinity of the e-linac in order to minimize losses associated with LHe transfer. The warm part of the installation, including two Kaeser He compressors, OR/GMS, and sub-atmospheric helium pumps, will be located outside the e-hall in the separate compressor building. A warm gaseous He piping brings the pressurized gas from the compressor building to the e-hall. A cold gaseous sub-atmospheric trunk returns the He to the compressor building. A counter-flow heat exchanger between these flows restores the SA gas to ambient temperature. The main compressor may also send He to a storage tank. The He circuit design places a strong emphasis on monitoring and maintaining He purity that is free of oil, moisture, or other contaminants. A low power recovery compressor returns the He to second tank in the event of failures or power outages and may invoke a bypass for He scrubbing.

The e-linac cryogenic distribution is based on a parallel feed of atmospheric LHe from a main trunk to each cryomodule. The LHe is drawn from a main Dewar supplied from the 4 K cold box. A LHe reservoir in each cryomodule acts as a phase separator. Cold gas returns in parallel back to a common return trunk and is delivered back to the cold box where it represents a refrigerator load. Then, 2 K liquid is produced in each cryomodule (see 4 K/2 K cryoinset above) by passing the 4 K liquid through a heat exchanger in counter flow with the returning exhaust gas from the 2 K phase separator and expanding the gas to 31 mbar through a Joule-Thomson expansion valve. The header pipe above the cavity string acts as a 2 K phase separator. The cold helium gas passes through a 4 K/2 K heat exchanger, and then, after warming up to ambient temperature, reaches the warm sub-atmospheric pumping system. This fraction constitutes a liquefaction load to the He cryoplant. A siphon circuit from the 4 K reservoir is used to cool the 4 K intercepts, with vapour return back to the reservoir. Initial cooldown is done by delivering 4 K liquid from the 4 K phase separator to the bottom of the cold mass through a dedicated cool down valve.

Conceptual design of e-linac cryomodules and cryogenic system went through external reviews September 2010 and March 2011, respectively. Subsequently, the refrigerator-liquefier specification for helium supply to three cryomodules (ICM and two ACMs) was produced and tendered in June 2011. The contract for supplying He cryoplant consisting of HELIAL 2000 cold-box, main, and recovery compressors with oil removal and gas management systems (OR/GMS), and multi-component purity analyzer was awarded to Air Liquide Advanced Technologies (France). This is class 700 W cooling power at 4.6 K machine with maximum liquefaction rate of 288 l/h. The final design was approved June 2012. The Kaeser compressors were received January 2013; and the OR/GMS and cold box were delivered March 2013. The contract for helium gas storage tank was awarded May 2012 and delivery taken January 2013. The refurbished He Dewar and auxillaries was received December 2013. The 4 K LHe distribution was awarded November 2012, and delivery is anticipated for the first quarter of 2014.

The sub-atmospheric units will pump continuously on He gas to maintain a suction pressure within 24–28 mbar measured at the pumps inlet. The exhausting clean He gas is sent to a helium compressor at 1.05–1.1 Bara. A modular design is adopted with 4 units for ICM and first ACM having a combined throughput totalling 5.6 gm/sec, and 6 units totalling 9.3 gm/sec after the addition of the second ACM. The contract for supply of four sub-atmospheric helium pumps, type DS3010-B, was awarded to Busch Vacuum Technics Inc. in August 2012; and delivery was taken in March 2013.

At the time of writing, efforts are concentrated on preparedness for the 4 K cryoplant acceptance tests in the summer of 2013. Further developments are related to the forward GHe lines, sub-atmospheric The He return lines, and LN2 distribution from an existing storage tank exterior to the south face of the Cyclotron Building.

Radio-Frequency (RF) Equipment

The injector cryomodule (ICM) contains one cavity and the two accelerator cryomodules (ACM) will each contain two superconducting radio frequency (SRF) cavities. Each cavity is equipped with two 50 kW c.w. input couplers for a nominal minimum power of 100 kW per cavity. The couplers are manufactured by CPI following the design adopted for the Cornell ERL injector prototype. The cryomodules will be installed in stages. In the first stage, to be completed in 2014, the ICM and the first ACM will be installed and each will be powered by a high-power c.w. klystron. For the ICM, the klystron is run at half power, while for the ACM, the full power is divided between the two cavities. Six input couplers for three cavities have been procured. At a later stage, a second ACM will be added and will take over one of the klystrons; at that time a 150 kW-level RF source will be developed for the injector. The e-linac radio frequency systems procurement will be a challenge because there are few high-power c.w. sources available at 1.3 GHz, and few vendors. Indeed, one of the established vendors ceased production of scientific klystrons shortly after the project was funded.

Buncher Cavity and Amplifier

The buncher is installed between the electron gun and injector cryomdule and acts to match the longitudinal emittance of the beam to the acceptance of the 9-cell cavity. The buncher is a 1.3 GHz normal conducting cavity of the Daresbury-EMMA design, and has been procured from Niowave Inc., USA. The measured Q and shunt resistance are 20,000 and 3.3 Mohm respectively. With these parameters, a gap voltage of 30 kV and beam current of 10 mA exists, while the maximum generator power is 290 W. A solid-state amplifier, model BLA500CW operating in class AB and providing 400W has been procured from Bruker BioSpin, France. The buncher is installed at ISAC/VECC and operates routinely.

Inductive Output Tube and HVPS

As part of the collaboration agreement with VECC, an injector cryomodule will be tested in 2013, with beam at peak power up to 25 kW and duty factor of 1% at the ISAC/VECC test stand. A 30 kW-rated inductive output tube (IOT) has been selected as the RF power source for that test. The IOT is also the RF source for the coupler conditioning facility (see below). An IOT with solenoid and trolley was purchased from CPI, USA, in 2010. A HV power supply and drive amplifier from Bruker BioSpin, France, was purchased on behalf of VECC and is on long-term loan to TRIUMF. The IOT system is installed and was tested in 2011 to the maximum-rated output power of 30 kW on a water-cooled load, and is now run routinely for the coupler conditioning stand.

High Power c.w. Klystron and HVPS

The continuous-wave (c.w.) klystron is specified with a saturated power of 290 kW and usable linear range (incremental gain of 0.5 dB/dB) up to 270 kW, which leaves plenty of margin for transmission loss to the 200 kW nominally rated EACA. After a tender process, coordinated as a joint venture with Helmholtz Zentrum Berlin (HZB), orders were placed with CPI, USA: one for TRIUMF and 3 units for HZB. The klystron is a factory-tuned multi-cavity, high-efficiency, high-gain, broadband, water-cooled tube. The final design was completed in August 2012 and factory tested to 300 kW output power in February 2013. TRIUMF took delivery in March 2013.

The contract for the klystron high-voltage power supply, rated at 65 kV 8.65 A, plus focus, filament, vacuum ion pump power supplies, and trunk RF distribution system, including all control, interlocks, protection and integration of the klystron was awarded to Thomson Broadcast in June 2012. The power supply is based on a voltage controlled power module type *PM-14-10-VR-1* derived from the modulator PSM12-2400 for DESY. The factory acceptance test is scheduled 2013 May, and delivery to TRIUMF in 2013 July. The 300 kW c.w. circulator and loads are subcontracted to AFT Microwave. Waveguide layout of the high-power RF system has been completed and support structures for the waveguides are being designed.

RF Conditioning of Power Couplers

An important step before mounting the power couplers into the accelerating cavities is their conditioning with RF power to process the surfaces and eliminate multipacting. The couplers have been tested under conditions differing from those under which they will be operated. Tests are performed at room temperature with compressed air cooling for inner conductors and watercooling for flanges at the waveguide to coax transitions, whereas operation will be with the cold RF window at 77 K on a LN2 intercept. Very roughly, 5 kW operation at 300 K translates to 50 kW capability at 77 K.

After baking, the couplers were subjected to various regimes of pulsed and c.w. RF power conditioning for prolonged durations. RF Power from the IOT was applied either in travelling wave or in standing wave mode. In the latter, a waveguide short circuit terminates the couplers leading to voltage levels double that in traveling wave mode for the same RF power. In the standing wave mode, the couplers were conditioned at 10 kW peak power at 1% duty cycle (in January 2013) Prolonged pulse conditioning was very effective in cleaning the couplers. CW conditioning was done in traveling wave mode: 5 kW was reached and held, with good vacuum, for several hours.

Control System

The control system provides control and monitoring of most or all subsystems. Those subsystems include cryogenics and cold distribution, ARIEL building nuclear ventilation, cooling water, beam line vacuum, beam line optics and diagnostics, RF systems, e-gun, oxygen depletion monitoring, and machine protect systems. All controls will employ the EPICS software toolkit that is used to produce controls for the ISAC-I and ISAC-II projects. Except for the machine protect subsystem, all controls will use technologies previously employed in ISAC. The control system will use strategies and standards developed with the experience gained in the ISAC project, and will use in-house productivity and quality control tools and methods. Adherence to ISAC standards is intended to result in consistent end-user interfaces as well as minimizing maintenance efforts by control system personnel and minimizing equipment costs for spare components.

Roughly speaking, controls for each subsystem will be based upon one or more predominant technologies. The cryogenics subsystem will employ a PLC for control of cold distribution elements and a network interface to the turnkey cryogenics plant. RF systems will use a different programmable logic controllers (PLC) network interface for control of RF power supplies, as well as the LLRF interface developed in-house for ISAC. Beam line controls will use PLCs, CANbus and VME-based technologies for vacuum, optics, and diagnostics respectively. Nuclear ventilation and oxygen depletion monitoring will be done using PLC systems, replicating as much as possible of prior ISAC designs. Beam loss monitoring for the machine protect system is in development, but will use a VME module designed and produced at Thomas Jefferson Laboratory. Cooling water controls will be integrated with beam line vacuum and cold distribution control PLCs.

Some control system components have been or will be developed as part of the VECC project, and will be migrated to the e-linac. These include controls for the e-gun, including SF6 gas control, RF controls, and optics controls. Also developed and test in VECC will be controls for the cryogenics sub atmospheric pumping system and beam line optics, diagnostics and vacuum. The beam line vacuum control system incorporates a new portable roughing system that introduces new requirements for control system flexibility. Gathering of information for procurement, assignment of work, and detailed design are underway for all controls subsystems.

Radiation Safety System

The personnel radiation safety system for ARIEL/e-linac will consist of two sub-systems: (1) the Access Control System, which will keep people away from prompt radiation hazards inside shielding during facility operation; and (2) the Radiation Monitoring System, which will directly measure prompt radiation levels outside shielding and terminate facility operation should unacceptable levels occur. Functional requirements documentation for both sub-systems have been written, reviewed, and approved. Detailed design for both sub-systems is progressing well. Operational beam inhibit devices, which will define e-linac as being "off" or "on," have been identified and interface specifications communicated to device owners. A first version of Access Control System PLC logic is being tested on a simulator system. Radiation Monitoring System gamma and neutron detectors have been selected based on measurement requirements. The data acquisition components for this system are being developed and will be used for radiation monitoring of VECC/ICM in the ISAC vault before being moved to ARIEL/e-linac.

The ARIEL e-linac project has witnessed outstanding progress across all areas. The building's construction will be complete in June 2013. Beam lines, cryogenic, and high-power RF equipment design and procurements are on schedule. Two key facility milestones are anticipated: the ICM beam test in May 2013 and the ACM initial beam test in October 2014.

5.3.3. ISOTOPE PRODUCTION RESEARCH AND DEVELOPMENT

ARIEL will use proton-induced spallation and electron-driven photo-fission of ISOL (isotope separation on-line) targets for the production of short-lived rare isotopes that are delivered to experiments at the existing ISAC facility. ARIEL will support delivery of three simultaneous rare-isotope beams (RIBs), up to two accelerated, new beam species, and increased beam development capabilities. To do so, the ARIEL complex will include, in addition to the electron accelerator and beam line, a new proton beam line from the 500 MeV cyclotron to the targets; two new high power target stations; mass separators, and ion transport to the ISAC-I and ISAC-II accelerator complexes. Conceptual design work on these elements has proceeded as Phase 1 of the ARIEL project moves toward reality.

Beams of rare isotopes are challenging to produce, especially the short-lived ones, which do not occur naturally. They have to be produced artificially in the laboratory. The ISOL method can be described as a process in which the isotope of interest is fabricated artificially by bombarding the nuclei in the target material nucleus with fast projectiles. In a thick target, the reaction products are stopped in the bulk of the material. The target container is attached directly or indirectly to an ion source, allowing the reaction products to be quickly ionized and accelerated to form an ion beam that can be mass analyzed and delivered to experiments. The requirements for producing high intensity RIBs are: (1) a high-energy driver with sufficient intensity; (2) a target material inserted into an oven made of refractory material, connected to an ion source; (3) an ion source at high voltage to produce an ion beam; and, (4) a high-resolution mass separator.

In ISAC, the target stations are located in a sealed building called the Target Hall, which is serviced by a specialized remote-controlled crane. The Target Hall facility includes a hot cell for active materials handling, conditioning station for testing of targets off-line, mechanical service systems for activated target cooling water and active gas from the target vacuum system, a nuclear ventilation and exhaust filtration system, a decay storage vault for spent target materials, and storage space for shielding and equipment modules. The target area is sufficiently shielded so that the building is accessible during operation at the maximum proton beam current.

Beam line elements near the target are installed inside a large T-shaped vacuum chamber surrounded by close-packed iron shield. This general design eliminates the air activation problem associated with high-current target areas by removing all the air from the surrounding area. The design breaks naturally into modules; an entrance module containing the primary beam diagnostics, an entrance collimator and a pump port; a beam dump module containing a water-cooled copper beam dump; a target module containing the target/ion source, extraction electrodes and first guiding component and heavy ion diagnostics; and two exit modules containing the optics.

The ARIEL project will use some of the technologies developed and exercised over the past 14 years at ISAC, but by and large it will be based on an improved, second-generation target station design for high power RIB production, which incorporates the ISAC experience and lessons learned. To guide the detailed design of the ARIEL target station, we evaluated the existing ISAC technologies and practices using a method called Design Failure Mode and Effect Analysis (DFMEA), used primarily in product development and manufacturing. The findings from this analysis, both positive and negative, were incorporated in the design concept of the ARIEL target stations and target module.

As with ISAC, the ARIEL target stations are located in a sealed building serviced by an overhead crane. The target maintenance facility includes a hot-cell for target diagnostics and storage preparation, decontamination facilities, and a radioactive storage vault. And, as in ISAC, the ARIEL target stations will be surrounded by steel and concrete blocks.

In a departure from the ISAC paradigm, the two ARIEL target stations are designed with completely independent services (e.g., cooling water, vacuum system, electrical, and nuclear ventilation), and adequate shielding such that personnel access to one target station will be permitted while the other is producing and delivering beam. In addition, the target stations will employ new vacuum joint technology and will be equipped with remote connection and disconnection of services for rapid target exchange (2-3 days).

Figure 5 shows a 3D view of the next generation of target station proposed for the ARIEL project. The new target station concept consists of a target module, heavy ion beam line, pre-separator and beam dump. In ARIEL, the heavy ion optics modules will be replaced by beam pipe sections with a vertical pumping duct, surrounded by shielding blocks composed of steel and concrete. As in ISAC, the pumping duct may serve to insert diagnostics at the beam level, specifically Faraday cup, slit, and beam profiler. The rationale is to keep the turbo pumps and sensitive equipment as far as possible from the high-prompt-radiation field. The beam dump and the entrance module might also be replaced by a stand-alone diagnostics box, and beam dump with a water-cooled copper plug, respectively. Again, the rationale is that these devices never had to be replaced since ISAC went into operation 14 years ago. These decisions simplify the vacuum envelope of the target station compared to ISAC. It also reduces the cost of the target station since 4 module steel plugs with intricate service chase penetrations are replaced by less expensive, simpler, solid shielding.

The ARIEL target hall will house two ISOL target stations, east and west, actinide and conventional laboratories, target assembly laboratories, and a dedicated hot-cell facility for target diagnosis. The two target stations will be compatible with actinide target operation and up to 500 kW electron beam and up to 50 kW proton beam power. The west ARIEL target station will be initially operated with electrons. Once the new proton beam line becomes operational, it will receive proton beam only, and electrons will be confined to the east target station, where RIB delivery to users will take place simultaneously with development activities, primarily of the photo-converter. During the operation of both targets with electrons, the sharing of the beam current on the targets will be flexible, to maximize both the user and the development programs.

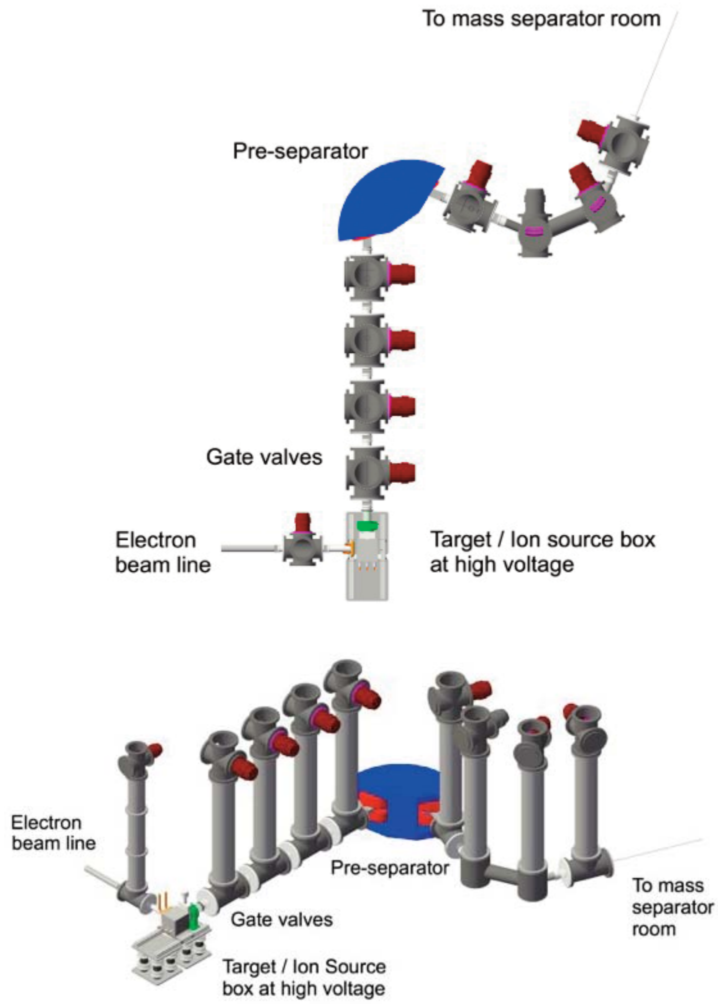


Figure 5: 3D view of the next generation of target stations proposed for ARIEL.

During Phase 1 of the ARIEL Project, the e-linac will deliver a 100 kW, 25 MeV electron beam on target. The electron beam will impinge onto a converter made of water-cooled Ta discs; an Al disc placed after the converter will stop the remaining electrons before they reach the target. Since most of the services required to operate actinide targets will not be present in the first phase we envision using a non-actinide target to carry out the ARIEL target and front-end commissioning. It is advantageous to consider the production of Li-8 using Be-9 target via the $^{9}Be(\gamma,p)^{8}Li$ reaction. There are multiple advantages to using Li-8 on a ^{9}BeO target, including:

The level of radiation is not extremely high and the Li-8 has a very short half-life of 840 ms. The longest half-life nuclei produced is Be-7 with half-life of 53 days. With Li-8, we can start the experimental program while we are preparing for operation with an actinide target. This will allow a complete commissioning of the whole system from target station to the experimental facility.

The Li-8 beam is used by the β-NMR material science community. The Li-8 beam is polarized using | a collinear optical pumping system in which the polarized light from a laser beam is directed along the heavy ion beam axis. This method is well established at ISAC. The first step is to neutralize the Li-8 ion beam by passing it through a Na vapour cell. The neutral atoms then drift nearly 2 m in the optical pumping region in presence of a small longitudinal magnetic holding field of 1 mT. Then the beam goes through a He cell where a large fraction of the now polarized Li-8 is ionized and then sent to the β-NMR or β-NQR station.

Results from FLUKA simulations show that the in-target production of Li-8 is as much as 10^9 particles/s during Phase 1.

Looking beyond this five-year plan, the e-linac energy may ultimately be upgraded to 50 MeV and the power to 500 kW. At these power levels, the simple water-cooled Ta discs approach will no longer work. Due to the large power density, it may be preferable to use a liquid metal converter, such as Hg or Pb because of their high Z. Lead is preferable to mercury because of health concerns, active waste disposal, environmental issues, and chemical compatibility with the system. Furthermore, mercury produces more long-lived isotopes by (γ,n) reactions than lead does. Simulation shows that 375 kW is deposited into the converter and 75 kW in the target itself. This is 7 times larger than the power we can handle in one single target. To handle the power deposition in the UCx material, we may use a composite target technique, involving coated graphite foils. We may also divide the target into assemblies of the smaller targets or investigate alternative coolants.

Partners

In Canada: University of Victoria, University of British Columbia, Simon Fraser University, University of Alberta, Carleton University, l'Université de Montréal, University of Toronto, University of Guelph, University of Saskatchewan and Canadian Light Source, McMaster University, University of Regina, Saint Mary's University, Laval University, PAVAC Industries Inc.
International Partners: France (1), India (1).

TRIUMF's Role

The design and construction of ARIEL e-linac is led by TRIUMF under the guidance of Principle Investigator Dean Karlen (University of Victoria). TRIUMF's contribution includes workforce for general management, technical design and development, procurement and fabrication, assembly, installation and commissioning. Materials and equipment are contributed by the CFI grant.
The TRIUMF labour contribution to e-linac falls under the contribution agreement with the NRC.

5.4 ACCELERATOR AND BEAM LINE INFRASTRUCTURE

At the heart of TRIUMF is the 520 MeV cyclotron. It supplies a proton beam to ISAC to produce the rare isotopes that are then accelerated and delivered to the experimental area. This is not as easy as it sounds. The production target must handle high heat and radiation load. The desired isotope must then be extracted from the production target, separated from other unwanted isotopes and delivered to the experiment either accelerator or unaccelerated. The main cyclotron also supplies protons to the meson hall for muon and pion production.

Also included in this section is a discussion of the helium recycling. To reach temperatures required for most superconductors it is necessary to use liquid helium. Recently there has been a shortage of liquid helium and the price, when it is available, is prohibitively large. It thus becomes imperative to recycle the helium used in the meson hall. The plans for this are also given in this section.

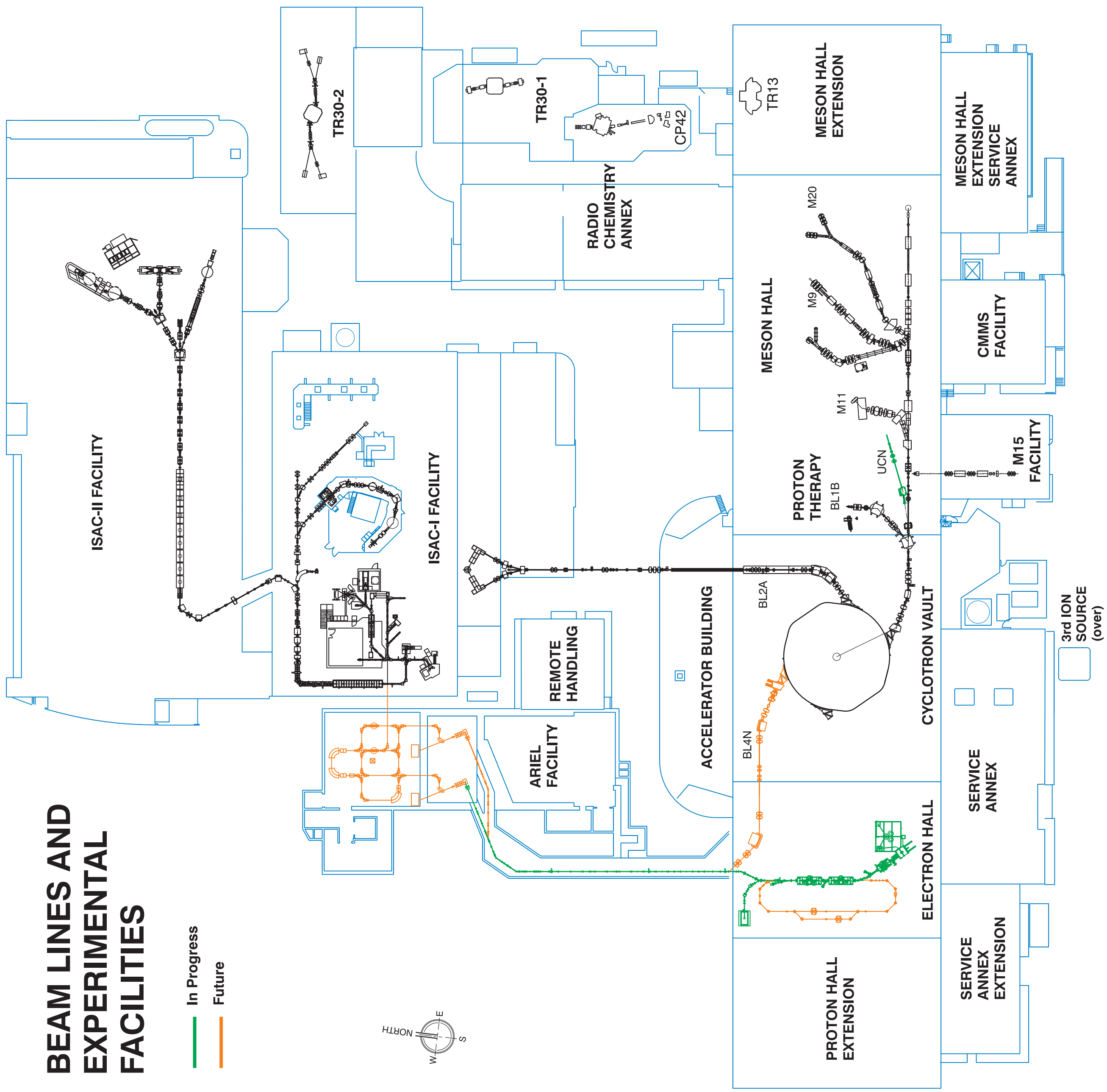


Figure 1: Main beam lines of the cyclotron.

5.4.1 MAIN CYCLOTRON AND PRIMARY BEAM LINES

At the heart of TRIUMF is the 520 MeV cyclotron that produces the primary proton beams and supports many of the laboratory's programs, including: ISAC, the Centre for Molecular and Materials Science programs in μSR and β–NMR, and the Proton Treatment Facility. The operation of the main cyclotron has enabled TRIUMF to acquire the expertise to operate the three cyclotrons for MDS Nordion and the TR-13 cyclotron used to produce medical isotopes and assist companies to exploit commercial opportunities for the sale of cyclotron and other accelerator technologies.

The 520 MeV Cyclotron

TRIUMF produces negatively charged hydrogen ions (H^-: 1 proton, 2 electrons) from an ion source. The ions are transported through an evacuated electrostatic beam line containing elements to focus and steer the beam over its 46 m to the cyclotron. The 520 MeV (million electron volts), variable energy cyclotron accelerates these ions with a high frequency alternating electric field and uses a massive six-sector magnet to confine the beam in an outward spiral trajectory. Inserting a very thin graphite extraction foil strips the electrons from the H^- ion while allowing the proton to pass through. The proton, because it is a positively charged particle, is deflected in the outward direction due to the magnetic field and is directed to a proton beam line (see Figure 1). The accelerating process takes approximately 0.3 ms before the proton achieves three-quarters the speed of light.

The cyclotron is capable of delivering four independently controllable proton beams at energies from 70 to 520 MeV with a total current of up to 300 μA. This flexibility is made possible by the use of negative hydrogen ions, which have a binding energy of only 0.75 eV, and so can be extracted in a simple and highly efficient way by stripping them to protons in thin pyrolytic graphite foils. The fragility of H^- ions, however, means that they can also be readily disrupted in strong electromagnetic fields or by collisions with gas molecules. Their use therefore incurs design penalties: to limit the beam power loss by electromagnetic stripping to 7% by 500 MeV, the magnetic field strength must not exceed 0.58 T; to limit that by collisions to 3%, the vacuum must be better than 10^{-7} Torr. The former requirement implies much larger orbits than in a proton accelerator, perhaps by a factor of 3. Thus the TRIUMF cyclotron has the dubious distinction of having the largest diameter of any yet built: for the magnet poles, 17.2 m; for the yoke, 21.5 m. As the electromagnetic stripping is only significant above 450 MeV, it is possible to run higher currents for the same absolute loss by extracting the beam at energies below 500 MeV.

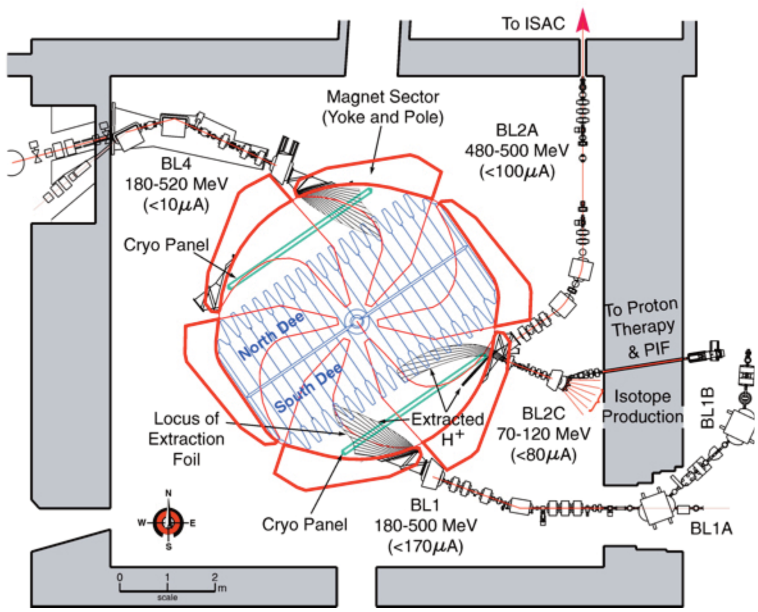


Figure 1: 500 MeV cyclotron and four primary proton beam lines: BL1, BL2A, BL2C, and BL4

The success of TRIUMF's programs depends on the ability to deliver protons from the cyclotron reliably. Typically the beam is delivered for about 5,000 hours per year with one major (three month) and one minor (one or two week) maintenance periods. The cyclotron beam properties and capabilities have improved over the years as a result of systems upgrades. The fundamental infrastructure providing the magnetic and electrical fields and the RF resonators, as well as the vacuum vessel, remain sound and will serve TRIUMF for many more years. In order to maintain and improve the accelerator facilities, TRIUMF has an ongoing refurbishment program that replaces old and obsolete equipment. This strategy has allowed TRIUMF to maintain the availability of the extracted beam steady at more than 90% (see Figure 2, 3 and 4). Replacement of the trim and harmonic coil power supplies was completed during shutdown 2012. Also, after 36 years of continuous service, the original vertical section of the injection line was decommissioned and replaced with a new one in April 2011.

Cyclotron Systems

The 4000-tonne magnet is composed of six separate sectors, radial near the centre, but increasingly spiralled at large radii to provide sufficient vertical focusing. The space between them is left free of iron to maximize the magnetic flutter. The magnet is excited by a pair of circular coils 19 m in diameter, each consisting of 15 vertical sheets of aluminium (45.7 cm x 2.5 cm) with internal water cooling channels, and weighing 77 t. The power supply provides 18,400 A at 75 V with stability 10^{-6}. The vacuum chamber is roughly circular (maximum diameter 17.9 m) and 46 cm in height, the lid being sealed by a pair of

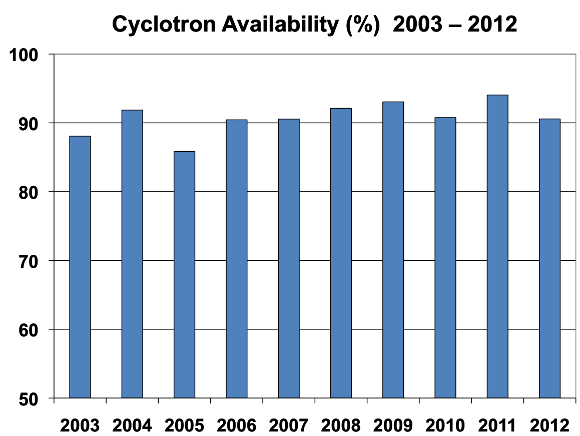


Figure 2: Cyclotron uptime as a percentage of scheduled operational hours per year.

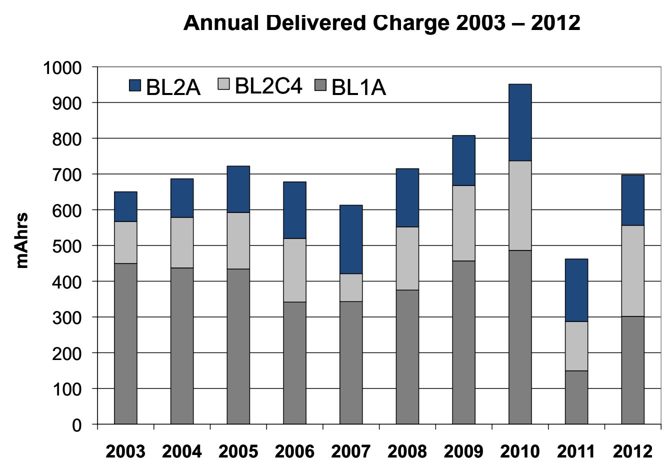


Figure 3: Total delivered charge per year from the main cyclotron over the past decade.

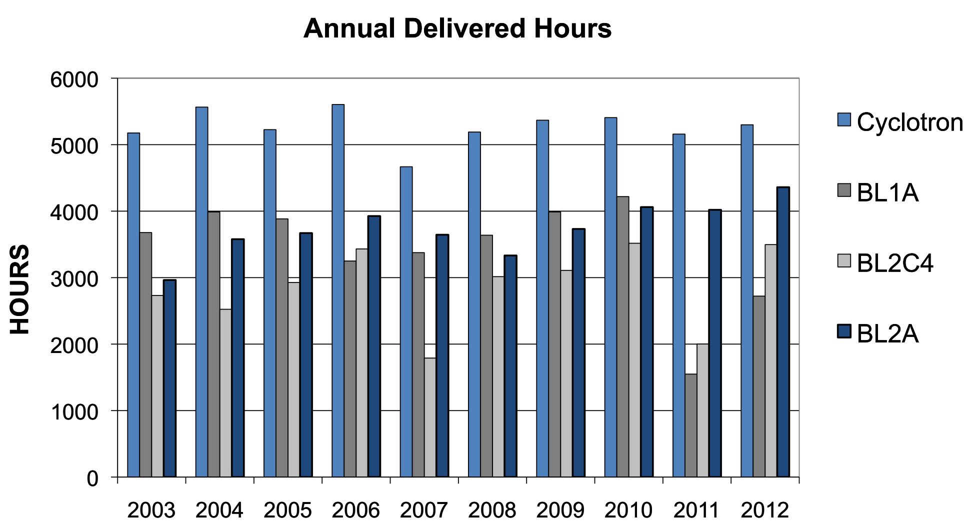


Figure 4: Total annual proton charge (mAh) delivered to three beam lines.

rubber O-rings. A vacuum better than 5 x 10^{-8} Torr is maintained by two long 4-K cryopanels and 6 cryopumps, backed up by turbopumps. Externally, the lid and base carry 54 circular and 78 harmonic trim coil pairs for fine adjustment of the magnetic field. The 2400-t atmospheric load on the base is supported by 332 steel tie rods anchored to the vault floor; that on the lid by another 332 tie rods bolted to a 109-t "spider" of steel I-beams above. The upper half of the magnet, the spider and the tank lid can all be raised 1.22 m by 12 electrically-driven jacks to permit maintenance work inside the tank. Much of this work can be carried out remotely (including replacement of the rf resonator sections) using a 9-m-long bridge that can be inserted and rotated about a central pivot.

H^- ions are produced in an external cusp source mounted in a Faraday cage raised to 300 kV by a Cockcroft-Walton set. The 300-keV ion beam is then transported horizontally over the cyclotron vault roof and bent 90° downwards for axial injection. Electrostatic focusing and steering is used throughout the 46-m-long injection beam line. An electrostatic spiral inflector and horizontal deflector are then used to steer the beam into the median plane of the cyclotron for acceleration by the dees.

Acceleration is by 5th harmonic rf (23.055 MHz), the two 180° dees each being composed of 40 half-wave resonators 75-cm-wide, 3-m-long, half mounted on the vacuum tank base and half on the lid. The system is powered by eight 250-kW Eimac tetrodes, producing a dee voltage of 95 kV (with 10^{-4} stability) and maximum energy gain/turn ΔE = 380 keV. There is also a 92-MHz booster cavity to increase ΔE by ≤ 200 keV above 450 MeV, significantly reducing the beam loss.

The primary beam diagnostic tools are two "low-energy" and three "high-energy" intercepting probes equipped with multi-finger heads that can be moved radially to cover the whole energy range. These provide data on total beam current, radial and vertical intensity distributions, and time of flight. Visual access is also available via periscope equipped with CCTV camera and rotatable mirrors.

Extraction systems are provided for four external beam lines (see Figure 1):

- **BL1:** ≤ 170 µA at 180-520 MeV for pion and muon production;
- **BL2A:** ≤ 100 µA at 472-500 MeV for radioactive ion production;
- **BL2C:** ≤ 100 µA at 70-120 MeV for radioisotope production, proton irradiations and cancer therapy; and
- **BL4:** ≤ 10 µA at 180-500 MeV (1975-2010); ≤ 200 µA at 470-500 MeV for radioactive ion production in the next five-year plan via the ARIEL project.

The stripping foils may be moved radially to change the extracted beam energy, and azimuthally to direct the beam to an external "combination" magnet that steers it down the beam line. Multiple foils are available in each extraction probe cartridge, and they may be changed remotely, either in case of damage, or when a different foil shape is required (as for the lower energy beams, where only a fraction, ranging from 1/50,000 to 100/1, is to be extracted). The extracted beams typically have an energy spread of 1 MeV, radial and vertical emittances $4e_{\mathrm{rms}}$ = 1 - 2 pmm, and a 4-ns, 23-MHz, bunch microstructure. A chopper in the injection line allows a pulse macrostructure with a duty cycle variable from 0.1% to 99% at 1 kHz repetition rate.

Operation and Performance

For decades the cyclotron operated in a fairly steady mode of 24/6 production with regular weekly 8- to 36-hour maintenance periods and two annual shutdowns: 7 days in September and 3-4 months in winter, depending on service and repair needs. Lately, aiming at higher scientific production and as a result of multiple machine upgrades, the number of maintenance days has been greatly reduced (by >30%).

Long maintenance periods are usually driven by ion-source filament replacements (every 3 weeks) and cryo-panel preventative defrosts (every 6 weeks). Over the last decade the machine has demonstrated reliable operation with annual availability around 90%.

Both peak and integrated beam production are driven by the beam delivery schedule determined by the users' needs. With the recent deployment of actinide targets in ISAC, beam demand down Beam Line 2A has dropped from 70-100 µA (high power targets) to 10 µA for a significant fraction of experiments. A histogram of beam charge delivered over the last decade is presented in Figure 3. The reduction in BL1 charge in 2011 and 2012 is associated with an extended shutdown of this beam line for installation of a new M20 secondary channel and repair of a vacuum leak at the T2 target extraction port; the reduction in BL2C4 charge in 2011 was due to an FDA investigation of an isotopes breach in the USA for a similar product and the subsequent interruption of Sr-82 production.

The most significant issues impeding operations and requiring extended effort during shutdowns are usually associated with water leaks (cyclotron resonator panels, Meson Hall magnets) or vacuum leaks (distorted joints and damaged seals in high radiation areas).

Under optimal conditions transmission up to 70% has been measured between injection and extraction to all beam lines. The extracted beams have small spot sizes (3-7 mm) at the targets and a 4-ns-long time structure.

Hardware Upgrades

Over last five years the cyclotron has received government funding for its refurbishing and upgrade of ~400 k$ annually. Within this program many subsystems and components have been upgraded:

RF System

Power amplifier (PA) resonators and filament power supplies upgrade, dee-voltage monitoring upgrade, rf coupler upgrade, new 12-kV AC switch gear.

Injection System

A new 12 metre long vertical section of the electrostatic beam line [1] employing low-maintenance reliable design dramatically extended the diagnostics and tuning capabilities, and supports high-intensity (up to 5 µA) beam transport (see Figure 5); an Alison-type emittance scanner has been installed downstream of the ion source, greatly expanding beam characterization and tuning capabilities; a new deflector was installed, that can provide, in addition to horizontal steering, some transverse focusing: this is achieved by an additional curvature of the deflector electrodes in vertical direction—new deflector allowed improvement of the cyclotron transmission by ~5%.

Figure 5: The installation of the vertical section of TRIUMF's new main injection line. The line is used to transport hydrogen ions from the ion source to the centre of the cyclotron.

Diagnostics and Probes

New non-intercepting beam position monitors have been installed in the beam lines, allowing on-line monitoring and tuning; old leak-prone devices in the central region were removed and a new vertical flag developed and installed; deployment of new highly oriented pyrolitic graphite material has dramatically improved the life time of the extraction foils (by a factor of 4).

DC Power Supplies

All of the 3-10 kW power supplies (120 units) feeding the cyclotron's trim and harmonic coils have been replaced with modern (switching mode) units.

Cyclotron Vault Cable Infrastructure

Wiring in the vault is exposed to harsh conditions of radiation, humidity, and temperature. This leads to premature failures and destructive damage. To address this issue TRIUMF has embarked on replacement of all the cables (~1500 units) ending in the cyclotron vault. A complementary parallel cable tray infrastructure has been created and more than half of the cables have been replaced.

Cyclotron Beam Development

Since 1995, when the ISAC project got under way, new requirements for beam quantity and quality have been established. First of all, the total beam intensity demand has grown from 200 to 300 μA. However, this growth in production had to be achieved without increasing facility activation due to beam loss. Also, due to the vulnerability of the ISAC targets and to the high sensitivity of their yields, stringent limits have had to be set on fluctuations in intensity and beam position on the BL2A target, setting high demands on machine stability and reproducibility. To address these issues a number of beam developments have taken place and several machine improvements have been implemented.

The cyclotron design does not support operation much beyond 520 MeV because above ~450 MeV there is a rapid rise in electromagnetic stripping losses (see Figure 6), due to the Lorentz force tearing one of the weakly coupled electrons off the hydrogen ion. In 2009, after careful evaluation of the impact on the experimental program, the extraction energy was reduced from 520 MeV to 480 MeV. This has led to ~30% reduction in both prompt and residual activation for the same beam intensity [2]. Alternatively, it allows an equivalent intensity boost within the traditional activation dose budget.

Several improvements were made to get the required higher stability for the ISAC primary beam. First, the BL2A beam intensity was stabilized to ±1% by introducing a feedback loop between the electron

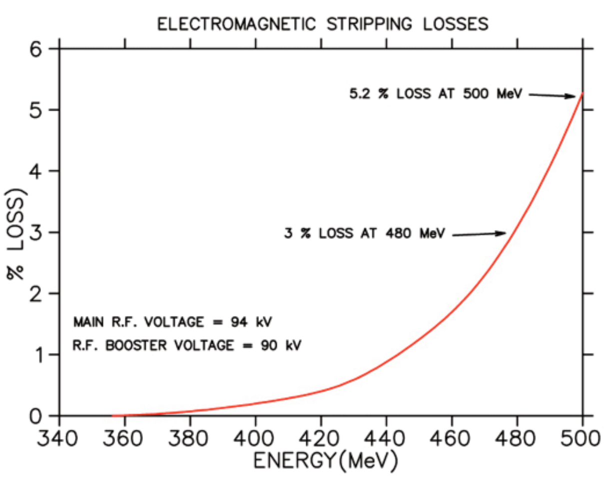


Figure 6: Electromagnetic stripping loss as a function of energy.

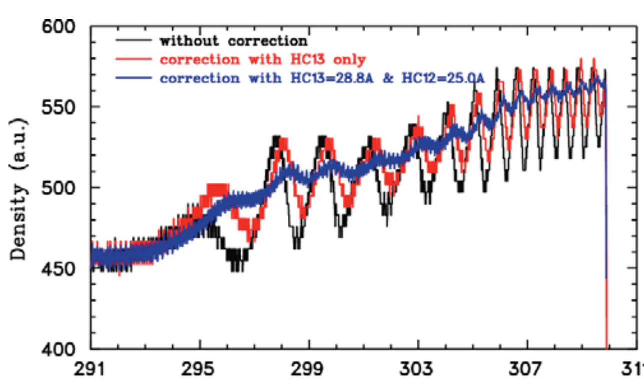


Figure 7: Suppression of the $\nu_r = 3/2$ resonance. Current density around extraction with 0, 1 and 2 correction coils. Top: simulation; Bottom: experimental results.

current caught on the stripper and the pulser at injection, regulating the beam's duty cycle. Decreases in the stripper current are compensated by increases in duty cycle and vice versa [3]. Second, automatic beam steering was implemented to keep the beam centred on the production target. Thirdly, the beam line 2A tunes were developed to form an image at the target of the spot on the stripping foil, thereby minimizing the beam halo on the target. Automatic beam steering was also implemented for all targets in BL1A.

Stabilizing the BL2A intensity was found to produce a side effect—magnified intensity fluctuation in the other primary beam lines. The root cause of the instability was traced to the $\nu_r = 3/2$ resonance driven by field imperfection in the cyclotron, that causes radial beam intensity variation after resonance crossing, at energies above 450 MeV (see Figure 7) [4]. To suppress this resonance, a delicate machine tune was developed employing two independent sets of harmonic coils near the extraction radii (HC12 and HC13) energized in the third harmonic mode. This reduced the intensity instability in the unregulated beam lines (BL1A and BL2C) from ±10% to ±2%. To further diminish this source of current instability, we implemented an active feedback system. It regulates the amplitude of the first harmonic Bz produced by a set of harmonic coils (HC13). A proper choice of the phase of this first harmonic correction allows variation of the split ratio, without changing the energy of the extracted beams.

The ISAC production targets operate at extreme temperatures, very close to the material's destructive damage limit. Therefore, they are very vulnerable to abrupt thermal changes and thus sensitive to any beam interruptions, causing big changes in power deposition on the target. Instead of the full beam trip previously induced by an over-current or some other abnormal beam condition, a so-called "soft" beam trip was therefore implemented, where the beam intensity is dropped down to 80% without interruption, allowing the operator to address the anomaly and restore normal production. Also, slow ramping of the beam intensity (~1 minute, up or down), has been introduced to mitigate target thermo-cycling issues.

Also, we made important developments on the extraction probes and stripping foils. One of the issues was related to the beam spills. We can only tolerate beam losses of about 1nA/meter in the primary beam lines. This is 10^{-5} level at 100uA. Beam spills are primarily due to the large angle scattering from the stripper foil. For a 5mg/cm^2 foil, which is the usual thickness used in the past, 10^{-5} particles have an angle driving them into the 4-inch beam pipe. So, it was suggested that 2.5-5 times thinner foils be used to minimize the scattering. Another issue was that foils deformed or even cracked in the past. The cause was believed to be a temperature rise on the foil frame on the top. Concerning these two issues, improvements were made such that (1) highly orientated pyrolytic graphite foils, of thicknesses about 2mg/cm^2 are now used, and (2) a Tantalum frame, with a thin copper cushion, is now used in place of the previous stainless steel as Tantalum has better thermal conductivity. Also, additional heat relief features were introduced in the probe head mechanism. With these improvements, we have achieved 4 times longer lifetimes for the BL1 foils. As a result, the Be-7 contamination surveyed at the Ex1 probe has been reduced by a factor of 5 that is also attributed to foil vertical position optimization leading to lower foil temperature.

Primary Proton Beam Lines

TRIUMF has four independent extraction probes with various sizes of foils, providing the capability to deliver protons simultaneously to up to four beam lines. New foils, composed of highly oriented pyrolytic graphite, were employed, improving the quality of the extracted beam and decreasing the amount of foil changes, which in turn decreases the amount of possible problems associated with the foil change procedure. Because of the high energy of the proton beam, these beam lines use magnetic rather than electrostatic focusing and steering elements.

Beam Line 1A (BL1A) can deliver 180 to 500 MeV protons to two target systems, T1 and T2. The beam power ranges from 50 to 75 kW. The first target, T1, services three experimental channels, one of which is used as a detector test facility by multiple users. The second target, T2, services two µSR experimental channels. Downstream of T2 is the 500 MeV Irradiation Facility used to produce strontium isotopes for medical-imaging generators as well as the TRIUMF Neutron Facility (TNF).

Beam Line 1B separates off BL1 at the edge of the cyclotron vault and provides international users with the Proton Irradiation Facility (PIF) that is used for radiation testing of electronic circuits, for example, mimicking space radiation for testing computer chips. The protons can be converted into neutrons for terrestrial electronic testing by companies, such as CISCO.

Beam Line 2A (BL2A) is capable of providing 475 to 500 MeV proton beams at up to 50 kW to the ISAC target facility, which produces rare-isotope ion beams for a host of Canadian and international experiments.

Beam Line 2C (BL2C) is used for the Proton Therapy Program (PT) to treat choroidal melanomas (eye tumours). It is also used for proton irradiation to produce strontium isotopes, which are chemically processed and then used for medical imaging generators. This beam line also has the flexibility to provide protons of lower energy for PIF users and these protons can be converted into neutrons for NIF users. The energy range for this line is 70 to 120 MeV. Recent foil improvements now allow high current running in BL2C4 when no other beam lines are available.

In the past, Beam Line 4 (BL4) could deliver protons of energy from 180 to 500 MeV, albeit at only 5 kW, and was last used as a production facility in 2000 for the parity violation experiment. Delivery to this line is on hold while it is under construction as part of the ARIEL project. Currently, only the vault section of the beam line remains since the Proton Hall was decommissioned during the 2011–2012 shutdown. An extension of this line, Beam Line 4 North (BL4N), will be used for the proposed ISAC expansion, to deliver protons to a target at the ARIEL facility.

Summary

The 520 MeV cyclotron delivers three simultaneous proton beams for both production and test purposes. The total mAh charge has generally increased since ISAC came on-line in 1999. During this period, there has been no corresponding increase in downtime, which demonstrates the cyclotron's capacity to deliver increased beam currents.

Developments in support of high intensity operation were initiated in 1988; more recent development initiatives have demonstrated that accelerating to 300 µA over five years is a realistic and attainable goal. This goal was reached in November 2010 when we ran for 12 days at 315 µA. The new intensity would support beams for four beam lines: BL1A (for meson production), BL2A (for ISAC), BL2C (for strontium production), and the proposed Beam Line 4 North (BL4N) for ISAC expansion.

IEEE RECOGNIZES TRIUMF'S MAIN CYCLOTRON

09 August 2010

The Institute of Electrical and Electronics Engineers (IEEE), the world's largest professional association for the advancement of technology, has recognized the extraction of the first high-energy proton beams from TRIUMF's main cyclotron on December 15, 1974 as an historic engineering milestone. A dedication ceremony was held at TRIUMF on the 36th anniversary of the event.

The main cyclotron at TRIUMF is the world's largest such device of it's kind, measuring 18 metres across and producing intense beams of protons at energies up to 520 Million electron-Volts (MeV). Since 1974, TRIUMF has used these proton beams (and secondary beams of pions, muons, neutrons, and rare isotopes produced in its experimental halls) to conduct pioneering studies that have advanced nuclear physics, particle physics, molecular and materials science, and nuclear medicine.

Prof. David G. Michelson, chair of IEEE Vancouver Section and a member of the Department of Electrical and Computer Engineering at the University of British Columbia, said, "The quality of the initial design and engineering of the TRIUMF 520 MeV cyclotron is underscored by the cyclotron's longevity. Thirty-five years after the first full energy proton beam was extracted, the cyclotron is still the main engine of TRIUMF's world-leading research program."

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5.4.2 ISAC TARGET AND ION SOURCES

TRIUMF's ISAC uses the isotope separation on line (ISOL) technique to produce rare isotope beams (RIB). The ISOL system consists of a primary production beam, a target/ion source, a mass separator, and beam transport system. The rare isotopes produced during the interaction of the proton beam with the target nuclei are stopped in the bulk of the target material. They diffuse inside the target material matrix to the surface of the grain and then effuse to the ion source where they are ionized and extracted as ion beams that are mass separated so that pure beams of rare isotope can be delivered to the experimental facilities.

When the driver proton beam interacts with the target material a number of protons or neutrons can be ejected from the target nuclei, the nuclei can shed fragments or fission, so that a wide spectrum of isotopes are produced in the reaction – will all products being lighter than the original target nuclei. Hence the isotope production can be tailored only to some degree by the particular choice of target material. Ion sources then are selected primarily by their ability to ionize the isotope / element of interest to highest possible efficiency. Therefore a suite of different ion sources is required to deliver all isotopes of interest to the experimental program.

Initially when the ISAC project was funded, existing target designs could only accommodate up to 2 µA incident proton beam intensities. During the last five years we have developed techniques that allow us to operate special ISOL targets with up to 100 µA. Among the techniques that were developed was a high-power target equipped with radial fins that can dissipate up to 20 kW.

For the target material we used mainly refractory (high-temperature) foils—Ta, Nb, and carbide foils. The development of composite carbide target was a breakthrough that permits the ISAC facility to produce rare isotopes with a larger target material inventory, and this allows us to produce intense, rare isotope beams. At the time of writing, composite carbide targets operate routinely at an intensity of 70µA.

Because ISAC operates at very high proton intensity, the development of ion sources that can operate in such a high radiation environment is a challenge. Like the targets, a RIB ion source typically has to be replaced after an ion source run. Supplying currents, high voltage and cooling to the ion sources, typically operating at 20kV-60kV is an additional challenge. The hot surface ion source was the first ion source implemented at ISAC, and this was followed by an electron cyclotron resonance (ECR) ion source, a resonance ionization laser ion source (RILIS) and a forced electron beam ion arc discharge (FEBIAD) ion source. Currently an improved type of ECR ion source with improved electron confinement—and thus higher ionization efficiency—is under development. However, such an ECR would require a dedicated target module to be operational, where the current focus is on the refurbishment and replacement of the inventory of aging target modules in operation.

The TRIUMF RILIS delivered first beams on-line in 2004 and was the first all solid state laser based on-line laser ion source. TRIUMF pioneered this new development in order to minimize operations cost, yet benefitting from the unique feature of laser resonance ionization: element selectivity.

With a RILIS only the desired element is ionized–whereas all other isotopes remain in the target ion source, thus producing some of the cleanest beams of isotopes available. Still, some residual surface ions are created in the hot ionization cavity and heated transfer tube elements. The cost of implementing a state of the art, solid state laser based RILIS was that–element by element–new laser excitation schemes, suitable for the solid state lasers in use had to be developed. The development goal laid out was two new RILIS beams per year.

The priority of the last five-year plan was on the completion of the ISAC RIB production facility to its full specifications in order to improve the reliability of the target/ion source assemblies, the predictability of the produced RIB intensity, new rare-isotope beams, and sustainability of the ISAC production system.

ISAC Production Target/Ion Source: Improving Reliability

The major reliability issues encountered in ISAC were due to water leaks in the target heat shield cooling lines under vacuum. To provide context, the target ion sources used are mainly made of tantalum (Ta), a refractory material. The target/ion source operates at a high temperature—2200 ºC. At this temperature, tantalum glows white and is very sensitive to oxidation in contact with water molecules where the following reaction is very favorable:

$$Ta + xH_2O \rightarrow TaO_x + H_2.$$

Due to the long turnaround time of the target exchange process, the target/ion source must operate online for a period of four to five weeks. This means that even a tiny water leak will eventually damage or destroy the Ta in the target /ion source assembly. The techniques, skills, and experience used to produce the target ion sources assembly were lost in the machine shop due to a combination of staff turnover and retirements. It was not feasible to mitigate this through training of new people, and historical documentation was not sufficiently detailed to ensure proper quality assurance and resulted in several failures.

Once the diagnosis of the various failures pointed to water leaks, a failure mode and effects analysis (FMEA) was implemented. The analysis revealed that the design of the brazed water joints had to be changed. In addition, the original brazing alloy used for years had been changed to a less favorable alloy with a high cadmium content. In addition, the brazing techniques used in the production of the components that leaked were identified to cause premature failure.

The following measures have been implemented to improve the reliability: (1) a new protocol for brazing was developed, and the specification for the alloy was revised; (2) machine shop personnel have been trained to perform the required brazing (see Figure 1); (3) some of the joints were redesigned entirely to simplify the brazing; and, (4) an engineer specialized in product development and manufacturing has been hired to follow up the complete manufacturing process of the target ion source assemblies.

Now, new target ion sources are tested prior to installation. To achieve this objective, an existing ion source test stand was converted into a production test facility. Now each target and the ion source are tested prior to installation onto the target module. As a result, any problems identified during the testing can be corrected prior to the on-line production run.

For laser ion source laser ionization scheme development (laser spectroscopy) and ion source development a dedicated laser ion source test stand and laser system was completed in 2011 and has helped in the speedy development of new laser ionization schemes, laser system development and the prototyping and detailed testing of the radiation hard ion guide laser ion source prior to scheduling of the first on-line run with radioactive ion beams. TRILIS operation hours have more than doubled in the course of the running five-year plan.

As a result of these improvements in the targets and ion sources department in the past two years, a substantial increase in beam delivery reliability has been achieved with higher than 75-85% availability for accelerated and non-accelerated beams respectively.

Target Module Refurbishment

The ISAC Target Modules (four total) are used for transport of targets and contain the ion extraction system in a sub-assembly called the source tray. They have a finite operational life and eventually require refurbishment. During 2010/2011, several high-voltage problems during operation initiated a failure analysis and refurbishment of Target Module 1 (TM1). Due to the design of the module, and its radioactivity from operating under beam, it was only possible to replace the source tray sub-assembly.

A failure mode and effects analysis (FMEA) was performed on these items, leading to the redesign of certain components for improved durability and functionality. Drawings were updated to capture the changes, and replacement components were manufactured, cleaned, and assembled (see Figure 2). The rebuilt source tray was installed during summer 2011 in the ISAC South Hot Cell facility completely by tele-manipulator.

The replacement source tray was unable to resolve the high-voltage issues, but the refurbishment allowed the problem to be isolated to the module service chase, which is unfortunately inaccessible in this design. Target Module 1 is in service and reliable up to 20 kV for ISAC operations. This particular module is also limited as it can only accept certain types of target ion-source assemblies.

The refurbishment process for Target Module 3 (TM3) was formally initiated in spring 2013. Assembly and testing of the refurbished module is on-schedule for fall 2013 (see Figure 3). Lessons learned from previous refurbishments will be applied so that TM3 will be able to reliably operate all ISAC target designs up to the 60 kV design voltage. The refurbished TM3 will replace TM1 in the module rotation. Refurbishment of TM2 will begin immediately after. TM4 is currently operating reliably. The ISAC facility design requires two operational modules in the rotation to run at full capability. Having three modules (two primary and one spare) in rotation will vastly improve facility reliability and simplify operations.

ISAC Facility Upgrades

Other areas of improvement include both equipment and facilities required to generate a faster turnaround time for target exchanges. In order to accommodate the relatively long period of time required to change a target/ion source assembly (three to four weeks), it is necessary to run the same target/ion source assembly for at least four weeks. Most of the time, a significant degradation is observed in the yield after two weeks of continuous operation at an 80 μA proton beam on target. To reduce turnaround time for targets, three major upgrades are required for the ISAC facility. These are: (1) a Conditioning Station, which will allow off-line conditioning and testing of a target module equipped with a fresh target/ion source prior to installation on-line, (2) a second and dedicated North Hot Cell for target exchanges, which will reduce dependence on a single hot cell for both routine target exchanges and radioactive repair or refurbishment jobs, and (3) a Remote Quick Disconnect mechanism for the target and ion source services, which will eliminate the for long cool-down periods currently required before a technician can disconnect the service connections manually.

The combination of these three systems will allow us to reduce our target exchange cycle from weeks to days.

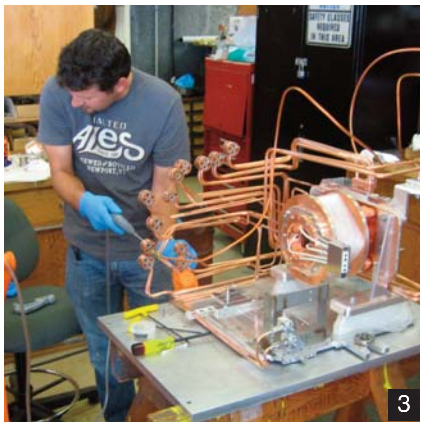

Figure 1: Inspection of brazing assemblies for target ion source heat shields.

Figure 2: An ion-source for ISAC is inspected in TRIUMF's clean room.

Figure 3: Elements of the target source tray are inspected during refurbishment.

Figure 4: ISAC Conditioning Station and members of the engineering team.

Figure 5: ISAC Conditioning Station with high-voltage terminal and chase.

Figure 6: Arrival of three-piece manipulators for North Hot Cell project.

The TRIUMF resonant ionization laser ion source (TRILIS) moved into a dedicated laser clean room laboratory in late 2008; in 2010 laser beam transport to the east target station was completed so that TRILIS achieved full scheduling flexibility. The number of isotopes from different elements increased from 6 elements in 2008 to 24 elements from which isotopes have been successfully delivered on-line. In 2013 the development of an ion-guide laser ion source target ion source module resulted in an unprecedented suppression of residual isobaric contamination from Na by a factor of 106. This ion guide laser ion source development has the potential to opening up experiments in mass regions that have traditionally been dominated by isobaric contamination – even when beams were ionized by use of the selective RILIS.

ACTINIDE TARGET DEVELOPMENT AT TRIUMF'S ISAC FACILITY

October 1, 2008

The first test of an actinide production target at TRIUMF's ISAC facility was carried out between August 29 and September 20, 2008. The use of actinide targets at ISAC is a key component of TRIUMF's Five-Year Plan.

Such targets are required for use by the proposed 50 MeV electron linac as a driver for rare isotope beam production by photo-fission. This approach will produce intense beams of isotopes with extreme neutron-to-proton ratios, including those sought by nuclear astrophysicists interested in the processes by which heavy elements are created. Simultaneously, a dedicated beam line has been proposed for use with actinide targets at higher proton currents than can be used with the existing Beam Line 2A target stations.

This will allow the production, primarily by spallation, of the Radon (Rn), Francium (Fr), and Astatine (At) isotopes of particular interest to those studying fundamental symmetries. This first test represents a significant milestone in TRIUMF's efforts to prepare for the next five years and beyond.

ISAC Conditioning Station

Preliminary concepts and design started in 2009, and the main structural elements, penetration coring, shielding, vacuum vessel and diagnostics were completed by autumn 2011. The high-voltage terminal and services, isolation transformer, power supplies, cooling water services, controls, and safety enclosures were installed throughout 2012. The first high-voltage bias test with a target module was done in February 2013 and full system commissioning is targeted for completion by end of spring 2013. Formal commissioning on a test target was successfully executed in March 2013. Several system faults and improvements have been identified, both during commissioning and also as a result of the first conditioning of a production target (Ta #40) in Target Module 4 during May 2013. Efforts are underway to document the results of commissioning, implement changes to address the improvements, and document the as-built system with updated drawings, schematics, and procedural manuals. The completed Conditioning Station and associated high-voltage services terminal are shown in Figures 4 and 5.

North Target Exchange Hot Cell

Preliminary specifications and design began in spring 2010. The CRL model N three-piece tele-manipulators were purchased in 2011 and received in February 2012 (see Figure 6). Design of the contamination enclosure, nuclear ventilation, shielding as well as services was delayed due to resource limitations but may commence again in 2014. Commissioned system completion is targeted for 2014. Departmental review of this project is underway to determine when resources will be available to work on it in conjunction with ARIEL Phase II.

ISAC Remote Quick Disconnect

Preliminary design concepts began in summer 2010. The manufacture of a mock-up target station to test concepts began in 2010 but was stopped. The project has been delayed due to resource limitations and cannot proceed until a dedicated project engineer and support staff can be hired. This project will resume as part of the upcoming designs for the ARIEL target stations. It is planned to modify the green field – remote quick disconnect design to be integrated into new ISAC target modules.

5.4.3 ISAC ACCELERATORS

TRIUMF's isotope facilities are presently based on proton beams extracted from the main cyclotron. The beams strike target materials, and exotic species of isotopes are extracted and distributed to experimental facilities for study. This complex is called ISAC—Isotope Separator and Accelerator. The experimental halls are called ISAC-I and ISAC-II.

In linear accelerators (linacs) such as those in ISAC, the accelerating fields are produced in a series of RF cavities through which the particles move and gain energy. One important parameter of such linacs is the gradient or energy gain per unit length measured in mega-electron volts per meter (MV/m). Superconducting radio frequency accelerating cavities are used in ISAC-II.

In the ISAC facility, 500 MeV protons from the cyclotron, with a maximum current of 100 µA, impinge on one of two production targets to produce radioactive isotopes. The isotopes are ionized, and the resulting beam is mass-separated and transported in the low-energy beam transport (LEBT) electrostatic beam line to either the low-energy experimental area or through two room temperature accelerating structures, a radio frequency quadruple (RFQ) and a drift tube linac (DTL), to the ISAC-I medium energy experimental area. The 35.4 MHz RFQ accelerates ions with $3 \leq A/q \leq 30$ from 2 keV/u to 150 keV/u, and the post-stripper (106.1 MHz) DTL accelerates ions with $A/q \leq 7$ to energies fully variable from 117 keV/u to 1.8 MeV/u. The accelerated beam can also be transported to the ISAC-II 40 MV superconducting linear accelerator (SC-linac) for acceleration above the Coulomb barrier and delivered to the ISAC-II high-energy area. The ISAC electron cyclotron resonance (ECR) charge breeder, CSB1, installed in the ISAC mass-separator room, is used to boost the charge state of masses with $A>30$ to allow acceleration in the RFQ. The accelerator chain is shown in Figure 1.

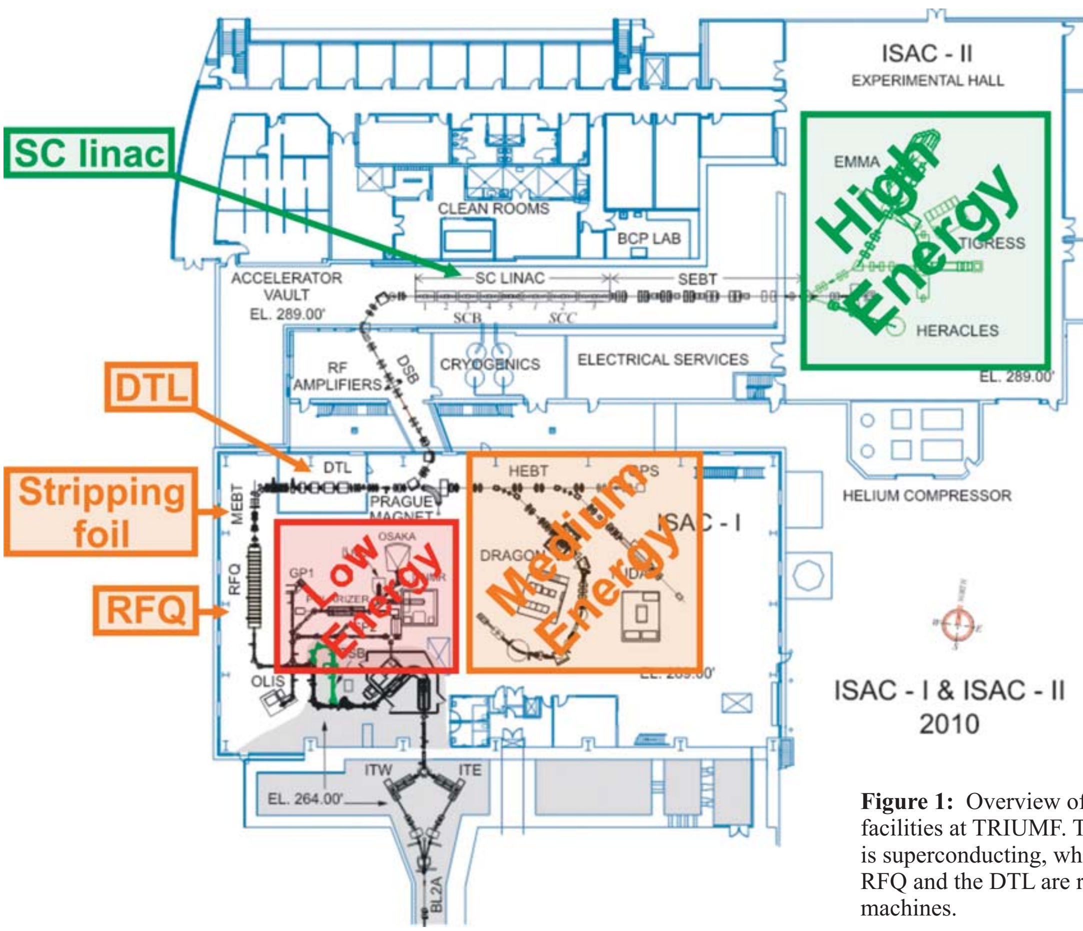

Figure 1: Overview of the ISAC facilities at TRIUMF. The ISAC-II linac is superconducting, while in ISAC-I the RFQ and the DTL are room temperature machines.

The eight meter long RFQ structure is composed of nineteen split rings supporting the electrodes. The RFQ itself doesn't have a bunching section; the beam is pre-bunched at the entrance with a three harmonics radio frequency buncher, the fundamental being 11.78 MHz. This configuration produces a high quality longitudinal emittance after the RFQ (0.5 π keV/uns) and a beam time structure convenient for experiments with a period of 85 ns. The RFQ accepts 80% of the beam with the rest of the beam unaccelerated and lost in collimators in the MEBT.

After the RFQ the ion charge state is increased by means of stripping through a thin carbon foil (4 $\mu g/cm^2$) with charge selection done in the MEBT dipoles. The dipoles accept ions with $A/q \leq 7$. The efficiency of the stripping foil depends on the mass of the stripped ions; in most of the cases it ranges between 30% to 50% for $A/q \leq 30$, with the most probable charge state given by $q \simeq 0.12A+1.5$.

The DTL is a variable energy machine covering the entire range of energies between 150 keV/u$\leq E \leq$1.5 MeV/u for A/q=6. The DTL maximal external energy is somewhat A/q dependent where the relation $E \simeq -0.074A/q+1.95$ MeV/u gives a reasonable fit with limits from $2 \leq A/q \leq 7$. As well, the lower limit can be decelerated to 117 keV/u. The DTL is a separated function machine composed of five IH inter-digital structure accelerating cavities and three split ring bunchers located between the first four cavities. This layout produces good beam quality at every energy in the range. Transverse focus through the linac is provided by quadrupole triplets between each cavity. The transmission through the linac is typically greater than 95%.

The SC-linac boosts the beam energy with an accelerating potential of up to 40 MV. It is composed of eight cryomodules; the first five cryomodules house four superconducting cavities and one superconducting solenoid (see Figure 2). The last three cryomodules house respectively six, six, and eight superconducting cavities, each with one superconducting solenoid (see Figure 3). The superconducting cavities are bulk niobium quarter-wave resonators at 106.08 MHz operating at 4K. The cavities are independently phased and have a broad velocity acceptance, and thus acceleration can be optimized for each ion with lighter ions able to reach energies of up to 16 MeV/u. The maximum final energy capability is roughly given by $E \simeq 1.5+35q/A$ MeV/u, so that all ISAC ions can be accelerated above the Coulomb barrier.

Figure 2: A ISAC cryomodule in the TRIUMF clean room.

The energy of the ISAC-II SC-linac was doubled with the completion of the Phase II upgrade. The ISAC-II facility acts as an energy booster to the radioactive ion beams produced in the ISAC facility, delivering rare isotopes to experiments such as TIGRESS and EMMA.

Figure 3:A superconducting RF cavity manufactured by PAVAC for the ISAC-II accelerator.

The superconductor of choice is ultra-pure niobium, fabricated into the correct shape and cooled in a bath of liquid helium. The challenge in superconducting cavity fabrication is to maintain the niobium in its ultra-pure state. Microparticles of other metals from machining, or absorbed gases during welding, can contaminate the material and lead to a cavity that has sufficient imperfections to dramatically reduce its effectiveness in an accelerator. For this reason the niobium surface is chemically etched before each welding step and welding is done in a vacuum using an electron beam.

The accelerating modules consist of superconducting structures (cavities) that accelerate the beam using electromagnetic energy oscillating at 100 million times a second. The cavities are fabricated from highly refined niobium—a superconductor at temperatures less than 9K. Consequently, the cavities produce high field energy with almost no power loss.

The facility itself was installed in phases. The first phase, consisting of the addition of five cryomodules and twenty cavities, was commissioned in 2006. The second phase consisting of twenty more accelerating cavities housed in three cryomodules was completed on schedule and on budget to coincide with the end of TRIUMF's fiscal year 2010 (see Figure 3).

The first phase of linac installation utilized cavities fabricated in Italy. In the second phase, TRIUMF collaborated with a local company, PAVAC Industries Inc., of Richmond, BC to master the difficult technology.

PAVAC is the first Canadian company ever to produce bulk niobium superconducting cavities. This success is a first for Canada and registers the country in an exclusive group of only five in the world with this coveted capability.

The first experiment to use the new accelerating energy at TRIUMF was "Lifetime measurement of 6.791 state in 15O" where 10.8 MeV/u 16O5+ was delivered to the experiment. This is equivalent to E=6.5MeV/u for A/q=6 and matched the ISAC-II goal.

In the first half of 2010, two important milestones were met: hardware was on the floor before the end of March, and beam was accelerated before the April 25 start of the science program.

5.4.4 CMMS/UCN/SRF HELIUM LIQUEFIER FACILITY

TRIUMF'S Centre for Molecular and Materials Science (CMMS) facility at TRIUMF and its Superconducting Radio Frequency (SRF) program have historically utilized about 30,000 litres of liquid Helium (L-He) per annum for its operations (see Figure 1). Within two years the inauguration of new CMMS beam line infrastructure will increase this figure to ~35,000L/yr. Whereas L-He used to be "cheap," over the past decade its availability has been ever more restricted and, consequently, the price has more than doubled from ~$7/L to the current value of ~$15/L (see Figure 2). Compounding this fiscal impediment, in recent years, poor quality and supply restrictions (and sometimes even suspensions) have plagued TRIUMF to the point where these restrictions threaten to cripple, even suspend, the CMMS research program, which is so sensitively dependent on high quality L-He being readily available.

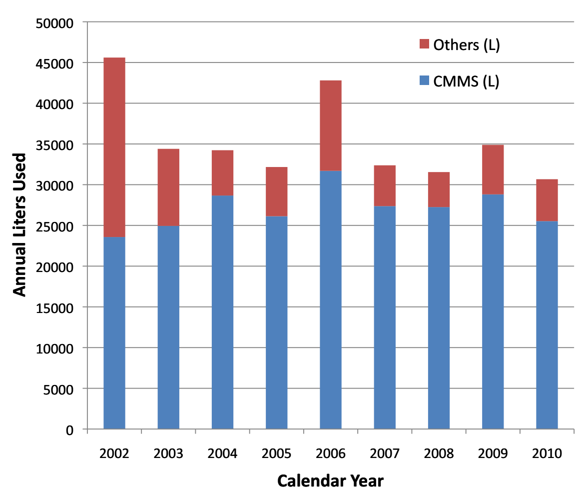

Figure 1: The historical usage of open-system liquid Helium at TRIUMF. A fully operational CMMS facility will use from 30–35,000 L/yr.

If TRIUMF continues its past policy—purchasing L-He— it would have to fund an ever-rising annual operating cost for the CMMS program; its current base cost is at a "crushing" level of $400,000/yr. Economically, a much better option is to purchase a Helium liquefier and gas recovery system (for a capital cost of ~$1,600,000) so that the TRIUMF can continuously re-supply itself with the L-He it requires to operate its programs. Indeed, the case for an in-house liquefier is further intensified by the knowledge that in 2016 the nascent ultra-cold neutron (UCN) Project will begin to require significant quantities of L-He, which ultimately will significantly eclipse the utilization of the CMMS. To these ends, TRIUMF has invested in a Helium liquefier system (HLS) which is being currently being installed. This system will serve the needs of the CMMS, the SRF program, and the initial phases of UCN. This installation has been planned so that a second liquefier can be added at a later time when the needs of UCN dictate that such an increase in liquefaction capacity is required.

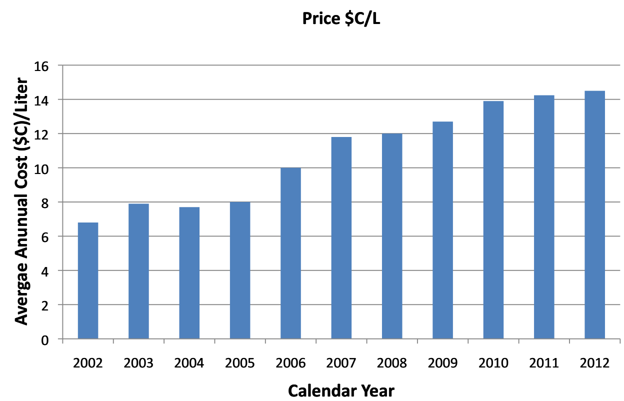

Figure 2: The cost of liquid Helium over a decade.

Description of Facility

There are three basic sections to the system (see Figure 3): the liquefier system on the right produces liquid into portable Dewars, which are then transported to various experimental stations/spectrometers, denoted by the area surrounded by the dashed dark blue lines on the left. Here the L-He is used to cool cryostats, magnets, and samples, and the resultant gas is exhausted into stainless steel recovery lines that travel back to the location of the liquefier. The return path is indicated within the dashed light blue lined box.

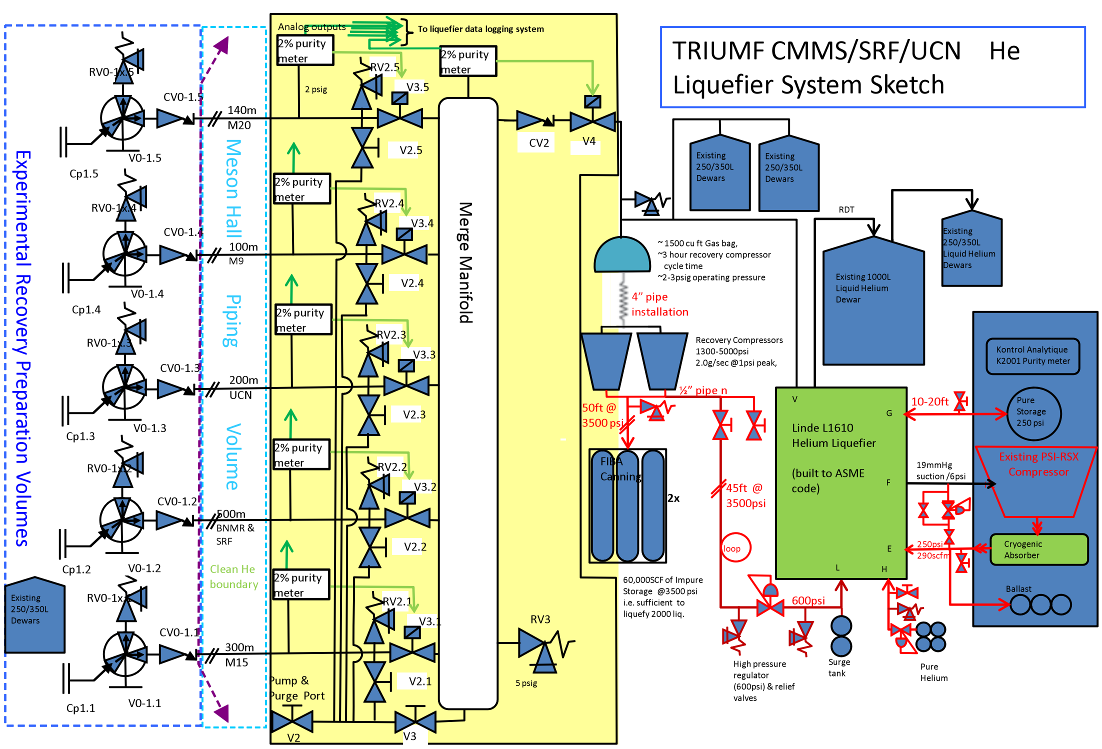

Figure 3: A schematic of the CMMS/UCN/SRF Helium liquefier system installed in 2013.

The returning gas is then monitored for purity, (which determines the ultimate efficiency of the liquefier), merged into a common volume, and then fed back into a high capacity high-pressure recovery volume from which it is destined to be re-liquefied as required.

Some features of this system are: (1) an all stainless steel recovery system and redundant He purity monitoring system, (2) sufficient high-pressure storage for 2000 L of L-He, (3) sufficient recovery speed to ensure that no He gas is lost due to the high rate of gas production from ongoing SRF tests, which the liquefier is designed to also support, and (4) sufficient liquefaction capacity (with LN2 pre-cooling) so the liquefier can support a nascent UCN operation in addition to CMMS and SRF needs, and (5) adequate piping infrastructure to enable the addition of a second liquefier for UCN, if required.

Recent Developments

The He recovery portions of this system are due to come online in October 2013 in order to be able to recover the L-He that is used in the final months of the year's experimental schedule. Operations of the liquefier itself will commence as soon as the system is tested and operating normally.

TRIUMF's Role

The $1.6M required funding for this system is being supplied by TRIUMF (with a contribution from KEK ($250k), a proponent of the UCN project, in recognition that it is the only financially sustainable means of meeting the laboratory's long-term requirements to programs that will depend on a secure and high-quality source of L-He.

5.5 EXPERIMENTAL FACILITIES AND INFRASTRUCTURE

While accelerators provide the beams, experimental detectors are needed to exploit them. TRIUMF has an array of state-of-the-art detectors to exploit the array of beams it produces. These detectors tend to be large multi-million dollar facilities with each facility devoted to one type of measurement. In some cases two or more detectors are used in combination. This is particularly true of the TIGRESS detector in the ISAC-II experimental hall which can use an array of auxiliary detectors.

TRIUMF has three large experimental areas in active use:

- **ISAC-I** for use of the low and intermediate energy rare-isotope beams
- **ISAC-II** for high-energy rare-isotope beams
- **Meson Hall** and associated annexes for molecular and materials science, ultra-cold neutron physics and in the recent past meson-decay studies.

In addition to the onsite facilities TRIUMF has collaborated on the construction of detectors located at other laboratories, notable in Ontario, Switzerland and Japan. These collaborations provide a two-way path for the propagation of expertise so that TRIUMF can stay current on detector technology while at the same time helping Canadian researchers working elsewhere. To this end, TRIUMF maintains detector development facilities.

In this section, we describe the on-site detector facilities, the offsite detectors TRIUMF has helped build and the on-site detector development facilities.

5.5.1 ISAC-I

ISAC-I is devoted to the use of low- and intermediate-energy beams from the ISAC facility. It has a large array of experimental facilities, each with different capabilities that can exploit the rare isotope beams in a number of different areas: nuclear structure, nuclear astrophysics, fundamental symmetries and material science. One of the detectors, the 8π, is being retired after over 25 years of service in a number of different laboratories and is being replaced by a new detector, GRIFFIN, with superior capabilities. Aside from the major facilities described in this section, special set-ups are being installed for specific experiments, such as the OSAKA experiment for decay spectroscopy of polarized ions, or the 3Hen neutron detector that will allow for the study of beta-delayed neutron emission.

5.5.1.1 THE DRAGON FACILITY

Our universe is filled with ordinary stars but also less understood objects and events, such as novae, supernovae, and X-ray bursts, in which nuclear reactions occur in cataclysmic explosions, creating radioactive nuclei whose signatures can be observed by orbiting space telescopes.

DRAGON is a high-performance recoil separator (see Figure 1), designed and built to measure just such nuclear reactions of importance in astrophysics — the nucleosynthesis reactions that occur in these exotic explosive stellar environments. The separator takes advantage of TRIUMF's intense beams of the kind of short-lived, rare isotopes that are involved in stellar burning and cataclysmic stellar explosions.

The first reaction ever measured by DRAGON was $^{21}Na(p,\gamma)^{22}Mg$ in 2001 and measurements continued until 2003. This was an especially important reaction to understand and calculate the processes occurring

Figure 1: Plan view of the DRAGON recoil separator, showing the gas target where the nuclear reactions occur, the electromagnetic devices that separate the recoil nuclei from the unreacted beam, and the detectors that measure properties of the recoil nuclei. Photograph courtesy of Craig Damlo.

in classical novae, a white dwarf star that accretes material from a companion star in a binary system. In classical novae, the reaction happens when a proton impinges on a sodium nucleus and is absorbed, forming an excited state of magnesium. The excited magnesium then de-excites or goes back to its lowest energy state by emitting the energy in the form of a γ ray.

DRAGON studied this reaction using a technique called "inverse kinematics," putting a heavy beam of heavy elements onto a target made of light elements. In this technique, the short-lived Na-21 nucleus, produced by ISAC-I, impinges on a proton in a hydrogen target. It is then absorbed forming Mg-22 and de-exciting, giving off a γ ray just as in the nova. The DRAGON spectrometer separates the recoiling magnesium nucleus from the beam that has passed through the hydrogen target and measures its properties. The de-excitation γ-ray energy is measured in a bismuth-germanate (BGO) crystal array that surrounds the thin-walled hydrogen gas target volume.

Using this technique as the yardstick, DRAGON has, over the last 12 years, waged successful campaigns to study some of the most important proton- and alpha-capture reactions to astrophysics, including the $^{21}Na(p,\gamma)^{22}Mg$, $^{12}C(\alpha,\gamma)^{16}O$, $^{26g}Al(p,\gamma)^{27}Si$, $^{40}Ca(\alpha,\gamma)^{44}Ti$, $^{23}Mg(p,\gamma)^{24}Al$ and $^{18}F(p,\gamma)^{19}Ne$ reactions.

Description of Apparatus

DRAGON is a high-performance recoil separator for the measurement of astrophysical fusion reactions in inverse kinematics. Using radioactive and stable beams in the range 0.15–1.8 MeV/nucleon provided by the ISAC-I accelerator, DRAGON studies the radiative (emits a γ ray) capture on hydrogen and helium relevant to nucleosynthesis on the neutron-deficient side of stability, for scenarios such as supernovae, classical novae, and type I X-ray bursts. The hydrogen or helium is circulated within a windowless gas target capable of holding up to 6×10^{18} atoms/cm^2. Fusion reactions that occur within the gas target produce excited recoiling nuclei in a forward-focused cone that quickly de-excite with the emission of one or more γ rays. An array of 30 BGO crystals almost entirely surrounds the thin-walled gas target, enabling the detection of the de-excitation γ rays with high efficiency.

The recoiling nuclei, mixed among unreacted beam particles of similar momentum, travel through a dipolar magnetic field and a set of slits to select the most populated charge state originating from in-gas atomic interactions. Particles of the selected mass-to-charge ratio are then analyzed by an electric dipole field, which separates the similar momentum particles according to mass, filtering out the unreacted beam with high efficiency. After continual refocusing and a second stage of separation, the recoiling reaction products are detected at the end of the 21-m long separator using a variety of techniques, including position-sensitive silicon detectors, a dual micro-channel plate system, and an ionization chamber for chemical-element identification.

The DRAGON separator is designed to accept recoils within a 1^o half-angle at the tuned energy, and with a momentum spread of less than ±2% [1]. The momentum and angle spread are induced by the range of momenta given to the recoil as the γ rays are emitted. This spread is thus dependent on the γ-decay branching ratios and angular distributions. The separator is capable of accepting all recoils from most proton-capture reactions of astrophysical interest using rare-isotope beams.

For some lower-mass beams and some alpha-capture reactions, including $^{12}C(\alpha,\gamma)^{16}O$, the cone angle of recoils is larger than the geometric acceptance of the separator. In this case, the transmission of recoils is deduced by modeling the entire separator using a full-transport ion-optical Monte Carlo simulation based on GEANT and RAYTRACE. In cases where decay branching ratios and angular distributions are unknown, the full envelope of possibilities is explored and the resulting acceptance spread incorporated into the systematic measurement uncertainties of the experiment.

The efficiency of the BGO array has been extensively studied by comparing GEANT calculations to laboratory measurements, and shows impressive consistency [2]. This efficiency ranges from around 40% to 80%, depending on the number and energy of γ-rays available.

Recent Developments

The beam suppression capability of the electromagnetic separator has been demonstrated in several experiments. For proton-capture, this ranges from around 1–2 x 10^8 at low energies to 10^{13} at around 1200A keV. More recently during tests for the $^3He(\alpha,\gamma)^7Be$ reaction, a record beam suppression factor of greater than 10^{14} was achieved [3]. The total background suppression capability of DRAGON, when combining γ-ray detection, recoil separation and particle identification is at minimum 10^{13}, and for certain cases as high as 10^{17}, making DRAGON sensitive to extremely small resonance strengths, with a strength of 13 μeV being the lowest measured so far.

In the past five years DRAGON has been using a local-time-of-flight system with time resolution Δt = 300-400 ps, providing an extra layer of background rejection and enabling the measurement of even more difficult measurements [4] This system has become a crucial advancement in the capabilities of the DRAGON.

The combination of ISAC-I's accelerated ISOL beams and DRAGON is unique, and it is the only facility capable of measuring the majority of the important radiative-capture reactions with rare-isotope beams. The results reported in Section 4.2.2.4 highlight the important contributions of DRAGON to the field of nuclear astrophysics over the period of the last five-year plan. These include several radioactive beam reactions. To date, DRAGON is responsible for 63% of the world's measurements of radiative capture reactions in inverse kinematics using radioactive beams.

The DRAGON program has continually been re-funded by NSERC over the years with the comments that it has provided "outstanding contributions" to the field and is a "key, cutting-edge program at a world-class facility."

Over the course of the next Five-Year Plan years (2015–2020), DRAGON will continue to pursue the measurement of difficult and important astrophysical reactions with the development of novel radioactive beams. In addition, DRAGON has recently demonstrated the ability to successfully measure capture reactions with beams as heavy as A=58 (proton capture) and A=84 (alpha capture). This goes far beyond the design limit of the system, which was for A<30. This will enable opportunities in measuring reactions for more astrophysical scenarios, such as the 'p-process' present in core collapse supernovae.

Partners

In Canada: McMaster University, Simon Fraser University, University of Alberta, University of Guelph, University of Northern British Columbia, University of Prince Edward Island, Thompson Rivers University, University of Toronto, University of Victoria.
International Partners: Austria (1), Belgium (1), China (1), France (1), Germany (2), India (1), Israel (1), Spain (1), Switzerland (1), United Kingdom (3), United States (7).

TRIUMF's Role

TRIUMF's dedicated research scientists and technicians make up the core of the DRAGON Group, which is joined by a large number of Canadian and international academic collaborators in both experimental physics and astrophysics theory. In addition TRIUMF's support for the large infrastructure commitment to the DRAGON separator is crucial to the ongoing success of the facility.

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5.5.1.2 TRIUMF NEUTRAL ATOM TRAP FOR DECAY STUDIES: TRINAT

TRINAT uses laser trapping and cooling techniques to accurately study the decays of short-lived isotopes produced by ISAC, to search for physics beyond the Standard Model of particle physics. The pressure of laser light traps the atoms in a 1-mm-sized cloud in an excellent vacuum. The recoiling nucleus from each decay has very low kinetic energy, and would stop in ten atomic layers of material. But it freely escapes the shallow atom trap, and its momentum can be precisely measured. By also measuring the momentum of the emitted electron, the momentum of the (otherwise invisible) neutrino is deduced for each event. Unique experiments test predictions of the Standard Model for the average decay direction of the neutrinos with respect to the electrons and with respect to the spin direction of the nucleus, and deviations from these predictions would indicate the presence of new forces. The average decay direction tests whether the neutrino is always “left-handed,” with spin oriented opposite its momentum.

Description of Apparatus

The complete two-trap system fits on a large tabletop. Laser beams from all six directions cool and gather the atoms in the “collection” trap. To avoid radiation backgrounds from untrapped atoms, the atoms of interest are then transferred with laser beams to the “detection” trap where the decay detectors are housed (see Figure 1). The transfer time is about 40 ms, with more than 75% efficiency demonstrated; the atoms that are not trapped end up on surfaces baffled from the recoil detector. The result is millions of atoms trapped at a time in a 1-mm-sized cloud at temperatures of less than 1 mK, i.e. typical velocities of about 1 m/s. These velocities are negligibly small compared to the recoil velocities produced in the decays.

The recoiling daughter nucleus from each decay is collected in a carefully characterized uniform electric field and detected with a microchannel plate (see Figure 2). The momentum is reconstructed from its time of flight and position on the detector. The time-of-flight start trigger is either the beta or a low-energy atomic electron produced in beta decay.

The nuclei can also be spin-polarized by optical pumping, which adds angular momentum to the trapped atoms by absorption of circularly polarized light. Spin-polarization of over 97% in unstable K-37 has been achieved in the previous geometry, with 99.5% achieved in stable test isotope K-41 in the new geometry. Together with the beta-recoil coincidence method, this enables the measurement of new observables, like the asymmetry in neutrino direction with respect to the nuclear spin.

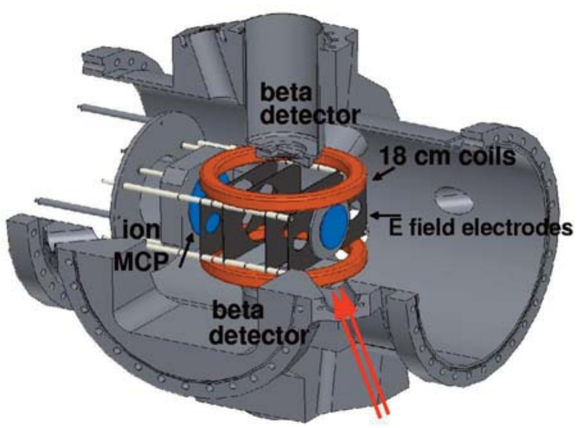

Figure 1: Cutaway view of upgraded chamber and ion detector geometry. One optical pumping beam is shown by the red arrows; the SiC mirror in front of the beta detector directs this beam downwards.

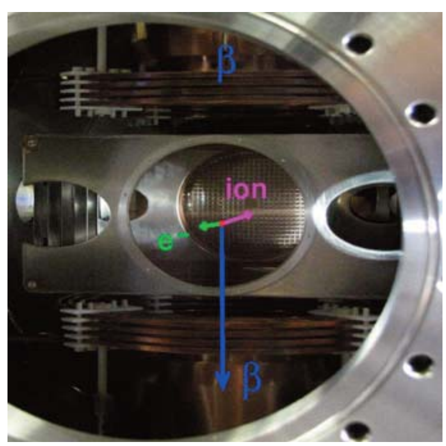

Figure 2: Magnetic field coils, electrodes, and ion microchannel plate of the new apparatus, before installation of the electron MCP in the 15 cm port.

A small percentage of the trapped atoms are photoionized and accelerated onto the same MCP, which provides a textbook measurement of the average electric field by placing a test charge in it and measuring its acceleration. It also precisely probes the cloud size (important for the beta-neutrino correlations) and the excited state atomic population (important to deduce the degree of spin-polarization).

The main collection trap laser is a tunable Ti:Sapph ring laser driven by an argon ion laser. The detection trap laser is a tapered amplifier semiconductor diode laser. A smaller diode laser is used for optical pumping. The material replacement value for the experiment is $C750,000 ($C500,000 in lasers and $C250,000 in the vacuum systems, detectors, and other equipment).

Recent Developments

The entire detection apparatus and optics have been upgraded to improve spin-polarized experiments. A larger vacuum chamber has materials that are less magnetic, with larger and more efficient beta detectors and recoil ion detectors. A new type of trap, an AC MOT with a sinusoidally varying magnetic quadrupole field, allows the trap magnetic field to be switched off to less than 1% of its value in 100 microseconds, four times faster than before. A new ion MCP readout design allows it to be floated to a higher voltage to increase uniformity of collection of all of the nuclear recoils. A more compact geometry that combines the same optical beam path for polarizing and trap lasers has better detection efficiency. A more powerful diode laser for optical pumping is now fiber-coupled for spatial beam quality and reproducibility. Optical pumping mirrors in the vacuum in front of the beta detectors now are 0.25 mm thick SiC, a stiffer material than the fused silica used before to preserve the spatial wavefronts. A new VME-based DAQ system digitizes the waveforms from a much larger number of silicon strip detector channels for the delta-E beta detectors.

A highly efficient technique measuring the recoiling daughter nuclei in coincidence with low-energy atomic electrons collected in an additional MCP by the same electric field has been developed. The atomic electron provides a time-of-flight trigger for the recoil nuclei, so their momentum can be determined. This technique was used to set complementary limits on one type of short-range contact interaction ("tensor") by measuring the recoil asymmetry with respect to the nuclear spin of Rb-80 [1]. It was also used to detect recoiling nuclei from the gamma decay of the Rb-86m isomer in a feasibility study concerning direct searches for emission of exotic massive particles by their missing momentum [2].

The new apparatus was used to measure the beta asymmetry with the respect to the spin of K-37 in December 2012, with statistical error of 1 to 2%, and systematics still being evaluated. The asymmetry of recoiling nuclei with respect to the nuclear spin was also measured. Goals for these observables of better than 0.2% would begin to be sensitive to new physics (e.g., radiative corrections from new particles in SUSY [3] still allowed by other experimental constraints).

Partners

In Canada: University of British Columbia, University of Manitoba.
International Partners: Israel (1), United States (1).

TRIUMF's Role

TRIUMF supplies the short-lived isotopes via rare-isotope beams from ISAC-I, along with 1.2 FTE research scientists, and half-support for two undergrad co-op students per year. TRIUMF also provides technical support via the electronics, machine, and design shops, the detector facility, and the Data Acquisitions Group.

References

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[3] Profumo et al. PRD 75 075017)

5.5.1.3 8π, GRIFFIN, AND GPS

The 8π facility, and future GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei), facilities are microscopes into the structure of atomic nuclei. These facilities use the radioactive decay of exotic beams delivered from ISAC to access and probe nuclear excitations in the daughter nuclei through detection of the emitted radiations. Transition energies, decay branching ratios, and half-lives are measured and from these nuclear properties can be determined. The investigations made possible by decay spectroscopy forward our understanding in fundamental symmetries, nuclear structure, and astrophysical processes.

The 8π spectrometer was installed at ISAC in 2000 and with the addition of the ancillary detection systems described below was transformed into a world-unique facility for decay spectroscopy experiments. Operation of the 8π will come to an end in 2013 and will be followed by the installation of the GRIFFIN facility. GRIFFIN upgrades the hyper-pure germanium and data acquisition aspects of the facility. These upgrades dramatically improve the detection efficiency and count-rate capabilities that will enable full exploitation of all ISAC and ARIEL beams for the science program.

In addition to the 8π spectrometer, the GPS (General Purpose Station) Lifetime Facility is a moving tape collection system and 4π gas counter used for precision half-life measurements as part of the fundamental symmetries program.

Description of Apparatus

The primary feature of the 8π spectrometer is the 20 Compton-suppressed, hyper-pure germanium (HPGe) detectors. HPGe provides excellent energy resolution of around 0.15% for gamma-ray transitions emitted from decaying nuclei. This allows for accurate determination of excited level energies in nuclei. The detectors are arranged to fill the 20 hexagonal faces of a truncated icosahedron around the vacuum chamber with the central focus of all HPGe detectors coinciding with the beam implantation location (see Figure 1). The array provides a full photo-peak efficiency for single events of around 1% at 1.3 MeV.

The vacuum chamber is designed in a modular fashion such that any combination of in-vacuum ancillary detector subsystems can be utilized to meet the spectroscopic requirements of experiments. A central component of the facility, which is employed in every experiment, is a fast in-vacuum continuous-loop tape-moving system that was funded by the United States Department of Energy (DOE) and built by Louisiana State University (LSU). In a typical experiment, a rare-isotope ion sample is deposited on the tape, at the central focus of all detectors. After a measurement period, the tape system then removes the sample in a programmable cycle out of view of the detectors to remove background that arises from long-lived daughter nuclei or beam contaminants.

Figure 1: Photograph of the east hemisphere of the 8π spectrometer. Photo credit to Mikey Enriquez of the Global Photowalk 2010.

The vacuum chamber can also accommodate SCEPTAR (SCintilator Electron-Positron Tagging ARray). SCEPTAR, funded by NSERC, counts beta particles with 20 plastic scintillators covering 80% of the full 4p solid angle. SCEPTAR can be used simultaneously in a “singles” mode for normalizing of high-precision branching ratio measurements or high-precision half-life measurements [1] and for β-γ coincidence spectroscopy to eliminate the ~2000/s γ room background events from one to two decays per second of weakly produced, exotic beams [2]. The geometry is such that each HPGe views the sample through one, and only one, unique SCEPTAR element. Applying a veto to events with collinear SCEPTAR and HPGe detection reduces continuum bremsstrahlung background in the γ-ray spectra. The upstream and downstream hemispheres of SCEPTAR can be used together for maximum beta efficiency, or individually in combination with another ancillary detector type.

While SCEPTAR is well suited for simply counting beta particles with high efficiency, PACES (Pentagonal Array for Conversion Electron Spectroscopy) measures electron energies with high resolution [3,4].This enables spectroscopy of internal conversion electrons, an alternative decay process to γ -ray emission for excited nuclear states. PACES occupies the upstream hemisphere with five Si(Li) detectors cooled to near liquid nitrogen temperature. The efficiency of PACES for conversion electrons is approximately 5%. Internal conversion electron emission is much more likely for heavy nuclei so conversion electron spectroscopy is an essential tool for studying the heavy beams produced from the ISAC actinide targets. In lighter nuclei certain nuclear structure phenomena generate intense internal conversion transitions, such is the case in nuclei displaying shape coexistence around shell closures. PACES was supported by the DOE and NSERC. The cryogenic cooling system and detector housing assembly were designed by LSU.

Another ancillary detector of the 8π is DANTE (Dipentagonal Array for Nuclear Timing Experiments), which is located outside of the vacuum chamber and fills the spaces in the support structure between HPGe detectors. Ten barium fluoride (BaF_2) counters provide relative timing information for detected γ-rays with a resolution two orders of magnitude superior to HPGe [5]. These measurements, with stopped beams, access lifetimes down to 10 ps, covering the upper end of lifetime ranges for which in-beam techniques (Doppler-shift attenuation method or Coulomb-exchange) are appropriate. Building on experience gained by equipment on loan from the University of Surrey, the remainder of the array was funded by TRIUMF.

The data acquisition system of the 8π facility is arranged into four parallel FERA readout streams for each of the HPGe, plastic scintillator, Si(Li), and BaF_2 systems. The data acquisition infrastructure was funded by TRIUMF, NSERC, and the U.S. Lawrence Livermore National Laboratory.

High-precision β-decay half-life measurements have been carried out at ISAC since 1999 by direct beta counting using a technique that was first developed in Chalk River [6]. Although the measurements are simple in principle, great care must be taken to achieve the required precision (<0.05% for superallowed beta emitters whose half-lives range from 69 ms to 70 s). The low-energy (29 keV) radioactive ion beam from ISAC is implanted into a 25 mm wide 25 micron thick aluminized mylar tape of a fast tape transport system. After a collection period of roughly 4 half-lives, the ISAC beam is interrupted and the sample is moved out of the vacuum chamber through two stages of differential pumping and positioned in a 4π continuous-gas-flow proportional counter. After multiscaling the signals from the 4π counter for about 25 half-lives the data is stored and the cycle repeated continuously until sufficient statistical precision are accumulated. A 1 MHz ± 2 Hz laboratory clock is used to provide a time standard for the experiment which is controlled by a Jorway 221, twelve channel timing and sequence module. Sample purity is monitored using a HPGe detector located just outside the 4π β-counter or by delivering the beam of interest to the 8π which is a much more sensitive instrument to detect gamma-rays emitted by low intensity isobaric contaminants. Recently, the highest precision ever achieved in a single measurement for any superallowed beta emitter, 0.011%, was obtained using the GPS lifetime facility for Al-26m[7] and represents the experimental limit of this technique.

Recent Developments

With the development of actinide targets at ISAC, radioactive beams that undergo alpha decay can now be delivered to the 8π facility. In order to study the decay of these nuclei an upgrade to the electronic readout of the PACES lithium-drifted silicon detectors was necessary. The PACES detectors are sensitive to both the conversion electrons and the alpha particles seen in such decays, but the alpha particles produce much larger signals than conversion electrons, which would saturate the conversion electron readout channel. The addition of a parallel low-gain readout channel for each PACES detector allows for simultaneous observation of both conversion electrons (high-gain channel) and alpha particles (low-gain channel) in the same experiment. This capability was used in a preliminary search for decays of Astatine nuclei to access the excited states in neutron-rich Radon nuclei of interest for an atomic permanent electric dipole moment measurement.

The most recent development has been to replace seven of the ten barium fluoride detectors with lanthanum bromide ($LaBr_3(Ce)$) detectors, which offer a factor of three superior energy resolution. These detectors were funded by NSERC. This improved energy response dramatically improves coincidence-gated timing spectra and can therefore increase the sensitivity to weakly populated transitions.

In 2012 the GPS lifetime facility was moved to a new dedicated location in ISAC-I to make room for the new francium trap facility. At the same time, in collaboration with Louisiana State University, a new tape transport system was designed to use 50 micron mylar tape with a thick, 25 micron, aluminum layer on one side, to eliminate the problem of diffusion of gaseous isotopes of interest such as O-14 and Ne-18,19 encountered when these ions were implanted into the 25 micron aluminized mylar tape that must be used with the existing fast tape transport system. This upgraded GPS lifetime facility is now fully operational and the first high-precision lifetime measurement was carried out in summer 2013.

The final operation of the 8π facility will be in December 2013, at which time there will be a significant upgrade to the decay spectroscopy capabilities at ISAC with the installation of the GRIFFIN facility. GRIFFIN is supported through funding from the Canada Foundation for Innovation, TRIUMF, and a funding application led by the University of Guelph. With initial operation in the fall of 2014, GRIFFIN will be a major upgrade to the HPGe aspect of the 8π to an array of 16 large-volume HPGe clover detectors (see Figure 2). This will represent a factor of 17x increase in single gamma-ray efficiency, as well as close to 300-fold increase of gamma-gamma coincidence efficiency (see Figure 3) at 1.3 MeV. This upgrade of the HPGe aspect will be accompanied with the addition of a custom-designed, state-of-the-art digital electronics data acquisition system that will allow high counting rates and high accountability for precision measurements. GRIFFIN will be compatible with all existing ancillary detector systems of the 8π facility: the in-vacuum tape system, SCEPTAR, PACES, DANTE, as well as the new DESCANT array of deuterated scintillators for neutron-tagging, which has been developed

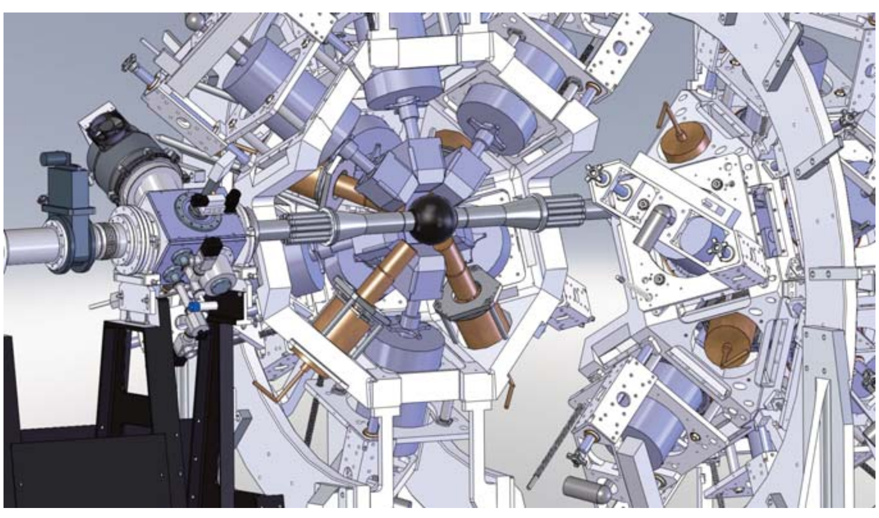

Figure 2: Schematic of 8π clover-detector arrays.

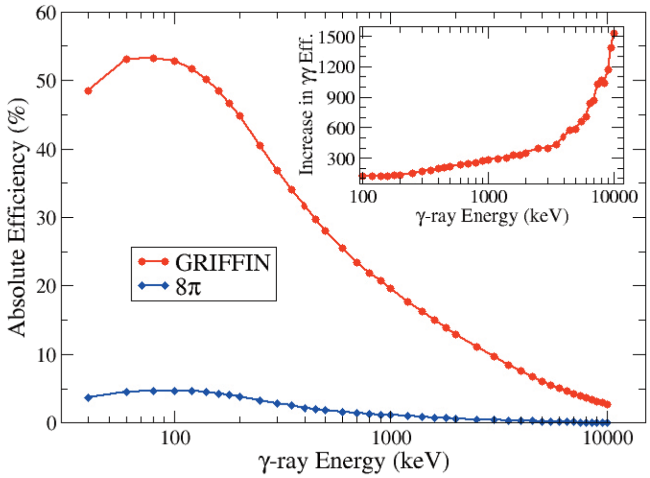

Figure 3: Gamma-gamma coincidence efficiency of 8π compared to GRIFFIN.

for use with TIGRESS in accelerated beam experiments. The support structure of DESCANT is fully compatible with GRIFFIN to enable the study of the beta-delayed neutron process in neutron-rich nuclei produced by ISAC and ARIEL.

Partners

In Canada: University of Guelph, McMaster University, l'Université de Montréal, University of Toronto, Saint Mary's University, Simon Fraser University, and Queen's University.
International Partners: Belgium (1), France (2), India (1), United Kingdom (1), United States (3).

TRIUMF's Role

The TRIUMF Gamma-ray Spectroscopy Group plays a lead role in the scientific program of these facilities. TRIUMF provides a dedicated technician for 8π, TIGRESS, and GPS. During the construction phase of GRIFFIN an additional dedicated technician will support the effort. One staff scientist manages the 8π and GPS programs as well as the GRIFFIN construction and installation project; a second staff scientist provides support. TRIUMF designed, fabricated, and installed several components of 8π, including the beam line, modified detector mounts, and Hevimet collimators for the HPGe, rails, the stand for the tape system, target chambers for SCEPTAR and PACES, detector mounts for DANTE, cable trays, electrical service, and an enclosed, cooled enclosure for the electronics.

TRIUMF also provides front-end readout computers, back-end workstations, data acquisition software, networks, and mass data storage for the 8π that will continue for GRIFFIN.

TRIUMF also plays a major role in the design, fabrication and development of the custom-built digital data acquisition for the GRIFFIN spectrometer. The TRIUMF design office is designing all aspects of the GRIFFIN support structure, dedicated beam line and climate-controlled electronics enclosure. A large fraction of the mechanical components of the GRIFFIN mechanical support structure are being fabricated in the TRIUMF machine and scintillator workshops.

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5.5.1.4 TITAN

Understanding the interactions at play in atomic nuclei requires that precision data on the fundamental properties of nuclei be determined with accuracy. TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN) is currently one of the world's leading facilities for performing precision measurements using ion trap techniques. TITAN's goal is to perform these precision measurements on fundamental properties, such as the mass of atomic nuclei and the shape of nuclei via X-ray detection; however, it also serves as a one-of-a-kind system that prepare the exotic beam for other experiments, such as supplying cooled and bunched beams for laser spectroscopy. With ISAC, the source of some of the most exotic beams produced anywhere, and when connected in the future to ARIEL (please see Section 5.3), it makes for a unique and powerful combination.

Recent Developments

Precise mass measurements performed at TITAN have greatly impacted the knowledge of how nuclear structure evolves toward the neutron drip-line. These measurements have shown the importance of three-body forces in medium-mass nuclei. In addition, the recent installation of X-ray detectors in the electron-beam ion trap (EBIT) has allowed for proof of principle measurements of electron capture branching ratios. These ratios are important in determining matrix elements in double-β-decay experiments, which will be exceedingly important in determining the mass of a Majorana-neutrino, if, in fact, they do indeed exist. TITAN is the only Penning trap in the world that can perform measurements on very short-lived nuclei ($T_{1/2} < 10$ms), and developments are underway to go to even shorter lived nuclei (Be-14, $t_{1/2}$=4.5 ms). With all the recent developments in beam production at ISAC-I, we expect TITAN to break this record again (i.e. measure Be-14 with 4.5 ms), which is less than the half live of Li-11 with 8.6ms.

TITAN is based on atomic physics techniques adapted to the requirements of nuclear physics with short-lived radioactive beams. This is done by using well-established ion trapping techniques very similar to the techniques used in the work that received the 2013 Nobel Prize in Physics, i.e. the precise control and quantum manipulation of single ions. These single ions are stored using electric and magnetic fields, which provide well-defined environments, and which, in return, provide an ideal laboratory for performing precision measurements.

Description of Apparatus

The TITAN facility currently comprises three ion traps: a radio frequency quadrupole (RFQ) cooler and buncher for beam preparation, an electron beam ion trap (EBIT) for charge breeding, and a measurement Penning trap (MPET) for high-precision mass measurements on both singly and highly charged ions. The RFQ is used to cool and bunch the beams delivered from ISAC. The beam typically arrives with 20 keV of energy, where the RFQ then stops and captures the beam with only a few tens of eVs of energy. The cooling is provided by an inert buffer gas. Once the beam has reached thermal equilibrium and is accumulated in a defined trap region, this RFQ trap is opened and the ions are released as a bunch. TITAN's RFQ is noteworthy because it is the only RFQ that is capable of "forward" and "reverse" extraction. In forward extraction the beam is sent towards the other TITAN traps, for example the EBIT or MPET. Reverse extraction enables other ISAC experiments, such as the co-linear laser spectroscopy experiment, to use cooled and bunched beams.

The EBIT's predominant role is in charge breeding the singly charge ions (SCI) delivered from the RFQ. Charge breeding is important because the precision achievable in a mass measurement is directly proportional to the charge state of the ion. In the EBIT a beam of high-energy electrons is directed at the trapped cloud of SCIs. The charge state of the trapped ions is increased by subsequent impact ionization, and hence removal of electrons of the atomic shell. EBITs have been successfully used in Penning trap experiments with stable beam. Today, TITAN is the only Penning trap facility in the world that is able to perform measurements on highly charged rare isotopes. Since rare isotopes are typically short lived, and are produced in small quantities, a stringent requirement is that the charge breeding process be both fast and efficient. The EBIT is designed to have electron beam energies of up to tens of keV and currents of 0.5 A that will allow ions to be bred to high charge states extremely quickly. The EBIT is also equipped with 7 radial view ports, which allow for optical access to the trap centre. This access facilitates a different class of unique in-trap decay spectroscopy experiments such as the TITAN Electron Capture (EC) experiment.

The Cooler Penning trap (CPET), currently in development, is designed to prepare beams of HCIs for injection into MPET. CPET can originally utilize electrons to cool the HCIs; however, in the future, cooling with protons will be investigated as well. The cooling of antiprotons with electrons has already been shown, and simulations indicate that electron cooling of HCIs is possible, with high survival rates. Currently the major components of CPET have been assembled and offline testing has commenced.

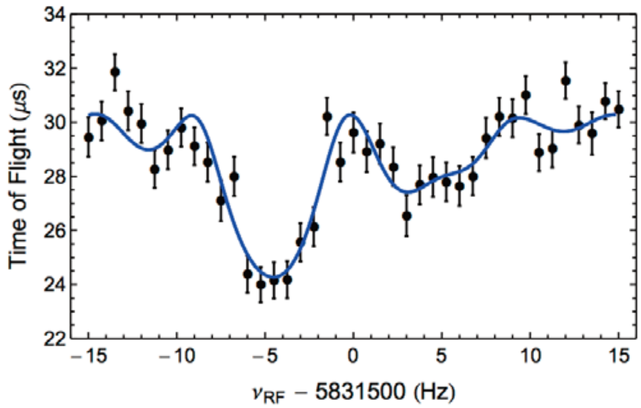
Bunches of either singly or highly charged ions are then sent to MPET for precision mass measurements. Penning traps provide an ideal environment to conduct precision experiments: A single ion is stored near rest in high vacuum (pressures approximately one trillion times smaller than atmosphere) and is subjected to well-defined electric and magnetic fields. The combination of a strong magnetic field and a weak electric field was used to confine ions both radially and axially, respectively. The motion of these trapped ions is well understood, which allows for a high-precision determination of the mass through a measurement of the cyclotron frequency. When an ion is placed in a magnetic field, it will begin to revolve at the cyclotron frequency $\nu_c = qB/(2\pi m)$. By exciting the ion's motion with this frequency it is possible to shorten the time-of-flight to a detector when the ion is extracted from the trap. By measuring this minimum time-of-flight, the cyclotron frequency can be extracted.

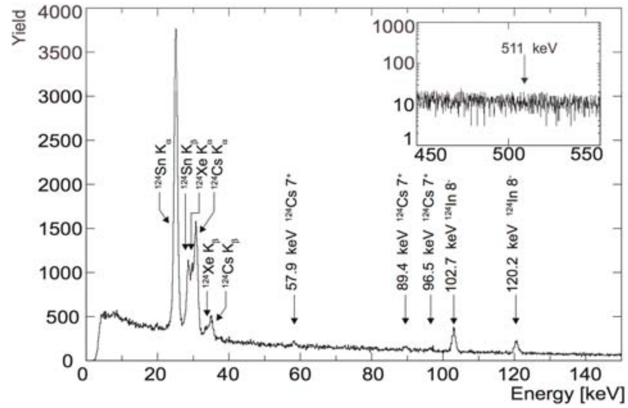
The in-trap experiments currently carried out include the above-mentioned TITAN-EC that aims to measure electron-capture branching ratios (ECBRs) of the intermediate nuclei in double-beta ($\beta\beta$) decays. Those ECBRs are important because they provide information about the ground-state properties of the nuclear wave function connected to the nuclear matrix elements involved in the $\beta\beta$ decay for both decay processes, the two-neutrino ($2\nu\beta\beta$) and the neutrino-less ($0\nu\beta\beta$) decay. The latter is particularly interesting since its detection would validate the Majorana character of neutrinos (i.e. whether the neutrino is its own anti-particle). The X-rays following the EC decay are detected by a set of detectors mounted in the view ports of the EBIT. The presence of the EBIT's magnetic field offers the additional advantage that electrons or positrons from the much more intense β^-/β^+ decays are directed on axis out of the trap and away from the detectors surrounding the EBIT. Hence there is no background created by β^- particles.

Recent Developments

TITAN has recently begun to harness the gain in precision made possible through the use of highly charged ions. The first measurement completed was of Rb-74, which is an important nuclide to test the Standard Model. A previous measurement of Rb-74 at ISOLTRAP achieved a precision of ~6 keV during a run time of ~60 hours. TITAN was able to reach a similar precision by using HCIs, and the measurement was completed in only 20 hours and with much less statistics required (see Figure 1). Next, it was demonstrated that HCIs could be used to resolve the mass difference between the ground state and low-lying isomeric states.

A Q-value measurement of Ge-71 and Ga-71 was completed using a novel threshold charge breeding technique. By tuning the EBIT to limit the maximum charge state that could be achieved, and combined with the increased yields from the TRILIS laser ionization source it was possible to produce beams of highly charged isobarically pure beams. The Q-value measured in this experiment was important to help clarify a long-standing discrepancy between the SAGE and GALLEX solar-neutrino experiments. With an accurate value for the Q-value, the uncertainties in the nuclear physics inputs have been removed, which may lead to new physics being the explanation for the observed difference between the two experiments.





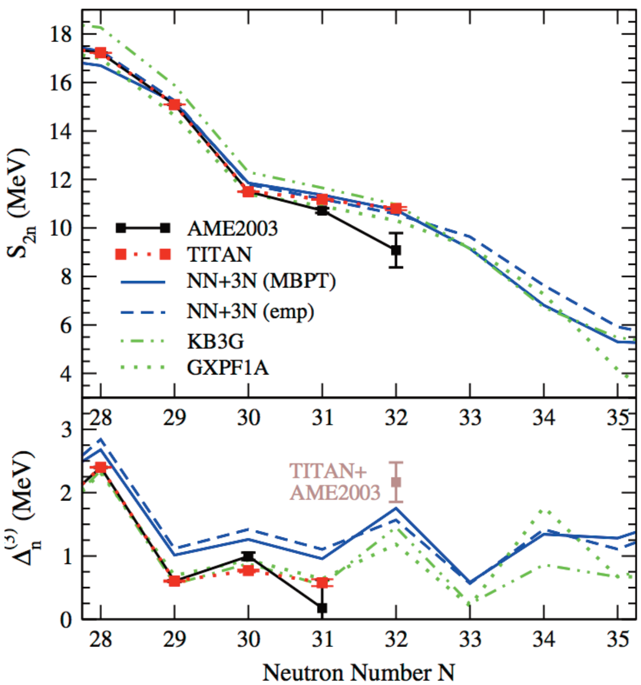


Figure 1: Highly charged resonance of Rb-78 showing the resolved ground (right dip) and isomeric (left dip) states.

Figure 2: Evolution of two-neutron separation energy, measured versus theory.

Figure 3: Electron-capture spectra. The lack of a 511keV line in the inset shows that background producing beta particles are guided away from the detectors.

Highly charged ions have also been used to explore how elements heavier than iron are created in core-collapse supernovae. The so-called *r*-process occurs during these supernovae, which are characterized by the rapid capture of neutrons. The exact path the *r*-process follows is not known due to a lack of knowledge of the basic nuclear properties of these nuclei. The masses of the neutron rich nuclei Rb-(94, 97, 98) and Sr-(94, 97, -99) were performed in a charge state of q=15+. In many cases, the uncertainty in the mass value was improved by over an order of magnitude and has eliminated any dependence on these masses in *r*-process model calculations.

TITAN has also recently investigated the evolution of nuclear shell structure near the limits of stability. Much theoretical and experimental work has been undertaken to explore the region near N=32 and 34. It has been predicted that new sub-shell closures should appear here, and while experiment and theory agree on the existence of the N=32 sub-shell closure, theory disagrees on the existence of the N=34 closure, while experiment has found no evidence. The TITAN mass measurements of Ca(51,52) and K(50,51) (N=31,32) show a much more flat behaviour in the mass surface than tabulated by the 2003 mass evaluation (see Figure 2). Large deviations of up to 1.7 MeV/c^2 in the mass were seen. This behaviour was predicted by new state-of-the-dart theory calculations that take into account the effects of three-body forces.

VANESSA SIMON RECOGNIZED AT 2011 WNPPC

07 March 2011

Vanessa Simon, a Ph.D. student from the University of Heidelberg and Max-Planck-Institut für Kernphysik (both in Germany) who is working here at TRIUMF was awarded 3rd prize for Best Student Presentation at the 2011 Winter Nuclear and Particle Physics Conference in Banff, Alberta. The conference focused on topics of research that are of great interest to the Canadian community. Geared towards junior researchers such as students and post doctorate students, it featured sessions focusing on areas of research such as nuclear astrophysics, anti-matter physics, and neutrino physics.

Simon's topic was the "TITAN Penning Trap for Cooling Highly-Charged Radioactive Ions at ISAC." In her 20-minute presentation to the audience of Canada's top researchers in nuclear and particle physics, she gave an overview of the TITAN experiment. She explained the development of the Electron Beam Ion Trap (EBIT), which helps prepare highly charged ions for improved precision in mass measurement.

"It feels quite good to be recognized." Ms. Simon said, "I appreciate the interest in my project and the recognition. It's an honour, and it motivates me to continue working hard."

The feasibility of the TITAN-EC set-up for measuring low branching ratios was proven by a test experiment on the isotope Cs-124 was performed in November 2012 (see Figure 3). A trapping time of up to 30s was demonstrated, which allows for half-life measurements in a region from seconds to minutes. These tests show that with further improvements, branching ratio measurements on the order of 10^{-3} are possible within the year.

Partners

In Canada: McGill University, University of Manitoba, University of Windsor, University of Calgary. International Partners: France (2), Germany (3), Switzerland (1), United States (5).

TRIUMF's Role

The scientific program and TITIAN collaboration are led by a TRIUMF staff scientist. TRIUMF provides a dedicated technician for the TITAN facility and delivers RIB beams to it. TRIUMF and NSERC invested approximately $3,500,000 into the TITAN facility.

5.5.1.5 LASER SPECTROSCOPY

An atom, by its very nature, consists of a nucleus surrounded by electrons. It therefore follows that one of the most sensitive probes of the nucleus are those electrons that are naturally interacting with it by matter of course. Laser spectroscopy makes use of this interaction by means of probing the electron's state in order to obtain detailed information on the shape and size of the nucleus. When implemented at a radioactive beam facility, where long chains of isotopes of the same chemical element are available, the evolution of nuclear structure can be probed from the relatively stable isotopes found in nature out to the extremes of nuclear structure. The techniques employed are almost universal across the chemical chart allowing information to be gained from the lightest Li and He isotopes out to francium, astatine, and beyond.

The basic technique of choice at ISAC has been collinear laser spectroscopy on beams prepared using TITAN's radio frequency (RF) buncher. This is a variant on the traditional collinear laser spectroscopy technique that was pioneered in Jyväskylä, Finland and is now in use at almost all radioactive beam facilities around the world where laser spectroscopy is performed. A schematic overview of the system is shown in Figure 1.

Description of Apparatus

The collinear, fast beam, laser spectroscopy facility utilizes the polarizer beam line as well as the radio-frequency quadrupole (RFQ) buncher that is the first trap in the TITAN mass trapping facility. A unique feature of the system at TRIUMF is that the RFQ is out of the plane of ion transport system. This allows the beam to either be directed into it, accumulated, and then ejected back into the beam line, or simply bypass the RFQ and proceed directly to the interaction region. Depending upon the details of the species to be studied, the ion beam can either be neutralized by passing through an alkali vapour cell or proceed purely as an ionic beam. In either case the beam is overlapped with a counter propagating laser and the laser frequency in the rest frame of the beam is scanned. When the laser is resonant with an atomic transition resonance, absorption occurs, resulting in spontaneous emission of light at the resonant wavelength. These resonantly scattered photons are detected by a photomultiplier tube mounted perpendicular to the direction of propagation of both radioactive and laser beams. Primary background suppression is achieved by means of a series of filters, often including a narrow bandwidth interference filter, placed in a parallel section of the light collection optics.

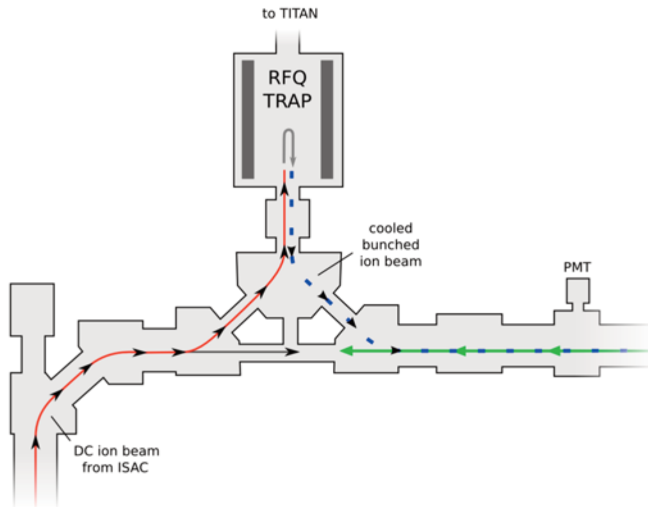


Figure 1: A schematic of the laser spectroscopy system.

Unique to the TRIUMF facility is a dedicated data-acquisition system designed around an FPGA-based multichannel scaler system. This system not only permits the usual scanning of beam energies and/or laser frequencies but also is completely time synchronized to the buncher injection and extraction timing. This permits for the time evolution of the expected signals to be mapped out and used not only for background reduction but also for investigations into any time dependant systematic effects. A typical spectrum is shown in Figure 2, with the raw two-dimensional data shown along with both time and energy projections.

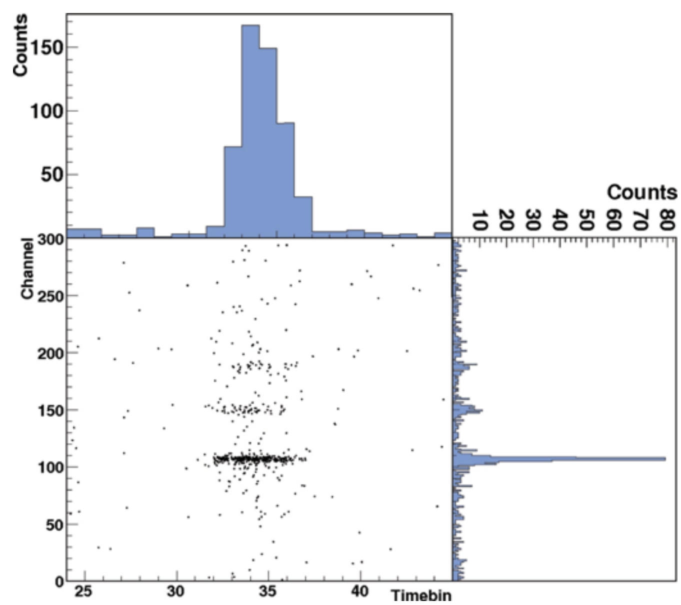


Figure 2: A typical 2D spectrum.

In addition to using the atomic electrons to probe the nucleus, the hyperfine interaction can be used in reverse. By manipulating the electrons it is possible to influence the nucleus. Most notably this method can be used in order to produce a polarized beam. Once again, unique to TRIUMF, is a pair of highly sensitive beta-detected nuclear magnetic resonance spectrometers. Whilst normally used for materials science work, these spectrometers have also been utilized for nuclear physics purposes. The dual spectrometer system at TRIUMF allows nuclei to be probed in both high (several Tesla) and low (down to zero) magnetic environments. This unique ability allows the magnetic and electric moments to be decoupled from each other and probed independently, resulting in significant improvements in sensitivity over other systems.

Recent Developments

Over the last five years this project has gone from starting out to being operational. The major developments include a new dedicated laser laboratory. Housing narrow line width ring dye and Titanium Sapphire lasers pumped with traditional Argon ion lasers along with frequency doubling capabilities, it is possible to access virtually all wavelengths that can be fibre coupled to the beam line. In the near future it is envisioned that this laboratory will be coupled to others around the ISAC Hall to allow for the sharing of laser light between projects ensuring the most efficient use of equipment. Currently, long-term laser stabilization is achieved by using a reference cavity stabilized to a commercial frequency standard, currently a polarisation stabilized Helium Neon laser.

Major developments have included not only the data-acquisition system but also the development of radio-frequency (RF) techniques to manipulate the laser light in order to make better use of the available atoms. Basic techniques have been developed to prevent atoms being pumped from one atomic hyperfine state to another in the region between charge exchange and observation. This involves switching the narrow linewidth, continuous wave laser beam via an electro-optic modulator such that each atom is only able to interact with a single, approximately two atomic lifetimes wide pulse of light. This allows the light, when present, to be of significantly higher intensity, resulting in higher probabilities of excitation in the region of interest. This technique was first demonstrated on neutron deficient Francium atoms and later used with great affect on the neutron rich Rb-98m and 99.

Runs over the past five years include B-NQR on Li8, 9 and 11 (S1155) as well as collinear spectroscopy on neutron-deficient Francium atoms (Francium 208,206,206m, 205,204,204m,204m') and neutron-rich Rb isotopes (92,98,98m,99). This data is in the process of being analyzed and published.

Partners

In Canada: McGill University.
International Partners: Finland (1), Japan (1), United Kingdom (1), United States (1).

TRIUMF's Role

TRIUMF leads the laser spectroscopy program with a staff scientist and provides ongoing support for the polarizer beam line and data acquisition as well as providing beams. Over the past five years, TRIUMF has also provided and funded the renovation of space to enable a dedicated laser laboratory to be established. TRIUMF has invested approximately $70,000 in this program, along with an NSERC investment of approximately $500,000, with a replacement cost of all equipment ~$1,500,000

5.5.1.6 FRANCIUM TRAPPING FACILITY

Francium is the heaviest known alkali element. Its high nuclear charge, large mass, and relatively simple atomic and nuclear structure make it an ideal laboratory for the study of many fundamental properties. These range from basic nuclear and atomic structure measurements, both of which enhance the knowledge of this region of the nuclear chart and also provide stringent tests of theoretical models, to high-precision tests of the Standard Model via the weak interaction. However, along with the many advantages of using Francium for this purpose comes a drawback: francium is the least stable of the first 103 elements on the periodic chart. With no stable isotope, and an estimated worldwide inventory of 20 g at any one time, these studies are required to be carried out at radioactive beam facilities. Facilities such as ISAC at TRIUMF do not naturally provide the required controlled environment to permit such high-precision studies to be performed.

To this end the Francium Parity Non-Conservation (FrPNC) collaboration has constructed and commissioned a Francium trapping facility within the ISAC experimental hall, supplied with radioactive beams from ISAC (and, in the future, from ARIEL, please see Section 5.3). This facility consists of a fully enclosed Faraday cage with independent climate control into which the francium is brought as an ionic beam. The ions are then neutralized and injected first into a magneto optical trap (MOT) where the atoms are cooled and trapped using laser beams. From here they can either be probed directly in order to obtain atomic hyperfine structure information or transferred to a second, more specialized trapping system where high precision, weak interaction studies can be performed. The trap system allows for high precision measurements, which can probe the very basics of fundamental forces because the environment in which the atoms are held is highly controllable.

Description of the Facility

The facility consists of a commercially purchased Faraday enclosure with a shielding factor in excess of 100 dB between 14 kHz and 1 GHz. This is sufficient to totally remove any measurable electrical noise from the ISAC hall, including leakage from the nearby accelerators. In addition to providing RF shielding, the entire enclosure is electrically isolated from the ISAC hall, permitting a single point earth to be established, significantly reducing any electrical noise. The enclosure also permits the environment within to be controlled independently of the environment in the surrounding ISAC hall. This enables temperature and humidity control consistent with the requirements for delicate measurements of the weak interaction to be achieved. All penetrations into the room, which provide compressed air, HVAC, cooling water, telephones, Ethernet, and most importantly the ISAC beam, have been engineered so as to not break either the earth isolation or the RF shielding.

The enclosure houses all the elements required to load incident alkali ions from ISAC into a magneto optical trap and from there into more specialized trapping systems. This includes the laser systems that are mainly Titanium Sapphire ring lasers frequency stabilized by transferring the stability of a commercial, polarization stabilized Helium Neon laser using a scanning Fabre Perot cavity [1]. The use of tunable ring lasers affords the versatility to change the alkali element being trapped whilst using the same laser systems.

A new development to decouple the light production from the trapping system is a fully fiber coupled trap. All of the laser light required for trapping, manipulation of the trapped atoms, and any measurements made, is fiber coupled across to the trap using single mode fiber combiners and splitters. Not only does this significantly reduce the complexity of optics around the trap region but also eliminates the dependence of the trap alignment on the laser's output direction as well as preventing high-powered, free laser beams from crisscrossing the enclosure.

Francium (or other alkali) beams enter the enclosure through a differentially pumped vacuum system that transitions from the usual ISAC beam line vacuum (~1e-5Pa) to the ultra-high vacuum required for a trap (~10-8Pa) where it impinges upon an yttrium foil. Based upon a concept developed at Stony Brook [2], the MOT is loaded in a pulsed mode. The yttrium foil is normally in the *down* position whereby the ion beam is in incident upon it, and accumulated on it. Once saturated with activity, the foil assembly is flipped into the *up* position whereby it closes the input to the trapping glass cell. The foil is rapidly, resistively heated for approximately one second, releasing the surface francium predominantly in atomic form. This vapour is then trapped in the MOT and either ready for measurements or, in the future, ready to be transferred to a second, science chamber located below the capture trap and optimized for the measurement to be performed rather than for the accumulation of atoms. A drawing of the assembly with the foil in both *up* and *down* positions is shown in Figure 1.

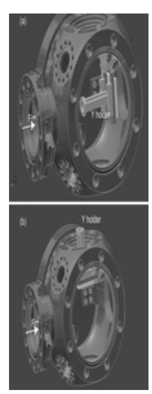


Figure 1: Neutralizer chamber with the neutralizer holder in the catching down position (a). Neutralizer chamber with the neutralizer holder in the delivery up position (b).

In addition to using the online beam directly a method of collecting a long-lived, albeit somewhat smaller, sample of Fr-221 has been developed. By utilizing the availability of long-lived Ac-225 (t-1/2=10.5d) beams after protons have stopped irradiating an ISAC target, a source can be collected that releases a small amount of Fr-221 over the half-life of the Ac. This has successfully been used to investigate systematic effects within the trapping system. It is envisioned that in the near future this system will allow for technical developments to take place over a period of a couple of weeks following an actinide target run at ISAC, irrespective of what is happening elsewhere within the hall.

Recent Developments

To date several isotopes have successfully been trapped, namely Fr-206,207,209,213. For each of these the atomic $P_{1/2}$ state hyperfine splitting has been successfully measured using a technique of rapidly sweeping a pair of sidebands using microwave-scanning techniques. In a technique developed at TRIUMF by the collaboration, the probe laser light is passed through a high bandwidth (20 GHz) fibre modulator. To this microwaves are applied at a frequency similar to that of the required hyperfine splitting. By rapidly sweeping the microwave frequency, one sweeps the frequency of these sidebands relative to the stabilized laser. With the carrier placed approximately central, with respect to the atomic hyperfine states of interest, a modest size scan (~few hundred MHz) can result in a statistically, high precision measurement of the state splitting. A typical spectrum for Fr-206 is shown in Figure 2. The rapid (a full scan taking ~20 ms) microwave scanning almost eliminates the systematic errors due to the long-term laser frequency shifts

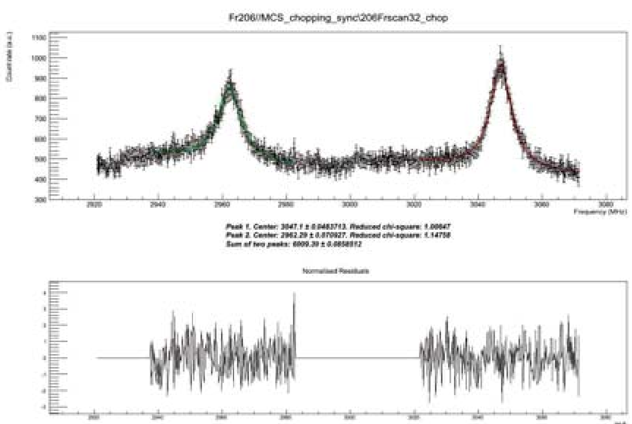


Figure 2: A typical spectrum Fr-206. The rapid (full scan taking ~20ms) microwave scanning almost eliminates the systematic errors due to the long-term laser frequency shifts.

Partners

In Canada: TRIUMF, University of Manitoba.
International Partners: Australia (1), China (1), Mexico (1), United States (3).

TRIUMF's Role

TRIUMF has a leading involvement in the FrPNC program through two staff scientists. Over the past few years TRIUMF has not only provided space in the ISAC Hall but also relocated the two running experiments that used to operate in that space. TRIUMF has also provided the beams required for experiments to take place as well as a custom, high vacuum to ultra-high vacuum transitional beam line and significant amounts of technical expertise in building, controlling, and running the required systems. In addition to this over the past two years TRIUMF has hosted two sabbatical visitors dedicated to this project. In terms of money, TRIUMF has invested approximately $100,000. In addition, the U.S. Department of Energy has provided approximately $900,000. The entire replacement value would be approximately $1,500,000

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5.5.1.7 MTV: TEST OF TIME REVERSAL SYMMETRY USING POLARIZED UNSTABLE NUCLEI

Time reversal symmetry is one of the most fundamental symmetries of physics. It is equivalent to symmetry between matter and antimatter. In order to explain why our universe is dominated by ordinary matter, unknown interactions that violate time reversal symmetry are required to exist. The MTV (Mott polarimetry for T-Violation) experiment searches with the highest precision for violation of time reversal symmetry, which is predicted by models of physics beyond the Standard Model, in the nuclear beta-decay of the radioisotope Li-8 using a new type of particle position detection device. Following first tests at TRIUMF in 2009 the first physics data taking was performed in 2010, achieving the finest statistical precision. A next-generation device was developed in 2011, tested in 2012 and will begin taking data in 2013. This experiment will produce the most precise result on this particular test of time reversal symmetry.

Description of the Apparatus

The MTV experiment was originally performed at KEK in Japan where a 10% precision was achieved [1] using a newly developed particle detector that could precisely measure the polarization of electrons emitted in the beta decay of polarized Li-8 nuclei.

Existence of electron polarization perpendicular to its momentum direction is the signal for the violation of time reversal symmetry. In a first stage, a planar multi-wire drift chamber (MWDC) is applied as the polarimeter to detect the position of the electron path with hundreds of thin wires in a gas-filled chamber. In 2009 this setup was placed at a low-energy polarized beam line at ISAC (see Figure 1) and a first test experiment was performed with polarized Li-8 beam from ISAC with up to 107 particles per second and around 80% polarization. These numbers were compared with 105 particles per second and 8% polarization at KEK.

In addition, the performance of the MTV detectors was tested with the high beam intensity, which is a hundred times larger than at KEK. The tests confirmed that a statistical precision of at least 0.1% could be achieved with this set-up [2-3]. After improving the detector and electronics performances a first physics run was performed in November 2010, and this run yielded sufficient statistics to achieve the expected precision. In order to further improve the experimental precision, the original MWDC was replaced by a cylindrical drift chamber (CDC), which was developed in Japan in 2011. By utilizing the cylindrical symmetry of the CDC, the experimental precision could be improved by cancelling undesired systematic effects, which limited the final precision achievable with the MWDC. The CDC was commissioned in November 2011, and final tests of the full detector setup were carried out in 2012 (see Figure 2). The physics data taking with the new CDC setup will start in 2013.

The Standard Model of particle physics predicts negligible signals for the MTV experiment. Therefore, it can be said that this experiment is sensitive to the signals of new physics by suppressing the Standard Model background. Expected precision of 0.01% with the CDC promises to explore such new physics signals.

Figure 1: The MTV setup with the MWDC at ISAC in 2010.

Figure 2: The MTV setup with the CDC at ISAC in 2012.

Partners

International Partner: Japan (4).

TRIUMF's Role

TRIUMF delivered the world highest intensity and polarization Li-8 beam to the experiment, operated the collinear laser facility to produce the polarized beam, provided ongoing detector maintenance.

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5.5.1.8 β-NMR FACILITY

The beta-detected nuclear magnetic resonance (β-NMR) facility at ISAC is constructed specifically for using radioisotopes for experimental studies in materials science, utilizing a probe beam of spin-polarized radioactive ions such as Li-8^+ (half-life = 848 ms) to monitor the local electromagnetic properties of the host material sensed at the atomic scale. A crucial capability of this technique is control of the average implantation depth of the probe, thus obtaining *depth resolution* on an interesting length scale (5–200 nanometers).

The β-NMR facility at TRIUMF is unique in the world. Similar to the low-energy muon facility at PSI in Switzerland (using polarized μ^+ as probes) it applies a low-energy spin-polarized probe to studying magnetic and related phenomena on nanoscale depths into materials. However, β-NMR is sensitive to much longer timescales than low-energy muons. These local probe techniques provide important complementary tools to reciprocal space methods like polarized neutron reflectometry (PNR) and synchrotron techniques such as resonant inelastic X-ray scattering (RIXS)—that also study depth-dependent electromagnetic properties of materials. As with conventional NMR, the nuclear spin senses its local environment, specifically the local magnetic field (which is determined by the surrounding electronic structure of the host), and the electric field gradient via the quadrupolar coupling, as well as fluctuations of these quantities that result in relaxation of the probe nuclear spins.

The β-NMR facility is used for a number of experiments in magnetism and superconductivity as well as on novel ultra-thin heterostructures exhibiting properties that cannot occur in bulk materials. Recently the scope of research using this facility has expanded into soft condensed matter and ionic conductivity. The science program is described elsewhere in this Plan. Here we give a technical description of the facility, its operation, and TRIUMF's role.

Description of Facility

The facility consists of a polarizer and a suite of spectrometers.

Polarizer. The polarizer does the essential step: the alignment of the probe ion beam's nuclear spins. To do this, it uses circularly polarized laser light whose wavelength is tuned to an atomic transition of the probe. The layout of the polarizer and two spectrometers is illustrated in Figure 1. The polarizer consists of a section of low-energy beam line situated 6 m upstream from the experiments and associated laser facilities. In detail, the polarizer functions as follows. A 20–30 keV incident Li-8^+ beam is partially neutralized with ~50% efficiency in a Na vapour charge-exchange cell (CEC). Unneutralized ions exiting the CEC are removed from the beam by electrostatic deflection plates. The fast atomic Li-8 beam is nuclear-spin polarized in flight via collinear laser optical pumping with circularly polarized light on the D_1 electronic transition at 671 nm. Polarization as high as 80% can be achieved. In principle, ion beams of many chemical elements can be polarized through optical pumping. The alkali metals are the most straightforward, with high polarization achieved by pumping with visible wavelength lasers on the $^2S_{1/2}$ - $^2P_{1/2}$ or $^2S_{1/2}$ -$^2P_{3/2}$ atomic ground state transitions. Most sodium and lithium isotopes have been polarized in this facility, which also serves other experimental groups besides condensed matter physics.

The polarized beam is re-ionized through impact ionization in a windowless, cooled helium gas cell with over 60% efficiency. Re-ionizing the beam has several advantages: (1) The ion beam can be directed by electrostatic elements to different experimental stations. (2) Two experiments can share the same beam, through the use of a kicker. (3) The experimental target is not exposed to laser light. (4) The absolute polarization direction, initially longitudinal with respect to the beam motion, is unchanged by electrostatic elements. Therefore the beam polarization can be transformed from longitudinal to transverse simply by steering the beam through a net angle of 90 degrees, with no loss of polarization. (5) The beam energy at the target, and hence implantation depth, can be adjusted by applying a variable potential to the target. All of these features have been used to advantage at ISAC.

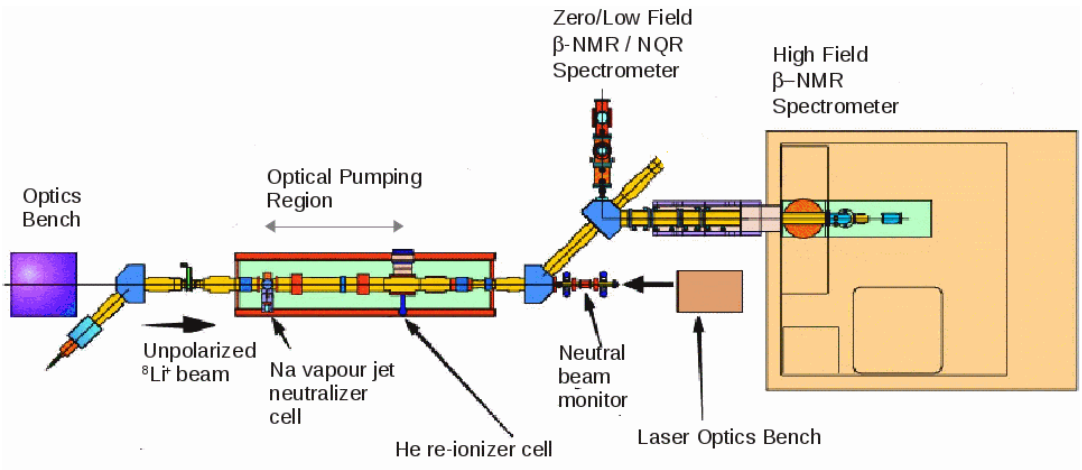

Figure 1: General layout of the in-flight polarizer and high- and low-field spectrometers. Beam (from the left) is longitudinally polarized while in-flight by counter-propagating circularly polarized laser light, then steered electrostatically to one of the two spectrometers.

Spectrometers. Two spectrometers have been constructed to cover different ranges of applied magnetic fields. Their purpose is to measure the spin polarization of the implanted Li-8$^+$. Two basic types of experiments can be performed with either spectrometer. Time-differential spin relaxation experiments, performed with pulsed beam, measure the rate at which the initial spin polarization is lost due to dynamic processes, usually as a function of temperature and/or applied DC magnetic field. In the frequency domain, by applying a weak radio frequency (RF) magnetic field and scanning over a range of frequencies, the resonance lineshape can be recorded, which measures the distribution of magnetic fields at the site(s) occupied by the probe Li-8 within the material being studied. Each spectrometer is equipped with a helium flow cryostat that provides stabilized sample temperatures in the range of 3–325 K. In order to reduce the accumulation of residual vacuum gases on the sample surface at cryogenic temperatures, spectrometers operate under ultra-high vacuum (UHV) conditions in the 10^{-10} Torr range. Samples are mounted to and removed from each of the cryostats via vacuum load-lock chambers, which can be isolated, vented, accessed, and pumped independently of the main vacuum system, thereby preserving the spectrometer UHV. When both spectrometers are running experiments that require pulsed beam, the beam can be kicked alternately to both spectrometers. In this mode of operation beam pulses typically 1 to 4 s long are sent to both spectrometers every 10 to 20 s, making the best use of beam time with no overhead. Each spectrometer is mounted on an electrically isolated platform that may be biased to a high electrostatic retarding potential. Simple electrostatic optics are used to decelerate the ions in the last few cm before impacting the sample surface. Deceleration close to the sample minimizes the lateral spread of the beam on arrival at the sample. Due to the very small energy spread of the beam and its small transverse momentum, well-focused beam spots, with energies down to a few hundred eV and stopping range of about 5 nm, are possible. Typically the beam lands within a ~2 mm diameter spot on the sample without the use of beam collimation at the spectrometer. At single-counter event rates of about 10^6/s, each resonance or spin relaxation run typically requires 20–40 minutes to accumulate. A temperature scan on one sample, at one implantation energy, can be completed in a day.

High Magnetic Field Spectrometer. The high field spectrometer (see Figure 2) uses a 9 T superconducting solenoid with field oriented along the incoming beam momentum. The implanted beam has nuclear polarization normal to the sample surface. Two detectors are situated along the direction of initial polarization to count the decay betas —one inside the cryostat 10 cm in the forward direction with respect to the sample position and one annular detector upstream of the magnet 75 cm in the backward direction. Although they are very different in physical dimensions, focusing of the decay electrons in high magnetic field results in nearly equivalent effective solid angles. The RF magnetic field is generated with a non-resonant helical transmission line having a flat 50 Ohm impedance and frequency response up to 45 MHz. The RF synthesizer, under control of the data acquisition system, can be programmed to generate continuous wave (CW) or complex-modulated pulsed RF excitation for various types of resonance experiments.

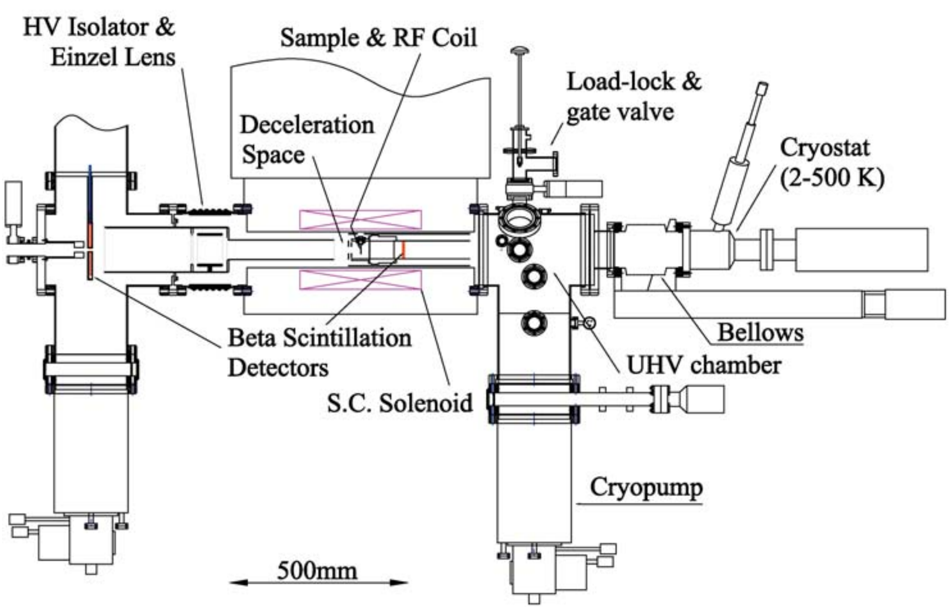

Figure 2: Schematic side view of the high-field β-NMR spectrometer. A polarized beam of Li-8+ ions enters from the left and comes to rest in a sample held in the cryostat at the magnet's center. The entire experiment may be raised to a high positive potential, creating a retarding electric field between the grounded end of the beam line and the front of the cryostat, thereby controlling the ion energy and implantation depth. Beta-decay events are counted by one detector located downstream of the sample within the cryostat, and another annular backward detector situated outside the magnet.

Zero- and Low-Field Spectrometer. Being optimized for low magnetic fields (0–24~mT), the low field spectrometer (see Figure 3) differs from the high field spectrometer in several fundamental ways. Due to the use of electrostatic dipoles in the low-energy beam line, the orientation of spins of the positive Li-8 ions exiting the polarizer is preserved while the beam momentum is bent through 90 degrees. Polarized $^8Li^+$ ions therefore arrive at the low field spectrometer with spin polarization transverse to their momentum and in the plane of the face of the sample. Two pairs of scintillation detectors and phototubes are situated outside the vacuum chamber on the left and right sides, arrayed along the initial polarization. A small coil generates an RF magnetic field perpendicular to H_0, in the plane of the sample surface. The RF system is capable of CW and complex-modulated pulsed-mode operation over a frequency range of 0–2 MHz. The external DC magnetic field H_0, if applied, is parallel to the initial polarization and therefore also in the plane of the sample face, an arrangement suitable for measuring the depth dependence of magnetic field in the Meissner state of superconductors. Trim coils can be employed to permit zeroing of the ambient magnetic field to within 1 μT. Therefore, in zero field, this spectrometer can perform nuclear electric quadrupole resonance (NQR) experiments. Samples are mounted into the low field spectrometer on a four-stage multiple sample ladder via a vacuum load-lock. The use of a ladder enables rapid changes among the loaded samples and beam spot imaging scintillator.

Recent Developments

In 2012, TRIUMF committed to providing at least five weeks of beam time per year for β-NMR experiments. Prior to this, the available beam time was substantially less and would fluctuate from year to year. Sufficient beam time with a predictable schedule was crucial to the viability of the program. Even with this increase, it will be difficult to compete with the PSI LEμSR facility that has much more available beam time and a much higher level of support in terms of facility manpower. With such restricted availability, it will be difficult to grow the user base. The ARIEL facility, which will start its science program with the delivery of Li-8 for β-NMR offers the prospect of alleviating this shortage in beam time. In the meantime, there are have been several developments specific to both spectrometers and the polarizer.

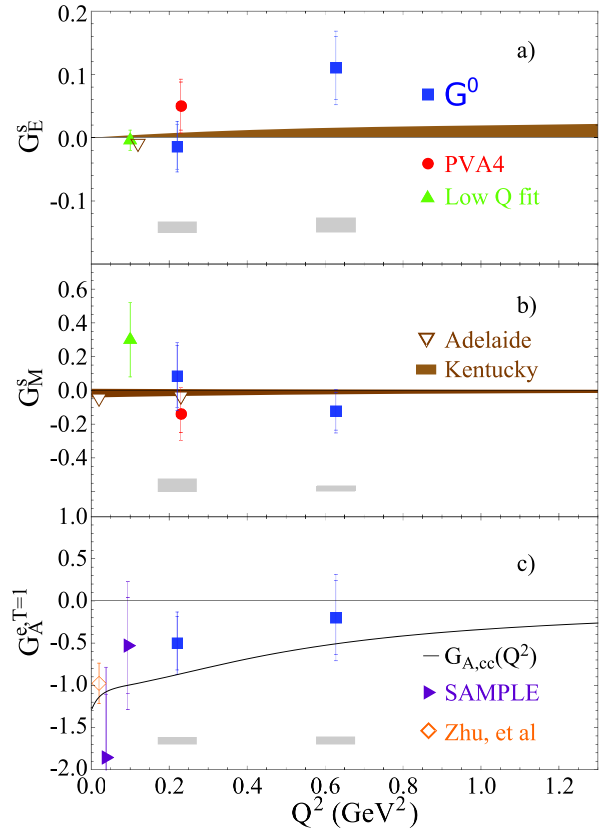

Figure 3: Schematic view of the zero-/ low-field β-NMR spectrometer from above. Unlike the high field apparatus in Figure 2, the initial polarization and applied magnetic field are in the plane of the sample face. Beta detectors are situated on either side, outside the vacuum vessel. Particularly when operated at zero magnetic field, this spectrometer also performs beta-detected nuclear quadrupole resonance (β-NQR) experiments, yielding information about the electric field gradient and crystallography symmetry at the site of the probe Li-8.

Modifications that allow electrical contact to the sample during the measurement have been commissioned. These modifications will allow a new set of experiments in which an applied current or voltage is an important independent parameter, like controlling the magnetic properties of the electrons of a material via current or voltage, or causing ionic diffusion as in an operating lithium ion battery. Electrical connections to sample holders in the high field apparatus have been added to permit current injection through magnet/semiconductor interfaces. A similar capability is under development for the low field sample holder to apply potential gradients across interfaces, thereby generating very high electric fields within the thin interfacial region.

Efforts in data acquisition control software is aimed at improving immunity to beam rate instabilities that introduce spurious signals into the data, and data analysis software is under constant development, and all of the effort to develop analysis tools is provided by the experimenters.

The possibility of polarizing spin-1/2 $Be\text{-}11^+$ was tested. The required modifications were: (1) Magnetic coils were added to the beam line for transporting paramagnetic ions without loss of polarization, (2) A frequency doubler was purchased for generating ultraviolet light, and (3) A system of biased collinear tubes, which spread the beam energy over a range of a few eV in discrete steps, was invented as a way to cover the Doppler width of the ion beam with a fixed frequency laser. The usual method of broadening the laser with electro-optic modulators was not available due to the cost of EOMs in the ultraviolet.

It was found that the Be-11 effective asymmetry parameter is too low for β-NMR studies without energy discrimination because the two main beta transitions have opposite sign asymmetry parameters that nearly cancel.

The TITAN RF cooler was built and can be used to cool and bunch an incoming ion beam and direct it towards the polarizer beam line. This has been used to increase the signal to noise ratio in laser spectroscopy measurements of Rb isotopes.

A second charge exchange cell has been built to allow quick changes between Na and Rb vapour cells. A Rb vapour cell is more efficient for neutralizing elements such as Rb and Fr, which have low ionization potentials.

Partners

In Canada: Simon Fraser University, TRIUMF, the University of Alberta, the University of British Columbia, University of Waterloo.
International Partners: Australia (1), German (2), Japan (3), Switzerland, (1) United Kingdom (1), United States (3).

TRIUMF's Role

TRIUMF has supported the costs of maintaining, repairing and operating the polarizer and associated laser systems. It has also paid for developing the new charge exchange cell and the costs of polarized Be-11^{+} development.

TRIUMF contributed the design and construction effort of the beam lines and ~2/3 of the initial instrument development costs. TRIUMF funds on-going maintenance costs (~$15k/y) of the core facility equipment and related beam lines, vacuum and controls systems. TRIUMF also provides manpower. Additional support is provided by the TRIUMF CMMS technical and scientific staff, and data acquisition groups.

During experiments, TRIUMF is responsible for delivering the probe ion beam to the experimental stations at the end of the beam line. This includes operating the cyclotron that provides the primary driver beam (500 MeV proton at 30 to 100µA) transported down Beam Line 2A to the ISAC production target. TRIUMF designs, fabricates and operates the targets that convert the primary proton beam into secondary radioactive ion beams, such as Li-8^{+}. High yields of Li-8^{+} are produced by surface ionization targets made of Tantalum or Niobium. TRIUMF is responsible for delivering well-tuned high-flux beams with stable rates and beam spots to the experimental spectrometers. This involves sophisticated design and fabrication of the target, beam transport and tuning, and depends upon the ISAC operations, beam delivery and targets groups.

A significant amount of beam time is still being used in the tuning process (at least 10%). TRIUMF is making a continuing effort to reduce this fraction, making tune-ups more systematic, reproducible and expeditious, so that more beams—of higher quality—is available for science.

Monetary Investment

Polarizer: $535k in parts, including lasers, optics, beam line, vacuum, controls, and supporting infrastructure.
Spectrometers: high field $555k; low field $315k in parts including beam lines, vacuum system, control system, high voltage and platforms, detectors, data acquisition, RF systems, magnets and cryogenics. Approximately $250k of this was obtained via NSERC equipment grants.

Additionally, approximately 33 person-years of combined effort from TRIUMF scientists, technicians, and engineers, plus university faculty, graduate, undergraduate students, and post-docs has been spent developing the facility and conducting experiments to date.

5.5.1.9 RADONEDM

The RadonEDM experiment is an online, precision measurement of the NMR precession frequency of 20–30 minute half-life nuclei in combined electric and magnetic fields, with an anticipated total running time of about 100 days over several years. A change in the precession frequency correlated with the relative orientation of the magnetic and high-voltage electric fields (parallel or antiparallel) is the signal of an EDM (electric dipole moment) (i.e. proportional to the EDM); however, because the magnetic moment of the nucleus couples to the magnetic field, it is essential to minimize and monitor changes of the magnetic field correlated with the electric field

Description of the Facility

The facility for the RadonEDM experiment has several requirements: online beam position to which low-energy radioactive beams will be delivered with maximum efficiency coupled to the gas-transfer system for the experiment; the gas-transfer system similar to the one developed at TRIUMF in 2004 [1], including radioactive-gas exhaust; active and passive magnetic shielding and magnetic field coils surrounding the EDM cell and EMI shielding; magnetometers incorporated into the active shielding and within the passive shield for magnetic-field monitoring (magnetometry); laser safety and optic components for noble-gas (Xe and Rn) polarization; EDM cells; and high-voltage systems. Each component is described in more detail below in Recent Developments.

The desired low-energy isotope beam is implanted in a metal foil (e.g., zirconium) for about two half-lives. After implantation, the foil is heated, driving the activity off into a sealed chamber with a LN_2-cooled trap located near the EDM cell. After quickly warming the trap to free the sample into the gas phase, a piston of N_2 gas pushes the sample into the EDM-measurement cell. The first version of the collection-and-transfer apparatus, reported in Nuss-Warren [2] provided a transfer efficiency of 40%. This was improved to approximately 100% by improving the cold-trap and the rates of warming and cooling. The apparatus, consists of the foil, heating, remote-actuated valves, vacuum pumps and the cold-trap and control system.

Magnetic shielding reduces the effects of static and time-dependent external fields and is provided by the combination of active and passive shielding. Active shielding is effected by feedback to a set of magnet coils, a combination of magnetic field measurements in the vicinity of the experiment. Changes of up to a few hundred µT (a few Gauss) are accommodated by measurements with an array of flux-gate magnetometers, and the coil system has outer dimensions of 3-4 m in all three dimensions. Detailed

FIRST ACCELERATION OF CHARGE-BRED RIB AT ISAC

12 November 2008

On November 11, 2008, a team of scientists led by Dr. Friedhelm Ames successfully accelerated a beam of positively charged Rubidium isotope ($^{80}Rb^{14+}$) ions at TRIUMF's ISAC facility. This represents the first accelerated, charge-bred rare isotope beam (RIB) at ISAC, making ISAC one of only three facilities in the world with this capability and signaling the beginning of a new program of nuclear physics at TRIUMF.

Until now, the heaviest RIB accelerated at ISAC had been. To achieve higher charge states for accelerating ions heavier than 30 atomic mass units, a new Charge State Booster (CSB) was designed and installed. In the case of Rb-80, beam was extracted with the rubidium atom's full complement of 37 electrons removed. The team then confirmed its acceleration using a gamma ray detector to detect the decay signature associated with Rb-80.

This milestone marks the culmination of five years of development by ion source physicists and technical teams. There is significant experimental interest in accelerated rare isotope beams with atomic masses greater than 30. Having the CSB available will greatly extend ISAC's capabilities at TRIUMF, strengthening its position as one of the world's premier Rare Isotope Beam facilities.

designing of the active shield requires knowing the magnetic field environment in the final position of the experiment, with the expectation that the field will be quieted to the μT level. Within the active shield, passive shielding made up of 3-4 mu-metal enclosures is expected to have axial and transverse shielding factors much greater than 10^3 and 10^5, respectively, for cylindrical shields. The optimal shape and size of the final mu-metal shields depends on the free-precession detection technique; however the principles and design procedures for both active and passive shielding are well established and proven, for example by the system developed for the Munich neutron EDM experiment which has achieved these specifications.

Within the shields, a small uniform magnetic field, e.g., 1 μT, is maintained by a set of coils and stabilized with signals from a set of optical magnetometers, e.g., Cs magnetometers [2] will complement the field measurement provided by the co-magnetometer within the EDM cell. A co-magnetometer is provided by a second species that has a similar magnetic-moment interaction, but an intrinsically much smaller electric-dipole moment interaction. For example, for the Xe-129 EDM measurement, the co-magnetometer was He-3, which was chosen due to the Z^2 dependence of the atomic EDM in diamagnetic atoms [3]. For the Radon-EDM measurement, possible co-magnetometer species include xenon isotopes and non-octupole enhanced radon isotopes, e.g., Rn-209, which will also be polarized by spin-exchange optical pumping.

Narrowed diode lasers for spin-exchange optical pumping of Rb, providing 20–50 watts, have been developed and are inexpensive, stable, and easy to operate. Laser safety, including containment and procedures, are based on standard operating protocols that have been implemented at several facilities, including the Radon-EDM test beam. Optics are standard, off-the shelf items.

EDM cells for noble gases are continually developing. In the current design, the cylindrical cells consist of a fused silica body with conductive silicon endcap electrodes. These are commercially manufactured to our specifications. The cell materials are compatible with producing the electric field with minimized leakage current at temperatures of 50–100°C, low spin relaxation of polarized noble gases. An automated Teflon valve has been tested and it will close the cell after transfer of the gases.

Electric fields of 10 kV/cm, applied across the EDM cell, require high voltage of 20–25 kV, depending on the final cell dimensions. The polarity on each electrode is reversible.

Recent Developments

It is crucial to establish the experimental as well as theoretical basis for octupole enhancement of Schiff moments in specific systems, i.e. radon and radium. There has been significant theoretical effort on estimating the sensitivity of the Schiff moment to the isospin 0,1,2 components of a CP-violating pion-nucleon coupling, with the most specific quantitative work in Hg-199, and Ra-225. The isotope Ra-225 is particularly interesting because it is relatively long lived (14 d) and its nuclear structure has been well studied. By contrast, there is little data on levels of the odd-A radon isotopes, specifically Rn(221/223). We have therefore set out to collaborate with experts in several approaches to the needed measurements at TRIUMF, NSCL, and ISOLDE. We have played a major role in motivating and extracting science from these efforts.

The use of actinide targets at TRIUMF-ISOLDE has allowed development work that will lead to beams to populate excited states of Rn for identification of spin and parities. A new efficient 3-step laser ionization process was developed by the TRILIS group starting with At-199 and moving up to neutron-rich At-219. The 8π spectrometer was used to identify the isotopes. One problem is contamination from easily ionized Fr isotopes, but for short-lived alpha emitters this is manageable. In contrast, longer lived Fr and Ac isotopes with lifetimes > 1 m led to a large-surface ionized contamination of the beam that completely dominated the much less intense laser-ionized At isobars. TRIUMF has assigned Beam Development Priority 1 to the At-221 beam for S929, and a major effort to suppress surface-ionized beam contamination by combining the TRILIS ion source with a new RFQ system has since been made, with plans to test a TRILIS+RFQ .

Noble gas polarization by spin-exchange has been studied most extensively for Xe-129 and He-3, motivated in part by applications to medical imaging, EDMs, polarized targets, and neutron polarization. Our earlier work with Rn-209 at Stony Brook (and much earlier work with Rn-209 and Rn-223 at ISOLDE) show that spin-exchange will provide significant polarization (>10%) for an EDM experiment [5]. We have recently developed a 50-watt, narrowed laser source for Rb optical pumping, with 0.11 nm linewidth. This is being tested in a new-generation Xe-129 EDM set-up that uses He-3 as a co-magnetometer. Improvements to Rn polarization are also expected and can be tested at ISAC.

We have developed a new method of detecting the NMR-precession of noble gases, specifically Xe-129 using a 2-photon transition. This will be directly applicable to a RadonEDM experiment and will provide the most sensitive possible measurement—more sensitive than the previously proposed methods observing nuclear decays. This work has been motivated most directly by the ideas for a Xe-129 co-magnetometer for neutron-EDM measurements (the Xe-129 would take the place of Hg-199 used in the ILL experiment [6]). Conventional 1-photon magnetometers are not practical for the 147 nm transition; however, two-256 nm photons will populate the triplet-D state from the ground state. In our scheme, the two photons are circularly polarized, and will thus effect only Dm=2 transitions serving to probe the ground state polarization. Precession of the nuclear spin will lead to modulation of the fluorescence, absorption, or optical rotation at the Larmor frequency. We have been working on a model-experiment in Yb, which is a 2-electron atom with atomic structure similar to xenon, and we will test the scheme with xenon in collaboration with E. Babcock and P. Fieleringer groups at Munich, who have appropriate lasers for both Xe-129 polarization and 2-photon magnetometry.

Partners

In Canada: Simon Fraser University, TRIUMF, University of Guelph.
International Partners: Switzerland (2), United Kingdom (1), United States (3).

TRIUMF's Role

TRIUMF has provided the Radon-EDM test facility and beam line at ISAC from 2008–2013 and is involved through a staff scientist. Improvements to the radioactive noble-gas collection and transfer apparatus, as well as extensive optical pumping studies, were completed with this set-up. TRIUMF has provided radioactive Xe-120 and Xe-121 for development and has developed the actinide targets and relevant yield measurements and will provide the Ac-221 beam for Rn-221 structure studies in December 2013.

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5.5.2 ISAC-II

ISAC-II is the newest and highest energy of the rare-isotope areas at TRIUMF. It has a number of advanced detector facilities each optimized for a different purpose: TIGRESS for gamma rays, EMMA for recoil mass spectrometry, HÉRACLES for multi-particle detection, IRIS and TUDA for charged particle reaction studies, and so on. The large detector TIGRESS is movable so that it can be used with EMMA when needed. Smaller detector set-ups can be installed for specific programs, such as the fusion reaction studies with halo nuclei. HÉRACLES is the senior detector having been used at Chalk River and Texas

A&M before moving to TRIUMF in 2003. It is used to studying heavy ion reaction mechanisms in particular related to the nuclear equation of state. The other detectors are used for the study of nuclear structure including halo nuclei, direct nuclear reactions and nuclear astrophysics.

5.5.2.1 THE TIGRESS FACILITY AND ITS AUXILIARY DETECTORS

Some of the most exciting recent results in nuclear structure are associated with the evolution of novel nuclear behaviour at the extremes of nuclear existence, including (but not limited to) halo nuclei [1,2], dissolution of the classical shell gaps [3,4], emergence of new magic numbers with special stability [3], and proton-neutron pairing [5]. These manifest themselves as excitation properties of exotic nuclei, for example, through in-beam γ-ray spectroscopy with accelerated exotic radioactive ion beams (RIBs). Heavy-ion collisions near the Coulomb barrier with RIBs, directed upon stationary targets, can lead to a wide range of reaction channels and excitation modes. Nuclei excited in the collision process will then emit one to ~40 γ rays, with typical energies from ~50 keV to ~8 MeV. These emitting nuclei will be fast-moving sources ($v/c \sim 0.03$ to 0.10), so the detected photons will be Doppler-shifted in the laboratory frame. These features generally point towards a need for high purity germanium (HPGe) gamma-ray detectors with anti-Compton shields and high accuracy in γ-ray vector determination. In RIB experiments, beam intensity is limited by RIB production technology and cannot be easily increased so high total γ-ray detection efficiency is essential. The most sensitive experiments require the use of additional sophisticated radiation detectors; one must take due care in the mechanical layout of the γ-ray detectors to accommodate these. Finally, to maximize the physics output of a RIB facility, the experimental end-stations must allow for rapid reconfiguration; beam scheduling is driven more by production targets than experimental setups [6,7].

Description of Facility

The TRIUMF-ISAC Gamma Ray Escape Suppressed Spectrometer, TIGRESS, is used at the ISAC-II facility primarily for RIB experiments. It consists of up to 16 units of so-called clover HPGe multi-crystal detectors and scintillator suppressor shields, with waveform sampling digitizers. TIGRESS has operated with arrays of highly segmented silicon detectors for charged-particle detection, BAMBINO and SHARC, and will also be used with a plunger and CsI(Tl) detector (TIP), electron conversion spectrometer SPICE, and neutron detector DESCANT, as well as recoil separators.

The 16 high-energy-resolution γ-ray spectrometers in TIGRESS consist of four HPGe n-type bulleted-coaxial detectors in a single cryostat. The crystals are nominally 60 mm in diameter and 90 mm long before they are machined and tapered. Each crystal has a photopeak efficiency of ≥38%. The cryostat is also tapered. This allows for close packing of the detectors in a truncated cube. The inner-core coaxial contact holds positive bias and collects charge from the full volume of the crystal. The outer surface of the detector has eight electrically isolated contacts, with four quadrants around the axis of the core contact and a lateral segmentation 30 mm from the front of the crystal. The centre contact is instrumented with a cold FET and feedback front-end network within the cyrostat volume, while for the outer contacts the network is at room temperature. All contacts are instrumented with charge-sensitive preamplifiers.

In multi-crystal detectors such as the TIGRESS detectors, γ rays that enter one crystal and escape have a high probability of striking another crystal. The incident photon energy can be measured by adding the energy deposition in two (or more) neighbouring crystals. This add-back results in a relative efficiency for a full TIGRESS clover detector of between 215% and 220%.

Each clover is outfitted with a set of escape suppression scintillators to detect and veto escaping photons. Backplug and sidecatcher suppressors detect small-angle scattering out of the back and flat side of the cryostat, and are bolted directly to the HPGe assembly. Trapezoidal front suppressors fit around the front, tapered part of the clover cryostat for large-angle Compton scattering, especially from the front of the HPGe volume. In the high-ε (efficiency) configuration, the front shields are withdrawn and the clovers are inserted within 2 mm of each other for maximum photopeak efficiency. Alternatively the clovers may be withdrawn, and the front suppressors inserted between them to afford the maximum coverage for large-angle Compton scattering; this is the high-P/T (peak-to-total) mode. In both configurations a full 22.0 cm diameter inner sphere is available for vacuum and auxiliary detectors, and the entry and exit ports for beam are identical.

The mechanical support structure holds eight clover and suppressor units on a central corona perpendicular to the beam axis. To this main frame, lampshade frames may be fastened to hold up to eight more clover and suppressor units, four at 45º and four at 135º to the beam axis. The lampshades and their clovers may be removed to accommodate auxiliary detectors.

It is possible to change between the high-P/T and high-ε modes in under a day. During the 2010 experimental campaign, TIGRESS comprised ten clover units (including suppressors) on the central corona and backward lampshades. It was operated in both modes, and for the high-P/T mode an absolute photopeak efficiency of 4.7% was measured, including add back. In the high-ε mode the absolute photopeak efficiency was 7.4%. This included add back within a clover unit but not between neighbouring cryostats.

The data acquisition system [8] uses a hierarchal, scalable multi-level triggering system and digital waveform sampling. Signals from the HPGe and suppressor charge-sensitive preamplifiers are digitized by VXI-C modules consisting of ten channels of 100 MHz 14-bit flash ADCs called TIG-10s. The waveforms are continuously sampled. Contemporaneously, a large FPGA on each channel evaluates features of the waveform in real time. The hierarchical trigger consists of a Level 0 per-channel pretrigger, Level 1 triggers on each TIG-10 card, and a Level 2 trigger implemented in TIG-C VME collector cards that provide master triggers for up to 12 lower level digitizer cards. After trigger validation the digitized signal trace and evaluated features (energy and time) are read out over the VME backplane into a front-end computer.

TIGRESS: Recent Developments

The most significant upgrade of TIGRESS itself in the period 2008–2013 was the integration of the TIG-64 high-density digitizers into the data acquisition system. This upgrade project, led by Saint Mary's University, commissioned the University of Montreal to develop 12-bit, 50 MHz waveform digitizers suitable for the less restrictive requirements of large arrays of Si or CsI(Tl) detectors. These have been used in experimental campaigns in 2010 and 2012. Although TIGRESS was only funded for 12 detectors, cost savings during construction and additional funding through partners have allowed us to procure a total of 16 TIGRESS-compatible clovers. Otherwise, TIGRESS has been operational since 2008, in configurations with up to 14 operational clovers, limited only by the needs of the auxiliary detector required for the experiment(s).

BAMBINO

The BAMBINO facility, optimized for detection of inelastically scattered heavy ions (for example, Coulomb excitation), was used in the first TIGRESS experiments (see Figure 1). BAMBINO consists of up to two, so-called S2 or S3 CD-style segmented annular silicon detectors from Micron Semiconductor, a spherical scattering chamber, and feedthroughs. The two CDs may be arranged as a dE-E telescope or may be placed on either side (upstream and downstream) of the target ladder, which holds up to five targets or apertures and which can be biased to suppress delta electrons. The nominal position places an S3 detector 30 mm either

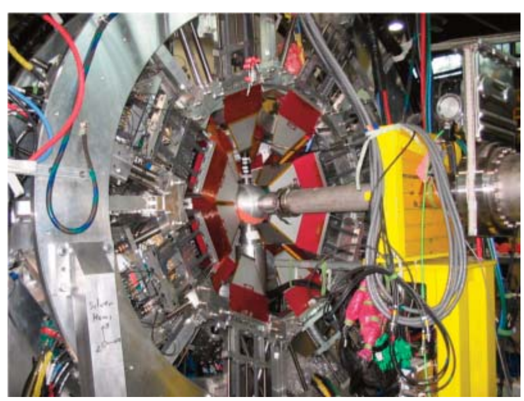


Figure 1: Photograph of TIGRESS with BAMBINO.

upstream or downstream of the target ladder. At this position, two S3 detectors will span laboratory-frame polar scattering angles from 20˚ to 49.4˚ at forward angles and the back-angle supplements, for a total angular coverage of 3.63 Sr, or 29% of a full sphere, with rings subtending $\Delta\theta \approx 0.8˚$ to $1.7˚$ and $\Delta\varphi \approx 11.2˚$. The aluminum target chamber vacuum vessel has an outer radius of 102 mm (diameter 8") and thickness of 1.5 mm (0.06"). The S3 holder is designed so that, with appropriate standoffs, the S3 may be placed anywhere from ~3 mm to 70 mm from the target. The Si signals are processed through charge-sensing amplifiers, and the rise and decay times of the signals are sufficiently similar to HPGe signals so that they may be digitized for energy, time, and trigger evaluation with TIG-10 modules [2,9,10,11].

Recent Development. Bambino was used in the first experiments at TIGRESS and has been used without modification since 2006. Bambino has become the *de facto* standard upon which all other TIGRESS scattering detectors are based.

SHARC

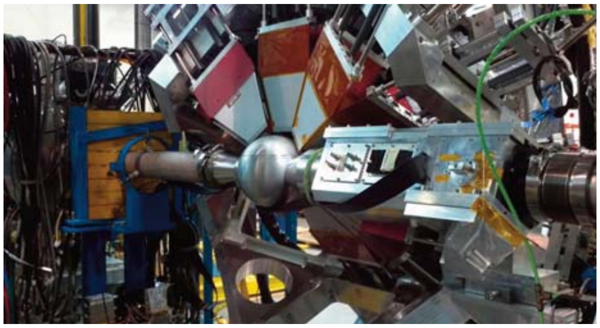
The combination of γ-ray spectroscopy and charged particle spectroscopy is a powerful tool for the study of nuclear reactions with beams of nuclei far from stability. SHARC [12], the Silicon Highly-segmented Array for Reactions and Coulex, is a new silicon-detector array designed for use in reactions with radioactive ion beams in conjunction with the TIGRESS γ-ray spectrometer. SHARC is built from custom Si-strip detectors, utilizing the fully digital TIGRESS readout (TIG-64 modules) (see Figure 2). SHARC has more than 50% overall efficiency and approximately 1000-strip segmentation yielding angular resolutions of $\Delta\theta \approx 1.3$ deg. and $\Delta\varphi \approx 3.5$ deg. Preamplifiers custom-built at TRIUMF provide four gain ranges nominally from 15 MeV, suitable for protons or dE detectors, to 600 MeV for beam-like heavy ions. Furthermore, 25-30 keV energy resolution, and thresholds of 200 keV for up to 25 MeV particles have been achieved.

Figure 2: Photograph of TIGRESS with SHARC.

Recent Developments. SHARC was first used for experiments in 2009. A major upgrade in 2011 saw the introduction of selectable-gain preamps spanning nominal ranges from 15 to 600 MeV, i.e. suitable for low-energy light-charged particles through to beam-like heavy ions. SHARC collaborators also provided a thin-film scintillating heavy-ion detector called a Trifoil, which, despite using fast-readout phototubes and NIM coincidence electronics, was seamlessly integrated into the data stream as a fusion-evaporation veto counter [13].

The TIGRESS Integrated Plunger (TIP)

TIP was developed by collaboration between Simon Fraser University, Saint Mary's University, and TRIUMF for recoil distance method (RDM) lifetime measurements of short-lived excited states in exotic isotopes using TIGRESS. It was designed to provide precise (submicron) control of distance shifts between thin target and stopper/retardation foils while maintaining parallel alignment between the two to achieve picosecond-order lifetime sensitivity. TIP offers a high degree of versatility for lifetime measurements, employing a variety of reaction mechanisms and several particle-tagging techniques. It can run in stand-alone mode with TIGRESS, or in tandem with an extensive suite of auxiliary charged particle detector systems (see Figures 3). For Coulomb excitation reactions, a highly segmented annular silicon detector and modular PIN diode array have been implemented for precise kinematic reconstruction of inelastic scattering events in coincidence with gamma-ray detection in TIGRESS. A compact 3π CsI(Tl) scintillator ball is being developed for lifetime measurements of exotic nuclei along the N=Z line produced by fusion-evaporation reactions. The identification of evaporated charged particles via digital pulse-shape analysis will enhance the experimental sensitivity through reaction channel discrimination. TIP is also designed to be coupled with DESCANT, SHARC, and the electromagnetic spectrometer EMMA.



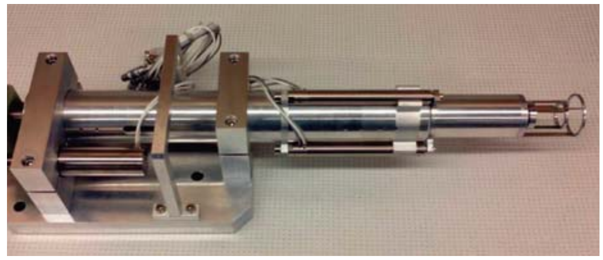


Figure 3: Photographs of TIP: a) plunger b) vacuum chamber installed on TIGRESS.

Recent Developments. The TIP alternate target system and several of its ancillary charged-particle detector arrays were first used in late 2011 and early 2012. The beam times were devoted to various tests of the TIP target and detector systems; at the same time, high-statistics lifetime and Coulomb excitation data were collected for Ar-36.

The most recent developments involve the construction of a CsI(Tl) wall as a precursor to the 3π ball. Twenty-four detectors coupled to Hamamatsu silicon PIN diodes are under construction at SFU. Using SFU custom-built 8 channel charge-sensitive preamplifiers, typical resolutions for the 5.5 MeV alpha particle from Am-241 have been below 275 keV. An in-beam demonstration of reaction-channel selectivity following fusion-evaporation reactions using CsI pulse shape analysis was performed in spring 2013. Significant effort on the control system for precision target-stopper alignment is also ongoing at SFU.

SPICE

SPICE (SPectrometer for Internal Conversion Electrons), currently underway at TRIUMF, is a project to design and build an in-beam electron spectrometer ancillary detector for the TIGRESS array (see Figures 4). SPICE will have a particular sensitivity to higher energy electrons in the energy range 100 keV to 4000 keV which is required for the study of shape-coexistence in nuclei. In-beam electron spectrometers operating today are limited to below about 500 keV electron energies. Electrons emitted from the reaction target of TIGRESS following a nuclear reaction will be collected by a rare earth permanent magnetic lens and directed around a photon shield into a 6.1 mm thick lithium-drifted silicon electron detector. Coincident gamma rays will be detected in the TIGRESS clover detectors.

Recent Development. Since 2010, a full GEANT4 simulation of SPICE has been developed and used to optimize the detailed design of the components of the spectrometer. The fabrication of the spectrometer has been completed. A first in-beam test of SPICE coupled to TIGRESS will take place in fall 2013, followed by the first physics experiment in 2014.

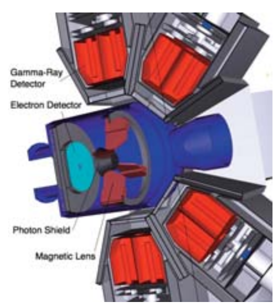


Figure 4: (a) Model of SPICE with TIGRESS and (b) a photograph of assembled magnetic lens.

DESCANT

The DESCANT spectrometer is designed to be coupled with both the TIGRESS, (see Figure 5), and the future GRIFFIN spectrometer. It will replace the forward “lampshade” of four clover-type HPGe detectors (with their BGO suppression shields), and will occupy a solid angle of 1.08π sr with the maximum angle of 65.5 degrees with respect to the initial beam direction. The target-to-detector distance is 50 cm, and the individual detector cans are 15 cm thick. When fully loaded, DESCANT contains 70 individual neutron detectors. DESCANT is designed so that the inner and adjacent ring of detectors surrounding the beam line can be removed to facilitate larger forward detector systems that may be placed downstream of the target. The detector units contain liquid deuterated scintillator, BC537, and were fabricated by the Bicron division of Saint-Gobain. Signals from the DESCANT detectors will be digitized by custom-built 1 GHz waveform digitizers manufactured by Instrumentation Services of the University of Montreal. Onboard digital signal processing will integrate the pulse to yield the total charge, determine the event time via a constant-fraction algorithm, and perform neutron-γ discrimination.

Figure 5: Photograph of DESCANT.

Recent Developments. During the 2008–2013 period, the DESCANT detectors were delivered and tested, the support structure was designed and built, and the first prototype of the electronics was tested. Testing of the second TIG-4G prototype is nearing completion with production to commence immediately thereafter. The components are on track for commissioning in-beam experiment in fall 2013.

Partners

In Canada: Saint Mary's University, l'Université de Montréal, University of Toronto, McMaster University, University of Guelph, Simon Fraser University.
International Partners: France (1), Italy (1), Spain (2), United Kingdom (3), United States (4).

TRIUMF's Role

Two TRIUMF research scientists and one emeritus work on TIGRESS; one of these is responsible for all aspects of TIGRESS on-site management, operation, maintenance, planning, coordination, and safety. TRIUMF provides one technician in support of the gamma-ray and GPS tape-station facilities; approximately 1/3 of his effort is devoted to TIGRESS. TRIUMF provides support for data acquisition including firmware development and long-term data storage. The TIGRESS detector facility provided conceptual design for TIP, SPICE, and the SHARC preamplifiers, and manufacture of the SPICE magnetic lenses. The TRIUMF Engineering Division provided detailed mechanical design, engineering analysis, and machining of the DESCANT superstructure and some TIP components. The TRIUMF electronics shop fabricated and modified, as needed, the SHARC preamplifiers and all cables.

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ISAC ACHIEVES ACCELERATED, "SCRUBBED" BEAMS OF HEAVY ISOTOPES

31 July 2013

Providing pure beams of short-lived isotopes for precision science experiments is a challenging endeavour. Studies of such rare isotopes are carried out at different energies, depending if ground state or decay properties are studied or the aim is to carry out nuclear reactions. At TRIUMF's ISAC facility, a variety of rare isotopes are produced in the target when struck by the proton beam from the main cyclotron. A series of sophisticated online systems ionize, separate out and select the singly charged isotopes of interest for the downstream science experiments. The mass and ionization properties (largely dictated by the electron structure around the nucleus but subtly influenced by the nucleus, too) are used in concert to manipulate, electrically charge, purify, and control the beam. To accelerate heavy beams (more than 29 nucleons) for nuclear reaction experiments at ISAC it is necessary to ionize them to higher charge states by removing more electrons in a so-called charge state booster, in TRIUMF's case an electron cyclotron resonance source. However, the charge breeding process introduces new contaminations into the beam, rendering it potentially useless for the experiments.

Over the past week at ISAC, a combined team of accelerator, target, and nuclear physicists demonstrated a breakthrough in providing an intense beam of Sr-94 to the ISAC-II accelerators for use in the TIGRESS germanium gamma-ray spectrometer augmented by the SHARC silicon detector array for charged particle detection. The experiment aimed to study the nuclear structure of the neutron-rich isotope Sr-95 via a one-neutron transfer reaction. Beams of this isotope are subject to contamination with various stable isotopes from the charge state booster, a feature that prevented this research for some time. This was the first high-mass experiment with accelerated rare isotope beam at ISAC.

By using a combination of cleaning techniques and beam identification tools developed by TRIUMF's "High Mass Task Force," the team was able to separate out the desired Sr-94 isotopes with an intensity of up to 300,000 particles per second enabling a successful experiment! The techniques combine careful optimization of the charge-state booster and the network of subsequent accelerators and collimators to deliver a clean, pure beam of energetic Sr-94 isotopes. With the available simulation tools and cleaning procedure the way for numerous high-mass accelerated beams has now been prepared and many exciting experiments will follow.

Congratulations to the ISAC and TIGRESS teams!

This photo shows as substantial part of the collaboration and High Mass Task Force that is currently successfully running experiment S1389 with charge-bred Sr-94 beam to TIGRESS in ISAC-II.

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5.5.2.2 EMMA: ELECTROMAGNETIC MASS ANALYZER

The superconducting ISAC-II linear accelerator has enabled the delivery of intense, high-quality beams of radioactive ions with masses up to 150 u and maximum energies of at least 6.5 A MeV. These beams will allow the study of the single-particle structure of exotic nuclei, the evolution of nuclear structure and shapes far from stability and at high spin, and nuclear astrophysics. Fusion-evaporation and transfer reactions initiated by radioactive ions in inverse kinematics promise to yield invaluable information about these subjects that cannot be obtained by other means. The study of many of these reactions will require detection and identification of the heavy recoil nucleus, in addition to light charged particles, neutrons, and γ rays. The ElectroMagnetic Mass Analyzer (EMMA) was designed to be ideally suited to study the products of fusion-evaporation reactions induced by the heavy radioactive beams of ISAC-II because its large acceptance implies high transmission efficiency and its high mass resolving power provides high selectivity and excellent beam rejection capability.

Description of Apparatus

EMMA is a recoil mass spectrometer designed to separate the recoils of nuclear reactions from the beam and to disperse them in a focal plane according to their mass-to-charge ratio (m/q). Measurements of position, energy loss, residual energy, and time-of-flight are expected to uniquely identify the transmitted recoils. In addition to having a large solid angle of 20 msr, the spectrometer will accept recoils within a large range of m/q (±4%) and energies (±20%) about the central values. These large acceptances result in high detection efficiencies approaching 50% for the recoils of many fusion-evaporation reactions. The trajectories of monoenergetic ions of a single mass within the spectrometer are calculated to be isochronous within 0.1%, allowing high-resolution time-of-flight measurements and large real-to-random ratios in coincidence experiments. These properties are anticipated to make EMMA a recoil mass spectrometer of very high quality that will enable previously impossible experiments with ISAC-II

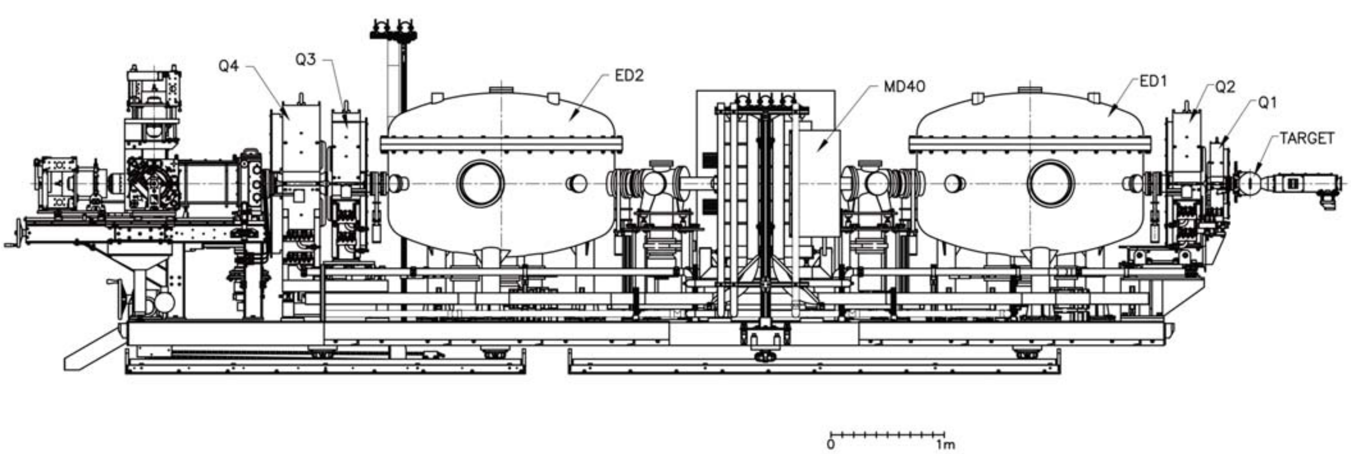


Figure 1: Schematic view of EMMA showing the two large electric dipoles on either side of the central magnetic dipole. Magnetic quadrupole doublets at the front and back serve to spatially focus the recoiling nuclei and allow for variable mass dispersion.

beams. Separation of reaction products from the primary beam at 0° allows the detection of recoils from fusion-evaporation reactions as well as transfer reactions induced by radioactive heavy ions, which emerge from the target in narrow cones centred about the beam direction. The capacity to disperse ions according to m/q combined with multiwire gas detectors in the focal plane will allow high resolution determinations of the atomic masses and atomic numbers of recoils. These capabilities of large acceptance, beam rejection at 0°, and high mass resolution are likely to make EMMA an exceptional instrument for nuclear physics research. When coupled with the unique radioactive ion beams from ISAC-II and the advanced γ-ray spectrometer TIGRESS, EMMA will position TRIUMF as a world leader in the field. EMMA is schematically depicted in Figure 1.

One area of research in which EMMA is expected to make an important contribution is the production and study of nuclei far from stability under extreme conditions, such as high excitation energy or angular momentum. This will be accomplished through the study of weak, otherwise inaccessible reaction channels by using EMMA as a mass filter in coincidence experiments. For example, in the study of high-spin states, events in TIGRESS detectors positioned around the target will be gated by signals from a particular nucleus in the focal plane detectors of EMMA. This technique permits the low background study of weak reaction channels without the concomitant large loss of efficiency normally encountered when these measurements are carried out with small-acceptance detectors. Without the recoil detection and identification, the weakest channels, which are often the most interesting, would be totally obscured by the large number of γ rays from more copiously produced nuclei. The large energy, mass, and angular acceptances of EMMA will be crucial in these experiments, and will provide high sensitivity by allowing triple coincidence measurements in which two γ rays are detected in coincidence with the recoil.

While being well suited to the detection of recoil nuclei from fusion-evaporation reactions, EMMA will also be able to detect the projectile-like recoils of transfer reactions in inverse kinematics with high efficiency and good beam rejection capability. In one- and two-nucleon transfer reactions induced by heavy projectiles on light targets such as (d,p), (p,^{3}He), and (d,t), the recoil nuclei are strongly forward focused and have relatively small energy spreads. They can therefore be detected with geometric efficiencies near unity. The detection of recoils from these transfer reactions will represent one of the important uses of the spectrometer. In studies of both fusion-evaporation and transfer reactions, EMMA will be used in conjunction with TIGRESS. We anticipate that between 1/2 and 2/3 of TIGRESS experiments will require EMMA, which has led to detailed considerations of how EMMA can be designed to take full advantage of it.

Recent Developments

In 2006, EMMA was funded by a C$2M NSERC Subatomic Physics Research Tools and Instruments award, with the understanding that TRIUMF would furnish the additional C$1M required to complete the spectrometer. Following the initial award, a dedicated effort was required to precisely specify the electromagnetic and mechanical properties of the spectrometer components that are crucial in determining its quality. The firms that bid on the large electromagnetic elements of EMMA were evaluated on their ability to meet these rigorous technical specifications as well as cost.

In 2007, after a tendering process, a contract to build the two electric dipoles, the dipole magnet, and four quadrupole magnets was awarded to Bruker BioSpin GmbH of Germany. The fabrication of the electromagnetic components was considerably more challenging than originally anticipated by the manufacturer, resulting in long delivery delays. All of the magnets were delivered in 2012. Figure 2 shows them on the common support structure. Three positive and three negative high voltage power supplies capable of providing 350 kV were built and tested at TRIUMF. High voltage testing at the Bruker factory revealed a number of design and manufacturing flaws in the electric dipole components. After remediation of these flaws, the electric dipoles were shipped to TRIUMF in 2013.

Partners

In Canada: University of Guelph, McMaster University, Saint Mary's University, and Simon Fraser University.
International Partners: Germany (1), Italy (1), Japan (1), United Kingdom (3), United States (5).

TRIUMF's Role

TRIUMF has made major contributions to the design of EMMA and the fabrication and installation of its components. The ion optical design was done by a TRIUMF research scientist who also is the EMMA project leader. All of the design effort for the EMMA mechanical support structure, the target chamber, and the focal plane box is being carried out by TRIUMF. TRIUMF designed and built the high voltage power supplies for the electric dipoles of EMMA. The TRIUMF Detector Group is constructing and testing the position-sensitive multi-wire gas detectors and the ionization chamber for the focal plane.

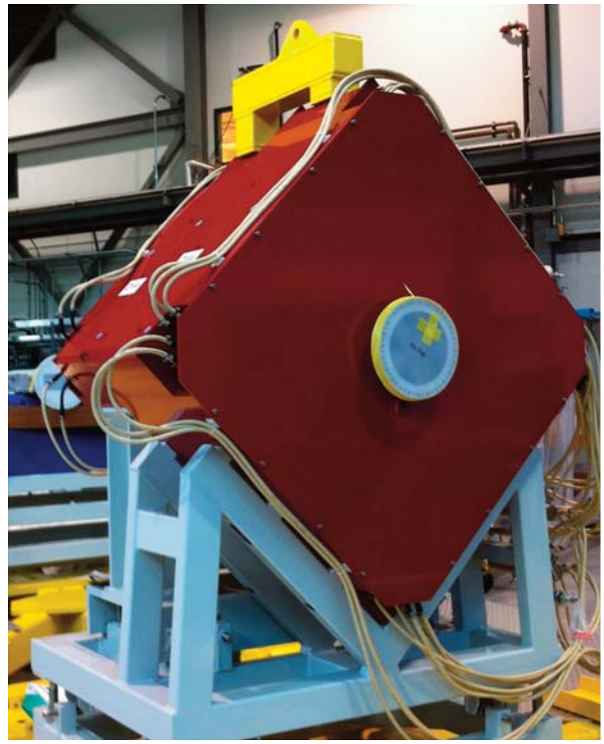


Figure 2: Photograph of the EMMA platform showing the red quadrupole doublets and the bottom half of the dipole magnet with its vacuum chamber.

5.5.2.3 IRIS: THE ISAC CHARGED PARTICLE REACTION SPECTROSCOPY STATION

The charged particle spectroscopy in direct reactions of rare isotopes is one of the most effective ways to unveil new features in the proton- and neutron-rich nuclei. These exotic forms of rare isotopes exhibit unusual ordering of nuclear orbitals. The low-energy reaccelerated beams can allow precision studies to find which orbitals the valence neutrons/protons occupy, how the neutrons in the neutron-rich surface are correlated, and whether new facets of pairing surface in such regions.

These questions are addressed using the newly built ISAC Charged Particle Reaction Spectroscopy Station (IRIS) through nucleon transfer reactions and inelastic scattering. One-nucleon transfer reactions provide angular momentum selectivity to decisively determine the unknown spin of energy levels in the exotic nuclei. The orbital occupied by the valence nucleons is reflected in the shape of the angular distribution. Reactions of interest in the IRIS facility are those using hydrogen isotopes as target, such as, (p,d), (d,p), (d,^{3}He). Contrary to reactions using stable isotopes, due to the short lifetime of the unstable nuclei, the targets in these reactions are the light hydrogen isotopes, and the projectile is the heavy unstable isotope. IRIS is particularly well suited for experiments with very low intensity RIBs ($\sim\geq 10^2$ /sec) and low-energy level density in the residual nucleus (light nuclei and heavy nuclei near shell closures). As such it complements reaction studies with TIGRESS that can resolve close-lying energy levels via gamma-ray spectroscopy but needs RIB intensities in excess of 10^5/sec.

The (p,d) and (d,^{3}He) reactions, where one neutron from the unstable projectile nucleus is transferred to the target, provide information on the configuration mixing in the ground state of the unstable nucleus of interest with mass number A. They also serve as the tool to determine the spin and excitation energy of the nucleus A-1.

The (d,p) and (d,n) reactions are those where the unstable projectile nucleus picks up a nucleon from the target, thereby producing a more neutron-rich or more proton-rich nucleus, respectively. These reactions can also serve as alternate ways to understand the neutron capture (n,γ) and proton-capture (p,γ) reactions relevant to the nucleosynthesis reaction networks for the rapid-neutron and rapid-proton capture processes.

The two-nucleon transfer reactions of the type (p,t), (p,^{3}He) and their inverses are important ways to learn about pairing correlation in the exotic isotopes.

Description of the Facility

The IRIS facility is designed to study the reactions in the energy range from ~ 3-15*A* MeV. The layout of the facility and schematic detector arrangement are shown in Figure 1. The rare-isotope beams can be tagged for isobaric contaminants as they lose energy in passing through a low-pressure ionization chamber before interacting with the reaction target. A compact ionization chamber of 16 cm x 5 cm x 5 cm with a coplanar anode configuration was constructed. The chamber is segmented into 16 anodes which can be combined together in sections to optimize for desired energy loss, depending on each case. The ionization chamber is designed to operate with isobutane at 10–25 mbar. Thin silicon nitride (50 nm) or mylar (900 nm) windows with a dimension of 10mm x 10mm are used to separate the gas volume from the vacuum.

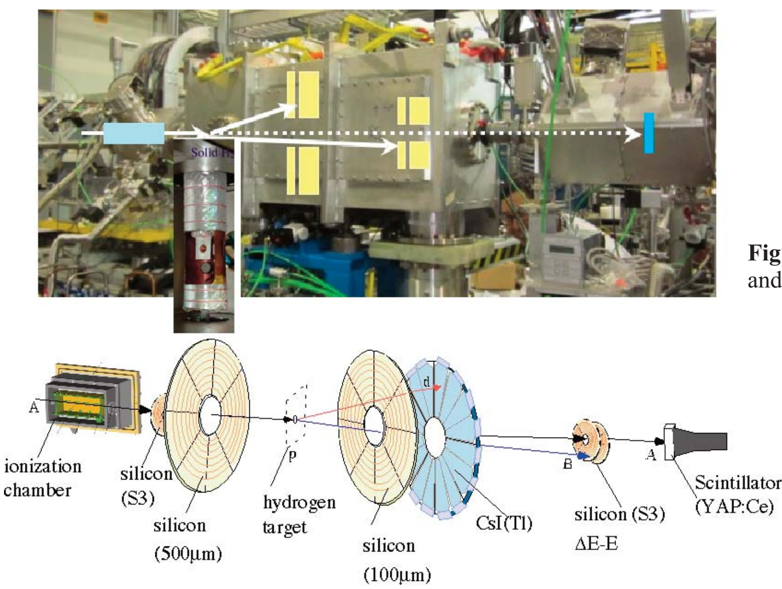


Figure 1: Snapshot of the IRIS beam line (top) and schematic layout of the detectors (below).

The novel feature of IRIS is the development of a thin solid hydrogen target. The solid hydrogen target cell is backed by a thin silver foil. The target cell with the foil is cooled by a Sumitomo cryocooler with a helium compressor to a temperature of ~ 4K. The hydrogen gas is then sprayed through a diffuser onto the silver foil to form a solid hydrogen target. By controlling the gas volume, the desired target thickness can be achieved. Typical thicknesses range from ~ 50–150 µm. The target assembly is surrounded by a copper cylinder whose temperature is around 30K. This acts as a heat shield to restrict heating of the target from the ambient temperature. The reaction products from the target are emitted through an opening in the heat shield. IRIS is also designed to have the possibility of using thin polyethylene foils $(CH_2)_n$ and $(CD_2)_n$ as targets. Tritium implanted foils for use as triton target are also planned.

The main focus of the IRIS facility is to detect the charged particle reaction products following reactions with isotopes of hydrogen as targets. Therefore, the detection system is designed to detect both the light target-like reaction ejectiles as well as the heavy beam-like reaction residues. The light particles that are emitted at backward angles in the laboratory frame usually have rather small energies ~ less than 1 MeV. Therefore, these reaction channels are identified using the energy-angle kinematic correlation. This involves detecting the particles using an annular array of 500 μm thick segmented silicon detectors. The forward scattered particles have higher energy, which allows identifying them through a ΔE-E correlation. This is achieved using a detector telescope with a 100 μm thick segmented silicon detector layer followed by a 12 mm thick annular CsI(Tl) array that matches the silicon array in overall configuration. The CsI(Tl) detectors form an array of 16 individual crystals each of which are read out using silicon photodiodes. The annular silicon detector array for both upstream and downstream have 8 independent azimuthal detector sectors. Each sector is segmented into 16 rings which provides the scattering angle information. Figure 2 shows the particle identification spectrum from reactions of O-18 with the solid hydrogen target.

In the upstream direction, a smaller silicon array of 500 μm thick MICRON Semiconductor-S3 type detector provides additional smaller scattering angle coverage for particles that pass through the hole of the larger YY1 array. Further downstream to the YY1-CsI(Tl) telescope, is a detector telescope that is made up of a 60 μm thick layer of S3-type silicon followed by a 500 μm thick silicon of same type. This allows a ΔE-E identification of the heavy reaction residue. The detector arrays can be placed at any distance from the target ranging from 7 cm to 75 cm, the choice of which will be optimized for the specific reaction to be studied.

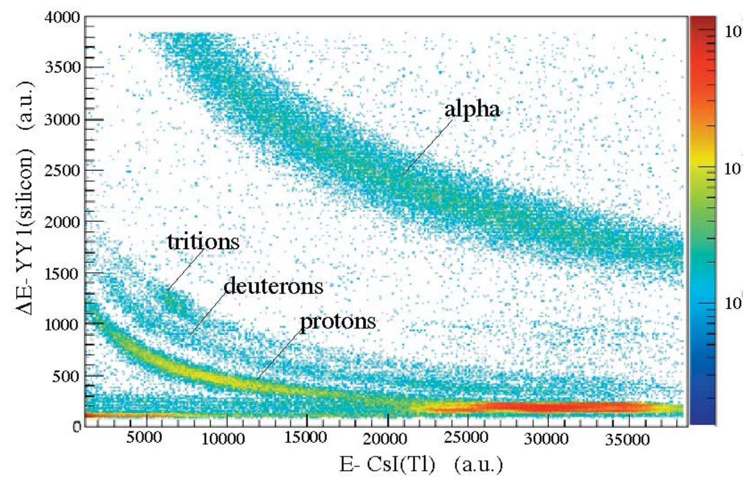


Figure 2: Particle identification spectrum using ΔE-E correlation of the downstream YY1-CsI(Tl) detector telescope from reactions of O-18 on a 100 μm solid hydrogen target.

The unreacted beam passes through the hole in all the detectors and is eventually stopped and counted using a radiation hard YAP:Ce inorganic scintillator readout by a photomultiplier tube which is placed in the last vacuum chamber.

Recent Developments

The IRIS facility was successfully commissioned in 2012 and has started full-fledged operation with radioactive beams from 2013.

Partners

In Canada: TRIUMF and Saint Mary's University.
International Partner: Japan (3).

TRIUMF's Role

The TRIUMF Detector Group has been intensely involved in the project and has designed and fabricated the IRIS ionization chamber. They have also laid out the conceptual design of the IRIS scattering chamber that was detailed by the TRIUMF Design Office. All components were fabricated at the TRIUMF Machine Shop. The Beam Lines Group installed all the components, with the Vacuum Group, Electrical Group and Controls Group taking responsibility for implementing the relevant components of the beam line. Several TRIUMF research scientists are a part of the IRIS collaboration.

5.5.2.4 TRIUMF UK DETECTOR ARRAY: TUDA

The TRIUMF nuclear astrophysics program is carried out at a set of complementary facilities in the ISAC post accelerator areas: the two key detectors are: (1) a large-suppression recoil spectrometer system called DRAGON, and (2) a large-acceptance scattering facility called TUDA. The scientific objective of the TUDA facility is to study the nuclear reactions important to our understanding of explosive astrophysical scenarios, such as novae, supernovae, and type I X-ray bursts, i.e. events that create the heavy elements of our universe and provide spectacular light shows in the skies over the millennia. In particular, TUDA is designed for the direct and indirect study of those reactions with charged-particle exit channels. The results of these measurements play a significant role in the understanding of explosive astrophysical phenomena.

The TUDA experimental technique, solid and gaseous targets surrounded by upstream and downstream solid-state detectors, is extremely versatile and adaptable to other nuclear physics measurements. TUDA's collaborators are involved in nuclear structure programs, including proposals involving Li-11 beams to study the properties of this exotic halo nucleus. The availability of TUDA for these nuclear structure investigations attracts proposals from the Canadian and international nuclear physics community.

Description of Apparatus

Presently located at ISAC-II, the TUDA facility was built to be interchangeable between ISAC-II and ISAC-I to enable different types of measurements: the direct measurements in the lower energy ISAC-I area, and indirect studies in the higher energy ISAC-II area. Radioactive ion beams are focused onto targets inside the chamber, and products from nuclear reactions between the ion beam and the target material are detected both downstream and upstream in arrays of silicon strip detectors. The chamber itself (see Figure 1) is divided into three rectangular sections separated by two cylindrical sections, and can accommodate a variety of detector mounts, target ladders/structures, and diagnostic instruments.

The LEDA detector is mounted on long poles attached to the downstream flange. The structure behind the LEDA houses the electronics. The detector shown is composed of 8 azimuthal sectors (only 4 are installed in the picture), each having 16 individual concentric silicon strip detectors, 0.3 mm thick. Thus, each detector array has 128 individual independent channels. When one of the individual strip detectors detects a particle, the energy and position are measured. The hole in the centre of the array allows the unscattered beam to pass through. It is possible to stack several detector arrays together and assemble TUDA experiments in a variety of configurations depending on the reaction being studied. LEDA detectors of 0.3 and 1.0 mm thicknesses have been used, as well as a variety of other silicon detectors such as CDs and S2s. The 512 channels of high-quality analog electronics, as well as electrical isolation for noise suppression, enables the TUDA facility to operate at extremely high sensitivities and energy resolutions, making it not only a versatile facility, but a precision one.

Recent Developments

During the present five-year plan period, experiments at TUDA have been shared between experimenters with nuclear astrophysics aims and those with nuclear structure aims. Much work has been done to exploit radioactive F-18 beams, when TUDA was stationed at ISAC-I. In particular, an experiment was performed to simultaneously measure the ^{18}F(p,p)^{18}F and ^{18}F(p,α)^{15}O reactions using solid targets. This successful experiment paved the way for more studies and was the first time an R-Matrix fit to (p,p)/(p,α) channels was performed in a RIB experiment. Later, a direct measurement of ^{18}F(p,α)^{15}O was done at the lowest energy ever for that reaction, right in the astrophysically relevant region. Further direct measurements are planned.

When TUDA then moved to ISAC-II, several measurements were performed. For nuclear astrophysics, a determination of the ^{18}Ne(α,p$_0$)^{21}Na reaction was performed via a measurement of the inverse reaction, ^{21}Na(p,α)^{18}Ne with radioactive beam (see Figure 2). Also, a determination of the ^{18}F(α,p)^{21}Ne reaction rate was performed by filling the entire TUDA chamber with He gas, enabling high efficiency and a wide

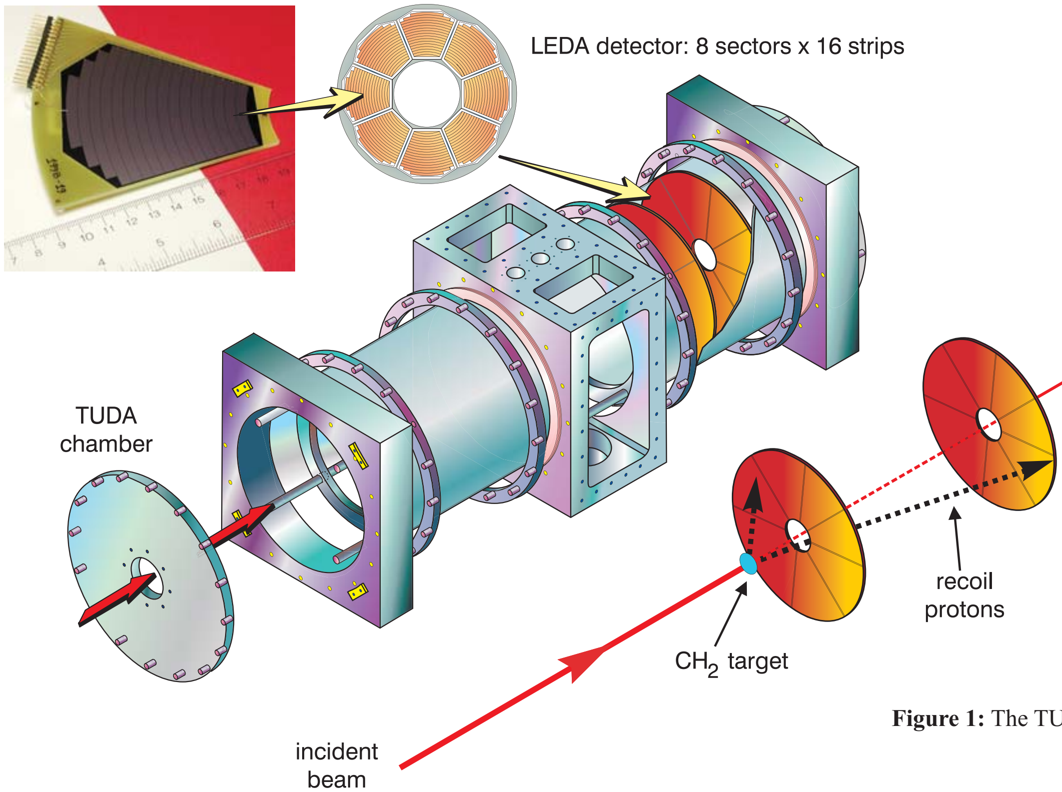


Figure 1: The TUDA chamber.

excitation function to be measured. Also for astrophysics, measurements of $^{7}Li(^{8}Li,^{7}Li)^{8}Li$ and $^{12}C(^{8}Li,^{8}Li)^{12}C$ cross-sections were performed using radioactive Li-8 beams. Nuclear structure studies were performed with Li-8 and Li-11 beams on a variety of targets. A wide variety of silicon detector array types were used in these experiments, as well as gas and solid targets, showing the versatility of the TUDA facility.

Partners

In Canada: McMaster University, Saint Mary's University, Simon Fraser University, University of British Columbia, TRIUMF.
International partners: Belgium (1), Spain (1), Switzerland (1), United Kingdom (2).

TRIUMF's Role

TRIUMF provided the electronic housing environment for the TUDA electronics and continues to provide annual maintenance support for the facility. This provides access to the design office and the electronics and machine shops. Three TRIUMF research scientists contribute significantly to the experimental collaboration.

5.5.2.5 DSL

The mean lifetimes of excited nuclear states are of considerable interest in nuclear structure and nuclear astrophysics research. Motivated primarily by the latter, the Doppler Shift Lifetimes (DSL) facility is a scattering chamber designed to provide a clean environment conducive to detecting the γ-ray emission from excited nuclear states populated in heavy ion-induced transfer reactions in inverse kinematics, in particular on He-3,4 targets. To carry out such experiments, the use of actively cooled He-implanted foil is essential in order not to evaporate the He and keep the target surface free from contamination that would limit the precision of line shape analyses of transitions from excited states with fs lifetimes. With this infrastructure the DSL facility complements the TIGRESS gamma-ray spectrometer.

Description of Apparatus

The DSL scattering chamber is made from thin Al and contains provisions for mounting cooled He-3-implanted target foils along with a Si surface barrier detector telescope at 0°. A schematic view of the DSL facility is shown in Figure 1. The scattering chamber was designed with a cold trap to ensure a clean target surface and also to prevent losses of the implanted He-3. This was achieved using a narrow differential pumping aperture followed by a copper cylinder enclosing the path of the beam to the target. The copper cylinder is cooled using liquid nitrogen. To avoid any condensation of impurities on the surface of the target, the copper cylinder is not in direct contact with the target ladder. Indirect contact of the cold copper cylinder with the copper target ladder is achieved using BeCu fingers mounted on a boron nitride plate, which provides electrical isolation as well. This arrangement maintains a temperature difference between the copper cylinder and the target ladder. In this way the target can be cooled below room temperature to ensure that He-3 does not diffuse out when heated by bombardment with a beam power of up to 300 mW. Moreover, the colder surfaces surrounding the target foil and the beam path in front of it reduce the buildup of carbon and other contaminants on the target itself during the experiment.

In all DSL measurements to date the target foils were prepared at l'Université de Montréal by implanting 30 keV He-3 ions into Au and Zr foils, yielding an areal He-3 number density of 6×10^{17} cm^{-2}. The concentration of He-3 in the foil is monitored via yields of elastically scattered He-3 during bombardment.

Recent Developments

As described in the nuclear astrophysics science highlights (Section 4.2.2.4) the lifetime of the 6.79 MeV state in O-15 is one of the dominant uncertainties in determining the rate of the $^{14}N(p,\gamma)^{15}O$ reaction, on which the estimated ages of the oldest stars in the Milky Way Galaxy strongly depend. After its initial use in ISAC-I, the DSL facility was moved to ISAC-II, where it has been used with a TIGRESS γ-ray detector to measure the mean lifetime of this state using a 50 MeV O-16 beam. This measurement was performed using the ISAC-II accelerator in order to reach a bombarding energy at which the state of interest was known to be populated; a TIGRESS n-type γ-ray detector was employed due to its resistance to fast neutrons, which are copiously produced at these energies. In 2012 the DSL facility was used to

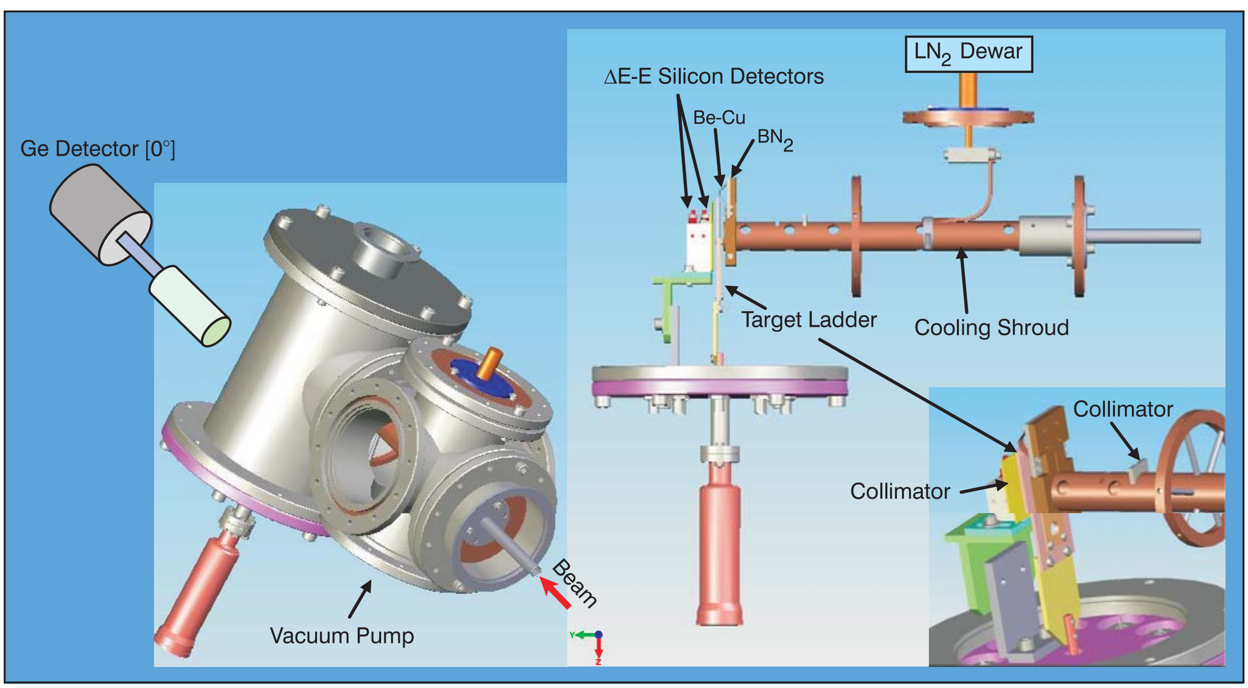


Figure 1: TRIUMF's DSL facility, showing the liquid nitrogen-cooled shroud along the beam axis, the target ladder, the Si detector telescope, and the high-purity germanium detector used to measure Doppler-shifted γ rays.

measure the lifetimes of states in Mg-23 that serve as resonances for the $^{22}Na(p,\gamma)^{23}Mg$ reaction via $^{3}He(^{24}Mg,^{4}He)^{23}Mg$. A spectrum of γ rays detected at 0° in coincidence with α particles emitted during the bombardment of a He-3-implanted Au foil by a 75 MeV Mg-24 beam in ISAC-II is shown in Figure 2.

Partners

In Canada: Saint Mary's University, l'Université de Montréal, Queen's University, Simon Fraser University, University of Guelph.
International Partners: United States (2).

TRIUMF's Role

TRIUMF was solely responsible for the design and fabrication of the DSL facility. It was conceived by two TRIUMF research scientists and implemented with the help of students and postdoctoral fellows.

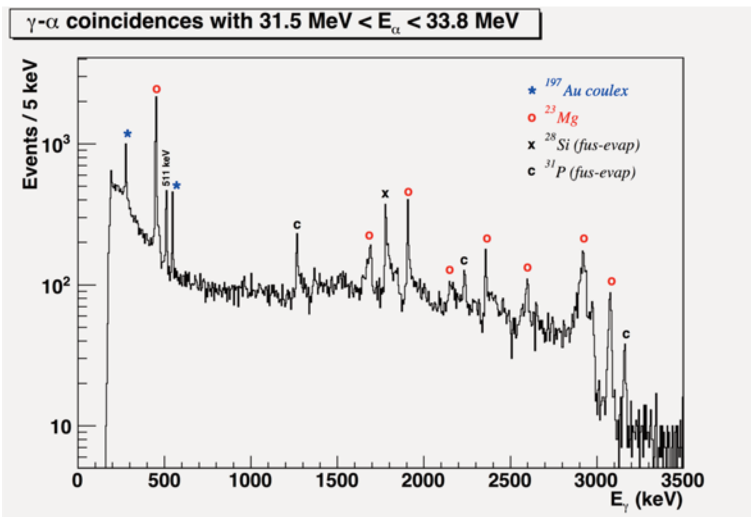


Figure 2: Spectrum of γ rays detected at 0° in coincidence with α particles of energy between 31.5 and 33.8 MeV emitted during the bombardment of a He-3-implanted Au foil by a 75 MeV Mg-24 beam. Observed transitions from excited states in various nuclei are indicated.

5.5.3 MESON HALL

TRIUMF's Meson Hall (see Figure 1) is one of the oldest parts of the laboratory site but it still supports a variety of important activities. The central feature is Beam Line 1A (BL1A) that carries 500 MeV protons from the main cyclotron to two meson production targets through an irradiation facility, followed by the beam dump. The first target station produces muons for the M15 beam line, pions for the M13, which was used for the PiENu experiment but will be phased out to make way for the ultra-cold neutron facility, and both muons and pions for M11.

M11 is a unique facility that provides low-energy beams of pions and muons for detector testing. The second target station is used to produce muons for the M9 and M20 beam lines. These two beam lines, along with M15, provide the muons for TRIUMF MuSR program (see Figure 2). The 500 MeV irradiation facility at the end of BL1A produces strontium for Nordion, Inc., along with other isotopes. BL1A beam dump produces neutrons that are then used at the TNF for neutron irradiation facility (NIF). Also coming off BL1 is BL1B used for both the proton irradiation facility (PIF) and NIF. PIF & NIF are used primarily for testing the effects of radiation on electronics. The meson hall also houses the proton therapy facility used for treating ocular melanomas.

In this section we describe the primary beam line BL1 (Section 5.5.3.1), the muon beam lines (Section 5.5.3.2) and the ultra-cold neutron facility (Section 5.5.3.3) being built at the current location of M13.

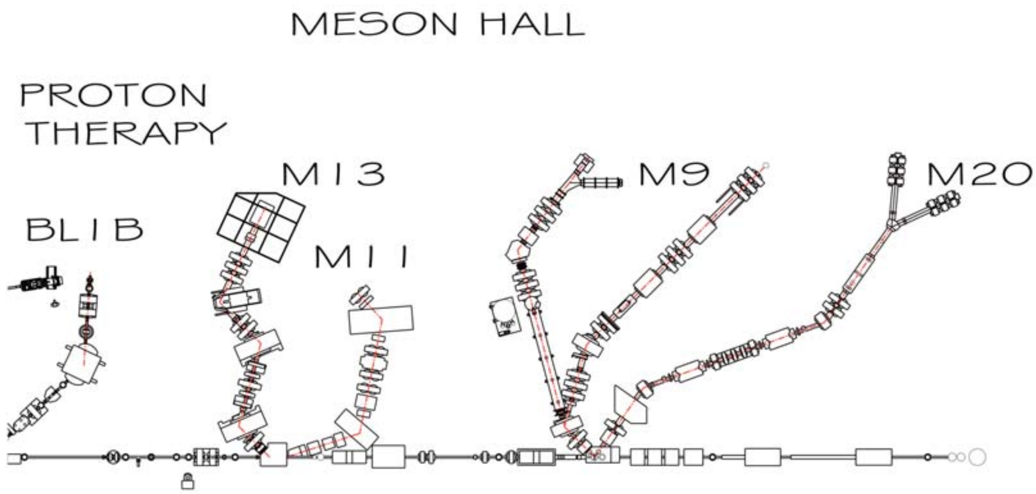


Figure 2: The current Meson Hall secondary beam lines: M15 comes off the first target opposite, and M11 and is located in a Meson Hall Annex.

5.5.3.1 MuSR BEAM LINES AND SPECTROMETERS

TRIUMF provides intense beams of spin-polarized positive and negative muons and radioactive ions for Canadian and international researchers to probe materials at the molecular level. Material properties are determined using a set of magnetic resonance techniques known as μSR (muon spin rotation, relaxation, and resonance) and β-NMR (beta-detected nuclear magnetic resonance). These techniques are used to study a wide range of inter-disciplinary and multi-disciplinary topics in condensed-matter physics (such as magnetism, superconductivity, and defects in semiconductors) and chemistry (including radical kinetics and the structure and dynamics of free radicals).

These capabilities at TRIUMF are managed through the Centre for Molecular and Materials Science (CMMS), established in 1990 and supported by several funding sources. Operated as a user facility, CMMS collects proposals from scientists around the world twice a year, and with the advice of an international, independent review panel screens, prioritizes, and schedules the high-priority proposals. Scientific results obtained from the beam time at TRIUMF have been published by visiting scientists and students with the support of their home institutions.

Muons are present in cosmic radiation but high-intensity beams of spin-polarized muons required for spectroscopic studies are only available at TRIUMF's CMMS facility and three other facilities throughout the world (Paul Scherrer Institute, Switzerland; ISIS, UK; J-PARC, Japan).

TRIUMF also manages a Proton Irradiation and Neutron Irradiation Facility (PIF & NIF) that is used for academic research and industrial testing of electronics performance during and after irradiation. Although PIF & NIF is primarily operated as a stand-alone facility, its focus on radiation effects in matter overlaps with the molecular and materials science focus of the CMMS.

Description of Facility

The CMMS facility has two surface muon beam lines (M15 and M20) with a third (M9A) nearing completion. These transport μ^+ with a nominal momentum of 28 MeV/c, having selected muons coming only from the decay of pions that are at rest on the surface of the production target. Surface muon beams are essentially 100% spin polarized and are also largely monochromatic, with a nominal kinetic energy of 4.1 MeV and a stopping range of ~0.15 g/cm^3, which corresponds to a penetration depth of about 0.2 mm in copper, 1.5 mm in water, or 1 m in He gas at STP. This type of beam is very important in the study of thin samples or in gases at low pressures.

The CMMS has a fourth beam line, M9B, which is used to study thick target samples or high-pressure environments, where more penetrating muons are required, or when a μ^- beam is required. The muons in the M9B "decay channel" are collected from the decay of π^+ or π^- in flight. Both the pion and muon momenta are selected by bending magnets, with muon momenta that can be tuned down to as low as 40 MeV/c, but are more typically in the range 60 to 120 MeV/c. The polarization is lower than from a surface (μ^+) beam, but nevertheless can be as high as 80%. The corresponding particle energy is about 40 MeV, and the stopping range in matter is about 8 g/cm^2, which means decay muons have sufficient energy to penetrate a thick sample or container, such as a pressure cell. The penetration depth is about 1 cm in Cu and 1 m in He gas at 500 bar and 300 K. The CMMS facility at TRIUMF is unique in that all of its beam lines can provide beams with the muon spin either transverse or longitudinal to the momentum.

M9A, M20C, M20D are all surface muon beam lines that are ideal for MuSR studies on materials that do not require confinement in enclosures that support high pressures. M9B services the latter environments where higher energy muons are required to penetrate respective enclosures before encountering the sample under study.

The major new μSR beam line infrastructures implemented at TRIUMF within the 2010–2015 year plan are represented by the total redevelopment of the previous M20 beam line into a dual channel and the addition of a new M9A channel (see Table 1). Both of these beam lines are outfitted with modern achromatic high transmission Wien filter/spin rotators which act to both remove contaminants in the beam and allow the muon spin to be rotated up to 90 degrees as the beam traverses the device. Additionally, both beam lines have ultra-fast electrostatic kickers, which enable a "Muons on Request" (MORE) feature. This mode of operations ensures that one and only one muon is allowed into the sample by rapidly switching the electric field in the device after muon detection and thereby diverting the trajectory of any subsequent muon. Ensuring only one muon has entered the sample allows one to reduce the random background to a level that permits the μSR measurement to extend much farther out in time. Figure 2 illustrates by the inset, in which the muon signal oscillations in the spectra endure for a much longer time with the MORE mode active. The dual channel M20 is in fact designed to accept the kicked beam into the second leg to accommodate a simultaneous conventional MuSR experiment that is running there. The combined capabilities of these beam lines, i.e. 90 degree spin rotation + MORE, are unique in the world's muon facilities.

Beam Line		Characteristic				Flux	Beam	MORE
		MeV/c	Δp/p%	Spin Rotation	Polarization	10^6	h x v	y/n
M15	μ^+	29.5	2-10	0-90°	>98%	2	1.2 x 1.6	n
M9B	μ^+	<70	11	0°	>90%	3	10 x 10	n
	μ^+	>70	11	0-90°	70-90%	2-.5	7 x 7	
	μ^-	30-80	11	untested	>90%	1.4	10 x 10	
M20C, D	μ^+	29.5	2-10	0-90°	>98%	1.5	1.5 x 1.5	y
M9A	μ^+	29.5	2-10	0-90°	>98%	2	1.5 x 1.5	y

Table 1. TRIUMF's four main beam lines and their characteristics.

Another one of a kind capability also resides in the M9B beam line, which is the world's sole provider of spin-rotated high-momentum muons. This feature (i.e. spin rotation) is essential for high magnetic field transverse field MuSR, and the Helios spectrometer (see below) has been used extensively on this beam line for such experiments.

The array of MμSR spectrometers provides a variety of experimental configurations, some of which are tailored to very specific requirements. For example the DR (Dilution Refrigerator) is an instrument designed to achieve very low (15×10^{-3} Kelvin < -273° C) temperatures, where the random thermal motion of the atoms and electrons is suppressed compared to higher temperature environments. For experiments in very high transverse magnetic fields (up to 7 Tesla or 70,000 Gauss) the HiTime spectrometer, with its 180×10^{-12} sec timing resolution, has dominated this experimental space for the last decade. The use of this spectrometer has heralded many breakthrough scientific results in the field of superconductivity, and specifically, the elusive underlying mechanisms of high-temperature superconductivity. Also of note is the development of a super-conducting general purpose spectrometer for the new M9A beam line, which, coupled to the capabilities of the M9A beam line, promises to be the most flexible and general purpose μSR spectrometer in existence.

Associated with the spectrometers is a significant array of supporting equipment including cryostats, temperature/flow/vacuum/magnetic field controllers, pressure cells, electric field devices, and highly specialized data acquisition electronics/computers.

The scientific support, which the facility extends to its user base, can be categorized into four categories: (1) the setting up of an experiment, i.e. preparing the beam line and spectrometer so that a user can quickly embark on the experimental program when beam is delivered; (2) assisting the users with the execution of their experiments, both technically (data acquisition) and scientifically (data analysis); (3) supporting an active outreach program, the goals of which are to educate new users and to introduce the technique to those research institutions that would benefit from it; and (4) the development of new research capabilities (i.e. advanced spectrometers and beam lines) so that cutting-edge research continues to be available to the TRIUMF CMMS user community.

User access to CMMS is managed by TRIUMF's Science Division with the advice of the Molecular and Materials Science Experiment Evaluation Committee (MMS EEC). During the 2008–2013 performance period, the EEC met at least once a year and approved hundreds of shifts per year. Subject to scheduling and backlog, CMMS provided users with nearly 3,600 shifts of beam time (see Table 2).

	2008			2009			2010		
	Requested	Approved	Delivered	Requested	Approved	Delivered	Requested	Approved	Delivered
MMS1	408	328		485	314		695	269	
MMS2	567	445		697	459		106	24	
Total	975	773	956	1182	773	1147	801	293	506

	2011			2012		
	Requested	Approved	Delivered	Requested	Approved	Delivered
MMS1	520	362		411	284	
MMS2		(EEC met only once)			(EEC met only once)	
Total	520	362	163	411	284	825

Table 2. Beam time requested and delivered 2008–2013.

Access to PIF & NIF for academic research is managed in a similar manner to the CMMS facility; industrial or commercial access is managed by TRIUMF's senior management to balance revenue-generating activities with the core science program. From 2008 to 2013, non-commercial use of PIF & NIF for basic research was (please see Section 4.4 for commercial usage):

2008	214 hours
2009	150 hours
2010	172 hours
2011	184 hours
2012	240 hours

Recent Developments

The major developments relate to M20 and M9A above, as both of these were rebuilt during 2011–2013 into the advanced capability μSR beam lines they now are. The M20 project received support from the Canada Foundation for Innovation (40%), British Columbia Knowledge Development Fund (40%) and TRIUMF/National Research Council (NRC) (20%), whereas the M9A project was funded solely by TRIUMF/NRC.

For many years, PIF & NIF has been using the Monte Carlo simulation code FLUKA to model its facilities to help better characterize its beam lines and to provide input to potential upgrades. In 2011, a student project was used to create a model of the low-energy BL2C facility that was then enhanced in 2012 to design a double-scattering system. From the FLUKA modeling, this new device was able to be quickly built and implemented and allows a larger, homogenous area of electronics or materials to be irradiated at a higher rate. It has increased PIF & NIF capabilities and has already been used by several commercial customers.

FLUKA modeling was used to both design and characterize the BL1B upgrade with support from Cisco Systems, Inc. The necessary infrastructure was installed during the Spring 2013 Shutdown period and first beams have already been generated to verify diagnostics, controls, shielding, and beam characteristics. It is anticipated that this upgrade will be embraced by both industry and research groups worldwide.

Partners

International partners: Japan (1), Switzerland (1), United Kingdom (1).

TRIUMF's Role

Although for M20 the majority of capital funding came from external sources, provision of the intellectual, technical, and administrative human resources required for the successful completion of these beam lines was almost entirely provided by TRIUMF. It is estimated that 12 man-years of effort was devoted to these beam lines and included substantial technical innovation in the design and implementation of the high-voltage Wien filters.

With respect to personnel, the eight dedicated individuals that comprise the CMMS facility staff consist of five facility scientists and three technicians; the majority of these are supported by a renewed major research support grant via NSERC. The scientists are the facility manager, deputy manager, operations manager, IT/DAQ support, and outreach Liaison/EEC secretary. In addition to the duties implied by their titles, they provide general experimental user support and have collective expertise in semiconductor, surface, and theoretical physics, as well as that in reaction kinetics and physical chemistry, inclusive of soft materials. The CMMS technical staff members also have individual specializations including high vacuum expertise, design technologies, and millwright/mechanical fabrications.

5.5.3.2 ULTRA-COLD NEUTRONS

Ultra-cold neutrons (UCN) are neutrons of such remarkably low energies that they are totally reflected from the surfaces of a variety of materials. UCN can therefore be stored in magnetic bottles for long periods of time. Typically, UCN have kinetic energies that are less than 300 meV. Correspondingly, UCN may also be trapped by the Earth's gravitational field, and by magnetic bottles. Since UCN can be stored in such a fashion, it makes them the perfect laboratory to study the fundamental properties of the neutron.

TRIUMF has seized upon a window of opportunity to capitalize on the successes of our Japanese collaborators in developing new technology to produce UCN. This collaboration will allow the Canadian project to surpass other proposed sources. The UCN source will be located at TRIUMF, which is ideal because of the high-intensity high-energy proton beam that is used to drive the UCN source. The high UCN density that will be obtained at TRIUMF will allow a class of precision measurements of the fundamental properties of the neutron to be conducted with significantly higher precision than ever before. A description of the science program for the UCN source is presented in Section 4.2.1.3.

Description of Facility

The UCN facility planned for TRIUMF is shown schematically in Figure 1. It is comprised of a fast kicker magnet, septum magnet, beam line, spallation target, and associated shielding. Above the spallation target, and within the shield package, will be located the UCN production volume containing superfluid helium. (The UCN source cryostats have been constructed and are being tested by the Japanese branch of the collaboration.) UCN will diffuse out of the source to experiments. The goal UCN density is 1300 polarized UCN/cm^3, to be delivered to the EDM measurement cell. This value can be compared with typically ~ 1 UCN/cm^3, used for the previous best experiment.

This goal is also comparable to the goals of other UCN facilities elsewhere. The chief difference in our strategy is the use of a spallation-driven UCN source, where the UCN converter is superfluid helium. An advantage of this type of source over spallation-driven solid deuterium sources (at e.g., LANL and PSI) is that the lifetime of UCN in the superfluid helium is much longer. This means that a longer pulse structure can be used to accumulate density over hundreds of seconds, resulting in competitive densities with smaller instantaneous beam power. The challenge in our case is the cryogenic issue of placing a 0.8 K bath close to the spallation target, whereas the solid deuterium need only be >5 K. We believe that the cryogenic issues can be dealt with, at least at TRIUMF beam intensities, and therefore that, ultimately, our technology will be successful for the present generation of UCN sources.

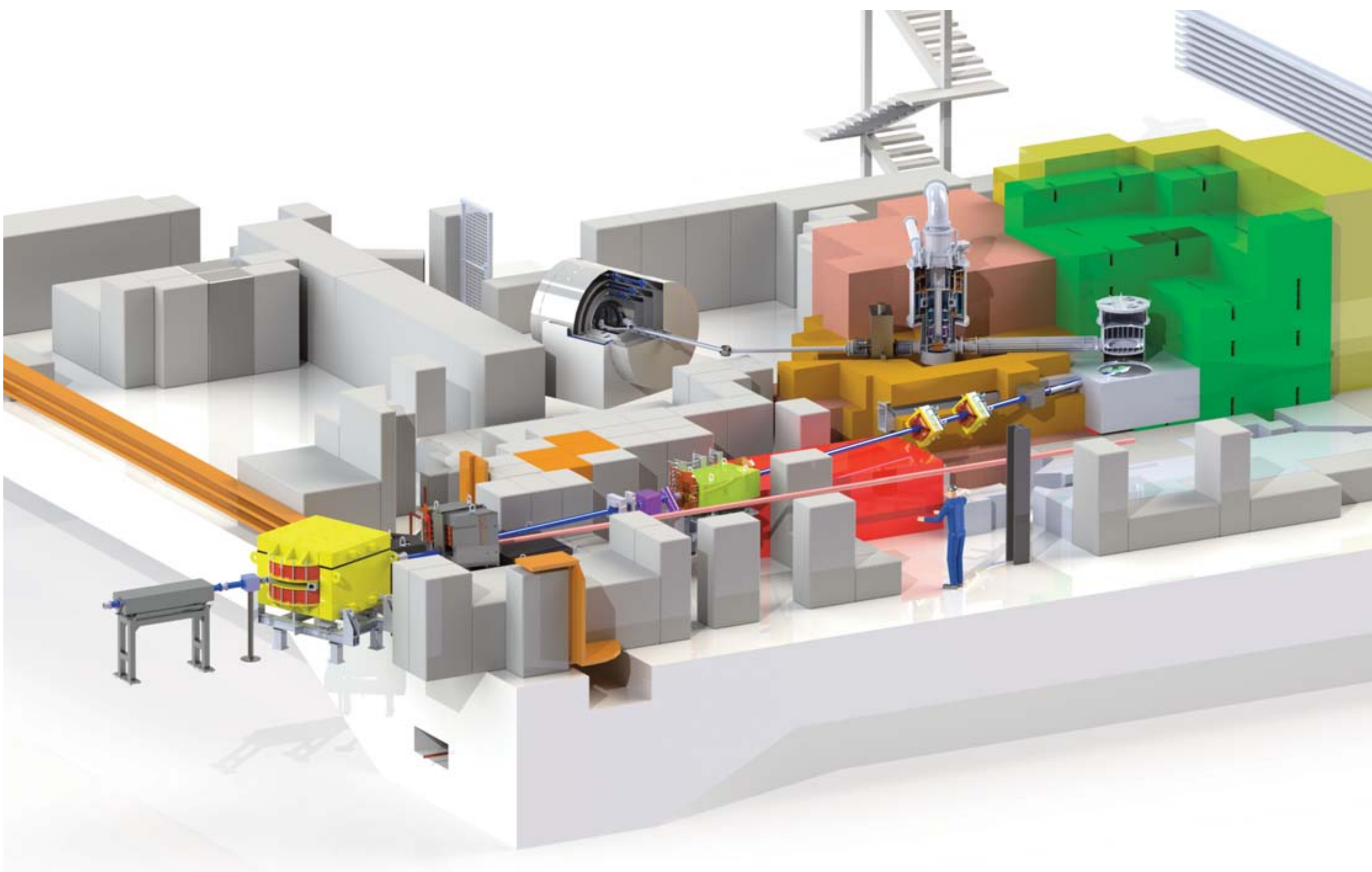


Figure 1: Location of the UCN facility in the Meson Hall.

Recent Developments

The UCN facility was funded by the Canada Foundation for Innovation (New Opportunities Fund, 2009), with partner contributions from the Japan Society for the Promotion of Science (JSPS), TRIUMF, KEK, RCNP Osaka, Acsion Industries (Pinawa), and the Government of Manitoba.

In September 2010 the project successfully underwent a review by an international expert panel commissioned jointly by KEK, RCNP, and TRIUMF.

A memorandum of understanding (MOU) between KEK, RCNP, TRIUMF, and the University of Winnipeg was completed in January 2011 for the UCN source and EDM Experiment. Canadian funds for the project were released in April 2011. The project has been supported by NSERC since April 2010 and now supports 14 eligible signatories over three separate subatomic project grants. Renewal of this support with three new cosignatories is being sought this year.

Support for the EDM experiment itself is through NSERC, and we have received two RTI grants for related work. The project has been supported by separate CFI grants to its members at the Manitoba universities, the most recent being the CFI Learning Opportunities Fund to Martin and Bidinosti to support a Xe lab for fundamental physics related to comagnetometer development. As a part of the MOU, JSPS and internal support from both KEK and RCNP Osaka have been committed. The internal support from the laboratories is particularly important; it supports beam line components and cryogenic equipment destined for TRIUMF, as well as EDM equipment crucial for completing experiments at RCNP Osaka.

The project underwent another successful review by an international expert panel in December 2012, this one commissioned by KEK's Institute for Particle and Nuclear Science (IPNS). As a result of this review, the TRIUMF project was selected (over another neutron EDM project at J-PARC) for additional KEK support (beyond the support specified in our MOU) for 2013 and beyond.

Technical Status

The prototype UCN source at RCNP Osaka delivered a UCN density of 20 UCN/cm^3 to a detector located outside the shield package [9], a second-generation source being developed at this time (see Figure 2). The new source features improvements to the geometry, production volume, storage lifetime, transport efficiency, and higher energy transported UCN, which are anticipated to result in higher UCN density.

Figure 2: Left Top: Photo of Helium-II cryostat. The pumping for the He-3 and natural He (1 K) pots may be seen projecting out towards the viewer. Right: High voltage prototype of the storage cell for the measurement of the neutron electric dipole moment at TRIUMF. Left Bottom: Photo of cryostat. The long horizontal section that would connect the two cryostats is also shown.

The new UCN source cryostats, which contain the superfluid helium UCN conversion volume, and the cold moderator materials are under development at RCNP Osaka. Figure 2 shows photos of both cryostats. The superfluid helium cryostat will undergo cold tests throughout 2013. The UCN source will be available for experimentation at RCNP with lower intensity proton beam until 2015, when relevant parts of the apparatus will be moved to TRIUMF for installation.

Substantial progress has been made on the major subsystems of the TRIUMF facility: The bender magnet was completed in fiscal year 2011–2012 by KEK. The kicker and septum magnets underwent internal review at TRIUMF in March 2012. The kicker magnet and its associated power supply entered the bidding process at TRIUMF in early 2013. At time of writing, detailed drawings for the septum magnet are being completed. The proton spallation target will be water-cooled tungsten, and this has been studied in detail using MCNPX and ANSYS CFX simulations. Conceptual designs of the target and remote handling systems have been completed. Basic radiation shielding concept drawings have been studied and simulations of the radiation shield package are ongoing. Space has been reserved for the neutron electric dipole moment experimental area.

Facility Status

The UCN facility at TRIUMF began construction in early 2013, with the first step being general area clean up and a few modifications to quadrupole magnets in the existing Meson Hall beam line. A detailed plan for successful completion has been formulated, taking into account availability of TRIUMF resources as appropriate. A project manager and a project engineer at TRIUMF have begun work on the project. Monthly meetings are being held with the relevant TRIUMF division heads to ensure open lines of communication and to monitor progress.

Partners

In Canada: University of British Columbia, University of Manitoba,
University of Northern British Columbia, University of Winnipeg.
International partners: Japan (4), Switzerland (1), United States (1).

TRIUMF's Role

Through this project, TRIUMF has developed a new discipline of research in subatomic physics in Canada: the field of fundamental physics using UCN. TRIUMF scientists have taken on leadership roles for several key parts of the nEDM experiment: magnetic environment, high-voltage, UCN detectors, cold neutron moderator design, and studies of heat transport through superfluid helium. In addition, TRIUMF provides the expertise to develop the new proton beam line and associated spallation target, shielding, and cryogenics for the UCN facility. [8,4,5].

CANADIAN MILESTONE IN JAPAN-BASED EXPERIMENT

08 October 2009

The Canadian group associated with the T2K (Tokai to Kamioka) neutrino experiment in Japan achieved a major milestone in October 2009, with the installation of two fine-grained detectors (FGDs).

Neutrinos are nearly massless subatomic particles that interact very weakly with matter. There are three types (or flavours) of neutrinos, and as shown by the Sudbury Neutrino Observatory, they can oscillate from one flavour to another. The T2K experiment will study these oscillations in unprecedented detail.

Operational tests of the FGDs will now be conducted making use of cosmic rays. The experiment is scheduled to start taking data in December 2009.

T2K Canada consists of groups at TRIUMF, Victoria, UBC, Alberta, Regina, York, and Toronto and is the largest group of collaborators outside of Japan. The entire T2K collaboration includes groups from Japan, Canada, the US, Europe, and Russia.

5.5.4 DETECTOR DEVELOPMENT AND FABRICATION FACILITY

All experiments in particle and nuclear physics, as well as condensed matter experiments at TRIUMF, require instruments to detect energetic subatomic particles. Detectors are required to measure various kinematic properties of each particle, such as its energy, momentum, the spatial location of its track, and its time of arrival at the detector. New scientific opportunities arise from advances in detector capabilities, such as enhanced precision in kinematic properties; the rate at which particles may be detected, which leads to improved statistical precision; and in reduced costs, which make possible larger systems with greater sensitivity to rare processes.

Over the last several decades, TRIUMF's Detector Group (DG) has established a strong international reputation for developing, designing, and constructing state-of-the-art detectors, as well as developing new detector technologies. A steady progression of new instruments has been successfully deployed in measurements at TRIUMF and in collaborative projects elsewhere in Canada and abroad. As was typical in previous years, every detector or detector element produced by the DG during 2008–2013 has performed as required, with no disappointments. These successes are noted in the corresponding descriptions of those experimental activities in the scientific section of this document.

Detectors exploit various special technologies. One example is scintillating materials, which emit a flash of optical light when stimulated by impact or passage of an energetic particle. The intensity of light is typically proportional to the energy that the particle deposited in the material, thereby leading to arrays of such scintillators being known as calorimeters. The light can, in turn, be collected and detected by a variety of devices, which themselves are a topic of recent advances. The scintillator material, which can be organic or inorganic, a solid, liquid or gas, is chosen from a set of established possibilities to optimize the precision in time or energy of the measurement while minimizing the cost. New materials with improved properties continue to be developed. The most prominent example of scintillator construction during 2008–2009 was a close collaboration with the T2K collaboration in the construction of two large fine-grained plastic scintillator arrays for the T2K neutrino experiment in Japan, as described in Section 5.5.5.3. This project was large and ambitious, successfully employed, for the first time, a new photo-sensor technology on a large scale. The DG also provided the design concepts and construction techniques for a potentially commercial application of scintillator technology on a substantial scale to the identification of subterranean ore bodies through the detection of cosmic-ray muons by scintillator assemblies deployed underground.

Another widely used detector technology exploits the trail of ions and free electrons produced in the track of a charged particle, which typically passes through gases but also through certain liquids, to determine the spatial location of that track to a precision that may be as small as the thickness of a human hair. The electrons are collected on a lattice or array of many electrodes in the medium. The tiny electrical signal on each electrode is amplified by the avalanche process in the high electric fields near the electrode and is detected by a sensitive electronic device. Such tracking detectors are often used in the magnetic field of a large magnet in which the tracks of charged particles are curved to a degree related to their momenta. Measuring a track's curvature thus determines the particle's momenta. In addition, the density of the ionization along the track can be recorded and used to identify the type of charged particle.

The largest gas detectors constructed during 2008–2009 were three large time-projection chambers (TPCs) for precisely tracking charged particles produced by neutrino interactions in the T2K Experiment, as described in Section 5.5.5.3. This was the first large-scale application to TPCs of a recently developed technology for sensing clouds of electrons drifting in the gas. The mechanical design of these and most other detectors produced by the DG depends on the inventive and tireless efforts of Robert Henderson. The Group also has strong skills and experience, and an impressive track record, in the design and production of the complex systems for circulating, re-purifying, and precisely controlling the pressure of the special gases for this type of detector.

All particle detectors ultimately produce information in the form of electrical signals that must be processed by electronic circuits, digitized to produce numerical data, which in turn may be further processed in real time and then recorded for further analysis. The initial signals may be so tiny that they need to be amplified by sensitive devices that have very little intrinsic noise. Continuing advances, in both this analogue technology as well as in the digital processing devices and techniques, have played crucial roles in rapid enhancements in the capabilities of detector systems. The Group's success in this area flows from the experience and insight of Leonid Kurchaninov.

The investigation and application of new detector technologies is a principle interest of Fabrice Retière. He led the application of the new optical sensors to the T2K project, as well as the design and construction of the signal processing and digitization electronic system. Overall leadership of the Group is provided by Andy Miller, which brings the total number of Ph.D. scientists to four. There are eleven other designers and technicians in the Group, many of them in the later stages of their careers. Their collective seniority has major advantages concerning the wealth of experience in the Group but it will require a concerted effort to maintain the Group's capabilities over the period of succession that looms ahead of us.

Description of Facilities

The facilities for detector construction occupy four substantial areas on the TRIUMF site.
The Scintillator Shop is equipped with:

- a Haas VF-5/40XT CNC vertical milling center with a 5-axis spindle and 2-axis rotary table yielding a precision of ± 5 µm over a working volume of 1.5 m × 0.66 m × 0.64 m (see Figure 5.5.4-1)
- a Haas TL-3 CNC lathe with a maximum cutting diameter of 0.5 m and a maximum cutting length of 1.5 m (see Figure 5.5.4-2)
- a Manfred manual 3-axis precision turret mill and a manual lathe, both with about 4' travel
- a Band-saw, pneumatic press-brake, and pneumatic shear
- a temperature controlled oil bath for shaping plastic scintillators and light-guides, often into exotic shapes to fit into the complex geometries of experimental instruments

In another building is a large tent housing a Multicam CNC router with a precision of ±100 µm over a working volume of 3 m × 3 m × 0.4 m (see Figure 5.5.4-3). Linear encoders within its ball rails enhance its precision for static operations such as hole drilling to ±25 µm. Furthermore, its spindle has an angle encoder in a spindle-rotation servo loop for "rigid tapping" (synchronized rotation and thrust) of hole threads. Finally, its spindle carriage can be equipped with a CCD camera for coordinate measurements, or a surface scanning probe to precisely map the varying height of the surface of a work-piece before machining accordingly. All of these machine tools are housed in temperature-controlled areas with internal 5t crane coverage and dust extraction systems suitable for machining the composite materials that play a major role in the fabrication of modern instruments. This facility also machines such materials for other TRIUMF Divisions. Any machining of metals is done with only slight lubrication to avoid subsequent contamination of plastic work-pieces that can result in cracking and other degradation. The machine tools are operated by a journeyman machinist and two other technicians, all with many years of experience with CNC equipment. They are also particularly well suited to interact effectively with the scientific clients in developing practical solutions for the varied requirements.

The Group also has three temperature-controlled class-1000 clean rooms, with volumes 7.8 m × 11.5 m × 5 m, 8 m × 10 m × 2.4 m, and 8 m × 9 m × 2.8 m, for assembling instruments of all sizes. The largest such room has full coverage by an internal 5t crane, and can house a 3 m × 2.4 m and/or a 1.2 m × 4.3 m precision-ground granite slab with pneumatic or hydraulic presses (see Figure 5.5.4-4). Finally, there is a 10 m × 27 m detector development area with 2t crane coverage, equipped with several high-purity gas mixture manifolds. This area is serviced with a stainless steel gas distribution and return system from an adjacent gas mixing shack, and typically hosts half a dozen separate activities involving assembly and testing of detectors and related equipment. In this area the Group also has a QMS gas analysis system. The replacement value of the entire infrastructure of the detector facility for construction is about C$1M.


Figure 1: The Haas VF-5/40XT CNC vertical milling center. **Figure 2:** The Haas TL-3 CNC lathe. **Figure 3:** The Multicam CNC router. **Figure 4:** The 3 m × 2.4 m precision-ground granite slab in the 7.8 m × 11.5 m × 5 m clean room.

The Detector Electronics subgroup has an 8.4 m × 12 m space for design and development of electronic systems for precisely sensing and processing the tiny signals typically produced by detectors. This laboratory is well equipped with modern test equipment. An experienced designer combines his broad knowledge of the great array of applicable electronic component technologies with advanced skills in both 3D mechanical and multi-layer printed-circuit board design tools to produce integrated detector solutions. A more junior technician in this group combines appropriate capabilities for such design with cryogenic and vacuum experience, skills in constructing prototypes, repairing production instruments, and coding of instrumental firmware and software. This subgroup undertakes not only detector instrumentation projects, but also some design and development work for the TRIUMF Accelerator Division.

Partners

The Detector Group has collaborated with many experiments, local, national and international to design and produce instruments essential for their success.

TRIUMF's Role

The Detector Group is a major component of the TRIUMF Science Division. All of the personnel are permanent TRIUMF staff. Only machining and assembly work done in the Scintillator Shop is charged to the clients on an hourly basis.

5.5.5 TRIUMF CONTRIBUTIONS TO OFF-SITE INFRASTRUCTURE

TRIUMF expertise in detector development is sought out by foreign collaborators and TRIUMF has made significant contributions to a number of offsite experiments: ATLAS (Switzerland), T2K (Japan), ALPHA (Switzerland) and four at SNOLAB (Ontario). These contributions to the detectors facilitates TRIUMF staff and other Canadian scientist involvement in these experiments.

5.5.5.2 ATLAS UPGRADES

The ATLAS detector at the CERN Large Hadron Collider (LHC) has been running with proton-proton collisions since the autumn of 2009. In total, about 25 fb^{-1} of data with centre-of-mass energies of 7-8 TeV have been analyzed by ATLAS scientists, with leading roles by Canadians in many physics areas. In 2012, ATLAS announced the discovery of a particle consistent with the Standard Model Higgs boson, a discovery enabled by Canadian-built detectors, computing systems, data analyzers, and analysis reviewers.
In summer of 2013, the LHC entered a two-year shutdown period in order to consolidate and upgrade the facility to allow higher intensities and to nearly double the beam energies. At the time of writing, ATLAS is undergoing a detector upgrade program to enable full exploitation of this future running. Canadians are fully engaged in the ATLAS upgrade program, including significant efforts since 2008 involving TRIUMF facilities and personnel. Further details of the scientific program at ATLAS can be found in Section 4.2.1.1.

The ATLAS Detector

A full description of the ATLAS detector [3] is beyond the scope of this document. ATLAS is a multipurpose particle physics apparatus with forward-backward symmetric cylindrical geometry.
The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a straw-tube transition radiation tracker. The ID is surrounded by a thin superconducting solenoid which provides a 2~T magnetic field, and by high-granularity liquid-argon (LAr) sampling electromagnetic calorimetry. The electromagnetic calorimeter is divided into a central barrel and end-cap regions on either end of the detector. An iron-scintillator/tile calorimeter gives hadronic coverage in the central rapidity range, while a LAr hadronic end-cap calorimeter (HEC) provides coverage in the forward regions. The HEC was designed at TRIUMF, and half its modules were built in Canada and assembled at TRIUMF. The final assembly at CERN was directed and overseen by TRIUMF personnel. The regions closest to the beampipe are instrumented with LAr calorimeters for both electromagnetic and hadronic measurements. The hadronic forward calorimeters were built in Canada with the participation of TRIUMF staff.
The muon spectrometer surrounds the calorimeters and consists of three large air-core superconducting magnets providing a toroidal field, each with eight coils, a system of precision tracking chambers, and fast detectors for triggering. The combination of all these systems provides charged particle measurements together with efficient and precise lepton and photon measurements.

The data from ATLAS are selected with a three-level triggering system to which Canada contributed significantly. After initial processing at CERN, the data are distributed to ten Tier-1 Data Centres around the world. TRIUMF hosts Canada's ATLAS Tier-1 Data Centre (please see Section 5.8.1).

ATLAS performance has been exceptionally good, with 93.5% of delivered data being recorded with sufficient quality to use for physics analysis. The LAr calorimeters were over 99% efficient in 2012, when the bulk of the data were taken.

Description of Facilities

ATLAS has made use of several TRIUMF facilities for upgrade studies since 2008.
Neutral Beam Irradiation Facility (NBIF)

The TRIUMF neutral beam irradiation facility (NBIF) is located in the cyclotron vault near the beam line 1 and beam line 4 extraction points, taking advantage of the neutral hydrogen beams that result from the stripping of a single electron from the H- ions by the magnetic fields at the outer orbit. The neutral hydrogen leaves the magnetic field region in a planar beam, which is fully stripped as it leaves the vacuum region, exiting as a proton beam at nearly full energy (500 MeV). Each NBIF station has an ion chamber which tracks the relative local beam intensity, and users calibrate the dose received during irradiation using thin aluminum foils which are analyzed after irradiation runs. ATLAS has used the NBIF for several tests of polycrystalline chemical vapour deposition diamond detectors, and plans further tests of new electronics technologies in the future. Total fluences of 5 x 10^{16} protons cm^{-2} were reached in the current tests. The NBIF facility is shown in Figure 1.

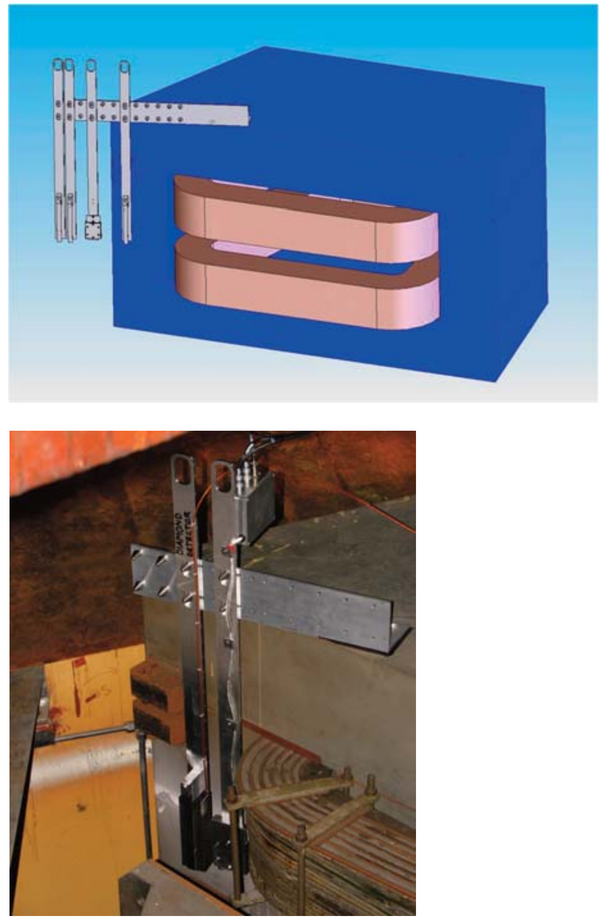


Figure 1: Neutral beam irradiation facility. The left-hand diagram shows a schematic of the NBIF, and the right-hand photo shows an ATLAS sample installed to the left of the NBIF ionization chamber.

Beam Line 1A (BL1A)

The NBIF irradiation fluences are insufficient to reach the levels expected in the ATLAS forward calorimeter region in ten years of upgraded LHC operation when the required safety factors are included. Installing samples directly into TRIUMF Beam Line 1A makes it possible to

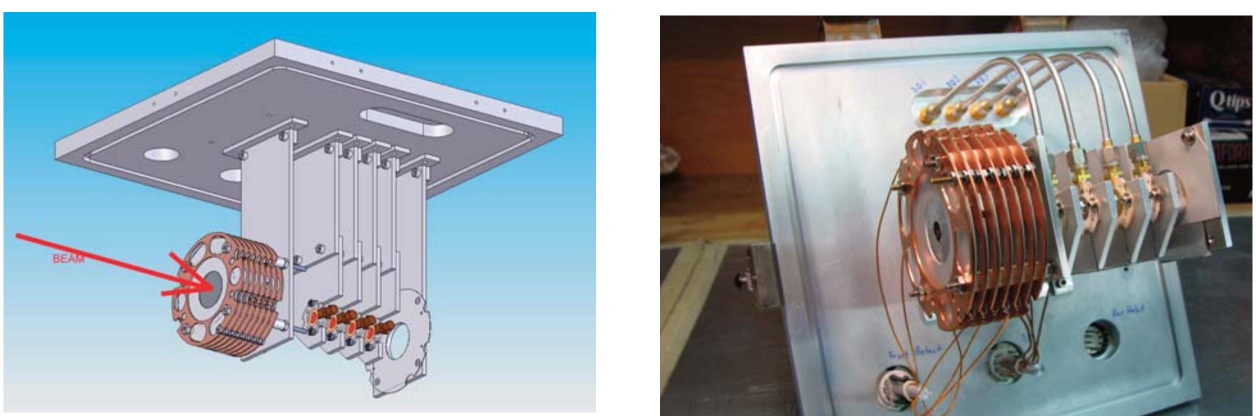


Figure 2: Beam Line 1A high intensity ATLAS irradiation tests. The schematic on the left shows the beam impinging upon a diagnostics system, with four pCVD diamond detectors mounted downstream. The photo on the right shows the same setup. The detectors are mounted on an aluminum plate, which is then mounted as the lid of a standard beam line “diagnostics box,” and then installed directly into Beam Line 1A.

achieve the desired dose in about two weeks of low-intensity operation. ATLAS has used BL1A for high intensity irradiation tests, reaching fluences of 2.5 x 10^{17} protons cm^{-2}. The BL1A irradiation setup used for high intensity ATLAS pCVD diamond tests is shown in Figure 2.

M11 Beam Line

TRIUMF beam line M11 is a secondary muon and pion beam line running at low intensity. ATLAS has used M11 as a precision muon source for measuring the response of particle detectors. ATLAS used M11 muon beams to characterize the uniformity of pCVD diamond detectors. A sketch of the ATLAS tests in M11 is shown in Figure 3.

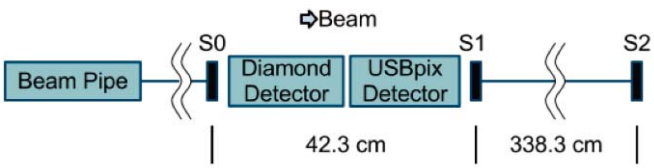


Figure 3: Diagram of the ATLAS detector tests in the M11 beam line, where the beam exit is labeled "Beam Pipe." S0, S1, and S2 are scintillators used to trigger muons that have passed through the entire detector. The diamond detectors and precision pixel tracking detectors (USBPix) are located between two of the trigger scintillators.

TRIUMF Engineering Division Personnel and Facilities

Members of the TRIUMF engineering division led the planning of ATLAS end-cap calorimeter upgrade scenarios, including designing both new detector elements and the tooling required to carry out the installation of new detectors, and handling of the existing activated detectors in the ATLAS experimental area. These TRIUMF staff members have experience working with ATLAS technical coordination and radiation safety groups at CERN, including TRIUMF members who led the installation of the current ATLAS endcap calorimeters in cryostats and the transport and installation of the 250-ton assemblies in the ATLAS detector.

TRIUMF Detector Group Facilities

The TRIUMF Detector Electronics Group plays a critical role in ATLAS upgrade activities, both on- and off-site. This group also designed and deployed the readout electronics and data acquisition systems for the irradiation and uniformity tests described in this section and also assisted in data taking. NIM modules, crates, oscilloscopes and other equipment from the detector group are used throughout our program. Detector group members also designed and constructed electronics used for ATLAS high-rate calorimetry tests at IHEP/Protvino, Russia and neutron irradiation tests at the IBR reactor facility in JINR, Russia.

TRIUMF Diagnostics Group Facilities

The TRIUMF diagnostics group designed, built, and installed the NBIF facility and also packaged the ATLAS components for use in the NBIF and BL1A tests. They constructed all of the beam instrumentation and assisted in cabling both the NBIF detectors in the cyclotron vault and the BL1A pCVD diamond detectors with cable runs from the beam line to a data acquisition platform in the TRIUMF Meson Hall.

Recent Developments

ATLAS has seen many developments since 2008.

Tooling for Endcap Calorimeter

ATLAS is exploring two options for the forward calorimeter, the complete replacement of the current system with a "super Forward Calorimeter" (sFCal) or the less expensive option of installing a smaller, high-rate calorimeter (MiniFCal), which shields and protects the existing detectors while maintaining precise energy measurements.

TRIUMF's engineers and designers were critical to the overall design of the current ATLAS LAr end-cap calorimeters and supervised the assembly and installation of the detectors at CERN. If the FCal is replaced with an sFCal, significant tooling will need to be installed in the ATLAS pit to handle the highly activated, massive detectors. The installation of the MiniFCal would be simpler and less risky than the full replacement option but would still involve working in a challenging environment with radiation-shielding issues. TRIUMF engineers and designers have led the effort to design the full set of tooling needed for handling the forward calorimeters for ATLAS upgrades, whether we need to replace the

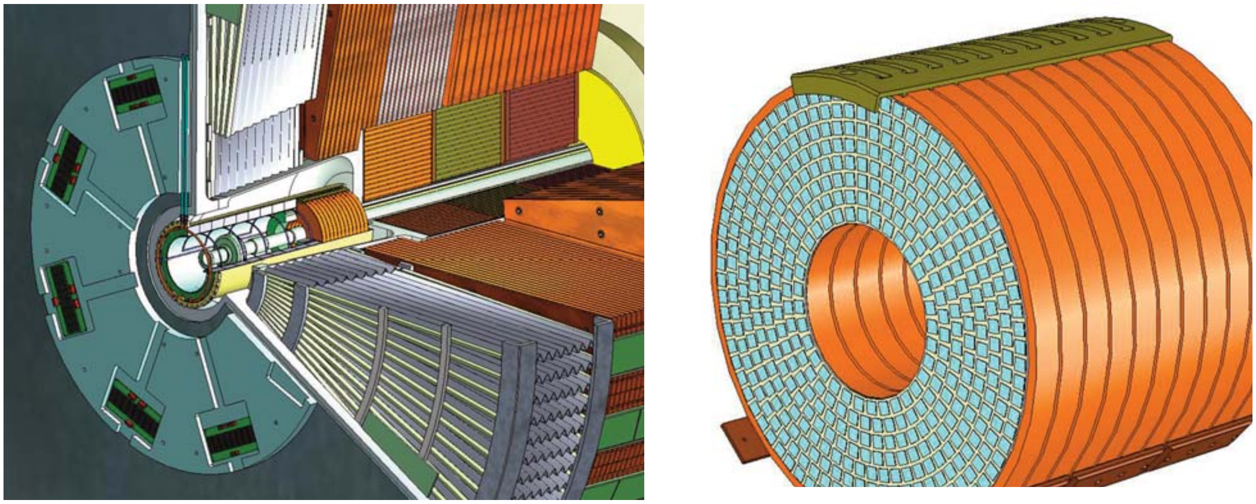


Figure 4: On the left is a SolidWorks design by Roy Langstaff showing the installation of a MiniFCal, shown on the right, in ATLAS. Langstaff and Lenckowski have developed complete installation scenarios for both the MiniFCal, and complete FCal replacement, options, as well as designed tooling for handling the HEC calorimeter required for replacement of electronics mounted on the edges of the detector.

complete forward calorimeter system or just to install the MiniFCal. They have also completed designs of tooling required to remove the hadronic end-cap calorimeters (HEC) for replacement of the electronics mounted on the detectors should that be required. A sketch of the MiniFCal option is shown in Figure 4, developed by members of the TRIUMF engineering division based at the University of Victoria.

Radiation Hardness of Polycrystalline Chemical Vapour Deposit (pCVD) Diamond Detectors
Developing an active detector able to handle the high rates and radiation fluxes near the ATLAS beam pipe is essential for the MiniFCal. Diamond technology promises very fast response from radiation hard

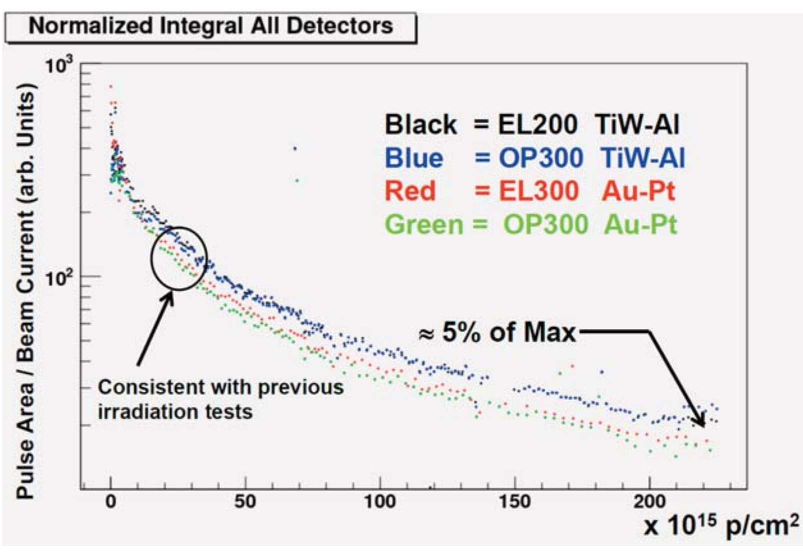


Figure 5: Normalized response of four different detectors irradiated in TRIUMF Beam Line 1A. These tests extend the levels of previous measurements by about an order of magnitude. "EL" and "OP" refer to the grades of the pCVD diamonds (high quality electronics grade and medium quality optical grade), "200" and "300" refer to the detector thicknesses in microns, while the chemical symbols refer to the composition of the electrodes coating the pCVD diamond surfaces.

detectors, but pCVD diamonds had only been tested to fluences of 10^{16} particles/cm^2, about an order of magnitude less than that expected in the ATLAS FCal region over 10 years of running at the upgraded LHC. In a set of continuing irradiation tests at TRIUMF, we have tested different grades and thicknesses of pCVD diamond detectors above 2.5×10^{17} particles/cm^2, the level required for use in ATLAS forward calorimetry. We have performed tests in both the "NBIF" facility in the TRIUMF cyclotron vault and using TRIUMF Beam Line 1A. The highest fluence results, from tests in TRIUMF Beam Line 1A, were published in [1]. The normalized detector response is shown in Figure 5 for the Beam Line 1A tests.

The irradiation tests performed at TRIUMF on pCVD detectors used protons, while the ATLAS calorimeters predominantly see neutron fluxes. The TRIUMF ATLAS group, along with members of the TRIUMF Detector Group, led Canadian participation in neutron irradiation tests of pCVD diamond detector at the IBR reactor at JINR/Russia. Preliminary results of the neutron irradiation test are shown in Figure 6.

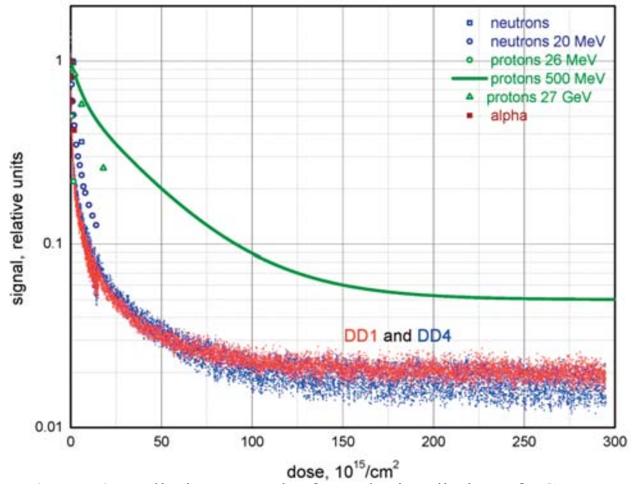


Figure 6: Preliminary results from the irradiation of pCVD diamond detectors with neutrons. Also overlaid are our results with proton beams at TRIUMF, which seem to cause less damage than the neutrons. Calibration of the neutron fluxes is pending, and the results are subject to change.

Spatial Uniformity of pCVD Diamond Detectors

For use in a calorimeter, the active detector elements must also be uniform since their signals are summed prior to digitization. Using muons in TRIUMF beam line M11, we studied the response uniformity of pCVD diamond detectors to single particles. The analysis from those studies is completed, and the paper submitted to JINST (preprint number JINST_002P_0712). Figure 7 shows the spatial uniformity results from the detector tested in M11.

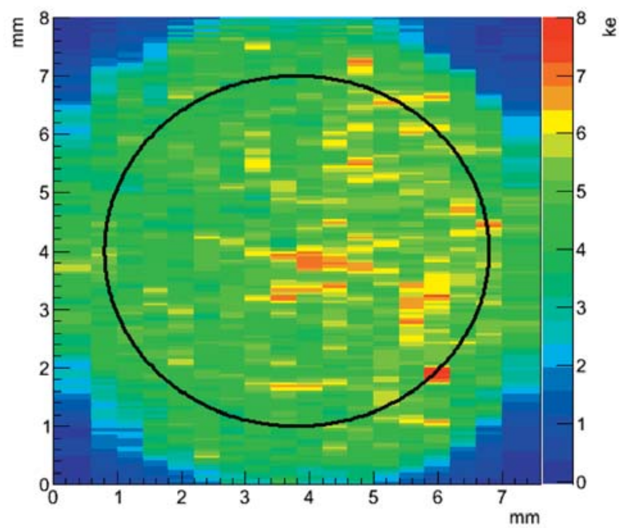


Figure 7: Response uniformity of a diamond detector tested in Beam Line M11 at TRIUMF. The plot shows the results for negative bias voltages on the pCVD diamond detectors. The uniformity varies by nearly a factor of two across the detector surface, which is problematic for use in a precision calorimeter.

High Rate Liquid Argon Calorimeters

Several of the technology options being considered for ATLAS calorimeter upgrades requires the construction of Liquid Argon calorimeters that operate at higher rates than the current ATLAS forward calorimeters. These options include the possible replacement of the current ATLAS forward calorimeters by similar devices with smaller liquid argon gaps, or a possible MiniFCal using liquid argon technology. Canadians proposed high rate calorimeter tests at the IHEP/Protvino facility in Russia, and members of the TRIUMF ATLAS and detector groups continue to play critical roles in those tests (see Figure 8). A critical result of these test, published in, is that a liquid argon calorimeter with a viable gap size of 119 microns can be constructed which has good linearity at any possible upgraded LHC beam intensity.

Partners

In Canada: Carleton University, McGill University, Simon Fraser University, TRIUMF, University of Alberta, University of British Columbia, l'Université de Montrèal, University of Toronto, University of Victoria, York University. ATLAS also has many partners associated with computing and networking, including Compute Canada and CANARIE.
International Partners: 156 in 38 countries.

TRIUMF's Role

TRIUMF has roles across all aspects of the ATLAS program, including faculty, graduate students, undergraduate students, engineers, designers and technicians. TRIUMF faculty members conceived several of the possible ATLAS calorimeter upgrade possibilities, initiated detector design concepts, and advocated for both high rate and high particle fluence tests of new technologies. Planning of ATLAS endcap calorimeter upgrades, including the design of the massive tooling required in the ATLAS detector cavern, is led by TRIUMF engineers and designers. Members of the TRIUMF ATLAS and detector groups designed and assembled the electronics for irradiation, uniformity and high-rate studies new detector technologies for ATLAS upgrade R&D.

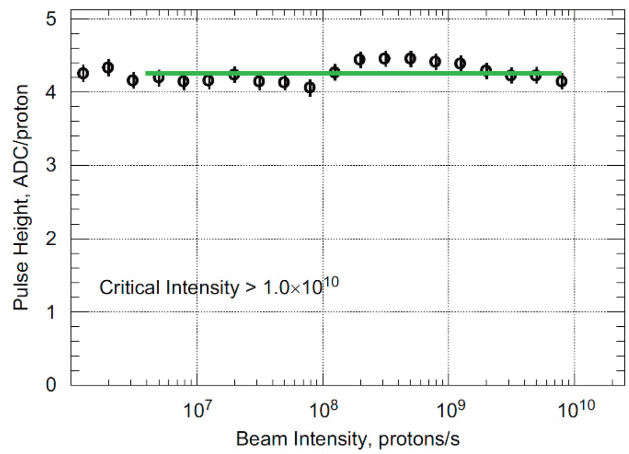


Figure 8: Pulse height response as a function of beam intensity for a liquid argon calorimeter with a gap of 119 microns in the tests at IHEP/Protvino. The highest intensities exceed those in the ATLAS forward calorimeter region at the upgrade LHC. The results indicate that it is possible to build a liquid argon forward calorimeter for ATLAS that will function at the highest LHC intensities.

TRIUMF managed the entire Canadian in-kind contribution to the LHC accelerator project, valued at $41.5M over the course of the 1995–2000 and 2000–2005 Five-Year Plans. TRIUMF provided resources for design and construction of two of the four hadronic endcap (HEC) wheels of the ATLAS liquid argon calorimeter, including machining the copper plates in Alberta, and participated in the design and engineering of the liquid argon cryostat feedthrough project at Victoria. TRIUMF personnel helped design and build the forward calorimeter modules at Carleton University and the University of Toronto. TRIUMF personnel played several key roles in ATLAS data quality assessment and assurance, both for the liquid argon calorimeters, and for the "global" ATLAS data quality.

TRIUMF'S SIMON VIEL IS 2011 VANIER SCHOLAR

03 August 2011

Simon Viel, a UBC physics graduate student under the joint guidance of TRIUMF's Oliver Stelzer-Chilton and UBC Professor Colin Gay, was selected as a recipient of the prestigious Vanier Canada Graduate Scholarships, which is valued at $50,000.

Working with ATLAS, Viel analyzes data to observe the pair production of muons, in order to determine if there is any excess signal that could lead towards a new discovery. The Standard Model successfully combines together three of the forces we know: electromagnetism, and the strong and weak nuclear forces (leaving aside gravity) – but there is strong theoretical and experimental evidence hinting that this description is incomplete, fueling speculation as to models with new forces. Viel's aim is to aid the search for new force-carrying particles. The discovery of a new force would greatly enhance our understanding of the fundamentals of our universe

TRIUMF PRODUCES AND DELIVERS MAGNETS FOR CERN'S LHC

08 May 2008

The end of the winter season marked another assembly milestone of the Large Hadron Collider (LHC) at CERN. A total of 154 'warm' magnets arrived from around the world, and TRIUMF oversaw the contribution of 52 (48 plus 4 spares) units to the project.

The TRIUMF-designed warm magnets are called warm because they are normal conductors (as opposed to superconductors). These twin-aperture quadrupole magnets were fabricated from TRIUMF designs by ALSTOM in Tracy, Quebec. TRIUMF supplied the contract management, design, and quality assurance, while ALSTOM completed the physical production. The first prototype was completed in 1996, the order was delivered in 2003, and installation completed in February 2008.

Although the LHC is famous for its use of superconducting cold magnets, warm magnets are essential to directing the proton beam along the path of the world's most powerful particle accelerator.

The magnets represent one of the many ways in which TRIUMF has contributed to cutting-edge particle physics at CERN. TRIUMF is also home to Canada's Tier-1 Data Centre for the ATLAS detector as well as being a contributor to the detector.

TRIUMF scientists hold or have held a number of key roles in the management of ATLAS and in the coordination of ATLAS physics and performance groups. TRIUMF hosts the Canadian ATLAS Tier-1 Data Centre, a roughly $20M project initially funded by Canada Foundation for Innovation, with matching funds from the British Columbia Knowledge Development Fund and computing hardware vendors, which hosts 5% (currently 10%) of the ATLAS RAW data, and are one of the ten international computing centres responsible for hosting and distributing ATLAS data and Monte Carlo samples.

TRIUMF research scientists, TRIUMF-paid faculty members at ATLAS-Canada universities, and their students and post-doctoral fellows participated actively in most of the search examples described in this section.

References

[1] D. Axen et al., "Diamond detector irradiation tests at TRIUMF", JINST vol 6 no. 05, P05011, 2011.
[2] A. Glatte et al., "Liquid argon calorimeter performance at high rates", Nucl.Inst.Meth. A669 (2012) 47-65
[3] G. Aad et al., JINST 3 (2008) S08003.

5.5.5.3 T2K

The T2K long-baseline neutrino experiment uses an intense muon neutrino beam produced at the J-PARC (Japan Proton Accelerator Research Complex) proton accelerator in Tokai, Japan to study neutrino oscillations. The primary goals of the experiment are to carry out precise and highly sensitive measurements of muon neutrinos oscillating to electron or tau neutrinos. As elementary particles, whose properties profoundly impact, the evolution of the universe, T2K follows Theme 1 "Understanding the building blocks of the Universe and how they fit together." A detailed description of the science of the T2K project is presented in Section 4.2.1.2.

T2K uses a magnetized near detector, with key components built at TRIUMF, to study the properties of the neutrinos prior to neutrino oscillation effects, and the existing Super-Kamiokande detector, located 295 km west of Tokai, a distance optimized to coincide with the first maximum from neutrino oscillations. TRIUMF has made significant contributions to both the beam line and near detector facilities. In Canada, TRIUMF provides facilities for analysis (T2K Tier-1 centre) and detector R&D and calibration.

Description of Facilities

The T2K experiment consists of the beam line, near detector, and selected facilities at TRIUMF.

T2K Beam Line

The Canadian group contributed to the T2K beam line from inception, introducing the idea of producing a neutrino beam with a narrow energy spectrum peaked at the neutrino oscillation maximum by placing the detector slightly off-axis, as well as the design of the FODO lattice using combined bending and focusing magnets for the proton beam transport.

With up to a megawatt of proton beam power hitting the target, devices in the target station, such as the target and horn magnet, can only be serviced by a full remote handling mechanism. The remote handling system in the T2K target station is based on the TRIUMF ISAC Target Hall design: the horn and target hang under tall shielded modules with service connections at the top where human access is possible when the beam is off. Servicing the horn and target is done by moving the module to the hot cell.

TRIUMF's remote handling group built a beam monitor station for the final focus beam section upstream of the T2K target, along with a hot cell handling facility for remotely exchanging the target in the horn magnet. A novel design approach that allows insertion of the manipulator from the top was developed for this.

The Canadian group also built an optical transition radiation detector (OTR), which monitors the profile of the primary proton beam right at the target in an extreme radiation environment. The optical transition radiation image on a Ti-alloy foil is transported using four parabolic mirrors through the target-shielding module to a radiation-hard camera. Monitoring of the beam position and profile is critical to the operation of the beam line: the magnetic horn provides point-to-parallel focus, which translates the proton beam position at the target into the neutrino beam axis. The neutrino beam axis, in turn, determines the peak energy of neutrinos incident towards Super-Kamiokande. The beam line was successfully commissioned in 2009 with the OTR monitor.

The large earthquake that hit the east coast of Japan on March 11, 2011 significantly damaged the J-PARC facility. Buildings and roads were damaged, and realignment of the accelerator and beam line components was necessary. The beam line equipment built by the Canadian group played a key role in the damage assessment and subsequent realignment of components. In the target station, displacements of the order of 1 cm were observed in the horn modules, leading one to suspect damage. As a result, one of the horn modules was moved to the hot cell (using the remote handling system for examination), and found to be

TRIUMF SHIPS T2K EXPERIMENT PARTS TO JAPAN

22 July 2008

Six hundred thousand dollars worth of equipment from TRIUMF was recently shipped on a vessel from Vancouver bound for Tokai, Japan. Members of TRIUMF's Remote Handling group packaged and sent an important contribution to the T2K (Tokai to Kamioka) Neutrino Oscillation experiment at the J-PARC facility. The 4m-tall focus-monitor stack was designed and built at TRIUMF. The stack will control the position and intensity of the neutrino beam, as well as guide the beam to the target.

In addition to the focus monitor, the design for the experiment's hot cell was influenced by a collaboration of TRIUMF remote-handling specialists and researchers from the UK's Rutherford Appleton Laboratory.

"Many of the remote handling techniques used in this target hall are modeled after TRIUMF's ISAC and Meson Hall target area experience," says Ewart Blackmore, Coordinator for TRIUMF's J-PARC contribution. "The Remote Handling group at TRIUMF has made an important contribution to the design of the neutrino target station at J-PARC."

undamaged. The OTR, which is attached to the target plate, provided re-calibration of the target position when the beam came back on in December 2011.

Near Detector

The T2K off-axis near detector complex (ND280) measures neutrino interactions prior to oscillation effects, with the goal of constraining large systematic uncertainties in neutrino flux and cross-sections and predicting the far detector neutrino interaction rates and spectrum with minimal systematic uncertainty. In addition, the near detector studies neutrino-nucleus interactions with the goal of fundamentally improving our understanding of these interactions.

ND280 is a magnetized spectrometer located 280m from the production target, which consists of a central tracker formed from three large-volume time projection chambers (TPCs) alternating with two fine-grained detectors (FGDs) made from polystyrene scintillator bars. The TPCs and FGDs sit inside a magnet, which produces a 0.2T horizontal field, and are surrounded by an electromagnetic calorimeter. The FGDs provide target mass for the neutrino interactions, and they track particles emerging from the neutrino interaction vertex, while the TPCs provide sign/momentum information from the curvature of the track in the magnetic field and particle identification through the ionization yield in the gas. The magnet also contains a p^0 detector (P0D) and side muon range detectors embedded within the magnet yolk.

The TPCs and FGDs were designed and built at TRIUMF. The TPCs are large rectangular structures, with parallel horizontal electric and magnetic fields, an Ar:CF4:isobutane gas mix, and micromegas pad readout on both sides. TRIUMF also designed, and maintains, the accompanying TPC gas systems.

The FGDs use 1 cm x 1 cm x 200 cm square extruded polystyrene scintillators with wavelength-shifting fibre readout attached to Hamamatsu Multi-Pixel Photon Counters (MPPCs). Thin passive water layers in the second FGD provide a means of measuring neutrino interactions on a water target. T2K is the first experiment to use MPPCs (or so-called silicon PM) on a large scale, and the muSR group at TRIUMF recently adopted this equipment.

In 2008 and 2009, the Canadian T2K group tested the detectors in TRIUMF's M11 beam line, and the detectors were shipped to Japan in summer 2009, reassembled and tested in Tokai, and then installed inside the magnet. These detectors have operated reliably with little downtime since their installation and have provided the primary input for the T2K neutrino oscillation analyses from the ND280.

In addition to these tracker detectors, TRIUMF also provided the global slow controls system for ND280, which monitors the status of all detector elements. TRIUMF also provided several pieces of common ND280 infrastructure, such as the detector electronics cooling system, which uses chilled water at sub-atmospheric pressure to avoid water leak, a dry air system, and scaffolding and mezzanines used to access the inside of the magnet during installation or repairs.

T2K Facility at TRIUMF

TRIUMF hosts one of the two T2K Tier-1 data storage facilities (the other being at Rutherford Appleton Laboratory in the UK). It also hosts the slow control database and the T2K collaboration web page (t2k.org). A large fraction of the T2K-Canada collaboration (approximately six graduate students, five post docs and a few undergraduates, along with TRIUMF and UBC staff/faculty) is hosted at TRIUMF, forming one of the largest analysis groups in the collaboration and the only one that spans across the beam, near detector, and far detector. Apart from the critical mass afforded by the concentration of people and expertise, nearly all of the post docs and faculty/staff have held formal convener positions in the T2K collaboration, making TRIUMF an intellectual centre for T2K analysis activity.

A miniature version of the FGDs, called HARPSICHORD, was built at TRIUMF and operated in the M11 beam in the 2010–2012 period. Together with an all-scintillating fiber tracker detector built by Kyoto University, this detector has primarily been used to study the tracking and particle identification performance of the detector and to measure the scattering and absorption of pions in scintillator, which is an important systematic uncertainty for understanding neutrino interactions in the near detector. It has also served as a testing facility for firmware and software updates for the FGD, allowing TRIUMF DAQ experts to work and validate updates locally before performing the updates on the FGDs at J-PARC.

A new PMT test facility is being prepared in 2012–2013 to calibrate the PMTs for the far detector and to develop new photosensors for the future detector, Hyper-Kamiokande. The facility provides a magnetically shielded water tank with a movable laser and monitor system to study the PMT response and passive optical properties (reflectivity, etc.) in water.

TRIUMF's Role

TRIUMF provided key elements of the neutrino beam line for T2K and the design and construction of the fine grained detectors and time projection chambers that form the core tracking system for the near detector (ND280). TRIUMF has also provided essential support in the data acquisition, slow control monitoring, computing and services for the entire near detector complex. Currently, TRIUMF hosts one of the largest T2K analysis communities, with leading roles on all aspects of the experiment. It hosts the T2K website (t2k.org) as well as one of two major data servers for the experiment.

Partners

In Canada: TRIUMF, University of Alberta, University of British Columbia, University of Regina, University of Toronto, University of Victoria, University of Winnipeg, York University.
International Partners: Japan (8), France (4), Germany (1), Italy (4), Korea (3), Poland (6), Russia (1), Spain (2), Switzerland (3), United Kingdom (9), United States (10).

5.5.5.4 ALPHA: CASTING LIGHT ON ANTIHYDROGEN

ALPHA (Antihydrogen Laser Physics Apparatus) at CERN aims at producing and trapping antihydrogen atoms to carry out microwave and laser spectroscopy to test a fundamental symmetry, CPT, between matter and antimatter at the highest possible precision, and violation which is a possible explanation for the observation that our universe is composed entirely of matter.

Atomic hydrogen is one of the best-studied systems in all of physics, and seminal discoveries such as the Bohr atom and Lamb shift underlie the basis of modern quantum physics. A comparison of properties of hydrogen and its antimatter counterpart, antihydrogen (Hbar), belongs to this class of fundamental experiments. It is designed to address the validity of CPT that occurs in quantum field theories that are relativistic, local, and unitary. More details on CPT symmetry can be found in Section 4.2.1.3.

After the design, construction, commissioning, and development over several years, first antihydrogen trapping has been demonstrated in 2010 [1]. In 2011, confinement of antihydrogen for as long as 1000 seconds have been reported [2], an extension by more than a factor of 5000 from the initial confinement time. In fall 2011, the first spectroscopic measurement on antihydrogen was performed, leading to the announcement in March 2012 [3].

Description of Facilities

The central part of the ALPHA antihydrogen trap is shown schematically in Figure 1, where the Hbars are synthesized by mixing of antiproton (pbar) and positron (e^+) plasmas, and then trapped. The experiment was approved in 2005, and within a short period of time, the main parts of the trap apparatus [4] had been constructed and commissioned [5]. Antiprotons from the Antiproton Decelerator, caught in the catching trap, and the e^+ obtained from the positron accumulator, are transferred into the central region for mixing. These charged particles are confined and controlled by an arrangement of 34 cylindrical electrodes which are contained in the innermost ultra-high vacuum (UHV) region. The magnetic trap, consisting of

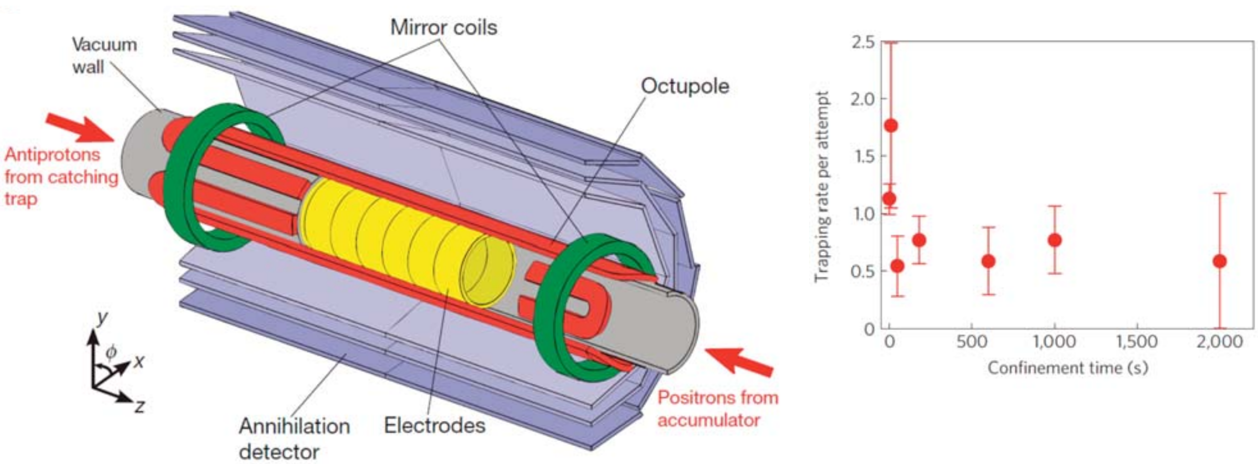


Figure 1: (Left) The ALPHA-1 central apparatus. (Right) Antihydrogen trapping rate as function of confinement time.

state-of-the-art superconducting octupole and mirror coils, has a depth of 50 μeV, while the e^+ and antiproton plasmas have space-charge potentials of up to 10V. The difference in these characteristic energy scales necessitates precise control of plasma processes in order to produce cold enough antihydrogen that can be trapped.

Around the magnetic trap lies a cylindrically symmetric silicon strip annihilation vertex detector that was fully deployed in 2009 after three years in construction. Trapping of antihydrogen atoms is detected by observing their annihilations upon release from the trap. The basic performance parameters obtained were a 7 mm position resolution for the annihilation vertices and an overall efficiency for detecting annihilations of 58% [17]. Cosmic rays were eliminated with an efficiency of 99.5% by topology cuts; later a multivariate analysis technique was developed that reduced the cosmic background by an additional order-of-magnitude [3].

Microwave spectroscopy techniques have been developed at UBC/SFU since 2005 [5]. In 2010 a microwave injection system was deployed and microwaves were first introduced into the atom trap to enable microwave probing of cold plasma via a study of plasma modes. In 2011 high-power microwaves were introduced into the trap via an internal horn in order to perform the first spectroscopy on an anti-atom via the positron spin resonance transitions at 28 GHz.

Following the success in initial microwave spectroscopy, the collaboration has taken on a major upgrade project: ALPHA-2. Prime motivations for ALPHA-2 are to allow laser access to trapped antihydrogen, and to provide improved and more flexible magnetic field configuration for microwave spectroscopy and anti-atom manipulations. By the end of 2012 major components for ALPHA-2 were mounted on the floor at CERN and successfully commissioned with antiproton (see Figure 2). These include: a new “catching” trap dedicated to efficiently capturing antiproton, a new atom trap with laser access with a Canadian designed and built cryostat hosting eight custom-made superconducting magnets, an augmented Si detector appropriate to the larger trap with an improved data acquisition system, and a new external solenoid.

In order to perform laser spectroscopy on anithydrogen, powerful laser sources that are not commercially available need to be developed. In 2012, a Lyman-alpha laser (122 nm) was demonstrated at the University of British Columbia. It had sufficient power to allow initial laser measurement on antihydrogen. Other laser developments, as well as microwave resonator developments, are currently being actively.

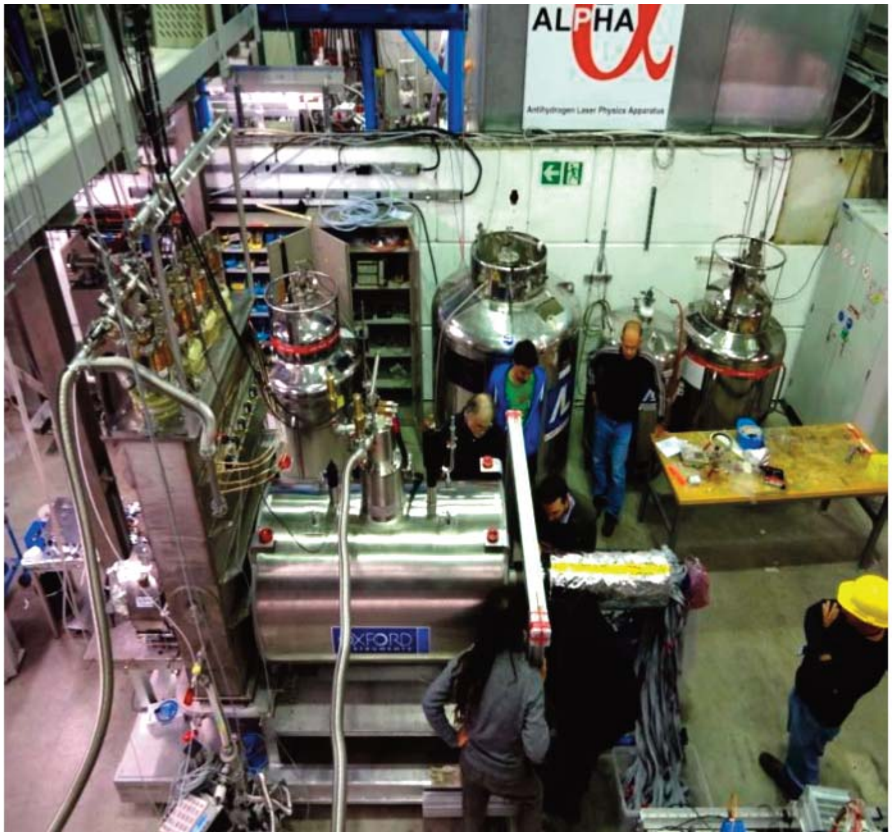


Figure 2: Construction of the ALPHA-2 apparatus and the Canadian-built cryostat.

Partners

In Canada: University of British Columbia, University of Calgary, Simon Fraser University, and York University.
International Partners: Brazil (1), Denmark (1), Israel (1), Sweden (1), Switzerland (1), United Kingdom (3), United States (2).

TRIUMF's Role

TRIUMF is the lead institution for ALPHA-Canada, and its leadership allowed Canadian university-based researchers to make significant impacts on the international project. TRIUMF and York University collaborators were responsible for the readout, data acquisition, software, and analysis for the Si vertex detector. Ancillary detectors, such as scintillator paddles, were built by TRIUMF and operated by ALPHA-Canada students. ALPHA-Canada scientists have developed techniques and equipment for microwave spectroscopy and are now developing lasers for antihydrogen spectroscopy, with significant intellectual and infrastructure support by TRIUMF.

In the area of trap/plasma physics, ALPHA-Canada has introduced techniques for microwave probing and manipulations of cold plasmas. A major TRIUMF and University of Calgary contribution is the engineering design and fabrication of the cryostat for the atom trap that will be the core of the new ALPHA-2 apparatus.

TRIUMF also contributed in the electronics for the particle traps in ALPHA, as well as in the expansion of the Si detector system for ALPHA-2. Canadians were lead authors on two major publications, and four ALPHA-Canada scientists served as run coordinators leading the experimental efforts

5.5.5.5 SNOLAB

SNOLAB is located two kilometers below the surface in the Vale Creighton Mine located near Sudbury. It has 5,000 m^2 of clean space underground for experiments and the supporting infrastructure. It offers a very low radiation environment for experiments that require very low background. These are typically related to the detection of neutrinos or dark matter. TRIUMF was involved in the original SNO experiment and has continued that involvement with SNOLAB.

TRIUMF provided critical infrastructure support to SNO during the construction phase. The ten rope equalizers from which the acrylic vessel (AV) holding the heavy water is hung were fabricated in the Machine Shop, as were the seals that prevent water from passing through the rope penetrations in the phototube sphere. The Universal Interface, which provides access to the interior of the AV for insertion of calibration sources, was both designed and fabricated at TRIUMF. The mechanism used to store the umbilical carrying services to calibration sources while they were deployed inside the vessel was designed in the Design Office. All of the data acquisition electronics were tested at TRIUMF before seeing service in the experiment. In addition, several other components of the electronics chain were fabricated in the Electronics Shop. Finally, the TRIUMF Data Acquisitions Group provided considerable assistance to the SNO DAQ group in preparation for the turn on of the experiment.

TRIUMF is expected to play a major role in the design, construction and operation of the next generation of the Enriched Xenon Observatory (nEXO). The nEXO experiment is designed to achieve unprecedented sensitivity to the possible neutrinoless double beta decays of Xe-136 that would show that neutrinos are their own antiparticle, violate lepton number conservation and allow us to determine the absolute neutrino mass. TRIUMF will play a leading role in designing, prototyping and fabricating the scintillation light detection system that is one of the key elements that must be optimized to achieve the required energy resolution. TRIUMF will also be a major player in the development of the barium ion trapping system that will allow ultimate background rejection. By contributing to nEXO and T2K in the next five years, TRIUMF scientists will contribute to pinning down the properties of neutrinos, one of the most elusive and unusual particles.

SNO+ Universal Interface

SNO+ is a new experiment that will take place in the SNO cavity at SNOLAB in Sudbury, Ontario. The acrylic vessel (AV) that held the heavy water in SNO will be reused with the water replaced by a liquid scintillator linear alkyl benzene. The higher light output of the scintillator will allow SNO+ to search for neutrinoless double beta-decay, measure the fluxes of pep, CNO, and B-8 solar neutrinos and and the fluxes of geoneutrinos and, neutrino oscillations from several nearby reactors, as well as to search for neutrinos from supernovae. The neutrino is a fundamental particle that had a profound influence on the nuclear processes that played a part in on the evolution of the universe and fuel stars like the sun. For the science of SNO+ please see Section 4.2.1.2.

Besides the AV, much of the equipment originally used in SNO will be reused in SNO+. One item that cannot be reused is the universal interface (UI) that provides access to the inside of the AV from the outside world.

Description of Apparatus

The UI has an upper and a lower part. Liquid for filling the AV passes through the lower part while ports in the upper part permit the introduction of calibration sources and various monitoring devices. Because the radioactivity requirements of SNO+ are about one hundred times more stringent than in SNO, it is essential that mine air, heavily laden with radioactive radon gas, be prevented from entering the AV. Thus the UI must be sealed directly to the AV.

This task is accomplished by a double O-ring seal with pump/purge capability of the space between the O-rings. In addition, the seal between the two halves, and the seals between each piece of apparatus that attaches to a port, must also be robust against mine air penetration. Each of these seals consists of either a double O-ring seal similar to the one between the UI and AV, or a conflat seal. Thus there is a minimal chance of mine air reaching the inside of the UI and AV, and this will allow the exacting experimental program to be carried out.

Ropes for manipulating the position of calibration sources inside the AV also pass through the UI (see Figure 1). Apparatuses for changing the lengths and tensions in these ropes are attached to the UI and are an essential part of its design. Again, the design of the boxes containing this equipment is such as designed to prevent any incursion of mine air.

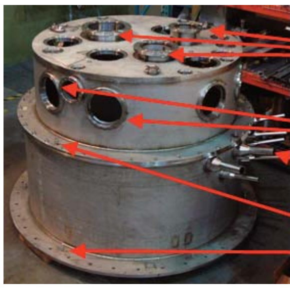


Figure 1: Photo of the UI while various vacuum and fitting tests of apparatus were being carried out at TRIUMF.

Recent Developments

The design of the UI was completed in 2010 and fabrication was complete in December 2011. The lower half of the UI was shipped to SNOLAB in December 2012. It is scheduled to be installed in March 2013, at which time filling of the AV can commence. In the meantime, design of the rope boxes was completed in November 2012 and fabrication is underway. The complete upper half is scheduled to be installed at SNOLAB in June 2013.

Partners

In Canada: Laurentian University, University of Alberta, University of Toronto, and Queen's University. International Partners: Germany (1), Portugal (1), United Kingdom (6), United States (8).

TRIUMF's Role
The design of the UI as described above was carried out in the TRIUMF Design Office. Fabrication of all the small components was done by the TRIUMF Machine Shop. Larger components, such as the barrels of the UI, were fabricated in an outside shop. Labour charges for the DO and MS were waived by TRIUMF. One TRIUMF Emeritus Researcher is member of the SNO+ collaboration.

HALO

The Helium and Lead Observatory (HALO) is a dedicated supernova neutrino detector located 2 km underground in SNOLAB. It is almost unique in that it is primarily sensitive to electron neutrinos, and is thus complementary to the water Cherenkov and liquid scintillation detectors that are mainly sensitive to electron anti-neutrinos. When fully commissioned, HALO will be sensitive to neutrinos from a core-collapse supernova anywhere in our galaxy and will be a member of the international SuperNova Early Warning System (SNEWS). A comparison of the data from neutrino detectors of different flavour sensitivities will allow understanding of the neutrino flavour transitions that occur in the core of the supernova, with important consequences for supernova explosion dynamics and for R-process nucleosynthesis. More details on the supernova dynamics can be found in Section 4.2.2.4.

Description of Facility

HALO is a "detector of opportunity," constructed largely from surplus equipment, namely: (1) 79 tonnes of lead blocks from a decommissioned cosmic ray station, worth $1M, (2) the He-3 neutron detectors from the third phase of the SNO experiment, worth $6M, and (3) the SNO electronics. The 869 annular lead blocks are stacked into a matrix measuring roughly 2.5 m wide x 2 m high x 3 m deep. The cylindrical He-3 neutron detectors are located inside the cylindrical voids in the lead matrix. A 30-cm thick layer of water and polystyrene shields the detector from neutrons emitted from the rock walls of the cavity.

Neutrinos from a supernova would undergo charged (neutral) current interactions with the lead nuclei and produce bismuth (lead) nuclei in excited states that decay by emitting one or two neutrons, which would thermalize and be captured by the He-3 neutron detectors. Monte-Carlo simulations indicate that the overall neutron detection efficiency will be around 43%, but this will be measured by placing a Cf-252 neutron source of known strength inside the lead matrix. A canonical supernova at the galactic centre with temperature T=8 MeV is anticipated to result in about 40 detected neutrons; a closer supernova at Eta Carinae or Betelguese, both of which are known to be unstable, would result in several hundreds to tens of thousands of neutrons. Because lead has a large cross-section for neutrino interactions, the 79-tonne mass of HALO will yield about the same number of interactions as the only other detector primarily sensitive to ν_e , namely the 600-tonne ICARUS liquid argon detector at the Gran Sasso laboratory in Italy. A rough statistical measure of the neutrino energy will be given by the ratio of 1-neutron to 2-neutron emission events.

Construction began in summer 2009 with the cleaning and painting of the lead blocks, which were then moved into the underground clean-room environment of SNOLAB and stacked, starting in March 2010. The He-3 neutron detectors, which had been welded together in long strings for the SNO experiment, had to be carefully cut apart into their constituent modules, refurbished with new endcaps, and individually tested. HALO began data taking in May 2012 with a full set of 128 He-3 neutron detectors. The activities still underway include calibration of the neutron detectors, and replacement of the legacy electronics and data acquisition system with a modern system that has built-in redundancy to ensure that no single-point failure will cause HALO to miss the ~20 second long neutrino burst from the next galactic supernova. Figure 2 shows a view of HALO, with the front shielding wall not yet installed.

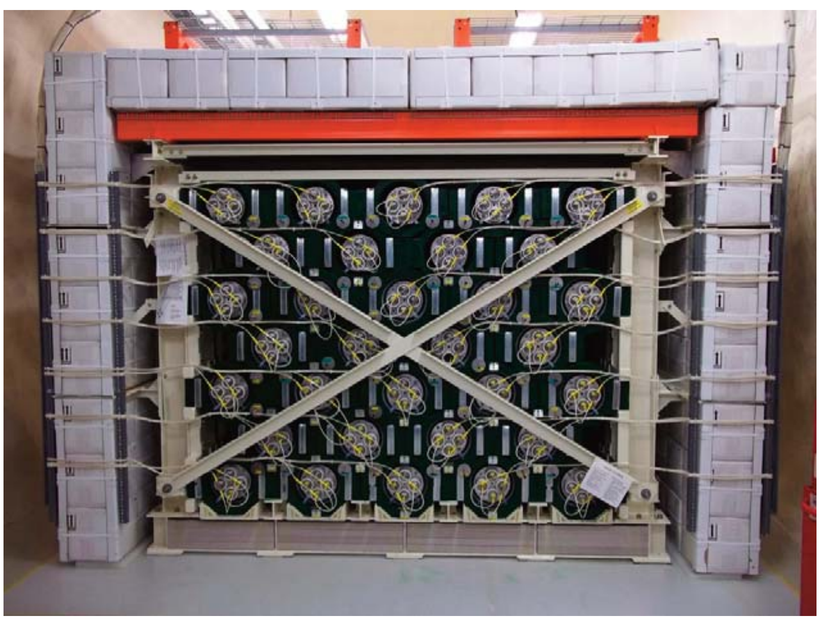


Figure 2: HALO, front shielding wall not yet installed.

Partners

In Canada: Laurentian University.
International Partners: Germany (1), United States (5).

TRIUMF's Role

TRIUMF has played several important roles in the development of HALO: defining the physics potential of HALO to elucidate neutrino flavour transitions in supernovae designing and assembling the detector, fabricating the high-voltage and signal cables and the test stand for testing the neutron counters before installation, and the ongoing operation and upgrades to HALO.

References

M. Schumacher et al. [HALO collaboration] Data Acquisition for the Helium and Lead Observatory, IEEE Conference Record 2010 Nuclear Science Symposium, paper ID N65-3.

SuperCDMS

Numerous astrophysical and cosmological observations indicate that nearly a quarter of the energy content of the universe is in the form of a non-luminous matter that cannot be explained by known particles. This so-called "dark matter" problem is one of the most pressing issues in physics today. The most compelling explanation consistent with the observations is that dark matter is composed of heretofore-unidentified weakly interacting massive particles (WIMPs) produced in the Big Bang.

The SuperCDMS-SNOLAB experiment is the next step in a series of very successful dark matter experiments that use superconducting transition edge sensors to detect the phonons from nuclear recoils produced by interactions of WIMPs in germanium and silicon crystals. The ionization is also collected and measured, providing discrimination against background. By employing larger, improved detectors at SNOLab, where cosmogenic backgrounds will be greatly reduced, SuperCDMS-SNOLab aims to have nearly two orders of magnitude more sensitivity to WIMPs than current experiments.

Description of Facility

CDMS (cryogenic dark matter search) technology detects WIMPs by measuring the ionization and phonons produced in WIMP-nucleus interactions in germanium and silicon crystals. The ionization and phonon information provides a powerful means to detect and reject backgrounds caused by contaminants on the surface of the detector. Results from this method have been at the forefront of the direct dark matter detection field for many years. It has also weighed in on a purported claim of evidence for direct dark matter detection, in particular low-mass signals reported by the DAMA, CoGeNT and CRESST experiments, rejecting most of the allowed region of WIMP mass and cross-section inferred from these claims. This technology is generally considered the most proven in terms of background rejection among dark matter experiments and can obtain lower thresholds and sensitivity to lower-mass WIMPs than most competitors.

Recent Developments

Recent R&D efforts have led to a new detector configuration ("iZIP") (see Figure 3) in which interlaced electrodes on both sides of the detector provide a large improvement in discrimination against surface contamination, as well as larger detectors that provide more detector mass (hence sensitivity) and further reduce the impact of surface contamination. The proposed SuperCDMS-SNOLAB experiment will place these new detectors in SNOLab, where the backgrounds from cosmogenic sources will be greatly reduced. The combination of these improvements will result in sensitivity to WIMP-nucleon cross-sections of $\sim 10^{-46}$ cm^2, comparable to the projected sensitivity from experiments using other methods, and cover a large fraction of WIMP masses and cross-section predicted by extensions to the Standard Model.
The total project cost for SuperCDMS is $29M.

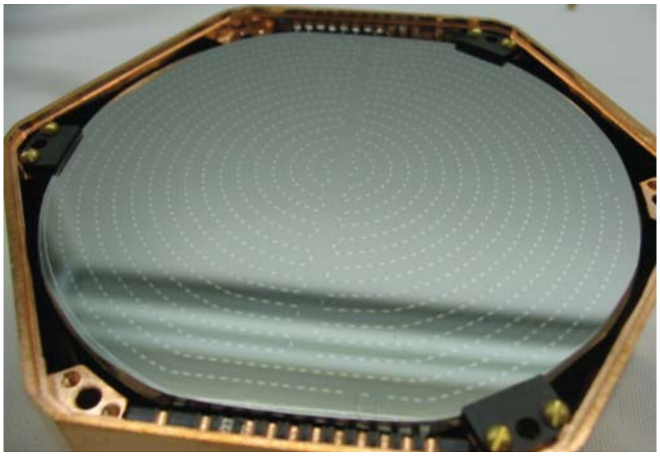


Figure 3: An interlaced z-dependent ionization and phonon detector ("iZIP") for SuperCDMS.

While CDMS detectors have been in operation for some time, the SuperCDMS-SNOLab project is in the R&D phase. In 2012, SuperCDMS-SNOLab responded to a solicitation from US funding agencies for one-year R&D proposals for "second generation" direct dark matter experiments. The outcome of this competition is expected soon. This will be followed in approximately one year by an additional competition to select a few projects for construction.

In Canada, SNOLab has responded positively to hosting SuperCDMS. A request to the Canada Foundation for Innovation Leading Edge Fund for $4.2M to provide the cryogenic and shielding infrastructure for the project was successful, contingent on the US selection process. The University of British Columbia (UBC) joined collaborators at Queen's University to enlarge the Canadian component. In 2012, a proposal to develop a MIDAS-based DAQ system for the experiment was accepted.

Partners

In Canada: Carleton University, Laurentian University, Queen's University, TRIUMF, University of Alberta, University of British Columbia, University of Guelph.
International Partners: Spain (3), United States (75).

TRIUMF's Role

Canadian collaborators at UBC, with technical support from experts in the TRIUMF DAQ Group, have recently taken a leadership role in the development of a MIDAS-based data acquisition system for SCDMS. Continued expert support from the DAQ group is needed to finish the development program and to maintain the system once the experiment is in operation. TRIUMF also provided a MIDAS-based DAQ for the DEAP (please see Section 5.5.5.5) experiment, creating synergy, allowing the sharing of expertise between the two experiments, and creating the possibility that MIDAS will become the preferred in-house DAQ solution at SNOLab as it is at TRIUMF.

DEAP

The Dark Matter Search Experiment with Liquid Argon Pulse Shape Discrimination (DEAP) was constructed 2009–2013 at SNOLAB in Sudbury, Ontario, roughly 2 km underground. The aim of the experiment is to detect weakly interacting massive particles (WIMPs) interacting in 1 ton of liquid argon.

While dark matter nicely explains a number of astronomical and cosmological data, its nature is not known. WIMPs are compelling dark matter candidates, but they have not been detected unambiguously, either directly, or at the Large Hadron Collider through their production in p-p collisions. DEAP's aim is to achieve a sensitivity to the WIMP interaction cross-section of 10^{-46} cm^2 for WIMP mass of 100 GeV, which is about a factor of 10 better than the best existing large underground xenon (LUX) dark matter experiment in South Dakota. DEAP is expected to start taking physics data in 2014.

Description of Apparatus

The core of the DEAP experiment is 3.6 tons of liquid Argon enclosed in an acrylic vessel (see Figure 4). WIMPs are expected to interact elastically in liquid argon, bouncing on Argon nuclei that subsequently recoil, producing scintillation light. The scintillation photons are detected by 255 8" diameter photo multiplier tubes (PMTs) that surround the acrylic vessel. The PMTs are attached to 20 cm long acrylic light guides bounded onto the acrylic vessel. The light guides absorb the neutrons emitted by radioactive material inside the PMTs and bring the temperature from 100°K at the acrylic vessel surface to about 250°K at the PMT front face, which simplify their operation. The whole detector is enclosed in a steel shell, itself immersed in a water tank. The water tank is instrumented with 48 PMTs in order to detect and veto residual cosmic muon interaction.

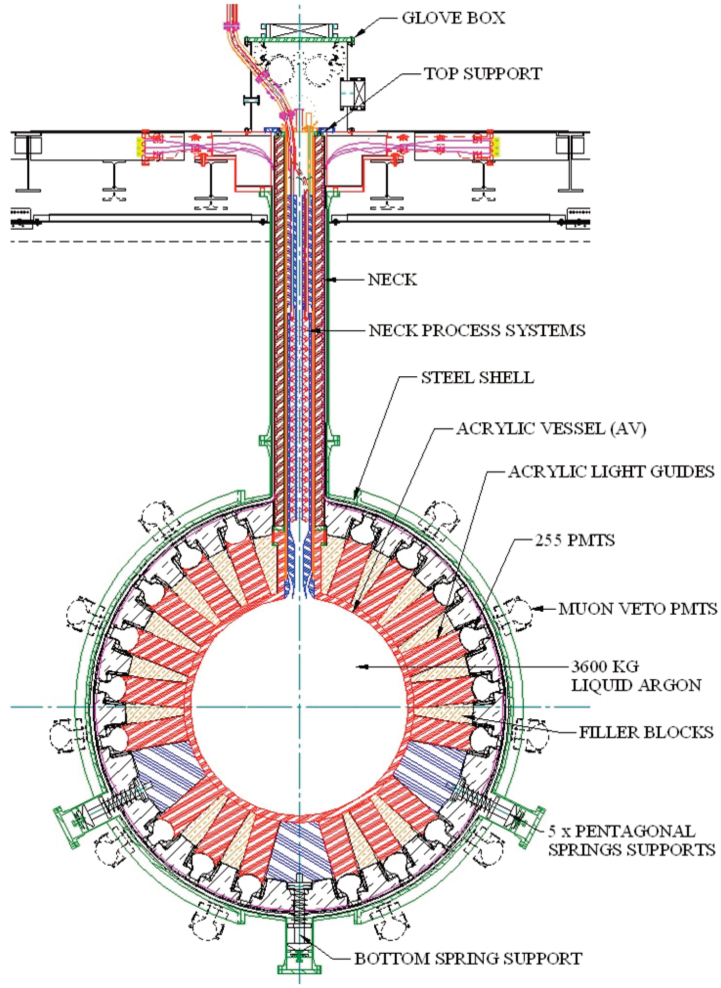


Figure 4: Schematics of the DEAP experiment.

The vast majority of the interactions in liquid argon are due to the beta decay of the Ar-39 isotope. It occurs at a rate of about 3.6 kHz, while the WIMP interaction rate will be, at best, μHz. Hence, reliable Ar-39 background rejection is critical to the success of the experiment. It is achieved by measuring the fraction of scintillation light emitted by Argon atoms in the singlet and triplet excited states that decay in 7 ns and 1.6 μs, respectively. Electron recoils from beta decay or gamma-ray interactions yield a much larger fraction of atoms in the triplet state than nuclear recoils (from WIMP and neutron interactions) do. The pulse shape discrimination technique relies on measuring the number of prompt photons (i.e. coming from the de-excitation of atoms in the singlet state) over the total number of photons. One of the main experimental challenges of DEAP will be to achieve an electron recoil leakage in the nuclear recoil sample of 10^{-10}. The electronics readout system was designed to allow counting every single scintillation photon detected by PMTs in order to optimize the background rejection.

Recent Developments

The DEAP experiment construction spans the entire time between 2009 and 2013. Figure 5 shows the acrylic vessel as of February 2013. Machining of the acrylic vessel was completed in June 2013 and the light guide bounding is proceeding with completion expected by October 2013. The steel shell, the process system, the calibration systems, and the electronics are being constructed in parallel. The acrylic vessel is expected to be ready for filling with liquid argon by April 2014. Detector commissioning will start in January 2014 using calibration light sources.

Partners

In Canada: Carleton University, Laurentian University, Queen's University, TRIUMF, SNOLab, University of Alberta.
International Partners: United Kingdom (3).

TRIUMF's Role

TRIUMF's contribution to the experiment includes engineering support for the design of the steel shell, the fabrication of the acrylic light guides, and the design, construction and commissioning of the complete electronics readout system. 265 optical quality light guides were machined and polished from raw square blocks in TRIUMF's scintillator shop from February 2012 to April 2013.

TRIUMF has complete responsibility for the readout electronics system. The electronics hardware fabrication and installation was completed in April 2013. Data acquisition and trigger software development will be completed by early 2014. The optimization of the trigger system is likely to be an active field of research in 2014.

Figure 5: Acrylic vessel, underground at SNOLab.

5.6 NUCLEAR MEDICINE INFRASTRUCTURE

TRIUMF's expertise in the production and handling of rare isotopes has given it the opportunity to expand beyond the physical sciences to the biological sciences and nuclear medicine. The use ranges from proton therapy to treat ocular melanoma to the production of rare isotopes for medical imaging. Each requires its own specialized facilities. The isotopes are used for diagnoses or treatment related to human subjects; the requirements are even more stringent than for normal science.

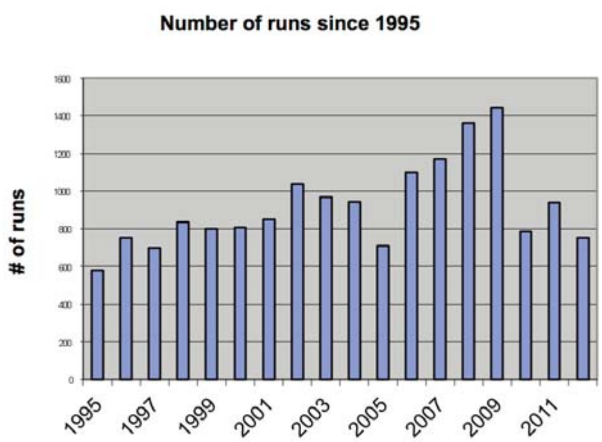
5.6.1 TR-13 CYCLOTRON

The TR-13 is the smallest cyclotron at TRIUMF, accelerating H^- ions to 13 MeV. It is located in the Meson Hall extension and produces isotopes that are primarily used for the production of carbon-11 (C-11) and fluorine-18 (F-18) containing radiopharmaceuticals. The main programs supported are the Pacific Parkinson's Research Centre (PPRC) and the BC Cancer Agency (BCCA).

Description of Facility

From 2008–2012, the TR-13 operations group delivered 49,948.7 µA-hrs in 5,282 separate runs with a very good reliability of 98.7% (see table below and Figure 1) The following isotopes were produced: N-13, F-18 (as F^- ion and F_2 gas), C-11 (as CH_4 and CO_2), Co-56, Co-55, Tc-94m, Mn-52, Sc-44, and Ga-68. Currently, there are eight targets mounted at two target stations, three water targets, four gas targets and one solid foil target.

Year	Number of runs	Number Lost runs	Reliability	Delivered beam
				(µA-hrs)
2008	1361	9	99.3%	14151.0
2009	1445	5	99.7%	13947.1
2010	784	12	98.5%	8960.5
2011	939	25	97.4%	6533.3
2012	753	17	97.8%	6356.8
Total	5282	68	98.7	49948.7



Until 2010, F-18 was produced twice daily for the FDG production needed by the BC Cancer Agency. Since then the BCCA has been operating their own cyclotron, and TRIUMF only delivers F-18 to them during their maintenance periods.

Recent Developments

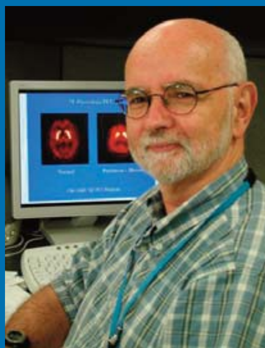
In 2011, the aging cyclotron control system was upgraded to EPICS, the TRIUMF site standard. The hardware for the target control was upgraded and expanded to deliver different isotopes to five different hot cells in three different locations. Several new targets were introduced for production of [C-11]CO_2, Tc-94m, Sc-44, and Ga-68 (please see section 4.2.3.3). A total of 11.3 % of all runs were classified as development runs to improve existing targets or to investigate new targets or isotopes. Five undergraduate students were trained during the course of these projects.

Partners

In Canada: BC Cancer Agency, Pacific Parkinson's Research Centre, University of British Columbia.

TRIUMF's Role

TRIUMF's TR-13 cyclotron and the operations team have been essential for the production and study of novel isotopes.



TOM RUTH WINS THE MICHAEL J. WELCH AWARD

11 April 2011

TRIUMF's Dr. Tom Ruth was awarded the 2011 Michael J. Welch Award of the Radiopharmaceutical Sciences Council, which is given to individuals who have made a significant contribution to the field of radiopharmaceutical sciences.

"It is an honour to receive this award, however this award really reflects on the great people with whom I have had the opportunity to work," said Dr. Ruth who is a research scientist at TRIUMF and a jointly appointed BC Cancer Agency senior researcher. This award is significant as it indicates North American recognition of Dr. Ruth's work.

Dr. Ruth was recruited as a Research Scientist by TRIUMF in 1980 to help develop the UBC PET (Positron Emission Tomography) group, which he lead as associate director from 1989 to 2008. During that time he oversaw the installation of 4 PET scanners and the TR-13 cyclotron, which is specially designed for producing medical isotopes and lead to the local manufacturing of low energy TR series of cyclotrons by ACSI in Richmond, BC. Dr. Ruth also collaborated with Dr. John Vincent at TRIUMF to develop techniques to generate Rb-82, which are now used by the Ottawa Heart Institute for heart imaging on a daily basis.

5.6.2 LABS AND FACILITIES FOR NUCLEAR MEDICINE INFRASTRUCTURE

TRIUMF has undertaken steady, incremental renovations of its nuclear medicine laboratory space to provide modern facilities that meet established standards for preparation of preclinical and clinical pharmaceuticals.

Description of Facilities

The nuclear medicine laboratories include the GMP lab and the Meson Hall Extension Service Annex (MHESA) laboratory.

Recently a new good manufacturing practice (GMP) lab (see Figures 2, 3), containing three new hot cells for the production of radiopharmaceuticals for human use was completed in the lower level of the Chemistry Annex at TRIUMF. Western Economic Diversification Canada provided nearly $1M of capital assistance for this project.

This lab is designed with a clean air room area surrounding the hot cells so that the production of radiopharmaceuticals can be prepared in a controlled air environment. The hot cells also have air filtration that increases the clean room level inside the hot cells where the processes are carried out. The lab is equipped with surfaces that can easily be cleaned and sterilized. It also has an area outside of the clean room where quality

Figure 2: GMP labs at TRIUMF.
Figure 3: Chemistry synthesis unit at GMP labs.

control analysis, shipping, and workflow conform to the regulatory criteria defined by Health Canada. This lab also has restricted access to authorized personnel only. It is expected that all of the current PET radiopharmaceuticals, such as C-11 methyphenidate, raclopride dihyrotetrabenzine, DASB, MRB, yohimbine, and fallypride as well as F-18 dopa will all be prepared in this new GMP lab space in 2013. These are agents currently being use in the Pacific Parkinson's Research Centre's research program, funded by a Canadian Institutes of Health Research team grant.

A new joint TRIUMF/Nordion in the MHESA basement contains 4 new hot cells for research radiochemistry and became operational in April 2013. The lab is equipped with a state-of-the-art ventilation system and control systems to meet current regulatory requirements. This new ventilation system will allow us to do research on a wide variety of radioisotopes in a safe manner. It is intended that research will be conducted on collaborative projects between Nordion and TRIUMF researchers.

Five projects have been identified for 2014, with particular emphasis on the interaction between TRIUMF and Nordion on the production of Tc-99m using cyclotrons.

Figure 4: Hot cell robotic arms at the MHESA Lab.

TRIUMF JOINS CUTTING-EDGE ALZHEIMER'S STUDY

26 August 2009

The University of British Columbia (UBC) and TRIUMF Positron Emission Tomography (PET) group is playing a major role in a groundbreaking new study that could significantly advance the understanding and management of Alzheimer's disease. The much larger Alzheimer's disease Neuroimaging Initiative (ADNI) is being supplemented by a new subset of studies involving 16 North American PET centres, including the UBC and TRIUMF PET group. These sub-studies will image extracellular deposits of protein aggregates on the brain (called amyloid plaques) using PET scanners and [C-11] Pittsburgh Compound B (PIB) in a subset of study participants who are scheduled to receive normal PET scans.

"Originally, researchers could not demonstrate the presence of these telltale amyloid plaques, which would definitively diagnose a patient with Alzheimer's, until the time of autopsy," explained Dr. Tom Ruth, Senior Research Scientist participating in the project at UBC and TRIUMF.

The development of biomarker and imaging studies that track the development and progress of Alzheimer's may lead to a predictive test or better treatments for the disease. According to Dr. Ruth, if pharmaceuticals to remove amyloid plaque are developed from the research being conducted worldwide, scientists may be able to intervene at an earlier stage and slow or even halt the progression of Alzheimer's disease.

With one new laboratory nearly complete, future expansion has begun on renovations in two additional labs to serve as an intermediate-level nuclear medicine/ radiochemistry facility with shielded fume hoods, as well as a new target manufacturing facility.

Installation of a new CFI-funded trimodal PET/SPECT/CT pre-clinical imaging camera was completed in the fall of 2012 in the new Centre for Comparative Medicine (CCM) building across Wesbrook Mall from TRIUMF. Work on a pneumatic transfer line for subterranean transport of radiotracers is slated began in August 2013.

Partners

BC Cancer Agency, Hevesy Laboratory (Denmark), Nordion, Inc., University of British Columbia, General Electric, Pacific Parkinson's Research Centre, and Simon Fraser University

TRIUMF's Role

TRIUMF's TR-13 medical cyclotron where much of this work took place under the supervision and guidance of researchers in the Nuclear Medicine Division. TRIUMF's lead radiochemists have led several of these research efforts and collaborate closely with researchers at the Pacific Parkinson's Research Centre and the BC Cancer Agency. In addition, TRIUMF's Paul Schaffer leads the Genome BC effort and the collaboration with General Electric.

5.6.3 PROTON THERAPY FACILITY

TRIUMF provides radiotherapy in collaboration with the BC Cancer Agency and the UBC Eye Care Centre by operating Canada's only Proton Therapy Facility.

Since 1995, patients with ocular melanomas have come to TRIUMF to receive treatment, achieving a local tumour control of 91%. Between April 1, 2008 and April 1, 2013, 40 patients were treated with protons during five scheduled treatment sessions each year. This brings the total number of patients treated with protons at TRIUMF since the start of the program to 170, with an average per year of 9.4 (see Figure 4).

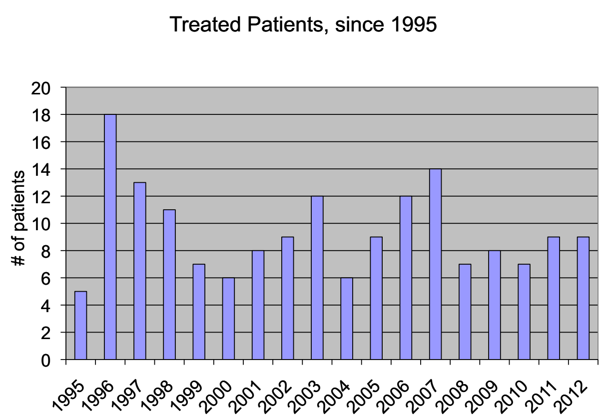


Figure 4: Patients since beginning treatment in 1995.

Description of Facility

Treatment is carried out using a modulated beam of 74 MeV protons at Beam Line 2C1 with the dose delivered over 4 daily fractions, each taking about 90 seconds. The alignment of the tumour to the proton beam is made by taking X-rays of tantalum marker clips that are placed around the tumour by the ophthalmologist in a surgical procedure a week or so before treatment (see Figure 5). These clip positions are then compared to the desired locations determined by the treatment-planning program. The patient chair is then moved to correct for any errors.

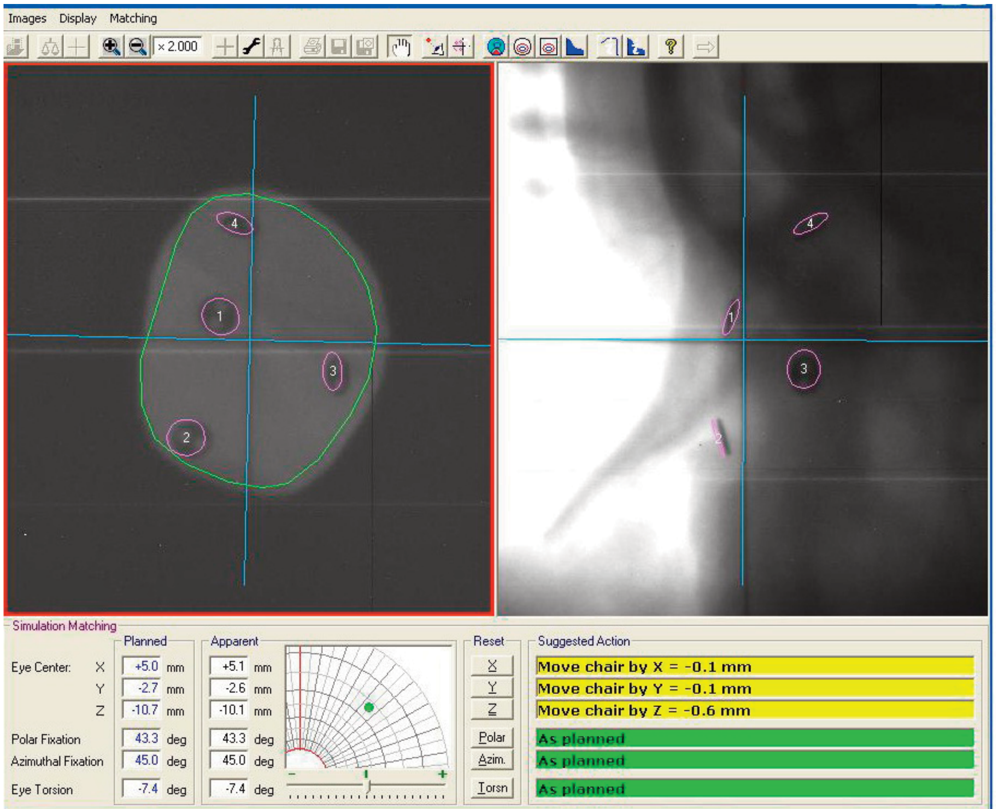


Figure 5: Digital X-ray image, lateral and axial. This patient had four metal clips inserted around the tumour. The software is used to match the expected position of the clips (purple circles) with the actual clip position in the X-ray image, thus aligning the patient.

Recent Developments

Since the beginning of TRIUMF treatments, X-rays have been imaged using a Lanex intensifying screen and Polaroid film. As the type of Polaroid film used is no longer being manufactured, alternative methods for imaging X-rays have been tested over the past years. The solution that has been selected is a digital X-ray camera based on a CMOS image sensor manufactured by the Rad-icon Imaging Corporation. This camera has an active area of 5 cm x 5 cm with 1024 x 1000 pixels. X-ray tests have shown the desired sensitivity and, in 2009, the images were integrated into the Eye Plan Treatment Program to provide rapid patient position information. It was successfully introduced to align patients in December 2009 and has been in use ever since.

In 2012, the waiting room and patient washroom were renovated to maintain a pleasant and welcoming environment for patients and their accompanying families. The waiting room received new flooring, ceiling, paint, and some new furniture. The washroom was updated with new fixtures, tiles, and paint.

Partners

BCCA, University of British Columbia's Eye Care Centre, University of British Columbia PET Centre.

TRIUMF's Role

TRIUMF has taken the lead in exploring PET after PT, as well as the modelling of the local treatment facility. In both cases, the local FLUKA expertise has been used. A Ph.D. student has been recruited to continue this work.

5.7 THEORY TOOLBOX

The TRIUMF Theory Group pursues a broad research program in the areas of low-energy nuclear physics, hadronic physics, and high-energy particle physics.

5.7.1 NUCLEAR PHYSICS

Atomic nuclei are made of nucleons, protons, and neutrons that themselves are composite particles made of quarks and gluons. The fundamental theory of the strong interaction, the quantum chromodynamics (QCD), is, however, non-perturbative at the low-energy regime relevant for nuclear physics. At present we are not able to calculate nuclear properties directly from the QCD or even to derive exactly the nucleon-nucleon interaction from the QCD. Currently, the most promising bridge between the QCD and the low-energy nuclear physics is the chiral effective field theory (EFT), allowing for derivations of nucleon-nucleon and three-nucleon forces consistent with the underlying QCD symmetries. Such forces then serve as a starting point for various many-body techniques that can be applied to solve the quantum-mechanical nuclear many-nucleon problem.

We have developed the capability to describe light nuclei as systems of nucleons interacting by realistic inter-nucleon forces, i.e. forces derived from the QCD by means of the chiral EFT that accurately fit nucleon-nucleon and three-nucleon data. At TRIUMF we concentrate on studying nuclear structure and reactions with *ab initio* approaches, which allow us to address a variety of observables.

Weakly bound or even unbound exotic nuclei produced at TRIUMF experiments cannot be understood using only bound-state techniques. Our *ab initio* many-body approach, no-core shell model with continuum (NCSMC) focuses on a unified description of both bound and unbound states. Within such an approach, we can simultaneously investigate the structure of nuclei as well as their reactions. The method combines a square-integrable harmonic-oscillator basis accounting for the short- and medium-range many-nucleon correlations with a continuous basis accounting for long-range correlations between clusters of nucleons. With this technique, we can predict the ground- and excited-state energies of light nuclei (p-shell, $A \leq 16$) as well as their electromagnetic moments and transitions, including weak transitions. Furthermore, we can investigate properties of resonances and calculate characteristics of binary nuclear reactions, i.e. cross-sections, analyzing powers etc.

Recent applications of our *ab initio* techniques included an investigation of the unbound He-7 [1], calculations of the ^{3}H(d,n)^{4}He and ^{3}He(d,p)^{4}He fusion (see Figure 1) [2], the calculation of the ^{7}Be(p,γ)^{8}B radiative capture [3] important for the Standard Solar Model and the neutrino physics (see Figure 2). Our calculations also supported the TRIUMF experiment to determine the sign of the quadrupole moment of the first excited state in Be-10 [4]. We were also able to demonstrate a unique role of the chiral three-nucleon interaction in the origin of the anomalously long half-life of C-14 used for archaeological dating [5].

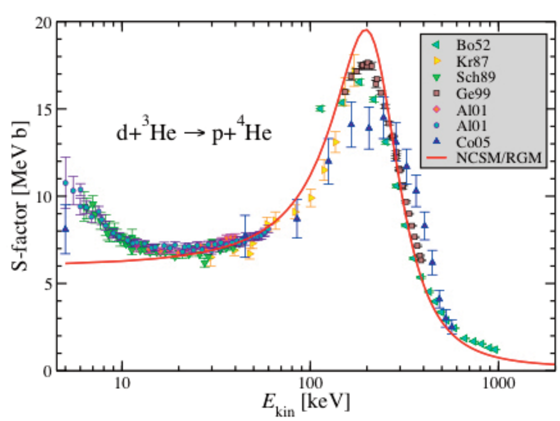
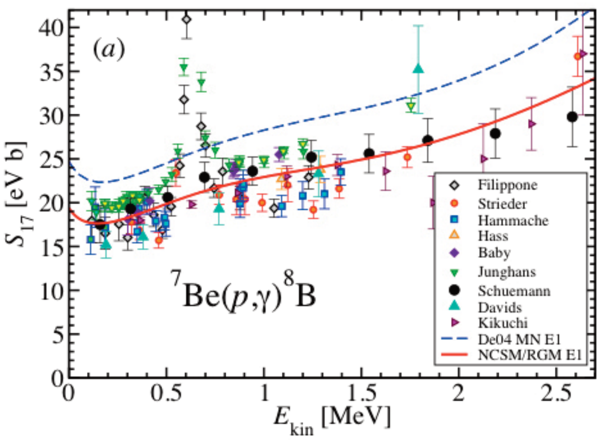


Figure 1: Experimental results for S-factor of ^{3}He(d,p)^{4}He reaction from beam-target measurements. The full line represents the *ab initio* calculation. No low-energy enhancement is present in the theoretical results, contrary to the laboratory beam-target data.



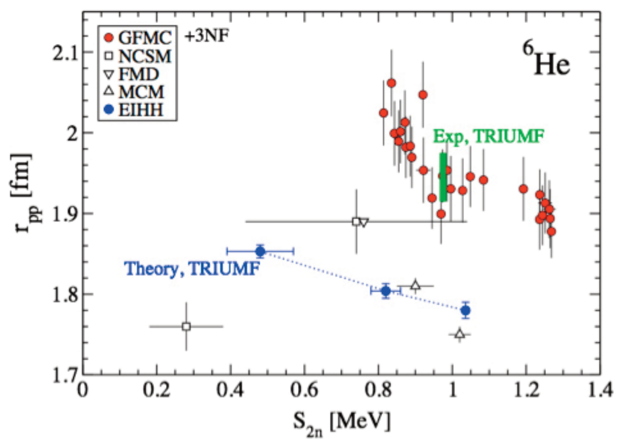


Figure 2: The *ab initio* calculated $^{7}Be(p, \gamma)^{8}B$ S-factor (full line) compared to experimental data and the calculation used in the latest evaluation (dashed line).

Figure 3: Correlation plot of the He-6 point-proton radius r_{pp} versus the two-neutron separation energy S_{2n}. The experimental range is compared to theory based on different *ab initio* methods. All calculations, but the red circles, omit three-nucleon forces. The fact that they do not go through the experimental band points towards the importance of three-nucleon forces in nuclear physics.

Our *ab initio* approach can be extended to reach *sd*-shell and medium-mass nuclei by employing various techniques of basis reduction such as the importance-truncated no-core shell model or the coupled-cluster method. These approaches were recently successfully applied to carbon, oxygen, and calcium isotopes [6,7]. We also work on a three-cluster extension of the method to describe, e.g., the Borromean nuclei such as He-6 and Li-11. Finally, we are implementing the capability to study reactions of nuclei with electroweak probes with the possibility to calculate, e.g., neutrino cross-sections on light nuclei.

An alternative method to calculate ground-state properties of light nuclei is to use hyperspherical harmonics (HH) expansions. They are typically employed in few-body physics to study nuclei with mass number A=3 and 4, but can be extended to larger mass number like A=6,7 and 8. The HH approach has the advantage that an exponential fall-off of the wave function is implemented, which accelerates the convergence of the expansion.

At TRIUMF we recently used this method to calculate the two-neutron separation energy and the point-proton radius for the He-6 halo nucleus from low-momentum chiral forces (see Figure 3). Theoretical results were published together with experimental data obtained at the TRIUMF TITAN Penning trap [8,9]. TRIUMF is a unique place to merge theory and experiment concerning the physics of halo nuclei.

One can use bound state techniques like HH even to calculate break-up reactions induced by perturbative probes, like photons, electrons, or neutrinos. This is achieved using the Lorentz Integral Transform (LIT) method, in which the continuum problem is reduced to the solution of a bound state–like equation.

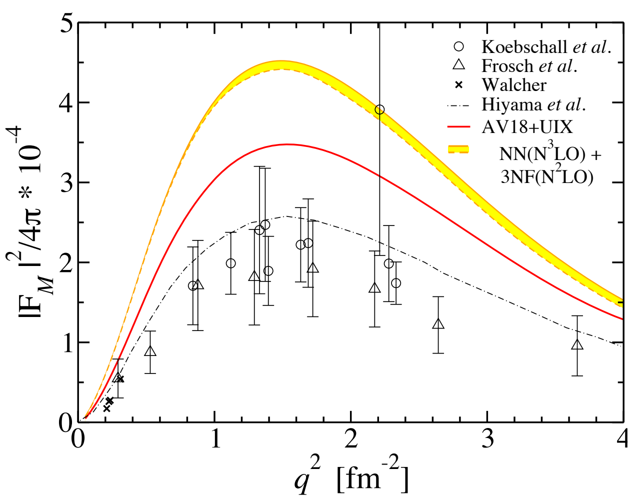


Figure 4: Theoretical He-4 transition form factor $0^{+}1 \rightarrow 0^{+}2$ as a function of the squared momentum transfer q^2 calculated with various Hamiltonians, which all include three nucleon forces, in comparison to the available experimental data from electron scattering off He-4.

One of our recent case studies with the LIT method is the monopole transition form factor from the ground state 0^+_1 to the first 0^+_2 excited state in He-4 [10], which can be extracted from electron scattering data. We have used several different nuclear Hamiltonians, which include three-nucleon forces as the sole input of our calculations. Such Hamiltonians lead to the correct experimental binding energy of He-4. Interestingly, we observed a very strong dependence of the theoretical results on the input Hamiltonian (see Figure 4), which makes this observable extremely interesting. We have also calculated the nuclear dipole polarizability of the halo He-6 nucleus [11] with simple two-nucleon potentials and found out that theory under-predicts experimental data.

For the future, we plan on using the LIT method in conjunction with other bound state techniques, like coupled cluster theory, which will allow us to extend the present limits on mass number. We aim at studying, for example, giant dipole and quadrupole resonances in medium mass nuclei from first principles.

5.7.2 HADRONIC PHYSICS

Quantum chromodynamics (QCD) is the theory of the strong force. At high energies, the relevant degrees of freedom are quarks and gluons, while at lower energies the coupling among these states becomes so strong that they confine into colour-neutral hadrons. It is not known how to compute analytically the properties of hadrons from the underlying theory of quarks and gluons, so other methods must be used.

TRIUMF's Theory Group has the capability to study low-energy QCD and many different kinds of hadronic systems using the methods of lattice field theory. All aspects of numerical simulation of lattice field theory can be dealt with including Hybrid Monte Carlo for generation of field configurations, conjugate gradient methods for the calculation of fermion propagators, and advanced analysis methods such as constrained fitting for extraction of excited hadronic states. At present it may be optimal to use different methods in different quark mass sectors. The Group can handle simulations over the whole quark mass range from light to bottom using clover, highly improved staggered, or non-relativistic, fermions as appropriate.

Recent applications of these methods include a study of D meson resonances [1], and the calculation of radiative decay amplitudes for excited bottomonium states [2]. More details may be found in Section 4.2.2.1. These methods for studying QCD have also be applied to other field theories such as the lattice Higgs model or the Higgs-Yukawa model, as well as to other gauge theories which may be relevant beyond the Standard Model [3].

Partners

In Canada: Simon Fraser University, York University
International Partners: Austria (1), Germany (1), Slovenia (1), United States (1).

TRIUMF's Role

The work described here was led by a research scientitst and/or a post-doctoral research fellow in the TRIUMF Theory Group with participation of Canadian and international collaborators. Some calculations were carried out using the TRIUMF Theory Group computer cluster.

5.7.3 HIGH-ENERGY PARTICLE PHYSICS

The primary research focus of the Theory Group in high-energy particle physics is the search for new particles and forces. Our current understanding of elementary particles is given by the Standard Model (SM). While the SM is able to explain the results of a broad range of experiments, there are many key questions the theory is not able to answer. Most important among these are the mechanism of electroweak symmetry breaking that separates the weak from the electromagnetic force, the cosmological puzzles of dark matter, the excess of matter over antimatter, and the origin of neutrino masses.

In the SM, electroweak symmetry breaking is induced by the Higgs field. A recent major advance in this direction has been the discovery of a new particle at the CERN LHC with the right properties to be the corresponding Higgs boson. The Theory Group has extensive expertise in Higgs physics and has the capability to predict the rates of Higgs boson production and to simulate the signals these processes would generate in collider detectors for both the Higgs of the SM and in more complicated extensions. The Group has used this expertise to interpret the new experimental data and to apply it to test whether the newly discovered particle is the Higgs boson predicted by the SM or something more exotic [0a, 0b].

The strong sensitivity of the SM electroweak sector to quantum corrections suggests that there exist new particles and forces with masses just above the weak scale, a range that is currently being probed by the CERN LHC. Members of the Theory Group have contributed significantly to the development of consistent theories for what this new physics might be [1]. They are also able to apply Monte Carlo simulation tools to model how such new phenomena would appear in high-energy colliders and estimate the discovery prospects [2,3]. Having such theories in hand has helped the LHC experimenters to focus their searches in the most promising directions. The experience of the Theory Group in developing new theories also places them in a competitive position to interpret any new discoveries or deviations from the SM at the LHC and other experiments [4].

The SM also fails to account for the observed cosmology. In particular, it is unable to explain the origin of dark matter (DM) or why there is more visible matter than antimatter. Theory Group members have proposed novel candidates for DM [5], and they have developed new mechanisms to account for the asymmetry of matter [6a, 6b]. The group has the capability to compute the signal rates of DM candidates in deep underground direct-search experiments, cosmic-ray telescopes, astrophysical systems, and at particle colliders [6a,6b, 7]. This is essential for testing whether a DM candidate is consistent with current experimental data and it helps to guide future searches for that candidate.

A second area of expertise of the Theory Group is in developing and investigating mechanisms to explain the asymmetry of matter relative to antimatter. A process for creating both the DM density and the matter asymmetry was proposed where the DM consists of hidden antibaryons [6a,6b]. An implication of this mechanism is that DM can scatter inelastically with a nucleon to create a meson and an anti-DM particle. The resulting signal mimics nucleon decay and can be searched for in nucleon-decay experiments. Figure 5 shows the cross-section for such a scattering process, with the grey shaded regions illustrating where the scenario is constrained by existing SuperKamiokande data. The Theory Group has also studied the implications of recent Higgs data at the LHC for mechanisms of baryon creation during cosmological electroweak symmetry in the early Universe [8]. This broad research focus allows the group to connect the results of many different types of experiments to each other, allowing for a maximal usage of the experimental data.

A further shortcoming of the SM is that it does not explain the origin of the broad range of particle masses that have been observed, from the very heavy top quark to the very light neutrinos. While the masses of the charged fermions can arise in a simple way from the Higgs field, neutrino masses are more puzzling. To explore the origin of neutrino masses, the Theory Group constructs models for how these masses can arise [9]. Such models can potentially be tested in neutrino experiments such as T2K (please see Section 4.2.1.2).

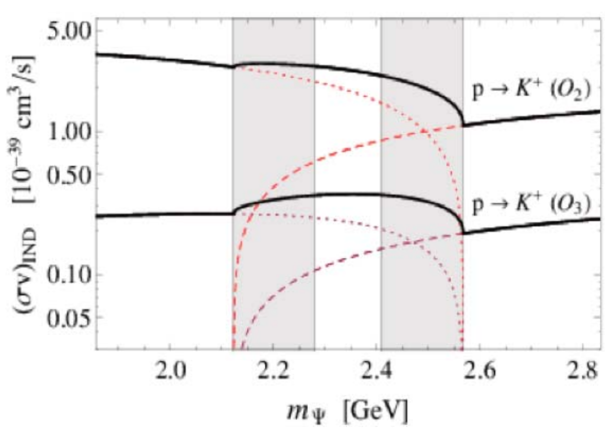


Figure 5: Cross-sections for nucleon destruction by hidden antibaryonic DM scattering.

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5.8 SCIENTIFIC COMPUTING

There are two aspects to computing at a laboratory like TRIUMF. One is the cutting edge computing, data collection and storage required for scientific research. This is typified by the ATLAS TIER-1 Data Centre and the light pipe connecting it to CERN in Switzerland. The other aspect is the computing requirements of any modern enterprise: internet connections, office software, e-mail etc. These do not exist as separate entities, but are connected by a common infrastructure like network switches and shared physical spaces. TRIUMF only runs smoothly, with the needs of both scientists and general users being met, when the various parts of the system work harmoniously together.

5.8.1 CANADIAN ATLAS TIER-1 DATA CENTRE

Computing resources play a critical role in extracting the science from the ATLAS experiment. The Large Hadron Collider (LHC) has been in full operation since 2010 and an enormous amount of data has been produced since then. The ATLAS experiment is collecting close to 3 Petabytes of raw data each year and producing several derived and simulated datasets that are of similar sizes. The data is stored and analyzed on an international network of high-performance computing centres that are linked together by high-speed networks and Grid tools: the Worldwide LHC Computing Grid infrastructure (WLCG). Part of this infrastructure, the Canadian Tier-1 Data Centre at TRIUMF is a key player and has been ramped up to full production at nominal capacities for data storage and processing. There are ten Tier-1 centres around the world and they are primarily responsible for storing and processing the raw data and to produce various derived datasets to be distributed to the worldwide ATLAS community in a timely fashion.

Description of Facility

The Tier-1 centre is a large-scale data-intensive facility that is maintained and operated 24 x 7 in full compliance with the WLCG Memorandum of Understanding (MOU). The Canadian Tier-1 is a leader in the field by being consistently at the top, or near the top, in terms of availability, reliability, and efficiency when compared to other sites in the world. The Tier-1 centre provides the dedicated resources necessary for the storage of the raw and secondary datasets, as well as compute nodes for data processing, simulation, and physics group activities in a secure environment. For the successful operation and exploitation of ATLAS, the Tier-1 centre is presently providing 10% of the required Tier-1 resources worldwide.

SFU/TRIUMF PHYSICIST SELECTED FOR ATLAS LEADERSHIP ROLE

23 January 2012

Effective this March, Project leader for the ATLAS Canadian Tier-1 Data Centre, Michel Vetterli (TRIUMF scientist and SFU physics professor), has been appointed deputy chair of the ATLAS Publications Committee (PubCom).

Vetterli will take over as chair of the ATLAS PubCom in March 2013 and move to Geneva for a year to be near the ATLAS particle detector at the CERN Large Hadron Collider. The PubCom is responsible for reviewing all papers and scientific notes published by ATLAS, an international collaboration of nearly 3,000 physicists and engineers.

"It's like being on a thesis supervisory committee, but you're interacting with more senior people so it's more challenging," says Vetterli of his new role. "As part of the executive board, you're in on many high-level discussions and you get to express your opinions."

The Tier-1 centre also plays a central role for the Canadian Tier-2 centres that are located at the Compute Canada shared facilities. Today, the Tier-1 centre consists of 7.2 Petabytes of usable disk storage, 5.5 Petabytes of tape storage, 4830 processor cores and 90 servers. Figure 1 shows the Tier-1 centre architectural diagram. As part of WLCG and ATLAS distributed computing operations, several critical services are being provided: a set of Compute Elements that act as gateways for ATLAS Grid jobs; a Storage Resource Manager layer to store and access the data; a top- and site-level Berkeley Database Information Index (BDII) to publish Grid resources and services access points; a Grid accounting service to collect and publish usage information; Squid proxy servers for caching database information and ATLAS software; a Frontier service to provide access to Oracle database information related to detector conditions; an Oracle database repository of meta data information related to the properties of ATLAS collision events (used for event and file selections); and, finally, a File Transfer Service (FTS) that is used for file movements between Grid sites and data replication. In terms of connectivity, the Tier-1 centre has dedicated network links to CERN (Tier-0), BNL (U.S. Tier-1), SARA (Netherlands Tier-1), and to the Tier 2 centres. The networking infrastructure was put into place in collaboration with and with support from CANARIE, BCNet and HEPNet-Canada. The network topology is shown in Figure 2. With respect to the Tier-1 operations and user support staff consists of 10 people (9.5 FTE), the smallest of any of the LHC Tier-1 centres. To date, the total project costs are close to $26.5M.

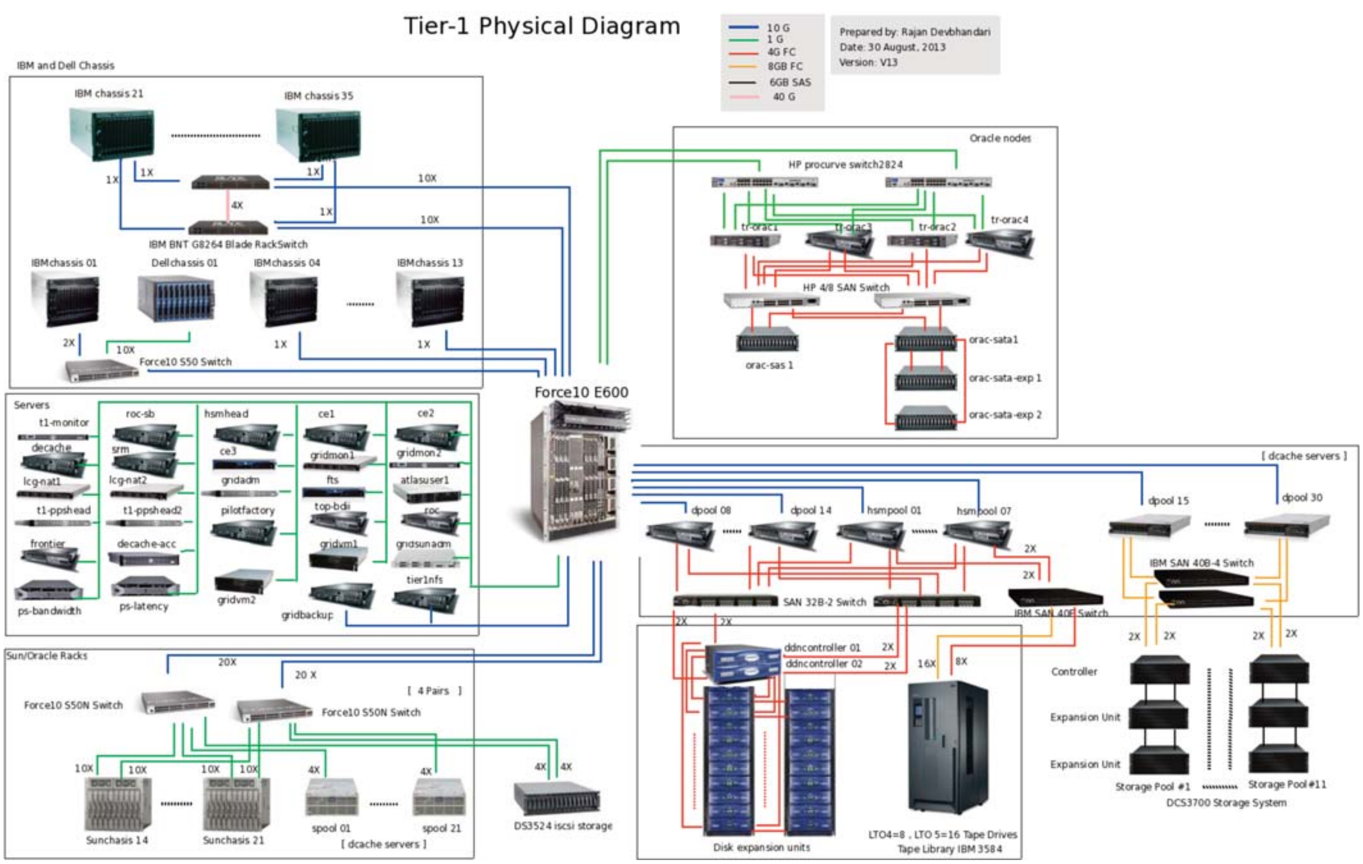

Figure 1: ATLAS Tier-1 architectural diagram.

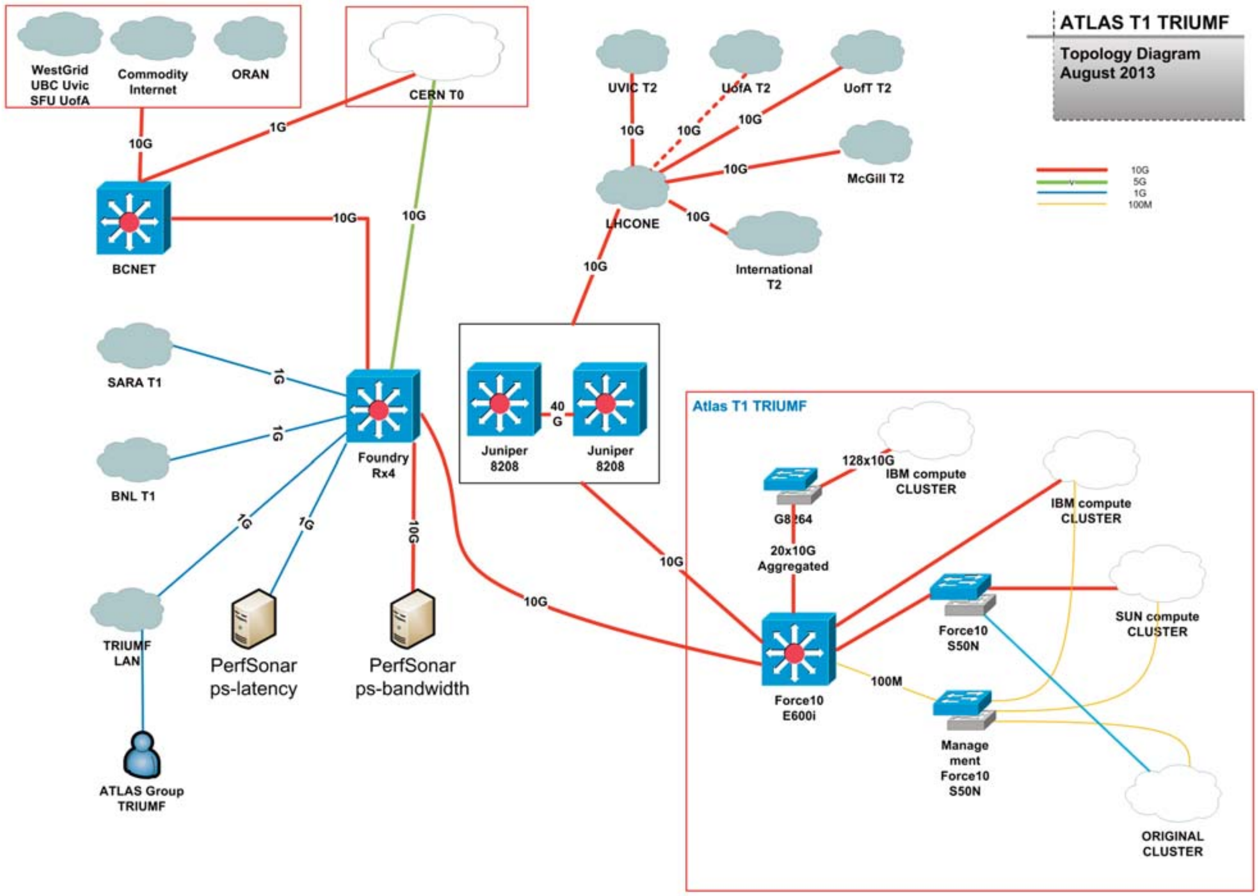

Figure 2: ATLAS Tier-1 network topology diagram.

Recent Developments

The ATLAS computing model has matured and evolved in order to adapt to real operating conditions with respect to data distribution and analysis on a global scale. At TRIUMF, the Tier-1 resources expanded by a factor of ten from the initial deployment of the facility back in 2007. Two large systems acquisitions were completed in the fall of 2009 and in late 2011, bringing the Tier-1 capacity to what it is today. In 2011, ATLAS-Canada submitted another proposal to CFI and was successful in securing $3.3M to cover the operating costs for the period 2012–2015. In 2012, another successful CFI proposal secured capital money for the replacement of computing equipment purchased in 2007 and 2009 ($2.5M as a total project cost with $1M from CFI).

The ATLAS Tier-1 is a centre of excellence, where highly qualified personnel and co-op students are trained using the best known practices with respect to data centre design, applications development, and systems administration for mission critical operations. A solid base of expertise has been assembled over the years while deploying large-scale storage systems, databases, complex clusters and network topologies, and Grid technologies. TRIUMF runs also the Canadian Regional Grid Operation Centre (ROC Canada) to oversee several Grid sites as part of the overall WLCG operations.

The ATLAS Tier-1 centre at TRIUMF also played an important role in the Higgs boson discovery that was announced in July 2012; it produced several simulation samples that were urgently needed in order to complete the analysis in time. During the last five years, nearly 20M Grid jobs have been processed and 60M hours of computing time have been utilized at TRIUMF; these resources were necessary to produce numerous ATLAS results.

Partners

In Canada: University of Alberta, University of British Columbia, Carleton University, McGill University, l'Université de Montréal, Simon Fraser University, University of Toronto, University of Victoria, and York University.

TRIUMF's Role

TRIUMF provided contributions to several key areas: electrical and mechanical engineering, wide area networking infrastructure and expertise, and logistics with respect to shipping and receiving. TRIUMF scientists have played a leading role for the project as a whole since its inception.

5.8.2 COMPUTING FOR SCIENCE AND DATA ACQUISITION

Four computing groups provide computing and networking services at TRIUMF.

- **CCN -** Core-Computing and Networking, 8 FTE's provide the central computing and networking services for the site. Principal responsibilities include centralized email, printing, file and web servers, site backups, PC desktop support, networking and security.
- **MIS -** Management and Information Systems, 3 FTE's provide the computing support for the business and administration services, finance, human resources and supply chain management. It is also responsible for the development and support of custom applications to meet the unique requirements of TRIUMF.
- **DAQ -** Data Acquisition - 4.3 FTE's provide computing support to the TRIUMF experimental program. This small group is responsible for maintaining and supporting approximately thirty active experiments both locally and internationally. It is one of the key developers and maintainers of the MIDAS data acquisition system used by experiments at research facilities worldwide.
- **ATLAS Tier 1**, 9.5 FTE provides 24/7 operational support of the Canadian ATLAS Tier-1 Data centre. The TRIUMF Tier-1 is presently hosting ~5000 processor cores, 7 PB of disk storage and 5.5 PB of tape storage. It is the number one rated ATLAS Tier-1 site for availability and is providing 10% of the ATLAS LHC data to the international ATLAS community.

All four groups provide critical and in many cases unique IT services to TRIUMF staff and research scientists. The last five years have seen several significant developments. In 2009 an external international review committee was convened to examine the resources, services, organizational structure and prioritizing procedures of TRIUMF Computing groups. This resulted in several organizational changes. All four computing groups report to one computing group leader. The computing group leader was appointed to the senior management group. The CCN computing group has assumed responsibility for core services that were common amongst the other computing groups, reducing duplication of effort. The computing groups were also encouraged to take advantage of outsourcing various commodity IT services were feasible and to focus internal IT support in those areas unique to TRIUMF. TRIUMF is following this recommendation and is in the process of replacing the 30-year-old in-house custom developed ERP system with a modern commercial ERP (Enterprise Resource Planning) application. Commercial email and calendaring services are also being pursued. Software development is being limited to those applications that have unique TRIUMF requirements.

The following summarizes achievements specific to each of the TRIUMF computing groups.

CCN

The primary role of the Core-Computing and Network Group (CCN) is to provide a highly available, reliable and secure computing and networking infrastructure for the TRIUMF laboratory and staff. Its secondary role is to provide advice and expertise on a wide range of IT issues that assist laboratory staff and research scientists.

Traditionally the CCN Group provided scientific computing support for the TRIUMF research community. Over the last decade the focus has transitioned and broadened from scientific computing to all aspects of computing and networking services. This has become necessary in order to adapt to the widespread use and demands for computing by all staff, where previously the demand was driven by the research scientists.

To meet the demands of TRIUMF's research programs external networking requirements have been increased substantially. TRIUMF's 1GbE connection to the Canadian and international research networks was upgraded to 10GbE in 2010. TRIUMF in collaboration with BCNet and CANARIE have establish a high-speed, dedicated 10GbE network, connecting the Canadian eastern and western ATLAS Tier-2 sites to the Canadian Tier-1 centre and ATLAS sites internationally. In late 2011, an RFP was issued to replace aging 1GbE internal network core with 10GbE. The RFP was awarded to Juniper Networks in 2012. Full deployment is anticipated by the end of the summer of 2013. The new network core has been designed to meet TRIUMF's requirements for the next 7–10 years and will support the 100GbE, a requirement of the TRIUMF ATLAS Tier-1 by 2016/17.

TRIUMF IT has embraced the benefits of virtualization over the past few years. In 2012, CCN deployed both a virtualized storage and virtualized server environments based on the Red Hat Enterprise Virtualization (RHEV) and Nexenta virtualized storage. This has allowed CCN to operate a highly performant and reliable data centre with minimal staffing and infrastructure resources. In 2013, the virtualization will be extended to blade-based infrastructure, reducing further the resources needed for space and management.

CCN have adopted TRIUMF's strong and increasing commitment to documentation and monitoring. In the last five years it has incorporated new revision control procedures and enhanced existing monitoring systems for documenting, maintaining and monitoring configuration changes and availability of its IT services. This has improved significantly its ability to quickly deploy new, failed or failing services and to track and maintain a history of system changes.

MIS

Since the start of the current Five-Year Plan, the MIS Group has developed three new JavaEE applications: Human Resources (put into production use early 2010, but developed the previous year), Identity Management, and the Work-Request System. In addition, the transition of the Science Application from PHP prototype to JavaEE was completed when the Experiments Database component was re-written (the Beam Schedule and Beam Request components had been done prior to the Five-Year Plan). These applications continue to be updated, with the most notable enhancements being access-group maintenance and distributed identity management (both for IM) and the Experimenter's Dashboard (for Science).

Preparatory work to integrate TRIUMF applications with the new Agresso ERP has also been done. Agresso logins are now created and managed by the Identity Management application, and cost centre work orders are being propagated to the Agresso database. Further development in the integration of account validation and financial transaction postings are underway and will be completed before Agresso is "live."

The TRIUMF website was converted to a Drupal framework to coincide with the start of the previous Five-Year Plan. Since then, the most notable improvements have been automatic personal profile maintenance (integrated with the Identity Management application) and enabling group pages that allows groups to maintain their own portions of the public website.

DAQ

Over the past five years the small but productive DAQ group have supported and deployed real-time computing systems for an increasing number of successful TRIUMF experiments. This is a direct result of the recent success of CFI funded experiments over the last several years. The following is a condensed list of the groups' achievements over the past few years:

ALPHA : Electronics, Firmware, Full DAQ (2009–2011)

The DAQ system developed and maintained by the TRIUMF DAQ Group has been key to the successful science results obtained by the ALPHA collaboration in 2011. As for most major experiments, our involvement started from the beginning of the project.

Geotomo: VME-Based DAQ (2009–2010)

The first Geotomo detector based on standard VME boards required a fair amount of time for testing the VF48 waveform digitizers and reliability of the overall system, including the satellite communication.

AAPS/Geotomo/Cript: New DAQ Architecture (2011–2012)

For the next version of the Geotomo detector, we suggested designing the DAQ with custom hardware boards to make the system more flexible and more reliable. Its realization has been a great success, with the DAQ Group involved mostly for concept and problem solving and acting as consultant.

T2K-FGD: Electronics Development and Acquisition (2009–2011)

We developed custom hardware for the FGD, test bench for other sub-detectors DAQ, and successfully helped the T2K-UK group to take DAQ responsibility using MIDAS as their main DAQ.

TIGRESS: (2011–2012)

We improved time and energy resolution using dedicated firmware in the digitizers as well as completed the firmware for the TIG64 board (64ch. 50Msps) used for the TIGRESS auxiliary detectors.

GRIFFIN: (2011–2012)

We revised the design of the overall DAQ, designed a new digitizer (100Msps), and associated trigger module in collaboration with the Electronics Development Group.

DESCANT: (2012)

We developed firmware for the 1Gsps digitizer.

DEAP-3600: DAQ Architecture, Implementation, and Infrastructure (2010–2012)

Presently in full testing phase, the DAQ required the use of new commercial Waveform Digitizers and precise timing sychronization of all the acquisition boards. The large number of channels and the anticipated event rate required special front-end applications (multi-threaded) and in-line data filtering (event builder) in order to reduce the overall data collection to the experimental goal.

TRINAT: Successful DAQ Migration (2012)

TRINAT has been converted and is running VME modules. In particular, the use of the VMEIO custom trigger circuit has been extremely powerful.

IRIS: Successful DAQ Implementation (2012)

This experiment required multiple acquisition processors to ensure proper data synchronization, which has been achieved with the VMENIMIO32.

VF48 Firmware Development for LiXe, PiENu, TACTIC (2009–2011)

The VF48 have been used in several experiments but required a lot of firmware development to accommodate the different experimental requirements.

New DAQ Hardware Development: VMENIMIO32, VMEPPG32, MSCB (2010–2012)

These main VME units have been designed and programmed by the DAQ group with realization by the Electronics Group. So far, several units have been placed in experimental setup and are found to be very useful as custom trigger circuitry or as default standard DAQ functions (Scaler, Time Stamp, TDC). These boards can replace a good section of NIM modules and therefore address the aging state of the unmaintained NIM electronics.

5.9 LABORATORY ORGANIZATION

In addition to the physical plant, the productivity and performance of TRIUMF is determined by its administrative structures and the accumulated knowledge about how to operate and manage a laboratory effectively. TRIUMF has evolved a management structure and process that allows setting priorities and implementing them in a timely manner. In its December 2012 report to the NRC President, the Advisory Committee on TRIUMF noted:

The Committee finds that TRIUMF is performing its mission very well across the full spectrum of operating programs and future projects. The Director and the Heads of the Science, Accelerator, Nuclear Medicine, and Engineering Divisions work coherently as a team and provide outstanding leadership for the scientific and technical staff. Particularly notable is the coherence of the priorities and goals enunciated by the senior management team.

In this section we outline the laboratory management structure and give insights into how the laboratory is run. Over the last five years a number of improvements have been made to TRIUMF management and operating procedures (see Sidebar: Continuous Improvement).

5.9.1 LABORATORY OVERVIEW

The Government of Canada funds TRIUMF's core operations; however, the laboratory is owned and operated as a joint venture by a consortium of Canadian universities. This unique governance structure has been and continues to be a very successful model for operating a national facility. The Joint Venture Agreement establishes TRIUMF's Board of Management to operate, supervise, and control the laboratory.

Over the past five years membership in the joint venture has grown reflecting TRIUMF's increased value to the Canadian university research community. The University of Manitoba (in 2009), Guelph University (in 2009), Queen's University (in 2009), and York University (in 2008) all became full members of the joint venture. The University of Calgary (in 2009), McGill University (in 2013), the University of Northern British Columbia (in 2011) and the University of Winnipeg (in 2012) received associate membership in the joint venture, a prelude to applying for full membership.

TRIUMF is headed by a laboratory director who reports to the Board of Management and is normally appointed to five-year terms. The laboratory staff are organized into five distinct divisions: Accelerator, Business and Administration, Engineering, Nuclear Medicine, and Science (see Figure 1). The Director's Office includes an executive assistant and the chief accountability holders: the five division heads; the head of strategic planning and communication; the manager of environment, health, and safety; the project-management coordinator, and the chief financial officer.

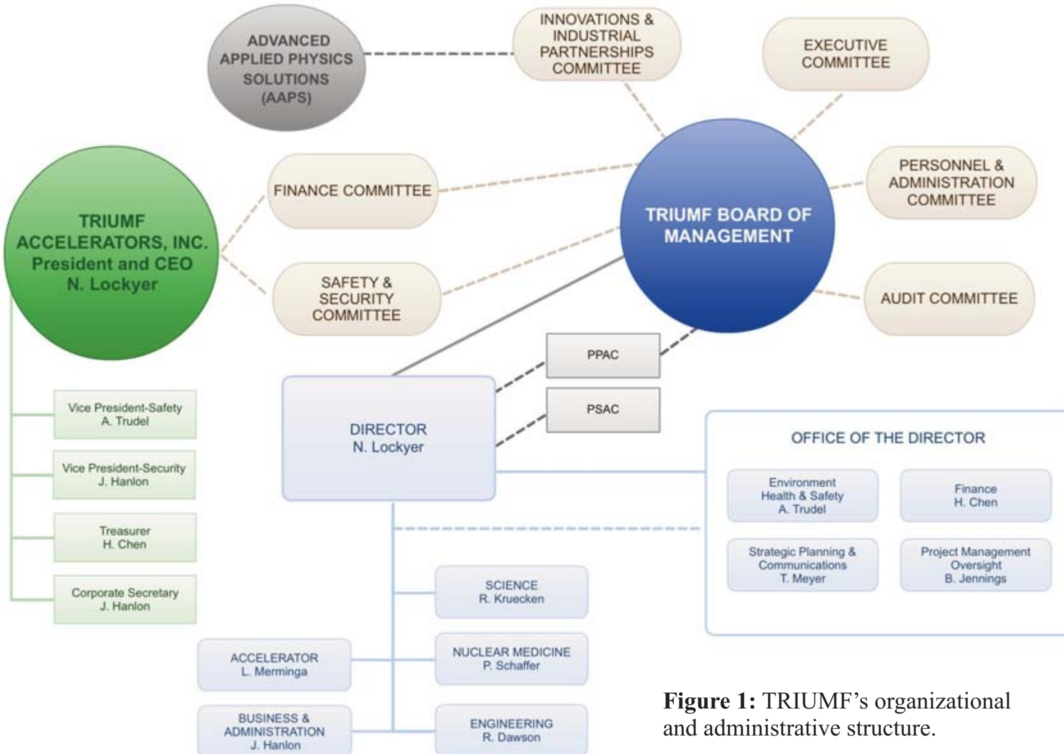

Figure 1: TRIUMF's organizational and administrative structure.

5.9.2 ACCOUNTABILITY

TRIUMF's Board of Management is made up of two voting representatives from each full member university, one non-voting member from each associate member and two voting private sector representatives nominated and appointed by the Board of Management. It is expected the private sector members will bring a unique expertise to the Board, particularly in assisting TRIUMF to evaluate its commercial activities and opportunities. The TRIUMF Board of Management meets twice a year and is responsible for the financial and administrative affairs of TRIUMF. The executive committee of the Board of Management has six members including the chairman of the Board. It normally meets in between Board meetings on an "as needed" basis.

Funding from the Government of Canada flows to TRIUMF through a "Contribution Agreement" between the National Research Council of Canada (NRC) and the full members of the TRIUMF Joint Venture. NRC provides the federal government oversight and accountability for the funding on the basis of Five-Year Plans prepared by TRIUMF. The Contribution Agreement defines the terms and conditions under which TRIUMF receives funding for the Five-Year Plan and defines a "Statement of Work," the work that TRIUMF must complete during the five years and upon which TRIUMF's success will be evaluated.

In addition to the NRC contribution, TRIUMF receives funds from a number of other sources, either directly or through collaborations with its university partners, from a number of other sources: The Natural Sciences and Engineering Research Council (NSERC), the Canadian Institutes for Health Research (CIHR), Natural Resources Canada, Western Economic Diversification, the Canada Foundation for Innovation (CFI), the British Columbia Knowledge Development Fund (BCKDF), commercial partners and affiliated institutions. For TRIUMF's funding, ending March 31, 2010, see Table 2. TRIUMF's buildings have been funded by the Province of British Columbia and are owned by the University of British Columbia.

Monitoring the laboratory's performance is a joint responsibility of the Agency Committee on TRIUMF (ACT), represented by Industry Canada, NSERC, and the NRC, who normally meet semi-annually to oversee the Government of Canada's investment in TRIUMF and the economic benefits accruing to Canada from that investment. ACT has a particular focus on financial and commercialization matters. In addition, the Advisory Committee on TRIUMF (ACOT), a panel of internationally recognized scientists, monitors the scientific performance of the laboratory and commercial activities through semi-annual meetings held at TRIUMF. Once during each five-year funding period, NRC appoints an International Peer Review Committee (IPRC) to review TRIUMF's scientific performance and evaluate its proposals for the next Five-Year Plan. The last one was in 2008. CFI and CIHR are invited to attend.

The organizational and administrative structure of TRIUMF is shown in Figure 1. Under the Board of Management are TRIUMF Accelerators Inc. (TAI) and TRIUMF proper. TAI is an incorporated non-profit company that holds the operating license from the Canadian Nuclear Safety Commission (CNSC) for TRIUMF's accelerators and is a party the land lease between UBC and the full members of the Joint Venture.

TRIUMF proper is divided into five divisions and the Office of the Director. The Office of the Director contains the Heads of essential administrative services groups. They are the CFO, the Safety Officer, Head of Environment, Health and Safety, Head of Strategic Planning and Communication, and the Project Management Office. The five divisions are: Accelerator, Business and Administration, Engineering, Nuclear Medicine, and Science. They reflect the top-level work breakdown structure for the laboratory.

Experiment Evaluation Committees advise the Division Heads about which experiments to run on TRIUMF beam lines. There are three such committees: Subatomic Physics Experimental Evaluation Committee (SAP-EEC), Molecular and Materials Science Experiment Evaluation Committee (MMS-EEC), and Life Sciences Projects Evaulation Committee (LSPEC). For general policy issues, the Director is advised by the Policy and Planning Advisory Committee (PPAC), which is made up of members chosen from Canadian Universities.

Insurance

TRIUMF carries a $50M Nuclear Energy Liability policy from the Nuclear Insurance Association of Canada (NIAC) that complements other Commercial General Liability coverage of $50M and coverage for Directors and Officers of $10M. In addition TRIUMF is a "named insured" on the University of Victoria's Property Insurance policy through the Canadian University Reciprocal Insurance Exchange program (CURIE).

Site Security

The Head of the Business and Administration Division is responsible for day-to-day site security and works closely with the Manager, Environment, Health and Safety to ensure that Canadian Nuclear Safety Commission, CNSC, is made aware of any security enhancements or breaches. The Manager, Environment, Health and Safety is responsible for day to day communication with CNSC on physical security matters. All activities regulated by CNSC are within a fenced compound area. This fenced compound area is randomly patrolled in the off-hours and weekends by a contract security guard.

CNSC staff perform ongoing compliance monitoring activities in the area of security to verify that the TRIUMF security program, including its implementation, continues to meet regulatory requirements for a Class 1B nuclear facility. TRIUMF is in compliance with all aspects of its security operations. Concurrent with the ARIEL construction project, a new badge room was built to allow access to the controlled area that has optical turnstiles designed to eliminate tailgating and improve secure access to the site.

TRIUMF has a Main Control Room that is staffed 24/7 – 365 days per year. Video surveillance cameras monitor the main access gates. Any security breaches are reported to Main Control Room personnel, who then contact the appropriate authority.

Security and site access as identified in TRIUMF Standard Operating Procedure 10 is included in the employee orientation Program and the Basic Safety Orientation Training. All staff and visitors are required to have a security access card and access cards will not be issued without the appropriate authorization.

CNSC staff continues ongoing compliance monitoring activities in the area of security to verify that the TRIUMF security program, including its implementation, continues to meet regulatory requirements.

All employees and long-term visitors are required to wear a photo ID security access card. All short-term visitors, those visitors of less than three weeks, are required to wear a visitor badge.

Human Resources

TRIUMF has a dynamic and diverse workforce of highly skilled people working together to deliver excellent service and support. Our resource planning initiatives have allowed us to proactively manage our human resources to meet current and future workforce needs through succession planning, demographic analysis, and staff redeployment based on cross departmental and divisional cooperation. The introduction of an online orientation program in 2011 has strengthened our onboarding process, and reference guides for new employees and supervisors have been introduced to better acquaint new hires with TRIUMF's policies, practices, and procedures.

With respect to employee health benefits, a comprehensive market survey analysis was undertaken to determine the financial impact of introducing a harmonized and improved health benefit plan for all employee groups. The results of this analysis indicated that the current TRIUMF employee benefit plans are cost effective and competitive, and supported no change at this time.

Our current strategic HR priorities include strengthening leadership training and development, performance management, and position classification and compensation practices. Our performance-based compensation program supports fiscally responsible budget planning, and the current project of introducing job families and salary scales includes the review of positions and salaries across the organization. The ability to differentiate the pay of one occupational group from another is central to the benefits of TRIUMF's job family implementation project that has a number of goals, including increasing retention of competent employees and improving attraction of new employees. In 2009, a market salary review was conducted for all technicial positions, and six job families were introduced as a result. At present we are conducting a compensation market review for all administrative, professional, and supervisory positions at TRIUMF with the goal of introducing relevant job families and corresponding pay ranges for all employee groups.

TRIUMF has performance based pay philosophy and merit is awarded to those employees who demonstrate strong performance during a given performance review period. For approximately 350 employees paid from operating funds, performance is reviewed on an annual basis and merit is awarded in the form of an increase or honoraria, as allocated in the annual budget. While those employees whose salaries are supported through sponsored research are subject to the administrative policies of the institution, salary administration may be dictated by the availability of funds allocated to salaries in the applicable research grant.

TRIUMF has a very strong undergraduate student program and hires some 70 summer students per year in addition to approximately 10 university co-op students each term. In addition there are around 35 graduate students and 45 post-doctoral research fellows at TRIUMF.

TRIUMF has established an on-line office where users and visitors can contact the Visitor Services Coordinator who assists with sign-in procedures and facilitates the issuance of security access cards, radiation badges, computer accounts, and safety training. The Coordinator also provides experimenters with basic information about TRIUMF and directs them to appropriate TRIUMF contacts, such as the Scientific Liaison for experimental facilities.

Finance, Procurement, and Logistics

The Finance Office is responsible for those activities associated with Treasury, Accounting, Procurement, and Logistics. Managing the financial risks and supporting the laboratory's goals and ongoing reviews of TRIUMF's business practices in order to maximize the efficiency and effective use of resources are the objectives of this group. In the current five-year cycle, several initiatives were undertaken to support the group's objectives:

Agresso: A New Enterprise Resource Planning (ERP) System

In September 2009, TRIUMF held an external review of its core computing facilities, including its Management Information System. In its recommendation, the review committee stated that TRIUMF requires a flexible and responsive information system to comply with the changing and increasingly stringent regulatory demands, and to provide reliable management reporting. Subsequently, the TRIUMF Board of Management approved the purchase and implementation of a new ERP System called Agresso Business World.

Since the Board's approval, a project team was formed in 2011 and the process of discovery to implementation began. The project has proven to be more challenging than originally envisioned. The new system, while less flexible than the current highly customized system, still requires complex configuration to meet TRIUMF's needs. The start of commissioning will occur in the 4th quarter of 2013.

The new system offers many advantages. The procurement process, from requisition to accounts payable, is becoming paperless, with electronic approval replacing signatures on paper. This change precludes processing gridlock associated with a paper based system. It allows for on-line approval of requisitions from anywhere, providing there is access to the Internet. Stores purchases and travel approval are integrated into the same procurement process. The laboratory Work Breakdown Structure (WBS) is being fully incorporated into the accounting architecture for consistency in tracking expenditures and as an aide to project management. The flexible reporting capabilities of the new system make information far more accessible then with the present system and will give account holders and TRIUMF senior management direct access to information that at the present time requires involvement of Management Information System (MIS) staff. This will facilitate corrective actions and increase responsiveness to issues as they arise.

Preliminary Decommissioning Plan: Financial Guarantee

One of the requirements of TRIUMF's Accelerator Operating Licence is the Preliminary Decommissioning Plan (PDP). The main objective of the plan is to ensure that the site is brought to a safe state of closure in the event of decommissioning. The Financial Guarantee, a significant component of the plan, demonstrates the funding measures and provides assurance that adequate resources will be available to fund decommissioning activities. TRIUMF has conducted an extensive review and updated the PDP and the Financial Guarantee in late 2011. The cost study was prepared in accordance with generally accepted accounting and quantity surveying methods and procedures by an independent quantity surveyor firm.

The decommissioning fund, a restricted fund governed by an escrow agreement had a balance of $10.4M at the end of Fiscal Year March 31, 2013. The Escrow Agent (The Royal Bank of Canada) commented on the state of the PDP and Financial Guarantee: "…escrow account is in a solid position to fund the activities of decommissioning…".

Finance

As a result of a review of its cash management practices, and with the cooperation by funders, TRIUMF has minimized its cash flow concerns for funding operations and large-scale projects.

Cash transfers from funders are timed to occur before or at the time TRIUMF disburses funds for expenditures. This adjustment relieved prior practice whereby expenses were incurred and TRIUMF would wait for reimbursement from funders after a monthly billing cycle. This change enhances TRIUMF cash flow and coupled with an improved process to obtain competitive interest rates means that TRIUMF has systemically increased its ability to generate higher investment income on available cash balances.

In August 2011, Elections BC announced that the Harmonized Sales Tax (HST-12%), which came into effect on July 1, 2010, had officially been repealed by a majority vote of 55% to eliminate the tax. This tax change took effect April 1, 2013.

As a registered charity, TRIUMF was adversely impacted by this change when a portion of rebates claimable on taxes paid were also eliminated. The value of lost rebates cost TRIUMF $1.2M per year from its program. TRIUMF has fully reviewed the tax changes and systems and procedures have been modified accordingly. Over the months leading up to April 1, 2013, coordinated efforts in expediting and advancing purchases in order to claim rebates before they became unavailable resulted in tax savings of $0.1M.

TRIUMF employs in excess of 500 employees (350 paid from operating funds and 150 funded through grants or affiliated institutions). Given the diversity of its labour pool, and the demarcation required between personal activities and work activities, the Director instructed TRIUMF's administration team to develop a Political Activity Policy. The coordinated efforts between Human Resources, Strategic Planning and Communication, and Finance resulted in a Political Activity Policy and with assistance of legal counsel, a policy was created that gives employees clear direction when interacting with politicians and/or volunteering in partisan political activities. This was passed by the board on November 16, 2012.

TRIUMF consumes roughly 30kL of liquid helium (LHe) annually to support its material sciences and SRF research programs. Full helium recovery systems are in place or the ISAC-II superconducting linear accelerator and the new electron linear accelerator (e-linac) so they consume much less. LHe is used as a cooling agent in scientific experiments and superconducting equipment. The annualized cost to purchase LHe is in excess of $0.4M and the cost/litre has been steadily rising in excess of inflation. Therefore, the reliability of supply in both quantity and quality has become a recurring issue.

Starting in 2016 (plan), the Ultra-Cold Neutron (UCN) Project is forecasted to require 50kL, rising to 150kL per year by 2018. If LHe requirements continue to be purchased on the open market (assuming its availability), TRIUMF's annual cost would swell to $2.8M at today's prices.

Over the past few years, TRIUMF's Centre for Molecular and Materials Science (CMMS) group has been studying alternatives to recover LHe during consumption, and after an extensive review, they developed a solution described in detail in section 5.4.4. In October 2012, a Gate Review Committee concluded its review and recommended the proposed solution be accepted. Shortly after, the Senior Management group convened to review the recommendation, and the solution was accepted along with the funding plan. The cost of the project is $1.6M, and the payback of the capital cost will occur after four operating years, based on current consumption. Furthermore, the value of the investment is compounded significantly when considering the cost avoidance in future years due to the LHe required for the UCN project.

Procurement

After exporting the final goods and securing materials for the T2K project in Japan, Procurement began establishing the purchasing requirements for the Advanced Rare Isotope Laboratory (ARIEL) at TRIUMF. This included preparing and managing the tender documents for the Architectural and Engineering Services for the infrastructure, participating in the tendering processes for the construction of the new Stores building, the Badge Room, and the main construction of the ARIEL infrastructure, including excavation and site preparation.

After the main construction was started, Procurement focused on purchases of specialized components and items related to the electron linear accelerator (e-linac), while maintaining a high level of customer service to the rest of the laboratory. During this time, TRIUMF's purchasing policies and procedures were reviewed and updated in 2012. The result is a continued support of the objective of utilizing resources in the most efficient and effective manner.

Logistics

The Stores facility was relocated in 2011 because of the demolition required to clear the ARIEL construction site and build the northern annex ("RIB building") of the ARIEL facility. The move of Stores to its new location was completed with minimal impact on service to the TRIUMF site.

The introduction of a "virtual" inventory system enabled the efficient and cost-effective distribution of non-stock inventory items like helium dewars and office supplies. This system follows a "Just In Time" concept of inventory management.

In addition, the Logistics Group facilitated an effort to create usable storage space in an area of the Proton Hall. The effort resulted in an increase of usable storage space and a systematic process for the storage or disposal of unusable items.

TRIUMF House

Ensuring the comfort of visiting scientists staying at TRIUMF House is paramount to its operations. In 2011, TRIUMF House achieved a "perfect score" when reviewed by Tourism BC in their annual assessment visit. This rating reflects the cleanliness and state of repair, two important guest services factors in the accommodation industry. Several relationships outside of the scientific community were cultivated as a revenue source for those periods when TRIUMF House is not required by TRIUMF users.

CONTINUOUS IMPROVEMENT

Over the last five years, TRIUMF has systematically reviewed it procedures and made changes to increase productivity and reduce risk. The changes are spread widely across the laboratory and affect all areas of operation. The new procedures are process driven and stress documentation and site-wide standards.

Three examples typify the changes: the Document Type Index, the Commitment List and improved training (a comprehensive list is given below). With the emphasis on documentation, a plan for identifying and managing documents in different fashions based on their use is needed. The Document Type Index fulfills this need and also provides a pointer to where each type of document is stored. The main document repository is a backed-up web-based system with access controlled by specially trained documents controllers. Included among the controlled documents are the TRIUMF Standard Operating Procedure documents, the risk registry, and training plans.

In addition to the traditional organization chart maintained by Human Resources, there is a hierarchical arrangement of TRIUMF's program of work. This hierarchy is the work breakdown structure (WBS). The WBS, documented in the Commitment List, has all TRIUMF's activities, both operational and projects, organized into a logical hierarchical structure. The Commitment List provides the framework to monitor resource usage. It also has each activity ranked by its importance to the TRIUMF program. Each project on the commitment list undergoes a series of gate reviews as it progresses from conception to completion. The combination of the importance rating and gate reviews are used to set site-wide priorities and monitor and document the progress of projects.

With the highly specialized activities that take place at TRIUMF, it is important not only that processes are documented but also that staff are trained to carry out the processes. While generic training is all that is required for some tasks, much that goes on at TRIUMF requires specialized knowledge. TRIUMF is working to improve its training, starting at the top with supervisors and extending to individual groups who are developing training programs suited to their individual needs.

To indicate the wide spread nature of the changes, here is comprehensive list of changes to process:

Accelerator Division

- Weekly shutdowns replaced by shutdowns on demand.
- Increased engineering oversight of ISAC target production
- Systematic Approach to Shutdown
- Installation, commissioning, and operation of conditioning station, north hot cell for ISAC target conditioning
- Combining accelerator control rooms (in study stage)
- Controls (standardize on one system, EPICS)
- Cyclotron uptime
- Target reliability
- Increased beam to ISAC

Science Division

- Modified EEC process to better manage backlogs for experimenter requests for beam time
- Increased publications
- LHe Recovery

Quality Management System

- Work request system
- Training program – group specific
- Document control
- Group manuals
- Calibration and inspection index
- Uniformity in reporting non-conformities
- 10 year license
- Environmental protection program
- Safety program

Project Management

- Commitment list developed to provide an overview of all activities at TRIUMF
- Importance rating of each commitment to set relative priorities between tasks
- Gate Reviews to define transitions between project phases by gathering information and subjecting to expert review before resources are made available
- Expanded time sheets to better track all work on all activities

Finance, Procurement, and Logistics

- New Enterprise Resource Planning system (Agresso)
- Developed a sustainable financial plan for Decommissioning
- Overhauled TRIUMF's methods of accounting, reporting and budgeting
- Enhancements to the NRC/TRIUMF Contribution Agreement
- Re-engineered cash management and treasury processes
- Updated procurement policies (RFP/Tendering)
- Inventory management improvements (virtual inventory)

Human Resources

- Old pay-grid model of compensation replaced with pay ranges, job families and pay for performance
- Improved onboarding process to include online orientation prior to commencing employment
- 90 day new employee surveys for critical feedback
- Introduction of new employee handbook and supervisors handbook
- Formal supervisor training for new supervisors
- Phase 1 of Succession Planning, identifying the critical positions and identifying future turnover

Engineering Division

- Risk registry
- Neighbourhood District Energy Program

Business and Administration

- Partnering with like-minded organizations for community and outreach events to share costs and increase impact: Science World for public science lectures, University Neighbourhoods Association for open houses, Perimeter Institute for Theoretical Physics and SNOLAB for national high-school teaching awards.
- Reduced meetings and travel costs

5.9.3 EH&S, QMS, AND LICENSING

Operation of TRIUMF's accelerator facilities is regulated under the terms of a Class IB Accelerator Operating Licence issued by the Canadian Nuclear Safety Commission to TRIUMF Accelerators Inc. The terms of the licence mandate a suite of regulatory programs in different safety and control areas that include all aspects of personnel and environment health and safety, as well as a quality management system. The suite of regulatory programs are managed and administered by the Environment, Health, and Safety (EH&S) group that consists of a team of physicists, engineers and technicians with expertise in radiation safety systems, radiation protection, safety analysis and shielding design, as well as occupational health. Over the reporting period 2008–2012 TRIUMF devoted significant effort and resources to upgrading its regulatory programs with the goal of improving the laboratory safety record.

TRIUMF began to develop a Quality Assurance (QA) Program in 2002 to meet CNSC requirements. In 2006, the CNSC conducted an audit of TRIUMF QA. In response to directives and a recommendation, TRIUMF's director created the Quality Management System Implementation Panel, which was chaired by the Head of the Engineering Division with strong guidance from the QA Manager. Panel members included senior staff from all divisions who had the broadest and deepest knowledge of TRIUMF activities. The panel was charged with ensuring that documentation was up-to-date and that staff was properly trained and followed TRIUMF Standard Operating Procedures (TSOPs).

Over this reporting period 2008–2013, Quality Management System TSOPs have become well established in TRUMF's everyday processes and activities. The QA Manager, responsible for the day-to-day operation of the Quality Management System, also manages the auditing of the system procedures and regular reporting of progress to the senior management team. In addition, the QA Manager provides on-going assistance with implementation across the site, sets the schedule of internal assessments, and selects assessment teams with the appropriate independence to perform the assigned assessments.

The TRIUMF Quality Manual, 14 TRIUMF Standard Operating Procedures (TSOPs), the TRIUMF Document Manual, and a collection of Group Manuals now define the laboratory's operating processes and cover everything from access to the TRIUMF restricted site to project management.

Some of the tools put in place to facilitate implementation of a Quality Management System at TRIUMF are:

- A QMS leaders panel to promote communication and provide opportunities for continuing QMS education;
- Site-wide performance metrics and annual assessments at the Quarterly Safety Management Meeting;
- A site-wide database for nonconformity reporting and corrective action resolution to allow better tracking and opportunities for analysis of operational experience;
- A trained team of experts in incident investigation to identify root causes associated with nonconformities;
- A QMS newsletter to assist with dissemination of information during the implementation phase of the program;
- A TSOP for project management with well-identified gate reviews to provide oversight and regular reporting for projects;
- An enterprise resource package to allow better tracking of resources;
- An annual schedule of internal audits and assessments that is one of the processes in the Quality Program TSOP;
- A document-type index to systematically categorize QMS document types and their associated workflows;
- A calibration and inspection index to facilitate tracking of inspections and calibrations for instrumentation and equipment across the site; and,
- A site-wide work request system to provide a single entry point for all groups on site and to facilitate tracking.

The resources required for both the implementation and sustainability of the QA program was, and continues to be, reviewed at the Quarterly Safety Management Meeting, thus ensuring that TRIUMF has a QMS system that both works for the laboratory and demonstrates to its stakeholders, staff, and visitors, as well as its regulators—the Canadian Nuclear Safety Commission (federally) and the Worker's Compensation Board of BC (provincially), that TRIUMF is a safe, efficient, and productive research environment.

Following on the success of the QMS Implementation Panel, TRIUMF addressed deficiencies in its training program with the creation of the Training Implementation Panel. Led by head of the Science Division, the Panel's mandate was to oversee the work of the Training Task Force and ensure a timely implementation of training requirements for all groups on site.

The Task Force assessed the training requirements for all positions where performance could affect the operation of beam delivery facilities, or where incorrect performance could result in injury, downtime, expense, or radiation dose. It also identified and prioritized these positions, completed the task analysis for the more critical positions, and is now in the final stages of completing the process of design, development, and implementation of training for all positions by September 2013.

TRIUMF's suite of EH&S programs were also revised and upgraded to remain compliant with regulations and standards in the nuclear industry. A summary of the programs that received significant upgrades from 2008–2013 are included below.

Personnel Safety Systems. Maintaining the high level of reliability and performance of TRIUMF's personnel protection radiation safety systems continued to be a focus. The main cyclotron central safety system and radiation monitoring system microprocessors were upgraded to newer technology. In addition, the January 2012 shutdown saw the culmination of a five-year long project to replace all Access Control System Area Safety Units microprocessors for the main cyclotron.

Fire Protection Program. Documents were revised, approved and released in October 2010. These included procedures for inspection, testing, and maintenance of fire protection systems, thereby bringing all of these activities into compliance with he latest versions of regulatory codes and standards.

Emissions and Environmental Monitoring Programs. A review of stack calibrations was undertaken as part of the continual improvement process for the Emissions and Environmental Monitoring Program. In addition, in the context of upgrading ISAC operations for higher mass targets, a safety analysis showed the need for increased engineering controls for the Target Hall nuclear ventilation system to ensure that doses to personnel, members of the public, and the environment remained below regulatory limits. These upgrades were completed in time for the amended operating license in October 2011.

Radioactive Waste Management Program. Documents were revised to comply with the new regulatory clearance levels for defining waste as nonradioactive. In-house upgrades to the instrumentation used for monitoring radioactive waste were also completed to meet the new clearance level criteria. With these changes the Radiation Protection Group was able to put into place a comprehensive program to address the safe disposal of a significant fraction of its low-level radioactive waste and leave TRIUMF in a position to better manage, at lower costs, the low-level waste generated from ongoing projects involving refurbishment of beam lines.

OH&S Programs. All workplace occupational health and safety (OH&S) programs, mandated under the provincial occupational health and safety board WorkSafe BC, were reviewed and updated. These programs include safety training in ten distinct areas ranging from laboratory chemical safety to rigging and crane operator training. The training programs are either developed by the OH&S coordinator or a third-party contractor, and are administered by the training program coordinator.

Flexibility in regulatory licensing for a facility such as TRIUMF is crucial to maintaining a vibrant research program. By dedicating resources to its regulatory programs, TRIUMF demonstrates its due diligence in matters of environment health and safety and facilitates the regulatory process for new projects that require changes to the Operating Licence. Several licence amendments have been required since April 2010: (1) an upgrade to the energy and beam current for the ISAC II rare isotope beam accelerator; (2) changes to the ISAC irradiation facility to include target materials heavier than lead; (3) increases in beam current, energy and target thickness for the Solid Target Facility; and (4) site preparation for construction of the ARIEL facility.

At the time of writing this report, TRIUMF has received a construction licence for ARIEL and has just applied for a separate operating licence for the electron gun and injector cryomodule portion of the e-linac.

In addition to the above operating licence amendments, TRIUMF's Accelerator Operating Licence was successfully renewed in June 2012 for a ten-year term. Licenses are usually renewed for a five-year term, but given TRIUMF's safety record and strong regulatory program performance, a renewal for a 10-year term was requested and granted.

TRIUMF's operating performance for environment, health, and safety (EH&S) metrics continued to do well between 2008–2013. The average total personnel radiation dose decreased over the previous five-year average by ~15%, or 50 person-mSv.

Environmental releases continued to remain well below the regulatory limit of 0.05mSv/year. TRIUMF annual airborne releases were just below 0.01mSv/yr and sump effluent releases at less than 10-6/yr for this period. Steps were taken to reduce airborne emissions by decreasing the maximum acceleration energy in the cyclotron. This reduction will allow for future cyclotron beam increases while still keeping emissions below 0.01mSv/yr.

TRIUMF's average lost-time injuries during the reporting period was 12.5 days/100 person-years and continued to be better than that for BC Universities (16.2 d/100p-y), the WorkSafe BC equivalent industry group. TRIUMF had one significant lost-time injury on the beam line shielding blocks during this time. A full incident investigation was carried out and corrective measures identified, including the implementation of fall protection equipment for rigging work together with procedures and training for all workers working on the shielding blocks.

QMS metrics were used to assess performance with respect to EH&S goals for this operating period. Goals were largely met and, in a few areas where performance was not fully met, EH&S group identified corrective actions with the aim of continual improvement.

5.9.4 PROJECT MANAGEMENT AND COORDINATION

The successful running of a laboratory depends on understanding what resources are available, and on what time scale, so that management can schedule current projects and plan for future ones. In the last five years, TRIUMF has made major improvements to how it tracks resource usage and projects future requirements. It has, in fact, migrated to an explicit matrix organization structure that consists of two parts: the organization chart, which is the human resources record of who reports to whom and the work breakdown structure (WBS), which breaks up the work at the laboratory into its logical structure. The matrix structure facilities the sharing of resources across organizational units to maximize resource usage and allow expertise residing in one area of the organization chart to be available to all projects.

As part of this matrix organization structure, TRIUMF has established a Project Oriented Management System. In this system, the allocation of any TRIUMF resource is keyed to a specific project—or commitment—on an official Commitments List approved by Senior Management and the Director. This commitment is the third level in the WBS. The four commonly used levels are shown in Figure 1. The top level is the Division and corresponds to the divisions on the organization chart. The next level is the program and would correspond, for example, to nuclear physics or accelerator MRO. The individual projects or commitments are then assigned to their programs. For example, the commitment TITAN is part of nuclear physics.

Each commitment is given an importance rating that is used in conjunction with the project schedule to assign priority in accessing TRIUMF resources. If a resource is needed in a time-critical manner for a commitment rated "crucial," like the e-linac, then it takes precedence over all other demands for that resource. The importance rating is set by a committee including the director, division heads, and the head of the Program and Policies Advisory Committee. The list of commitments, each with its own importance rating, is available to all TRIUMF staff members.

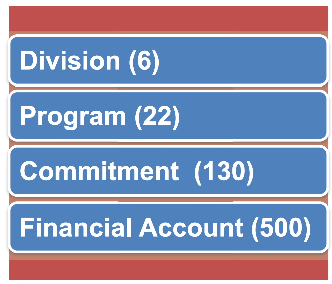

Figure 1: The top four levels of the work break structure.

All TRIUMF employees, except students, fill out timesheets, recording their time against individual commitments. Entries in the Commitment List fall into two broad categories: operations and projects. Operations are commitments that are ongoing and roughly the same from year to year. Timesheets from past years can be used to estimate requirements for future years and to help pinpoint where additional operational efficiencies can be found.

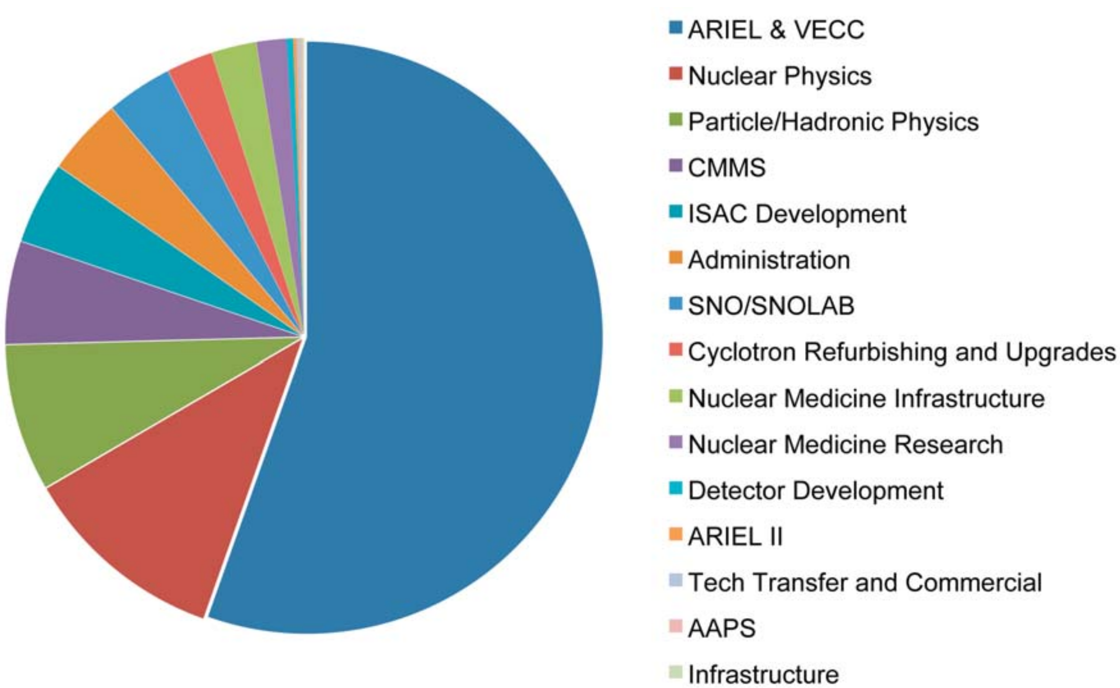

Figure 2: A pie chart for manpower usage by project for fiscal year 2012.

Projects have finite lifetimes and are managed based on the phase of the project. There are a series of gate reviews that each project must pass before it can proceed from one stage to the next. The first gate review is used to decide if the project can be added to the commitment list or must be abandoned; these are normally held before requests are made to external funding agencies. The remaining gate reviews determine if the project is progressing according to schedule, or if it must be reassessed. The entire process is described in the TRIUMF Standard Operating Procedure document TSOP-15.

As an example of the information that can be extracted from the time sheets using the WBS, Figure 2 below shows the relative resources usage for projects in the fiscal year 2012. From it, we can see that the ARIEL collection of commitments uses over half of all the human resources devoted to projects, with the total for all projects being 86 full time equivalents (FTEs). The lowest level shown for the WBS is the Financial Account. This level ties accounting information directly into the project management system.

This complete integration will only be available when the new enterprise resource planning (ERP) software goes live in 2013. TRIUMF will then have the unprecedented ability to track financial and human resources in a uniform manner.

5.10 INNOVATION AND INDUSTRIAL PARTNERSHIPS

TRIUMF has developed a significant portfolio of specialized knowledge, skills, and abilities through its cutting-edge research in particle physics, nuclear physics, nuclear medicine, materials science, and accelerator physics and through its interactions with Canadian universities and international researchers. In academic arenas, TRIUMF freely shares this expertise in collaborations intended for mutual benefit, as time and energy allow. In some cases, this expertise has potential commercial value or relevance to industry. The challenge is to discriminate wisely between academic relevance and business relevance while maintaining integrity, using public funds responsibly, and encouraging Canadian success.

The following discussion outlines the overall framework that TRIUMF uses to be effective in addresses the "create societal and economic growth" element of its mission. (Section 4.4 summarizes accomplishments in this area over the past five years.) The source of value creation is fundamentally intellectual property in the form of know-how, invention, disclosures, or patents. A five-year business development plan (prepared separately) assists TRIUMF in forecasting emerging opportunities and tracking new developments. TRIUMF has several vehicles to exploit intellectual property; the primary agent is Advanced Applied Physics Solutions, Inc. (AAPS) a stand-alone non-profit company that collaborates closely with the laboratory for market analysis, product development, and commercialization. Finally, success cannot occur in a vacuum: TRIUMF's network of partners, typically scoped and shaped by formal agreements, provide resources, markets, and contacts.

Although knowledge development, transfer, and commercialization is not a linear, one-way process, Figure 1 illustrates the basic relationships. In this simplified model, TRIUMF conducts basic research and develops knowledge and platform technologies (in the Technology Readiness Level (TRL) scheme, these outcomes would be at TRL 1-4). In turn, AAPS is guided by interactions with industry and analyzing the market. When AAPS sights a potential match between a platform technology and a market opportunity, it identifies an industrial partner and conducts product development (TRL 5-8) and commercialization (TRL 9) to generate business. The outcome of these efforts would normally be a spin-off venture that takes the product to market. Finally, the activities of TRIUMF (and its network of research partners) are generally guided by interactions with the marketplace (typically via industrial partners) to identify opportunities for developing potential technologies.

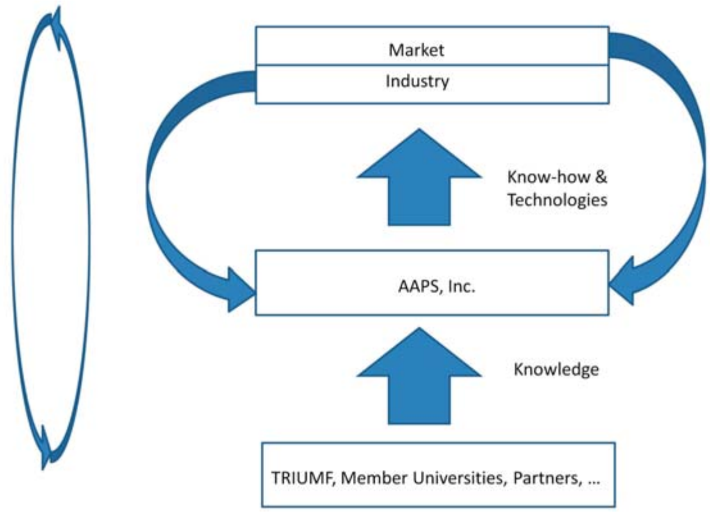

Figure 1: Positioning diagram of TRIUMF and AAPS Inc. relative to developing and exploiting techniques for commericialization.

As an example, consider the superconducting electron linear accelerator (e-linac) being constructed at TRIUMF as the heart of the ARIEL project. The e-linac uses superconducting radio-frequency (SRF) cavities as the core technology for accelerating an intense beam of electrons. When generalized from the specific application of 10 MeV/m, 1.3 GHz cavities for electron acceleration, SRF cavities represent a platform technology developed at TRIUMF. AAPS surveyed the world market along with TRIUMF and industrial vendor PAVAC Industries, Inc., and an opportunity was identified for widespread commercial use of SRF accelerating cavities. Moreover, the "cryomodule" technology that modularizes the SRF cavity and its life-support systems was identified as a more advantageous business opportunity because it is higher up the value chain. AAPS is now facilitating a technology-transfer agreement with PAVAC for TRIUMF. As part of a work package between TRIUMF and India, PAVAC will manufacture and deliver its first cryomodule product to India using TRIUMF technology. Subsequent to this demonstration deliverable, PAVAC will manufacture and sell cryomodules to other customers under a licensing arrangement.

5.10.1 KNOW-HOW AND INTELLECTUAL PROPERTY

To fulfill its research objectives, TRIUMF maintains a broad portfolio of technical and engineering capabilities. Several of these have immediate relevance to the commercial sector and are summarized below. Innovation and industrial partnership activities are managed through the Business and Administration Division at TRIUMF.

Irradiation and Radiation Effects in Materials

TRIUMF's Proton Irradiation Facility (PIF) and Neutron Irradiation Facility (NIF) regularly make use of three beam lines and provide testing facilities for aerospace and high-performance computing vendors. TRIUMF's expertise in radiation effects in materials is well recognized. In 2011, Ewart Blackmore, the chief scientist for PIF & NIF, was asked by the Canadian Space Agency to provide expert support to a technology assessment related to radiation prediction, monitoring, and protection technologies for future space missions. (See Section 4.4 for a discussion of performance over the 2008–2013 period.)

In a related topic, TRIUMF's expertise in environment, health, and safety especially with regard to radiation and radioactivity is regularly tapped by industrial partners. Ranging from consultations to assist the Chief Medical Officer of British Columbia during the Fukushima crisis of March 2011 to assistance with development of precautions for neutron exposure at one company's product-development laboratory and particle flux calculations to validate designs for shielding around medical equipment, TRIUMF's Radiation Protection Group and Manager of Environment Health and Safety are often in demand by external organizations.

Isotope Production and Chemistry

TRIUMF is expert in the physics and chemistry of isotopes and plays a crucial role in their biological applications, in particular, medical diagnosis and treatment. The nuclear medicine team has mastered the chemistry needed to isolate, purify, and combine the isotopes with biologically active target molecules for use by TRIUMF and its partners. As a particle-accelerator laboratory, TRIUMF's expertise in cyclotron design, engineering, and operation has led to the development of a variety of novel targets that enable the production of selected isotopes in relatively high yields.

TRIUMF's operational expertise in cyclotron production of medical isotopes is embodied in the Applied Technology Group, a team of about 30 scientists, technicians, and engineers that operate Nordion's on-site cyclotrons. This group is increasingly in demand by external organizations for technical consultations or project-management advice.

Other Technologies

Additionally, TRIUMF has established technical prowess in the following areas:

- Ion beam dynamics;
- Mechanical design, engineering, and fabrication;
- Advanced electronics: digital and analog;
- Advanced computing for scientific and facility control;
- Particle and radiation detection, modeling, and shielding;
- Radio-frequency (RF) technology including low-level RF and high-power RF;
- Precision magnet design, engineering, and measurement;
- Vacuum technology; and
- Cryogenic technology.

For instance, TRIUMF's expertise in cryogenic systems in vacuum environments was tapped by Westport Innovations, Inc., to discuss optimizing certain aspects of a product line they are developing that deals with pressurized natural gas.

Intellectual Property Management

The laboratory has a standard set of invention-disclosure requirements and policies that apply to all staff. TRIUMF reserves the right to protect (or not to protect) each invention with a patent or other type of arrangement.

In general terms, any invention created or discovered in whole or in part by any member of the TRIUMF staff is owned by the inventor. If it is determined that this invention has potential commercial opportunities then all rights would be assigned to TRIUMF for commercial exploitation unless TRIUMF makes a written agreement to the contrary with that member of the TRIUMF staff. The staff member would be entitled to royalties from the invention.

Income derived from the sale or licencing by TRIUMF of inventions or discoveries will be distributed such that the inventor(s) will receive 50% of the net revenues and TRIUMF will retain 50% of the net revenues. Net Revenues means royalty, licensing and other income received from the assignment or licensing of the rights to an Invention, less legal and other fees and expenses incurred directly in the process of establishing and maintaining the legal protection of those rights.

In conjunction with AAPS, TRIUMF manages a modest portfolio of registered intellectual property. TRIUMF surplused its historical patent holdings to AAPS in 2009; the portfolio is presented in Appendix 7.3.11.

> “The FY 2011 survey of U.S. university licensing activity conducted by the Association of University Technology Managers (AUTM) reports a total of 38,600 active licenses and options, with 591 commercial products introduced.”
>
> FY2011 Survey, prepared by the Association of University Technology Managers (AUTM).

5.10.2 ADVANCED APPLIED PHYSICS SOLUTIONS, INC.

The physical sciences continue to be a rich source of inspiration, invention, and innovation that drive new technologies and products into the marketplace. Increasingly, however, the development of physics-derived technologies into real-world products and services requires substantial technical and financial resources. Canada is ripe with opportunities in this sector, from medical isotopes and particle accelerators to radiation detection and control at TRIUMF to faculty and student discoveries and innovations at the universities and academic laboratories. AAPS was established to capitalize on these opportunities and be the sector’s business-development and commercialization resource for all of Canada.

AAPS is a federally funded Centre of Excellence for Commercialization and Research (CECR), launched in 2008 based on a proposal filed by TRIUMF. AAPS is fulfilling its goal of leading national efforts to commercialize physics-derived technologies, driven by seasoned business professionals and young entrepreneurs within a well-established governance structure. By end of 2012, AAPS had spent or encumbered about $10M of the original CECR funding and engaged another $9.5M (including cash and in-kind) from other sources.

The relationship between TRIUMF and AAPS is structured in a manner that respects TRIUMF’s status as a charity and the need for AAPS to be a separate non-profit corporation. As availability allows, TRIUMF resources are made available to AAPS at standard charge-out rates with a premium for priority access.

The mission of AAPS is to develop and commercialize advanced physics technologies for the social and economic well-being of Canadians and for the benefit of people around the world. To accomplish this mission, AAPS works to create new commercial opportunities by leveraging disclosures generated from local entrepreneurs, expanding projects with private sector partners, or commercializing projects with TRIUMF and its network of partners. Since inception in 2008, AAPS’ deal flow has come from all three sources, in part because of pent-up demand for a robust and capable commercialization vehicle.

The three commercial spaces in which AAPS is focusing are: natural resources (mining exploration), health and life sciences (medical isotopes and imaging radiation), and national security (detection of nuclear materials). Since Canada is a small market, international relevance is stressed. AAPS will normally not get involved in a project unless there is a commercial partner.

The AAPS Board of Directors is composed of primarily business and financial leaders. The business experience of the Board has been crucial to not only running the company, but also to steering the process towards greater and greater business best practices. The AAPS governance model is successful and remains unchanged after nearly five years (see Figure 1). The Board membership has been adjusted to include TRIUMF member universities and key entrepreneurs in the high-tech physics sector. The AAPS organization supports about 8 FTEs at present.

Leveraging its network of partners, including governments, universities, national laboratories, and industry, AAPS fulfills the following strategic goals:

- Identify research outcomes that can be moved rapidly to commercialization in partnership with the private sector to generate profitable income streams within a reasonable time-period;
- Develop and maintain a portfolio of activities that generate revenue sufficient to support operations and selected investments;
- Provide increased opportunities for science, technology, and engineering personnel to work at the R&D interface, helping train the entrepreneurs of tomorrow; and
- Serve as a strategic advisor and resource for innovation and commercialization activities to increase opportunities for Canadian companies in the areas of natural resources, health, environment, and information and communications technologies.

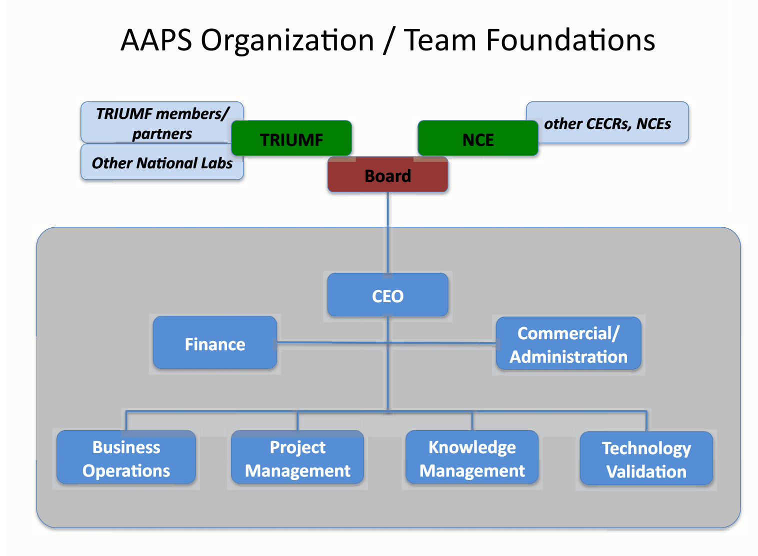

Figure 1: The AAPS governance model.

The AAPS business strategy uses a four-stage flow to manage technology development and commercialization.

- Applied Research. AAPS is involved in monitoring in this stage, but does not provide resources or investment. Applied research includes both technology-push (development on the bench) and technology-pull (market formulation and preliminary evaluation) activities.
- Proof of Principle. When a technology enters this stage, AAPS becomes more involved. Potential commercial partners are identified and consulted to assist in producing a prospective market analysis that identifies any sustainable differentiators and the value propositions. If these are compelling, AAPS will work with the principal proponents to prove the research can be productized. Opportunities to protect intellectual property are investigated and actions taken as required.

"EARTHLY" CT SCANS ATTRACTS FUNDING

01 April 2011

An ingenious idea that borrows techniques from medical imaging is looking for ore deposits deep in the earth. "Muon geotomography" is a technology initiated by Prof. Douglas Bryman, long-time TRIUMF scientist and the J.B. Warren Chair at the University of British Columbia. The technique uses an array of detectors deep underground to detect cosmic-ray muons. A grid of muon sensors work much like a CT scan and these sensors can map out in 3D regions of high density, where potentially valuable ore deposits could reside. This technique works as the underground muon flux picked up by the sensors is dependent on the density of the earth through which the muons pass.

Advanced Applied Physics Solutions Inc. (AAPS) completed a first round of proof-of-principle tests in collaboration with NVI-Breakwater, TRIUMF, the Geological Survey of Canada, and the BC Ministry of Energy and Mines. This project has enabled AAPS to attract $1.8 million in federal funding from the Western Economic Diversification office that will allow AAPS to develop and commercialize the technology.

- Development. A project moves into this phase when external partners are engaged with the goal to license technology or form a business venture. AAPS and the selected partner(s) work together to develop a profitable business plan. AAPS supplies, as required, the project and business-management expertise while the technology moves from prototype to pre-production versions.
- Commercialization. In this stage, AAPS continues to support the partner(s) while retaining either an equity or debt-instrument stake in the venture.

AAPS engages on a regular basis with its host, TRIUMF, to ensure that both parties are aware of major projects and initiatives, and that goals and operations are aligned. AAPS holds weekly project oversight meeting where all project managers attend and review project status including commercialization opportunities. Those TRIUMF group leaders that are involved in shared projects are invited to attend. These meetings ensure that adequate attention and resources are made available to keep projects on track and on budget.

A full discussion of AAPS, its corporate structure, and financial statement can be found in its annual reports. A strategic-planning session with the Board of Directors scheduled for September 2013 will generate a fresh roadmap for the organization and its support of TRIUMF's mission.

5.10.3 PARTNERSHIPS AND AGREEMENTS

TRIUMF's partnerships are shaped by formal agreements. These agreements not only facilitate TRIUMF's technical participation in certain private-sector consultations and development projects, but they also give TRIUMF expert informal advice on technologies, potential applications, and market forecasting. Formal agreements for collaboration with other academic-research organizations also add to TRIUMF's resources.

TRIUMF has arrangements with the following organizations for shared research and development activities. These agreements are reviewed on a regular basis and renewed, adjusted, or closed. Formal agreements allow TRIUMF to interact informally with key partners to seek advice on market trends, product-development trends, and overall commercial potential.

Canadian

- Advanced Cyclotron Systems, Inc.
- AECL, Inc.
- BC Cancer Agency
- BC Preclinical Research Consortium
- British Columbia Innovation Council
- Burnaby Board of Trade
- Canada Border Services Agency
- Canadian Association of Physicists
- Canadian Institute for Nuclear Physics
- Canadian Light Source, Inc.
- Canadian Mining Innovation Council
- Canadian Space Agency
- CANARIE
- Carleton University (CRIPT)
- Centre for Probe Development and Commercialization
- D-Pace, Inc.
- Defence R&D Canada (DRDC)
- General Electric
- Genome BC
- Geological Survey of Canada
- GPN Petroleum Technology, Ltd.
- IKOMED Technologies, Inc.
- Institute of Particle Physics
- International Safety Research, Inc.
- Jubilant-Draximage, Inc.
- Lawson Health Research Institute
- Nordion, Inc.
- NVI Mining Ltd.
- Pacific Parkinson's Research Centre
- PAVAC Industries, Inc.
- Perimeter Institute For Theoretical Physics
- Positron Emission Tomography Imaging at UBC
- Radiation Protection Bureau, Health Canada
- Science World British Columbia
- Selkirk College
- Shad Valley
- SNOLAB
- Teck Resources, Ltd.
- UBC Geophysical Inversion Facility
- University of Saskatchewan
- Vancouver Board of Trade

International

- Argonne National Laboratory, Argonne, USA
- Brookhaven National Laboratory, Upton, USA
- China Institute of Atomic Energy, China
- Chinese Tri-University Cluster, China
- Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany
- CERN, Geneva, Switzerland
- Fermi National Accelerator Laboratory, Batavia, USA
- GANIL, Caen, France
- GE Healthcare
- Gesellschaft für Schwerionenforschung mbH (GSI), Darmstadt, Germany
- High Energy Research Organization (KEK), Tsukuba, Japan
- Institut des Sciences Nucléaires (ISN), Grenoble, France
- Institute of Basic Science (IBS), Republic of Korea
- Institute for High-Energy Physics (IHEP), Beijing, China
- Institute for Nuclear Research (INR), Russia
- Inter-University Accelerator Centre (IUAC), Delhi, India
- International Atomic Energy Agency (IAEA), Vienna, Austria
- IsoTherapeutics Group, LLC, USA
- Istituto Nazionale di Fisica Nucleare (INFN), Italy
- Japan Atomic Energy Agency (JAEA), Tokai, Japan
- Japan Proton Accelerator Research Complex (J-PARC), Tokai, Japan
- Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
- Kavli Institute for the Physics and Mathematics of the Universe (IPMU), Kashiwa, Japan
- Korean Institute of Radiological and Medical Sciences, Korea
- Laboratori Nazionali di Frascati, Frascati, Italy
- Lantheus Medical Imaging, Inc.
- Lawrence Berkeley National Laboratory (LBL), Berkeley, USA
- Lawrence Livermore National Laboratory (LLNL), Livermore, USA
- Los Alamos National Laboratory (LANL), Los Alamos, USA
- Manhattan Isotope Technology, LLC, Lubbock, USA
- MEPhI (National Research Nuclear University), Moscow, Russia
- Ministry of Education, Science, and Technology (MEST), Seoul, Korea
- National Superconducting Cyclotron Laboratory (NSCL), East Lansing, USA
- Oak Ridge National Laboratory (ORNL), Oak Ridge, USA
- Osaka Graduate School of Science, Osaka, Japan
- Paul Scherrer Institut (PSI), Switzerland
- Rutherford Appleton Laboratory (RAL), UK
- RIKEN Nishina Centre for Accelerator-Based Science, Wako, Japan
- SLAC National Accelerator Laboratory, Menlo Park, USA
- SOREQ, Israel
- Thomas Jefferson National Accelerator Facility (JLab), Newport News, USA
- Toyota Central R&D Labs, Inc.
- University of Missouri Research Reactor (MURR), USA
- UT-Batelle, LLC, USA
- Variable Energy Cyclotron Centre, Kolkata, India

TRIUMF has amassed a good deal of technical expertise and experience that when leveraged with external partnerships offers an extraordinary set of innovation commercialization opportunities. Combined with the business and market expertise at AAPS, TRIUMF brings a lot to the table for Canada.

[1]For details, see http://www.ieeeghn.org/wiki/index.php/Milestones:First_500_MeV_Proton_Beam_from_the_TRIUMF_Cyclotron,_1974.