TRIUMF IMPLEMENTATION PLAN 2020-2025

TRIUMF

ACKNOWLEDGEMENTS

TRIUMF's activities are supported through a combination of public funds, revenues generated from commercial activities, and contributions received through scholarships, awards, and philanthropic donations. Our discoveries and innovations wouldn't be possible without the contributions made by our global network, which includes member universities, partner laboratories, our user community, private sector partners, and community organizations. We are deeply grateful to all those who help us push the frontiers of knowledge and harness its power for the benefit of all. Together, we're unlocking a universe of possibilities for Canada and the world.

Learn more about our plan at https://fiveyearplan.triumf.ca

Photo credit: Trisha Dickins

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INTRODUCTION

Our Five-Year Plan lays out a vision for TRIUMF for the next five years and the decades beyond. It is designed to maximize our impact, build on our existing strengths, and capitalize on emerging opportunities. To achieve these objectives, our plan invests in three critical dimensions:

SCIENCE AND TECHNOLOGY

TRIUMF's multidisciplinary expertise and state-of-the-art infrastructure enable the Canadian science and technology community to carry out internationally recognized cutting-edge research in a range of disciplines, from nuclear and particle physics and nuclear medicine to the life and materials sciences. Our ground-breaking discoveries extend the frontiers of knowledge.

PEOPLE AND SKILLS

TRIUMF offers a unique training ground for the next generation of science and innovation leaders. We educate students at all levels, providing them with the skills they need to drive and adapt to change, and to succeed in the knowledge economy. We broaden and deepen Canada's talent pool, with a strong focus on strengthening the STEM pipeline and increasing access for our diverse population.

INNOVATION AND COLLABORATION

TRIUMF connects science to society and Canada to the world. A central hub for discovery and collaboration, we connect leading universities and research centres across the country and act as Canada's gateway to international big science projects. Through TRIUMF Innovations, we apply science to produce technology and innovations that benefit Canada.

For each dimension, we present two primary goals and a set of strategies that will help us achieve them. The Strategic Plan describes how TRIUMF creates value and it summarizes the exciting opportunities in the ARIEL era.

This Implementation Plan provides further details on the specific activities we propose to take in support of the Strategic Plan. The initiatives included here have been selected as the highest priorities for the laboratory from a larger pool of proposed initiatives. The selection process was guided by extensive internal and external community consultation, as well as by risk assessments and opportunity analysis.

The Implementation Plan provides succinct summaries of the initiatives for reviewers of our plan as well as for the larger community. It also includes a high-level summary of the core operational budget and describes how it supports our goals and strategies.

The initiatives included in our plan are ambitious, but they can be achieved with $320M of core operational funding from the Government of Canada through the National Research Council (NRC) Contribution Agreement. In addition to these core operational funds, TRIUMF and its community will need to secure project support from Canada Foundation for Innovation (CFI), Natural Sciences and Engineering Research Council of Canada (NSERC), Canadian Institutes of Health Research (CIHR), and other sources, including provincial governments. Based on our track record, we believe we are well positioned to secure the additional funds. TRIUMF itself will contribute through the delivery of products and services for our commercial and academic customers, as well as through commercial work-for-others contracts.

In what follows, we describe the environment in which we operate. We then delve into specific initiatives that advance each of the high-level goals, and conclude with a summary of the operating budget that requires $320M of core operational funding via the NRC.

OPERATING ENVIRONMENT

As a legal entity, TRIUMF is a non-profit charity, which operates as a joint venture of 20 Canadian universities. We are accountable to a variety of public stakeholders who bring resources to the table. In addition, we interact with numerous national and international partners and collaborations, a series of external regulators, an expanding user community from 39 countries, as well as a growing number of private-sector partners, all of whom add texture to the TRIUMF network. With this diverse and complex stakeholder environment, TRIUMF must work across a wide array of interests to set priorities and execute plans.

As TRIUMF continues to grow, we must manage an increasing number of operational and project commitments in an ecosystem with constantly evolving regulatory requirements. It is in this context that TRIUMF is strengthening its governance, organizational structure, and management practices to ensure that TRIUMF will continue to thrive.

INTERNAL CONTEXT

TRIUMF is owned and operated as a consortium of 20 universities, located from Victoria to Halifax. The strategic direction of the laboratory is guided by TRIUMF's Board of Management (the Board), which is composed of delegates from our member universities plus two from the private sector. The Board oversees the activities of TRIUMF management, which has the responsibility of operating the facilities, implementing the Board's strategic vision, ensuring financial accountability, and leading the more than 500 employees who work on site.

BOARD OF MANAGEMENT

TRIUMF is a national facility with an international reach. In recent years, TRIUMF has expanded from its core competencies in subatomic physics into new fields of research, such as the life and materials sciences. As more institutions have joined, TRIUMF has built a national network that contributes researchers, students, and pathways to funding. In exchange, university members guide the laboratory's strategic direction through participation on the Board of Management and its committees.

The TRIUMF Board of Management has two types of members: full members, who are distinguished from associate members by their agreement to assume legal liability for TRIUMF, receiving voting privileges and two seats, while associate members are non-voting and receive one seat. The Board also includes two representatives from the private sector who have voting privileges, as well as several non-voting members, including a representative from the National Research Council Canada (NRC), the Chair of the Advisory Committee on TRIUMF (ACOT), the TRIUMF Director, and an appointed Secretary.

The Board sets TRIUMF's strategic direction and holds ultimate responsibility for laboratory operations. Led by an elected and rotating chairperson, the Board holds in-person meetings biannually, and also oversees TRIUMF via a series of committees (composed of Board members and external subject matter experts) who meet regularly to address operational topics, including safety, personnel, and finance.

As TRIUMF has continued to grow, the Board has come to recognize that a new structure would better enable the lab to operate effectively and efficiently. A Board-level governance committee is presently reviewing options to transition towards a competency-based Board structure, a change that would bring greater oversight and accountability as TRIUMF enters the ARIEL era. The Board intends to have the new structure in place for the beginning of the Five-Year Plan 2020-2025. The Board has also decided to pursue incorporation of TRIUMF.

TRIUMF MANAGEMENT

Over recent decades, TRIUMF has been managed as a flat organization even though the number of staff, number of visitors, and amount of grants and projects managed has steadily increased. With over 500 staff and students, more than 800 visitors annually, tens of millions of dollars in new infrastructure coming online, and an ever-growing number of external stakeholders, TRIUMF is modernizing its approach to management and is taking a number of bold steps to prepare the laboratory for the future.

Recently, two Deputy Director positions — one focused on research and the other on laboratory operations — were put in place to support the Director in delivering on TRIUMF's mission. These new roles increase the bandwidth at the leadership level, enabling TRIUMF to advance its multidisciplinary science program and drive improvements in the laboratory infrastructure, organization, and processes — all to support safe and effective operations. In addition,

TRIUMF MEMBER UNIVERSITIES

University of Alberta
The University of British Columbia
University of Calgary
Carleton University — Canada's Capital University
University of Guelph
University of Manitoba
McGill
McMaster University
Université de Montréal
UNBC University of Northern British Columbia
Queen's University
University of Regina
Saint Mary's University — Since 1802 — One University. One World. Yours.
Université de Sherbrooke
SFU Simon Fraser University
University of Toronto
University of Victoria
Western University · Canada
The University of Winnipeg
York University

project governance has been systematically improved through the establishment of a Project Management Office that monitors project commitments and has introduced new standards and tools into TRIUMF's work processes. These changes allow TRIUMF to maintain a resource roll-up for planning and executing the sizable projects that are currently underway, with a special focus on large-scale projects like the Advanced Rare Isotope Laboratory (ARIEL) and the Institute for Advanced Medical Isotopes (IAMI). TRIUMF has also established an enterprise risk management program with associated risk registries at the enterprise, divisional, and project levels, with these tools driving budget development and priorities for resource deployment and infrastructure refurbishments. The existing quality management system is also undergoing a consolidation and will be brought in line with the Canadian Standards Association (CSA) Standard N286-12 Management system requirements for nuclear facilities.

TRIUMF STAFFING

At present, TRIUMF's total staffing complement stands at over 500, ranging from scientists, postdoctoral researchers, and graduate students to engineers, technicians, tradespeople, and administrative staff. These positions are supported from a variety of sources, of which the operating funds provided through the National Research Council (NRC) make up the largest proportion. A significant number are supported by "soft money" originating from grant funding, capital, and project funds, work for others, and commercial revenues.

TRIUMF hires both continuing and term positions, ensuring that the laboratory has the right complement of skills as projects and priorities change over time. Also, TRIUMF is proactively engaged in increasing diversity across the four federally designated groups, with a particular focus on improving the laboratory's gender balance.

In April 2015, at the beginning of the Five-Year Plan 2015-2020, TRIUMF's staffing levels were affected by two competing factors: 1) the expiry of several soft funding sources; and 2) an increase in TRIUMF's operating budget — the first in ten years. As a result, TRIUMF shifted a number of staff to NRC funds, which allowed us to retain the skills we needed for certain critical projects. Following this reallocation, TRIUMF made incremental hires to critical areas such as safety, project management, and operations. Between March 31, 2016 and March 31, 2018, the total increase supported by NRC funds amounted to fewer than 20 positions. During the same time period, the total number of term positions increased by 27 (an increase of over 20%). The term positions allow rebalancing of TRIUMF's skills mix as needs evolve.

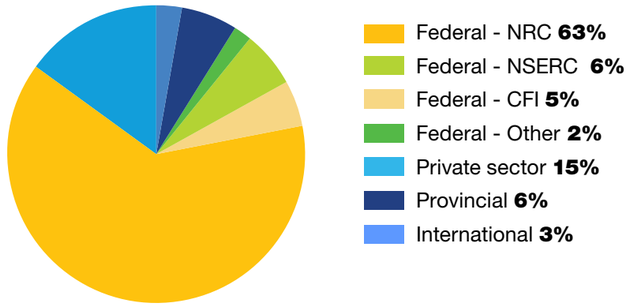
April 1, 2016 to March 31, 2018	NRC			NON-NRC			
	Continuing	Term	TOTAL	Continuing	Term	TOTAL	TOTALS
Administrative Staff	37	7	44	1	1	2	46
Board Appointed Research Scientists	47	0	47	0	0	0	47
Staff Scientists	29	5	34	1	8	9	43
Engineers	71	8	79	5	9	14	93
IST Staff	19	1	20	0	1	1	21
Technicians/Technologists	123	7	130	23	5	28	158
Facility and Site Services	17	4	21	5	7	12	33
Postdocs & RAs	0	14	14	0	35	35	49
Graduate Students	0	7	7	0	27	27	34
Faculty Joint Appointments (50% FTE)	8	3	11	0	0	0	11
TOTALS	351	56		35	93		
	Total NRC		407	Total Non-NRC		128	535

Table 1. This chart illustrates TRIUMF's staffing level as of March 31, 2018. Note that undergraduate students are not among this count, as the short-term nature of co-op placements requires that they be accounted for separately.

EXTERNAL CONTEXT

TRIUMF's success is highly dependent on its ability to navigate a complex series of partnerships across the provincial, national, and international arenas. Operating in this multidimensional space, TRIUMF engages with partners from governments, international institutions, and industry, which not only fund the laboratory, but also provide important oversight, expertise, and advice that is critical for effective and efficient operations. Managing and maintaining strong relationships with this mosaic of external partners is critical to sustaining and expanding TRIUMF's record of excellence.

TRIUMF REVENUE BY SOURCE (2015-2020)



FEDERAL GOVERNMENT

The federal government has been a critical partner since TRIUMF's inception. From providing the initial funding for construction in 1968, to supporting core operations for 50 years, the Government of Canada is TRIUMF's oldest and most important stakeholder. Today, federal involvement in TRIUMF spans across several departments and agencies, each providing targeted contributions to maintain, improve, and expand TRIUMF's capabilities for the benefit of Canada.

The NRC is TRIUMF's lead federal partner. Having managed and administered the laboratory's core operational funding for decades, the NRC plays an essential role in the funding operations through five-year contribution agreements, as well as oversight of advisory and review committees that monitor the laboratory's activities. TRIUMF's NRC Contribution Agreement represents the largest single fraction of TRIUMF's total funding (approximately 63% for 2015-2020). This funding supports most of core and continuing operations, including salaries, utilities, and other operating costs (supplies, equipment, and repairs and maintenance).

Given its large stake in TRIUMF's success, the NRC is also charged with several administrative responsibilities, including evaluating TRIUMF's performance at the end of each Five-Year Plan, participating as an ex-officio member on the TRIUMF Board of Management, an observer on the Audit Committee, and convenor of the Advisory Committee on TRIUMF (ACOT), an international group that oversees the laboratory's operational and scientific performance. ACOT advises and reports to the NRC on all aspects of the TRIUMF program insofar as they relate to the federal government's contribution to the facility.

At the highest level, NRC also coordinates the Agency Committee on TRIUMF (ACT), a deputy minister-level committee that is responsible for stewarding the federal investment in TRIUMF and ensuring that economic benefit is derived from this commitment, with a focus on management, financial, and commercialization matters. NRC, Innovation, Science and Economic Development Canada (ISED), and the Natural Sciences and Engineering Research Council (NSERC) constitute ACT's core members. Additional federal stakeholders — such as the remaining Tri-Council Agencies, the Canada Foundation for Innovation (CFI), Western Economic Diversification Canada, and Health Canada — may also be invited to participate in ACT meetings upon invitation from the NRC President, the chair of the committee.

Complementing NRC's role in TRIUMF's operations, the Government of Canada also supports research, primarily through competitive, peer-reviewed funding processes of the Tri-Council Agencies, which are comprised of NSERC, the Canadian Institutes for Health Research (CIHR), and the Social Science and Humanities Research Council (SSHRC). The bulk of TRIUMF's sponsored research funding flows through the NSERC subatomic physics (SAP) envelope. Projects involving TRIUMF received an average of $18M annually from 2013-2017, representing over 76% of total funding of the SAP envelope. This support allows researchers from across Canada to carry out research at TRIUMF and at other facilities around the world. A large fraction of this funding supports students and postdoctoral fellows. With increased activities in the life and materials sciences, more TRIUMF researchers are securing NSERC grants outside the SAP envelope. Furthermore, although NSERC is TRIUMF's primary research sponsor, in recent years the laboratory has also collaborated on projects funded by the other Tri-Council Agencies, a fact that illustrates TRIUMF's growing multidisciplinarity.

Beyond the Tri-Council Agencies, TRIUMF also receives research funding from other federal departments on an ad hoc basis, usually to address specific national needs or objectives. One prominent example of this occurred when Natural Resources Canada (NRCan) funded TRIUMF to lead the development and deployment of new isotope production technology to fill a critical gap left with the closure of the National Research Universal (NRU) nuclear reactor in Chalk River, Ontario. From 2010 to 2016, NRCan, via the Non-reactor Isotope Supply Contribution Program and the Isotope Technology Acceleration Program, provided TRIUMF and its partners with approximately $13M to carry out this important research for the benefit of Canada.

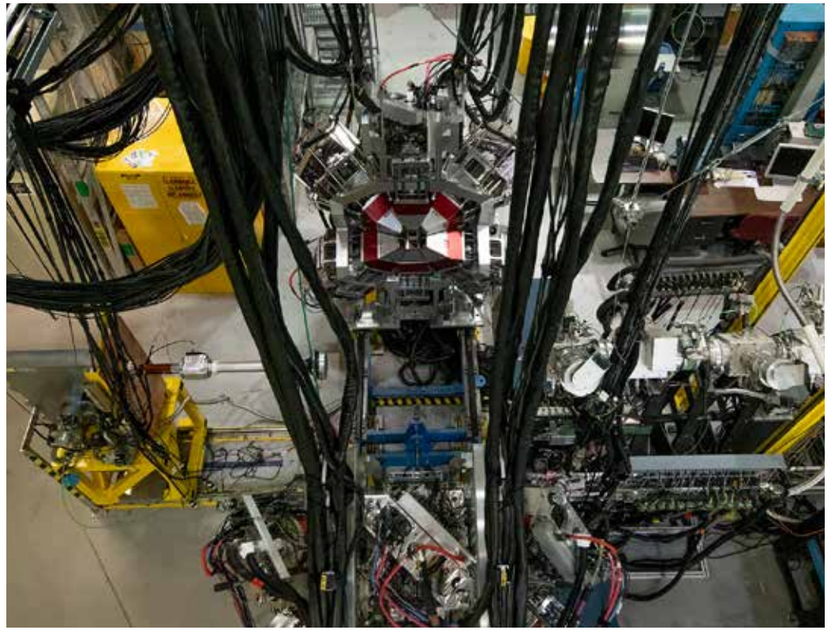


Photo credit: Rick Etkin

Alongside operations and research, TRIUMF also secures federal funding for the construction and deployment of new experimental facilities and research infrastructure from CFI, which invests in state-of-the-art research infrastructure at universities, colleges, research hospitals, and non-profit research institutions through a peer-reviewed competitive process. CFI awards typically provide up to 40% of the total project budget, and proponents must secure the remaining 60% through other sources. Provincial governments are often asked to provide 40%, and the remaining 20% may come from international, industrial, or other partners. Depending on the specifics of the project, CFI may also provide some degree of support for the initial operation of new infrastructure.

Although TRIUMF cannot apply for CFI funding, universities across Canada are eligible and often partner with TRIUMF to place infrastructure — such as ARIEL — on our campus or to leverage our talent or capabilities to build components for other facilities, such as CERN or SNOLAB. In the case of ARIEL-II, the second phase of the ARIEL project, all of the 19 member universities at the time jointly supported the funding application, each contributing a portion of their institutional envelope — a bold commitment that placed ARIEL above projects on their own campuses. Broadly speaking, TRIUMF's support for community-driven capital requests has resulted in a very high caliber of funding proposals — reflected in the 83% success rate tied to TRIUMF-related CFI proposals in 2017 — more than double the national average. The following is a list of CFI projects involving TRIUMF since 2013, totalling $81.1M in CFI contributions alone:

PROJECT NAME	COMPETITION YEAR	LEAD INSTITUTION	TOTAL PROJECT COST	CFI CONTRIBUTION
ALPHA-g: An Apparatus to Explore Antimatter Gravity with Cold Trapped Antihydrogen	2015	Calgary	$20.4M	$6.1M
Detectors for the Exploration of New Frontiers in High Energy Physics with ATLAS in the Higgs Era	2015	Carleton	$29.4M	$6.2M
ARIEL-II: Driving Scientific Discovery and Health Science with TRIUMF's Advanced Rare Isotope Laboratory	2015	UVic	$37.6M	$13.6M
GRIFFIN Compton and Background Suppression Shields	2015	Guelph	$3.6M	$1.4M
High-Momentum and High-Luminosity Muon Beamlines for Molecular and Materials Science and Fundamental Muon Physics	2017	SFU	$10.7M	$4.3M
Upgrades to the ATLAS Detector at the Large Hadron Collider	2017	Toronto	$237M	$29.8M
Ultracold Neutron Electric Dipole Moment Experiment	2017	Winnipeg	$15.5M	$5.0M
Hybrid PET/MRI: an integrated approach to the investigation of brain function in health, disease and populations at risk	2017	UBC	$10.3M	$4.1M
ATLAS Tier-1 Data Centre	2017	SFU	$8.8M	$3.5M
Rare Isotopes for Cancer Therapy	2017	UBC	$9.9M	$4.0M
Facility for Development of Cryogenic Detectors and Readout Systems for Subatomic Physics and Particle Astrophysics	2017	Carleton	$9.2M	$3.1M

Table 2. This chart shows CFI projects involving TRIUMF since 2013.

Supplementing CFI, other federal funding for capital is provided on an ad hoc basis. For example, Western Economic Diversification Canada and Infrastructure Canada occasionally provide capital funding to TRIUMF on a competitive basis, usually building on existing commitments from other stakeholders, including industry partners or provincial governments.

PROVINCIAL GOVERNMENTS

Provincial governments play key roles in supporting the development of infrastructure at TRIUMF. Since TRIUMF is situated in Vancouver, it is not surprising that the Government of British Columbia is the laboratory's largest provincial partner, supporting infrastructure investment both through a CFI-matching mechanism, the BC Knowledge Development Fund (BCKDF), and also through ad hoc processes for CFI and non-CFI projects alike. The ARIEL project benefited from both types of contributions: The ARIEL-I project received $30.7M from British Columbia through a direct allocation that supported the construction of a new experimental building, whereas ARIEL-II received an additional $8.7M investment from British Columbia directed through BCKDF.

In addition to support provided by British Columbia, it is noteworthy that other provincial governments have also directed funds to TRIUMF to support infrastructure projects involving universities within their jurisdictions. For example, Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN), the Muon Beamlines, Canadian Rare Isotope Facility with Electron Beam Ion Source (CANREB), and ARIEL-II all received support from provincial governments outside BC. Impressively, ARIEL received $9.2M from a combination of five provinces outside BC — Alberta, Manitoba, Nova Scotia, Ontario, and Quebec. The decision of these provincial governments to invest their resources in TRIUMF is a testament of the importance of the laboratory across Canada.

REGULATORY OVERSIGHT

Both federal and provincial regulatory bodies have authority over TRIUMF. The Canadian Nuclear Safety Commission (CNSC), which regulates all nuclear facilities across Canada, is our most prominent regulator. As the national authority in the field, the CNSC provides comprehensive oversight of TRIUMF's safety and environmental practices as well as security, management systems, and human performance, particularly as they pertain to the requirements of the laboratory's Class IB operating license. The CNSC conducts regular inspections of TRIUMF to ensure our ongoing compliance.

In addition to CNSC, several other authorities monitor particular aspects of TRIUMF's programs. Health Canada oversees TRIUMF's life sciences program, particularly the chemistry facilities and processes related to the laboratory's radiopharmaceutical production. WorkSafe BC and the Technical Safety BC (formerly BC Safety Authority) are our primary provincial regulators. The former is responsible for industrial occupational health and safety, while the latter oversees the installation and operation of technical and engineering systems (i.e. electrical, boilers, pressure vessels, etc.). Maintaining good relations with each of these entities, TRIUMF mandates safety as its highest operational priority.

INTERNATIONAL PARTNERS

As one of the main Canadian players on the international science stage, we are a partner of choice for major international laboratories and a strong competitor in the race for major scientific discoveries and innovation breakthroughs. By bringing the ARIEL facility online before major competitors — namely the Facility for Rare Isotope Beams (FRIB) in the US, the Facility for Anti–proton and Ion Research (FAIR) in Germany, and the Rare Isotope Accelerator Complex for On-line Experiment (RAON) in South Korea — Canada has a window of opportunity to seize global leadership and competitive advantage in this fast-moving area of nuclear and particle physics. Furthermore, as a result of this work, Canada has the opportunity to lead the world in creating new cancer curing drugs using isotopes such as ^{225}Ac.

TRIUMF competes and collaborates on the international stage to advance discovery and innovation for the benefit of Canadians. To advance the frontiers of science with world-class infrastructure and talent, it is critical that TRIUMF be closely connected to the international research community. Forging new partnerships, exchanging talent, and cooperating to realize mutually beneficial investments are all vital to TRIUMF's continued growth and relevance. Typically supported by a formal Agreement or Memorandum of Understanding (MOU), these connections keep Canada at the cutting edge. They leverage TRIUMF's capabilities and expertise to enable new science and innovation opportunities that are beyond the capabilities of a single country or facility. Examples include:

- **CERN (EUROPE):** TRIUMF enjoys a long history of cooperation with CERN, codified through a series of agreements dating back more than two decades. From overseeing Canada's contribution to the construction of the Large Hadron Collider (LHC) to supporting national participation in major experiments like ATLAS and ALPHA, TRIUMF is Canada's primary portal into the research taking place at CERN. The TRIUMF-CERN relationship continues to grow with our recent commitment to continue our collaboration and expand it to new projects related to isotope beam development and accelerator technologies. TRIUMF is also leading the delivery of the Canadian contribution to the High-Luminosity LHC (HL-LHC) upgrade.
- **VARIABLE ENERGY CYCLOTRON CENTRE (INDIA):** Since 2008, TRIUMF has worked collaboratively with the Variable Energy Cyclotron Centre (VECC) in Kolkata, India to jointly develop superconducting radio-frequency technologies for next-generation particle accelerators and rare isotope production target technologies. The TRIUMF-VECC partnership arose from common needs; both laboratories were developing advanced electron accelerators and rare isotope beam facilities. This partnership is bringing Indian researchers and engineers to Canada to help produce specialized components that will be used at both facilities. Underpinned by an MOU and three subsequent addenda, this mutually beneficial collaboration has a total value of over $16M.

- **KEK (JAPAN):** Canada and Japan have enjoyed decades of collaboration in subatomic physics, central to which has been cooperation between TRIUMF and KEK, Japan's High-Energy Accelerator Research Organization. Formal engagement dates back to 2002, with the most recent umbrella MOU between the laboratories signed in 2013. Under the current agreement, TRIUMF and KEK have strengthened cooperation not only by supporting projects in Canada (i.e. the Ultracold Neutron facility) and Japan (i.e. the T2K and Belle-II experiments), but also through the establishment of branch offices at the other's respective institution. The TRIUMF office at KEK was opened in May 2016 by Canada's Minister of Science, Dr. Kirsty Duncan, while the KEK office at TRIUMF was opened in December 2017 as part of the TRIUMF-KEK symposium, a biennial research meeting held in cooperation with the two facilities.
- **HELMHOLTZ ASSOCIATION (GERMANY):** TRIUMF has cooperated for decades with several Helmholtz centres in Germany, including DESY Hamburg, GSI Darmstadt, HZ Berlin, and FZ Jülich. The cooperation spans nuclear and particle physics, accelerator science and, most recently, a new collaboration in quantum computing and machine learning.

PRIVATE SECTOR

TRIUMF's private-sector activities are supported through a variety of mechanisms, including cost-reimbursements for services rendered, commercial transactions including royalty agreements, and partnered research agreements. TRIUMF also creates intellectual property for technologies and spin-off companies. With the recent revitalization of our innovation arm, TRIUMF Innovations, our knowledge transfer and commercialization efforts are becoming ever more important to our laboratory.

TRIUMF's activities in the area of innovation and commercialization span a number of sectors:

- TRIUMF has a 40-year partnership with the global health sciences company Nordion Inc. for the commercial production of medical isotopes. This partnership has resulted in more than 50 million patient doses shipped to patients around the world, with 9.5 million produced in the last five years. This represents roughly 15% of the isotopes that Canada exports. With the recent acquisition of Nordion's medical isotope business by BWX Technologies Inc. (BWXT), we hope to take our partnership to the next level.
- TRIUMF's expertise in the accelerator production of isotopes enabled us to provide solutions to solve a national medical crisis. In the face of an increasingly unreliable isotope supply from nuclear reactors, TRIUMF, with government support, assembled a team of experts from across our network to find a solution. We discovered a way for hospitals and radiopharmacies to produce ^{99m}Tc and other metallic radioisotopes directly on medical cyclotrons already in place around the country. Recently commercialized through a spin-off company, ARTMS™ Products, Inc., this technology offers a sustainable option for isotope security that is being implemented in several countries around the world.
- As the only proton therapy facility in Canada, we work with the BC Cancer and UBC Eye Care Centre to treat approximately 10 patients per year with ocular melanomas. We have a 91% success rate for controlling the associated tumours.
- TRIUMF technologies extend into a variety of sectors, including some that may appear surprising. For example, our spin-off company CRM GeoTomography Technologies Inc. uses TRIUMF-developed muon detectors for mineral exploration, creating 3D images that highlight the density of ore deposits. Other applications of the technology are being explored in defense and security.
- TRIUMF provides commercial users with irradiation services at our Proton Irradiation and Neutron Irradiation Facilities (PIF & NIF), a premier test site for space-radiation effects using protons and neutrons. Many of the proton users are Canadian space-related companies such as MDA, while neutron use is primarily by international companies, such as Boeing and Cisco Systems, for avionics, microelectronics, and communications equipment.

The diverse and complex stakeholder environment described above sets the scene for the specific initiatives that advance each of our high-level goals set forth in the Five-Year Plan. It also provides context for how the operating budget, with the requested support of $320M core operational funding via the NRC, fits into the larger picture.

SCIENCE AND TECHNOLOGY: SEIZING OPPORTUNITY, EXPANDING FRONTIERS

GOAL 1 **Make ground-breaking discoveries across our multidisciplinary research portfolio**

OUTCOME **Extension of the frontiers of knowledge and global recognition of Canada's contributions to discovery research**

Propelled by advances in the accelerator-based physical and life sciences, and inspired by discoveries in fields from astrophysics to medicine, TRIUMF's Five-Year Plan 2020-2025 will ensure Canadian excellence in rare isotope science, enrich our understanding of fundamental physics, and help the global scientific community make ground-breaking discoveries. With the completion of the Advanced Rare Isotope Laboratory (ARIEL) and Institute for Advanced Medical Isotopes (IAMI), TRIUMF's world-class infrastructure will enable breakthrough science across our broad multidisciplinary portfolio.

Driven forward by TRIUMF's rich expertise and international collaborations, we will tackle challenging rare isotope science problems including how heavy elements are synthesized in astrophysical environments, explore new physics beyond the Standard Model of particle physics, develop new radiopharmaceuticals for medicine, advance materials for quantum technologies, leverage TRIUMF's unique expertise in accelerator technologies to keep Canada at the forefront of international partnerships and make significant advances in the multidisciplinary utilization of data science to drive discovery and innovation.

> **"You are at the very forefront of the frontier of knowledge. And yet, you are very practical and very applied because you are solving problems that help people every day."**
>
> **HER EXCELLENCY THE RIGHT HONOURABLE JULIE PAYETTE, GOVERNOR GENERAL OF CANADA**

1.1 DISCOVERING HOW STARDUST IS MADE

With the completion of ARIEL and the existing capabilities of the Isotope Separator and Accelerator (ISAC) facility, TRIUMF will embark on an unprecedented voyage of discovery, using rare isotope science beams to help us uncover the origins of atomic nuclei. We are already a world-leading laboratory for rare isotope research, but our new ARIEL facility creates an opportunity for us to examine the properties of atomic nuclei at a capacity and sophistication that are currently unavailable anywhere else. The co-location of numerous cutting-edge experiments under one roof, combined with the availability of the variety and intensity of rare isotope beams, will attract many leading scientists from around the globe.

Central to our curiosity is the understanding that every heavy element in our universe has been forged through ongoing astrophysical processes; cooked in the cores of stars and ejected from energetic stellar events, producing stardust. This material goes on to fuel the next generation of stars, create planetary systems and, ultimately, deliver the building blocks for life. Understanding the details behind this nucleosynthesis requires the combined efforts of astronomical observations from the processes in our Sun back to the first stars in the universe, advanced astrophysical modelling of the life and death of stars as well as a deep knowledge of the nature of atomic nuclei, the heart of matter and the fuel of stars. Progress on these efforts has been spurred on by rapid advances in computing power and complex theoretical models, and TRIUMF is at the core of these efforts. To test these sophisticated models and challenge them with observations, however, we need physical measurements and, in 2017, the universe obliged.

Elements from iron to uranium cannot be created from fusion in stellar cores. Instead, half of these elements are created through the slow neutron-capture process (“s-process”) inside massive stars (i.e. AGB stars). The process is “slow” because there is enough time for radioactive (beta) decay to occur in the newly-created isotopes before more neutrons are captured. Therefore, stable isotopes of these heavy elements are produced and settle into the so-called “valley of stability.” The other half of these heavy elements are produced via the rapid neutron-capture process (“r-process”), and the creation of these isotopes can only occur in extremely energetic and neutron-rich environments, such as merging neutron stars, where the synthesis of isotopes occurs very quickly. When neutron stars collide, neutron capture happens faster than beta decay, creating heavy neutron-rich isotopes that are, by their nature, very far from stability and difficult to study.

Until recently, direct observational proof of neutron star collisions remained elusive, and we depended solely on computer modelling of complex astrophysical r-process isotope production. The discovery of gravitational waves, however, has ushered in a new era not

only for astronomy, but also for nuclear science — specifically the study of rare isotopes. On August 17, 2017, the US-based Laser Interferometer and Gravitational-wave Observatory (LIGO) and its European counterpart Virgo (near Pisa, Italy) detected gravitational waves generated by the collision and merger of two neutron stars (before this, only black hole mergers had been detected). This gravitational wave detection, plus the simultaneous detection of a short gamma-ray burst (GRB) from roughly the same location millions of light years away, provided the first direct observational proof that short gamma-ray bursts can be triggered by neutron star mergers. A new era of "multi-messenger astronomy" had begun. While an exciting and transformative time for astronomy, this event provides a "ground truth" for nuclear physics, confirming neutron star collisions as heavy isotope factories. Spectroscopic measurements of the GRB's kilonova revealed the presence of newly-synthesized heavy elements, providing strong evidence for r-process isotopes.

Understanding how these nuclei were formed requires sophisticated modeling of cataclysmic astrophysical events, and we also need a deep knowledge of the nuclear processes occurring in this neutron-rich environment. So, recent advancements in the production of these neutron-rich short-lived nuclei, as well as modern nuclear theory that describes complex heavy atomic nuclei with nuclear forces constructed from first principles (ab-initio), are essential. TRIUMF is already a leader in this research, and we plan to continue to pursue a rich research portfolio, including key experiments on rare isotopes with the ISAC and ARIEL facilities, and by further developing nuclear physics theory. These efforts will not only advance our deep understanding of the nature of atomic nuclei and the forces that hold them together, but they will also will help advance astrophysical models.

This is an exciting time for nuclear physics, and TRIUMF will undertake the following key initiatives to reveal the origins of the stardust that we are made of:

- Investigate the nature of atomic nuclei using the portfolio of ISAC experiments to develop a unified theory for all nuclei.
- Elucidate the origin of the elements by studying nucleosynthesis processes via rare isotope beams to rectify gaps in our theoretical knowledge of astrophysical events.

OUTCOMES

- Advances in ab-initio theory of nuclear structure and dynamics.
- Improved knowledge of the forces that govern existence of atomic nuclei.
- Expanded knowledge of the limits of nuclear existence.
- Expanded knowledge of the astrophysical origins of heavy nuclei.

IMPLEMENTATION

INVESTIGATE THE NATURE OF ATOMIC NUCLEI

A central goal of nuclear physics is to explain the properties of atomic nuclei and nuclear matter, from hydrogen to the superheavy elements and even the composition of neutron stars. Major advances in nuclear theory, in part driven by TRIUMF researchers, have enabled the development of nuclear forces that are rooted in the properties of quantum chromodynamics (QCD) and enable ab-initio calculations of nuclear properties and reactions of light nuclei, nuclear matter, and increasingly heavier nuclei. The goal of a unified theory for all nuclei and nuclear matter is finally within reach.

TRIUMF's ISAC facility is among a handful of rare isotope beam facilities around the globe that can explore the nature of atomic nuclei at the extremes of proton-to-neutron ratio, or isospin. Using the existing cutting-edge technologies of the multi-faceted array of experiments at ISAC and new capabilities of ARIEL that will become available between 2020 and 2025, novel rare isotope beam experiments will be carried out to answer some of the most enigmatic questions facing nuclear physics, firmly establishing TRIUMF as a world-leader in nuclear science.

We will elucidate the nature of atomic nuclei and the forces that hold protons and neutrons together by developing and testing ab-initio theories of nuclei and nuclear reactions at the limits of nuclear existence. This involves the measurements of nuclear ground state properties, such as masses utilizing TRIUMF Ion Trap for Atomic and Nuclear Science (TITAN), spins and electromagnetic moments via laser spectroscopy, and half-lives and nuclear structure via decay spectroscopy with Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN). We will also use nuclear reactions to study intricate aspects of the nuclear forces and excitation modes with the ISAC Charged Particle Reaction Spectroscopy Station (IRIS) and the TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) coupled to the new Electromagnetic Mass Analyzer (EMMA).

ELUCIDATE THE ORIGIN OF THE ELEMENTS

High fidelity computer models have provided an intimate view of stellar evolution and how extreme stellar events such as novae, supernovae, and neutron star collisions enrich the cosmos with heavy elements; however, gaps in our understanding of how certain isotopes are created have left these models incomplete. To alleviate this knowledge gap, TRIUMF will exploit rare isotope beams of short-lived atomic nuclei produced by ISAC and ARIEL to mimic natural isotope creation inside these cataclysmic astrophysical events. In doing so, a better appreciation for the natural production of heavy elements will be attained, and theoretical models improved upon, bringing us closer to understanding our origins.

BEYOND MULTI-MESSENGER ASTRONOMY

TRIUMF's investigations into neutron-rich isotopes were well-established before the advent of multi-messenger astronomy. "It was a cherry on top of the cake to get this confirmation, but the experimental program was already going on," said Dr. Iris Dillmann, Nuclear Physics Research Scientist at TRIUMF. "What we do is multi-messenger nuclear physics; we are not looking directly into stars. TRIUMF is doing experiments here on Earth."

Whereas the combination of gravitational waves and electromagnetic radiation from astrophysical events gives rise to a new era of multi-messenger astronomy, TRIUMF facilitates the investigation of heavy isotopes through an array of nuclear physics experiments all under one roof that can illuminate the characteristics of isotopes that have been identified in neutron star mergers.

"For example, astronomers can identify one interesting isotope and realize that they need more experimental information on this one isotope," said Dillmann. "We then have the capability to go through the different setups and, say, measure the mass of the isotope with the TRIUMF Ion Trap for Atomic and Nuclear Science (TITAN) experiment's Penning trap."

From there, Dillmann added, the GRIFFIN experiment can use decay spectroscopy to investigate the half-lives of rare isotope beams and their underlying nuclear structure. Other nuclear properties such as moments and charge radii can be measured using laser spectroscopy. At ISAC, we also directly measure the reaction cross-sections of explosive hydrogen and helium burning in star explosions with the Detector of Recoils And Gammas Of Nuclear reactions experiment (DRAGON) and the TRIUMF UK Detector Array (TUDA). With ISAC, all these measurements are carried out in one place, where teams from each experiment work side by side to solve problems quickly and collaborate effectively.

"We have the setups in the hall to investigate an isotope from different perspectives to try to get a complete picture just from one department — the nuclear physics department," said Dillmann.

The world-leading experimental infrastructure of ISAC, powered by the new beams and multi-user capabilities of ARIEL, with triple the beam hours, will enable major advances in the field of nuclear astrophysics by providing insights on the origins of the elements, explosive nuclear burning, and the properties of neutron stars. For example, we will directly measure nuclear reaction rates with DRAGON and TUDA that have a direct impact on stellar modelling, particularly stellar explosions, and their comparison to astronomical observations such as radioactivity from core collapse supernovae, ground- and space-based chemical composition spectroscopy in novae, and the analysis of pre-solar grains in meteorites. Guided by nucleosynthesis sensitivity studies and astronomical observations of r-process enriched stars, we will also study the properties and reaction rates of key neutron-rich nuclei involved in the astrophysical r-process to clarify if neutron star mergers are the predominant site of the r-process.

Supported by NSERC, CFI, TRIUMF, and contributions from provincial agencies and international partners, the ISAC experimental facilities will enable major breakthroughs, in particular through recent additions such as the multi-reflection time-of-flight mass spectrometer (MR-TOF-MS) for TITAN, IRIS, GRIFFIN, as well as for EMMA. An important new development will be the planned addition of a beamline from the laser polarizer to GRIFFIN, enabling beta-decay studies with spin-polarized nuclei, significantly enhancing the decay spectroscopy program.

1.2 UNDERSTANDING THE ORIGINS AND EVOLUTION OF THE UNIVERSE

With our international collaborations in big science projects, TRIUMF plays a central role in the world's cutting-edge particle physics experiments. These experiments are seeking solutions to confounding problems facing modern physics, pushing our knowledge of the fundamental structure of nature into new and mysterious realms.

The Nobel Prize-winning discovery of the Higgs boson at CERN's Large Hadron Collider (LHC) in 2012 highlighted the current unease about the accepted theoretical framework of particle physics. As a landmark prediction of the Standard Model, the Higgs field was proven to exist after a decades-long search that had been the focus of high-energy physics programs around the world. The Higgs field gives mass to elementary Standard Model particles, while its particle excitation is a boson with spin zero. The Higgs boson discovery completed the bedrock "Standard Model recipe book" of fundamental particles and their interactions. However, this discovery was a cliff hanger for physicists: Now that the Standard Model ingredients have been found, what kind of "exotic recipe book" might explain the biggest puzzles in particle physics that the Standard Model does not? What strange ingredients might it have? It was well understood that using the framework of the Standard Model wouldn't uncover solutions to many of these puzzles, but the fact that a Standard Model Higgs boson was discovered means we are forced to look for solutions that are either beyond the current reach of the LHC or buried in datasets that have yet to be fully understood.

We now must pursue new ideas and theories beyond the Standard Model — so-called "new physics" — that might reveal exotic particles that are currently hiding in the dark corners of nature. In this new physics realm, TRIUMF is working with national and international partners to gain knowledge about new particles hypothesized to exist within reach and beyond the high-energy frontier, nature's fundamental symmetries and how they are violated, the puzzle of the dominance of matter over antimatter, the properties of neutrinos, and the perplexing nature of dark matter. Even the Standard Model Higgs isn't safe — might the Higgs discovered at the LHC be just one of a family of Higgs particles? The LHC experiments have already constrained and excluded an enormous parameter space for new particles and the High-Luminosity LHC will further expand that reach.

TRIUMF is strategically placed to make further ground-breaking discoveries by using a variety of modern experiments, leveraging our extensive international network, and collaborating with world-class laboratories to ensure Canada remains a leader in the most impactful physics experiments on the planet.

With our extensive network of collaborators, we will pursue the following initiatives:

- Search for new physics at the energy frontier with ATLAS at the LHC.
- Zero in on how nature's symmetries are broken by pushing the precision limits on electric dipole moments (EDMs) in neutrons and rare isotopes, the CP violating phase and masses of neutrinos, CPT violation and gravity of antihydrogen, and electroweak precision tests using rare isotopes.
- Investigate the nature of dark matter with world-leading dark matter searches at SNOLAB, advanced theories of the dark sector, and possibly direct production at ATLAS.

OUTCOMES

- Precision measurements of Standard Model processes at the energy frontier.
- Expanded knowledge of neutrino properties and their role in the matter-antimatter asymmetry.
- Discovery of, or leading limits on, new physics beyond the Standard Model.
- Discovery of, or leading limits on, EDMs and CP violation, CPT tests, and antimatter gravity.
- Discovery of, or leading limits on, dark matter particles

IMPLEMENTATION

EXPLORE THE HIGH-ENERGY PHYSICS FRONTIER

The theoretical predictions of the Standard Model have been tested extensively by a series of cutting-edge experiments at increasingly higher energies, and the theory has been wildly successful at explaining the plethora of experimental data. Even so, there is a growing realization that we have only probed the surface; lying below is a deep ocean full of new fundamental phenomena to be found. The discovery of neutrino masses, leading to the Nobel Prize for McDonald and Kajita in 2015, and the astronomical evidence for dark matter are but two glimpses into these depths. There are also deep theoretical puzzles that suggest new fundamental physics, such as the nature of the Higgs boson and its stability under quantum corrections, the origin of the excess of matter over antimatter in the universe, and how to incorporate the known particles and forces into a complete theory of gravity.

Bigger and more powerful particle accelerators will be crucial to exploring beyond the Standard Model, since higher energies provide greater resolution to see new phenomena. TRIUMF scientists are playing key roles in the most exciting international projects in this field. Chief among these is the ATLAS experiment at the CERN LHC that is already studying the highest-energy collisions ever achieved by humankind. Construction is underway to improve the detectors and boost the number of particle collisions. This will allow a doubling of the data in the coming science run (Run 3) from 2021 to 2023.

The LHC's first operational run (Run 1) began in 2009 and ended in 2013 to begin a two-year shutdown that saw upgrades to the accelerator so that 14 TeV particle collisions could be possible. Run 2 began in 2015 and ends in 2018, when the LHC will shut down for luminosity upgrades before Run 3 begins in 2021. Further improvements planned for 2023 to 2026 will begin a new phase of discovery, dubbed the "High-Luminosity Large Hadron Collider" or HL-LHC, which will increase the total amount of data by yet another factor of ten.

With these essential upgrades comes an increased potential for discovery. The upgraded LHC and HL-LHC will have the power to study the Higgs boson in exquisite detail and to search more deeply for new fundamental particles and elementary forces that have yet to be found. We have set off on an exploration into the unknown, beyond the confines of the Standard Model, on a voyage of discovery that may or may not affirm our wildest theoretical ideas. No matter what is found, the voyage will forever change our understanding of the fundamental structure of the universe.

SEARCHING FOR NEW PHYSICS WITH ATLAS AT THE LHC

ATLAS is one of two general-purpose detectors, with CMS, at the world's most powerful particle accelerator facility and with an international collaboration of scientists to make historic particle physics discoveries, such as the detection and characterization of the Higgs boson and the ongoing search for physics beyond the Standard Model. Over 150 Canadian particle physicists are involved in the ATLAS experiment. Long Shutdown 3 (LS3) will be a period of intense activity as Phase-2 upgrades must be completed, installed, and commissioned (see Strategy 1.5: "Leveraging Our Strength in Accelerator Science and Detector Technology" below). In tandem with the upgrades, data analysis efforts will focus on using the full LHC dataset obtained so far to push the discovery limits and test Standard Model predictions at the highest energies. The dataset should be sufficiently large to approach the kinematic limits of most searches for new particles and to measure most of the electroweak-scale couplings to unprecedented precision. Analysis efforts by the Canadian ATLAS team — with significant TRIUMF involvement — will intensify to focus on measurements of very small couplings, like the Higgs self-coupling, and searches for very massive and weakly interacting new particles, i.e., dark matter candidates (see Strategy 1.2: "Dark Matter Searches with ATLAS").

The research activities of ATLAS-Canada are supported by NSERC. Current and forthcoming work on the ATLAS upgrades has received over 60 million dollars by CFI and NSERC as well as provincial agencies.

HUNTING FOR NEW PHYSICS

ATLAS Canada is specifically interested in finding significant excesses in the dataset that may indicate the presence of physics beyond the Standard Model.

“We’d want to see a clear sign of new physics that we then can study in more detail with the new high-luminosity data — there’s the prospect of a ten-fold increase in data,” said Dr. Oliver Stelzer-Chilton, TRIUMF Research Scientist and member of ATLAS Canada. “Run 3 will produce 300%, and the High-Luminosity LHC will give 3,000%. Ideally, we’ll have a sign of new physics in the Run 2 or Run 3 dataset, and then we can study it in the HL-LHC.”

So far, physics at the LHC has been running along a “railway track,” added Stelzer-Chilton. While there have been some hints at new physics, experimental observations have been very much in line with the Standard Model, including the discovery of the Higgs boson. But the discovery of a relatively low mass Higgs that requires large radiative corrections (on the order of M_{Planck}), hints that there may be new particles around the TeV scale that stabilize the Higgs mass and cancel the quadratic divergences in the Higgs sector.

One model that may explain the identity of new particles is supersymmetry (SUSY), which predicts that known particles possess hypothetical partner particles (known as “sparticles”), producing a new symmetry of nature, beyond the Standard Model. Although there has, so far, been no detection of sparticles, theorists are hopeful that the LHC’s new high-luminosity regime may produce evidence of SUSY in ATLAS datasets. TRIUMF will be on the forefront of this endeavor.

EXPLORE HOW NATURE’S SYMMETRIES ARE BROKEN

The laws of physics suggest that matter and antimatter should have been created in equal measure when the universe was born from the Big Bang. If this were the case, however, there would be no matter in the universe; the matter particles would have annihilated with their antimatter cousins, leaving only energy in their wake. No stars, galaxies, planets or life would have been able to form in this grim alternate reality. But the fact that the universe has a preponderance of matter (compared with tiny quantities of antimatter) suggests that our understanding is lacking. This inexorable reality suggests that something was out of kilter in the early universe that allowed matter to prevail over antimatter — a situation that apparently breaks the symmetry of matter and antimatter production. Over the past few decades, particle physics experiments have revealed that nature doesn’t treat matter and antimatter equally, but the observations so far do not explain the dominance of matter in the universe.

An asymmetry in the production or decay mechanisms of matter versus antimatter requires significant violations in CP symmetry (charge and parity symmetry). However, the known cases of CP violation in kaons or B-mesons cannot account for the observed preponderance of matter over antimatter. One strategy is to search for electric dipole moments (EDMs) in several systems, which can only occur if there is CP violation. Systems of interest include the electron, the neutron, atoms, and molecules. Another strategy is to search for CP violation in neutrino oscillations with long-baseline experiments.

Other precision measurements, for example, of electroweak processes and rare decays in subatomic systems provide important tools to search for hints of broken fundamental symmetries and new physics beyond the Standard Model. One might even ask if CPT symmetry, the cornerstone of quantum field theory, is indeed conserved as stated in the CPT Theorem. A breaking of CPT symmetry would completely overturn the foundations of the Standard Model, and the very precise comparison of the properties of antihydrogen and hydrogen can possibly reveal if this is the case.

PRECISION MEASUREMENTS OF ELECTRIC DIPOLE MOMENTS

While the Standard Model predicts vanishing or exceedingly tiny EDMs, many theories of new physics predict larger EDMs, still smaller than today’s experimental limits but possibly within reach of future experiments. For example, finding a tiny EDM of the neutron would suggest that the negative and positive charges within the neutron do not overlap, but for this to occur in nature, there must be a new CP-violating mechanism at play. In short, if physicists can measure a finite EDM that is much higher than the Standard Model predicts, we can better understand nature’s symmetry breaking mechanisms.

To make world-leading, precision measurements of the neutron electric dipole moment (nEDM), TRIUMF, together with partners from Canada and Japan, is developing a flagship experimental facility for the trapping and analysis of neutrons from our new Ultracold Neutron (UCN) facility. Using protons from TRIUMF’s main cyclotron, directed into a neutron-rich tungsten target, a high-intensity stream of fast-moving neutrons is produced that are cooled in a complex three-stage process to a temperature of around of 0.003 Kelvin (-273.15 Celsius). Operating at such low temperatures is necessary so that the neutrons can be slowed, trapped, and studied long enough so that any extremely small nEDM can be measured

The nEDM we are trying to discover is so small that, if a neutron were expanded to the approximate size of the Earth, the charge separation allowed by the Standard Model would measure one micron — a fraction of the width of a human hair! Therefore, years of measurement and analysis are necessary before this minute deviation can be distinguished. TRIUMF’s UCN nEDM experiment is designed to measure the nEDM to a precision of 30 times better than the world’s best measurements. In addition, a second UCN port will enable other experiments to be carried out in parallel to the nEDM experiment between 2020 and 2025. Beyond 2025, TRIUMF aims to install a major new experiment on this port that could harness the ultracold neutrons to investigate other outstanding questions.

The UCN facility has received significant funding from CFI, NSERC, TRIUMF, and provincial agencies, as well as from the Japan Society for the Promotion of Science (JSPS) for the planned UCN source upgrade and the nEDM experiment.

Other potential EDM experiments at TRIUMF have been proposed and would make use of the intense actinide rare isotope beams available at ISAC/ARIEL and the extensive beam time available, afforded by the purpose-built multi-user capability of ARIEL. A proposal that is under consideration is the search for an EDM of the electron using a laser-cooled francium (Fr) fountain supplied by an intense beam of ^{211}Fr. An international collaboration is forming to pursue funding for the Fr fountain experiment via CFI, NSERC, provincial, and international contributions. An experiment testing related time-reversal symmetry in the decay of spin-polarized ^{8}Li has finished taking data and is under analysis, while an experiment in radiative beta decay is starting with the TRIUMF Neutral Atom Trap (TRINAT) utilizing its ability to determine the neutrino direction.

CP VIOLATION IN NEUTRINOS

Ghostly neutrinos have been the focus of intense scrutiny since their theoretical inception by Wolfgang Pauli in 1930 and then their eventual discovery in 1955. Neutrinos are the most abundant fundamental particles in the universe, but because they are so weakly interacting with other matter, trillions pass through our bodies every second without hitting an atom. Given enough time and a big enough target, however, neutrinos do, occasionally, directly collide with nuclei, and this means we can detect them. But to do this, huge detectors are required, buried deep underground to shield them from radiation sources and cosmic rays. The more we become familiar with these particles and their nature, the more they become a key tool to search for CP violation through long-baseline experiments that study neutrino oscillations.

Canada has a rich history in neutrino studies. The Sudbury Neutrino Observatory (SNO) was explicitly constructed at the Creighton Mine near Sudbury, Ontario — with TRIUMF as a participating institution — to find the answer to the observed deficit in solar neutrinos when compared with theoretical predictions. Taking data from 1999 to 2006, SNO was uniquely suited to revealing, in combination with data from Super-Kamikande, that neutrino oscillations were the cause of this solar neutrino deficit, a discovery that resulted in Canadian physicist Dr. Art McDonald and Japanese physicist Dr. Takaaki Kajita being awarded the 2015 Nobel Prize in Physics.

The fact that neutrinos exhibit oscillations between their three flavours (electron, muon, and tau) — a behavior not predicted by the Standard Model — also means that neutrinos must have non-vanishing masses. Since neutrino oscillations only reveal the differences between the masses of the neutrino flavours, it has so far been impossible to determine the absolute values of their tiny masses. However, neutrino oscillations can be used to carry out fundamental investigations into CP violation.

CP violation in neutrino oscillations has yet to be discovered experimentally, but TRIUMF is actively working with several experiments that are designed to look for a difference in the oscillation probabilities of neutrinos and their antiparticles: antineutrinos. Should experiments show that neutrinos and antineutrinos oscillate differently, CP violation in the lepton sector may be confirmed, and part of the reason why matter prevailed over antimatter early in the universe's history may be revealed. Japan's T2K (Tokai to Kamioka) long-baseline neutrino experiment, with its baseline of 295 kilometers from source to detector, is at the forefront of investigating this critical question. TRIUMF is committed to supporting future long-baseline neutrino efforts by the Canadian community in Japan, including a new water Cherenkov near detector (NuPRISM) and the Super-Kamiokande's successor, the Hyper-Kamiokande (HyperK) detector.

HyperK will be constructed at the Kamioka Observatory, Japan and is currently awaiting a funding decision. The Canadian long-baseline community will seek funding from CFI for major infrastructure, and the research component will be supported through NSERC. TRIUMF will also provide support through two recent hires and its expertise in the development of photodetectors, based on an innovative multi-photomultiplier concept that will be prototyped at NuPRISM and is under consideration for deployment within HyperK.

Another opportunity lies with the Deep Underground Neutrino Experiment (DUNE) that is scheduled to begin operations by 2027. DUNE will measure neutrino oscillations of an intense beam of neutrinos from a production facility at Fermilab in Illinois (LBNF), through the Earth's crust, to a liquid argon detector at Sanford Lab in South Dakota, some 1,300 kilometers away.

Other critical investigations of neutrinos are carried out through the search for neutrinoless double beta decay. If discovered, it would, in one stroke, establish the existence of lepton number violation and elementary Majorana fermions, implying they are their own antiparticles. The fact that neutrinos have non-vanishing masses is a prerequisite for the existence of this possible but extremely rare decay, which would also provide unique access to the absolute neutrino masses. Next-generation ton-scale experiments will dramatically expand the reach of current generation experiments, like SNO+ at SNOLAB, in which TRIUMF is involved. TRIUMF is playing a significant role in the developments of the next Enriched Xenon Observatory (nEXO) detector. Anticipated to be located at SNOLAB, nEXO will search for this decay in five tons of liquid Xe enriched in the isotope ^{136}Xe and aim to improve current measurements by almost two orders of magnitude. Together with Canadian and international partners TRIUMF will work on the design and construction of this next-generation detector with tremendous discovery potential. The nEXO-Canada collaboration, which is carrying out developments supported by NSERC, CFI, and provincial agencies, will be seeking CFI and provincial funding to make a significant Canadian contribution to the experiment. The nEXO experiment is led by the U.S. and awaiting formal project approval by the U.S. DOE.

Another potential future large-scale neutrino experiment would leverage Canada's unique world-leading expertise in scientific operations in the deep ocean with Ocean Networks Canada (ONC) and in detector development at TRIUMF and Canadian universities.

The ONC's scientific site, the Cascadia Basin, has been identified as a potential site for a future large-scale neutrino detector array. Currently, very early stage exploratory studies are under way to investigate the viability of the site for such an endeavor and, if suitable, a detailed proposal for the physics case could be developed for a next-generation neutrino telescope, superseding the IceCube experiments at the South Pole.

ANTIHYDROGEN VS. HYDROGEN

The CPT theorem demands that atomic spectra of hydrogen and antihydrogen be identical. During the last few years the ALPHA collaboration at the CERN Antiproton Decelerator, with key contributions from TRIUMF, has led the way to move the field of anti-hydrogen trapping and spectroscopy from the technical demonstration phase to the precision symmetry test phase, culminating in a recent measurement of the spectral structure of the antihydrogen 1S-2S transition with a precision of 2×10^{-12}.

From 2020 to 2025, the ALPHA collaboration will aggressively exploit two new experiments, the ALPHA-2 and ALPHA-g. ALPHA measures the properties of anti-hydrogen (atoms that consist of an anti-proton and positron) by capturing these antimatter atoms in a magnetic trap and then cooling them so that experiments can be performed. Central to this investigation is to understand whether hydrogen and its antimatter counterpart, anti-hydrogen, have different energy levels. If they do, evidence for CPT violation will have been discovered.

With large Canadian investments, including unique equipment designed and constructed at TRIUMF, ALPHA-2 is a brand-new assembly that will advance the ALPHA experiment well beyond its original capabilities, facilitating the use of advanced laser technology. The ALPHA-g experiment is a variation on this theme. It will allow physicists to test the limits of Einstein's equivalence principal, which states that all (classical) particles with the same initial position and velocity should follow the same paths in a given gravitational field. Our current understanding of gravity combined with quantum mechanics predicts that anti-hydrogen should behave in the same way as hydrogen; however, differences do arise in some attempts at quantum theories of gravity. So, by studying the free-fall of anti-hydrogen in ALPHA-g, precision measurements can be performed to seek out any equivalence violations.

The simultaneous availability of these two experiments, coinciding with the boosted anti-proton flux from ELENA (a compact ring upgrade to CERN's Antiproton Decelerator), provides a special opportunity for the most impactful investigations into this physics frontier. Also, by using these two experiments in tandem, ambitious upgrades can be performed on one apparatus while the other can continue its physics investigations.

These ALPHA measurements will represent a very significant improvement in precision over previous measurements, and some of these measurements will be the first of their kind to be carried out in CPT violation tests. These experiments will have sensitivities, within certain theoretical frameworks, that can probe new effects that would otherwise be suppressed by a very high-energy scale, for example, the Planck scale.

The ALPHA-Canada collaboration is supported by NSERC. The ALPHA-g project is supported by CFI as well as TRIUMF, provincial agencies, and international partners.

ELECTROWEAK PRECISION TESTS USING RARE ISOTOPES

Researchers are utilizing the rare isotopes available at TRIUMF as a laboratory for precision tests of the electroweak interaction, searching for evidence of physics beyond the Standard Model. TRIUMF's TRINAT carries out investigations of spin-polarized beta-neutrino angular correlations in beta decays, which tests whether neutrinos are always left-handed. A concerted effort of several experimental facilities — GRIFFIN, GPS, TITAN, and laser spectroscopy — will continue to test the unitarity of the Cabbibo-Kobayashi-Maskawa quark mixing matrix. The Francium Trapping Facility studies atomic parity non-conserving in francium atoms, a tiny effect that tests physics complementary to neutrino scattering and parity violating electron scattering. The dramatic increase of rare isotope beam hours provided through ARIEL, coupled with the highest intensities of the isotopes of interest, will significantly advance this program in precision physics.

The rare isotope beam research programs on electroweak precision experiments is supported by NSERC as well as international contributions.

EXPLORE THE NATURE OF DARK MATTER

Arguably the most pressing cosmological problems of our time are the mysteries of dark energy and dark matter, and particle physics is uniquely positioned to reveal a solution to the latter. Through astronomical studies — such as observing galaxy rotation rates and gravitational lensing events — we know that approximately 85% of the mass of our universe is invisible and placed in a mysterious category labeled "dark." The matter that makes up all the planets, stars, and all the visible stuff in between makes up a tiny (~15%) quantity of the universe's total mass. Ordinary matter is therefore just the bright frothy foam churning atop a vast dark matter ocean.

Theorized to be composed of non-baryonic particles that only interact through the weak force or a new force, and yet exert a gravitational influence over "normal" (or baryonic) matter, searches for dark matter have focused on so-called Weakly-Interacting Massive Particles (WIMPs). Because WIMPs have such small interaction cross-sections, experiments rely on detecting direct collisions of these particles with the nuclei of ordinary matter. When these (rare) collisions occur, depending on the type of detector, a signal (electromagnetic scintillation, charges, or vibrations in a crystal, for example) should be produced and arrays of sensitive detectors can then measure the collision. WIMPs, however, have yet to be detected — but we are closing in.

"There's really good motivations for WIMP dark matter, and there's a really good chance we'll see this dark matter candidate in a direct-detection experiment," said TRIUMF Research Scientist Dr. David E. Morrissey. "We're involved in some leading dark matter experiments and there are other experiments that are making good progress too, but this is an area for dark matter searches that's really getting interesting. For the next 10 years or so, we'll do a very good job of really testing this WIMP paradigm."

DARK MATTER SEARCHES AT SNOLAB

TRIUMF is committed to several key initiatives, including the Dark Matter Experiment using Argon Pulse-shape discrimination (DEAP) collaboration, and the Super Cryogenic Dark Matter Search (SuperCDMS). These experiments are located two kilometers underground in a nickel mine in Sudbury, Ontario, at the world's second-deepest underground lab facility, SNOLAB. Conducting WIMP studies deep underground provides essential shielding against noise sources, such as cosmic rays that continuously bombard Earth's atmosphere.

With significant contributions from TRIUMF, the DEAP-3600 experiment is directly searching for WIMPs using a chamber filled with 3.6 tons (3,600 kilograms) of liquid argon (LAr) as a scintillation detector. Concluding operations in 2020, DEAP-3600 will publish its final results within a few years after that. TRIUMF will leverage its expertise and infrastructure for detector developments to contribute to developments of advanced photodetectors for the next generation of LAr based dark matter detectors like DarkSide - 20k, a 20-ton (20,000 - kilogram) LAr detector that is currently being constructed in Gran Sasso National Laboratory in Italy, and other potential future detectors.

Through its partnership in the new Arthur B. McDonald Canadian Astroparticle Physics Research Institute at Queen's University, TRIUMF has recently taken on a significant role with the SuperCDMS experiment, which has just started construction. In the early 2020s, it will begin hunting for WIMPs with unprecedented sensitivity. Using state-of-the-art cryogenic germanium detectors, SuperCDMS will measure the phonons generated in the crystal matrix caused by direct WIMP-nuclei collisions.

DEAP and SuperCDMS are supported by NSERC, CFI, and provincial agencies.
The SuperCDMS experiment is a major project of the U.S. DOE.

ENTER THE DARK PHOTON

Searches for dark matter particles through direct-detection and particle collider experiments have yet to turn up evidence for WIMPs, but they have strongly constrained the possible mass range of these hypothetical particles. There is therefore a growing appreciation that WIMP dark matter may consist of a lighter particle that may very weakly interact with normal matter via a new force mediated by a so-called "dark photon." TRIUMF is uniquely positioned to develop the theory behind this hypothetical gauge boson while evaluating the feasibility of using existing experiments to possibly detect it.

"If dark matter interacts with regular matter, weak interaction can get too weak for dark matter to get the right density in the early universe, unless you have a new force," said TRIUMF Research Scientist Dr. David E. Morrissey. "So, this motivates a new force that dark matter feels, but regular matter doesn't feel very much. One manifestation of this is the dark photon." Structurally, the theory behind the dark photon is very similar to electromagnetism, but in reality, "it's a whole new fundamental force," he added.

TRIUMF will also evaluate the scientific reach and the technical feasibility of a proposal for a dark photon search experiment using the ARIEL electron linear accelerator (e-linac) to look for dark photons through their interactions with light dark matter. Compared with the high-energy collisions that are available at the LHC, ARIEL's energies are very low (around 50 MeV), but a low-energy, high-intensity beam might be a boon for dark photon searches.

"Typically, with accelerators, the lower the energy, the higher the intensity you can get," added Morrissey. "So, if you're looking for [a dark matter particle] that's pretty light, that only interacts with regular matter very weakly, you may be able to do better using a lower energy experiment with a really high intensity."

DARK MATTER SEARCHES WITH ATLAS

To date, there has not been any evidence of the production of dark matter particles in the ATLAS datasets, there remains the possibility that dark matter may weakly interact with matter non-gravitationally, via dark photons or another mechanism. Should this be the case, dark matter particles may be produced via the proton-proton collisions at the LHC. Through the development of dark matter theories and TRIUMF's involvement in ATLAS, we are searching for dark matter and other particles in the dark sector at the energy frontier. While dark matter itself is expected to be invisible to the LHC's detectors, it may still lead to new signals from Standard Model or dark sector particles that are produced together with dark matter in high-energy collisions. For more on TRIUMF's work on the search for new physics in ATLAS datasets, (see Strategy 1.2: "Searching for New Physics with ATLAS at the LHC").

Using expertise from TRIUMF's significant involvement and investment in dark matter searches, we will advance theory of the nature of the dark sector and support further research and development efforts for next-generation detectors using liquid noble gas and other innovative technologies.

1.3 DEVELOPING NEW RADIOPHARMACEUTICALS TO DIAGNOSE AND TREAT DISEASE

We live in an exciting time for the development of novel approaches in the diagnosis and treatment of various diseases of the human body. While the use of radioisotopes in medical situations isn't new, TRIUMF has been central to pushing the frontiers of radiopharmaceuticals for decades, forming strong links between the nuclear physics and medical communities. The UBC/TRIUMF PET program is the most prominent example. For decades, it has advanced the understanding of the human brain by using positron emission tomography (PET) to study brain function related to several neuro-degenerative conditions.

"What does TRIUMF offer that's different from all the other nuclear medicine, isotope or medical isotope centres around the world? We try to operate upstream from everyone else because of our specialty in the accelerator realm," said Dr. Paul Schaffer, Associate Laboratory Director of TRIUMF's Life Sciences Division. "We hope the technology we develop will benefit people all over the world. We're already seeing some evidence of that."

TRIUMF will capitalize on our already strong capabilities in accelerator-based medical isotopes and, with the commencement of our new medical isotope production facility, IAMI, we will boost radioisotope output. In addition to IAMI, TRIUMF's ARIEL facility will also be coming online. It will use a proton beam from the 520 MeV cyclotron and a beam from the new e-linac for research into radioisotopes that have characteristics suitable for radiopharmaceuticals. These significant advances, combined with advances in nuclear science, accelerator technology, and detector design will strengthen Canada as a leader in isotope-based medical imaging and treatment of disease.

To further strengthen our world-leading radiopharmaceutical programs and turn TRIUMF into the hub for Canada's isotope-based personalized medicine revolution, we will pursue the following initiatives:

- Develop radiopharmaceuticals for novel treatments of disease, driven by the expanded capabilities of IAMI.
- Identify new research avenues that could result in ground-breaking biochemistry applications, including betaNMR and perturbed angular correlation (PAC) spectroscopy.
- Advance proton therapy dose delivery through theoretical (Monte Carlo) modeling and experimental measurements to improve treatment delivery and patient outcome.

OUTCOMES

- New radiopharmaceuticals for diagnosis and therapy from IAMI.
- Improved knowledge of brain health.
- Treatment perspectives for degenerative diseases.
- New applications of betaNMR in biological systems with unprecedented sensitivity.
- New technologies for improved dose delivery and patient outcomes for proton cancer therapy.

IMPLEMENTATION

DEVELOP RADIOPHARMACEUTICALS USING IAMI

Radiopharmaceuticals are a class of drug that consist of an organic molecule that is labeled with a radioisotope, which can be used for a range of diagnostic and therapeutic purposes, from the imaging and treatment of neurological diseases and cancers to advancing our understanding of biological processes at the cellular level. The organic molecules provide the delivery mechanism to the specific organ, tissue or group of cells, whereas the radioisotope is chosen depending on the intended application: imaging or therapy. When chemically bonded, these radiopharmaceuticals are designed to be used by specific biological processes while delivering the radioisotope through that process, so it can be imaged and/or treated.

The production and characterization of radioisotopes in accelerator facilities therefore forms the backbone of this effort, and TRIUMF is a leader in the field, keeping up with demand and also pursuing new isotopes and new therapies that can be used for novel treatments that will enrich the health of all Canadians.

This Five-Year Plan includes the commencement of operations of IAMI with a negative-ion medium energy (18-24 MeV) TR-24 cyclotron at its heart, which is designed for rapid, reliable and high yielding production of medical isotopes. The investigation of new and useful radioisotopes for use in medicine is critical to address Canada's demand for radiopharmaceuticals, but this demand currently outstrips supply. When IAMI is at full production capacity, however, the production of radioisotopes at TRIUMF is expected to approximately double. While this may not revolutionize the problems dogging global supply, an increased output at TRIUMF means we can harness radioisotopes in new and novel ways and provide supply security for BC.

“The increased production capacity of having another cyclotron will be a big boost to the neuroimaging program, but having access to new labs that are built according to good manufacturing practice guidelines will allow us to get a drug establishment license from Health Canada,” said Ken Buckley, TRIUMF PET Research Engineer. “This will open up the availability of other tracers working with drug companies to evaluate therapies. IAMI will help us get into clinical trials with drug companies to evaluate potential new therapies — this will be a game changer.”

One area of interest is research into novel ^{18}F labelled amino acid PET tracers as alternatives for the well-established ^{18}F fluorodeoxyglucose (FDG)-PET for the diagnosis and monitoring of cancers for which FDG is not effective, such as prostate cancer, glioma (brain cancer), certain types of ovarian, breast, or lung cancers, and lymphomas. TRIUMF has been working to establish two tracer classes targeting different biomarkers associated with cancer progression and poor prognosis, specifically related to cellular response to oxidative stress and enhanced amino acid demands in cancer metabolism. With IAMI, TRIUMF will have the necessary facilities and partnership to pursue clinical translation of the novel tracers, enabling a deeper understanding of diseases such as Alzheimer’s and cancer at the molecular level.

To further understand how a healthy brain ages, and investigate the early onset of neurological disease and its progression, TRIUMF and UBC will build on their long-standing successful partnership to establish a cutting-edge multi-modality neuroimaging program, positioning TRIUMF as a leader in the development of brain imaging compounds. PET allows researchers to study many aspects of brain function in an interdependent way and to understand disease-induced alterations mediated by abnormal protein behavior, inflammation, impaired cellular energetics, and abnormal neurotransmitter signalling. The knowledge gained from this enhanced neuroimaging program will enrich searches into novel therapeutic targets and help to identify the biomarkers produced by the early onset of brain disease — such as Parkinson’s disease, dementia, and Alzheimer’s. TRIUMF’s expertise in radiotracer development and production will help drive new research, extending UBC’s neuroimaging program to investigate brain function in novel areas.

To do this, we will expand much needed isotope production and radiochemistry capacity through IAMI as well as pre-clinical imaging capabilities and scope at UBC. In addition to the ongoing clinical neuroimaging program, the PET program will also benefit by expanding its pre-clinical imaging capabilities for new research avenues. This is driven by a growing need to understand basic disease mechanisms through characterization and investigation of animal models of disease; development and testing of new radiotracers, as well as development and testing of new therapeutic agents.

We have access to a wealth of expertise, from accelerator scientists to experts in the targets that produce the radioisotopes, plus a mix of physicists and chemists on site, so these goals will see fast results and challenges can be rapidly troubleshot. “We’re able to build this very multidisciplinary network within TRIUMF and with our collaborators that really spans a range of technologies and expertise that are required to do this kind of imaging and therapy,” added Buckley.

With the capabilities of the IAMI facility TRIUMF will scale up its recent TR13-based efforts to broaden the available isotopes to produce several radiometals, including ^{68}Ga, ^{44}Sc, ^{86}Y, ^{89}Zr, ^{192}Ir, ^{52}Mn, ^{61}Cu and ^{94m}Tc to clinically relevant levels. This program will increase and broaden the spectrum of biomolecules available for imaging. Scientists at TRIUMF are planning to continue to develop and expand a ”toolbox” for molecular imaging, which involves the use of both known and novel bifunctional metal chelators, to allow researchers to pair metal isotopes with biological targeting agents.

Despite their clinical utility and impact in disease treatment, the use of radiometals so far has been limited in part by the lack of appropriate chelate chemistry used to tether the radioactivity to a biomolecular targeting vector. As such, TRIUMF researchers will investigate the design, synthesis, and characterization of novel hybrid acyclic/macrocyclic bifunctional chelating ligands for less explored yet emerging radiometals such as ^{225}Ac, ^{212}Pb, ^{149}Tb, and ^{45}Ti. These isotopes have several properties that make them potent therapeutic and/or dual-purpose imaging/therapeutic (i.e. theranostic).

TRIUMF has unique infrastructure through its 520 MeV cyclotron, and associated ISAC and ARIEL facilities that enable production and research into isotopes for targeted radionuclide therapy for cancer treatment using difficult to obtain alpha- and beta- (^{225,224}Ra, ^{225}Ac, ^{212,213}Bi, ^{212}Pb, ^{211}At) as well as Auger-emitting (e.g. ^{119}Sb,^{103m}Rh, ^{197}Hg) isotopes. With the new CFI-funded symbiotic target station in the ARIEL proton target station, the production of alpha emitting isotopes will be vastly increased. Targeted Radionuclides Therapy (TRT) is a powerful tool for selective cancer treatment even if other options (e.g. surgery and chemotherapy) are not applicable. TRT is based on combining therapeutic radionuclides (β^-, alpha, and auger emitters) with selective delivery systems (e.g. peptides, antibodies, polymers, etc.) to accumulate most of the radionuclides within the tumour and minimize damage to the surrounding healthy tissue.

TRIUMF researchers will also produce novel metal chelates that can be attached to biomolecular targeting vectors and/or for the linkers that can modify the kinetics of pharmaceuticals. Appropriate biomolecular targets will be chosen in conjunction with collaborators and experts in molecular oncology. Conjugates displaying favorable properties will be put through pre-clinical imaging and therapy studies. This chemistry-centric research will rely heavily on TRIUMF’s unique infrastructure to produce radioisotopes, where the goal is to identify successful radiopharmaceutical candidates for nuclear imaging and targeted radionuclide therapy.

With infrastructure investments into IAMI and supported by the Federal Government, CFI, WD, the Province of BC, UBC, and BCC, the research program obtains funding from a variety of agencies, including NSERC, CIHR, and the Canadian Cancer Society.

ACTINIUM-225: A SERENDIPITOUS CONNECTION

Although accelerator science is seen as TRIUMF's core competency, we'd argue that our multidisciplinary approach is also a key secret to our success. The fact that we have experts in radiopharmaceuticals rubbing shoulders with accelerator scientists means that potentially transformative medical discoveries and connections can be made — sometimes by chance.

"One of the most potent examples is actinium-225," said Dr. Paul Schaffer, Associate Laboratory Director of TRIUMF's Life Sciences Division.

The radioisotope actinium-225 (^{225}Ac) has been used in targeted cancer therapies and has demonstrated outstanding results in clinical trials on late-stage cancers where other medical treatments have failed, particularly in prostate cancer patients. As an alpha emitter with a short half-life, this ^{225}Ac isotope is very potent against tumours, while limiting the exposure of healthy tissue by damaging irradiation. Like many radioisotopes used in the treatment of cancer, however, the supply of ^{225}Ac is very limited. But after a conference a few years ago, where Schaffer heard about the medical effectiveness of this isotope, a serendipitous connection was made.

"Knowing it was such a heavy element, I remember thinking 'that must be a reactor problem' and dismissed it," he said, "but I came back from that conference, and I crossed paths with our Safety Group here at TRIUMF and overheard complaints about a contaminant that they didn't know what they were going to do with. And that contaminant was called actinium-225!"

When Schaffer inquired about how much of it the accelerator experiments were producing, his jaw dropped, "it was triple the current global production of that isotope!"

"So, on the one hand, I had a clinician complaining that they can't get enough of it … and yet here we are tripling what the world can produce, potentiating thousands, perhaps tens of thousands of patient doses for treating late-stage cancer," he said.

Without an active radiopharmaceutical research group in TRIUMF, Schaffer wouldn't have known about this surprisingly useful contaminant and its cancer-beating qualities and our experiments would have just kept on producing ^{225}Ac that, at face value, had no obvious use. But when different scientific disciplines regularly work together under one roof, collaborating to find novel answers to hard questions, "^{225}Ac moments" are never far away.

"We collaborate to find solutions to known problems, but we also recognize that we may have already found solutions to problems that we don't yet know we had," added Schaffer.

INVESTIGATE NEW BIOCHEMISTRY RESEARCH AVENUES

Beyond the characterization and production of radioisotopes for imaging and therapy, TRIUMF recognizes the need to identify new research avenues that could result in ground-breaking biochemistry applications. For example, betaNMR is an extremely sensitive form of nuclear magnetic resonance (NMR) currently used in materials science where the nuclear spin precession signal is detected through the beta decay of a radioactive nucleus. This signal can be translated to probe the local magnetic and electronic environment in which that nucleus is embedded. There are some exciting biochemistry applications for betaNMR spectroscopy, and we are planning on the establishment of a dedicated betaNMR spectroscopy station for chemical and biological applications, including studies of peptides, proteins, DNA, and RNA. These experiments will be carried out under biologically relevant conditions, in aqueous solutions, bringing the established power of betaNMR to bear on biological problems that cannot be addressed by conventional NMR or other techniques.

"BetaNMR is mostly used in materials science, but we are looking at applying that technology to study the way metals interact with biological environments, such as with proteins," said Schaffer. "It's a very sensitive spectroscopic technique that is not currently widely used, but the potential is there. Ten years from now this technology will be commonplace."

We will also establish a dedicated Perturbed Angular Correlation (PAC) of gamma-ray spectrometer for applications into chemistry, biology and medicine. Like betaNMR, PAC spectrometry can expose the environment surrounding a material undergoing radioactive decay. By measuring the angular correlation of gamma-rays being emitted through a cascade of decays, the influence of the surrounding material can be detected and measured. In a biochemical environment, PAC spectroscopy can reveal the structure of different biomolecules, probe the metal binding sites of metalloproteins and study the influence of non-native metal ions on protein structure. PAC can also observe the metal ion promoted folding/mis-folding and association of proteins and investigate the exchange dynamics at the protein metal binding sites as well as assess DNA damage after irradiation.

We will seek funding from CFI and provincial agencies to expand the experimental infrastructure for this research, which is supported by NSERC.

REFINE PROTON THERAPY DOSE DELIVERY

Since 1995, more than 200 patients have undergone successful treatment for ocular melanoma at TRIUMF proton therapy facility. Although proton therapy has been used internationally for several decades, it is only now becoming widely available; yet there is much room for research and development to improve dose deposition, dose verification, spatial control of the irradiation, 4-dimensional tracking of the proton beam to account for organ motion, beamline design, dose minimization, and optimization of treatment plans.

Research within TRIUMF's proton therapy program will improve treatment delivery and patient outcomes through both theoretical (Monte Carlo) models and experimental measurements. TRIUMF researchers will also investigate new detectors for dosimetry in proton therapy and radiotherapy which, in general, is in a period of rapid scientific and clinical development. This work is supported by NSERC.

TRIUMF's research efforts centre on advancing proton therapy technology to improve the survival and quality of life for more Canadian cancer patients by producing new understandings that will translate to broader applications of proton therapy.

1.4 DRIVING THE REVOLUTION IN QUANTUM MATERIALS

Quantum mechanical phenomena on the molecular, atomic and sub-atomic scale will soon drive a global technological revolution in areas of sensing and imaging, computing, communications, as well as more efficient energy storage and transport. TRIUMF's Centre for Molecular and Materials Science (CMMS) is one of only a handful of facilities in the world that are uniquely qualified to take full advantage of this revolution through the development of the powerful techniques for MuSR and betaNMR for materials characterization while supporting a broad, multidisciplinary, user base.

These advances are pushed forward by the discovery and development of new quantum materials with fascinating electronic, magnetic, and optical properties that enable new functionalities. Successfully harnessing quantum phenomena for new technologies depends on focused research aimed at understanding the quantum states of matter and on using precise engineering to apply this knowledge to quantum technologies. To understand the underlying exotic behavior of electrons driving functionalities of new quantum materials, it is essential to gain a fundamental knowledge of their electronic and magnetic behavior.

As the materials are becoming more complex, more innovative ways are required to understand their properties. Muons and short-lived radioactive ions, such as ^{8}Li, which are implanted into materials under investigation, act as unique and powerful local probes of these properties. Through their intrinsic spin and associated magnetic moment they act as tiny probe magnets of the interior of the materials which spin around internal magnetic fields of the material. Through the highly-efficient detection of their radioactive decay, their spinning motion can be made visible. The spinning frequency is a direct measure of the intrinsic magnetic field, which can be observed as a function of time.

Therefore, the collection of techniques known as muon spin rotation/relaxation/resonance (MuSR) and betaNMR, an exotic form of conventional Nuclear Magnetic Resonance (NMR), make a sensitive toolkit to study the critical intrinsic properties of new quantum materials. In fact, the CMMS is the only facility for MuSR in North America and the only facility worldwide that is capable of depth-controlled betaNMR, which allows for the investigation of electronic and magnetic properties at surfaces and across interfaces. This ability is particularly important with the further miniaturization of electronics components, where electronic and magnetic phenomena at surfaces and interfaces play a larger role in overall functionality. To stay at the forefront of these fields, CMMS will continue its long-standing leadership in developing innovative new techniques and technologies.

Quantum materials research at the CMMS is advancing a broad spectrum of topics including magnetism and superconductivity (high Tc, conventional and exotic), semiconductors, radicals, gas phase dynamics, diffusion, battery materials, quantum phase transitions, topological states, spintronics, spin caloritronics, frustrated systems, reactor moderators, heavy fermions, interfaces, and surfaces, and super-critical fluids. For example, the fields of spintronics and spin caloritronics aim to combine the data storage capabilities of magnetic media with the data processing capabilities of the semiconductor industry to develop next-generation computers. Other examples are MuSR and betaNMR studies of lithium diffusion in polymer electrolytes, which are used in lithium ion batteries that will aid the development of higher storage capacity and charging/discharging properties of next-generation batteries.

Muons can also be utilized to gain critical insights into chemical processes, be it chemistry in the extreme pressure environment of next generation (Gen IV) nuclear reactors or the study of the dependence of reaction rates on isotopic masses, especially hydrogen and helium, through the substitution of protons by lighter positive muons or electrons by heavier negative muons.

To take full advantage of the opportunities that lie ahead in the quantum materials revolution, TRIUMF will tackle these initiatives:

- Upgrade the CMMS MuSR facilities to stay at the cutting-edge in materials research.
- Unleash the full potential of betaNMR, by fully transitioning it to a user facility taking advantage of the increased rare isotope production of ARIEL.
- Develop an in-house quantum materials research program to take a more active role in the development of quantum materials and technologies.

OUTCOMES

- New quantum materials and expanded applications.
- Expanded multidisciplinary CMMS user base.
- Increased beam time for betaNMR studies utilizing expanded facility.
- Expanded CMMS user facility with increased personnel and new instrumentation.
- Established in-house quantum materials research program.

IMPLEMENTATION

UPGRADE THE CMMS MUSR FACILITIES

TRIUMF's CMMS plays a critical role in Canada's and international efforts for the development of new functional quantum materials, supporting a broad, multidisciplinary user base. To continue to enable a high-impact user program at the CMMS, one that carries out the most important experiments and has access to the most recently developed quantum materials, it is of utmost importance to ensure that the most advanced characterization techniques and probe environments are available.

We will continue the step-by-step upgrade of the MuSR facilities at the CMMS, by completing the CFI-funded initiative for a new high-momentum muon channel (M9B) equipped with a novel MuSR spectrometer that enables studies of quantum systems under extreme conditions, such as high pressures, high magnetic fields, very low or very high temperatures and the combination of these different sample environments. Most importantly, we will modernize the Beamline 1A (BL1A) that provides the primary beam of the MuSR program, ensuring the longevity of this unique in North America program. (see Strategy 2.3: "Investing in State-of-the-Art Laboratory Infrastructure")

"Any phenomenon that you can imagine that perturbs the muon polarization, you can, in principle, study," said Dr. Gerald Morris, Deputy Manager for CMMS. "You can probe superconductivity through the magnetic interplay in a material; you can also study chemical dynamics … It's a tool, like a microscope."

There is enormous flexibility in these tools, and the CMMS facility is capable of quickly reconfiguring, designing and building new equipment to respond to user needs. "This gives this facility an edge over other facilities worldwide," added Morris.

We will also implement advanced automatization technologies in the experimental stations and increase personnel to act as local scientific contacts, which will enable non-expert users to carry out MuSR experiments, boosting our effectiveness at delivering sophisticated instrumentation for a multitude of multidisciplinary users. This will increase the user community, attract more samples of the newest quantum materials to be tested at TRIUMF and broaden the use of this powerful technique to a much wider community of quantum matter scientists. Further updates of other muon channels are also planned, ensuring that the CMMS facility continues to stay at the forefront of quantum materials research.

OBSCURE PHYSICS MEETS REAL-WORLD APPLICATIONS

Often, the study of quantum systems can seem far removed from reality, but a core strength of TRIUMF's CMMS group is the realization that quantum studies drive industrial needs and can enrich people's lives.

"A Japanese researcher from RIKEN with industrial partners came to TRIUMF to study the vibrational modes of rubber, using muons," said Morris. "It turns out that the MuSR can provide insight to how a particular polymer could behave in a car tire — and it's related to the pitch of the squeal when the tire skids on the pavement."

These same vibrational modes that produce the tire squeal can be probed with muons, and MuSR is ideally suited to carry out studies that could impact the manufacture of products that have very tangible applications, from evaluating safety standards to developing new materials.

"There's a direct connection with what you can do with our facility and something that can impact people daily. We cover everything with obvious industrial applications to things as obscure as the quantum tunneling of muons in some metal or thin film — obscure phenomena that aren't going to touch daily life and won't appear in your hi-tech devices any time soon. The facility does an enormous range of science."

UNLEASH THE FULL POTENTIAL OF betaNMR

With the ARIEL facility coming online, providing additional ^{8}Li beam starting in 2021 and expanding to its full capability of three independent rare isotope beams in 2023, the full potential of depth-controlled betaNMR can be exploited. With the three-times increase of rare isotope beam hours it is possible to increase the beam time available for betaNMR studies by a factor of 4-5 from its current limitation of 5 weeks per year. Facilitated though this beam time increase, the facility will be fully transitioned to a user facility with more support staff. With an upgrade of the laser polarizer used to spin-align the ^{8}Li ions as well as an expansion of the betaNMR experimental capabilities, this unique technique will be able to develop its full potential. For example, a closed cycle vector superconducting magnet utilizing new radio frequency (RF) spin echo techniques will enable next-generation, depth-resolved betaNMR investigations of magnetic heterostructures.

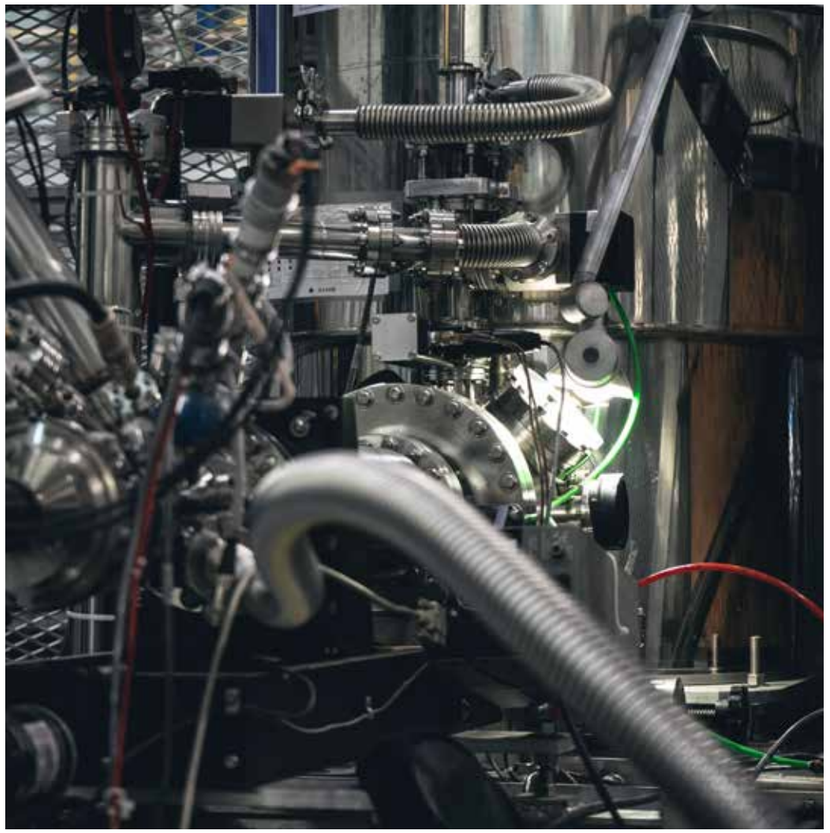
This will enable researchers to study materials for spintronics in a currently difficult to access magnetic field range and will enable users to take advantage of spin manipulation techniques in betaNMR that are available in conventional NMR. An additional channel will enable betaNMR on liquid samples, enabling experiments on biomolecules (see Strategy 1.3: "Radiopharmaceuticals"), and even provide polarized radioactive ions for nuclear physics experiments with GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei), that will help elucidate the origin of the elements (see Strategy 1.1: "Discover How Stardust is Made").

DEVELOP AN IN-HOUSE QUANTUM MATERIALS RESEARCH PROGRAM

By recently attracting two world-leading quantum materials scientists who are experts in utilizing and developing MuSR and betaNMR techniques, TRIUMF will also develop its own in-house quantum materials research program, strengthening its ties with the Stewart Blusson Quantum Matter Institute at UBC, which will take the CMMS to the next level from user facility to a leader in quantum materials, which will further be reinforced with the expanded capabilities both in MuSR as well as betaNMR.

With a strong investment in people, equipment and the development of new techniques, the CMMS will become an essential player in the Canadian ecosystem of quantum materials research, driving not only the discovery of new quantum materials, but also advancing the quantum technology revolution overall.

In addition to the research support from NSERC and CFI and provincial funding for the upgrade of the M9 muon channel, we will work with our partners to seek additional funding from CFI and provincial agencies for an expansion of the betaNMR facility and further upgrades of the MusR infrastructure.



1.5 LEVERAGING OUR STRENGTH IN ACCELERATOR SCIENCE AND DETECTOR TECHNOLOGY

Particle accelerators are the gateway to the foundations of matter and the origins of universal forces, but to expand TRIUMF's capabilities in the fields of nuclear physics, particle physics, medical isotopes, and quantum materials, we need to further enhance our core competencies in accelerator science and detector technologies. We are Canada's particle accelerator centre and, as such, TRIUMF possesses a unique and proud tradition of leveraging infrastructure, expertise, and technology in a myriad of ways. Our research and development in advanced particle accelerator, and radiation detection technologies helps us understand the origins of matter and realize novel isotopes that can be used in breakthrough cancer therapies. Due to our unique expertise in detector technologies, TRIUMF is a key partner in upgrades to the ATLAS detector, and we are committed to assembling and supplying detector components in anticipation for the increased particle collision rates and radiation doses that will arise from the HL-LHC.

Also, with our expertise in superconducting radio frequency (SRF) technologies, advanced beam dynamics, high-power targets, and remote handling, TRIUMF is well positioned to make significant contributions to major international accelerator projects such as the International Linear Collider (ILC), Long-Baseline Neutrino Facility (LBNF), or an Electron-Ion Collider in the U.S. We will engage with our international sister laboratories and identify opportunities where TRIUMF's core competencies and the ambitions of the Canadian scientific community are aligned to mutual benefit.

The transfer of technical expertise is seamless throughout the TRIUMF scientific portfolio, and our knowledge expands beyond national borders, supporting some of the biggest and most exciting accelerator facilities and experiments on the planet. From performing upgrades to the LHC's cryomodules, enabling the world's most powerful particle accelerator to launch into a new and exciting "high-luminosity" era, to supporting the development of next-generation dark matter and neutrino detectors, TRIUMF puts Canada in the driver's seat of international big science initiatives.

To advance our core competencies in accelerator science and technologies as well as radiation and photo detectors we will carry out the following initiatives to enable Canadian scientists to make significant contributions to large-scale international experiments and facilities:

- Contribute to HL-LHC accelerator upgrades, through beam dynamics studies and by delivering five cryomodules to the LHC.
- Contribute to Phase-2 ATLAS detector upgrades in preparation for the HL-LHC era.
- Develop SRF technologies to further advance the performance of superconducting cavities.
- Develop high-power isotope production targets to improve rare isotope beams for experiments.
- Carry out detector research and development.

OUTCOMES

- Contributions to the HL-LHC.
- Contributions to ATLAS detector Phase-2 upgrades.
- Advances in beam dynamics of intense beams in LHC, cyclotrons, and linear accelerators.
- Advances in SRF accelerator technologies for TRIUMF's and international accelerator facilities.
- New and higher intensity rare isotope beams.
- Contributions to neutrino and dark matter detectors at SNOLAB and international laboratories.

IMPLEMENTATION

CONTRIBUTE TO THE HL-LHC ACCELERATOR PROJECT

At CERN's request, Canada has a significant commitment to the HL-LHC's accelerator hardware. Five cryomodules, each containing two superconducting radio-frequency (SRF) dipole cavities, will be delivered to the LHC between 2021 and 2025

Cryomodules contain all the cryogenic apparatus and essential functional systems that maintain the SRF cavities at extremely low, superconducting temperatures and ensure maximum efficiency of the accelerator ring. The dipole cavities, which are the backbone of the powerful accelerator, will be supplied by the DOE as a U.S. contribution to CERN, but the overall cryomodule design and assembly will be led by TRIUMF, with significant interactions with Canadian industrial contractors. Funding for the cryomodules is provided by the Federal Government.

TRIUMF is also contributing to beam physics studies for the HL-LHC design focusing primarily on investigations of the beam-beam interaction and its influence on beam quality, which in turn affects the maximum achievable luminosity of the collider. Long-term (millions of turns) tracking of protons around the ring at top energy and at collision

settings, when the two beams meet each other inside the four interaction regions, is used to estimate the dynamic aperture, i.e. the domain of stable particle trajectories. These studies are carried out by numerically evaluating the dynamic aperture under the influence of the beam-beam effect for a variety of machine setups for various optical tunes and in the presence of theoretical magnet error tables.

“We are asked by the accelerator community to contribute our superconducting RF know-how, particularly the cryogenics environment — the cryomodule where superconducting cavities need to operate. We have unique knowledge in this field,” said Dr. Oliver Kester, TRIUMF’s Associate Laboratory Director of the Accelerator Division. “The design of the cryomodules that are used to house the crab cavities in the LHC after the upgrade … their construction was derived from the cryomodules of the e-linac at TRIUMF. The community as a whole has benefited from our design, and we want to give back our know-how by contributing the integration of cavities and modules to the LHC.”

Crab cavities are used to manipulate the tilt of particle bunches at the collision points in the accelerator (i.e. where the detectors are located) to maximize the collision probability of the billions of protons in the counter rotating bunches and, therefore, the luminosity. This tilt gives the impression that the proton bunches have moved sideways, hence the “crab” moniker.

CONTRIBUTE TO ATLAS UPGRADES

The building-sized ATLAS detector at the LHC is now the catalyst for novel approaches in high-energy physics and the focal point for new physics discoveries (see Strategy 1.2: “Searching for New Physics with ATLAS at the LHC”). Canada’s ATLAS Group commits over a hundred scientists to the ATLAS collaboration, with TRIUMF being a key partner in the effort to contribute to ATLAS.

The LHC and its detectors are constantly in the process of being upgraded to deal with an increased collision rate, or luminosity, of the main accelerator. After 2025, the HL-LHC will be accelerating particles to about seven times the facility’s originally-designed luminosity values. Steadily boosting the beam’s luminosity over the LHC’s operational lifespan will increase the particle flux and collision rates, cranking-up the potential for discovery. But an increase in particle flux puts pressure on the LHC’s detectors to continue to perform at a very high cadence and resolution under an increasing radiation dose.

To keep up with the increased collision rates while protecting the detectors from radiation, upgrades to key technologies are continuously being planned and fabricated. Funded by CFI, NSERC and provincial contributions, ATLAS-Canada is carrying out ATLAS detector upgrades for Phase-1 and Phase-2. In this context TRIUMF is currently engaged in partnership with several Canadian universities, with the Phase-1 upgrades, with detector component production, and assemblies taking place in-house. Liquid argon (LAr) calorimeter baseplanes and the Small-Strip Thin Gap Chamber (sTGC) cathode planes for the ATLAS New Small Wheel are being assembled at TRIUMF. By 2020, both projects will have been completed, and TRIUMF is fully committed to installing and commissioning work at the LHC. TRIUMF will also be heavily involved in Phase-2 upgrade projects, with a focus on the fabrication of Inner Tracker (ITk) silicon-strip detectors (beginning in 2020), which are hardened against the increased radiation dose and capable of dealing with increased particle rates, as well as liquid argon readout calorimeter electronics (beginning in 2021), which will boost the calorimeter performance. These new detectors will be ready for installation during the LHC’s LS3, which is scheduled to begin at the end of 2023 and run through to mid-2026.

ADVANCE SRF DEVELOPMENT

We are also carrying out research, supported by NSERC, to further advance the performance of superconducting cavities by developing new cavity materials and new processing techniques. Through the utilization of the unique capabilities of TRIUMF’s CMMS facility in MuSR and betaNMR (see Strategy 1.4: “Driving the Revolution in Quantum Materials”), we are characterizing the magnetic properties of potential new cavity materials, beyond pure niobium. A better understanding of these fundamental properties has the prospect to develop cavities with much higher acceleration gradients than

possible today, which would significantly reduce cost for next-generation high-energy particle accelerators, like the ILC. Another aspect of the SRF research is the development of plasma cleaning techniques to significantly enhance the reliability of TRIUMF's existing SRF accelerator cavities.

PURSUE HIGH-POWER TARGET AND ION SOURCE DEVELOPMENT

TRIUMF not only operates the highest power isotope separation on-line (ISOL) rare isotope facility with 50 kW proton beams and the forthcoming 100 kW electron beam from the ARIEL e-linac, it also has unique expertise on high-power medical isotope production targets utilizing proton energies from 10 to 500 MeV. We will continue to carry out research and development of high-power targets, new target materials and corresponding ion sources, including the resonance ionization laser ion source (RILIS), to push the frontiers of rare isotope beams available for our multidisciplinary research program, from nuclear physics and astrophysics to the study of biomolecules and quantum materials. At the same time, we advance target technologies for high-intensity medical cyclotrons to produce radiometals and other new medical isotopes, broadening the suite of available medical isotopes for the development of new radiopharmaceuticals.

ADVANCE DETECTOR RESEARCH AND DEVELOPMENT

TRIUMF utilizes its unique expertise and capabilities in the development of advanced particle and photon detectors to position Canadian scientists to make leading contributions to next-generation international experiments tackling the most foundational questions of our time.

For example, together with key partners, we are advancing the development of single photon detectors based on 3D integration, which are expected to revolutionize many applications by combining single photon imaging capabilities with sub-nanosecond timing resolution. Potential applications include the neutrinoless double beta decay detector nEXO, next-generation liquid Argon dark matter detectors, high time resolution μSR spectrometers, time of flight detectors for nuclear reaction studies, and even applications like time-of-flight PET imaging or Light Detection and Ranging (LiDAR).

The ability to work on novel detector concepts will open the possibility to contribute solutions to difficult problems and have a pivotal role in the early stages of next-generation detectors at SNOLAB or future colliders like ILC or FCC. This research and development effort relies on R&D seed funding as well as investments into state-of-the-art infrastructure and equipment. We will pursue a pan-Canadian effort to upgrade detector facilities at TRIUMF and universities across Canada, for which we will seek, together with our partners, funding from CFI, and provincial agencies. Detector R&D that is not project specific will be supported and incentivized through our new R&D seed fund.

1.6 APPLYING DATA SCIENCE AND MACHINE LEARNING EXPERTISE ACROSS OUR PORTFOLIO

Data science is a rapidly-growing discipline in science, industry and business, and TRIUMF is naturally positioned to spearhead development and leverage innovations in the data science and machine learning fields. Also, with the prevalence of big data and the advent of quantum computing, the need for experts in data science fields is becoming crucial and may lead the way to the next industrial revolution, driven not by coal and steel, but by the complex intersection of where data and machine-meet-human ingenuity. As such, TRIUMF recognizes the need for active data science research, not only to comprehend the petabytes of data streaming from particle accelerators and theoretical models, but to also boost Canada's leadership in this field and, ultimately, bolster the nation's economy and international standing.

TRIUMF, in cooperation with its university partners, offers a multitude of opportunities for development in the field of high performance computing and big data. We have unique expertise in high performance computing, through the ATLAS Tier-1 Data Centre that delivers huge datasets for analysis from CERN to users in the Worldwide LHC Computing Grid (WLCG), in the applications of machine learning algorithms, e.g. for ATLAS data analysis, and in ab initio nuclear theory calculations performed on the world's largest supercomputers, like the ORNL Titan machine and the new Compute Canada Cedar machine at SFU. While the backbone of TRIUMF's research is focused around accelerator science, our high performance computing and data science knowhow will enrich other particle physics experiments, nuclear physics experiments (such as large datasets in gamma-ray spectroscopy), nuclear medicine, and other areas that have yet to be identified.

In a world that is increasingly driven by data we see advancing progress in data science research as a necessity, so we can prepare for the data revolution that is currently unfolding in science and society. To enrich TRIUMF's growing expertise in data science, thereby boosting our ability to support a variety of science programs, we will pursue these initiatives:

- Build a data science platform that will enrich and support a growing multidisciplinary user base throughout the TRIUMF community.
- Support the ATLAS Tier-1 Data Centre to ensure the continued delivery of ATLAS data for the Canadian and international subatomic physics community.

OUTCOMES

- Machine learning applications across a multidisciplinary portfolio.
- Established data science platform.
- Established quantum computing network.
- High performance of the expanded ATLAS Tier-1 Data Centre.

IMPLEMENTATION

DEVELOP TRIUMF'S DATA SCIENCE PLATFORM

To prepare for the inevitable explosion in data science applications and discover exciting new data science techniques, we will build on our proud heritage as experts in large-scale particle physics experiments by developing and applying data science techniques (such as machine learning), embodied by an application and training platform to facilitate the translation of these techniques to other areas of our multidisciplinary portfolio. By embracing data science as a core component of TRIUMF's mission, new discoveries and innovations in nuclear physics, accelerator science, and nuclear medicine will be made. This effort is spearheaded by data scientists, with particle physics and data science application background who will establish a machine learning and development platform that utilizes the state-of-the-art of big data applications and quantum computing, while providing support for the TRIUMF community's data science needs. They will also be connected to data science communities at our member universities and Compute Canada and will foster industry connections in collaboration with TRIUMF Innovations.

The data science platform will be an opportunity to build a tangible testbed to provide hands-on training sessions and workshops for scientists throughout TRIUMF's multidisciplinary portfolio and from across the wider TRIUMF member network where state-of-the-art machine learning algorithms can be learnt and shared across research groups. To this end, we are considering the establishment of a dedicated computing cluster and merit-based access to computing resources to enable Canadian researchers to run and operate classical and quantum computing machine learning systems for science applications. TRIUMF's Data Science platform will be a vehicle for connecting data science communities from across TRIUMF member universities, Compute Canada, and local industry.

We are working with TRIUMF Innovations, D-Wave Systems Inc, 1QBit, and several institutions of Germany's Helmholtz Association to jointly establish a Canadian quantum computing network and a corresponding German quantum computing network to facilitate national and international collaboration in the use of quantum computing tools to enhance research output.

UPGRADE ATLAS TIER-1 DATA CENTRE

The planned ATLAS detector upgrades (see Strategy 1.5: "Leveraging Our Strength in Accelerator Science and Detector Technology") will result in the inevitable increase in data that need to be stored, processed and analyzed. Facilitating the Worldwide LHC Computing Grid (WLCG), which is a four-level global system of computer centres, specific services are performed for the flow of LHC data. There are four Tiers, with Tier 0 being the CERN Data Centre, through which all data from the LHC passes. Tier 0 delivers approximately 20% of the WLCG total computing power. Tier 0's responsibility is to store all data and perform initial processing of raw data into meaningful information before it is distributed to Tier-1 computer centres.

Through the LS3 period, demand on the 10 international Tier-1 centres will be significant. So, in anticipation of this increased load, the TRIUMF Tier-1 centre is being relocated to Simon Fraser University (SFU), Compute Canada's newest and most powerful data centre, in 2018, enabling the required significant expansion of the centre. After this move, uniquely experienced TRIUMF personnel will continue to operate and maintain the facility to ensure high-availability access to the ATLAS community. The expertise of these experts will also benefit the broader Canadian research community using the SFU computing centre.

CFI funding will be sought for further expansions and renewals of the computing hardware of the ATLAS Tier-1 data centre and operational support by Compute Canada.

GOAL 2 Strengthen our position as a world-leading particle accelerator centre

OUTCOME Increased capacity for world-class, multidisciplinary research and development in Canada

Particle accelerators recreate the conditions of the Big Bang, strip matter down to its subatomic foundations, create exotic isotopes, and drive humanity's thirst for discovery into new and exciting realms. While we strive for innovations in newer, more powerful, and higher luminosity beams, a single machine does not make ground-breaking discoveries alone; it takes an established infrastructure to support the science, technology, and human resources to drive our curiosity forward. As Canada's particle accelerator centre, TRIUMF has five decades of experience in building a rich infrastructure that nurtures the cutting-edge and multidisciplinary facilities that we possess today. While we are large enough to compete with other world-class institutions, our agility allows us to create a culture that harnesses cross-collaboration and rapid problem-solving all under one roof, focused around state-of-the-art instrumentation. We believe that to extract the best from our world-class facilities, we need to foster a safe, inclusive, and modern working environment that attracts international collaborators and better serve the scientists, engineers, and tradespeople who work together every day.

This Five-Year Plan 2020-2025 drives our proud multidisciplinary heritage forward, while also highlighting our expertise in high-performance accelerator technologies, in the pursuit of a robust science program that is as achievable as it is visionary. Two foundational facilities for the future of TRIUMF — the Advanced Rare Isotope Laboratory (ARIEL) and the Institute for Advanced Medical Isotopes (IAMI) — will go online in this plan's timeframe and solidify our leadership as an innovative rare isotope research centre. At the same time, research that utilizes proton, electron, muon, and rare isotope beams will continue to attract collaborators from around the world. Together, new and existing cutting-edge facilities will usher in a new age for TRIUMF, primed to make huge advances in nuclear physics, particle physics, and quantum materials to support industrial applications across a range of sectors, including nuclear medicine, mining, telecommunications, and aerospace.

> "[TRIUMF is] on the cusp of absolute world-class stuff and they do it cheaper than anyone else who has that same technology and they fight for funding all the time … innovations shouldn't be limited by budgets."
>
> **CMD (RET), CHRIS HADFIELD, CANADIAN ASTRONAUT (RETIRED 2013)**

2.1 UNLEASHING THE FULL POWER OF OUR ACCELERATOR COMPLEX

In nature, the production of rare isotopes is an extraterrestrial affair; these unstable and often short-lived nuclei are produced in the cores of stars and in the wake of cataclysmic events in deep space, such as neutron star collisions (see Strategy 1.1: ”Discovering How Stardust Is Made”). Producing rare and short-lived isotopes on Earth, however, can be achieved using accelerators and sophisticated target systems — techniques that have been pioneered and developed by TRIUMF and are only available to a handful of facilities around the world. When the ARIEL facility goes online, TRIUMF’s rare isotope research will be propelled into a new era of discovery. ARIEL’s collection of cutting-edge experiments will be supplied with unprecedented intensities of rare isotope beams, allowing simultaneous studies across a diverse portfolio of isotopes.

While our accelerator systems are already among the most advanced in the world, with the completion of ARIEL, we will be promoted to one of the top global facilities for accelerator science. Showcasing a made-in-Canada high-power superconducting electron linear accelerator (e-linac), ARIEL will work alongside our original cyclotron to triple TRIUMF’s rare isotope beam capacity. With this incredible boost in capacity comes an increased supply of exotic isotopes for cutting-edge science, medicine, and business, supporting a variety of projects that will lead the way to profound and transformative breakthroughs in nuclear physics and astrophysics, life sciences, and materials science.

ARIEL will triple the scientific capabilities of TRIUMF’s rare isotope program by providing more exotic short-lived isotope species with very high intensities and by adding two production targets that will provide beams in parallel with the existing Isotope Separator and Accelerator (ISAC) target station. The new production targets will be driven by the new superconducting e-linac and a new proton beamline from our 520 MeV cyclotron. Together, the three production stations will enable state-of-the art research on the origin of the elements, medical isotopes for cancer therapy, quantum materials, and biomolecules, the nature of atomic nuclei and precision studies of electroweak processes and fundamental symmetries. These studies will be facilitated by ARIEL’s world-wide unique and purpose-built multi-user capabilities that enable more beam time for experiments, as well as a broader variety of isotopes with unprecedented production intensities.

These advances will allow for a full exploitation of the available experimental facilities at TRIUMF, leveraging investments from the Canada Foundation for Innovation (CFI), Natural Sciences and Engineering Research Council of Canada (NSERC), National Research Council (NRC), several provinces, and international partners. The launch of ARIEL, in conjunction with the sophisticated array of experiments already operational

at ISAC, will propel TRIUMF to the forefront of research into the origins of the heavy elements in our universe, specifically through the astrophysical r-process in neutron-star mergers and other cataclysmic events. In addition, medical isotopes will be harvested for a research program on alpha emitters, providing a very promising avenue for effective alpha-tumour therapy.

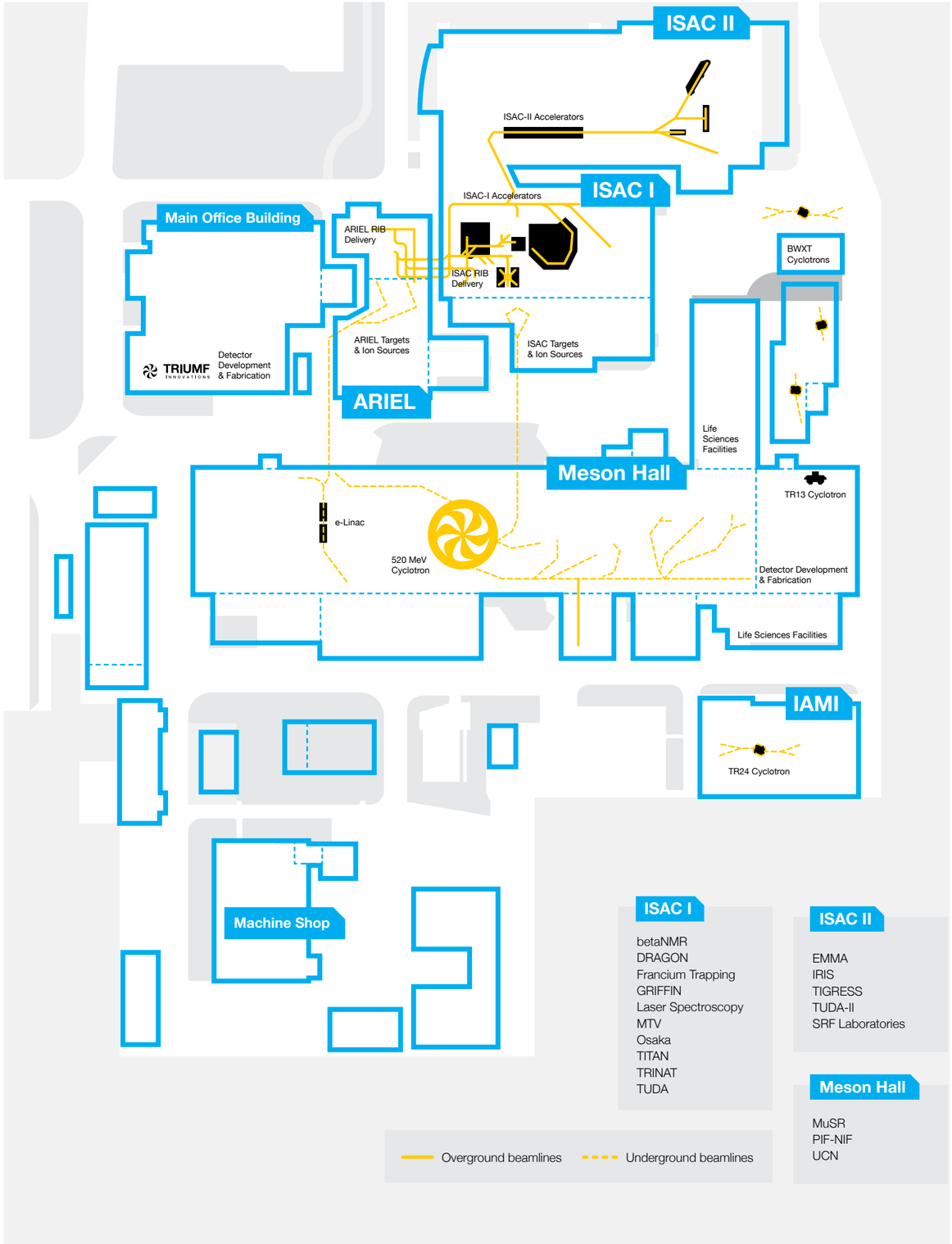
These ambitious plans will be accomplished by fulfilling these initiatives:

- Deliver first science from ARIEL with clean accelerated high-mass RIBs from the CANadian Rare isotope facility with Electron Beam ion source (CANREB).
- Deliver first science from the ARIEL e-linac with ^{8}Li for betaNMR and fission fragment for r-process studies.
- Complete ARIEL, providing three independent rare isotope beams, while enabling production of therapeutic medical isotope production in a symbiotic target.

OUTCOMES

- 9,000 hours of rare isotope beams per year.
- Fully interdisciplinary research program at ARIEL and ISAC.
- Tripled output of rare isotopes.

OVERVIEW OF TRIUMF'S SCIENTIFIC AND TECHNICAL INFRASTRUCTURE



ISAC I

betaNMR
DRAGON
Francium Trapping
GRIFFIN
Laser Spectroscopy
MTV
Osaka
TITAN
TRINAT
TUDA

ISAC II

EMMA
IRIS
TIGRESS
TUDA-II
SRF Laboratories

Meson Hall

MuSR
PIF-NIF
UCN

IMPLEMENTATION

DELIVER HIGH-MASS ACCELERATED RIBS FROM CANREB

We will complete the ARIEL facility by delivering CFI projects — including the CANadian Rare isotope facility with Electron Beam ion source (CANREB), ARIEL-II, and the Symbiotic Target Station — on time and within budget.

After completion of CANREB in 2019, our research on nuclear reactions with the ISAC Charged Particle Reaction Spectroscopy Station (IRIS), TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) and ElectroMagnetic Mass Analyzer (EMMA) will be brought to the next level, by utilizing CANREB for the charge breeding of rare isotope beams produced in the existing ISAC targets for acceleration in the ISAC heavy-ion linac. With the higher efficiency and lower background of unwanted species, we will have access to higher intensity and cleaner accelerated beams with mass above 30, not only fully realizing the potential of the ISAC-II accelerator and associated experiments EMMA, IRIS, and TIGRESS, but also expanding the reach of the nuclear astrophysics reaction program with DRAGON and TUDA.

DELIVER FIRST SCIENCE FROM THE ARIEL E-LINAC

Starting in 2021, ARIEL's e-linac will produce rare isotope beams, first ^{8}Li beams through photo-production for betaNMR and, shortly thereafter, very neutron-rich isotopes using photo-fission. Photo-production is achieved by converting the electron beam from the e-linac to produce gamma-rays, which, in-turn, fall onto a production target, made from uranium carbide in the case of photo-fission, to generate the rare isotope beams for experiments. With the delivery of science from the e-linac, TRIUMF will already enter an era of multi-user RIB delivery, doubling TRIUMF's rare isotope beam capacity. Combined with the planned expansion of the betaNMR experimental facility, the larger quantities of ^{8}Li will allow us to elevate the worldwide unique betaNMR materials characterization from a boutique method to a full user facility, advancing knowledge in quantum materials and biochemistry.

The production of very neutron-rich isotopes via photo-fission induced by the e-linac is an inherently cleaner way than the production via proton-induced fission, fragmentation, and spallation reactions. Therefore, the e-linac will enable unprecedented access to the short-lived nuclei involved in the astrophysical r-process.

COMPLETE ARIEL WITH ADDED SYMBIOTIC MEDICAL ISOTOPE TARGET

With the completion in 2023 of the new proton beamline and associated target station, TRIUMF will be the world's only facility with three independent rare isotope beam production targets, and for the next decade, we will reinforce our leadership as the highest power Isotope Separation On-Line (ISOL) facility in world.

We will take full advantage of the new beams and the multi-user capability of ARIEL and ISAC to enhance our experimental capabilities for a fully interdisciplinary research program, which will lead to discoveries that will undoubtedly challenge our current understanding of fundamental nuclear research while advancing knowledge and nurturing innovation.

"We already have all of the detectors on the floor, so we will utilize these detectors to do even more exciting, more exotic physics," said Dr. Iris Dillmann, Nuclear Physics Research Scientist at TRIUMF. "We are looking forward to unleashing the full power of the ARIEL facility, to have more beamtime, less downtime, cleaner beams, and more beam development."

Basing ARIEL and ISAC's target operation on a highly-efficient factory model, we will be able to reliably deliver triple the number of rare isotopes by operating a significantly larger infrastructure of driver accelerators, production targets, and beam delivery systems, with only marginally more staff. This factory model is based on utilizing the fast target exchange systems designed for ARIEL in conjunction with weekly target exchanges rotating among the three online production targets, each operating for three weeks.

The ARIEL proton target station will also be used to install a symbiotic medical isotope production target, an effort funded by CFI and the province of BC, to deliver research quantities of key medical isotopes — particularly ^{225}Ac for targeted tumour therapy — to our nuclear medicine program and that of our partners.

"Installing a symbiotic medical isotope target in ARIEL will use the unused proton beam that travels through the science target and typically dispensed into a beam dump composed of a benign material," said Dr. Paul Schaffer, Associate Laboratory Director of TRIUMF's Life Sciences Division. "Rather than just wasting that beam, we're actually going to put in some specific target material which can be implanted and extracted independent of the science schedule, allowing us to make medical isotopes symbiotically to the science programs."

The addition of a medical isotope production target in the beam dump of ARIEL highlights the multidisciplinary nature of the facility. The same beamline that will be used to peel back the mysteries surrounding neutron star mergers will be applied to produce rare isotopes for cutting-edge research into rare isotopes that can be used in the treatment of disease, thereby allowing TRIUMF to carry out complementary studies with both ARIEL and IAMI.

ARIEL: THE EPITOME OF MULTIDISCIPLINARY SCIENCE

ARIEL is TRIUMF's flagship multidisciplinary research facility that will house a suite of experiments, all under one roof, leading Canada's research capabilities in particle physics, nuclear physics, nuclear medicine, and materials science. When combined with the already robust suite of experiments at ISAC, TRIUMF will strengthen its role as the global destination for accelerator-driven science.

The ARIEL facility will host a new and sophisticated made-in-Canada superconducting e-linac that will accelerate electron beams to 99.99% the speed of light and steer them into targets to produce rare isotope beams. Combined with a new proton beamline from TRIUMF's 520 MeV cyclotron, ARIEL will be the focal point for innovative research into a myriad of experiments — from investigating the inner workings of stars to novel uses of radioisotopes in medicine — a diverse portfolio that TRIUMF's accelerator infrastructure is uniquely qualified to lead.

"It's the combination of the people with absolutely unique experience, with built-up knowhow over many years," said Dr. Oliver Kester, TRIUMF Associate Laboratory Director of the Accelerator Division. "It's also the combination of people; you have all these different disciplines, with people sitting side-by-side in the office. You have the superconducting cavity people and you have the beam physicists sitting beside one another. This is a great environment for communication and collaboration, and it's a unique setting for a powerful accelerator lab."

It's the combination of skills across many disciplines at TRIUMF that allows facilities like ARIEL to be built and operated. The combined knowledge across the sciences will converge to create a unique platform to strengthen TRIUMF's culture of collaboration and propel Canada's participation in world-class science investigations to a new level.

2.2 ESTABLISHING TRIUMF AS A GLOBAL CENTRE FOR NUCLEAR MEDICINE

The commencement of science activities at IAMI will be transformative for TRIUMF's medical radioisotope research, performing cutting-edge research for the radiopharmaceuticals used in therapeutic and imaging applications. Building on our expertise in developing and producing accelerator-based isotopes, we will launch IAMI with two regional partners, University of British Columbia (UBC), and the BC Cancer (BCC), to create a multi-institutional research facility. The state-of-the-art facility will be a global hub for developing and producing life-saving medical isotopes, as well as new radiopharmaceuticals for imaging and treating diseases. This new centre will place Canada at the leading edge of research and development in nuclear medicine while, at the same time, improving the health of Canadians. In the face of potential supply shortages, IAMI will secure British Columbia's supply of critical medical isotopes (such as ^{99m}Tc) and will also provide additional capacity and supply security for other isotopes, both novel and those currently in clinical use.

IAMI will also offer commercial enterprises the space to develop new isotope-based medicines, giving Canadian firms a first-mover advantage in global markets. By the virtue of its location on the TRIUMF site, IAMI will be able to serve as a conduit for isotopes using TRIUMF's other accelerators; solidifying the province's status as a world leader in isotope-based life sciences research and radiopharmaceutical development.

These endeavors will be achieved via the following initiatives:

- Complete IAMI and initiate an unprecedented program of rare isotope production and radiopharmaceutical research.
- Provide medical isotope security for the province of BC.

OUTCOMES

- Internationally-renowned radiopharmaceutical research and production centre.
- Increased knowledge of radioisotope production and radiopharmaceutical research.
- Supply of medical radioisotopes for BC.
- Radiopharmaceutical clinical trials enabled through IAMI.
- Accelerated research and development of radiopharmaceuticals and other drugs.

IMPLEMENTATION

COMPLETE IAMI AND COMMENCE TR-24 OPERATION

Following the completion of the construction of the IAMI building in 2020, we will expeditiously complete the installation, commissioning, and licensing of the TR-24 medical cyclotron as well as good manufacturing practices (GMP) radiochemistry laboratories to initiate isotope production, and radiopharmaceutical research. Once this start-up phase has been completed, the IAMI TR-24 will begin supporting the various components of the research and commercial program.

TR cyclotrons are the most technologically advanced commercial cyclotrons in the world. Coupled with an integrated series of state-of-the-art labs, IAMI will boost the potential for new innovations in radiopharmaceutical science, for research of novel radiopharmaceuticals and for advanced targeted cancer therapy.

When IAMI is online, we will aggressively carry out the GMP production of radiopharmaceuticals for the UBC PET imaging program and the production of clinical isotopes for UBC and BC Cancer PET programs. This will also provide access to an array of imaging isotopes and chemistry applications to facilitate radiochemistry R&D and/or radiopharmaceutical development for TRIUMF's academic and private sector partners. By doing this, IAMI will naturally function as a hub, connecting TRIUMF, UBC, BCC and other partners in BC, and beyond with cutting-edge expertise, infrastructure and oversight of accelerator-based isotope research and its applications.

IAMI: A GAME-CHANGER FOR NUCLEAR MEDICINE

When complete, IAMI will feature sophisticated labs, cutting-edge experiments, and a room-sized TR-24 cyclotron in a modern 2,500 square-metre building. Beyond the impressive array of high-end technologies, however, the facility will serve as a powerful catalyst on a regional, national, and international level for innovation at the interface between TRIUMF's expert knowledge of rare isotope production, and the demands of medicine. Perhaps most significantly, through our extensive collaborations with industry partners, radiopharmaceutical development and delivery will be accelerated.

"IAMI will help us get into clinical trials with drug companies to evaluate potential new therapies — this will be a game changer," said Ken Buckley, TRIUMF PET Research Engineer.

As the laboratory space will comply with strict medical production standards, TRIUMF will, for the first time, be able to carry out clinical trials across a range of radiopharmaceuticals. Also, whereas many cyclotron centres may have access to one type of tracer that they base all their expertise around, TRIUMF will have access to the whole range of tracers when IAMI is operational. This creates a prime opportunity for advancements and innovations along the whole pathway, from production to chemistry to application, added Buckley.

IAMI will serve as a conduit for technology developed from the TR-24 cyclotron, but also from all aspects of TRIUMF, including our 520 MeV cyclotron, ISAC, and ARIEL infrastructure. The facility will also bring together interdisciplinary teams of researchers, clinicians, entrepreneurs, and technicians from academia, the private sector, and not-for-profit organizations from across Canada and the world.

The facility will advance research into isotopes for targeted radionuclide therapy for cancer treatment using difficult to obtain alpha- and beta- (^{225,224}Ra, ^{225}Ac, ^{212,213}Bi, ^{212}Pb, ^{211}At) as well as Auger-emitting (e.g. ^{119}Sb, ^{103m}Rh, ^{197}Hg) isotopes. We will also complete the CFI-funded project to implement a symbiotic target station for ^{225}Ac production in the beam dump of the ARIEL proton target station, significantly advancing research into targeted cancer therapy (see Strategy 2.1: "Unleashing the Full Power of Our Accelerator Complex").

ENABLE MEDICAL ISOTOPE SECURITY FOR BC

IAMI will also act as a critical producer of ^{99m}Tc, thus securing BC's supply and utilizing the technologies developed by the TRIUMF-led Isotope Technology Acceleration Program (ITAP) consortium and now available from the spin-off company ARTMS™ Products.

In addition, when the BCC's cyclotron is offline for repair or maintenance, IAMI will serve as a back-up producer of ^{18}F in support of the clinical PET program at the BCC. We will also initiate, through TRIUMF Innovations, private sector partnerships for other commercial utilization of the TR-24 and IAMI GMP laboratories.

IAMI will also be leading the efforts to take the production of the alpha-emitting isotopes for radionuclide therapy to market. For this, we are planning, in partnership with commercial partners, upgrades to the Isotope Production Facility at the end of the main proton beamline in the Meson Hall (BL1A) to enable commercial production levels of alpha-emitting isotopes.

2.3 INVESTING IN STATE-OF-THE-ART LABORATORY INFRASTRUCTURE

Although innovation is an important activity in the advancement of science, industry and commercialization, the maintenance of the infrastructure that supports these advances is of equal importance. Without a continuously modernizing of infrastructure, carrying out cutting-edge experiments would be difficult, and a culture of discovery would diminish. So, to fully harness the enhanced capabilities of ARIEL and IAMI, we must maintain and upgrade our existing infrastructure deploying the latest technologies, best practices, and processes, while ensuring the continued safe and effective operation of our accelerator facilities. The continued stewardship of our accelerator infrastructure optimizes reliability and ensures the smooth operation of an extremely complex, dynamic and unique working environment, while protecting the environment and maintaining a high standard of safety.

As a part of these efforts, the modernization of the Meson Hall proton beamline will enable us to take the quantum materials program to the next level, advance the Ultracold Neutron (UCN) facility, and enable expanded commercial utilization of our high-energy protons for irradiation services and production of therapeutic isotopes.

State-of-the-art infrastructure is key to driving science of the highest caliber, not only with regard to accelerator and experimental facilities but also the laboratory overall. In the interest of modernizing TRIUMF's site infrastructure overall, we will seek funding for a new building that will address the basic need for more offices and laboratory space to accommodate a growing number of staff and visitors, foster a collaborative working space, and provide increased interaction opportunities for TRIUMF's scientific community and the public.

To implement these enhancements throughout TRIUMF, we will pursue the following projects:

- Implement our "Master Plan" that will incorporate extensive upgrades to our facilities with a focus on improving TRIUMF's working environment.
- Upgrade TRIUMF's 520 MeV cyclotron to supply a growing number of experiments and upgrade the ISAC accelerator facility to bring it up to par with ARIEL's new capabilities.
- Modernize the Meson Hall facility to expand its capabilities, especially for the development of robotic techniques.
- Expand the capabilities of betaMNR and establish the world's most advanced Positron Emission Particle Tracking (PEPT) facility.

OUTCOMES

- Safe, modern, optimized, and environmentally-sound working environment.
- Well-maintained facilities.
- Productive applications of beamtime.
- Boosted science output.

IMPLEMENTATION

IMPLEMENT THE MASTER PLAN

TRIUMF is a world-class facility, not only for the expansive multidisciplinary science program that we carry out, but also for the quality of the working environment that we value for the collaborative opportunities it provides. As infrastructure ages and facilities become more advanced, modernization is inevitably required to make TRIUMF an even better place to work. Through the implementation of our "Master Plan," we will invest in the development of the site, including the modernization of office and laboratory space. Upgrades to the detector facilities and life sciences facilities will ensure that we can stay at the forefront of discovery and innovation.

The construction of the new IAMI building will bring new space for isotope production and radiochemistry, and a modest expansion of office space. However, there is a pressing need for additional space. Roughly 150 TRIUMF employees are currently housed in trailers which were intended as temporary offices, but which have persisted on site for years, even decades, in many instances. Given our perennial and increasing space constraints in buildings, we recognize that the status quo is no longer viable. We must move to decommission the trailers in the poorest state of repair in short order and decant those occupants into existing building space which may or may not be currently configured as offices. We have also identified an urgent need to commence the planning of a modern office complex to replace our aging 40-year-old Main Office Building which is no longer adequate for a contemporary TRIUMF whose needs have evolved significantly over the decades. Deploying the latest in building technologies with greener more energy efficient infrastructure will allow us to reduce our footprint and operating expenses. In addition to the dramatic growth of scientific visitors and students, our outreach activities have far outgrown our current facilities. Our intention would be to purposely design a new facility to provide much needed office space over the next decade for all stakeholders as well as showcase TRIUMF's capabilities and host outreach activities in publicly-oriented facilities such as a visitor centre auditorium, meeting spaces, and cafés for staff and external visitors.

We will develop plans and pursue support from the province of British Columbia, our private sector partners, and philanthropy, to construct this new building that includes space for science experiences for the general public, an auditorium, a central accelerator control centre inside the security perimeter that is visible to the public, incubator space for new spin-offs and industrial partners, offices, and laboratories.

ENHANCE THE 520 MEV CYCLOTRON AND ISAC ACCELERATOR FACILITIES

With the completion of ARIEL construction, TRIUMF is poised to ramp-up the rare isotope program to 9,000 hours per year and become the premier Isotope Separation and Acceleration (ISOL) facility in the world. Pushing the limits in rare isotope science in nuclear physics, materials science, and life sciences requires not only the most intense rare isotope beams and a growing portfolio of available isotopes, but also a highly efficient and reliable operation. Our main 520 MeV cyclotron will drive the ARIEL/ISAC rare isotope program while continuing to deliver beams for MuSR, UCN, plus commercial isotope production,and irradiation services. With addition of the new beamline to ARIEL, the cyclotron will deliver four parallel proton beams to drive our multidisciplinary program. We will invest in refurbishments and upgrades to ensure highly reliable operation and higher total beam intensity from the cyclotron. To bring the 20-year-old ISAC facility on par with the brand-new ARIEL capabilities, we will continue our program to refurbish ISAC target modules and beam delivery infrastructure, while investing into R&D infrastructure for the development of new isotope capabilities. We will also invest into targeted enhancements of the ARIEL capabilities to ensure that we stay ahead of the growing international competition.

520 MEV CYCLOTRON: EXCEPTIONAL ENGINEERING AT THE HEART OF TRIUMF

At the heart of TRIUMF's operation is the 520 MeV cyclotron; a dependable work-horse that feeds our experiments with four proton beamlines. Housed beneath the Meson Hall and usually entombed under 2,000 tons of concrete radiation-shielding blocks, the cyclotron measures over 17 meters across, making it the largest cyclotron on the planet.

While its stature is impressive, arguably more impressive is that the cyclotron was constructed around the time that Neil Armstrong took his first small step on the Moon. Through a series of upgrades, the cyclotron is now operating at a performance that outpaces its original 1960's design and we expect it to continue to do so for many years to come.

"The overall technology of the cyclotron was planned over 40 years ago and constructed. It is still up to a high level and even goes beyond this high level. No other cyclotron worldwide has this level of performance, serving several users at the same time. When I came here and learned about this, it was fascinating for me. It's amazing," said Dr. Oliver Kester, TRIUMF Associate Laboratory Director of the Accelerator Division.

The cyclotron consists of a six-sector magnet that is supplied with negatively-charged hydrogen ions (one proton with two electrons) from an ion source. When in operation, the cyclotron accelerates the ions in a spiral path outward from the centre using an alternating electric field. When traveling at approximately three-quarters of the speed of light, the ions pass through thin graphite extraction foil, which strips away the electrons, while allowing protons to pass through. Magnetic fields are then used to direct the protons out of the cyclotron and into one of the four proton beamlines.

"It was a visionary endeavor to build such a cyclotron; it's exceptional engineering," added Kester. "It could keep running for another 40 years."

UPGRADE THE MESON HALL INFRASTRUCTURE

We will invest in the modernization and expansion of capabilities of the Meson Hall facilities, an important pillar of TRIUMF's multidisciplinary program. This includes the completion of the CFI-funded upgrades to the M9 MuSR channel and the UCN facility with its flagship neutron EDM experiment (see Strategy 1.2: "Precision Measurements of Electric Dipole Moments"). The central new element of this strategy is the modernization of the main proton beamline in the Meson Hall (BL1A) through a refurbishment and replacement program for the magnets, beamline, and target infrastructures. We will pursue CFI, provincial, and private sector funding to implement robotic remote handling technologies that will allow for the refurbishment of the existing, activated beamline components without exposure to staff. To mitigate the significant risk for a failure of beamline elements in BL1A we plan to start part of this project as soon as possible with NRC funds to get a head start on prototyping and preparatory work for the warm cell.

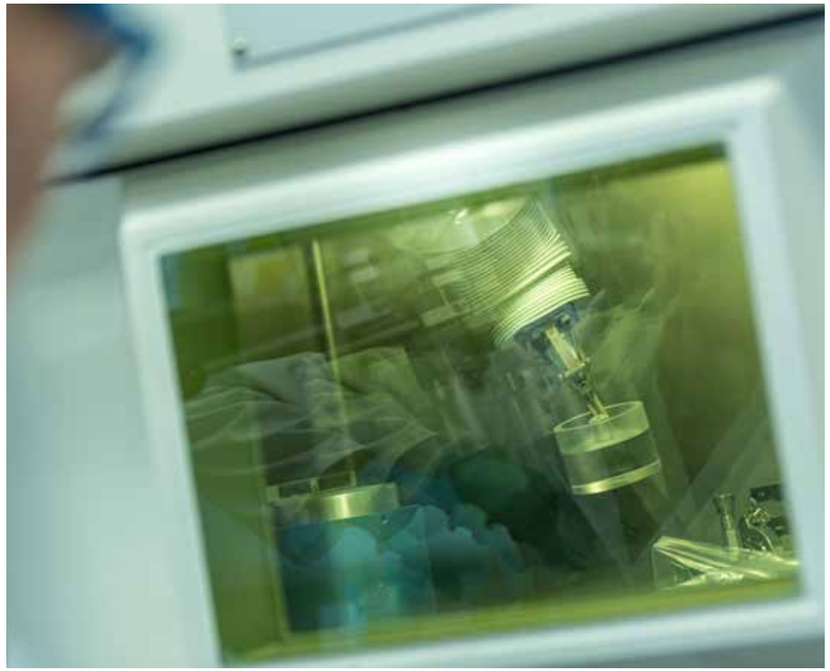
The implementation of such advanced technologies in a Robotic Warm Cell in the Meson Hall Extension will also allow for the development of robotic techniques for the disassembly and decontamination of activated and irradiated components such as isotope production targets from ARIEL and ISAC. This will reduce long term storage needs for radioactive components at TRIUMF as well as reduce off-site shipments of radioactive waste. The facility will provide a testbed for engineering developments for the advancement of robotic handling of radioactive components for the decommissioning of nuclear facilities.

The modernization of BL1A will ensure the long-term reliable operation of this critical infrastructure and will guarantee sustainable operation of the MuSR facility, advance the expanding UCN science program, and enable the potential for commercial level production of the therapeutic medical isotope ^{225}Ac in the Isotope Production Facility at TRIUMF, which will be upgraded in the next years. Work on BL1A will be done in steps, ramping up as the ARIEL construction is ramping down, transitioning to operation. The completion of the CFI-funded upgrade of the UCN facility to a liquid deuterium cryostat, designed and built in Japan, will propel TRIUMF's UCN sources to the global forefront internationally and enable the push for the best measurement of the electric dipole moment of the neutron.

EXPAND ISOTOPE CAPABILITIES

By tripling of the rare isotope beam hours enabled by ARIEL, the unique betaNMR capabilities can be fully exploited for advanced studies of quantum materials and biomolecules, leading to significant growth of the user community. Together with our university partners we will pursue CFI and provincial funding for an expansion of the betaNMR experimental end-stations and an upgrade of the laser polarizer while also enhancing the user support for the program.

Taking advantage of TRIUMF's core capabilities of radioisotope production for PET imaging and design and construction of advanced radiation detectors, we will establish the world's most advanced and first purpose designed facility for Positron Emission Particle Tracking (PEPT), a method for visualizing the motion of particles within complex opaque multiphase systems with applications in mining, engineering and other industrial sectors. We will work with our partners at UBC and Imperial College London (ICL) to develop, design, and construct a custom modular detector array as well as the procedures for generation, manipulation, and transport of tracers.



2.4 ATTRACTING THE BEST SCIENTISTS TO OUR WORLD-CLASS FACILITIES

Improving our facilities and adding new infrastructure will make TRIUMF a preferred destination for the world's best scientists, commercial users, and industrial partners. Building new office and research facilities to attract, engage, and welcome the world's best scientists, commercial users, and industrial partners allows TRIUMF to continue to thrive and strengthen its own capabilities. From a user experience perspective, we are competing with the world's best research facilities, and we must confidently demonstrate that we are able to offer state-of-the-art infrastructure that is capable of enabling top-notch research. These services include not only providing access to state-of-the-art research facilities but also assistance ranging from immigration consultation services to offering transportation and accommodations as well as access to temporary office space.

To attract the best talent, we are aware that we need to engage them by considering their views when developing new capabilities, ensure our accelerators are reliable with minimal downtime, and provide technical and scientific support when needed. Our expertise and excellence in a wide range of disciplines creates an intellectually stimulating environment that increases user satisfaction and fosters a culture of curiosity, collaboration, and inclusion, a culture that we aim to cultivate so that scientists and collaborators return to TRIUMF time and time again.

TRIUMF's scientific program thrives from the best ideas for the scientific program, which is driven by our user community from Canada, from around the world, and our own researchers. Attracting the best scientists from around the world requires world-leading technical capabilities and that we deliver on our promises to the users of our facilities. This requires a highly efficient and reliable facility operation to ensure that we deliver the requested beam at the requested intensity as scheduled. However, best-in-class user support goes beyond this. It requires support for proposal development and submission, a smooth and transparent onboarding process, plus administrative and technical support during their time at TRIUMF. To maximize the scientific impact of our world-class facilities, like ARIEL and IAMI, we recognize the need to invest into our infrastructure and people, and to invest in the support of the user program itself.

By tripling the number of rare isotope beam hours, more active meson channels and an expanded user program in the life sciences, TRIUMF will see a significant increase in our userbase, and it will be more important than ever that we have efficient support in place.

Building on the advances made during the last several years, we will further enhance the user experience at TRIUMF by carrying out the following improvements:

- Establish a visitor office and expand technical support for users.
- Expand our visitor program to support sabbatical visitors.

OUTCOMES

- Better user experiences.
- Boosted collaboration across disciplines.
- Improved communication between TRIUMF and our userbase.
- Established as premier site for cutting-edge studies by the world's best scientists.

IMPLEMENTATION

IMPROVE USER SUPPORT

We will establish a visitor office that will provide enhanced support for users on site. Also, in preparation for visitors' arrival, we will formalize a service that provides information about visa requirements, invitation letters, housing options, and other essentials. In parallel, we will further develop our online platform for user registration, proposal submission, and onboarding towards a "one stop service" with all required resources in one place. We will endeavor to provide a best in class user experience and monitor feedback from our visitors in order to continuously enhance our offerings to better customize the user experience.

We will also boost technical support resources for experimenters, supported by the recently appointed liaison scientists, whose role it is to assist visitors with their technical needs, and through additional hires of support scientists. This will include support for proposal development and submission, especially for non-expert users, help with equipment implementation and data taking, as well as support with data processing and analysis tools.

To ensure that user needs drive technical developments, we will be proactive and transparent in our user engagement and priority setting for these developments, so that the best ideas will be realized and implemented, enhancing user experience. To this end, we will allocate more time and resources to the development of new beam and technical capabilities.

EXPAND OUR VISITOR PROGRAM

Building on our established exchange programs with Perimeter Institute, KEK and Osaka University in Japan, and Helmholtz Institutions (DESY, Jülich) in Germany, we will expand our program for long-term sabbatical visitors, in particular from within TRIUMF's network of member universities, providing local housing support, and office space as well as offering opportunities for their students to come for extended stays. We will foster more interaction between long term visitors and in-house researchers through lectures, seminars, and informal get-togethers to initiate new ideas and collaborations.

The implementation of our "Master Plan" for the site includes the development of spaces for staff and visitors in a way that encourages interaction and scientific discourse. While the planned new building will have a focus on supporting interactions between staff and visiting users, we will develop the existing space with these goals in mind.

TRIUMF'S "SECRET SAUCE"

TRIUMF prides itself in attracting world-class scientists to a world-class laboratory space that fosters innovation through collaboration. What makes us truly unique, however, is that we are a multidisciplinary lab that's big enough to make ground-breaking discoveries, yet small enough to quickly implement ideas.

"The secret sauce of TRIUMF is multi-faceted: we're a laboratory that is small enough that you have enough flexibility to go after science goals in a very targeted manner and move along the cutting-edge of discovery. It's big enough to have a very professional staff and infrastructure," said Dr. Jens Dilling, Associate Laboratory Director for TRIUMF's Physical Sciences Division. "The other aspect is that we are very multidisciplinary, so we are big enough to afford this multidisciplinary aspect, but small enough that you have this cross-fertilization [of ideas] as everyone knows each other."

"TRIUMF is a national lab, but we act as a university lab where accessibility and transparency are paramount. Users can come and go from this thriving internal community where knowledge is shared and fostered," Dilling added. "It's a very permeable barrier … we're able to follow the cutting-edge of discovery."

2.5 BUILDING A MODERN AND INCLUSIVE ORGANIZATION

Inclusivity and diversity throughout the TRIUMF organization are ingrained in our values and mission, factors that enrich our community and culture of collaboration. With this in mind, we will transition TRIUMF to a modern, flexible organizational structure over this Five-Year Plan to manage our facilities, projects, and people more efficiently, with clarity and purpose, and guided by opportunity and risk analysis. Enabling a culture of continuous improvement will help transition TRIUMF into a learning organization with a mature safety culture and highly engaged people focused on finding creative solutions to complex problems. Drawing upon best practices at our member universities as well other global laboratories in the United States and abroad we will develop modern, inclusive business practices with the additional transition to a new governance model for the laboratory — from a highly effective board to the appropriate legal underpinning — TRIUMF will be healthy for the next fifty years.

We will achieve these goals by carrying out these logical steps:

- Complete alignment of TRIUMF's organizational structure.
- Improve recruitment practices and enhance employee engagement, guided by transparent and accountable implementation strategies.
- Optimize our facilities so we can deliver on our goals both reliably and efficiently.

OUTCOMES

- Diverse and inclusive laboratory culture.
- Efficient organization and laboratories.
- Smaller, more effective Board structure.

IMPLEMENTATION

REALIGN THE ORGANIZATIONAL STRUCTURE

We will continue the transition of improving the alignment of TRIUMF's organizational structure and process flow to better support the delivery of value to our users and stakeholders, from the member universities to funders, and private sector partners. We will establish effective management structures that will enable cross training for our technical and administrative staff. With further improvements in our project management processes we will develop a robust laboratory-wide resource allocation plan that enables, together with a nimble organizational structure, the flexible on-demand deployment of personnel in support of facility operation and projects.

In addition to the internal improvements to the organization, we will also advance the modernization of the governance structure of TRIUMF with a smaller, more effective Board structure and a modernized legal framework.

IMPROVE RECRUITMENT PRACTICES AND ENHANCE ENGAGEMENT

Our goal is to recruit and retain a diverse and exceptionally talented workforce and trainees, and to support them in ways that allow them to achieve their highest potential. TRIUMF aspires to be a diverse, welcoming science community with a demonstrated commitment to equity, diversity, and inclusion. We will enhance engagement within our TRIUMF family and implement a transparent and inspiring equity, diversity, and inclusion action plan with clear accountabilities, all supported by the expertise and best practices of our member universities. We will design and create equity, diversity, and inclusion deliverables such as recruitment strategies including, but not limited to, a range of training modules such as sensitivity training and unconscious bias training. We will also develop a toolkit of retention strategies and continuously review our equity policies and practices to monitor any systemic gaps such as equal pay parity, accessibility, and developing a mentoring program. We will evaluate the implementation of more flexible work arrangements as well as the feasibility of securing several daycare spaces at UBC or a nearby centre. We will also further strengthen our engagement activities, building on the implementation of regular Town Halls to enable discussion on important topics, as well as initiatives supporting work-life balance and health and wellness.

OPTIMIZE FACILITIES

Guided by Lean Principles, we will continue our efforts in process evaluations and improvements to operate the expanded facilities with highest reliability and efficiency, without requiring significantly more resources. We will pursue operational excellence by completing the implementation of site-wide standards for processes and documentation. We will also invest in modern software tools for managing staff, assets, and processes. This will ensure the best-in-class compliance with the CSA standard N286-12 for the management system requirements and further improve the efficiency of the laboratory. We will empower and support everyone at TRIUMF to identify opportunities for continuous improvement and implement innovative solutions, increasing engagement from frontline workers to top management, and taking our strong safety culture to the next level. The development of a strong continuous improvement culture will further increase safety, quality, and engagement.

PEOPLE AND SKILLS: DEVELOPING TALENT, INCREASING ACCESS AND EQUITY

GOAL 3 **Become a hub for interdisciplinary education and training**

OUTCOME **A new generation of highly-skilled Canadians ready to compete in the knowledge and innovation economy**

To foster a healthy knowledge economy, Canada must continue to develop and attract a well-educated, highly skilled and agile workforce. In doing so, we can confront the world's most challenging problems while fortifying our nation's global competitiveness. Equity, diversity, and inclusion are integral to the achievement of excellence and enhance TRIUMF's ability to accomplish its mission as a world-leading particle accelerator centre. At TRIUMF, we are aware that to drive discovery and innovation, we need a cohesive and comprehensive training and education plan that puts the well-being and development of our workforce and our trainees front and centre. We will also expand our education program to ensure that students from across Canada have access to our unique knowledge and expertise through remote teaching or through hands-on experiences at TRIUMF. By doing these things, we will be a key asset to Canada's evolving knowledge economy and will continue to attract and develop the brightest minds, while creating a support network that will set Canadians up for success, wherever they are from.

TRIUMF will continue to create professional development opportunities so that our workforce never stagnates and is always adapting, creating a fertile and healthy environment in which to work. We pride ourselves on quickly adapting to change, and this nimbleness can only be achieved by ensuring that our workforce is the best it can be. We will provide training and advancement opportunities for all of our personnel and trainees, with a special focus on early-career researchers so that they can have experience and exposure to our diverse, socially conscious, multicultural, and global society.

> **"If you ask me about our impact, I would have to say it's our people."**
>
> **DR. JONATHAN BAGGER, DIRECTOR, TRIUMF**

3.1 FOSTERING A CULTURE THAT EMBRACES EQUITY, DIVERSITY, AND INCLUSION

It is well-established that the most successful scientific projects require highly skilled, adaptive, and collaborative individuals who possess a varied set of skills. With diversity comes a rich mix of backgrounds, experience, and outlooks — attributes that build a healthy problem-solving culture in research programs. It is therefore of top priority that we actively strive to increase the diversity of our work force, while maintaining inclusive hiring and training practices. It is not enough to simply be aware of diversity and inclusion, we must lead by example and hardwire these attributes into our values and culture. To accomplish this, we will actively focus on nurturing opportunities for women, Indigenous Peoples and other underrepresented groups across Canada and beyond. To keep us accountable and to track our progress, we will measure where we stand, develop action plans, set targets, and review them regularly. This system will help us enrich the TRIUMF community and support our overarching goal to be a leading Canadian research facility in the hiring and the development of our workforce.

To build, maintain, and advance equity in our workforce, we will implement the following initiatives:

- Develop and review targets, best practices, and policies related to equity, diversity, and inclusion.
- Enhance diversity training programs, while improving governance with clear accountability measures.

OUTCOMES

- Improved recruitment process and policies, procedures, and programs fostering equity and inclusion.
- Equity, diversity, and inclusion training from recruitment to workplace behaviour.

IMPLEMENTATION

DEVELOP AND REVIEW TARGETS, BEST PRACTICES, AND POLICIES

TRIUMF recognizes that there are many opportunities for improvement at all levels to advance our standards, practices, and procedures related to the under-representation of individuals from federally designated groups (FDGs), women, persons with disabilities, Indigenous Peoples and visible minorities. To seize upon these opportunities, we will improve transparency and implement best practices within the recruitment process while setting benchmarks to meet equity targets. We will also review our existing policies, procedures, and programs through an equity lens, so we can identify elements of our policies that may generate systemic barriers to participation.

For example, we will review employment systems to understand the extent to which TRIUMF's current recruitment practices are open and transparent, while identifying barriers or practices that may be having a negative effect on the employment and retention of individuals from FDGs and to ensure a fair process and an equitable outcome. In response to this introspective analysis, we will implement corrective measures to fix areas where our practices fall short, ultimately improving governance and accountability.

DEVELOP DIVERSITY TRAINING PROGRAMS

To proactively strengthen TRIUMF's tradition of diversity and inclusion, we will further enhance training programs to support our staff and implement culture change programs relating to recruiting practices and workplace behaviour. Our training programs will include recruiting for diversity, competency-based interviewing, cultural sensitivity, mentoring and coaching, and sensitivity training. In the implementation of these programs we will utilize the experience and best practices established at our member universities and industry leaders.

We will also partner with the highly-successful First Nations training programs run by institutions such as British Columbia Institute of Technology (BCIT), UBC, UVic, and the University of Manitoba, to benefit from their experience and take guidance from them.

3.2 INCREASING EARLY-CAREER RESEARCH OPPORTUNITIES

TRIUMF is a hub that attracts the best early-career researchers, and we ensure that these young and inquiring minds have access to the best training and development tools to excel in their fields. Early-career researchers create opportunities to advance TRIUMF's research; they will make breakthrough discoveries, highlighting Canada's significant contributions to international advances in science. It is our aim to foster leaders across our multidisciplinary portfolio, and to create international teams with diverse skill sets to enhance their abilities, thereby boosting confidence and preparing them for a rich career in academia or the private sector. To achieve this, we will expand training opportunities in entrepreneurship, commercialization, communications, cross-cultural teamwork, project management, and data science. We already have a variety of programs — from work experience for undergraduates to Ph.D. programs, and postdoctoral fellowships — that we aim to expand and develop.

Solving society's biggest problems and pursuing ground-breaking discoveries requires the work of multidisciplinary teams of scientists, engineers, technicians, and tradespeople, and it is TRIUMF's mission to ensure the right mix of diversity, skills, and training opportunities to ensure our workforce is as prepared as it can be.

To propel our early-career researchers forward, thereby enriching TRIUMF's workforce, we will pursue the following initiatives:

- Expand and enhance experiential learning opportunities (e.g. internships, practicums) including the work experience program for Canadian and international undergraduate co-op students.
- Expand graduate education programs.
- Establish postdoctoral fellowships targeted on increasing diversity.
- Establish a mentoring program.

OUTCOMES

- 50% growth of our work experience program.
- Increased education and training opportunities for early career researchers.
- Transparent performance and diversity targets for training programs.

IMPLEMENTATION

EXPAND OUR WORK EXPERIENCE PROGRAM

We will significantly increase the number of training opportunities across all disciplines at TRIUMF, from science and engineering to communications, business, and administration. To achieve this, we will expand our undergraduate work experience program to include polytechnic institutions, and colleges, utilizing recent government funding of the Mitacs research internship program for their students. In alignment with our core values, we will implement equity, diversity, and inclusion targets (see “Strategy 3.1: Fostering a Culture That Embraces Equity, Diversity, and Inclusion) for all of our new and existing work experience initiatives. The program will also continue to focus on inter- and multidisciplinary opportunities, breaking down traditional boundaries of fields and educational sectors. To make us accountable, we will overhaul the hiring process and implement tools that allow for the analysis of the applicant pool, so targets can be set, and our performance tracked. We will also implement post-placement tracking to follow the careers of our trainees.

TRIUMF will also expand the program to include more opportunities for international students, utilizing funding programs through Mitacs, international funding opportunities, and our partner institutions. Attracting international students to Canada and the TRIUMF community will bring the top talent from emerging national economies (BRIC countries, i.e., Brazil, Russia, India, China, and South Africa) and other partner countries such as Germany, Italy, UK, and Japan. The impact of expanding our international scope will be two-fold: it will attract the best talent, while enriching the breadth of cross-cultural experiences for Canadian students.

Lastly, we will capitalize on our strategic partnerships with international partner laboratories and institutions, such as CERN, KEK, DESY, and other institutions around the globe, to expand the opportunities for Canadian students to have international work experiences.

EXPAND TRIUMF’S GRADUATE EDUCATION PROGRAMS

Accelerator science is TRIUMF’s core competency, a field of research that underpins a broad spectrum of science disciplines. Accelerators enable studies into Nuclear and Particle Physics, Materials Science, Accelerator Physics, and Nuclear Medicine, thereby underpinning the full breadth of work that TRIUMF does. It is, therefore, of high priority that we establish a formal Ph.D. program in accelerator science with research projects on the most advanced accelerator technologies.

This program builds on the successful — yet currently informal — education of graduate students at TRIUMF and the lectures that are offered currently on accelerator science. As Canada’s particle accelerator centre and an internationally recognized leader in Accelerator Science, TRIUMF has world-leading technical expertise in cyclotrons, superconducting RF, high-power targets, ion sources, and advanced beam dynamics calculations. Advanced research in these areas aligns itself perfectly for graduate research projects, while ensuring that TRIUMF continues to advance our cutting-edge accelerator-based research and support our contributions to the next generation of international accelerator facilities.

TRIUMF will establish an accelerator test-bed infrastructure to provide hands-on experience for students with accelerator systems outside of the ongoing accelerator operation of the user program. Thus, the education program will not interfere with the TRIUMF beam delivery priorities for research being carried out. Hands-on experience in an early stage of the academic education of students is important to bring young researchers into the field and advance cutting-edge accelerator research in Canada.

Other opportunities exist to enhance graduate education and research at TRIUMF. The current NSERC CREATE program Isotopes for Science and Medicine (IsoSiM) is a very successful platform that we intend to build upon. Jointly created by UBC and TRIUMF, the program will end in 2020, but we will continue to be energized by the momentum the initiative created so we can pursue new opportunities for similar programs that enhance multidisciplinary research and collaboration, professional development, and workforce readiness for trainees. Opportunities exist in the areas of data sciences, radiochemistry, and other fields.

FOSTER DIVERSITY THROUGH TARGETED POSTDOCTORAL FELLOWSHIPS

To advance TRIUMF’s strategic objectives, and with a few strategic additions, we plan to expand our program of postdoctoral fellowships beyond the accelerator science and theory programs.

We will create an additional postdoctoral fellowship with a special focus on promoting the advancement of women in science. To complement the high-profile Otto Hausser Fellowship, a unique position that is offered to exceptional young researchers seeking to advance their work in any area of TRIUMF’s broad research program, we will establish the Harriet Brooks Postdoctoral Fellowship for Women in Science. This highly prestigious fellowship will be a unique position at TRIUMF — honoring the first Canadian female nuclear physicist Harriet Brooks who, in 1901, was one of the first scientists to discover the radioactive element of radon and measure its mass. The fellowship will recognize the postdoctorate’s outstanding achievements with opportunities to enhance the visibility of her research both within their field and the scientific community at large.

We will also establish joint postdoctoral fellowships with international partner institutions to foster collaboration on topics of common interest and to increase diversity. We have recently established a joint fellowship with the Institute for Nuclear Theory at the University of Washington in Seattle, and we will explore the possibility to establish new joint fellowships with, for example, CERN, KEK, and RCNP Osaka.

3.3 EXPANDING PROFESSIONAL DEVELOPMENT TRAINING

The most valuable resource of any research facility is its people, and this is even more significant for TRIUMF than other facilities. Our workforce drives innovation, tackles the most complex problems in science and society, maintains some of the world's most complex machines, and collaborates with big international projects to make historic discoveries. It is therefore a top priority that we provide our workforce with opportunities to develop and hone their skills. To properly support this strategy, we must improve our professional development efforts across our diverse facility. We will create individual development plans for our staff, with access to external training opportunities, so they can better envisage the evolution of their careers. We will also launch two new programs that will build staff diversity through formal apprenticeships in a variety of Red Seal trades as well as Engineers-in-Training. In addition, we will create a new training program that will offer professional development options and personalized plans for all of TRIUMF's graduate students and postdocs. With a keen eye on expanding TRIUMF's professional development options, we will not only strengthen our workforce, we will also deepen Canada's talent pool in crucial areas, such as science, engineering, the trades, as well as communications and business.

To deliver on these goals in professional development across TRIUMF's workforce, we will endeavor to achieve the following initiatives:

- Implement a professional development program for graduate students and postdocs.
- Implement a professional development program for staff.
- Establish a formal apprenticeship program in the trades and develop an Engineers-in-Training program.

OUTCOMES

- Professional development opportunities for staff that support career progression.
- Increased workforce readiness of graduate students and postdocs.
- TRIUMF established as a Designated Training Provider in the trades.

IMPLEMENTATION

IMPLEMENT A PROFESSIONAL DEVELOPMENT PROGRAM FOR STAFF

We will implement a professional development program for staff that will expand on the opportunities that we already provide. TRIUMF has already begun utilizing a variety of tools, such as LinkedIn Learning, and other targeted initiatives, to ensure our workforce remains connected to the broader professional community. To promote employment practices which advance equity and access for all, we will expand and strengthen the professional development opportunities within TRIUMF and support the pursuit of further academic development. Guided by examples at our member universities, we will provide in-house training as well as establish a Professional Development Fund for each staff member that can be applied to professional development, skills training, and continuing education programs that are either organized by TRIUMF or offered externally. Supported by a professional development coordinator, staff and the supervisor can jointly develop annual development plans and career progression perspectives.

ESTABLISH APPRENTICESHIP AND ENGINEERS-IN-TRAINING PROGRAMS

TRIUMF currently has only a handful of apprenticeships, and they are typically utilized by existing staff members who are in the process of acquiring new skills. We want to expand our apprenticeship program to move to a more deliberate approach and create a formal apprenticeship system so many others can benefit from TRIUMF's unique environment to gain practical training in a variety of skills. We can provide training in Red Seal Trades — a program that sets common standards to assess the skills of tradespeople across Canada — for tradespeople such as industrial electricians, gasfitters, plumbers, welders, and many others. TRIUMF's facilities are very broad and multidisciplinary, filled with cutting-edge infrastructure and advanced technology that requires support from many trades. It is the ideal environment in which to train apprentices who can work on advanced facilities and benefit from seeing how their trade fits with our infrastructure, while exposing them to skills beyond the training they'd receive elsewhere. As part of TRIUMF's commitment to equity, diversity, and inclusion, we believe that educational and employment excellence includes the enactment of education in intentional ways. Students can experience first-hand an environment that challenges each person to achieve at high levels in a community that supports them to reach their potential. TRIUMF will seek to become a Designated Training Provider for a certain number of apprenticeships across a number of trades — fulfilling the Industry Training Authority's strict program standards. A stated goal of this program will be to increase the number of women in careers in male-dominated Red Seal trades.

In addition, TRIUMF will explore a partnership with BCIT to develop an Engineers-in-Training program at TRIUMF with positions across the organization to take advantage of the various opportunities, in particular in mechanical electronics, and

electrical engineering. We will focus our efforts in BCIT's Industry Days, their information fairs and sessions, and networking opportunities to boost the number of women in this male-dominated field.

To increase the numbers of FDGs in all job areas and at all levels where they are underrepresented, we will set numerical goals and track the progress as well as establish qualitative goals with clear processes and strategies for recruitment and retention.

IMPLEMENT A PROFESSIONAL DEVELOPMENT PROGRAM FOR GRADUATE STUDENTS AND POSTDOCS

Building on the successful professional development program that was developed specifically for the students and postdocs associated with the IsoSiM CREATE program we want to sustain and expand this program beyond the end of the IsoSiM funding in 2020. This includes offering all postdocs and graduate students hosted at TRIUMF the support of a newly established professional development coordinator to develop individualized development plans. Students from non-local universities (across Canada and internationally) as well as postdoctoral fellows hosted at TRIUMF cannot currently access professional development programs offered by UBC or SFU. In order to close this significant gap in their development we will work with Mitacs, NSERC, and our local university partners to offer relevant workshops and program, specifically for the trainees at TRIUMF. The new professional development coordinator will connect with these partners, organize events, and communicate external opportunities to the postdoctoral students and workshops. This program will be developed in close consultation with the TRIUMF Graduate Student and Postdoc Society (GAPS).

3.4 TRAINING STUDENTS ACROSS OUR NETWORK

TRIUMF's national network incorporates many academic institutions across Canada that would greatly benefit from access to our unique teaching and training environment. To expand TRIUMF's reach, and enrich the institutions across our network, we will establish a new training platform that will combine distance-learning opportunities and on-site, hands-on laboratory experiences. By doing this, we can expand the footprint of TRIUMF's unique training environment across Canada. These training options could include traditional teaching methods such as lectures, summer courses, and intensive hands-on laboratory training at TRIUMF's facilities, blended with online courses featuring regular TRIUMF teaching staff and international guest lecturers. The time is right for TRIUMF to reach out to students no matter where they live; leveraging our national network of institutions can be transformative in this endeavour.

To achieve these goals, we will pursue the following initiative:

- Develop a training platform for the post-secondary sector in the core disciplines of TRIUMF.

OUTCOME

- Increased reach of TRIUMF's education program.

IMPLEMENTATION

DEVELOP A TRAINING PLATFORM FOR THE POST-SECONDARY SECTOR

The unique expertise and qualification of our staff and our local facilities can tremendously benefit the education mission of our member universities. For example, we are uniquely qualified to offer specialty lecture courses, in topics from nuclear and particle physics to accelerator physics and nuclear medicine. Remote-access lectures offered by TRIUMF enable students at universities across Canada access to topics that are not offered at their institution, due to lack of expertise or insufficient number of students to make a course viable at their university. This is an opportunity to showcase the expertise and knowledge at TRIUMF while providing a more accessible platform for learning. The long-standing annual TRIUMF Summer Institute (TSI), with annually changing topics, is another example of the unique education we provide. The popular Tri-Institute International Summer School on Elementary Particles (TRISEP), rotating between TRIUMF, Perimeter Institute, and SNOLAB is an offspring of this format.

To expand on our current ad-hoc educational offers, we will develop a comprehensive training platform for the post-secondary sector in the core disciplines of TRIUMF, based on multi-access lecture courses with laboratory training experiences. TRIUMF will provide lecturer training and state-of-the-art classroom facilities to ensure a high-quality, multi-access teaching environment for local and distance-learning students.

Students at polytechnic institutions, colleges, and universities can participate in state-of-the-art training, either remotely or at TRIUMF. The curriculum of the overall program will cover topics in nuclear and particle physics, nuclear chemistry, nuclear medicine and life sciences, advanced material and quantum material, advanced engineering, accelerator sciences, and applications of artificial intelligence and quantum computing. The platform will include a portfolio of curriculum elements, including semester-long lectures on one specific topic, e.g. accelerator science, module-based compact summer courses that may extend for up to four weeks, week-long summer schools and workshops, as well as one-off lectures. The lectures will be accompanied with hands-on experiences utilizing TRIUMF's unique research infrastructure. The teaching will be carried out by world-class experts, including TRIUMF staff, scientific leaders from within the TRIUMF network, as well as international guest scientists on sabbatical at TRIUMF.

An example for taking our summer school program to the next level is the 2018 GRaduate Instrumentation and Detector School (GRIDS), organized as part of the annual TRIUMF Summer Institute's (TSI), jointly with the CFREF-funded Arthur B. McDonald Canadian Astroparticle Physics Research Institute at Queen's University. GRIDS is aimed at graduate students and postdoctoral fellows whose work is focused on the practical applications of particle and radiation detection. We will also offer member universities opportunities to bring graduate and senior undergraduates to TRIUMF to conduct educational laboratories at lab facilities as part of their coursework. TRIUMF will offer some financial support for cost of living, accommodation, and local teaching assistant support. We will also allocate dedicated instrumentation and experiments for student use. TRIUMF will also build capacity and expertise to run these schools by participating in the 2018 Excellence in Detector and Instrumentation Technology (EDIT) school at Fermilab, which is a well-established format consisting of plenary lectures in the morning followed by hands-on experience with technology in the afternoon. We encourage all students to attend, especially those who identify as belonging to a group which has been historically underrepresented.

Another format under consideration is a for-credit university-based approach that prepares students at their university, after which they travel to TRIUMF to assemble and perform an experiment as a student collaboration. This approach fosters collaborative problem solving of a complete experimental program, from conception, to set-up, data-taking to analysis and science extraction and report writing, while executing research in an operational laboratory environment.

The example of the detector school can be transferred to other topics, be it accelerator science, MuSR and betaNMR based quantum materials science, rare isotope science, or radiochemistry.

GOAL 4 **Inspire Canadians to discover and innovate**

OUTCOME **Greater access to STEM opportunities for all Canadians**

Outreach is more than just communicating science to the public; it's a chance to directly connect and engage with all individuals from all backgrounds and communities. For young Canadians, this is especially important as they may be inspired to pursue careers related to science, technology, engineering, and math (STEM) that will, ultimately, unlock opportunities for them to shape our future and enrich Canada's economy and standards of living. To this end, as Canada's particle accelerator centre, TRIUMF has a responsibility to tell our story and engage with the nation's young and inquiring minds in a variety of ways. From understanding how stars generate energy to developing a novel radioisotope for the treatment of cancer, communicating TRIUMF's work in accelerator-based science creates an unparalleled opportunity for our multidisciplinary portfolio to stimulate curiosity beyond our facility. With curiosity comes excitement for the work that we do and how it can be applied to impact the lives of Canadians. Stimulating curiosity is a priority when engaging with the wider community, but it requires a strategic communications approach to inspire the next generation of problem solvers, critical thinkers, discoverers, and innovators.

> "I have a son and a daughter, and I want both of them to have role models. And they know that in Canada they can do anything that they want to. I think Canada and TRIUMF are beacons."
>
> **DR. NIR NEVO DINUR, TRIUMF POSTDOCTORAL RESEARCHER**

4.1 EXTENDING PUBLIC ENGAGEMENT TO COMMUNITIES ACROSS CANADA

To extend TRIUMF's reach, we will boost our capacity to deliver high-impact public engagement and outreach efforts to tap into the curiosity of communities from all across Canada, with an emphasis on school-age children from underrepresented groups and remote communities. To achieve this strategy, we will develop partnerships so we can leverage new and emerging digital technologies and platforms such as virtual and augmented reality, gaming, apps, and more, connecting more young people to impactful and enjoyable STEM experiences. We will lead with TRIUMF's stories of science, discovery, and innovation to inspire young minds with goals to propel their curiosity forward. We will also deliver learning and development tools that encourage young Canadians to continue to unleash their curiosity and pursue higher education and pathways that lead to STEM-related careers. To increase our reach, we will deliver professional development opportunities for educators, journalists, and science communicators nation-wide, supporting their efforts to deliver high-quality content. We will also collaborate with partners in our established network to develop and share resources so communities, no matter where they are, can engage with our outreach efforts.

To build TRIUMF's outreach capacity, we will implement the following engagement activities:

- Build on the development opportunities for educators engaged in outreach activities in the TRIUMF community and beyond.
- Curate outreach resources from and for our members and partners.
- Leverage TRIUMF's nationwide network to connect more communities to STEM opportunities.

OUTCOMES

- Increased public engagement and outreach capacity across our network.
- More public engagement and outreach for under-supported communities.
- More pathways and resources available to give more Canadians access to STEM opportunities.

IMPLEMENTATION

CREATE PROFESSIONAL DEVELOPMENT OPPORTUNITIES

Individuals involved in outreach activities, such as journalists, science communicators, educators, students, early-career scientists, TRIUMF staff, and trainees, will be provided with development opportunities through a broad portfolio of activities and resources building on their own expertise and life experiences. TRIUMF staff and trainees are key to the lab's outreach activities, activities that we intend to continue and improve upon. This, in turn, provides great professional development opportunities for the entire TRIUMF team, including our scientists, engineers, technicians, tradespeople, administrative staff, and students. We will grow the TRIUMF Ambassador Program (TAP), a component of the expanded professional development program for our own students, postdocs, and workforce.

To prevent duplication of efforts and to maximize the impact of this strategy, we will work with partners such as the Science Writers and Communicators of Canada, BC Science Charter members, Laurentian University and Science North graduate program in science communication, Perimeter Institute and its established PI Teacher Network, and others. We will also actively seek out new partnerships and develop new programs when opportunities arise.

CURATE OUTREACH RESOURCES

A key priority in optimizing outreach initiatives will be to curate resources for our extended network and resources that are produced by the network. Bringing the various best-practice and innovative outreach materials and programs that have been developed by TRIUMF, our member universities, and various partners together into a central location will be a logical step to ensure efficient use of outreach materials. These pooled resources will include links to best practices, explainers (such as how to host your own public talks and how particle accelerators work), and information on partner organizations, demonstration ideas, visualization data sets, toolkits, and dates of key events. In addition, we will also be vigilant for events that we can leverage as opportunities for TRIUMF and partners to get involved in, such as Dark Matter Day, π Day, the International Day of Human Space Flight, and others. Our involvement may focus around social media campaigns, open days, community events, or other public engagement opportunities.

Through these efforts, we will establish a "community of practice," a group that is established to grow knowledge around a specific field, for member university outreach contacts who will connect with each other on a regular basis, building contacts, sharing insights and becoming part of the TRIUMF story of discovery, innovation, and empowerment. This community will be further strengthened by holding annual workshops that will rotate across member universities.

CONNECT COMMUNITIES

The ultimate aim of this multifaceted strategy is to connect communities on a local and national level, using TRIUMF's established and trusted brand to drive science outreach and engagement throughout Canada. By leveraging the geographical reach of our network, we will connect more people across the nation than ever before, giving them sustainable access to STEM initiatives. Sustainable access means communities will continue to return to an evolving and growing portfolio of outreach resources. This will be achieved by partnering with both diverse and like-minded groups and individuals to increase access to quality STEM outreach touchpoints for people across Canada via real-world interactions and virtual technologies.

These plans can only be achieved through respectful partnerships with organizations in BC and across Canada that specialize in reaching underrepresented and underserved communities. For example, there's an opportunity for us to reinvigorate TRIUMF's arts and culture program, strengthening our partnership with Emily Carr University of Art and Design while cultivating new relationships. We will open our doors to expose people to a rich environment of cutting-edge technology, an effort that will expose non-specialists to science.

TRIUMF is also involved with the Global Physics Photowalk that is coordinated by the Interactions Collaboration. This international competition invites photographers of all abilities into science laboratories to capture the art of science through their camera lens. Through TRIUMF's involvement, we can showcase our advanced research technology alongside other laboratories, such as CERN. It's through competitions such as these, where science and art become intertwined, that we can further promote our brand on a national and international stage while inspiring participants with the incredible work that we do.

4.2 COMMUNICATING THE VALUE OF SCIENCE, TECHNOLOGY, AND INNOVATION

TRIUMF's story is one of science, discovery, and community, stretching over five decades of proud Canadian history, with a scientific future that will fuel our nation's ingenuity for the next 50 years. Telling our story needs to be central to TRIUMF's outreach message and the message of our impact is clear: we are a particle accelerator lab that nurtures the biggest ideas to make ground-breaking discoveries that drive innovation. Centering our outreach strategies around TRIUMF's story demonstrates how our applications and innovations contribute to Canada's progress and prosperity, thereby fueling the nation's evolving and diverse knowledge-based society. Conveying our excitement for what we do will inspire others, not just to engage with TRIUMF's work, but it will also communicate the value of science, technology, and innovation. TRIUMF is a uniquely Canadian success story, so we need to shine a light on what we do and how our work impacts all Canadians; to know they are part of the same story will ignite their curiosity and enthusiasm.

To put a spotlight on Canadian progress and emphasize the value TRIUMF brings, we will promote and celebrate our successes using a range of communication tools and initiatives, namely:

- Work with stakeholders and partners to celebrate shared successes.
- Build tools and cultivate communications connections that can be leveraged across our network.

OUTCOMES

- Enhanced efforts to celebrate and share TRIUMF's, our partners', and Canada's successes.
- Strengthened brand of TRIUMF, our partners, and Canada.

IMPLEMENTATION

CELEBRATE SHARED SUCCESSES

When embedded in a scientific facility that carries out ground-breaking work on a daily basis, it can often be difficult to appreciate the value or impact of the work that is being done. A small breakthrough made in the lab may not seem like a big deal to the scientist, but with a skilled communications team that has an innate understanding of the work being done, an opportunity to communicate the importance of that breakthrough to society may present itself. This can be done by celebrating our successes. Through careful coordination with our stakeholders, member universities, funding bodies, partners, and industry collaborators, we can identify shared successes and coordinate accordingly.

With our established network, we will work on identifying these successes to carry out joint PR campaigns, issue joint press releases, and prepare collaborative digital stories and social media campaigns. For example, should an industry partner develop a new radiopharmaceutical that uses radioisotopes produced at TRIUMF facilities, there will be a communications code of conduct in place that ensures all collaborators are aware of the development. From the outset, plans will be set in motion to ensure that joint press releases are issued so that announcement messaging is coherent across all partners involved. Such a coherent and shared approach will ultimately amplify our voices.

BUILD TOOLS AND RESOURCES AND CULTIVATE COMMUNICATIONS CONNECTIONS

To further enhance our message, we will work with our partners to build tools and resources that can be leveraged across the network. For example, we might want to develop and curate digital communications resources to link our network's research with its benefits to society. In this case, the resources may include media libraries, key network contacts, explainers, and webinars that can be quickly accessed and managed.

These efforts will ultimately streamline our communications through our network, simplifying the process of delivering shared stories emerging from the network, while inspiring Canadians with the ground-breaking work TRIUMF does. We strive to be world leaders in simplifying the complex, to inspire the next generation of scientists and inform Canadians about how investments into science and technology have wide-ranging positive impacts on society and quality of life.

INNOVATION AND COLLABORATION: CONNECTING SCIENCE TO SOCIETY AND CANADA TO THE WORLD

GOAL 5 **Translate science and technology into innovation**

OUTCOME **New game-changing technologies that support business-led innovation and improve the lives of Canadians**

Innovation is the lifeblood of society; ideas are born, new technologies invented, technologies turn into products and are commercialized, and standards of living enhanced. However, understanding the pipeline of how ideas turn into technologies that positively impact society requires an innate knowledge of how those ideas are incubated and how cutting-edge technologies can be applied to solve real-world problems. Canada's high standard of living is becoming increasingly reliant on advancements in the knowledge economy and central to this is the emergence of innovations from the nation's science organizations. In the case of TRIUMF, as Canada's particle accelerator centre, we occupy the crossroads where science meets application, and TRIUMF Innovations Inc. is strategically placed to be the interface that translates our world-leading scientific discoveries into new technologies and applications, thereby strengthening our nation's economy and, ultimately, improving the lives of Canadians.

Central to the mission of TRIUMF Innovations is to seek out commercialization opportunities across TRIUMF's multidisciplinary science portfolio — from embracing the quantum computing revolution to developing advanced radiopharmaceuticals to cure cancer — to becoming a national commercialization centre with an established national network linking academic institutions with the private sector. We are uniquely-placed to uncover potentially transformative opportunities by leveraging our network to identify game-changing technologies, so they can be turned into innovative products or services that can be taken to market. Combined with the opportunities created by the completion of the Advanced Rare Isotope Laboratory (ARIEL) and the Institute for Advanced Medical Isotopes (IAMI), the time is now for TRIUMF Innovations to take centerstage in several exciting developments in science, technology, and application, thereby helping to boost Canada's wellbeing and galvanizing our nation's reputation as one of the world's leading knowledge-based societies.

> **"TRIUMF and TRIUMF Innovations have been instrumental in helping us get to this stage of commercialization of the ^{99m}Tc production solution."**
>
> **DR. PAUL SHAFFER, ASSOCIATE LABORATORY DIRECTOR – LIFE SCIENCES DIVISION, TRIUMF/ CTO, ARTMS™ PRODUCTS INC.**

5.1 COMMERCIALIZING TECHNOLOGIES DEVELOPED AT TRIUMF

First and foremost, to turn an interesting technology into a viable product or service, TRIUMF Innovations will work with industrial partners to bring them to market. These technologies include the development of novel cancer therapies with pharmaceutical companies, the realization of new, environmentally-sound methods to optimize output for mining companies and the development of technologies that can help batteries last longer. Not all technological applications may be apparent to industry. Therefore, TRIUMF Innovations will play a key role in this Five-Year Plan — to identify what these technologies are and how they can be integrated into the mainstream.

This process creates financial opportunities for TRIUMF, so we intend to take advantage of this through licencing agreements, milestone payments, royalties, and equity deals for the promising technologies we will develop. Should the opportunities arise, we will create new start-up companies that will allow us to benefit financially from new technologies by spinning off TRIUMF's investment in science and technology to create a tangible economic resource. To this end, we will also engage UBC and other partners to develop plans for a major high-impact Innovation Park to supercharge the commercialization of disruptive technologies and build new partnerships to further enhance our diverse network of industrial partners.

To accomplish these bold initiatives, we will:

- Create and advance technologies with industry partners.
- Licence technologies to existing companies.
- Create new start-up companies to create an economic resource for TRIUMF.
- Create new proprietary intellectual property based on TRIUMF discoveries.
- Initiate plans for a TRIUMF-branded Innovation Park on the UBC campus..

OUTCOMES

- Enhanced industrial partner network.
- New start-up companies.
- New intellectual property, including patents for TRIUMF inventions.
- Increased revenues, company growth, jobs.
- Advanced plans for an Innovation Park

IMPLEMENTATION

INDUSTRIAL PARTNERSHIPS

TRIUMF Innovations will strive to grow TRIUMF's partnership network to find exciting opportunities to create or advance technologies spawned from TRIUMF's multidisciplinary portfolio of science investigations. Also, existing relationships with industry partners will be nurtured and strengthened. For example, TRIUMF's long standing partnership with Nordion Inc., a leading producer of medical isotopes used for the prevention, diagnosis, and treatment of disease — has led to the production of over 50 million patient doses of medical imaging isotopes for the last 40 years, generating over $100 million in funding and revenue. The Nordion Inc. medical isotope business was recently acquired by BWX Technologies Inc. (BWXT) with whom we are planning to continue the successful partnership. With the boosted radioisotope production capabilities afforded when IAMI goes online, TRIUMF will secure BC's medical isotope supply while identifying strategic partners that can bring radiopharmaceutical products to market.

"This will be a new era for TRIUMF with the combination of ARIEL, IAMI, and TRIUMF Innovations," said Kathryn Hayashi, CEO of TRIUMF Innovations. "A new era with more productivity and connectivity with the private sector and more industry partners and collaborations. Whereas the business opportunities in nuclear medicine have been limited by the science and production output, now the technology landscape has presented new opportunities for business, collaborations, partnerships, and new breakthroughs in nuclear medicine," Hayashi added.

Beyond medicine, TRIUMF's detector experts will also collaborate with mining manufacturers to develop new cost-saving and environmentally-friendly mining tools for use in other industries. Tools, such as a custom-made PET scanner, used to provide a detailed analysis of mining slurry, may also have applications in monitoring other liquid samples in municipal water supplies or even food production.

LICENCING TECHNOLOGIES

Through licencing agreements with companies, TRIUMF Innovations will bring innovation to the marketplace. These agreements may take the form of royalties or equity in the licensee company, helping TRIUMF monetize its in-house developments in accelerator and detector technology, radioisotope development, and novel imaging techniques.

For example, a new type of cyclotron component designed and developed at TRIUMF could be licenced and manufactured by an industry partner, reducing downtime and operating costs in thousands of cyclotrons around the world, thereby solving ubiquitous engineering problems while providing revenue for TRIUMF. The TRIUMF industry partner D-Pace, Inc., founded by a former TRIUMF alumnus, already does this to great effect, providing state-of-the-art engineering products and services to the particle accelerator industry while licencing cyclotron component technologies where possible. As an internationally-recognized, award-winning company, that has secured global investment into its Canadian operations from Buckley Systems (New Zealand), D-Pace maintains a strong relationship with TRIUMF, by subcontracting our uniquely specialized staff and utilizing assembly space at our facilities.

"TRIUMF is exceptional in its importance to the advancement of science, technology, and technological commercialization in Canada. TRIUMF's scientific impact per government dollar invested is extremely high. Globally speaking, our national investment over the years has been relatively modest, yet TRIUMF is grouped in with billion-dollar national laboratories in the consciousness of the global scientific community." — Morgan Dehnel, Founder and Chief Science & Innovation Officer, D-Pace, Inc.

NEW START-UP COMPANIES

Identifying new technologies for commercialization is a key component of TRIUMF Innovations' work, and a growing responsibility will be to identify which products or services can form the foundations of new start-up companies. These TRIUMF start-ups will commercialize technologies that have a sustainable competitive advantage and significant market potential to generate a revenue stream for the lab. The establishment of these start-ups will be made possible through partnerships with other research organizations, investors, and corporate partners.

TRIUMF Innovations has successfully launched five start-up companies to market, each one encompassing TRIUMF's key competencies from the production of isotopes used in medical imaging to applying neutron imaging for oil and gas recovery:

- **ARTMS™ Products Inc.** A world leader in the development of novel technologies and products will enable the production of the world's most-used diagnostic imaging isotope, technetium-99m (^{99m}Tc).

- **CRM GeoTomography Technologies Inc.** Helps exploration geologists reduce cost and waste by providing new 3D insights into dense ore bodies using its field-proven muon detectors, tomographic imaging, and integration with other geological data.
- **Frontier Sonde Inc.** Provides neutron imaging for enhanced oil and gas recovery, leveraging the nuclear and particle physics experts, materials science teams, detector excellence, and advanced readout technologies.
- **Micromatter Technologies Inc.** Specializes in thin film deposition technologies, including accelerator target foils and X-ray fluorescence (XRF) calibration standards.
- **IKOMED.** Develops a patented system to reduce X-ray radiation exposure to both patients and medical staff during minimally-invasive surgery.

Other start-up companies will be founded based on TRIUMF's areas of expertise when commercialization opportunities present themselves.

HELPING EXISTING COMPANIES GROW

Although establishing start-up companies is an important endeavour to make technologies available for use in society, a large part of TRIUMF Innovations' work will continue to focus on growing existing companies, from start-ups to established companies seeking new opportunities. In the case of D-Pace, which has been a long-term partner of TRIUMF's, we licence new technologies that strategically help to expand and cultivate their business. Other established global industry partners from the EU and USA are currently trying to establish a presence in North America to expand their business, and TRIUMF Innovations is working with them to make this possible. TRIUMF's established history of excellence makes it a very desirable brand for companies at home and abroad to work with, providing valuable inroads to Canada's growing knowledge-based economy.

NEW PROPRIETARY INTELLECTUAL PROPERTY

The invention of new devices and technologies that can potentially improve industrial processes, boost radioisotope production or uncover a novel quantum material will inevitably result in the creation of new proprietary intellectual property. From the outset, we need to invest in targeted technology development, being mindful of new inventions, with commercialization being of high priority. TRIUMF Innovations will foster this business perspective from the early stages of a project, as well as provide early feedback and support for potential industry partners. By achieving this, we will speed up technology development and adoption, and create new opportunities for commercialization.

TRIUMF INNOVATION PARK

With our partners, we will initiate planning for an Innovation Park (or Hub) that will showcase TRIUMF's spirit of advancing discovery and stories of finding innovative solutions for business and industry. TRIUMF is located on the south campus of UBC and neighbours UBC and NRC research facilities. This is one of the last areas of the UBC campus that could support the size and scale of a sizable Innovation Park. The Park would be strategically placed to act as a catalyst for an expanded innovation and training ecosystem, encouraging connections and academic partnerships with industry, government, and non-profit sectors. This initiative would provide companies with access to researchers, students, and campus facilities, students with access to real-world applications and training, and both student and non-student communities with industrial-level makerspace that will enable technology development.

TRIUMF's IAMI project is a good example of bringing together government, academia, and industry to create the core of a nuclear medicine cluster based at TRIUMF. This model can be expanded to other opportunities in commercialization of advanced science-based technologies. To make this possible, we will identify and secure partners from academia, industry, and government to begin development of a master concept and a plan of action.

5.2 HARNESSING OUR TECHNOLOGIES TO SOLVE REAL-WORLD PROBLEMS

The revenue generated from industrial partnerships will provide long-term sustainability for TRIUMF and TRIUMF Innovations, in large part driven by public organizations and governments seeking solutions to real-world problems. Through the application of our world-class facilities, our partners can take full advantage of our efficient infrastructure to address pressing national and international challenges.

With the completion of IAMI, for example, comes an opportunity to greatly increase the output of rare isotopes that are used in nuclear medicine and develop new technologies for the delivery of radiopharmaceuticals that are used to diagnose and treat cancer. We can therefore address the radioisotope supply problem while developing novel radiopharmaceutical and companion diagnostics for late-stage and hard to treat cancers, helping to fill potential supply gaps while finding new methods to ultimately save lives. Also, through our work with industry, we can help to find ways to improve efficiency while striving for environmentally-sound solutions.

To achieve these goals, we will:

- Help solve real-world problems — such as bringing life-saving cancer treatments to patients and securing medical radioisotope supplies in the event of shortages — through strategic partnerships.
- Work with industry partners to “de-risk” their technologies.

OUTCOMES

- More opportunities for bringing life-saving medical isotopes to market, and ultimately to patients around the world.
- Canada’s medical isotope supply bolstered.
- More industry partners using TRIUMF facilities.
- Technology/product improvements.

IMPLEMENTATION

BRINGING LIFE-SAVING CANCER INNOVATIONS TO MARKET

TRIUMF is a world-leader in the production of medical isotopes, but for innovations in radiopharmaceuticals to benefit society, they must be developed and brought to clinical use. For example, TRIUMF will build two start-up companies around the commercialization of ^{225}Ac, a radioisotope that has been used in targeted cancer therapies and has demonstrated outstanding results in late-stage cancers (see Strategy 1.3: “Developing New Radiopharmaceuticals To Diagnose And Treat Disease”). One company is focused on new technologies to increase the production of actinium, whereas the other is based on development of novel radiopharmaceuticals using actinium.

SECURING MEDICAL ISOTOPE SUPPLY

Medical isotopes — such as ^{99m}Tc that is used in medical imaging — are produced inside nuclear reactors, accelerators, and cyclotrons. But the closure of Canada’s Chalk River reactor in 2016, a key producer of the generator for ^{99m}Tc, highlighted a potential global crisis for the supply of ^{99m}Tc and the security of other medical isotopes. To help alleviate the impact of any future isotope shortages, IAMI’s new TR-24 cyclotron will complement the production of medical isotopes from our 520 MeV cyclotron, thus boosting TRIUMF’s output. This will, in turn, result in more patient doses of radiopharmaceuticals and help bolster BC’s medical isotope security. Although nuclear reactors produce larger quantities of radioisotopes than cyclotrons, cyclotrons generate much lower levels of radioactive waste. Thus, the radioisotopes produced at TRIUMF facilities have a lower environmental impact than reactor sources.

We will continue to work with our valued partners (such as BWX Technologies Inc. — formerly Nordion Inc.) and TRIUMF start-ups (such as ARTMS™) while seeking out new partnership opportunities, so we can become a major resource for the cyclotron production of medical isotopes around the globe, as well as supporting the Province of BC’s efforts to secure isotope supply for patients in BC.

“The 40-year partnership with TRIUMF has been rewarding in providing medical isotopes for the health and well-being of mankind. The products produced by the partnership touch the lives of millions of people. We look forward to many more years of the successful relationship.” — Jerry Porter, General Manager (Canada) of BWX Technologies Inc. (formerly Nordion Inc.).

DE-RISKING TECHNOLOGIES

TRIUMF operates an irradiation facility that is used by dozens of industry partners — such as Boeing, MDA Corporation, and Cisco Systems — for essential proton and neutron radiation tests on components designed to be operated in space. Beyond our protective atmosphere, space is filled with high-energy particles that damage sensitive equipment; through irradiation tests at our facility, industry partners can "stress test" hardware components before they are installed on spacecraft, satellites or aircraft, thereby fulfilling a critical role in advancing satellite, communications, and aerospace technologies. This process of de-risking technologies has mission-critical applications that ultimately provide our industry partners with quality assurance and cost-saving opportunities when designing new technologies.

"TRIUMF provides us with a unique ability to test our space borne systems, and present insights into how our electronics will behave in a harsh radiation environment of space over several years. Testing at TRIUMF allowed us to save time, money, and significantly reduced the risk of failure of our products for our customers. The TRIUMF team played a vital role in the success of our test campaigns by accommodating us in various ways to ensure we could complete our tests in a more efficient manner than originally scheduled." — Valeri Kirischian, FPGA/Embedded Systems Engineer, MDA Robotics and Automation

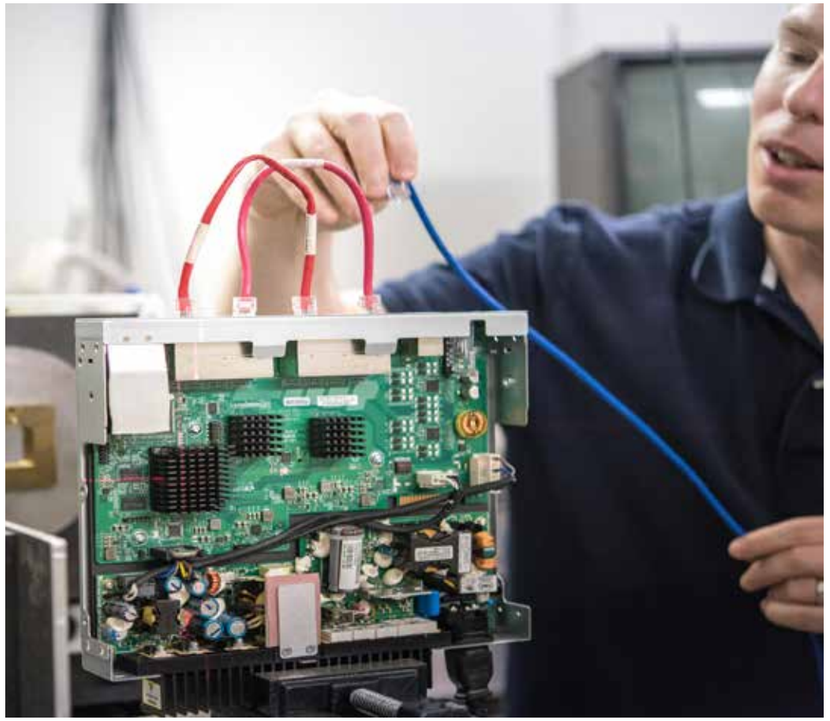
TRIUMF: WE SOLVE PROBLEMS

There are few scientific research centres in the world that have the freedom to pursue ground-breaking science while identifying technologies that may be spun-off as new and transformative products or services. Due to our unique governance and funding model, we are well positioned for our mission to find solutions to the most pressing regional and global problems. We seek out interesting discovery science, but couple this with an unparalleled focus on applying our knowledge across a myriad of topics to make a positive impact on society.

"We are trying to answer some of the biggest and smallest mysteries in the universe, looking at how stars are born, as well as how the tiniest particles in an atom function, with curing cancer with isotopes somewhere in the middle! The kinds of science questions being asked at TRIUMF are incredible," said Kathryn Hayashi, CEO of TRIUMF Innovations. "What happens when stars collide? That's a fascinating question. Can this new isotope cure a cancer that's currently treatable? That's an exciting opportunity."

The research infrastructure and expertise at TRIUMF attracts scientists from all over the globe to Canada, as it's the best place in the world to do their research. "The people here are brilliant, and very collaborative. They want to make an impact on the world. We solve problems here," Hayashi added.

With such a fertile problem-solving lab, operating at a scale that provides the nimbleness of decision-making and multidisciplinary collaboration that allows us to effectively pursue answers to these questions, makes for an unprecedented environment for the emergence of innovative ideas that can be embraced, commercialized, and released to the mainstream. TRIUMF Innovations is what makes this happen, giving us a competitive advantage on the world stage.



5.3 CONNECTING OUR NETWORK WITH OPPORTUNITIES IN THE PRIVATE SECTOR

Canada is a large country with a comparatively small, spread-out population that, from the outset, can be daunting to potential industry partners as they seek new opportunities with experts in science and technology. TRIUMF's long-established network, which links 20 globally-recognized Canadian research universities, alleviates this problem, and provides our partners with unprecedented access to highly-qualified personnel across a vast geography.

The network has a strong history of successfully working with academic and industry partners — with TRIUMF as the hub that connects this network to a rich array of opportunities. Our maturing national network will continue to grow to further exploit strategic opportunities with the business sector, while connecting member universities with potential investors to accelerate technological developments that lead to commercialization opportunities. In parallel, we will also spearhead a national data science training program to support members of our network find jobs in the industrial sector.

To continue to leverage our national network and find new opportunities for TRIUMF and our partners, we will carry out the following actions:

- Connect research institutions with industry partners and investors to grow our network.
- Create a new data science training program for network partners

OUTCOMES

- New business opportunities for network partners.
- New Data Science Training Program provides training and job opportunities for students and researchers from across the national TRIUMF network.
- Larger national network with more training and commercialization opportunities.
- Stronger national and international TRIUMF brand recognition.

IMPLEMENTATION

TRIUMF NETWORK: CONNECTING ACADEMIC INSTITUTIONS WITH THE PRIVATE SECTOR

To bring private sector opportunities into the TRIUMF network, we will be strategic in always adding value and complementing the work that our network is doing without duplicating the efforts of other networks or national programs. To pull the technologies from TRIUMF's network and connect them with the private sector, we will introduce member universities to innovation intermediaries and funders. We will provide business services and support for high-potential technologies from across the national network. This work will require more outreach to boost the visibility of the TRIUMF network and to showcase the advanced technologies that emerge from our members.

The TRIUMF brand is nationally and internationally recognized as being associated with a long history of multidisciplinary scientific excellence and the ability to work successfully with both industry partners and academics, bolstering the legitimacy of the network.

"The global brand of TRIUMF is very strong and very associated with Canada," said Hayashi. "We have a strong history of science excellence. We are independent and multidisciplinary, advancing technologies based on each technology's merit and market impact." In addition, if a scientist or someone from the private sector has a problem that needs solving, they can submit a proposal, and we can build collaborations to pursue it. The combination of TRIUMF's strong brand, an established network and a world-class facility and team, makes our network a fertile environment for collaboration, access, training, and accelerated commercialization.

An example of the network in action can be found in the founding of ARTMS™ Products Inc. As a TRIUMF spinoff company (formed in a cross-Canada partnership with BC Cancer, Centre for Probe Development and Commercialization, and Lawson Health Institute), ARTMS™ specializes in the development of novel technologies that enable the production of the world's most-used diagnostic imaging isotopes. But from the outset, the company required nuclear medicine, radiochemistry, engineering, and business development partners from across the country to work together to develop and market an innovative new technology. This collaborative approach is necessary to advance many of the most innovative technologies (which often bridge such disparate sectors and engineering, data science, physics, and biology), and it was only possible by leveraging the TRIUMF network to provide the resources the company needed.

DATA SCIENCE TRAINING PROGRAM

Physicists are increasingly being exposed to more complex datasets as they carry out their research, a trend that will only increase. For example, TRIUMF specialists manage the Canadian Tier-1 ATLAS Data Centre (one of only ten in the world) that processes data products for physicists analyzing the terabytes of data streaming from the Large

Hadron Collider (LHC) ATLAS experiment (see Strategy 1.6: “Advancing Discovery Through Data Science and High-Performance Computing”). This is a mission-critical component of the LHC computing infrastructure that requires highly-skilled experts to maintain, skills that are being increasingly sought after across many industrial sectors. It is therefore not surprising that many data scientists in industry have been trained as physicists — to doctorate and postdoc levels — only to find themselves migrating into data science roles in finance, business, and other industrial sectors that require individuals to have a high level of understanding of data collection and analysis. Although this may be the case, the path from academia to industry is often not clear, and there is an increasing need for data science training opportunities so highly-qualified personnel (HQP) can better prepare for a shift in career and smoothly transition from research to industry.

Through our partnership with the established Silicon Valley-based company Insight Data Science (founded by a Canadian physicist), we will roll out a unique Data Science Training Program that is complementary to existing programs at Canadian universities, filling a training gap and providing opportunities for postdoctoral fellows to transition from academic careers into high-in-demand industrial data science ones. The program will end up retaining highly-qualified scientists in Canada and filling high-skill jobs at Canadian companies. Canadian institutions will have access to data science training, job search, and mentoring resources that will help highly qualified people find employment opportunities across the TRIUMF network.

5.4 TRAINING THE NEXT GENERATION OF SCIENTIST-ENTREPRENEURS

The pursuit of ground-breaking science discoveries will often result in the creation of new technology and proprietary intellectual property that have opportunities for successful commercialization. While TRIUMF Innovations maintains the role of actively seeking out these opportunities within TRIUMF and our network partners, we are keenly aware that to take a new technology to market and to launch a successful start-up company based around a science-based product, entrepreneurs need a scientific mindset, and scientists who pursue commercialization opportunities require entrepreneurial training. Ideally, science-based start-ups should have skills in business and commercialization and have access to investors, partners, and mentors who can guide them.

In addition to identifying, nurturing, and mentoring people who will be the next generation of start-up founders, it is also important to grow and foster a culture of commercialization. Even for students and researchers who wish to pursue an academic career path, it is important to understand the significance and proper procedures related to confidentiality, publication, disclosures, intellectual property, and inventions. This training and understanding enables better research collaborations, as well as commercialization opportunities.

To encourage entrepreneurship throughout the TRIUMF community, thereby boosting commercialization potential across our multidisciplinary portfolio, we will pursue these opportunities:

- Develop a commercialization and entrepreneurship training program.
- Hire potential CEOs of science-based start-ups to work with TRIUMF and other stakeholders.

OUTCOMES

- More start-up companies managed by TRIUMF-trained CEOs.
- More science products brought to market.
- Enriched entrepreneurial environment across the TRIUMF community.

IMPLEMENTATION

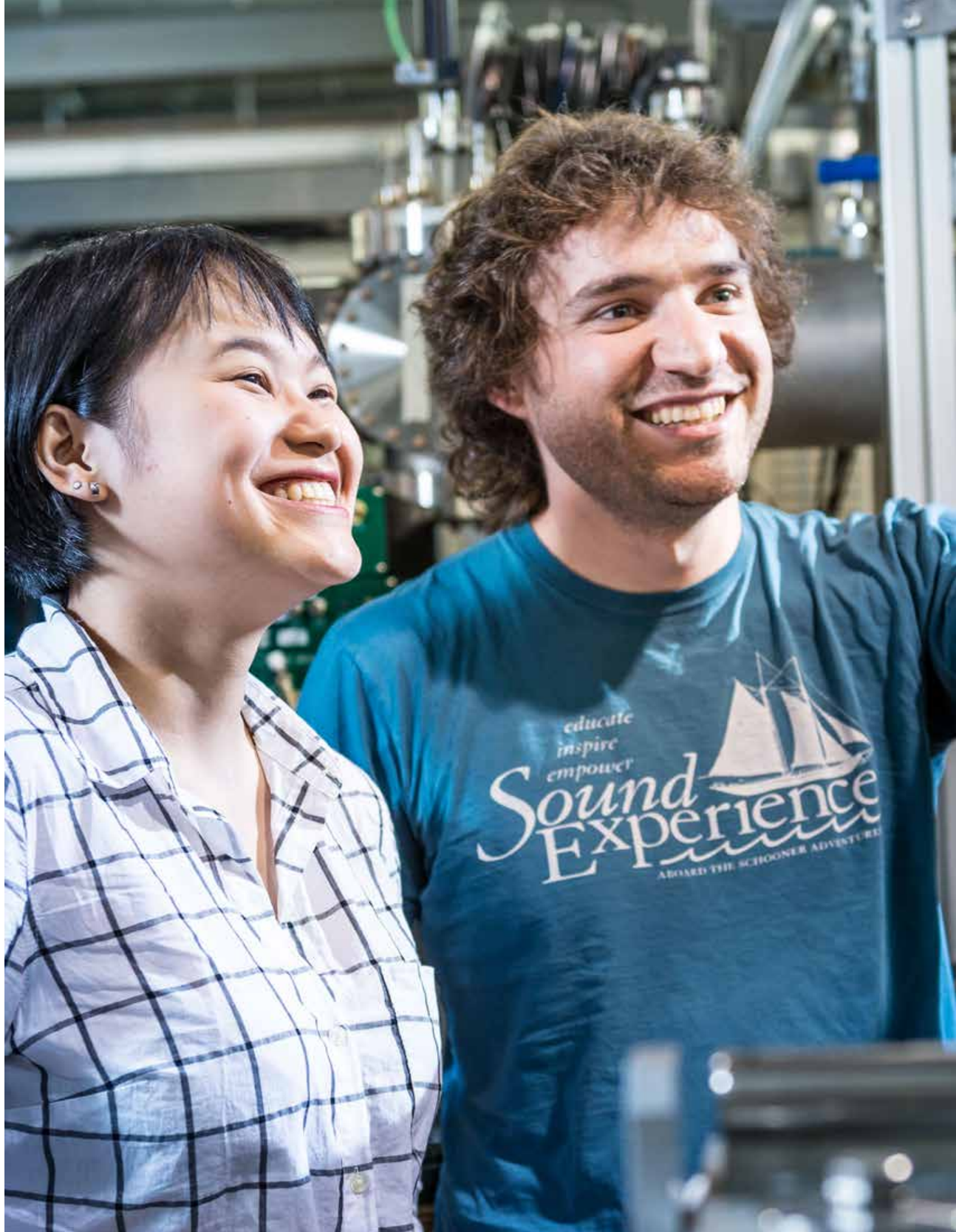
COMMERCIALIZATION AND ENTREPRENEURSHIP PROGRAM

In partnership with the UBC Sauder School of Business, TRIUMF Innovations is developing a commercialization and entrepreneurship training program specifically designed for our research community. This program will provide training for TRIUMF community members who wish to establish, or work in, a start-up company and members of our community who want to work within TRIUMF to find innovative technologies with commercialization potential — so-called “intrapreneurs.” The program will also help TRIUMF researchers better understand business-related concepts of confidentiality and inventive collaboration.

The training program will include speaker series, lunch seminars, workshops, venture validation programs, and start-up acceleration. Ultimately, as TRIUMF technologies and our teams of researchers get close to realizing the commercialization potential of their research, industry-based mentors, selected from our broad network base, will be matched with TRIUMF entrepreneurs so they can fully realize their potential.

HIRE POTENTIAL CEOs FOR SCIENCE-BASED START-UPS

We will hire Experienced Entrepreneurs-in-Residence as potential CEOs of TRIUMF start-ups. They will be engaged to identify strategic commercialization opportunities, and then in partnership with TRIUMF researchers and other stakeholders, drive the building of a new companies that can develop those opportunities.



GOAL 6 Drive national and international collaboration in research, technology, and innovation

OUTCOME A stronger, more competitive Canada in discovery and innovation

National and international collaborations are essential for the biggest science projects to make progress. To catalyze the development of disruptive technologies and make science breakthroughs, thus finding innovative solutions to problems, financial burdens need to be shared between nations and institutional expertise pooled. The International Space Station, the Large Hadron Collider, and the Human Genome Project are just three examples of wildly successful multi-billion-dollar international collaborations that no singular nation would financially support, but every collaborating institution brings their unique expertise to the table to enrich global science and discovery. As a result, international science collaborations often rise above politics and conflict, forging new alliances through the peaceful pursuit of advancing science frontiers.

TRIUMF is acutely aware of how science collaborations can enrich Canada's society, boost our nation's competitiveness on a global level, and embolden the international community to embark on new voyages of scientific discovery. By leveraging our extensive network and learning from a rich history in collaborating with institutions in industry, government and academia on game-changing projects, TRIUMF will consolidate Canada's resources to become the focal point of our nation's contributions to big science projects. TRIUMF is an internationally-recognized brand for excellence across a broad, multidisciplinary portfolio and it's our goal to galvanize TRIUMF's national and global leadership in accelerator technology and nuclear science, while exploiting our network to grow Canada's knowledge-based society in new and exciting ways.

> "From illuminating dark matter to discovering new particles and forces, Canadians will work alongside scientists from many nations. Through this work, Canada will increase its capacity for innovation and economic growth. And TRIUMF is happy to help."
>
> **DR. JONATHAN BAGGER, DIRECTOR, TRIUMF**

6.1 LEVERAGING OUR NETWORK TO CREATE NEW COLLABORATION OPPORTUNITIES

Our growing network provides incredible opportunities for research, innovation, commercialization, and training, making the TRIUMF network a premier resource for new and existing partnerships. It is our goal in this Five-Year Plan to continue building on our successes in nuclear and particle physics, and launch new collaborative research initiatives in detector technologies, life sciences, materials science, and engineering. We will work with our member universities and other partners such as the National Research Council (NRC), SNOLAB, Perimeter Institute for Theoretical Physics, and industry to solve targeted problems. To boost our effectiveness, we will recruit more Canadian universities to full membership status in the network and welcome our first international associate members. This will result in better connectivity between industrial partners and scientists, while broadening the variety of resources that can be accessed.

Through the utilization of TRIUMF Innovations, commercial opportunities for technologies that emerge from the network will also be found. By establishing a quantum computing network and initiating a data science training program, TRIUMF will leverage the skills and expertise of our network while providing training opportunities so highly-skilled personnel can transition between research and industry, and vice versa.

In pursuit of these goals, we will carry out the following initiatives:

- Attract more talent to Canada from around the world, as users and visitors as well as students, postdocs, and faculty.
- Forge new partnerships, strengthening Canadian impact on compelling science and pursuing new innovations to the benefit of Canadians.

OUTCOMES

- Increased user numbers from more countries.
- New pan-Canadian and international collaborations established.

IMPLEMENTATION

NATIONAL QUANTUM COMPUTING NETWORK

Although quantum computing is in its infancy, major advances have been made in recent years that have allowed the first application of quantum computers in the analysis of particle physics data from the LHC and the calculation of the properties of deuterium. To invigorate new applications for quantum computing and machine learning across different science disciplines, TRIUMF and TRIUMF Innovations recently initiated a partnership with Germany's Helmholtz Association and two Canadian companies that are active in the quantum computing space, D-Wave Systems Inc. and 1QBit. The Helmholtz Association is Germany's largest science organization, consisting of 18 research centres with a combined annual budget of 4.5 billion Euros (~7 billion CAD); D-Wave produces the world's only commercially available quantum computer, and 1QBit is a software developer for quantum computing applications. This exciting partnership will lead to the development of national quantum computing networks in Canada and Germany. These networks will provide the resources and expertise to fast-track the adoption of quantum computing across a range of fields of science.

In addition, we will establish a quantum computing system that will identify and facilitate quantum computing applications. Access to this quantum computing system across the Canadian network will be done in the same way TRIUMF allocates beamtime for researchers using our facilities for experiments, the quality of the research that requires quantum computing time will be assessed by an expert committee and then time will be allocated accordingly. TRIUMF's network has taken decades to build and, with the trusted reputation the TRIUMF brand brings to the table, seeding Canada's quantum computing network from our own connects D-Wave, 1QBit, and other partners to a wealth of expertise, boosting their advantage on the world stage.

Our commitment to exploit opportunities with quantum computing was highlighted recently by the first data science and quantum computing workshop that was hosted by TRIUMF on June 27-29, 2018. The meeting was in collaboration with D-Wave, 1QBit, and the Helmholtz Association with additional support for the Province of British Columbia — Ministry of Jobs, Trade & Technology.

"It was so interesting to have a conference where we had both academic researchers and industry partners discussing a common problem of how we can use quantum computing as a tool, how we can work together to build collaborations, and how can we work together to find funding opportunities. It was really exciting," said Kathryn Hayashi, CEO of TRIUMF Innovations.

Meetings such as these embrace the spirit of collaboration across our national network and, with interest from international collaborations such as Helmholtz, the TRIUMF network will hardwire Canada's growing excellence in quantum computing know-how with other global networks and strengthen our nation's prominence in this new and exciting technological advance.

NUCLEAR ASTROPHYSICS

The recent “multi-messenger” observation of the production of heavy elements in the neutron star merger that was observed through gravitational waves and across the full electromagnetic spectrum has opened the door to finally gaining a full understanding of the origin of the heavy elements from iron to uranium (see Strategy 1.1: “Discovering How Stardust Is Made”). To make further advances requires the concerted effort of observations of elemental abundances throughout the galaxy, high fidelity simulations of the astronomical environment in neutron star mergers, multi-dimensional nucleosynthesis network calculations, and laboratory nuclear astrophysics with rare isotopes.

Canada has unique assets to advance this quest with the NRC’s Herzberg Astronomy and Astrophysics Research Centre, expertise in the spectroscopy of metal poor stars and computational stellar astrophysics at the University of Victoria, as well as computational astrophysics of star explosions and neutron stars at Perimeter Institute, as well as several universities. Building on the Astronomy Research Centre (ARC) at the University of Victoria, which involves TRIUMF and NRC and working with the Joint Institute for Nuclear Astrophysics Center for the Evolution of Elements (JINA-CEE), a multi-institutional NSF-funded Physics Frontiers Center in the U.S., we intend to develop a concerted effort across nuclear physics, astrophysics and astronomy in Canada to make leading contributions to elucidating the origin of the heavy elements.

QUANTUM MATERIALS

Quantum materials are the essential building blocks for improved superconductors, spintronics, sensors, transducers for quantum communication, and quantum computers. They are often enabled by correlated interactions of electrons, leading to emergent properties that are only well understood once an underlying structure is identified. This step always requires experiments to explore and verify effective models, and further refine theories that guide towards more advanced materials.

Canada has a rich history in this field, bolstered by an extraordinary group of researchers and a world-leading infrastructure. Through sustained investment by the government and other stakeholders, Canada has built centres of excellence, each uniquely specialized to advance a certain, somewhat narrow slice of quantum science. But to advance quantum technology overall, we need to connect these capabilities more broadly. Therefore, the opportunity for Canada is to broaden its reach and increase its impact by strengthening the connections between centres.

We already collaborate with UBC’s Stewart Blusson Quantum Matter Institute and through our Centre for Molecular and Materials Science (CMMS) we will join partners at other Canada First Research Excellence Fund (CFREF) funded centres for quantum technologies at Waterloo, McMaster, and Sherbrooke, as well as the Canadian Light Source and NRC in the push to establish a pan-Canada virtual lab to enable the strong community of researchers easy access to infrastructure for development of quantum materials and technologies and to connect ideas across centres. The goal is to inform and connect researchers to facilities, to keep facilities well-staffed via high use, to be strategic in developing infrastructure, and to use the collective capacity to help recruit new researchers. The virtual lab will improve the efficiency of moving processes from one centre to another.

NUCLEAR MEDICINE

IAMI will be a national hub for the development and application of radiopharmaceuticals, strengthening cooperation with our long-standing local partners and fostering new collaborations with partners across Canada. The IAMI research laboratories will allow visiting scientists to carry out research with short-lived radioisotopes at TRIUMF. IAMI will also have production capabilities for many new radioisotopes, with long-lived isotopes being available for delivery to partner laboratories across our member network. An example is the production of ^{225}Ac for development of radionuclide therapy.

Aside from the expanded collaboration within Canada, the nuclear medicine program will also seek out additional international partnerships, such as institutions in Europe, U.S., Japan, and others.

6.2 PROVIDING A GATEWAY TO INTERNATIONAL BIG SCIENCE PROJECTS

TRIUMF is no stranger to participating in the biggest and most exciting international science experiments. We are the gateway for Canada to be involved in these projects, with our network acting as an interface between Canada's research and industry communities, while forging ties with international collaborations. We also serve as a conduit for international groups to connect with the rich expertise of Canadian scientists and innovators. Our expertise and infrastructure for advanced detector and accelerator systems is key to enable Canadian universities to contribute to the next-generation experiments.

TRIUMF will continue to build collaborations and work with our partners to advance world-leading dark matter and neutrino experiments at SNOLAB and grow our efforts on major international projects particularly our work with CERN on ATLAS, the HL-LHC, ALPHA, and rare isotope production. We will also be deeply involved with next-generation long-baseline neutrino facilities, in particular supporting the Canadian contribution to the Hyper-Kamiokande (Hyper-K) experiment in Japan, and possibly the accelerator and target systems of the Long-Baseline Neutrino Facility (LBNF) facility in the U.S.

To grow our involvement with the biggest domestic and international projects, we will:

- Strengthen partnerships with domestic and international partners.
- Become a key player in international projects and serve as an access point for TRIUMF's partners in research and industry to also participate.

OUTCOMES

- Increased benefits to Canada from existing collaborations.
- Leading Canadian involvement in a major international project.

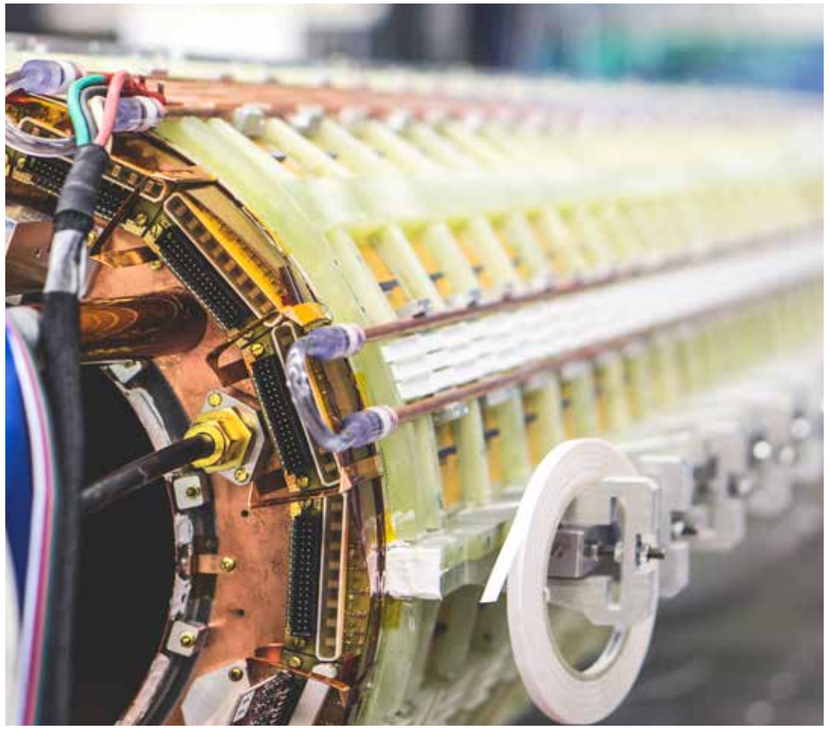
IMPLEMENTATION

STRENGTHEN EXISTING COLLABORATIONS

TRIUMF is committed to strengthening Canada's leading research into subatomic physics by advancing our cooperation with CERN. We will continue to make key contributions to the ATLAS detector upgrades, work closely with CERN on the construction of cryomodules for the High-Luminosity LHC (HL-LHC) and complete the ATLAS Tier-1 data centre transition and its expansion as planned.

We will continue to lead the Canadian collaboration to explore antimatter with the ALPHA experiment and work with CERN experts on the development of rare isotope production technologies to the benefit of ARIEL. Also, building on existing partnerships in accelerator science and nuclear physics, we are expanding our partnership with the Helmholtz Association in Germany in machine learning and quantum computing (see Strategy 6.1: "Leveraging Our Network to Create New Collaboration Opportunities").

TRIUMF will continue to cultivate Canada's long-standing involvement with the Japanese T2K (Tokai to Kamioka) long-baseline neutrino experiment and continue development of the detector systems and electronics for the next-generation Hyper-Kamiokande (Hyper-K) neutrino detector.



BECOME A KEY PLAYER IN INTERNATIONAL PROJECTS

To ensure Canada remains at the forefront of ground-breaking international physics efforts, TRIUMF is committed to identifying opportunities and developing new collaborations while continuing to expand existing partnerships. For example, the Hyper-K detector will be an order of magnitude bigger than its predecessor, the Super-Kamiokande (Super-K), and holds huge potential in the quest to understand CP violation in the leptonic sector. TRIUMF's early involvement in the project will ensure Canada benefits from the science Hyper-K generates, while the collaboration benefits from our expert knowledge of high-sensitivity detector systems.

Another promising project is the planned nEXO experiment, the successor to the Enriched Xenon Observatory (EXO-200) experiment that was the first experiment to detect double beta decay of ^{136}Xe. nEXO ("next EXO") and will build on this work to investigate the neutrinoless double beta decay of ^{136}Xe, trying to reveal whether the neutrino is its own antiparticle. Primary funds for the experiment will be provided by the U.S. Department of Energy (DOE), and the detector would be located at SNOLAB. TRIUMF is a leading partner in the Canadian effort to bring nEXO to Canada and develop the photodetector technologies.

To foster new collaborations with other exciting international projects, TRIUMF will explore joint interests with Fermilab to advance high-power target and superconducting radio frequency (SRF) accelerator technologies, pursuing the possible involvement with the Long-Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE). We will also explore how we can support the Canadian community in potential contributions to a U.S.-based Electron Ion Collider (EIC), a project that would undertake ground-breaking studies in nuclear physics and has been identified as highest priority for new major facility construction in the U.S. Nuclear Science Long-Range Plan.

Being at the cutting edge of accelerator and detector technologies through nurturing existing expertise, continuous R&D efforts, and by leveraging world-class infrastructure enables TRIUMF to make contributions to future accelerator concepts — such as the proposed International Linear Collider (ILC) and Future Circular Collider (FCC), and associated experiments. TRIUMF's unique accelerator and detector expertise will firmly establish Canada as the preferred partner for the international physics community and enable leading contribution by faculty and students of Canadian universities in these large-scale projects.

6.3 ADVANCING INTERNATIONAL COOPERATION IN SCIENCE AND RESEARCH

TRIUMF's history of excellence and international engagement makes it a trusted ambassador for Canada and we are often the first national science organization that international entities reach out to, beginning discussions that result in lasting partnerships that directly impact our nation's scientific prowess. Our long-standing strategic partnerships with CERN as well as KEK in Japan are primary examples of this. New international cooperation agreements not only serve to increase the reach of TRIUMF's network, but they also create major new international alliances, benefiting Canada overall. For example, the Helmholtz Association, Germany's biggest science organization, is continually seeking out new international partners and TRIUMF is their preferred Canadian partner to work with, as recently demonstrated through our new partnership on quantum computing and machine learning, which brings together strong research and private sector partners from Canada and Germany.

To fully embrace our standing as Canada's leading ambassador in science and research and growing international collaborations, we will take the following steps:

- Foster targeted relationships with international partners to bring investments to Canada.
- Expand the TRIUMF membership network beyond Canada.
- Foster international exchange of young researchers.

OUTCOMES

- International investments into TRIUMF infrastructure.
- First international TRIUMF member.
- New exchange programs for students and early career researchers.

IMPLEMENTATION

FOSTER TARGETED RELATIONSHIPS

The TRIUMF brand is internationally recognized not only by scientists and leaders of academic institutions but also by the governments of Canada's partners. For example, the 2017 visit of the Italian President, recognized the historical, ongoing, and future science and technology collaborations between Canada and Italy. This cooperation between Canada and Italy will be further strengthened with the forthcoming agreement between TRIUMF and Istituto Nazionale di Fisica Nucleare (INFN) LN Legnaro, which will foster research on accelerators and isotope production targets to the benefit of both laboratories.

With the recent announcement of funding from the Canadian government for contributions to the HL-LHC Canada continues the prominent involvement of Canada in forefront research at CERN. As with the initial Canadian contributions to the LHC, TRIUMF's expertise will play a central role in delivering this international contribution. This cooperation will further strengthen the partnership between CERN and TRIUMF, which not only benefits Canadian researchers carrying out research at CERN but will also lead to advances in isotope production technologies for ARIEL. Together, we are pursuing further opportunities for strengthening cooperation between our two laboratories, for example in the area of training and outreach.

Japan's High Energy Accelerator Research Organization (KEK) and TRIUMF are continuing to strengthen this partnership, already manifested through the respective offices at each other's laboratories. The TRIUMF office at KEK was inaugurated by the Federal Minister of Science, demonstrating the visibility and value of this special partnership for both countries.

We are also working with Osaka University to take our partnership to the next level. This includes greater involvement by Japanese researchers in TRIUMF's UCN facility (including substantial investment (~$2M) into the facility), which is building on developments at the Research Center for Nuclear Physics (RCNP) Osaka, as well as the initiation of new collaborative research efforts, particularly in nuclear medicine where the expertise from Osaka researchers with targeted radionuclide therapy isotopes will benefit the IAMI program.

EXPAND THE TRIUMF NETWORK

The TRIUMF network already spans from coast to coast across Canada involving most of the major research universities and it is still growing. Membership secures a seat at the table in setting the strategy for TRIUMF's multidisciplinary program.

Our recent joint faculty appointment with international partners such as the Kavli Institute for the Physics and Mathematics of the Universe (IPMU) at the University of Tokyo, or a joint postdoc fellowship with the University of Washington are examples of internationalizing the TRIUMF concept.

These types of initiatives will be the seed to expanding the TRIUMF membership network to international universities. While international associate members would not have formal voting rights, their voice will be important in setting the best path for the lab in the global context.

FOSTER INTERNATIONAL EXCHANGE

By attracting leading scientists from 39 countries, most of which collaborate with Canadian researchers, TRIUMF is already at the forefront of promoting international cooperation in science and outreach. We will pursue opportunities to attract, in particular, early career researchers and students from additional countries, South America, Asia, Africa, utilizing a variety of funding mechanisms, e.g. through Mitacs. Building on our arrangements with universities in the U.K., Germany, and Spain, we will pursue agreements with Asian and African universities to enable their students to gain valuable research experiences in our multidisciplinary and multicultural environment. These students will become ambassadors for international science and Canada.

We will also utilize our existing and forthcoming partnerships to bring talented researchers to TRIUMF for extended visits while giving Canadian early career researchers opportunities to spend time at our partner institutions. Our partnership with CERN already includes the exchange of personnel, which will be increased through our expanded cooperation. Going forward we are also expanding our engagement with KEK and Osaka University by adding an exchange program for young researchers to initiate and foster the development of new collaborative efforts.

CORE OPERATIONAL BUDGET FOR 2020-2025

This section describes the proposed core operational budget for TRIUMF for the period 2020-2025. The budget will enable us to increase our impact and fulfil our mission by executing the strategies laid out in our Five-Year Plan. We will leverage past investments by government and harness our strong brand and global network to deliver a new level of top-tier science, training, and innovation to Canada. As an integral part of that work, we will redouble our efforts to build a laboratory with a diverse, welcoming community and a demonstrated commitment to equity, diversity, and inclusion.

Our Five-Year Plan is the result of extensive community consultation with workshops, in town halls, and through community-based proposals reviewed by our Policy and Planning Advisory Committee (PPAC), which advises the Director and the Board of Management on scientific policy and facilitates two-way communication with the research communities at the member universities. Along the way, we made hard choices, but the final result is ambitious, achievable, and fully consonant with TRIUMF's vision, mission, and values.

We constructed the budget following a set of high-level principles set forward by PPAC:

- Prioritize the Advanced Rare Isotope Laboratory (ARIEL) the Institute for Institute for Advanced Medical Isotopes (IAMI) as foundational for the future of TRIUMF.
- Focus on the existing multidisciplinary, high-impact science portfolio, including strong on- and off-site components.
- Make balanced investments into core infrastructure, science support, and selected new opportunities to maximize the benefits from ARIEL and IAMI.
- Position TRIUMF for its long-term future by further developing particularly promising new ideas without affecting the efforts on ARIEL and IAMI.

The proposed core operational budget permits full exploitation of our three platforms — ARIEL, IAMI, and TRIUMF Innovations — and enables us to maximize the value and benefit we deliver to Canada and Canadians over the life of the Plan. As described in section "Operating Environment," however, TRIUMF's total funding comes from a variety of sources. In what follows, we describe the proposed core operational budget, present key supporting details, and outline our assumptions with respect to other sources of income.

ASSUMPTIONS

- NRC Contribution Agreement: TRIUMF will receive $320M from the Government of Canada to support TRIUMF's core operations through a Contribution Agreement with the National Research Council Canada (NRC).
- Sponsored Research: TRIUMF and its member universities will continue to secure competitive funding from the Natural Sciences and Engineering Research Council (NSERC) and other funding agencies to support cutting-edge research across TRIUMF's full multidisciplinary portfolio. We project $26M — a constant level of sponsored research support during the period 2020-2025.
- Capital Investments (CFI + Provinces): TRIUMF and its member universities will continue to secure competitive funding from the Canada Foundation for Innovation (CFI) and provincial agencies to support capital initiatives. Some of the research infrastructure will be placed at TRIUMF; the rest will serve as Canadian contributions to international science initiatives at SNOLAB, CERN, and other laboratories. Based on previous successes in such competitions, we believe that a substantial portion of this additional funding will be secured. We anticipate an amount on the order of $55M of capital investment during 2020-2025 from projects already in the pipeline.
- Cost Centers and Work for Others (WFO): TRIUMF maintains a number of cost centres, such as a design office, machine shop, and scintillator shop, all of which have a significant number of technology experts who provide unique capabilities, but must be paid for from project funds. Our WFO system enables us to maintain a larger cadre of in-house expert staff than would otherwise be possible. These staff form a resource that benefits the larger community. The budget assumes that TRIUMF will provide WFO services at a level of 16 FTE per year, consistent with recent history from CFI and other international projects.
- Commercial Revenues: Estimates for commercial revenues, predominantly from irradiation services and from isotope production for BWXT (formerly Nordion Inc.), are projected to be at a level of $4.0M in 2020, and then to increase annually by 5%. Additional opportunities for private sector investment might also be realized.

BUDGET DETAILS

Guided by the high-level strategic goals outlined in our Five-Year Plan, a risk analysis for the safe and reliable operation of our existing infrastructure, and a bottom-up planning and prioritization exercise, TRIUMF is requesting $320M over five years from the Government of Canada through a Contribution Agreement from NRC.

The $320M figure represents an approximately $5M/year increase over inflation as compared to the period 2015-2020. At $320M, TRIUMF will be able to increase its impact along the three dimensions described in the Five-Year Plan: Science and Technology, People and Skills, and Innovation and Collaboration.

During the 2020-2025 time period, our highest priority will be to complete and bring into full operation, ARIEL and IAMI, the two platforms that PPAC identified as foundational for the future of TRIUMF. As recommended by PPAC, we will also focus on strengthening our existing multidisciplinary, high-impact science portfolio. And, finally, during the period of the Plan, we will expand our commercialization activities through TRIUMF Innovations, TRIUMF's third supporting platform.

CORE OPERATING BUDGET 2020-2025	M$
Salaries and Benefits	244.1
Site Operating Costs	24.4
Electricity	24.9
Divisional MRO	26.2
Site Stewardship	11.6
Accelerator Refurbishments and Upgrades	10.7
Science and Technology Initiatives	6.1
Training, Outreach and User Support Initiatives	5.1
SUM	**353.1**
Commercial and WFO Revenues	23.1
Efficiency Savings	10.0
NRC ASK	**320.0**

Table 3. A breakdown of the proposed core operational budget for TRIUMF for the period 2020-2025.

SALARIES AND BENEFITS ($244.1M)

To achieve the goals set forth in our Five-Year Plan, we will raise the number of staff supported from core operational funding from 407 to 430 for the period 2020-2025. (Additional personnel will be supported by "soft funding" from NSERC, CFI, and other sources. They are not included in this budget.)

With 407 FTE — our existing staff complement — we will be able to complete ARIEL and IAMI, transitioning from project construction to initial operations. The additional staff will enable us to tackle important improvement initiatives, such as preparatory work for the modernization of BL1A, increased user support, enhanced education and outreach activities, and updated processes and tools for increased organizational efficiency. The added staff will allow us to start modernizing the last major piece of 40-year-old infrastructure, strengthen our focus on people and skills, and leverage our unique expertise to benefit communities across Canada.

SITE OPERATING COSTS ($24.4M)

Over the five-year period, we will spend $24.4M on site operations, including safety and security, quality and project management, education and training, communications and user support, outreach, utilities and cryogens, and administrative services (such as insurance, procurement, grounds maintenance, and janitorial services).

ELECTRICITY ($24.9M)

We anticipate that our site electricity costs will grow 5% per year because of rate increases from BC Hydro (our provincial power authority). Projected electricity costs do not include the increased demand from ARIEL, as ARIEL will only ramp up to full operation in the last two years of the funding period (and these added costs will be offset by CFI Infrastructure Operating Funds). In the longer term, we expect that ARIEL costs will be partially offset through savings from the BC Power Smart program.

DIVISIONAL MRO ($26.2M)

The divisional materials, refurbishment, and operations (MRO) budgets cover materials, supplies, and equipment to operate laboratory infrastructure, such as accelerators, experiments, laboratories, machine shops, buildings, etc., as well as divisional travel and other administrative costs. Divisional MRO will be held flat, modulo a 2% increase per year from inflation.

SITE STEWARDSHIP ($11.6M)

Guided by the TRIUMF Facilities Master Plan, which provides a framework for the development of future capital building and infrastructure projects, we will continue to be a responsible steward of our site. We will make strategic, risk-driven investments to refurbish the existing infrastructure, ensuring a safe and healthy workplace as well as the safe and reliable operation of our laboratory. This includes, in particular, improvements to the mechanical and electrical infrastructure, which are necessary to improve the reliability of the accelerator operations (e.g. by improving cooling of specific rooms and equipment) and which will also lead to significant cost savings. We will continue to seek economies in utilities and will use incentive programs, when available, such as the BC Hydro Power Smart, which helped support replacement of our cyclotron's Main Magnet Power Supply.

We will continue to modernize space and improve accommodations for a growing number of staff, users, and students. In addition, we will invest in software tools to improve and standardize processes across the organization. This includes a site-wide maintenance and asset management system, an upgraded quality management system, as well as our Enterprise Resource Planning system.

Our Five-Year Plan calls for the modernization of the Meson Hall and Meson Hall Extension to accommodate the robotic warm cell required for BL1A modernization and

the safe and effective management of radioactive components. This includes investments into radiation shielding, nuclear ventilation, safety systems, and crane upgrades, as well as prototyping of robotic remote handling systems and beamline components for the full BL1A project, for which we will seek CFI funding.

ACCELERATOR REFURBISHMENTS AND UPGRADES ($10.7M)

We will continue our accelerator refurbishment and upgrade program to ensure reliable and efficient operation. As part of this program, we will upgrade the 520 MeV cyclotron to improve reliability and to raise the beam current to 400 μA to deliver maximum beam intensity to all beamlines.

ISAC is integral to ARIEL, so we will also need to upgrade elements of the ISAC infrastructure. Between 2020 and 2025, we will upgrade the existing target stations and build a new target module to replace a radiation-damaged module that has been in operation for over 20 years. Parallel investments into the ISAC laser ion source and beam development infrastructure will expand the reach of the science program in nuclear physics and the betaNMR program. We will also invest in the reliability and scientific reach of ARIEL by producing a spare cavity for the e-linac and adding a laser ion source to the proton target station.

These investments will make it possible to operate ARIEL and IAMI, as well as the Meson Hall program in quantum materials and ultracold neutrons, with no long-term increase in operational staff. Efficient operation demands that the 20-year old ISAC infrastructure be as reliable as the brand-new ARIEL infrastructure; the projects proposed here will help us achieve an appropriate level of reliability.

SCIENCE AND TECHNOLOGY INITIATIVES ($6.1M)

We will invest in expanding our rare isotope beam capabilities in order to maximize the scientific impact of ARIEL and to stay at the forefront of the field in the face of growing international competition. In particular, we will develop new rare isotope beams and increase the intensity and purity of our existing beams. Investments include a target ion source test stand for the development of new target materials, development of new laser ionization schemes, and improvements of the existing ECR-based source for nuclear astrophysics reaction studies with Detector of Recoils and Gamma Rays for Nuclear Astrophysics (DRAGON) facility. We will also invest into user support and enhancement of our experimental infrastructure support.

To fully exploit our world-class betaNMR and MuSR capabilities, we must better support the scientists who come to use our facilities. To take full advantage of ARIEL's isotope production capabilities, we will seek, in cooperation with our university partners, CFI funding for an expansion of our betaNMR facility, along with further upgrades of the MuSR infrastructure, including the aging M15 channel.

We will further advance superconducting radio-frequency (SRF) research, not only to train students and benefit our two SRF accelerators (ARIEL e-linac and ISAC-II heavy ion linac), but also to position Canada as leader in SRF technologies for future international accelerator projects. For example, our SRF expertise is enabling Canada to make a critical contribution to the High-Luminosity Large Hadron Collider (HL-LHC) at CERN through the production of made-in-Canada crab cavity cryomodules. We will add infrastructure to our SRF research laboratories to develop better and more reliable accelerator cavities for our own accelerators, enable contributions to next-generation accelerator facilities, grow capacity in Canadian industry, and train the next generation of leaders in accelerator science.

In order for Canada to continue to play a leading role in large international projects, it is essential to keep pushing the limits in detector developments. This can only be achieved with state-of-the-art facilities. As part of our Plan, we will upgrade TRIUMF's unique detector facilities (through a pan-Canadian CFI initiative) to support the design and construction of complex detector projects by the Canadian subatomic physics community, both at home (TRIUMF, SNOLAB) and abroad (CERN, Japan, USA).

In addition, and to stay at the cutting edge of technologies for scientific and commercial applications, we will establish a modest Research and Development Fund, financed through commercial revenues, which can be accessed through an internal competitive application process.

TRAINING, OUTREACH, AND USER SUPPORT INITIATIVES ($5.1M)

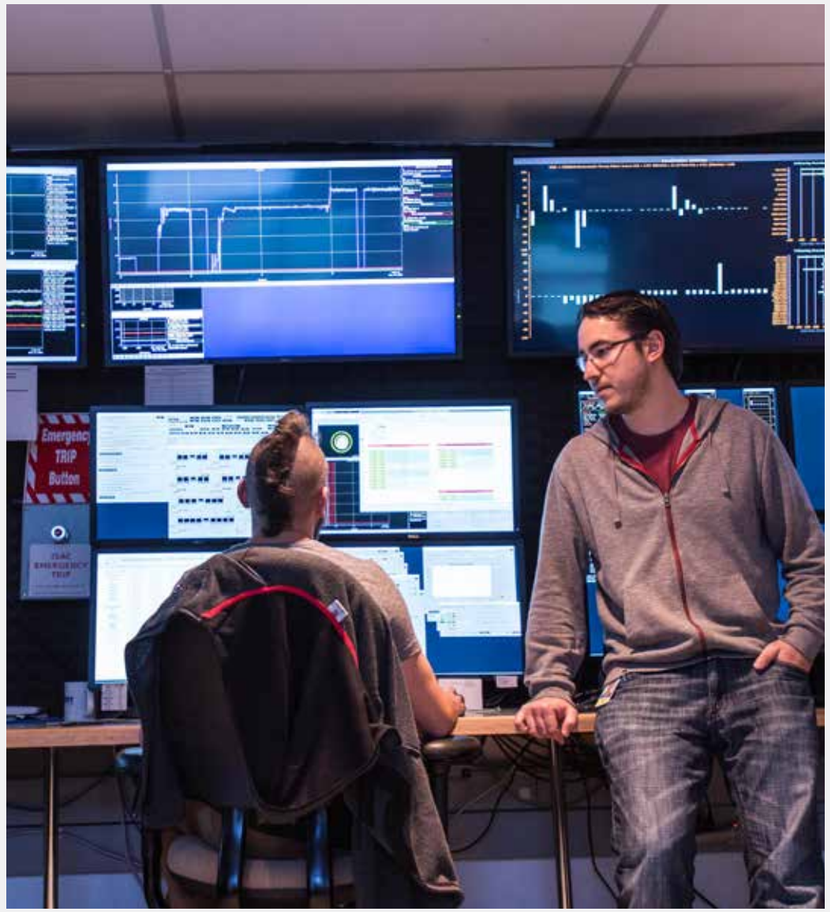
We will invest into building and retaining our world-class workforce. We will implement an equity, diversity, and inclusion action plan that features best practices regarding recruitment, onboarding, and retention, in particular to enable flexible work arrangements, launch recognition programs, and offer partial support for employee child care.

We will invest into professional skills development for our workforce and trainees. We will maintain a modern learning management system for our staff and the over 800 visitors who require training each year. We will continue to develop online training (i.e. LinkedIn Learning) for our staff. In addition, we will create a professional development fund to support individualized career progression plans for our staff and trainees through on- and off-site programs.

Our Plan also proposes to expand outreach activities beyond Vancouver. We will partner with diverse and liike-minded organizations to increase access to education, research, and opportunities in science, technology, engineering, and math (STEM) across Canada, in particular in remote and underprivileged communities. To do this, we will invest into the development of digital content, virtual tools, and an outreach and communications repository that can be accessed by partners across our extensive network.

Finally, we will invest into the growth and improvement of our undergraduate co-op work experience student program. We will seek additional funding (e.g. from Mitacs) to support students from outside the Canadian university system, including those from colleges, polytechnic institutions, and international partner institutions around the world. We will also expand the existing annual TRIUMF Summer Institute to include several detector schools and lab courses per year, providing funds for external lecturers as well as travel and housing support for the participants.

The core operational budget laid out above will enable us to increase our impact and fulfil our mission by executing the strategies laid out in our Five-Year Plan. It will allow us to fully exploit our three platforms — ARIEL, IAMI, and TRIUMF Innovations — and will enable us to maximize the value and benefits we deliver to Canada and Canadians over the five-year period.



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TRIUMF

4004 Wesbrook Mall
Vancouver BC V6T 2A3 Canada

t 604.222.1047

Learn more about
our Five-Year Plan 2020-2025

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