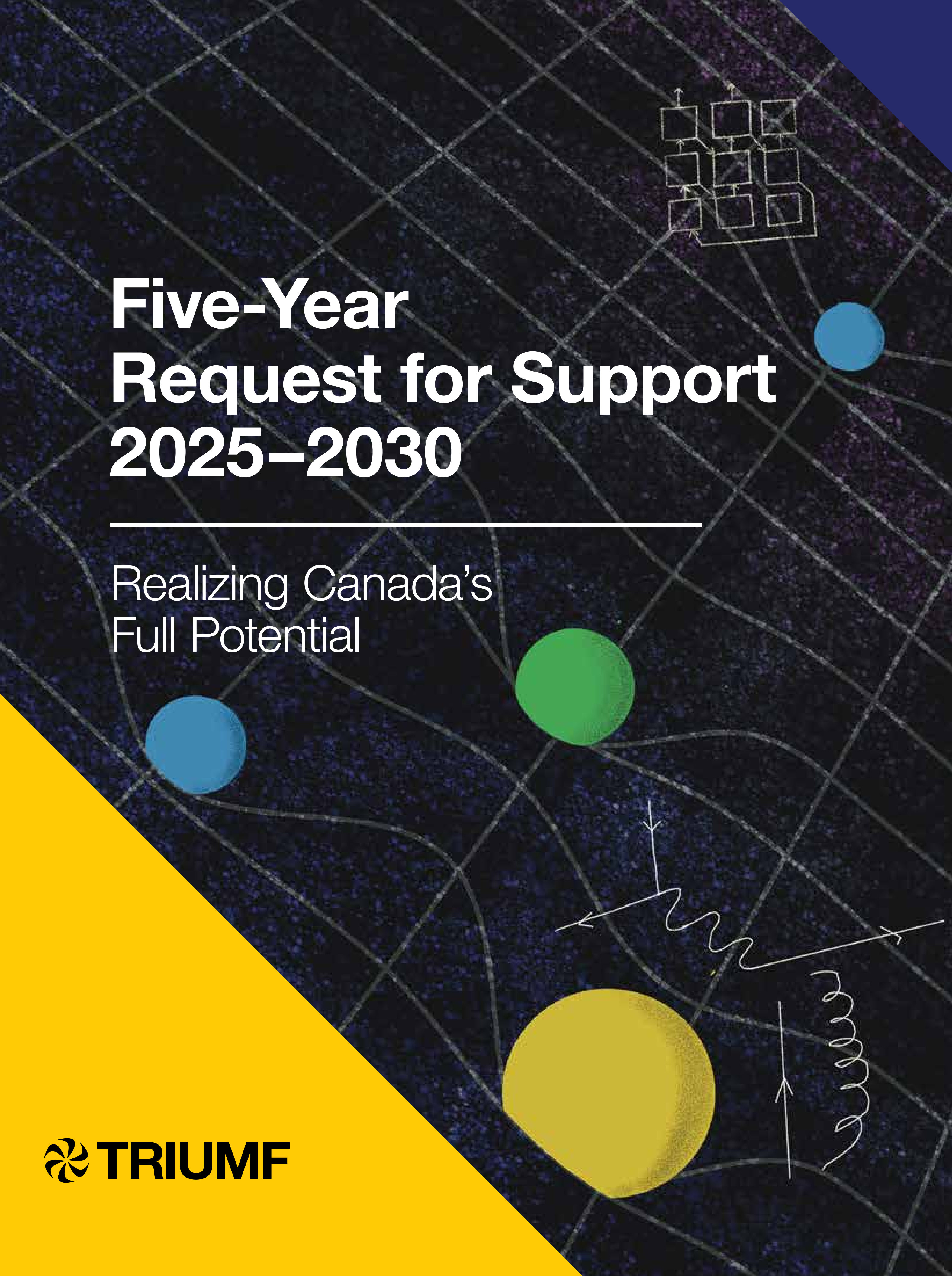
Five-Year Request for Support 2025–2030

Realizing Canada's Full Potential



TRIUMF

ACKNOWLEDGEMENTS

TRIUMF is located on the traditional, ancestral, and unceded territory of the xʷməθkʷəy̓əm (Musqueam) people, who for millennia have passed on their culture, history, and traditions from one generation to the next on this site. TRIUMF's home has always been a seat of learning, and we are honoured to continue to use these lands as a centre of knowledge and education.

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.

EXECUTIVE SUMMARY

TRIUMF is a national asset. From supporting Nobel-prize winning research that elucidates unknown facets of the Universe, to creating new life-saving drugs and devices, we use our particle accelerator complex and highly skilled community for the betterment of society.

Founded in 1968, TRIUMF is host to over 1.5 billion dollars in large-scale scientific and research infrastructure, including recent substantial investments in two new world-leading research platforms. As Canada's particle accelerator centre, we enable the country to collaborate and compete with other major international facilities in the delivery of world-class science and innovation and attract top global talent to Canada. As a research-oriented, university-owned facility, we operate and develop infrastructure too large for any one organization and drive large-scale collaborative research across the country through close interlinks with faculty. TRIUMF has become the leading component of the Canadian "Big Science" ecosystem, underpinning and acting at the intersection of academia, government, and industry. We contribute to major national priorities, such as training the next generation of innovators, transferring knowledge to industrial and mission-driven purposes, providing capacity to pivot to shifting needs and priorities and supporting health care resiliency.

Through the provision of new infrastructure and the exploration of new techniques and technology, we are entering a new era for Canadian science, with TRIUMF applying its excellence in basic science to other research areas, including contemporary mission-driven challenges. Two new major world-class facilities for radioactive ion beams and medical isotopes will come online during the next five-year period, providing a step-change in capability for Canada to explore new research and innovation areas, develop and produce new medical isotopes, and attract global talent to Canada.

TRIUMF pushes the boundaries of knowledge, creates and commercializes innovative solutions, maintains and operates world-class infrastructure, and inspires and educates some of the brightest minds in the world. Our student training program is one of the most competitive in the country, providing unique opportunities for the development of highly qualified personnel. As a globally sought-after collaborator, we project Canadian leadership and innovation onto the international arena, connecting to national and international laboratories around the world, and translating our research into socioeconomic benefits for Canada.

TRIUMF is at a pivotal moment in its life cycle as a major research facility; the lab faces a critical inflection point as it balances the demands of aging and essential infrastructure while seeking to complete and operate new world-class facilities. Canada is currently in a unique position to secure competitive advantages against global competition due to both external factors (such as planned shutdowns at other international facilities) and internal advantages (such as unique capabilities for isotope production) which can be capitalized upon.

The degree of federal support provided in the next five-year cycle will dramatically impact the future trajectory of Canada's position in global "Big Science" research and our ability to ensure we realize the nation's full potential in research endeavours.

To ensure Canada remains among the top-tier in international large-scale research, TRIUMF seeks $450M in operational funding over the next five-year cycle. This support will enable TRIUMF to deliver world-class science, complete and start operating two new world-class infrastructures, train the next generation of leaders and innovators, and maintain Canada's leadership position in major international research collaborations. This funding also secures the added socioeconomic benefits of the TRIUMF science program (i.e., medical isotopes, new technologies, and spin-off companies), which are not possible without strong and stable facility operations.

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1.

OVERVIEW OF TRIUMF AND OUR REQUEST FOR SUPPORT

1.1 INTRODUCTION

TRIUMF is a national asset. Founded in 1968, TRIUMF is Canada's particle accelerator centre, host to well over a billion dollars in large-scale scientific and research infrastructure. From supporting Nobel-prize winning research that elucidates unknown facets of the Universe, to creating new life-saving drugs and devices, we use our particle accelerator complex and highly skilled community for the betterment of society.

As one of the largest research facilities in the country, we support and drive the Canadian university-based research ecosystem, tackling problems too large for individual universities and addressing fundamental questions in contemporary science. TRIUMF enables Canada to collaborate and compete with other major international facilities in the delivery of world-class science and innovation and the attraction of top global talent. Domestically, TRIUMF connects other major research laboratories in Canada, underpinning their research programs with our capabilities and technological developments. By giving all our members an equal footing, we help support universities from Victoria to Halifax, and give smaller institutes the ability to undertake large-scale science projects they otherwise could not. The laboratory has become the leading component of the Canadian "Big Science" ecosystem, acting at the intersection of academia, government, and industry. The recent pandemic has illustrated that national resilience to emergent crises and risks relies on a bedrock of scientific and research capabilities, and the ability to rapidly deploy them to mission-driven challenges. TRIUMF plays a major role in this regard, with a dynamic governance and leadership structure, and a wealth of expertise, capability, and world-leading research facilities.

A recent government evaluation confirmed TRIUMF's exceptional performance, with the laboratory delivering both significant science and socioeconomic benefit to Canada. Furthermore, the international peer review that took place as part of this process reaffirmed that "TRIUMF demonstrated scientific excellence across all of the areas reviewed," with the laboratory commended for "performing high impact research, developing new technologies, building and operating an expanding array of unique experimental capabilities."

TRIUMF pushes the boundaries of knowledge, creates and commercializes innovative solutions, maintains and operates world-class infrastructure, and inspires and educates some of the brightest minds in the world. As a globally sought-after collaborator, we project Canadian leadership and innovation onto the international arena, connecting to national and international laboratories around the world, and translating our research into socioeconomic benefits for Canadians.

TRIUMF is a national asset and a globally recognized symbol of Canadian scientific and technological excellence.

1.2 HIGHLIGHTS OF ANTICIPATED WORLD-LEADING SCIENCE AND INNOVATION

Our globally unique infrastructure provides Canada the opportunity to host and deliver world-leading science, with research capabilities that reinforce our status as a sought-after international collaborator and destination of choice.

Domestically, this science is primarily supported through tri-council grant-driven research, with 80% of Canadian sub-atomic research involving TRIUMF. This 5-year request provides the bedrock of operational support to enable that science. Amongst other research highlights more fully articulated later, over the period supported by this request we anticipate delivering world-leading science and innovation. We will:

- Test the limits of the Standard Model of particle physics and shed light on one of the greatest challenges in physics, the matter-antimatter asymmetry in the universe, by studying the electric dipole moment of the neutron and radioactive molecules, only possible due to TRIUMF's unique combination of infrastructure and capabilities.

- Leverage our expertise in superconducting radio frequency acceleration and beam physics to deliver international commitments for new accelerator components for the high luminosity upgrade and the future operation of the Large Hadron Collider (LHC) at CERN in Geneva; and for the new billion-dollar Electron Ion Collider accelerator complex being developed at the Brookhaven National Laboratory in the US.

- Develop new radiochemical processes and radiopharmaceutical drugs, such as actinium-225 labelled compounds for targeted alpha therapy, leading to new life-saving technologies that will be transitioned to production scale and distributed by our commercial partners to deliver innovative treatments to patients in Canada and around the world.

- Drive and support physics exploitation of the ATLAS experiment at CERN, leading the construction of the ATLAS inner tracker upgrade, and maintaining the central CERN Tier-1 data storage and analysis systems, supporting the largest sub-atomic physics research collaboration in Canada.

- Secure Canada as the host of the next-generation neutrinoless double-beta decay detector, continuing the legacy of Canadian leadership in the neutrino sector, and illuminating the fundamental nature and properties of these elusive particles.

- Apply our expertise in scientific computing to develop novel applications of machine learning and other techniques, which will optimize the use of our accelerator beams and our science and support the development of a greener facility.

- Explore new technologies and techniques to develop and improve quantum and green technologies such as materials research, quantum sensors, fusion energy, small modular reactor component testing, accelerator-driven systems to convert nuclear reactor waste into energy, and real-time water quality monitoring for remote communities. These technologies provide opportunity for intellectual property development and commercialization.

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Working at TRIUMF, you have the privilege of being surrounded by cutting-edge research and a community of experts from a variety of fields. It’s an incredible privilege for early-career researchers - it encourages confidence in young scientists, and enables us to make connections and begin paving paths to our career goals. I began in nuclear physics, which I love, but I wanted my work to help people. At TRIUMF, I have had the opportunity to continue my training and move into a new area, life sciences. Now, I’m applying the skills I built during my nuclear physics PhD into the development of therapeutic isotopes, which are used for diagnosing and treating disease.

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ELEANOR DUNLING
RESEARCH OFFICER
THERAPEUTIC ISOTOPE TARGET DEVELOPMENT

1.3 KEY THEMES THAT WILL BE ENABLED BY THIS REQUEST

To support the Canadian program of world-class science that TRIUMF embodies, this request will provide a secure operational platform for the facility. There are five key areas that will be realized through the requested operational support:

- **Delivering new infrastructure for research and scientific impact:** The next five-year period will see TRIUMF dramatically increase its output of world-leading science following the completion of two major infrastructure projects that have each been in development for over a decade. Together, the Advanced Rare Isotope Laboratory (ARIEL), a transformative facility that will triple the production of rare isotope beams at TRIUMF, and the Institute for Advanced Medical Isotopes (IAMI), a cutting-edge life sciences centre and incubator for new medical isotope development, represent the culmination of Canada's vision to lead the world in accelerator technology and rare isotope science. Together, these new large-scale facilities, valued at approximately $250M, ensure Canada remains at the very forefront of this highly competitive branch of global "Big Science" research, with potential outcomes ranging from Nobel-winning fundamental science breakthroughs to the possible curing of a range of terminal illnesses, including several types of untreatable cancer.

- **Ensuring operational excellence:** As a high-profile national asset, it is imperative that TRIUMF maintain compliance and operational excellence across its spectrum of programs. Since TRIUMF's operational funding was last committed in 2019, tightening regulatory requirements and geopolitical considerations – including research and cyber security – have led to an increase in compliance and oversight requirements that have strained the laboratory's operational capacity.

- **Training the diverse talent of tomorrow:** A major objective of the next 5-year request is to ensure TRIUMF has the staff complement to operate the laboratory and new infrastructure effectively and efficiently. The request envisions an increase of 55 FTEs, equal to 12% growth to core operations against current planned staffing levels. Increased staffing levels, in conjunction with planned implementation of market-competitive compensation, will not only ensure TRIUMF is able to deliver on its infrastructure and science objectives, but also enhances the laboratory's ability to develop a pipeline of talent, both for internal requirements and for growing Canada's innovation ecosystem. These objectives will ensure TRIUMF and Canada remain a global attractor for top talent in this sector.

- **Refurbishing legacy facilities:** Commissioned in 1976, many TRIUMF facilities are approaching 50 years in operation. As such, there is a critical need for deferred maintenance beyond what can be supported as part of regular operations and repairs. Furthermore, recent funding competition results have demonstrated that there exists no viable way to address these needs in the current funding system. It should be noted that it is not viable to decommission this older infrastructure, as much of it is still in active use and is required as drivers for the operation of TRIUMF's newest facilities, such as ARIEL. Examples of key projects to be addressed in the next 5-year period include the major refurbishment of an original beamline at ~$20M, maintenance of the foundational 520MeV cyclotron, as well as the $10M+ replacement of an electrical substation that provides power to the laboratory. This work was not previously possible due to lack of funding in previous funding cycles, but investing now will mitigate major risks for long-term operations.

- **Evolving TRIUMF's program towards the future and addressing societal challenges:** Alongside the infrastructure and operational improvements targeted for the next five years, TRIUMF will also take the first concerted steps towards achieving the goals in its 20-Year Vision. In particular, resources will be directed towards reconfiguring existing program areas to better align with stated national objectives and priority areas. Complementing the new frontiers of science that will be unlocked with ARIEL and IAMI, the pivot towards mission-driven centres of excellence in areas such as quantum, green technologies, detectors, and data/artificial intelligence will enable Canada to innovate and respond to emergent challenges quickly and effectively. TRIUMF has a legacy of world-leading expertise in discovery science and the development and application of new techniques and technologies, which will be applied to address major contemporary societal challenges.

1.4 CONNECTION TO TRIUMF'S 20-YEAR VISION

Released in October 2022, TRIUMF's 20-Year Vision articulates our future potential and that of the various communities we support, as shown in Figure 1.

It signals our ability to undertake world-leading research and translate our capabilities for societal benefit and commercial opportunities. This request is the first step in achieving this bold but realizable vision. As the first stage of delivering the longer-term vision, this 5-year request lays the groundwork by seeking support to complete and operate new world-leading research infrastructure, deliver world-class science, and foster leading talent from around the world. It introduces the consolidation of research themes around green and quantum technologies and enhances our ability to deliver innovative solutions for socioeconomic impact.

Our 20-Year Vision leverages past investments by government and builds on our strengths to deliver a new level of top-tier science, training, and innovation for Canada. It was developed over an 18-month period in full consultation and collaboration with a broad stakeholder group, including our research community, university members, and national and international research partners. Following a detailed 'bottom-up' process articulating the scientific and innovation ambitions of the research community, this was consolidated into core key themes that position TRIUMF to become:

- **A global leader in discovery science, delivering breakthroughs that unlock the deepest mysteries of the universe:** *Strengthening Canada's leadership in groundbreaking particle and nuclear physics.*
- **A world-class accelerator centre driving use-inspired research – from the life sciences to quantum and green technologies:** *Leveraging our unique infrastructure to pursue research in Canada that will change the world.*
- **An inclusive multidisciplinary talent incubator, attracting and developing the best people from around the world:** *Producing Canada's future science leaders and innovators.*
- **A leader in a flourishing national Big Science ecosystem:** *Catalyzing the success and growth of Canada's network of major research facilities.*
- **A national innovation hub translating discovery science into health and sustainability solutions:** *Responding nimbly to complex societal challenges for the benefit of Canadians.*

Figure 1: *TRIUMF's research activities as imagined in our 20-Year Vision*

1.5 THE REQUEST

Over the next five-year period, TRIUMF will usher in a new era in accelerator-based science and radioisotope innovation with the operation of ARIEL and IAMI, ensuring Canada remains a leader in international "Big Science". We will ensure delivery of the new world-leading science programs and innovations outlined in Section 1.2; ensure our facility is maintained for science delivery with high efficiency and for decades to come; and play a full role in developing talent and projecting Canadian science onto an international stage, thereby fully exploiting Canada's investment in TRIUMF. To provide the operational capacity required to support this vision, TRIUMF is requesting $450M for operations from 2025 – 2030.

The request supports the key themes articulated above, with several specific strands of these themes discussed in greater detail below. These cover the core facility operations required to expand on the current research program (Section 3), develop the infrastructure and operational excellence for the future (Section 4), and deliver new science and innovations (Section 5). A summary of the requested staff support against these themes is provided in Figure 2, showing the general requirements for each category, with Figure 3 showing the resource requirements against each category.

As with past funding cycles, TRIUMF's operations are supported in five-year tranches via direct allocations in the federal budget that flow through the National Research Council Canada (NRC). This funding stream is the only mechanism available to support core operations and the laboratory's capacity for research. Beyond federal support, there is no viable alternative funding source to cover TRIUMF's operational needs, as there is neither capacity nor precedence to transfer this responsibility to another source, such as provincial governments or industry partners.

Without a funding commitment in Budget 2024, TRIUMF will lack the certainty required to prepare and effectively execute a strategic plan in time for the next five-year operational cycle that is set to run from April 1, 2025 to March 31, 2030. A delay in receiving an adequate level of funding puts the laboratory at critical risk. Beyond the logistics challenges, this uplift in funding level comes at a pivotal time in TRIUMF's operational life cycle, with the confluence of new facilities coming online, coupled with the need for essential maintenance to legacy facilities, means that delayed funding would incur significant risks across all aspects of the laboratory – from stalling science and innovation output and damaging Canada's international reputation to risking the loss of major talent. Furthermore, a delay would also incur significant opportunity costs, as TRIUMF's proposal for 2025-2030 operations would see Canada realize first-mover advantages with the commercial-scale production of new cancer-curing treatments, as well as seize upon new science opportunities by ensuring ARIEL's rare isotope beam production facilities are operational during the extended CERN shutdown planned for 2026-2029.

Figure 2: *Staffing requirements (FTE.years) across the proposal categories. Full request is for 2505 FTE.years over the five-year period*

Inner Circle Colour	Category	Number of FTE
(light blue)	ARIEL Construction	75
(teal)	ARIEL Operations	137
(green)	IAMI Operations	74
(pink)	Operational Excellence	56
(orange)	Directorate	55
(yellow)	Research Scientists	230
(dark navy)	Core Facility	1878

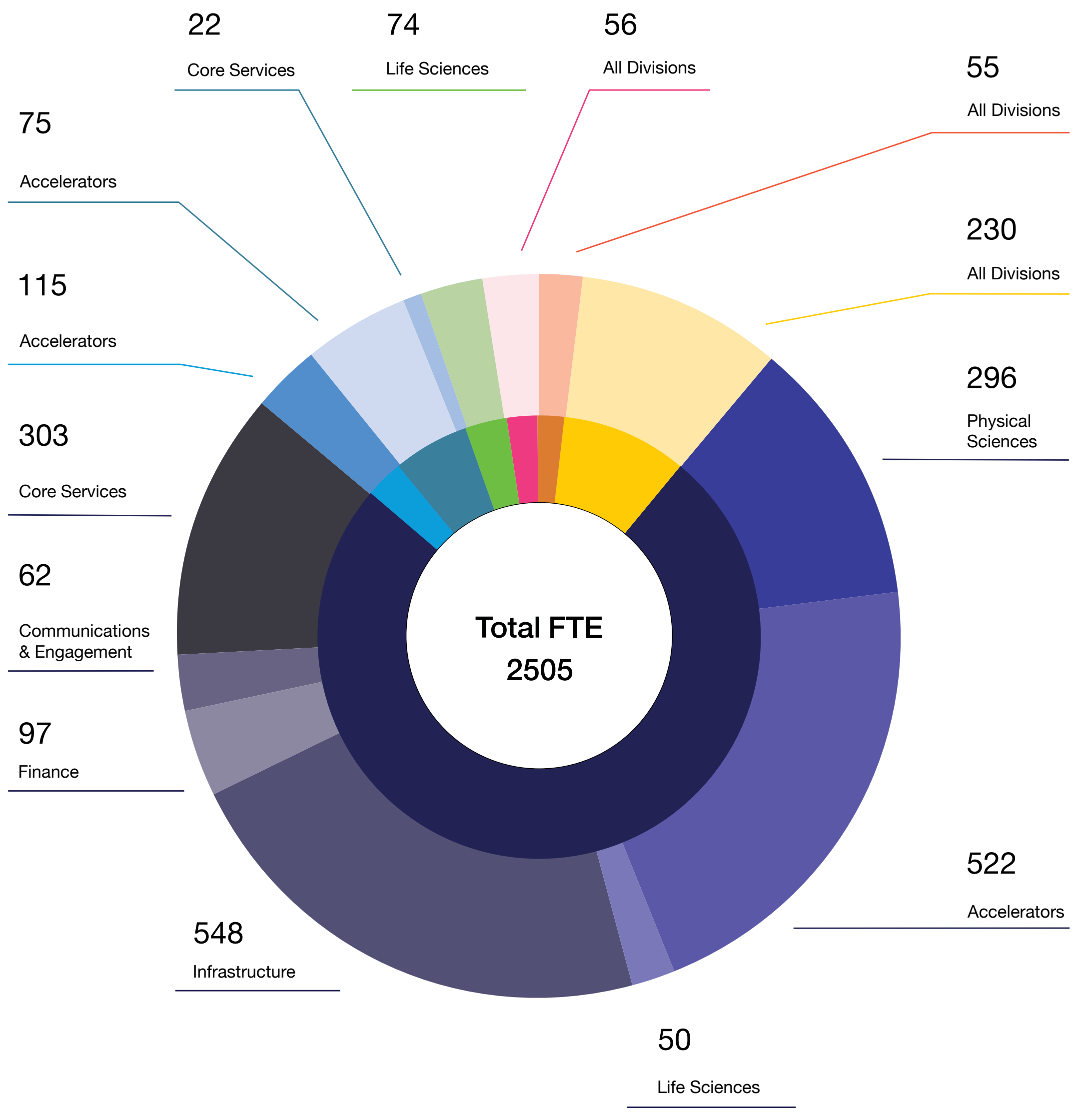
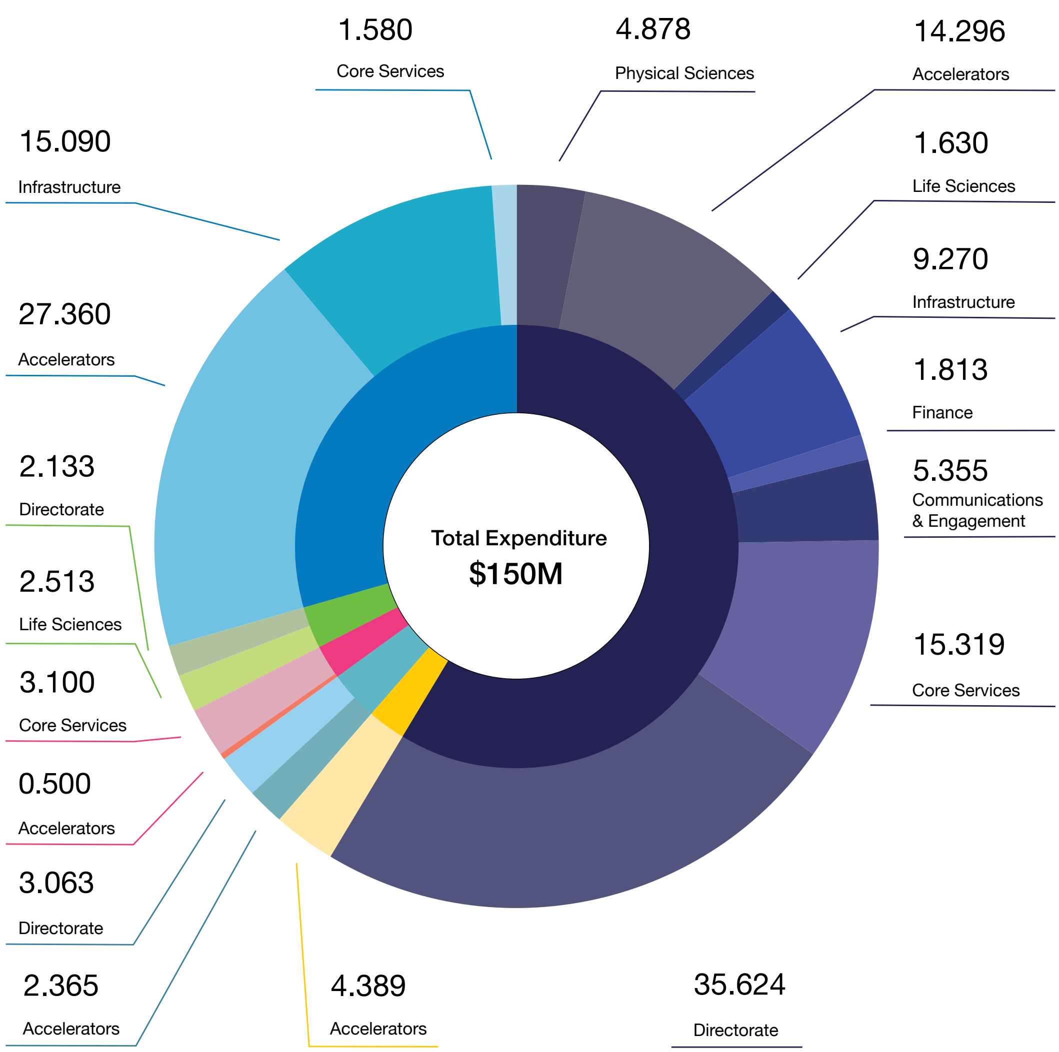


Figure 3: *Resource requirements ($M) across the proposal categories. Full resource request is $150M across the five-year period*

Inner Circle	Category	Resource Requirement ($M)
(yellow)	ARIEL Construction	4.3
(teal)	ARIEL Operations	5.4
(pink)	Operational Excellence	3.6
(green)	IAMI Operations	4.6
(blue)	Deferred Maintenance	44
(dark navy)	Core Facility Operations	88.2



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My experience at TRIUMF has had a profound impact on my career choices. When I first started my co-op, I expected to be most interested in mechanical components of radiopharmaceutical production; however, as my project evolved, I was able to experiment with different facets of engineering. Now, I am headed towards a career path where I will continue to apply the knowledge and skills I acquired at TRIUMF: I plan to use my expertise in coordinating mechanical, software, and electronic elements to engineer devices that can address medical challenges. I am immensely grateful for the invaluable mentorship and learning opportunities generously provided by my supervisors here.

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NICOLAS FEDRIGO
TRIUMF CO-OP STUDENT
APPLIED SCIENCE
UNIVERSITY OF BRITISH COLUMBIA

2.

TRIUMF AS A NATIONAL ASSET

TRIUMF is Canada's particle accelerator centre and an international hub for discovery and innovation. For over 50 years, we have been advancing fundamental, use-inspired, and interdisciplinary research for science, medicine, and industry.

We will continue to address fundamental and emerging challenges in these areas, including health, environment, energy, and green materials. TRIUMF's state-of-the-art accelerator complex – featuring the world's largest cyclotron and the most powerful superconducting electron linear accelerator for the production of radioisotopes – is the foundation upon which our competitive advantage rests. It is a magnet for attracting leading talent to Canada. Further, over 50 years, TRIUMF has developed core expertise in accelerator systems, including the ability to manage high particle beam currents; high power targets for producing intense beams of radioisotopes; particle detector and data acquisition systems; and data management and analysis for the large data sets collected from our experiments.

TRIUMF's current core programs exist in the areas of accelerator science, nuclear physics, particle physics, molecular and materials science, and life sciences – with strategic focus applied to growth in new areas advocated from community discussion, such as quantum and green technologies, as we progress through the laboratory's inaugural 20-Year Vision, which was released in 2022. This growth will be supported by the new infrastructure that will come online during the next five-year period. We are home to more than 500 staff and students, whose broad scope of knowledge and expertise provide us with the capacity to answer fundamental questions beyond the reach of any single academic institution.

Critically, TRIUMF also has strong legacy of excellence that anchors Canada's reputation in many of the fields that the laboratory supports. A comprehensive evaluation conducted by the NRC in 2023 found TRIUMF to be a high-performing and an "agile organization with leadership that keeps a pulse on evolving scientific and technological needs worldwide." This sentiment was further articulated by an international Peer Review Committee (PRC) that found "TRIUMF demonstrated scientific excellence across all of the areas reviewed and is on a good trajectory to achieve the goals laid out in its twenty-year vision." Our research impact was demonstrated clearly through a bibliometric analysis showing a highly collaborative environment with citation impact greater than twice the global average, amplifying Canadian university research with tremendous effect.

Supported by a modern governance structure and robust oversight mechanism, TRIUMF is well-positioned for the future, with the PRC concluding that "TRIUMF has the capacity, competencies, and facilities to achieve its objectives moving forward".

With world-class talent and "unique infrastructure that enables significant contributions and meets the research needs of the Canadian physics community," the NRC evaluation found TRIUMF to enable and deliver scientific excellence; to drive social and economic impact through research, innovation, and skills training; and to help maintain Canada's relevance in the global science ecosystem.

2.1 DELIVERING IMPACT FOR CANADA

Although located in Vancouver on the campus of the University of British Columbia, TRIUMF is truly a national endeavour operating on the international stage, with the laboratory engaging a network of 21 Canadian universities spanning coast to coast.

This broad-based and inclusive structure has produced an environment which enables community-driven, large-scale multidisciplinary research in a manner that is nationally unique. The benefit and value that TRIUMF affords the university sector was clearly reaffirmed when all members rejoined TRIUMF following a recent governance transition from a joint venture to an incorporated entity. In total, TRIUMF plays host to over 1000 users per year from across the country and around the world, all of whom come to the laboratory to take advantage of the unique collection of infrastructure and talent that has been curated on our site over the last half-century.

TRIUMF contributes to the broader national prosperity in many ways, from driving discovery and innovation to developing talent and skills. We have a history of excellence in fundamental science, supporting core programs in particle and nuclear physics, accelerator-based science, nuclear medicine and isotope science, and materials science. We also translate science into innovations that benefit Canada, from transferring superconducting and radiation detection technology to local industry, to developing novel processes for producing life-saving medical isotopes and new tumour irradiation technologies, as well as new technologies that make mining greener and more cost efficient. And, over the decades, we have trained generations of discoverers and innovators, equipping them with the skills needed to keep Canada competitive in the global knowledge economy.

Offering world-unique infrastructure and leading talent, TRIUMF is positioned at the nexus of government, academia, and industry – collaborating and providing skills and expertise beyond what any of these groups could do alone. With agility and comparative independence, TRIUMF has proven its ability to rise to challenges and leverage our science for impact. For example, in response to global shortages for a critical medical isotope, technetium-99m, a TRIUMF-led consortium – with support from the federal government – developed an alternative production process, taking this technology all the way from concept to a successful spinoff company, ARTMS Inc. Today, this technology provides essential supply chain stability for technetium-99m, and novel opportunities to produce new and innovative isotopes for healthcare. Another TRIUMF spinoff company, Ideon Technologies, leads an international collaboration supported by the national Digital Supercluster, coupling TRIUMF-invented particle detection technology with artificial intelligence to create an "Earth x-ray" to as much as one kilometre below the earth's surface. The COVID-19 pandemic has also highlighted the requirement of having resilience within the national research and development ecosystem. In this case, TRIUMF – alongside several other Canadian major research labs – worked together to rapidly design, prototype, and move to market a new type of ventilator to assist in the pandemic response, within an unprecedent timeframe of just 6 months. This endeavour would not have been possible without the laboratory's community of expert scientists, engineers, and technicians, and its major research infrastructure.

Through its commercialization arm, TRIUMF Innovations, TRIUMF has played a leading role in the establishment of the new Canadian Medical Isotope Ecosystem (CMIE), supported by the Strategic Innovation Fund program to build new national ecosystems for producing and commercializing medical isotopes. This initiative brings together public and private sector leaders including CNL, Bruce Power, McMaster University, BWXT Medical, and the Centre for Probe Development and Commercialization to accelerate and advance Canada's position in the fast-growing medical isotope sector.

Beyond emergent needs, TRIUMF's programs can also seed upstream research with clear societal benefit that would not be possible without the unique infrastructure and multidisciplinarity inherent in the laboratory's operation. For instance, leveraging decades of accelerator and life sciences expertise and proven ability to work successfully with industry partners, TRIUMF has been able to make world-leading breakthroughs in the production of novel technologies and radiopharmaceuticals for the treatment of various cancers, dramatically improving health care outcomes for patients across Canada and beyond. TRIUMF has been producing isotopes for patients for over 40 years, and currently produces more than 1.5 million doses per year annually, needed by patients in Canada and around the world. Moving forward, TRIUMF's 20-Year Vision seeks to chart a path whereby the laboratory will leverage its base of expertise to make strategic engagements in sustainability and green technology to help combat the global threat posed by climate change.

The breadth of infrastructure and research at TRIUMF provides a unique training opportunity for Canadian and international talent. This includes the research community itself, which attracts global talent to Vancouver, but also in the technical and administrative areas required to support such an endeavour. This includes the specialized personnel and engineers required to maintain the research and conventional infrastructure, to design and build the unique and often bespoke components required for research, and the management and administrative services needed to deliver the research program. TRIUMF is home to one of the most sought-after co-op student programs in the country, which is oversubscribed by a factor of ten and trains more than 150 students per year. Similarly, our technical teams are a key part of a pipeline for Canadian industry, with personnel having the opportunity to gain experience in a world-class, multidisciplinary facility.

Furthermore, TRIUMF's work can also help address systemic societal challenges, particularly those within Canada's science, technology, engineering, and math (STEM) research communities and beyond. Taking a leading role in developing the next generation of leaders, TRIUMF nurtures a culture of equity, diversity, and inclusion across disciplines and programs, with the objective of creating a laboratory that more accurately reflects the makeup of Canada itself. Steps are also underway to embed a reconciliation framework within both the organization itself and the work we conduct.

2.2 THE TRIUMF ORGANIZATION

TRIUMF operates as an incorporated not-for-profit owned by a consortium of 21 Canadian member universities who assume ultimate liability for the laboratory's eventual decommissioning.

Management of TRIUMF is done through an executive Leadership Team led by the Executive Director and CEO, who is accountable to a skill-based Board of Governors. The Board is appointed by representatives of university Members, who collectively form the Members' Council. Complementing this skills-based governance board, a Science Council – comprised of appointees from the Members and TRIUMF – also support the Board with scientific guidance and direction from TRIUMF's various research communities.

TRIUMF's current funding model is unique within the Canadian system. Predating other funding mechanisms, such as those administered by the Canada Foundation for Innovation, TRIUMF's operational funding comes in five-year tranches via direct allocations in the federal budget which flow through the NRC. This is the only funding mechanism available to support core operations and the development of capacity for research make up approximately two-thirds of TRIUMF's total revenues of approximately $100M annually. All other public funding sources, both federal and provincial, are fully restricted, typically reserved for research or project activities. As compared to its international peers, TRIUMF also generates a significant proportion of its revenues from engagement with the private sector; however, the vast majority of these funds are used to cover project or operational costs due to shortfalls in the five-year requests or the ineligibility of certain expenses (i.e., capital construction) under the NRC funding arrangement.

The uniqueness of TRIUMF's funding structures means that it stands alone in the broader ecosystem, with few viable options within the current model to address major challenges. For instance, while TRIUMF has existed as an active concern since its founding over 55 years ago, the current model of a sun-setted project provides limited assurance of long-term sustainability, which does not align with the long timescale and operational commitments associated with the type of research undertaken at the laboratory. Beyond the risk of being precipitously shut down at the end of each five-year cycle, the fact that the lifecycle costs of new facilities, infrastructure renewal, and economic contingencies are not built into operational funding severely and negatively impacts TRIUMF's success and the benefits it can deliver to Canada.

However, many challenges faced by TRIUMF are also shared by a series of smaller, but similar facilities across the country. Taking a unified approach to addressing the common challenges faced by Canada's major research facilities – while maintaining sensitivity on the unique nature of each – would create a critical mass around Canada's approach to "Big Science", enhancing coordination, reducing redundancies, and returning added value to the country. This approach has been articulated within the reports of the 2017 Fundamental Science Review (Naylor) and the 2023 Advisory Panel on the Federal Research Support System (Bouchard).

2.3 TRANSLATING SCIENTIFIC DISCOVERY INTO COMMERCIAL OPPORTUNITIES

TRIUMF Innovations Inc. is the business interface and commercialization arm of TRIUMF, acting as a portal into TRIUMF and its network for the private sector world of industry partners, customers, and investors.

Through TRIUMF Innovations, companies can access the multidisciplinary expertise, world-class infrastructure, and global network at TRIUMF to:

- Create life-saving nuclear medicine technologies, including new diagnostics and radiotherapeutic treatments.
- Commercialize particle detector technologies for use in sectors ranging from fusion energy, mining, and security to oil and gas.
- Radiation-test new technologies for small modular reactors, computing, communications, and aerospace electronics.
- Develop and validate new technologies in emerging areas like quantum and green technology using TRIUMF's global network of top researchers.
- Co-lead the new Canadian Medical Isotope Ecosystem, supported by the Strategic Innovation Fund, providing a new collaboration, networking, and funding platform to support Canada's growing medical isotope sector.

TRIUMF Innovations' business team brings new discoveries to market through industry partnerships, licensing, and start-up companies. TRIUMF Innovations identifies, assesses, develops, incubates, and commercializes technologies in collaboration with partners in industry, academia, and government. To date, six spin-off companies have successfully gone to market, with more in the pipeline. TRIUMF Innovations helps navigate business challenges, including intellectual property management, fundraising, and scale up.

A Commercialization and Entrepreneurship Training Program is equipping our people with the skills necessary to accelerate innovation. Through a range of courses, workshops, and individual mentoring programs, TRIUMF Innovations provides effective, hands-on business training to Canada's research community.

In addition, TRIUMF Innovations also functions as a hub to connect private sector partners with TRIUMF's national network of top researchers and institutions. For example, the federal Strategic Innovation Fund is supporting the new Canadian Medical Isotope Ecosystem, co-led by TRIUMF Innovations and the Centre for Probe Development and Commercialization. This initiative provides matching funding to innovative new medical isotope projects from McMaster, CNL, Bruce Power, BWXT Medical as well as from academic researchers and small/medium enterprises from across Canada.

A TRIUMF physicist makes adjustments to the ALPHA-g antimatter detector, which was constructed at TRIUMF before being installed at the ALPHA experiment at CERN.

> "My experience at TRIUMF has been transformative in shaping my career choices. Being at TRIUMF has allowed me to see the wider topography of modern science and engineering. It's like having a panoramic view of the landscape, which has reaffirmed my passion for my chosen career while also opening my eyes to new ideas and pathways within my field."

DENIZ SOGUTLU
TRIUMF CO-OP STUDENT
ENGINEERING
UNIVERSITY OF BRITISH COLUMBIA

3.

OUR CURRENT RESEARCH PROGRAM

TRIUMF research covers a broad, multidisciplinary, program that both develops and exploits research infrastructure at the local site and connects Canada to the world. This section provides a brief overview of the various research areas that TRIUMF and our community are engaged in, demonstrating the world-class nature of the facility, and the international reputation that TRIUMF possesses. This research program is enabled by TRIUMF's core competencies, which include accelerator and detector expertise, data management and analysis, and talented staff with a broad skillset supported by local infrastructure. Accordingly, the research threads are closely interwoven with the capabilities of the laboratory.

3.1 ACCELERATOR SCIENCE

Our expertise in developing, operating, and maintaining our advanced accelerator technologies and infrastructure is the bedrock of TRIUMF's leadership in cutting-edge research and technology development.

TRIUMF excels in building and operating unique, high-performing accelerator systems featuring a wide variety of particle beams, from protons and electrons to rare isotopes, neutrons, and muons. These systems drive our multidisciplinary science and innovation portfolio, from nuclear and particle physics and quantum materials to applications in nuclear medicine, telecommunications, clean power, and aerospace.

Our expertise and infrastructure empower Canada to compete at scale in global "Big Science" and make significant in-kind contributions to many of the world's leading physics experiments, from the frontier of high-energy physics at the LHC to the hunt for dark matter or the characterization of neutrinos. Further, we can realize important domestic projects like a compact accelerator-based neutron source (CANS) or a unique source for intense THz radiation based on TRIUMF's superconducting electron linear accelerator (e-linac). Driving impact both domestically and internationally, our accelerator facilities serve as a training ground for the next generation of accelerator scientists, engineers, technicians, students, and other professionals, significantly enhancing Canada's STEM-based knowledge economy.

TRIUMF's accelerator physics research team ensures that the beams required to satisfy the demands of the TRIUMF science program are delivered, and the accelerator complex operates at optimal performance. This group provides support for operation of all accelerators and beamlines, as well as their development and extension; develops collaborations with other accelerator-based laboratories; and undertakes research in the three key areas of accelerator science and technology in which TRIUMF excels (superconducting radio frequency (SRF)), theoretical and experimental aspects of accelerator beam physics, and secondary particle production techniques.)

TRIUMF's accelerator science program is positioned as a critical factor in the development of the next generation of rare isotope production facilities and key technologies for particle accelerators, from TRIUMF's ARIEL to facilities across the globe where our contributions support critical areas of cutting-edge research.

3.2 NUCLEAR ASTROPHYSICS

Nuclear reactions play an important role in astrophysics and cosmology. The lightest elements are synthesized in the early universe during the Big Bang reaction chain.

Heavier nuclei, those up to iron, are produced by fusion, transfer, and radiative capture processes in the stars, while still heavier nuclei are produced by the slow, intermediate, or rapid neutron capture (i.e., s-process, i-process, r-process) in neutron-rich environments and by the proton capture in the rp-process.

To understand the abundances of elements in our solar system, in the Milky Way galaxy, and beyond requires knowledge of the rates of the relevant nuclear reactions and various reaction chains, many of which involve radioactive isotopes. TRIUMF's ability to produce many species of radioactive isotopes in substantial amounts positions the laboratory at the forefront of the nuclear astrophysics research. With experimental facilities like DRAGON and TUDA, cross sections of many astrophysics nuclear reactions can be measured. Mass measurements of neutron rich isotopes at TITAN provide important inputs for i- and r-process simulations.

TRIUMF theorists contribute to these simulations by performing extensive reaction network calculations. TRIUMF theorists are also developing and applying first-principles, or ab initio techniques, to calculate cross sections of nuclear reactions relevant for astrophysics. Theoretical investigations become important for reactions that occur in the cosmos at very low energies not accessible to experiments. Theory then provides an extrapolation from the measured cross sections to the astrophysical relevant low energies.

Notable recent investigations comprised a series of decay spectroscopy experiments with the GRIFFIN facility in the neutron-rich N=82 region, important for r-process nucleosynthesis in explosive astrophysical environments. These include the resolution of a controversy regarding the half-life of the "waiting point" nucleus cadmium-130 and studies of the beta and beta–delayed neutron decays of indium isotopes.

With the coupling of the EMMA and TIGRESS facilities, we are now able to directly measure the cross sections of reactions induced by radioactive beams that take place in astrophysical processes such as the p-process at the relevant energies. We have demonstrated that we can study reactions on both hydrogen and helium, utilizing plastic and novel silicon-magnetron sputtered thin film targets, respectively.

The first TIGRESS+EMMA science result was a direct measurement of the ^{83}Rb(p, γ)^{84}Sr radiative capture cross section at energies relevant to p-process nucleosynthesis in core collapse supernovae using an accelerated radioactive beam, the first such measurement ever reported. The cross-section results confirmed that the abundance of strontium-84 produced in the astrophysical p process is higher than previously predicted based on statistical model calculations.

The DRAGON collaboration performed the first ever isomeric beam radiative capture measurement of the ^{26m}Al(p, γ)^{27}Si reaction, which is important for the understanding of stellar and galactic evolution.

3.3 NUCLEAR STRUCTURE AND DYNAMICS

Nucleons, protons, and neutrons, interacting by strong short-range nuclear forces, give rise to the complex properties of atomic nuclei. How the structure of nuclei emerge from nuclear forces is one of the key questions of nuclear physics. TRIUMF nuclear physicists investigate rare isotopes that challenge conventional nuclear structure observed in stable nuclei.

Studying exotic nuclei, we observe novel features such as extended halo states, the coexistence of spherical and deformed configurations at low excitation energies, the evolution of nuclear shells with the changing numbers of protons and/or neutrons, and even rare processes such as beta decay to continuum. TRIUMF experimental facilities investigate reactions of rare nuclear isotopes on targets, study excitations of exotic nuclei, and measure masses of short-lived isotopes. These studies feed back into our understanding of basic nuclear forces between nucleons.

Working alongside experimentalists, TRIUMF theorists also develop and apply ab initio techniques to calculate properties of atomic nuclei. Theoretical studies help to interpret and inform TRIUMF experiments that then provide feedback on the quality of the nuclear forces serving as input for the theory, as well as on the adequacy of the applied quantum many-body methods.

A notable recent beta-decay study at TRIUMF's Isotope Separator and Accelerator (ISAC) facilities revealed multiple shape coexistence in cadmium isotopes. This was part of a series of measurements in palladium, cadmium, tin, tellurium, and xenon isotopes around magic proton number Z=50, which made significant contributions to the understanding of shape coexistence as a ubiquitous feature of the nuclear many-body system. This work was featured as a Research Highlight in the prestigious journal Nature.

3.4 QUANTUM MATERIALS

Quantum materials are solids with exotic physical properties which arise from the quantum mechanical properties of their constituent electrons.

Well-established quantum materials include magnets, semiconductors, unconventional superconductors, and heavy fermion- and multiferroic systems. More recently discovered quantum materials, such as topological insulators, Weyl semi-metals, quantum spin liquids, and spin ices arise from geometrical frustration, spin-orbit coupling and time and crystal symmetry-protected ground states. Many quantum materials derive their properties from reduced dimensionality, in particular from confinement of electrons to two-dimensional sheets. Some of the more esoteric but observable effects displayed by quantum materials include unusual fluctuations, quantum entanglement, quantum coherence, and the dependence of properties on the topology of the quantum mechanical wave functions. Topological insulators, which are materials where electrons on surfaces have a metallic character that is distinct from the electrons in the bulk, have a particular kind of electrically insulating character. The surface electrons could protect electronic charge transport and could form the basis for a new generation of energy-efficient electronics.

Quantum materials have significant applied and/or technological potential, but much fundamental scientific research needs to be done before it may be realized. To advance this research, TRIUMF provides Canadian and international researchers with unique and cutting-edge tools such as muon spin resonance (μSR) and beta-detected nuclear magnetic resonance (ßNMR) to characterize quantum materials and better understand the complex interplay between crystalline, magnetic, and electronic structure and properties. By understanding why they behave the way they do, we can design the next generation of materials with optimized properties.

- μSR has been extensively used to characterize magnetic fields inside a material and their associated fluctuations. In addition, the technique is a unique tool to determine magnetic phase diagrams in materials such as superconductors, quantum spin liquids and spin ices. μSR is particularly powerful for studying systems with frustrated magnetic interactions, weak magnetic moments, and disordered magnetism, as well as the coexistence of different phases within a material of interest.

- ßNMR has been used to perform depth-resolved measurements on quantum materials to show differences in behaviour near a free surface or an interface. It is possible to perform measurements within a few nanometers of a surface, to study ultra-thin films, and to probe buried interfaces between materials.

3.5 RESEARCH AT THE HIGH-ENERGY FRONTIER

Researchers working at the energy frontier accelerate particles to the highest energies created by humanity, and then collide them to produce and study the fundamental constituents of matter and the architecture of the universe – including the Standard Model of particle physics, the leading paradigm for explaining particles, fields, and forces.

While it is very successful in what it can predict about known particles, the Standard Model is not complete in its description of the universe. Many advanced theoretical models predict additional fundamental particles, beyond those in the Standard Model, that may be produced in very high energy particle collisions.

Working together with colleagues from several Canadian universities, TRIUMF particle experimentalists participate in the ATLAS (A Toroidal LHC ApparatuS) experiment at the Large Hadron Collider (LHC) at CERN, one of the two main detectors that enabled the discovery of the Higgs boson and subsequent Nobel prize in 2012. Today, researchers on ATLAS continue to search for new discoveries in the head-on collisions of protons at energies as high as 14 trillion electron-volts (TeV). Building on the discovery of the Higgs boson, these additional searches will allow in-depth investigation of the particle's properties and thereby of the origin of mass, as well as will probe new physics at high energy and mass scales. Since 2012, researchers with the ATLAS collaboration have improved understanding of the Higgs boson and found it to agree with all the Standard Model predictions with high precision. For example, they have measured the Higgs coupling to vector bosons to about 5%. Also, they have performed measurements of the Higgs self-interaction – an incredibly rare process to which the detectors are just beginning to develop precision sensitivity.

In order to analyze the enormous amount of information from LHC experiments, CERN coordinates an international network of large high-performance computing centres that are linked by "grid" tools so that they may act as one global system to study one of the largest data sets in history. On behalf of the Canadian community, TRIUMF computer scientists manage one of the world's ten ATLAS Tier-1 centres, located at Simon Fraser University (SFU).

Providing critical support to many of Canada's contributions to ATLAS, TRIUMF scientists successfully built and installed the Phase 1 upgrades – highlights of which are the Liquid Argon calorimeter readout and the New Small Wheel muon detectors. The liquid argon readout is already having a tremendous impact on the trigger strategy of the detector, enabling a dramatic improvement in the trigger of electrons and photons, while the New Small Wheels are also entering the trigger operations as their commissioning continues.

3.6 PRECISION TESTS OF FUNDAMENTAL INTERACTIONS

In the last 50 years, the Standard Model has been extremely successful in describing fundamental interactions and predicting particles. This work culminated in the discovery of the Higgs boson in 2012. However, there is strong evidence that the Model is not yet complete.

Searches for new particles beyond the Standard Model at the high energy frontier is one avenue to probe this, while precision tests of fundamental interactions at low energies are the other. TRIUMF is well positioned to realize the latter by testing fundamental symmetries, such as the symmetry between matter and antimatter (with the CERN-based Antihydrogen Laser Physics Apparatus, ALPHA), time-reversal symmetry (TUCAN nEDM), or the mirror-symmetry between left and right-handed systems (TRINAT and Francium). TRIUMF is now embarking on a new experimental program utilizing radioactive molecules (RadMol) which has the potential to provide unique sensitivity to electric dipole moments (EDMs) and nuclear anapole moments.

Results of experiments confirming the Standard Model prediction will lead to better constraints of “beyond the Standard Model theories”, such as supersymmetry. Reducing the limit for the T-violating neutron electric dipole moment has significantly challenged many particle physics theories. Deviations from Standard Model predictions, such as the muon g-2 experiments, provide smoking guns for its incompleteness. TRIUMF has the unique capability to carry out some of the most precise measurements of the fundamental interactions and symmetries utilizing systems where experiments can have the same precision as Standard Model predictions or where the observable would clearly stand out above Standard Model background. These capabilities are complemented by advanced theoretical support including ab initio calculations of symmetry-violating moments and investigations of beyond the Standard Model particle theories.

3.7 MEDICAL RADIOISOTOPE RESEARCH

Throughout its 40-year history, TRIUMF's radioisotope program has been pushing the frontiers of diagnostic and therapeutic radioisotope and radiopharmaceutical production for critical, life-saving isotopes, which in many cases are becoming a standard of care for diagnosing and treating a variety of diseases. In tandem, researchers continue to explore an expanding repertoire of radioisotopes for future generations of radiopharmaceuticals.

From the onset, the TRIUMF program has enabled scientists to examine the molecular nature of neurodegenerative conditions, including Parkinson's Disease, dementia, addiction and mental health, and traumatic brain injury. More recently, the program is working to scale, and remains one of very few centres capable of producing emerging and game-changing alpha-emitting isotopes now in clinical trials for treating late-stage, untreatable, prostate, pancreatic, and blood-based cancers. The list of currently incurable cancers is growing, and TRIUMF-enabled research will soon include clinical efforts for treating skin, breast, brain, ovarian, colorectal cancers and many more.

Working with TRIUMF's Accelerator Division teams, the Life Sciences Division is innovating high-powered, versatile target solutions to produce a wide array of known and novel isotopes critical to fuel new radiochemistry research and, ultimately, radiopharmaceuticals used for visualizing, diagnosing, and treating diseases. These efforts also encompass leveraging TRIUMF's deep expertise in accelerator-based isotope production to address the recent medical isotope crisis and enabling global cyclotron infrastructure to meet isotope production requirements within hospitals today.

This research builds on TRIUMF's core competencies in accelerator science and a growing suite of dedicated radiochemistry research and radiopharmaceutical production facilities; empowered by our expertise and infrastructure, these capabilities further amplify TRIUMF's impact as an international hub, connecting communities of accelerator and nuclear physicists, chemists, and health researchers with the collaborators and companies that bring the benefits of radioisotope applications from lab bench to bedside.

Built in part on its deep expertise in accelerator science (including high power production targets for radioisotope production), TRIUMF's radioisotope research and production program is globally unique in that it operates further upstream compared to many sector-adjacent institutions and market competitors, creating a unique ecosystem of cross-disciplinary innovation that continues to benefit and advance the field of radioisotope research. This philosophy has allowed TRIUMF's research community and market-facing commercialization experts to enrich partnerships through the application of fundamental science principles, further amplifying the impact of the downstream, real-world solutions.

3.8 APPLIED ION BEAMS

Leveraging over five decades of experience and knowledge gained in the design and implementation of accelerators, targets, and beamlines, TRIUMF produces beams of ions (protons, as well as isotopes) to fuel a diverse portfolio of research, applied use, and production.

In TRIUMF's Life Sciences Division, applied ion beams are used for biological research. Discovery efforts into the more exotic radioisotopes of today have tremendous promise to fuel the novel applications of tomorrow. For example, TRIUMF is capable of making certain rare isotopes that are not only difficult to produce, but also gaining attention as key building blocks for innovative targeted molecules capable of treating cancers and autoimmune diseases, as well as opening new lines of broad-spectrum antibiotics, antivirals, and antifungal agents to combat increasing resilient infections.

At TRIUMF's unique ßNMR (beta-detected Nuclear Magnetic Resonance) facility, scientists are using radioactive isotopes to take inside-out, atomic-level snapshots to guide the way to new materials and medicines. Short-lived isotopes of commonly used elements are used to obtain some of the highest-sensitivity NMR measurements on the planet; such sensitivity enables scientists to glean important structural and dynamic information not possible using conventional analytical techniques.

TRIUMF and collaborators are also investigating the potential of the FLASH radiotherapy technique in both photons and protons, where a specified radiation dose is delivered at ultra-high dose rates over a much shorter period of time than traditional radiation therapy. This technique, first observed in the 1950's, appears to provide comparable impact on tumours while reducing impact on surrounding tissue when compared to multiple lower dose irradiations. In TRIUMF's unique, multidisciplinary environment, teams of experts are able to design materials and configure hardware to provide real-time beam delivery analytics that will ultimately enable both the accelerator and healthcare communities with technologies to optimize isotope production and patient treatment regimens.

In another area of applied use, TRIUMF has established the unique Proton & Neutron Irradiation Facility (PIF & NIF), where commercial partners can access ion beams – proton and neutron beams produced using the 520 MeV cyclotron – that simulate the radiation conditions of low-orbit space and provide highly valuable information for materials characterization and design and development for space-bound technologies. These facilities can be used to test the performance of aerospace components and systems in specific radiation fields and assess any subsequent harmful effects they may be exposed to in use.

3.9 NEUTRINOS AND DARK MATTER

Even though the Standard Model provides excellent descriptions and explanations for an enormous range of experimental data in contemporary particle physics, it cannot be the complete theory of elementary particles and fundamental forces.

For instance, the discovery of neutrino masses and dark matter both point towards new physics beyond the Standard Model. The Standard Model is also unable to explain why there is more matter than antimatter in the universe, or why gravity is so much weaker than all the other known forces. Solving these outstanding questions about the basic building blocks of matter and the architecture of the Universe requires close collaboration between theory and experiment.

TRIUMF convenes a community of physicists, engineers, technicians, and others to contribute to a variety of accelerator-based and deep underground experiments to elucidate the properties of neutrinos and to uncover the nature of dark matter particles.

TRIUMF particle physicists participate in the T2K and Hyper-K neutrino experiments. Located in Japan, the T2K experiment is a long-baseline neutrino experiment intended to measure neutrino oscillation parameters, including the phase that governs CP symmetry breaking. Hyper-K, the successor to T2K, will include a far detector with 8-fold larger active volume and a neutrino beam 2.5 times more intense, and is planned to start operation in 2027. TRIUMF personnel have played a leading role in the analysis of T2K data to measure the CP symmetry parameter, culminating in the publication of a Nature paper in 2020 showing the strongest constraint on the parameter. TRIUMF is leading the development of the Intermediate Water Cherenkov Detector (IWCD), which has been adopted by Hyper-K and its prototype, the Water Cherenkov Test Experiment (WCTE), which has been approved by CERN. TRIUMF has successfully developed essential water Cherenkov detector technologies for WCTE, IWCD and Hyper-K, including multi-PMT photosensors and photogrammetry calibration devices. TRIUMF has also initiated and led the development of machine learning event reconstruction techniques, which are being applied in the IWCD, WCTE and Hyper-K data analysis frameworks.

As part of the global hunt for dark matter, TRIUMF collaborates on numerous experiments with partners both national (e.g. SNOLAB and the McDonald Institute) and international, providing critical expertise and production facilities for some of the world's most sensitive particle detection apparatus. TRIUMF provides critical expertise and technology around data acquisition systems and photon detection systems, including silicon photo-multiplier devices and ancillary electronics and optical systems. This expertise has been instrumental in the DEAP-3600 and Darkside experiments, two liquid argon dark matter systems, and in SuperCDMS, a germanium-based experiment for low mass dark matter.

TRIUMF theorists also investigate potential candidates for dark matter, theories of neutrino masses, and mechanisms for the creation of matter in the first seconds after the Big Bang. This work is essential for guiding experimental tests and searches. Members of TRIUMF's Theory Department also calculate nuclear matrix elements of the neutrinoless double-beta decay needed for the interpretation of experiments. These calculations are at the leading edge of this field using ab initio approaches in determining the matrix elements, illuminating a long-running discrepancy between alternative phenomenological models.

A researcher in TRIUMF's Theory Department

> “TRIUMF’s unique networks and infrastructure provide an incredibly strong convening force that holds together all of Canada’s nuclear and particle physics communities. The hub of knowledge that we have created at TRIUMF, which is enhanced by our facilities and our people, is essential for the STEM community in Canada and beyond.”

PIETRO GIAMPA
DETECTOR INFRASTRUCTURE DEVELOPER
SCIENCE TECHNOLOGY

4.

DEVELOPING CAPACITY FOR RESEARCH

During the period from 2025 – 2030, two new major infrastructure investments on the TRIUMF campus will come to fruition. The $250M investment in the ARIEL and IAMI facilities will provide TRIUMF with capabilities that will generate world-leading research for many years to come, and benefit society through newly generated knowledge and upstream innovations.

This request includes resources required to complete these constructions, commission the infrastructures, and transition to initial science operations.

As our major priority, the ongoing construction of ARIEL has required the de-prioritization and deferral of other science projects through our internal program management processes. The current ARIEL construction phase is planned to complete in 2026/27, delivering the capability to increase TRIUMF's science output by providing three targets for radioactive ion beam production.

This five-year funding request covers the core operation of the unique TRIUMF accelerator complex, enabling incremental accelerator upgrades for priority performance and reliability enhancements. The request addresses activities that mitigate operational risks, gain efficiency, and expand the capabilities the new infrastructure will provide. These initiatives will address deferred maintenance, improve the operational performance, and maintain the accelerator systems at their highest performance level. In addition, the increase in efficiency of the accelerator operation will be a hallmark of the ARIEL era, delivering a high return on investment that also produces world-unique science output.

The first phase of IAMI is currently in final outfitting, with the expectation that the Phase-II projects will be completed during the next 5-year timeframe. This work includes projects to complete outfitting for all laboratories, and the possible inclusion of an additional cyclotron. All projects are interlinked due to shared services within the IAMI facility, driving the desire to complete construction simultaneously.

Following construction of ARIEL and IAMI, we will transition to an operational phase. Operations of the ARIEL's superconducting e-linac, the rare isotope target stations, and the new beamlines will require resources beyond the construction level. Efficiencies are planned through the consolidation of the control centres for the accelerators (which use common control systems), new automatic tuning technologies, and the standardization of electronics components for all accelerator systems.

4.1 PROBING FUNDAMENTAL SCIENCE USING A MULTIDISCIPLINARY FLAGSHIP RESEARCH FACILITY—ARIEL

TRIUMF's international reputation for high profile science is driven by its unique rare isotope production capabilities.

The demand for beam time from experiments using rare isotopes exceeds the capacity by an order of magnitude. The Advanced Rare Isotope Laboratory (ARIEL) is Canada's answer to the requests from the science communities to provide more beams for leading edge multidisciplinary research.

Funded by the Canada Foundation for Innovation (CFI), as well as six provinces, and with backing from 21 universities, construction of ARIEL has progressed in two major stages. The first stage (2010-2014) included the construction of the ARIEL outer building envelope, as well as development and construction of an electron accelerator (e-linac), which produced its first accelerated beam in 2014. The second stage (2017-2026) involves the construction of the two target stations, associated laboratory, and hot-cell infrastructure, as well as the rare isotope beam transport beamlines, mass-separator, and an electron-beam ion source for charge state breeding. Additional beam delivery infrastructure, like the high-resolution mass separator and the charge state breeder, was funded in a separate CFI project, the CANadian Rare-isotope facility with Electron Beam ion source (CANREB), which has been commissioned and will be fully operational in 2023.

ARIEL is one of the world's only purpose-built multi-user rare isotope facilities in the world, as well as the world's most powerful Isotope Separation Online (ISOL) complex. ARIEL will enable world-class research on the nature of atomic nuclei, the origin of the heavy chemical elements, quantum materials and biomolecules, as well as medical isotopes for the imaging and treatment of disease. It will massively expand TRIUMF's rare isotope program by providing more exotic isotope species with very high intensities and by adding two production targets in parallel to the existing ISAC target station. Together, the planned completion of ARIEL in 2026/27 will allow TRIUMF to fully exploit the numerous existing experimental facilities at a time when CERN's ISOLDE facility, the strongest competitor to TRIUMF, will be shut down for maintenance. This fortuitous timing presents Canada with a unique opportunity to be at the forefront of science and research in this space.

At the heart of ARIEL is a built-in-Canada superconducting e-linac for isotope production via photo-nuclear reactions like photo-fission, as well as a second proton beamline from TRIUMF's cyclotron for isotope production via proton-induced spallation, fragmentation, and fission. ARIEL employs next-generation target stations and associated infrastructure. The development of these systems was guided by many lessons learned from ISAC and other major ISOL facilities worldwide. A new advanced rare isotope beam preparation system (the completed CANREB), will in future allow the parallel operation of three rare isotope beams. Furthermore, the installation of a symbiotic target in the beam dump of the ARIEL proton target station will enable the production of high-value medical isotopes, such as actinium-225 for targeted radionuclide cancer therapy, using unspent energy from particle beams. Although actinium-225 is being produced at the Isotope Production Facility on beamline 1A (noted below in 4.4), world demand far outstrips current global production capacity, and the addition of this second beam dump production facility will enhance TRIUMF's ability to support these health benefits for society.

4.2 A WORLD-CLASS CENTRE FOR DEVELOPING LIFE-SAVING RADIOPHARMACEUTICALS—IAMI

Building on TRIUMF's 40 years of experience in nuclear medicine and life sciences, the Institute for Advanced Medical Isotopes (IAMI) will be a major new part of the TRIUMF life sciences program for research into next-generation, life-saving medical isotopes and radiopharmaceuticals.

The IAMI facility, located on the TRIUMF campus, convenes an interdisciplinary community of TRIUMF faculty and students, research partners, government stakeholders, and industry collaborators into a new frontier of medical isotope development for both health research and clinical use. IAMI comprises an integrated series of labs and a TR24, one of the most technologically advanced commercial cyclotrons in the world (the TR refers to a TRIUMF design manufactured by a commercial cyclotron company, ACSI, in Richmond, BC, and the 24 refers to the 24 MeV energy of the protons accelerated.) Providing both capability for isotope production and extraction through radiochemistry laboratories and Good Manufacturing Practice capable facilities, IAMI will be able to span the full spectrum from medical isotope production through to human injectable doses. This capability will facilitate the development of clinical trials and open the potential for incubating new companies. Within the context of the expertise and surrounding infrastructure at TRIUMF, the TR24 in IAMI will be one of the most versatile and potent isotope and radiopharmaceutical research machines in the world.

IAMI will significantly increase Canada's capacity for the sustainable and reliable production and distribution of medical isotopes currently critical for Canadian health research and clinical use, including technetium-99m and fluorine-18. It will synergize the Vancouver region's diverse nuclear medicine sector, acting as a research hub and centrally managing the production of radioisotopes and radiotracers for commerce and clinical research. It will give TRIUMF, the University of British Columbia, BC Cancer, and others, centralized access to leading-edge expertise, infrastructure, and oversight of accelerator-based isotope research and applications.

As TRIUMF's first purpose-built life sciences facility in decades, IAMI will enable a broad-based research and development program, providing capacity not available elsewhere in Canada – and in some respects, unique in the world. From routine production of much-needed isotopes to novel development of next-generation therapies, IAMI will serve as a hub for Canadian excellence in radioisotope innovation. In addition to providing critical capacity to start-ups and spin-offs, the facility will also backstop the local healthcare system and maintain a domestic base of expertise and resilience that can be leveraged in times of national or international need.

4.3 LEGACY INFRASTRUCTURE AND DEFERRED MAINTENANCE

Where possible, TRIUMF's 55-year-old accelerator infrastructure has been upgraded with new materials and modern controls. However, due to a lack of viable funding avenues within the current paradigm, major deferred maintenance projects have gone unfunded for decades. Further, many of these accelerator facilities and systems are deeply embedded within the infrastructure plan and will remain crucial to the future operations of the laboratory.

The importance of accelerator technologies and the existing infrastructure has not declined as new capabilities have become available – this criticality drives the need for continued maintenance and innovation of the machines within TRIUMF's accelerator complex.

To preserve leadership in science and technology and capitalize on government investments into TRIUMF's world-leading capabilities, infrastructure maintenance must be a high priority for the lab's ageing accelerator complex. Facilities of such scale and impact must have a program of development and improvement projected over extended timescales; inevitably, however, tight operational budgets over successive funding cycles have resulted in significant deferred maintenance.

As a facility with a broad range of legacy infrastructure that is still required for operations of a heavily integrated accelerator complex, deferred maintenance is a fact of life. Securing funds for deferred maintenance and refurbishment of critical systems has been challenging through grant-driven request processes, and operational support has been insufficient to address all but the most urgent needs. Given budgetary constraints over the previous funding cycles, only critical risk deferred maintenance has been possible, including through a one-off injection of $25M during the current five-year cycle. An analysis of anticipated deferred maintenance has been completed at the Divisional level, with critical and high-risk deferred maintenance anticipated through to 2030 included in this funding request. Overall, this totals some $44M capital over the five-year period, including the refurbishment costs of beamline 1A detailed in Section 4.4. Should additional funding be made available to TRIUMF beyond the $450M request, this would be a key area of focus, to reduce and mitigate future risk by setting aside resources to complete additional deferred maintenance and upgrade projects.

Planned deferred maintenance falls into three main categories: operational excellence, accelerator infrastructure, and conventional service infrastructure. For operational excellence, replacement of ageing IT and network infrastructure is required to improve cyber security and reliability, and replacement of radiation assay capabilities with modern systems to improve compliance monitoring. For the accelerator systems, deferred maintenance includes work on the main cyclotron control systems, RF systems, target station and target operation infrastructure, remote handling reliability maintenance, beam instrumentation and liquid cryogen systems. Conventional service deferred maintenance primarily revolves around replacement of ageing electrical infrastructure, including transformer and distribution systems and the replacement of our main electrical substation, a long-standing item of risk for the organization, valued at over $10M itself. Additional conventional systems include replacing a 45-year-old cooling tower, as well as addressing crane and elevator infrastructure reaching end of life.

TRIUMF engineers within the 520 MeV cyclotron

4.4 BEAMLINE 1A REFURBISHMENT

Beamline 1A provides beam to a significant fraction of the TRIUMF science and application portfolio. It delivers protons from the 520 MeV cyclotron with intensity range from few nano-Amperes to about 120 μA within an energy range of 180-500 MeV. Although it is the oldest proton beamline system on campus, beamline 1A has been highly productive due to the simultaneous parallel operation of several independent users sharing a single continuous wave proton beam.

The maximum beam intensity the beamline can provide for experiments is limited by the original beam optics design and by the aged and partially obsolete equipment employed.

This high energy proton beam is used to produce a number of rare and exotic isotopes that are finding their way into mainstream applications. This application leverages the unique 520 MeV facility at TRIUMF to produce and study known and novel alpha and beta-emitting isotopes with potential application in targeted radionuclide therapy. Research and application of these isotopes is currently limited by their scarce availability, with demand far outstripping global supply; however, TRIUMF's facility stands to dramatically change this situation. Using the 520 MeV cyclotron and beamline 1A, TRIUMF can irradiate thorium-232 metal targets, producing select actinide radioisotopes such as radium-225 and thorium-228, which are not only potential therapeutic radioisotopes themselves, but also serve as parent isotopes that naturally generate high-value products, including actinium-225, bismuth-212 and bismuth-213, and lead-212. All of these isotopes have noted applications as therapeutic beta and alpha emitters and currently maintain intense community interest.

In addition to medical isotope production, beamline 1A is essential to produce and provide muons as part of the only North American μSR facility for studies of quantum materials, critical chemistry for fundamental and applied questions, including energy production and storage for society, and probing of properties of magnetic materials for information processing and retention. This capability is a key component of the TRIUMF user program and supports about 1000 international and domestic academic users and researchers every year. The spectrometers connected to M15, M9a, M9A and M20 have been recently upgraded or are in the process of being upgraded with support from CFI, NSERC and TRIUMF on the level of $20M. The experimental program typically supports 50 experiments per year and a corresponding annual number of peer-reviewed publications. Beamline 1A is also supporting the radiation detector tests on M11, the PIF/NIF facilities, as well as the new ultracold neutron facility dedicated for neutron EDM experiments.

While a critical piece of infrastructure, the beamline increasingly experiences downtime and performance limitations due to ageing equipment and infrastructure, including a substantial failure risk due to water absorption in the concrete of the main pedestals. If either the beamline or its supporting infrastructure were to fail, the likelihood of an extended outage is very high. With a number of focused refurbishment activities, reliable beam operation can not only be restored, but performance can also be gained through tailored improvements to the experimental equipment and industrial applications. This refurbishment is costed at ~$20M, requested as part of maintaining our capacity for research.

TRIUMF's Meson Hall

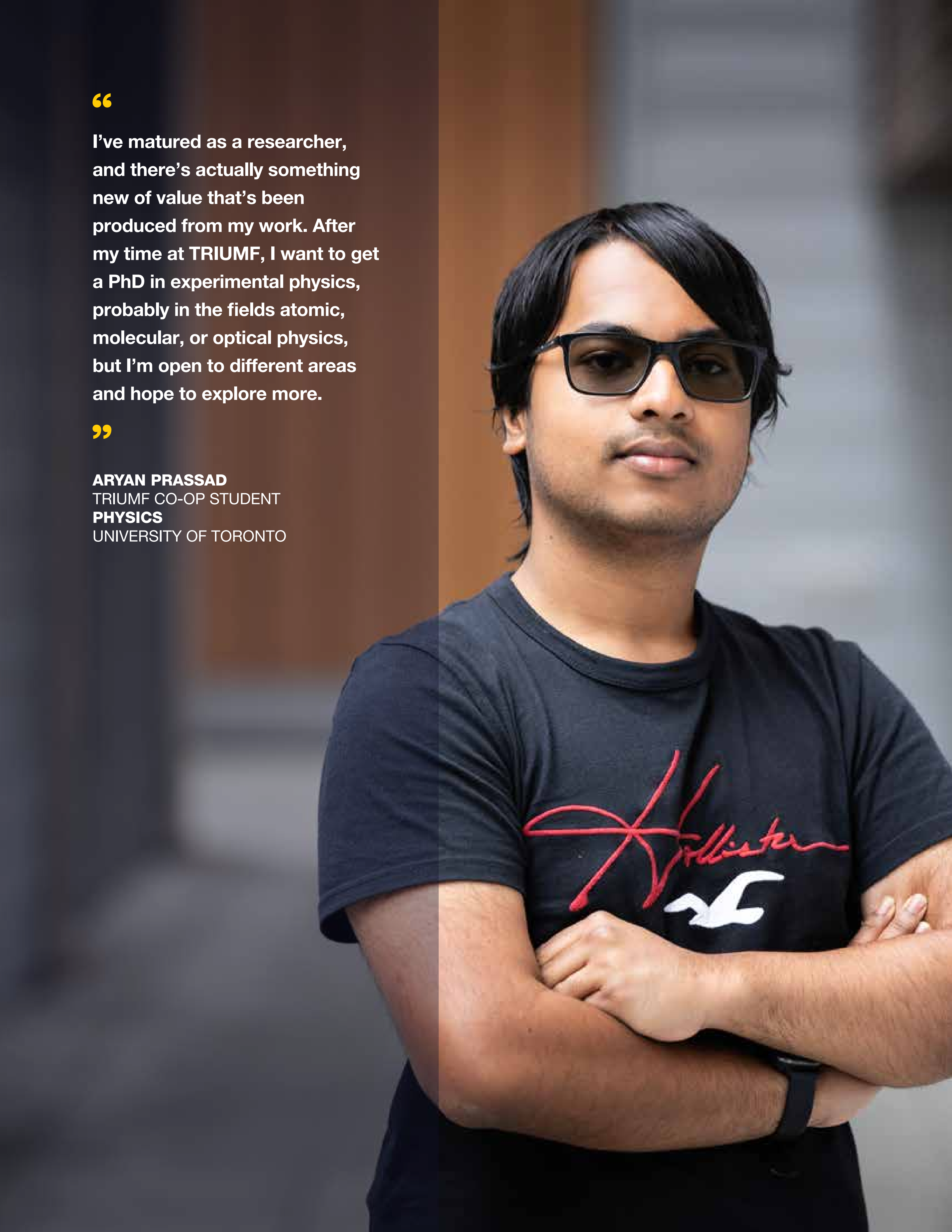
4.5 OPERATIONAL EXCELLENCE AND COMPLIANCE

TRIUMF is a high profile and very visible national asset, and as such is required to ensure operational excellence at all times, including regulatory compliance and adherence to stakeholder expectations.

These expectations have become more rigorous as cyber and research security requirements – compounded by geopolitical implications – have become more stringent. This has led to an increase in compliance and oversight obligations that have strained the laboratory's operational capacity.

TRIUMF has also been working to align to evolving and tightening requirements from the Canadian Nuclear Safety Commission, Engineers and Geoscientists British Columbia, and other regulatory bodies. This work is representative of the requirement for TRIUMF to further develop operational excellence across all systems, through ensuring enterprise services align with the needs and requirements of both external stakeholders and the laboratory itself. This includes the development of an integrated asset management system, which will improve efficiency of asset maintenance and facilitate compliance requirements for those assets.

The stated objective within the requested five-year budget is to support this capacity building within the enterprise services team, to maintain compliance against all requirements and ensure operational excellence.



> I've matured as a researcher, and there's actually something new of value that's been produced from my work. After my time at TRIUMF, I want to get a PhD in experimental physics, probably in the fields atomic, molecular, or optical physics, but I'm open to different areas and hope to explore more.

ARYAN PRASSAD
TRIUMF CO-OP STUDENT
PHYSICS
UNIVERSITY OF TORONTO

5.

DELIVERING RESEARCH AND IMPACT FOR CANADA

5.1 REALIZING TRIUMF'S SCIENTIFIC POTENTIAL THROUGH RESEARCH CENTRES

Over the next five years TRIUMF will take the first concerted steps towards achieving the goals set out in its 20-Year Vision. Resources will be directed towards reconfiguring existing program areas to better align with stated national objectives and priority areas. To facilitate the development of mission-focused research threads encapsulated within the 20-Year Vision, complementing our research infrastructure, TRIUMF is anticipating the creation of three centres to drive this work. These centres will primarily utilize existing resources, connecting across Divisions to ensure efficient delivery of the research threads, creating multidisciplinary teams seeding the development of future programs.

5.1.1 QUANTUM SENSING AND PRECISION PHYSICS

We recognize new and emerging opportunities for TRIUMF to engage in quantum sensing and precision physics research over the next decades. As a first step, we propose the establishment of a new centre to act as a "wedge" for initiating and spurring future developments. This Centre for Quantum Sensing and Precision Physics will be dedicated to the exploration of new directions in fundamental physics with quantum systems and will help develop new opportunities for applying quantum characterization techniques to new types of problems and questions. The Centre will build upon pre-existing research efforts on precision, atomic, molecular, and materials science at TRIUMF. It will leverage TRIUMF as a national laboratory that is uniquely placed in the Canadian research ecosystem to pursue and support large-scale research developments that are beyond the reach of a single university or institution.

The Centre will enable new capabilities in quantum sensing technologies for fundamental research and societal applications, as well as new flagship experiments (RadMol, HAICU, nEXO, PIONEER, etc.) by providing resources, project management support, and specialized expertise to drive this work forward. The Centre will also offer capabilities to seed new research, quickly developing new initiatives and making them ready to compete for external research funds, such as CFI or tri-council support. This program will also strengthen emerging efforts at TRIUMF to investigate functional materials of relevance in quantum information transfer. We will establish a Quantum Characterization Laboratory to enable multi-pronged material characterization capabilities targeted at sustainable research and quantum sensing and quantum material characterization for environmental applications. The Centre will also deliver added impact to TRIUMF's existing experimental programs using precision and quantum techniques, such as μSR,ßNMR, TUCAN, ALPHA, the Francium trapping facility, TRILIS, TITAN, and TRINAT.

5.1.2 AI FOR SCIENCE AND TECHNOLOGY

TRIUMF will strengthen its capabilities in and applications of data science, machine learning, and artificial intelligence (AI). TRIUMF exists at the nexus of science expertise, advanced technology deployment, and commercialization. TRIUMF's access to data from diverse streams – on-site nuclear physics experiments, accelerators, global "Big Science" efforts, and more – gives us a unique opportunity to advance scientific progress through the applications of new machine learning and artificial intelligence, but also enables the laboratory an opportunity to optimize the operation of its scientific complex by using such tools. By developing a new centre of expertise in this space, TRIUMF will position Canada at the forefront of applying these tools to realize new efficiencies in accelerator and accelerator-based research. This opportunity has been reaffirmed with the commissioning of TRIUMF's newest facilities (i.e., ARIEL and IAMI), as TRIUMF is well placed to take advantage of these new trends in science and technology for the benefit of Canadian research.

5.1.3 A DETECTOR DEVELOPMENT PLATFORM AT TRIUMF

We will also develop a focused commitment on enhancing detector development capabilities at TRIUMF to the benefit of our member institutions and our network in Canada and abroad. The proposal is to establish a Detector Development Platform that is complementary, but also has synergies with the existing Science and Technology department in the Physical Sciences Division. This new platform would have parallels to how IAMI operates next to the Life Science divisions.

The Detector Development Platform has several components that make it a unique addition to TRIUMF beyond the current Science and Technology department's current project-focused capabilities in world-class detector R&D. The platform is envisioned as enabling broad design and simulation capabilities, characterization, and substrate fabrication that currently do not exist at TRIUMF. This approach will build a critical mass of high-level detector expertise in Canada that will benefit TRIUMF's full array of programs, projects, and partners, strengthening opportunities for knowledge transfer and student training in these areas.

5.2 OUR FUTURE RESEARCH AND DEVELOPMENT PROGRAM

TRIUMF's extraordinary suite of experimental stations and the availability of extended measurement time with rare isotope beams courtesy of ARIEL will enable the pursuit of new range of major science questions. For instance, one area of focus planned for 2025 – 2030 is further study into how elements are produced in stars and extreme astrophysical environments, and subsequently spread across the Universe.

Direct measurements of astrophysical reaction rates will be made with DRAGON and TIGRESS-EMMA, and complementary measurements of reaction rates, masses, beta-decay half-lives, beta-delayed neutron branching ratios, and masses will be made with these devices and GRIFFIN, DESCANT, TUDA and TITAN. These measurements, combined with in-house modeling and ab initio nuclear theory initiatives, will pave the way for: (i) establishing the path of the intermediate neutron capture processes, resulting in a detailed understanding of the abundances of rare earth elements in our solar system; (ii) understanding how heavy chemical elements from iron to uranium are produced in the Universe by the rapid neutron capture process; (iii) understanding how light and medium-mass elements are synthesized in the Big Bang and in the stars.

Experiments with the same suite of experimental stations will allow TRIUMF nuclear physicists, in collaboration with the in-house ab initio nuclear theory team, to obtain a deeper understanding of the detailed nature of the nuclear forces and how atomic nuclei emerge from them. With new capabilities such as polarized beams at GRIFFIN station, and taking advantage of three simultaneous rare isotope beams, TRIUMF nuclear physicists will study exotic nuclei such as lithium-11 whose nuclear radius is as big as lead-208; the coexistence of spherical, deformed, and triaxial shapes across the nuclear chart (drawing parallels to recent work in A~100); the evolution of nuclear shells in isotopic chains with increasing imbalance between numbers of protons and neutrons; and the limits of nuclear stability in isotopes with extreme excesses of protons or neutrons.

The long run times of rare isotope beams enabled by ARIEL will also pave the way for sterile neutrino searches at TRIUMF. Sterile neutrinos are well motivated, natural extensions to the Standard Model that have the ideal characteristics to serve as a warm dark matter candidate. The recently launched BeEST (Beryllium Electron-capture with Superconducting Tunnel junctions) experiment conducts searches for sterile neutrinos in the keV mass range using the nuclear electron capture decay of beryllium-7 implanted into superconducting tunnel junction radiation detectors (STJs). The planned experimental program for the BeEST, which is scaled to multi-pixel STJ arrays with four orders of magnitude higher sensitivity than the current limits, will require months-long run times – a capability that will only become possible in the ARIEL era.

By 2030, TRIUMF's new flagship laboratory on radioactive molecules at ARIEL will be fully operational, hosting a series of unique precision experiments in search of new physics beyond the Standard Model. In the wider context of electric dipole moments (EDM), ultracold trapped ^{223}FrAg molecules will have provided the most stringent limit on Charge-Parity (CP)-violating phenomena inside the atomic nucleus. Moreover, radioactive molecules will have been exploited to measure nuclear anapole moments of (short-lived) radionuclides. We project an initial sensitivity to fundamental hadronic CP-violating parameters by factors of 1000 or more compared to the best present limits.

In the next five-year period, TRIUMF will be operating the highest intensity ultra-cold neutron (UCN) source in the world. This will enable a measurement of the neutron EDM with a 10-fold higher sensitivity compared to the best present limits, as well as world's most precise neutron lifetime measurement. The beta-decay lifetime of the free neutron is an important fundamental constant that plays a role in tests of the Standard Model of particle physics and big-bang nucleosynthesis; TRIUMF UCN measurement will resolve a long-standing discrepancy in the neutron lifetime determination.

By fielding two world-leading experiments exploring time-reversal and CP-violation, the neutron EDM and the ultra-cold trapped ^{223}FrAg radioactive molecules enabled by ARIEL, TRIUMF will be on the forefront of discoveries shedding light on the matter-antimatter asymmetry in the Universe, which is one of the greatest challenges in physics. If successful, these endeavours would represent Nobel-winning research.

Addressing similar physics questions, TRIUMF participates in and significantly contributes to the Hyper-Kamiokande (Hyper-K) experiment in Japan, which probes the CP symmetry violation in the neutrino oscillations. Hyper-K explores fundamental physics including neutrino oscillations, nucleon decay searches, dark matter searches and supernova neutrino detection. With a planned start date of 2027, Hyper-K will quickly accumulate accelerator neutrino data, and should surpass the sensitivity of currently operating experiments such as T2K and NOvA by 2030. Hyper-K will measure the level of CP-violation in neutrino mixing with a high accuracy by 2030.

Our unique capability to produce radioactive isotopes of Francium at ISAC/ARIEL will enable not only the RadMol ^{223}FrAg CP-violation measurement, but also probe the electron-quark weak neutral current strength to high accuracy, thereby enabling a competitive search for new physics beyond-the-Standard-Model (BSM).

Additional focus will be brought to bear on physics beyond the Standard Model by the TRIUMF's TRINAT experimental system. TRINAT will achieve a direct measurement of the electron neutrino helicity, to 0.5% accuracy, thereby enabling the measurement of a key Standard Model parameter, the Vud element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, in the beta-decay of the radioactive isotope potassium-37, at similar accuracy to the most accurate current measurement of 0+ to 0+ beta decays, but in a system with nonzero spin sensitive to other beyond-the-Standard-Model physics. Further, this will enable competitive search for time reversal breaking, isospin breaking, and beyond Standard Model parity-even interactions.

TRIUMF will also pursue new applications of the quantum sensing technology of superconducting tunnel junctions (STJs), via the SALER (The Superconducting Array for Low-Energy Radiation) experiment, with the purpose of investigating beyond Standard Model physics via Low-Energy Nuclear Recoils in cases of shorter-lived isotopes, where transport after implantation will not be feasible. While the initial commissioning work for SALER is foreseen to be performed at FRIB (Michigan), the experiment will be eventually moved to TRIUMF to study, e.g., the beta decay of carbon-11 with the goal to measure a key Standard Model parameter, Vud element of the CKM matrix. Following demonstration of experimental feasibility, the experimental concept of in-situ implantations into STJs will be extended to a range of cases with relevance for subatomic physics and astrophysics.

The quantum materials program at TRIUMF will take advantage of the refurbished M15 beamline and the newly commissioned M9A and M9H beamlines. The muSR will play an important role in identifying and understanding the effects of disorder on the exotic physical properties of quantum materials, leading to improved synthesis methods.

> “Most people would say that working at a particle accelerator is very niche, but being an engineer at TRIUMF means you get to tackle all sorts of problems, from the mundane to the ‘no one has ever done this before’. Being able to take on tasks across a broad range of subdisciplines is my favourite part of the job – and helping to expand the frontiers of science is pretty cool, too.”

NAGMA MATHUR
VACUUM MECHANICAL ENGINEER IN-TRAINING (EIT)
ACCELERATOR SYSTEMS

The muon probes will also be applied for sustainable materials and environments. These goals will be accomplished with the advent of the M9H beamline, the first muon decay channel with full transverse polarization spectroscopic functionality, and by the development of new ßNMR techniques that take advantage of sophisticated NMR type pulse sequences. For M9H, TRIUMF will pioneer the scope of muSR research by expanding the extreme pressure/temperature/magnet field parameter space available for the muon spectroscopy, applicable over the range of its quantum and sustainable material perspectives. For ßNMR, capabilities to selectively detect and measure the electronic environment of near-neighbour nuclei in complex interfaces will yield detailed information on these technologically important quantum structures.

TRIUMF particle physicists and accelerator scientists will mount DarkLight – a small, fixed-target experiment – at the ARIEL e-linac. The experiment will use measurements of electrons and positrons produced in the scattering of the electron beam from a thin foil to search for new light bosons (i.e., BSM particles). Because this measurement probes only leptonic couplings of such a new boson, it provides complementary data to similar searches in the same parameter space which depend in whole or in part on coupling to hadrons. As a secondary motivation for the experiment, the apparatus can also be used for measurements of Standard Model processes such as higher order corrections to scattering processes. The experiment is pursuing possible paths to increasing the e-linac energy, since the dark photon mass range accessible at the current energy provides limited scope for discovery.

The completion of IAMI brings with it powerful new tools in the form of a high-current 24 MeV cyclotron, and several radiochemistry labs with research and good manufacturing practices (GMP) laboratories to enable the future of TRIUMF's Life Sciences program. The repertoire of radioisotopes that can be produced on the TR24, coupled with those available from TRIUMF's other drivers, provides unmatched capabilities to produce known and new isotopes that can be used to advance the pillars of TRIUMF's Life Sciences research program. Through IAMI, TRIUMF will support the development of new technologies for advanced, high-power isotope production; and also pursue basic and applied radiochemistry transformations and novel radiopharmaceuticals – all while enabling translation into the commercial and clinical realms.

IAMI will enable discovery research to advance the concept of personalized medicine, which in turn will advance our understanding of disease at the molecular level, a capability enabled by tools such as molecular imaging and targeted radionuclide therapy (TRT). Molecular imaging has long been a part of TRIUMF's program, with decades-long work into a number of main-group and transition metal isotopes used for producing radiopharmaceuticals in single photon emission computed tomography (SPECT), and positron emission tomography (PET) studies of the brain and in cancer.

Beyond imaging, alpha-, beta- and Auger-emitting radioisotopes produced at TRIUMF can be used for TRT research, which involves the conjugation and injection of these particle-emitting isotopes as targeted biological vectors that deliver a selective and lethal dose to unwanted tissue. When applied to cancer, the short range and highly cytotoxic nature of alpha-, beta-, and Auger-particles provide a mechanism for destroying small, diffuse and post-operative residual tumours, while minimizing damage to surrounding healthy tissues. The strength of TRT lies in the diversity and adaptability of the available targeting molecules, including monoclonal antibodies, antibody fragments, nanoparticles, and small peptides and molecules. This diversity makes it possible to target an array of diseases by developing an optimal regimen for each application.

TRIUMF's high-intensity 520 MeV cyclotron is capable of large-scale production of numerous known and novel isotopes that hold therapeutic and theragnostic potential. Using thorium-232, TRIUMF produces more than 300 products during high-energy proton-induced spallation, and many are subject to intense global interest for use in certain applications. Isotopes such as terbium-149/155, astatine-211, bismuth-212/213, lead-212, radium-223/224/225, actinium-225, thorium-227 and uranium-230 can be made available via thorium spallation to support radiopharmaceutical development and emerging clinical trials.

Many other target materials potentiate the identification and further development of several promising radionuclides that can be incorporated into novel radiopharmaceuticals to treat late-stage, metastatic disease lacking current therapeutic options. Many of these isotopes are the focus of a New Frontiers in Research Fund Transformations six-year grant initiative in which more than a dozen Canadian institutions will utilize radioisotopes produced at TRIUMF to pursue numerous preclinical, and ultimately clinical trials for Canadians with currently untreatable disease.

5.3 CANADA AS AN INTERNATIONAL LEADER

With ARIEL coming online in 2026, Canada is ideally positioned to fill a void in the international landscape following CERN's planned shutdown from 2026 to 2029. If capitalized upon, TRIUMF will be able to step in and become the preeminent international facility for rare isotope beam research. This will propel TRIUMF into a key leadership position internationally by attracting leading-edge research and talent to the laboratory, and thereby elevating Canada's standing within the global "Big Science" ecosystem.

In addition to this, TRIUMF's expertise in accelerator science situates Canada in a position as a strong collaborator in advanced accelerator technology development. Our research excellence in superconducting radio frequency technology, theoretical and experimental aspects of accelerator beam physics, and secondary particle production techniques is essential in providing world-leading technologies, which in turn are leveraged to increase the performance and optimize the operation of our accelerator complex. This allows TRIUMF to add capabilities like ARIEL, but also to provide expert knowledge for international projects such as the High-Luminosity upgrade to the Large Hadron Collider (HL-LHC), the Brookhaven-based Electron-Ion Collider (EIC), and future flagship facilities for particle physics research such as the International Linear Collider (ILC) or the Future Circular Collider (FCC). Our expertise and status within the sector are recognized internationally; worldwide, several rare isotope facilities under construction have requested design and development specifications, expertise, or direct contributions from TRIUMF. Further, our innovations in beam physics research are leading a change in the paradigm of tuning accelerators, beamlines and high-power secondary particle production facilities in that we are employing beam physics models-assisted beam tuning and machine learning, improving availability of the beams for science, and maximising efficiency and use of resources.

This expertise in accelerator science and technology is also demonstrated by participation in the TESLA Technology Collaboration (TTC) for advanced superconducting accelerator structure, the RADIATE collaboration for exploration of high power targetry and accelerator materials and accelerator science collaborations with CERN, VECC in India and SCK-CEN in Belgium.

A key contribution by Canada in particle physics is to the ATLAS experiment at CERN LHC, in which TRIUMF particle physicists play a major active role, providing capabilities and infrastructure that underpin the national contribution. By 2030, the High-Luminosity phase of the LHC will be starting in earnest. The ATLAS data set will not only contain three times more events than it does today, but they will be higher quality due to the improved triggers and detectors made possible by the recent and ongoing upgrades (a new innermost layer in the inner detector, new muon detectors, and more granular and faster readout of the calorimeters). These contributions – coupled with better analysis techniques, including greater use of artificial intelligence – will dramatically increase researchers' understanding of the Higgs boson. Canada's commitment to ATLAS puts Canadian scientists at the forefront of this knowledge, with TRIUMF playing a critical ongoing role by supporting 10% of the global computing capacity for the project through operating the SFU-hosted Tier-1 computing centre.

TRIUMF particle physicists also play a major role in ALPHA, an international antimatter experiment located at CERN, including substantial collaboration leadership roles. The primary objective of ALPHA is to test fundamental symmetries between hydrogen and antihydrogen with the highest possible precision. Thanks to rapid developments in the past decade, the precision of antihydrogen measurements is approaching that of normal hydrogen. However, to make further progress, we will need to develop entirely new techniques – some of which will be pioneered at TRIUMF. HAICU is a new project at TRIUMF aimed at developing quantum sensing techniques applicable to antimatter. By 2030, we anticipate establishing novel techniques such as the anti-atomic fountain, and conducting initial measurements using them.

Strengthening the Canadian contribution substantially, TRIUMF scientists joined the international nEXO collaboration led by the US Lawrence Livermore National Laboratory. The experiment will conduct a search for the neutrinoless double-beta decay in 5 tons of xenon-136 isotope with a beyond 1028-year half-life sensitivity. The experiment will be located 2 km underground at SNOLAB in Ontario. Currently, there are two Canadian CFI projects funded supporting the nEXO research. TRIUMF leads the development of the Silicon Photo-Multipliers (SiPMs) with the goal of delivering all SiPMs for nEXO by 2030, when the experiment will start taking data. In addition, TRIUMF-led ab initio nuclear theory is applied to compute nuclear matrix elements required for the analysis. The TRIUMF Executive Director is playing a leading role in coordinating national funding agencies between North America and Europe to deliver an international program in this area.

5.4 DEVELOPING THE LEADERS AND HIGHLY QUALIFIED PEOPLE OF TOMORROW

As a unique and major international accelerator centre, TRIUMF provides a compelling and attractive venue to undertake research and develop knowledge. The infrastructure and science programs outlined above provides an illustration of the world-class research that TRIUMF will enable and deliver during the five years between 2025 and 2030. As an attractor, TRIUMF brings together technical, professional, and scientific proponents, ensuring a thriving and stimulating learning environment. The value of TRIUMF as a centre of learning for the university sector is illustrated through the growth of our membership, and additional expressions of interest.

As an attractor for highly qualified people, TRIUMF runs a competitive undergraduate co-op student training program, which is currently substantially overcommitted. Through the support and growth of our research community, we develop highly qualified people who have broad skills that are transferrable to many areas of industry and society. These include critical thinking and analytical skills, collaborative and team engagement skills, presentation, and communication, as well as the technical and creative capabilities inherent in undertaking world-class science. These skills are developed directly through working in multi-skilled groups, but also through direct training, workshops, and schools. These highly qualified individuals become the leaders of tomorrow.

Many of the TRIUMF research staff are connected to university departments. We also support temporary joint appointments directly with universities to strengthen research connections between our community and TRIUMF. As such, TRIUMF staff engage in teaching and course development, including undergraduate and graduate courses, and seminar/colloquia. Through these connections we ensure close ties with the research community and enhance the university capabilities around highly qualified personnel (HQP) development.

The technical requirements of many of the experimental and commercial programs envisaged over the next five-year period require expert technical and engineering support. The stringent requirements of these systems ensure our technical teams are challenged and constantly learning new techniques and capabilities which enhance the technical skill base at TRIUMF, and in many cases provide a pipeline to other opportunities within the local and national areas. TRIUMF contributes directly to the knowledge economy through this training and development.

A continued commitment at TRIUMF is to ensure we support a respectful work environment and fully support the development of equity, diversity, and inclusion (EDI). TRIUMF already has an EDI Committee and EDI Officer, and through the development of an action plan that has near, medium, and long-term objectives, we strive to ensure TRIUMF reflects the full breadth of Canadian culture and maintains a supportive environment for all. As a key value for the organization, this work will continue through iteration of a rolling action plan, incorporating best practice and committing continued investment into this critical area.

Researchers working on TRIUMF's GRIFFIN experiment

6.

PROJECTED OUTCOMES: REALIZING CANADA'S FULL POTENTIAL

This funding request comes at a critical time for TRIUMF. We are committing to delivering exceptional science and infrastructure within our next 5-year funding period, with the understanding that we must ensure our 55-year-old facility continues to be a stalwart in Canada's research landscape.

This request for operational support, centred on delivering new infrastructure, ensuring operational excellence, training the diverse talent needed for tomorrow, refurbishing our legacy facility, and evolving our work to align to national priorities, will allow TRIUMF to succeed into the future – and with it, allow Canada to show the world we remain at the highest tier of the international scientific community. This request also closely aligns with a number of major national priorities, including the attraction, development, and retention of talent, providing space for small businesses to scale up to market, and providing needed resilience in the health-care sector.

6.1 SUPPORTING TRIUMF'S MISSION

TRIUMF is at a critical juncture in its lifecycle as a major laboratory, with the outcome of this request for support dramatically altering the organization's trajectory. Canada must evaluate its commitment to the organization's mission and consider the nation's desire to compete at the highest levels of global science and research.

To this end, TRIUMF's request for support for the next 5-year period (2025 – 2030) sets out a viable plan to deliver on the laboratory's potential as a world-class major research facility. This ambition aligns with TRIUMF's existing mission and vision, complements many aspects of the organization's current logic model, and supports key national priorities. The consistency between the existing model and this proposal is illustrative of TRIUMF's enduring commitment to delivering science and research excellence for the benefit of Canada.

This 2025–2030 5-Year Request for Support request reaffirms this approach, requesting a realistic level of funding to deliver on themes and objectives outlined in this document.

6.2 ANTICIPATED RESULTS AND DELIVERABLES

Supporting and evolving from the existing logic model, this request for operational support will deliver outcomes and outputs over the five-year period which support the themes outlined above. These include, but are not limited to:

OUTCOME	OUTPUTS
Increased knowledge production and scientific capacity	▪ Increased output of academic publications ▪ Increased research impact ▪ Increase in high-profile awards to Canadian researchers
Strengthened STEM talent pipeline	▪ Increased training opportunities for Highly Qualified Personnel (HQP) ▪ Increased representation and training opportunities for under-represented communities in STEM ▪ Increased capacity to educate and train at the K-12 levels
Increased socio-economic benefit and resiliency	▪ Increased economic impact (direct, indirect & induced) ▪ Increase in the number of industrial partnerships, spin-off companies, and licencing arrangements ▪ Increase in the number of new technologies and medical therapies enabled by TRIUMF research ▪ Increased capacity to support national resiliency and mission-driven research

Increased effectiveness and efficiency	▪ Class-leading operational excellence and regulatory compliance ▪ Enhanced site reliability and efficiency ▪ Reduced risk of unplanned shutdown events or infrastructure failures
Enhanced international reputation and profile	▪ Increased opportunities for Canadian researchers to engage in and lead major international projects ▪ Increased global profile for Canadian science and researchers ▪ Increase in the attraction and retention of top international talent

Many of these outcomes and outputs, and more, will be refined upon the confirmation of the level of TRIUMF's operational funding, with performance targets to be set out in the subsequent Contribution Agreement.

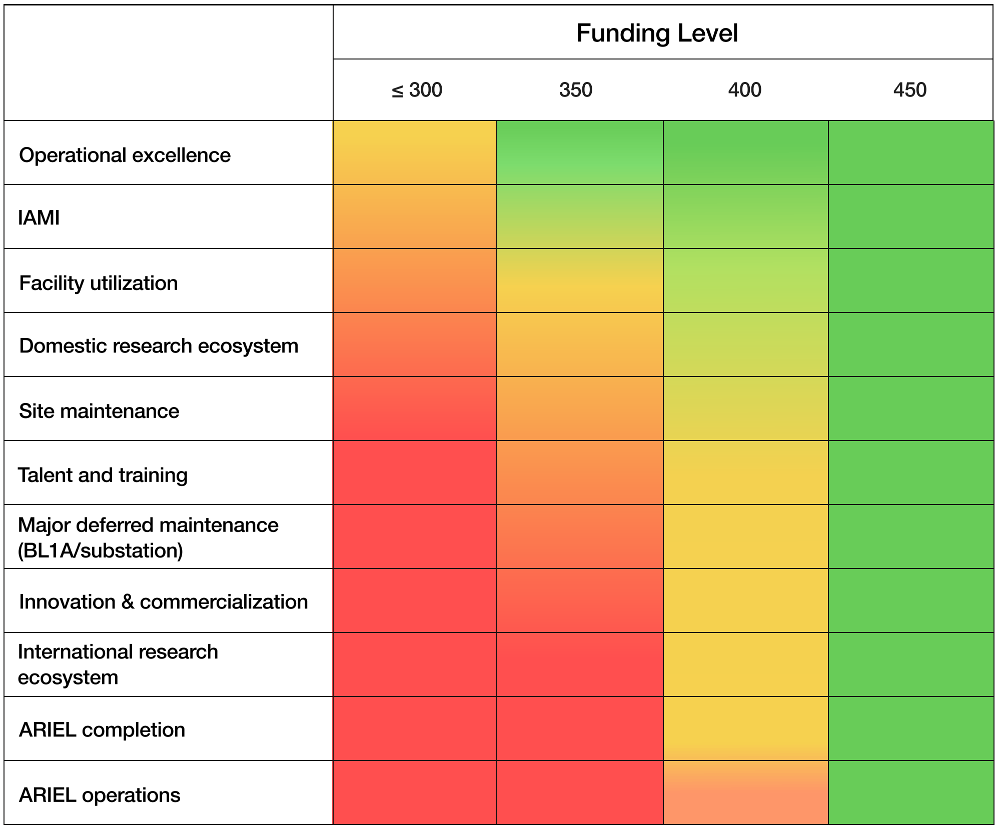
6.3 OVERVIEW OF THE CONSEQUENCES OF REDUCED FUNDING

Over the last two decades, TRIUMF's operational funding has consistently fallen below requested levels. These shortfalls, combined with the increasing operational pressures – due to new infrastructure, deferred maintenance, regulatory requirements – have had the impact of limiting the laboratory's flexibility moving forward.

As outlined in this request for operational support, funding at the requested level will allow TRIUMF to consolidate its infrastructure and scientific capacity, putting it to work for Canadians – not only now, but for decades to come. In contrast, reduced support will necessitate a significant narrowing of scope that will undermine the investments that have been made over decades and compromise Canada's ability to scientifically compete at a global level. Projected scenarios at reduced funding levels include:

Loss of opportunity ($400M)	▪ ARIEL construction is slowed and operations of ARIEL and IAMI are delayed, resulting in the loss of first-mover advantage against international competition in key research and technology areas ▪ Increased risk of infrastructure failure due to reduced investment in deferred maintenance ▪ Decreased science output with internal resources and staff reorganized to fill operational requirements
Loss of capability and science ($350M)	▪ Loss of science capacity and departure of talent from Canada ▪ Diminished capacity to support and develop talent and HQP ▪ Reduced scope to support existing on-site infrastructure; withdrawal from most international programs ▪ Deferred completion and operations of ARIEL, resulting in the loss of first-mover advantage against international competition in key research and technology areas ▪ Increased risk of infrastructure failure due to reduced investment in deferred maintenance
Dismantling of research programs & transition to a user-only facility (≤$300M)	▪ Curtailment of most talent development and HQP training efforts ▪ High risk of infrastructure failure due to limited investment in deferred maintenance ▪ Work on ARIEL is halted and deferred to beyond 2030; all efforts shift to running existing infrastructure for external users only ▪ Limited internal capacity to undertake science, research and innovation beyond maintenance and user support

Figure 4: *Heat map visualizing various funding-level scenarios, including those of reduced funding from the $450M ask over five years. The impact on key areas of the program is demonstrated through a colour coding, running from green to red to illustrate the anticipated level of delivery possible.*



The consequence of each scenario, including the requested funding level, can be visualized through a heat map, as shown in Figure 4. As evidenced above, $450M is the level at which TRIUMF is best positioned to deliver benefit to Canada across all program areas. In summary, a funding outcome lower than the requested level would trigger the need to pull back on internal science programs in order to responsibly operate and steward existing laboratory infrastructure.

To unleash TRIUMF's potential and capitalize on the decades of investment, the full request is necessary to move the laboratory towards achieving its mission, enabling Canada to lead in science, discovery, and innovation, to improve lives and build a better world.

Underpinning the delivery of all that we do is the core vision and mission of the facility, coupled to the values that we embrace in our work.

OUR VISION

Our vision is for Canada to lead in science, discovery, and innovation, to improve lives and build a better world.

OUR MISSION

TRIUMF's mission is to serve as Canada's particle accelerator centre. We advance isotope science and technology, both fundamental and applied. We collaborate across communities and disciplines, from nuclear and particle physics to the life and material sciences. We discover and innovate, inspire and educate, creating knowledge and opportunity for all.

OUR VALUES

Excellence & Integrity

- We have a passion for excellence in all that we do.
- We are decisive, bold, courageous, and compassionate.
- We take responsibility for our actions, our commitments, and our contributions to the larger community.

Equity & Inclusion

- We empower our workforce and foster an inclusive work environment, enriching our science and our community.
- We value teamwork and open communication to ensure that everyone belongs and all voices are heard.
- We respect each other, take care of each other, and support the success of all.

Safety & Accountability

- We respect the health and safety of our workers, our visitors, and our neighbours.
- We build quality into our processes and seek continual improvement in all of our systems.
- We embrace transparency and authenticity, and hold ourselves and each other accountable.

TRIUMF

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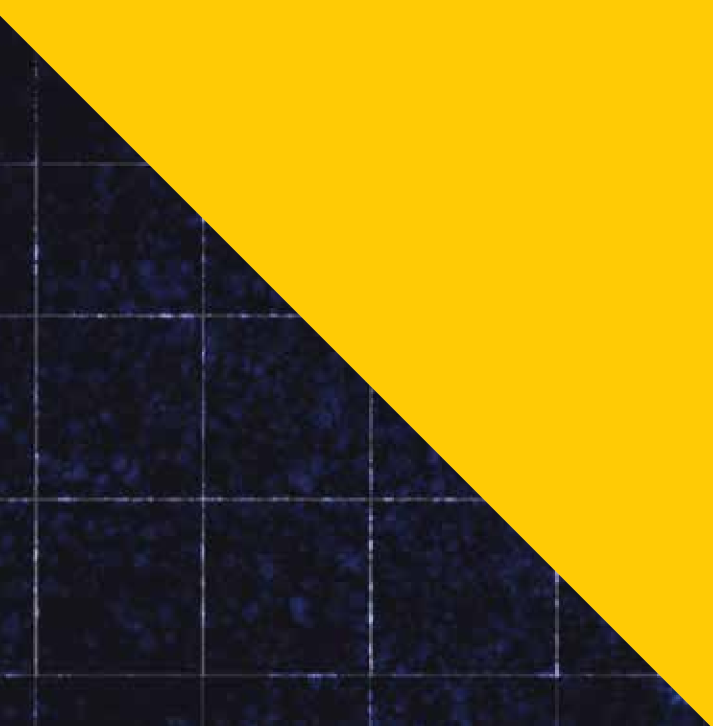

Discovery,
accelerated