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TRIUMF IN THE ARIEL ERA*

J. Bagger,† R. Laxdal, Y. Bylinsky, O. Kester, A. Gottberg, P. Schaffer, K. Hayashi,
S. Koscielniak, M. Marchetto and F. Ames,
TRIUMF, 4004 Wesbrook Mall, V6T 2A3, Vancouver, Canada

Abstract

The Advanced Rare Isotope Laboratory (ARIEL) is TRIUMF's flagship project to create isotopes for science, medicine and business. ARIEL will triple TRIUMF's rare isotope beam capability, enabling more and new experiments in materials science, nuclear physics, nuclear astrophysics, and fundamental symmetries, as well as the development of new isotopes for the life sciences. Beams from ARIEL's new 35 MeV, 100 kW electron linear accelerator and from TRIUMF's original 520 MeV cyclotron will enable breakthrough experiments with the laboratory's suite of world-class experiments at the Isotope Separator and Accelerator (ISAC) facility. This invited talk will present an overview of TRIUMF, the ARIEL project, and the exciting science they enable.

INTRODUCTION

For 50 years, TRIUMF has stood at the frontier of scientific understanding as Canada's leading particle and nuclear physics centre. Driven by two made-in-Canada cutting-edge accelerators – the world's largest cyclotron, and our new high power superconducting linear accelerator – we continue to ask the big questions about the origins of the universe and everything in it. TRIUMF is owned and operated by a consortium of 20 Canadian universities and is the centre for accelerator science and technology in Canada. Together with our community, our family of 20 Canadian universities, our fellow laboratories and research institutes, and our international partners, we collaborate in science and technology including the forefront of accelerator physics and technology. Funding in 2017/18 totalled \$95.2M, with sources including National Research Council (66%), private sector (11%), capital (11%) and sponsored research (12%), averaged over five years. We are well connected internationally with TRIUMF users coming from 39 countries, totalling 875 users in 2017/18 with 42% from Canada, 25% from the Americas, 17% from Asia and 16% from Europe. TRIUMF's research portfolio ranges from particle and nuclear physics to the material and life sciences, and includes research translation to the commercial arena. The experimental program in 2017 included 27% of users in nuclear physics, 22% commercial irradiation, 18% materials science, 14% particle physics, 8% life science, 6% theory, and 5% accelerator.

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† email address bagger@triumf.ca

TRIUMF HISTORICAL VIEW – 50 YEARS YOUNG

2018 marks an important anniversary year for TRIUMF as the initial funding for the project was received 50 years ago in April 1968. The milestone offers a meaningful moment to look backward at our history. By the early 1960s a major fraction of Canada's nuclear physicists were graduates of UBC, with active nuclear physics (NP) groups of their own. By 1964, the NP faculty at UBC decided that it was time to replace the Van de Graaff by a higher energy accelerator offering wider experimental opportunities. It was agreed that a joint project be proposed, combining input from UBC, University of Victoria (UVic, formed 1963) and Simon Fraser University (SFU, then nearing completion). Various proposals were considered but emerging as a front runner was the 550 MeV proposal for an H^- cyclotron by Richardson and colleagues [1] at UCLA, which stood out for its operational versatility and flexibility through simultaneous extraction of several proton beams over a wide range of individually variable energies, and for its 100% duty factor. Since UCLA could not secure funding Richardson (a Canadian) agreed that UBC would be an appropriate site, but the energy was scaled down to 500 MeV to meet funding expectations.

The project was named the Tri-University Meson Facility (TRIUMF) and a proposal was submitted in November 1966. The cost was estimated at \$19M (≈\$145M today), greatly exceeding any previous university research project in Canada. As noted above, federal approval was announced in April 1968 with a now four-university collaboration (University of Alberta had joined in 1967). Construction of the cyclotron (see Fig. 1) culminated in beam commissioning in the latter half of 1974.

On Dec. 15, 1974 the long-awaited goal of 500 MeV was reached and within hours the beam was extracted down an

Figure 1: Staff on the lower magnet (Jan 1972). Note the single aluminum coil (with V-shaped connectors) and the studs along each magnet edge for the steel shim plates.

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external beamline to a scintillator screen – a great demonstration of the simplicity of extraction by stripping. 37 years later, the first 500 MeV proton beam extraction from the TRIUMF cyclotron was cited by the IEEE as a major engineering milestone.

TRIUMF's early years were marked by physics, but also by the pursuit of a new project on an expanded TRIUMF campus, the KAON Factory. The project comprised a series of 5 rings, two for acceleration and three for bunch manipulation, to produce a high intensity (100 μA) beam at 30 GeV with the TRIUMF cyclotron as injector [2]. A PDS report was published in May 1990, and although funding for significant hardware development was awarded, full funding was never realized despite significant global interest. Eventually the project would be realized in Japan as J-PARC.

More successful was the proposal to evolve TRIUMF into a centre for radioactive ion beam research. ISAC was funded in June 1995 and the first proton beam on target followed in May 1998 [3]. ISAC first delivered radioactive beams to experiments on Nov. 28, 1998. First accelerated radioactive beam from the RFQ/DTL was delivered in March 2001 [4]. In 2000, TRIUMF began a Superconducting RF (SRF) program culminating in the addition of 20 MV of heavy ion SRF acceleration to ISAC in 2006, with the addition of a further 20 MV utilizing made-in-Canada Nb cavities in 2010 [5].

The ARIEL proposal represented a major expansion of the TRIUMF radioactive beam program. It was first discussed in 2008, resulting in the first accelerated electron beams from a new superconducting electron linac in Sept. 2014. Today, two new target stations – one for RIB production from electrons and one from RIB production from protons – are being engineered for greatly expanded scientific capability starting in 2019.

Along the way TRIUMF has made significant contributions to external collaborators including HERA, LHC and J-PARC, created active life science and material science programs, and advanced local industry through various initiatives, chief among them the development of ACSI as a commercial industrial cyclotron provider.

TRIUMF TODAY

The present fleet of accelerators and types of accelerator technologies at TRIUMF is impressively varied. Within one facility there are several high intensity H^- cyclotrons, an array of heavy ion linacs including a room temperature RFQ linac, a variable energy drift tube linac, a 40 MV superconducting linac, as well as a MW class superconducting electron linac, all shown in Fig. 2. Particle intensities set specifications for beam diagnostics and beam handling and range from a few 10s per second in ISAC to the mA range for protons and electrons.

The 520 MeV H^- Cyclotron

TRIUMF's core accelerator is a sector-focussed H^- cyclotron capable of delivering four independently controllable proton beams at energies from 70 to 520 MeV with a total current of up to 300 μA. The cw operation and the

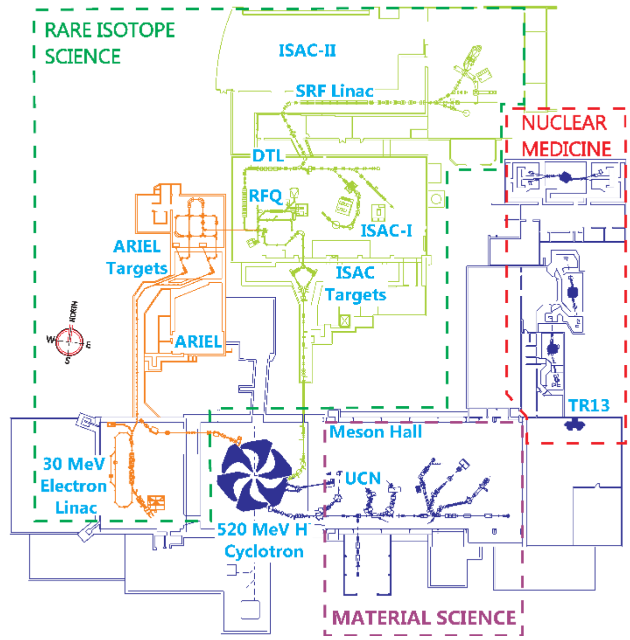

Figure 2: The TRIUMF campus.

flexibility provided by multiple beam extraction and variable energy have enabled continuous scientific productivity.

The cyclotron's 4000-tonne magnet is composed of six separate sectors, radial near the centre, but increasingly spiraled at large radii. The extreme 70° spiral angle is necessary to provide sufficient vertical focusing at ~500 MeV because the top field is constrained to be below 0.56 T to avoid Lorentz stripping. H^- ions are produced in an external cusp source mounted in a Faraday cage raised to 300 kV by a Cockcroft-Walton HV supply. The 300 keV H^- beam is transported via a 46 m long electrostatic beam line and injected vertically into the cyclotron centre region through a spiral inflector. Acceleration utilizes the 5th harmonic rf (23.055 MHz), with 80 resonator segments arranged above and below the median plane to define an accelerating gap (Fig. 3).

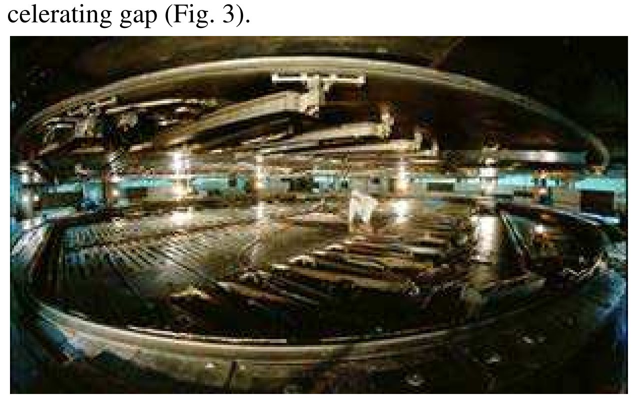

Figure 3: Inside the vacuum tank with lid raised– showing the 80 rf resonator segments fixed to the base and lid, and (right) one of the long 4.2 K cryopanels.

A dee voltage of 95 kV is achieved in push-pull mode yielding a maximum energy gain/turn of ΔE = 380 keV. From 300 keV to cyclotron extraction, transmission of 70% is regularly achieved.

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RARE ISOTOPES AT TRIUMF – ISAC FACILITY

TRIUMF operates the rare-isotope beam facility ISAC, which provides intense beams of short lived isotopes in the energy range from 0.15 to 6 MeV/u for A/Q < 30 to a full suite of world-class experimental apparatus, enabling a forefront research program focused on understanding the evolution of nuclear structure towards the limits of existence, elucidating the origin of the chemical elements in the universe, searching for physics beyond the standard model of particle physics, and characterizing magnetic properties of new materials at surfaces and interfaces.

ISAC RIB Production

The TRIUMF's rare-isotope beam facility, ISAC, provides a wide variety of intense beams of exotic short-lived isotopes using the Isotope Separation On-Line (ISOL) method. Currently, there exist several ISOL-type facilities worldwide that can produce RIBs by either spallation reactions initiated by high-energy protons, such as ISAC (500 MeV protons) and ISOLDE-CERN (1.4 GeV protons) [6], or by fission products generated inside of actinide targets irradiated by low-energy protons, such as SPES (40 MeV) [7] or RISP (70 MeV) [8]. ISAC, however, is the highest power ISOL facility worldwide (50 kW), with proton beam intensities of up to 100 μA impinging on one of two high-power target stations to produce radioactive isotopes. Targets used at ISAC range from compound materials (e.g. SiC, TiC, ZrC) and metal foil targets (e.g. Ta, Nb), to actinides (e.g. UCx, UO_2, ThO_2). ISAC targets are operated at high temperatures (up to 2000°C) to enhance the diffusion of radioisotopes from the target material to an adjoined ion source where they are ionized, before being extracted, mass separated and delivered to the low-energy experimental area in ISAC I, or further accelerated in the ISAC post-accelerator.

ISAC Post-Accelerator

Linear accelerator technology was chosen for the ISAC post-accelerator based on efficiency, flexibility and high beam quality. All machines were developed, designed and assembled at TRIUMF with components sourced primarily from Canadian industry. The ISAC post-accelerator performance and flexibility make it arguably the leading RIB post-accelerator in the world.

The RFQ does not possess a bunching section – instead a pre-buncher upstream of the RFQ focusses the beam longitudinally with an acceptance of ~80% resulting in a reduced longitudinal emittance and a shorter RFQ. The 8 m room temperature RFQ at 35 MHz accelerates heavy ions with A/q≤30 from 2 keV/u to 150 keV/u. A medium-energy beam transport (MEBT) includes a stripping foil, charge selection section and matching section to the downstream separated function drift tube linac (DTL).

The Drift Tube Linac (DTL) utilizes five interdigital H⁻ mode (IH) tanks, quadrupole triplets for periodic transverse focusing and three gap spiral bunchers (produced in collaboration with INR Troitsk) for periodic longitudinal focussing [9]. The 106 MHz DTL accelerates beams with A/q ≤ 6 from 150 keV/u up to 1.5 MeV/u for delivery to the medium-energy experimental area. The design combines the efficiency of IH acceleration with the flexibility of separated function operation to give full energy variability without sacrificing beam quality. Transmission is typically >95% [10]. Acceleration to nuclear astrophysics experiments for RIBs with A ≤ 30 is highly efficient defined primarily by the stripping efficiency (30-60%) in MEBT.

The beam can also be sent to the ISAC-II superconducting heavy ion linac for acceleration to the ISAC-II high-energy experimental area. The SC-linac consists of 40 λ/4 niobium cavities at 106 MHz and 141 MHz. The ISAC-II experimental program concentrates on nuclear physics near the Coulomb barrier. The 40 MV superconducting linac [11] provides extremely flexible beam delivery with transmission near 100%. A second stripping foil after the DTL can be added to boost the charge state and achieve higher energies at slightly lower efficiency.

An ECR charge state booster is installed in the low-energy area to boost the charge state for ions with A > 30 for subsequent acceleration. The charge breeding efficiency is a few percent. The long accelerator chain and optional strippers help filter unwanted background coming from the CSB. An EBIS charge state breeder is now being installed to improve the efficiency and purity of the charge-bred beams.

MEDICAL ISOTOPES – LIFE SCIENCES AT TRIUMF

TRIUMF has a long history of applying its science to innovations that benefit Canada and the world. Medical isotopes, often derived from nuclear reactors and critical for diagnostic imaging and therapy, can now be produced sustainably in local hospitals using medical cyclotrons equipped with TRIUMF-developed target technology. In addition to the 520 MeV cyclotron, there are four industrial cyclotrons operating on the TRIUMF site: two TR30s and a CP-42 that TRIUMF operates for Nordion for radioisotope production, and a TR13 that produces isotopes for UBC hospital PET centre and the BC Cancer Agency. TRIUMF will soon add a TR24 to its fleet, which will be the anchor machine for a new Institute for Advanced Medical Isotopes (IAMI) that will contain additional radiochemistry, chemistry and quality control laboratories (see below).

TRIUMF's recent work on the cyclotron production of ^{99m}Tc offers a compelling case study of the way in which accelerators can shift medical isotope production and distribution around the world. ^{99m}Tc is typically obtained from the in-situ decay of ^{99}Mo in a ^{99}Mo/^{99m}Tc generator. The parent isotope, ^{99}Mo, is typically produced in nuclear reactors by fission from ^{235}U. Motivated by issues concerning the reliability and then closure of Canada's NRU reactor, a consortium of Canadian partners, led by TRIUMF, developed a direct on-target production of ^{99m}Tc using medical

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cyclotrons [12]. During proton irradiation, the molybdenum target undergoes transmutation via the ^{100}Mo(p,2n)^{99m}Tc reaction. This approach provides a route to produce and distribute ^{99m}Tc (with a half-life of 6 hours) in a decentralized model. In January 2015, the team demonstrated a process that enables the routine production of sufficient ^{99m}Tc to satisfy the daily demand for a population the size of British Columbia – or 500 to 1000 patients – from a single six-hour run on a common brand of medical cyclotron. It is estimated that 550 operating commercial cyclotrons already installed globally are capable of producing appreciable quantities of ^{99m}Tc using this technique. A TRIUMF spin-off company, ARTMS Products, Inc. is commercializing the technology.

THE FUTURE OF TRIUMF - ARIEL

Although ISAC offers world-leading production capability, only one RIB beam is available at any one time. Therefore, all but one of the fifteen experimental stations are idle during RIB delivery. The single-user mode for RIB delivery is typical in all ISOL facilities worldwide due to the low intensity of the exotic beams and the complexity of production.

The ARIEL project [13] was conceived to provide a three-fold increase in the RIB delivery hours for the existing ISAC experimental facilities. ARIEL will add two new independent production targets and two new driver beams (one electron and one proton) to augment the existing production via protons at the ISAC target station. Beams will be produced in ARIEL and then sent via mass separators and low-energy beamlines that connect to the ISAC facility. Presently the ARIEL building is complete. A new high intensity electron linac (up to 10 mA) with 30 MeV capability (upgradeable to 50 MeV) has been installed and is being commissioned. A target station for producing RIBs through photofission is being designed for commissioning in 2020. By 2022 a new proton beamline will be added (BL4N) from the 520 MeV cyclotron and the second new target area will be outfitted with target modules and support facilities. Figure 2 shows the TRIUMF accelerator facilities with the 520 MeV cyclotron, existing proton beam lines, and the ISAC facility, as well as the ARIEL infrastructure highlighted in red.

RIB Production in the ARIEL Era

TRIUMF's users' demand for more and longer RIB times is constantly increasing each year, calling for a rigorous selection process and posing challenges in beam time allocation. The new ARIEL facility will address this issue and expand the RIB program at TRIUMF significantly. At the heart of ARIEL is a 10 mA, 30 MeV electron accelerator that will power RIB production in ARIEL electron target east (AETE) via photo fission using bremsstrahlung photons generated in an electron-to-gamma converter upstream of an actinide target. Worldwide, only one other facility uses the same process for RIB production, ALTO, but at considerably lower power of up to 500 W [14]. ARIEL's e-linac can be upgraded to electron beam energies of up to 50 MeV. However, looking at fission rates, the process begins to reach saturation at 35 MeV. The ARIEL target infrastructure will also include an ARIEL proton target station west (APTW) receiving 500 MeV protons at up to 100 µA, coupled to a target station for symbiotic medical isotope production (see Fig. 4).

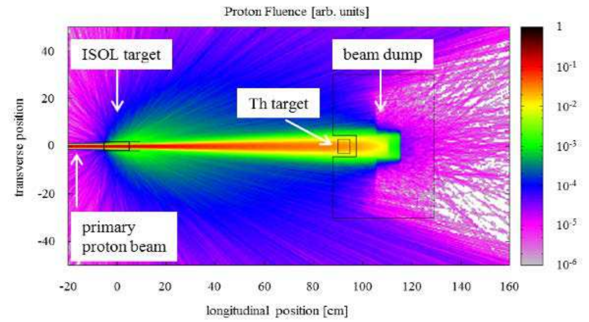

Figure 4: The symbiotic medical target designed to harvest protons that pass through the ISOL target before the beam dump.

Both target stations are designed using the established modular system, handled via a remote-controlled crane; they will be heavily shielded to allow for target hall occupancy during beam operation for optimum use of infrastructure. The target exchange time will be significantly decreased as compared to ISAC. A new concept, based on a direct target exchange at the target station, and not in a hot cell, is being developed. This new concept not only decreases the target exchange time significantly, but also prevents the modules from damage and degradation due to frequent moves. An additional symbiotic/parasitic medical target irradiation station, designed to harvest protons that pass through the ISOL target, as shown conceptually in Fig. 4, will allow for the co-production of hundreds of potentially relevant medical isotopes.

E-Linac

The ARIEL electron linac [15] is housed in a pre-existing shielded experimental hall adjacent to the TRIUMF 520 MeV cyclotron that was re-purposed as an accelerator vault (see Fig. 2). The e-linac as conceived consists of five 1.3 GHz superconducting nine-cell cavities housed in three cryomodules, with one single-cavity injector cryomodule and two double-cavity accelerating cryomodules. The e-linac is being installed in a staged way with the stages shown schematically in Fig. 5.

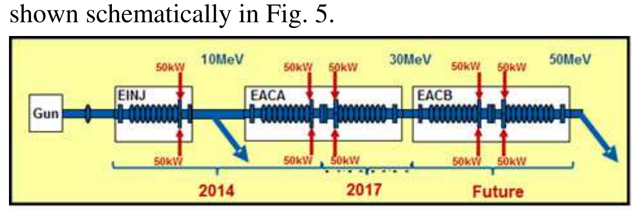

Figure 5: A schematic of the e-linac showing the installation stages.

A first phase, consisting of a 300 kV, 10 mA electron gun, an injector cryomodule (EINJ), and an accelerating cryomodule (EACA) with just one accelerating cavity on

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board plus interconnecting beamlines, was installed for initial technical and beam tests to 23 MeV in 2014. An upgrade that added a second 1.3 GHz nine-cell cavity to EACA was completed in 2017. This stage is designed to accelerate in continuous-wave (cw) mode up to 10 mA of electrons to 30 MeV, but the initial production targets will only be compatible with 100 kW operation. A future phase, pending funding, will see the addition of a second accelerating module and a ramp-up in beam intensity to the full 50 MeV, 0.5 MW capability.

An rf frequency of 1.3 GHz is chosen to take advantage of the considerable global design effort at this frequency both for pulsed machines (ILC) but also for cw ERL applications. The linac architecture was determined by the choice of final cw beam power and the available commercial cw rf couplers at the design rf frequency of 1.3 GHz. The CPI-produced coupler developed with Cornell for the ERL injector is capable of operation at ~50 kW cw. The cavity design considers the use of two CPI couplers per cavity delivering a total of 100 kW of beam loaded rf power. This sets a maximum gradient per cavity at 10 MV/m for the maximum beam intensity of 10 mA. A total of five cavities is required to reach 50 MeV and 0.5 MW beam power. To leave open the possibility of a future ERL ring with injection and extraction between 5-10 MeV, the design employs a single cavity off-line injector cryomodule plus two 2-cavity accelerating modules. The angular off-set between the injector and the main linac allows accommodation of the future ring.

CANREB

Purification and preparation for post acceleration of rare isotopes at ARIEL is being done within the CANREB (CANadian Rare isotope facility with Electron Beam ion source) project. The beam of rare isotopes will first be sent through a pre-separator and afterwards through a high resolution mass separator. With a resolving power of $M/\Delta M$ = 20,000, it will be possible to separate the desired isotope from isobaric contamination for many cases. The separator uses two 90° magnetic dipoles with a bending radius of 1.2 m and an electrostatic multipole corrector in between. It is located on a high voltage platform, which will allow an additional boost in energy to facilitate the separation and cleaning from non-isobaric components in the beam. The limited efficiency and background contamination experienced with the ISAC ECR are being addressed by installing an EBIS charge breeder. Ions are injected into a gas filled RFQ cooler buncher and bunches are injected into the EBIS for charge state breeding. The bunch repetition time is set to 10 ms. This will enable operation also with short lived isotopes. To guarantee high efficiency for the entire mass range, the EBIS is designed to operate at an electron beam density of up to 20,000 A/cm^2 with a magnetic field of 6 T. A drawback is the pulsed operation mode, which can cause pile up in some experiments, and the limitation in total beam intensity given by the buncher, which is at about 10^7 ions per bunch.

IAMI

IAMI will soon be built on TRIUMF's campus and is intended to provide a hub for seamless collaboration on the generation, processing, purification, testing, and regulatory oversight [via Good Manufacturing Protocol (GMP) production] of known and new medical isotopes. IAMI's isotopes will be used as radiotracers, radiopharmaceuticals, and radiotherapeutics; for discovery and clinical research; or for commercial product development intended for life sciences applications. IAMI will leverage TRIUMF's unique capabilities in advanced accelerator technologies that have potential applications to better life. Built around a state-of-the-art dual-beam TR24 (15-24 MeV) >500 μA H^- cyclotron, capable of irradiating gas, liquid and solid targets, IAMI will be a >2500 m^2 facility with adjoining laboratories capable of producing isotopes for both research and clinical use. These laboratories are also designed to accept targets and isotopes from any of TRIUMF's other isotope production sites (520 MeV IPF, ARIEL, etc.) and enable access to a broad range of novel and/or rare isotopes that could find use in medical imaging or radiotherapeutics of the future. Examples include a repertoire of mostly metallic radionuclides [16], such as ^{225,224}Ra, ^{225}Ac, ^{213,212}Bi, ^{212}Pb, ^{211}Rn, ^{211}At, ^{119}Sb, ^{90}Nb, ^{44}Ti.

TRIUMF INNOVATIONS

TRIUMF Innovations focusses on the business of science. It is TRIUMF's commercialization arm, dedicated to linking cutting-edge science and technology to tangible business opportunities. TRIUMF Innovations acts as a connector to the business world by providing market opportunities for physics-based technologies that emerge from the TRIUMF network – by streamlining access to TRIUMF's world-class expertise and infrastructure, and by connecting TRIUMF researchers and technologies to the world via industry partnerships, licensing, and business development. Since 2010, TRIUMF Innovations has helped five spin-off companies successfully go to market, with more in the pipeline. TRIUMF Innovations helps TRIUMF start-ups navigate complex intellectual property management, assisting with patent filings, invention disclosures, fundraising, partnering and investment.

SUMMARY

TRIUMF has a rich history. It continues to make significant contributions to science, technology and society, and is poised for an even brighter future. This summer, July 16-20, TRIUMF celebrates Science Week with events that celebrate the lab's 50-year history as well as its plans for the ARIEL era. We look forward to welcoming alumni, colleagues and collaborators to TRIUMF for this event.

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