Chapter 5

Assets: Physical and Intellectual Capital

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5.1

Introduction

TRIUMF's many important achievements (see Chapter 4) over the last five-year period were enabled by public funding from the provincial and federal governments and through the judicious use of all available resources: financial, intellectual, and physical. Similarly, TRIUMF's plans for the next five-year period (see Chapter 6) will be enabled by future funding and by continuing to build on the foundation of the current resources described in this section. These resources are a culmination of more than $C1 billion of public investments over the past 40 years coupled with the wisdom and experience of a highly trained staff with, at present, over 300 members. Taken together, these resources represent a formidable asset that can be deployed on key areas of the nation's research agenda.

TRIUMF's resources are very diverse but can be classified as follows:

Intangible resources:

- University partnerships
- International partnerships
- Commercial partnerships

Tangible resources unique to TRIUMF:

- Technically qualified people (technologists): cyclotron operators, specialized technicians, scientific computer programmers, other technologists.
- Hardware and infrastructure design for specific physics experiments: the accelerator, beam lines, detectors, detector development facilities, and other hardware.

Tangible resources not unique to TRIUMF, but key to its operation:

- Ph.D. scientific staff
- Senior management and administration
- Administrative and other supporting staff

TRIUMF's most valuable resource is its connection to the universities (see Section 3.1). TRIUMF has been successful and will continue to be successful only to the extent that it engages the university community. One clear example of this success is the awarding of the Canadian Association of Physicists 2008 Brockhouse Medal to the University of British Columbia's J. Brewer for pioneering µSR at TRIUMF.

TRIUMF also benefits enormously from its international collaborations.

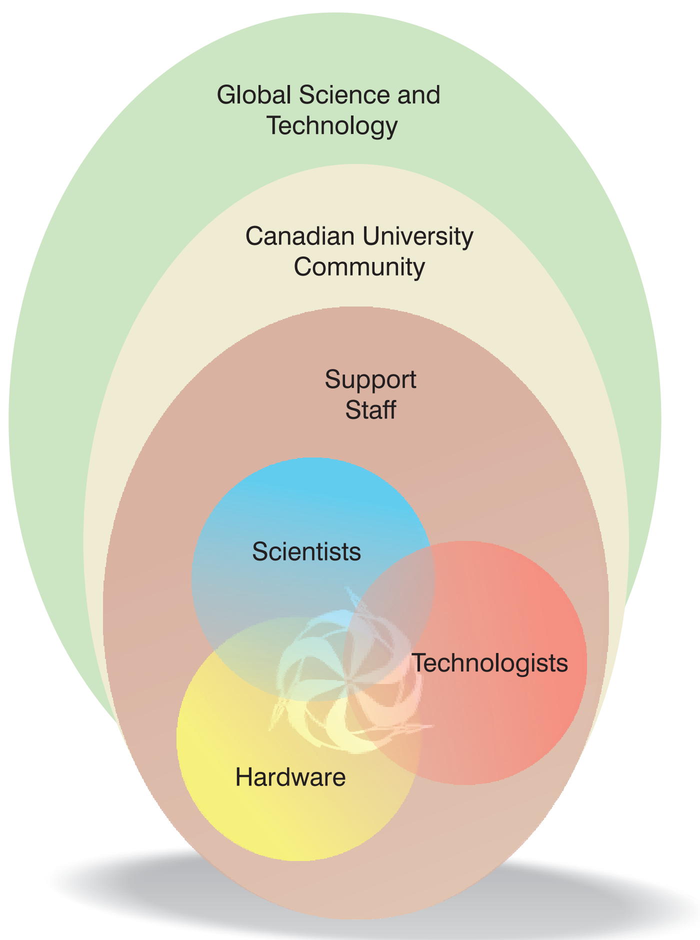


Figure 1: The yellow and red areas represent the TRIUMF unique resources (hardware and technologists), while the brown and blue areas represent the non-unique resources (scientists and support staff). The cream and green areas represent utilization of TRIUMF resources at the university and global levels.

TRIUMF's expertise, in areas like accelerator and detector development, is sought out by international collaborators who, in return, contribute their expertise to TRIUMF.

The collaboration with commercial enterprises also plays an important part in TRIUMF's success, providing TRIUMF with advanced technology. At the same time these collaborations allow Canadian companies to benefit from TRIUMF's accumulated expertise.

Section 5.2 discusses the highly skilled TRIUMF staff, which represents a key asset for Canada in the pursuit of national objectives in science, technology, and innovation. People provide the expertise to build, maintain, and operate TRIUMF facilities. TRIUMF's technologists have skills that simply are not available elsewhere in Canada and in some cases are very uncommon worldwide (see Figure 1). In addition to supporting the TRIUMF program, they are a unique resource for all Canada.

TRIUMF's scientific staff is not unique in the sense that universities also have scientists; however, the job description of a TRIUMF scientist is different from that of a university professor. The TRIUMF scientist can devote more of his or her time to research and has more knowledge of the other TRIUMF resources than outside users. They help set TRIUMF's priorities and provide a bridge between unique TRIUMF resources and the university community.

A comprehensive description of TRIUMF physical resources is given in Section.5.3, which details the accelerators, beam lines, detectors, and other facilities that are a part of TRIUMF. The facilities for the Centre for Molecular and Materials Science and for the Life Sciences program are given in the previous chapter in conjunction with their science results. TRIUMF has, on site, five cyclotrons (three operated for MDS Nordion), three linear accelerators, and a multitude of beam lines. Proton beams from the 500 MeV cyclotron are used to produce rare isotopes for ISAC and muons for the μSR program. The lower energy cyclotrons are used to produce rare isotopes for biological use. To use the particle beams, TRIUMF has many detector facilities; in ISAC-I alone there are six major detector facilities each with a dedicated beam line. There are another eight facilities for the μSR program. An overview of the TRIUMF site highlighting the different key areas of the program is shown in Figure 2.

Fundamental to the organizational success of TRIUMF's everyday operations are members of the senior administration and support staff. TRIUMF's structure for management and accountability is discussed in Section 5.4.

BEAM LINES AND EXPERIMENTAL FACILITIES

ISAC - I & ISAC - II EXPERIMENTAL HALLS

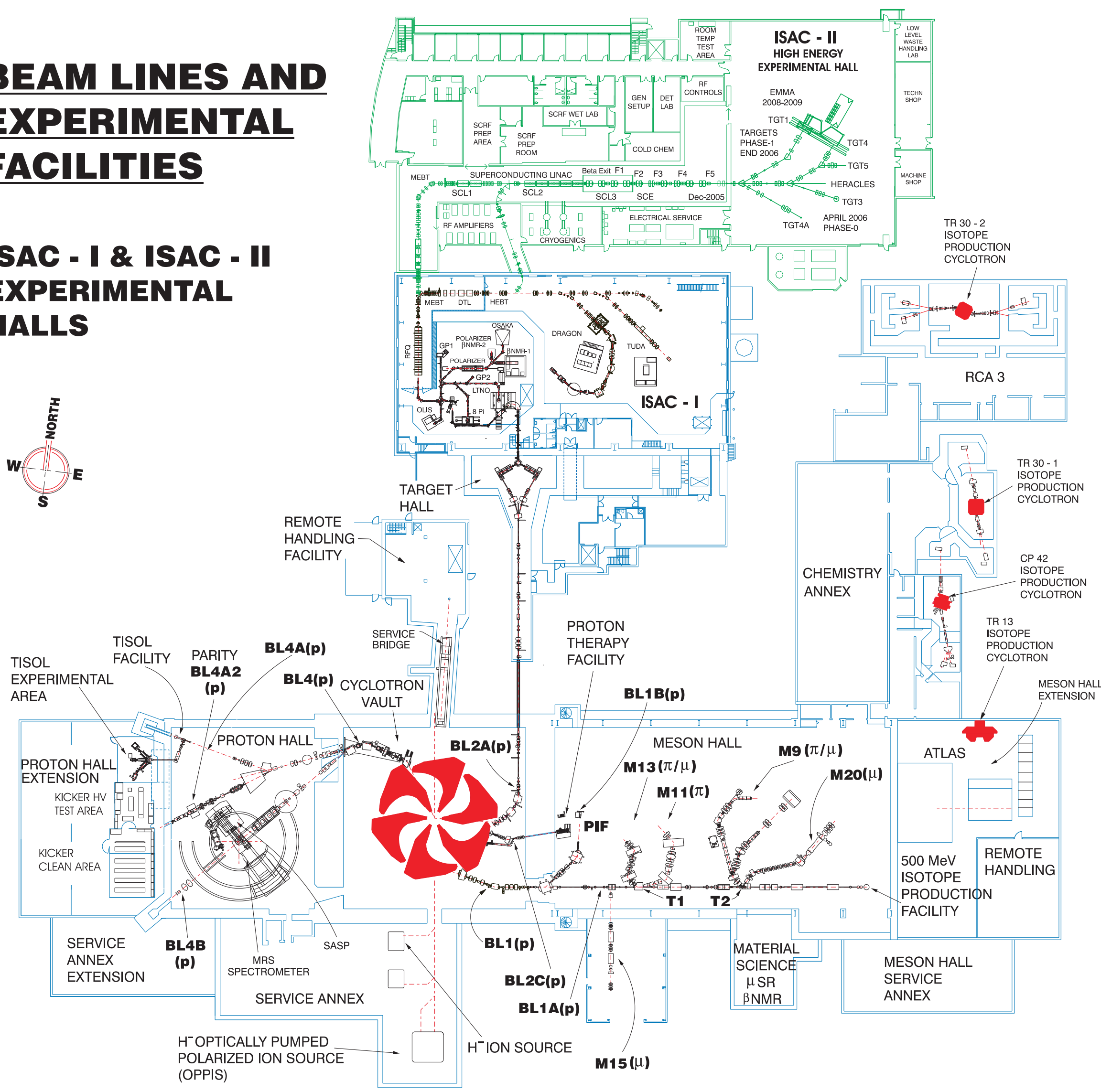


Figure 2. Schematic of the TRIUMF site showing the key experimental halls and resources. The cyclotron is the main engine of the laboratory. The ATLAS Canadian Tier-1 Data Centre is presently located in one of the power supply rooms of the ISAC-II building. The ISAC-II is outlined in green and was completed in the 2005-2010 five-year plan.

5.2

Expert Personnel

Over the 40 years of its existence, TRIUMF has assembled a core staff of approximately 350 people with a remarkably strong and diverse skill set. As Figure 1 illustrates, this skill set can be divided into four categories: scientific, engineering, technical, and support. The scientific staff, in collaboration with their university faculty colleagues, defines the scientific goals and manages the scientific challenges undertaken by the laboratory. The scientific, engineering, and technical staff provides the essential skills needed to undertake the extremely technical and complex tasks that allow TRIUMF to successfully achieve its goals and meet its challenges. The support staff provides a smoothly operating environment in which these goals will be met.

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 are resident at Canadian universities, strengthening both TRIUMF's and the universities' intellectual and scientific abilities. Scientists from Canadian universities and laboratories, as well as institutions from abroad, visit TRIUMF for periods ranging from a few days or weeks to a year. These visitors also add to TRIUMF's intellectual and scientific strength and diversity. The list below illustrates the skills of the scientific staff. These skills naturally match the core research areas of the laboratory as well as provide a key resource for technology transfer to Canadian industry.

- Accelerator Physicists
- Chemists
- Experimental Physicists

- Medical Scientists
- Molecular and Materials Scientists
- Theoretical Physicists

Engineering Staff

TRIUMF's engineering personnel are primarily qualified at the B.Sc. level, but they do have a diverse skill set ranging from high power radio-frequency engineers to specialists with unique skills in, for example, magnet design, and construction. About one-third of the engineering staff are resident at Canadian universities. This situation strengthens both TRIUMF's and the universities' intellectual and scientific abilities, especially in the area of detector modeling and design.

- Accelerator Engineers
- Electrical Engineers
- Mechanical Engineers

Technical Staff

Technical personnel represent 65% of TRIUMF's core staff. TRIUMF's technicians, many of whom hold M.Sc. degrees or other technical degrees, are highly trained personnel with unique skills (see list below). This extensive and

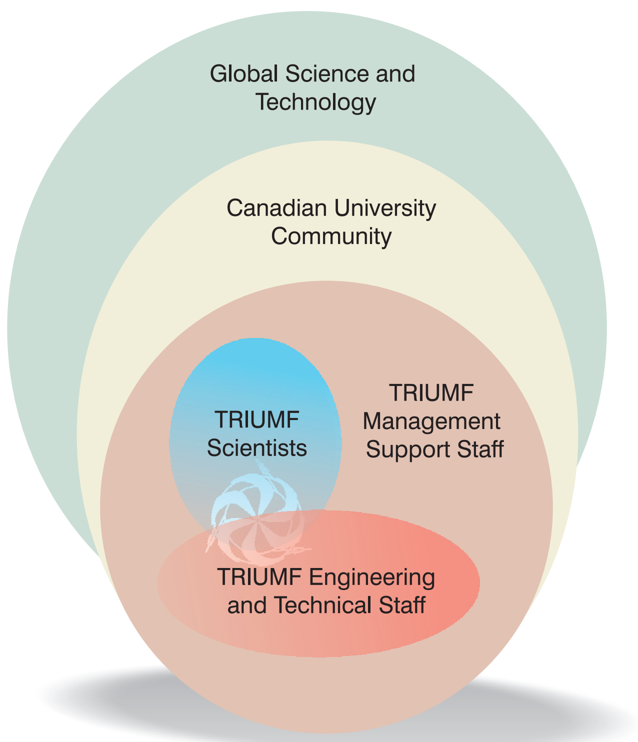


Figure 1: Simplified view of TRIUMF staff and the larger context.

diverse skill set allows technicians to operate effectively with TRIUMF's scientific staff and the university community.

TRIUMF technicians perform the extremely complex technical tasks required to successfully achieve the scientific goals of the laboratory, whether at the TRIUMF site, at other laboratories or institutions in Canada, or at laboratories abroad. Our technicians maintain, operate, and upgrade TRIUMF's infrastructure, which has a replacement value of approximately $C1 billion.

In addition to their responsibilities to the TRIUMF infrastructure and scientific program, TRIUMF's technicians are also responsible for the smooth and safe operation of the cyclotrons that produce medical isotopes for MDS Nordion Inc. TRIUMF technicians are integral to providing the BC Cancer Agency with isotopes used for clinical diagnostics and treatment as well as producing isotopes for the TRIUMF/UBC PET Centre for the study and treatment of Parkinson's disease and other neurological diseases.

The TRIUMF technical staff has also contributed their unique skills and talents to international collaborations. For example, at CERN in Geneva they have contributed to the construction of magnets, kickers, and control systems for the Large Hadron Collider accelerator system. Similarly, high power targets have been provided by TRIUMF to J-PARC in Japan. These contributions from the TRIUMF staff are highly valued by the international community and facilitate the participation of Canadian scientists in international experiments.

- Accelerator Operations
- Beam Lines
- Chemistry
- Controls Electronics and Software
- 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
- Technology Transfer

Support Staff

The TRIUMF's small but effective support staff, which makes up 19% of the total staff, provides and maintains the administrative infrastructure necessary for the efficient operation of the laboratory in several areas.

- Accounting
- Administration
- Human Resources
- Machine Shop
- Physical Plant
- Plant Engineers
- Purchasing
- Shipping and Receiving
- Senior Management
- Stores
- TRIUMF House Operations and Management

5.3

Accelerators and Experimental Facilities

5.3.1

Beam Lines and Beam Production

5.3.1.1

Main Cyclotron and Proton Beam Lines

Introduction

At the heart of TRIUMF is the 500 MeV cyclotron that produces the primary proton beams. A large fraction of the TRIUMF program relies on these beams. These include the ISAC, the Centre for Molecular and Materials Science programs in μSR and βNMR, 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 500 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 60 m to the cyclotron. The 500 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, or removes, 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 success of TRIUMF's programs depends on the ability to deliver protons from the cyclotron reliably. Typically, the cyclotron, although over 30 years old, averages an uptime of greater than 90% (2000–2007), with the 15-year average just under 90% (see Figure 2).

Typically the beam is delivered for about 5,000 hours per year with one major (three month) and one minor (one month) 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%.

The Four Primary Proton Beam Lines

TRIUMF has four independent extraction probes with various sizes of foils to provide protons simultaneously to up to four beam lines. Because of the high

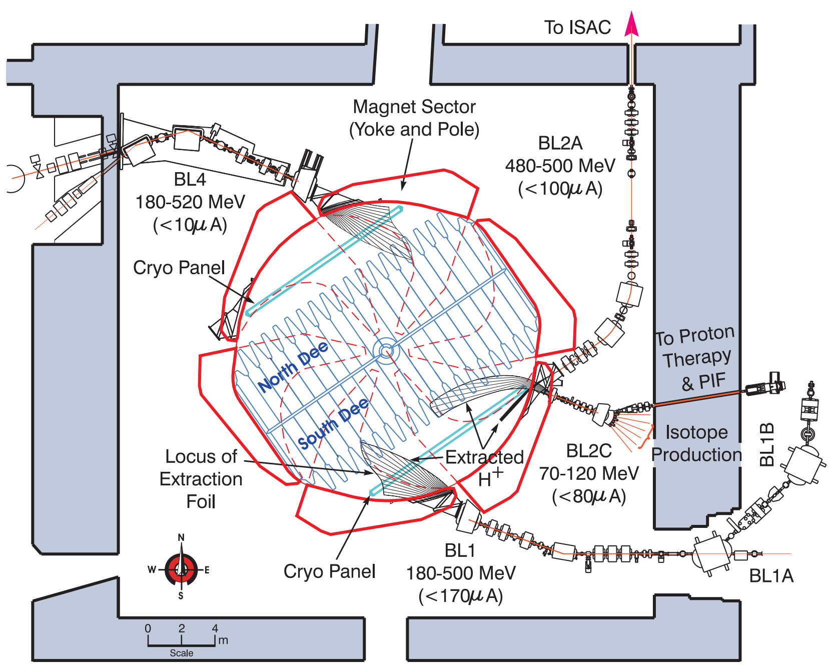


Figure 1: 500 MeV cyclotron and four primary proton beam lines: BL1, BL2A, BL2C, and BL4.

energy of the proton beam, these beam lines use magnetic rather than electrostatic focusing and steering elements.

Beam line 1A (BL1A) (see Figure 3) can deliver 180 to 500 MeV protons to two target systems. The beam power ranges from 50 to 75 kW. The first target, T1, services three experimental channels, one of which is used for detector tests for the T2K (Tokai to Kamioka) project. The second target, T2, services two μSR experimental channels. Downstream of T2 is a 500 MeV facility used to produce strontium isotopes for medical-imaging generators as well as the Thermal 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.

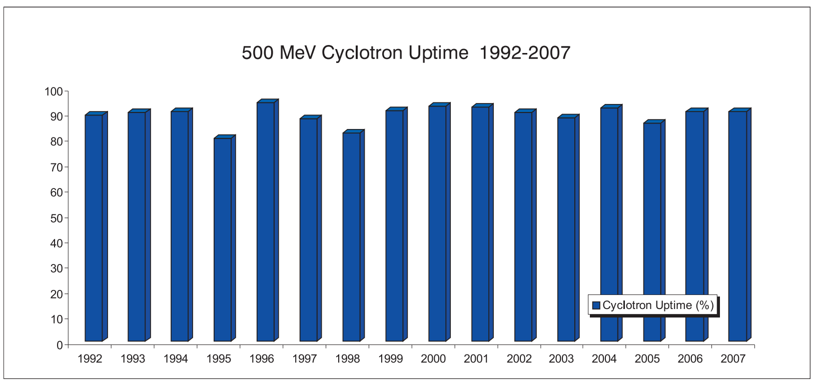


Figure 2: Cyclotron uptime as a percentage of scheduled operational hours per year.

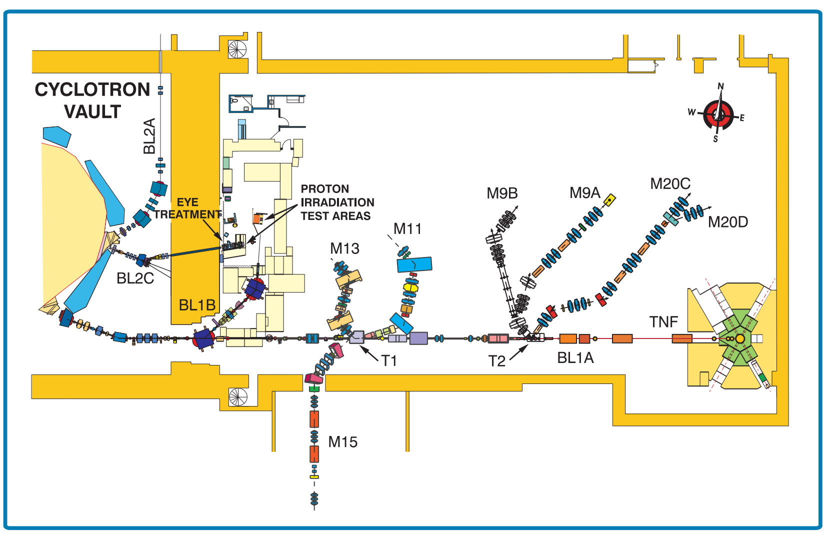


Figure 3: Schematic of BL1A, BL1B, and BL2C. BL4 is on the west side of the vault.

Beam Line 2A (BL2A) is capable of providing 475 to 500 MeV proton beams at up to 50 kW to the ISAC target facility that 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) and 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. The energy range for this line is 70 to 120 MeV.

Figure 4 shows the percentage of beam delivered as a fraction of the amount of charge scheduled for BL1A. The 15-year average is 95%, although the cyclotron uptime during this period averages about 90%. Similar beam delivery efficiency is available for the ISAC facilities from BL2A.

Beam line 4 (BL4) in its present configuration can 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. Other significant experiments on this beam line include charge symmetry breaking and TISOL, the TRIUMF Isotope Separator On-Line, the predecessor to the ISAC facility. An extension of this line, Beam Line 4 North (BL4N), will be used for the proposed ISAC expansion.

Summary

The 500 MeV cyclotron delivers four simultaneous proton beams for both production and test purposes. The total mAh charge has increased annually 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 (see Figure 5). The total charge delivered in 2007 was reduced by approximately 80 to 100 mAh due to the upgrade and recommissioning activities at the BL2C solid target facility. The total charge to BL2A (green) for ISAC has more than doubled in the past four years.

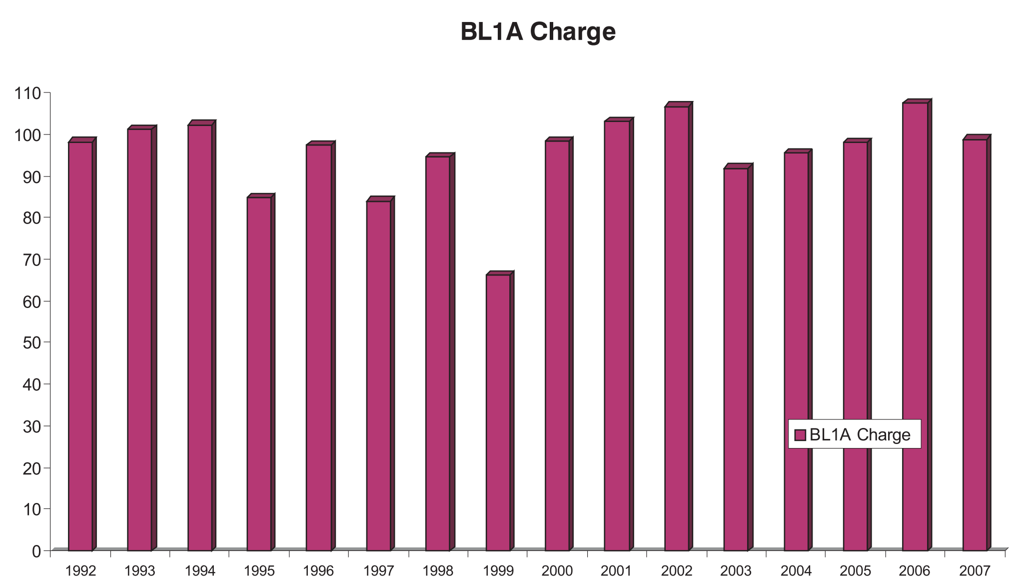


Figure 4: Beam delivered to BL1A as a percentage of charge scheduled per year.

Accelerator operation is proposed to expand in the 2010-2015 period to support new initiatives. The cyclotron intensity upgrade will allow increasing the extracted beam current to 300 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. 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.

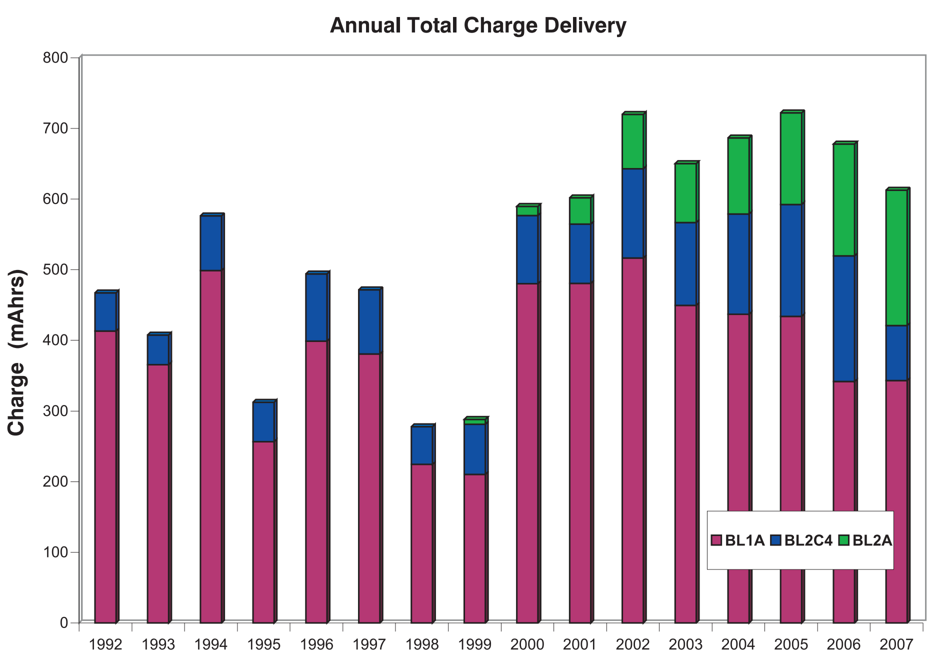


Figure 5: Total annual proton charge (mAh) delivered to three beam lines.

5.3.1.2

ISAC Target and Ion Sources Development

Introduction

The TRIUMF Isotope Separator and Accelerator (ISAC) facility 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 nucleus 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 to form an ion beam that can be separated by mass and then guided to the experimental facilities.

When ISAC was launched in its first phase (ISAC-I), existing on-line target designs could only accommodate up to 2 μA incident proton beam intensities. From 2003–2008, TRIUMF developed techniques that allow operation of the ISOL target up to 100 μA at 500 MeV. Among the techniques developed, were a high-power target that is equipped with radial fins that can dissipate up to 20 kW and composite targets that allow a larger variety of target material, which in turn allowed the production of a larger variety of intense beams of rare isotopes.

The overall release efficiency (diffusion and effusion) depends strongly on the operating temperature of the target material. For this reason, ISAC uses mainly refractory, or high-temperature, metals such as Ta, Nb, and carbide foils for the target material. The development of composite carbide target is a breakthrough that permits the ISAC facility to produce rare isotopes with a larger target material inventory thus allowing us to produce intense rare isotope beams. The composite carbide target presently operates routinely at an intensity of 70 μA.

Because ISAC operates uniquely at very high proton intensity (beam currents), the development of the ion source in such an environment is a challenge. The hot surface ion source was the first ion source implemented at ISAC, followed by an electron cyclotron resonance (ECR) ion source, resonant laser ion source (TRILIS), and a forced electron beam ion arc discharge (FEBIAD) ion source. Because of the gas load from the target, the first ECRIS had very low ionization efficiency; a new type of ECRIS with improved electron confinement is under prototyping. The ISAC-II accelerator requires the injection of ion beam with higher charge-to-mass ratio to extend the mass range from $A \leq 30$ to 150. To do this, TRIUMF have developed a charge-state

Figure 1. The ISAC target containers. The top photograph shows the normal target container that can dissipate up to 5 kW of proton beam power. The bottom photograph shows the high power version that can dissipate up to 20 kW of proton beam power.

booster (CSB) based on an ECR ion source. The device has been tested off-line, and TRIUMF is in the installation phase for on-line production during the summer 2008.

Off-line ion sources play an important role at ISAC because they are used to provide pilot beams for the accelerator tuning and for experiments. From 2003–2008, TRIUMF installed three types of ion source, which allow us to cover most of the periodic table. A new ECR ion source (SUPERNANOGAN from Pantechnik S.A.) is being installed, and it will improve the stable beam delivery by increasing the intensity and reliability of available stable beams.

Finally, polarized beams are being developed using a special facility. These polarized beams will be used for molecular and materials science experiments and nuclear physics research.

ISAC Production Targets

The major focus of target development at ISAC from 2003–2008 has centred on increasing operational p^+ intensity on targets by investigating high power target designs capable of using the full 50 kW of p^+ beam power available and developing composite foil target materials of high thermal conductivity to allow for higher p^+ currents on compound target materials such as SiC, TiC, ZrC and Nb_5Si_3 (see Figure 1).

ISAC High Power Targets

The high power target (HPT) design was developed by diffusion bonding radial Ta fins onto the standard ISAC target container. This surface modification increases the effective emissivity of the target surface from about 0.34 to 0.92 (a black body = 1.00) resulting in an increased radiative-power dissipation capacity. The HPT design was tested off-line between 2001 and 2003, and the first HPT was commissioned on-line in 2004. Since that time, HPTs of Ta metal foils and composite foil compound targets have been routinely operated with p^+ currents of up to 70 µA, double the intensity of standard ISAC target containers. During 2006, a HPT using Ta foil was operated at 100 µA intensity, the design limit of ISAC.

Composite Target Materials

Many rare-isotope beams are best produced from reactions on elements that do not withstand high temperatures. In such cases, refractory compounds of the elements in question (such as carbides, oxides, nitrides or borides) may exist that can be used as target materials. Initially, ISAC targets made of materials such as CaO and SiC were fabricated by pressing powders into pellets of ≤ 60% density. Due to the reduced thermal conductivity across the porous pellet and the poor thermal transfer between pellet rim and inner target container wall, the operational limit on p^+ intensity for SiC targets was ≤ 15 µA and ≤ 3 µA for CaO. To increase both internal heat transfer and to provide better thermal transfer to the target container, composite foil target forms of carbide ceramics were developed that mimicked the refractory (high-temperature) metal-foil target materials.

The composite foil fabrication starts with the desired carbide powders that are intimately mixed in a plenary ball mill with ~11% organic binders, plasticizers, and surfactants in either aqueous or non-aqueous solvents. The resultant slurry is slip cast onto sheets of flexible exfoliated graphite foil (0.13

mm thick). After solvent evaporation, the result is a flexible thin (~ 0.25 mm) layer of ceramic bonded to graphite foil. In the "green" form, the composite form can be cut to shape and inserted into the target container in a manner analogous to metal foils. The composite foils are cut slightly oversize to ensure good thermal contact with the target container wall, and the organic components are subsequently burned off during off-line sintering and conditioning of the target prior to irradiation. Ceramic layer densities of 50 to 60%, which are equivalent to what was previously achieved with pellet target forms, are routine. The thermal conductivity of the composite foils is a function of both the thermal conductivities of ceramic and graphite layers, and the high thermal conductivity of the graphite component allows increased beam power transfer.

With composite foils, the maximum p^+ current on SiC targets was increased to 35 µA. By using composite carbide/graphite forms of SiC, TiC, and ZrC in ISAC HPT containers, the operational limits of these materials have been increased to 70 µA. Table 1 shows an example of the combined development of the target material, target container, and ion source to deliver the required intensity for key experiments. In 2006, the technique was extended to a silicide ceramic when a composite target of Nb5Si3 bonded to 0.076 mm Nb metal foil was commissioned to 15 µA. The ongoing development of oxide/metal composites has seen the achievement of successful bonding of Al_2O_3 to Nb.

Isotope	Composite Graphite Target Material	Maximum Operating Current	Delivered Rate
^{26}gAl	SiC pellets	15 µA p^+	7.7 x 108/s
^{26}gAl	SiC/C_{gr} composite foils	35 µA p^+	3.8 x 109/s
^{26}gAl	SiC/C_{gr} composite foils in high power target	70 µA p^+	1.1 x 1010/s
^{26}gAl	SiC/C_{gr} composite foils in high power target with laser ionization	70 µA p^+	5.1 x 1010/s
^{62}Ga	ZrC/C_{gr} composite foils	35 µA p^+	2.9 x 102/s
^{62}Ga	ZrC/C_{gr} composite foils with laser ionization	35 µA p^+	9.6 x 103/s

Table 1: Beams developed using a combination of target and ion source development.

On-Line Ion Source

The on-line ion source is the set of systems used to extract and provide the rare isotopes produced in the target.

Hot-Surface Ion Source (SIS)

The hot-surface ion source was the first on-line ion source used at ISAC. Because of its simplicity, it has been the easiest ion source to use in the new high-radiation environment. The principle is quite simple, a high work function material such as Re is inserted into the transfer tube from the target container, which is operating at a high temperature of 2200ºC. The atoms with low ionization potential, such as alkali, are ionized with high ionization efficiency. It increases with the *Z* of the atom to reach nearly 100% for Cs and Fr.

Resonant Laser Ion Source

The second ion source that was installed on-line was the laser ion source (LIS). The principle of the LIS is the following: laser beams, usually three, enter into the transfer tube through a laser port in the pre-separator magnet. The laser beam pulses are synchronized to arrive at the same time in the ionization

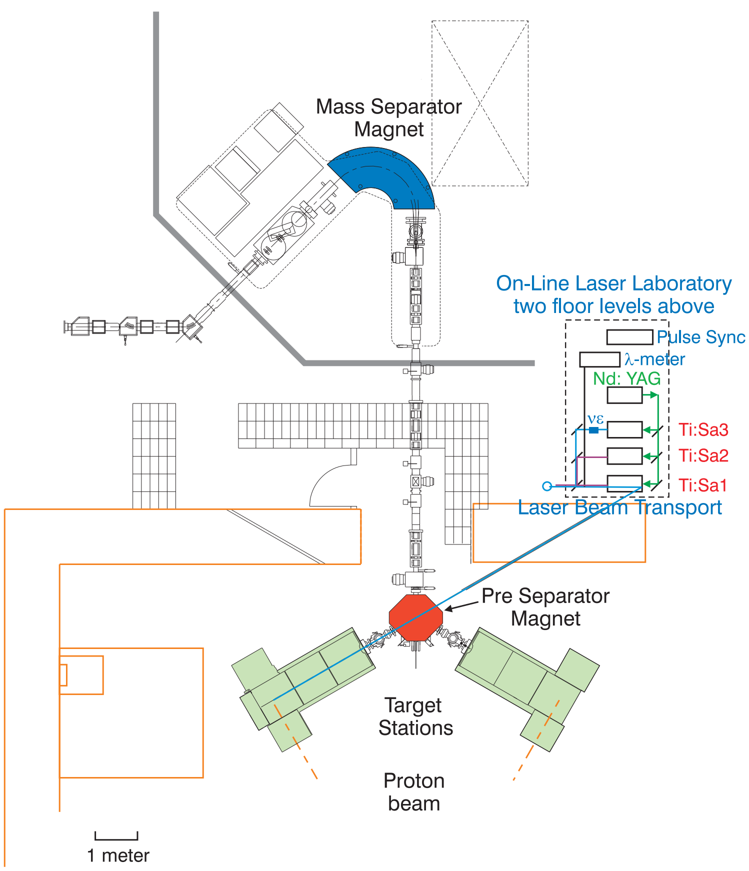


Figure 2: Layout of the mass separator showing the laser beams transport to the target transfer tube.

region. The repetition rate is such that each atom drifting inside the transfer tube sees at least one pulse of each laser beam. Such a resonant laser ion source operates by exciting an electron of a particular atom in multiple steps through a series of energy levels above the ionization potential. It is highly selective, in that resonant laser ionization only operates on a particular chemical element, which results in rare-isotope beams with minimal contamination.

The laser ion source utilizes the same hardware as the surface ion source. The laser beams are produced far from the high radiation environment of the target. Thus, the critical components of the ion source can be far removed from the high radiation area of the isotope production, allowing for ready access and serviceability while avoiding radiation damage to critical source components and minimizing the amount of material irradiated. The laser ion source is, therefore, ideal for on-line radioactive isotope production (see Figure 2).

In 2002, TRIUMF began developing a selective and efficient laser ion source for ISAC to expand the ISAC ion beams capabilities. The lab decided to employ state-of-the-art, all solid-state laser systems for a compact, low maintenance, high uptime laser ion source.

For a majority of elements, TiSa laser-based excitation schemes have been developed conceptually and are under investigation experimentally. By 2009, an independent LIS test stand for the development of laser ionization schemes will be operational. This test stand will allow direct transfer of developed ionization schemes to on-line production and facilitate rapid laser spectroscopy and development.

Overall, TiSa laser-based ionization scheme development is a collaborative effort within the TiSa network among several TRIUMF partners, including Mainz University in Germany, Oak Ridge National Laboratory in the United States, and the JYFL Laboratory in Finland. The success of the TRIUMF Laser Ion Source (TRILIS) as the only on-line, all-solid-state laser-based laser ion source is the basis for similar projects at GANIL in France as well as ORNL and JYFL. In our collaboration with Mainz University, TiSa lasers and laser applications for on-line facilities are continually being developed.

Plasma Ion Sources

For the elements that have a high ionization potential, such as He, B, C, N, O, F, Ne, etc., a surface or a laser ion source cannot be used. For those elements, we need to use a so-called plasma ion source. In this source, the plasma is generated using fast electrons that can be either produced by a forced electron beam induced arc discharge (FEBIAD), *i.e.*, a hot cathode or by an electron cyclotron resonant (ECR), a radio-frequency induced discharge ion source. Between 2003 and 2008, TRIUMF has been developing a FEBIAD ion source for the production of intense ^{18}F beams and a new generation of ECR ion source for on-line application.

FEBIAD Ion Source

TRIUMF has developed a FEBIAD to produce the F and Ne isotopes necessary for the nuclear astrophysics study of the proton capture reactions ^{18}F(p, γ) and ^{18}Ne(p, γ). The design is a combination of the Kirchner and Sundell FEBIAD types that were developed at GSI and CERN [R. Kirchner and E. Roeckl, Nucl. Instrum. and Methods 133, 187-204 (1976); and S. Sundell *et al.*, Nucl. Instrum. and Methods B70, 160-164 (1992)]. It is a very compact version that can be housed into the same volume as the usual ISAC target/ion source heat shield. The biggest challenge in designing any ion source for the ISAC facility is the extremely high radiation field produced at high proton intensity. It is very difficult to predict the behaviour of insulator material in such a harsh environment. For this reason, the prototypes were tested off-line.

In November 2006, the first prototype was installed on-line using a composite TiC/$C_{graphite}$ target. The main goal was to test the behaviour of the ion source under real conditions. Therefore, we operated the TiC target up to its maximum proton beam intensity, 70 μA. We produced several isotopes from ^{6}He to ^{45}Ar and demonstrated that the cathode, which is the weakest part of the ion source, could operate reliably for at least three weeks. During the test, we noticed a quick degradation of one of the insulators made from boron nitrite.

A modification of the insulators was made, and a second prototype was tested on-line in June 2007. This time, the ion source was combined with a high power composite SiC/$C_{graphite}$ target that was operated up to 70 μA proton intensity. During this development run, we produced $^{18}F^{+}$ for a ^{18}F(p,γ) measurement. In addition, the out gassing of the insulator was reduced, but the ionization efficiency decreased with time. Insufficient cooling of the magnets, which caused the axial magnetic field to degrade with time, caused this problem. The present prototype incorporates several up-grades: a radiation resistant electromagnet, a solid Ta grid to replace the W wires, and a water-cooled heat shield to protect the insulators. The electromagnet is made of a 6 mm x 6 mm copper conductor, insulated using the same fibrous material we used for the MISTIC ion source (see below). Calculation shows that, with 100 A and 16 turns coil, we can produce a 400 Gauss magnetic field in the centre of the plasma chamber. We have modified our design of the grid. This new grid is made from 1 mm thick Ta foil, and the slots are machined using a computer-controlled machine (see Figure 3). The grid transparency is 75%. A thick steel plate directly attached to a water-cooled copper plate is placed between the high power target and the FEBIAD ion source.

On-line tests during November 2007 were conducted using another high power SiC/$C_{graphite}$ target. The FEBIAD ion source produced 5.9 x 10^{7} $^{18}F^{+}$ per second, and the beam was used by the TUDA group for the ^{18}F(p,γ) radiative proton capture experiment. During that development run, we also produced ^{8}He for the high accuracy mass measurement with the new TITAN facility.

ECR Ion Source (MISTIC)

The demand for isotopes for the nuclear astrophysics program means that TRIUMF must be able to ionize, with high efficiency, the gaseous elements, C, N, O, F, Ne. These elements are ionized efficiently with an electron cyclotron resonance ion source (ECRIS).

An early version of an ECRIS operating at 2.45 GHz was first tested with stable beams in ISAC in the summer of 2002. In 2003 and 2004, we discovered that, during subsequent tests with various modifications to improve the performance, the pressure required to operate the ion source was not compatible with on-line operation. As a result, we started a different ECRIS approach that should be able to operate on-line under the nominal pressure from the heated target. After the initial test in 2007, with stable beams and on an ion source test stand, we decided to improve four aspects: the electron confinement, increasing the frequency from 4 to 8 GHz, lowering the gas pressure, and using a movable extraction electrode.

Collaboration between TRIUMF and GANIL allowed an engineer from GANIL to spend 18 months at TRIUMF working on the design and fabrication of a new ECRIS taking into account these specifications.

To improve the electron confinement, we used a design similar to the ECRIS MONOBOB developed at GANIL, where four permanent magnet rings produce the required magnetic field distribution. The design was modified because we could not use permanent magnets due to the high radiation level at the target. Instead, we used two symmetric pairs of coils surrounded by a ferromagnetic structure to produce the same magnetic field as MONOBOB's for axial and radial magnetic field confinements. The coils are made from hollow copper conductors for water cooling. They are wrapped with radiation-resistant glass insulation. When operating the coils at 600 A for one pair and -600 A for the other pair, the magnetic field has an axial symmetry, and the last closed equipotential field surface is at 0.4 T.

The new ECR ion source test stand is equipped with four 1,000 A-15 V independent power supplies supply and an analogue broadband signal generator in conjunction with a 500 W RF amplifier. The RF signal is transported into the ion source via a coaxial cable coupled to a coaxial antenna.

From the first tests, it appears that the ECRIS is very stable over a large range of frequency, pressure, and magnetic field. The plasma is very easy to ignite, even at pressures as low as 2.6 x 10^{-6} mbar. A quartz chamber has been

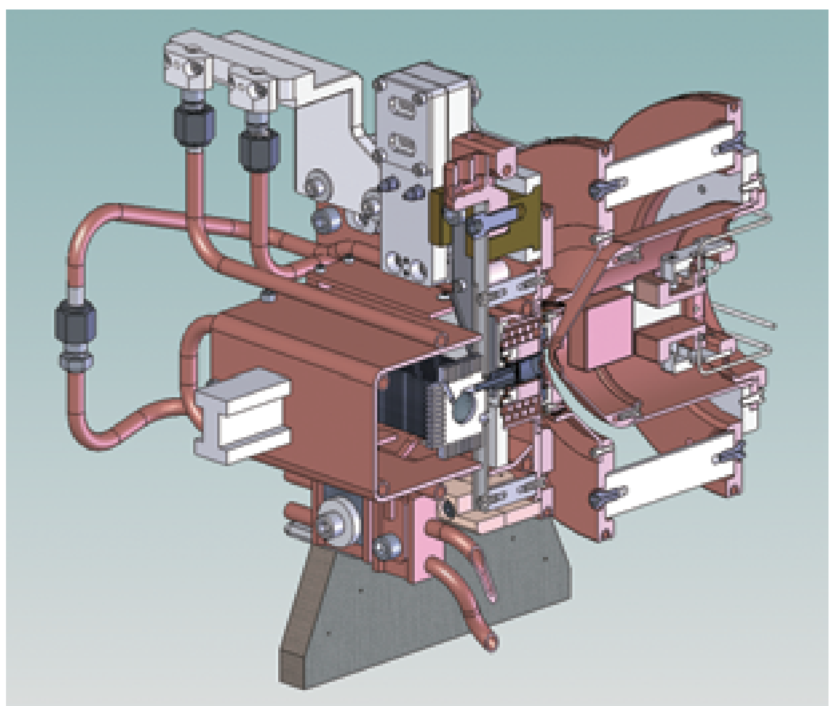


Figure 3: A section view of the FEBIAD ion source. The target is located on the left. The transfer tube is connected directly to the target and also acts as the hollow cathode.

manufactured that will allow us to bias the plasma at high voltage while the magnet coils and the steel yoke are at ground potential.

The extraction system is an adjustable, three-electrode system equipped with an Einzel lens. The objectives for 2008 are to determine the best operating conditions for this source, which will allow us to specify the next ECRIS target module. The design and fabrication of this target module will then be undertaken.

Off-Line Ion Source and Upgrade: OLIS

Until 2002, the off-line ion source (OLIS) terminal employed a microwave-driven ion source and provided charge +1 beams from gaseous elements up to 58 kV. In 2002, the microwave ion source was upgraded (OLIS upgrade I) with the incorporation of two ovens (0–1200 °C) and a sputtering system. This upgrade enabled the OLIS to provide ISAC with beams from liquid and solid elements.

OLIS upgrade II has started with the addition of a "Y" box, which enables us to add two more ion sources to the system. A surface ion source is installed onto the left port of the "Y" box while the microwave ion source is mounted to the right side of the "Y" box. The surface ion source is equipped with an ionizing chamber and three ovens. The three ovens give the flexibility to run three different temperature regions simultaneously: 25–600 °C, 600–1200 °C, 1200–2000 °C, to provide low-energy spread beams from alkali and semi-alkali elements.

In 2005, a hybrid, surface-arc, discharge ion source was developed to meet specific ISAC needs. This ion source produces 10^3 times less impurities for specific beams. These sources provide a variety of beams to ISAC experiments, for commissioning the accelerators, for setting up the radioactive experiments, and for tuning the beam lines.

In 2007, the OLIS high-voltage cage was modified to add a multi-charge ion source to increase ISAC's stable beam production above mass 30. The multi-charge ion source SUPERNANOGAN, purchased from Pantechnik, arrived in March 2007 and mapping of the magnetic field of the source was finished by the end of April 2007. It will be installed in the OLIS HV cage as a third independent ion source, which will go up to 30 kV extraction. The present two ion sources will keep performing up to 65 kV for charge +1 and +2 requirements. The concept of the design was completed, and detailed design work started in mid-December 2007. After installation of this multicharge ion source, OLIS will be able to provide beams of all stable elements to ISAC as pilot beams for highly charged ions from the CSB or directly for experiments.

Charge-State Booster: CSB

The ISAC ion sources are producing mainly singly charged ions. The front-end radio-frequency quadrupole (RFQ) can only accept mass-to-charge ratio less than 30. At ISAC, the beam delivery of masses greater than 30 requires the use of highly charged ions. The conversion of singly charged ions, which are normally emitted from the on-line ion sources into highly charged ones, has been investigated at TRIUMF over the past four years.

An ECR ion source (ECRIS), the 14.5 GHz Phoenix, was purchased from Pantechnik in France, in 2003. To determine the optimum operation parameters suitable for ISAC, it has been installed as an extension of the ion source test stand (ISTS) so that singly charged ions could be injected. The source and the analyzing beam line were commissioned with gaseous ions directly emitted from the source. A combination of a magnetic and two electrostatic sector fields was used to analyze the beam coming from the ECRIS. This combination proved to be very useful because it cleaned up the beam from scattered or charge exchanged ions and allowed the detection of weak beams.

Singly charged ions have been injected from ion sources similar to those used on-line at ISAC. Additionally, a small test surface ion source for Cs ions has been used. Source parameters for the breeding of highly charged ions have been optimized. Both the ion optics for the injection and the extraction have been changed from the original design from Pantechnik to adapt to the special needs at ISAC, mainly the possibility to operate at different extraction voltages. Efficiency, charge-state distributions, and breeding times have been determined as function of source parameters for different elements (see Table 2).

Element	Mass	Charge state with maximum efficiency (A/Q)	Efficiency (%)	Rise time (90%) for charge state with maximum efficiency (ms)	Charge 1+ ion source
Ar	40	8+ (5)	5.5	102	ECRIS
Kr	84	12+ (7)	6.3	401	ECRIS
Xe	129	17+ (7.6)	4.8	432	ECRIS
K	39	9+ (4.3)	2.1		surface
Rb	85/87	13+ (6.5)	3	230	surface
Cs	133	20+ (6.7)	3.5	300	surface + test source

Table 2: Efficiency, maximum charge state, and breeding time for different ion charges bred with the Phoenix source at the ion source test stand.

Figure 4 shows a plan view of the charge-state booster in the mass separator room. The singly charged ions will be reflected out of the existing beam line with a movable electrostatic bender into the charge booster beam line. The highly charged ions produced will be separated with a combination of a magnetic and two electrostatic sector fields. Eventually, they will be brought back into the existing beam line by an additional movable electrostatic bender. The installation in the ISAC mass separator room will be carried out in the winter shut down period of 2008, and first results on charge bred radioactive ions are expected by 2009.

The efficiency for transporting the highly charged ions from the source to the accelerator is limited by the charge exchange with residual gas molecules in the beam lines. The cross sections for this process will determine the requirements on the vacuum for a given length. Very little data on these cross sections in the energy range of the ion the source are available in literature. Therefore measurements have been performed with highly charged Rb and Cs ions at 10 and 15 q keV in O_2 and N_2. In contrast to extrapolations from low charged ions, no significant dependence on the ionization energy of the gas could be found for charge states above 10+. Within an estimated accuracy of about 30%, the dependence on the charge state q can be described by a simple linear function as

$$\sigma = (6.58\times10^{-19} + 1.01\times10^{-19} \times q)\ \mathrm{m}^2.$$

At ISAC, the distance to transport the ions from the CSB to the RFQ is about 25 m. This transport would result in a 20% beam loss for the transport of ions with charge state 20 at an average pressure of 1×10^{-7} Torr.

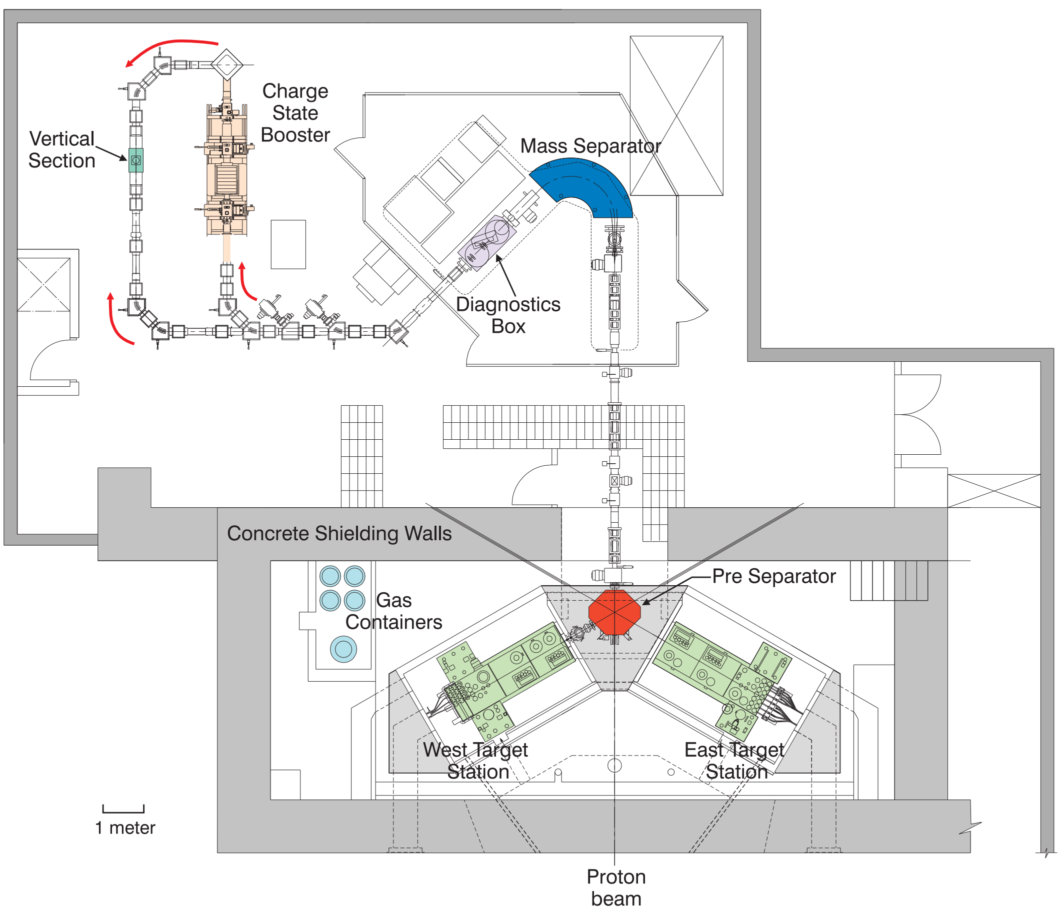


Figure 4: Plan view of the target station hall and mass separator. The Charge State Booster is installed in the mass separator pit just after the mass separator. A switchyard will bring the beam to the booster, if needed. Otherwise, it will go straight to the vertical section to be delivered to the experiment.

Polarizer

The ISAC polarizer is a facility in which the alkali isotopes ^{8,9,11}Li and ^{20,21,26,28,29}Na have been nuclear-spin polarized in flight by optical pumping with collinear laser light. The polarized ions are implanted into a target and the ensuing β-decay spatial asymmetry detected as a function of time or other experimental variable. This powerful experimental tool has been used at ISAC to study thin films in condensed matter, fundamental symmetries, and nuclear structure.

Alkali-metal beams are relatively easy to polarize, using neutralization and re-ionization steps to access the neutral atom and its loosely held valence electron. The polarizer has been further developed to polarize elements that have paramagnetic ions, where the nuclear polarization is easily destroyed in transit to the experiment by precession of the total angular momentum in the Earth's magnetic field. The simple solution was to add a guide field between the polarizer and the experiment that extends the east-west direction of the guide field in the polarizer. Polarized ^{11}Be will be provided to the condensed matter β-NMR program. It is a spin half isotope, which has no electric quadrupole moment, unlike the spin 2 ^{8}Li in use by the condensed matter group up to now. Polarized Be production has also required frequency doubling of the laser light into the ultraviolet. We have demonstrated the feasibility of polarizing fluorine beams, motivated by the interest shown by a group led by Osaka University in Japan.

Partners

The work on the CSB has been performed in a collaboration with the Laboratoire de Physique Subatomique et de Cosmologie, in France. Work on MISTIC was performed in collaboration with GANIL in France.

TRIUMF's Role

The beam development and targetry group is a core resource at the laboratory; all researchers using exotic beams rely on this expertise and equipment.

5.3.1.3

ISAC-I Accelerators and Beam Lines

Introduction

In the ISAC-I facility, 500 MeV protons at up to 100 µA can be steered onto one of two production targets (see Figure 1) to produce radioactive isotopes. The isotopes pass through a heated tube to a source where they are ionized, accelerated off the source's high-voltage platform at up to 60 kV and sent through a mass separator to select the ion beam of choice. The beam is transported in the low-energy beam transport (LEBT) electrostatic beam line and sent via a switchyard to either the low-energy experimental area or to a series of room-temperature accelerating structures to the ISAC-I medium-energy experimental area.

Description of Facility

The mass separator consists of a pre-separator magnet and mass-separator magnet in series. The pre-separator magnet, at a resolution of ~100, gives a rough species selection and localizes the ions. A series of optics match the beam to an object slit before passing through the mass separator for mass selection. The mass separator is a single dipole with a bending radius of one metre, a bending angle of 135 degrees, and a radial gradient index of 0.5. The magnet and optics layout is capable of a resolution of >8,000 but is usually run with a resolution of ~2,000. It is installed on a high voltage platform (V ≤ 60 kV) to improve further the mass resolution for low-mass beams.

A LEBT system composed of electrostatic optics elements transports the beam to the experimental hall. An electrostatic switchyard is used to select whether the beam will be sent to the linear accelerators for accelerated beam delivery or to the low-energy experimental area. Beams to the low-energy experimental area can be at any energy available from the source (E ≤ 60 kV) and any mass. Beam acceleration requires a fixed velocity for matching into the radio-frequency quadrupole (RFQ) given by a normalized energy of 2.04 keV/u and only a specific range of mass-to-charge ratio of $4 \leq A/q \leq 30$ is possible. Because the ISAC-I sources produce 1^+ charge states, a charge-state booster is required when accelerating ions with $A > 30$.

An electron cyclotron resonance (ECR) charge-state booster is installed just downstream of the mass separator on the ion source level (see Figure 1). The ECR is a PHOENIX type from Pantechnik with a 14.5-GHz RF source operating in continuous mode. The device produces modest efficiencies in the 3 to 5% range with mass-to-charge ratios ranging from 5 for $A \sim 50$, 7 for $A \sim 1$ 50, and up to $A = 9$ for heavier masses. A modest separator ($m/\Delta m = 200$) consisting of a separate magnetic and electrostatic dipole is used to select the correct ion after charge breeding.

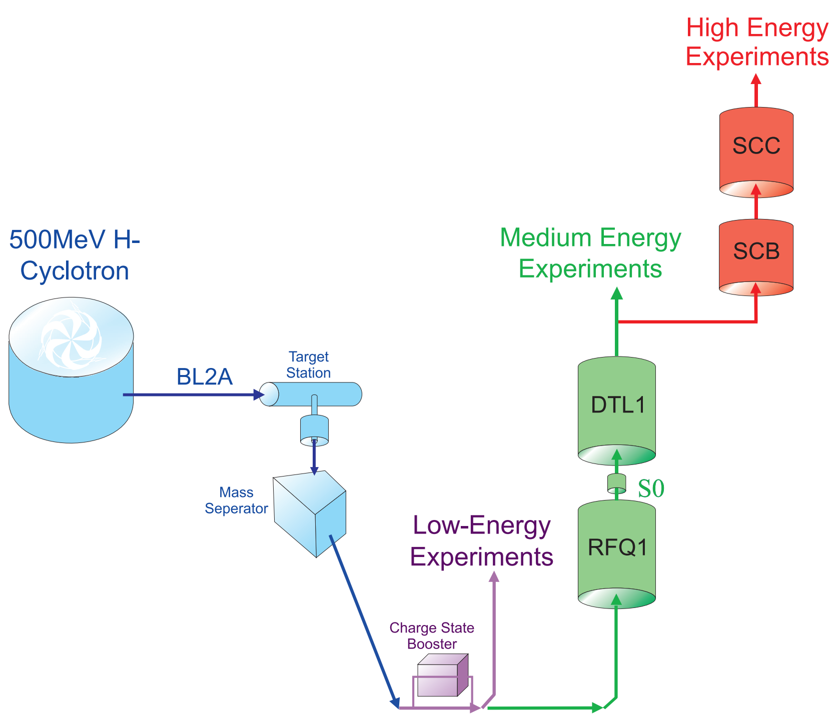


Figure 1: A schematic view of the ISAC-I downstairs facility including target station, mass-separator area, charge-state booster, and the ISAC-I and ISAC-II accelerator chain.

The ISAC-I accelerator chain consists of an RFQ to accelerate the beam from 2.04 keV/u to 153 keV/u and a post-stripper, variable energy, drift tube linac (DTL) to further accelerate the ions to a maximum of 1.8 MeV/u for delivery to the medium-energy experimental area. For high-energy delivery, the DTL beam is deflected north along an S-bend transfer line to the ISAC-II superconducting linac for acceleration above the Coulomb barrier (4-12 MeV/u). A plan view of the ISAC-I and ISAC-II accelerators, beam lines, and experimental areas is shown in Figure 2.

The RFQ was designed and fabricated at TRIUMF and is capable of accelerating ions with $4 \leq A/q \leq 30$, while the post-stripper section, including medium-energy beam transport (MEBT) and DTL accept ions with $2 \leq A/q \leq 6$ (see Figure 3). The RFQ is an 8 m long split ring structure operating in continuous mode at 35.4 MHz and producing up to 4.5 MV of accelerating potential. The RFQ is unique in that there is no bunching section; it accelerates at a continuous synchronous phase of 25 degrees. Capture efficiency is improved by the addition of a multi-harmonic buncher (pre-buncher) located 5 m upstream from the RFQ. The combination of pre-buncher and no capture section produces a reduced acceptance but results in beams with a reduced longitudinal emittance of 0.5π keV/u-ns and therefore better quality beams. Typical capture transmissions through the RFQ are ~75%. The pre-buncher's fundamental frequency is 11.8 MHz, the third sub-harmonic of the RFQ. Users thus have about 85 ns between bunches.

A medium-energy beam transport section delivers the beam from the RFQ to the DTL and is composed of three basic sections. A first section focuses the beam both transversally and longitudinally onto the stripping foil to reduce the emittance growth due to multiple scattering and energy straggling. The beam is focused in time using a 106 MHz buncher. A dual frequency chopper is available to clean up the trace of beam in the 35 MHz satellite buckets or to eliminate every second bunch to produce 170 ns between bunches. The second

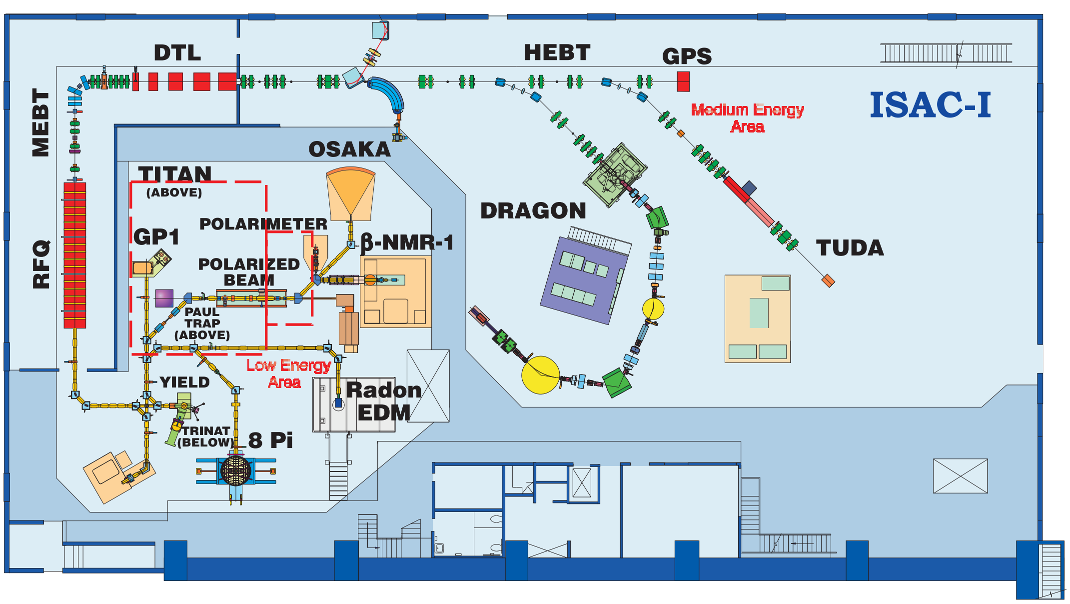


Figure 2: Plan view of the ISAC-I accelerator chain and experimental areas.

section is an achromatic bend section that selects the charge state of choice after stripping. The final section matches the beam both transversally and longitudinally in the DTL. A 35 MHz spiral buncher provides the longitudinal matching.

The DTL, which was designed and fabricated at TRIUMF, is a unique separated function device that provides up to 8.1 MV of accelerating potential and operates in continuous mode at 106 MHz (see Figure 4). The linac provides a full continuum of energy variability from 0.15 to 1.5 MeV/u for ions with $2 \leq A/q \leq 6$, with maximum energies up to 1.8 MeV/u for ions with lower A/q values. The linac is composed of three basic elements: five accelerating tanks with an interdigital H-mode structure to provide the acceleration, quadrupole triplets between tanks to provide periodic transverse focusing, and three triple-gap split ring bunchers before the second, third, and fourth tanks to provide periodic longitudinal focusing.

The linac design is flexible, so it is possible to accelerate the beam for ions up to $A/q = 7$ but at a lower final energy. At present, we are limited by the MEBT dipole power supplies which limit the beam to maximum mass-to-charge values of $A/q = 6$. The MEBT section could be upgraded to $A/q = 7$ with a modest capital expenditure.

The high-energy beam transport (HEBT) delivers the beam from the DTL to one of two experimental areas. The two areas are the DRAGON recoil mass spectrometer and the TUDA scattering chamber and detector array. The HEBT is equipped with a diagnostic station for accelerator tuning, bunchers for optimizing the longitudinal phase space, achromatic bend sections, and matching sections to tune the beam to the targets. The diagnostic station consists of a magnetic spectrometer to measure both the energy and the energy spread in the beam. The bunching section consists of a low-β buncher of 11.8 MHz designed

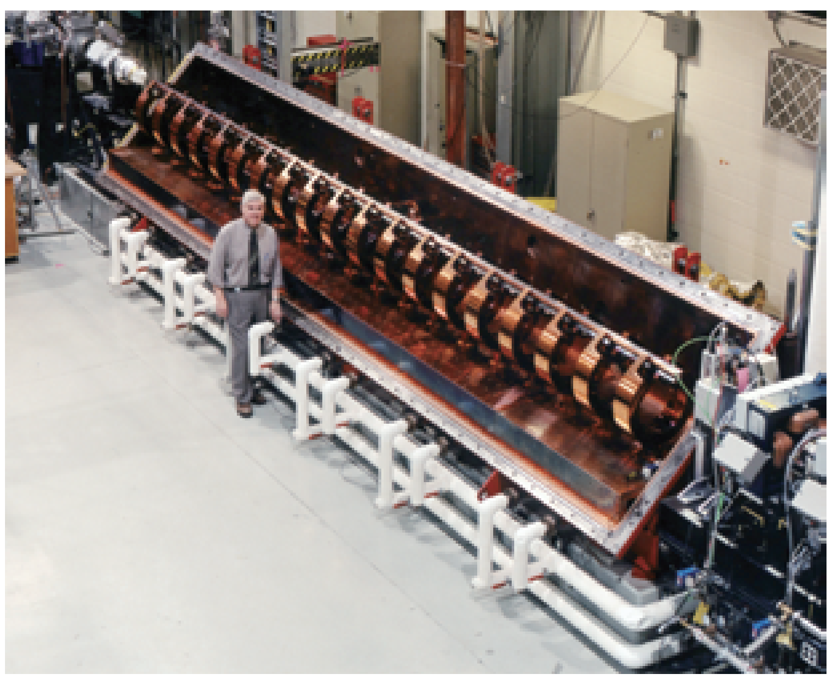


Figure 3: The ISAC-I 35 MHz split ring RFQ.

for beams with $E < 400$ keV/u and a 35 MHz spiral high-β buncher for higher energy beams. The bunchers have been tuned both in bunching mode for a time focus at the target or in debunching mode to minimize the energy spread. The accelerators and transport lines have been operational since 2001, producing high-quality beams with high reliability. Typical beam spots are 2 mm with a focused time spread of ~1 ns and accompanying energy spread of 4 keV/u.

The room-temperature ISAC-I accelerator complex has been optimized for nuclear astrophysics experiments. Beams with mass up to $A = 30$ can be accelerated with full energy variability from 150 keV/u to 1.5 MeV/u and with an efficiency given by the stripping efficiency and the accelerator transmission. The global efficiency ranges from 20 to 40% depending on the mass. The high beam quality, low-emittance beams, and high reliability are strong features of the medium-energy experimental program.

Partners

In Canada: Atomic Energy of Canada, Limited.

International Partners: Germany (2); Russia (1); Switzerland (1), and the United States (1).

TRIUMF's Role

The ISAC-I accelerators and beam lines were developed in-house. TRIUMF was responsible for the beam dynamics design, specification, and engineering design. In most cases, parts were detailed at TRIUMF and fabricated in British Columbia. TRIUMF provided the specifications for the DTL bunchers, which were designed and fabricated at INR-Troitsk.

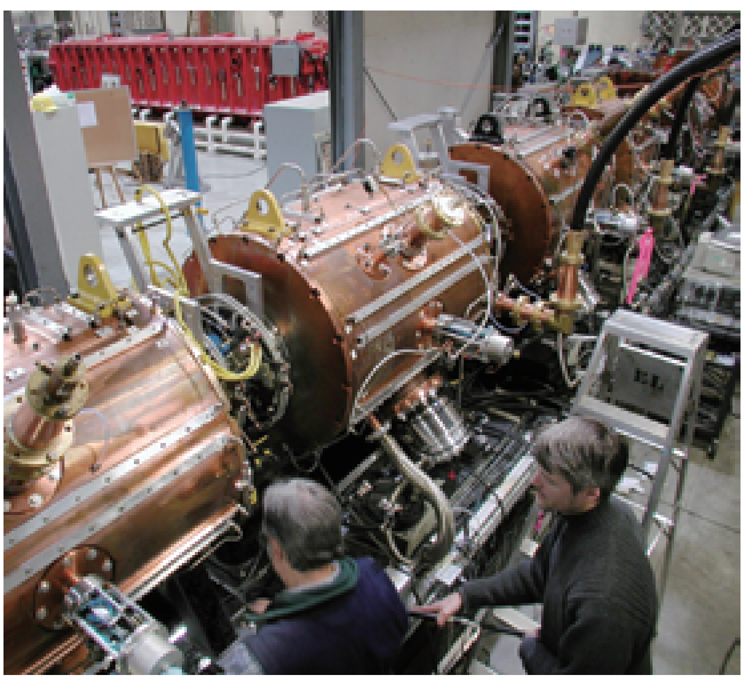


Figure 4: The ISAC-I separated function DTL

5.3.1.4

ISAC-II Accelerators and Beam Lines

Introduction

The rare-isotope beams produced in the ISAC-II facility are transported in the low-energy beam transport (LEBT) electrostatic beam line and sent via a switchyard to either the low-energy experimental area or to a series of room-temperature accelerating structures in the ISAC-I medium-energy experimental area. For high-energy delivery, the drift tube linac (DTL) beam is deflected north along an S-bend transfer line to the ISAC-II superconducting linear accelerator (SC-linac) for acceleration above the Coulomb barrier (5-11 MeV/u) (see Figure 1). TRIUMF began developing superconducting accelerator technology in 2001 and is now a leader in the field with a demonstrated accelerating gradient significantly above other operating facilities.

Description of Facility

The ISAC-I accelerator chain consists of a radio-frequency quadrupole (RFQ) to accelerate the beam from 2.04 keV/u to 153 keV/u and a post-stripper variable energy DTL to further accelerate the ions to a maximum of 1.8 MeV/u for delivery to the medium-energy experimental area. A first phase of the SC-linac has been installed in the ISAC-II vault and was commissioned in March 2006 (see Figure 2). The first rare-isotope ion beam was accelerated in January 2007.

The SC-linac is divided into three sections defined by the beta or velocity acceptance of the section's RF cavities where beta (β = v/c) is the fraction of the velocity of light. The designations are the low-β (SCA), the medium-β (SCB), and the high-β (SCC) sections. Only the medium-β section has been completed so far. The high-β section is scheduled to be installed during 2009. The low-β section is part of the Five-Year Plan for 2010–2015.

The present medium-β installation consists of five cryomodules with four 106 MHz cavities in each cryomodule for acceleration and one superconducting solenoid for transverse focusing. The cavities, fabricated in Italy, are two-gap, quarter wave structures made from bulk highly purified niobium. The cavities and solenoid are cooled to 4K using liquid helium delivered from a cryoplant in an adjacent room. A cryomodule top assembly showing the cold mass is illustrated in Figure 3. One cavity delivers about 1 MV of accelerating potential but with only ~5W of RF power due to the extremely low surface resistance of the niobium. The short, independently phased cavities have a broad velocity acceptance and provide a flexible beam delivery because ions do not have to follow a fixed velocity profile as in the ISAC-I RFQ. Ions with a lower mass-to-charge (*A/q*) ratio can be accelerated to a higher velocity than those with a larger *A/q*, and full energy variability can be achieved by turning cavities off. The 20 cavities of the medium-β section add 20 MV of accelerating potential to the 1.5 MeV/u beam from ISAC-I, yielding beams with final energies ranging from 5 MeV/u to 11 MeV/u.

A second phase, consisting of twenty 141 MHz resonators grouped into three cryomodules, is scheduled for installation by the end of 2009 (see Figure 4). The technical infrastructure for this section essentially copies the very successful technology developed in the first phase. The main technical goal for

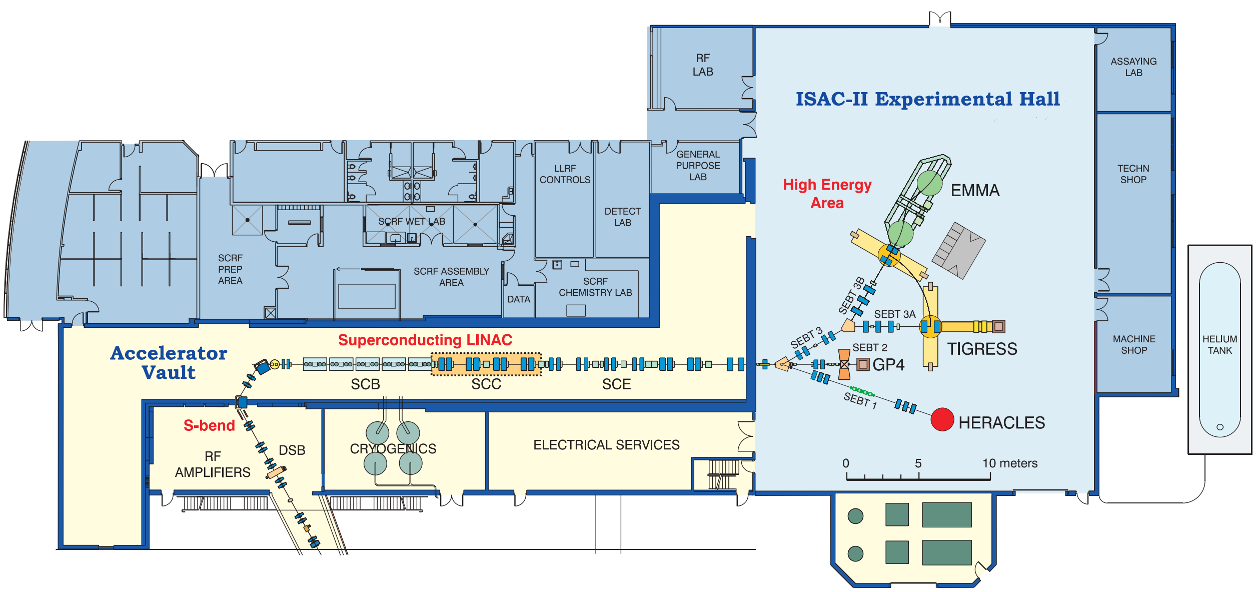


Figure 1: Plan view of the ISAC-II accelerator chain and experimental area.

this section is to develop a local supplier for the superconducting RF cavities, a technical capability currently absent from Canadian industry.

TRIUMF has worked with PAVAC Industries of Richmond, BC, since 2005 with the goal of producing two prototypes of the 141 MHz high-β cavity. This collaboration performed a first successful cold test using technical knowledge transferred to PAVAC from TRIUMF. Based on the test results and its strong technical capability, PAVAC has been awarded the contract for supplying the 20 production cavities for the second phase. Once on-line, the cavities will add a further 20 MV of accelerating potential to the ISAC-II beam, giving the full energy capability of the original ISAC-II proposal, with beams of $2 \leq A/q \leq 6$ ranging from final energies of 8–18 MeV/u.

The beam from the ISAC-II SC-linac is injected directly into the SEBT beam line (see Figure 1) and is transported into the ISAC-II experimental hall (see Figure 5). Various diagnostics in the SEBT line help to tune and monitor the beam delivery. Cavity tuning is done via a phase monitor directly downstream of the linac while a time-of-flight monitor near the end of the vault measures the beam energy. A non-intercepting intensity monitor is installed in the vault to monitor beam intensity during delivery. At present, two stations are available: SEBT2, which serves as a general-purpose station, and SEBT3A, which serves the TIGRESS γ-ray spectrometer. A third beam line, SEBT1, will be installed in 2008 to serve the TUDA-II and HÉRACLES experimental stations. The SEBT3B beam line to the recoil mass separator EMMA is scheduled for completion in 2009.

The full program of nuclear physics experiments in ISAC-II is dependent on the operation of the charge-state booster scheduled to begin operation in August 2008. Beams with mass up to $A = 30$ can be accelerated with an efficiency given by the stripping efficiency at 150 keV/u (~30 to 40%) and the

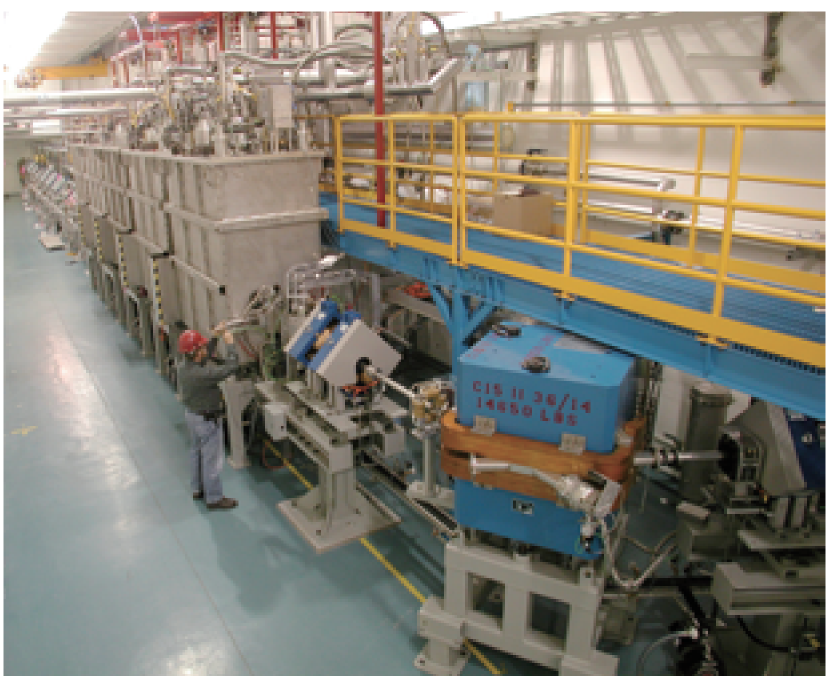


Figure 2: The ISAC-II SC-linac phase I.

accelerator transmission (~70%). Masses with $A > 30$ require a boost to higher charge states to overcome the voltage limitation at the RFQ. Masses up to ~120 are charge boosted with most probable charge states yielding mass-to-charge values given by $A/q = 6$ and compatible with ISAC acceleration with overall efficiency of ~5%. Masses heavier than $A = 120$ cannot be accelerated efficiently. Plans for the 2010-2015 era propose to lift this limitation.

Partners

International Partners: INFN (International Laboratory at Legnaro), Italy, and in the United States: the Argonne National Laboratory.

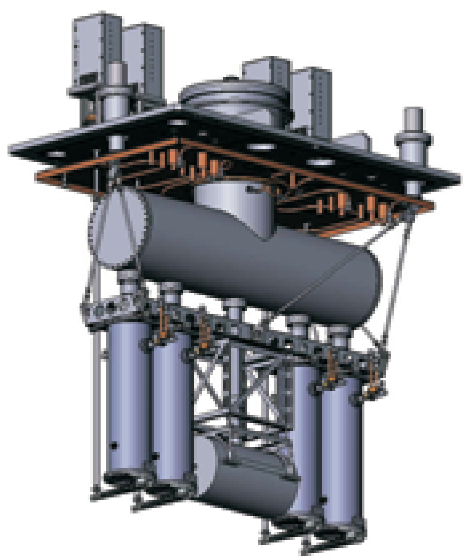


Figure 3: The medium-β cryomodule top assembly.

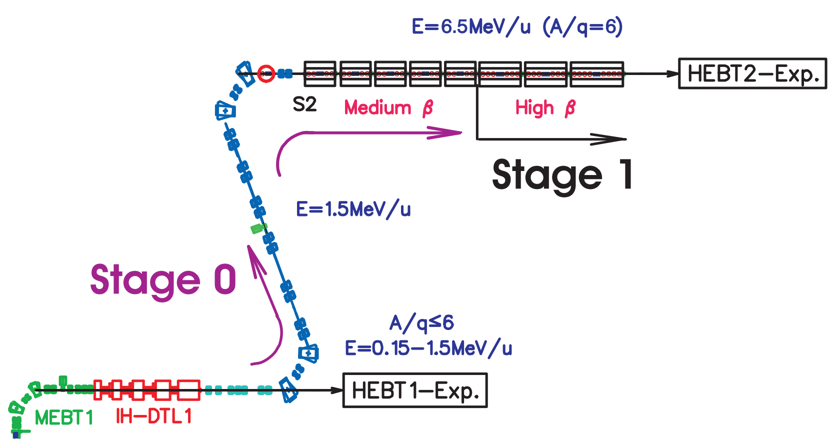


Figure 4: A schematic of the S-bend transfer line and expected status of the ISAC-II SC-linac by the end of 2009.

TRIUMF's Role

The cavities of the ISAC-II SC-linac were developed by a collaboration between TRIUMF and INFN-LNL and based on an existing design used on the low-β section of Legnaro's ALPI accelerator. The cavities were produced in Italy.

TRIUMF was responsible for the beam dynamics design and specification and the engineering design of the cryomodules and cryogenic infrastructure. In most cases, parts were detailed at TRIUMF and fabricated in British Columbia. The high-β section of the linac is based on cavities modeled at TRIUMF and fabricated at PAVAC Industries, Inc., the first Canadian company ever to produce bulk niobium superconducting cavities.

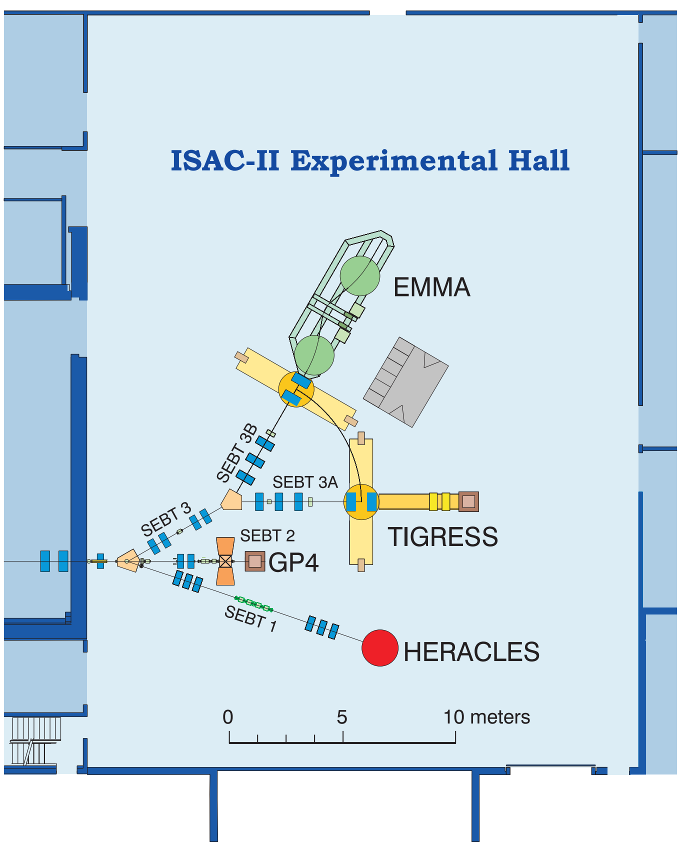


Figure 5: The ISAC-II experimental hall.

5.3.2

Facilities

5.3.2.1

ATLAS Canadian Tier-1 Data Centre

Introduction

The standard model predicts that a particle called the Higgs boson determines the mass of all subatomic particles. This prediction has never been proven, but proof of the existence of the Higgs boson and exciting new discoveries in particle physics may be found when the ATLAS experiment begins in 2008.

The ATLAS experiment at the Large Hadron Collider (LHC) at CERN will use proton-proton collisions at the highest energy ever achieved in the laboratory to look for the Higgs boson, the particle central to the current model of how subatomic particles attain mass. ATLAS will also search for phenomena "beyond the standard model" of particle physics such as supersymmetry, extra dimensions, and quark compositeness. The ATLAS detector will observe the particles emerging from the roughly 900 million proton-proton collisions per second and, although fast electronics will filter the events so that only those most likely to be of interest will be recorded, ATLAS will produce 3.5-5.0 petabytes of data per year (one petabyte is one million gigabytes). In addition, secondary data sets will be produced that could double the amount of data produced.

In order to analyze this enormous amount of information, CERN is coordinating an international network of large high-performance computing centres that are linked by "grid" tools so that they act as one huge system. This network is called the Worldwide LHC Computing Grid (WLCG). Canada has

MICHEL VETTERLI

Professor of Physics, SFU-TRIUMF Research Scientist

Michel Vetterli graduated with a First-Class Honours degree in physics from McGill University in 1980 and a Ph.D. from McMaster University in 1985. After graduation, he moved to SFU-TRIUMF where he was a post-doctoral fellow until joining the laboratory's staff in 1989.

Dr. Vetterli's early work was in intermediate energy nuclear physics, in particular the study of nucleon charge-exchange reactions with implications for stellar evolution. During the 1990s, he studied the substructure of the proton and the neutron at the HERMES experiment at DESY in Hamburg, where he was the Canadian project leader from 1989 to 2001. He was also the deputy spokesman of HERMES during the construction, installation, and commissioning phases of the experiment.

In 2001, Mike moved to SFU where his work has focused on ATLAS. He is currently the computing coordinator for ATLAS-Canada and the project leader of the ATLAS Tier-1 Data Analysis Centre at TRIUMF. He has also worked on the liquid argon calorimeters, which detect the energy of the particles emerging from the high-energy proton-proton collisions at the LHC.

Dr. Vetterli is a founding principal investigator of WestGrid, a network of high-performance computing facilities in Western Canada that serve the needs of academic computing in the sciences and engineering. ■

provided one of the world's eleven Tier-1 centres (10 for ATLAS, one for CMS). The Canadian Tier-1 Data Centre, located at TRIUMF, will work with nine of the other ATLAS Tier-1 centres in the world to reprocess the raw data produced by the experiment. In addition, Tier-2 centres will be built in universities, both in Canada and abroad, to further process the results of the Tier-1 analysis and extract groundbreaking physics results from the data. The Tier-2 centres will also be the primary sites for computer simulations of ATLAS, which is an integral part of the data analysis.

The requirements at a Tier-1 centre are such that a dedicated facility is mandatory. One can think of the Tier-1 centres as extensions of the experiment. In Canada, it was decided to build such a facility at TRIUMF because of the laboratory's experience with providing 24/7 data and networking services in large volume. The data centre was funded in late 2006 by an Exceptional Opportunities Grant from the Canada Foundation for Innovation (CFI) to a consortium of Canadian universities. This was supplemented by a grant from the British Columbia Knowledge Development Fund (BCKDF). The grants totaling just over C$15 million are summarized in Table 1, where contributions from vendors and TRIUMF are also included, bringing the total value of the project to about C$23.5 million.

	Capital	Operating	Total
CFI	8,179	2,450	10,629
Vendors	8,268		8,268
BCKDF	4,060		4,060
TRIUMF		525	525
Total	20,507	2,975	23,482

Table 1: Grants for the Canadian Tier-1 Data Centre in thousands of dollars. Vendor contributions come from discounts available beyond educational pricing.

The expanded Canadian Tier-1 Centre began full operations in August 2007 and is participating in ATLAS data and service challenges, as well as cosmic-ray tests and a full-dress rehearsal of the data-taking.

Description of Dedicated Apparatus

Analysis of particle physics experiments is done in several stages. First, digitized electronic signals from the various detectors are calibrated and the information is combined to reconstruct particle trajectories and energy deposits in the detectors for the particles emerging from the proton-proton collisions. This results in Event Summary Data (ESD) files. This information is processed further to produce a list of the particles coming from each collision, as well as their properties (energy, scattering angle, etc.). These lists, stored as Analysis Object Data (AOD), form the basis of physics analyses on a multitude of phenomena. Groups concentrating on specific physics topics then further filter the data and refine the analysis to produce Derived Physics Data (DPD) from which final results will be extracted.

This staged analysis, with data sets of decreasing size at each stage, lends itself well to a layered network of computing facilities. The ATLAS computing model is illustrated in Figure 1, as a tiered structure of centres ranging from the Tier-0 at CERN to relatively modest-sized clusters in the universities, the Tier-3 centres. The Tier-0 stores all of the raw data from the experiment on tape, distributes one copy across all of the Tier-1 centres and performs a first-pass analysis using the best knowledge we have of the detector at the time of data-taking. As calibrations and analysis algorithms improve, the raw data are reprocessed in the Tier-1 centres in a coordinated way, producing new ESDs and AODs. The Tier-1 centres are also responsible for storing the simulated data generated in the Tier-2 centres. The new AODs are distributed to the Tier-2s in the universities where further analysis is done. The Tier-1 centres require large compute farms and large storage systems to fulfill their role. Fast network interconnection to CERN and the other centres on the grid is crucial.

The access patterns to the AODs are such that peaks and valleys occur in the CPU requirements. It was therefore felt more appropriate to build the Tier-2 centres in the context of shared facilities in the universities, where ATLAS-Canada would have access to very significant resources for short periods of time, above and beyond its steady-state requirements. Tier-2 centres have been

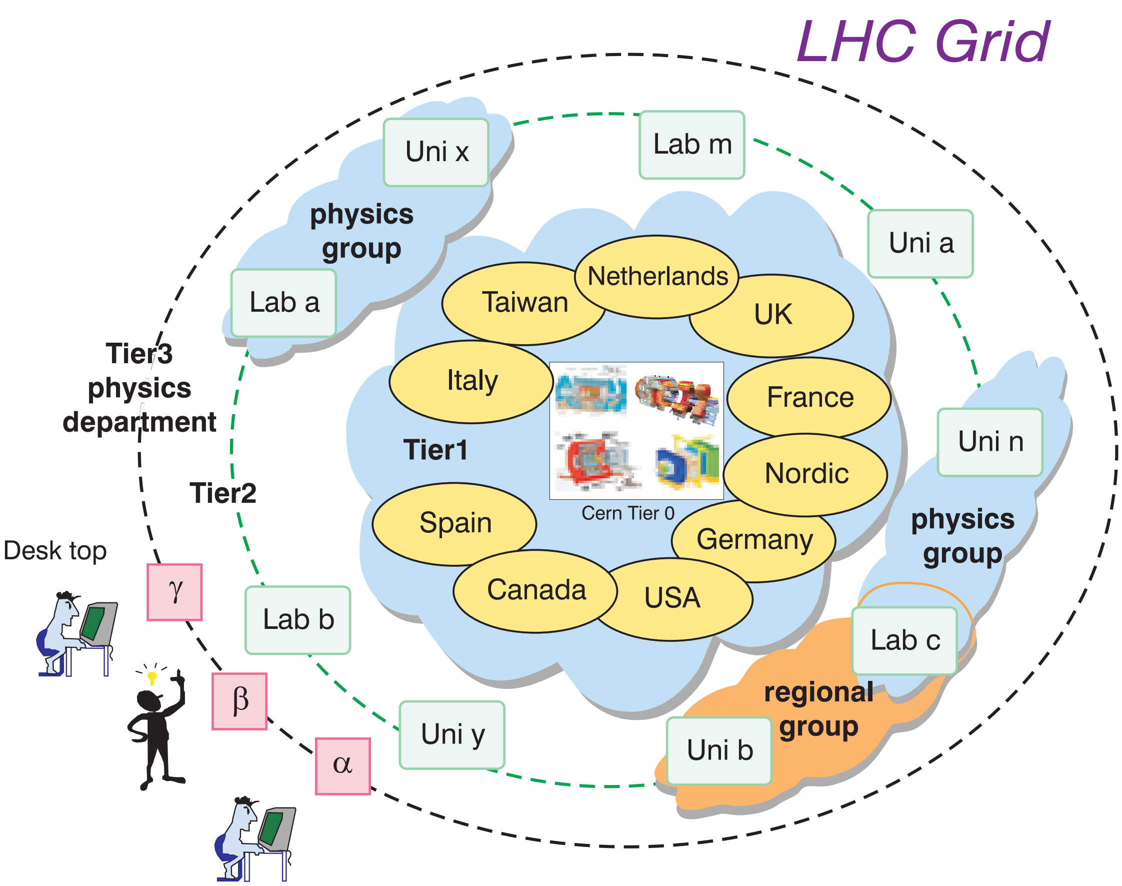


Figure 1: The Worldwide LHC Computing Grid showing a layered structure of high-performance computing centres distributed around the globe.

funded through the CFI National Platforms Fund (NPF) and will be built at McGill University, Simon Fraser University, the University of Alberta, the University of Toronto, and the University of Victoria.

The Tier-1 centre will be built in stages as requirements for equipment increase during data-taking. The anticipated resources are summarized in Table 2. Note that resources for 2008 have already been purchased and commissioned. Note also that the size of the data centre was increased beyond WLCG requirements by 20% to provide Canadians with dedicated resources to allow them to fulfill their responsibilities with respect to detector calibration, as well as to give them a competitive advantage in the analysis of the data.

The data centre is housed in the power supply hall of the ISAC-II building. A portion of this room was renovated in order to handle the high-density heat load generated by the new equipment. The renovations were designed with a capacity that should be sufficient until 2011. Beyond this, a new site will be required to allow for expansion driven by the ever-increasing data from ATLAS.

Year	2007	2008	2009	2010	2011
CPU (kSI2k)	228	1304	2179	3801	5423
Disk (TB)	156	716	1544	3063	4344
Tape (TB)	111	554	1171	2226	3471

Table 2: Planned resources for the Canadian Tier-1 Data Centre at TRIUMF. The numbers are cumulative. Computers are quoted in kSI2k, which is a benchmarking unit; a typical desktop computer corresponds to 2.5-3 kSI2k. Storage is quoted in terabytes and is the useable space available.

Results and Progress

As mentioned above, the Canadian Tier-1 Data Centre underwent a significant expansion in August of 2007. The Tier-1 is now at full capacity for 2008 and will be expanded each year as data are collected by ATLAS. Prior to August 2007, resources were purchased using funds from SFU, TRIUMF, and UBC to provide a modest scale data centre that nevertheless had all of the grid services required of a Tier-1. This allowed Canadians to participate in large-scale ATLAS simulation exerciseswhich help in the design of the experiment, to develop the analysis software by providing pseudo-data that could be treated in the same way as real data, and finally to develop and test the computing model and the WLCG. These tests were referred to as Data and Service Challenges.

Canada is responsible for providing 5% of the common computing for ATLAS, based on our fractional membership in the collaboration. Figure 2 is a chart of contributions in 2007 by the Tier-1 centres to ATLAS simulation, which shows that the goal to provide 5% of the total was met. Canada's fraction increased to almost 9% in October–November 2007 after the expansion to a full-scale Tier-1 centre.

Another performance yardstick for Tier-1 centres is uptime. WLCG requirements for reliability are very high, ranging from 91% in June of 2007 to 98% by the time data-taking starts in 2008. Note that TRIUMF ranks among the best for this metric, averaging 95% in the latter half of 2007, despite having the smallest staff of all the Tier-1 centres.

Networking is important for the WLCG because of the large amount of data continuously transferred from CERN to the Tier-1s, as well as the large amount of traffic between Tier-1s and Tier-2s. A dedicated point-to-point connection (a "lightpath") has been established between TRIUMF and CERN by CANARIE, Canada's optical research network, and HEPNet-Canada, which is responsible for networking for Canadian subatomic physics. This link is currently 5 gigabits per seconds (gbps), but can be increased to 10 gbps if the need arises. Dedicated lightpaths: between TRIUMF and Brookhaven National Laboratory (the US-ATLAS Tier-1) and between TRIUMF and the Canadian Tier-2 centres have also been set up. This communication network was tested under realistic conditions in 2007 during cosmic-ray data-taking tests. Data from cosmic rays passing through the ATLAS detector were sent to the Tier-0 at CERN. Reconstruction was performed, and the data (raw, ESD, and AOD) were distributed to the Tier-1s in the same way it will be with data from collisions when the LHC starts up. An example of transfer rates between CERN and the Tier-1 centres is shown in Figure 3. TRIUMF exceeded the requirement of 50 MB/s continuous transfer rate.

The ATLAS experiment will launch a full-scale test of the computing system in 2008, including the analysis chain all the way from raw data in the experimental area to physics results at the Tier-3 centres. This Full Dress Rehearsal will test all aspects of the hardware and software a few months before the LHC starts up. The Tier-1 Centre is fully ready for this exercise.

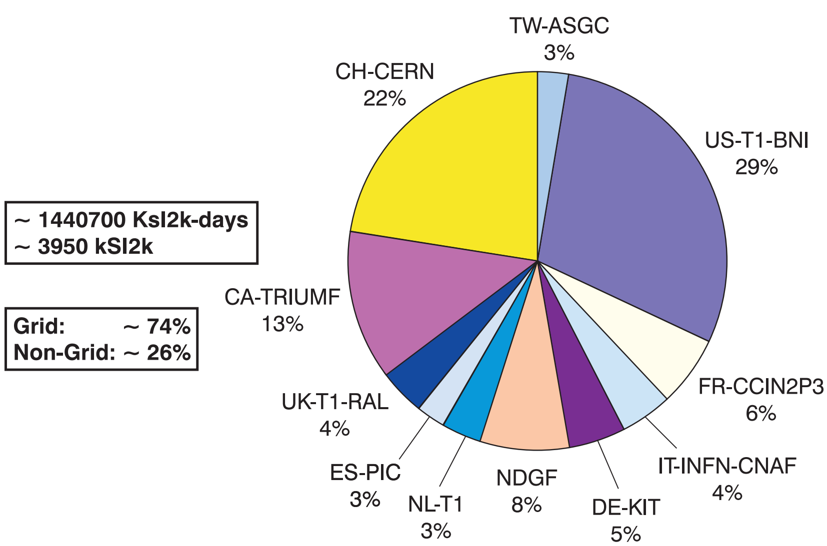


Figure 2: TRIUMF's contribution to the Tier-1 share of the simulation of the ATLAS experiment (Jan. –Sept. 2007).

Partners

The Canadian Tier-1 Data Centre consortium members are: Carleton University, McGill University, Simon Fraser University, University of Alberta, University of British Columbia, l'Université de Montréal, University of Toronto, University of Victoria, and York University.

TRIUMF's Role

TRIUMF has been the ideal site in Canada for the Tier-1 Data Centre. The laboratory has extensive experience in large international collaborations and can provide 24/7 support for the equipment. TRIUMF also has long-standing expertise in long-distance file transfers and international networking. Although all but one Tier-1 employee is paid through the CFI and BCKDF grants, TRIUMF is committed to pursuing ongoing support and funding for the data centre beyond 2011.

The experience gained through running the Tier-1 facility has made TRIUMF a centre of excellence in large-scale distributed grid computing. The LHC experiments are the first large-scale deployment of grid technology. It is difficult to imagine that this technology will not be further deployed in science and industry. It has the potential to do for large-scale serial computing what the World Wide Web (also developed at CERN) has done for the global sharing of information. Through this involvement in early deployment, TRIUMF is well placed to ease Canadian entry into any further developments in grid computing technology.

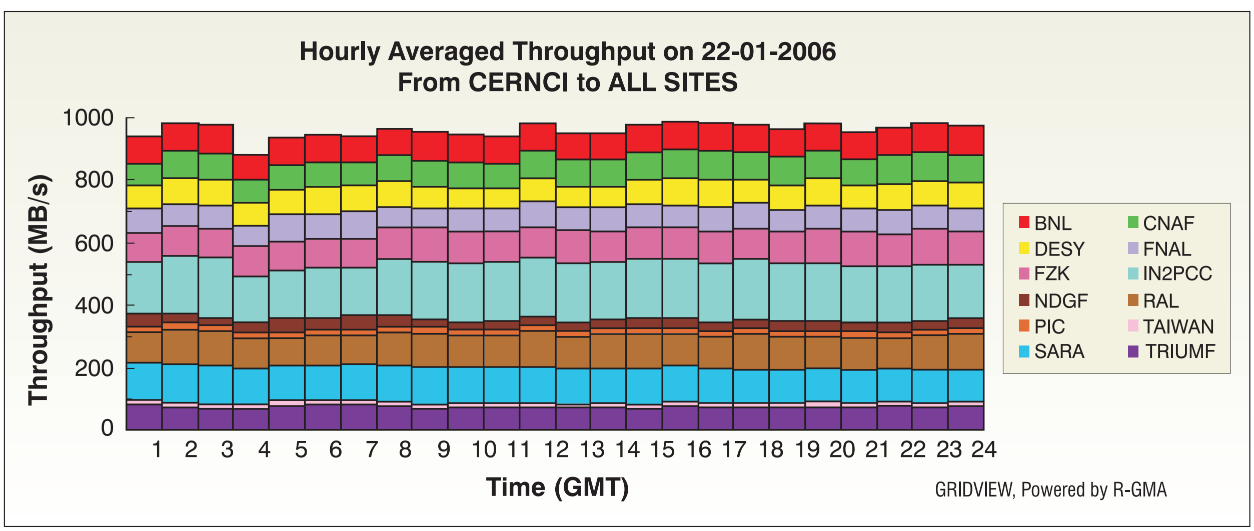


Figure 3: Data transfer rates from CERN to the Tier-1 centres during a coordinated test in 2006. The target for TRIUMF of 50 MB/sec was comfortably achieved.

5.3.2.2

ISAC Facilities

5.3.2.2.1

ISAC-I Facilities

5.3.2.2.1.1

Detector of Recoils and Gamma Rays for Nuclear Astrophysics: DRAGON

Introduction

Our universe is filled with ordinary stars but also less well understood objects such as supernovae and X-ray bursts, where 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, designed and built to measure nuclear reactions (see Figure 1) of importance in astrophysics, the nucleosynthesis reactions which occur in the explosive environments of novae, supernovae and X-ray bursts.

The first reaction measured by DRAGON was $^{21}Na(p,\gamma)^{22}Mg$, an especially important reaction to understand in order to calculate the processes occurring in classical novae, a white dwarf star which 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, which acquires extra energy when it absorbs the proton. 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 studies 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 ^{21}Na nucleus, produced by ISAC-I, impinges on a proton in a hydrogen target. It is then absorbed forming ^{22}Mg which de-excites, giving off a γ-ray. 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

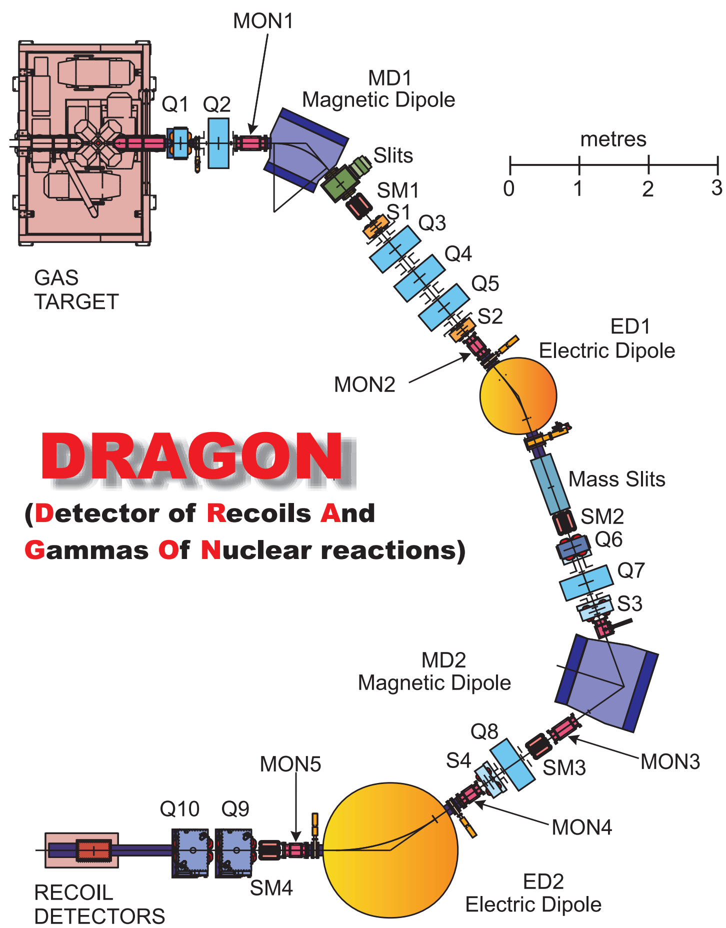


Figure 1: Plan view of the DRAGON recoil separator, showing the gas target where the nuclear reactions occur, the electromagnetic devices that separate the recoil nuclei from the unreacted beam, and the detectors that measure properties of the recoil nuclei.

measured in a bismuth-germanate (BGO) crystal array that surrounds the thin-walled hydrogen gas target volume.

Using this technique, DRAGON has, over the last seven years, waged successful campaigns to study some of the most important proton- and alpha-capture reactions to astrophysics, including the ^{21}Na(p,γ)^{22}Mg, ^{12}C(α,γ)^{16}O, ^{26g}Al(p,γ)^{27}Si and ^{40}Ca(α,γ)^{44}Ti reactions (see Section 5.1.2.3).

Description of Dedicated 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 150–1800 keV/A provided by the ISAC-I accelerator, DRAGON studies the radiative capture on hydrogen and helium relevant to nucleosynthesis on the neutron-deficient side of stability, for scenarios such as supernovae, classical novae, and X-ray bursts. The hydrogen or helium is circulated within a windowless gas target capable of holding up to 4 x 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 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 microchannel plate, and an ionization chamber for chemical-element identification.

The DRAGON separator is designed to accept recoils within a 1° half-angle at the tuned energy, and with a momentum spread of less than ±2% [S. Engel *et al.*, Nucl. Instrum. Methods A553, 491 (2005)]. The momentum and angle spread are induced by the range of momentum given to the recoil as the γ-rays are emitted and are thus dependent on the 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(α,γ)^{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 the 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 [D.G. Gigliotti *et al.*, Nucl. Instrum. Methods B204, 217 (2003)]. 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. For favourable alpha-capture reactions such as $^{12}C(\alpha,\gamma)^{16}O$, the suppression is around 10^{12}–10^{13} for the energy range 750A–1250A keV.

The total background suppression capability of DRAGON, when combining γ-ray detection, recoil separation and particle identification is at minimum 10^{13}, making DRAGON sensitive to extremely small resonance strengths, such as the 34 μeV resonance recently measured in the $^{26g}Al(p,\gamma)^{27}Si$ reaction.

In 2008, DRAGON upgraded its detection system to include a local-time-of-flight capability with time resolution $\Delta t \sim 400$ ps, providing an extra layer of background rejection and enabling the pursuit of even more difficult measurements.

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 5.1.2.3 highlight the important contributions of DRAGON to the field of nuclear astrophysics.

The DRAGON program was recently fully funded again by NSERC 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 (2010–2015), DRAGON will continue to pursue the measurement of difficult and important astrophysical reactions with the development of novel radioactive beams.

Partners

In Canada: McMaster University, Simon Fraser University, University of Alberta, University of Guelph, University of Northern British Columbia, University of Prince Edward Island, University of Toronto, and the University of Victoria.

International Partners: Austria (1), Belgium (1), China (1), England (2), France (1), Germany (3), India (1), Ireland (1), Israel (1), Italy (1), Japan (1), Scotland (1), Spain (2), and the United States (5).

TRIUMF's Role

TRIUMF's dedicated research scientists, post-doctoral research assistants, and technicians make up the DRAGON Group, which is joined by a large number of Canadian and international academic collaborators in both experimental physics and astrophysics theory.

5.3.2.2.1.2

TRIUMF Neutral Atom Trap: TRINAT

Introduction

A revolution has recently occurred in subatomic physics. Physicists can now cool neutral atoms, those atoms with an equal number of electrons and protons, to very low energies and trap them in a vacuum, using new laser technologies. TRIUMF is harnessing these new laser technologies, which function like a thick liquid to slow the atoms' movements and confine them to a small region, to do precision, low-energy experiments that allow scientists to study the individual atoms in great detail with glimpses of their inner structure.

TRIUMF's neutral atom trap uses the pressure of laser light to confine atoms of radioactive isotopes and measure their decay properties. The atoms are held very weakly in space, so that the momentum of the low-energy daughter nuclei is unperturbed after the decay and can be measured accurately. This lets us measure the neutrino momentum from the momentum of the other products in three-body β-decay. The angular distribution of the neutrino with respect to the beta and the nuclear spin is predicted in the standard model. The techniques are being extended to let us search for exotic massive particles in missing-mass spectra in two-body γ-decay of nuclear isomers, metastable excited nuclear states. The best isotopes for such experiments are often short-lived, so we have optimized the trap to collect the isotopes from the ion beam produced by ISAC-I.

Description of Dedicated Apparatus

The complete trap system fits on a large table top (see Figure 1). 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. The transfer time is about 40 ms, with more than 75% efficiency; 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 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 β- 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 99.6% in stable species and over 97% in unstable species has been achieved. 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.

A small percentage of the trapped atoms is 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). For future atomic parity violation work in francium atoms, similar collection schemes will be used, but for the measurement trap, geometries optimized for atomic physics will be used.

The main trap laser is a tunable Ti:S ring laser driven by an argon ion laser.

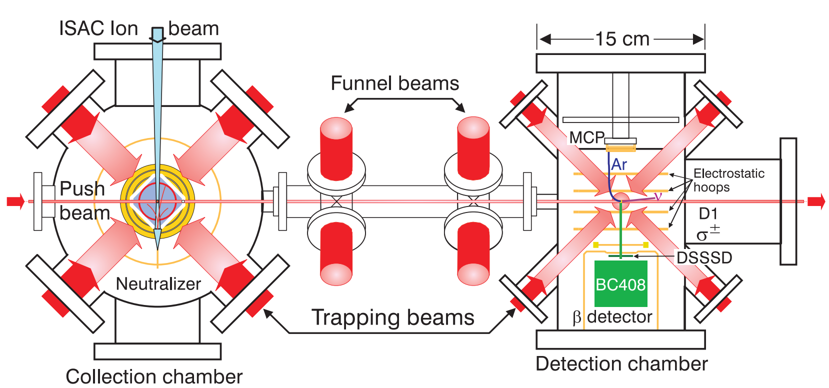


Figure 1: Top view of TRIUMF’s neutral atom trap.

Another Ti:S is better optimized for very narrow-frequency work. Several smaller diode lasers are used for optical pumping. The dollar 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

Recent physics results include the best measurement of a beta-neutrino angular correlation in the pure Fermi decay of ^{38m}K. This observable is deliberately insensitive to the absolute handedness, *i.e.*, helicity, of the outgoing particles, which makes it sensitive to all types of new scalar interactions independent of this "chirality" property.

More recently, 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. This should help with the beta-neutrino correlation, along with missing-mass searches for exotic massive particles in two-body decay of nuclear isomers. Using the spin-polarization techniques together with the recoil-coincidence technique, a neutrino spin asymmetry measurement has been published [Melconian *et al.*, Phys. Lett. B649 370 (2007)].

Partners

In Canada: University of British Columbia, University of Manitoba , and Simon Fraser University.

International Partners: Israel (1) and the United States (1).

TRIUMF's Role

TRIUMF supplies the short-lived isotopes via rare-isotope beams from ISAC-I, along with 1.4 FTE research scientists. TRIUMF also provides technical support via the electronics, machine, and design shops

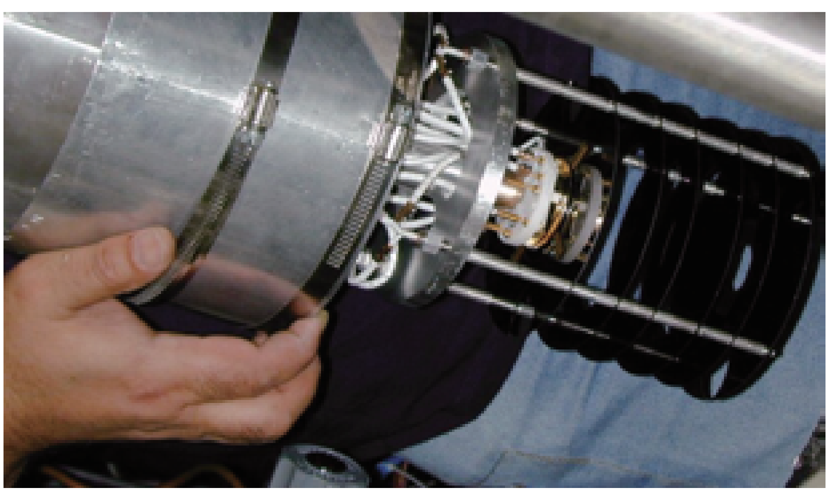


Figure 2: The electrodes and microchannel plate used to detect ions from atoms decaying in the neutral atom trap.

5.3.2.2.1.3

8π Facility

Introduction

The 8π detector, in its current configuration, is the only large high-resolution, high-efficiency γ-ray spectrometer in the world dedicated to measuring the decay of stationary rare-isotopes. Between 2003 and 2008, collaborators have integrated a full complement of ancillary detectors for measuring beta particles, conversion electrons, and fast lifetimes. This facility has made high-precision measurements of weak branches, discovered new rare decay branches, made precision measurements of nuclear lifetimes by electronic and Doppler-shift techniques, and investigated exotic nuclei produced at rates as low as 1 ion per second.

Scientists using the 8π spectrometer at ISAC-I recently discovered a small, never-before-seen γ-decay of the 0^+ excited state in the rare-isotope ^{38}K. By nuclear decay standards, it is a weak branch — the state is 30,000 times more likely to decay by beta decay than by γ emission. The discovery of this branch means that previously reported measurements were in error. This branch is a non-analogue decay and is 16 times larger than the upper limits for such decays established in previous measurements. Ultimately, this and similar 8π experiments show whether or not we really understand the subatomic world, from the standard model of fundamental particle interactions to the standard shell model of nuclear structure.

Description of Dedicated Apparatus

In the early 1980s, scientists from l'Université de Montréal, McMaster University, and the Atomic Energy of Canada Limited (AECL) forged a collaboration to build the 8π. The $C5 million (in 1982) construction cost was shared equally between NSERC, through the universities, and AECL. For over a decade, the 8π operated at the Chalk River Tandem Accelerator and Superconducting Cyclotron laboratory for nuclear physics research with heavy-ion beams. In 1997, it was moved to the 88" Cyclotron at Lawrence Berkeley National Laboratory. In 2000, the 8π was moved back to Canada, and reconfigured for use in β-decay experiments. In its current configuration, the 8π includes 20 high-purity germanium (HPGe) high-resolution γ spectrometers, with bismuth-germanate (BGO) escape suppressors.

Recent Developments

The main permanent addition to the device is a fast in-vacuum continuous-loop tape-moving system (see Figure 1) 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, in view of the HPGe detectors. 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 progeny or beam contaminants.

The vacuum chamber can also accommodate SCEPTAR (SCintilator Electron-Positron Tagging ARray). SCEPTAR, funded primarily by NSERC, counts beta particles with 20 fast plastic scintillators covering 80% of a full 4π solid angle (Figure 2). SCEPTAR can be used simultaneously in a "singles" mode for normalizing of high-precision branching ratio measurements and for β-γ coincidence spectroscopy to eliminate the ~2000/s γ background events from one to two decays of weakly produced, exotic beams. The geometry is such that each HPGe views the sample with one, and only one, unique SCEPTAR element. Applying a veto to events with collinear SCEPTAR and HPGe detection reduces continuum bremsstrahlung in the γ-ray spectra.

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 [P.E. Garrett *et al.*, Acta Phys-

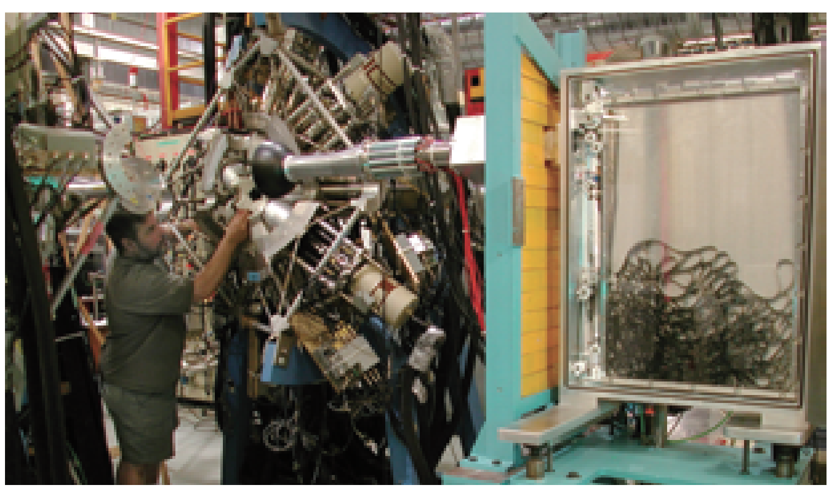


Figure 1: The east half of the 8π spectrometer, the tape system, and the downstream half of SCEPTAR during experiment set up.

ica Polonica B38, 1169 (2007); P.E. Garrett *et al.*, Nucl. Instrum. Methods B261, 1084 (2007)]. PACES replaces half of SCEPTAR with five Si(Li) detectors cooled to near liquid nitrogen temperature (Figure 3). PACES was supported by the DOE and NSERC. The cooling system was designed by LSU, and a variant has been adopted for the Doppler-shift lifetimes program. Conversion electron spectroscopy probes nuclear structure phenomena such as shape coexistence, which can arise from shell gap crossings and impact the nuclear structure corrections to superallowed beta-decay determinations of V_{ud}. PACES' efficiency for conversion electrons is approximately 10%.

The most recent addition to the 8π is DANTE (Dipentagonal Array for Nuclear Timing Experiments). Ten barium fluoride (BaF_2) counters provide relative timing information for detected γ-rays with a resolution two orders of magnitude superior to HPGe. 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.

These new detectors were accompanied by upgrades and expansion of the readout system. There are now four parallel FERA readouts for each of the HPGe, fast plastic, Si(Li), and BaF_2 systems. These data acquisition upgrades were funded by TRIUMF, NSERC, and the US Lawrence Livermore National Laboratory.

With the extensive ancillary detector development and electronics upgrades done between 2003 and 2005, the 8π spectrometer at ISAC-I now represents a world-unique facility for decay spectroscopy with rare-isotope ion beams. A further dramatic increase in the sensitivity of this unique facility could be realized by replacing the 8π HPGe detectors (now more than 20 years old) with state-of-the-art large-volume clover-type HPGe detectors. This upgrade would increase the efficiency of the spectrometer by a factor of 20 (a factor of 400 for

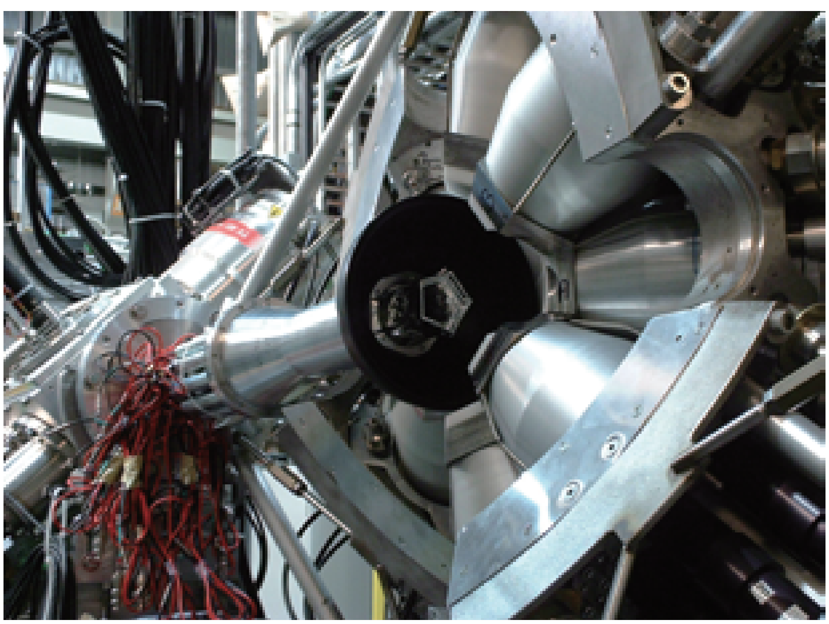


Figure 2: Upstream half of SCEPTAR with the east half of 8π.

γ-γ coincidence detection) and would allow detailed spectroscopic studies of the most exotic nuclei produced by the ISAC-I facility with intensities well below 1 ion/second. This proposed new facility, Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN), is currently being considered as a Canada Foundation for Innovation application led by collaborators at the University of Guelph.

Partners

In Canada: McMaster University, Queen's University, Saint Mary's University, Simon Fraser University, the University of Guelph, and the University of Toronto.

International Partners: France (1), the United Kingdom (3), and the United States (7).

TRIUMF's Role

TRIUMF provides a dedicated technician for 8π, TIGRESS, and GPS. One staff scientist manages the 8π and GPS programs; 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, and the stand for the tape system, target chambers for SCEPTAR and PACES, detector mounts for DANTE, cable trays, electrical service, and an enclosed, cooled hut for the electronics. TRIUMF also provides front-end readout computers, back-end workstations, data acquisition software, networks, and mass data storage.

Figure 3: PACES. As installed, it replaces the upstream half of SCEPTAR shown in Figure 2.

5.3.2.2.1.4

TRIUMF's Ion Trap for Atomic and Nuclear Science: TITAN

Introduction

To understand the nature of the atomic nucleus and to generate a coherent picture of how all the elements in the universe were made in a process called nuclear synthesis, it is necessary to determine both the basic properties of these "exotic nuclei," and to study their interactions. TITAN (TRIUMF's Ion Trap for Atomic and Nuclear Science) is ideally suited to perform these measurements. It is a multi-purpose, multi-component apparatus, designed and built to carry out precision experiments on the most exotic isotopes available at ISAC-I; it is a unique facility in the world.

Experimenters using the TITAN facility will determine such fundamental properties as the mass of the atom, and the shape and internal interactions of the nuclear core by using X-ray and laser-spectroscopy techniques. They will investigate the decay of exotic nuclei to help solve the Majorana neutrino puzzle of whether the anti-neutrino and the neutrino are actually the same particle.

Their contribution is via precision branching ratio measurements of double β-decay, which tests the underlying nuclear theory. Matrix elements are needed to determine the mass of the Majorana neutrino, when found.

The key to making successful measurements is achieving precision through excellent control of the nuclei and the experimental apparatus. This level of control is reached by carrying out the measurement on only a single ion at a time. The measurements are performed using ion-trapping techniques, employing Penning and Paul traps, devices for which their inventers, H. Dehmelt and W. Paul, received the Nobel Prize in Physics in 1989.

The TITAN facility started construction in April 2003 with an NSERC Research Tools and Instruments grant. A year later, a significant Canada Foundation for Innovation component of $C250,000 was awarded to G. Gwinner of the University of Manitoba. In December 2006, ISAC successfully delivered the first test beam, and TITAN achieved proof of principle. In August 2007, the TITAN Group carried out its first successful on-line mass measurement on singly charged ions. Next steps will include the integration of the electron beam ion trap (EBIT) for experiments on highly charged ions in summer 2008. The collaboration partner from the University of Giessen, Germany, will bring an isobar separator multi-time-of-flight reflectometer for tests in the winter of 2008–2009. The double-β decay experiments are scheduled for detector testing in the winter of 2008–2009, and the first branching ratio measurements in the summer of 2009.

Description of Dedicated Apparatus

The TITAN facility consists of three independent ion trap systems: the radio-frequency quadrupole (RFQ) cooler and buncher; the electron-beam ion trap (EBIT), charge breeder, and the Penning trap for the mass measurements (see Figure 1). Later, a Cooler Penning trap will be installed from University of

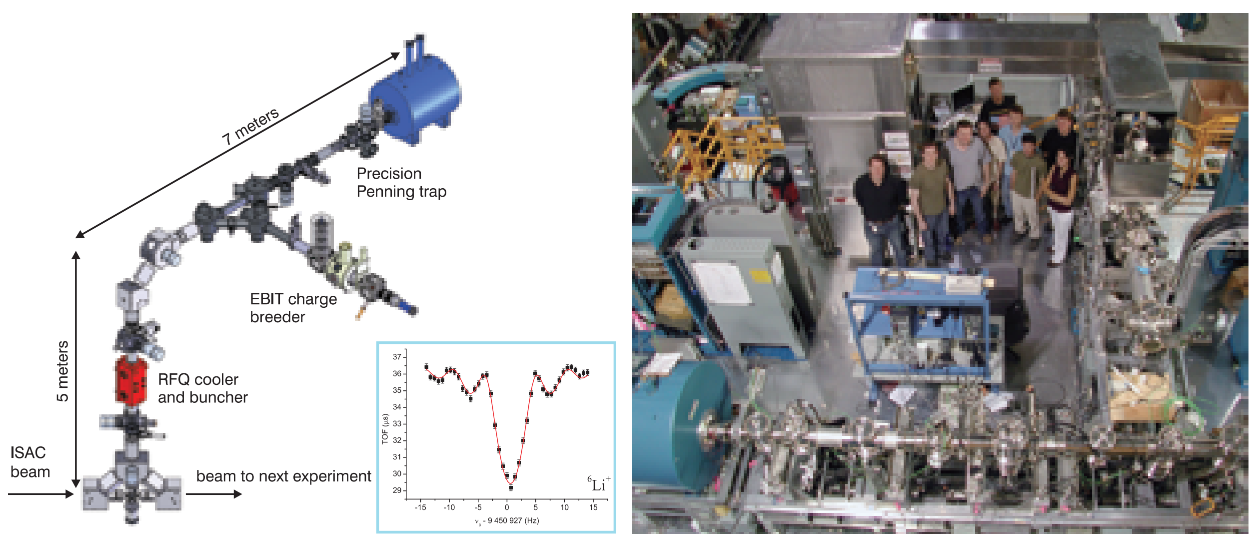


Figure 1: Schematic diagram, photograph of the TITAN Group, and spectrum from TITAN. The diagram of TITAN shows the RFQ cooler and buncher, the EBIT, and the precision Penning trap. Centre: the characteristic time-of-flight resonance curve for $^{6}Li^{+}$ from the Penning trap.

Manitoba to allow for cooling of highly charged ions, and for isobar-cleaning. The system is set up following the principle of separation of functions, which makes the individual units maximally efficient and allows optimal flexibility.

The RFQ is coupled to the ISAC-I beam (from the left in Figure 1). The 60 keV DC ion beam is decelerated in the RFQ to a few tens of eV. It is then trapped and cooled with inert buffer gas. Once the ions are cool, the trap potential is opened, and the ions are released as a bunch. This can be done uniquely at TITAN, either in the forward or backward direction. The backward option brings the beam back to the ISAC-I beam line, and makes a cooled and bunched ion beam available for the next experiments (to the right in Figure 1), such as collinear laser spectroscopy, or β-NMR. In the forward extraction mode, the beam is delivered to the next TITAN component, which is the EBIT or the Penning trap.

The EBIT's main function is to change the charge state of the ions from singly charged to highly charged ions, which is done by trapping the ion in the EBIT and stripping electrons away with an energetic electron beam. EBITs are typically employed for stable isotopes, and this is the first and only EBIT coupled to a rare-isotope beam facility. The requirements of short-lived isotopes demand very fast and efficient charge breeding, hence the TITAN device is adapted to that by having a factor of ten higher electron currents than typical EBITs, and it is fitted with seven radial ports for on-line diagnostics and for experimental purposes. Once the ions have reached a high charge state, they are delivered to the Penning trap.

In a Penning, charged particles are trapped by the combination of a strong homogeneous magnetic field and a weak quadrupolar electric field. The motion of the particles is well understood, and we can determine the mass via the cyclotron frequency. For a particle with mass m and charge q in a magnetic field B, the cyclotron frequency is given by $\nu_c = q/m \times B/2\pi$. A typical time-of-flight resonance curve for stable Li is shown in the inset of Figure 1. The

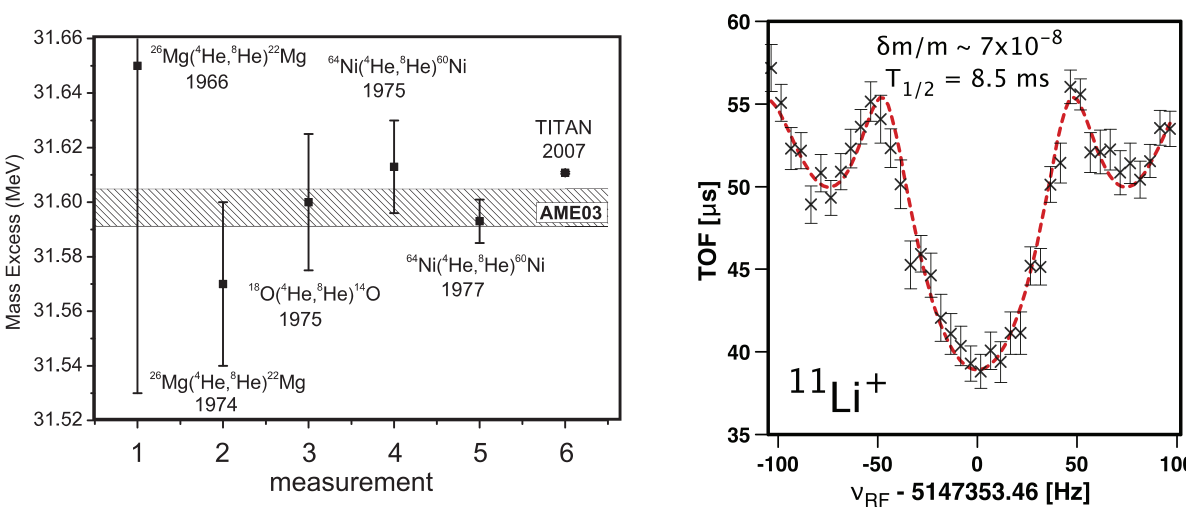


Figure 2: Examples of TITAN's experimental capabilities. Left: Older measurements of the mass of the 4-neutron halo ^{8}He are compared with the new TITAN result. Right: The characteristic time-of-flight resonance curve, of the neutron halo ^{11}Li, of the Penning trap.

JENS DILLING

TRIUMF Research Scientist
Adjunct Professor of Physics, UBC

Jens Dilling is an expert in precision experiments for nuclear physics using atomic physics techniques, expertise he acquired during his graduate studies at the University of Heidelberg. In 1997, he carried out his M.Sc. work at TRIUMF with the TRIUMF Neutral Atom Trap facility (TRINAT) and investigations of the standard model of weak interactions, measuring beta-neutrino correlations.

Dr. Dilling completed his Ph.D. thesis in 2001 at CERN's ISOLDE facility and at SHIP, the super-heavy ion in-flight facility at GSI in Darmstadt. His thesis focused on the ion trap technique of 1989 Nobel prizewinners Dehmelt and Paul and was the first to include measurements carried out both with Penning traps at ISOL-type and in-flight facilities.

Dr. Dilling returned to TRIUMF in 2001 as a research scientist and leader of the TITAN (TRIUMF Ion Trap for Atomic and Nuclear science) project. This highly successful program now delivers the most precise mass data on the halo-nuclei, such as ^{11}Li.

Jens is actively involved in the Canadian and international physics community. He served on the TRIUMF Users' Group from 2005–2007 and on the NSERC Long-Range Planning Committee. He is currently the Canadian representative on the IUPAP (International Union for Pure and Applied Physics) C2 commission for masses and fundamental constants, and Chair of the 2010 International Nuclear Physics Conference (INPC) to be held in Vancouver.

precision of the mass measurement scales with the charge state q, and hence the use of the EBIT for charge breeding.

Recent Developments

At present, TITAN is the most advanced mass spectrometer in the world coupled to a rare-isotope beam facility. It has the unique capabilities to carry out experiments on highly charged ions that will lead to an increase in precision in the mass determination of almost two orders of magnitude, for example, for francium isotopes.

TITAN holds the record for measurements on short-lived isotopes on both the lightest nuclei ever trapped and the shortest-lived isotopes (see Figure 2). For the half-life, an improvement of almost an order of magnitude was reached. These two unique features enabled the precision measurements on the halo nuclei, for example ^{11}Li ($t_{1/2} = 8.5$ ms).

TITAN's future scientific program will include the full exploitation of ISAC-I's capabilities to produce very exotic nuclei for mass measurements, laser spectroscopy, X-ray spectroscopy on highly charged rare isotopes, and to determine electron-capture branching ratios. Electron-capture branching ratios represent an ideal way to probe the framework, which is used to determine the nuclear transition matrix element for double beta decay. These, in turn, are needed for neutrinoless β-decay and the search for Majorana neutrinos, for example at the Sudbury Neutrino Laboratory.

Partners

In Canada: McGill University, the University of British Columbia, University of Calgary, University of Manitoba, University of Windsor, and York University.

International Partners: France (4), Germany (4), Japan (1), the United Kingdom (1), and the United States (2).

TRIUMF's Role

J. Dilling, TITAN's principal investigator, is a TRIUMF scientist. TRIUMF's staff and university scientists together drive the science program. TRIUMF provides the vast majority of technical support including engineering and design, mechanical and electrical machine shops, and control support for the system. TRIUMF plays a decisive role by providing continued maintenance by a full-time technician.

5.3.2.2.1.5

Laser Spectroscopy Facilities

Introduction

By its very nature in an atom, the nucleus is surrounded by and interacts with a cloud of atomic electrons. The use of high-precision laser spectroscopy as a probe of electronic structure yields detailed information about the interaction between the nucleus and its orbiting electrons. Detailed spectroscopic studies of the electronic structure along a chain of radioactive isotopes of the same chemical element can yield information not only on electronic structure, but also on nucleus-electron interactions. When undertaken at very high precision, these studies provide a method to determine some nuclear properties: the changes in the mean squared charge radii and the ratio of ground and long-lived isomeric state nuclear moments. To achieve the high precision necessary for these measurements at a radioactive beam facility, where beams of exotic species are available as slow (~metres per second) ionic beams, it was necessary to remove the inherent velocity spread of the ions that occur during production and ionization. TRIUMF has achieved this by using two different methods.

The first method provided the measurement that gave the first direct evidence for the ^{11}Li nucleus having a single neutron halo. In collaboration with

GSI, which developed the technique, TRIUMF, determined the measurement of the charge radius of ^{11}Li by first stopping the beam within a carbon foil prior to being re-evaporated, giving a thermal vapour upon which laser spectroscopy could be performed. This ensured the ^{11}Li atoms lost any memory of their production mechanism.

The second, and more universal, method increases the energy of an ionic beam to reduce the velocity spread of the beam. With this method, it is possible to reduce the Doppler width to levels where it is possible to extract the nuclear information of interest. If an ionic (or atomic) beam is arranged to propagate collinearly with a narrow line-width, tunable laser beam, the resulting fluorescence spectrum exhibits a line-width greatly reduced from one that would be achieved within the ion source. A schematic of the set-up is shown in Figure 1. This method has been used to make measurements of the ground state moments of ^{131}La, giving the first evidence for the existence of tri-axially deformed or pear-shaped ground state nuclei in this region.

Description of Dedicated Apparatus

The collinear fast beam, laser spectroscopy facility utilizes the polarizer beam line as well as the radio-frequency quadrupole (RFQ) cooler buncher within the TITAN facility. Beams from the ISAC target are either taken directly into the beam line where they either pass through as an ionic beam or are neutralized to provide an atomic beam. This fast beam is then overlapped with a laser beam and the laser frequency scanned. When the laser frequency exactly matches that of an atomic transition, light is absorbed and then re-emitted. As the re-emission is isotropic in space, a detector mounted at 90° to the direction of propagation of the laser and atomic/ionic beams sees predominantly photons from the re-emission providing a direct measure of the adsorption of the laser light. A plot of laser frequency (in the centre-of-mass frame) against emitted fluorescence gives a direct measure of the energy of the atomic transition (see Figure 2). A fast beam is used to compress the velocity spread inherent from the ion source. The incorporation of the TITAN RFQ into the beam line prior to the light interaction region has further increased the sensitivity of the system. The energy and therefore velocity spread is greatly reduced by cooling and bunching the beam. Also, by bunching the beam and only

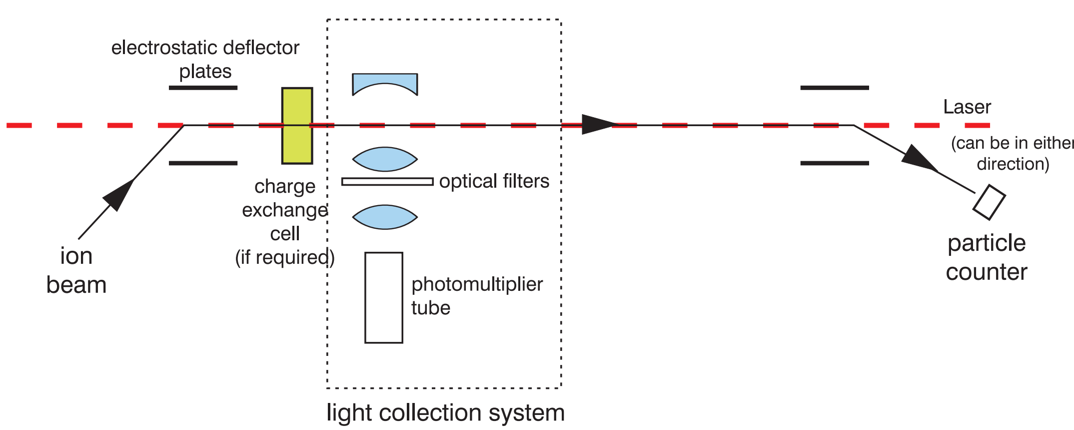


Figure 1: The collinear spectroscopy facility.

accepting photons from the light collection region while the ion beam is passing through it, the background is reduced by the duty cycle of the bunched beam (currently a 2 μs bunch produced at a frequency of 10 Hz therefore an increase in sensitivity of 50,000) with negligible loss of real fluorescence photons.

Recent Developments

Since the commissioning as a collinear beam line, several upgrades have been performed. The post-acceleration region and light collection optics have been constantly upgraded. In 2007, the TITAN RFQ came on-line, which allowed cooled, bunched beams to be utilized. The data acquisition system has been adapted to incorporate this facility.

Partners

In Canada: McGill University, University of Calgary, and the University of Western Ontario.

International Partners: Japan (1); Sweden (1), the United Kingdom (1), and the United States (1).

TRIUMF's Role

Besides being the world's premier rare-isotope beam facility for the production of the most intense radioactive beams, TRIUMF has contributed in many other ways to the success of laser spectroscopy. The beam quality within the ISAC facility is second to none, and results in high spatial overlap of the laser and ion beams. The construction and continuing support of the TITAN RFQ has permitted spectroscopy on cooled, bunched beams to enhance the sensitivity of the system by many orders of magnitude.

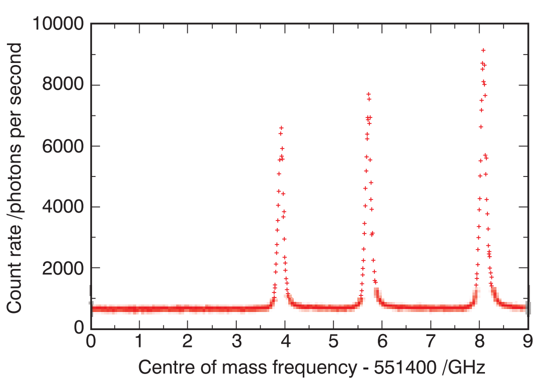


Figure 2: The intensity of the fluorescence light as a function of the laser light frequency on the ^{139}La atom. The electronic transition is from the metastable $6s^2\ ^1S_0$ to the $5d6p\ ^3D_1$ state. The three transitions arise from the hyperfine splitting of the $J = 1$ upper state (the lower state is $J = 0$, therefore there is no splitting).

5.3.2.2.2

ISAC-II Facilities

5.3.2.2.2.1

TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer: TIGRESS

Introduction

The TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) is a major new international user facility. It is a state-of-the-art γ-ray spectrometer developed specifically for use at TRIUMF's higher mass and higher energy Isotope Separator and Accelerator (ISAC) rare-isotope ion beam facility. TIGRESS has been designed and built to answer many important questions on nuclear structure using several different reaction mechanisms. Each of these reaction mechanisms accesses different energies, spins, and components of the wave functions, and each shines a different light on the nucleus. The two features they share are that they require beams accelerated to the energies provided by ISAC-II, and the γ-rays are measured with TIGRESS.

We think we know that nuclei contain protons and neutrons. But what does a nucleus look like? Do the protons and neutrons (or together, called nucleons) stick together to form a bumpy, round ball? The answer to this question is very definitely no: the nucleus is small enough that the nucleons are better described as waves than as particles. Beyond that, the questions become more challenging. Do the waves act independently of one another, like the orbits of planets around the sun? Or do they pile up on one another? If they pile up on one another, does the nucleus end up looking like a drop of wiggling goo, or a solid, spinning pear-shaped lump?

The answer to all of the above is "yes and no", or, "depends on the numbers of protons and neutrons." The question can be better asked, "What is the structure of the nucleus?" From an experimental perspective, the answer means measuring the energy, spin (a quantum mechanical property analogous to rotation), and parity (does it look the same in a mirror) of states of the nucleus. Theoretically, the question is whether the structure is dominated by the wave functions of a small number of valence nucleons outside a closed shell, the single-particle picture, or do the wave functions become coherent and resemble a semi-classical vibrating or rotating object, *i.e.*, the collective picture. Understanding nuclear structure means searching for the closed shell numbers and understanding how the wave functions change from single-particle to collective by adding or removing protons or neutrons.

One aspect of nuclear structure is the mass of a nucleus, which is measured with TRIUMF's TITAN (see Section 5.3.2.2.1.4). Another aspect is energy of the excited states. Quantum systems can absorb or release energy in well-defined steps corresponding to the energy differences between states. One way of releasing energy is by emitting photons, which, when they come from a nucleus, are called γ-rays. The energy of the γ-rays directly measures the difference in energies between states, while the direction of emission depends on the spins of the states.

Energy can be put into an individual nucleus by turning it into a projectile. By accelerating the nucleus to high enough speeds, it can overcome the electric repulsion between the beam nucleus and a stationary nucleus in a fixed target. If the nuclei touch, *i.e.*, the wave functions of the projectile and target overlap, the two nuclei can stick together. These "fusion-evaporation" reactions impart the most energy to the final, residual nucleus, and several γ-rays (and possibly particles) are released in the process. If the wave functions just barely overlap, a "transfer reaction" may occur in which several, or possibly only one or two neutrons or protons move from one nucleus to the other. In these experiments, γ-rays are valuable for identifying whether the projectile, target, or both are excited, and if so, by how much. Finally, in a near-collision, where the nuclei do not touch, the violence of the repulsion of the target and projectile is enough to shake one or both into an excited state. Because this process occurs solely due to electric repulsion, it is called Coulomb excitation.

Description of Dedicated Apparatus

TIGRESS will comprise of twelve 32-fold segmented clover-type high-purity germanium (HPGe) detectors purchased from Canberra Canada. Each of these detectors consists of four individual HPGe crystals packed in a four-leaf-clover geometry (see Figure 1). Each crystal is read out by 8 ground connections: one on each of the volumes (labeled 1 to 8). The high voltage is applied to the central bore of each crystal, on an electrical contact on a hole drilled from the back of the crystal through about two-thirds of the crystal (not visible in the orientation of this figure). A signal is also taken from this core contact to measure the full energy for each crystal. This segmentation provides coarse-grained information about the locations of the γ-ray interactions within the crystals. Fine-grained position information is then obtained by pulse-shape analysis of the 9 charge-collecting signals. By the combination of these techniques, sub-mm position resolution for single γ-ray interaction has been demonstrated for the TIGRESS detectors.

Reconstruction of the initial γ-ray interaction positions within ± 2.5 mm is expected in typical in-beam experimental conditions. This position sensitivity allows the angle of emission of the γ-rays relative to the recoiling nuclear sources (which determines the Doppler broadening of the resulting γ-ray energy resolution) to be well determined even for detectors positioned in close proximity (11 cm) to the target location. The resulting large solid-angle coverage by a modest number of detectors (12) leads to large gains in γ-ray detection efficiency, compared to previous generation spectrometers, without sacrificing γ-ray energy resolution in in-beam experiments. The full TIGRESS array will, for example, have an absolute detection efficiency of 10% for 1 MeV γ-rays. This high-detection efficiency enables in-beam experiments with accelerated rare-isotope beams with typical intensities that are orders of magnitude below stable beam standards.

In addition to the highly segmented HPGe clover detectors, TIGRESS also employs 20-fold segmented bismuth-germanate (BGO) and CsI(Tl) Compton

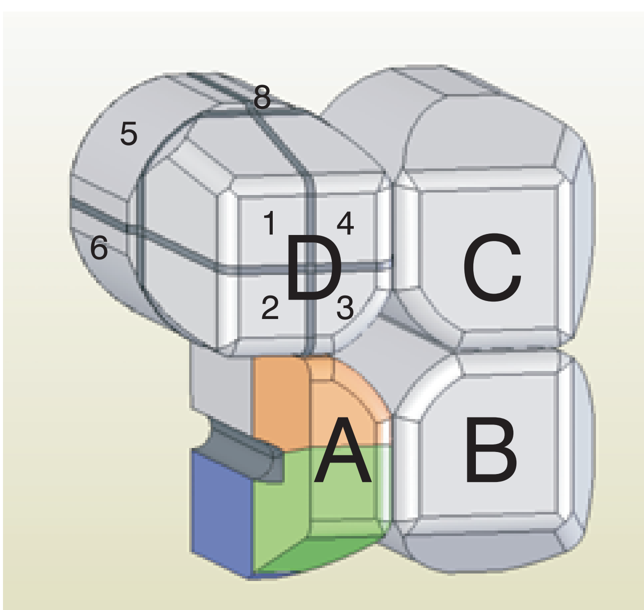


Figure 1: The TIGRESS clover detector consisting of four HPGe crystals labeled A, B, C and D.

suppression shields to provide segment-specific vetoing of events in which γ-rays escape the HPGe volume without depositing their full energy. These are mounted in a versatile mechanical structure that enables rapid redeployment of the array between a maximum-efficiency and an optimal suppression configuration. Both the HPGe and BGO detectors are read out by fast (100 MHz, 14-bit) 10-channel waveform digitizer (TIG-10). Collector (TIG-C) modules make trigger decisions and provide dataflow between the TIG-10 modules and the data acquisition computers. Both types of of modules have been custom designed for TIGRESS and produced at l'Université de Montréal.

Recent Developments

TIGRESS was funded in 2003 by an C$8 million, six-year NSERC Major Installation Grant. Six of the twelve HPGe plus Compton suppressor systems have now been received, fully tested, and installed in the TIGRESS mechanical support structure at ISAC-II (see Figures 2 and 3).

The final version of the TIG-10 digitizer cards is in production, and 45 of these modules, together with 6 TIG-C collector modules that demonstrate the full multi-level TIG-C hierarchy, have been tested and are now operational at ISAC-II. This six-detector early implementation of TIGRESS was used in the first experiment with accelerated radioactive beam (^{29}Na) from the newly commissioned ISAC-II superconducting linac in July and August 2007. All subsystems of the spectrometer were interfaced flawlessly, representing the achievement of a major milestone for the project.

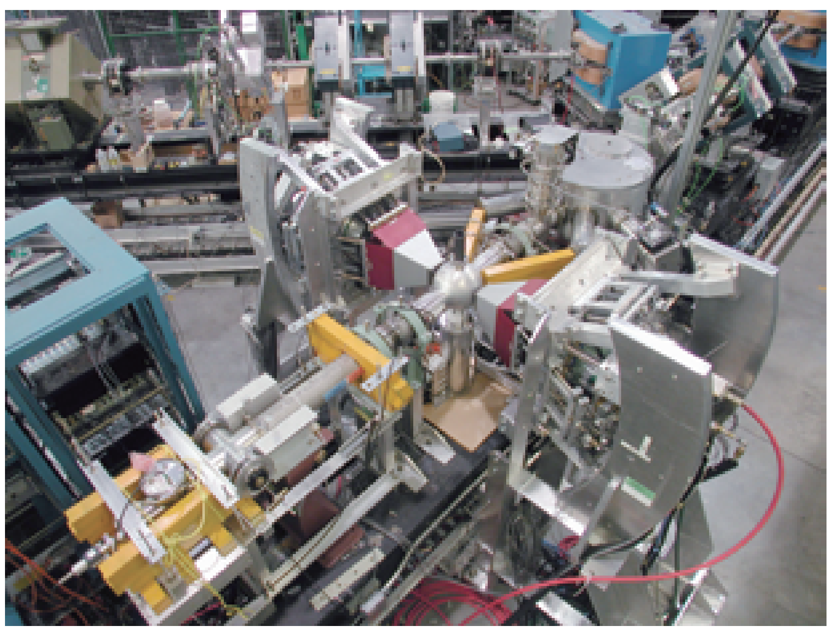


Figure 2: Two TIGRESS detector systems at the ISAC-I zero-degree beam line used for the first TIGRESS Coulomb excitation experiments with accelerated radioactive beams ^{20,21}Na in July 2006. The detectors have their Compton suppression detectors in place, as will be the case when the full array is in its maximum signal-to-noise configuration.

TIGRESS is now operational as an experimental user facility for the Canadian and international γ-ray spectroscopy communities. Additional experiments with light accelerated beams (^{11}Be and ^{21}Na) are being carried out in the spring and summer of 2008, as well as the first heavier ($A > 29$) accelerated beams from the new ISAC charge-state booster scheduled for spring 2009. These latter experiments are expected to be performed with 9 TIGRESS detector systems, with the full complement of 12 detector units installed and operational in summer 2009.

In parallel with the installation of TIGRESS itself, rapid development has been taking place in the implementation of the suite of associated detectors necessary to provide detection of scattered heavy ions, light charged particles, and neutrons in coincidence with the γ-rays detected by TIGRESS. The first of these, employed in the ^{20,21}Na and ^{29}Na Coulomb excitation experiments at ISAC-I and ISAC-II, respectively, is the Bambino Si CD detector, (so named because it is shaped like a compact disc), which was assembled at Lawrence Livermore National Laboratory and mounted in a TIGRESS target chamber designed and built at the University of Rochester (see Figure 4). The new Silicon Highly Segmented Array for Reactions and Coulex (SHARC), comprised of 576 channels of double-sided silicon strip detectors for use with TIGRESS, has been funded by the United Kingdom and is under construction at the University of York in the UK and Louisiana State University and Colorado School of Mines in the US. The York TIGRESS collaborators are also building an

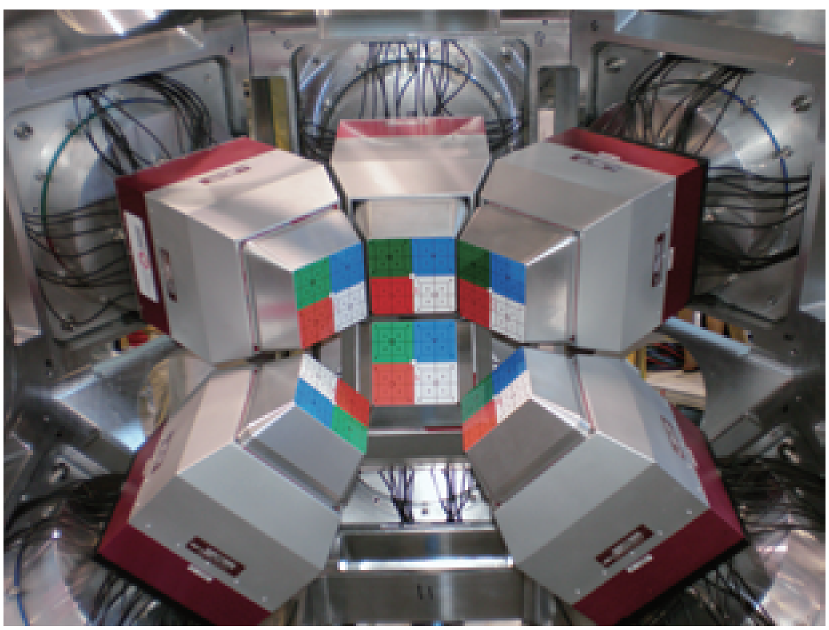


Figure 3: Six TIGRESS detector systems used in the first Coulomb excitation experiment with accelerated radioactive beam (^{29}Na) from the new ISAC-II superconducting linac in July 2007. The detectors are in a close packed configuration, and do not have their Compton suppression detectors in place, as will be the case when the full array is in its maximum efficiency configuration.

array of five Bragg curve detectors that will couple to TIGRESS for heavy-ion detection and Z identification.

The C$1.79M Deuterated Scintillator Array for Neutron Tagging (DESCANT) was funded by the Canada Foundation for Innovation (CFI) in 2007 and is under development at the University of Guelph and TRIUMF. A CsI(Tl) charged-particle detector for TIGRESS was funded by NSERC for C$71,833 in 2006 and is under development at Saint Mary's University, together with a pool of TIG-10 and TIG-48 waveform digitizers for TIGRESS auxiliary detectors funded by a C$324,089 award from the CFI. For many experiments at ISAC-II, TIGRESS will also operate together with the ElectroMagnetic Mass Analyser (EMMA) funded jointly by a C$2.085 million NSERC award and a C$1.0 million TRIUMF contribution in 2006. Each of these associated devices will provide unique capabilities that will enhance the sensitivity of TIGRESS and permit whole classes of experiments at ISAC-II that would otherwise be impossible.

Partners

In Canada: Laval University, l'Université de Montréal, the University of Guelph, McMaster University, Saint Mary's University, Simon Fraser University, and the University of Toronto.

International Partners: France (1), the United Kingdom (3), and the United States (4).

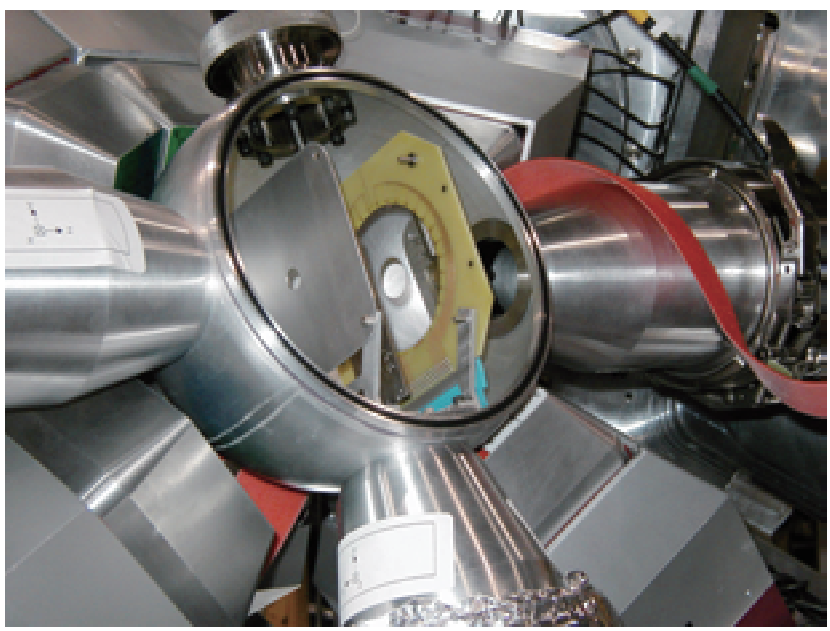


Figure 4: The BAMBINO Si CD detector mounted inside the TIGRESS target chamber. The beam enters from the left, impinges on a thin foil target (behind the Al collimator plate) and passes through the hole in the centre of the Si CD detector.

TRIUMF's Role

TRIUMF has made major contributions to the design and installation of TIGRESS. F. Cifarelli of the TRIUMF Design Office designed all of the TIGRESS mechanical support structure and detector mounting machines, and TRIUMF engineers verified them through finite element analysis. The machining of components was carried out in parallel by the TRIUMF and the University of Guelph machine shops, as well as by external contractors.

TRIUMF has also provided a dedicated detector laboratory in the ISAC-II building for the testing, characterization, and maintenance of TIGRESS detectors. The precision scanning table in this laboratory was supported through the Laboratory for Advanced Detector Development at TRIUMF.

In addition to the ISAC-II superconducting linear accelerator, the TRIUMF Accelerator Division designed and constructed the dedicated high-energy beam transport line (SEBT-3A) to the TIGRESS location in the ISAC-II hall.

A dedicated TRIUMF technician, R. Churchman, provides ongoing technical support for TIGRESS, while a second technician, R. Maharaj, coordinated design, procurement, parts, and machining during the mechanical construction phase. Staff Scientist G. Hackman manages all on-site activities related to TIGRESS and is supported by G. Ball, a second TRIUMF scientist.

Two members of the TRIUMF Data Acquisitions Group, P. Amaudruz and C. Pearson, provide ongoing support for TIGRESS. They have been, and continue to be, instrumental in the development and implementation of the custom TIGRESS waveform digitizer modules. Isolated electrical power distribution, an air-conditioned electronics enclosure, an instrumented beam dump, front-end readout, back-end workstations, and networks for TIGRESS data acquisition have all been provided by TRIUMF.

5.3.2.2.2.2

ElectroMagnetic Mass Analyser: EMMA

Introduction

Nuclear astrophysics is concerned with the creation of the elements that make up our world. To do this, physicists have had to develop a wide range of tools to probe, study, and understand the nuclei and the many reactions nuclei undergo. Different tools are required for different applications. The ElectroMagnetic Mass Analyser (EMMA) is one of the tools that will be used at TRIUMF's Isotope Separator and Accelerator (ISAC) rare-isotope ion beam facility.

EMMA is an advanced recoil mass spectrometer for use with heavy rare-isotope ion beams. ISAC-II will provide intense, high-quality beams of radioactive ions with masses up to 150 atomic mass units and maximum energies of at least 6.5 MeV/nucleon. These beams will be used to study the single-particle structure of exotic nuclei, the evolution of nuclear structure and shapes far from stability and at high spin, fundamental symmetries, and nuclear astrophysics.

EMMA will be an integral part of the experimental program at ISAC-II, both as a stand-alone device and in conjunction with other particle detection systems. One important avenue of research will involve the coupling of EMMA with the TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer

(TIGRESS). By positioning TIGRESS around the target position of EMMA, prompt gamma rays emitted by a recoiling nucleus formed in a fusion-evaporation or transfer reaction can be correlated with the arrival of the recoil at the focal plane of EMMA. Focal plane detectors will allow the determination of the mass, and in many cases the atomic number of the recoil using position, energy loss, and time-of-flight measurements. The recoil information allows very weak reaction channels to be studied in the presence of very high yield background channels, enabling the exploration of high-spin states in exotic nuclei as well as their low-lying, single-particle structures.

In 2006, EMMA was funded by a $C2 million NSERC Subatomic Physics Research Tools and Instruments award, and a $C1 million contribution from TRIUMF. This will allow EMMA to be commissioned in 2010. When it begins operation, EMMA will be an important new international user facility for nuclear structure and astrophysics with accelerated rare-isotope beams, demonstrated in part by overwhelming interest in the two recent EMMA workshops.

Description of Dedicated Apparatus

EMMA is an electromagnetic recoil mass spectrometer designed to separate the recoils of nuclear reactions from the primary beam and to disperse them in a focal plane according to their mass-to-charge ratio (*m/q*) (see Figure 1). Measurements of position, energy loss, energy, and time of flight will serve to uniquely identify the transmitted recoils. In addition to having a large solid angle of 16 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 mono-energetic ions of a single mass within the spectrometer are isochronous within 0.1%, allowing high-resolution time-of-flight measurements and large real-to-random ratios in coincidence experiments. These properties make EMMA a recoil mass spectrometer of unprecedented quality that is ideally adapted to the very strin-

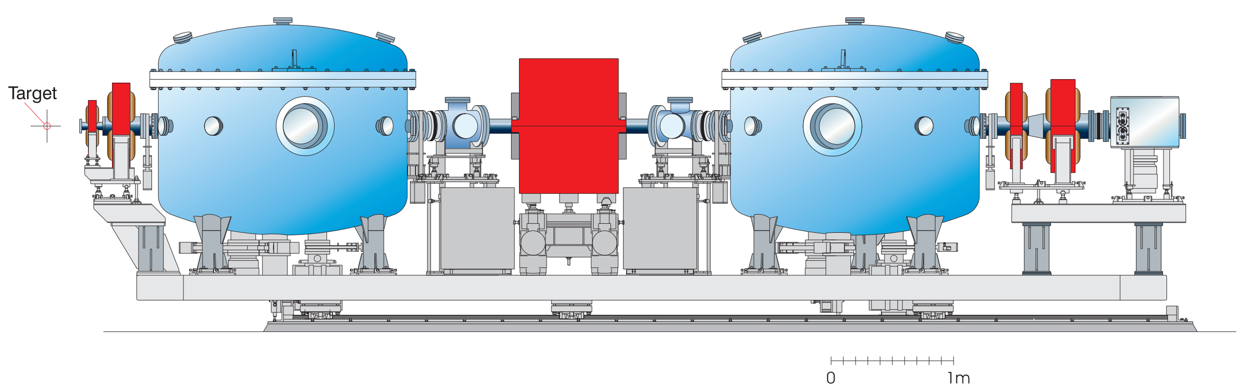


Figure 1: Schematic view of EMMA showing the two large electric dipoles on either side of the central magnetic dipole. Magnetic quadrupole doublets at the front and back serve to spatially focus the recoiling nuclei and allow for variable mass dispersion.

gent requirements for precision ISAC-II experiments at the edge of nuclear existence.

Figure 2 shows the calculated focal plane position spectra for EMMA and the FMA, a similar recoil mass spectrometer at Argonne National Laboratory. The same recoil mass, energy, and angular distributions were used as input in the simulations, which show the results for 11 masses centred about $A = 100$ with charge state $q = 20$ having uniform ±10% spreads about the central energy of 1.8 A MeV and uniform angular distributions filling 30 msr (± 5°). As the figure shows, EMMA has twice the angular acceptance of the FMA and a larger m/q acceptance without compromising m/q resolution.

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 rare-isotope 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 multi-wire 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 make EMMA an unparalleled instrument for nuclear physics research. When commissioned in 2010 and coupled with the unique radioactive ion beams from ISAC-II and the advanced γ-ray spectrometer TIGRESS, EMMA will position TRIUMF as the world leader in rare-isotope beam physics at the Coulomb barrier.

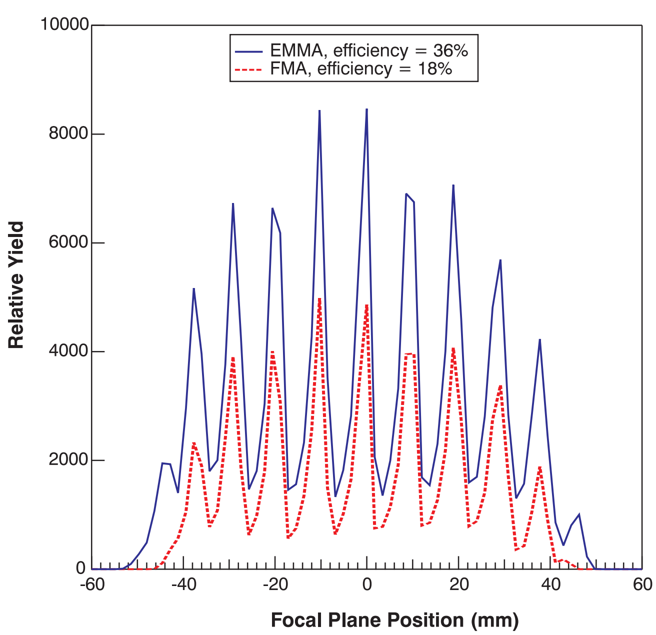


Figure 2: Calculated mass spectra for EMMA and the FMA of Argonne National Laboratory with identical recoil mass, energy, and angular distributions. EMMA exhibits efficiency twice as large as that of the FMA while preserving superior mass resolution.

Recent Developments

After funding was obtained in 2006, a dedicated effort was required to precisely specify the electromagnetic and mechanical properties of the spectrometer that are so 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. The contract was awarded to Bruker BioSpin in 2007, and fabrication has begun.

In addition to the work on EMMA, substantial progress has been made on other ISAC-II detector systems. EMMA will operate together with many experiments at ISAC-II, and its associated detector systems such as the Silicon Highly Segmented Array for Reactions and Coulex (SHARC) and the Deuterated Scintillator Array for Neutron Tagging (DESCANT). Each of these detector arrays will provide unique capabilities to enhance the utility of EMMA and enable experiments at ISAC-II that would otherwise be impossible.

Partners

In Canada: University of Alberta, University of Guelph, McMaster University, Saint Mary's University, and Simon Fraser University.

International Partners: Germany (1), Japan (1), United Kingdom (3), and the United States (5).

TRIUMF's Role

TRIUMF has made major contributions to the design of EMMA and will make major contributions to its installation. All of the design effort for the EMMA mechanical support structure, the target chamber, and the focal plane box is being carried out by the TRIUMF Design Office, led by Mechanical Designer F. Cifarelli and Project Engineer N. Khan. TRIUMF also will provide the high voltage power supplies for the electric dipoles of EMMA. The TRIUMF Detector Group will construct and test the position-sensitive multi-wire gas detectors and the ionization chambers for the focal plane.

5.3.2.2.2.3

DEuterated SCintillator Array for Neutron Tagging: DESCANT

Introduction

Much of the structure of neutron-rich nuclei is unknown, and extrapolations using current theories and knowledge possess a high degree of uncertainty due to the modifications of shell structure as the neutron drip line is approached. Studies of neutron-rich nuclei using reactions, such as fusion-evaporation reactions, which have formed the backbone of techniques to study nuclear structure, will be hampered because of the tendency of the compound system to emit multiple neutrons during the cooling phase. Thus, methods for nucleus identification that rely on charged-particle detection will not be as useful, and neutron or recoil detection will be an absolute necessity. However, for many reaction networks, the recoil will not be sufficiently energetic or constrained within the narrow acceptance cone of EMMA (ElectroMagnetic Mass

Analyser). Furthermore, there will be a definite need to characterize the number of neutrons, or neutron multiplicity, emitted in the reaction. Thus, there is a definite need for a neutron detector array that can be coupled with TIGRESS.

ISAC-II represents major advancements in the technology that produces and delivers rare-isotope beams for experiments. Along with the need to continually develop production and accelerator technology to boost the beam intensity, is the need to develop advanced detector capabilities. TRIUMF and its partners have developed state-of-the-art γ-ray detectors such as TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS); with a team at TRIUMF, a principal investigator at the University of Guelph is now developing the Deuterated Scintillator Array for Neutron Tagging (DESCANT), a major new capability in neutron detection that will serve as an auxiliary detector for the TIGRESS spectrometer. The proposed array of neutron detectors, using a liquid scintillator based on a deuterated hydrocarbon, will be the first detector array based on this technology ever developed.

In addition to the need for neutron detection in fusion-evaporation studies, a neutron detector array will also be used in reaction studies, notably those involving halo nuclei such as ^{11}Li. Small-angle correlations between neutrons emitted in reactions of ^{11}Li off of various targets contain structural information about the halo neutrons in the parent nucleus. However, in typical neutron detector arrays, these small opening-angle events must be rejected due to the large amount of detector-to-detector scatterings that are always present. A method that could successfully distinguish between multiple scattering events and true high-multiplicity events would offer a tremendous advantage.

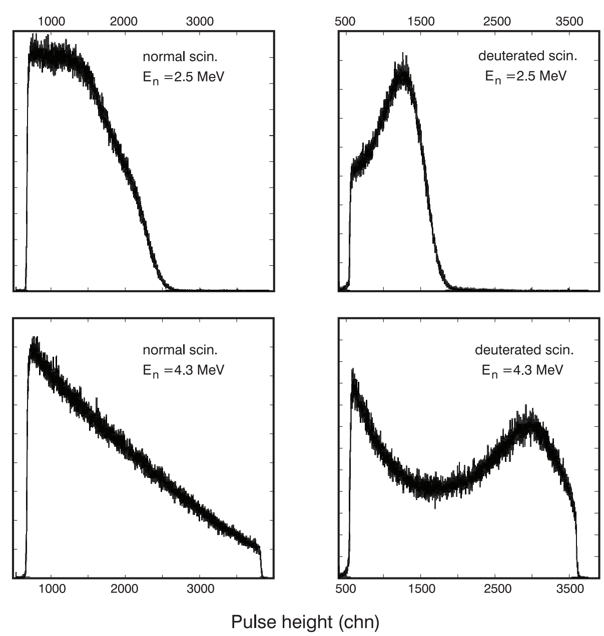


Figure 1: Pulse-height spectra for neutron energies of 2.5 MeV (top) and 4.3 MeV. (bottom) incident on a normal liquid scintillator (left) and a deuterated scintillator (right). The position of the peak in the deuterated scintillator varies as ~$(E_n)^{3/2}$.

Description of Dedicated Apparatus

DESCANT is an innovative design that will use a deuterated-benzene liquid scintillator. Due to the asymmetric nature of *n-d* scattering in the centre of mass (unlike *n-p* scattering that is isotropic), the pulse-height information from the deuterated scintillator contains information on the initial neutron energy. While deuterated detectors have been used in active-target experiments, and as γ-ray detectors in the presence of large thermal neutron fluxes, they have not been used in an array of detectors for fast neutrons.

Recent Developments

To evaluate the performance of deuterated scintillators for fast-neutron detection, a small container with active-volume dimensions of 4.5 in. diameter and 1 in. thickness filled with BC537 from St. Gobain was acquired and tested at the University of Kentucky accelerator facility. Nearly mono-energetic neutrons were produced by either the $t(p,n)^3$He or $d(d,n)^4$He reactions, and pulse-height and time-of-flight (TOF) data were recorded from both the BC537-filled cell and a cell filled with a normal scintillator like BC501 (see Figure 1). The superiority of the pulse-height spectrum over the deuterated scintillator is obvious, and it displays a definite peak-like structure. Combined with the TOF, the pulse height will allow for a much more efficient rejection of multiple scattering than has been achieved previously, yielding much higher quality data, particularly from adjacent detectors.

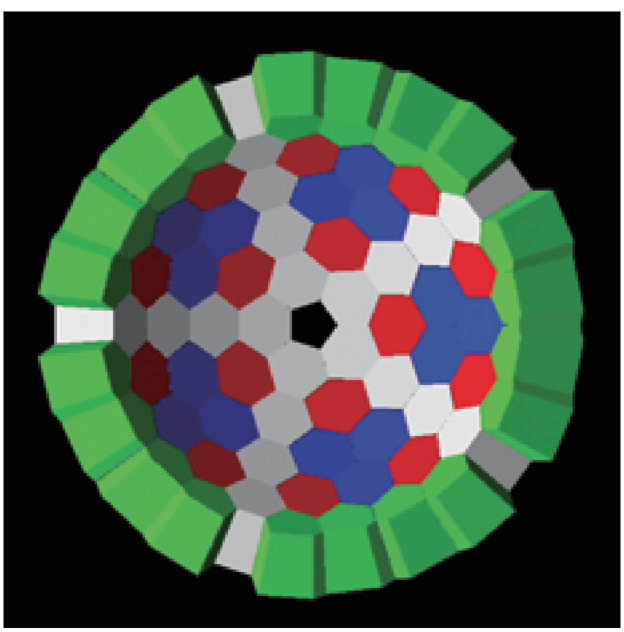


Figure 2: Arrangement of detector cells for DESCANT, seen from the upstream position looking downstream. Four different shapes, distinguished by their colour, are used to cover the available 65.5°. The detectors subtend a total solid angle of 1.08π sr.

A proposal for \$C1.8 million was submitted to the Canada Foundation for Innovation in February 2006 to construct an array of 70 approximately hexagonal-shaped truncated cones using up to 190 litres of deuterated scintillator. The proposal was accepted in November 2006, and matching funds from the Ontario Ministry of Research and Innovation (OTR) were approved in April 2007. The final budget was submitted in October 2007, and the funds released in April 2008. Included in the proposal was the development of new TIG-4G modules that will contain 4 channels of 12-bit 1-GHz waveform digitizers to be used to analyze the pulses from the anodes of the photomultiplier tubes. These cards will be engineered to be completely compatible with the TIGRESS data acquisition system.

The design of the scintillator cans, which defines the geometry of the array, has been finalized at the University of Guelph. They will be approximately 15 cm thick with the front faces at a distance of 50 cm from the target. Four different shapes are used to fill the open 65.5° in the downstream direction of the TIGRESS array (see Figure 2).

Partners

In Canada: Laval University, l'Université de Montréal, McMaster University, Saint Mary's University, Simon Fraser University, the University of Guelph and the University of Toronto.

In the United States: the Colorado School of Mines, the Georgia Institute of Technology.

TRIUMF's Role

TRIUMF's Design Office will design and manufacture the frame to accommodate the DESCANT detectors, as well as the VME64 crates required for data acquisition with the TIG-4G cards. Construction should be completed in late fall 2008 or early winter 2009. TRIUMF's personnel activities for DESCANT are coordinated by Staff Scientist G. Hackman.

5.3.2.2.2.4

Silicon Highly-Segmented Array for Reaction and Coulex: SHARC

Introduction

The Silicon Highly-segmented Array for Reactions and Coulex[1] (SHARC) is a very compact detector array designed to fit within the inner volume of the TIGRESS γ-ray spectrometer. SHARC's main purpose is to enable the study of closely spaced excited states in unstable nuclei by considering coincidences of charged particle and γ-rays. The combination of SHARC and TIGRESS will create a powerful tool to study the spectroscopy of nuclei far from stability and to understand better the structure of short-lived nuclei some of which are involved in astrophysical processes responsible for the nucleosynthesis in stars.

Description of Dedicated Apparatus

The array consists of one CD detector at backward angles and two box sections, one at backward angles, and one at forward angles with ΔE-E capability

1 Coulex is a term used to refer to the Coulomb-exchange process.

(see Figure 1). Each box's front face is made of a double-sided silicon strip detector with 48 transverse strips and 24 longitudinal strips to satisfy the required angular resolution ($\Delta\theta < 2°$ and $\Delta\phi < 5°$) (see Figure 2).

Through simulations with GEANT4, the optimal thickness of the ΔE detector was established to be 140 µm, while the E detector was made as thick as possible (1.5 mm). One of the major design challenges will be to accommodate the large number of electronics channels (732) required to instrument it within the constraint of the relatively small inner volume of the TIGRESS array (11 cm radius sphere). To get all the electronic signals out without interfering with any part of the full TIGRESS array, it will be necessary to remove the forward lampshade of the TIGRESS support structure to provide a path for the signals to exit the chamber.

Partners

In the United Kingdom: the University of York and the University of Surrey.

In the United States: The Colorado School of Mines and Louisiana State University.

TRIUMF's Role

TRIUMF will provide the designs that will integrate SHARC with TIGRESS and its beam line. TRIUMF's partners will design and construct the SHARC array.

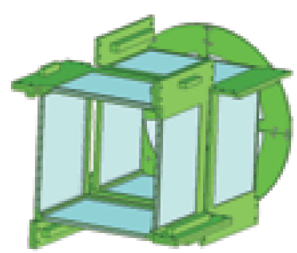


Figure 1: The SHARC array.

Figure 2: Left: Current chamber design. Right: SHARC inside TIGRESS.

5.3.2.2.2.5

HEavy-ion Reaction Array for the Characterization of Light, Excited Systems: HÉRACLES

Introduction

Why do nuclear scientists study exotic nuclei far from the valley of stability? The answer is that these nuclei were created in the thermonuclear fusion reactions that power the stars and produce the chemical elements with which the earth and all of us were made. Many of the atomic nuclei born in these reactions are rare and they decay very quickly, making them difficult to study in the laboratory. Nevertheless, because they play an important role in stellar energy generation and the synthesis of the chemical elements, nuclear scientists must understand the properties of these nuclei.

To study these rare and very short-lived nuclei, specialized tools such as the TIGRESS, EMMA and HÉRACLES detectors are required. The HEavy-ion Reaction Array for the Characterization of Light, Excited Systems (HÉRACLES) multi-detector is dedicated to the study of heavy-ion reaction dynamics. It was operated extensively at the Chalk River Tandem Accelerator and the Superconducting Cyclotron at the Chalk River Laboratories. It moved to the Cyclotron Institute at Texas A&M University in 1997. In 2003, it was moved to TRIUMF where it has been adapted to ISAC-II energies and subsequently mounted in the ISAC-II experimental hall.

The detector will be used to understand the effect of changing the ratio of protons to neutrons on the nuclear energy, referred to as the asymmetry term in nuclear mass formulae. This term is poorly determined in stable nuclei because of the limited range of proton-to-neutron ratios available. Information on its value can be obtained by studying nuclear reaction dynamics for a string of isotopes with the same number of protons but different numbers of neutrons.

Heavy ion reaction dynamics studies at ISAC-II offer the opportunity to measure nuclear interactions in which both the static and dynamical nuclear properties are important. To disentangle the various effects taking place in nuclear reactions, the HÉRACLES multi-detector will study the difference between reaction dynamics for a variety of isotopes of the same element. In this way, the effect on reaction dynamics of nuclear asymmetry can be studied on an individual element. By studying a variety of elements in this manner, nuclear scientists will gain a better understanding of the effect of asymmetry on reaction dynamics.

Description of Dedicated Apparatus

HÉRACLES is designed to detect and measure the properties of all the particles and fragments produced in a nuclear collision. Each reaction can be

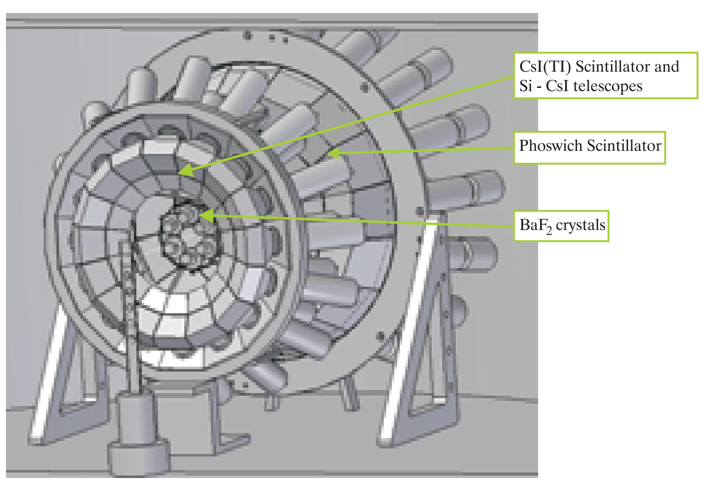


Figure 1: Sketch of the HÉRACLES multi-detector in which the three rings of segmented combined ΔE and E can be seen.

reconstructed from the measurements made on its particles and fragments. The detector is segmented in order to give directional information (see Figure 1). To measure the energy and species of the particles and fragments, most of the detectors in the array are composed of a thin detector to provide timing information and measure $\Delta E/dx$ in front of a crystal that measures the total energy. Table 1 lists the detector systems used in each ring. The first innermost ring (2–5°) is a single ring of five BaF_2 phosphorus mounted detectors. The second ring (6–10°) is a single ring of five Si – CsI telescopes. The third ring is composed of two rings each of 16 Phoswich scintillator detectors, and the outermost ring (24–46°) is made of two rings comprising a mixture of CsI(Tl) scintillator and Si – CsI telescope detectors.

Detector System	Angular Coverage (degrees)	ΔE thickness (μm)	E Threshold (MeV/nucleon)
BaF_2 Phosphorus Mounted	2 – 5	100	^{32}S : ~ 6.6
Si – CsI telescopes	6 – 10	50	^{12}C : ~ 3.5
Phoswich Scintillator	10.5 – 24	100	^{12}C : ~ 4.6
CsI(Tl) Scintillator	24 – 46	None	p,α : < 2 MeV
Si – CsI telescopes	24 – 46	50	^{24}Mg : ~ 4.6

Table 1: HÉRACLES multi-detector components: angular coverage and detector type of the various rings.

Partners

In Canada: Laval University.

In France: INDRA Collaboration at Ganil (France).

TRIUMF's Role

TRIUMF will provide the beam line, data acquisition system, the vacuum system, and the technical support for installation. HÉRACLES is mounted in its own vacuum chamber for which a new stand has been designed and ordered by the TRIUMF Design Office. Once available, the newly adapted detection units will be installed inside the scattering chamber. The silicon detectors have been ordered, and test runs will be held when the beam line for the facility is installed.

5.3.2.2.3

ISAC-I/II Facilities

5.3.2.2.3.1

TRIUMF UK Detector Array: TUDA

Introduction

The TRIUMF ISAC-I nuclear astrophysics program is carried out at a set of complementary facilities in the ISAC-I post accelerator area: the two key detectors are a large-acceptance recoil spectrometer system called DRAGON, and 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 X-ray bursters, *i.e.*, events that create the heavy elements of our universe. 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 gas cell 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 ^{11}Li 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 Dedicated Apparatus

Radioactive ion beams from ISAC-I 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. The cylindrical sections provide drift space for the beam and nuclear reaction products. The rectangular sections house the internal apparatus. The beam entrance section houses a collimator wheel, the middle section holds the target, and the end section houses the downstream flange to which the detectors are mounted.

In Figure 2, the downstream flange has been pulled back from the chamber to expose a LEDA detector pancake and its mounting. As shown, the LEDA detector (the flat plate with the cross) is mounted on long forks attached to the downstream flange. The structure behind the LEDA houses the electronics. The detector shown is composed of 8 pie-shaped segments (only 4 are installed in the picture),each having 16 individual concentric silicon strip detectors, 0.3 mm thick. Thus, each detector pancake has 128 individual independent channels. When one of the individual strip detectors detects a particle, not only is the energy measured, but the position is also determined. The hole in the centre of the array allows the unscattered beam to pass through. It is possible to stack several detector pancakes 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

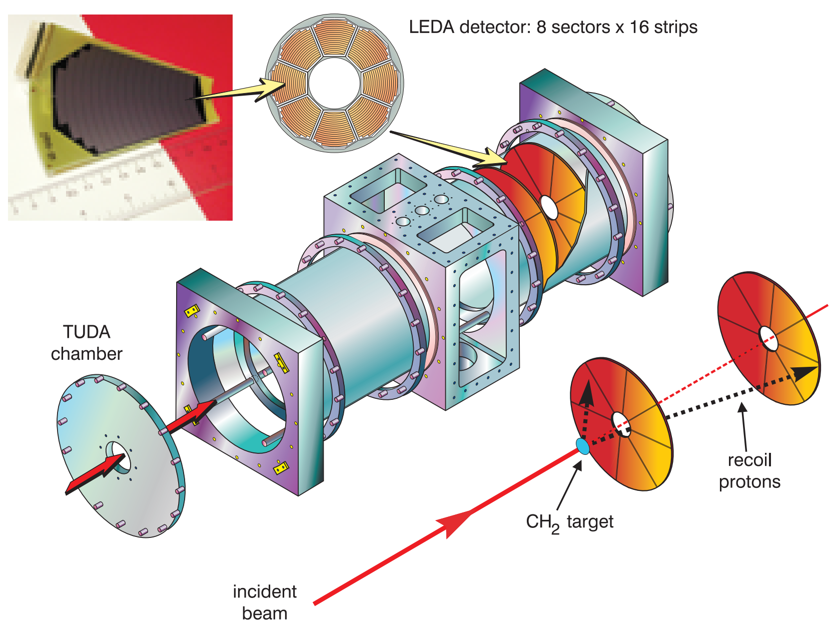


Figure 1: Artist's rendition of the TUDA facility.

detectors such as CDs and S2s. In fact, any detector can be used as long as it is properly mounted.

TUDA was designed to be mobile. It can be removed to install another facility at its beam line location. In 2007, it was removed to install TACTIC (TRIUMF Annular Chamber for Tracking and Identification of Charged Particles) for a stable beam test run and was subsequently reinstalled after the test. In 2008, TUDA will be moved to the SEBT1 beam line on ISAC-II. The higher ISAC-II energies will allow indirect studies of reactions of astrophysical significance, using (*d,p*) and (^{6}Li, *d*) reactions, plus time-reversed studies of (α,p). The facility will also be used for studies of nuclear structure such as ^{11}Li. Future TUDA experiments will be run at the ISAC-I and ISAC-II locations.

Recent Developments

As an example of how TUDA complements experiments at other TRIUMF nuclear astrophysics facilities, a TUDA proton elastic scattering experiment, which used a radioactive ^{21}Na beam on a polyethylene hydrogen target $(\text{-CH}_2)_n$ was run for energies of 0.45–1.4 MeV. This study complemented the radiative-capture reaction ^{21}Na(p,γ)^{22}Mg experiment at DRAGON. The TUDA experiment observed protons elastically knocked out of the target. With thick targets, a complete scan of the excitation function was obtained using a few energy settings by correlating the recorded proton energy to the beam energy as it slowed while transversing the target. Thin targets were used to investigate selected energy regions in more detail. Particle ID was assisted by a time-of-flight correlation with the ISAC-I accelerator RF signal. Background β-decay was completely uncorrelated to the RF signal.

Figure 3 shows the composite excitation function derived from several thick target measurements using eight detector elements at 4.8° (lab). The prominent monotonically decreasing cross section in the upper plot is from Coulomb

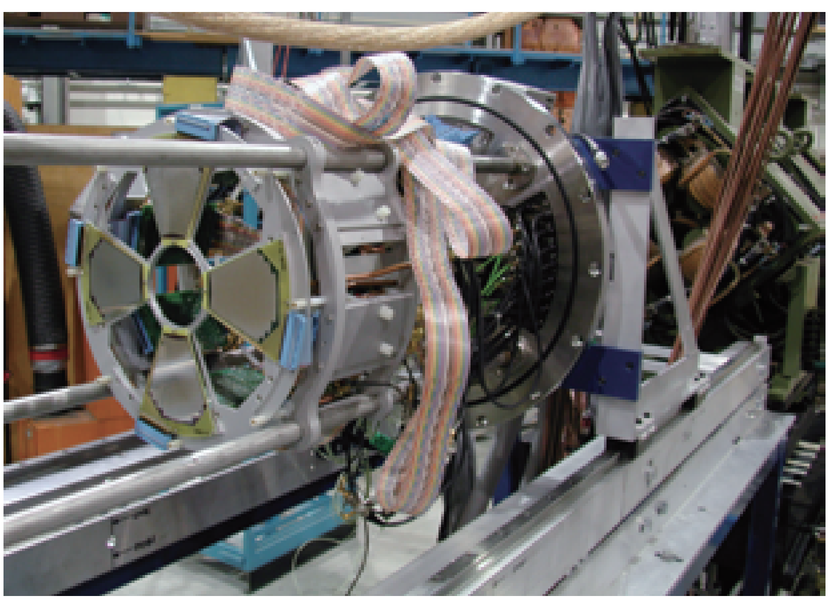


Figure 2: Picture of the TUDA detector system.

scattering. The resonances, or nuclear excitations of ^{22}Mg, interfere with this amplitude. The interference of the resonance amplitude with that of Coulomb scattering can determine the spin-parity of the resonance. Four states of ^{22}Mg have been identified in this plot. These states will dominate high-temperature burning as well as influence the low-temperature stellar rate of this reaction. The 1^- state at 1083 keV, mainly produced with ^{21}Na promoted to the 332 keV-excited state (lower plot), had not been seen before. DRAGON later measured the $^{21}Na(p,\gamma)^{22}Mg$ reaction rate through this resonance using the TUDA-measured resonance parameters to tune the facility.

Partners

In Canada: McMaster University, Saint Mary's University, Simon Fraser University, and the University of British Columbia.

International Partners: Belgium (1), Spain (1), the United Kingdom (2), and the United States (1).

TRIUMF's Role

TRIUMF provided the electronic housing environment for the TUDA electronics. TRIUMF also provides annual maintenance support for the facility. This provides access to the design office and the electronics and machine shops. TRIUMF is also financing the move to ISAC-II. Two TRIUMF Scientists, P. Walden and L. Buchmann, contribute significantly to the experimental collaboration.

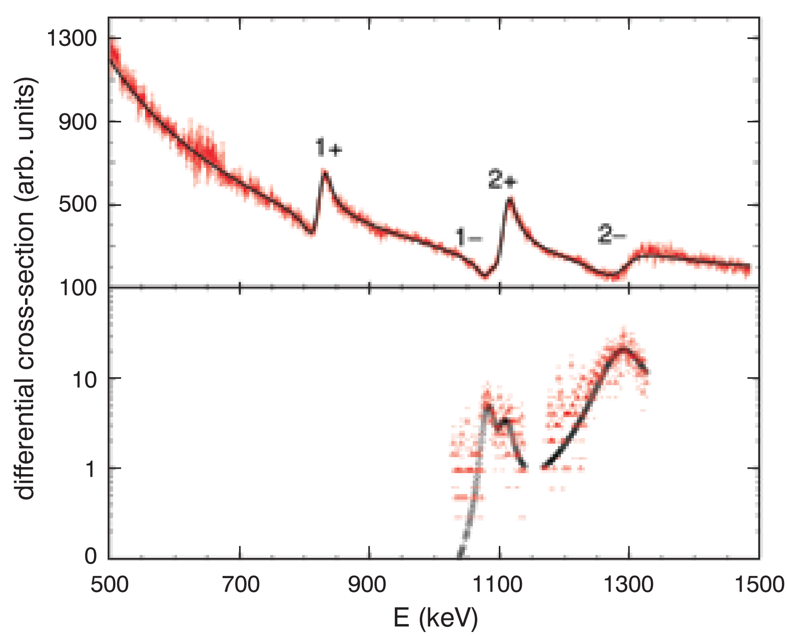


Figure 3: Excitation function for $^{21}Na(p,p')^{21}Na$.

5.3.2.2.3.2

TRIUMF Annular Chamber for Tracking and Identification of Charged Particles: TACTIC

Introduction

TACTIC (TRIUMF Annular Chamber for Tracking and Identification of Charged Particles) is a pioneering instrument that will improve our understanding of some of the most spectacular explosions in space and provide clues that could help us understand the origins of the elements in the universe. TACTIC will measure the strength of significant astrophysical nuclear reactions that occur in stars, such as the seed reaction that feeds the nucleosynthesis of the heavy elements inside supernovae.

Together with TUDA, DRAGON, and EMMA, TACTIC will study astrophysical reactions that have charged particles in their exit channels. However, because the ion chamber gas serves as the target, the reaction studies can proceed down to very low ion energies required in astrophysical nuclear reaction studies. In addition, the chamber has an extremely large solid angle (almost 4π) that allows the detector to track the exiting ions. Unlike active target ion chambers, TACTIC can take high beam fluxes because of a reduced-sensitivity target region. TACTIC is a unique detector, and future developments will very likely see it incorporated in many areas of nuclear physics research at TRIUMF.

Description of Dedicated Apparatus

The TACTIC detector is a cylindrical time projection chamber with an electric field in the radial direction. The central or target region (see Figure 1) is marked off by two sets of longitudinal wires strung at slightly different radii. The outer set provides the negative high voltage of the drift region. The inner set, at a slightly more positive bias, sweeps up electrons generated by beam particles ionizing the detector gas. Hence, the TACTIC detector is not sensitive to beam particles like active target ionization chambers, and subsequently can take higher beam fluxes. The detector gas, however, is the target gas. The target length is defined by vacuum inserts projected into the gas enclosure.

Ions, emanating from a nuclear reaction in the target region, pass through the wire grid into the drift or detection region where they range out by ionizing detector gas particles along their track. Electrons produced along the track move towards the anode pads on the outer radius of the region (see Figure 1). The (ϕ,z) coordinates of the activated pads give the projection of the ion track on the cylindrical surface. The r coordinates are provided by the electron drift times to the pads. Thus, the complete three-dimensional track can be reconstructed (see Figure 2).

The charge collected at each individual pad is proportional to the energy-loss rate of the ion at that point along the path. A summation of the charge of each pad along the path gives a value proportional to the total kinetic energy of the ion. With track position, energy loss, and energy, all the information necessary to identify the reaction is present.

Before the electrons reach the pads, they pass through a gas electron multi-

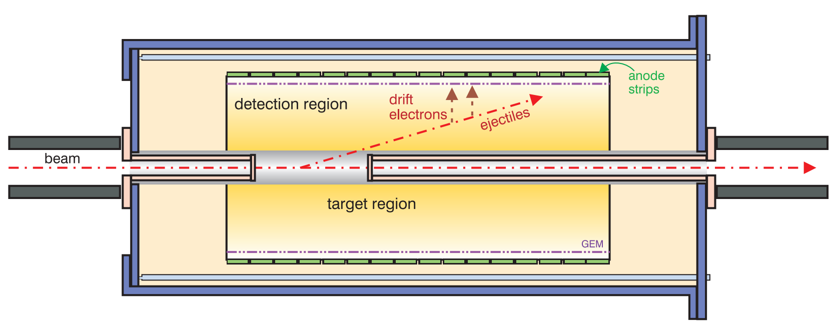


Figure 1: Schematic view of the TACTIC chamber.

plier (GEM) foil. The GEM works as preamplifier. It is a 50 μm-thick isolating foil with a conducting copper layer on both sides, perforated by a grid of 50 μm-large pinholes with a 150 μm pitch. There is a high voltage (450 V) applied between the layers, which produces a high field gradient through the holes. The high field inside the holes causes an avalanche effect that produces an electron multiplication of about 100. The signal that arrives at the pad is strong enough for direct electronic amplification.

The design of the TACTIC chamber will allow the use of suitable γ-ray detectors such as the bismuth-germanate (BGO) array from DRAGON in close proximity to the drift region. Coincidences between TACTIC and γ signals from the BGO array will be crucial to disentangle some astrophysical processes. For example, detecting the γ emitted by an ^{11}B excited state is essential to resolve the $^{8}Li(\alpha,n)^{11}B$ process, which is an experiment approved for TACTIC.

TACTIC is instrumented by pre-amps attached to the chamber (see Figure 3) along with VME-based flash ADCs (VF-48s) and a VMIC processor. VF-48s will also be used to process the BGO signals. There are a total of 512 channels.

Different detector gases can be used depending on the reaction to be studied. Nuclear astrophysics studies require ^{1}H and ^{4}He targets. The ^{4}He target for the $^{4}He(^{8}Li,n)^{11}B$ experiment is provided by a 90% Helium–10% CO_2 mixture. This mixture was tested in the initial stable ^{11}B beam commissioning run in 2007. For a ^{1}H target, isobutene has been proposed. This can be used for the approved $^{1}H(^{7}Be,p)^{7}Be$ experiment. With a modified TACTIC chamber, two gases can be used: one gas for the detector region and one gas for the target region.

Additional TACTIC chambers can be built for a modest cost and, with slightly different configurations, could be used as target chambers for the TIGRESS and EMMA facilities. The current TACTIC chamber will be used at the TUDA locations in both ISAC-I and ISAC-II. Its small size makes it very transportable.

Partners

In Canada: McMaster University, Simon Fraser University, and the University of British Columbia.

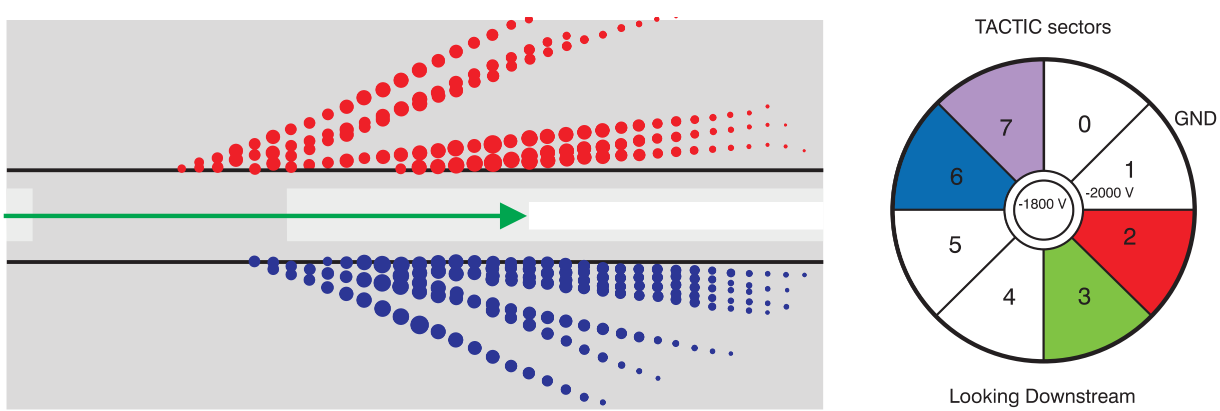


Figure 2: Track reconstruction during the initial run. Colours indicate different φ sectors activated.

International Partners: The University of Edinburgh, and the University of York.

TRIUMF's Role

TACTIC will use the infrastructure provided by TRIUMF for the TUDA facility, both at ISAC-I and ISAC-II. This infrastructure includes access to the design office and the electronics and machine shops for labour costs. TRIUMF provided invaluable services in the design and initial operation of TACTIC in terms of loaned equipment and expertise. Two TRIUMF scientists contribute to the experimental collaboration.

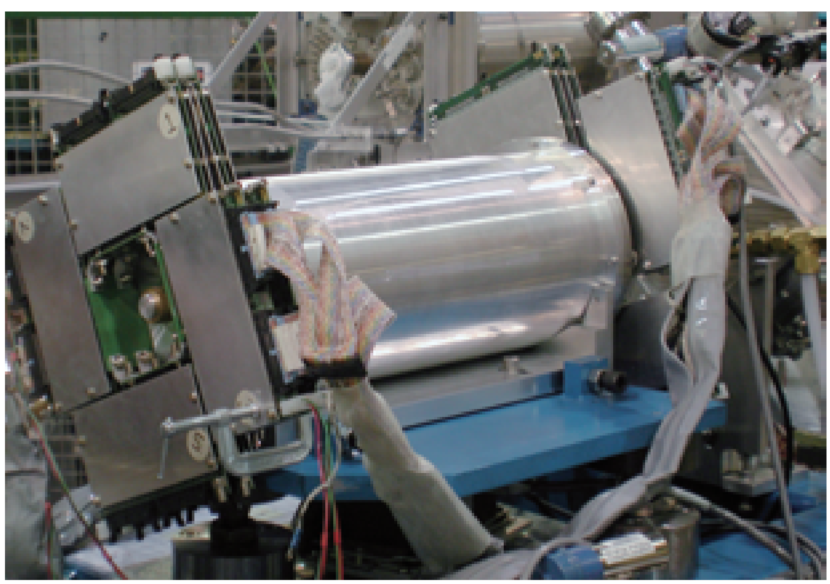


Figure 3: TACTIC on stand with preamp cards.

5.3.2.2.3.3

Doppler-Shift Lifetimes Facility: DSL

Introduction

Nuclear astrophysicists want to understand how stars and other astrophysical phenomena produce energy and the chemical elements that make up our world. To do this, nuclear physicists measure the rates of nuclear reactions. Ideally, these measurements are done in the laboratory by directly measuring the probability that a particular nuclear reaction will occur at the energies present during the big bang or in stars. Unfortunately, in most cases, these measurements are impossible because the probabilities of a reaction occurring are so low that experimental backgrounds or time constraints prevent direct measurements. Another difficulty is that many of the atomic nuclei involved are radioactive and don't survive long enough for an experiment to be performed.

Even when a direct measurement is impossible, there are indirect ways to determine a nuclear reaction rate. One such measurement uses the Doppler effect, which is the change in the energy of the photons measured by an observer moving relative to the source, to study what is known as "resonant capture." This process, in which a nucleus interacts with a proton or another nucleus creating an excited state of the compound nucleus, dominates most reaction rates of astrophysical importance. Resonant capture occurs when the wave function describing the two reacting nuclei of interest is very similar to the wave function of the excited state in the compound nucleus. When resonant capture is the dominant process in a reaction, the reaction rate can be deduced by studying the energies of the emitted γ-rays, inferring the lifetimes of the excited states of the compound nucleus that is the end product of the reaction.

TRIUMF's Doppler-Shift Lifetimes (DSL) facility is an experimental apparatus for the measurement of the lifetimes of excited states of nuclei. A measurement of an excited nuclear state's lifetime requires several steps. First, one must populate the excited state. At the DSL facility, this is accomplished by transfer reactions, in which two reacting nuclei exchange one or more protons or neutrons, leaving the recoiling nucleus in an excited state. Experimenters induce these reactions by colliding a beam of nuclei with a thin metal target into which a layer of a lighter nuclei has been implanted.

Recent Developments

DSL's first experiment used a gold target implanted with ^{3}He ions. The reaction occurred in the thin implanted layer, and the products of the reaction passed through that layer, continuing through the metal foil. The two products of the reaction had drastically different properties. The lighter of the two passed right through the metal foil, losing a small amount of energy, and was detected in a Si charged-particle detector telescope. Measuring the remaining energy of the light product determined which state in the heavy recoiling nucleus was excited. The heavy recoil nucleus on the other hand lost all of its energy in the metal foil, slowed down, and eventually stopped. The time it took to stop depended on the energy and charge of the recoiling nucleus and some properties of the foil's atomic nuclei, such as their charge and mass. Many measurements of the stopping powers of different materials along with theo-

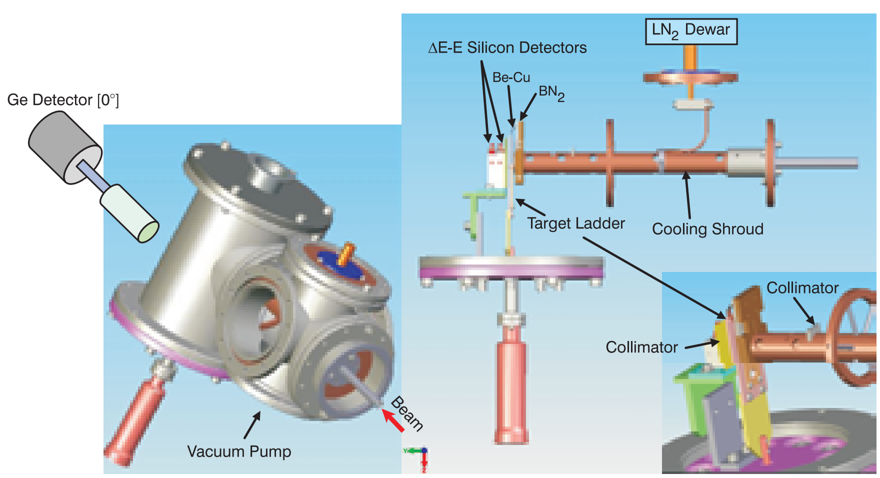


Figure 1: TRIUMF's DSL facility, showing the liquid nitrogen-cooled shroud along the beam axis, the target ladder, the Si detector telescope, and the high-purity germanium detector used to measure Doppler-shifted γ-rays.

retical calculations allow reasonably precise determinations of the stopping times for nuclei with speeds around a few percent of the speed of light.

How can one measure the lifetime of the excited state formed in the reaction? These lifetimes typically range from femtoseconds to picoseconds. When the excited states we're interested in decay, they usually do so by emitting a γ-ray. The lifetime is determined by measuring the energies of the γ-rays that are emitted when the state decays. Depending on the lifetime of the excited state, the recoiling nucleus will emit its γ-ray while still moving or after it has stopped in the foil. The energy of the γ-ray depends on the speed of the nucleus at the time it was emitted. One of the γ-ray detectors is located just beyond the target along the beam path. The energies of γ-ray emitted by recoil nuclei that are still moving forward are measured by this detector to have larger energies than γ-rays emitted by already stopped recoils because of the Doppler effect.

By measuring the spectrum of the γ-ray from the excited state of interest, we obtain a distribution of γ-ray energies that is characteristic of the lifetime of the state. The reason is that the decay of the excited state is a random process like the decay of radioactive nuclei. One can't predict exactly when a given nucleus will decay, but the distribution of decay times can be understood on the basis of simple statistics and characterized by a single number: the mean lifetime. Finally, by knowing the stopping characteristics of the recoil nucleus in the metal foil, we can deduce the mean lifetime of an excited state from the energy distribution of the γ-rays it emits. The DSL facility is schematically depicted in Figure 1.

Recently, the DSL facility made the most precise measurements of the lifetimes of excited states in ^{19}Ne relevant to the rate of the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction on accreting neutron stars. Figure 2 shows experimental data and the best fitting calculations of two γ-ray transitions from the most important state.

The DSL facility will soon move to ISAC-II, where it will be used in conjunction with TIGRESS γ-ray detectors to measure the lifetime of the 6.79 MeV state in ^{15}O. The lifetime of this state is one of the dominant uncertainties

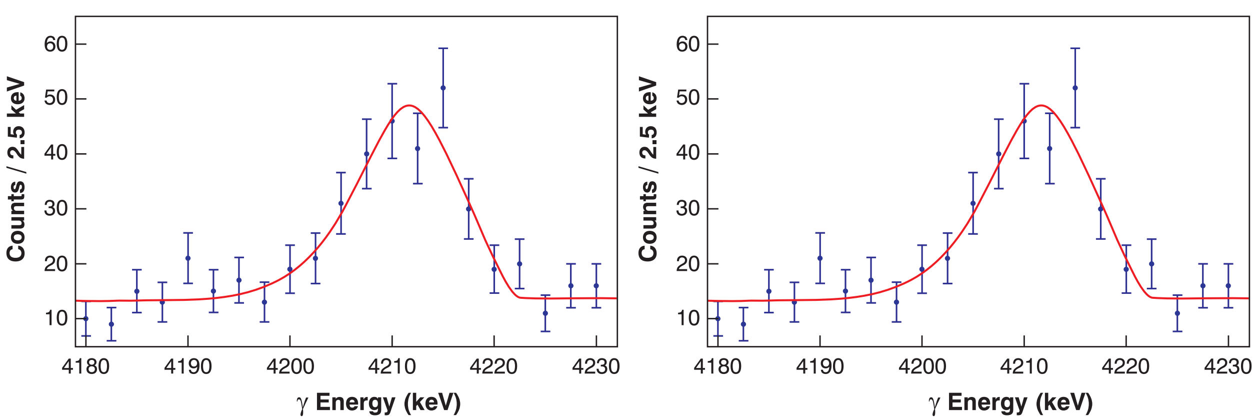


Figure 2: Doppler-shifted line shapes due to two transitions of the 4035 keV level in ^{19}Ne. The experimental data are shown along with the calculated line shape and background that best fit them. (a) Decay to the ground state with a lifetime of 7.1 ± 1.9 (stat.) ± 0.6 (sys.) fs; and (b) Decay to the 1536 keV level with a lifetime of (stat.) ± 0.7 (sys.) fs.

in determining the rate of the $^{14}N(p,\gamma)^{15}O$ reaction, which strongly affects the estimated age of the oldest stars in the Milky Way Galaxy.

Partners

In Canada: Saint Mary's University, l'Université de Montréal, Simon Fraser University, Queen's University, University of Guelph.

TRIUMF's Role

TRIUMF was solely responsible for the design and fabrication of the DSL facility. It was conceived by scientists G. Ball and B. Davids and implemented by R. Churchman and M. Subramanian in 2005 with some assistance from R. Kanungo.

5.4

Ensuring Accountability and Performance

Scientific Administration

Introduction

TRIUMF is Canada's national laboratory for particle and nuclear physics, and the need for scientific discovery is the reason for TRIUMF's existence. Individual scientists proposing projects that lead to scientific discovery drive scientific discovery from the bottom up. In contrast, TRIUMF's advisory bodies deliver general advice on scientific policy, a process that must be driven from the top down. Good management of the laboratory requires that TRIUMF manage and merge, to good effect, these important bottom-up and top-down processes.

Management of Scientific Projects

All science is curiosity driven: curious individuals try to understand how our world and the universe around us work. In addition, these enquiring and curious individuals challenge established ideas, playing an essential role in scientific progress. In Canada, such individuals drive subatomic research by creatively exploiting TRIUMF's facilities and infrastructure. With demand for access to TRIUMF far beyond what the laboratory can supply, TRIUMF has developed a process to evaluate and prioritize proposed research (see Table 1).

All experimental proposals for internal research programs are submitted to an Experiments Evaluation Committee (EEC) (see below). Experiments approved by the EECs must have independent peer-reviewed funding in place before TRIUMF management will schedule the experiment. This funding may come from the Natural Sciences and Engineering Research Council of Canada (NSERC) for Canadian experimentalists, or external foreign funding for experimentalists from abroad. In addition, if the experiment requires material infrastructure support, TRIUMF management must determine if, or when, this infrastructure support can be provided. Experiments are not scheduled for beam shifts until TRIUMF is able to supply the beam and beam intensity required, and the researcher is able to provide documentation showing they are technically ready to do the experiment, and that all safety requirements have been met.

The external science program supported by TRIUMF may be initiated by TRIUMF scientists or by other members of the Canadian scientific community. The capital costs and operating funds for the Canadian involvement are not provided by TRIUMF, but rather through peer-reviewed NSERC grants. Before funding is secured for a program that requires substantial TRIUMF infrastructure support, TRIUMF, NSERC, and the principal investigators of the proposal determine whether sufficient TRIUMF infrastructure can be identified and provided to support the program. For those projects TRIUMF is able to support, engineering, technical and infrastructure support for detector development and construction will be provided. TRIUMF may also provide accelerator expertise. Scientific peer-reviews for external experiments are undertaken at the laboratory where the experiment will be conducted. Figure 1 shows the oversight bodies that provide advice and accountability on TRIUMF's programs.

External Scientific Advisory Committees

The National Research Council (NRC) appoints three separate committees to review TRIUMF's activities and performance. These three committees are composed of international scientists and representatives from Canadian industry who are internationally known for their expertise and experience in the areas of science and technology transfer. The three external committees appointed by NRC are:

The Agency Committee on TRIUMF (ACT) consists of the President of NRC, the President of NSERC, and a senior representative from Industry Canada. This committee meets twice a year to review TRIUMF's progress in meeting the scientific and technology transfer milestones set by NRC in the Five-Year Plan Contribution Agreement.

The International Peer Review Committee consists of senior, internationally known scientists who meet once every five years to review the scientific progress TRIUMF has made during the five years under review, and evaluate the strengths and weaknesses of the proposed new Five-Year Plan.

The Advisory Committee on TRIUMF (ACOT) is a committee of internationally known scientists and business people. ACOT meets twice a year and has the expertise to comment, evaluate, and offer suggestions to NRC and TRIUMF on TRIUMF's progress in meeting scientific and technology transfer goals.

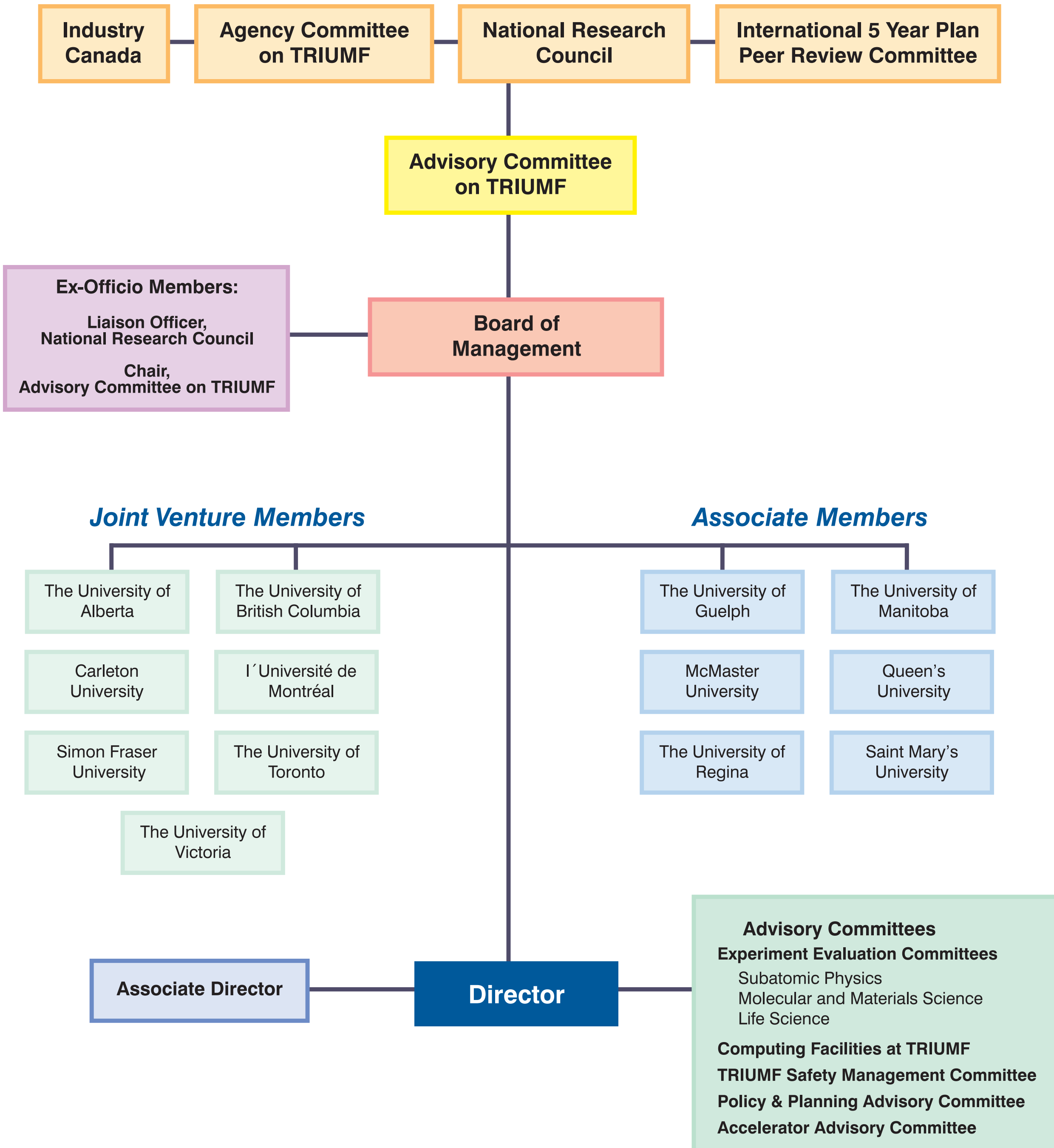


Figure 1: Accountability structures at TRIUMF. This diagram shows schematically the structure and relationship of the internal and external committees that oversee TRIUMF's programs.

The TRIUMF joint venture universities also appoint a committee to oversee TRIUMF's activities.

The Board of Management (BOM) consists of two voting representatives from each of the seven joint venture universities and a non-voting representative from each of the six associate member universities. The BOM also includes two members from the private sector appointed by the universities. In addition, NRC and ACOT each appoint a non-voting member to represent them. The BOM meets quarterly to review TRIUMF's financial, human resources, technology transfer and security activities, as well as the progress TRIUMF has made on the scientific program and priorities assigned in the NRC Five-Year Plan Contribution Agreement.

Internal Advisory Committees

The TRIUMF Director, in consultation with the TRIUMF Division Heads, senior administrative staff and several advisory committees appointed by TRIUMF, is responsible for the day-to-day management of TRIUMF and the long-term planning of the laboratory's scientific program and activities. The senior committees appointed by TRIUMF are:

The TRIUMF Operating Committee (OPCOM) membership consists of the Director, Associate Director, two members nominated by the TRIUMF Users' Executive Committee (TUEC), a TRIUMF staff representative, and a member from each of the joint venture universities. OPCOM was designed as a mechanism to inform university members and users of TRIUMF's activities and progress. OPCOM meets bi-monthly to discuss the operational requirements of TRIUMF, including reviewing budgets and human resource issues, as well as facility operations and concerns. In early 2007, TRIUMF management determined that OPCOM, as structured and mandated, was no longer the optimal means of providing university input to TRIUMF. In November 2007, OPCOM was disbanded in favour of a new committee called PPAC.

The TRIUMF Policy and Planning Advisory Committee (PPAC), which reports to the Director and Board of Management, advises on scientific policy and facilitates two-way communication with the research communities at the member universities. To ensure the entire community is well represented, the Director appoints the members of the Committee, which include one member from each of the joint venture universities, one of whom the Director may appoint as Chair, and one or more members from the larger TRIUMF community. Non-voting, *ex-officio* members of the Committee include the Head of Strategic Planning and Communications, the Associate Director and a Scientific Secretary appointed by the Director to assist the Chair. The Director does not sit on this Committee.

The Experiments Evaluation Committees (EECs) consist of three separate committees, Subatomic Physics (SAPEEC), Materials Science (MMSEEC) and Life Sciences (LSPEC). SAPEEC and MMSEEC meet twice a year and LSPEC once a year. Each committee evaluates and prioritizes experimental proposals submitted by scientists wishing to use the TRIUMF facility. Membership on these three committees consists of Canadian and international scientists who are well qualified to judge the scientific merits of an experimental proposal. Without EEC and LSPEC approval, no experiment can be carried out at TRIUMF.

Activity	Internal Experiments	External Experiments	Initiator
Scientific Ideas	Proposal	Proposal	Scientific Community
International Scientific Reviews	TRIUMF EEC	External Laboratory PAC	Laboratory
Funding Reviews	NSERC (RTI)	NSERC (RTI)	NSERC
Resource Review	TRIUMF (MOU)	TRIUMF (MOU)	TRIUMF
Safety Review	TRIUMF	External Laboratory	Management

Table 1: TRIUMF's experimental research approval process. MOU: Memorandum of Understanding; RTI: Research Tools and Instrumentation.

Laboratory Administration

Laboratory Organization

In July 2005, with funding in place for 2005–2010, Dr. Shotter believed it was the appropriate time to review the organizational structure of TRIUMF and determine how best this structure could be arranged to support the operations of the laboratory, meet the needs of the TRIUMF user community, and accomplish those tasks requested by the federal government in the NRC Contribution Agreement. It was understood that any reorganization recommendations and decisions had to take into account existing budget resources, and that any increases in resource allocation had to come from a redistribution of existing resources.

Dr. Shotter set up eight task groups to review various aspects of TRIUMF's operations:

- Science Support and Administration
- Computing
- Beam Delivery from Accelerators
- Support Groups for Accelerators, MRO
- Accelerator and Beams R&D
- Engineering and Technical Support
- QA and Safety
- Communications

After all reports were received from the task groups and reviewed by senior management, it was agreed that the process would move forward in three stages; immediate, intermediate, and long term. The new organization came into effect February 1, 2007 and encompassed most of the short-term recommendations of the various task groups.

Intermediate and long-term changes are under review by the current Director, Nigel Lockyer, who assumed the Directorship of TRIUMF May 1, 2007, and most recommendations are being implemented.

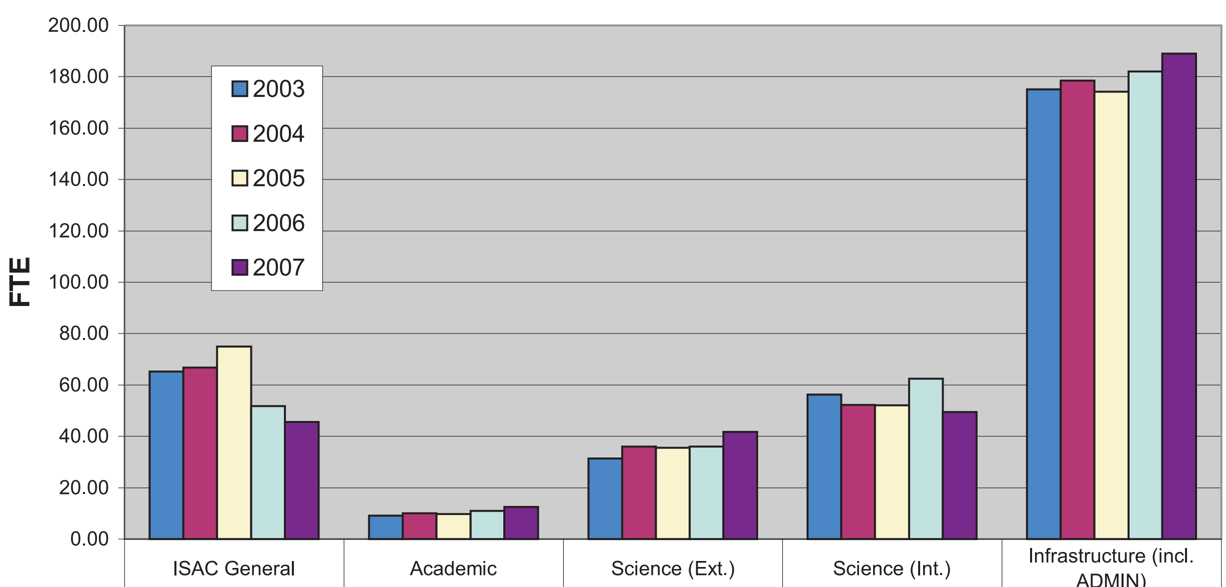
Staff Deployment

TRIUMF staff work on a variety of projects and activities. Table 2 shows the deployment of TRIUMF staff supported by the NRC contribution through the period April 1, 2003 to March 31, 2008. The areas shown in Table 2 are ISAC development and operations, academic activities, science internal and external to the TRIUMF site and infrastructure.

The ISAC component shows a ramp-up through 2005 for ISAC-II construction, as components of the facility were completed and construction personnel began operating and maintaining facilities full time. This staff deployment pattern should continue until early 2010 when all components will be complete.

Direct TRIUMF contributions to the Large Hadron Collider (LHC) at CERN ended with the completion of the construction project, but TRIUMF continues its involvement in the ATLAS experiment at CERN on behalf of the Canadian physics community. In addition, TRIUMF is involved in building accelerator components for T2K at J-PARC. TRIUMF's involvement in T2K has resulted in a small but steady increase in manpower committed to external science projects.

TRIUMF staffing efforts for internal science projects have decreased



	ISAC General	Academic	Science (Ext.)	Science (Int.)	Infrastructure (incl. ADMIN)
2003	65.29	9.19	31.43	56.24	175.07
2004	66.78	9.97	36.01	52.28	178.50
2005	74.91	9.73	35.49	52.15	174.19
2006	51.80	10.93	35.95	62.40	182.10
2007	45.66	12.53	41.70	49.39	189.04

as of January 8, 2008

Table 2: Deployment of TRIUMF's NRC contribution supported staff from April 1, 2003 to March 31, 2008.

between 2003 and 2008 as construction of several major experimental installations were completed and technical and engineering staff were able to return to their operation and infrastructure activities. When new installations are ready for construction, their services will once again be split between capital construction and operations.

Finally, from 2003 to 2008, TRIUMF scientists continued their efforts to become more involved and connected to the academic activities of their university colleagues through teaching, writing, external committee work, and supervising students.

Financial Resources

The NRC contribution to TRIUMF for the 2005–2010 Five-Year Plan was $C222.3 million. This funding will maintain the laboratory's operations and complete most of the ISAC-II major facilities. Table 3 shows the annual operating and capital expenditures or budgets for the current Five-Year Plan. Completing the ISAC-II facility and beginning the science program as quickly as possible has been a major focus for the laboratory. The NRC Contribution Agreement specified the facilities and experimental stations that must be completed within the five years and TRIUMF has met all ISAC-II facility and experimental milestones set by NRC.

During 2005–2007 the Director and university academic staff involved with TRIUMF, pursued additional funding from CFI for capital projects. TRIUMF cannot apply directly for CFI awards; grants must come through one or more Canadian universities. The effort spent on obtaining CFI funding met with considerable success. The capital projects funded for 2005–2010 were:

ATLAS Tier-1 Centre: In 2006–2007, a consortium of Canadian universities, led by Simon Fraser University, was awarded $C23 million for the ATLAS Tier-1 Data Centre, which was operational by August 2007.

Centre for Molecular and Materials Science: TRIUMF undertook to provide funding for partial refurbishing of the M9 beam line at a cost of $C1.8 million. A consortium of Canadian universities, led by Simon Fraser University, obtained $C6 million in funding for the refurbishment of the M20 beam line. TRIUMF will provide 20% in matching funds through an in-kind contribution of labour and cash. It is expected the M20 project will begin in late 2008 or early 2009.

It should be noted that CFI does not fund 100% of a project. CFI contributes 40% of the required funds with the expectation the host province will contribute an equal 40%. The host institution must contribute the final 20%, either through in-kind contributions, special supplier discounts, or cash. Where TRIUMF has been expected to provide the final 20% of matching funds, we have reduced our operations in order to provide a combination of cash and in-kind labour contributions from our technical and engineering staff.

Licensing, Safety, and Security

TRIUMF Accelerators Inc. (TAI) was established September 1, 2006 to address the CNSC regulatory requirements as legislated by the Nuclear Safety and Control Act. TAI was awarded an operating license effective April 1, 2007 and is responsible for those aspects of TRIUMF's operations identified in the operating license as well as control over the assets of the TRIUMF facility. As a result of incorporating TAI, the joint venture members of TRIUMF agreed to redraft the Joint Venture Agreement to incorporate a Management Agreement between TAI and TRIUMF. The revised Joint Venture Agreement, completed March 31, 2008, fully defines the rights and responsibilities of each party.

The agreement put in place ensures the owners of TRIUMF, the full members of the joint venture, control TAI. TAI's officers, who carry out the day-to-day activities, are appointed by the TRIUMF Board of Management and consist of the President and Chief Executive Officer, Vice-President of Finance, Vice-President of Safety and Vice-President of Security, who hold these positions by virtue of their equivalent TRIUMF appointments.

The TRIUMF Accelerators Inc. Operating License was renewed April 1, 2007, but CNSC set conditions that had to be met by March 31, 2008, for the license to be issued for the full term of five years. These conditions were:

1. Funding of an approved preliminary decommissioning plan for the future decommissioning of the TRIUMF facility.

2. A revised Joint Venture Agreement signed by the member universities recognizing the role of TAI and the funding of the decommissioning plan. In addition to this requirement, it was necessary for TRIUMF to arrange a Management Agreement between the Joint Venture and TAI, and negotiate a lease between TAI and the University of British Columbia, on whose lands the TRIUMF facilities are located.

3. Submission of an Environmental Protection Program in compliance with CNSC regulatory standard S-296.

4. Upgrade to the Fire Protection Program to ensure that the TRIUMF facility is operated, maintained, tested and inspected annually in compliance with the NFPA-801(2003) Standard for Fire Protection for Facilities Handling Radioactive Materials.

By the March 31, 2008 deadline, TRIUMF had met all the CNSC requirements of the license conditions on which the Operating License was issued. In addition, between 2003 and 2008 TRIUMF has put additional effort into continuing the development and expansion of TRIUMF's regulatory programs. A summary of the programs where significant changes have occurred is included below.

Decommissioning Plan

A preliminary decommissioning plan (PDP) to address eventual decommissioning of the TRIUMF facility is a CNSC requirement for all Class I facilities.

The TRIUMF PDP, written in 2003, was updated in 2007 to include the new TR30-2 and ISAC-II facilities. Additional changes included definition of a 'safe state of closure' to ensure that all highly radioactive material is removed and secured immediately after shutdown; definition of a conceptual schedule for the licensing and review activities prior to decommissioning; and costing using outside contractor rates for the project management and all radiological as well as conventional demolition tasks. The total cost of decommissioning TRIUMF facilities to a green-field site, including a 30% contingency, was estimated at \$C44 million (2007).

TRIUMF FUNDING ALLOCATIONS FIVE YEARS ENDING MARCH 31, 2010						
	ACTUAL 2005/06	ACTUAL 2006/07	BUDGET 2007/08	BUDGET 2008/09	BUDGET 2009/10	TOTAL
SALARIES & BENEFITS	27,265	28,648	28,900	31,125	32,185	148,123
OPERATIONAL COSTS						
ADMINISTRATIVE SUPPORT	774	1,035	1,121	1,000	1,000	4,930
SITE INFRASTRUCTURE/ OPERATIONS	3,094	3,998	3,878	3,075	3,075	17,120
EXPERIMENTAL SUPPORT	3,014	3,670	3,332	2,700	2,700	15,416
NET POWER COSTS	1,914	2,192	2,200	2,200	2,200	10,706
TOTAL OPERATIONAL SPENDING	8,796	10,895	10,531	8,975	8,975	48,172
CAPITAL PROJECTS						
ISAC FACILITY	4,402	2,967	3,642	2,400	1,130	14,541
ISAC TARGET DEVELOPMENT	1,052	1,795	653	850	1,010	5,360
CYCLOTRON UPGRADE	594	650	563	300	200	2,307
LIFE SCIENCES	0	0	0	0	0	0
CENTRE FOR MATERIALS SCIENCE	0	0	825	750	250	1,825
TRIUMF/ATLAS DATA ANALYSIS CEN-TRE	351	234	0	0	0	585
INTERNATIONAL ACCELERATORS	540	311	186	200	250	1,487
INTERNATIONAL DETECTORS	0	0	0	0	0	0
ATLAS COMMONG FUND	0	0	0	0	0	0
CERN MAGNET REPAYMENT	1,500	0	0	0	0	1,500
TOTAL CAPITAL SPENDING	8,439	5,957	5,869	4,500	2,840	27,605
TOTAL EXPENDITURES	44,500	45,500	45,300	44,600	44,000	223,900
CONTRIBUTION FROM OTHER FUNDS	(500)	0	0	(1,100)	0	(1,600)
NRC CONTRIBUTION	44,000	45,500	45,300	43,500	44,000	222,300

Table 3: TRIUMF funding allocations between operations and capital for the five years ending March 31, 2010.

The preliminary decommissioning plan for TRIUMF includes three phases. The first phase is the cleaning out of all structures that do not have radioactivity concentration above the “clearance” levels and either reusing or demolishing them at the time of decommissioning. The remaining radioactive components would be consolidated and secured in two areas. The first area is the low-energy cyclotron vault and target caves whose concrete enclosure and components would need an additional 20 years to decay below clearance levels. The second phase of decommissioning would involve the removal of all materials having decayed to below clearance levels and the consolidation of the remaining radioactive materials such as the low-energy cyclotron magnets and some components of the high current beam lines into the second area, the 500 MeV cyclotron vault.

Those remaining components and the vault enclosure would be allowed to decay for an additional 25 years for a total of 45 years after shutdown. At that point, the third phase of decommissioning would be completed resulting in the release of all the material below clearance levels and disposal as radioactive waste of the components still above clearance levels, such as parts of the main cyclotron magnet.

Funding the Decommissioning Plan

The Canadian Nuclear Safety and Control Act requires that all nuclear facility PDPs be fully funded, either with cash or a combination of cash and financial guarantees from reputable and financially stable organizations. A proposal for funding TRIUMF’s eventual decommissioning costs was developed between TAI and the TRIUMF Joint Venture member universities. The funding plan, which was approved by CNSC in late December 2007, consists of a cash deposit of $C9.6 million, which is sufficient to pay the Phase 1 costs of decommissioning, and financial guarantees from the member universities for the balance of the costs.

The funding and maintenance of the financial guarantee is the responsibility of TAI, the TRIUMF Joint Venture and each full member university of the Joint Venture.

Fire Protection

A review of TRIUMF facilities was performed to ensure that operation of the TRIUMF facilities, maintenance and testing of the fire protection systems is carried out in compliance with the regulatory code NFPA-801. TRIUMF enlisted the assistance of outside fire protection expertise to perform the review.

One area that was identified as needing remediation in the context of the new regulatory requirements is the area at the end of the Meson Hall, used for storage of low-level radioactive waste. TRIUMF has reduced the fire load through the elimination of the wooden containers and reduced the volume of flammable material stored in this area. This has resolved this identified area of weakness and reduced or eliminated the potential for spread of contamination in the event of fire.

In addition, the annual inspection of the fire protection program will in future include an ongoing assessment for compliance with NFPA-801.

Quality Assurance Program

TRIUMF began developing a Quality Assurance Program (QA) in 2002 to meet CNSC requirements. TRIUMF submitted a QA Manual and a set of TRIUMF Standard Operating Procedures (TSOPs) to CNSC in 2003, and these were accepted in 2004 on the condition of acceptable implementation.

The CNSC conducted an audit of the TRIUMF QA in September 2006. The audit report highlighted seven directives, seven action notices, and one recommendation. The audit team assigned an inspection grade of "C – Does Not Meet Requirements". Most of these concerns were with the implementation of the program.

To address the issues identified in the CNSC audit, the TRIUMF Director created the QA Implementation Panel, composed of a cross section of group leaders. The panel reviewed the audit report and the QA program and concluded that the best course of action was to rewrite the TSOPs in a manner that would address the audit concerns and facilitate implementation. The panel drafted these documents and they were sent to the CNSC in November 2007.

The new TSOPs are more generic so the specifics of implementation will be addressed in group manuals outlining the procedures each group has in place that demonstrate their compliance with the TRIUMF QA Program. It is expected that these manuals will be completed by July 2008.

Emergency Preparedness

The CNSC requires all Class I facilities to have an Emergency Preparedness Plan, based in part on the CNSC Regulatory Guide G-225, Emergency Planning at Class-I Nuclear Facilities and Uranium Mines and Mills.

The TRIUMF Emergency Preparedness Plan (TRI-EHS-05-05) addresses the planning for, response to, and recovery from emergencies or disasters that may occur at TRIUMF. This plan applies to all facilities, employees and visitors at TRIUMF. The scope of this plan and the extent of emergency planning and preparedness are based on the hazards and potential consequences associated with the location and operation of TRIUMF.

This plan identifies the roles and responsibilities of emergency responders, and provides broad guidance for preparing for emergencies as well as responding to them effectively. The plan describes the emergency facilities on site, defines optimum and minimum staffing levels for the various components of emergency response and defines the type and frequency of training, drills and exercises for the emergency response organization and TRIUMF staff. To facilitate access to this information in times of emergency, response procedures for various types and severity of emergencies are contained in a separate document, TRIUMF Emergency Response Plan (TRI-EHS-05-06). The plan received final approval by the CNSC in July 2007.

Accelerator Safety Systems

The radiation safety systems for several facilities were either expanded or upgraded between 2003 and 2008. TRIUMF installed an ISAC Safety System that includes an ISAC-II vault lock-up and interfaces to ISAC rare-isotope beams, off-line ion sources, and radio-frequency devices. Considerable development of the ISAC Radiation Monitoring System also took place and gamma/neutron monitor pairs were added in ISAC-II to complement the original gamma monitors in ISAC-I.

The hardwired CP42 Access Control Interlock System and the CP42/TR30-1 Radiation Monitoring System were upgraded in 2005 allowing the control rooms for all three ATG accelerators to be consolidated into the new control room built for the TR30-2.

Some very old 500 MeV facility equipment also received attention, most noticeably the accelerator “trip” and “beam inhibit” systems, and the M20, M15 and BL1B Area Safety Units, all of which were redesigned for reliability and maintainability.

All safety systems work, including design, calibration, commissioning and routine testing, met evolving Standard Operating Procedures in Quality Assurance policies.

Site Security

As a result of general increased security awareness, TRIUMF augmented its own security by increasing the number of daily patrols made by the University of British Columbia Security Services and increasing the coverage of its external contracted security service.

In 2003, TRIUMF installed a security system using photo access cards. This system enabled site access to be monitored and ensured that only those authorized could access the site. Site access is now managed through a TRIUMF Standard Operating procedure (TSOP) and improvements to the process are ongoing.

A confidential site security plan, summarizing all the components of TRIUMF’s security program was prepared and submitted to CNSC. The plan defines the roles and responsibilities for monitoring and maintaining security, the site access control procedures, contingency plans and response during a security breach. In addition, the plan addresses the role of off-site security services and co-ordination with TRIUMF’s head of security. The TRIUMF Security Plan was approved by CNSC in March 2007.