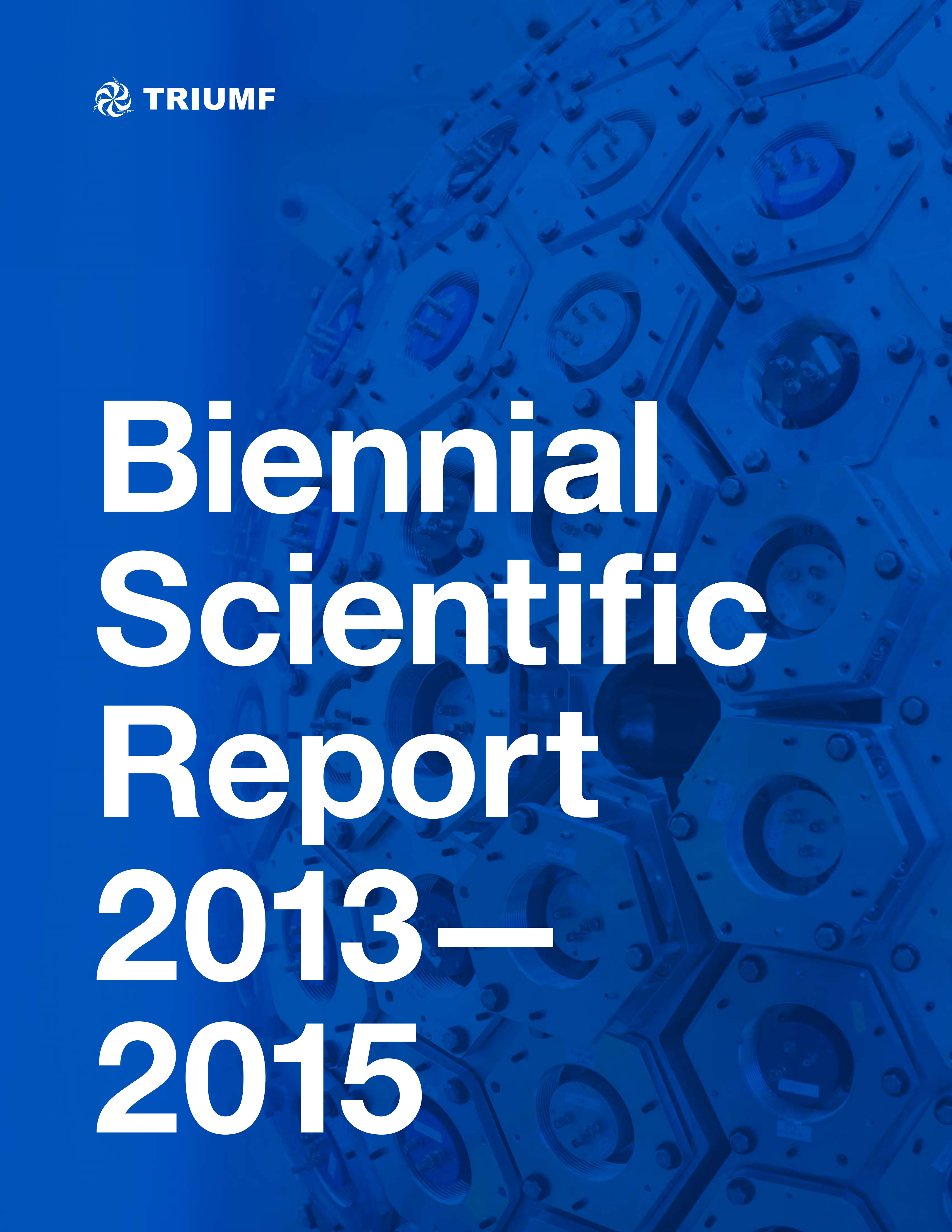


TRIUMF

Biennial Scientific Report 2013—2015

TRIUMF

Editor-in-chief: Marcello Pavan
Scientific Editors: Greg Hackman, Reiner Kruecken, David Morrissey, Colin Morton
TRIUMF Editors: Melissa Baluk, Byron Jennings, Carla Rodrigo
Copy Editor/Proof Reader: Melva McLean

TRIUMF's activities are supported through a combination of public funds, revenues generated from commercial activities, and small contributions generated from commercial activities, and small contributions received through scholarships, awards, and personal donations. We gratefully wish to acknowledge the following sources of public support (in alphabetical order): Canada Foundation for Innovation, Canadian Institutes of Health Research, Genome BC, National Research Council Canada, Natural Resources Canada, Natural Sciences and Engineering Research Council, Province of British Columbia, Province of Manitoba, Province of Ontario, Province of Nova Scotia, and Western Economic Diversification Canada.

For additional copies of this report or for more information, please contact:
Strategic Communications Office, TRIUMF
4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada
Telephone: 604-222 1047
E-mail: communications@triumf.ca
Website: www.triumf.ca

Design and Layout: BurnKit, Inc., Vancouver

TABLE OF CONTENTS

TABLE OF CONTENTS

EXECUTIVE SUMMARY

1

1

EXECUTIVE SUMMARY

1.1 TRIUMF’S MISSION

TRIUMF is Canada’s national laboratory for particle and nuclear physics. It is owned and operated as a joint venture by a consortium of 19 Canadian universities via a contribution through the National Research Council Canada (NRC), with additional capital support provided by the Government of British Columbia.

Its mission is to:

— **Make discoveries that address the most compelling questions in particle physics, nuclear physics, nuclear medicine, and materials science;**

— **Act as Canada’s steward for the advancement of particle accelerators and detection technologies; and**

— **Transfer knowledge, train highly skilled personnel, and commercialize research for the economic, social, environmental, and health benefit of all Canadians.**

1.2 TRIUMF'S VISION

TRIUMF's Vision is to:

— LEAD IN SCIENCE

The world sees TRIUMF as Canada's leader in probing the structure and origins of matter and in advancing isotopes for science and medicine.

— LEVERAGE UNIVERSITY RESEARCH

The Canadian university research community views TRIUMF as a way to strengthen and expand their research programs.

— CONNECT CANADA TO THE WORLD

International subatomic physics laboratories look to TRIUMF for partnering with Canada and its research community.

— CREATE SOCIAL AND ECONOMIC GROWTH

The global scientific community sees TRIUMF as a bridge between academia and the private sector and as a model for commercialization and social impact.

1.3 TRIUMF’S CORE VALUES

TRIUMF operates as one of the leading physics laboratories in the world, and its values guide how the laboratory approaches its goals. They are instilled in all those who work there.

— EXCELLENCE AND IMPACT

A commitment to excellence in achieving TRIUMF’s mission and vision while making a real difference.

— COLLABORATION AND TEAMWORK

Working together with others (individuals, groups, or institutions) for our mutual benefit.

— HONESTY AND TRANSPARENCY

Being responsible and accountable for our actions and their consequences; respecting people, their ideas and diversity; working safely and sustainably with openness, authenticity, generosity, and equity.

— INNOVATION AND RELEVANCE

Approaching assignments, tasks, and problems in new and efficacious ways; creating novel ideas and techniques.

1.4 TRIUMF WELCOMES NEW LEADERSHIP

The period 2013–2015 saw wholesale changes at the top of TRIUMF's management structure. In 2013, (then) TRIUMF Director Nigel Lockyer was chosen to become the new Director of the Fermi National Laboratory in Batavia, Illinois. In response, TRIUMF's Board of Management instituted an interim leadership structure effective August 1, 2013, the date the laboratory commenced a search for a new Director. The interim leadership was provided by the Board and a team of senior staff, with (then) Head of the Business and Administration Division Jim Hanlon appointed as Interim Chief Executive/Chief Administrative Officer.

This leadership structure remained in place until Dr. Jonathan Bagger, Krieger-Eisenhower Professor, Vice Provost, and former Interim Provost at the Johns Hopkins University, began his tenure as TRIUMF Director on July 2, 2014. Bagger will lead the laboratory for a six-year term ending July 1, 2020.

Dr. Paul Young, Vice President Research at the University of Toronto was Chair of TRIUMF's Board of Management throughout the interim leadership period. Young stepped down as Chair and handed the reins over commencing July 1, 2014 to Dr. Steven Liss, Vice-Principal Research at Queen's University in Kingston, Ontario.

1.5 MESSAGE FROM THE DIRECTOR

TRIUMF is run by a consortium of 19 Canadian universities and receives the bulk of its funding from federal, provincial, and commercial sources. Over the decades, TRIUMF has reinvented itself time and time again, and the laboratory has grown stronger with each new reinvention.

The years 2013–2015 were pivotal for TRIUMF. This period saw our laboratory begin its transition into the Advanced Rare IsotopE Laboratory (ARIEL) era.

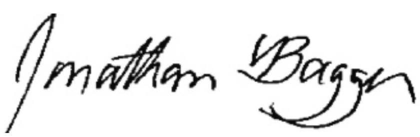
Figure 1. Director Dr. Jonathan A. Bagger

ARIEL represents one of the most significant upgrades that TRIUMF has ever undertaken.

Going from one beam line to three is no small feat; its development will reshape the laboratory in ways that we can only begin to imagine.

During this transformation, TRIUMF's existing facilities will continue to deliver world-class science, and its scientists and staff will strive to maintain and even increase our excellence and impact.

I am excited to be part of this adventure and look forward to this exciting new era for TRIUMF.



Dr. Jonathan A. Bagger

1.6 FULFILLING THE AMBITIONS OF THE 2010–2015 FIVE-YEAR PLAN

This report details the scientific activities that TRIUMF has undertaken during fiscal year 2013–2015 to fulfill its mission and the ambitions of the 2010–2015 Five-Year Plan. It does not progress since then. Funding for TRIUMF's core operations flows in five-year cycles from a federal Government of Canada contribution through the National Research Council of Canada. In addition, the Province of British Columbia provides capital funding for TRIUMF. The activities chronicled in this report are part of the 2010–2015 Five-Year Plan that started April 1, 2010 and completed March 31, 2015.

On March 24, 2010, through a federal budget announcement, the Government of Canada confirmed $222.3 million in operational support for TRIUMF. The Canada Foundation for Innovation also approved a proposal led by the University of Victoria for the superconducting electron linear accelerator project

Figure 2. Aerial photo of TRIUMF site, highlighting the new ARIEL facility (light-orange fasade, centre).

at TRIUMF; this would provide approximately an additional $18 million to the five-year budget. In response, the Government of British Columbia announced $30.7 million of support for capital infrastructure at TRIUMF on June 22, 2010. Together, this funding was sufficient to launch TRIUMF's flagship initiative, ARIEL (see Figure 2)

TRIUMF has emerged on the international stage as a leader,

by building on the investments, as well as the efforts of our member universities and strategic partners. For example, TRIUMF along with Canadian physicists are known for their contribution to the discovery of the Higgs boson. TRIUMF scientists received international attention for trapping antimatter. The laboratory is known globally for pursuing an alternative, innovative solution for producing the world's most-popular medical isotope (Tc-99m) with existing accelerators. TRIUMF's rare isotope program is among the best in the world, attracting hundreds of users to Vancouver each year. Two small Canadian firms, building on TRIUMF's accelerator technologies, were transferred superconducting radiofrequency technology. TRIUMF is partnering with India and Japan to further technology developments and open new markets for Canadian companies. And TRIUMF's 35-year partner company, Nordion, continues to touch the lives of millions of people each year with medical isotopes produced on small TRIUMF-designed, Canadian-manufactured cyclotrons in Vancouver.

This report demonstrates that with the support of government, member universities, and partners, TRIUMF has lived up to the ambitions set out in the 2010–2015 Five-Year Plan.

1.7 REALIZING THE VISION: THE 2015–2020 FIVE-YEAR PLAN

The five-year planning cycle necessitates initiating the next plan about half way through the existing cycle. To that end, planning for the 2015-2020 began in earnest in mid-2012, with the final planning document released in October 2013. Entitled “Realizing the Vision”, the 2015–2020 Five-Year Plan exploits TRIUMF’s existing infrastructure, highly trained staff, and network of partnerships to craft an ambitious plan to implement the second half of the decadal vision set forth in the 2010–2015 plan.

In this plan, TRIUMF begins its march towards major scientific discoveries

with ARIEL, a new facility for ultra-cold neutrons shared with Japan, and with critical support for Canada’s engagements on the international stage of particle physics. TRIUMF will commercialize new technologies, stimulate and train students, challenge engineers and technicians with the latest accelerator-associated technologies, and impact the world with the accelerator-produced medical isotopes.

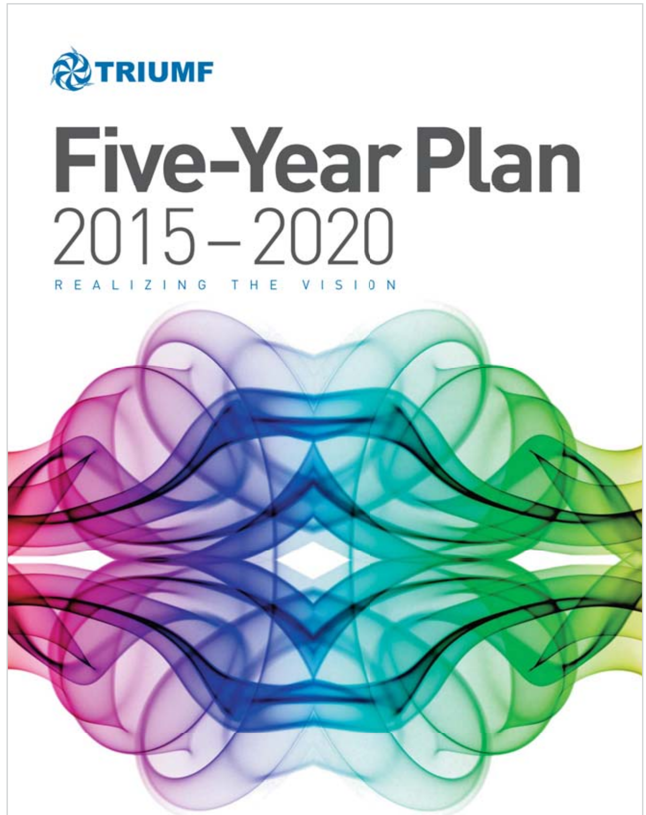


Figure 1. Five-Year Plan 2015-2020

1.8 INTERNATIONAL PEER REVIEW

As part of the strategic planning cycle for 2015–2020, in 2013 the National Research Council Office of Audit and Evaluation conducted a review of TRIUMF, culminating in an International Peer Review (IPR) that combined multiple lines of evidence and a site visit to fully judge TRIUMF's performance. On November 13–15, 2013 the IPR Committee (IPRC) conducted its site visit to the laboratory.

The IPRC was chaired by Dr. Samuel Aronson, former Director of Brookhaven National Laboratory and included nine distinguished scientists and industry leaders, who brought skills from research, science, technology, commercialization, and laboratory management from Canada, the U.S., and Europe. The IPRC's report was the final evaluation, which was critical input to federal and provincial governments regarding investments in the next five-year plan.

The IPRC engaged in various activities to gain more understanding about the vitality, structure, and impact of the laboratory. The TRIUMF Board of Management, the Advisory Committee on TRIUMF, and the laboratory's leadership team gave talks demonstrating recent successes and ambitious goals for the IPRC to scrutinize and examine. In addition to the plenary talks, the IPRC connected with over 25 scientists and researchers through five parallel sessions, each with several talks by staff scientists and students at TRIUMF and visiting researchers dedicated to the various research areas. In these sessions, the IPRC explored topics such as particle physics, nuclear physics, accelerator physics, nuclear medicine and materials science. TRIUMF hosted several of its partner companies (IKOMED Inc., Nordion Inc., and PAVAC Industries Inc.) in a panel discussion about innovation and industrial partnerships with the committee. All presentations were open to the greater TRIUMF community to attend.

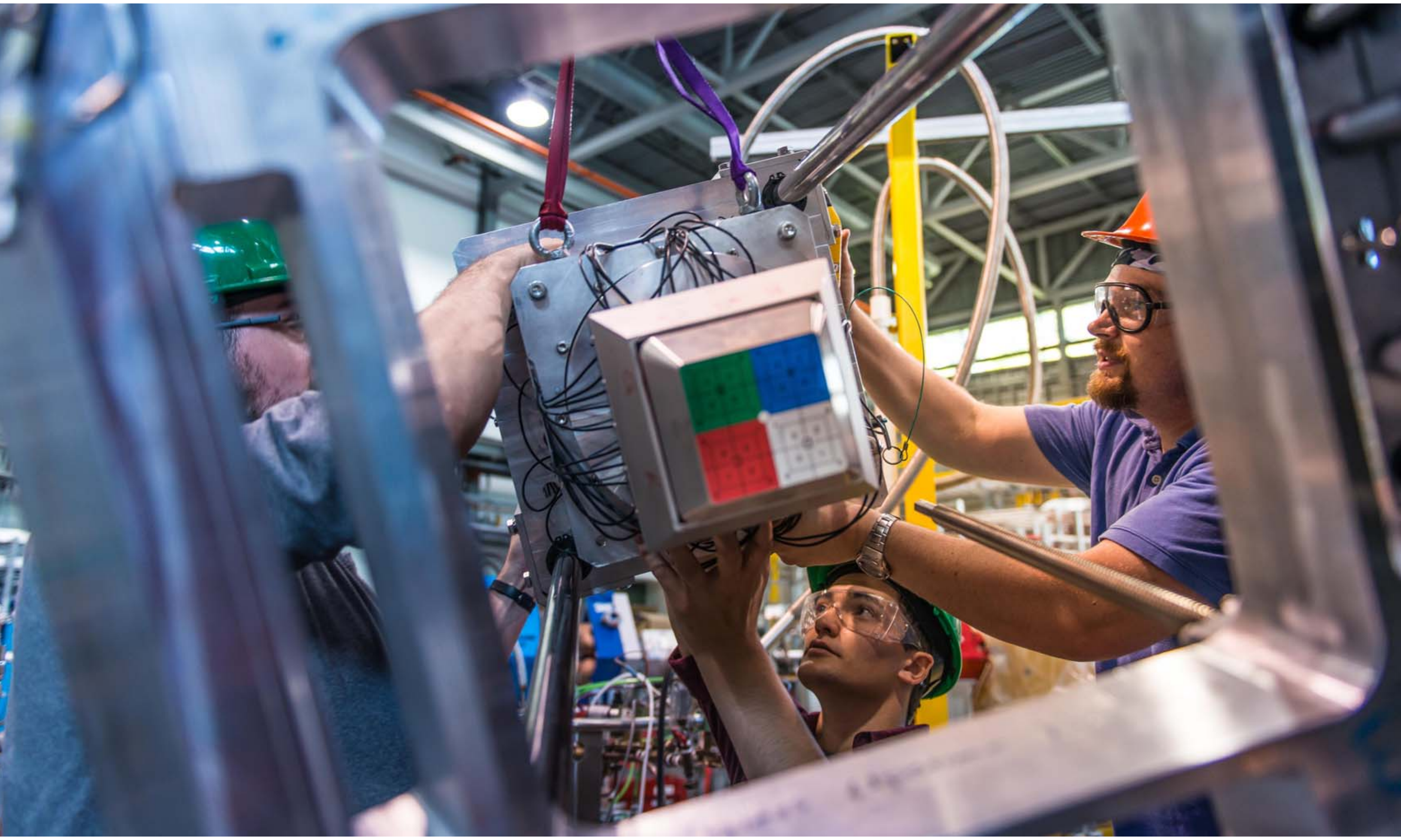
The IPRC commended TRIUMF for outstanding accomplishments in the existing five-year cycle,

in its final report and identified some areas for growth, and commented on the "fantastic esprit de corps" they experienced at the site. The IPRC supported the goals of the Five-Year Plan 2015–2020 and applauded the entire TRIUMF laboratory for their commitment to the success of the program for the benefit of all Canadians.

1.9 FUNDING FOR FIVE-YEAR PLAN 2015–2020

After reviewing all the information provided by the review agencies involved, the Federal Government of Canada committed to the core tenets of the plan with a $222 million commitment in its Economic Action Plan 2014 of February 11, 2014.

To more fully implement the program in the plan, TRIUMF is seeking a $68M supplement to maintain core operations, and enhance critical mass in strategic areas such as nuclear medicine and materials science [1].



[1] On April 21, 2015, the Federal Government of Canada committed an additional $45 million in operating funds to support the core operations outlined in TRIUMF's Five-Year Plan 2015–2020.

ADVANCING KNOWLEDGE

2

ADVANCING KNOWLEDGE

2

ADVANCING KNOWLEDGE

2

2.1 INTRODUCTION

TRIUMF expands the boundaries of knowledge through its world-leading and diverse research program in subatomic physics. This program makes extensive use of the on-site facilities at the laboratory and also involves experiments located all over the world. The primary goal of much of the research at TRIUMF is to improve our understanding of the nature and properties of the fundamental elements of our Universe. Along with this pursuit of pure knowledge comes a broad range of economic and societal benefits. These include training and inspiring the next generation of innovators, discovering new ways to use subatomic particles to study complex materials, to revolutionize medical treatments, and to develop new technologies for industrial applications.

Our current understanding of subatomic particles is encapsulated in the Standard Model of particle physics, which describes the basic buildings blocks of matter, the elementary particles, and how they interact with each other through a set of fundamental forces. Combinations of these elementary particles, connected by the fundamental forces, form the atoms that make up the everyday matter around us. Other elementary particles in the Standard Model are much more elusive and exist only for a fraction of a second before they disappear, but play a central role in the structure of the theory.

TRIUMF researchers use a broad range of techniques to study the elementary particles and forces of the Standard Model

and to search for new physical phenomena beyond it. High-energy collisions in particle accelerators allow for the creation of rare, short-lived elementary particles. The ATLAS experiment, which is based at the Large Hadron Collider (LHC), uses this approach.

Lower-energy experiments allow for measurements of very high precision that probe the Standard Model structure in exquisite detail. TRIUMF is involved in many such experiments, including ALPHA, PIENU, UCN, TRINAT, Qweak, and NA62.

A third technique measures nearly invisible particles in large underground detectors. The T2K and EXO experiments use this technique to determine the properties of neutrinos, while the DEAP experiment at SNOLAB uses it to search for dark matter.

A central question beyond the structure and interactions of the elementary particles is: “How do they combine to make nuclei and more?” The quarks of the Standard Model bind through the strong force to form protons and neutrons, which combine further to make atomic nuclei. Even though the basic constituents of nuclei are understood, the complicated dynamics of how they come together is not. TRIUMF scientists investigate the strong force and the structure of nuclei using theoretical calculations and precision experiments that employ beams from the TRIUMF cyclotron.

Studying nuclei also provides crucial information about the structure of stars and the distribution of elements in the cosmos. Stars are fuelled by the energy released in the fusion of lighter atomic nuclei to heavier ones, and even heavier nuclei can be created in iolent stellar explosions. By measuring the properties of nuclei under extreme conditions in the laboratory, the relative abundances of elements in the Universe can be predicted and compared with astrophysical observations.

Particle accelerators were initially developed to study elementary particles, but they have found applications in many other areas of science and industry. TRIUMF’s Molecular and Materials Science program uses muons and lithium ions created by beams from the main cyclotron to probe the magnetic properties of unusual materials such as superconductors and state-of-the-art batteries. Subatomic particles are also used for medical imaging and treatments. The TRIUMF nuclear medicine program studies medical applications of rare atomic nuclei, and develops new methods to create them more efficiently. The program also runs a proton therapy treatment centre.

Advances in accelerator technologies may allow new discoveries of subatomic particles and lead to important applications in other areas. The TRIUMF accelerator division performs basic and applied research on particle accelerators, and develops and maintains the beams needed for the other research programs at the laboratory.

2.2 THE ENERGY FRONTIER

The most direct way to study elementary particles is to create them in high-energy collisions using particle accelerators. This is the approach of the ATLAS experiment based at the Large Hadron Collider (LHC) near Geneva, Switzerland.

TRIUMF scientists who were working on ATLAS helped to investigate the Standard Model of elementary particles at higher energies than ever before and also contributed in an essential way to the 2012 discovery of a new particle consistent with the Higgs boson of the Standard Model [1].

This discovery has led to a dedicated research program to study the new particle, but it also raises theoretical questions that suggest the existence of new particles and forces beyond the Standard Model.

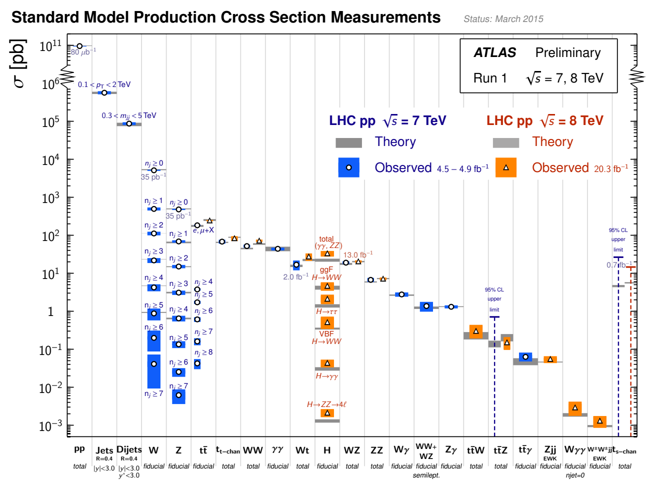


Figure 1. Summary of several Standard Model, total and fiducial production, cross-section measurements corrected for leptonic branching fractions, compared to the corresponding theoretical expectations that were calculated at next-to-leading (NLO) order or higher.

2.2.1 ATLAS: Tests of the Standard Model

I. Trigger, O. Stelzer-Chilton, A. Canepa

In its first run, from 2010–2012, ATLAS recorded about 25 fb^{-1} of data from proton-proton collisions at centre-of-mass energies of 7 and 8 TeV. These data were used by the collaboration to perform precision studies of top quarks, gauge bosons, and jets. Figure 1 shows ATLAS measurements of the total and differential cross-sections for the simultaneous production of multiple vector bosons and the associated production of vector bosons with jets or top quarks, as well as a number of other processes. These measurements test the Standard Model at the next-to-next-to-leading order in precision; they provide further evidence for the Standard Model at high energies, and they are essential for understanding the backgrounds to searches for new interactions or particles.

2.2.2 ATLAS: Discovery and Characterization of the Higgs Boson

I. Trigger, O. Stelzer-Chilton, A. Canepa

Excitement was felt around the world on July 4th, 2012 when the ATLAS and CMS collaborations announced the discovery of a new particle consistent with the Higgs boson of the Standard Model, the last particle in the theory to be discovered.

The TRIUMF ATLAS group played an essential role in this discovery: it built parts of the detector, validated many of the particle detection systems, and performed Higgs data analyses. A specific analysis spearheaded by TRIUMF researchers was the search for decays of the Higgs boson to two W bosons, an analysis that helped confirm that the newly discovered particle was consistent with the Higgs of the Standard Model.

Figure 2 shows the Higgs boson signal rates measured by ATLAS relative to the Standard Model expectations in a number of channels, including the W boson decay.

A key property of elementary particles is their spin, and the Higgs boson of the Standard Model is predicted to have a spin value of zero. In combination with other channels, the study of decays of the Higgs to two W bosons strongly suggests that the newly discovered Higgs-like particle has spin zero, as opposed to the competing spin one and two hypotheses. Measurements of the couplings, spin, and parity of the new particle were among the papers cited by the Nobel committee that awarded the 2013 Nobel Prize in Physics to François Englert, and Peter Higgs.

More recently, the ATLAS collaboration optimized search methods and improved detector performance to reanalyze the full dataset from the first run of the LHC. With these data, TRIUMF group members studied Higgs production in the vector-boson-fusion (VBF) channel,

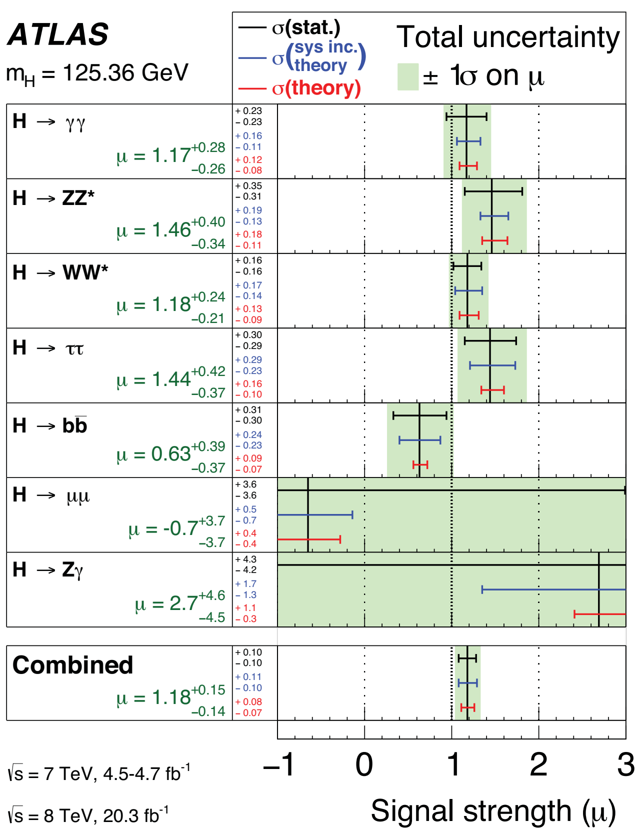


Figure 2. The observed signal strengths and uncertainties for different Higgs boson decay channels and their combination for m_H=125.36 GeV.

where two weak vector bosons radiate off colliding quarks and fuse to produce a Higgs boson. The quarks can be detected as jets in the hadronic endcap and forward calorimeters [2]. The study of this process has allowed for stringent constraints to be placed on the fundamental W-Higgs interaction strength.

2.2.3 ATLAS: Searches beyond the Standard Model

I. Trigger, O. Stelzer-Chilton, A. Canepa

The discovery of the Higgs boson at the LHC created a new puzzle. Owing to the spin-zero property of the Higgs, this particle is extremely sensitive to quantum mechanical corrections and thus it is puzzling that its mass is not much larger than the value measured (or zero). Historically, when such problems were encountered, new physical phenomena were soon discovered. Many solutions to this Higgs sensitivity puzzle have been proposed, including supersymmetry, new fundamental forces, and additional spatial dimensions. Other motivations for new phenomena beyond the Standard Model come from the observations of dark matter, the excess of matter over antimatter, and neutrino masses. The TRIUMF ATLAS group has made important contributions to the search for new physics at the LHC.

Supersymmetry predicts that every particle in the Standard Model has a superpartner particle with similar properties. Production of these superpartners at the LHC can give rise to a diverse and topologically complex range of signals in the ATLAS detectors. The TRIUMF group has focused on superpartner channels motivated by the stabilization of the Higgs boson mass. These include searches for charginos and neutralinos, expected to have a mass close to that of the Higgs boson, gluinos with masses at the TeV scale, and scalar top quarks.

The analyses performed were tailored to both supersymmetric models with a stable lightest superpartner particle (LSP) leading to large missing transverse momentum, and to those where the LSP decays into Standard Model particles. No clear signal of supersymmetry was found in these searches, but their

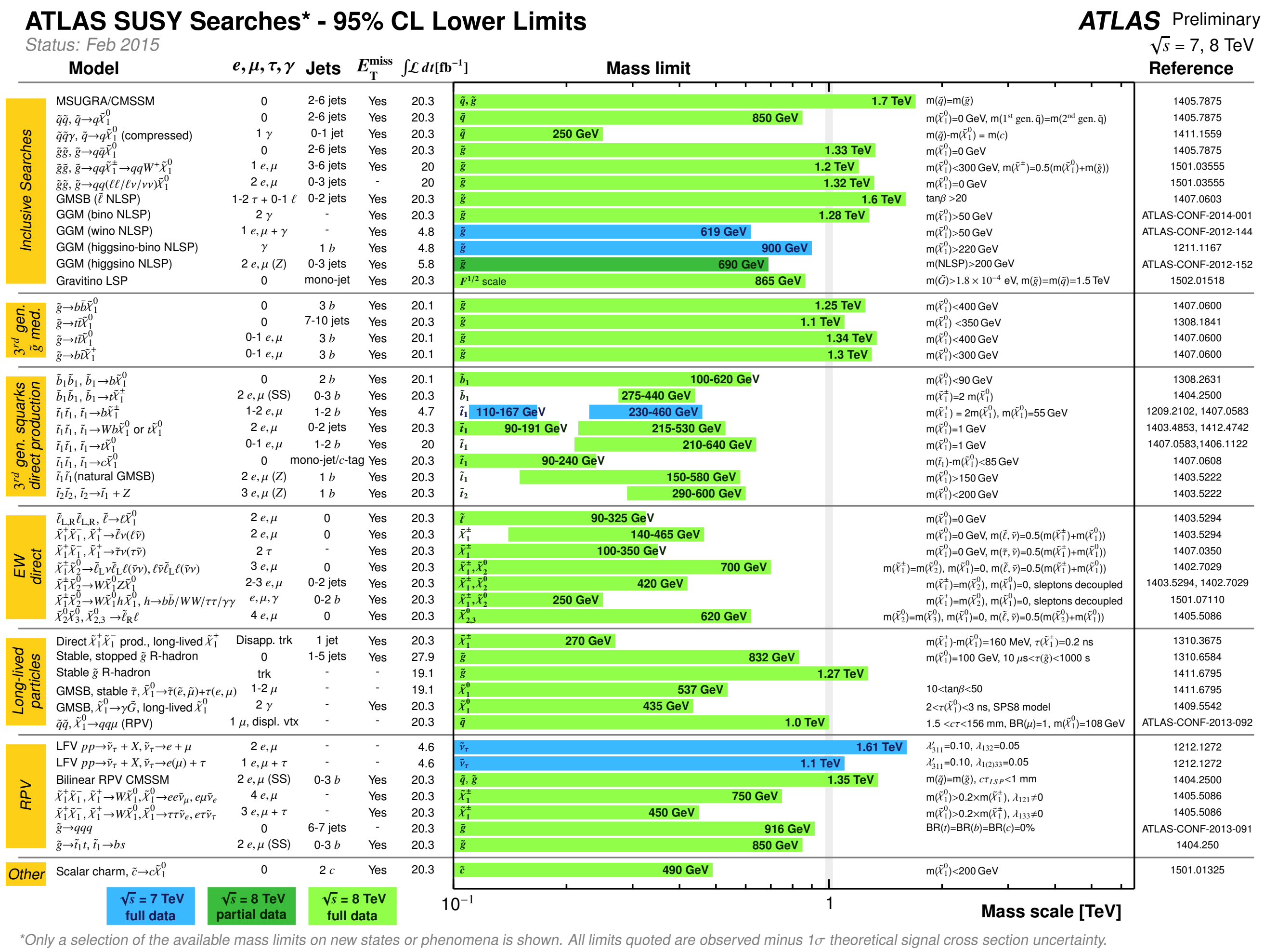


Figure 3. Mass reach of ATLAS searches for supersymmetry. A representative selection of the available results is shown.

unprecedented sensitivity led to stringent world-leading new limits on the masses of the superpartner particles. A summary of the ATLAS exclusions on superpartner masses is shown in Figure 3.

The Higgs stability puzzle can also be addressed by the existence of very small extra spatial dimensions. The first evidence of such dimensions in high-energy collisions is usually expected to be the appearance of new scattering resonances, similar to heavier versions of the Standard Model Z boson resonance but with decays into leptons or quarks dictated by the structure of the additional dimensions. The ATLAS group developed innovative search methods for new resonances based on the reconstructed mass line-shape, and has made use of the energy distribution of the constituents of resonance decays to top quarks. These searches have achieved sensitivities to new resonances with masses beyond 2 TeV.

The first run of the LHC was a resounding success and led to detailed tests of the Standard Model at unprecedented energies, and much stronger limits on new physical phenomena. The second run of the LHC began in the summer of 2015, with collisions starting at 13 TeV. Collisions at this much higher energy open the prospect of finding new particles too heavy to have been produced in detectable quantities at the first run, and allow for more precise studies of the Standard Model and the Higgs boson. Researchers at TRIUMF, across Canada, and around the world are actively analyzing these new data.

2.2.4 Theoretical Investigations

N. Blinov, J. Kozaczuk, T.A.W. Martin, D.E. Morrissey, J.N. Ng, A. de la Puente

The experimental searches of the TRIUMF ATLAS group are complemented by the theoretical studies of the Theory Department. This work seeks to find new mechanisms to stabilize the Higgs boson mass, to investigate candidates for dark matter and the asymmetry of matter over antimatter, and to probe the origin of neutrino masses. A particular focus is the range of possible signals these new phenomena could produce at the LHC.

Recent work includes studies of new methods to detect light supersymmetric partners of weak vector bosons [3], investigations of possible connections between neutrino masses and the top quark [4], and tests of dark matter and baryogenesis mechanisms in high-energy colliders [5].

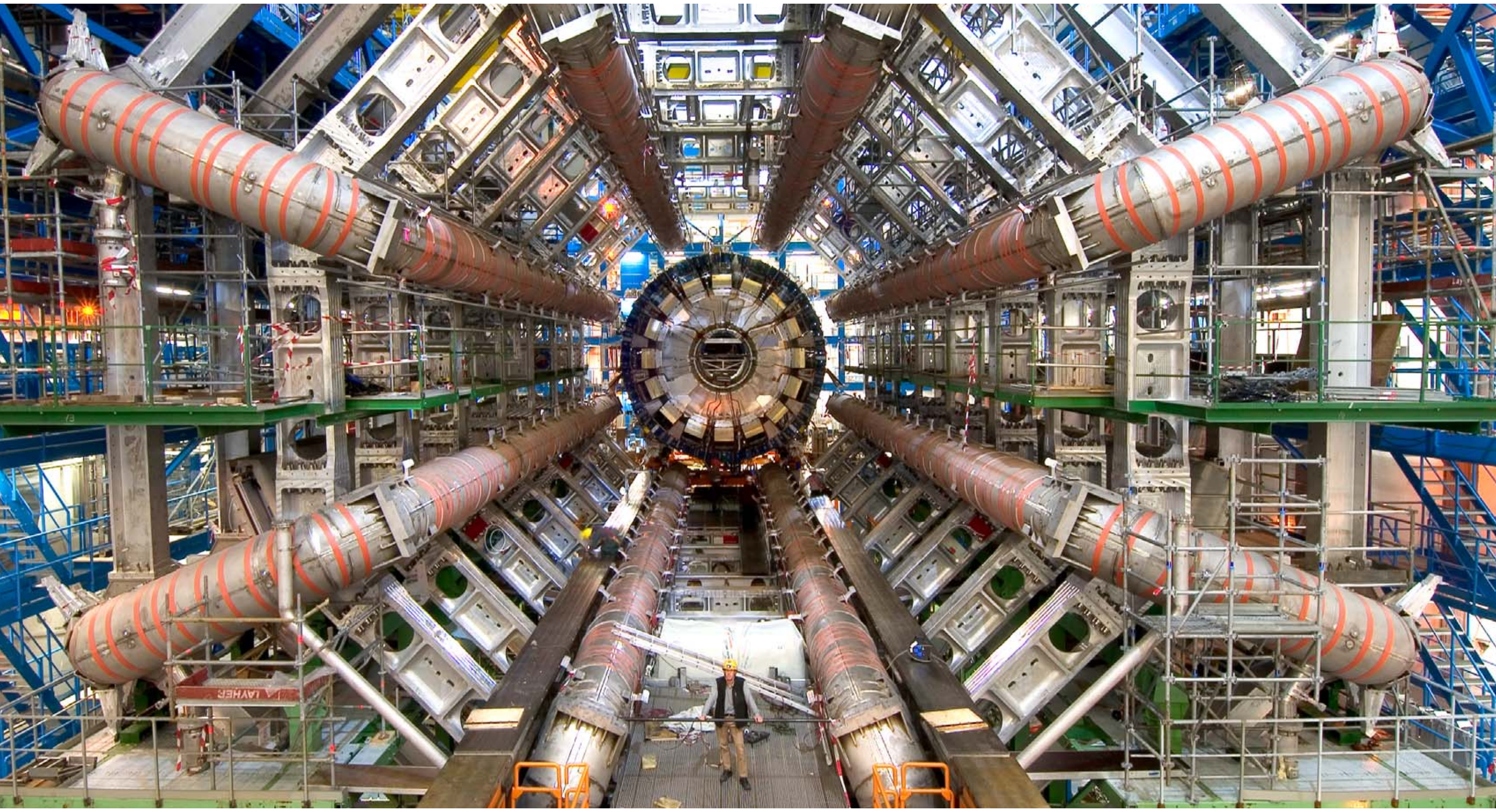


Image Credit: Maximilien Brice, CERN 2005 - CERN-EX-0511013-01

[1] ATLAS Collaboration, WWW Documents, (https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Publications)
[2] D.M. Gingrich et al., JINST 2, P05005 (2007)
[3] T.A.W. Martin and D.E. Morrissey, JHEP 1412, 168 (2014)
[4] J.N. Ng and A. de la Puente, Phys. Rev. D 90, no. 9, 095018 (2014)
[5] J. Kozaczuk and T.A.W. Martin, JHEP 1504, 046 (2015)

2.3 PRECISION TESTS OF FUNDAMENTAL INTERACTIONS

High-precision measurements offer another way to probe the basic building blocks of the Universe and are crucial in determining the underlying structure of the Standard Model. They can also provide evidence for new physical phenomena if deviations from the predictions of the Standard Model are found. Precision measurements are usually performed at energies well below those of the LHC, and their results are complementary to those obtained at the energy frontier.

One of the primary goals of precision experiments is to the test the symmetries that play a central role in our understanding of elementary particles.

In addition to the space-time symmetries that give rise to laws like the conservation of energy and the gauge invariances underlying the fundamental forces, there are the discrete symmetries of parity (P), time reversal (T), and charge conjugation (C). Precision measurements have shown that all three discrete symmetries are broken by the weak force, and these discoveries were essential to the construction of the Standard Model. Scientists at TRIUMF are developing new and improved precision experiments to test these symmetries in more detail than ever before.

2.3.1 ALPHA: Anti-hydrogen Symmetry Tests

M.C. Fujiwara, D. Gill, L. Kurchaninov, K. Olchanski, A. Olin

While the discrete symmetries of C, P, and T are violated by the weak force, the combination of CPT is respected by all known interactions and is an essential element of the relativistic quantum field theories that underlie the Standard Model. Preservation of CPT implies that matter and antimatter must behave in nearly the same way. The goal of the ALPHA experiment is to trap and study anti-hydrogen atoms in order to search for fundamental differences between matter and anti-matter that would signal the breaking of CPT. TRIUMF researchers have played a leading role in the building, running, and analysis of the ALPHA experiment.

The ALPHA trap, located at CERN and shown in Figure 1, confines anti-hydrogen atoms in a magnetic minimum. Anti-atoms with temperatures below 0.5 K were confined for periods close to 1000 s and probed with spectroscopic methods [1,2]. Three primary physics results were obtained from the 539 confined anti-hydrogen atoms observed in the 2010 and 2011 data: the charge of anti-hydrogen was determined to be zero within 20 ppb [3]; the energy splitting of ground state anti-hydrogen in a magnetic field was measured to lie within 0.4% of its value in hydrogen [4]; and the ratio of its gravitational to inertial mass was limited to less than 75 [5]. These first results on anti-hydrogen spectroscopy were recognized by NSERC with the 2013 Polanyi prize.

More recently, the ALPHA collaboration designed, built, and commissioned a completely new apparatus to enable precision spectroscopy. A dedicated Penning trap was added for the initial capture of the antiprotons, which cools and compresses them before passing them to the atom trap. The new atom trap has access ports for four laser beams, an efficient microwave guide, and a cryogenic build-up cavity for the 243 nm laser that will drive the 2-photon 1S-2S transition. Lasers of 243 nm and 121 nm wavelengths, for Lyman alpha spectroscopy and laser cooling, have been installed. TRIUMF supplied the requisite electronics and software, UBC produced the 121 nm laser, and TRIUMF and the University of Calgary designed and fabricated the atom trap cryostat. The new apparatus was commissioned in 2014 and immediately achieved an increased yield of trapped anti-hydrogen.

The initial physics goal with the new apparatus was to measure the optical spectroscopy of anti-hydrogen atoms to high precision. Differences in the spectroscopic spectrum, relative to ordinary hydrogen, could signal the breaking of CPT. Detailed design and construction is also underway for a new vertical trap that will permit the first direct free-fall measurements of the effects of gravity on anti-atoms.

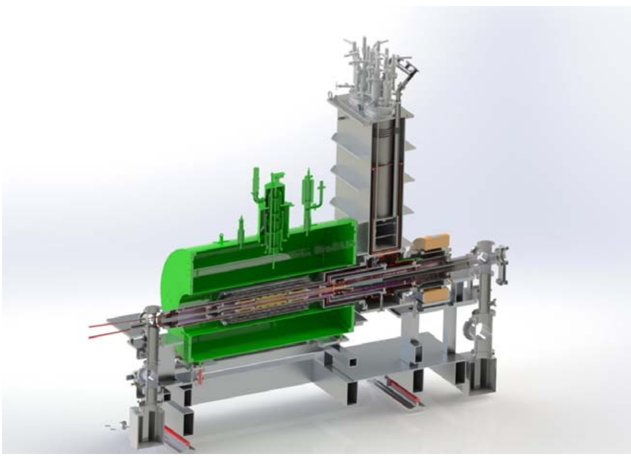


Figure 1. The ALPHA2 atom trap. The atom trap magnets and Penning trap electrodes are centered in the bore of the outer trap solenoid and are shown in green. The silicon vertex detector surrounds the atom trap. Laser paths through the trap are shown in red. The vertical tower on the right is a LHe reservoir carrying the HTC leads to the atom trap magnets. Antiprotons enter from the left, and positrons from the right.

2.3.2 UCN: Neutron Electric Dipole Moment Search with an Ultra-cold Neutron Source at TRIUMF

Y. Masuda, J. Martin

The Standard Model treats matter and antimatter in nearly the same way. For this reason, it is puzzling why the Universe contains so much more matter than antimatter. The only part of the Standard Model that distinguishes between them is CP violation, and there does not seem to be enough of it to explain the matter of asymmetry. It follows that new sources of CP violation beyond the Standard Model are needed, and they can give rise to electric dipole moments (EDMs) in subatomic particles.

The neutron is a very promising system for measuring an EDM because it does not suffer from the large theoretical uncertainties associated with more complicated nuclear or atomic systems. One of the primary goals of the ultra cold neutron (UCN) facility at TRIUMF is to detect a neutron EDM by making use of the very long neutron storage times in the apparatus. The search for a neutron EDM with UCN will proceed in two stages. In the first stage, an existing EDM prototype detector from RCNP (Research Center for Nuclear Physics, Osaka) will be upgraded and employed towards obtaining Ramsey cycles at TRIUMF [6]. Data will be taken in an initial run from 2017–2019 following the commissioning of the UCN source. The second stage will be a search for the neutron EDM, to begin in 2019 and likely to feature a magnetically shielded room surrounding additional passive shielding [7,8], a double EDM cell, and a dual-co-magnetometer, together enabling a sensitivity in excess of $d_n = 10^{-27}$ e cm.

In order to facilitate development of the EDM cells, the central elements of the planned neutron EDM experiments, a high-voltage test facility was established at TRIUMF. Here, the interplay between the co-magnetometer gases and the necessary electrical field in the cells are investigated, and are aimed at an optimum combination of cell geometries, materials, field strengths, and gas pressures. Eventually, this setup could be integrated with a prototype magnetic shield existing at the University of Winnipeg and the ^{129}Xe and ^{199}Hg co-magnetometers to perform a measurement of the Xe EDM.

2.3.3 Precision Measurements of Nuclear Beta Decay

edited by J. Behr

Parity, the operation of spatial reflection, is not respected by the weak force. This Nobel Prize winning discovery arose from measurements of nuclear beta decay in 1957, where it was found that fewer electrons are emitted in the direction of the spin of nuclei undergoing beta decay than against it. Detailed measurements of nuclear beta decay remain a key tool for investigating the structure of the Standard Model and searching for new physics beyond it. Experiments at TRIUMF studied nuclear beta decay to investigate parity violation, quark mixing under the weak force, and to search for new sources violation of time-reversal invariance.

The TRIUMF neutral atom trap for beta decay (TRINAT) measures the beta asymmetry in positron decays of ^{37}K. This nucleus decays to its isobaric mirror, ^{37}Ar, with one proton changing to a neutron, implying that the asymmetry has very little dependence on the underlying nuclear structure. The data taken in May and June of 2014 measured the beta asymmetry of ^{37}K to a statistical precision close to 0.3%. The experiment included an accurate determination of the ^{37}K spin polarization by atomic physics techniques and benefitted from a much higher sample production rate using an ISAC high-power titanium carbide target and better laser-trapping efficiency. Determination of systematic uncertainties and a blind analysis of the data are underway. The precision of the final result is expected to rival world-leading measurements in neutron beta decay. A preliminary result for the asymmetry as a function of the emitted electron energy based on data

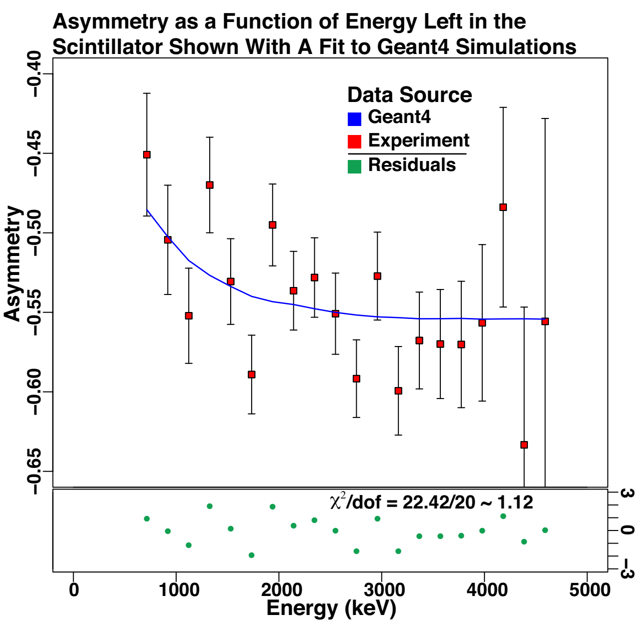


Figure 2. Beta asymmetry as a function of beta energy for ^{37}K decay, from [9].

from 2012 was obtained in a Ph.D. thesis [9], and is shown in Figure 2. This measurement yields an asymmetry of A_β = -0.5635(63) (71), in agreement with the Standard Model prediction of A_β = -0.5739 [9].

The weak force connects quarks of different types to each other. This mixing is described by the Cabbibo-Kobayashi-Maskawa (CKM) matrix, and the first element of the matrix, V_{ud}, determines the rate of nuclear beta decays. Experiments at TRIUMF by gamma-ray groups, and the TITAN and TRIUMF collinear laser collaborations, have measured the properties of a number of nuclear beta decay cases with the goal of improving the determination of the V_{ud} matrix element. Better measurements of the rates of the low-Z superallowed beta decays ^{10}C, ^{14}O, and ^{18}Ne were performed [10,11,12]. These cases are the least sensitive to isospin mixing corrections for the determination of V_{ud}, and there is hope that ^{10}C can be calculated better by modern nuclear theory approaches.

To better understand the theoretical methods used to extract V_{ud} from beta decay rates, branching ratio measurements of ^{74}Rb were done [13,14]; isospin mixing is enhanced in these decays providing an excellent test of the theoretical description of this effect. The TITAN collaboration also made mass measurements of ^{74}Rb with highly charged ions. Future related plans include measuring ^{62}Ga branching ratios and charge radius, and studies of ^{35}Ar, ^{21}Na, and ^{19}Ne, which need angular correlation measurements.

The Mott Polarimetry for T-Violation Experiment (MTV) at TRIUMF seeks to measure new sources of time-reversal invariance (T) violation in the beta decays of polarized ^{8}Li nuclei [15]. Violation of T would appear as a net electron spin polarization perpendicular to its momentum and to the polarization of the parent ^{8}Li nucleus. A new cylindrically symmetric chamber was constructed to reduce systematic errors [16], and includes a polarimeter to detect the tilt of the beam polarization. The data acquisition speed of the time projection chamber was also improved [17]. Data taking is planned in the next two years with the goal of obtaining the best measurement of this type.

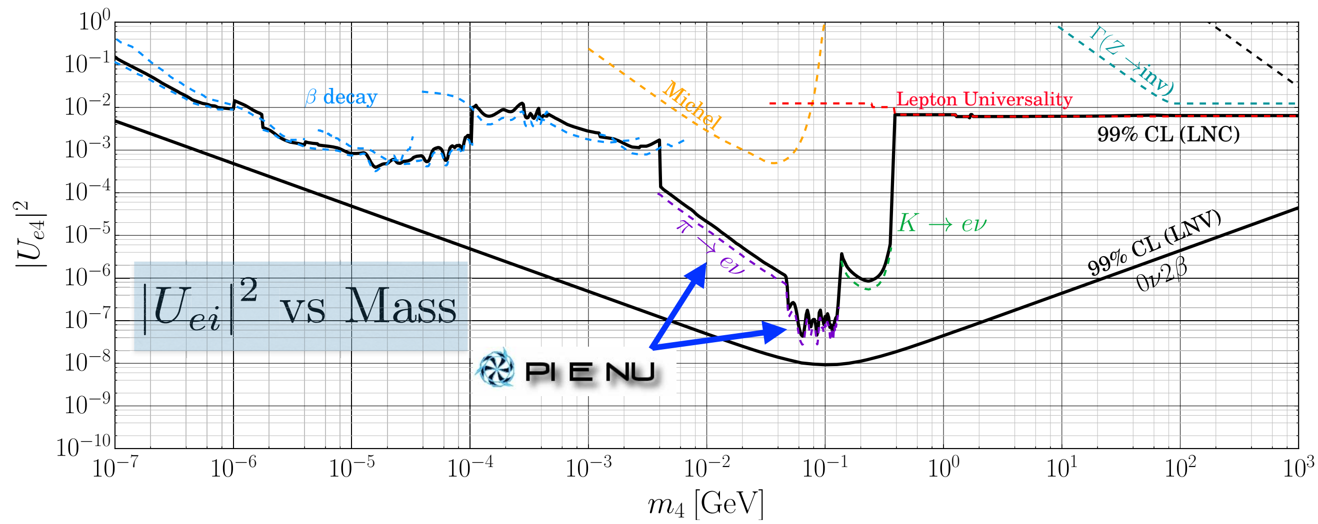


Figure 3. Constraints on the mixing ($|U_{ei}|^2$) versus mass of heavy neutrinos coupled to electrons. Regions covered by the TRIUMF PIENU experiment are indicated [18]. Figure from [19].

2.3.4 PIENU: Measurement of π → e ν Decays

D.A. Bryman, T. Numao

The Standard Model predicts the universality of lepton weak couplings, with all three lepton flavours treated in the same way by the weak force. This hypothesis can be tested most precisely for the first two generations by measuring the ratio of π→eν and π→ μν decays. The PIENU experiment aims to improve the measurement of these decay branching ratios to a precision below 0.1%. At this level, the experiment will be sensitive to the effects of new physics phenomena as heavy as 1000 TeV, far beyond the direct search reach of the LHC.

Data for the PIENU experiment was collected in the TRIUMF M13 channel in 2008–2012, and more than ten million clean π→ e ν decay events were accumulated. Since then, the PIENU group has completed and published the analysis of 5% of the data, reducing the uncertainty on the π→e ν branching ratio measurement by a factor of two to the level of 0.2 %. This work also provided the best constraint on the existence of massive neutrinos that couple to electrons [18] in the range accessible to pion decays, as shown on Figure 3. Final results, expected in 2017, aim at a statistical uncertainty of 0.05% and systematic uncertainty below 0.1 %, with the analysis in progress using careful studies of the data and intensive Monte Carlo simulations.

2.3.5 TWIST

G.M. Marshall

Muons, the heavier cousins of electrons, decay exclusively through the weak interaction in the Standard Model. The TWIST experiment measures the products of polarized muon decays to a very high precision to test the structure of the weak force and to search for new physics [20]. While the data-taking phase of TWIST was completed in 2007, interesting results are still being obtained from its data. A recent search for exotic muon decays, involving a light axion or dark matter particle, has obtained new limits on such processes [20]. The seeming deviation from the Standard Model observed in a previous analysis of TWIST data has also been resolved by a recently improved theoretical prediction [21]. An ongoing TWIST analysis studies the spectrum of 80-250 MeV/c protons and deuterons following muon capture in Al, which will be of use to future measurements by the mu2E and Comet collaborations.

2.3.6 J-PARC Muon g-2/EDM Experiment

G.M. Marshall, A. Olin

Measurements of the difference between the orbital and spin rotation frequencies of elementary particles in a magnetic field, generally referred to as “g-2”, provide some of the most precise tests of the Standard Model and give important constraints on many proposed extensions. Moreover, the most recent measurement of the g-2 value of the muon by the E821 experiment at Brookhaven finds a deviation from the Standard Model by three standard deviations. The proposed E34 muon g-2/EDM experiment at J-PARC will measure the same quantity using a new technique with very different systematic errors, complementing a new measurement being mounted at Fermilab by a collaboration that includes the previous E821 team.

The J-PARC E34 experiment will measure the muon g-2 value and EDM with a new method, using an extremely low emittance muon beam derived from ultra-slow thermal muonium atoms emitted from silica [22]. This cold muon beam technique allows for rapid muon spin reversal that helps to control systematic uncertainties in a way that is not possible at the Fermilab experiment. Recently, TRIUMF experiment S1249 found that the addition of structure to the aerogel surface produces a factor of ten increase in muonium yield [23], establishing the feasibility of a precise g-2 measurement. This has helped the experiment to progress to Stage I approval at J-PARC, and the technical design report required for Stage II has been submitted [24]. The Canadian collaborators will continue to focus their efforts in this area with measurements planned at J-PARC and the RIKEN/RAL facility in the UK.

2.3.7 Qweak: Measurement of the Proton’s Weak Charge

W. Van Oers, L. Lee, D. Ramsey

The Qweak experiment tests parity violation in electron-scattering processes. Longitudinally polarized electrons are scattered on a liquid hydrogen target and the change in the scattering rate when the electron polarization is reversed is measured. This asymmetry in the scattering rates is due to parity violation, and in the Standard Model is proportional to the net interaction strength of the proton with the Z vector boson, the so-called proton weak charge.

The Standard Model predicts an asymmetry of about -250 parts per billion (ppb), while many examples of proposed new phenomena, such as supersymmetry or exotic vector bosons with masses near a TeV, induce deviations in this prediction by tens of ppb. The Qweak experiment, in Jefferson Lab’s Hall C, is designed to make just such a measurement, aiming for a combined systematic plus statistical uncertainty of 6 ppb. This accuracy will also determine the weak mixing angle at low momentum transfer to 0.3%, an important measurement in its own right.

Installation and commissioning of the Qweak experiment took place from 2010 to 2011, and data was taken from 2011 to 2012. About 4% of the total was obtained during the commissioning phase, and results derived from it, including a first determination of the proton’s weak charge, were published in late 2013 [25]. The reduced asymmetry measured with this data is shown in Figure 4. It is anticipated that when the full data set is analyzed, a statistical error close to the design goal will be achieved.

TRIUMF played a crucial role in the design and fabrication of much of the Qweak equipment

and TRIUMF and the University of Manitoba oversaw the design, fabrication and magnetic verification/mapping of the Qweak toroidal spectrometer (QTOR). In addition,

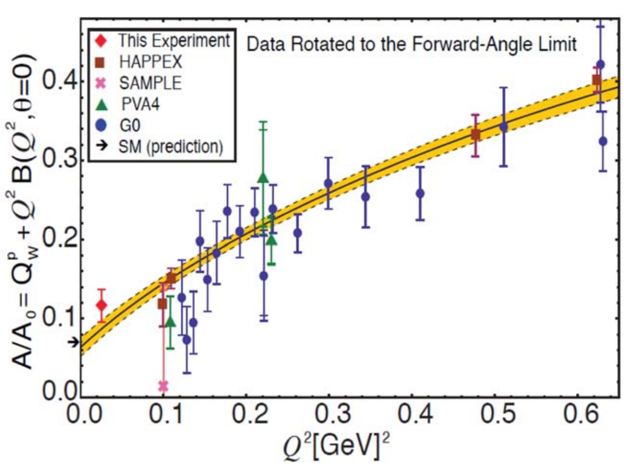


Figure 4. Reduced asymmetry, with data rotated to the forward angle limit--from the Qweak commissioning data, which represents 4% of the full data set, from [25].

the high-precision main detector electronics at the heart of the experiment, the beam line (parity) electronics, and the Compton polarimeter electron-arm electronics, were designed and fabricated at TRIUMF.

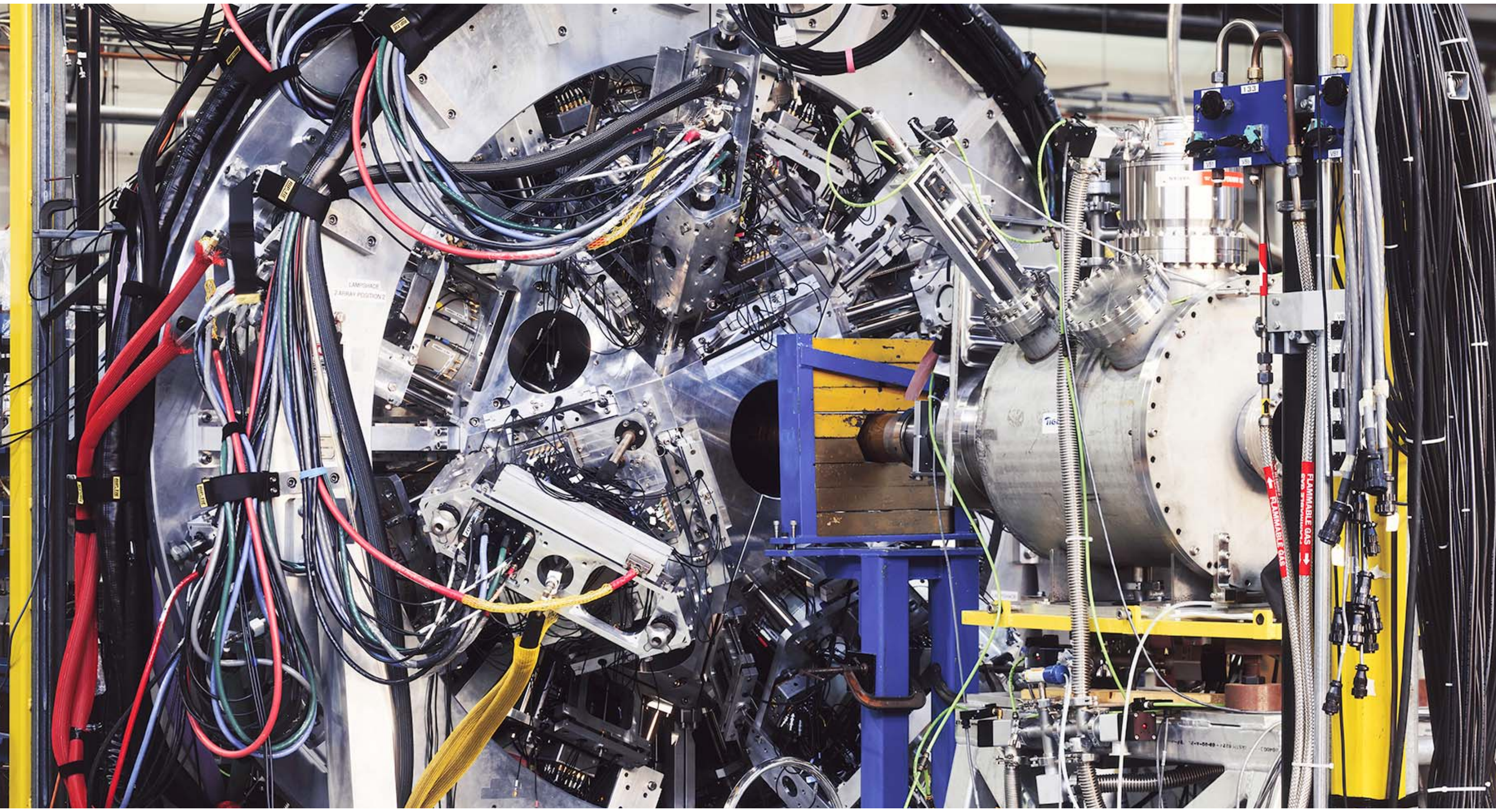
2.3.8 NA62: Measurement of the Rare Kaon Decay $K^+ \to \pi^+ \nu\bar{\nu}$

D.A. Bryman, T. Numao

High precision measurement of the ultra-rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$ (KPNN) at the CERN NA62 experiment will be one of the most incisive probes of quark flavour physics. This process is very suppressed in the Standard Model, which predicts that it occurs at the level of only once per ten billion decays. As a result, KPNN is very sensitive to new physics beyond the Standard Model. A high-precision measurement of KPNN would probe nearly all models of new physics that couple to light quarks within the reach of the LHC, and could be sensitive to many models with mass scales well beyond the direct reach of current high-energy colliders.

NA62 is a fixed-target experiment that uses the CERN SPS to produce 75 GeV/c kaons that decay in flight. It runs coincidently with the LHC. Data taking is underway and the experiment is planned to run to 2018. The TRIUMF-UBC group, that discovered

$K^+ \to \pi^+ \nu\bar{\nu}$ in a series of experiments at Brookhaven National Laboratory, is concentrating on data analysis related to background processes that need to be suppressed by 12 orders of magnitude. NA62 expects to have sensitivity for observing 100 events at the SM level, $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (9.11 \pm 0.72) \chi 10^{-11}$, with a signal to noise ratio of 5-10. The experiment will also study many other rare or forbidden reactions to search for dark matter, heavy sterile neutrinos, neutral pion decays, and radiative processes.



[1] G. Andresen et al., Nature 468, 673 (2010)

[2] G. Andresen et al., Nature Physics 7, 558 (2011)

[3] C. Amole et al., Nature Commun. 5, 395 (2014)

[4] C. Amole et al., Nature 483, 439 (2012)

[5] A. Charman et al., Nature Commun. 4, 1785 (2013)

[6] Y. Masuda et al., Phys. Procedia 51, 89 (2014)

[7] J. W. Martin et al., Nucl. Instrum. Meth. A 778, 61 (2015)

[8] C. P. Bidinosti and J. W. Martin, AIP Advances 4, 047135 (2014)

[9] S. Behling, Texas A&M University Ph.D. Thesis, Figure 6.20b, 2014 (Unpublished)

[10] G.F. Grinyer et al., Phys. Rev. C 87, no. 4, 045502 (2013)

[11] A.T. Laffoley et al., Phys. Rev. C 88, 015501 (2013)

[12] A.T. Laffoley et al., Rev. C 92, no. 2, 025502 (2015)

[13] R. Dunlop et al., Phys. Rev. C 88, no. 4, 045501 (2013)

[14] S. Malbrunot-Ettenauer et al., Phys. Rev. C 91, no. 4, 045504 (2015)

[15] Y. Totsuka et al., Phys. Part. Nucl. 45, 244 (2014)

[16] R. Tanuma et al., Report of the Next Generation TRIUMF-MTV Experiment Run-IV Using Cylindrical Drift Chamber, JPS Conf. Proc. 1, 013069 (2014)

[17] S. Tanaka et al., Nucl. Instrum. Meth. A 752, 47 (2014)

[18] M. Aoki et al., Phys. Rev. D 84, 052002 (2011)

[19] A. de Gouvêa and A. Kobach, Phys. Rev. D 93, no. 3, 033005 (2016)

[20] R. Bayes et al., Phys. Rev. D 91, 052020 (2015)

[21] F. Caola et al., Phys. Rev. D 90, no. 5, 053004 (2014)

[22] P. Bakule et al., PTEP 2013, 103C01, (2013)

[23] G. Beer et al., PTEP 2014, 091C01 (2014)

[24] H. Ando et al., Technical Design Report for the Measurement of the Muon Anomalous Magnetic Moment g-2 and Electric Dipole Moment at J-PARC, May 2015.

[25] D. Androic et al., Phys. Rev. Lett. 111, no. 14, 141803 (2013)

2.4 NEUTRINOS AND DARK MATTER

Two of the deepest puzzles in subatomic physics are the origin of neutrino masses and the nature of dark matter. In both cases, the particles involved are invisible, in that they interact with ordinary matter primarily through the weak force (or something even more feeble), and can only be probed directly in dedicated underground detectors.

Evidence for neutrino masses comes from the observation of neutrino oscillations, a phenomenon that was first confirmed by neutrino measurements at Super Kamiokande and SNOLAB. This discovery of neutrino oscillations, which implies new physics beyond the Standard Model, was awarded the 2015 Nobel Prize in physics. Astrophysical observations also point toward another type of invisible particle in the form of dark matter. No Standard Model particle can account for dark matter, and with its nature unknown, detecting dark matter in the laboratory is crucial to understanding its origin.

TRIUMF is involved in the study of neutrinos through the T2K, EXO, HALO, and SNO(+) collaborations,

and with the search for dark matter in DEAP-3600 and SuperCDMS, along with theoretical investigations by the theory department. The T2K experiment measures neutrino oscillations to better understand the neutrino masses and properties. Neutrino masses can also give rise to a very rare neutrinoless double beta decay process, which is being searched for by the EXO and SNO+ collaborations. Energetic neutrinos from violent astrophysical events are being searched for by HALO, while SNO studies neutrinos from the sun. Finally, the DEAP-3600 and SuperCDMS experiments will look for direct dark matter interactions with nuclei.

2.4.1 T2K

S.M. Oser, H.A. Tanaka

The T2K (Tokai-to-Kamioka) experiment measures neutrino oscillations, a quantum mechanical process in which neutrinos of one of the three known types transmute into the other two. Neutrino oscillations require that neutrinos have non-zero masses, and can be characterized by these masses and a set of three mixing angles. The oscillations of neutrinos can also differ from those of antineutrinos in the presence of CP violation. By studying neutrino oscillations, T2K seeks to clarify the origin of the neutrino masses and mixings and test whether CP violation is present in the mixing. Together with four other neutrino oscillation experiments, the T2K collaboration was awarded the 2016 Breakthrough Prize in Fundamental Physics.

For these investigations, T2K uses a neutrino beam produced at the J-PARC accelerator facility on the Pacific coast of Japan. The beam is sent 295 km across the country to the Super-Kamiokande (SK) underground detector. Oscillations are measured by comparing the composition of the neutrino beam in a near detector close to J-PARC to what is found farther away in SK, as shown in Figure 1. In 2014, a comparison of neutrino and anti-neutrino oscillation modes resulted in the first constraints on CP violation in the neutrino sector [1].

TRIUMF-based researchers led an effort to refine the analysis of events in the far Super-Kamiokande detector, and this refinement will increase both the efficiency for detecting neutrino signal events and events that include pion production (which are currently discarded). The dataset of T2K will be increased in the coming years and can also be applied to searches for proton decay and atmospheric neutrinos. The inclusion of pion-production channels will be improved by data from DUET, a TRIUMF-based

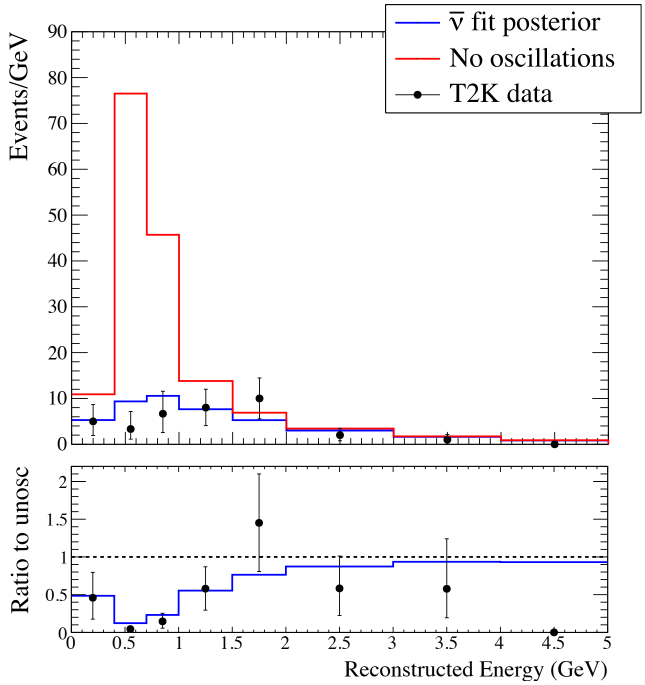


Figure 1. (Top) Energy distribution of muon antineutrino candidates observed at SK in the T2K beam. The red histogram shows the expected distribution in the absence of neutrino oscillation effects, while the blue histogram shows the best fit to the observed spectrum.

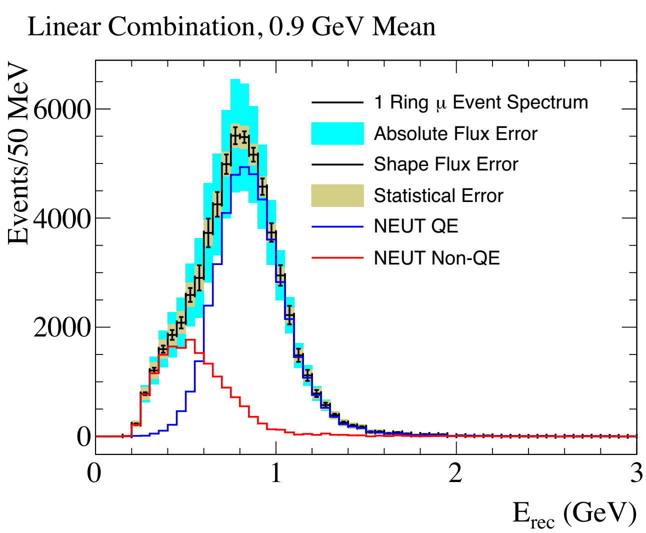


Figure 2. Demonstration of the NuPRISM concept: a 900 MeV neutrino beam can be emulated by considering α interactions across a range of off-axis angles, and the expected response of the detector measured. In this case, measurement of the expected neutrino energy distribution, which includes quasielastic and non-quasielastic interactions, is demonstrated.

pion scattering experiment that has increased our understanding of the relevant pion-nucleus interactions. Work was also begun on future upgrades of T2K and the development of the next-generation Hyper-Kamiokande experiment. TRIUMF contributions to T2K upgrades have concentrated on improvements to the near detectors that measure the neutrino beam close to production. These include a potential upgrade to the FGD2 water layers in the near detector using a new water-based liquid scintillator that will provide more tracking information, as well as the NuPRISM concept, illustrated in Figure 2, which uses the relationship between the neutrino energy spectrum and the angle from the beam axis to greatly reduce many systematic uncertainties in measuring the initial neutrino beam [2].

Over the next year, T2K will continue taking data with a roughly equal mix of neutrino and antineutrino running that will optimize sensitivity to CP violation while phasing in a number of analysis improvements. A fully joint analysis of neutrino and antineutrino mode oscillations will be implemented to maximize the sensitivity to the neutrino oscillation parameters. The R&D effort for NuPRISM and Hyper-Kamiokande will also be ramped-up in collaboration with Canadian collaborators on IceCube and PINGU, where similar photo sensor and readout electronics developments are planned.

2.4.2 EXO

G. Gratta, F. Retière

Neutrinoless double beta decay (0νββ) occurs when a pair of neutrons converts directly into a pair of protons and electrons. The EXO (Enriched Xenon Observatory) project is attempting to make the first observation of 0νββ through precision measurements of the decays of ^{136}Xenon nuclei. Observing 0νββ would be the first discovery of lepton number violation, and could provide important clues about the origin of neutrino masses, the absolute scale of these masses, and possibly even the

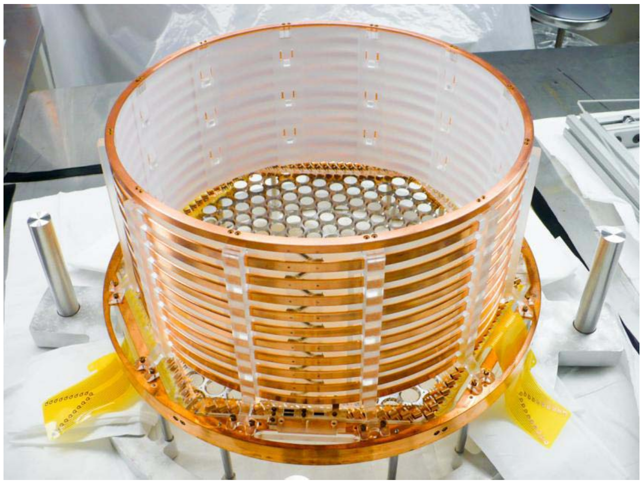


Figure 3. Picture of the Time Projection Chamber that is the core of EXO-200. Copper shaping rings surround the barrel covered with Teflon. The top of the chamber is a cathode mesh. The bottom includes a set of α anode wires (not visible on the picture) for charge collection and avalanche photo-diode disks for light detection.

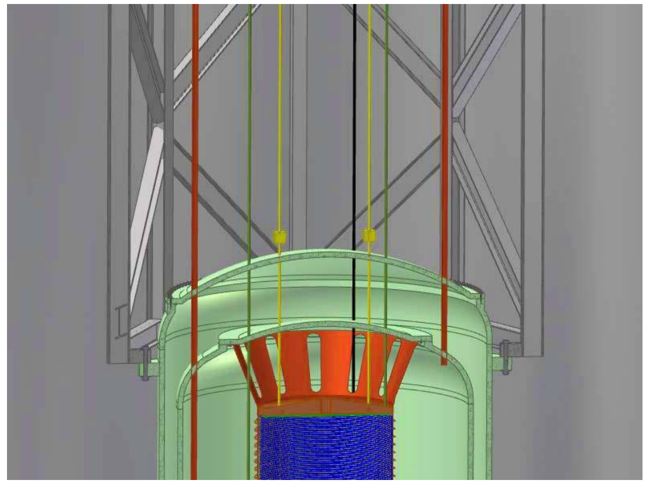


Figure 4. Conceptual drawing of the nEXO, assuming that it would be sited at SNOLAB. The grey volume is filled with water. The green volume is filled with coolant. The Time Projection chamber is shown mostly in blue.

source of the excess of matter over antimatter. The EXO project consists of two experiments: EXO-200 and nEX0. Data was taken by EXO-200, shown in Figure 3. No ^{136}Xe decays were observed above the expected background, and this allowed the experiment to set a new world-leading limit on the 0νββ lifetime of 1.1×10^{25} years in 2014 [3]. More data has been recorded, and further analysis is underway.

EXO-200 is presently situated at the WIPP underground laboratory. WIPP was closed for more than a year following two separate incidents involving a radioactivity leak and an underground fire, and as a consequence, the EXO experiment itself has been shut down for more than a year. EXO-200 is expected to restart in 2015, with TRIUMF ramping up its contribution from research scientists and professors holding joint positions.

Additional work was done in preparation for the next generation of the EXO project, nEXO, shown in Figure 4. TRIUMF joined the nEXO collaboration in 2013 and quickly took on a leadership role in the development of its photo-detectors. Improving the photon detection efficiency will help to reduce backgrounds and is essential to achieving the nEXO target sensitivity to 0νββ. The avalanche photo-diode technology currently used in EXO-200 is limited by electronics noise and manufacturing issues. As an alternative, nEXO is investigating a silicon photo-multiplier (SiPM) technology, which is being aggressively pursued by several manufacturers of applications in medical imaging and basic physics research. However, the requirements for nEXO are somewhat unique, and include ultra-low radioactivity and the specific sensitivity to ultraviolet light of wavelength 175 nm. TRIUMF has led the development of photo-detectors for nEXO by managing the photo-detector group and operating a test facility designed for characterizing SiPMs in nitrogen gas (which, unlike air, transmits 175 nm light) at liquid xenon temperatures.

In 2014, the TRIUMF setup was commissioned and led key measurements of several nuisance parameters (dark noise and correlated avalanche rates) at -100° C. The efficiency at 175 nm was measured at Stanford, but the TRIUMF setup is now operational for crosschecks and the investigation using wavelength shifting material that would allow using standard blue sensitive SiPMs but may compromise the liquid xenon purity. Overall, with relatively small resources, TRIUMF has had a very significant impact on nEXO in the last two years and will continue to play a major role as the project grows.

2.4.3 HALO
S. Yen

Supernovae, the violent explosions of massive stars at the end of their life cycles, emit much of their energy in the form of energetic neutrinos. The HALO detector is designed to detect such neutrinos, operating with a high live-time, low maintenance, and at low cost. HALO is located at SNOLAB, and consists of a core of 79 tonnes of lead instrumented with 376 m of ^{3}He neutron detectors from the SNO experiment, and surrounded by a layer of water shielding. The use of lead gives a dominant sensitivity to electron-type (ν_e) supernova neutrinos that is unique and complements the dominant antielectron-type supernova neutrino sensitivity of other water and liquid scintillator-based detectors. Supernova neutrinos interacting with the lead mass create excited daughter nuclei that decay by emitting one or two neutrons. A measure of the temperature of the neutrinos is given by the ratio of the number of events with two detected neutrons to the number with one detected neutron, since the energy threshold for two-neutron emission is higher.

From 2013–2015, HALO took data with 85% of the water shield installed. HALO will join the network of supernova-sensitive neutrino detectors and participate in the Supernova Early Warning System (SNEWS) on a trial basis by October 2015.

Neutrino bursts from galactic supernovae occur only a few times per century and last only about 20 seconds,

so high reliability of all components is of the utmost importance. In the reporting period 2013–2015, several equipment upgrades were undertaken to monitor and improve reliability and performance. The UPS power supply for the whole experiment was upgraded with a surge suppressor. Older power supplies (high and low voltage) were replaced with modern equipment. VME powered crates were replaced with new units that allow remote control and monitoring. Redundancy in high voltage supplies, data acquisition computers, and network connectivity were implemented. A GPS receiver was installed to provide a time-stamp for every neutrino event. A creep monitoring system was installed to monitor the possible gradual sagging of the lead annuli that make up HALO. Considerable effort was put into developing a procedure for cleaning and encapsulating a ^{252}Cf neutron calibration source to SNOLAB's increasingly strict standards. This encapsulation, and the measurement of the efficiency, will be done in the fall of 2015. Software improvements have been made concurrently with hardware improvements, in particular the implementation of a burst monitor to look for a series of successive neutron detections in HALO that may indicate a supernova event, and a web-based interface for the remote monitoring of all detector health parameters. On the detector side, gain-matching of the neutron detectors was done in July 2014 to improve the energy resolution and thereby give better neutron versus gamma discrimination. Plans for the next year include completing a pulser system to continuously monitor the gain of the pre-amps, measuring the absolute neutron detection efficiency, and enclosing the detector with the installation of the front shielding wall. This would mark the completion of HALO.
Progress was also made in planning for a much larger HALO-2 detector that may incorporate some of the 1.3 kilotons of low-radioactivity lead provided by the decommissioning of the OPERA detector in the Gran Sasso laboratory in Italy.

2.4.4 DEAP-3600
M. Boulay, F. Retière

Evidence for dark matter comes from its apparent gravitational influence on astrophysical systems such as galaxies and the cosmic microwave background radiation. To confirm the dark matter hypothesis, it is essential to find the particles that make it up and measure their detailed properties. The DEAP-3600 experiment is designed to detect the scattering of a certain class of dark matter, Weakly Interacting Massive Particles (WIMPs). If WIMPs exist, they will scatter off argon nuclei, and detecting these scatters will measure its interaction strength with ordinary matter [4].

The experiment is located deep underground in SNOLAB. It consists of 3600 kg of liquid Argon in a suspended acrylic vessel surrounded by photomultipliers (PMT), shown in Figure 5. These are designed to detect the light emitted when a DM particle scatters with an Argon nucleus in the vessel.

TRIUMF has been a leading contributor in the construction of the DEAP-3600 detector. The 255 light guides that connect the acrylic vessel to the PMTs were manufactured at TRIUMF in 2013 and 2014. TRIUMF also provided the electronics system for reading out the 255 (and associated 48) PMTs and for handling various calibration systems. The system was installed at SNOLAB in April 2013, followed by a period of commissioning. This included data taking with all PMTs operational while the acrylic vessel was filled with nitrogen gas. Large data sets were taken in 2015 to characterize the PMT response and to investigate rare triggers such as Cerenkov light produced in the light guides by gamma ray and the occasional cosmic ray interactions, as illustrated in Figure 6.

Construction of DEAP-3600 is nearing completion, with the following major steps pending: deposition of the wavelength shifter inside the acrylic vessel, attachment of the cooling apparatus in the vessel neck and filling with liquid argon. It is expected that DEAP will be ready to take data for dark matter searches in early 2016. In the coming years the experiment is expected to obtain a world-leading sensitivity to scattering cross-sections as low as 10^{-46} cm^2 for dark matter masses in the range of 100 GeV/c^2.

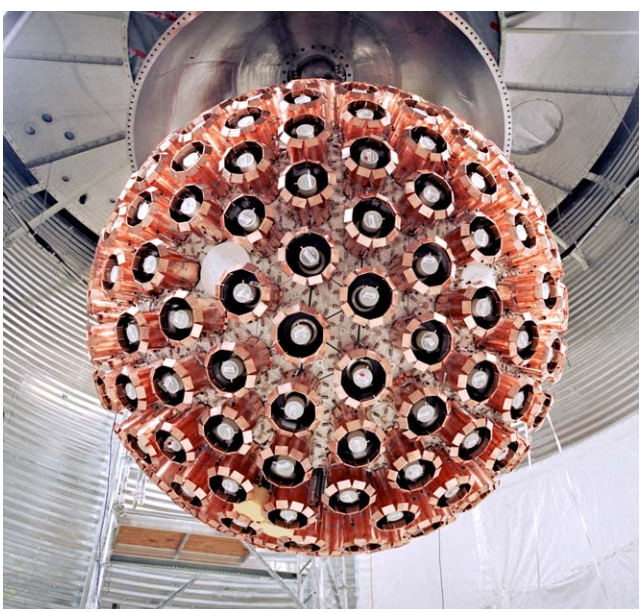


Figure 5. DEAP-3600 during the assembly of the PMTs on the TRIUMF-made light guides in 2014.

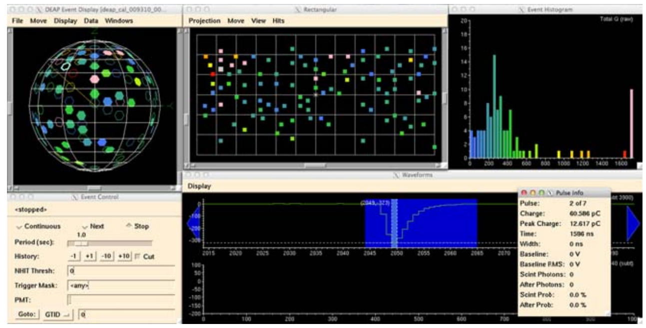


Figure 6. In March 2015, averaged light distribution measured with DEAP light injection system focused on the PMTs, shown in pink. Neighbouring PMTs also show significant light signals while all other PMTs see diffuse light.

2.4.5 SuperCDMS

SuperCDMS is a leading dark matter experiment that searches for interactions of dark matter particles, with shielded cryogenic germanium and silicon detectors placed far underground. Measuring the energy deposited in the form of phonon excitations in the semiconductor, as well as ionization, permits the separation of nuclear recoil events, such as those expected from Weakly Interacting Massive Particles (WIMPs), from background radioactivity that produces electron recoils.

The SuperCDMS technology has been developed over 20 years and has demonstrated excellent background rejection while having the lowest energy threshold, and hence the lowest mass reach, of any current dark matter direct detection techniques. SuperCDMS is currently operating detectors in the Soudan Underground Laboratory in Minnesota, but is now approved to build a much more sensitive setup, optimized for WIMPs with masses below 10 GeV/c^2, at SNOLAB. Canadian participation in SuperCDMS includes faculty members at Queen's Univerity, the University of British Columbia, and the University of Toronto.

TRIUMF is involved with the development of a new data acquisition (DAQ) system for the SNOLAB phase of the experiment. The UBC group leads the DAQ effort for SuperCDMS, and has developed a prototype DAQ based upon the MIDAS data acquisition framework developed at TRIUMF and PSI, with modest assistance from the TRIUMF DAQ group. It is proposed that TRIUMF DAQ staff will handle the DAQ computing and network hardware selection for the SNOLAB phase of the experiment.

2.4.6 SNO and SNO+

R. Helmer

The SNO experiment was designed to measure the total flux of active neutrinos coming from ^{8}B decays in the Sun. It was the first experiment to definitively show the flavour change of neutrinos due to oscillations, and it continues to produce new results. A recent joint analysis was performed using data from all three phases of SNO [5]. This analysis applied a new particle identification technique that improved the suppression of backgrounds in the proportional counters used in the third phase of the experiment. This was accomplished by measuring various parameters associated with the waveform differences between neutron and alpha events and establishing cuts to remove the alphas. The combined fit to all the data collected by SNO yielded a total flux of active neutrinos from ^{8}B decays in the Sun of 5.25 ± 0.16 (stat) +0.11/-0.13 (syst) x 10^6 cm^{-2}s^{-1}.

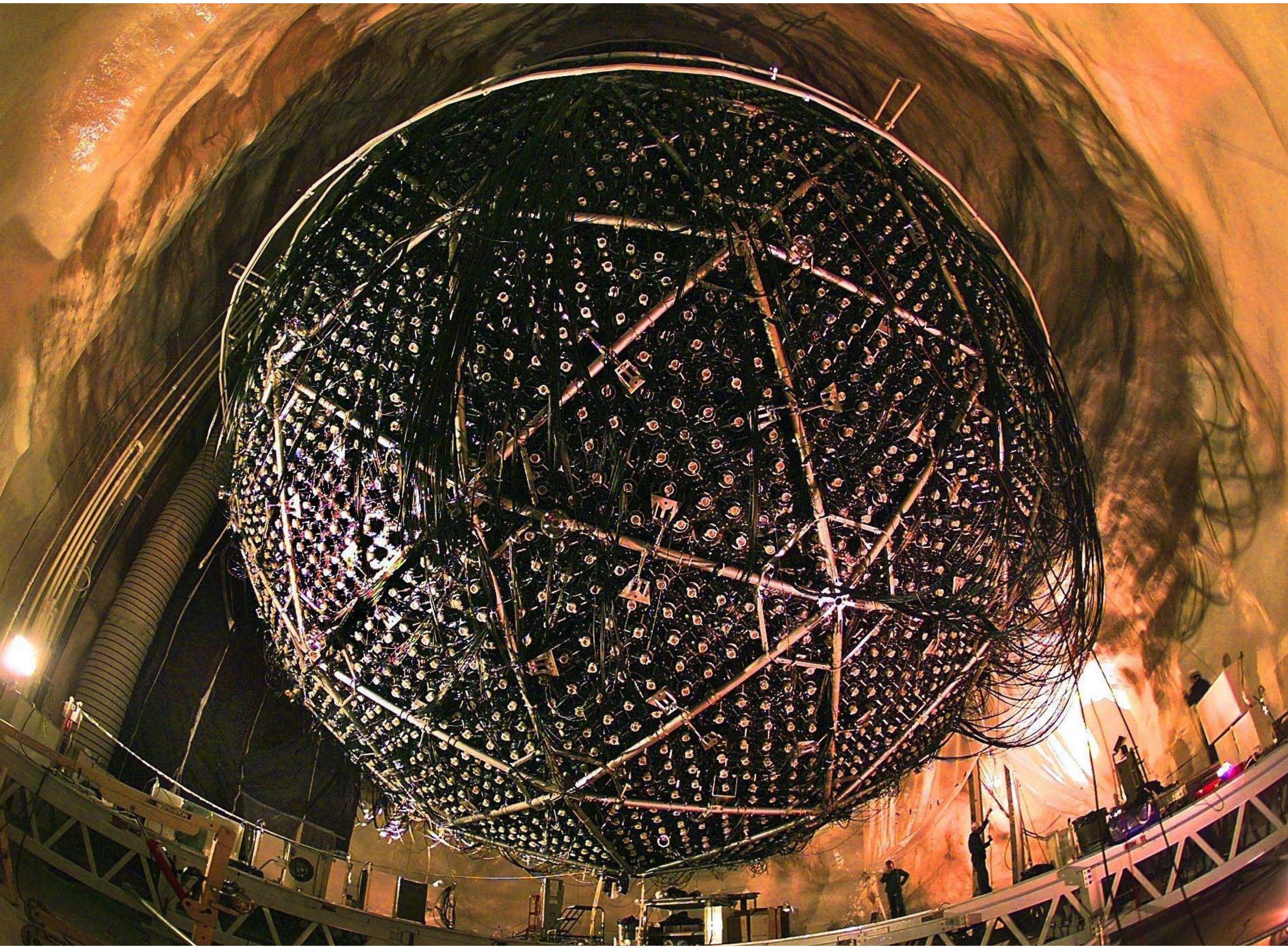
A second analysis searched for temporal correlations between solar flares or gamma ray bursts and neutrinos observed in SNO [6]. A maximum likelihood analysis burst analysis was developed, one that allowed the search to accommodate bursts whose intensities varied over many orders of magnitude. As a result, it was possible to use the integrated intensity over a large number of bursts rather than only the most intense burst. No correlations were found.

The SNO+ experiment is designed to search for neutrinoless double beta-decay. During the past two years, all of the remaining TRIUMF-supplied equipment for the SNO+ experiment was designed and fabricated. While most of the apparatus is now on site in Sudbury, some is still at TRIUMF for assembly. The lower half of the Universal Interface (UI) that sits atop the acrylic vessel was installed in May 2013 and is now in use as the vessel is being filled with water. A difficult problem, sealing the gates of the glove ports on the upper UI against mine air, arose as the base of the ports had warped during welding. The solution was to transfer the O-ring grooves on the bases to the gates and then to machine off the faces of the bases. A further problem arose: most O-rings, which are compatible with the liquid scintillator that will ultimately fill the UI, are too hard to provide a satisfactory seal. It was found that softer O-rings made of EPDM were acceptable. All equipment associated with the UI should be installed by the fall, 2016.

2.4.7 Theoretical Investigations

J. Kozaczuk, T.A.W. Martin, D.E. Morrissey, J.N. Ng, A. de la Puente

Dark matter and neutrinos are central research topics of the TRIUMF theory department, whose members develop theories of dark matter and seek to understand the source of neutrino mass. These studies to new predictions for existing and planned experiments. Recent work on dark matter includes studies of novel production mechanisms of dark matter in the early Universe [7], investigations of new methods to detect dark matter in high-energy colliders such as the LHC [8], and proposals for new connections between dark matter and the origin of the excess of matter over antimatter [9]. On the neutrino side, the department has investigated possible connections between neutrino masses and the top quark as well as tests of certain neutrino mass mechanisms at the LHC and proposed future colliders [10]. A central element of this work on dark matter and neutrinos is the search for new ways to connect the results of many different experiments.



[1] K. Abe et al., Phys. Rev .Lett. 116, no.18, 181801 (2016)
[2] S. Bhadra et al., Letter of Intent to Construct a nuPRISM Detector in the J-PARC Neutrino Beamline, arXiv:1412.3086 [physics.ins-det]
[3] J. B. Albert et al., Nature 510, 229 (2014)
[4] P.-A. Amaudruz et al., Nucl. Part. Phys. Proc. 273-275, 340
[5] B. Aharmim et al., Phys. Rev. C 88, 025501 (2013)
[6] B. Aharmim et al., Phys. 55, 1 (2014)
[7] N. Blinov, et al., Phys. Rev. D 91, no. 3,035026 (2015)
[8] J. Kozaczuk and T.A.W. Martin, JHEP 1504, 046 (2015)
[9] J. Kozaczuk, S. et al., JHEP 1501, 144 (2015)
[10] J.N. Ng and A. de la Puente, Phys. Rev. D 90, no. 9, 095018 (2014)

2.5 QCD AND NUCLEI

Quantum Chromodynamics (QCD) is the part of the Standard Model that describes the strong force underlying protons, neutrons, and atomic nuclei. The fundamental constituents of QCD are the quarks and gluons that carry a net "colour" charge under the strong force. At low energies, the quarks and gluons bind into colour-neutral particles such as nucleons and mesons in a process called confinement. Even after confinement, QCD predicts residual interactions among these colour-neutral states that are responsible for binding protons and neutrons into atomic nuclei. Consequently, QCD is relevant to a large part of the TRIUMF subatomic physics research program, from the lowest energies in nuclear physics experiments done at ISAC, to the highest energy collider studies at the LHC.

2.5.1. Structure of Hadrons

R.M.Woloshyn

Lattice QCD provides a non-perturbative theoretical framework to deal with strongly interacting systems of quarks and gluons, and describes how they combine to form colour-neutral bound states. Research at TRIUMF focuses on the spectroscopy of heavy quark systems, those with some charm or bottom quark content. The main activity during the past two years has been the completion of a program to calculate meson masses in the charm-quark sector.

The D_s meson is particularly challenging for lattice QCD calculations. The experimentally observed positive-parity orbital excitations of D_s do not fit the pattern expected from the quark model or earlier lattice QCD simulations. For the first time, TRIUMF researchers have explicitly included the coupling of 0^+ and 1^+ D_s states to the DK and D*K channels in a lattice QCD simulation [1,2]. Due to the proximity of these two-meson thresholds, the masses of the physical states are pulled down and brought into better agreement with experimental results.

Figure 1 shows the results of simulations [2] for D_s masses in two different ensembles of lattice gauge fields. For the ensemble labeled (2), the up and down quarks used in the simulation are sufficiently light that the pion mass is near physical. In this case, the coupling of the 0^+ state to the DK channel is crucial to bring the physical mass below threshold in accord with experiment.

Recently, the methods developed for the D_s program have been used to calculate the masses of the positive parity B_s mesons [3]. Predictions are made for the masses of the 0^+ B_{s0}^* and the 1^+ B_{s1} states. It is anticipated that these masses will be measured by the LHCb experiment at CERN in the near future.

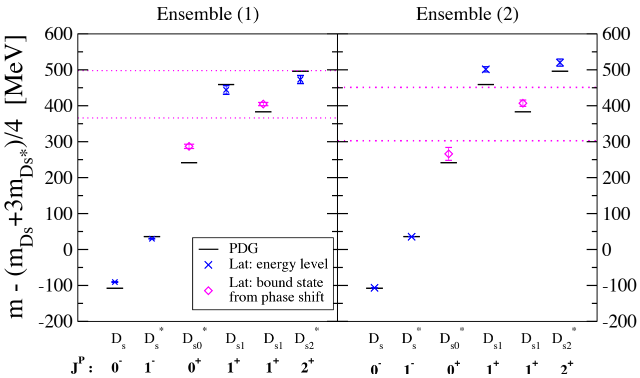


Figure 1. The calculated spectrum of D_s mesons presented as mass differences with respect to the spin-averaged S-wave masses.

2.5.2 Structure and Reactions in Nuclei

S.Bacca, J.Dilling, J.D.Holt, R.Kanungo, P.Navratil

A recent major breakthrough in the understanding of atomic nuclei has been the development of methods to predict their properties based on elementary interactions between nucleons derived from QCD. TRIUMF has played a leading role in this breakthrough by finding new theoretical techniques to describe light- and medium-mass nuclei, and by making key measurements needed to refine the underlying theory.

Studies of muonic atoms at the Paul Scherrer Institute (PSI) in Switzerland have measured a value for the radius of the proton in muonic hydrogen that differs from previous results from ordinary atoms by 7σ. Such a large discrepancy challenges the Standard Model, and has been termed the “proton-radius puzzle”. In response to this puzzle, a theoretical program was developed at TRIUMF to support future studies of muonic atoms at PSI with more complicated atomic nuclei. To test the proton radius puzzle using these measurements, theoretical nuclear structure corrections need to be very accurate. The first ab initio calculations of such nuclear structure corrections were recently carried out for on muonic Helium [4,5] and muonic Deuterium [6], which will be instrumental in shedding light on the proton-radius puzzle.

Weakly bound or even unbound exotic nuclei produced at TRIUMF experiments can only be understood using theoretical methods

that unify the description of both bound and unbound states. Using the no-core shell model with continuum (NCSMC) method, it is possible to predict the ground- and excited-state energies of light nuclei, as well as their electromagnetic moments and transitions, including weak transitions. Furthermore, properties of resonances and cross-sections of nuclear reactions can be calculated with this method.

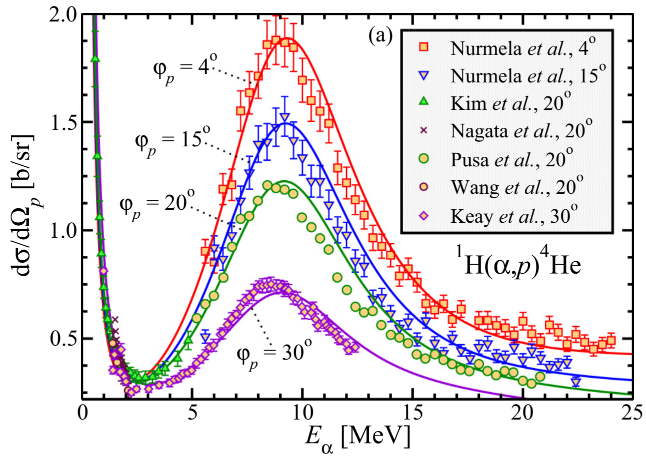


Figure 2. Computed (lines) ^{1}H(^{4}He,p)^{4}He angular differential cross-section as a function of the incident ^{4}He energy compared with data (symbols).

In the past two years, significant progress was made in the development and implementation of the NCSMC [7,8] enabling the investigation of resonances of the exotic ^{7}He nucleus. In addition, the development of a new capability to include chiral three-nucleon (3N) interactions in the NCSMC [9,10] has allowed for the study of continuum and 3N effects in the structure of ^{9}Be [10]. Resonances of the exotic unbound ^{11}N nucleus treated as a proton+^{10}C system were investigated as well.

Applying the NCSM, the first accurate ab initio calculations of proton-^{4}He scattering in the resonance region were carried out [11], with the results shown in Figure 2. A unified description of the structure of ^{6}Li and the cross-section of deuteron-^{4}He scattering has also been developed. It sheds light on the unresolved issue of the asymptotic D- to S-wave ratio in the ^{6}Li ground state wave function [12]. A generalization of the nuclear reaction theory framework to include three-body clusters, such as ^{4}He-n-n [13], was carried out and enabled the first ab initio study of resonances of the Borromean ^{6}He nucleus [14].

A new theoretical method combining the Lorentz Integral Transform method and the many-body coupled-cluster theory, LIT-CCSD, was developed by the Theory Department to tackle electromagnetic breakup reactions in the medium-mass regime. The first successful applications of the method have addressed the photo-absorption of oxygen and calcium isotopes [15,16] using chiral two-body interactions. The results on the neutron-rich ^{22}O isotopes are shown in Figure 3 and explain the low-energy soft-dipole mode measured at GSI.

To describe heavier nuclei, the in-medium similarity renormalization group (IM-SRG) method is being developed for open-shell nuclei [17] and will provide the first non-perturbative calculations of valence-shell Hamiltonians. Very promising first results have been obtained in oxygen [18], where the spectroscopy of very neutron-rich isotopes was of similar quality to the best phenomenological models. In addition, increasing the number of valence protons to the F and Ne isotopes finds the same level of excellent agreement with experiment [19].

New developments in ab initio reaction theory have led to experimental investigations of the role of 3N forces in proton elastic scattering cross-sections. As a first step in this program, the proton elastic scattering from ^{10}C was measured at the IRIS facility at TRIUMF. This was the first time an accelerated beam of ^{10}C was produced at TRIUMF, where the beam was found to have contaminant of ^{10}B. The IRIS facility is equipped with an ionization chamber that made it possible to make an event-by-event identification of the beam element, allowing for a simultaneous measurement for ^{10}C and ^{10}B. The measured cross-sections compare well in magnitude with theoretical predictions. The magnitude and shape of the measured angular distribution shows the first signature of 3N forces in a scattering cross section.

A unique feature of IRIS, its novel, thin, windowless solid H_2/D_2 target, made it possible to address the long-standing open question as to whether the soft dipole resonance, arising from an oscillation of the halo neutrons and the core, exists in the halo nucleus ^{11}Li. The inelastic scattering of ^{11}Li from solid D_2 and H_2 targets was measured at IRIS over the past two years. First evidence of dipole resonance with isoscalar character was observed at 1.03(03) MeV from deuteron inelastic scattering [20], shown in Figure 4. Shell model calculations, when compared to the data, show for the first time the signature of the tensor force playing an important role in ^{11}Li. New theoretical calculations were also performed using various approaches, including the first steps towards ab initio calculations in the framework of coupled cluster theory with the two-nucleon force. Plans to include three-nucleon forces and effects of coupling to the continuum are underway.

Understanding and predicting the formation of shell structure in exotic nuclei is a central challenge for nuclear theory. Atomic mass measurements performed at TRIUMF help to reveal the detailedinteractions of nucleons by providing access to the nuclear binding energies. The atomic masses are determined with significant precision and accuracy at ISAC using the TITAN Penning trap mass spectrometer (see facility section). Currently the fastest Penning trap system in the world, it has a minimum half-life requirement of only 5 ms [21]. Using this system, it was possible for the first time to determine the masses of the very

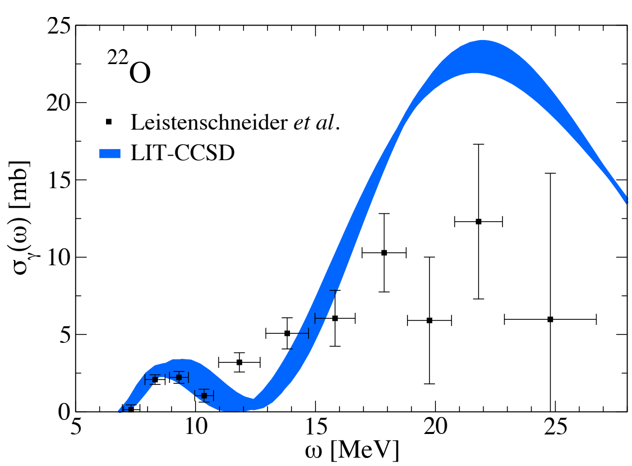


Figure 3. Theoretical calculation (band) of the ^{22}O dipole cross-section as a function of the photon energy compared to experimental data from GSI.

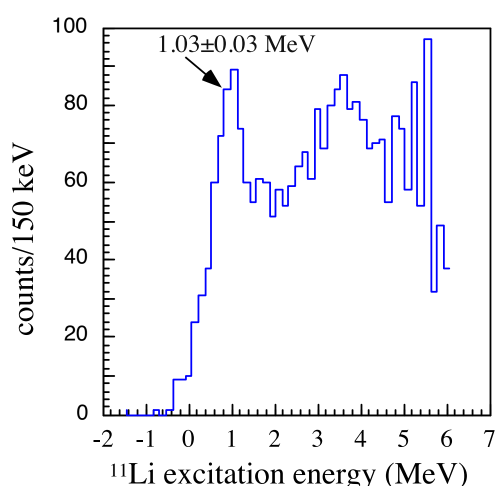


Figure 4. Excitation energy spectrum from $^{11}Li(d,d')$. The dipole resonance peak is seen at 1.03(03) MeV.

neutron-rich Ca and K isotopes [22] and to make interesting comparisons to state-of-the-art theory. Figure 5 shows such a comparison for the Calcium isotopes. The experimental results found for ^{52}Ca deviated by almost 2 MeV from previous measurements but agree well with modern theory predictions where 3N forces were included [23].

More recently, the ISOLTRAP collaboration at ISOLDE/CERN was able to confirm the TITAN measurements as well as further advance the limits of precision mass measurements out to ^{54}Ca using a new multi-reflection time-of-flight mass spectrometer. The new $^{53,54}Ca$ masses are in excellent agreement with modern theoretical predictions and unambiguously establish N = 32 as a shell closure [24], as shown in Figure 5.

In 2013, additional tests were carried at ISAC in order to repeat the ISOLTRAP mass determinations using the TITAN Penning trap system. At this point, no additional isotopes could be produced or identified. It was concluded that beam developments, such as the use of the proton beam rotator on ISAC production targets, are needed. The proton beam rotator (see section 3.3.2) was installed in fall 2014, and tests and commissioning were undertaken in 2015. It is expected that this will allow the production of the more neutron-rich Ca and K isotopes.

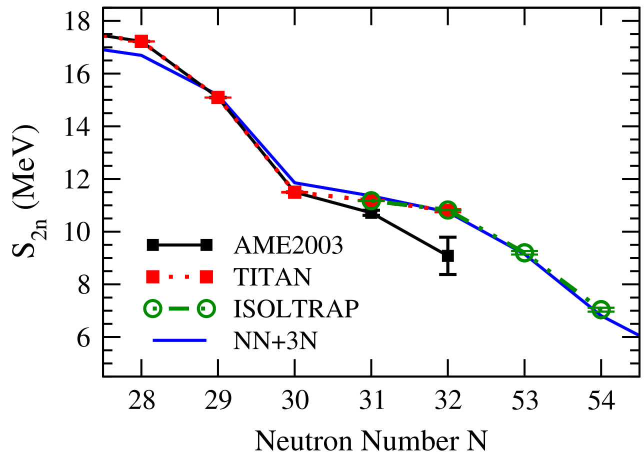
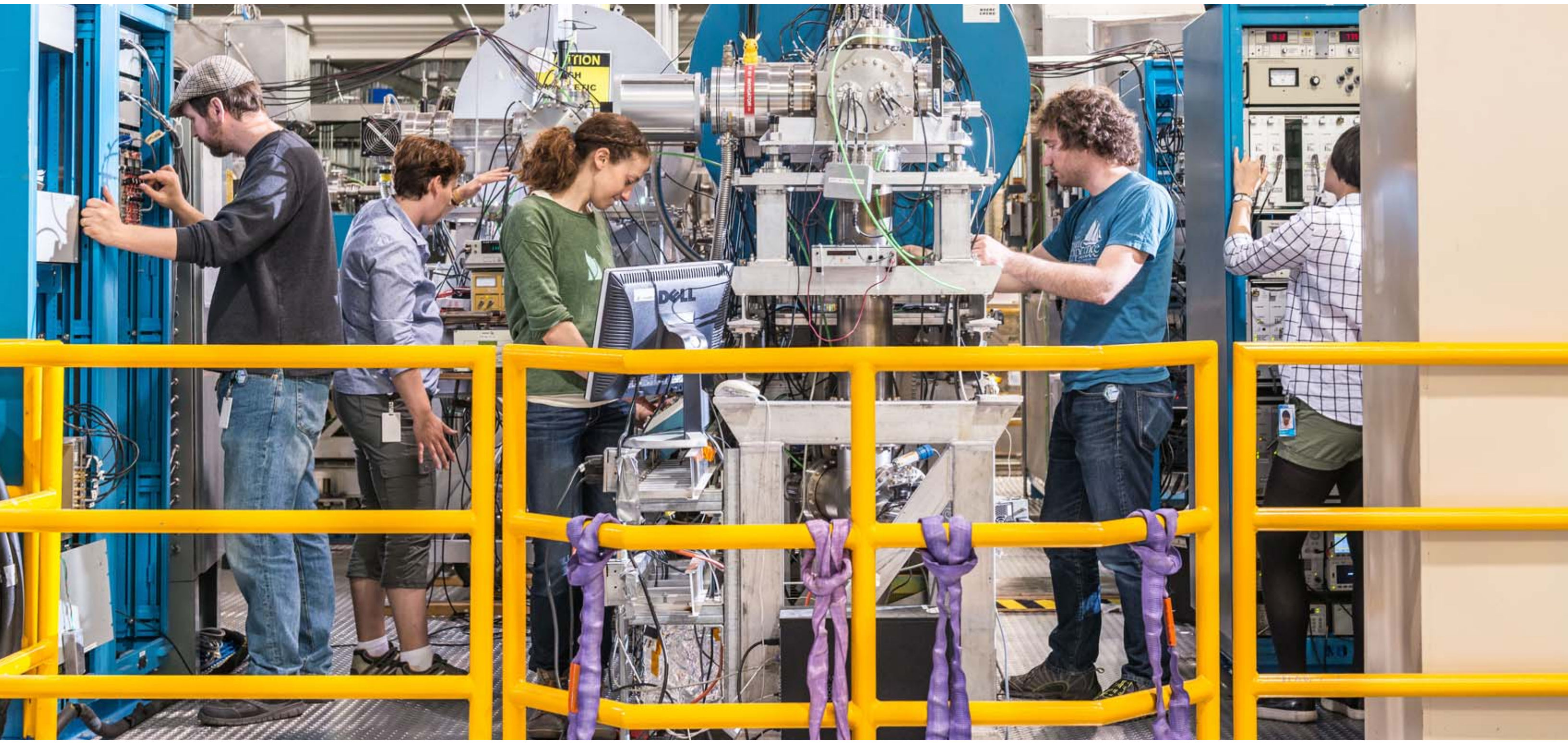


Figure 5. Two-neutron separation energy (difference of binding energies) of neutron-rich Ca isotopes: measurements by TITAN and ISOLTRAP in comparison to the atomic mass evaluations of 2003 and state-of-the-art theory calculations (blue line).



[1] D. Mohler et al., Phys. Rev. Lett. 111, no. 22, 222001 (2013)
[2] C. B. Lang et al., Phys. Rev. D90, no. 3, 034510 (2014)
[3] C. B. Lang et al., Phys. Lett. B 750, 17 (2015)
[4] C. Ji et al., Phys. Rev. Lett. 111, 143402 (2013)
[5] N. Nevo Dinur et al., Phys. Rev. C89, no. 6, 064317 (2014)
[6] O.J.Hernandez et al., Phys. Lett. B 736, 344 (2014)
[7] S. Baroni, P. Navratil, and S. Quaglioni, Phys. Rev. Lett. 110, no.2, 022505 (2013)
[8] S. Baroni, P. Navratil, and S. Quaglioni, Phys. Rev. C87, no. 3, 034326 (2013)
[9] Guillaume Hupin, et al., Phys. Rev. C88, no. 5, 054622 (2013)
[10] Joachim Langhammer, et al., Phys. Rev. C91, no. 2, 021301 (2015)
[11] Guillaume Hupin, Sofia Quaglioni, Petr Navratil, Phys. Rev. C90, no. 6, 061601 (2014)
[12] G. Hupin, S. Quaglioni, P. Navratil, Phys. Rev. Lett. 114, no. 21, 212502 (2015)
[13] S. Quaglioni, C. Romero-Redondo, and P. Navratil, Phys. Rev. C88, 034320 (2013)
[14] C. Romero-Redondo, et al., Phys. Rev. Lett. 113, 032503 (2014)
[15] S. Bacca et al., Phys. Rev. Lett. 111, no. 12, 122502 (2013)
[16] S.Bacca et al., Phys. Rev. C90, no. 6, 064619 (2014)
[17] K. Tsukiyama, S. K. Bogner, A. Schwenk, Phys. Rev. C85, 061304 (2012)
[18] S.K. Bogner et al., Phys. Rev. Lett. 113, 142501 (2014)
[19] S.K. Bogner et al., Phys. Rev. C93, 051301 (2016)
[20] R. Kanungo et al., Phys. Rev. Lett. 114, no. 19, 192502 (2015)
[21] A. Chaudhuri et al., Appl. Phys. B 114, 99 (2014)
[22] A.T. Gallant et al., Phys. Rev. Lett. 109, 032506 (2012)
[23] J.D. Holt, T. Otsuka, A. Schwenk, T. Suzuki, J. Phys. G 39, 085111 (2012)
[24] F. Wienholtz et al., Nature 498, 346 (2013).

2.6 NUCLEAR STRUCTURE AT THE EXTREMES

J. DILLING, A. GARNSWORTHY

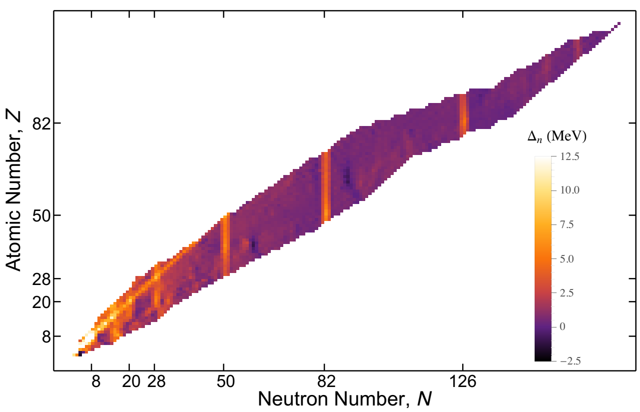


Figure 1. Empirical shell gap of the chart of isotopes; data taken from [1] and figure taken from [2].

The nuclear landscape displays a diverse variety of phenomena, including many different shapes, excitation and decay mechanisms, and stability and binding mechanisms. This diversity arises from a simple set of underlying forces connecting protons and neutrons. Studies of nuclear structure aim to understand and ultimately predict the nuclear landscape and its many features in terms of quantum many-body systems based on fundamental forces.

Many of the most interesting nuclear phenomena occur at extreme neutron-to-proton ratios,

corresponding to large net isospin. Figure 1 shows the range of the so-called empirical shell gap over the chart of nuclei, $\Delta_n = S_{2n}(N,Z) - S_{2n}(N-2,Z)$, where N and Z are the number of neutrons and protons, and S_{2n} is the two-neutron separation energy.

This figure shows regions with special neutron magic numbers as well as patches with higher shell gap energies. These occur mostly at extremes or in special regions where deformation or so-called inversion takes place. Understanding these features is a primary goal of both experimental and theoretical groups at TRIUMF investigating nuclear structure.

2.6.1 Studies of lighter nuclei

Nuclear structure studies at the TRIUMF ISAC facility make use of the powerful ISOL production mechanism to synthesize isotopes. These are studied using a suite of dedicated experimental facilities and devices.

Studies of lighter nuclei, up to mass numbers close to 100, were carried out on the neutron-deficient side, in particular for Mg isotopes (A=20,21), as well as in the vicinity of the so-called “island of inversion.” The Mg isotopes were selectively produced and ionized using the novel Ion Guide Laser Ion Source (IG-LIS) described in section 3.3.2, which allowed for a very clean delivery of Mg isotopes to the experiments. Mass measurements were carried out for these isotopes using the TITAN [3] ion-trap mass spectrometer, the tool of choice for precise and accurate mass determination [4]. Figure 2 shows cyclotron resonances for ^{20,21}Mg and the reference mass ^{23}Na. These measurements revealed that the well-established Isospin Multiplet Mass Equation (IMME) formalism with the standard quadratic form is not valid for these extreme isospins, and additional terms in the perturbative expansion must be included [5]. In addition to giving very sensitive tests of the underlying state-of-the-art theory, these measurements represent the most sensitive known isotope production technique, with a signal-to-noise improvement of almost six orders of magnitude achieved using the IG-LIS method [6].

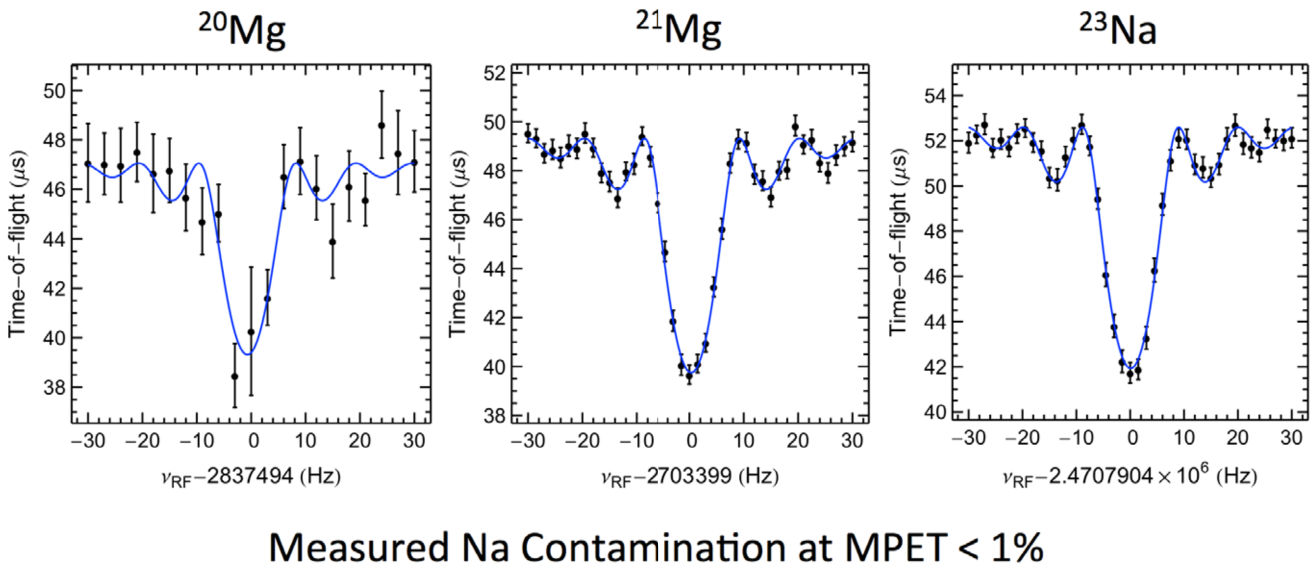


Figure 2. TOF-resonances for Mg and Na isotopes taken with the TITAN Penning trap mass spectrometer.

2.6.2 Island of Inversion, Mass Measurements

The region of nuclei centred at Z=12, N=20 has been called the "island of inversion". Nuclei within the island of inversion exhibit a peculiar behaviour: the ground states are deformed rather than spherical, despite N=20 being a good shell closure near stability. This deformation is evidently brought about by particles being promoted from the sd shell into the pf shell across the N=20 shell gap, forming intruder configurations. This phenomenon can be explained as a result of a reduction in the N=20 shell gap attributed to a reduced strength of the T=0 attractive monopole tensor interaction [7,8], making it possible for the np-nh states to form the ground state configuration, shown in Figure 3.

The strong deformation which characterizes Na and Mg isotopes at and around N=20 [9] in the region of the island of inversion can also be investigated with ground state masses. The TITAN mass measurement campaign [10,11] has led to the first direct mass measurements of these neutron-rich isotopes as well as the bordering Al isotopes. These measurements are also noteworthy for the very short half-lives involved, as low as 13 ms for ^{32}Na, and cannot be performed at any other Penning trap mass spectrometer worldwide.

Two irregularities were uncovered from these measurements. First, ^{32}Mg exhibits the lowest shell strength of any magic nuclide [10]. The second anomaly is the crossover of the two-neutron separation energy S_{2n} of ^{33}Mg and ^{34}Al [11], an occurrence found nowhere else on the mass surface. Large-scale shell model calculations [7] of the binding energy and S_{2n} are in good agreement with the TITAN data. Calculated energy gains from correlations peak at almost 3.5 MeV at N = 21 in the Mg isotopes; the same effect is weaker in the Al isotopes (< 2 MeV) and delayed (N=24). The offset between maximal gains leads to the S_{2n} crossover at N = 21 seen in Figure 3.

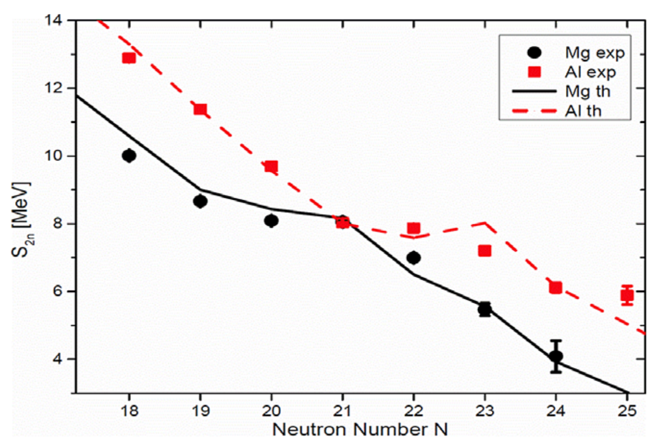


Figure 3. Two-neutron separation energy for the isotopes in the island of inversion as measured by TITAN and from theory [7].

Further efforts are being made to pinpoint the mass of the 1+ state of ^{34}Al, and such a measurement may determine the spin-parity of nuclide's ground state. Future mass measurements of ^{36,37}Al are needed to confirm the expected deviation [10] from the evaluated mass values [1], which may place these isotopes within the island of inversion.

2.6.3 Studies of Medium Heavy Nuclei

The neutron-rich even-even isotopes of Sr and Zr around neutron number 60 display an unusually sudden change in ground-state behaviour. Below N=60, the ground state configurations appear to be near spherical. With the addition of the 30th pair of neutrons, the system assumes a quadrupole-deformed shape in the ground state. This behaviour is further evidenced in the two-neutron separation energies [1] and in the mean-square charge radii measured through isotope shifts [12-16].

The TIGRESS gamma-ray spectrometer with the SHARC silicon barrel detector was used to perform (d,p) one-neutron transfer reactions on accelerated ^{94}Sr, ^{95}Sr and ^{96}Sr beams. The detailed analysis of this experimental data is underway, and will help to reveal the contributions from different single-particle energy levels to the wave functions of the ground and excited states in each nucleus around the N=60 sub-shell closure. This information is essential for understanding the mechanisms driving the change in ground-state structure.

Laser spectroscopy was performed on neutron-rich Rb isotopes out to ^{98}Rb, and the existence of hitherto only postulated long-lived isomeric states was confirmed unambiguously [12]. For all observed states, it was possible to extract the spins and nuclear magnetic dipole and electric quadrupole moments as well as the changes in mean squared charge radii. In ^{98}Rb, the results for the 90(10) ms spin 3 and 145(25) ms, spin 0 states show very similar deformations, smoothly following the trend in this region of the nuclear chart above N=60. The fact that both nuclear states were produced at ISAC in very similar quantities demonstrates the possibility for future experiments to be conducted with high-purity, isomerically separated beams.

In addition to laser spectroscopy, precision mass measurements were carried out for Rb and Sr isotopes. These experiments confirmed prior TITAN measurements of ^{98}Rb and ^{98,99}Sr [17], and extend the campaign to $^{99\text{-}100}$Rb and $^{100\text{-}101}$Sr [18]. This first direct mass measurement of ^{101}Sr revealed a 3σ deviation from the Atomic Mass Evaluation of 2012 [1]. The new measurements substantiate the transition from a spherical to prolate shape at N=60. The continuation of these measurements will provide the first mass determination of Rb for A ≥ 101, along the rapid-neutron-capture or r-process.

The 8π spectrometer was used to perform decay spectroscopy of ^{102}Rb, which is delivered at a rate of only five particles per second. This study extended the knowledge of the excited states in ^{102}Sr, which indicate a continuation of the large, prolate deformation as the N=66 mid-shell is approached. This study also allowed for the determination of the beta-delayed neutron branching ratio of ^{102}Rb, which was found to be 3.5 times larger than previous measurements, shown in Figure 4 [19,20].

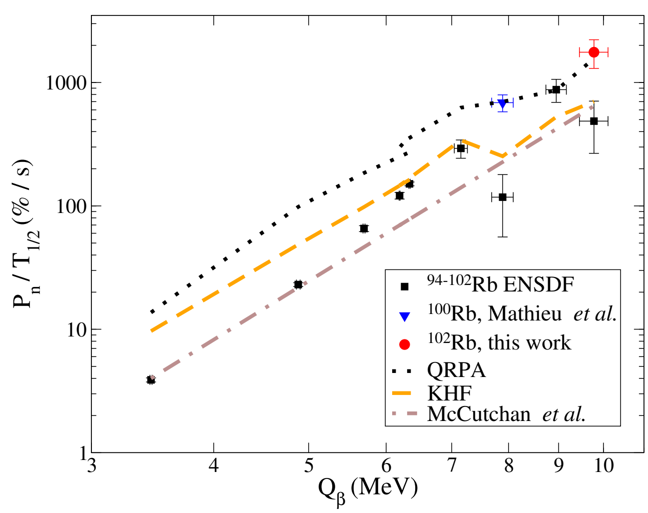


Figure 4. The ratio of beta-delayed neutron branching ratio to half-life plotted as a function of the Q value for neutron-rich Rb isotopes. Experimental data is from ENSDF. New experimental data for ^{100}Rb is taken from Mathieu et al. [19] and the ^{102}Rb value is from the 8pi work [20]. Comparison to three theoretical calculations is also made.

2.6.4 Studies of Heavier Nuclei

The neutron-deficient Francium isotopes ^{204,206}Fr have long been thought to contain at least one, and possibly two, long-lived isomeric states. Recent work at ISAC [21] has shown that these two isotopes have very similar structures, with each containing two long-lived isomeric states. Model independent determination of the nuclear spins was performed for all of these states, in addition to the ground state of ^{205}Fr, which has allowed for the extraction of the nuclear moments and changes in mean squared charge radii for all states seen. These results indicate an onset of collectivity around N=118.

[1] G. Audi et al., Chin. Phys. C 36, 1287 (2012)
[2] A.T. Gallant, Penning Trap Mass Measurements to Test Three-Body Forces in Atomic Nuclei, UBC Ph.D. Thesis, 2015 (Unpublished)
[3] J. Dilling et al., Int. J. Mass. Spec. 251, 198 (2006)
[4] K. Blaum, J. Dilling, and W. Noertershaeuser, Phys. Scr. T 152, 014017 (2013)
[5] A.T. Gallant et al., Phys. Rev. Lett. 113, no. 8, 082501 (2014)
[6] S. Raeder et al., Rev. Sci. Inst. 85, 033309 (2014)
[7] Y. Utsuno et al., Phys. Rev. C 70, 044307 (2004)
[8] T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005)
[9] O. Sorlin and M.G. Porquet, Prog. Part. Nucl. Phys. 62, 602 (2008)
[10] A. Chaudhuri et al. [TITAN Collaboration], Phys. Rev. C 88, 054317 (2013)
[11] A.A. Kwiatkowski et al. [TITAN Collaboration], Phys. Rev. C 92, 061301 (2015)
[12] T. J. Procter et al., Eur. Phys. J. A 51, 23 (2015)
[13] F. Buchinger et al., Phys. Rev. C 41, 2883 (1990)
[14] B. Cheal et al., Phys. Lett. B 645, 133 (2007)
[15] K. Baczynska et al., J. Phys. G 37, 105103 (2010)
[16] P. Campbell et al., Phys. Rev. Lett. 89, 082501 (2002)
[17] V.V. Simon, et al. [TITAN Collaboration], Phys. Rev. C 85, 064308 (2012)
[18] R. Klawitter et al. [TITAN Collaboration], Phys. Rev. C 93, 045807 (2016)
[19] L. Mathieu et al., AIP Conf. Proc. 1175, 285 (2009)
[20] Z.M. Wang et al. [8pi Collaboration], Phys. Rev. C 93, 054301 (2016)
[21] A. Voss et al., Phys. Rev. C 91, 044307 (2015)

2.7 NUCLEAR ASTROPHYSICS

C. RUIZ

Nuclear reactions are the power source of stars. Studying nuclear reactions in the laboratory is therefore an essential component in understanding the structure and evolution of stellar bodies. In the 2013–2015 period, the TRIUMF Nuclear Astrophysics Group and collaborators performed experimental and theoretical studies of explosive hydrogen and helium burning processes that occur in thermonuclear and core-collapse supernovae. Further experimental work investigated the production of neutrinos in the sun and Big Bang nucleosynthesis. This work was performed using the DRAGON Recoil Separator facility, the TRIUMF-UK Detector Array (TUDA) facility, and the ISAC Implantation Station (IIS).

2.7.1 Explosive Hydrogen Burning in Classical Novae

Explosive hydrogen burning occurs in regions with large hydrogen abundances and very elevated temperatures, as seen in thermonuclear runaways during stellar explosions. Here, protons are captured by stable and radioactive nuclei, with the emission of either electromagnetic radiation or charged particles following the capture. These burning processes have a large influence on energy generation and nucleosynthesis in many stellar scenarios, but they occur most commonly in classical novae; thermonuclear explosions in binary star systems resulting from the accretion matter from a less evolved companion star onto the surface of a white dwarf. Such novae are important targets for multi-wavelength astronomy (including infrared, optical, and gamma ray), and the understanding of stellar physics in general.

^{38}K(p,γ)^{39}Ca: In the higher peak-temperature oxygen-neon novae, large variations in the predicted amounts of argon, potassium and calcium ejected arise due to uncertainties in the ^{38}K(p,γ)^{39}Ca reaction. This reaction was measured for the first time ever in the DRAGON facility at ISAC using a radioactive ^{38}K beam with a peak intensity of 2 x 10^7 s^{-1}, which was charge-bred in the ECR charge state booster to charge state 7+. The strength of a key resonance in the reaction was measured, as shown in Figure 1, and experimental upper limits were obtained for two others. These results have helped to constrain the stellar reaction rate of ^{38}K(p,γ)^{39}Ca, and they have reduced the uncertainties in the abundances calculated for Ar, K, and Ca. This experiment also represents the highest-mass radioactive beam ever used in a radiative-capture measurement.

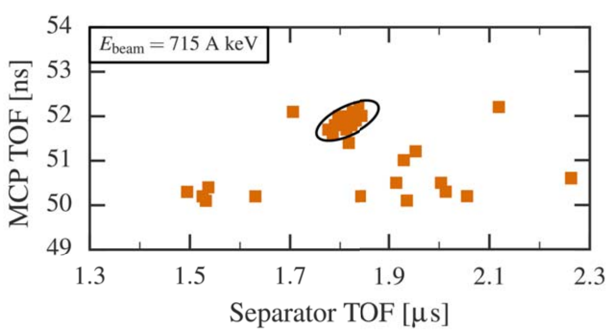


Figure 1: Particle ID plot of DRAGON ^{38}K(p,γ)^{39}Ca data, showing ^{39}Ca recoils, clearly grouped in local time-of-flight versus separator time-of-flight, while also showing background "leaky" beam events uncorrelated in separator time-of-flight.

^{18}F(p,γ)^{19}Ne via ^{15}O(α,γ)^{19}Ne and ^{15}O(α,α)^{15}O: The ^{18}F(p,γ)^{19}Ne reaction has a strong influence on the ejected abundance of ^{18}F in oxygen-neon novae [1]. This affects the observed spectrum of 511 keV positron-annihilation gamma rays from the nova explosion, which are a target for space-based telescopes. The ^{18}F(p,γ)^{19}Ne reaction was measured directly using the DRAGON facility [1,2]. From this work, it was determined that a resonance at 665 keV, previously thought to contribute significantly to the reaction rate, was much weaker than expected. This implies that a single lower resonance at 330 keV dominates the reaction rate and must be measured experimentally. While a direct measurement of this lower resonance with a ^{18}F beam is not currently feasible, the 330 keV resonance strength can be determined indirectly by populating the same excited state via the ^{15}O(α,γ)^{19}Ne reaction and simultaneously measuring ^{15}O(α,α)^{15}O elastic scattering. In preparation for this experiment, DRAGON measured the analogue resonance in ^{15}N(α,α)^{15}N and demonstrated the feasibility of determining the desired quantities to the precision required. The final measurement using ^{15}O is underway.

The Nova Project: As part of a new initiative to bring stellar modeling and nucleosynthesis activities to TRIUMF, a collaborative effort was initiated with the University of Victoria and the Joint Institute for Nuclear Astrophysics (JINA) in the U.S. to develop a new generation of Classical Nova models using the state-of-the-art codes MESA and NuGrid. So far, a series of carbon-oxygen and oxygen-neon nova models based on differing white dwarf masses have been generated. The initial results [3] focused mainly on CO novae. This was followed by a nucleosynthesis study [4] on both CO and ONe novae, with results shown in Figure 2, concluding that these models are robust enough to be used for reaction sensitivity studies and are in good agreement with similar models by other groups. These models now provide powerful tools for the TRIUMF astrophysics group to evaluate the significance of individual reactions and to determine the impact of experimental measurements made at the lab.

^{26}Al Implantation: The long-lived radioisotope ^{26g}Al ($t_{1/2}$=717,000 yr) is an important indicator of galactic nucleosynthesis, having been mapped by orbiting γ-ray telescopes. The ^{26g}Al(p,γ)^{27}Si and ^{25}Al(p,γ)^{26}Si reactions both contribute to the amount of ejected ^{26}Al from novae. The indirect study of these reactions can be carried out with an implanted ^{26g}Al target, which can be produced at the ISAC Implantation Station. The target will be used in both experiments at spectrometer facilities in Orsay or Munich, using the ^{26g}Al(^{3}He,d)^{27}Si and ^{26g}Al(^{3}He,t)^{26}Si reactions. In early 2015, a test target prepared at TRIUMF (containing 5 x 10^{14} atoms of ^{26g}Al implanted into a thin carbon foil) was sent to Orsay to measure experimental

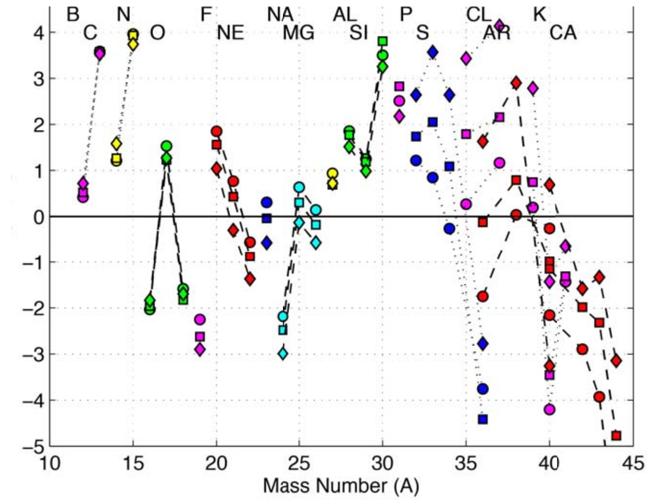


Figure 2. Final stable mass fraction relative to solar from NuGrid models of ONe novae with three different white dwarf central temperatures, showing significant enhancements in the A=25-40 region [4].

backgrounds in preparation for the full target of nearly 10^{16} atoms. The test run was a success and showed that the fragile implanted target can be shipped intact to the experiments.

^{21}Ne(p,γ)^{22}Na and ^{20}Ne(p,γ)^{21}Na: These reactions have a strong influence on the amount of ^{22}Na synthesized in novae. The 1.275 MeV gamma ray from the decay of ^{22}Na is a prime astronomical target due to the large amount of ^{22}Na synthesized in novae and the favourable 2.6 year decay lifetime of this isotope. From 2013–2015, the DRAGON facility used an intense ^{21}Ne beam to measure some key resonances in ^{21}Ne(p,γ)^{22}Na [21], as well in preparation for the final ^{20}Ne(p,γ)^{21}Na measurement. An initial ^{20}Ne(p,γ)^{21}Na measurement led to a publication showing that a higher-lying resonance had been treated incorrectly in the literature [5], which has important implications due to its use as a calibrating resonance for others of astrophysical interest.

2.7.2 Massive Stars, Thermonuclear and Core-Collapse Supernovae

Massive stars are important contributors to galactic nucleosynthesis, both in their mass loss through stellar wind phases and their evolutionary endpoints, exploding as type II supernovae. Reducing nuclear physics uncertainties in the reactions that influence model predictions of elemental and isotopic yields from these scenarios is a crucial step in understanding the chemical evolution of the galaxy. In addition, compact objects in binary systems that have type Ia (thermonuclear) supernovae as their endpoints are also important because they contribute to the iron peak and other elements, and play a crucial role as standard candles providing constraints on observational cosmology. The astrophysics group has addressed several reactions that pertain to these stellar scenarios using the DRAGON and TUDA facilities:

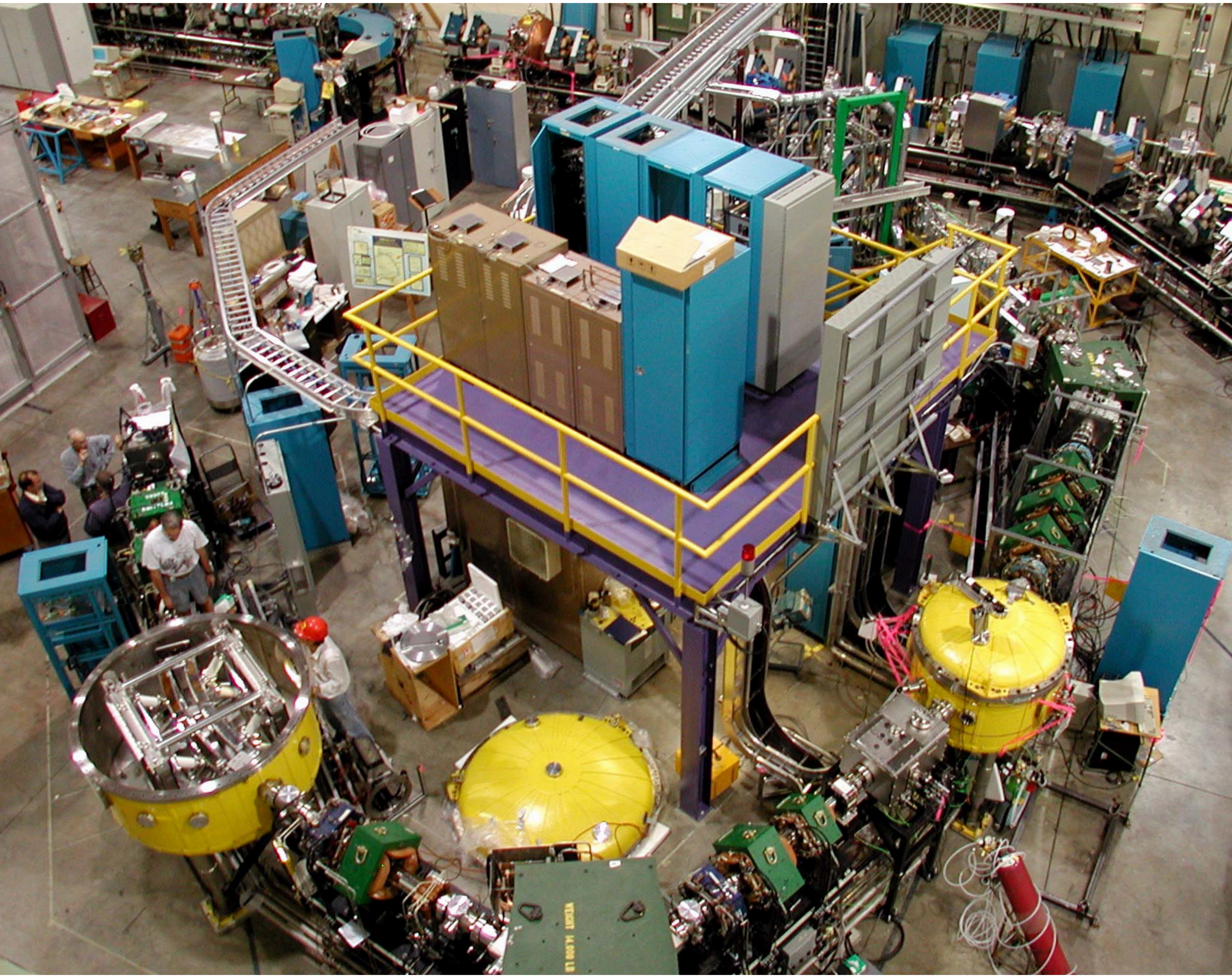
$^{76}Se(\alpha,\gamma)^{80}Kr$: Measurement of this reaction enables the determination of the strength of the reverse reaction, $^{80}Kr(\gamma,\alpha)^{76}Se$, an important branching point in determining the ratio of $^{76}Se/^{74}Se$ produced in core-collapse supernovae during the "α-process". It involves pushing the DRAGON recoil separator far beyond its design limit, with electric fields of 4.6 MV/m on the electrostatic dipoles used to bend the massive ^{76}Se beam [6]. A ^{80}Kr beam was also used to determine the recoil separator background rejection capabilities. Data were taken on the $^{76}Se(\alpha,\gamma)^{80}Kr$ reaction and are under analysis, with a further set at different energies to be taken in the coming period.

$^{34}S(\alpha,\gamma)^{38}Ar$: This reaction is important in determining the amounts of various isotopes from A=34-40 synthesized in explosive oxygen burning in particularly massive stars. A measurement was required because of large discrepancies in the experimentally determined strengths of resonances in the reaction. Measurements of those resonance strengths were made at DRAGON using a ^{34}S beam, and analysis of the data is underway, with collaborators at Colorado School of Mines and Notre Dame University.

$^{23}Na(\alpha,p)^{26}Mg$: The importance of the radioisotope ^{26}Al as a fingerprint of ongoing nucleosynthesis in the galaxy is well established. Recent sensitivity studies investigated the effects of varying nuclear reaction rates on the ^{26}Al abundance in the context of massive stars and have found the $^{23}Na(\alpha,p)^{26}Mg$ reaction to be among the four most important. Beyond the production of ^{26}Al, this reaction is important in thermonuclear supernovae, significantly affecting the abundances of 13 different isotopes. The cross-section of this reaction was directly measured with TUDA, using a ^{23}Na beam of 1×10^9 s^{-1}. Sixteen centre-of-mass energies ranging from 1.38-3.10 MeV were measured. The resulting cross-sections and the derived stellar reaction rate are in excellent agreement with Hauser-Feshbach statistical model calculations [7], but disagree with a previous measurement by a group at Argonne National Laboratory using similar methods.

2.7.3 Solar Neutrinos and Big Bang Nucleosynthesis

$^{3}He(\alpha,\gamma)^{7}Be$: This radiative capture reaction plays an important role in Big Bang nucleosynthesis. In particular, the primordial ^{7}Li observed today is thought to have been created by the radioactive decay of ^{7}Be formed mainly in the $^{3}He(\alpha,\gamma)^{7}Be$ reaction minutes after the Big Bang. For this reason, measurements of this reaction rate are an important step in resolving the stark discrepancy that exists between current nucleosynthesis predictions of ^{7}Li abundances and astronomical observations. The DRAGON collaboration measured the rate of the $^{3}He(\alpha,\gamma)^{7}Be$ reaction at three different relative energies (1.5, 2.2, and 2.8 MeV) using a ^{3}He recirculating gas target. In addition, the radiative capture of protons by ^{7}Be and the radioactive decay of ^{7}Be produce the best-measured solar neutrino fluxes. Because of the importance of this reaction, careful measurements were made at ISAC between 2010 and 2015, including determinations of the Be charge state distribution after DRAGON's gas target using a ^{9}Be beam [8]. Final refinements are being made in the determination of systematic uncertainties, but initial results show excellent agreement with ab initio calculations performed by the TRIUMF theory department [9].



[1] C. Akers et al. [DRAGON Collaboration], Phys. Rev. Lett. 110, 262502 (2013)

[2] C. E. Beer et al. [TUDA Collaboration], Phys. Rev. C 83, 042801 (2011)

[3] P. A. Denissenkov et al., [TRIUMF-UVic-JINA Collaboration], Astrophys. J. 762, 8 (2013)

[4] P. A. Denisenkov et al. [TRIUMF-UVic-JINA Collaboration], Month. Not. Astron. Soc. 442, 2058 (2014)

[5] G. Christian et al. [DRAGON Collaboration], Phys. Rev. C 88, 038801 (2013)

[6] A. Simon et al. [DRAGON Collaboration], Eur. Phys. J. A 49, 60 (2013)

[7] J.R. Tomlinson et al. [TUDA Collaboration], Phys. Rev. Lett. 115, 052702 (2015)

[8] Mariano Carmona Gallardo, Estudios Experimentales de la Reacción Nuclear con Interés Astrofísico ^{3}He(^{4}He,γ)^{7}Be, PhD thesis, Institute of Structure and Materials, Consejo Superior de Investigaciones Cientificas, Madrid, 2014 (Unpublished)

[9] J. Dohet-Eraly, et al., Phys. Lett. B 757, 430 (2016)

2.8. MOLECULAR AND MATERIALS SCIENCE

Subatomic particles can also be used as tools for scientific and practical applications. A specific example is the use of positive muons and ^{8}Li ions as microscopic probes of materials. These radioactive particles can be implanted into materials, where they reside in the inter-atomic volume, interact with the internal magnetic fields, and develop an ensemble spin polarization that varies in time and space according to the local environment. The structure of the material can then be measured by detecting the spin polarization of these probes from the angular distributions of their radioactive decay products. In some materials, a positive muon can also acquire an electron and form an isotope of hydrogen called muonium (Mu), thereby opening up and expanding the field of H-atom chemistry into a range of compounds that would otherwise be unavailable.

Implanted muons are studied at TRIUMF using magnetic resonance techniques known as muon spin resonance/rotation/relaxation, or μSR, while implanted ^{8}Li nuclei are studied with a technique called beta-detected nuclear magnetic resonance (β-NMR). Muons and ^{8}Li can be implanted into any material, so μSR and β-NMR do not suffer the restrictions faced by other probes, such as neutron scattering or Mössbauer spectroscopy. The initial polarization of implanted muons (~100%) and ^{8}Li (~70%) is several orders of magnitude larger than in traditional magnetic resonance experiments, and this leads to enhanced sensitivity.

μSR experiments routinely extract information over five orders of magnitude in time from 10^{-9}–10^{-5} seconds and can be used to measure a broad range of reaction and/or fluctuation rates in either chemical or condensed matter systems. β-NMR provides information in the time range of 10^{-3}–10^{2} seconds and can be implanted at specific depths from a surface, which allows for studies of the magnetic and electronic properties of surfaces, layered structures, and buried interfaces.

The Centre for Molecular and Materials Science (CMMS) at TRIUMF is the only source of intense muon beams in the Americas and is one of only four such facilities in the world.

Two of these facilities (J-PARC in Japan and ISIS in the UK) currently provide low time-resolution pulsed muon beams, and the other two (PSI in Switzerland and TRIUMF), deliver high time-resolution continuous wave (CW) beams. These two complementary methods of muon delivery serve distinct sets of experiments. The CMMS β-NMR facility is the only one in the world to focus on materials science and is capable of performing depth-resolved measurements.

The development of a broad user program has been limited by the small amount of beam time, but this will improve substantially with the completion of ARIEL. The experiments performed at CMMS cover a broad range of scientific topics in condensed matter physics and chemistry. A selection of these topics is presented here.

2.8.1 Probing Reactivity with Muonium

Optimizing industrial processes and developing improved materials requires detailed knowledge of chemistry to answer such questions as: which parts of the molecule are reactive, how fast do reactions occur, and are the reaction products stable? Muonium (Mu) is an excellent and unbiased probe of reactivity, having no charge or dipole moment. It is generated by muon implantation at TRIUMF, and has been used to study the reactivity of a range of organometallic compounds based on silicon and germanium and the structure and dynamics of the novel silyl and geranyl radicals [1].

Figure 1. UBC Prof. Robert Kiefl at β-NMR facility

2.8.2 Chemistry in Extreme Environments and Custom Tailoring Reactivity

Supercritical water and CO_2 can be used as solvents instead of toxic organic compounds, and therefore have a considerable benefit to the environment. Little is known about how the water or CO_2 molecules interacts with solutes and what effect they have on chemical reactions. The high temperatures and pressures of supercritical phases make it difficult to study these systems with traditional techniques, but high-energy muons (and their decay positrons) can penetrate the pressure vessels.

Researchers at TRIUMF and Mt. Allison University have studied the reaction of Mu with ethylene, vinylidene fluoride, and vinylidene chloride in supercritical CO_2 over a range of pressures and temperatures. They found that, near CO_2 critical point, the addition of Mu to ethylene exhibits critical speeding up, while addition to the halogenated compounds displays critical slowing [2]. This suggests that supercritical CO_2 can be used to modify the selectivity of reactions between nonpolar reactants and control reaction kinetics.

2.8.3 Lithium Ion Mobility in Battery Materials

The development of lithium-ion batteries is tremendously important for advancing a wide range of consumer products and developing greener technologies. Their performance is superior compared with previous battery technologies.

A key part of the battery is the electrolyte, which separates the anode and cathode. Poly(ethylene oxide) (PEO) is one of the most widely used solid polymer electrolytes, and understanding the microscopic dynamics of lithium ions embedded in a polymer matrix is crucial for interpreting ionic transport and optimizing battery performance. TRIUMF scientists used β-NMR to study the microscopic diffusion of lithium ions in pure PEO and PEO with added lithium salts. Bulk measurements indicated that the α relaxation dominates the long-range Li^+ transport process. In contrast, the β-NMR measurements found the hopping of Li^+ in both samples, in the high-temperature viscoelastic phase, follows an Arrhenius law and depends significantly on the salt content [3]. Further work is being done to relate the microscopic diffusion parameters to the structure of the polymer.

2.8.4 β-NMR Shows Differences Are Only Skin-Deep (At Least in Polymers)

Materials behave differently near interfaces but are very difficult to study, both experimentally and theoretically. Previous experiments on thin films of polystyrene suggested that there was a very thin region near the free surface where the polymer chains are more mobile than in the bulk, but no experiment had been able to verify it. TRIUMF scientists have used β-NMR with $^8Li^+$ probes to provide the most direct evidence for enhanced dynamics at the free surface. The $^8Li^+$ binds the phenyl rings of polystyrene and the spin relaxation rate is sensitive to the rate at which these rings flop about. They discovered that the spin relaxation rate dramatically increases within about 10 nm of the surface and concluded this is the length scale for the region with faster polymer chain motion [4].

2.8.5 Topology of the Superconducting Gap in $CaIrSi_3$

TRIUMF μSR facilities were used to determine the symmetry of the superconducting gap function in a mosaic of high-quality crystals of non-centrosymmetric $CaIrSi_3$. When cooled below the superconducting transition temperature, T_c = 3.55K, in a modest applied magnetic field of 30mT, this type-II superconductor permits the magnetic field to thread through the material in a triangular array of normal flux cores. The characteristic magnetic field distribution inside the sample resulting from this flux line lattice depends on the London penetration length and coherence length.

Measuring this distribution with μSR, the London penetration length was found to become independent of temperature approaching T=0 (and below the critical temperature) [5]. This finding is consistent with an isotropic gap function and an s-wave order parameter, surprisingly devoid of any detectable hint of the lower symmetry of the crystal structure. Zero field muon spin relaxation was also used to search for the presence of spontaneous time-reversal symmetry breaking. The signature of this would be the observation of either a coherent precession signal in the case of ordered magnetism, or simply an increased muon spin relaxation rate in the case of isotropic internal fields from static (or nearly so) electronic moments. At the level of 0.05G, no such magnetism was detected in the superconducting state.

2.8.6 Novel Origin of Frustrated Magnetism in $CuIr_2S_4$

The interplay of charge, spin, and orbital degrees of freedom can lead to complex behaviour when no single interaction dominates. The spinel compound $CuIr_2S_4$ undergoes a transition from metal to insulator at 230K, accompanied by a lattice distortion and appearance of charge ordering in alternating Ir3+ and Ir4+ ion octamers. The lattice distortion creates magnetically inequivalent bonds in four pairs of Ir4+ ions. Using μSR techniques in zero and weak applied magnetic fields, researchers working at TRIUMF discovered a quasi-static weak-disordered magnetism below about 100K, which they have identified as resulting from magnetism in a fraction of the Ir4+ dimers [6].

The observation of this glass-like magnetism led researchers to suggest the presence of frustration and high degeneracy in the electronic ground state. This is a novel route to the generation of frustrated magnetism, more commonly exhibited by equivalent magnetic ions fixed on a triangular lattice. Substitution of as little as 1% of Cu with Zn destroys the charge order and consequently also the novel magnetic behaviour.

[1] R. West, K. Samedov, P.W. Percival, Chem. Eur. J 20, 9184 (2014)
[2] P.J. Cormier et al., J. Am. Chem. Soc. 136, 2200 (2014)
[3] I. McKenzie et al., J. Am. Chem. Soc. 136, 7833 (2014)
[4] I. McKenzie et al., Soft Matter 11, 1755 (2015)
[5] B.A. Frandsen et al., Phys. Rev. B 91, 014511 (2015)
[6] K.M. Kojima et al., Phys. Rev. Lett. 112, 087203 (2014)

2.9 NUCLEAR MEDICINE

TRIUMF's program in nuclear medicine develops new methods to identify and treat disease using subatomic particles. Radioactive isotopes are particularly useful in this regard: by attaching them to biologically active molecules, the uptake of these molecules in the body can be tracked by measuring the isotope decay products in particle detectors. Researchers at TRIUMF work in collaboration with universities and hospitals to find new ways to produce and refine medical isotopes for basic research and medical applications. TRIUMF also treats patients directly with its proton therapy program.

2.9.1 ^{99m}Tc Production on Canada's Existing Cyclotron Network

P. Schaffer

The isotope 99m-technetium (^{99m}Tc) is critical for medical imaging. In response to the pending shutdown of the National Research Universal reactor in Chalk River, Ontario, the leading global producer of ^{99m}Tc, Natural Resources Canada, through the Isotope Technology Acceleration Program (ITAP), funded a TRIUMF-led consortium to demonstrate routine large-scale production of ^{99m}Tc using cyclotrons. This effort is a continuation of previous projects that proved the feasibility of producing ^{99m}Tc on small medical cyclotrons in Canada. Different models of cyclotrons have differing operating parameters, and a primary goal of this project was to develop ^{100}Mo irradiation targets that would take advantage of the full production capabilities of each cyclotron in the consortium.

Several milestones were achieved in the past two years. Full-scale production at the maximum power capacity of the consortium cyclotrons was demonstrated on the General Electric PETtrace, Advanced Cyclotron Systems Inc. (ACSI)TR-19, and (ACSI)TR-24 (using a TR-30 at TRIUMF as a surrogate). A good manufacturing practice (GMP) compliant purification process of ^{99m}Tc-pertechnetate was implemented on a commercially available automated synthesis unit (Trasis Mini AIO). A preclinical study of cyclotron-produced ^{99m}Tc-pertechnetate (CPP) demonstrated equivalence to generator-derived ^{99m}Tc-pertechnetate. And, a clinical trial application, for comparing CPP to generator-produced pertechnetate, was submitted to Heath Canada in July 2015 and, at date of this publication, human trials have begun in Vancouver.

The ITAP team at TRIUMF is now routinely producing ^{100}Mo targets in a new target-making lab in the MHESA.

Multiple patent applications have been made for the associated processes. The radionuclidic purity of technetium produced through the irradiation of molybdenum is not the same as that of generator-derived technetium, which is the product of ^{99}Mo decay, and depends on the isotopic profile of the irradiated molybdenum and the irradiation parameters of energy and time. There are seven stable isotopes of molybdenum, with ^{100}Mo being 9.63% abundant naturally. To maximize the ^{100}Mo(p,2n)^{99m}Tc reaction occurrence, and minimize side reactions, the irradiation energy and molybdenum enrichment profile must be chosen carefully. Development efforts over the last two years have addressed the interplay between these parameters and defined an operational envelope that yields a high-quality product. A proposal has been submitted to Health Canada to seek approval for a product in which any radionuclidic impurities would contribute at most a 10% radiation dose over that of hypothetically pure ^{99m}Tc, well below the presently approved European impurity limit of 30% for generator-derived technetium.

In practice, the production conditions at TRIUMF result in a product that contributes a 1–3% additional dose.

The next steps in the project are to conduct a clinical trial to demonstrate the safety and accuracy of cyclotron produced ^{99m}Tc-pertechnetate and then pursue market approval from Health Canada. This will allow Canada to have a secure supply of this critical medical diagnostic compound.

2.9.2 Target Research and Development
C. Hoehr, P. Schaffer

Positron emission tomography (PET) is a medical imaging technique based on the detection of gamma rays generated by radioactive decays to positrons. The TRIUMF PET target group works on research, design, development, and implementation of targets that are used to produce isotopes suitable for PET when they are irradiated in medical cyclotrons. The goal is to expand knowledge of the processes occurring in targets during irradiation, and apply it to new target applications. It can provide images in real time that show the function of many structures in the body.

Several models and new targets were developed over 2013–2015.

An analytical model of a gas target was established and validated against experiments performed at the TR13 cyclotron and the literature [1]. This model is now being expanded to liquid targets. Monte-Carlo simulations with the well-established code FLUKA were performed to compare isotope yields of ^{18}F, ^{13}N, ^{94}Tc, ^{44}Sc, ^{68}Ga, ^{86}Y, ^{89}Zr, ^{52}Mn, ^{61}Cu, and ^{55}Co to TR13 experiments, and good agreement was found [2,3]. A new target design was also developed that incorporates a fan to introduce turbulence and mixing of the target gas, potentially increasing the yield of the [^{11}C] CH_4 produced. The design is currently being tested at the TRIUMF TR13 cyclotron [4]. In addition, a unique beam profile monitor for low-energy cyclotrons was developed and tested in operation [5].

In a separate effort, a number of radio-metals (^{44}Sc [6], as well as ^{68}Ga, ^{89}Zr, ^{86}Y, and ^{61}Cu [7,8]) were produced in a liquid target loaded with nitrate salt solutions. This unique technique allows for the irradiation of materials dissolved in a liquid solution, which are normally available in metal powder or foil form. The technique allows for the use of existing liquid targets and infrastructure of many PET cyclotrons and avoids the expenses and complications of a solid target station. Quantities of isotopes large enough for pre-clinical studies were produced, and the separation of the desired radiometals from the bulk solution and their radiolabelling were successfully implemented. These radiometals are now used by chemists at TRIUMF and by collaborators at UBC and the BC Cancer Agency [9].

2.9.3 Radiochemistry
C. Hoehr

For more than 25 years, the Radiopharmaceutical Production Group at TRIUMF has worked in conjunction with the Pacific Parkinson's Research Centre at UBC to study neurodegenerative diseases using PET techniques. Currently, 13 compounds are produced on a routine basis using TRIUMF-designed automated synthesis equipment as well as commercial systems. The radiopharmaceutical production lab, which was upgraded in 2010 with a contribution from Western Economic Diversification of Canada, is now fully operational for ^{11}C and ^{18}F compounds. Recently, a new tracer to image Tau proteins in the brain (^{11}C PBB3) was developed and is now in routine use. This tracer will be used in the Parkinson's program as well as for imaging Alzheimer's disease.

The core group also established the routine synthesis of [^{11}C] MRB (methyl reboxetine), a selective norepinephrine transporter (NET) blocker. [^{11}C] Yohimbine is another agent that is now in routine production for use in imaging adrenergic receptors in the brain. Also, [^{11}C] DASB is now in routine production, and will be used to assess the serotonin function in the brain. Both ^{18}F FDOPA and [^{18}F]EF5 shipped on a regular basis to the BC Cancer Agency were used for a clinical trial on the use of PET in prostate cancer imaging and for imaging brain tumours.

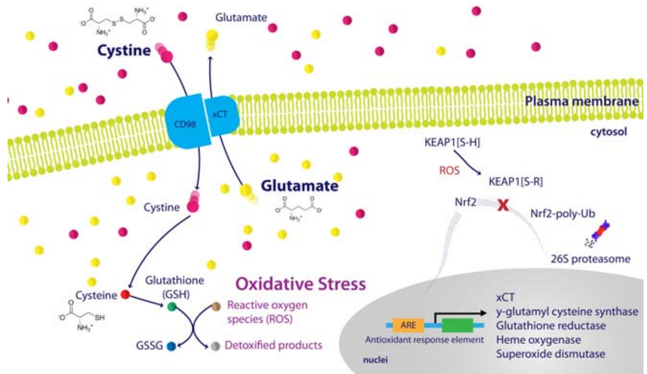


Figure 2. Cystine transporter upregulation mechanism during oxidative stress.

2.9.4 The Use of Positron Emission Tomography (PET) to Determine the Role of Cystine Transporter in Cancer

P. Schaffer

Oxidative stress is the imbalance between cellular antioxidants and reactive oxygen species. When cellular antioxidant regulatory mechanisms become overwhelmed, oxidative stress can result. A number of diseases are thought to be the result of acute or chronic oxidative stress, including cancers, neurodegenerative diseases, atherosclerosis, ischemia, organ transplant rejection, autoimmune diseases, and inflammatory conditions [10]. The cystine transporter system (xC- or XCT) is a potential biomarker for oxidative stress [11,12], and TRIUMF researchers have developed an ^{18}F labelled amino acid named [^{18}F]5-fluoroaminosuberic acid ([^{18}F]FASu) that acts as a potent substrate for the cystine transporter system, as illustrated in Figures 1 and 2. This tracer may allow for functional imaging of oxidative stress in real time and in vivo for cancer diagnostic purposes, particularly for ovarian cancer, lymphoma, and triple negative breast.

The radiosynthesis of [^{18}F]FASu was developed, optimized, and automated at TRIUMF over the past few years. In a typical synthesis, ^{18}F produced on the TRIUMF TR13 cyclotron is used in a two-step nucleophilic displacement and deprotection reaction to yield [^{18}F]FASu. This tracer is currently undergoing studies to establish its rate of uptake into cells expressing xC-, and to understand the pharmacokinetic profile in three different breast cancer tumour models, including so called “triple negative” breast cancers.

Triple negative breast cancer (TNBC) has poor disease-free survival and overall survival rates, and is often associated with aggressive and early recurrence [11]. It is reported that the cystine transporter is commonly expressed and functional in TNBC, and the inhibitor sulfasalazine can increase reactive oxygen species and slow cell growth [12]. Uptake of [^{18}F]FASu was evaluated in three separate breast cancer models, including a TNBC and two hormone-responsive cancer types. The results demonstrate that uptake is closely correlated to xC- protein expression in these tumour models. [^{18}F]FASu demonstrated tumour uptake in all three of the breast cancer cell lines studied. Among them, the TNBC had the highest cystine transporter expression and the corresponding highest tracer uptake in both cells and tumours. By enabling non-invasive analysis of the cystine transporter in vivo, this biomarker may serve as a valuable target for diagnoses and treatment monitoring of certain cancers, as illustrated in Figure 2.

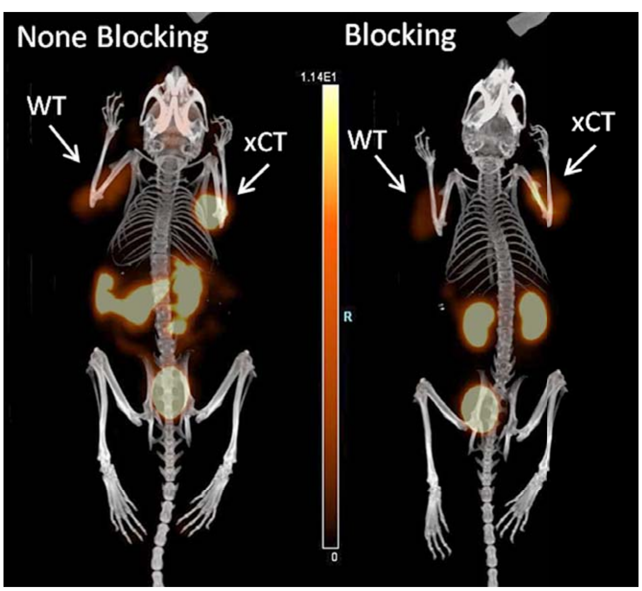


Figure 1. [^{18}F]FASu PET images in mice xenograft with HEK tumours. Left: cystine transporter over expressed tumour (xCT) has much higher tracer uptake compared to wild type (WT). Right: uptake blocked by cystine transporter substrate.

2.9.5 Targeted Radionuclide Therapy with α-particle Emitters

J. Crawford, P. Shaffer

Targeted radionuclide therapy uses radioactive isotopes to destroy specific areas of disease, such as cancerous tumours. The α-particle emitter astatine-211 (^{211}At) is especially promising in this regard, but the clinical application of ^{211}At-based therapies has been limited by the small supply of this radionuclide. This does not reflect complexities in production or purification technologies, but rather the limited availability of α-particle accelerators with appropriate beam characteristics. Currently, ^{211}At production is restricted to only three cyclotron facilities in North America. The distribution of ^{211}At is limited further by its 7.2 hour half-life. To access ^{211}At, TRIUMF developed a method using its Isotope Accelerator On-Line Separator (ISAC-ISOL) to produce and extract its longer-lived parent isotope radon-211 (^{211}Rn), from which the ^{211}At progeny grow in over 10 to 20 hours, thereby facilitating its transport over longer transit times. A small-scale study demonstrated that ^{211}At could be isolated from a $^{211}Rn/^{211}At$ generator system in a form suitable for clinical applications.

Using the same infrastructure, the related isotope ^{209}At was also isolated and evaluated for its use in imaging with single-photon emission computed tomography (SPECT). In contrast to the weak imaging properties of ^{211}At, ^{209}At has an abundance of X-rays and gamma rays emitted over a wide range of energies suitable for imaging with high-energy collimation. This effort produced the world's first set of SPECT images with ^{209}At and established a new tool for assessing and quantifying astatine activity distributions in the preclinical setting, an essential step before using ^{211}At as a therapeutic agent.

These developments provide a platform for pursuing a variety of other rare therapeutic radionuclides to enable further research into therapeutic and/or theranostic radioisotopes.

2.9.6 The TRIUMF Proton Treatment Facility

C. Hoehr

Along with research programs in nuclear medicine and molecular imaging, TRIUMF also provides radiotherapy in collaboration with the BC Cancer Agency and the UBC Eye Care Centre by operating Canada's only Proton Therapy facility. Since 1995, patients with ocular melanomas have come to TRIUMF to receive treatment, and the program has achieved a local tumour control of 91% [14].

Between June 2013 and March 2015, nine patients were treated with protons during six scheduled treatment sessions. This brings the total number of patients treated with protons at TRIUMF to 182, with an average number of nine patients per year.

Treatment is carried out at the main cyclotron using a modulated beam of 74 MeV protons, with the dose delivered over four once-per-day exposures of about 90 seconds each.

Improvements to the Proton Therapy facility were also investigated using FLUKA, a particle physics Monte-Carlo package for simulating the interaction of particles with matter. FLUKA was used to model the proton therapy beam line [15, 16], providing a means to study changes to the beam line quickly and economically while avoiding significant disruptions in beam line operations. As a first application, the manufacturing process of new energy modulator devices was developed and the devices were 3D printed [17, 18].

[1] P. Jahangiri et al., Appl. Radiat. Isot. 107, 252 (2016)

[2] A. Infantino et al., Nucl. Instr. Meth. B 366, 117 (2016)

[3] A. Infantino et al., Nucl. Med. Mol. Imaging 41, S450 (2014)

[4] T. Uittenbosch, K. Buckley, P. Schaffer, C. Hoehr, Development of a forced gas target for improved thermal performance, WTTC15 Conference Proceedings, 2014.

[5] C. Henriks et al., Rev. Sci. Instrum. 84, 113305 (2013)

[6] C. Hoehr et al., Nucl. Med. Biol. 41, 401 (2014)

[7] E. Oehlke et al., Nucl. Med. Biol. 42, 842 (2015)

[8] E. Oehlke et al., Nucl. Med. Mol. Imaging 41, S244 (2014)

[9] G. Dias et al., J. Nucl. Med. 55, 609 (2014)

[9] M. Conrad et al., Amino Acids. 42, 231 (2012)

[10] N. Koglin et al., Clin. Cancer Res. 17, 6000 (2011)

[11] J. M. Webster et al, J. Nucl. Med. 55, 1 (2014)

[12] P. Karihtala et al. BMC Cancer 11, 262 (2011)

[13] L. A. Timmerman et al. Cancer Cell 24, 405 (2013)

[14] E. Tran et al., Intl. J. Radiat. Onc. Biol. Phys. 83, 1125 (2012)

[15] C. Hoehr et al., Int. J. Particle Ther. 1, 220 (2014)

[16] C. Lindsay et al., Med. Phys. 41, 26 (2014)

[17] C. Lindsay et al., Phys. Med. Biol. 60, N231 (2015)

[18] C. Lindsay et al., Int. J. Particle Ther. 2, 219 (2015)

2.10 ACCELERATOR SCIENCE

Accelerators play an essential role in subatomic physics research, leading to new and vital discoveries and a broad range of practical applications. TRIUMF's accelerator division is a world leader in the field and has made recent important contributions in cyclotron physics, beam dynamics, and superconducting cavity development and construction, as well as applications for industry and medicine.

2.10.1 Cyclotron Beams and Development

T. Planche, Y. Rao

For 40 years, TRIUMF'S 500 MeV cyclotron has produced beams of high-energy protons that have driven the research program of the lab. Even though the cyclotron has run efficiently and effectively in this period, accelerator researchers continue to make new improvements and refinements of the device.

About 70% of the beam injected into the main cyclotron is accelerated and extracted. The majority of the remaining beam is lost during the first few turns around the cyclotron chamber due to the bunching efficiency, as shown in Figure 1. This loss is undesirable because it is the main contributor to both irradiation and activation of cyclotron components. The contribution to the loss from charge stripping of H- ions on residual gas was studied by creating a controlled vacuum leak in the cyclotron tank using nitrogen, helium, and hydrogen. This controlled leak showed that with the current vacuum level, the contribution of this stripping process to the net loss is negligible.

The TRIUMF main cyclotron routinely delivers beams simultaneously to three lines, with a total extracted current of up to 300 µA. An additional 100 µA will be required for the new 4-North beam line, which is part of the ARIEL-II project. This upgrade can only be accomplished if processes limiting the amount of beam injected into the cyclotron are well understood. For this reason, significant effort has been put into studying space-charge effects in the central region of the cyclotron. As a result, beam breakup due to space charge forces was detected in radial scans. Dedicated computer simulation tools were also developed to find ways to overcome this challenge.

A sustainable high-intensity tune (up to 100µA) was developed down to BL2C4 at higher energy (110 MeV) for longer target exposures. This was achieved with a wide extraction foil (0.400 inch) positioned properly in azimuth to pull protons out of the cyclotron with minimized beam halos at the exit horn. This extraction has led to an increase in isotope production at the ST (solid target) facility.

A new operating mode was also developed for proton therapy in BL2C1 by turning off the bunchers and inserting the pepper pot in the injection line. This mode has been demonstrated to be easy and quick to set up, and less sensitive and more robust to run.

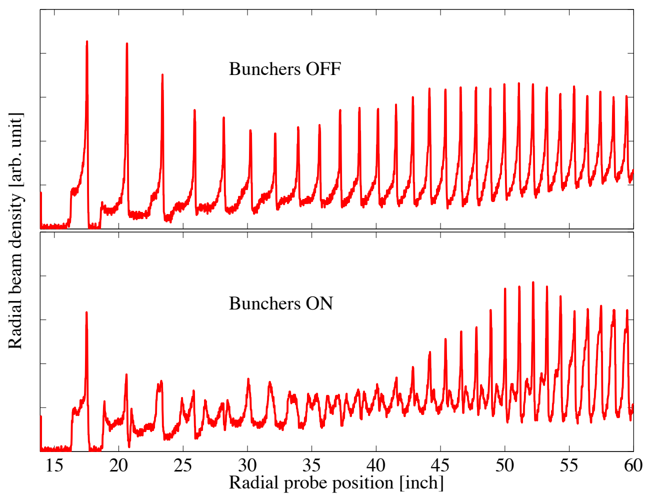


Figure 1. Turn structure in the central region of TRIUMF cyclotron. Strong space charge (lower) causes the central core to rotate, thus losing the turn structure after about 7 turns, and reappearing after about 15 turns.

2.10.2 Beam Modelling and Design

F. Ames, R. Baartman, Y. Chao, C. Gong, F. Jones, D. Kaltchev, J.A. Maloney, M. Marchetto, R. Newhouse, T. Planche, Y. Rao, S. Saminathan

High-energy particle beams must be very tightly controlled if they are to be used for scientific or practical applications. Accelerators are designed, built, and adjusted to achieve the desired beam properties. Central to this process is the development of beam simulation tools to model the output of a given accelerator configuration, and proceeds in conjunction which the construction of prototype devices and the precise measurement of beam outputs. Much of TRIUMF's beam design and modelling in the past two years has focussed on the e-linac for the ARIEL project, but a great deal of progress has also been made in other areas. A broad range of approaches and tools have been used to model accelerator beams, including analytical and numerical methods as well as simulation programs.

TRIUMF researchers have extended existing simulation tools to meet the specific needs of the laboratory accelerator program.

The Geant4 software package, a widely used package to simulate particle tracking and interactions in matter, was developed further into the dedicated package G4beamline. It incorporates 3D geometry, electric and magnetic fields, and particle interactions. TRIUMF researchers also developed new applications for the program by creating plug-in field maps, using both measured data or finite-element solutions (e.g. OPERA). These allow for accurate modelling of solenoids, magnets, and RF (radio frequency) devices, with unique designs that go beyond the standardized elements offered by Geant4. A benchmark for this effort is a full magnetic field map of the TRIUMF cyclotron, which was implemented in the software together with a time-varying electric field in the resonator gap. Tracking tests of equilibrium orbits, tunes, accelerated orbits, and phase acceptance all agreed in detail with dedicated cyclotron codes.

Many simulation tools were also developed for the ARIEL e-linac and used to model aspects of the accelerator. A simulation study of momentum collimation in the medium-energy beam transport area of the ARIEL e-linac demonstrated the mitigation of downstream beam losses in the low-energy tail of the beam. In the low-energy regime, a beam line model from the electron gun through the ELBD spectrometer arm was constructed, with high-resolution field maps for the solenoids and analyzing dipole, including slit and pinhole apertures and the time-varying RF deflector field.

For new operational and beam development applications for ARIEL, a unified approach was adopted via the open-source OpenXAL framework. This approach offers an extensive set of object-oriented software tools and libraries, and a streamlined development process. Efforts have been focused on the creation of a complete XML-based machine description of the beam lines to produce a virtual accelerator. Many specific applications will be connected to this framework.

An important example is a Java application developed at TRIUMF to handle large-scale and high-precision machine experiments in the EPICS environment. This tool can carry out free-form user prescriptions for stepping the machine through a sequence of multiple-parameter actuations with programmable interruptions and real-time screening and exception handling on the sequence through monitored control parameters. The next stage is to link it to the XAL virtual accelerator with added error capabilities to serve as an offline simulator for evaluating algorithm conditioning and signal-to-noise ratios of experimental concepts.

Beam modelling goes hand-in-hand with beam testing and commissioning. Significant progress was made by the TRIUMF accelerator division in the testing and commissioning of new electron beams from the ARIEL e-linac. The electron acceleration complex starts with an electron gun injector, followed by focussing elements, and a low-energy beam transport (ELBT) section, and then the injector and accelerating cryo-modules based on SRF cavities. Extensive testing of the injector and ELBT sections was performed in a dedicated VECC test facility and the ARIEL electron beam line to characterize the phase space distribution of the beam at various stages of the acceleration chain. Fluorescent “view screens” are located further down the acceleration complex to produce real-space images of the electron beam. They were used to reconstruct beam distributions from the e-linac in phase space for different settings of the beam optics elements, using a maximum-entropy tomographic reconstruction algorithm developed at TRIUMF for a quadrupole beam line.

The COSY Infinity package, a differential-algebra-based simulation code, was adapted to allow greater flexibility in accurately modelling electrostatic elements and their fringe fields. These modifications were benchmarked against the standard electrostatic elements existing within the COSY beam physics package [1].

The TRANSPORT code is used for quick calculations of beam sizes when designing beam line sections and for high-level applications to aid tuning. This program is an “envelope code” that tracks the six-dimensional matrix of a beam’s second moments, and is orders of magnitudes faster than macro-particle simulations. TRANSPORT was expanded by TRIUMF scientists to calculate beam envelopes through a linear accelerator given its on-axis electric field.

2.10.3 Designing for the Future

J.A. Maloney

The TRIUMF accelerator division actively pursues new designs for planned and proposed future facilities. These include future beam lines and upgrades for the ARIEL project, as well as designs for other facilities.

ARIEL will use proton-induced spallation and electron-driven photo-fission of ISOL targets for the production of short-lived rare isotopes to be delivered to experiments. It will contain two new drive beams: a 50-75 MeV, 10 mA CW superconducting e-linac with a beam line to transport the high-current electron beam to the target station, and a new proton beam line capable of transporting up to 100 µA from the main cyclotron to the target station. The layout and optics design for the electron line (EHBT) and the proton line (BL4N) have been reconciled and refined with sufficient detail to proceed to engineering design.

A proposed upgrade to the ARIEL e-linac is the Energy Recovered Free Electron Laser (ERL-FEL). A novel software platform for global optimization was developed to create a baseline design for this upgrade. Multiple designs for the recirculation lattice were considered, each differing in details of the transport arcs. A promising version uses a mirror separator system to create a completely symmetric arc, which is preferred for its intuitive design. The current arc beta functions from optimization are shown in Figure 2. The complete start-to-end optimization combines several prominent accelerator codes into one platform, including

MADX, DIMAD, and the TRIUMF-made Empirical Model simulation tool, and was used to model both passes of the main linac. Further optimization of the designs is underway.

The CANREB facility will extend ARIEL to generate beams of rare isotopes. Two of the key components of CANREB will be a High Resolution Separator (HRS) to separate different types of isotopes, and an electron beam ion source (EBIS) for charge breeding in conjunction with a Nier spectrometer.

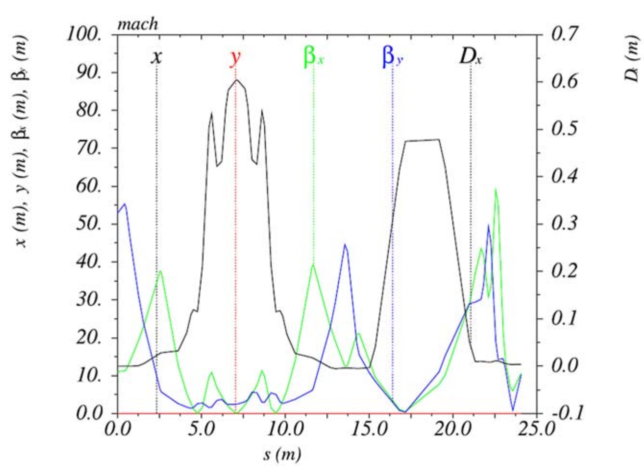


Figure 2. Optimized lattice for the proposed ARIEL ERL-FEL upgrade.

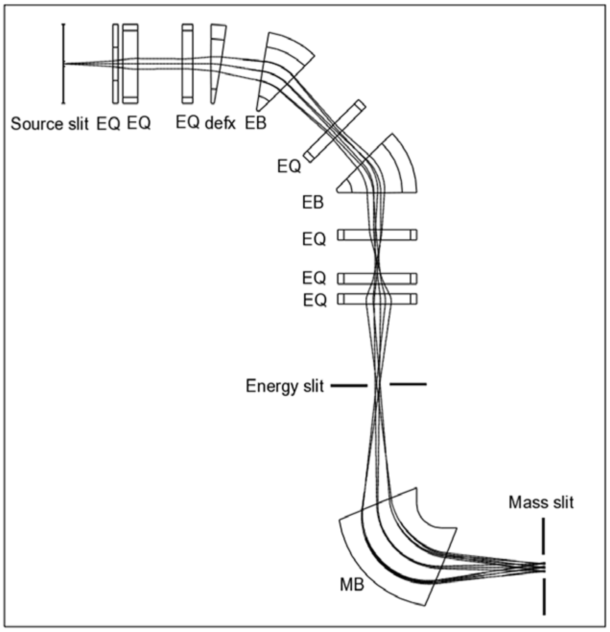


Figure 3. Nier spectrometer trajectories.

TRIUMF scientists made significant progress in designing both components. The HRS design effort included studies of the limiting factors affecting isotope separation, issues related to setup and beam tuning, and methods to maintain beam stability over reasonable experimental time frames. Simulations using field simulations in OPERA and COSY Infinity determined a design for the HRS dipole magnets that achieves both radial and integral flatness goals of less than 10^{-5}. The Nier spectrometer, to be used with the EBIS, consists of both an electrostatic and a magnetic bender that will allow for a high resolving power despite the large energy spread of the beam expected from the EBIS. TRIUMF scientists completed a design of the beam optics for a spectrometer that will achieve a mass resolving power of 200. Calculated ion trajectories through the Nier spectrometer are shown in Figure 3.

In the proposed pEDM experiment to detect a proton electric dipole moment, protons would circulate in a storage ring composed entirely of electrostatic optics [2]. TRIUMF is well versed in this kind of accelerator element, with over 30 spherical “benders” in ISAC. However, bender aberrations become a concern in a storage ring with long storage times. Detailed studies were completed to investigate this challenge and it was found that although the vertical focusing fields can, in principle, be made exactly linear by shaping the electrode vertical section to be parabolic rather than circular, the kinematic vertical aberrations nullify the gain [3].

Following the successful start of the LHC, a TRIUMF-CERN collaboration investigated beam-beam effects. Theoretical predictions were made for the dependence of low-order dynamic characteristics, such as emittance smear, on beam separation and intensity. These were compared with dedicated measurements at the LHC [4].

2.10.4 SRF Development

B. Laxdal, D. Storey, Z. Yao

An important component of the TRIUMF accelerator science program is the study and design of superconducting radio-frequency (SRF) cavities suitable for accelerator applications. They are a key component of the ARIEL accelerator complex, and the proposed acceleration technology for the future International Linear Collider. The SRF cavities for ARIEL are formed and welded from high-grade Niobium with a superconducting transition at 9.2K. Cavity performance, corresponding to the size of the achievable peak accelerating field gradient, is limited by RF heating. When the heating exceeds the maximum cryogenic load, superconductivity is lost, and along with it the accelerating potential. A central goal of SRF research is to better understand the energy loss mechanisms that lead to RF heating, and to find ways to reduce this loss with cavity treatments and beam guide optimization. TRIUMF activities include designing new cavity types, exploring the field dependence of the RF surface resistance as a function of RF frequency, and characterizing the limits of new materials.

The TRIUMF RF induction oven, shown in Figure 4, was developed for heat-treatment studies of SRF cavities and is nearing completion. It will be used to test and perform various heat treatments, including doping for single-cell 1.3GHz cavities. A pair of coaxial TEM-mode cavities designed to fit inside the induction oven will be built. These cavities, a quarter-wave resonator (QWR) and a half-wave resonator (HWR) shown in Figure 4, resonate at fundamental frequencies of 200 MHz and 400 MHz as well as at higher

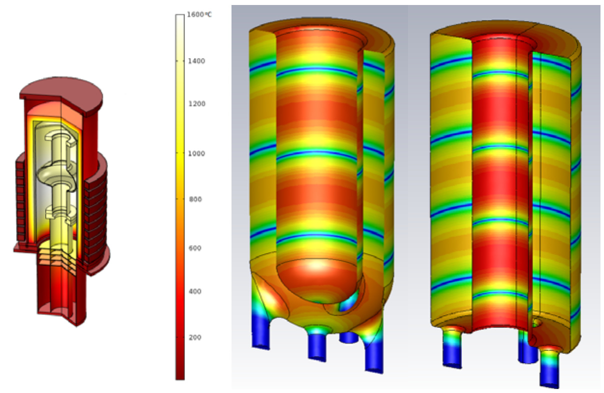


Figure 4. (a,b) The TRIUMF RF induction oven with a single cell 1.3GHz cavity inside; (b,c) the QWR and HWR coaxial test resonators with magnetic fields highlighted for some resonant modes.

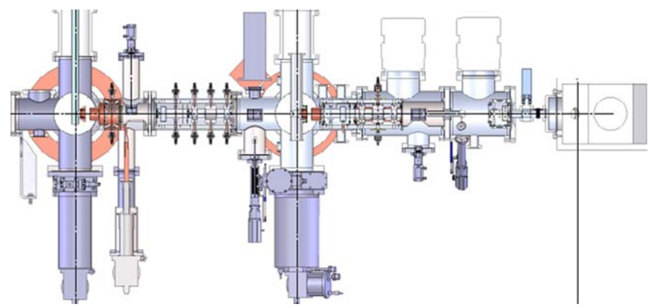


Figure 5. Newly designed high field spectrometer for β-NMR to study SRF materials in parallel field geometry.

harmonics, and will allow for the study of the RF surface resistance over a wide frequency range as a function of surface and bulk treatments. The facility will allow a unique set of measurements to characterize field-dependent loss mechanisms in SRF cavities.

A number of advanced materials-science techniques are applied by TRIUMF researchers to the development of SRF accelerating cavities. Muon spin rotation (μSR) was used to test the ability of superconducting materials to withstand magnetic flux penetration that can lead to RF heating. Niobium samples with different shapes and surface and temperature treatments were tested with this method over a range of applied fields and sample orientations [5].

The properties of SRF cavity materials can also be tested using β-NMR and β-NQR, which probe the electric and magnetic fields at and below the surface. These methods involve implanting hyperpolarized $^{8}Li+$ ions using a beam with the spin of the ions and an external applied magnetic field both aligned parallel to the face of the sample being tested and perpendicular to the beam direction. A particular challenge for this method is applying it with the very large external magnetic fields up to 2000 Gauss needed for SRF accelerator studies. A new high-field beam line and spectrometer, shown in Figure 5, were designed for this purpose. The beam line optics consist of two quadruple triplets, Helmholtz magnet and a unique decelerator system to compensate the Lorentz force due to external magnetic field. This facility will be unique to TRIUMF and allow for diagnosing new treatments, materials, and layered structures that show promise to enhance SRF performance and reduce accelerator costs.

New resonator shapes have been investigated extensively by TRIUMF scientists for SRF applications. A "mushroom"-shaped test resonator design was optimized at TRIUMF to enable the characterization of RF surface resistance in removable samples through a combination of Q perturbation and temperature mapping. The new design enables testing at frequencies below 2 GHz, the frequency range pertinent for accelerator applications, and uses a high-purity sapphire insert to enable fields on the test sample

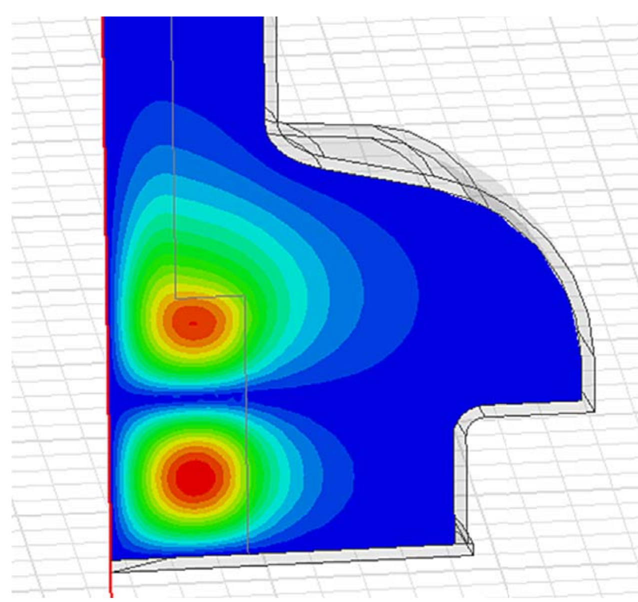


Figure 6: The TE012 mode of the sample test "mushroom" cavity.

more than six times higher than on the Niobium walls. To eliminate RF currents across the demountable joint where the samples are bolted, the cavity operates in the TE01n mode, shown in Figure 6.

Further research concentrated on optimizing spoke geometries for SRF cavities. A significant challenge to these geometries is the phenomenon of multipacting, which has been seen in recent tests and 3D simulations. TRIUMF scientists developed a phenomenological theory to highlight the details of the geometry that affect multipacting. This has led to the design of an optimized single spoke resonator with a “balloon” configuration, shown in Figure 7, which effectively suppresses multipacting by narrowing barriers and pushing them to lower field values.
An optimized 325 MHz β=0.3 balloon spoke resonator was also designed for an application at the RISP project in South Korea with comparable RF parameters and suppressed multipacting performance based on 3D simulations. Two prototypes will be built and tested by TRIUMF in collaboration with RISP.

Significant work is also underway to understand and minimize the RF surface resistance of 1.3GHz cavities in support of continuous wave (CW) applications like LCLS-II, as well as in the lower frequency range of 80-400 MHz for low-beta hadron CW accelerators. A particular mystery is the strong temperature dependence of the Q-slope, which describes the loss of efficiency with increasing accelerating fields in the medium field region near 60 mT. An 81 MHz QWR cavity was tested before and after a 120 C bake. The Q-dependence on cavity temperature during cool down was used to extract the superconducting (BCS) and residual components of the resistance as a function of RF field. Both components of the resistance were found to have some field dependence, with the BCS resistance and slope decreasing after the bake and the residual parts increasing. These data are being incorporated into a theoretical model, with tests on other cavities planned to elucidate it further.

A future extension of the ARIEL e-linac will be a recirculation loop to return electrons for a second pass through the last two accelerator modules. This could be operated as an Energy Recovery Linac (ERL), with the second pass brought back 180 degrees out of phase to recover the electron energy. The beam bound for rare-isotope beam (RIB) production has a repetition rate of 650 MHz and therefore occupies every second RF bucket of the 1.3 GHz accelerating RF. A second beam bound for the ERL may then populate the in-between buckets allowing for simultaneous beam delivery to both RIB and ERL users, but would require separating the bunches at the end of the linac at a frequency of 650 MHz. A deflecting-mode SRF cavity based on an H-mode resonator was designed for this purpose, shown in Figure 8, and fabrication is underway.

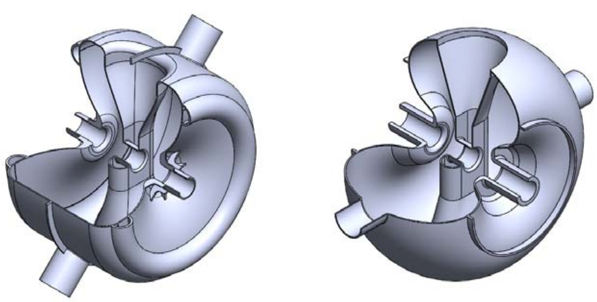


Figure 7. The left plot shows a standard spoke resonator and the right plot shows the balloon variant.

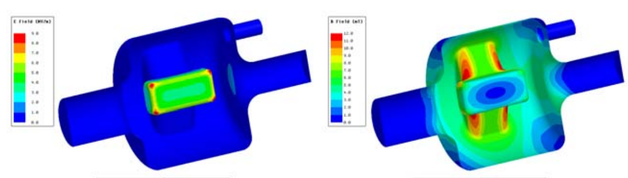
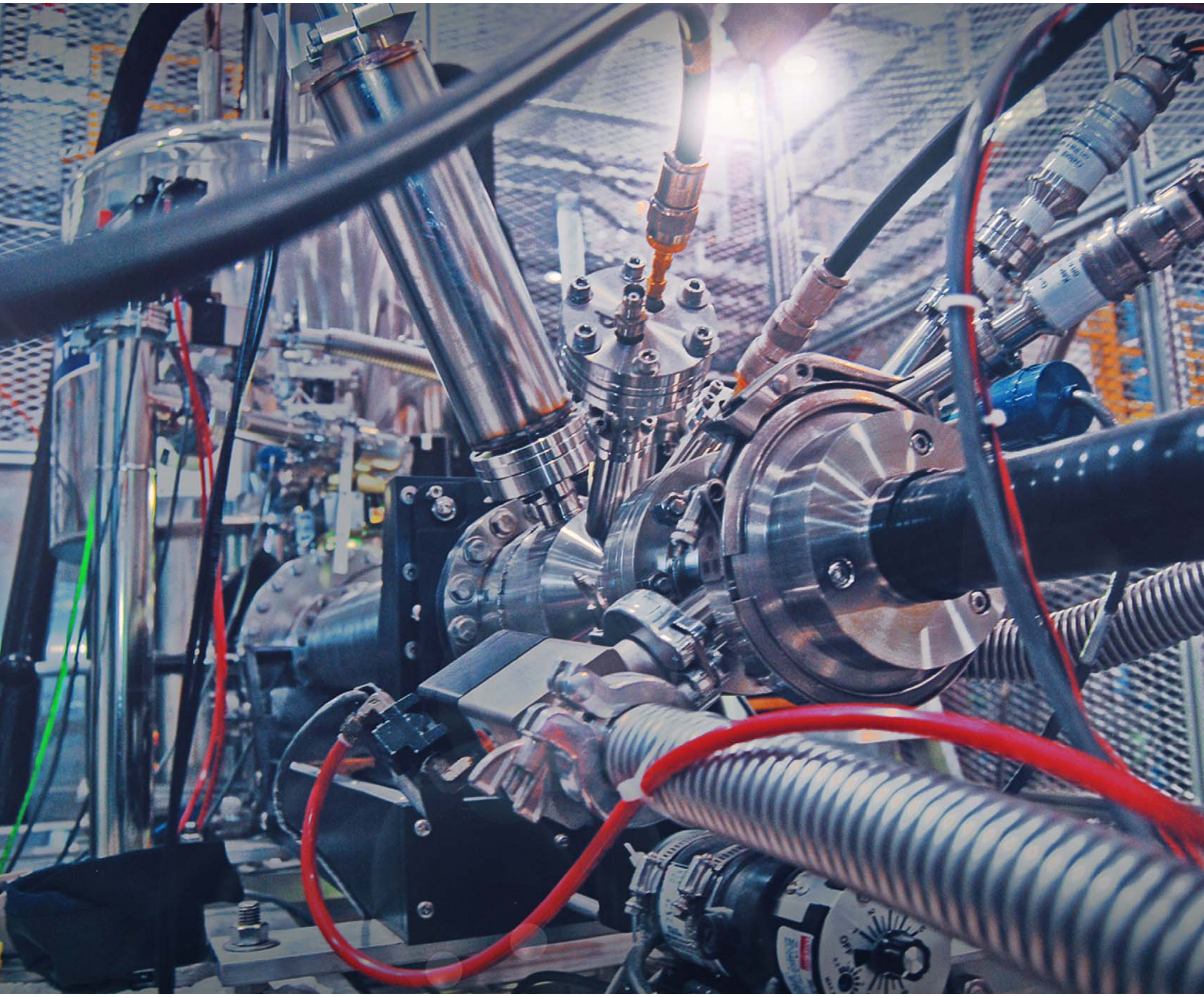


Figure 8. Peak electric and magnetic fields for the RF deflecting mode cavity.



[1] R. Baartman, Linac Envelope Optics, Technical Report TRI-BN-15-03, TRIUMF, 2015

[2] Y.K. Semertzidis [Storage Ring EDM Collaboration], A Storage Ring proton Electric Dipole Moment experiment: most sensitive experiment to CP-violation beyond the Standard Model, arXiv:1110.3378

[3] R. Baartman, Electrostatic Bender Fields, Optics, Aberrations, with Application to the Proton EDM Ring, Technical Report TRI-BN-13-08, TRIUMF, 2015

[4] W. Herr and G. Papotti, Proceedings, ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders (BB2013): CERN, Geneva, Switzerland, March 18-22 2013, arXiv:1410.6393

[5] A. Grassellino et al., Phys. Rev. ST Accel. Beams 16, no. 6, 062002 (2013)

FACILITIES

3

3

FACILITIES

3.1 INTRODUCTION

As a laboratory, TRIUMF manifests the knowledge and skills of its talented staff and provides the physical infrastructure that gives Canada a competitive advantage for discovery science, technology, and innovation. The origins of TRIUMF are in particle and nuclear physics, and thus the lab's key physical resources involve accelerators, beam lines, and detectors. This chapter discusses the advances and performance of TRIUMF's facilities and experiments in service of its mission.

Summary

The main cyclotron performed admirably during the period 2013–2014 following the upgrades of 2010–2012. On the ISAC side, post-acceleration of high mass beams has become routine, and a new ion-guide for the laser ion system has demonstrated several orders of magnitude reductions in isobaric beam contaminants. Work on ISAC production targets resulted in dramatic improvements in their reliability, which unfortunately was offset by target module radiation-induced aging.

The ultra-cold neutron source in the Meson Hall is proceeding apace, and the francium laboratory in the ISAC low-energy area is functional and making physics measurements. New experiments and detectors have been built and are being commissioned, both onsite and at peer institutions.
In nuclear medicine, a steady program of target innovation made increasingly effective use of its highly reliable medical cyclotron. In the area of scientific computing, TRIUMF's stewardship of the Canadian ATLAS Tier-1 Data Centre expanded simultaneously with an upgrade of the lab's core network fabric.

These enhancements were not without challenges or trade-offs. Elements of TRIUMF's infrastructure date from the original installations dating back to the 1970s. Talent and resources to maintain, repair, and expand TRIUMF's capabilities are in high demand, and the lab is identifying, assessing, and developing options to deal with aging infrastructure that underpins many of the laboratory's core capabilities.

3.2 CYCLOTRON AND PRIMARY BEAM LINES

3.2.1 520 MeV Facility Performance

Y. Bylinski and A. Hoiem

The 520 MeV cyclotron is the heart of TRIUMF. It operates around the clock, seven days a week, with a major three-month shutdown from January to March and a one to two week mini-shutdown in September.

The cyclotron has three independent extraction probes with various sizes of foils to provide protons to up to three beam lines (BL) simultaneously. BL1A routinely delivers protons at 480 MeV to two target systems: T1 and T2 for the μSR experimental channels, with beam power ranges from 50 to 75 kilowatts. Downstream of T2 is the 500 MeV Irradiation Facility and the Thermal Neutron Facility. Beam line 1B separates off BL1 at the edge of the cyclotron vault and provides international users with the Proton Irradiation Facility (PIF), which mimics space radiation for testing computer chips. The new BL1U provides beam to the UCN source (Section 3.5.10). BL2A provides 480 MeV proton beams at up to 50 kilowatts to either of two ISOL targets that produce exotic ion beams for a host of experiments in ISAC. The BL2C (70 to 116 MeV) line is used for the Proton Therapy (PT) Program, which treats choroidal melanomas (eye tumours), and proton irradiation of rubidium to produce strontium for medical imaging generators. BL2C is also used to provide lower energy protons to the PIF users.

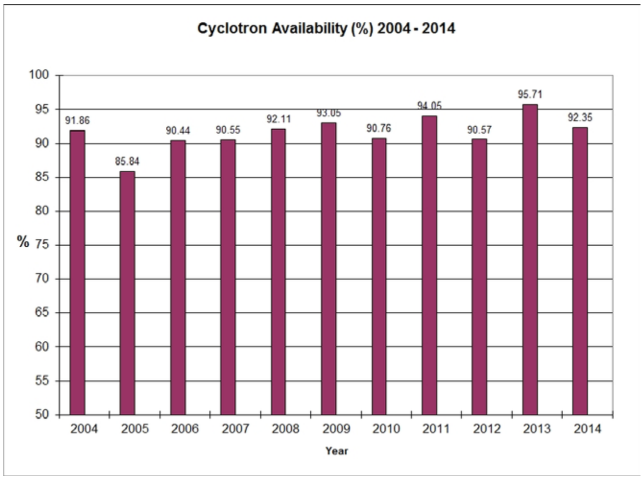


Figure 1. Cyclotron annual availability as a % of scheduled beam time for 2004–2014

520 MeV Facility Operation: 2013 Totals

In 2013, the cyclotron ran for 5,271 hours or 95.7% of the 5,508 hours scheduled, the highest cyclotron run ever achieved (see Figure 1). The major source of downtime (33% of the total 202.5 hours) was the RF intermediate power amplifier, and a sparking over that destroyed a 480 V break and damaged other components inside the amplifier cabinet.

BL1A ran for 4,181 hours or 98.3% of the 4,253 scheduled hours and received a charge of 484.5 mAh or 99.7% of the 485.9 mAh scheduled. BL1B delivered beam to the PIF for two weeks.

The 2C1 line was used for three PT sessions (five patients) as well as for seven weeks of Proton Irradiation Facility (PIF) operation. BL2C4 ran for 3,925.4 hours or 96.6% of the scheduled 4,063 hours and received 96.8% of the scheduled charge (360.7 mAh of the scheduled 372.5 mAh). The amendment in 2012 to the STF operating licence allowed operation with beam currents of up to 100uA, which resulted in 2013's record charge delivered to STF.

BL2A ran for 3,962 hours of beam or 91.3% of the scheduled 4,339 hours. BL2A received 136.6 mAh or 93.6% of the scheduled 146 mAh.

The total extracted beam charge was a record 981.8 mAh, 30 mAh greater than 2010's record of 951 mAh.

520 MeV Facility Operation: 2014 Totals

In 2014, a record 12,973 hours was delivered to all primary beam lines (see Figure 2). The cyclotron ran for 5,181.9 hours or 92.4% of the scheduled 5,611. The major downtime for the running period was the inflector, accounting for 51% of the total 442 hours.

Beam line 1A ran for a record 4,241.5 hours or 96.6% of the 4391 hours scheduled and received a charge of 427.9 mAh or 97.4% of the 439.2 mAh scheduled. Beam line 1B delivered beam to the PIF for four weeks.

The 2C1 line was used for five sessions of PT (seven patients) as well as for eleven weeks of PIF operation. BL2C4 ran for 3,758 hours or 92.4% of the scheduled 4,068 hours and also received 90.3% of the scheduled charge (345 mAh of the scheduled 382.2 mAh).

BL2A ran for 4,430 hours of beam or 88.7% of the scheduled 4,992 hours. BL2A received 170.8 mAh or 92.7% of the scheduled 184.2 mAh.

3.2.2 Cyclotron Beam Development

Y. Bylinski and A. Hoiem

The cyclotron tune was enhanced to correct for a parasitic 3/2 resonance that affected beam stability. A stability program, using the ISIS pulser and harmonic coils for regulation, was developed to maintain stable currents in BL1A and BL2A (see Figure 3). In 2013, there was an approximately 5% improvement in cyclotron

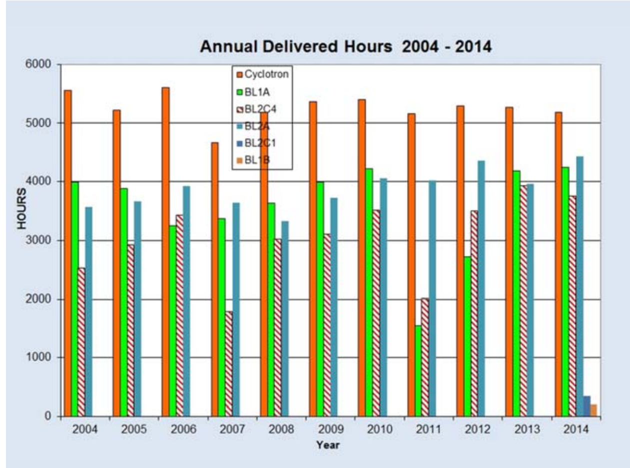


Figure 2. Beam hours delivered to the primary beam lines.

transmission attributed to an upgrade of the deflector electrode plates. The cyclotron transmission was routinely > 70% throughout 2013 (see Figure 4).

3.2.3 520 MeV Cyclotron Refurbishing

Y. Bylinski

Several upgrades aimed at improved performance were undertaken during the reporting period. Upgrades in the H^- ion source included: the addition of one electrostatic corrector, the installation of mu-metal shielding around the optics box, a reconfiguration of the skimmers, proper Einzel lens alignment, and an overhaul of the hydrogen supply system. A new full-scale H^- ion source test stand was built in the I3 HV terminal to allow for testing of operational sources and prototyping of a new spare source

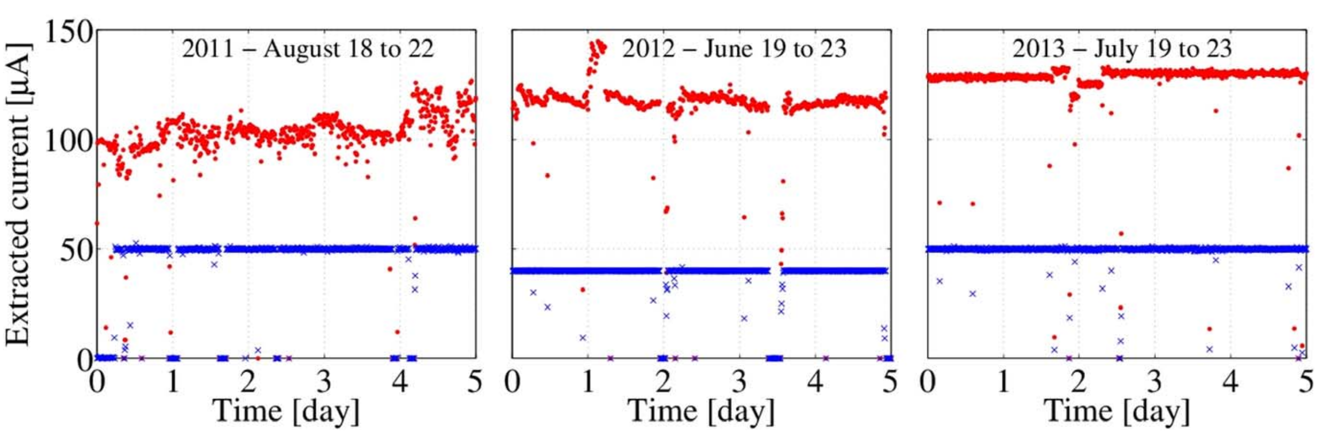


Figure 3. Beam stability improvement from 2011–2013. BL2A – blue, BL1A – red.

projected for the I2 HV terminal. A new long-lasting filament configuration proved to enhance the source lifetime from three to five weeks.

One hundred and twenty old trim and harmonic coil power supplies were replaced with a set of new units that included modern switching mode technology. The new supplies, rated up to 10 kW, came in two distinct configurations: bipolar devices and unipolar ones connected via polarity switches that were made in house. Project implementation benefitted from an accelerated schedule and was completed in three years instead of a projected five.

A replacement unit for the main magnet power supply (MMPS) was ordered in 2015 and will be installed in 2017. As well, the cyclotron RF tuning system was upgraded with a new motor drive concept implemented for seven resonators. A spare RF fundamental coupler feedthrough assembly was built and tested. New EPICS PLC controls were developed for the T1/T2 target systems. The M15 muon channel magnet power supplies were replaced with new-generation units. A spare helium compressor was refurbished and installed for the cyclotron LINDE-1630 cryogenerator.

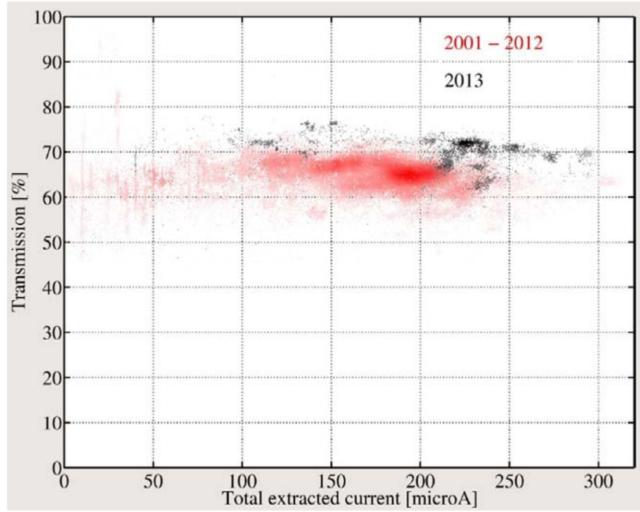


Figure 4. Cyclotron operating transmission vs extracted current BL1A – red.

With respect to vault and safety issues, a new Oxygen Deficiency Monitoring System was installed in the cyclotron vault. Service platforms with fall protection were installed at six cyclotron elevating system jack stations. (The remaining six will be completed during the 2016 shutdown.) A majority of the cables that are exposed to high radiation fields were replaced with new radiation-resistant ones. This is a multi-year project that is approaching completion.

3.3 ISAC

3.3.1 ISAC Performance

C. Morton and J. Aoki

The overall performance of TRIUMF's rare isotope beam (RIB) facility, ISAC, has been steadily improved since 2012 due to continuous upgrades. The delivery of high-mass beams at energies above the Coulomb barrier at ISAC-II has become a routine operation, while the investments that were made in 2010–2011 to improve the reliability of RIB production targets continued to pay dividends through 2014; these gains have been offset, however, by problems with aging ISAC target modules as the facility moves into its 17th year of operation (see Figure 1).

High-Mass Beam Delivery

Historically, accelerated beams at ISAC have been limited to those at relatively low masses. The first accelerator in the ISAC chain, a room-temperature RFQ, is limited to beams with mass-to-charge ratios less than 30 which, with beams from the online target ion source being predominantly singly charged, effectively limits acceleration to isotopes with masses less than 30.

Accelerating heavier isotopes requires charge breeding with the ISAC charge-state booster (CSB) to achieve lower mass-to-charge ratios.

A task force was struck in 2010 to develop the tools and techniques needed for the reliable delivery of post-accelerated high-mass. Those efforts culminated in the first delivery of an accelerated beam with mass greater than thirty, ^{76}Rb at 4.2 MeV/nucleon, to an experimental location in October 2012. That was followed by the delivery of ^{94}Sr at 5.5 MeV/nucleon to TIGRESS for a first experiment with a high-mass accelerated beam in August 2013. The availability of high-mass beams for experiments at energies above the Coulomb barrier, while still posing challenges that must be addressed on a case-by-case basis, is now considered a routine operation.

Reliability

RIB delivery in general remains challenging, but the nature of the challenges has changed in recent years. Improvements to the design and fabrication of target components in 2010 and 2011 resulted in greatly increased target reliability. Of the 28 targets used since 2012, 27 incurred no significant downtime due to target failures. The reliability of ISAC target modules, on the other hand, has become an issue as the facility ages. There are currently only two target modules available for use, TM1 and TM4. Neither are fully operational: TM1, the original target module manufactured for use at ISAC, was only designed for use with targets with surface ion sources or for use with the TRIUMF Resonant Ionization Laser Ion Source (TRILIS). An additional issue is that this module is limited in beam energy to about 20 keV due to high-voltage breakdown. TM4 can operate at beam energies approaching the ISAC design of up to 60 keV beam energy. It can operate targets with FEBIAD ion sources in addition to the sources used with TM1; however, a failure in 2013 of one of the cooling lines needed for FEBIAD operation has removed that option. A refurbished TM3 was put back into operation in late 2013 but forced back out of service in 2014 due to high-voltage failures. TM2, which has not been used since 2008, is currently being upgraded and is expected to re-enter service later this year. Like TM4, TM2 is designed to operate targets with all ISAC ion

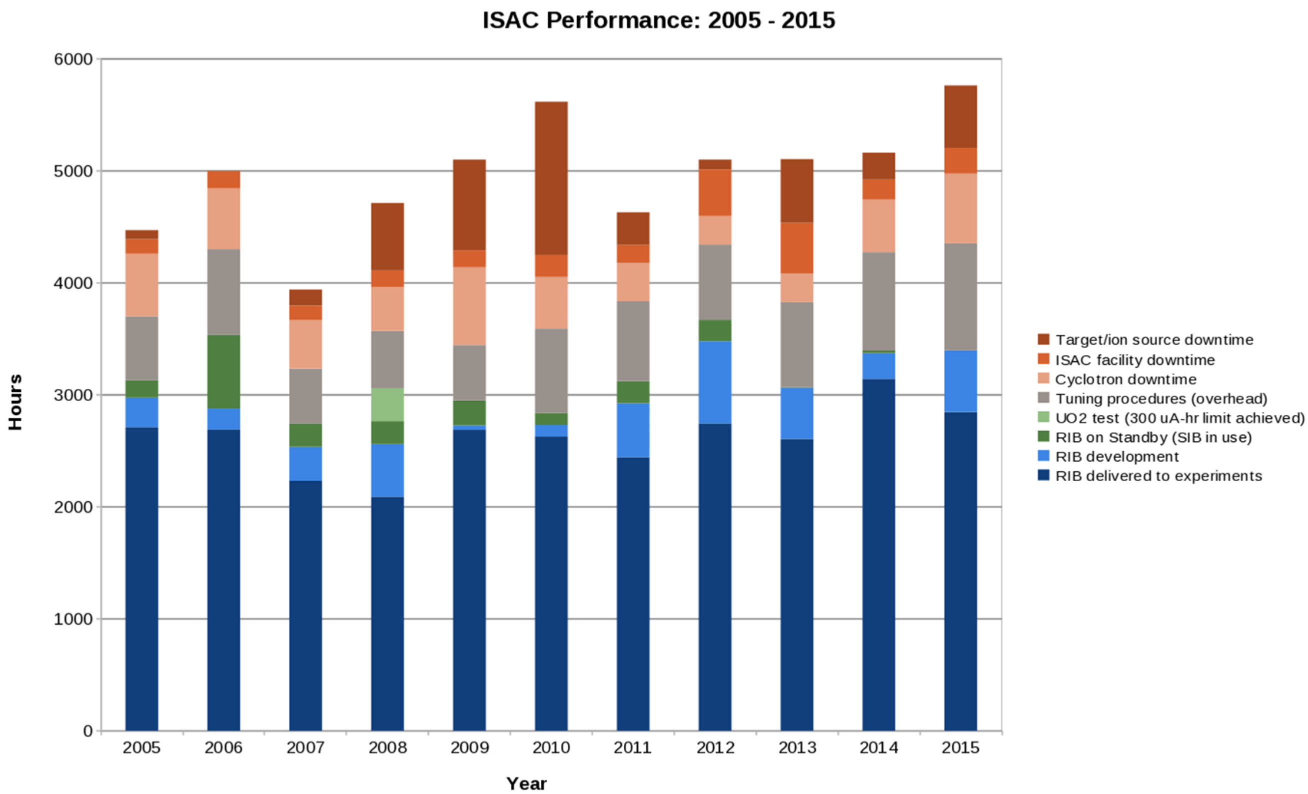


Figure 1. ISAC performance from 2005 through 2015.

source types: surface sources, TRILIS, and FEBIAD ion sources. It is anticipated that TM2 will replace TM1 in regular operation and that TM1 will remain available for use.

RIB Performance

Roughly 3,000 hours of RIB were delivered from nine production targets in 2013. There were, however, over 1,000 hours of downtime, More than half this was due to a failure of a FEBIAD cooling line in TM4 (see above). This was by far the greatest single source of downtime in 2013, followed by downtime due to a failure of the remotely controlled crane in the ISAC target hall, one that prevented the timely resolution of a water-flow issue in one target station. This is one of the few times in the history of ISAC that an extended period of downtime resulted from a breakdown of equipment outside the beam-delivery infrastructure.

Ten targets were run in 2014, and more than 3,300 hours of RIB delivered. Of those, 400 hours were delivered on a discretionary basis after the final target of the year suffered a mechanical failure that prevented it from being heated resistively. ISAC facility downtime was otherwise low, with fewer than 400 hours lost. Eight targets were run in 2015, and 3,400 hours of RIB delivered. However 230 of those, however, were delivered on a discretionary basis due to a target extraction electrode failure. ISAC facility downtime was higher than usual with 740 hours lost. A large portion (310 hours) resulted from TM2 refurbishment delays; the module's return to service slid from July to September.

3.3.2 Target and ion source development

F. Ames and J. Lassen

Target Materials

New beams at ISAC normally require novel target materials to optimize the production and release of a specific isotope. Several such materials have been investigated in recent years.

Nickel oxide (NiO) had already been investigated as a target material in 2012. In 2013, a NiO target was used with a FEBIAD ion source to deliver radioactive carbon beams in the form of CO molecules to several experiments.

Actinide target operation has been further consolidated, and uranium carbide (UC_x) is now one of the standard target materials used at ISAC. The presently used material processing technique allows the fabrication and use of up to 3 UC_x targets per year. The longevity of the target containers remains a problem. Offline tests to use graphite, either as a container material or as an insert in the normally used tantalum containers, have started.

Target Development

The 2014 target development highlight was the use of thorium as target material for the first time at TRIUMF. The ISAC operating license had to be amended to allow a first test with thorium oxide (ThO) to a total proton beam charge of 500 µA-h. The target was used with a surface/laser ion source, and a broad survey of the yields was done to
compare the performance of the target to that of UC_x targets. As an example, Table 1 shows the measured and theoretical production of two Ra isotopes. Both uranium and thorium targets have been found to be very useful because long-lived isotopes, including daughters of beam-induced activities, can be harvested even weeks after irradiation. This enables additional experiments to be conducted during shutdown periods. In-source laser spectroscopy of radium and actinium has been done like this.

Ion Sources and Beam Optics

Due to problems with the ISAC target modules (Section 3.3.1), only limited use of FEBIAD ion sources was possible in recent years. One development was the implementation of a cold transfer line to reduce beam contamination from condensable elements. Although off-line tests gave promising results, an on-line test with a silicon carbide (SiC) target failed due to a leak in a cooling line of the target module. Further development will require a functional target module capable of supporting FEBIAD ion sources.

For removing surface-ionized contamination from laser-ionized ion beams, an ion guide laser ion source (IG-LIS) has been developed (discussed in more detail below). Further improvements in beam transport efficiency from the target ion sources to experiments were implemented. These include new tools and strategies to facilitate beam tuning and the implementation of a low-intensity emittance meter after the mass separator.

Charge State Breeder

Beam purity has been identified as the limiting factor for the use of the charge state breeder. In order to reduce the background from ions emitted from the plasma of the charge state breeder source, the plasma chamber has been coated with pure aluminum and the material of the surrounding electrodes changed to aluminum as well. This, together with methods to use the entire accelerator chain as a mass filter for purification of the beam, has allowed several experiments with charge bred heavy ions, as described in the previous section.

Isotope	Measured Yield ThO_2 (ions/s)	Measured Yield UC_x (ions/s)	Yield Ratio ThO_2/UC_x	In-Target Production Ratio ThO_2/UC_x (Geant4 calculation)
^{223}Ra	6.8e8	1.9e8	3.6	7.5
^{224}Ra	1.4e9	2.0e8	7	7.9

Table 1. Measured yields and theoretical ratios for the production of $^{223/224}$Ra from ThO and UC_x targets

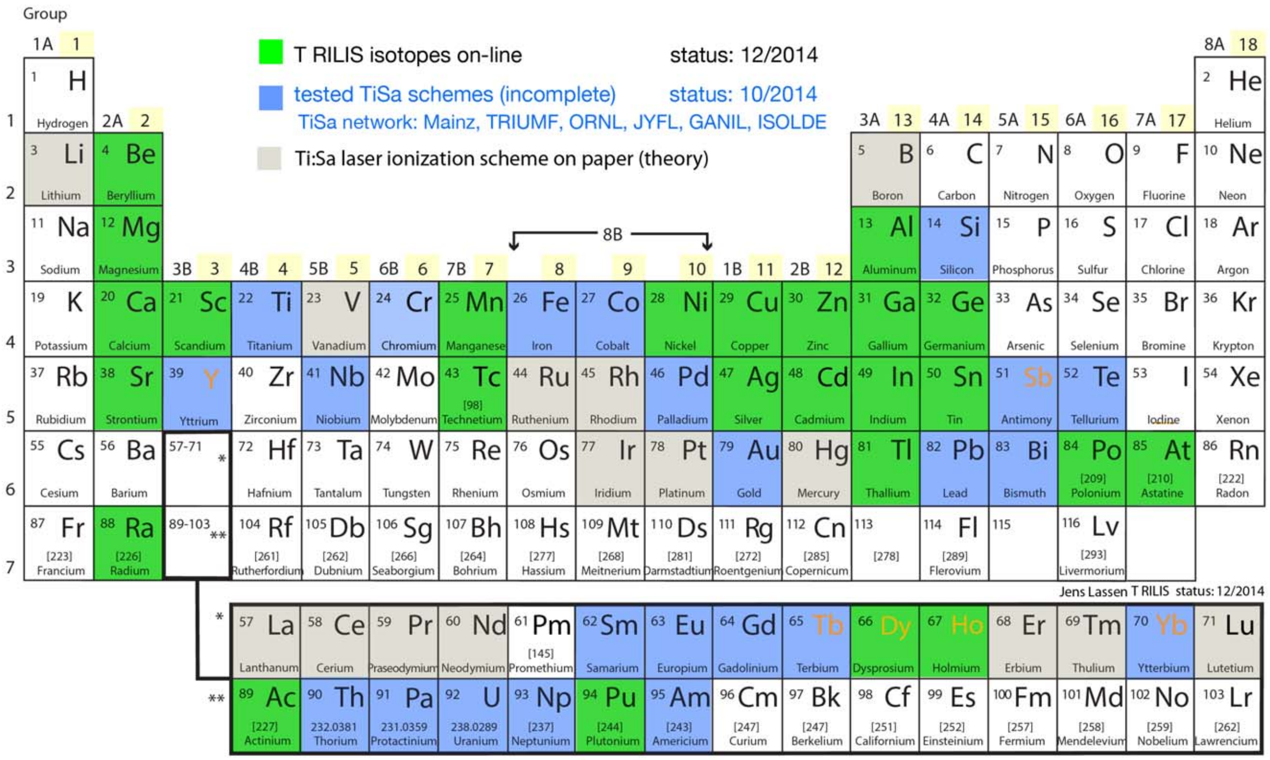


Figure 2. Elements from which radioactive isotopes have been delivered (green) to experiments at TRIUMF by use of TRILIS. Blue indicates elements for which suitable laser ionization schemes have been developed elsewhere. Orange lettering indicates that ionization schemes have been tested/developed at TRIUMF and are ready to be deployed.

TRILIS Activities

TRILIS, the Resonant Ionization Laser Ion Source, helps to provide intense beams of radioactive isotopes by element-selective ionization. In the reporting period, the number of elements delivered by TRILIS was increased from 20 to 25, with an additional 4 ionization schemes tested and ready for beam delivery (see Figure 2).

Frequency doubled laser light at several hundred mW output power in the wavelength range between 395 nm and 490 nm (blue), was generated by intra-cavity frequency doubling. This allows for enhanced laser ionization efficiency of several elements. (see Figure 3)

TRILIS operation now accounts for roughly 50% of all beams requested and will continue to play an even more important role in coming years with the development of ionization schemes for additional elements. Furthermore, TRILIS is being used with the ISAC Yield Station (Section 3.3.3) for a science program on in-source laser resonance ionization spectroscopy, investigating optical isotope shifts, hyperfine structure, and ionization potentials of actinide elements.

In the IG-LIS, a repeller electrode separates the hot target region from the ionization region, which is located within a radio frequency ion guide for radial confinement of produced ions. Laser beams are admitted into the ionization region from the front.

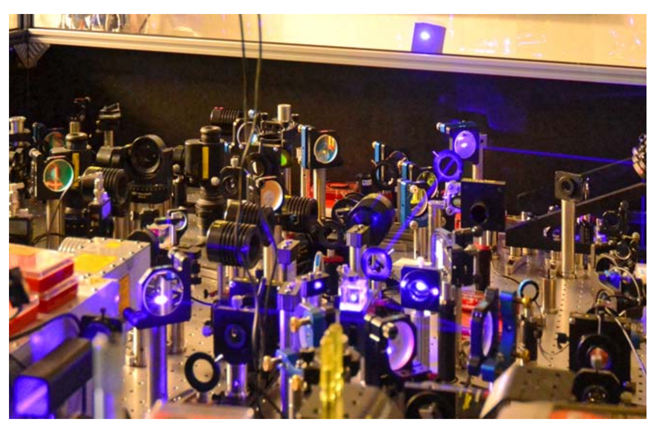


Figure 3. High-power frequency-doubled TiSa laser light in the clean room laser ion source laser laboratory.

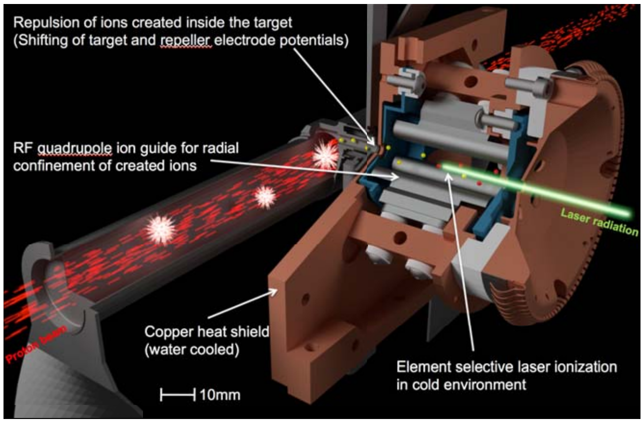


Figure 4. Section view of an IG-LIS, ion guide-laser ion source, coupled to an ISAC isotope production target.

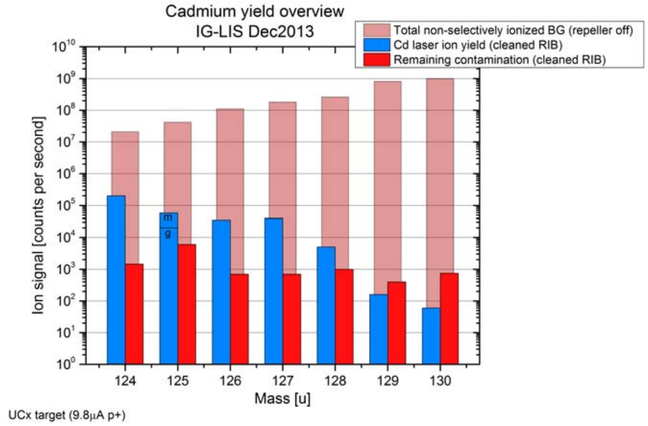


Figure 5. Increase in selectivity for Mg isotopes by suppressing surface ionized background from Na and Al isobars.

This results in the suppression of unwanted isobaric contamination and allows for, in principle, isobarically pure beams delivered to experiments, as can be seen in Figure 5.

Polarizer (Nuclear Spin Polarized, Radioactive Ion Beams)

The ISAC polarizer provides beams of polarized radioactive isotopes at energies of several tens of kilovolts. The nuclear spins of the ions in these beams are preferentially oriented in one direction. After implantation in a target, the spins are made to wobble in unison like an array of tilted spinning tops. When the nuclei randomly decay, beta particles are emitted preferentially in a direction aligned with the spin direction at the instant of decay. In this way the wobble can be observed using external particle detectors. The main use of these oriented radioactive nuclei is to serve as sensitive probes of structure in thin films using β-NMR (beta-detected nuclear magnetic resonance) and β-NQR (beta-detected nuclear electric quadrupole resonance). Other experiments, e.g. those of the MTV and Osaka groups, simply measure the asymmetric decay (without the wobbling) to infer properties of nuclear structure and fundamental nuclear and particle symmetries.

The polarization is produced by collinear laser optical pumping. The classical probe for the β-NMR experiments is ^{8}Li (nuclear spin = 2), which requires resonant pumping of the ^{8}Li atom on the D1 transition. The atom is produced by sending the $^{8}Li^{+}$ ion beam through an alkali-vapour charge-exchange cell. The atomic beam is then polarized and subsequently re-ionized in a helium gas cell and directed to the experiments by electrostatic benders. Recently, it has been shown that a rubidium vapour cell is operationally more reliable than the formerly used sodium cell and has comparable neutralization efficiency and beam-energy broadening properties. Results with cesium vapour, taken years ago, had been discouraging; the utility of rubidium was discovered because its use was mandatory for neutralizing francium beams for laser spectroscopy experiments at TRIUMF. In addition, a ^{31}Mg (nuclear spin = ½) probe for β-NMR has been developed and is awaiting on-line tests. A spin ½ nuclide is desirable because it has no electric quadrupole and therefore provides a pure magnetic probe.

3.3.3 ISAC Yield Station

P. Kunz

The ISAC Yield Station was upgraded in 2011. The old system was replaced with a more powerful, more versatile, easier-to-use, and fully remote-controlled apparatus (see Figure 1) for the detection and characterization of radioactive ion beams (RIBs) which are delivered to experiments in the ISAC-I and ISAC-II experimental areas. It is routinely used for RIB intensity (i.e., yield) measurements, the identification and quantification of isobaric contaminations, and the optimization of isotope production and beam transport. Furthermore, it is necessary for the measurement of charge state

Figure 1. The ISAC Yield Station in the ISAC-I experimental hall.

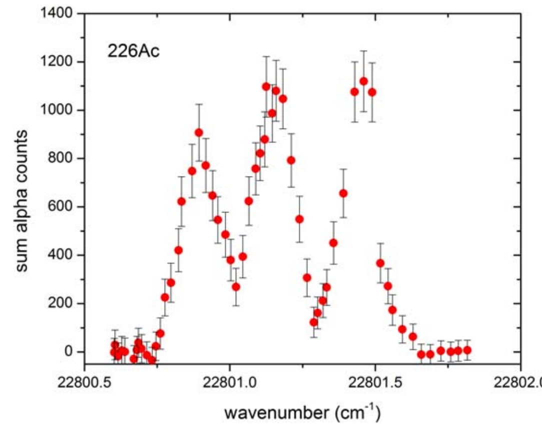


Figure 3. In-source laser spectroscopy with the ISAC Yield Station. The example shows α-decay events from the ^{226}Ac decay chain as a function of laser detuning, revealing the hyperfine structure in the first excitation step of the laser ionization scheme.

distributions from the ECRIS charge state breeder and the evaluation of the performance of new target materials and ion sources (as described in the previous section). To perform these tasks, the yield station features a tape station, an array of detectors for α, β and γ spectroscopy and an event-based data acquisition system coupled with data analysis software that was specifically designed for the quick and reliable determination of yield results [1].

An important objective of the ongoing R&D of new target materials and ion sources is the production of new, purer, and more intense ion beams. In on-line tests, the yield station has been used for extensive surveys of the release from development targets for RIB production. Yield data from production as well as development targets have been collected for a large number of isotopes. The results have been published online in the ISAC Yield Database [2]. Figure 2 depicts a summary of all the isotopes that have been investigated so far.

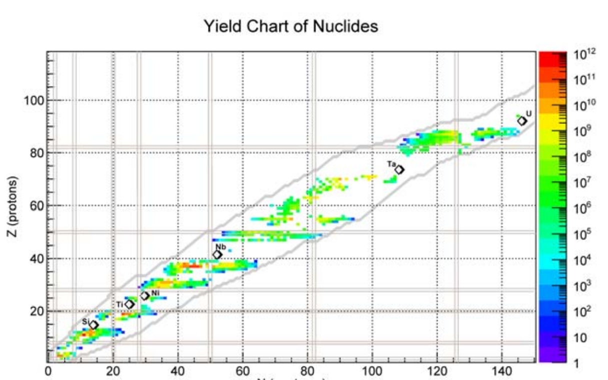


Figure 2. Isotope yields at ISAC. The colour-coded beam intensity of each isotope, defined by proton and neutron number, is given in ions/second.

Since the upgrade in 2011, 1,580 yield results have been added to the database, and have helped researchers plan experiments. Compared with the 1,159 entries of the previous 10 years, this corresponds to 3.4 times more yield data per year.

The yield station has also been used for nuclear spectroscopy investigations. For example, previously unknown γ lines from the decay of ^{46}K were discovered, and the isotope's half-life was determined with unprecedented accuracy by measuring its β^- decay [1]. Furthermore, the yield station data acquisition and control system was equipped with a direct communication link to the TRIUMF laser ion source TRILIS, thus enabling direct control of the TRILIS laser frequencies to determine their correlation with yield data.
As described above, TRILIS is based on the principle of resonant multi-step laser ionization. It is efficient, highly element-selective and, in some cases, enables the separation of spin-isomers. The combination of the radiometric yield station detection systems with TRILIS allowed in-source laser spectroscopy experiments on exotic isotopes, correlating radioactive decays with atomic properties. In particular, detailed investigations of optical isotope shifts and hyperfine structures (See Figure 3) on the elements cadmium, astatine and actinium were performed by obtaining radiometric data from the laser-ionized beam as a function of laser frequency detuning.

[1] P. Kunz et. al., Rev. Sci. Instrum. 85, 053305 (2014)
[2] P. Kunz, ISAC Yield Database, http://mis.triumf.ca/science/planning/yield/beam

3.4 MESON BEAM LINE DEVELOPMENT

S. KREITZMAN AND G. MORRIS

µSR, an acronym for Muon Spin Rotation/Resonance/Relaxation, is a technique in which spin-polarized muons are implanted and their decay positrons are detected. The technique is used to study a very wide variety of scientific and technological materials of interest. Information pertaining to the microscopic atomic, electronic, and chemical environment of the muon is extracted to study a wide variety of topics in the fields of condescended matter physics and physical chemistry. These would include fundamental investigations of magnetism, superconductivity, chemical reactions, and semiconductor doping along with more applied research into, for example, battery technology, hydrogen storage, materials fabrication, and nuclear moderator engineering.

The CMMS (Centre for Molecular and Material Sciences) µSR (Muon) User Facility provides access to, and support services for, the experimental infrastructure that TRIUMF makes available to the international scientific research community. This section predominantly describes the relevant beam lines, spectrometers, and professional scientific services available, whereas the scientific impacts of experiments carried out with these facilities can be found in section 2.8.

Beam Lines

TRIUMF supports four muon beam lines (see Table 1). M15, M9A and the M20s are all surface muon beam lines, which are ideal for µSR studies on materials that do not require confinement in enclosures that support high pressures. M9B services the latter environments where higher energy muons are required to penetrate respective enclosures before encountering the sample under study.

Of the two major new µSR secondary beam line infrastructures implemented at TRIUMF within the 2010–2015 Five-Year plan, the M20 beam line has become operational while the M9A and M9B beam lines remain offline awaiting a solution to a “creeping” misalignment of the front end of this channel where it meets the beam line 1A T2 target. Both of these beam lines are outfitted with modern achromatic high transmission Wien filter/Spin Rotators which act to remove contaminants in the beam and to allow the muon spin to be rotated up to 90^0 as the beam traverses the device.

Additionally, both beam lines have ultra-fast electrostatic kickers, which enables a Muons on Request (MORE)

Beamline		Beam Characteristics				Flux	BeamSpot	MORE
		p(MeV/c)	Δp/p	Spin Rotation	Polarisation	$10^6 s^{-1}$	(h × w) cm^2	y/n
M15	µ+	29.5[a]	2-10%	18-90°	>98%	2	1.2 × 1.6	n
M9A	µ+	29.5[a]	2-10%[&]	~18-90° [&]	>98%	2[&]	1.5 × 1.5[&]	y
M9B	µ+	<70	11%	0°	>90%	+	10 × 10	n
	µ+	>70	11%	0 - 90°	70-90%	2 – 5	~7 × *	n
	µ-	30-80	11%	not measured	>90%	1.4	10 × 10	n
M20 C/D	µ+	29.5[a]	1-8%	10 - 90°	>98%	0.6	0.5 × 1.1	y

[a]lower momenta possible at cost of lower rate. [b]estimated

Table 1. Properties of muon beamlines at TRIUMF.

feature. This mode of operations ensures that one and only one muon is allowed into the sample by rapidly switching the electric field in the device after muon detection and thereby diverting the trajectory of any subsequent muon. Ensuring only a single muon has entered the sample allows one to reduce the random background to a level that permits the µSR measurement to extend much further out in time.

The dual channel M20 is designed to accept the kicked beam into the second leg to accommodate a simultaneous conventional µSR experiment.

The combined design capabilities of these beam lines, i.e., 90^0 spin rotation + MORE, will augment the muon facilities with additional unique capability. Delivery of the M20 kicker is expected in 2015.

Finally, the M9B beam line is the world's sole provider of spin-rotated high-momentum muons. This feature (i.e., spin rotation) is essential for high-magnetic field transverse field µSR, and the Helios spectrometer (see Table 2) has been used extensively on this beam line for such experiments. The M9B channel, fitted with a superconducting decay solenoid serviced by an ageing compressor and control system, will need to see those subsystems upgraded for reliable operations.

µSR Spectrometers

The CMMS array of µSR spectrometers provides a variety of experimental configurations, some of which are tailored to very specific requirements. As an example, the dilution refrigerator is an instrument designed to achieve very low temperatures (15 mK) at which the random thermal motion of the atoms and electrons is suppressed compared to higher-temperature environments.

For experiments in very high transverse magnetic fields (up to 7 Tesla or 70,000 Gauss), the HiTime spectrometer, with its 180 ps timing resolution, has dominated the experimental space for the last decade. The use of this spectrometer has heralded many breakthrough scientific results in the field of superconductivity, specifically the elusive underlying mechanisms of high-temperature superconductivity.

The CMMS Group has recently received a new ultra-high homogeneity 7 T magnet (called NuTime) to replace the venerable HiTime magnet, thus removing any barriers for high-field experiments. Finally, of note

Spectrometer	Characteristics	Experiment Types
Gas Cart	10 mT **y**, 1π counters, HH design	LTF, LLF
Omni'	0.25 T **z**, 20 mT **y**, 4π counters, HH design	LF, ZF high **p** muons
LAMPF	0.5 T **z**, .5 mT **x-y**, 4π counters, HH design	LF, TF, ZF, RF-µWave
HiTime	7 T **z**, 1π 180ps counters, SC solenoid 1.5-300K	TF, LF
Helios	7 T **z**, 1-2π counters, SC solenoid	LF, TF, ZF, RF-µWave + high **p** muons
DR	5 T **z**, 1-1.5π 300ps counters, HH design, 10mK-40K	LF, TF, ZF, LLF
SFUMU	0.5T **z**, 2π counters, HH design	TF, ZF + high **p** muons
M9a S-Omni*	3T **z**, 2π SiPm counters, SC solenoid with **z** and **x** cryostat entry.	LF, TF, ZF, LLF, RF-µWave

TF=Transverse Field; LF=Longitudinal Field; LLF=Low LF; ZF=Zero Field; RF=Radio Frequency; µWave= Microwave * in progress

Table 2. Properties of µSR specgrometers.

is the development of a superconducting general-purpose 3 T spectrometer (ultimately for the new M9A beam line), one based on silicon photomultipliers, that promises to be the most flexible and general-purpose µSR spectrometer in existence. Associated with the spectrometers is a significant array of supporting equipment including cryostats, temperature/flow/vacuum/magnetic field controllers, pressure cells, electric field devices, and highly specialized data acquisition electronics/computers.

Scientific Support

The facility extends scientific support to its user base in many ways, including: the setting up of an experiment; assisting users with the execution of their experiments, both technically (data acquisition) and scientifically (data analysis); supporting an active outreach program; and developing new research capabilities (i.e., advanced spectrometers and beam lines) so that cutting edge research continues to be available to the TRIUMF CMMS user community.

Recent Developments

Infrastructure

Two major CMMS infrastructure projects were completed from 2012–2014. The first is the commissioning and routine operation of the M20 beam line (without the kicker). Bringing this beam line back into operation allowed CMMS to better cope with the research demand, which, during the construction of M20 was met only by the M15 channel. The second project to come online is the CMMS/UCN liquefier system, which is now providing the facility with a secure, high-quality source of liquid helium (LHe).

The importance of this development cannot be over-emphasized as LHe is the life-blood of the CMMS and UCN facilities at a time when its world-wide commercial availability is in steep decline, and market prices are skyrocketing.

In addition, a first step to address the T2-M9 misalignment issue has recently been carried out, and the absolute misalignment successfully measured, thereby establishing the scope of the required repair effort.

Spectrometer Development

With the addition of NuTime and the R&D effort devoted to the 3 T spectrometer, the parameter space for successful experiments will continue to grow. It is important to mention that NSERC has actively renewed its confidence in the CMMS program at TRIUMF by extending its support to the facility for an additional five years, coinciding with the TRIUMF 2015–2020 Five-Year Plan.

3.5 EXPERIMENTAL FACILITY DEVELOPMENT

3.5.1 Detector Development and Support

F. Retière

The Science Technology Department was created in September 2014 by merging the Detector Group and Data Acquisition Group within TRIUMF's Science (now Physical Sciences) Division with the Electronics Development Group, which was previously in the Engineering Division. The department now includes the following groups: R&D; simulation and management; detector facility; detector electronics; electronics development; and data acquisition. The merger brought together all the expertise and capabilities needed to design and build complete solutions for particle and subatomic physics experiments. The department is also involved in the development of solutions for medical imaging and provides technical support to activities driven by Advanced Applied Physics Solution Inc. (AAPS)

Recently, the Electronics Development Group played a major role in the successful operation of a small-animal Positron Emission Tomography (PET) scanner that is operated concurrently with Magnetic Resonance Imaging (MRI) at the University of Manitoba (see Figures 1 and 2).

TRIUMF first joined the Canadian group developing an MRI-compatible micro-PET scanner in 2010 by contributing to the research and development of the Silicon photo-multipliers (SiPMs) used to detect the light emitted by scintillating crystals. SiPMs are ideally suited to the task because they are insensitive to magnetic field and are very sensitive to the blue light emitted by scintillating crystals. In 2013–2014, TRIUMF's contribution to development from PET shifted from SiPM R&D to providing analog and digital electronics for the SiPMs' readout. Figure 1 shows two iterations of one of the boards developed by the Electronics Development Group for the project. The project was a successful collaboration between the University of Manitoba, UBC, the Lawson Research Institute, McGill, and TRIUMF.

The development of SiPMs and their associated readout electronics are the main R&D projects of the Science Technology Department. The Detector Facility Group and Detector Electronics Group are involved in particular in the development of a new SiPM-based spectrometer for muon spin rotation. New electronics were developed to achieve world-leading timing resolution. In collaboration with TRIUMF's Molecular and Materials Science Group, the mechanical design was optimized for maximizing light collection. The design and prototyping effort was completed in 2015, allowing construction to start in 2016. The latest design is shown in Figure 3.

The core responsibility of the science technology department is the design and construction of detectors for subatomic physics experiments.

In 2013–2015 the detector facility group led the construction of the Parallel Grid Avalanche Counter (PGAC) and Ionization chamber (IC) for the EMMA (see Section 3.5.4) (see Figures 4 and 5). Commissioning of the PGAC was completed in 2014, and the IC is still being commissioned.

In 2013–2015, the Electronics Development Group and Data Acquisition (DAQ) Group were involved together in the DEAP and GRIFFIN projects. While very different in their physics scope, the DEAP dark matter search and GRIFFIN gamma ray spectroscopy facility shared some common requirements for readout electronics.

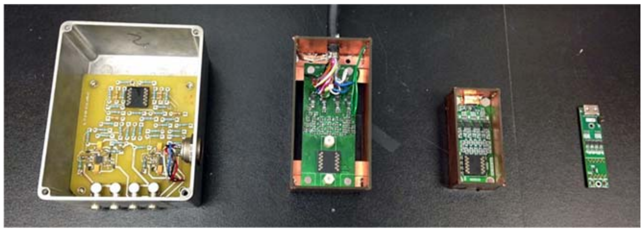


Figure 1. Detector module for the small animal PET insert for PET/MRI imaging. The first two modules on the left were designed at the University of Manitoba, while the modules on the right were designed and high miniaturized by TRIUMF Electronics Development Group.

Figure 2. Image of mouse head with the MRI on the left, the PET image on the right; and the fused image in the centre.

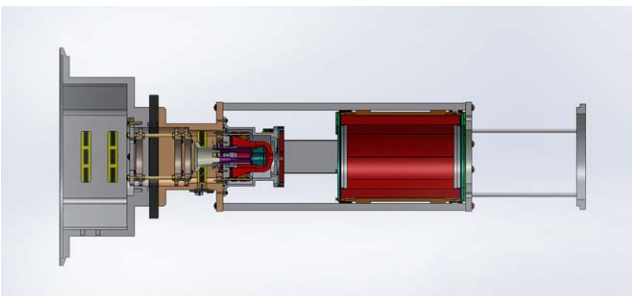


Figure 3. Side view of the 3 T spectrometer for muon spin rotation experiments. The positron counter is in red on the right-end side in its retracted position. The veto counter is the red bulbous shape in the centre. The muon counter is barely visible as a line embedded within the light blue volume in the centre.

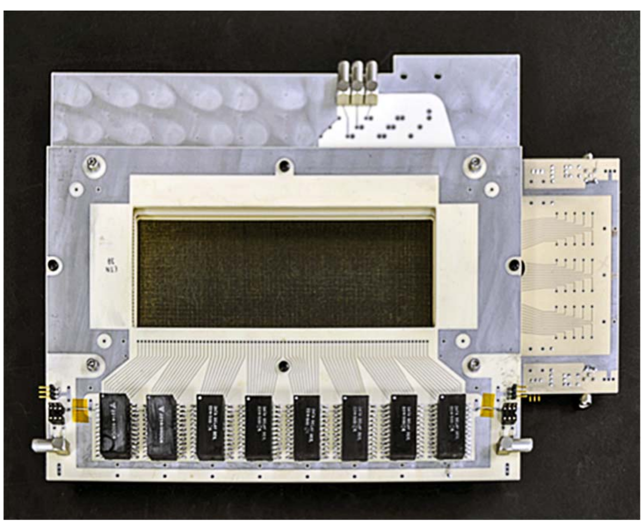


Figure 4. An assembled detector on the bench. The delay-line chips of the x-position.

The Electronics Development Group first produced a custom board, the Digitizer and Trigger Module for handling the DEAP trigger logic, which was then adapted for the GRIF-C boards that are used to gather and filter data coming from multiple digitizers in GRIFFIN. While DEAP used commercial 250 MS/s digitizers, new 100 MS/s digitizers were designed and built for GRIFFIN. The DAQ group provided data acquisition infrastructure for both facilities. GRIFFIN is now being used for radioactive ion beam experiments at ISAC, while DEAP is at SNOLAB awaiting a liquid argon target.

In addition to supporting major projects such as EMMA, GRIFFIN, and DEAP, the Science Technology department is a resource for the TRIUMF user community. It provides machining capabilities within the scintillator shop, supports the development of the simulation package GEANT4 and the data acquisition package MIDAS, and provides key expertise in detectors and electronics.

The Detector Facility Group continues to operate two large clean rooms for detector construction and provides laboratory space for detector testing. This group and the Data Acquisition Group also support the operation of the large-area photo-multiplier tube (PMT) testing facility that was constructed between 2013–2015 using CFI funds. This facility benefits the neutrino program, in particular the development of large-area PMTs for water Cerenkov detectors, as well as the dark-matter search program with the characterization of DEAP PMT.

From 2013–2015, the newly established Science Technology Department continued to provide key support at TRIUMF for detector development, construction, and operation. The new department organization has also allowed the realization of synergies between various groups, and will be critical for upcoming large projects, such as ALPHA, that require a wide variety of resources.

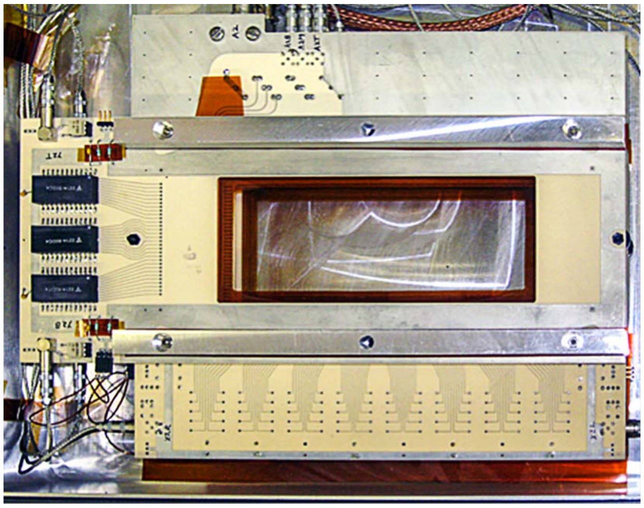


Figure 5. The test assembly installed in the PGAC box.

3.5.2. ATLAS Detector Development at TRIUMF

A. Canepa

Introduction and Schedule for ATLAS Upgrades

To fully exploit the discovery potential of the Large Hadron Collider (LHC) at CERN, the collider needs to be operated at higher luminosity. A significantly larger dataset will increase the discovery reach at the high-energy frontier and allow for more accurate measurements of the newly discovered Higgs boson and for the observation of rare processes. A staged upgrade of the machine is planned and referred to as the High-Luminosity LHC (HL-LHC). The upgrade will increase the instantaneous luminosity of the collider by a factor of 5–7.5 beyond the original design value and provide 3000 fb^{-1} of proton-proton collision data by 2035.

The ATLAS detector will undergo two major upgrades to adapt to the challenges of the accelerator and account for the detector aging. During Phase 1 (~2019/2020), the trigger system will be modified to cope with the increase of instantaneous luminosity. TRIUMF's contributions are described below in detail. During Phase 2 (starting in approximately 2024), the inner tracker of ATLAS, will be replaced in its entirety by a silicon-based detector. TRIUMF is planning significant contributions to the construction and commissioning of the tracker.

Liquid Argon Calorimeter Trigger Electronics Upgrades

The granularity of the ATLAS end-cap calorimeters greatly exceeds the corresponding granularity of the first-level trigger, where analog sums of the outputs of large "towers" of calorimeter cells hide shower shape information that could be used for online pattern recognition. By installing new digital electronics, it is possible to trigger based on so-called "super cells," allowing much better discrimination between electrons and hadrons and thus permitting electron trigger thresholds to be kept low enough to remain efficient for Higgs boson decays. ATLAS-Canada is designing, prototyping, and assembling the base plane that routes the signals from the Canadian-built hadronic endcap calorimeter (HEC) to the electronics boards as well as the analog part of the board that receives, digitizes, and re-transmits these signals to the first-level calorimeter trigger.

Muon End-Cap New Small Wheel Thin Gap Chambers

ATLAS-Canada is constructing 54 quadruplets of large high-resolution thin-gap chambers to allow the new "small" wheels of ATLAS to be used in the first-level trigger. This will reduce backgrounds not originating from the interaction point, and allow ATLAS to keep single-muon trigger thresholds low and remain efficient for events like Higgs boson decays.

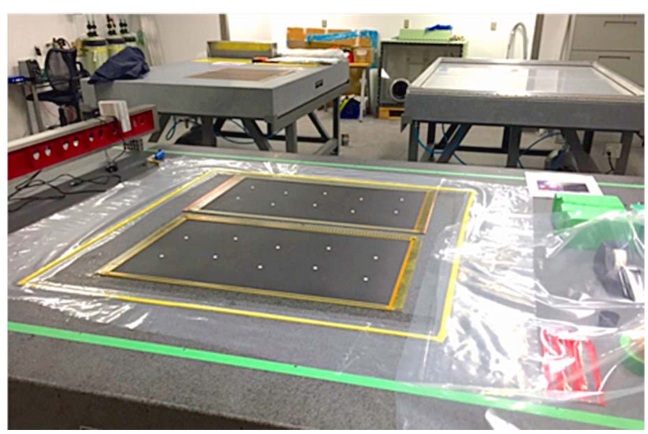


Figure 1. Sample cathode plane.

Figure 2. Paint booth.

A quadruplet comprises four gas gaps, each consisting of two resistive cathode planes (up to 2 m^2) sandwiching an anode plane of gold-plated tungsten wires. One cathode, with large read-out pads, allows for fast coincidence finding between layers. The other cathode, with narrow machined read-out strips, provides precision coordinates in regions of interest identified by pad coincidences. (See Figure 1.)

Cathode planes will be coated, polished, and assembled at TRIUMF. A conveyor-fed paint booth with a reciprocating shuttle has been installed in the ARIEL building (See Figure 2) to spray them with a thin graphite-based coating of uniform resistivity under uniform temperature and humidity conditions. The position of each strip must be known to within 30 µm in the precision coordinate and 80 µm along the beam.

On such large detectors, mechanical precision is key and must be controlled and monitored throughout construction. Four granite tables with vacuum systems have been installed in the ARIEL building for precision gluing and quality assurance of chamber frames and spacers. The large CNC router in the main cyclotron building is also used for quality assurance. Completed cathode planes are shipped to Carleton University for stringing and assembly, tested at McGill, and finally assembled into wedges, and then wheels, at CERN. Prototype chambers have been assembled and their performance has been evaluated in beam tests at Fermilab and CERN.

3.5.3. Auxiliary Detectors for TIGRESS

G. Hackman

The TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer, TIGRESS, is ideally suited for in-beam gamma-ray spectroscopy with weak (i.e., rare) accelerated beams and becomes far more powerful when coupled to auxiliary detectors that can select specific weak reaction events from terrestrial backgrounds [1]. There are, at present, five distinct auxiliary detector systems associated with TIGRESS: the Si-based ion detectors BAMBINO and SHARC, the DESCANT neutron detector array, the SPICE electron spectrometer, and the TIP plunger and CsI-based ion detectors. BAMBINO and the normal configuration of SHARC are very mature; no upgrades to either were needed during the reporting period 2013–2015. However, an informal collaboration between TIGRESS, IEM-CSIC Madrid, and Colorado School of Mines (CSM) used parts of the SHARC infrastructure in a unique configuration that was optimized for experiments with radioactive Be beams.

The remainder of this section will briefly discuss the DESCANT, SPICE, Madrid-CSM and TIP auxiliary detector systems and the progress on their integration into TIGRESS in the reporting period 2013–2015.

DEuterated SCintillator Array for Neutron Tagging (DESCANT)

The DESCANT neutron spectrometer detects neutrons from in-beam reactions or from beta-delayed decays. The detecting medium is a deuterated organic liquid scintillator, BC537. Unlike conventional hydrogen-based organic scintillators, the response of deuterated scintillators enables measurement of the neutron energy spectrum from pulse heights. The array consists of 70 liquid scintillator cells subtending 1.08π in a spherical geometry with an inner radius of 50 cm. DESCANT replaces four of the 16 TIGRESS high-purity germanium (HPGe) four-crystal clover detectors at a nominal angle of 45 degrees to the beam line. The fast pulse shapes from the photomultiplier tubes of these scintillators are digitized by 1-GHz waveform samplers.

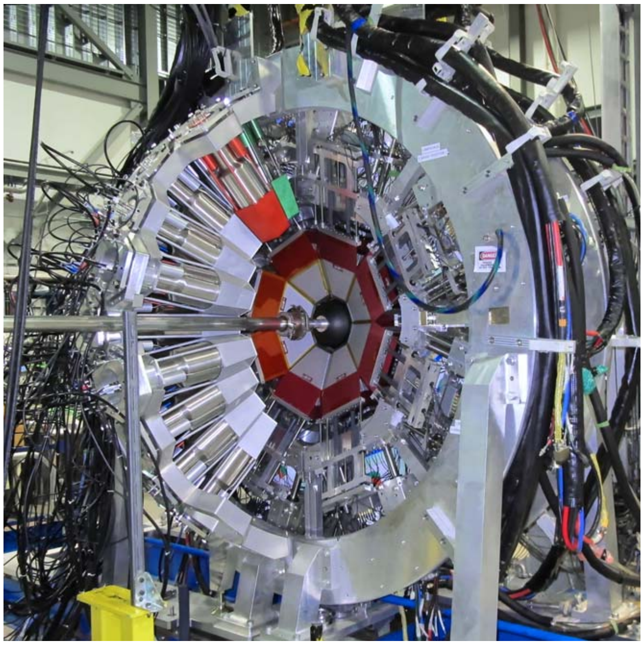


Figure 1. DESCANT and SPICE installed on TIGRESS for in-beam tests.

DESCANT construction was primarily a collaboration between the University of Guelph, responsible for detector geometrical design, procurement, testing and characterization [2]; Université de Montréal, responsible for the digitizers; and TRIUMF, responsible for mechanical design, fabrication, and integration.

The 70 detectors are mounted on two aluminum half-shells that were designed by TRIUMF and fabricated by Kaltech Manufacturing in Delta, BC. Guelph students assembled the detectors into the hemisphere. One half of DESCANT was fitted to TIGRESS for an in-beam test of the coupled system in late 2013, with an early version of the GRIFFIN triggerless readout system for a combined DESCANT and SPICE test run (see Figure 1). These tests showed that TIGRESS and DESCANT are mechanically compatible and that correlated events could be read out. Further work on the 1 GHz digitizers is ongoing. Since TIGRESS and GRIFFIN have largely similar structural design, DESCANT can work with either and will be deployed to each in response to user demand. In early 2015, DESCANT was moved to ISAC-I for a campaign with GRIFFIN.

Spectrometer for Internal Conversion Electrons (SPICE)

Electromagnetic transitions in nuclei can occur by coupling to and ejecting atomic electrons. Unlike gamma rays, electrons can couple to the E0 electric monopole moment, which has a correlated relationship to the change in radial charge density and wave function mixing between states. This additional nuclear structure information is key evidence for shape coexistence. In-beam electron spectroscopy, however, presents a number of challenges.

Large-area silicon detectors are well suited for high efficiency and high-energy resolution electron detection. However, these detectors are also sensitive to gamma rays and delta electrons (i.e., electrons scattered by heavy ions passing through a foil). One solution to these problems is to place the Si detector (in this case, a 128-segment lithium-drifted Si detector) upstream of the interaction location and shielded from direct illumination by gamma rays by a conical Heavimet absorber. This is the approach chosen with SPICE. Electrons of interest typically have energies in the range of 100 keV to 4 MeV, much larger than the typical delta electron energy (~20 keV), and are steered around the shield by an array of four permanent magnets.

In 2013, the permanent magnets' B-fields were mapped; the scattering vessel, including cryogenics, was fabricated; the Si(Li) detector was procured, received, and tested; and, preamplifiers were designed and built.

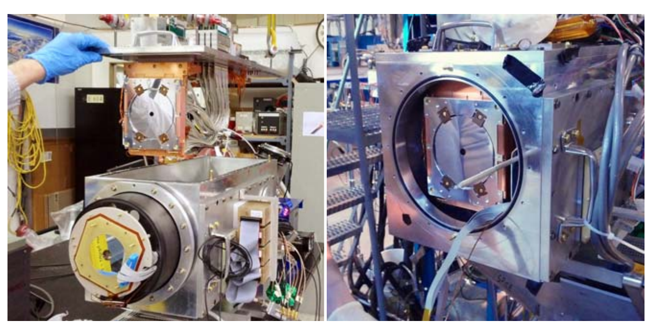


Figure 2. SPICE (left) being assembled in the detector lab, and installed on the TIGRESS beam line (right) in preparation for beam [6].

These tasks allowed SPICE to be assembled (see Figure 2) and installed on the TIGRESS beam line for two in-beam tests in late 2013 (see Figure 1) and early 2014. These commissioning tests led to a re-working of the vacuum and electronics systems in August 2015.

Madrid-CSM Silicon Array

Loosely bound exotic ions, such as ^{11,12}Be, challenge our basic understanding of nuclear physics. The structure of these nuclei is probed by a variety of reactions, including elastic, inelastic, and breakup experiments. TRIUMF-ISAC routinely delivers the most intense beams currently available at the right energies for these experiments. At the experimental end station, the challenge is to differentiate between these types of reactions; simply detecting the target-like reaction partner is inadequate to determine the final state of the beam-like Be nucleus. Breakup reactions can be identified with the aid of dE-E telescopes, while inelastic excitation to bound states can be tagged by the prompt emission of a gamma ray in coincidence.

A clever means of assembling arrays of dE-E silicon telescopes for these experiments has been developed by a group from Madrid. Once the kinematic angular coverage requirements of the experiment are specified, a printed circuit motherboard is designed with connectors for Si telescopes and detectors at the appropriate locations. The motherboard in turn connects to a grandmother board, and signals are taken from that board to vacuum feedthroughs and to preamplifiers. Such a setup has been successfully used for an investigation of the Coulomb scattering of ^{11}Li [3] where telescopes are needed to confirm that the scattered particle is indeed ^{11}Li and not ^{9}Li from the two-neutron breakup channel.

For ^{11}Be, a further complication is inelastic scattering exciting the 320 keV state. Si detectors do not have adequate energy resolution to distinguish this state from particle kinematics. However, TIGRESS is very well suited for detecting the gamma ray emitted following this inelastic process. This led the Madrid, CSM and TIGRESS groups to work together to adapt a SHARC flange to accommodate the Madrid motherboard concept, feedthroughs, and preamplifiers (see Figure 3).

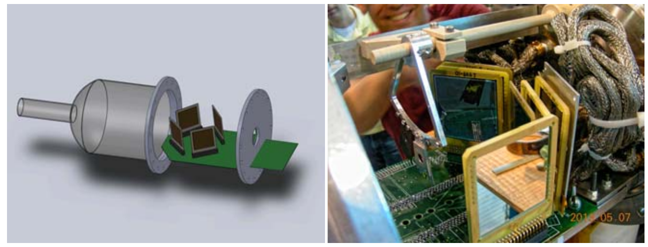


Figure 3. Engineering model of Madrid-CSM Si telescope array (left), S1202 design, shown mounted to SHARC back-flange [3,7]. S1297 configuration ready to insert into the SHARC chamber (right).

The first pair of experiments, “Exploring Halo Effects in the Scattering of ^{11}Be on Heavy Targets” and “Investigating halo states with the ^{11}Be(p,d)^{10}Be* transfer reaction at 10 MeV per nucleon,” led by Madrid and S1297, led by CSM, both used ^{11}Be beams but at different energies and scattering off different targets (Au-Pb and CD_2, respectively) and, as such, had very different kinematics. Both experiments ran in a single month on a single ISAC production target with motherboard reconfiguration between experiments. This detector concept has subsequently used for S1429 (CSM) with a ^{12}Be beam. All datasets are being analyzed by Ph.D. students at the lead institutions. The results from S1202 have been widely reported in conferences [3,4] with both a thesis and paper to be completed by the end of 2015.

TIGRESS Integrated Plunger (TIP)

Electromagnetic transition rates can reveal the nature and magnitude of collectivity in nuclei. These transition rates can be as low as femtoseconds and as long as years, so a wide variety of experimental techniques are needed to measure them. Lifetimes shorter than about 100 ps are beyond the capabilities of electronic techniques, and Doppler shifts are used instead.

The TIP apparatus consists of a plunger and a 3π-coverage CsI charged particle array [5]. There were two test beam times in 2013 and 2014 focused primarily on development of the charged particle array, namely a highly segmented annular detector, an array of inexpensive PIN diodes, and prototype CsI elements. Each of these detectors has its own relative merits and applications. The annular detector provides excellent scattered particle angular resolution and very good energy resolution; however, it is expensive, and sensitive to damage from the heavy ions. The PIN diodes are a cost-effective alternative with comparable energy resolution, although at lower angular resolution. CsI has poorer energy resolution but superior resistance to radiation damage. CsI's light curve exhibits two exponential components, the relative amplitude of which is sensitive to the Z of the detected charge particle.

All three charged particle detectors have been tested in-beam and performed as expected. For these tests, fusion-evaporation reactions producing both protons and alpha particles were used. Waveforms were captured for the CsI, and in offline analysis, the traces were fit to dual exponential curves. Particle identification by this technique was successfully demonstrated, as was reaction channel selection following particle ID (see Figure 4).

With the charged-particle detection part of TIP well in hand, development of a full spherical CsI ball will go ahead. Contemporaneously, experiments with the plunger and the existing charged-particle sub-arrays will take place. The full CsI ball should be ready for experiments in 2017. The TIP project is led by Simon Fraser University, which is responsible for scattering chamber fabrication, detector and plunger bench testing, and foil fabrication. TRIUMF's role has been the mechanical design of the device, instrumenting an evaporation chamber for target fabrication, and integration of TIP into the TIGRESS mechanical and instrumentation infrastructure.

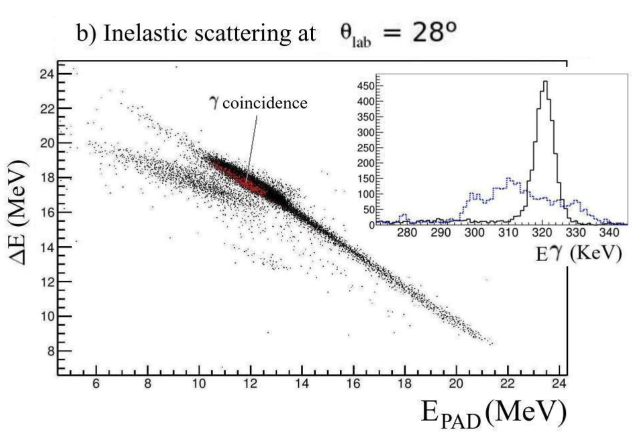


Figure 4. Typical particle-ID scatter plot and gamma-ray spectrum from S1202. The upper and lower diagonal branches correspond to ^{11}Be and ^{10}Be respectively. Red dots are from events in coincidence with the 320 keV gamma ray and fall on the same part of the ID plot as the ^{11}Be as expected. Inset is the gamma-ray spectrum before and after correction for Doppler broadening [4].

[1] V. Bildstein et al., Nucl. Inst. Meth. Phys. Res. A 729, 188-197 (2013)

[2] P. Garrett, TRIUMF Scientific Activities Report 2010-2102 , 62 (2012)

[3] V. Pesudo et al., Acta Physica Plonica B 45, 375-382 (2014)

[4] O. Tengblad, "Nuclear Structure of light Halo Nuclei determined from Scattering on heavy targets at ISAC-I," Nuclear Structure 2014 (unpublished; available at https://indico.triumf.ca/getFile.py/access?contribId=48&resId=0&materialId=slides&confId=1748).

[5] Voss, P. et al. "Digital rise-time discrimination of pulses from the TIGRESS Integrated Plunger silicon PIN diode wall," 23rd Conference on Application of Accelerators in Research And Industry, CAARI 2014

3.5.4 EMMA

B. Davids

An electromagnetic mass analyser, EMMA, is being constructed for use with the radioactive heavy-ion beams available from the ISAC-II accelerator at TRIUMF. EMMA is a recoil mass spectrometer designed to separate the products of nuclear reactions from the beam and to disperse them in a focal plane according to their mass-to-charge ratio (m/q). Focal plane detector measurements of position, energy loss, residual energy, and time-of-flight are expected to uniquely identify the transmitted reaction products. In addition to having a large angular acceptance, approximately corresponding to a cone of opening angle 7.4°, the spectrometer will accept recoils within a large range of m/q (±4%) and energies (±20%) about the central values, resulting in high detection efficiencies.

Large Electromagnetic Components

A contract to build the two electric dipoles, dipole magnet, and four quadrupole magnets of EMMA was awarded to Bruker BioSpin. The five magnets were delivered to TRIUMF in 2012 and installed on the EMMA platform in the ISAC-II experimental hall (see Figure 1).

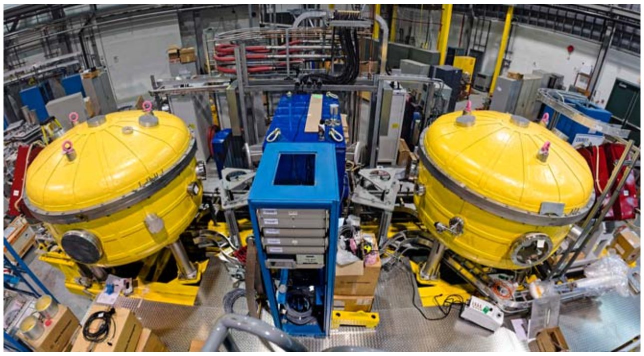


Figure 1. Photograph of EMMA in the ISAC-II experimental hall taken in April 2015.

In October 2014 the DC cables between the magnets and their power supplies were connected and the AC wiring and plumbing for water cooling was completed. High-voltage testing and subsequent inspection of the electric dipoles in the Karlsruhe Facility of Bruker BioSpin revealed design and manufacturing flaws that required substantial remediation efforts. The electric dipole components were delivered to TRIUMF in 2013 but 10 of the 16 ceramic insulating supports, designed to hold the solid titanium electrodes in place and maintain an electric potential difference exceeding 500 kV between them, were found to be cracked or broken. These insulating supports were redesigned at TRIUMF to be 20% stronger. In March 2015 the new ceramic insulating supports arrived at TRIUMF. Load testing performed after their arrival showed that they can support static loads 100% greater than will be required in EMMA without significant deflection.

Focal Plane Detectors

The parallel grid avalanche counter (PGAC), which will be the first detector intercepting recoils in the initial EMMA focal plane configuration, was tested at TRIUMF in April 2014 and again in April 2015 along with a spare. In the first test an 18 MeV ^{16}O beam impinged on a 250 µe cm^{-2} Au foil; elastic scattering was observed at lab angles between 25.5 and 33.0 degrees. This test was aimed at determining the optimal electric potential difference between the PGAC anode and cathode for isobutane pressures between 2 and 6 Torr. Timing resolution of 0.7 ns FWHM was demonstrated in this measurement.

The second test used the same experimental arrangement with a 24 MeV ^{22}Ne beam and was carried out with a mask in front of the detectors to determine the position resolution as a function of count rate and position within each detector.

Conclusion

Final polishing and cleaning of the electric dipole components is underway to prepare them for high voltage tests in summer 2016. A transmission and stopping ionization chamber is now being developed by the TRIUMF Detector Group while the TRIUMF machine shop is fabricating the target and focal plane vacuum boxes. All the components are expected to be ready in time to permit complete assembly of the spectrometer in 2016.

3.5.5 GRIFFIN

A. Garnsworthy

During the first half of 2014, the 8π spectrometer in ISAC-I was decommissioned and the new GRIFFIN facility for decay spectroscopy was installed. The new facility was commissioned in September 2014 and immediately began scientific operation.

Gamma-Ray Infrastructure for Fundamental Investigations of Nuclei (GRIFFIN) is a major new spectrometer that will significantly expand the radioactive decay spectroscopy capabilities at ISAC-I and ARIEL. Radioactive decay spectroscopy, using GRIFFIN, with the intense radioactive beams produced by ISAC, will allow detailed investigations of the evolution of nuclear structure with unprecedented sensitivity.
With the addition of ARIEL, the measurement of nuclear half-lives and the properties of excited states of nuclei at and beyond the astrophysical r-process path will be within our reach. GRIFFIN consists of an array of 16 hyper-pure germanium (HPGe) clover detectors (with 4 Ge crystals in a single cryostat resembling a four-leaf clover) coupled to a state-of-the-art digital data acquisition system and replaces the 8π facility that served

ISAC for over a decade. The gamma-gamma coincidence sensitivity for 1 MeV gamma rays with GRIFFIN is a factor of 300 greater than that of the 8π.

The GRIFFIN HPGe detectors are used to detect gamma rays emitted in the decay of excited nuclear states. The gamma rays carry information on the underlying behaviour of the protons and neutrons in the nucleus. GRIFFIN will make use of all the ancillary detection systems that were developed for use with the 8π. Combinations of sub-systems enable the investigation of all aspects of radioactive decay. These include the SCEPTAR array of plastic scintillators to detect beta particles, the set of 8 lanthanum bromide scintillators for measuring the lifetimes of excited nuclear states in daughter nuclei, the five cryogenically cooled lithium-drifted silicon counters of PACES to detect internal conversion electrons emitted in an alternative process to gamma-ray emission, and the DESCANT array of neutron detectors to investigate beta-delayed neutron emission of very neutron-rich nuclei.

The project was awarded $8.7M in funding through the Canadian Foundation for Innovation (CFI), TRIUMF and the University of Guelph over fiscal years 2011–2014. All 16 HPGe clover detectors passed initial acceptance testing performed by collaborators at Simon Fraser University. The GRIFFIN support structure was designed by the TRIUMF design office and fabricated in the machine shops of TRIUMF, the University of Guelph, and external companies in FY2012 and 2013. This support structure, low-energy beam line, and electronics shack were installed into the low-energy area of ISAC-I during 2014. The digital data acquisition system, including state-of-the-art new digitizer modules, was developed in a collaboration between the Université de Montréal, the TRIUMF Electronics Development Group and Data Acquisition Group.

The facility was commissioned in September 2014 and performed four initial experiments in the fall of that year. In 2015 the DESCANT array is being coupled to GRIFFIN to enable beta-delayed neutron emission studies. The data from these experiments is essential for understanding the neutron-rich nuclei that are involved in the astrophysical rapid-neutron capture process responsible for the creation of the heavy elements in the universe.

3.5.6 TITAN Cooler Trap

J. Dilling

As ISAC pushes the limits of radioactive nuclide production further from stability, and as ARIEL comes on line to push further still, the challenges of working with nuclides of ever decreasing lifetimes must be addressed. The precision possible in a Penning trap mass measurement is directly related to the amount of time the isotopes of interest can be excited inside the precision Penning trap. Longer radio frequency (RF) excitation times T_{RF} yield higher precision measurements. Based on this, Penning trap mass spectroscopy at TITAN [1], is limited to first order by the lifetime of the isotope being measured. This can be overcome by working with highly charged ions (HCIs) via charge breeding in an Electron Beam Ion Trap (EBIT) [2]. By decreasing the mass-to-charge ratio (M/q) of an ion, gains in precision can be made by virtue of that ion's larger cyclotron frequency in a magnetic field. However, the charge breeding process increases the energy spread of the ions to the level of several tens of eV/q. Ideally, an energy spread on the order of 1 eV/q is desirable for a precision mass measurement in a Penning trap.

In order to cool the energetic, charge-bred, short-lived isotopes, a Cooler Penning Trap (CPET) [2] has been built. CPET (see Figure 1) was designed and built specifically to cool highly charged ions from the EBIT down to the single eV/q range. CPET will cool ions using a trapped room-temperature plasma of electrons or protons as the cooling medium. The

Figure 1. Photo of the TITAN cooler Penning trap system installed on the TITAN platform.

HCIs will co-habitat with the plasma and will be sympathetically cooled via the Coulomb interaction before being sent to TITAN's precision Penning trap for mass measurements.

Beginning in 2013, the trap electrodes were cleaned, assembled and installed in alignment with the magnetic field of CPET's 7 Tesla superconducting magnet. In order to improve the vacuum inside the trap to UHV levels (10^{-10} torr or lower), which will help preserve the charge state of the ions trapped in CPET, a means of baking the trap in situ was developed. The vacuum tube was coated with a non-evaporable getter material that activates when heated. The outside of the tube was covered in a thermal blanket and the entire structure was placed inside the magnet [4].

CPET is currently undergoing offline commissioning. In the first phase, electrons will be used as the cooling medium because of their ease of production and their ability to self-cool because of synchrotron radiation in the 7-Tesla magnetic field. A self-cooling plasma in the trap will allow CPET to cool and eject multiple HCI bunches before the time must it would take to accumulate more electrons for the cooling plasma. Simulations that investigated the feasibility of cooling with protons indicated that multiple bunches of protons would need to be captured to properly cool a single bunch of HCIs [5].

Initially, detection of the trapped electrons was hindered by the fringe field of CPET's solenoid, which steered electrons away from the central beam axis as the magnetic field diverged.
This was overcome by developing a detector system based on a phosphor screen placed deep inside the magnetic field where the electron beam is sufficiently well collimated (see Figure 2).

By doing this, the time evolution and self-cooling of the so-called m=1 diocotron plasma mode was observed [6]. It was also possible, for the first time, to quantify the number of trapped electrons, which has been measured and shown to be between 10^9 and 10^{10}. This number and the corresponding electron density are well within the range of what simulations indicated is required for effective and fast cooling [5].

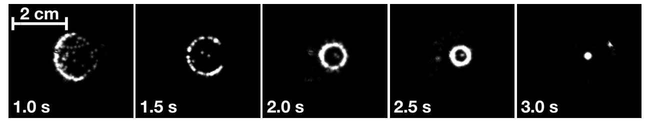


Figure 2. Time-evolved sequence of the extracted electron cloud from the CPET, recorded on the external phosphor screen. The radius decreases, indicating the cooling of the electrons in the radial direction and, hence, a reduction in overall spatial extent.

To advance further, the phosphor screen inside CPET, which prevents the introduction of ions into the trap, must be replaced with something that allows for beam transport. A wire mesh that can act as a detector will be put into CPET at roughly the same position as the phosphor screen now occupies. The mesh can be biased to drift tube potential and become essentially transparent to incoming charged particles, or it can be grounded and act as an anode on which to read the charge deposited. In this way, it is possible to detect electrons before the beam is steered away from the longitudinal axis by the diverging magnetic field.

Current developments include a detection scheme for electrons that allows unobstructed beam transport. After that, a trapping scheme will be implemented that will trap both electrons and ions so that cooling can be confirmed. For this, an ion source has already been constructed and awaits the installation and verification of the new mesh detector. After successful cooling with an electron plasma is observed, CPET can be incorporated into the existing TITAN beam line where it will assist in making mass measurements of highly charged radioactive isotopes.

[1] J. Dilling et al., Nucl. Inst. & Meth. B204, 492 (2003).
[2] J. Dilling et al., Int. J. Mass Spectrom. 251, 198 (2006).
[3] V. Simon et al., Hyper. Int. 227, 239 (2014).
[4] B. Schultz et al., Phys. Scr. T156, 014097 (2013).
[5] Z. Ke et al., Hyper. Int. 173, 103 (2007).
[6] U. Chowdhury et al., Proc. XII EBIST. 120, 120 (2015).

3.5.7 Toward atomic parity violation measurements with laser-trapped francium atoms

G. Gwinner

Physics with cold francium atoms at ISAC

Physics with laser-cooled and trapped francium, with an emphasis on tests of fundamental symmetries, is one of the motivations for the actinide target program at TRIUMF's ISAC radioactive beam facility. The ultimate goal is to search for "new physics" beyond the Standard Model of particle physics and to study the weak interaction between nucleons inside the nucleus by observing a tiny violation of mirror-symmetry in atomic transitions, known as atomic parity violation, in heavy atoms where these effects are particularly pronounced [1]. As the heaviest alkali element, francium possesses the required, simple, atomic structure needed to extract the weak interaction physics from the experimental data. It is, however, the least stable of the first 103 elements; its longest-lived isotope has a half-life of only 22 min. ISAC provides intense (up to 10^8/sec) beams of francium ions and is one of the very few facilities in the world capable of supporting francium research.

After the francium trapping facility was established in 2011–12, the first atomic and nuclear physics experiments were carried out, analyzed, and published as part of the commissioning efforts. Francium isotopes delivered by ISAC are slowed, cooled, and trapped in magneto-optical traps (MOT). Millions of atoms are suspended in a volume of less than 1 mm^3 for tens of seconds at µK temperatures, in the centre of an ultrahigh vacuum chamber with precisely controlled electric and magnetic fields [2]. This environment is ideally suited for atomic-spectroscopy-based investigations of fundamental symmetries because it provides unprecedented control over the atoms' internal and external degrees of freedom. During this commissioning period, the facility was used to measure very precisely the isotope shifts and hyperfine anomalies in a chain of francium isotopes and the photoionization rate of the $7p_{3/2}$ state.

Measurement of the $7s$–$7p_{1/2}$ (D1) isotope shift in $^{206m,206–213,221}Fr$

Combining our data with existing $7s \rightarrow 7p_{3/2}$ (D2) data, a King plot analysis was carried out and the difference between specific mass shift constants of these two transitions was determined, testing state-of-the-art ab initio calculations. This is a sensitive gauge of the ability of the atomic many-body calculation to describe the francium atom at a level necessary for the interpretation of future atomic parity violation measurements [3].

Measurement of the $7p_{1/2}$ hyperfine splittings in a chain of Fr isotopes

The ratio of the hyperfine splittings of s and p states is not constant across isotopes because the finite and isotope-dependent distribution of nuclear magnetization. This phenomenon is known as the hyperfine anomaly or the Bohr-Weisskopf effect. By carrying out measurements of the hyperfine splitting of the excited electronic $7p_{1/2}$ state at the 100 ppm level and comparing those to previously known ground state 7s splittings, it was possible to determine experimentally the hyperfine anomaly in $^{206m,206,207,209,213,221}Fr$. In concurrence with the known magnetic moments, the magnetic distributions were found to behave quite regularly from closed-shell N=126 ^{213}Fr through ^{207}Fr, while ^{206}Fr stops behaving like a spherical nucleus with valence nucleons [4]. This will be valuable input for calculations of both the anapole moments and the neutron radii needed for small corrections to atomic parity violation measurements for $^{207–213}Fr$.

Photoionization of the francium $7p_{3/2}$ state

The non-resonant photoionization cross-section of the $7p_{3/2}$ state of francium for 442 nm light was determined. Francium atoms were irradiated in the MOT with the photoionizing light, and the resulting change in trap lifetime was measured to deduce the ionization rate [5]. The result, consistent with a simple extrapolation of known cross-sections for lighter alkali elements, is of importance for future atomic parity violation measurements: The 506 nm light used to observe the parity violation effect will reduce the number of atoms in the MOT due to its photoionizing effect. Its intensity has to be carefully balanced to avoid trap losses while still producing the biggest possible parity violation signal.

Transfer of cold francium atoms between magneto-optical traps

A primary MOT, or capture trap, is interfaced directly to the ISAC francium beam line and is optimized to capture incoming francium as efficiently as possible into the trap. As a result, the environment in the capture chamber in terms of radioactive backgrounds, vacuum pressure, control of electric, magnetic stray fields, and optical/microwave access is far from ideal. To carry out high-precision experiments such as atomic parity violation measurements, the atoms have to be transferred to a secondary, or science chamber where another MOT receives the atoms and recaptures them. This chamber has now been commissioned and atom transfer demonstrated with a high efficiency of ≈50 %.

Outlook

The basic francium trapping facility was successfully commissioned with several physics experiments. Starting in 2016, the focus will shift to carrying out optical spectroscopy of the 7s – 8s highly forbidden transition towards an optical atomic parity violation measurement, and microwave spectroscopy within the ground-state hyperfine manifold with the goal of observing the parity-violating anapole moment in francium.

[1] J.A. Behr and G. Gwinner, J. Phys. G 36, 033101 (2009).

[2] M. Tandecki et al., J. Inst 8, 12006P (2013).

[3] R. Collister et al., Phys. Rev. A, 90, 052502 (2014). Including erratum Phys. Rev. A, 92, 019902 (2015).

[4] J. Zhang et al., Phys. Rev. Lett. 115, 042501 (2015).

[5] R. Collister et al., Photoionization of the francium $7P_{3/2}$ state, manuscript to be submitted.

3.5.8 ISAC Implantation Station

P. Kunz and C. Ruiz

The ISAC Implantation Station (IIS) is an extension of the ISAC beam line system for the collection of long-lived isotopes on solid-backed or thin-foil targets for offline experiments. It contains ion optics for focussing and fast-rastering the ion beam on a target. A Faraday cup, and user-definable read-outs to the ISAC-EPICS control system for beam current monitoring, are available.

Isotopes for Nuclear Astrophysics Experiments

Many experiments for nuclear astrophysics require access to long-lived radionuclides in implanted form. These are usually experiments performed at other stable beam accelerator laboratories where reaction studies using post-accelerated radioactive beams in inverse kinematics are precluded. In addition, long-lived radionuclides are required for experiments at neutron beam facilities. Experiments can include direct measurements of nuclear reactions on long-lived nuclei or spectroscopic studies with transfer and charge exchange reactions such as (^{3}He,d) or (^{3}He,t).

The precursor to the IIS, the ISAC Collection Station, was used to implant a target of radioactive ^{22}Na ($t_{1/2}$=2.6 years) of high activity, roughly 300 µCi. This was successfully used in a direct measurement of ^{22}Na(p,γ)^{23}Mg at the Center for Experimental Nuclear Physics & Astrophysics in Seattle [1,2]. In 2011, a test ^{26}Al target was fabricated, containing 5 x 10^{14} atoms implanted at shallow depth in a 40 mg/cm^2 diamond-like carbon (DLC) foil (see Figure 1); this year, that test target was used in a spectrometer (^{3}He,d) and (^{3}He,t)

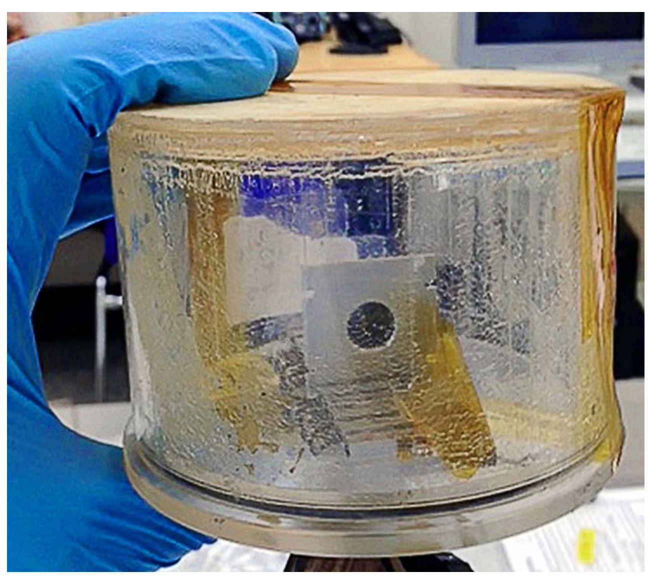


Figure 1. DLC foil implanted with 5×10^{14} atoms of ^{26}Al at the ISAC Implantation Station (IIS)

reaction study at the Institute for Nuclear Physics in Orsay, France, to determine experimental backgrounds. Future experiments, aimed at indirectly determining the stellar $^{26g}Al(p,\gamma)^{27}Si$ and $^{25}Al(p,\gamma)^{26}Si$ reaction rates, will require a target with more than 10 times the number of ^{26}Al atoms. Such a target is scheduled to be fabricated at the IIS in June 2015.

Yield Measurements of Very Long-lived Isotopes

The beam intensities for most isotopes delivered to experiments at ISAC are determined by α, β, and γ spectroscopy with the ISAC Yield Station (see section 3.3.3). For isotopes with very long half-lives (i.e. low activities), the detection efficiency of the yield station is not sufficient to perform reliable yield measurements within a reasonable amount of time. In 2013, an ion beam at mass unit 239 from a uranium carbide target was implanted for several hours at the IIS. An activity of 14 mBq was identified offline by low-level α spectroscopy measurements as ^{239}Pu, corresponding to a yield of $1{\times}10^7$ ions/s [3]. ^{239}Pu has a half-life of 24,110 years and is produced from ^{238}U solely via neutron-capture reactions. These results, in conjunction with theoretical models, will help to obtain a better understanding of the neutron flux in uranium targets.

Isotopes for Nuclear Medicine

The science of cancer research is currently expanding its use of α-particle emitting radioisotopes, typically with half-lives in the range of hours or several days. Within the past two years, nuclear medicine research projects have been initiated to use the ISAC facility for isotope production in quantities adequate to drive medical applications, in particular the isotopes $^{209,211}At$, $^{223,224,225}Ra$, ^{225}Ac, $^{212,213}Bi$, ^{212}Pb and ^{149}Tb.

As a first step in the development of these isotopes, implantations of ^{213}Fr, which decays rapidly into ^{209}At, have been performed. The ^{209}At activity has been successfully used in SPECT imaging experiments (see section 2.9). A compact sample collection vessel has been developed for such implantations (see Figure 1). The radioactive ion beam is implanted

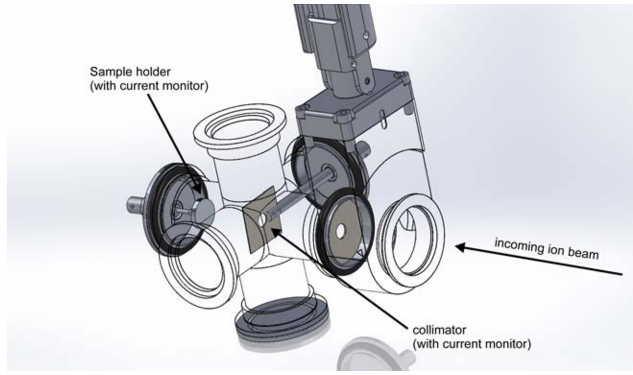


Figure 2. Collection vessel for alpha emitting isotopes.

on a sample holder in the back of a small vacuum chamber. Simultaneously, the beam current is monitored on the holder and a central collimator. A gate valve allows the vessel to be detached from the beam line while keeping it under vacuum during transport to the nuclear chemistry laboratory. There, the vessel can be placed in a hot cell or fume hood where the sample can be extracted for further processing.

[1] A. L. Sallaska et al., Phys. Rev. Lett. 105 (2010) 152501
[2] A.L. Sallaska et al., Phys. Rev. C 83 (2011) 034611
[3] P. Kunz, ISAC Yield Database, http://mis.triumf.ca/science/planning/yield/beam

3.5.9 IRIS

G. Hackman

The ISAC charged particle spectroscopy station, IRIS, investigates the structure of rare isotopes for understanding how new features emerge far from stability and to find how the new structural information guides our understanding of nucleosynthesis. This is accomplished through the measurement of elastic scattering, inelastic scattering and nucleon transfer reactions using solid H_2 and D_2 as reaction targets. [1]

The main unique feature of IRIS is its solid hydrogen and deuterium targets. A thin, 5 um Ag foil is mounted on a cold finger, which is itself thermally pumped by a commercial cryocooler. This brings the foil down to a low enough tempature to freeze hydrogen or deuterium. The gas is sprayed onto the foil by a diffuser in vacuum and under vacuum. In this way, solid hydrogen targets up to approximately 0.5 mm thick can be formed on the foil.

A second novel feature of IRIS is a low-pressure ionization chamber (IC). Exotic beams often are inseparable from less exotic isobaric contaminants or, in the case of CSB beams, A/q analogues. For the IRIS program it is necessary to identify the Z of the incoming ion. A dE type measurement of the incoming particle will do that. At re-accelerated beam facilities like ISAC, the challenge is that such measurements will reduce the incident beam energy and, worse, introduce scattering that broadens both the angular distribution and the energy resolution of the incoming particles. Low-pressure gas counters are the only reasonable solution; however, they need windows. The IRIS IC is designed to use SiN foils as windows. It also uses a coplanar anode configuration where transverse segmentation of the anode plane effectively acts as a Frisch grid, making the design very compact and simple (no grid wires).

Light target-like charged particles are detected with dE-E telescopes consisting of double-sided segmented Si wafers backed by CsI(Tl) crystals. Heavy projectile-like ions are detected downstream with CD-style annular Si detectors. All electronics are conventional, that is, no fast waveform capture; COTS pulse shapers, discriminators, and peak-sensing ADCs are used.

IRIS was commissioned with stable beam in December, 2012 and began its science program in the summer of 2013. From 2013–2015, four separate experiments: S1147, S1203, S1338, and S1483 all collected data with ISAC-II RIB. One of these beam times led to a PRL on the isoscalar character of the pygmy dipole resonance in the halo nucleus ^{11}Li, showing that essentially the ^{9}Li core oscillates back and forth within the two-neutron halo. [2]

[1] R. Kanungo, Hyperfine Interactions 225 235-240 (2014)
[2] R. Kanungo et al., Phys. Rev. Lett. 114, 192502 (2015)

3.5.10 The Ultracold Neutron Facility at TRIUMF

R. Picker

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

In the years 2014–2016, TRIUMF installed a new beam line and spallation target in its Meson Hall. This new infrastructure forms the basis for the UCN facility that seeks to discover an electric dipole moment (EDM) of the neutron. The project is only possible through the close collaboration of TRIUMF with a number of university partners in Canada and in Japan as well as in Canadian industry.

The UCN source

To produce ultra-cold neutrons, a primary proton beam from the TRIUMF main cyclotron is delivered to a tungsten target, releasing spallation neutrons. These are subsequently moderated by solid and liquid moderators at room temperature and a solid heavy water moderator at 10 K. This creates an intense cold neutron source in which a superfluid ^{4}He convertor is placed. Via downscattering on phonons and rotons in the superfluid helium, the meV-scale neutrons are slowed down to a few meters per second and a few hundred neV to become ultracold.

The new proton beam line (BL1U), dedicated for the UCN source was finished during the shutdown 2016. The primary transport elements in BL1U include: a fast kicker magnet and a Lambertson-style septum magnet, which enables simultaneous operation of BL1U and the main Meson hall beamline BL1A; and a

Figure 1. Completed beam line 1U before installing radiation shielding, April 2016.

dipole magnet, followed by two quadrupole magnets which transports the proton beam to the tungsten spallation target. Interspersed between the kicker magnet at the front, and the spallation target at the end of BL1U, are several correction magnets, many beam diagnostic monitors, and several safety-related devices. Since the 500 MeV proton beam is stopped in the spallation target, radiation shielding necessarily constitutes a very large component of BL1U, both in cost and floor space.

Installation of BL1U has been scheduled to take place over 3 years (2014–2016): the 2014 shutdown work saw the completion of the middle section of BL1U, with the installation of the septum and dipole magnets, and all associated monitors and devices in this region. It also saw the uncovering of the shielding blocks in the southwest corner of the meson hall, for the first time in over 40 years. This was needed to install hardware and reconfigure the shielding between the vault and the meson hall. In 2015, the shutdown work saw the decommissioning of the existing M13 beam line, the installation of the front (vault) and downstream sections of BL1U, and the installation of lower layers of the radiation shielding around the UCN target (see Figure 1). During the 2016 shutdown the spallation target, including its remote handling system were installed along with the kicker magnet to complete the new beam line 1U. Placement of the moderators as well as the 10 K solid heavy ice cryostat developed, constructed and tested by our collaborators at RCNP, Osaka concluded the shutdown. During fall 2016, commissioning of the BL1U, especially the kicker magnet and the heavy water cryostat will be conducted, creating the first ever cold neutron source at TRIUMF. First experiments include thermal and cold neutron flux measurements using neutron activation foils. A three-stage helium cryostat to cool the isopure ^{4}He down to 0.7 K, also developed in Japan, will complete the UCN source and enable first ultracold neutron production using a spallation target on Canadian soil in 2017. First experiments towards measuring the electric dipole moment of the neutron can commence right after. In time, a second UCN beam port will also be opened to external experimental proposals to facilitate a rich scientific program with ultra-cold neutrons.

3.5.11 Photosensor Test Facility

A. Konaka and H.A. Tanaka

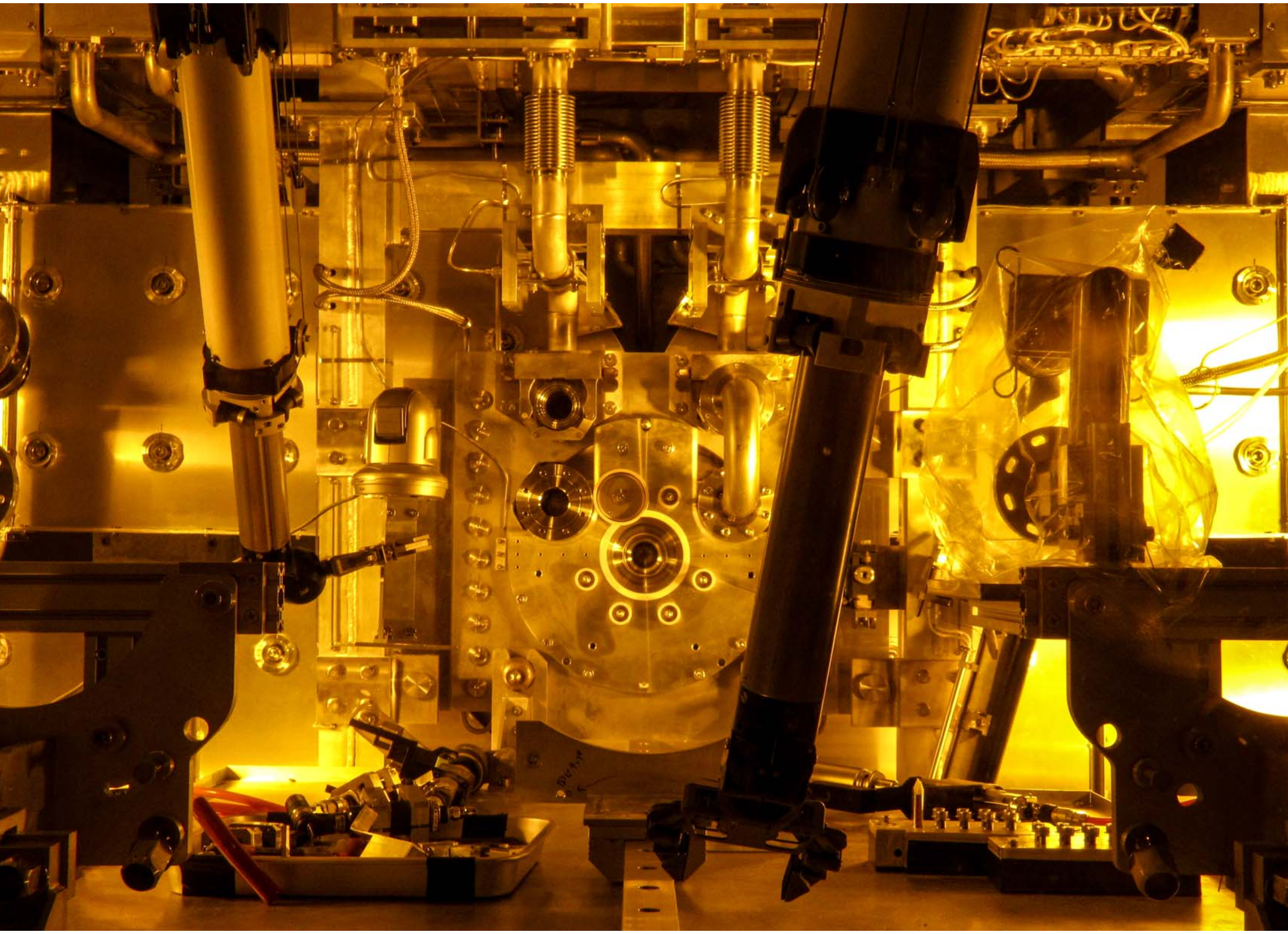
The Photosensor Test Facility (PTF) is used to measure and characterize the performance of the large-area photosensors that play a critical role in large neutrino detectors like the one used at Super-Kamiokande in the T2K experiment. The PTF allows the variation of the photosensor performance with the properties of the incident light (wavelength and polarization), and its trajectory (angle of incidence and position on the photosensor) will be studied in detail. These detailed measurements can be incorporated into detector simulations, increasing their accuracy and reliability and lead to more sensitive studies of neutrinos.

The facility was brought to completion over the period of 2013–2015. Helmholtz coils and magnetic shielding materials were installed to reduce the

Figure 1.1 Left: magnetic shielding system for PTF.
Figure 1.2 Right: water circulation and filtration system.

ambient magnetic field (see Figure 1.1 and Figure 1.2). The MIDAS-based data acquisition and control system was continuously developed, leading to complete functionality of the manipulator arms with feedback and monitoring. Laser tracking surveys of the photosensor were made in order to allow fully automated scans across the photosensor face. Initial measurements of a new 8” hybrid photosensor prototype, and the 20” photomultiplier used in the Super-Kamiokande detector, were performed in air. Concurrently, a water circulation and filtration system was built and commissioned and installed into the PTF. This allowed for photosensor measurements in water, thereby reproducing the optical environment in which they are typically used at Super-Kamiokande.

The collaboration plans to embark on a complete study of the 20” photomultiplier used in Super-Kamiokande and incorporate the measurements into the detector simulation. In the meantime, the collaboration will test new photosensors associated with R&D for the Hyper-Kamiokande experiment, including new “box and line” photomultipliers and hybrid photosensor prototypes.



3.6 NUCLEAR MEDICINE INFRASTRUCTURE

3.6.1 TR13 Performance

C. Hoehr

The TR13 is the smallest cyclotron at TRIUMF, accelerating H^- ions to 13 MeV. It is located in the Meson Hall Extension and produces isotopes that are primarily used for the production of medical isotope tracers. The main programs supported are the Pacific Parkinson's Research Centre (PPRC) and the BC Cancer Agency (BBCA).

Description of Facility

Between July 2013 and March 2015, the TR13 Operations Group delivered 13,207 µA-hrs in 1,555 separate runs. The following isotopes were produced:

Isotope	delivered runs 2013-2014
^{13}N	64
^{11}C	1205
^{94m}Tc	3
^{68}Ga	36
^{18}F	304
^{61}Cu	5
^{44}Sc	39
^{86}Y	11
^{55}Co	2
^{192}Ir	8
^{89}Zr	23
Development	182

Table 1. Isotopes produced by the TR13 cyclotron for 2013–2014.

^{13}N, ^{18}F (as the F^- ion and the F_2 molecule), ^{11}C (as CH_4 and CO_2), ^{94m}Tc, ^{44}Sc, ^{89}Zr, ^{192}Ir, ^{61}Cu, ^{86}Y, and ^{68}Ga (see Table 1). Currently, there are eight targets mounted at two target stations, three water targets, four gas targets and one solid target. The TR13 cyclotron provides backup for BCCA in the event that their cyclotron has to undergo maintenance or repair.

Ninety-two runs between July 2013 and March 2015 were lost due to problems with the cyclotron, resulting in a reliability of 94.4% (see Figure 1). A major RF failure occurred in January 2015. One of the RF dee structures in the cyclotron vacuum tank developed a water leak. This failure was diagnosed and repaired and the cyclotron put back into operation in only one month through the combined cyclotron expertise available.

Recent Developments

A total of 7.2 % of all runs were development runs to improve existing targets or to investigate new targets or isotopes. Four undergraduate students and one visiting graduate student from Italy were trained, and two graduate students are currently being trained in medical cyclotron targetry. A beam profile monitor has been developed to measure the proton beam profile in real time [1,2]. Several new targets were tested and commissioned for production of radiometals, with increased yields of up to a factor of five [3-9]. A new target with a built-in fan has been tested to improve the production of ^{11}C, with a yield increase of up to 40% [10]. The thermodynamic behaviour of gases and liquids in targets has been investigated experimentally and with a mathematical model [11] and the yield of isotopes produced at the TR13 cyclotron (see Figure 2) has been modelled with the Monte-Carlo code FLUKA [12,13]. Work on new target models and development will continue with the promise of higher yields and new isotopes available for the local community.

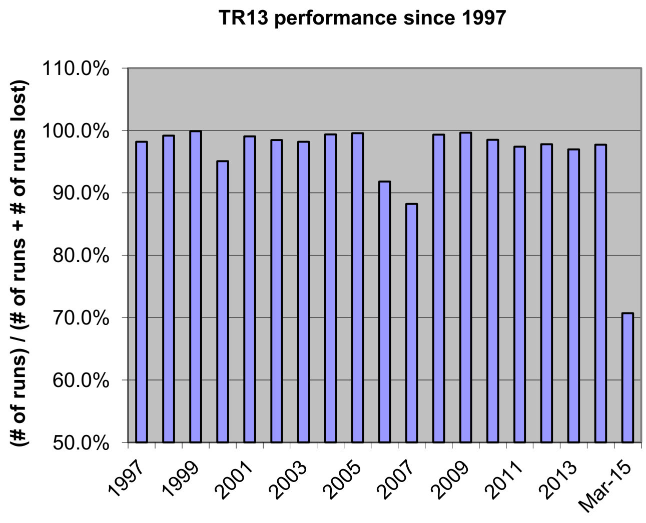


Figure 1. Reliability of the TR13 cyclotron since 1997.

[1] C. Hendriks et al., Rev. Sci. Instr. 84, 113305 (2013)
[2] C. Hoehr et al., WTTC15, Conference Proceeding, submitted
[3] E. Oehlke et al., Production of Y-86 and other radiometals for research purposes using a solution target system, submitted
[4] C. Hoehr et al., Production of radiometals in a liquid target, WTTC15 Conference Proceeding, submitted
[5] C. Hoehr et al., Nucl. Med. Bio. 41, 401 (2014)
[6] G. Dias et al., J. Nucl. Med. 55 Suppl. 1, 609 (2014)
[7] E. Oehlke et al., J. Nucl. Med. 55 Suppl. 1, 215 (2014)
[8] C. Hoehr et al., J. of Nucl. Med. 54 Suppl., 1096 (2013)
[9] C. Hoehr et al., Appl. Radiat. Isot. 70, 2308 (2012)
[10] T. Uittenbosch et al., WTTC15 Conference Proceeding, submitted
[11] P. Jahangiri et al., WTTC15 Conference Proceeding, submitted
[12] E. Infantiono et al., WTTC15 Conference Proceeding, submitted
[13] A. Infantino et al., WTTC15 Conference Proceeding, submitted

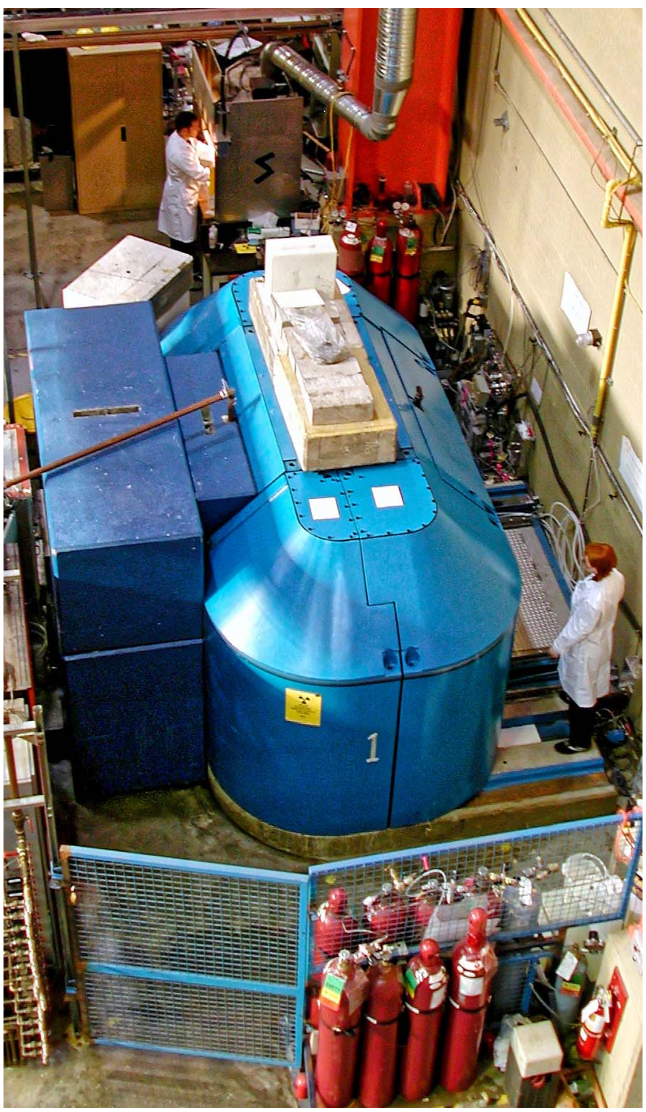


Figure 2. A photograph of the TR13 cyclotron.

3.6.2 Good Manufacturing Practices Laboratory (GMP)

Recently, a Good Manufacturing Practices Laboratory (GMP) containing three new hot cells for the production of radiopharmaceuticals for human use, was completed in the lower level of the Chemistry Annex at TRIUMF and is now fully commissioned. The research focus for this area, in combination with TRIUMF's partners at UBC, produce PET radiopharmaceuticals for use in Parkinson's and Alzheimer's research.

This lab is designed with a clean air room area surrounding the hot cells so that the production of radiopharmaceuticals can be prepared in a controlled air environment. The hot cells also have air filtration that increases the clean-room level inside the cells where the processes are carried out. The laboratory is equipped with surfaces that can easily be cleaned and sterilized. It also has an area outside of the clean room for quality control analysis and shipping. This laboratory also has restricted access. Currently, nine of the twelve C-11 tracers are being made in this lab with the other three to follow soon. F-18 FDOPA and EF5 will also be moved into this lab within the next year. These are agents currently being used in the Pacific Parkinson's Research Centre's research program and by the BC Cancer Agency. Standard operating procedures and other documents are being prepared that will bring this lab into full GMP) compliance.

3.7 SCIENTIFIC COMPUTING

S. MCDONALD

The TRIUMF computing and networking groups continue to evolve to address the challenges of the TRIUMF science and engineering programs. In the last two years there have been significant achievements: the core routing and firewalling infrastructure has been replaced; a reliable and scalable server and storage virtualization environment has been established; custom applications have been developed to meet TRIUMF reporting requirements; and the TRIUMF ATLAS Tier-1 Computing Centre has doubled its processor and storage resources.

3.7.1 Computing and Networking Infrastructure

TRIUMF's external network requirements are constantly challenged. The upgrade of the LHC to a higher luminosity will pose new challenges for the transfer of data between CERN and TRIUMF. In addition, there has been a significant increase in the utilization of the network to BCNET and Compute Canada facilities. To meet these challenges, TRIUMF has both increased its network capacity and improved the reliability of its connections to these organizations. The dedicated 5 Gbps connection to CERN for the TRIUMF ATLAS Tier 1 Centre has been increased to 10 Gbps. The network capacity to the LHC Open Network Exchange has been doubled to 20 Gbps (over two separate 10 Gbps links). Internally the TRIUMF Tier-1 Data Centre has been doubled to 40 Gbps. Furthermore, the two 10 Gbps links to LHCONE act as redundant links for the 10 Gbps connection to BCNET. All of this was made possible by the recent upgrade of the TRIUMF network core under an RFP awarded to Juniper Networks in 2012. Deployment began in 2013 and was completed in late 2014. The new network core has been designed to meet TRIUMF's requirements for the next 7–10 years. It will support 100 GbE links, a requirement of the TRIUMF ATLAS Tier-1 Centre by 2016–17. In addition to the upgrade to the network core the original 802.11a/b/g (~20 Mbps) wireless network was replaced with a modern 802.11ac wireless network from Aruba Networks. The new wireless network with its increase capacity (300-800 Mbps) and 802.1x security is a welcome improvement on the original wireless network installed in 2003. The number of access points has been doubled to 100, providing extended coverage both to indoor and outdoor areas of the TRIUMF site. In addition to the networking upgrades,

The CCN (Core Computing and Networking) group has established a reliable and scalable environment for the virtualization of servers and storage.

This has permitted CCN to operate a flexible and reliable data centre with minimal staffing and infrastructure. The environment is based on Red Hat Enterprise Virtualization (RHEV) and the Nextenta and Dell Equalogic storage virtualization.

In 2013, the underlying infrastructure was moved to blade-based hardware, reducing further the resources required for space, cooling, and management. In 2014, a fourth virtual host was added along with an additional 40 TB of Dell Equalogic storage capacity. In addition to the enhancements of the hardware infrastructure, the CCN Group continues to perform a critical role providing expertise and advice on a wide range of IT issues that assist the laboratory staff and research scientists.

The MIS (Management Information Systems) Group is responsible for the development of custom applications to meet TRIUMF's unique environment as well as the ERP (Enterprise Resource Planning) suite of applications for the day-to-day financial and administrative operation of the laboratory. The group continues to work with the financial, procurement, and project management departments to deploy new ERP software, ABW (Agresso Business World). This is a modern ERP solution that will meet TRIUMF long-term needs in flexibility, reporting, support, and maintainability.

In addition, the group has released new and enhanced applications unique to TRIUMF's operational requirements. Of note are: a suite of science applications for managing the beam schedule and experimental programs at TRIUMF; a new Work Request System for engineering projects; and a new dosimetry application for recording and tracking staff dose history. A new reporting tool for NCR's (Non-conformance Reporting), with ties into the Work-Request System, is in the process of being released. This year, work has begun on extending the TRIUMF identity management system to improve the handling of research scientists, contractors, and students visiting and working at TRIUMF.

3.7.2 ATLAS TIER 1

The overall ATLAS scientific program requires a large amount of disk storage and computing capacities at the global scale. The computing resources are a vital component of the research program and instrumental in making breakthrough discoveries. Since 2011, all of ATLAS-Canada's computing activities have been led and coordinated by a TRIUMF staff scientist.

The discovery of a Higgs boson in 2012 would not have been possible without the Worldwide LHC Computing Grid (WLCG) infrastructure. In particular, the ATLAS Canadian Tier 1 Centre (ATLAS Tier-1 Centre) at TRIUMF played an instrumental role and provided crucial extra computational resources and storage capacity that facilitated the discovery. In 2013 and 2014, the primary focus shifted into better understanding the newly discovered particle. Several measurements of its properties were made, further confirming the compatibility with the Standard Model Higgs boson (leading to a Nobel Prize in physics), while, in parallel, extensive searches for physics beyond the Standard Model were ongoing with several constraints and limits established. These accomplishments would not have been possible without the large-scale computing resources now available worldwide and, in particular, in Canada, including the data processing, analysis, and simulation campaigns conducted at the dedicated TRIUMF Tier-1 Centre and at the Compute Canada shared Tier-2 facilities.

The ATLAS Tier-1 Centre availability was kept above 99% with smooth daily operations and with ongoing demand from ATLAS-distributed computing activities. Regarding the overall Grid production (simulation and data processing), physics groups and user analysis tasks that were assigned to the Tier-1 centres worldwide, TRIUMF contributed close to 12%.

In the summer and fall of 2014, an initial phase of hardware and technology refreshment to replace systems that were purchased in 2007 and 2009 using a CFI LEF award. The tape storage capacity was also expanded by 3.3 Petabytes. Presently, the Tier-1 centre capacity consists of 7.8 Petabytes of usable disk storage, 8.8 Petabytes of tape storage, 4,830 processor cores, and close to 90 servers. Various upgrades to the network were also performed, and the wide area network capacity was brought to 40 Gbps, including a capacity increase in 2015 on the TRIUMF-CERN link from 5 to 10 Gbps.

ARIEL–ADVANCED RARE-ISOTOPE LABORATORY

4

4

ARIEL–ADVANCED RARE-ISOTOPE LABORATORY

4.1 INTRODUCTION AND SCIENCE MOTIVATION

In September 2014, TRIUMF completed the first stage of the construction of the Advanced Rare Isotope Laboratory (ARIEL), with the goal to significantly expand TRIUMF's Rare Isotope Beam (RIB) program for Nuclear Physics and Astrophysics, Nuclear Medicine, and Molecular and Materials Science.

Rare isotopes are powerful tools for scientific discovery, such as determining the structure and dynamics of atomic nuclei, understanding the processes by which heavy elements in the Universe were created, and enabling precision tests of fundamental symmetries that may challenge the Standard Model of particle physics. Rare isotopes or "radioisotopes" are also foundational for modern medical imaging techniques like PET and SPECT, and useful for therapeutic purposes, such as the treatment of cancer tumours. They can also serve as unique probes to characterize magnetic and electronic properties at surfaces and interfaces between materials.

At its heart, the full ARIEL project consists of a 500 kW, 50 MeV electron accelerator for isotope production via photo-production and photo-fission as well as a second proton beam line from TRIUMF's 500 MeV cyclotron for isotope production via proton-induced spallation and fission.

The ARIEL scientific program will be implemented in stages beginning with ^{8}Li photo-production for materials science. This stage will be followed by the implementation of the production of neutron-rich fission fragments through photo-fission of uranium with more than 10^{13} fissions per second in the final implementation. Photo-fission will enable the study of the very neutron-rich nuclei involved in the astrophysical r-process responsible for the production of the heavy elements from iron to uranium in supernova explosions or the merger of neutron stars. The new proton beam line (BL4N) will deliver up to 100 microAmp beam onto an additional production target. In conjunction with the e-linac production target TRIUMF will go from the current single ISAC RIB production target to the parallel production of RIBs on three target stations. This new and unique multi-user capability will allow for a much better exploitation of the available forefront experimental facilities at ISAC. Aside from the tremendous gain in available time for the materials science program, other experimental programs that need large amounts of beam time will be enabled by the multi-user capability of ARIEL. In addition, capabilities for the harvesting of medical elements will be implemented.

This first stage of the ARIEL project, which was funded through the Canada Foundation for Innovation and the BC Knowledge and Development Fund and spearheaded by the University of Victoria, comprised the civil construction for the full ARIEL project as well as the development of the new superconducting electron accelerator (e-linac) (see Figure 1).

The subsequent sections will describe the completion of the ARIEL building as well as details on the e-linac accelerator development, construction, and commissioning.

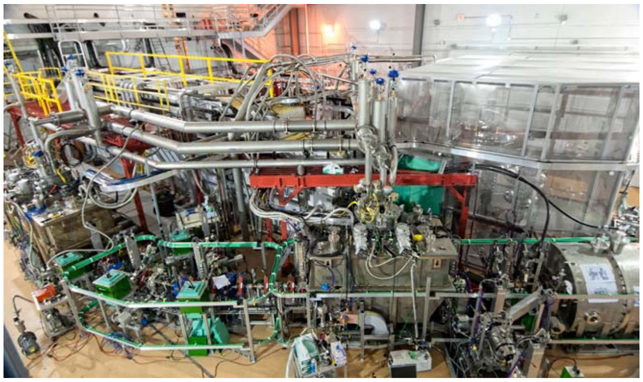


Figure 1. ARIEL electron linear accelerator complex.

4.2 ARIEL CIVIL CONSTRUCTION

R. DAWSON

In June 2010, the Province of British Columbia provided the University of Victoria with $30.7M through the British Columbia Knowledge Development Fund for ARIEL civil construction at TRIUMF. Chernoff-Thompson Architects led the overall architecture and engineering contract, which was awarded in October 2010. The schematic design report was received on March 4, 2011, and the design development report was received on July 4, 2011.

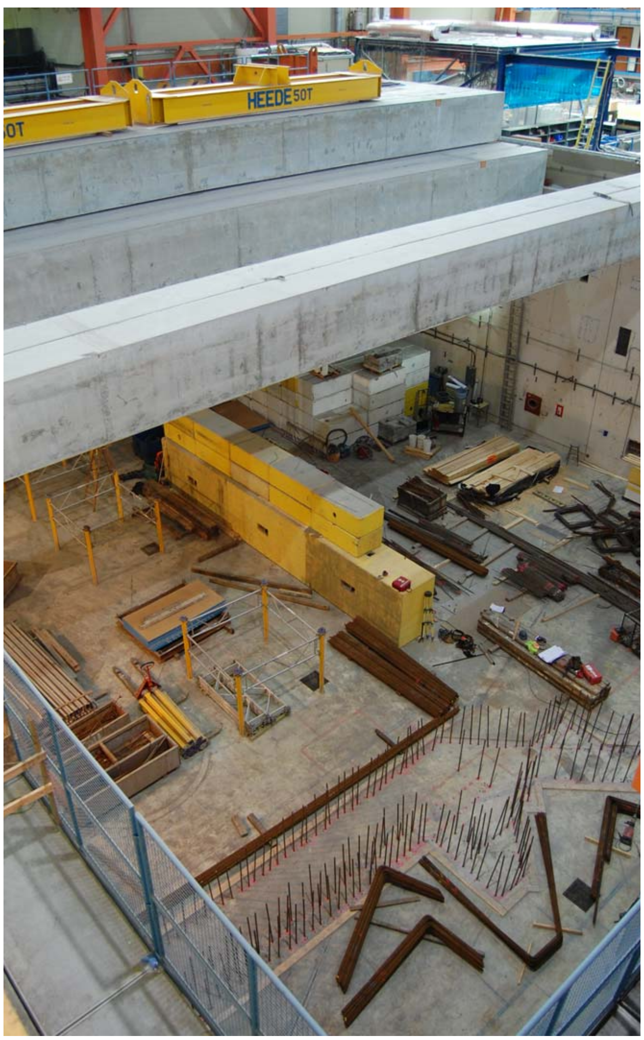


Figure 2. Electron linac hall during rehabilitation

The construction plan consisted of four main components: the demolition of the old Stores building and excavation of the ARIEL building sited; construction of the new Stores building; construction of the new Badge room; and construction of the ARIEL infrastructure, including the main building, the new Helium Compressor Building, and major renovations to transform the former Proton Hall to the new Electron Hall (see Figure 2).

The demolition and excavation contract was awarded and work started on October 17, 2011 and was substantially completed by April 2012. The completion target date of January 20, 2012 was delayed due to unforeseen ground water and soil conditions as well as a water main failure. Construction for the new Stores building and Badge room were completed in 2011. Work on the new Stores building started March 28, 2011 and occupancy was achieved on schedule on September 23, 2011. Construction on the new Badge room started August 3, 2011 and was completed slightly behind scheduled completion on December 10, 2011, primarily because of equipment delivery and coordination logistics (see Figures 3 and 4).

Figure 3. Helium compressor building and storage tank

The construction tender for construction of ARIEL was issued December 14, 2011 and awarded February 9, 2012. The ARIEL main construction contract included work in the Electron Hall, the Helium Compressor Building, and ARIEL building. Both the Electron Hall and the Helium Compressor Building were completed in late 2012. The ARIEL building was substantially completed on September 25, 2013.

In April 2013, the work of engineering consultants Stantee Consulting Ltd. (mechanical), Applied Engineering Solutions Ltd. (electrical), and Bush, Bohman & Partners Ltd. (structural) was recognized with the 2013 Engineering Excellence Award of Merit by the Association of Consulting Engineering Companies of British Columbia. In October 24, at the Vancouver Regional Construction Association's 26th annual Awards of Excellence gala, Ellis Don Corp took home the general contractor award for $15 million to $55 million projects for its work as primary contractor for the ARIEL building project.

Figure 4. New Stores building

4.3 ACCELERATORS AND BEAM LINES

S. KOSCIELNIAK

4.3.1 Introduction

On September 30, 2014, the Advanced Rare IsotopE Laboratory project (ARIEL-I) was complete, and a 23 MeV electron beam was delivered to the EABD beam stop. The second phase, ARIEL-II, will add target stations, mass separators and RIB beam Lines to deliver rare isotopes to the existing ISAC-II experimental facility. The e-linac science infrastructure and all components were funded by the Canadian Foundation for Innovation (CFI). As a contributing development, the electron gun and low-energy beam test stand were prototyped in the ISAC-II building under a collaboration with Variable Energy Cyclotron (VECC) of Kolkata, India.

Gamma-ray induced fission, using copious photons produced from a primary electron beam, is an invented-in-Canada mechanism for RIB production

that is complementary to proton-induced spallation, with the advantages of niche neutron-rich species and lower isobaric contamination. An order of magnitude higher RIB production requires a 50 MeV, 10 mA electron driver beam. Electron beams are easy to produce and are relativistic above 1 MeV, which confers the advantage of compact, constant frequency accelerating structures. L-band (≈ 1GHz) SRF technology has been pursued by the high-energy physics community as an enabling technology for a TeV-scale linear collider since the 1980s and is now considered “mature” for transfer to industry. Efficient operation of these cavities requires immersion in a 2K bath of liquid helium. Niobium SRF cavities have advantages over normal-conducting copper cavities of continuous rather than pulsed operation and much reduced operating costs. The e-linac provides an opportunity for TRIUMF to master this SRF technology and transfer the fabrication know-how to the local Richmond-based company PAVAC Industries Inc.

4.3.2 E-Hall Rehabilitation

The former proton hall was emptied of obsolete science equipment in 2012. Subsequently, the space was taken over by Ellis Don for the pouring of concrete: very massive shielding for BL4N to north, and massive shielding to south to support ERL operation (see Figure 2, p. 108) Occupancy of the e-hall was taken in February 2013 and equipment installations began at that time, starting with the LHe dewar and ALAT cold box.

4.3.3 Accelerators and Beam Lines

The mast head achievements from 2012–14 were: (i) development of two niobium 9-cell elliptical-type cavities both meeting the design specification of bare quality factor Q=10^10 at an accelerating gradient of 10 MV/m; (ii) acceptance testing of two 1.3 GHz c.w. klystrons to 270 kW each; (iii) acceptance testing of the 4K cryogenic plant beyond the design specification 800 W cooling power at 4.6K and maximum liquefaction rate of 380 l/h; (iv) construction of the e-linac beamlines; (v) integration of all e-linac systems; and (vi) delivery of the 23 MeV electron beam. Progress that led to these achievements is detailed below.

4.3.4 Electron Gun

The electron gun (e-gun) provides up to 10 mA of 300 keV kinetic energy electron beam. The main components are an in-air HV power supply, the gridded thermionic gun electrically isolated in an SF6 filled vessel, and an RF modulation feedthrough. Unique features of the gun are its inverted cathode/anode geometry to reduce dark current, and transmission of the RF modulation through a dielectric (ceramic) waveguide.

The gun interfaces to the waveguide through a shroud and corona domes inside the SF6 tank. The gun cathode, anode and ceramic stand-off were assembled May, 2013. The waveguide, shroud and corona domes were assembled to the gun in September. All e-gun components were installed at the VECC test stand, and the 300keV 10 mA beam demonstrated December 2013. The entire e-gun was moved to the e-hall April 2014 (see Figure 2). The SF6 gas management system will be added in 2015.

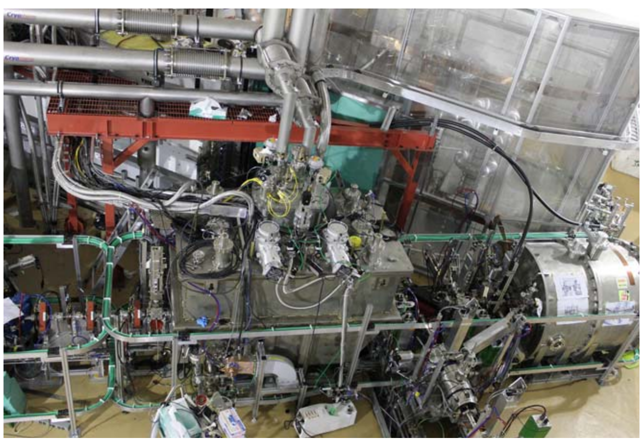


Figure 2. The electron gun and injector cryomodule

4.3.5 (VECC) Injector Test Stand

The purpose of the VECC test stand, initiated 2009, was to jump start the e-linac development activity in advance of the CFI funding. The 2010–12 bi-annual report records the use of a 100 keV prototype gun and testing of beam diagnostic devices, particularly the Allison scanner for transverse emittance measurements, in a low-energy beam transport (ELBT). There is also a momentum analysis stub (ELBD). Subsequently, the buncher RF cavity (in ELBT) and the transverse deflecting cavity (in ELBD) were used to reconstruct the longitudinal phase space in November 2012. This information is useful for matching into the acceptance of the first cell of the injector cryomodule. After the 300 keV gun was installed, many of the beam diagnostic measurements were repeated December, 2013 through January 2014 and more sophisticated algorithms developed for quantifying the strength of optics elements based on beam measurements.

4.3.6 Cryomodules Design

The ARIEL-I e-linac has two cryomodules: the injector cryomodule (EINJ) contains a single 9-cell cavity, and the accelerator cryomodule (EACA) contains two 9-cell cavities; together they can accelerate a beam to 30 MeV. The future ARIEL-II project will add a second accelerator cryomodule (EACB), bringing the beam energy to 50 MeV.

The cyromodules follow a common design that utiliz-esa box-type evacuated cryostat with a top-loading cold mass. To produce 2K helium liquid, a 4K phase separator, 4K/2K heat exchanger, and Joule-Thomson valve are installed in each module. The cold mass is suspended from the lid by mounting posts, struts, and strong back, and is surrounded by a LN2-cooled copper box for thermal isolation. A warm mu-metal shield is fastened to the inside of the vacuum vessel. The cold mass consists of cavity hermetic units, a cold mu metal layer and tuner for each cavity. The tuner cold part is the Jefferson-laboratory scissor type; driven by a long actuator and warm ISAC-II style rotary servo motor mounted on the lid. The hermetic unit includes the cavities, RF power couplers cold parts, rf pick-ups, the warm-cold transitions with higher order mode (HOM) damping material, and warm isolation valves. A silicon carbide material, CESIC, was chosen for the damping material. Tunable coaxial RF couplers of the Cornell design are adopted, and each is capable of transferring 50 kW; the coupler warm parts pass through the cryostat and shields. The coupler cold parts are cooled by 4K intercepts.

4.3.7 SRF Cavity Resonators

A program of single-cell Nb cavity fabrication, surface treatment (buffer chemical polish and high-pressure water rinsing), and cavity quality factor (Q) and accelerating gradient measurements culminated in Q=10^10 at 15 MV/m at 2K in August 2012.

The nine-cell 1.3 GHz elliptical cavity (see Figure 3) borrows the TESLA/ILC type inner cell geometry

but uses modified end groups to accommodate the large power couplers and to mitigate HOMs. A multi-pass beam breakup criterion establishes a limit of $R/Q^*Q_L < 10^7$ Ohm.

Development of multi-cell cavity fabrication techniques began with a 7-cell copper cavity (completed in February 2012), and continued with the first 9-cell Nb cavity delivered by PAVAC in May 2013. The cavity was subsequently etched at TRIUMF, cold tested in August, heat treated at FNAL for hydrogen contamination , and acceptance tested in November 2013; and then sent to PAVAC for cavity jacketing. The first of two EACA 9-cell Nb cavities was cold tested in October 2013, sent to FNAL for degassing, had its second cold test and etch, and after jacketing at PAVAC, was received in May 2014.

4.3.8 Injector Cryomodule

The injector cryomodule (EINJ) raises the beam energy to 10 MeV. The modest accelerating gradient, 10 MeV/m, accommodates the heavy beam loading of the cavity which must transfer up to 100 kW c.w. power to the electron beam. Under the terms of the collaboration agreement, TRIUMF and VECC both contributed engineering resources to the design of the EINJ. By November 2012,

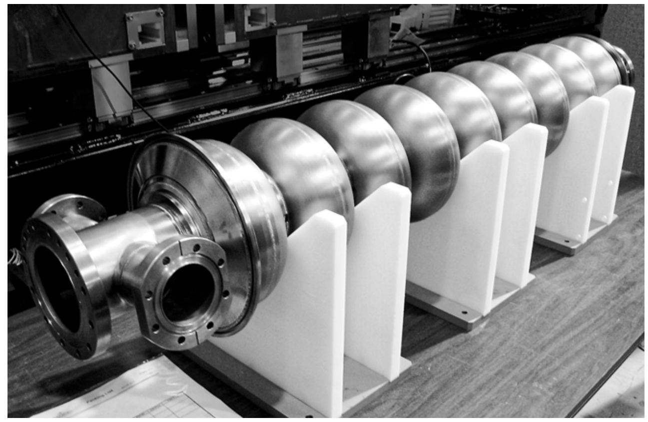


Figure 3. The nine-cell elliptical cavity.

the design was complete and the majority of the components fabricated, with the exception of the 9-cell niobium (Nb) cavity. A mock-up using actual parts, but with the cavity substituted by a dummy, verified the design prior to the final assembly. The jacketed EINJ cavity was received 2014 February. Final assembly followed, which led to the successful cold test of the entire injector cryomodule in April 2014, and subsequent move to the e-hall on May 1 2014.

4.3.9 Accelerator Cryomodule

The first accelerator cryomodule (EACA) raises the beam energy to 30 MeV. The cryomodule design is essentially the union of two back-to-back injector cryomodules (see Figure 4). It was hoped that testing of the EINJ would occur before completion of the design or EACA, so that lessons learnt could be applied to the latter; but this was not to be the case. Although EACA engineering design began in 2011, it did not gain momentum until fall, 2012 through spring 2013, and was finished in October 2013. However, many of the components are shared in common with EINJ, and EACA parts fabrication started June 2013. All sub-assemblies were received by May 2014, and final assembly of the cryomodule was coordinated in readiness for the first EACA SRF cavity. EACA final assembly was completed in July, and the cryomodule delivered to the e-hall in August. Cool down to 2K was achieved August 19, and RF was first applied August 26.

Figure 4. The first EACA raises the beam energy to 30 MeV.

4.3.10 4K/2K Inserts

Whereas the ISAC-II quarter wave cavities, operating at 140 MHz, need a 4K LHe bath, the e-linac elliptical cavities, operating at order 1300 MHz, need a 2K LHe bath to reduce the otherwise higher BCS RF power loss in the superconducting metal.

There is a 4K/2K insert on board each cryomodule, whose main purpose is to generate 2K liquid entering the cavities from 4K liquid entering the cryomodule. 2K liquid is produced by passing 4 liquid through a heat exchanger in counter flow with the returning exhaust gas from the 2K phase separator, and then expanding the gas to 30 mbar through a Joule-Thomson expansion valve. The header pipe above the cavity string acts as a 2K phase separator, and delivers cold gas back through the 4K/2K heat exchanger to the SA pumping system as a liquid load.

Further, a 4K LHe reservoir in each cryomodules acts as a 4K phase separator. Cold gas is returned to a common return trunk and then delivered back to the cold box where it represents a refrigerator load. A siphon circuit from the 4K reservoir cools the 4K intercepts, with vapour returning back to the reservoir. Initial cool down of the cold mass is done by delivering 4K liquid from the 4K phase separator to the bottom of the cold mass through a dedicated cool down valve. The prototype 4K/2K insert underwent preliminary testing at 77K & 4K October to November, and was found to be satisfactory May 2013, after modification of the 4K syphon to reduce convection in the 4K reservoir.

4.3.11 Radio-Frequency Equipment

The purpose of the RF equipment is to energize the cavity resonators with travelling wave electrical fields that accelerate the electrons. When superconducting cavities are used, almost 100% of the incident RF power is transferred to the particle beam.

The 2010–12 bi-annual report records the use of a 30kW Inductive Output Tube (IOT) as the basis for the RF coupler conditioning station. Two couplers at a time are tested/conditioned under either travelling or standing wave conditions ranging from 10 to 40 kW peak power.

The time frame covered by the 2012–14 report concerns the 1.3 GHz high-power RF system that supplies up to 100kW to each of the three SRF cavities. The basic layout is that an RF source (klystron) delivers power via a circulator and waveguide distribution system to the two coaxial input couplers that feed a single SRF cavity. The EACA distribution system must power and phase adjust the RF between the cavities.

A klystron is a very high-gain RF amplifier. The amplification is achieved by modulating a high current (9A) low energy (65 keV) electron beam inside the klystron. 100kW is delivered to EINJ and 200kW to EACA; and each cryomodule is powered by an individual klystron. The RF sources are long lead items. To achieve procurement efficiencies, both klystrons and their high-voltage DC power supplies (HVPS) are identical.

Two custom designed c.w. klystrons were ordered from CPI, USA, in August 2011 as part of a joint venture with Helmholtz Zentrum Berlin. The klystron is specified with a usable linear range up to 270 kW, leaving plenty of margin for transmission loss to the nominal 200kW rated EACA. The first and second were delivered to TRIUMF March 2013 and May 2014 respectively. The 65kV HVPS, rated at 300 kW output power, were procured independently from Ampegon, Switzerland. The HVPS uses IGBT-based, pulse step modulators, and DC/DC convertor to achieve 0.1% low ripple, and low arc energy (so no crowbar is needed).

The order was placed June 2012, and the first HVPS delivered was energized September 2013. The combination of EINJ klystron, HVPS and circulator was acceptance tested to 270 kW at a dummy load April 2014. The second HVPS was energized July 2014. In parallel with sources testing, the waveguide RF distribution systems were installed, with the EINJ and EACA systems ready for operation May and August 2014, respectively.

4.3.12 Cryogenic Equipment

The cryogenic system is tasked with supplying 4K He liquid to and recovering 2K sub-atmospheric (SA) He gas from the cryomodules. There are several cryogenic sub-systems: (i) compressors that provide 12 bar gaseous He to the cold box via the gas management system; (ii) a 4K liquid helium closed (re)-liquefaction/refrigeration loop, that comprises the cold-box, He dewar and 4K He distribution to the cryomodules; (iii) the oil removal and gas management system (OR/GMS) that monitors and purifies the helium, and may also pass He to a 113 m^3 storage tank in the case of a prolonged power outage; (iv) and the SA system, comprising SA pumps and a counter-flow heat exchanger (HX), that returns gaseous helium to the main compressor; and a 77K liquid nitrogen system that pre-cools He entering the cold box, and also cools the thermal shields within the cryomdules. The systems are distributed: the compressors, ORGMS and SA pumps are in the He compressor building; the cold box, dewar, 4K He distribution, 2K SA gas return and HX are all in the e-hall.

Components were delivered by a variety of vendors, and TRIUMF performed the system integration.

The contract for supply of He cryoplant consisting of HELIAL 2000 cold-box, Kaeser main and recovery compressors with OR/GMS, and multi-component purity analyzer was awarded to Air Liquide Advanced Technologies (ALAT), France in October 2011. This machine is class 700 W cooling power at 4.6 K with maximum liquefaction rate of 288 l/h. The SA HX is an innovation that warms the sub-atmospheric return He gas and cools the forward pressurized gas entering the cold box. Use of the SA-HX, which was designed by TRIUMF and Carleton University, increases the overall thermal efficiency, a so-called "green" technology.

The He Compressor building construction formed part of the ARIEL civil construction package awarded to Ellis Don; occupancy was taken December 2012. The helium storage tank delivered in January of 2013.

All ALAT-supplied systems, and the four SA pumps supplied by Busch, were delivered by March. [One SA pump was installed at the VECC test stand and used to support the 2K SRF program.] After installation of the LN2 distribution and GHe distribution to the e-hall, and all connections made, the 4K cold box was successfully acceptance tested in November 2013. The cold box performs at 800W cooling power in refrigeration mode, and 380 litre/hr in liquefaction mode.

The final stage, achieving 2K liquid helium, required progress with several components: LHe-to-cryomodule 4K distribution (vacuum jacketed line); LN2-to-cryomodule distribution line; the SA 2K He return line and HX; and the readiness of the cryomodules in the e-hall to process the cryogens in the 4K/2K inserts. All of these systems, with the exception of final connections to the cryomodules, were completed May 2014. The gaseous He purifier, the subject of a collaboration with FNAL, was delivered in July, but not integrated into the OR/GMS until 2015.

4.3.13 Electrical Infrastructure

A new 5 MW switchgear, connected to the BC Hydro electrical utility and diesel generator, augments the site power for ARIEL. The switchgear will feed: up to 1.5 MW to the klystrons; 2 MW north to the ARIEL building; 1 MW south to the He compressor building; and provide 0.5 MW of emergency power. The Siemens 12.47 kV switchgear was delivered to TRIUMF September 2012 and energized in December.

4.3.14 Beam Lines

Magnetic optics transport electron beam from the source and between the cryomodules, and finally delivers electrons to the converter/target. The beam transport sections are:

- The ELBT low energy (300keV) transport
- The EMBT 10MeV “merger” section, so-called because it could merge the injector beam with the recirculating beam from an Energy Recovery Linac re-configuration of e-linac.
- The EABT 30 MeV transport between two accelerator cryomodules
- The EHAT 50 MeV transport after the future EACB
- The EHDT transport to the 10kW tuning dump
- The EHBT high energy transport through the ARIEL tunnel to the photo-fission target.

Each of these lines forms a point of articulation where the beam may change direction, and is equipped with one or more dipole magnets. The dipoles were designed/procured in batches: 3 specialist magnets for EMBT/D, so-called Y-30 magnets in the EHDT and EHBT horizontal dogleg, and so-called S-34 magnets in the EHBT section leading to the target. The main bends are strong, and must be regulated to 0.01%, otherwise the mis-steering can swamp the correctors. This level of stability is challenging. Magnet current transducers and feedback on the power supply are implemented with controllers supplied by Bira, USA.

Solenoid focusing is used in the ELBT 300keV beam transport. The special “strong” solenoid immediately after the 300keV e-gun was received June 2012 whereas the weaker ELBT/D solenoids were delivered in 2011. The X-Y correction magnets in ELBT are a custom air-cored design that eliminates hysteresis effects; the design recuperates PCB coils and Al heat sinks supplied by RadiaBeam, USA.

From the injector linac onward, magnetic quadrupoles are used for beam transverse focusing. The quads come in three varieties: medium, weak and strong. The beam lines in the e-hall adopt the weak and medium quadrupoles, with integrated strengths up to 0.2 T and 0.7 T respectively. This is easily achieved with the short quadrupoles of aspect ratio 1 and cylindrical poles with spherical faces (see Figure 5). The weak quads are also used for the EHBT periodic section in the tunnel. At highest envisioned energy of 75 MeV, the shortest required focal length is 0.24 m in the EHBT dogleg sections. The required integrated gradient is 1.05 T; this is achieved with a more conventional strong quadrupole design with rectangular cross-section poles and hyperbolic faces. All quadrupoles were provided by Buckley Systems, New Zealand. Prototypes of all 3 types were received February 2013 and all production units were delivered August 2013. The hysteresis curve of all quadrupoles and dipoles were measured, and all were degassed, prior to installation. From the injector onward, the X-Y correction magnets are identical, using a steel core design fabricated by RadiaBeam. All correction magnets use true bi-polar power supplies, whereas the quadrupoles and main dipoles all use uni-polar supplies with polarity switching. Power supplies for all magnets in the e-hall were installed in the e-hall roof beams rack farm by May 2014.

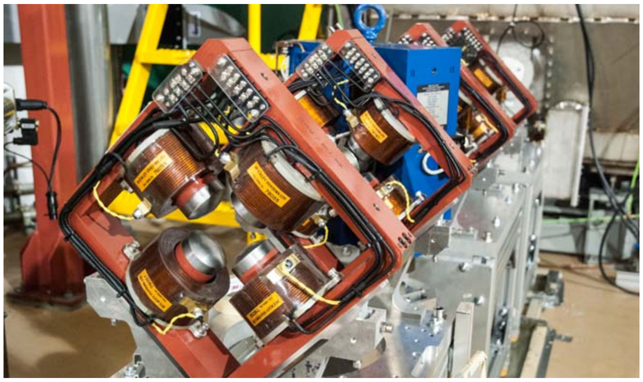


Figure 5. e-linac quadrupoles.

4.3.15 Beam Line Design and Installation

The design, manufacturing, and installation of the electron beam line was very different from any other TRIUMF has installed. New technologies introduced synergizes between three key offices on site: the Design Office, the Machine Shop, and the Beam Lines Group. The equipment stand concept is entirely new: aluminum extrusions for legs, transverse shear plates for torsional rigidity, stiff top plates with a precision milled key way for alignment, and precision machined mounting brackets for magnetic and diagnostic beam line components.

The Design Office modeled the entire beam line in 3D

using SolidWorks. These models produced drawings that went directly to the onsite Machine Shop. The new 3D numerically controlled (CNC) machines tools in the shop were leveraged to manufacture parts with very high precision. Ultimately, these advances changed the method of installation of the beam line. The beam line stands are positioned to sub-millimetre accuracy using the new 3D laser tracker alignment systems. The combination of precision stand alignment and high tolerance parts allowed to assemble quickly the beam line while maintaining accuracy.

The beam optics models were completed in 2012. The stands designs were completed in 2013. Static and dynamic loading of a prototype stand, equipped with

Figure 6. Quadrupoles in ARIEL transfer line tunnel.

quadrupole and diagnostic box and fast wire scanner, October to November 2013 was the gating for commencing mass production. Beam line stands were assembled and grouted in place, beam line equipment such as quadrupole magnets, diagnostic boxes, and vacuum pipes were mounted to support brackets, and beam line sections were aligned in the e-hall and in the periodic section of the ARIEL, all in the space of time between June–September 2014 (see Figure 6)

4.3.16 Beam Diagnostic Equipment

Measurements of beam position, profile and current along the beamline are essential for the beam set-up and for monitoring during the production run. Initial beam threading is performed with view screens, followed by trajectory correction with 4-button type four beam position monitors (BPMs) each measuring in two planes, horizontal and vertical. Electron beam charge is measured by Faraday cups. The view screen effort was led by the University of Victoria. Beam profile measurements can be performed at all energies with view screen systems comprising a thin screen, optical pathway and camera. At low/high energy, a scintillator/OTR screen is used. An optical pathway transports the light away from the beam line and into a lead-shielded camera box. The camera can be triggered by the output of the electron gun RF signal or through a software interface. Seventeen view screen actuators, foil ladders, optics, cameras and electronics were built; and 16 installed.

There are 54 BPMs at the facility: twenty-two along the e-linac itself and 32 along the high energy beam transfer line, and the majority have been installed. The button pickups are manufactured by Kyocera, and the button bodies/housings by TRIUMF. The BPM signal processing electronics operates in both the pulsed beam tune-up mode and the c.w. beam mode. Electronics consist of analogue front end (AFE) unit and Digital Signal Processor (DSP). Initial prototype and test of the AFE used a commercial Bergoz board customized for 650MHz. Subsequently, the AFE was modified at TRIUMF for higher gain, and the boards manufactured locally.

The view screens are ideal for commissioning, but too fragile for c.w. beam operation. At full power, a Fast Wire Scanner that travels at 3 m/s and intercepts the beam for less than a millisecond must be used. The challenge is to accelerate to that speed while the scanner only travels a few cm, and then returns to rest. A rotary motor turns a drum with a helical slot machined into its surface. A follower rides in the slot and pushes the wire holder fork through the beam. The motion is transferred from the air side to the beam line vacuum via bellows. A first prototype was built and bench tested (including vibration studies) in 2013; it ran consistently at 3 m/s after improvements were applied. The second prototype focuses on providing an increased stroke, more compact dimensions, a stiffer frame, and improved wire fork design, and safety features to protect the scanner were added. The prototype and one production unit were installed in 2014; and another will be added in 2015.

4.3.17 Vacuum Equipment

The electron beam travels in vacuum; if it passed through air, the majority of the beam would be scattered out of the beam pipe in a few meters of length. The e-linac has a challenging vacuum specification: 10^{-9} Torr in ELBT/D, 10^{-8} Torr through the linacs, and 10^{-7} Torr in the high-energy beam lines. These are ultra-high vacuum (UHV) conditions that minimize particulates contamination and migration to the SRF cavities, and minimize electron scattering on residual gas molecules. The cryomodule insulating and coupler vacuums are 10^{-6} Torr. Because of the ionizing radiation present during beam operation, all-metal seals are used throughout. The e-linac and beam lines are divided into a dozen vacuum regions that are pumped out separately. The beam line volumes through the linacs are separated by RF-screened, all metal electro-pneumatic gate valves. The vacuum volumes are evacuated from atmospheric pressure to high vacuum level with turbo-molecular pumps, which are then isolated via gate valves, and the pressure is further lowered by ion pumps.

Beam line stands innovations were not the only contributors to the rapidity of installation and readiness. A cleaning regime was introduced where all beam tube sections (BTS) and diagnostic boxes are UHV cleaned. Boxes and their diagnostics are then assembled and stored under clean room conditions. So carefully were the UHV conditions maintained that no (lengthy) in situ baking was required. All of the BTS were welded in the TRIUMF Machine Shop.

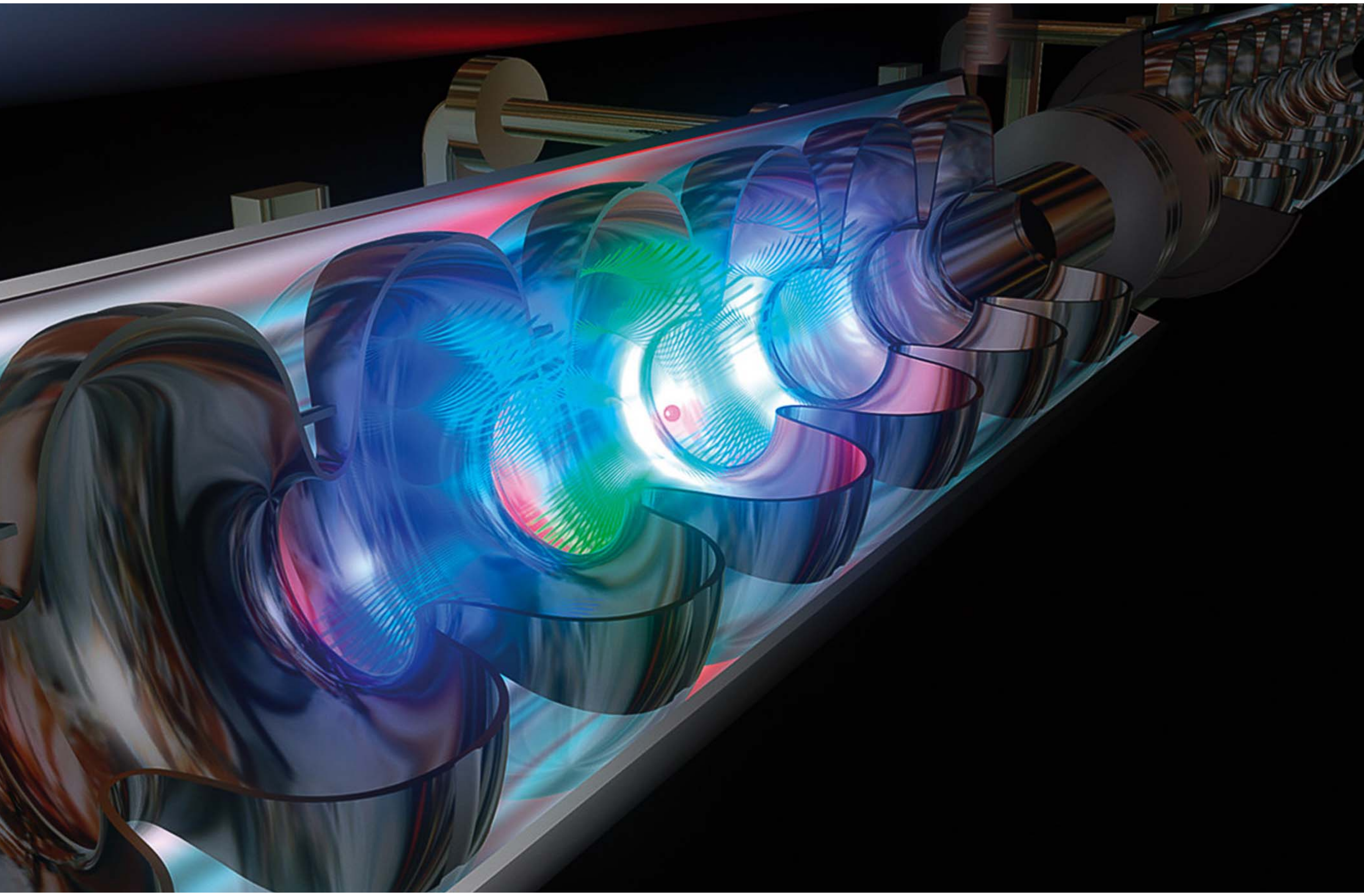
4.3.18 e-linac Beam Demonstration

Room 103-A, in proximity to the cyclotron Main Control Room (MCR) was chosen as the location of the e-linac Control Room (ELCR), for e-linac commissioning purposes, in July 2013. Requirements for the consoles layouts were developed in a workshop in January 2014. Refurbishment of the space took place in March, followed by installation of consoles in April, and integration with EPICS in May. The consoles for the Personnel Radiation Safety system were also installed in May. The e-linac commissioning team took over the ELCR in May and began to re-commission the e-gun and ELBT/D.

The final phase of the e-linac installations and pre-commissioning was fast paced and exhilarating. The 10 MeV injector was moved from the ISAC test stand to the e-hall in May, 2014, and injector services including cryo and RF were connected by June 1st. The 10 MeV medium energy beam transport was installed in June, and the 30 MeV momentum analysis beam line in July. The first accelerated beam, 5.5 MeV from EINJ, was celebrated on July 19.

The transport to the e-hall beam dump and the periodic section in the ARIEL tunnel were both installed in September. The Injector Cryomodule achieved 12 MeV acceleration September 23rd. The accelerator cryomodule, containing one SRF cavity, arrived in the e-hall August 29th. Immediately following, the EACA 4K LHe distribution and 2K SA return and the EACA RF waveguides were connected.

The EACA 4K cool down started September 7th, and the RF input couplers were conditioned to 10 kW level. The combination of EINJ and EACA cryomodules achieved 23 MeV on October 1st, delivered to the Faraday cup downstream of the EABD beam energy analyzer magnet.



CREATING SOCIAL AND ECONOMIC IMPACT

5

5

CREATING SOCIAL AND ECONOMIC IMPACT

5.1 INTRODUCTION

One of TRIUMF's key missions is to leverage scientific discovery for the benefit of all Canadians by transferring knowledge training personnel and commercializing research to maximize our socioeconomic impact.

TRIUMF's highly specialized staff drive the research done at the lab, and their expertise is an invaluable resource for students and researchers at TRIUMF as well as at our partner institutions across the country.

TRIUMF's nineteen Canadian member universities provide a strong network that encourages education, innovation, and collaboration.

Industrial partners bolster this network with business expertise that complements the work of researchers at TRIUMF and across Canada. Advanced Applied Physics Solutions (AAPS), Inc., TRIUMF's commercialization arm, provides the ideal platform to transform research into products, solutions and services. Together, what emerges is a national commitment to creating socioeconomic impact benefitting all Canadians.

5.2 TRAINING THE NEXT GENERATION OF LEADERS

C. RODRIGO

As a hub for world-class research, TRIUMF is fortunate to host many brilliant young researchers who are developing their passion for science. Through various initiatives that target these exceptional individuals, TRIUMF trains and fosters the next generation of scientists.

5.2.1 TRISEP

The TRI-Institute Summer School for Particle Physics (TRISEP) is a unique summer school for international graduate students and young researchers that is operated in cooperation with the Perimeter Institute, SNOLAB and TRIUMF. The school offers attendees the opportunity to interact with experts through lectures, Q&A sessions, and discussions with featured speakers (see Figure 1). In July 2013 over 40 students attended the inaugural summer school at TRIUMF, while the 2014 and 2015 sessions were held at SNOLAB and the Perimeter Institute, respectively.

Future TRISEP sessions will continue to rotate among the three institutions each year.

5.2.2 IsoSiM

Isotopes for Science and Medicine (IsoSiM) is an NSERC “Create” program that began in April 2014. Jointly operated by UBC and TRIUMF, IsoSiM is designed to give students the skills required to succeed in isotope-related fields of study and work. Students are given individualized professional development plans tailored to their personal goals. The program is unique as it emphasizes diversification and professional development by exposing students to applications for isotopes in areas outside their respective fields of study. Workshops allow them to hone their professional skills, and projects at facilities like TRIUMF give them first-hand experience with real-world scientific research. TRIUMF welcomed the first cohort of six students in September 2014. By June 2015 the program had gained another six students.

Figure 1. The TRI-Institute Summer School

Figure 2. Andrew Robertson, IsoSIM program student

5.3 CONNECTING SCIENCE TO SOCIETY

M.M. PAVAN

TRIUMF's public tours continue to be a major draw for visitors, young and old, scientists and science enthusiasts alike. From June 2013–March 2015, close to 8,000 guests visited the lab on over 1,100 tours. In September 2013, TRIUMF hosted an open house and invited its community friends behind the fence for a closer look at TRIUMF's research and discovery. Gusty winds and torrential rain weren't enough to discourage over 1,200 visitors from being greeted and entertained by a team of 130 researchers, post-docs, technicians, students, and staff (see Figure 2).

TRIUMF connects to the community through various local festivals and large-scale events.

Members of the lab represent TRIUMF at annual events such as the UNA Barn Raising, UBC Alumni Weekend, and the Wesbrook Village Festival, as well as local events, such as the Richmond Public Library Science and Technology Forum. Topics covered at these events include antimatter, radiation and Fukushima, particle physics, and proton therapy. For example, on April 2013 Dr. Anadi Canepa delivered a speech about her work on the ATLAS experiment at CERN to 500 attendees at Sam Sullivan's Public Salon, a Vancouver event promoting discussion of public policy ideas. TRIUMF also sponsored two films at local film festivals; "Particle Fever" at the Vancouver International Film Festival, and "The Circle" at DOXA Film Festival, with staff scientists participating in post-viewing Q&A sessions.

Through the ongoing Partners in Innovation relationship with Science World B.C., TRIUMF continues to offer the "Unveiling the Universe" lectures, which connected high-profile international scientists with the general public. Highlights of the 2013–2015 biennium included Dr. Hitoshi Murayama on "Mysteries of the Quantum Universe," Dr. Paul Schaffer on "Medicine

Figure 2. TRIUMF Open House in September 2013

Figure 3. "Unveiling the Universe" lectures at Science World

Accelerated," Dr. Rocky Kolb's "From the Quantum to the Cosmos," and Dr. Makoto Fujiwara's "What's the matter with Antimatter?" Approximately 1,200 guests participated in these lectures. In addition to the 400-seat Omnimax Theatre at the Telus World of Science in Vancouver, and interested viewers can now participate via a live webcast (see Figure 3).

In June 2013, invited members of the Vancouver entrepreneur and high-technology community gathered at TRIUMF for its inaugural Science & Technology Gala. The event served a dual purpose: first, to quench the "where do we come from" curiosity of the guests; and second, to appeal to their technical side with an introduction to advanced particle-accelerator technologies.

In September 2014, TRIUMF and AAPS welcomed Canadian leaders in knowledge mobilization and technology transfer to its annual "Innovations and Industrial Partnerships Workshop." This workshop engaged colleagues from TRIUMF's member universities and other partners in a forum to discuss innovation practices and explore opportunities for leveraging research to create positive social and economic impacts on Canadian society. Through conduits like TRIUMF, researchers and industrial partners harness their combined expertise to face common challenges in areas of knowledge translation and innovation.

5.4. INDUSTRIAL PARTNERSHIPS AND COMMERCIALIZATION

J. HANLON

AAPS' close partnership with TRIUMF provides access to knowledge and expertise their industrial partners to make use of this expertise and specialized infrastructure that TRIUMF offers. This further connects science to society and creates social and economic impacts for Canada.

5.4.1 Irradiation Services

It is possible to simulate natural-radiation exposures, either in space or terrestrial environments by using the low-intensity energetic proton and neutron beams available at TRIUMF. An upgrade to the 1B beamline in 2015, facilitated by AAPS and financed by Cisco Systems, allows for higher intensities of neutrons and greater access by users. Even at low intensity, electronics that experience a few minutes of exposure in these beams are submitted to radiation corresponding to years of operation in space, at high altitudes, or on the ground. Over 35 companies from Canada, US, and Europe have made commercial use of the irradiation facilities.

5.4.2 Isotope Production

TRIUMF's expertise in cyclotron operations, target engineering, and radiopharmaceutical production realizes extraordinary benefits for B. C. and Canada as a whole. The nuclear medicine team has mastery of the chemistry and facilities needed to isolate, purify, and combine the isotopes with biologically active target molecules enabling a world-class program that includes molecular imaging of neurodegenerative disease and cancer. In the 2013–2015 time frame, with funding from NRCAN, TRIUMF led a team that successfully demonstrated an accelerator-based solution capable of producing one of the most important and prevalently used isotopes in healthcare, Technetium-99m, eliminating the need for its production using highly enriched uranium at nuclear reactors.

5.4.3 Technical Consulting

TRIUMF's capabilities in physics, engineering, and technical design are often tapped in the form of short-term consulting arrangements. The responsible use of public funds by TRIUMF for its programs requires the laboratory to limit its "contract research" or "work for others" activities to those that directly advance its mission. TRIUMF staff might contribute to troubleshooting a private company's product line or providing advice for high-tech infrastructure development. TRIUMF's contributions to the success of AAPS initiatives fall into this category.

As TRIUMF's innovation and commercialization partner, AAPS leverages TRIUMF's know-how and expertise

to provide solutions to industry and academic institutions. In focusing on priority areas, like natural resources (mining exploration), healthcare (medical isotopes), safety and security (radiation detection and monitoring) and accelerator-driven technologies, these business lines are expected to grow and produce even more economic and social benefits to Canadians.

SAFETY, LICENSING, AND MANAGEMENT SYSTEMS

6

6 SAFETY, LICENSING, AND MANAGEMENT SYSTEMS

6.1 SAFETY AND LICENSING

A. TRUDEL

Licensing Activities

TRIUMF obtained a Class II Operating License for the commissioning of the ARIEL electron linear accelerator (e-Linac) up to 30 MeV, and 1 kW to the tuning dump in the Electron Hall. The license application included a safety analysis report, a detailed commissioning plan, the human factors program plan for the control room design and operation, and an operator training plan. Commissioning is ongoing and with an eventual commission at 10 kW by the end of 2017.

Work is also ongoing in the design and development of the ARIEL target irradiation and handling systems that will be installed in the Target Hall. The license application will be updated to include photo-production of rare isotope beams on an ARIEL target proposed for mid-2018. TRIUMF also obtained a Class II Operating License for the commissioning of a neutron generator used to develop a well-logging tool.

Regulatory program activities in this period included six program-specific Canadian Nuclear Safety Commission inspections

for quality management systems, human and organizational performance, training, packaging and transport, and environmental protection. Progress highlights for regulatory programs include the following:

- Safety training for the period 2013–2015, which was spearheaded by TRIUMF's Training Implementation Panel. The following training has been implemented:
- Group training plans to ensure competency of staff for all mission-critical operations;
- Building access training to make sure workers are aware of the requirements for safe occupancy and egress in their onsite place of work;
- Basic radiation protection training to make sure that all workers are familiar with the regulatory requirements, and TRIUMF's policy for working solely with radiation;
- Exclusion area training to make sure workers are familiar with alarms and associated procedures for access and egress from exclusion areas;

Fire protection program improvements received significant attention when an outside contractor with expertise in NFPA-801 fire code for nuclear facilities was retained to complete the 2013–2014 biannual review for inspection testing and maintenance. The review also included a site inspection to assess the operational program. This very thorough review against NFPA-801 and Canadian Fire Code requirements revealed numerous minor as well as a few more significant nonconformities. In 2015, with the help of an outside contractor, TRIUMF satisfactorily addressed all non-compliances stemming from the review. Starting in 2016, regular annual program reviews will be carried out starting to identify areas for continual improvement and adherence to regulatory requirements.

TRIUMF undertook a risk assessment of its access control system and the associated procedures that provide in-depth defense for protection of personnel against prompt radiation hazards in exclusion areas. As a result of the assessment, improvements in safeguards were made: the addition of automated voice-announcements in the larger and more complex exclusion areas; and the development of an online training module to address potential hazards and the importance of the thoroughness of the search in complex areas.

Ongoing efforts with the Radioactive Waste Management Program led to disposal of a backlog of nuclear ventilation filters and ion exchange resin material which had decayed to below the applicable clearance levels.

Also in 2015, TRIUMF's Environment, Health and Safety Group completed an internal review that was subject to scrutiny by an international panel of safety professionals from other accelerator laboratories and industry. Based on the findings from the reviews;

A strategic plan was developed with prioritized corrective actions to address gaps and areas for continual improvement in TRIUMF's safety program.

Some of the areas identified in the plan for additional staffing are: management safety, training, quality management, and computing.

A review of the controlled work process resulted in the deployment of an application to standardize site access for visitors and contractors to ensure that requirements for safety and orientation are addressed. It called for prohibited access to high-radiation areas by non-NEWs, additional QMS training for directors and project leaders, and initiation of a process to assess TRIUMF safety culture.

The operating performance for environment health and safety continued to do well in this period. The radiation dose to personnel, summarized in the table below, indicates excellent ongoing performance for dose management in all areas of operation at TRIUMF, with the total personnel dose continuing to decrease over the previous three-year average total site dose of 202 person-mSv. (see Table 1)

Environmental aspects of TRIUMF's operation continue to remain well below the regulatory limit of 0.05mSv/year dose to a member of the public. TRIUMF annual airborne releases were just below 0.01mSv/yr for the three-year period. This quantification takes into account a correction for the species composition of emissions and the correct release height of the exhaust point: two corrections that arose from studies completed by the Radiation Protection Group to better characterize the environmental impact of emissions.

Sump effluent releases continued to be less than 10^{-6}mSv/yr for this period. Lost-time injuries for TRIUMF averaged 7.2 days/100 person-years and continued to be better than that for BC Universities, the WorkSafe BC equivalent industry group. Environment, Health & Saftey metrics were used to assess performance with respect to goals for this operating period.

Annual Dose	Total Site Dose (person-mSv)	Maximum NEW Dose (mSv)	Average NEW Dose (mSv)	Average non-NEW Dose (mSv)
2013	144.9	6.49	0.77	0.02
2014	147.3	6.32	0.72	0.02
2015	150.7	5.87	0.69	0.03

Table 1. Radiation Doses, 2013-2015.

6.2 QUALITY MANAGEMENT SYSTEM

P. BAQUERO

The QMS Panel is responsible for implementing the Quality Management System at TRIUMF. It is chaired by the Engineering Division Associate Lab Director and includes representatives from each division as well as the QMS Leader. Previously, QA and Training were the responsibility of one person, in 2015 a full-time QMS leader position was created to devote additional resources to both areas.

TSOP-02 Nonconformity Reporting and Resolution is a key component of identifying areas for continual improvement of TRIUMF processes. The TapRooT® committee carries out root cause analyses (RCA) and documents findings in a report that includes recommendations for corrective actions assigned to appropriate divisions for completion. Tracking and ensuring timely completion of corrective actions has been a strong focus over the last several years (see Figure 1). Some other changes which have been made to improve the NCR process include:

- The addition of a section to the RCA template to capture the method of verification for the effectiveness of the corrective action;
- Inclusion into TSOP-02 of non-conformities associated with safety inspections;
- Addition of a review panel to streamline non-conformities that require a full root cause analysis; and
- Testing for a new web application for reporting and resolving nonconformities. This began in 2014 and updates were made in 2015.

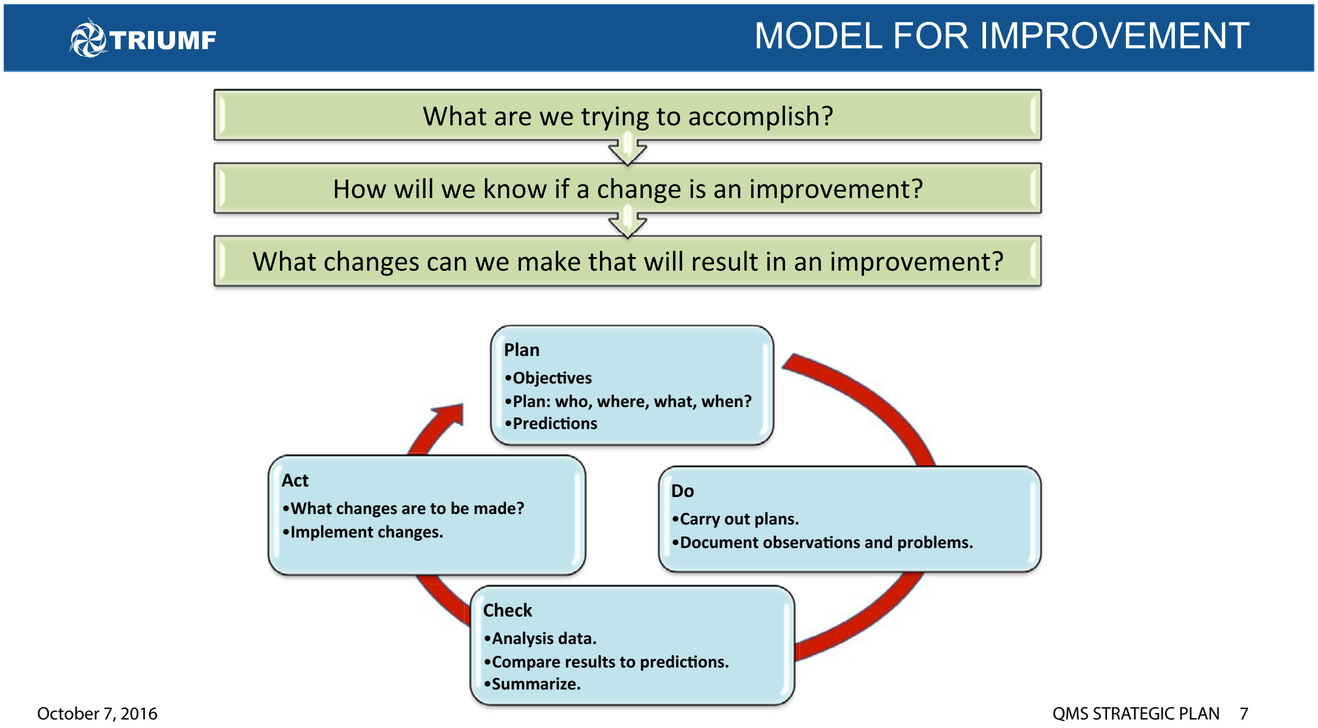


Figure 1. QMS Model for Improvement

Internal audits are part of TSOP-09 Quality Program Assessment and are an important tool in assessing implementation of TRIUMF's processes. Several internal audits were completed in each of the reporting years, and the following represent important areas that resulted in improvements.

An internal audit of training plans was carried out with a focus on how the identification of non-routine tasks is ensured. As a result, various training plans were updated, most notably (i) for the Solid Target Facility training plan to include responses to target failures, and (ii) development of a training plan for the TRIUMF Emergency Preparedness Plan.

The internal audit of the process for tracking and training of visitors led to the release of a specification for a new web application for tracking the onboarding process and training records for visitors.

The internal audit of the site access card system resulted in the deactivation of the access card for any worker who has not completed the basic site safety orientation. A priority for the new QMS leader hired in September 2015 has been to review all TSOPs and complete a gap analysis with the CSA standard N286-12 Management System Requirements for Nuclear Facilities.

6.3 PROJECT MANAGEMENT
R. KRUECKEN

TRIUMF continues to maintain a laboratory-wide Level 2 work breakdown structure (WBS) under the rubric of the Commitment List. The Commitment List details all the projects and ongoing operational commitments that TRIUMF is working on (WBS Level 2) and groups them into programs (WBS Level 1).

Through the different phases, projects follow a gateway process from initiation through planning and execution to closing of the project. During 2013–2015, a number of new projects were initiated. Noteworthy are several multi-institutional projects that were submitted to the 2015 Canada Foundation for Innovation (CFI) competition. These projects underwent Gate 1 reviews as well as status reviews to assess the realism of project planning and budgeting in advance of the proposal submission.

The successful projects with TRIUMF involvement are the ATLAS detector upgrade project, the ALPHA-gravity proposal, as well as the proposal to outfit GRIFFIN with BGO anti-Compton shields.

The preparation process for the CFI competition revealed the need for further improvements of the gateway process, and a revision of the Project Management TSOP-15 is under consideration to account for these.

EXPERIMENTAL FACILITIES

7

7

EXPERIMENTAL FACILITIES

7.1 MOLECULAR AND MATERIALS SCIENCE

Common name or acronym	Acronym expansion	TRIUMF Spokesperson	Description
B-NMR	Beta Nuclear Magnetic Resonance	Gerald D. Morris	An exotic form of nuclear magnetic resonance (NMR) in which the nuclear spin-precession signal is detected through the beta decay of a radioactive nucleus, located in ISAC-I.
B-NQR	Beta Nuclear Quadrupole Resonance	Gerald D. Morris	An exotic form of nuclear resonance (in which the nuclear spin-precession signal is detected through the beta decay of a radioactive nucleus, located in ISAC-I. It relies on the precession of the nucleus due to the interaction of the nuclear quadrupole moment with an electric field.
DR	Dilution Refrigerator	Syd Kreitzman	A µ-SR spectrometer combining a superconducting Helmholtz magnet and dilution refrigerator.
GasCart		Syd Kreitzman	A µ-SR spectrometer specifically designed for large gas targets. The main 1.5 m diameter Helmholtz coils provide magnetic field up to 330 G (33 mT) directly horizontally along or across the beam direction, and homogeneous to ~1% over a 5-litre volume.
Helios		Syd Kreitzman	A µ-SR spectrometer with a superconducting magnet with a 6-inch diameter, 24-inch long warm bore. It provides 6.7T at its maximum current of 70A; that's 961 G/A. The main counter array is for solid state work in narrow cryostats, and there is another set of counters for larger samples such as gas cells.
HiTime		Syd Kreitzman	
Omni-LAMPF		Syd Kreitzman	Omni-LAMPF, LAMPF Omni, or just "LAMPF", is a general purpose µ-SR spectrometer. R. Heffner kindly provided the magnet and stand which had enjoyed a career in µSR at Los Alamos. Hence the name from the Los Alamos facility of the same name.

Common name or acronym	Acronym expansion	TRIUMF Spokesperson	Description
New HiTime		Syd Kreitzman	A μ-SR spectrometer for studies with high transverse fields and high frequencies.
Omni, LAMPF, and Omni-Primed		Syd Kreitzman	Omni primed is, as its name implies, a multi-purpose spectrometer with flexible counter arrangements which accepts most inserts, transverse or axial.
SFUmu	Simon Fraser University MUon	Syd Kreitzman	The SFUMU apparatus has recently been converted from its original guise as a dedicated backward muon spectrometer to a dual-orientation device: with its coils transverse to the beam it fulfills its original role, but when turned axial to the beam, it is another Omni.

7.2 NUCLEAR PHYSICS

Common name or acronym	Acronym expansion	TRIUMF Spokesperson	Description
CFBLS	Collinear Fast-Beam Laser Spectroscopy	Matthew Pearson	An experiment designed to exploit the high beam intensity and radioisotope-production capability of the ISAC-I facility in order to measure the hyperfine energy levels and isotope shifts of short-lived isotopes.
DESCANT	DEuterated SCintillator Array for Neutron Tagging	Iris Dillman	A neutron detector array used at ISAC.
DRAGON	Detector of Recoils and Gammas of Nuclear Reactions	Chris Ruiz	A detector designed to measure the rates of nuclear reactions important in astrophysics, located in ISAC-I.
DSL	Doppler Shift Lifetimes facility	Barry S. Davids	An experimental setup for the measurement of the lifetimes of excited states of nuclei.
EMMA	ElectroMagnetic Mass Analyzer	Barry S. Davids	A device to study the products of nuclear reactions involving rare isotopes, located in ISAC-II.
FTF	Francium Trapping Facility	John A. Behr	A facility used to measure the anapole moment of francium in a chain of isotopes by observing its parity violating character, induced by the weak interaction.
GPS 4pi Gas counter	General Purpose Station 4pi Gas Counter	Adam Garnsworthy	A high-efficiency detector for making very precise measurements of beta-decay half-lives.
GRIFFIN	Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei	Adam Garnsworthy	A detector at ISAC for studying nuclear decays at high resolution.

Common name or acronym	Acronym expansion	TRIUMF Spokesperson	Description
IIS	ISAC Implantation Station	Friedhelm A. Ames	A station for collecting samples of long-lived isotopes from ISAC and implanting them in a carrier material, for use in physics or medical science.
IRIS	ISAC chaRged partIcles spectroscopy Station	Greg Hackman	A detector designed to use nuclear reactions as a microscope to look into the core of nuclear isotopes with large neutron to proton ratios, located in ISAC-II.
MTV	Mott Polarimetry for T- Violation	Matthew Pearson	The Mott polarimeter consists of a planer drift chamber, measuring backward scattering left-right asymmetry from a thin lead analyzer foil.
Radon-EDM	Radon - Electric Dipole Moment	Matthew Pearson	The Radon EDM experiment uses contemporary spectroscopy techniques to measure the influence of a parity-violating external field on the angular distribution of gamma rays from polarized odd-spin Rn atoms.
SHARC	Silicon Highly-segmented Array for Reactions and Coulex	Greg Hackman	Designed for stand-alone use or integration with TIGRESS, SHARC is a device suited for particle detection from reactions, located in ISAC-II.
SPICE	The SPectrometer for Internal Conversion Electrons	Adam Garnsworthy	An in-beam electron spectrometer that operates in conjunction with TIGRESS, located in ISAC-II.
TIGRESS	TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer	Greg Hackman	An array of 16 highly segmented high-purity germanium detector for studying nuclear gamma decays in-flight with high resolution
TIP	TIGRESS Integrated Plunger	Greg Hackman	A device that uses CsI detectors and precision-mounted scattering foils to measure electromagnetic transition rates in conjunction with TIGRESS
TITAN Measurement Penning TRAP (MPET)	TRIUMF's Ion Trap for Atomic and Nuclear science	Anna Kwiatkowski	An ion trap facility at ISAC-I for high precision mass measurements of rare isotopes

Common name or acronym	Acronym expansion	TRIUMF Spokesperson	Description
TRINAT	TRIUMF Neutral Atom Trap	John A Behr	A device to trap and study the radioactive decays of neutral atoms, located in ISAC-I.
TUDA	TRIUMF U.K. Detector Array	Chris Ruiz	A detector designed to measure the rates of nuclear reactions important in astrophysics, located in ISAC-I

7.3 PARTICLE PHYSICS

Common name or acronym	Acronym expansion	TRIUMF Spokesperson	Description
UCN	Ultra-Cold Neutrons	Rudiger Picker	The UCN source allows experimenters to precisely measure neutron beta decay and quantum levels of neutrons in Earth's gravitational field. It also facilitates the search for the non-zero neutron electric dipole moment (nEDM).

COLLABORATIONS: GROUP LEADERS AND STAFF (2013–2015)

8

8

COLLABORATIONS: GROUP LEADERS AND STAFF (2013–2015)

8.1 GROUP LEADERS AND STAFF (2013–2015)

8.1.1 Accelerator Research

Group Leader: Lia Merminga (TRIUMF)

TRIUMF Staff: Yuri Bylinski, Robert Laxdal, Rick Baartman, Pierre Bricault, Shane Koscielniak, Amiya Mitra, Yu-Chiu Chao, Yi-Nong Rao, Marik Dombsky, Keerthi Jayamanna, Jens Lassen, Friedhelm Ames, Marco Marchetto, Fred Jones, Dobrin Kaltche, Suresh Saminathan, Ken Fong, Conny Hoehr, Thomas Planche, Victor Verzilov, Peter Kunz

8.1.2 ALPHA

Spokesperson: Jeffrey Hangst, Aarhus University

Canadian Group Leader: Makoto Fujiwara, TRIUMF

TRIUMF Staff: Art Olin, Dave Gill, Simone Stracka, James Storey, Konstantin Olchanski, Leonid Kurchaninov

Canadian Institutions: University of British Columbia, Simon Fraser University, University of Calgary, York University

Other Countries: UK, USA, Denmark, Brazil, Israel, Japan, Sweden

8.1.3 ATLAS

Spokesperson: David Charlton, Birmingham

ATLAS-Canada Spokesperson and PI: Robert McPherson, IPP/U. Victoria

TRIUMF Staff (signing): Anadi Canepa, Oliver Stelzer-Chilton, Reda Tafirout, Isabel Trigger

TRIUMF Staff (non-signing): Valery Akhnazarov, Paul Birney, Leonid Kurchaninov, Roy Langstaff

TRIUMF Staff (ATLAS Tier-1 Centre): Denice Deatrich, Asoka De Silva, Rajan Devbhandari, Vitaliy Kondratenko, Simon Liu, Di Qing, Yun-Ha Shin, Reda Tafirout, Isabel Trigger, Andrew Wong

TRIUMF Post-docs and Research Associates signing ATLAS papers: Sergey Chekulaev, Dominique Fortin, Jelena Jovicevic, Alex Koutsmann, Estel Perez- Codina, Doug Schouten, Basil Schneider, Rolf Seuster

TRIUMF Co-supervised Students: Felix Cormier, Matthew Gignac, Alexander Held, Ewan Hill, Sam King, Sebastien Rettie, Stephen Swedish, Simon Viel

Canadian Institutions: University of Alberta, University of British Columbia, Carleton University, McGill University, Université de Montréal, Simon Fraser University, University of Toronto, TRIUMF, University of Victoria, York University

Other Countries: Argentina, Armenia, Australia, Azerbaijan, Brazil, Canada, Chile, China, Colombia, Czech Republic, Denmark, France, Georgia, Germany, Greece, Israel, Italy, Japan, Morocco, Netherlands, Norway, Poland, Portugal, Belarus, Romania, Russia, Serbia, Slovak Republic, Slovenia, South Africa, Spain, Sweden, Switzerland, Taiwan, Turkey, UK, USA

8.1.4 Centre for Material and Molecular Science

TRIUMF Staff: Iain McKenzie, Syd Kreitzman, Gerald Morris

8.1.5 DEAP

Project Leader: M. Boulay, Queens

TRIUMF Staff: P-A. Amaudruz, D. Bishop, S. Chan, K. Langton, C. Lim, T. Lindner, A. Muir, C. Ohlmann, K. Olchanski, F. Retiere; Temporary and paid by CFI: B. Kelly and S. Mead

Canadian Researchers: Aksel Hallin, University of Alberta; K. Graham, Carleton University; M. Boulay, Queens University; C. Jillings, Laurentian University; F. Duncan, SNOLAB;

Other countries: UK

8.1.6 GPS/GRIFFIN/TIGRESS

Group Leader: C.E. Svensson

TRIUMF Staff: G.C. Ball, A.B. Garnsworthy, G. Hackman, R. Kruecken

Canadian Institutions: Queen's University, Saint Mary's University, Simon Fraser University, University of British Columbia, Université de Montréal, University of Guelph, University of Toronto

Other Countries: England, France, Germany, India, Italy, Scotland, Spain, USA

8.1.7 Laser Spectroscopy

Group Leader: M.R. Pearson

TRIUMF Staff: T. Proctor

Other Universities: McGill: F. Buchinger (Lecturer); J. Crawford (Emeritus Professor), W. Al Tamimi (Ph.D. student); A. Leary (M.Sc. student)

Other Countries: University of Manchester, UK; J. Billowes (Professor), University of Liverpool: B. Cheal (Lecturer); A. Voss (Postdoctoral Researcher), Jyvaskyla University

8.1.8 Nuclear Astrophysics

Group Leaders: Lothar Buchmann, Barry Davids, Iris Dillmann, Chris Ruiz (rotating)

TRIUMF Staff: Petr Navratil, Sonia Bacca

Canadian Faculty: Falk Herwig (UVic), Alan Chen (McMaster)

Other Countries: USA, UK, Spain, Israel, Switzerland

8.1.9 Nuclear Medicine

Group Leader: P. Schaffer

TRIUMF Staff: M. Adam, K. Buckley, T. Ruth, J. Poutissou, G. Sheffer, M. Dodd, H. Yang, V. Hanaameyer, J. Klug, Q. Miao, S. Zeisler

8.1.10 SNO+

Project Leader: Mark Chen, Queen's University

TRIUMF: Richard Helmer

Canadian Institutions: University of Alberta, Laurentian University, Queen's University, SNOLAB

Other countries: USA, UK, Germany, Portugal

8.1.11 SuperCDMS

Group Leader: Wolfgang Rau (Queens);

Spokesperson: Blas Cabrera (Stanford)

TRIUMF research scientist: Thomas Lindner

Canadian Institutions: Queens University, University of British Columbia

8.1.12 T2K

Canadian Group Leader: Scott Oser (UBC)

Spokespeople: Takashi Kobayashi (KEK), Chang Kee Jung (Stonybrook)

TRIUMF: Research Scientists: Richard Helmer, Akira Konaka, Andrew Miller, Jean-Michel Poutissou, Renee Poutissou, Fabrice Retiere, Stanley Yen, Thomas Lindner

TRIUMF: Technical Staff: Pierre-Andre Amaudruz, Wayne Faszer, Peter Gumplinger, Robert Henderson, Phillip Lu, David Morris, Konstantin Olchanski, Robert Openshaw, Peter Vincent

TRIUMF: Postdocs: Kendall Mahn, Mark Scott, Dima Vavilov, Michael Wilking

Canadian Institutions: University of Victoria, University of British Columbia, TRIUMF, University of Alberta, University of Regina, , University of Winnipeg, University of Toronto, York University

Other countries: Poland, Switzerland, USA, France, Korea, Japan, Spain, UK, Italy, Russia, Germany

Theory Research Scientists: S. Bacca, J.D. Holt, D. E. Morrissey, P. Navratil, J. N. Ng, R. M. Woloshyn

Postdoctoral Research Associates: A. Calci, J. Dohet-Eraly, Chen Ji, J. Kozaczuk, A. Kumar, T. Martin, F. Raimondi, C. Romero-Redondo, A. de la Puente, R. Sharma, S. R. Stroberg

8.1.13 TITAN

Group Leader: Jens Dilling

TRIUMF Staff: Matt Pearson, Mel Good, Ernesto Mané, Martin Simon, Brad Schultz, Ankur Chaudhuri, Anna Kwiatkowski, Alexander Grossheim

Canadian Institutions: McGill University, University of Manitoba, York University, University of Windsor, University of Calgary

Other Countries: Germany, Switzerland, France, USA

8.1.14 TRINAT

Group Leader: J.A. Behr

TRIUMF Staff: J.A. Behr, M.R. Pearson, K.P. Jackson, Melissa Anholm, Matt Pearson, G. Gwinner

Other Countries: Texas A&M University: D. Melconian, Spencer Behling, Ben Fenker Tel Aviv University: D. Ashery

8.1.15 Ultra-Cold Neutrons

Spokespersons: Yasuhiro Masuda (KEK), Jeff Martin (Winnipeg)

TRIUMF Staff: Andrew Miller, Katrina Katsika, Tatsuya Kikawa, Akira Konaka, Thomas Linder, Charles Davis, Desmond Ramsey, William Van Oers, Larry Lee, Edgard Pierre,

Canadian Institutions: University of Winnipeg, University of Manitoba, University of Northern British Columbia, University of British Columbia, Simon Fraser University

Other Countries: Japan, China

TRIUMF