TRIUMF

Biennial Scientific Report 2013—2015

TRIUMF

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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.

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FACILITIES

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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.

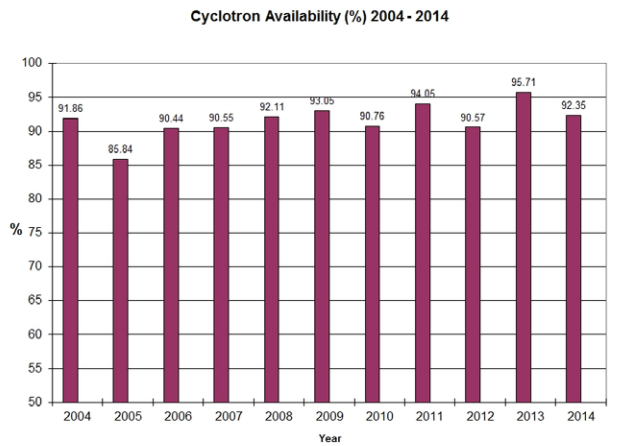

Figure 1. Cyclotron annual availability as a % of scheduled beam time for 2004–2014

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.

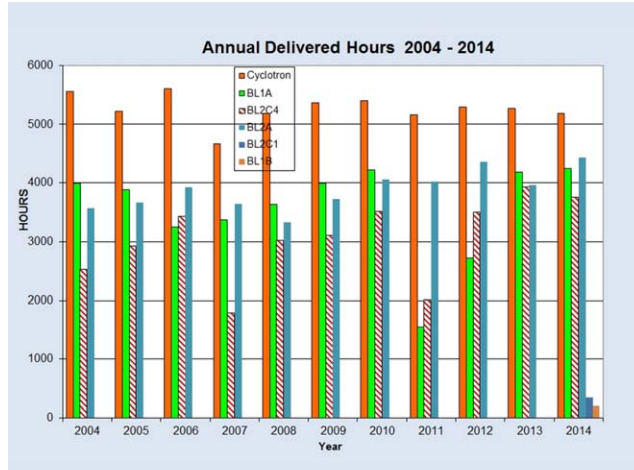

Figure 2. Beam hours delivered to the primary beam lines.

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 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

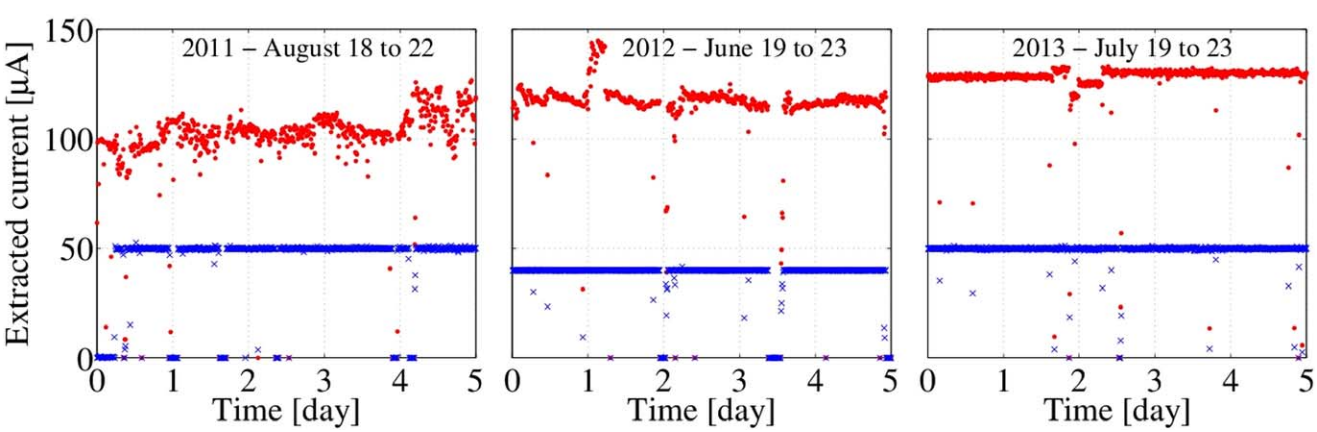

Figure 3. Beam stability improvement from 2011–2013. BL2A – blue, BL1A – red.

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.

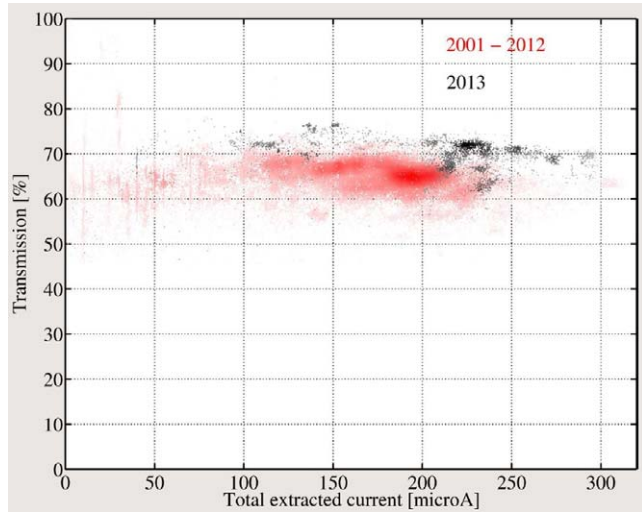

Figure 4. Cyclotron operating transmission vs extracted current BL1A – red.

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

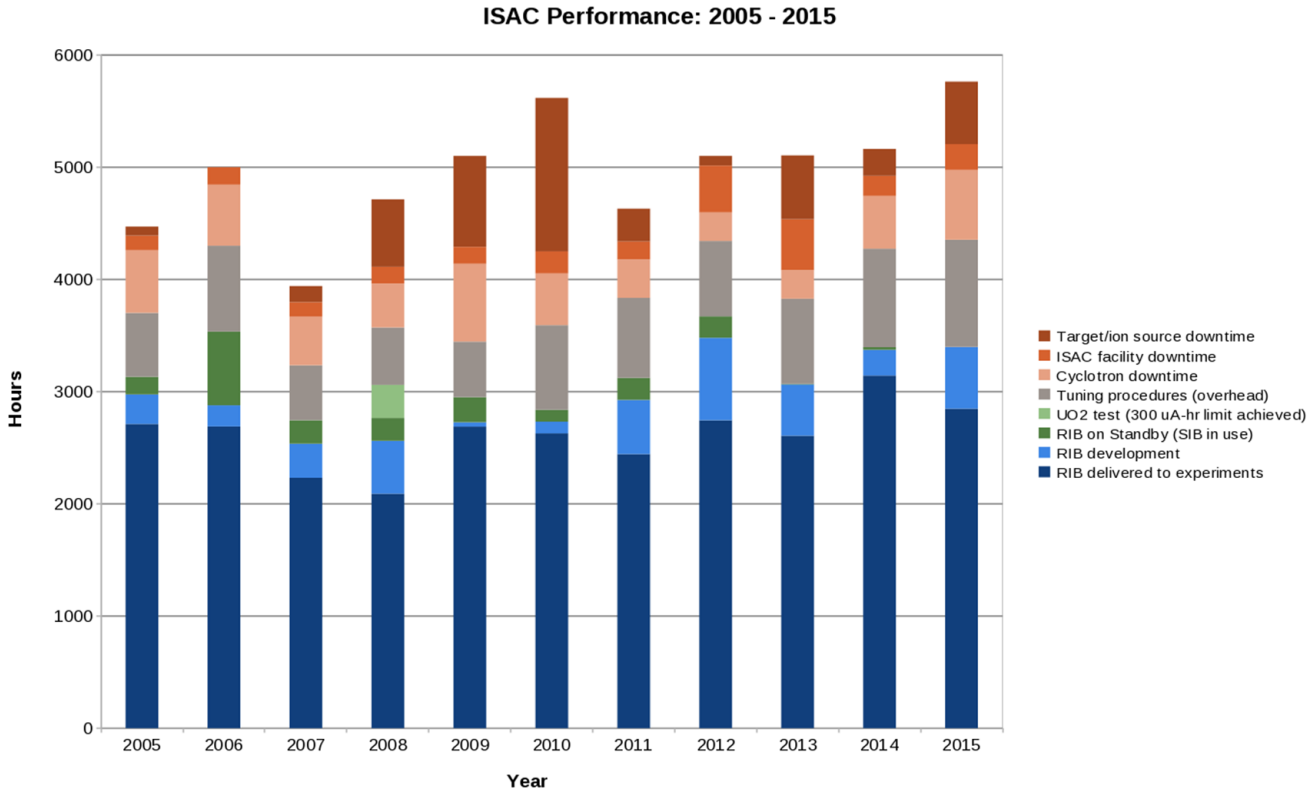

Figure 1. ISAC performance from 2005 through 2015.

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

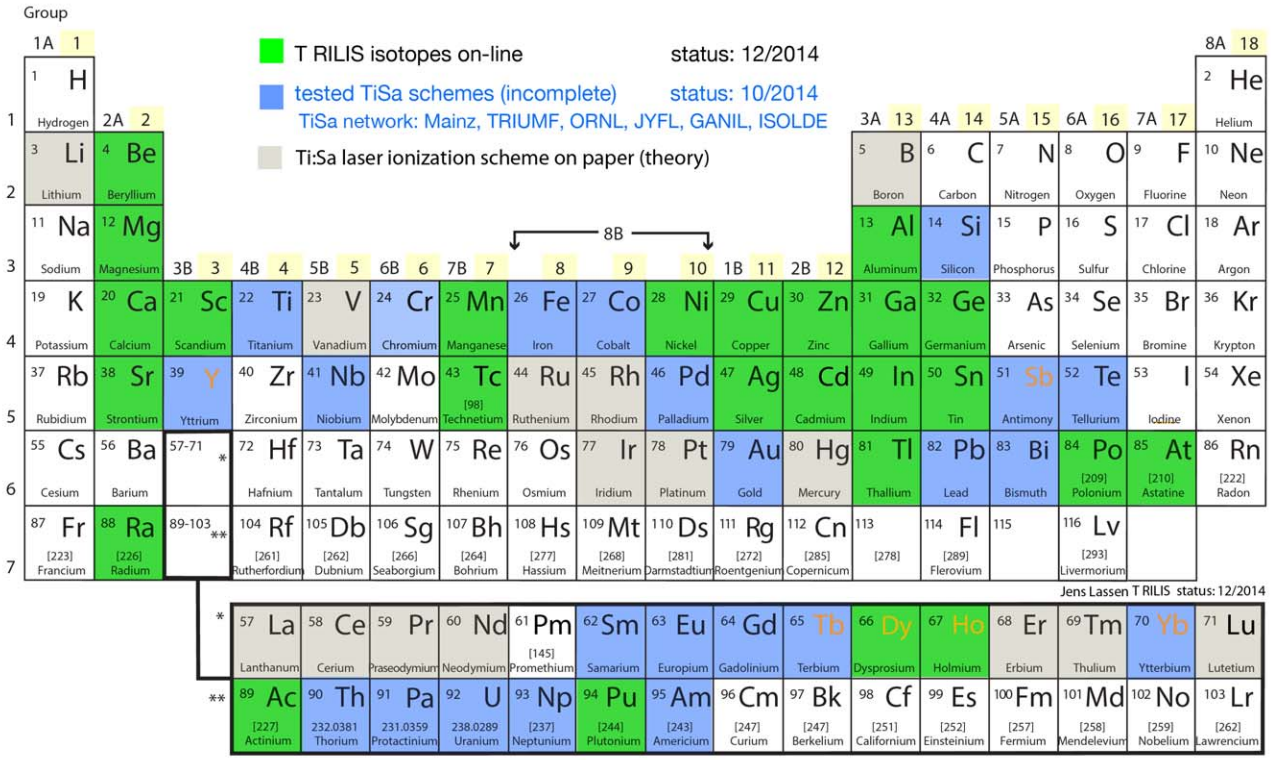

Figure 2. Elements from which radioactive isotopes have been delivered (green) to experiments at TRIUMF by use of TRILIS. Blue indicates elements for which suitable laser ionization schemes have been developed elsewhere. Orange lettering indicates that ionization schemes have been tested/developed at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

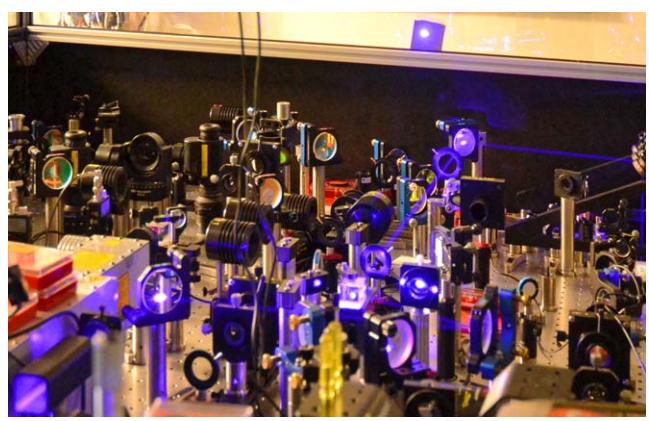

Figure 3. High-power frequency-doubled TiSa laser light in the clean room laser ion source laser laboratory.

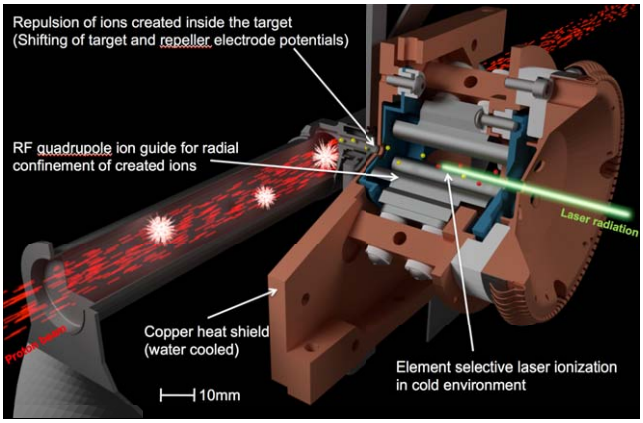

Figure 4. Section view of an IG-LIS, ion guide-laser ion source, coupled to an ISAC isotope production target.

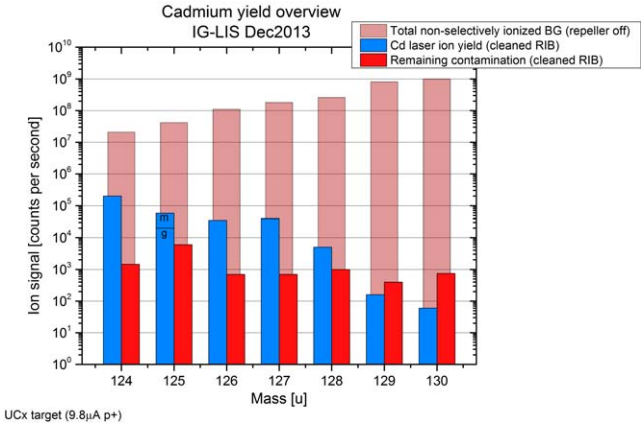

Figure 5. Increase in selectivity for Mg isotopes by suppressing surface ionized background from Na and Al isobars.

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.

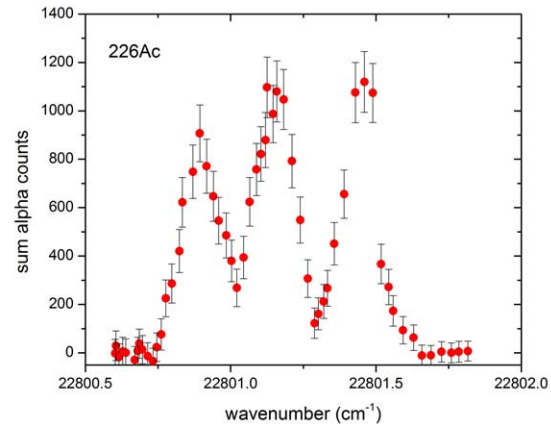

Figure 3. In-source laser spectroscopy with the ISAC Yield Station. The example shows α-decay events from the ^{226}Ac decay chain as a function of laser detuning, revealing the hyperfine structure in the first excitation step of the laser ionization scheme.

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.

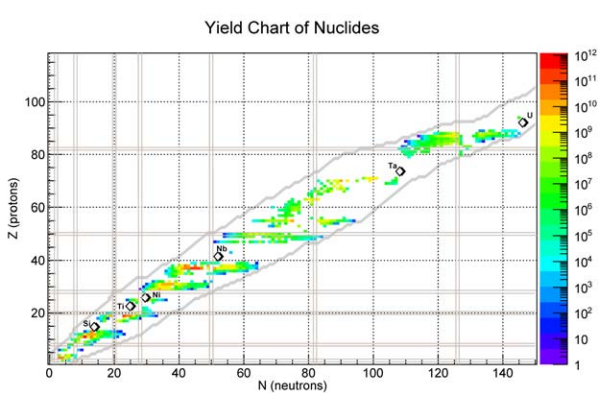

Figure 2. Isotope yields at ISAC. The colour-coded beam intensity of each isotope, defined by proton and neutron number, is given in ions/second.

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° 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.

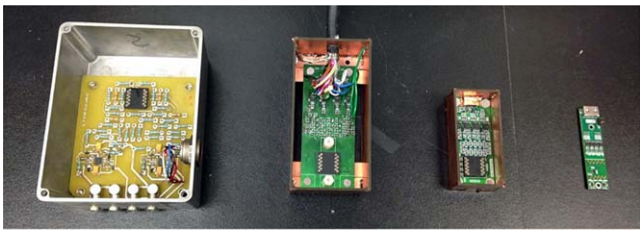

Figure 1. Detector module for the small animal PET insert for PET/MRI imaging. The first two modules on the left were designed at the University of Manitoba, while the modules on the right were designed and high miniaturized by TRIUMF Electronics Development Group.

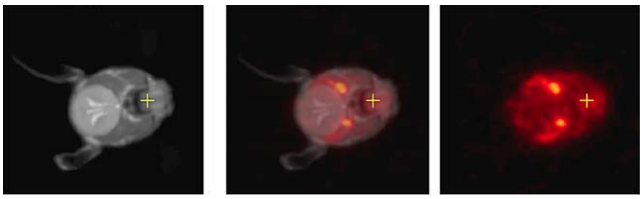

Figure 2. Image of mouse head with the MRI on the left, the PET image on the right; and the fused image in the centre.

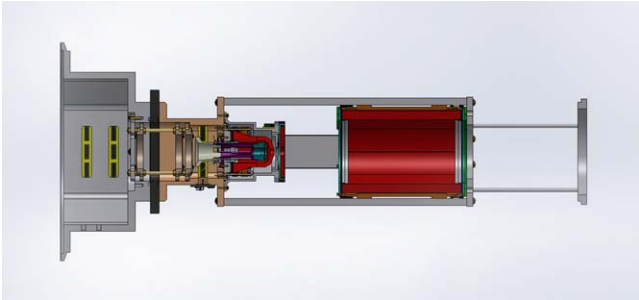

Figure 3. Side view of the 3 T spectrometer for muon spin rotation experiments. The positron counter is in red on the right-end side in its retracted position. The veto counter is the red bulbous shape in the centre. The muon counter is barely visible as a line embedded within the light blue volume in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

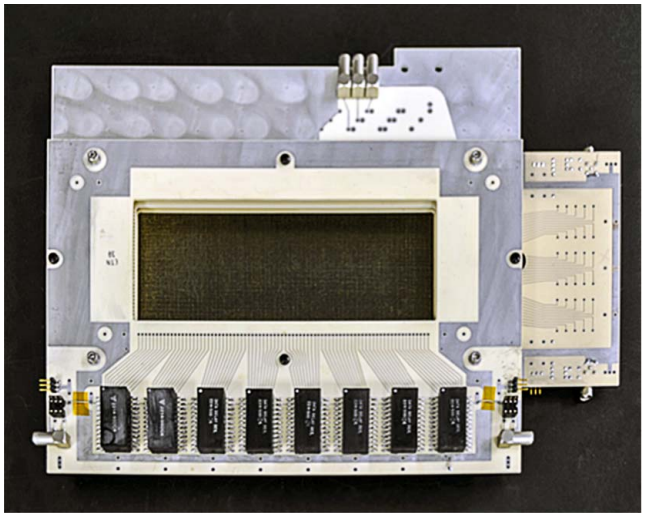

Figure 4. An assembled detector on the bench. The delay-line chips of the x-position.

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.

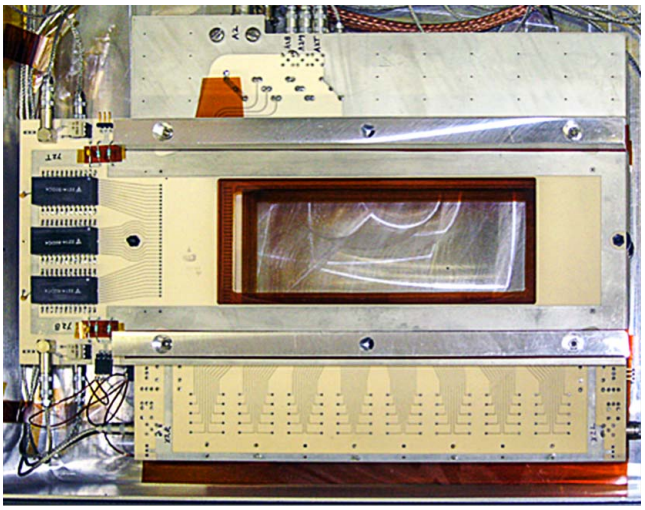

Figure 5. The test assembly installed in the PGAC box.

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.

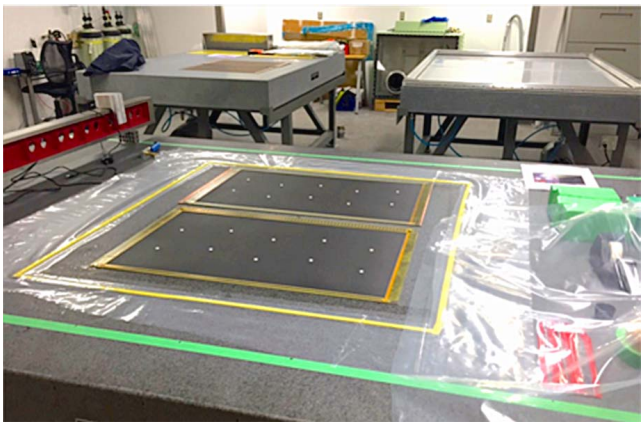

Figure 1. Sample cathode plane.

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.

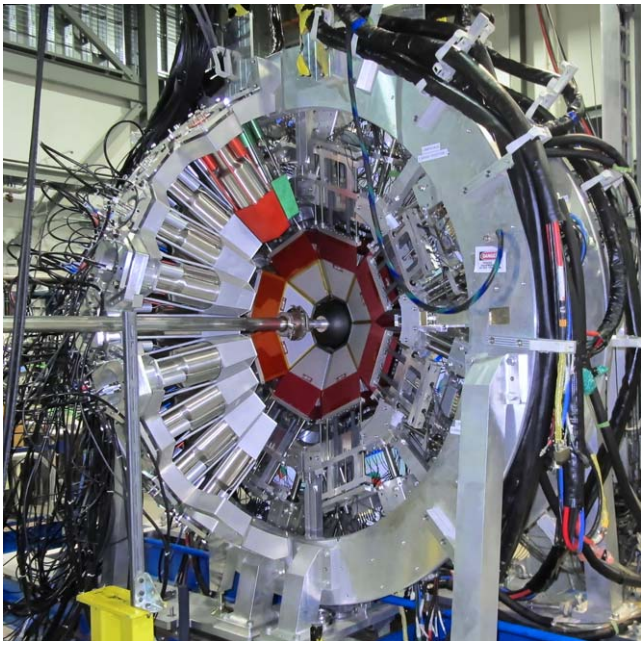

Figure 1. DESCANT and SPICE installed on TIGRESS for in-beam tests.

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.

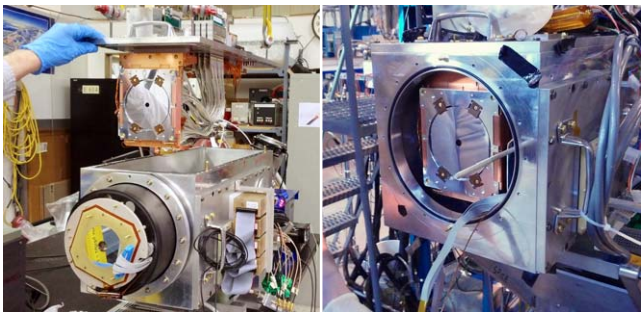

Figure 2. SPICE (left) being assembled in the detector lab, and installed on the TIGRESS beam line (right) in preparation for beam [6].

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).

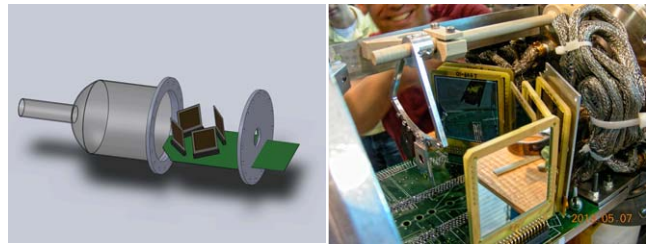

Figure 3. Engineering model of Madrid-CSM Si telescope array (left), S1202 design, shown mounted to SHARC back-flange [3,7]. S1297 configuration ready to insert into the SHARC chamber (right).

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.

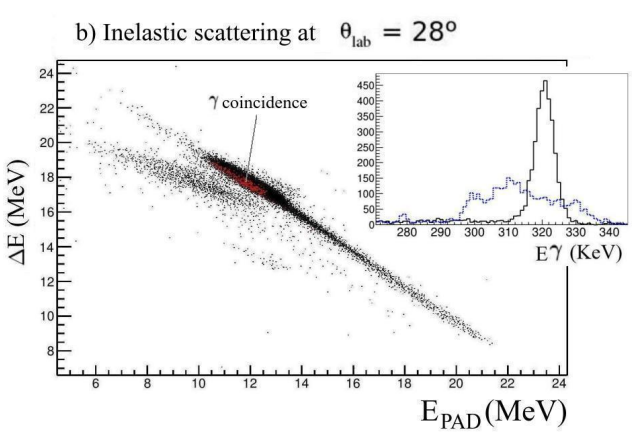

Figure 4. Typical particle-ID scatter plot and gamma-ray spectrum from S1202. The upper and lower diagonal branches correspond to ^{11}Be and ^{10}Be respectively. Red dots are from events in coincidence with the 320 keV gamma ray and fall on the same part of the ID plot as the ^{11}Be as expected. Inset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

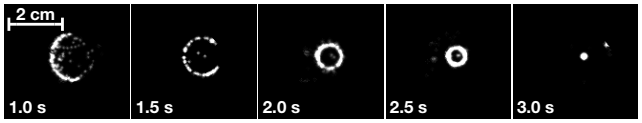

Figure 2. Time-evolved sequence of the extracted electron cloud from the CPET, recorded on the external phosphor screen. The radius decreases, indicating the cooling of the electrons in the radial direction and, hence, a reduction in overall spatial extent.

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.

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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.

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

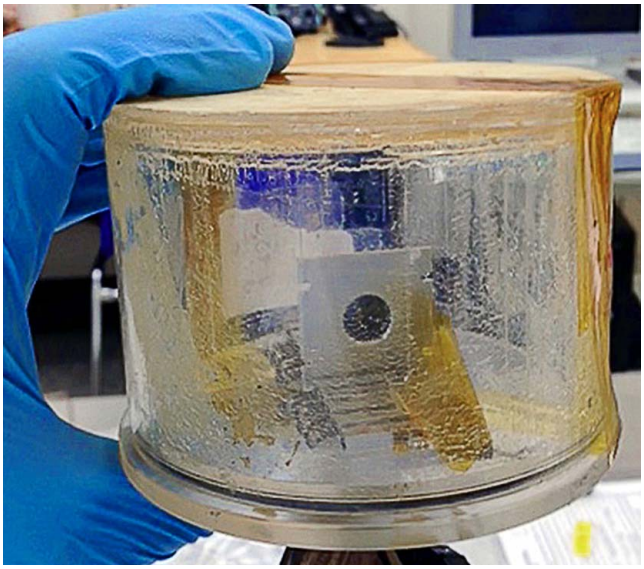

Figure 1. DLC foil implanted with 5×10^{14} atoms of ^{26}Al at the ISAC Implantation Station (IIS)

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,γ)^{27}Si and ^{25}Al(p,γ)^{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 1×10^7 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

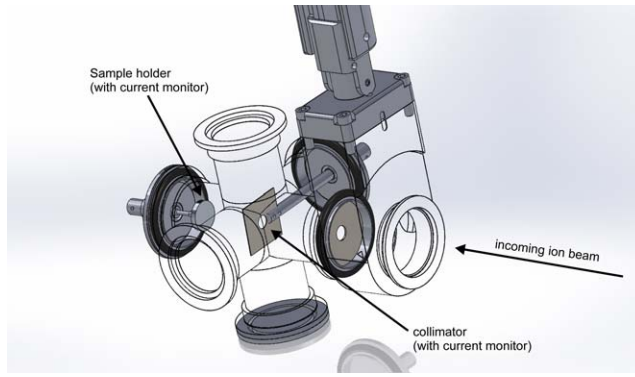

Figure 2. Collection vessel for alpha emitting isotopes.

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.

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[2] A.L. Sallaska et al., Phys. Rev. C 83 (2011) 034611
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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, discrimators, 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]

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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

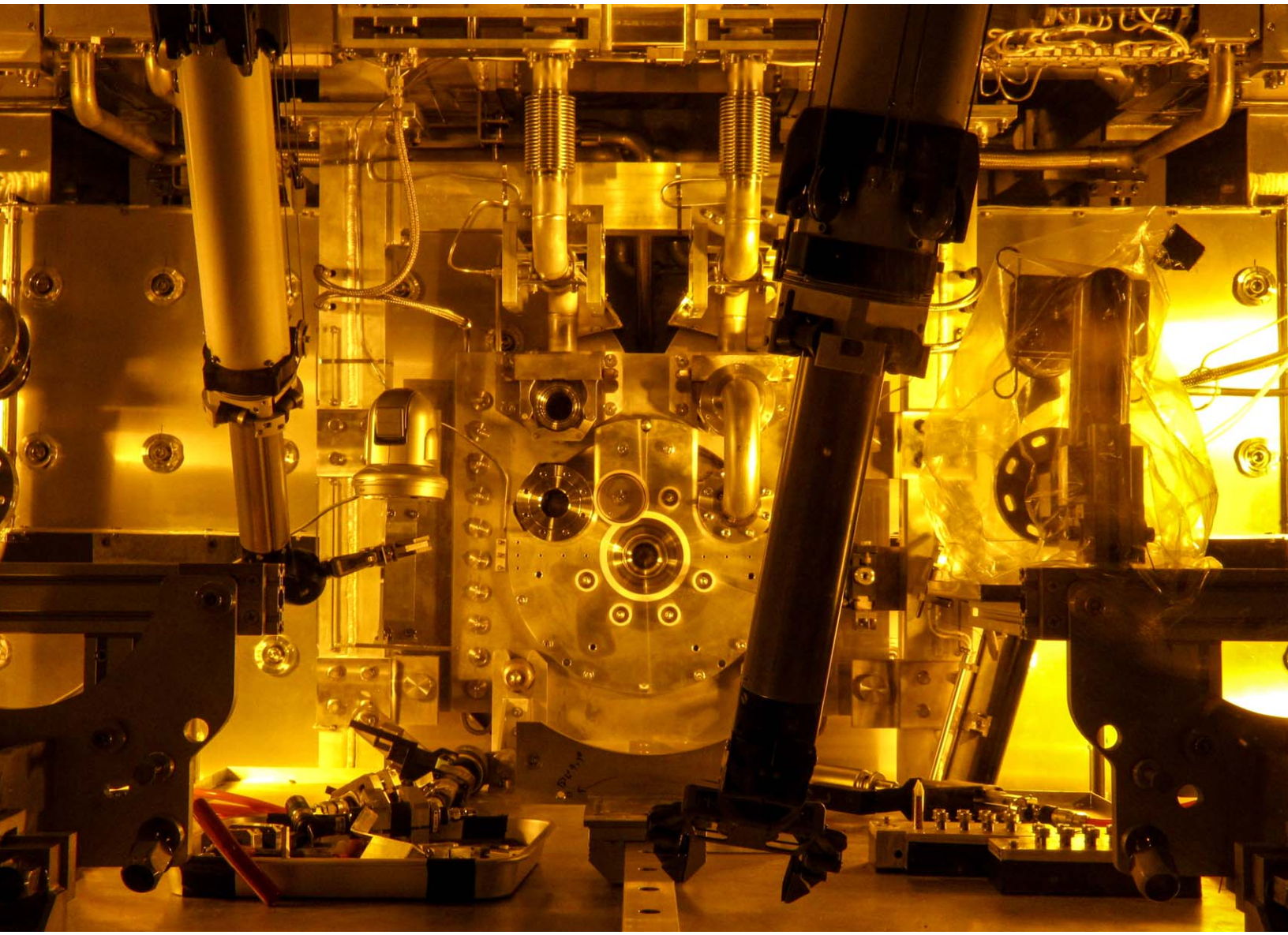
The Photosensor Test Facility (PTF) is used to measure and characterize the performance of the large-area photosensors that play a critical role in large neutrino detectors like the one used at Super-Kamiokande in the T2K experiment. The PTF allows the variation of the photosensor performance with the 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.

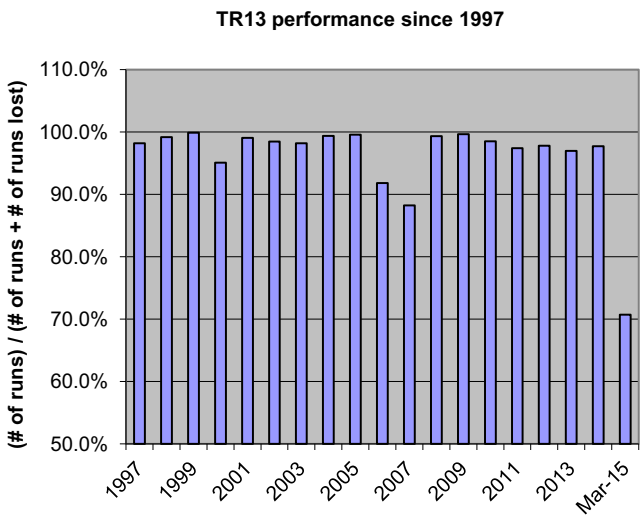


Figure 1. Reliability of the TR13 cyclotron since 1997.

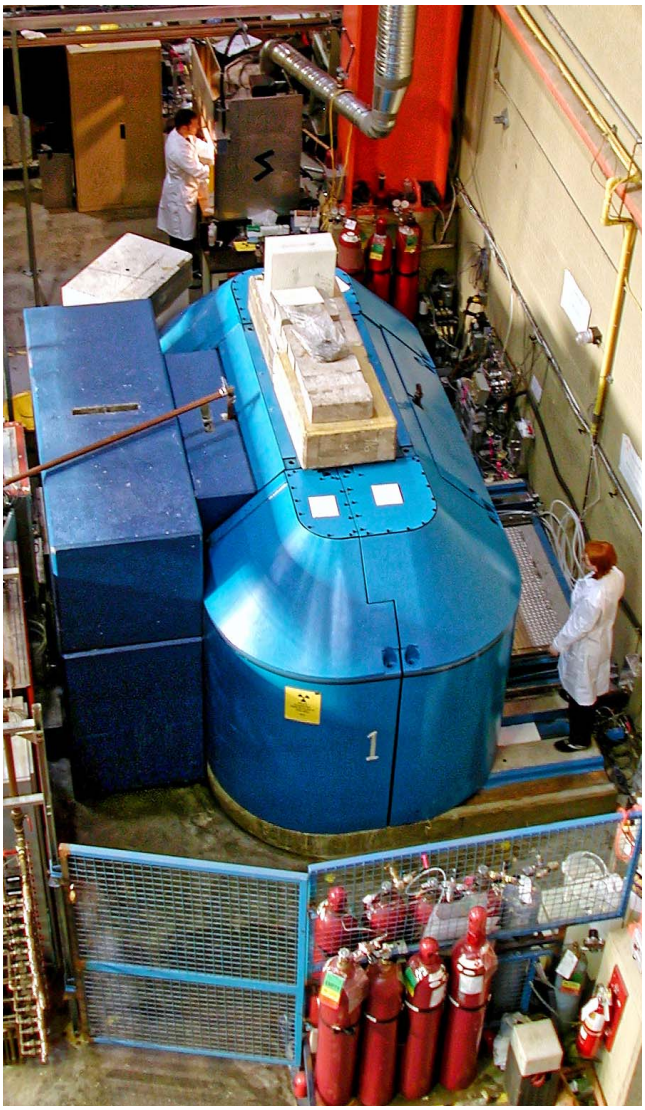


Figure 2. A photograph of the TR13 cyclotron.

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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.

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