TRIUMF

20-YEAR VISON - SUMMARY OF RESPONSES BY 12 TOPICAL GROUPS

This document is the collection of the responses by the12 Topical Groups that were set up as part of the TRIUMF 20-Year to contemplate and respond to a set of guiding questions. The responses are a result of various levels of engagement with the community through ideation platforms, questionnaires, workshops, and building on other community efforts.

August 2021

TRIUMF

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Discovery, accelerated

TRIUMF

Particle Physics

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The Particle Physics Topical Group engaged with the community and solicited feedback through multiple channels. These included input through the ThoughtExchange platform, a dedicated survey concentrating on Particle Physics questions, direct discussion with particle physicists at TRIUMF, and interviews with key community members including Joanne Hewett (SLAC chief research officer), Young Kee-Kim (U Chicago, chair of Snowmass process), Klaus Kirch (PSI head of particle physics section), Arthur McDonald (Nobel Laureate, Queen's U), Robert Myers (Perimeter Director), Tony Noble (Queen's U and Director McDonald Institute), Adam Ritz (UVic, IPP and LRP chair), Michael Roney (UVic and IPP Director), and Brigitte Vachon (McGill and Canadian Representative for European Particle Physics Strategy, LRP chair). This report reflects the input received through these various channels.

WHAT IS TRIUMF TODAY? WHAT ARE ITS KEY ADVANTAGES FOR THE FUTURE?

TRIUMF is a leading international science laboratory and a central hub for Canada in subatomic physics. It has achieved and maintains this status by:

- Focusing strongly on knowledge-driven fundamental research.
- Driving new discoveries in particle physics experiment and theory.
- Inspiring and training the next generation of intellectual leaders through its unique student programs and its collaboration with Canadian member universities and international partners.
- Enabling Canadian participation in international collaborations through scientific advances and leadership, technical support, advanced computing, and direct in-kind contributions to accelerator and detector components.
- Providing accelerators, facilities, and technical expertise to the Canadian community beyond the scope of what any single university can support.
- Using this infrastructure to host experiments and theory programs on site.
- Applying these discoveries to societal challenges.

TRIUMF has many distinct advantages that will enable its continued leadership:

- TRIUMF has developed unique and specialized expertise in scientific and technical areas that will be essential to future research projects.
- The lab occupies a unique position in the Canadian physics community through its relationships and collaborations with its member universities.

- TRIUMF plays a key role in many international collaborations and has close ties with other subatomic physics laboratories.
- TRIUMF's mid-sized structure and relatively flat management hierarchy allows it to respond quickly to new research directions and supports a high-level of cross-fertilization across disciplines, while also being large enough to act as a Canadian hub in international projects.
- Close working relationships between scientists, engineers, and technicians on staff at TRIUMF permit advances in detector development, electronics, data acquisition, precision assembly, scientific computing, and data science without much bureaucratic overhead.
- Expertise in accelerator physics and related technologies enables both in-kind contributions to international projects as well as world-leading contributions to particle and nuclear experiments and the local life science program.
- Relationships with member universities and other national laboratories together with local expertise and facilities allow TRIUMF to provide unique student and postdoctoral researcher development programs and to run international summer schools such as the TRIUMF Summer Institute, GRIDS, and TRISEP.

WHAT TRENDS AND CHANGES WILL SHAPE TRIUMF'S FUTURE?

- New discoveries in fundamental physics will guide future research directions.
- Participation in future particle colliders at the energy frontier will be subject to global decisions on which machines to pursue since the size and cost of these machines requires international collaboration. TRIUMF's experience in collider physics puts it in an excellent position to lead the Canadian contributions to any such future collider.
- Global decisions on future dark matter and neutrino experiments, and which of these projects are to be located in Canada, will impact research directions at TRIUMF.
- Advances in machine learning and quantum computing methods will lead to enhanced sensitivity in experimental analysis techniques, improved theoretical calculations, and provide new opportunities for HQP training and connections beyond academia.
- New techniques in quantum sensing and atomic measurement together with ARIEL will provide opportunities to expand the on-site program in particle physics.
- Increased understanding of equity, diversity, and inclusion will lead to a better working environment and a TRIUMF that is more representative of the people of Canada.
- Lessons learned from the pandemic will enable better off-site collaboration and international collaboration and may permit infrastructure and organizational changes.

- The Naylor Report promotes investigator-led research, training support, and facilities support, and may help TRIUMF increase its level of base funding.
- TRIUMF will be influenced by external factors, but it is ultimately up to the lab and its community to chart its future course. New trends should be examined critically to ensure that they provide increased scientific opportunities.

WHAT WILL TRIUMF BE? WHAT ROLE WILL IT HAVE IN CANADA'S S&T ECOSYSTEM?

- TRIUMF will be a site hosting research, technical, experimental and user facilities, as well as being a national hub for fundamental and accelerator-based science.
- Growing and nurturing long-term expertise in these fields is difficult for universities and TRIUMF can be a national resource by creating dedicated centers which will develop a strong on-site research and development programme that can support a long-term vision and be flexible enough to develop new expertise in an evolving environment.
- We consider establishing the following R&D centres in their own right
    - A detector development center - broad with a focus on future technologies
    - An accelerator platform - broad research program for future technologies
    - A general computing facility - managed on-site for high-level computing needs across Canada
- Strong R&D centers are necessary to support fundamental research on-site, to support Canadian universities needs and to allow Canadian participation in large international projects. Strong general R&D centers would also "naturally" foster enhanced technology transfer and provide larger immediate societal impact.
- TRIUMF will deepen connections with its member universities through joint faculty, engineering and technical positions as well as a flourishing student program.
- A transparent and well-defined process will allow member universities and users gain access to these expanded capabilities by defining quotas for external requests to be able to fulfill the universities' needs fairly while having secured resources for pursuing the laboratory fundamental science programme. It will enable TRIUMF to have the resources and scale to imagine and develop the "next big thing" for Canada.

WHAT WILL TRIUMF HAVE ACCOMPLISHED?

- TRIUMF will have played a key role in the international energy frontier program through major analysis, hardware and operations contributions to the HL-LHC, and will be leading the Canadian scientific and accelerator efforts for the next future collider.

- TRIUMF will have led new discoveries in neutrino physics through measurements of neutrino CP violation at HyperK, tests of neutrinoless beta decay with nEXO, and measurements of astrophysical neutrinos with P-ONE.
- TRIUMF will have pioneered new precision techniques allowing for unprecedented measurements of antimatter at ALPHA and beyond, world-leading tests of the neutron electric dipole moment and lifetime with the UCN facility.
- TRIUMF will have made essential detector and analysis contributions to the search for dark matter at SNOLAB through SuperCDMS, SBC, and DEAP, and will have developed new detector technology needed to test sub-GeV dark matter as well as enable the large scale high-mass ARGO detector.
- TRIUMF will have developed new on-site particle physics experiments based on TRIUMF beams such as PIENUX, DarkLight at ARIEL and its extensions, as well as searches for new ultra-light fundamental phenomena using atomic methods.
- TRIUMF will be a premier destination for the education and training of Canadian and international particle physicists. The vibrant local environment, with experts in conversation across a variety of fields and expertise, in experiment and in theory, will be a unique environment to host workshops, conferences and meetings.
- People trained at TRIUMF will have moved throughout Canada and the world and will be leaders of the next generation of scientists and innovators.
- TRIUMF will develop programs to support its members, such as accessible housing, transportation, and daycare, allowing it to attract a diverse group of highly talented individuals that will lead the lab into the future.
- TRIUMF will inspire Canadians from all walks of life by demonstrating that science is for everyone through a vibrant outreach program.

WHAT WILL TRIUMF BE DOING? WHAT WILL IT NOT BE DOING?

- It is essential that TRIUMF continue to focus on knowledge driven scientific research with particle physics as one of its central pillars. This research is the foundation on which the rest of the laboratories activities in science and innovation are built on and one of the highest priorities of our member universities for what TRIUMF should do.
- Future progress in many areas of particle physics will rely on new developments in detector and accelerator technology. TRIUMF has important resources and experience in these fields and should expand its capabilities further.
- The activities of TRIUMF in particle physics should be driven by the pursuit of answering the big open questions in our field. This means continuing our strong pursuit in

international collaborations but also expanding our local program in particle physics. TRIUMF should be both bold and flexible and ready to adapt its program in the event of a major new discovery and emerging new research directions.

- International programs:
  - TRIUMF's involvement at the LHC will transition to a new energy-frontier collider such as the International Linear or a Future Circular Collider.
  - The current involvement on T2K will transition to HyperK and beyond.
  - Precision and intensity-based experiments such as ALPHA and NA62 will evolve into new programs at CERN and elsewhere.
  - TRIUMF will continue to support these programs with local infrastructure through detector and accelerator development and construction as well as advances in theoretical, analysis, and computational methods.

- National programs:
  - Dark matter searches at SNOLAB such as SuperCDMS and DEAP will wrap up, and TRIUMF will continue on new experiments searching for low mass dark matter with novel detector technologies as well as higher masses with ARGO.
  - Searches for neutrinoless double beta decay will continue at SNOLAB supported by TRIUMF scientific leadership and technical contributions.
  - TRIUMF will continue to collaborate with the Perimeter Institute and SNOLAB on scientific programs and exchanges as well as on the training of HQP.
  - Detector R&D at TRIUMF will create new tools for discovery.
  - Accelerator research and development at TRIUMF will be essential to future research at the energy and intensity frontiers.

- Local programs:
  - TRIUMF will expand its local particle physics program.
  - In the near/intermediate term, TRIUMF will develop and support a UCN user facility and explore new programs such as DarkLight at ARIEL, PIENUX, and P-ONE.
  - Over the longer term, the lab could expand into a range of quantum sensing experiments such as atomic interferometry (example Fermilabs MAGIS), the use of cavities to detect dark matter (example UW's ADMX), and other possibilities studied in the Developing New Directions program that could include non-accelerator-based approaches if the science case is strong and supported by the community. A successful example of a laboratory expansion in this direction is the DESY Dark Sector program (ALPS, IAXO, MADMAX).

- TRIUMF will continue and expand its training of HQP by making full use of the unique facilities and connections that have developed from its scientific pursuits.
- TRIUMF will expand its engagement activities and share its scientific pursuits with Canada and the world:
    - Research that seeks to uncover and understand the fundamental building blocks of the universe is extremely appealing to the general public because of its potential to answer deep questions about the ultimate nature of the cosmos and reality, as well as the cutting-edge technology required by this work.
    - Research projects that take place in Canada are particularly enticing to Canadians for their potential to answer big questions right in our own backyard.
    - The Perimeter Institute has done an excellent job at connecting with the general public through its promotion and outreach based on its fundamental (theoretical) research. TRIUMF should expand its collaboration with Science World and other science museums in the country.

WHAT WILL TRIUMF LOOK LIKE? WILL THERE BE MORE THAN ONE SITE? WHAT WILL ITS ORGANIZATION AND COMMUNITY LOOK LIKE?

- TRIUMF needs to modernize its campus and use its limited space more efficiently
    - Larger, modern multi-story buildings will alleviate laboratory, office and meeting space crunch and provide a stimulating and creative research environment with engaging meeting and outreach components
    - TRIUMF can evolve into a facility with national laboratory status, removing the classification as a “sunset lab” with a limited timeline. The national facilities that can be hosted by TRIUMF include a detector development center, an accelerator platform for research and beam delivery (including beams for medical radiation therapy) and a national computing and data science center.
- Additionally, a new site would allow further expansion and if it were in the Eastern part of Canada this would alleviate the perception that TRIUMF is a Western-only laboratory. This new site could be located at a university in Eastern Canada with traditional large infrastructure capabilities.
- A possible scenario that could be an outcome of a carefully evaluated restructuring of Big Science in Canada could see SNOLAB and TRIUMF joining together.
- Establishing a joint venture between TRIUMF and SNOLAB could provide two centers for large experimental facilities in Canada and would strengthen collaborations and transfer of expertise between Canadian universities. It would allow pooling resources and administration and provide a common vision for experimental physics in Canada.

    - The two centers of particle physics research would however have different foci based on their historical set of expertise:
        - EAST: can host a dark matter-neutrino / quantum valley
        - WEST: can host a fundamental science / isotope valley
    - This would fundamentally broaden the mandate of TRIUMF as a national lab.
- TRIUMF will have a more diverse community of staff, users, and visitors that reflects the country and be an EDI champion through the establishment of concrete measures to foster diversity in the lab and publicly advocating for a diverse workforce
- Having established at TRIUMF an internationally renowned workshop and conference program will make it a global focal point for discussion and reflection of the field.
- An expanded academic program with online courses and summer schools on specialized topics will enhance the training of students in Canada and abroad.

TRIUMF

Nuclear Physics

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WHAT IS TRIUMF TODAY?

TRIUMF is Canada's particle accelerator centre, and the ISAC facility is only rare-isotope facility in North America that uses the ISOL (isotope-separation online) technique for the production of radioactive nuclei. It is seen as the "little sister" of the far more senior CERN-ISOLDE facility but is still able to compete (and excel) in many science programs with them, despite the much smaller research community and lower funding level. The research at ISAC is exploring the precision frontier and performs pioneering experiments in many fields. It is fully complementary to the new US$765M "Facility for Rare Isotope Beams" (FRIB) in the USA that will start in 2022.

The present nuclear physics program at TRIUMF has been developed over the last 20 years around the experimental capabilities of the ISAC facility and has established a world-leading Multi-Messenger Nuclear Physics Laboratory with state-of-the-art detector setups. The science program today is limited to isotopes produced via protons delivered by the 520 MeV cyclotron impinging on various target materials and is contingent on the subsequent beam purification steps.

The experimental and theoretical nuclear physics program is guided by the big science questions in Fundamental Symmetries, Nuclear Astrophysics, and Nuclear Structure, as taken from the recent Report by the Canadian Institute of Nuclear Physics (CINP):

- How does the structure of nuclei emerge from nuclear forces?
- What is the role of radioactive nuclei in shaping the visible matter in the universe?
- What physics lies beyond the Standard Model?

The experimental program at ISAC provides the foundation of the Canadian Nuclear Physics Community from which many new ideas have been conceived. The experimental program at ISAC is fully user-driven and provides 3000h of beamtime for more than 300 external users every year. 80% of this time is dedicated to nuclear physics experiments alone with one of the 13 available permanent setups.

The on-site experimental program is complemented by targeted offshore experiments at international radioactive beam facilities, for example in Japan (RIKEN), Germany (GSI/FAIR), and the USA (FRIB).

The in-house nuclear theory program has established itself as a hub specializing in state-of-the-art “ab- initio” (or first principles) description of nuclei across all mass regions. Rapid progress on these theoretical methods in the last several years has now expanded the reach of converged calculations to systems in the vicinity of medium-heavy nuclei, for example around doubly-magic ^{132}Sn. Heavier nuclei like ^{208}Pb are well within reach in the next years. For the lightest nuclei, quasi-exact methods have been developed that could be stringently tested by experimental data taken at the ISAC facility.

A recent hire in theoretical nuclear astrophysics has allowed to build a better connection to part of the inhouse nuclear astrophysics program which is focussed on the creation of elements heavier than iron.

This hire also brings in a stronger tie to the JINA-CEE (Joint Institute for Nuclear Astrophysics-Center for the Evolution of Elements, or its successor) in the USA.

In the past two decades the Nuclear Physics program at TRIUMF has been steadily growing. Unfortunately, the availability of desk space for students, postdocs, and external users has led to a stagnation and reached a point of saturation before the pandemic. Hiring of new students (especially CoOp undergraduates) was in the past years mainly limited by space, not by availability of projects. Due to these space constraints, external users that came to TRIUMF to carry out experiments or collaborate had to use and share the few spare desks in the counting rooms which sometimes led to overcrowding and distraction of ongoing experiments. This situation did not leave much space for further expansion of the Nuclear Physics program or encourage visiting scientists. For example, at RIKEN Nishina Center, every external user gets a desk assigned for their whole stay in a dedicated user area with about 30 cubicles, a printer, and lockers.

The pandemic has intensified the use of videoconferencing and remote work tools. Remote participating in experiments for external users is now possible to some extent although a large number of onsite staff is still required for day-to-day work like detector maintenance, cryogenics handling, preparation and setup of experiments, sample changes, calibrations, etc. The hybrid work model (some people on-site on shift, local experts on call, remote participants available for dedicated online monitoring and data analysis tasks) has proven to work well for nuclear physics experiments. Videoconferencing has been shown to be useful tool for participation in exciting external seminars, workshops, and Expert Evaluation Committees (NP- EEC) but the time

difference to Vancouver makes the long-time attendance from time zones with more than 6h time difference extremely challenging.

Common research projects at different RIB facilities could benefit from a better exchange of ideas and scientists. Possible topics/projects for closer collaboration and new MoUs with other facilities could be, e.g., recoil separators and underground accelerator facilities (for nuclear astrophysics reactions); multi- reflection time-of-flight systems (for mass measurements and beam purifications; existing MoU with KEK, exchange halted by pandemic); storage rings and neutron targets (collaboration with Los Alamos, FRIB, GSI started; initial workshop in June 2021); gamma-ray spectrometers; etc.

The present public outreach program is focussed on “catchy” topics around particle physics, like Black Holes, Dark Matter, Antiprotons, Quantum Computer etc. Unfortunately, these topics mirror only a fraction of the onsite research and reach only a small number of high school students since they are hard to visualize with table-top experiments in schools. Nuclear Physics - although more present in our daily lives - is commonly associated primarily with negative concepts (e.g. bombs, radioactive waste, contamination) and this disincentivizes it as an outreach topic. The words “radioactivity” and “nuclear” trigger negative emotions (due to Chernobyl and Fukushima) and are avoided as much as possible in the general public and at schools - for example by using the terms “rare beams” instead of “radioactive beams” or “atomic energy” instead of “nuclear energy”. Our goal for the next years should be to change the public perception of nuclear physics topics.

WHAT TRENDS AND CHANGES WILL SHAPE TRIUMF’S FUTURE?

At the two new large in-flight fragmentation rare-isotope facilities, FRIB in the USA and GSI/FAIR in Germany, the competition for beamtime will be very strong, and time span between experiment proposal and execution will be several years on average. However, these experiments will push the limits of our nuclear landscape to the extreme isospin frontier (the neutron- and proton driplines) and will lead to the discovery of hundreds of new exotic isotopes.

In contrast, the ISAC+ARIEL program will focus on the precision frontier and carry out new pioneering experiments thanks to longer beamtimes, which allow different classes of experiments to take place. The availability of multiple beams in parallel will allow more beam developments and make beam delivery more reliable. The average time span between proposal and running an experiment at ISAC could be pushed on average to less than a year. This will enhance the user experience and allow for fast response to exciting new topics in nuclear physics that are within the scope of the facility.

Partial remote participation in experiments and automatization of processes will allow the onsite staff to focus new tasks in the ARIEL era. This is crucial since TRIUMF's new flagship facility will within a decade triple the amount of beamtime delivered to users, up to 9000h per year. The ARIEL facility holds the promise of world-class, transformative research in five major, interlinked research areas of strategic priority for Canadian scientists, both for fundamental and applied research:

- Elucidating our fundamental understanding of nuclei,
- Searching for new forces in nature,
- Determining how the heavy elements were produced in the universe,
- Probing magnetism at interfaces and surfaces of new materials, and
- Advancing the molecular imaging of biological systems and the treatment of diseases.

This means the TRIUMF campus will see an increase of external users working onsite at several experiments at the same time, further increasing the demand for temporary working space. Future post- pandemic remote work options will ease the space problem only a bit but will not be able to solve it completely. The Nuclear Physics Program at TRIUMF is expected to grow in the next years by addition of new staff scientists and experimental setups. This will lead to an increased demand of desk and lab space. Every employee and student working full-time at TRIUMF should have their own desk space to allow them to work at TRIUMF anytime, creating a comfort zone and help to identify with TRIUMF as inclusive workplace.

Rapid developments in Nuclear Theory and potentially the advent of quantum computing will push the reach of ab-initio calculations to the most extreme regions of the nuclear chart, ultimately allowing for the creation of a unified approach to treat both structure and reactions for all nuclei.

After the end of the pandemic, climate change will again become the most pressing global issue. TRIUMF will need to ramp up its efforts on several topics that will help to contribute to reduce CO2 emissions to slow and hopefully reverse global warming processes. These include local adjustments to operational aspects of TRIUMF that use less or greener power, but also include the intellectual efforts of our scientists. While the installation of any next-generation nuclear devices (such as Small Modular Reactors or Generation IV molten salt reactors) as fully independent "green energy" sources is highly unlikely in BC in the next decades, TRIUMF can still contribute to this topic and could even consider a dedicated hire for "Green energy and nuclear transmutation". With the ambitious future Canadian involvement in clean nuclear energy projects such as Generation IV reactor technology and plasma-driven fusion projects, TRIUMF could play an important role to help make these giant technological leaps in Canada. Examples are material testing in specific radiation environments or providing critical nuclear reaction or

decay data to the community. Long-lived radioactive waste is seen as the biggest yet unsolved issue of energy production by fission reactors. Transmutation of these long-lived radioactive species via nuclear reactions to shorter-lived nuclides will allow for a reduction radioactive waste due to much shorter storage times.

WHAT WILL TRIUMF BE IF THERE WERE NO FUNDING CONSTRAINTS?

By 2030 the ISAC Experimental Halls will be as busy as a beehive since ARIEL will be in full operation and reliably delivering up to three beams in parallel, almost year-around. Two new dedicated Multi-Reflection Time-Of-Flight (MR-TOF) Spectrometers with resolving power M/ΔM> 20000 (larger than the existing ISAC and ARIEL mass separators) will provide additional isobaric purification for experiments pushing the precision frontier in the Low-Energy Area of ISAC even further (see Appendix).

Both ISAC halls are now fully occupied thanks to the recent addition of three new large experimental facilities that have been funded and installed in the past decade:

- The Radioactive Molecules for Fundamental Physics (RaMs) experiment, a facility that uses the enhancement of the eEDM sensitivity in heavy radioactive molecules as sensitive probe to detect a permanent electric dipole moment.
- POLARIS, a nuclear-spin polarizer beamline (used by Material Sciences, Nuclear Physics, and Life Sciences).
- The TRIUMF Storage Ring (TRISR), a low-energy storage ring for the direct measurement of astrophysically-relevant radioactive neutron capture cross sections and possibly implantation of ions into materials.

These large new experimental facilities are complemented by upgrades of existing facilities with smaller- scale setups, e.g. a dedicated Active Target Time Projection Chamber (AT-TPC) connected to the IRIS Solid Hydrogen Target setup that makes nuclear reactions in the gas target “visible”.

The new experimental opportunities at ISAC have allowed the Nuclear Physics Department to grow with the addition of 2 new joint positions at Canadian partner universities. Altogether, the nuclear physics research conducted at TRIUMF has been a continuing role model for the close collaboration between TRIUMF and its university stakeholders and provided work for hundreds of student theses throughout Canada and international. The hands-on experience these students and postdocs gain thanks to their training at TRIUMF is invaluable and has continued to produce

a highly qualified work force that will be the leaders of the next generation, not only in academia but also in industry.

External short-term experimenters will have the possibility to work in a dedicated user cubicle area when not on shift. Such users-only cubicles with 10-15 desks at TRIUMF would allow to avoid overcrowding in the counting rooms.

As offspring of the existing nuclear reactions program and thanks to the expertise in the Nuclear Physics Department and in the Accelerator Division, a new research direction has been created, investigating “Green energy and nuclear transmutation” with dedicated experiments at TRIUMF. This could include the potential use of photo-and proton-induced reactions to reduce the amount of long-lived radioactive waste, as well as a symbiotic irradiation test facility for the investigation of the transmutation of small amounts of radioactive waste, and for the research into the new generation of accelerator-driven systems.

On the Public Outreach and Engagement side we envision TRIUMF as containing a “Canadian Center for the Public Understanding of Science”, with a strong focus on hands-on experience in the Nuclear Physics that surrounds us in our daily life (Element Creation in Stars, Natural Radioactivity, Solar Fusion, Radiopharmacy, …). This Center would help to educate the general public about Science@TRIUMF and reduce the negative feelings for words like “nuclear” and “radioactive” and help to improve the understanding of basic nuclear physics phenomena. Engaged TRIUMF nuclear physicists would act as science ambassadors together with the Communications office. The center would be established as Canadian partner for nuclear outreach programs at Science World or other public events. It could promote e.g. LEGO’s “Building Blocks” nuclear chart to teach young people not only about the atomic elements but about the deeper structure of nuclei and how isotopes are critical to our world, from energy to medicine to our understanding of the cosmos. In this way the word “nuclear” is no longer associated with the negative connotations of weapons or archaic reactors, but realized for what it is, something more fundamental, more fascinating, more useful.

This would also help to establish Nuclear Physicists at TRIUMF as go-to partners whenever the media need a nuclear-related issue explained, from supernovae to neutron star mergers detected via gravitational waves, or new results of exotic nuclear shapes, or the latest developments in clean nuclear energy technology.

Nuclear Physics outreach would ideally target two different groups: the general public and students in schools and universities. For the general public, TRIUMF should organize open-lab days and science fairs (e.g. in collaboration with Science World and UBC Faraday Show) where people of all ages would enjoy lab tours, experiment demonstrations, lectures, and fun activities. In a year-round program, TRIUMF could organize public lectures and would also be active in

social media and channels like Youtube, showing the regular work in the lab (“24h in the life of a TRIUMF scientist”) in a way that would motivate young people to get into science and that would educate older people that do not necessarily have a science background.

In terms of outreach for schools and universities, TRIUMF could inspire the younger generations by organizing summer schools and lab tours. Since we envision the future generation of scientists to be equitable, diverse and inclusive, the TRIUMF outreach program for schools and universities should not be granting access to its programs only by academic criteria but should be supportive and open to anyone wishing to learn the wonders of natural science.

Also the selection of TRIUMF merchandise would become more diverse: who doesn’t want to have a snow globe with the colorful DESCANT detector or DRAGON inside? Or picturesque calendars with TRIUMF motives or the TRIUMF Card Deck or Experimental Setup Collection cards? Or even a LEGO model of the busy ISAC halls?

WHAT WILL TRIUMF HAVE ACCOMPLISHED?

The parallel beam operation at ISAC as well as the availability of beam almost year around has allowed to multiply the science output. The time between proposal and experiment is on average 6-12 months, which allows spokespersons to better plan the research of their students and postdocs.

The TUCAN (ultra-cold neutrons) and Radioactive Molecules experiments will have provided the world's most sensitive search for a permanent electric dipole moment (EDM) of the neutron ($\delta d_n < 1*10^{-27}$ e·cm) and electron ($\delta d_e < 1*10^{-29}$ e·cm), respectively. One or both of these experiments will either observe an EDM orders of magnitude larger than predicted by the standard model, or rule out numerous theories of physics beyond the standard model.

- Construction of the worldwide first storage ring coupled to an ISOL facility (TRISR): Thanks to the intense and clean beams from the ISAC+ARIEL+CANREB facility and a high-intensity neutron generator target, for the first time the measurement of direct neutron capture cross sections on radioactive nuclei with half-lives shorter than 1d can be performed. This will considerably reduce the uncertainty in astrophysical models for the creation of elements heavier than iron who have identified this quantity as main nuclear physics uncertainty. This success triggers the construction of larger facilities outside of Canada to access even shorter-lived nuclei and measure their neutron capture cross section.
- With the computational and theoretical advances in Nuclear Theory, the development of first principles many-body methods has allowed the first consistent treatment of structure and reactions for virtually all existing nuclei and provided essentially exact input for

beyond-standard- model searches such a neutrinoless double-beta decay (0vββ), WIMP-nucleus scattering, and fundamental symmetry violations. Atomic nuclei can now be described with a precision and accuracy akin to what is possible for quantum chemistry. Computations of superheavy nuclei, including predictions for potential new islands of stability will be made. The unified structure and reaction theory has been expanded to heavier nuclei as well, enabling even completely ab-initio descriptions of the nuclear fission process in the heavy region of the chart of nuclei.

- Creation of a “Canadian Center for the Public Understanding of Science”, with a strong focus on hands-on experience of the science done at TRIUMF, driven by TRIUMF scientists and the Communication Group. This center would allow to attract the future generations of scientists even earlier and strengthen the connection of TRIUMF with the general public even more, and at the same time allow to educate people about common misconceptions (e.g. radioactive = dangerous; nuclear = bad; …)

WHAT WILL TRIUMF BE DOING AND NOT DOING ANYMORE?

By 2030 all experimental facilities at the ISAC facilities have been upgraded or are new to allow a full exploitation of the science enabled by ARIEL and to maintain state-of-the-art uniqueness until far beyond 2040. Thanks to the streamlined and improved scientific communication within the laboratory, the newest detector technologies in nuclear physics are tested and used.

WHAT WILL TRIUMF LOOK LIKE?

The TRIUMF campus will be busier than ever. Onsite nuclear physics experiments will be able to run year- around thanks to the availability of more radioactive beams from the cyclotron and the electron linac.

A new building has been constructed to add the much-needed additional office space for employees, students, and users. A large gathering space onsite hosting up to 150 participants will allow to run medium-sized conferences and workshops, as well as celebrations. This building also has a larger cafeteria with some cozy spaces for small scientific discussions. The “Canadian Center for the Public Understanding of Science” is located in this building with a “TRIUMF Geek Shop” that sells more merchandise that will bring the TRIUMF closer to the general public and help them to identify with the great science program at Canada’s only particle accelerator laboratory.

ADDENDUM (Nuclear Physics)

Additional useful information collected during the consulation process:

MR-TOF (MULTI REFLECTION TIME OF FLIGHT) SPECTROMETERS FOR BEAM PURIFICATION AT ISAC

Benefits: An MR-TOF would provide additional isobaric purification of RIB beams for delivery to ISAC low- energy experiments, with resolving powers greater than currently available ISAC separators. A resolving power greater than 20,000 (the theoretical maximum for the ARIEL HRS) should also be possible. In addition, an MR-TOF could provide an additional beam diagnostic tool for beam characterization, as a complement to the ISAC/ARIEL yield stations.

Limitations: MR-TOF systems are typically space-charge limited to intensities < 1e7 pps (background plus isotope of interest), depending on mode of operation. Exceeding the space charge limit will significantly limit the achievable resolving power; therefore, a machine with a higher space charge limit would be required for delivery to ISAC experiments. Development of different operational modes may help to offset this issue. In addition, the bunched nature of the beam creates high instantaneous intensities, which could be problematic for some experiments.

Feasibility: To provide maximum flexibility for delivery, an MR-TOF would have to installed in the RIB transport system between the mass separator and experimental area (or between the preseparator and mass separator). A separate device would be required for purification of beams from ISAC and ARIEL target stations. In addition to the MR-TOF itself, an RFQ-type cooler buncher would be required to bunch the beam. Both the RFQ and MR-TOF would require matching optics to optimize injection and extraction of ion beam. Additionally, both devices would have to be floated on high voltage to facilitate deceleration and trapping. The physical footprint for this installation is significant, particularly when the necessary high voltage infrastructure (including HV platforms, enclosures, isolation transformers, etc) are factored in.

Available space for an MR-TOF installation is limited. For ARIEL, space adjacent to the HRS (in the ARIEL mass separator room) may be available, permitting transport of beam upstairs through the east vertical section. A ground floor installation in ARIEL would be difficult, given the existing network of installed beamlines adjacent to CANREB. There may be space in the ARIEL yield enclosure for an MR-TOF, but this would limit the available transport destinations to experiments, without modifications to the existing RIB transport installation. For ISAC, installation in the mass separator room would not be possible, requiring a ground floor location. It may be possible to do this adjacent to the ISAC low energy area. In any case, the installation must allow for a bypass if the MR-TOF is not required (or unsuitable) for a given beam. A detailed analysis is required to determine space requirements, access requirements, and attachment to the existing RIB transport system. Given the space requirements, installing a single MR-TOF for all low energy experiments would be more feasible than installation of multiple devices servicing the needs of individual experiments.

Operation: As part of the beam delivery chain, operation of an MR-TOF would likely fall under the Beam Delivery group in coordination with RIB Ops. If multiple devices were installed, an additional P&S may be required for support and development, as well as a TEC for maintenance.

TRIUMF

Fundamental Physics with AMO Techniques

Chair: Amar Vutha (U. Toronto)

Working Group Members: Beatrice Franke (TRIUMF), Chistopher Charles (TRIUMF), Stephan Malbrunot-Ettenauer (CERN), David McKeen (TRIUMF), Andrea Capra (TRIUMF), Ivana Belosevic (TRIUMF/MIT)

WHAT IS TRIUMF TODAY?

A. WHAT DOES IT DO?

TRIUMF is a world-leading laboratory for accelerator-based research. Even among nonexperts, TRIUMF has a reputation as the hub of particle physics and nuclear science in Canada. It hosts leading programs in nuclear and particle physics, materials science, life sciences, medical isotopes and technology transfer. Current projects operating out of TRIUMF with international visibility in nuclear and particle physics include ISAC, ARIEL, ALPHA, T2K, ATLAS, and UCN. One of TRIUMF's important roles is enabling Canadian physicists to achieve critical mass in order to compete with the rest of the world. TRIUMF is home to many mid- to large-scale experiments that would be impossible to operate within a university department, and thus allows Canadian scientists to scale up their efforts to an international level.

B. WHAT MIGHT BE ITS DIFFERENTIATORS ("UNFAIR ADVANTAGES") IN THE FUTURE?

The WG identified the following:

Technical advantages:

- The ability to produce rare-isotope beams at high intensities with one of the highest power proton driver beams in the world, and the ability to efficiently transport those rare isotopes to experiments. The exotic nuclides produced will enable unique and unprecedented nuclear research.
- The availability of 3 independent RI beamlines. This could allow TRIUMF to develop specialized AMO expertise and take the lead in precision measurements of isotopes that have minute quantities and short half-lives.
- A variety of strong technical support groups, with unique expertise for nuclear and particle physics experiments, building upon a long history.A strong theory department that integrates closely with the experiments on site.

Strategic advantages:

- TRIUMF is a unique centre for research in Canada, particularly due to its ability to operate at mid-scale (with ~20-50 scientists). It has the combination of sufficient size to carry out AMO experiments that are infeasible at universities, while being small enough that it is not held back by institutional inertia.
- Being a hub for science while functioning at a size scale where people from different fields can interact and find serendipitous opportunities, without being separated into different sub-organizations.
- A strong focus on fundamental science that is unique in Canada, supported by community of highly skilled TRIUMF staff and a wide array of users and visitors.

Potential problems:

- An increasing amount of managerial overhead and unnecessary rigidity could derail TRIUMF's traditional flexibility, close personal interactions and support for creative new ideas.
- Current staffing levels may not be sufficient to operate the new rare-isotope beam facilities and the experiments.
- Slackening the focus on fundamental science in pursuit of short-term applications wil deprive Canada of a unique and globally-visible institution.

What trends and changes will shape TRIUMF's future?

Technical developments:

- Increasing levels of automation of the accelerator and experiments. The ability to remotely participate in experiments could also improve opportunities for researchers (e.g. from developing countries) who may not have sufficient funding to travel to TRIUMF in person.
- Interdisciplinary links between TRIUMF's traditional work in AMO to areas such as astrophysics, isotope geosciences, cosmochemistry and beyond-Standard-Model physics.
- Depending on funding for the next big accelerators, international particle physics may tend to focus on smaller-scale experiments to enable quicker and more creative experiments. So TRIUMF may need to decide between expanding its local program or contributing to one or two large-scale experiments.
- TRIUMF might expand its theory group from traditional nuclear/particle physics to allied areas such as quantum chemistry and cosmology.

Operational factors:

- Scientific initiatives will be evaluated on their sustainability (e.g. energy, natural resources, environmental impact) and measures to promote equity, diversity and inclusivity.

- Less travel and more remote meetings. International experiments may use remote shifts with people from different time zones to optimize their run time. But in-person interaction should continue to be prioritized, to create opportunities to spark new ideas and allow close informal coordination.

What will TRIUMF be?

We envision that TRIUMF will continue to be Canada's premier physics laboratory for accelerator-based science, and one of the world-leading facilities for rare-isotope research.

a. Is TRIUMF a site, an idea, a governance model, a network hub?

TRIUMF is a site for accelerator-based science. It is a hub for the community of people that gather at the site and operate experiments.

b. What role will TRIUMF play in Canada's S&T ecosystem and why?

TRIUMF will be an innovative centre of training of scientists in Canada. It will continue to complement university efforts for training scientists. TRIUMF will enable university researchers to conduct accelerator-based research, and provide infrastructure, expertise and support for experiments. TRIUMF will continue to enable knowledge transfer from accelerator-based science to industry and society (e.g., transferring expertise in medical isotopes). TRIUMF will also continue to have a premier role in R&D for interdisciplinary science, and build collaborations and connections from basic physics to other disciplines.

What will TRIUMF have accomplished?

a. What achievements will we be proud of within Science & Technology, People & Skills, and Innovation & Collaboration?

- Beyond-Standard-Model discoveries through precision AMO measurements, and collaborations with particle physics.
- Technological innovations such as detector development.
- Training of PhD students and scientists.
- Experiments operating at the site and contributions to off-site experiments.
- Advancements in medical isotope research that lead to diagnostic and therapeutic applications.
- Expanding outreach to a wider range of different community partners, including, e.g. indigenous and traditionally under-represented groups.

- TRIUMF's leadership in improving the representation of researchers across the spectrum in fundamental physics research.

b. What would headlines be in 10 and 20 years that you would want to see about TRIUMF?

- "Research at TRIUMF shines new light on the origin of the Early solar system".
- "New physics discovered at TRIUMF: unambiguous signs of physics beyond the Standard Model found in [...]".
- "Theoretical physicists at TRIUMF discover solution to the hierarchy problem".
- "Canada celebrates TRIUMF's 75th anniversary with an unprecedented investment into fundamental research to further strengthen the laboratory's leadership in accelerator-based science".
- "Dr. Susan Abcd, outstanding physicist and First Nations member, appointed as next Director of TRIUMF 2030-2035".

c. How will TRIUMF have contributed to major societal challenges?

- Through deepening our understanding of fundamental laws that govern the universe.
- Promoting scientific, rational, evidence-based world views and international collaboration as a tool for progress in society. TRIUMF, with its focus on fundamental science, can act as a unifying force in an age when many scientific questions are becoming politically polarized.
- Providing Canadian society with continuing evidence of Canadian involvement in cutting edge fundamental science.
- Education and training of students who become future leaders in society.
- Active programs to promote diversity in collaboration with local high-schools and universities, connecting outreach activities to research at TRIUMF.

What will TRIUMF be doing and what will TRIUMF not be doing anymore?

a. What will TRIUMF be doing if there were no funding constraints?

Research:

- Building a large internal AMO group/centre which adapts the high-end tools in AMO physics into research exploiting radionuclides.
- Narrowing the large gap between laser-cooling and spectroscopy research at cutting edge AMO labs compared to efforts at RIB facilities such as ISAC and ARIEL. This could lead to improved measurements of nuclear moments, hyperfine anomalies, isotope shifts,

parity and time-reversal symmetry violation, highly-charged ion clock transitions, and quantum chemistry.
- Expanding the accelerator complex with higher energy proton or muon collider facilities, perhaps an anti-atom factory (deuterium).
- Establishing an accelerator mass spectrometry (AMS) facility with at least two tandem accelerators, one ~6 MV and another up to 15-20 MV for pushing the boundaries of ultralow level isotope ratio measurements, applications to medicine, astrophysics, environmental and geo-sciences. These could also be used for precision isotope ratio analyses of rare radioactive molecules.
- Creating a stronger TRIUMF summer student program, to attract excellent students from around the world.

b. What are the priorities for TRIUMF activities?

- Establishing an AMO research cluster focusing on fundamental physics.
- Current priorities are ARIEL and IAMI.
- International collaboration and openness to international researchers.

c. What activities capture the interest and imagination of the general public?

- Unique and exciting STEAM outreach activities (e.g., “Inventors Club” for kids and youth) with a dedicated outreach department.
- Anything related to “Einstein” or “anti-matter”.
- Radioactive ion beam science and its applications to medicine (cancer).
- Linking accelerators to astrophysics and solar system cosmochemistry.
- Annual TRIUMF open days could allow a stronger connection with local communities through facility tours and presentations/demonstration by scientists.

d. Which program elements or facilities will we have stopped because they have been completed or to make space for new initiatives?

- Depending on what new direction the lab wants to take, particle physics could end up being scaled back in favour of more fashionable areas. However, we consider it vital that TRIUMF continues to study fundamental physics and maintain a strong presence in this field.

What will TRIUMF look like?

We envision that TRIUMF will continue to be one of the world's best nuclear research facilities.

a. What buildings & infrastructures will be on the site?

- A new facility for AMO experiments, development of new techniques bridging AMO and nuclear physics, and precision studies of radio-nuclides for fundamental symmetry tests.
- Sufficient lab space for individual research programs.
- A new main cyclotron/proton accelerator.
- A new office building would reduce the pressure on existing space, and greatly help the science effort.

b. Will there be more than one site?

We believe that the TRIUMF campus should be the centre of all major activities. Splitting some research activities off to a new distant site carries the risk of diluting the attractiveness and recognition of TRIUMF. We also do not foresee it being easy to split off a new structure from the existing TRIUMF framework: splitting TRIUMF up could also give up many of its "unfair advantages" which rely on close contact between members of the TRIUMF team.

c. What will TRIUMF's organization and its community look like?

We envision a more diverse, community of staff, users and visitors at TRIUMF. We hope to see more transparent and open communication between management and scientists, and more opportunities created for free discussions between scientific colleagues. We have perceived a certain discontent within the scientific workforce about TRIUMF's current governance model. This may be because of decision-making power that is too heavily weighted towards senior management rather than scientific staff, opaque communications between management and scientific staff, and/or TRIUMF's general push towards corporatization. We have identified the close inter-personal interactions and the resulting highly motivated staff as one of TRIUMF's key "unfair advantages". To strengthen this central asset, we recommend there be an open discussion with representatives of all layers of TRIUMF's workforce to identify and resolve the origin of the present discontent.

TRIUMF

Life Sciences

Chair: Paul Schaffer (TRIUMF/ UBC)

Working Group Members: Conny Hoehr (TRIUMF), Valery Radchenko (TRIUMF), Alex Gottberg, (TRIUMF), Brooke McNeil (SFU), Carlos Uribe (BC Cancer), Lana Janes (admare)

Introduction

The year is 2041. Societal shifts in energy, healthcare and sustainability are well underway and remain at the forefront of research and technology advancements. Major advanced economies around the world are in an active transition from resource-based, toward predominantly knowledge-based and resource-sustainable financial ecosystems. Auto manufacturers are rolling out their last fossil fuel models, with commercial and public transportation having long led the transition to electric and/or fuel cell alternatives. The workforce is adapted to a mixed remote/on-site paradigm, helping many to achieve a more optimal work-life balance. Healthcare is changed as well, with major transitions in clinical thinking on disease which is now taking a more molecular approach to diagnostics and treatment, resulting in personalized medicine and individualized treatments emerging as the norm. Despite dramatic decreases in cancer-related deaths from the start of the century, some diseases (i.e., some cancers, metabolic and neurodegenerative conditions) remain stubbornly resilient to treatments that have long become the norm for others.

Molecular imaging, radioisotope and beam therapy is now pervasive in the healthcare system, and TRIUMF remains well entrenched into the R&D aspects of isotope science for British Columbia and elsewhere. TRIUMF has many established national and international collaborations based around its ownership and legacy capabilities in accelerator science, and its application to the life sciences. The lab continues to struggle with balancing opportunities against resources and making decisions around which interactions will be strategic for its future; this despite significant advances in revenues and systems for managing and assessing risks associated with financial and intellectual assets. TRIUMF is a major attractant for the public, complete with digital, interactive, on-site museum, routine science lectures with many attending virtual events.

The scenario described above provides a vision of a world TRIUMF, Canada's national accelerator facility, will find itself after spending the next 20 years building on its strengths to remain a potent R&D center, with an active and balanced fundamental and applied sciences program driven by world-class scientists working at TRIUMF with their collaborators around the world. In all, TRIUMF will remain and excel as an active and highly relevant multidisciplinary laboratory capable of tackling key societal issues given its people and unique infrastructure.

What is TRIUMF today?

TRIUMF is home to the largest cyclotron and the most advanced accelerator infrastructure in Canada. The laboratory is globally unique with few, if any, other accelerator labs having the beam potency and versatility across a fleet of drivers that enable all the Life Sciences applications in the Division's research portfolio.

Today TRIUMF is widely known as an expert in accelerator targetry and a producer of known and novel isotopes. The Life Sciences program is a globally recognized leader that develops new radiochemical separation and transformations, radiopharmaceuticals, and can develop new sensors for dosimetry and beam delivery monitoring, novel approaches to particle beam therapy (pion, proton, and FLASH therapy) and novel analytical techniques, such as bio βNMR. In all, TRUIMF Life Sciences is a 'physics applied to life' program consisting of both research and application-driven projects enabled by experts across the disciplines of chemistry, biochemistry, radiation physics/safety, medicine, biology and engineering.

To many, TRIUMF Life Sciences pursues relatable science, offering fascinating tools to help probe the inner workings of the human body and our environment. The program continues to gain momentum and the attention of several prospective partners that span the public-private spectrum who see a uniqueness in TRIUMF for its technologies and expertise which are nearly impossible to replicate elsewhere – if only for the decades of knowledge depth in certain fields. In addition to the demonstrated depth and R&D in specific disciplines (engineering, accelerator and medical physics, chemistry, biology), the Division relies heavily on collaborations internally and externally to perform translational, and thus higher-impact work. While this follows in international trend that acknowledges and celebrates interdisciplinary research, it is both a strength and weakness given the reliance on others for overcoming certain research challenges.

2 What trends and changes will shape TRIUMF's future?

Isotopes continue to find increasing use in health research and emerging clinical applications. While some of the earliest uses for radioisotopes were focused on their therapeutic nature, the past 70 years has seen a substantial focus on their use for diagnostic imaging as molecular imaging has transitioned into the clinical mainstream. More recently, a resurgence in interest in the use of specific beta- and alpha-emitting isotopes after significant clinical responses were observed during treatment of late-stage cancer patients injected with targeted radiopharmaceuticals. Couple these early clinical results with the virtual explosion in the number of disease-specific cellular recognition antigens and corresponding binding agents and several emerging methods to quantify dosimetry, the use of alpha-, beta- and Auger-emitting isotopes is poised to gain significant momentum – and many are poised to change the way many diseases are managed.

Accelerators are becoming key contributors to the global isotope development and supply landscape. With an increasing demand for superior yields and reliability, there will be a significant need for known and novel isotopes, newer target technologies, beam diagnostics, radiochemical

transformations, radiopharmaceutical design, and dose delivery monitoring. TRIUMF is uniquely capable of delving into all these areas.

TRIUMF's contribution to the field of isotope and radiopharmaceutical science is evident through its commitment to build and operate the Institute for Advanced Medical Isotopes (IAMI). Slated to be completed by the end of 2022, IAMI will leverage TRIUMF's existing and emerging infrastructure, including a new TR24 cyclotron, that will produce, isolate, and apply isotopes to emerging and novel radiopharmaceuticals. IAMI will also enable an interface between accelerator science, cyclotron and linac target development and irradiation, and radiochemical development. Add partners from across the research spectrum, and IAMI at TRIUMF is well-positioned to be a place to translate science into real world solutions.

TRIUMF also will explore novel external beam radiotherapy modalities. This will include novel treatments like FLASH with different particles and the combination of targeted radiotherapy with external beam therapy. Development of photon and proton FLASH is currently underway.

TRIUMF is also home to novel analytical techniques such as βNMR which offers orders of magnitude improved sensitivity for studying the magnetic environment, and thus chemistry of several elements in ways not possible with conventional analytical techniques. Increasing demands for understanding the world around us in greater detail will only drive demand for these techniques.

Many research projects will also benefit from the involvement of machine learning and AI and potentially quantum computing, greatly accelerating innovation.

Beyond health, TRIUMF with its capability in novel accelerator technology development can contribute fundamentally to developments in energy, environment, defence, and education. The lab has a track record of identifying unmet needs and responding to unanticipated society issues. Recent examples include responding to isotope supply shortages or rapidly developing ventilators in response to increasing demands due to COVID-19. Events like the pandemic have also spurred the world to become more digitally connected, and opportunities are emerging for TRIUMF to contribute to the education/training of new HQP, scientists and even the public using remote, or virtual tools.

TRIUMF has a reputation of nimbleness and for accomplishing much with comparatively little resource, due in part to the dedication and creativity of the people tasked with addressing any challenges presented to them. Care will have to be taken to protect the creativity and interaction time for TRIUMF staff to maintain the impact of its science.

3 What will TRIUMF be?

The physicality of what TRIUMF is today will continue for some time. Its many drivers maintain a potency few other facilities are capable of, and the infrastructure will remain relevant for the

laboratory's research and isotope production program for many years to come. TRIUMF will be a major supplier of both diagnostic and therapeutic radionuclides, but also new and advanced rare isotope and accelerator beam capabilities. These same advancements also provide opportunities to develop, evolve and adapt the facility, creating a feedback loop that will sustain the legitimacy of TRIUMF's program.

While newer, larger, higher-energy facilities will come on-line in the years and decades ahead, TRIUMF's driver potency will prove to be a major differentiator and will result in increase demand to produce and provide rare and common, known, and novel isotopes, some of which will be used for diagnostic and therapeutic applications. As a result, TRIUMF will continue to make Canada a world-leader in fundamental research in and around isotope targetry, production and chemistry, but also in applications of molecular imaging and radioisotope therapy, external beam therapy, dosimetry, beam monitoring, treatment planning and other aspects of accelerator physics applied to the life sciences. Current efforts on neurodegenerative and cancer research will continue, but new disease areas will emerge to which TRIUMF will offer some solution for insight or treatment.

The provincial clinical PET program is poised for rapid growth in the coming years, along with the possibility of Canada implementing a new generation of proton therapy facilities, will present opportunities for TRIUMF to expand its physical footprint by co-locating facilities and personnel in other cities around British Columbia. A similar model could be applied to other centres across Canada, which can benefit from TRIUMF's cyclotron and radiochemistry expertise. Implementing a multi-campus paradigm will mandate a strategic decision and require the implementation of a formal program to help keep all 'campuses' connected for the free exchange of people and information. This connectivity will also allow TRIUMF's program to be accessible by HQP and scientists from around the world.

In partnership with TRIUMF Innovations, the laboratory will also have proven to be a potent economic contributor via private sector partnerships and start-up company formation and launch. Royalties from these efforts will provide an important source of funding for the lab to further improve its facilities,

Overall, TRIUMF will continue to be a multi-disciplinary hub for a global research community to gather for research. TRIUMF's future will be more integrated into the provincial healthcare system, with translational facilities capable of preclinical *in vivo* work, but also strong ties to state-of-the-art clinical imaging and treatment (including FLASH proton therapy). The lab will remain rooted in its accelerator, physics, and chemistry expertise, relying heavily on symbiotic partnerships to drive clinical translation.

4 What will TRIUMF have accomplished?

For the reasons discussed above, both the 500 MeV and ARIEL e-linac drivers will be feeding a robust rare isotope science program at a dramatically higher pace than today. Large-scale symbiotic isotope production with custom target solutions from various beamlines across campus

will be the norm. IAMI will long be complete along with the construction of another adjacent facility which will be home to a new cyclotron design, additional office, and research laboratory space, as well as incubator space occupied by both short- and long-term partners for the development and translation of numerous accelerator-, isotope- and radiopharmaceutical-based technologies.

TRIUMF will also have developed into a platform to explore and develop novel radiotherapy modalities, including innovative combinations with other modalities, and taking nuclear physics technique to apply them to the Life Sciences. Novel computational and accelerator physics solutions will drive these developments.

TRIUMF's people will continue to flourish, further increasing the lab's legacy expertise across multiple disciplines. The lab will be a hub for international scientific visitors, further fueling interdisciplinary research with global reach.

5 What will TRIUMF be doing, or not doing any longer?

In 20 years, the laboratory campus of today will still be evident, but preserved amongst several new facilities brought online in the coming years. The new campus will have more technical space, but also incubation space where people can mingle and solve emerging problems. The lab organizational structure will have adapted to address increasing administrative overhead by simplifying operations and managing regulatory oversight.

TRIUMF will have an integrated science program, with fundamental and basic (accelerator, nuclear & particle physics, and life) research programs interspersed with many active inter-divisional collaborations enabling high-impact, applications-focused science. This will require seamless material and people flow and well-managed resource allocations for each commitment.

TRIUMF scientists will have a balanced working environment that allows time for creative focus and exploration, also serving to train HQP as technology experts and thought leaders of their generation. The laboratory will be known for its innovation and will have evolved to culturally to choose strategic initiatives by declining others, while lowering barriers between disciplines and protecting creativity time for its staff and scientists.

6 What will TRIUMF look like?

Facilities: The 500 MeV and e-linac facilities will continue to provide some of the most luminescent proton beams for basic and applied research. ISAC and ARIEL will provide a continuous array of rare isotope beams for experiments across the nuclear and particle physics spectrum, but also materials and life sciences. These drivers will be complemented by a suite of smaller, mid-energy cyclotrons that range from 13 to 120 MeV, producing a suite of isotopes for both internal and research and external collaborations. Novel accelerators will continue to be developed and applied to the Life Sciences. TRIUMF will also have a mature isotope production

and distribution program, delivering isotopes around the world both for basic research, but also for revenue generation.

Drivers: TRIUMF's foundational cyclotron and e-linac technology will continue to thrive in the decades ahead. The 500 MeV cyclotron will remain fully operational, having been adapted to deliver >400 uA of continuous beam year-round. The e-linac will have been adapted to deliver intense gamma irradiation capabilities for science and applied isotope production. The laboratory's lowest energy TR13 cyclotron will have been replaced with another machine capable of <13 MeV proton irradiation to provide a routine supply of various radiometals that are now in regular pre-clinical and clinical use. The TR24 will be slated to undergo a major retrofit to prepare for another 20 years of operation. BWXT will have opted to do the same for both TR30s while also investing heavily in a new TR100+ cyclotron built in a facility adjacent to IAMI.

Beamlines: BL1A underwent a rejuvenation effort in 2024, which was followed by the completion of BL4N. Routine, high-energy symbiotic medical isotope production on the refurbished IPF, ARIEL symbiotic (proton and electron/gamma) target stations.

FLASH photon and proton facilities will be available for exploring and optimizing a novel radiotherapy facility which has the potential to revolutionize cancer treatments.

ISAC and ARIEL will provide unique pure beams of rare medical radionuclides for pre-clinical evaluation on regular basis.

Isotope and Radiopharmaceutical Research (Health, Environment): With routine access to over two dozen isotopes, including ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{44,47}Sc, ^{45}Ti, ^{52,54}Mn, ^{61,64,67}Cu, ^{66,67,68}Ga, ^{86}Y, ^{89}Zr, ^{94m,99m}Tc, ^{111}In, ^{119}Sb, ^{123,124}I, ^{132,135}La, ^{134}Ce, ^{149,161}Tb, $^{197m/g}$Hg ^{203,212}Pb, ^{213}Bi, ^{223,224,225}Ra, ^{225,226}Ac and ^{227,228Th} – many of which will be in clinical use; and a well-established molecular toolkit of metal chelates and bifunctional linkers, TRIUMF will have several internal research programs coupled with local and international partnerships underway actively translating diagnostic, therapeutic and theragnostic radiopharmaceuticals for clinical use. Partnerships with cancer centres around the world will be critical for realizing the potential of this program.

Beam Therapy Research: FLASH and other novel external beam modalities will be explored and combined with other tools like nanoparticles to enhance the treatment or with medical isotopes for a synergistic effect.

Detectors and Spectroscopic Methods: Advanced beam profile monitors will the norm and high-power irradiations made safer through a number of new cyclotron interlocking systems. Novel detector solutions borrowed from the nuclear physics community will improve dosimetry and beam monitoring for improved and safer treatments, and advanced radiopharmaceutical development.

TRIUMF as an international research Hub: TRIUMF and TRIUMF Life Sciences will be a larger division with additional joint (national and international) faculty will provide a global stage for

visiting scientists and HQP along with lectures and teaching opportunities that are combined with university courses and hands-on summer schools and conferences. Joint faculty from across Canada and globally will come to TRIUMF to pursue innovative and novel solutions for the Life Sciences.

TRIUMF

Probes for Quantum Materials and Biomolecules

Chair: Kenji Kojima (TRIUMF)

Working Group Members: Sarah Dunsiger (TRIUMF), Monika Stachura (TRIUMF), Graeme Luke (McMaster), Alannah Hallas (UBC), Scott Hopkins (Waterloo), Edward Thoeng (UBC)

What is TRIUMF today?

What does it do?

TRIUMF is a world-leading laboratory for accelerator-based research. It currently runs two probe facilities adequate for condensed matter, quantum materials and biochemistry applications: the muon spin relaxation (μSR) and beta-detected nuclear magnetic resonance (beta-NMR/NQR) facilities. The μSR facility is one of the four such major facilities in the world (the only one available in north America), while the beta-NMR/NQR facility is the only one in the world with depth-resolving capability. Both of the facilities run well-established external experimenter programs and invite external scientists from around the world, who would like to characterize their specimen with these characteristic probes at the TRIUMF site.

One of TRIUMF's important roles is developing, maintaining and operating accelerator-based probes for molecular and materials science, which would be impossible within a single university department. These efforts enable not only Canadian scientists to compete world-wide in the advancement of science, but also provides unique hands-on-training and education of students using the unique infrastructure available on-site.

What might be its differentiators ("unfair advantages") in the future?

Technical advantages:

- Decades of in-depth expertise in running and operating two facilities: **50-year experience of muon** production and application, and **20-year experience of radioactive nuclei** production with laser induced spin polarization and implantation depth control. These includes:
    - Particle detector technology from photo sensors and GHz electronics (enabling ~10 nano second spin relaxation) and data acquisition, storage and handling in data base.

- Sample environment: wide temperature range (0.01~1000 Kelvin), high to zero magnetic field (0.1μ ~7 Tesla), high pressure (~GPa) and radio frequency radiation for spin manipulation.
- Capability to develop new technologies and infrastructure to reach new sample environment / requirement horizons: e.g. atmospheric sample pressures in ultra-high vacuum beamline of beta-NMR, small beam spot/ particle veto system to measure milli-meter / milli-gram samples.

Strategic advantages:

- TRIUMF owns unique spin probes for molecular and materials science.
- TRIUMF is located on the UBC campus in strong collaboration with UBC Quantum Matter Institute. TRIUMF also has a strong affiliation with SFU and has access to its unique facilities. These strong local universities have complementary and state-of-the-art characterization techniques and sample preparation facilities.
- The external experimenters originate from major Canadian universities as well as foreign universities and institutes world-wide, forming a global research network of personnel applying accelerator-based probe beams in molecular and materials science.

Potential problems:

- Aging infrastructure which is unique and does not exist elsewhere. Once its structural and operational knowledge is lost, it is difficult to maintain the current level of operations.
- Compared to other materials science facilities (e.g. neutron and synchrotron), current TRIUMF system has higher thresholds for new experimenters. Operational expertise is required for measurements, and site access process (either virtually or in person) is complicated.
- The proposal-measurement loop and time schedule (every half year) may not allow sufficient response to the quick evolution of quantum materials and biomolecular research. Greater flexibility in the proposal process / beam usage may be needed.

What trends and changes will shape TRIUMF's future?

Change of scientific subjects:

- Research subjects constantly evolving as new ideas (e.g. 2D quantum materials, topological materials or medical applications) appear.

- Characterizations of pure and nano-engineered samples (e.g. thin films or sub-millimeter size samples) in new sample-environment (high / low temperature, high magnetic field and high pressure) is required to test these ideas.

Technical developments:

- Passage to develop a THz Free Electron Laser from the knowledge gained from ARIEL (superconducting electron linac) at TRIUMF.
- Contribution to an accelerator-driven compact neutron source (CANS) from decades of experiences in the design and operation of particle accelerators and nuclear facility.
- Increasing levels of automation in experiments, enabling them to be run more efficiently with reduced demand on personnel. This made remote measurement possible in the Covid-19 era.
- Application of theoretical condensed matter (e.g. density functional theory (DFT)) and big data analysis using machine learning techniques in the computing resources (e.g.with Westgrid cluster).
- Development of a new spectrometer capable of measurements in higher requirements in sample environment: high-vapour pressure, nano-meter-size thin-films and sub-milli-meter single crystals, with particle tracking technologies to sample pixelated measurements.

Operational factors:

- Balance between the external demands and internal facility development and innovations. Strong scientific innovations from the internal scientist as well as needs from external scientists will strengthen the technical developments of the facility and benefit all experimenters with high impact results.
- Real time and web-based data visualization and automated measurement / analysis are needed to attract and help less experienced users to run experiments at TRIUMF facilities with minimal help from local staff / scientists.
- Education and hands-on training of students and early career researchers is important for sustainability of the facility.
- Joint PhDs with PIs working in quantum materials (where the student would spend ~half their time at TRIUMF).

What will TRIUMF be?

TRIUMF will continue to be Canada's centre of accelerator-based science which develops and hosts world-leading characterization facilities utilizing muons and radioactive isotopes.

Is TRIUMF a site, an idea, a governance model, a network hub?

TRIUMF is a site for accelerator-based science. It owns and operates spin probe facilities for molecular and materials science. It also is a knowledge hub for future development of on-site and/or off-site such facilities.

What role will TRIUMF play in Canada's S&T ecosystem and why?

TRIUMF will be an innovative centre for interdisciplinary training of scientists nationally and internationally. It will continue to complement university efforts for training researchers at all levels.

What will TRIUMF have accomplished?

What achievements will we be proud of within Science & Technology, People & Skills, and Innovation & Collaboration?

- Elucidating the magnetism, superconductivity, quantum phase transitions and hidden orders of various quantum materials.
- Spectroscopy of hydrogen centre and muonated radicals in semiconductors and (bio)molecules.
- Depth-resolved measurement of nano-meter thin films for magnetism and superconductivity.
- Direct measurement of Lithium diffusions in battery materials.
- Enabling NMR measurements of elements without a stable isotope, e.g. Actinium.
- Enabling beta-NMR experiments in vivo environment (zero magnetic field and in solution).
- Quantitative understanding of muon or nuclear spin relaxation in matter with advanced theoretical input.
- Providing complementary information to other beam probes, such as neutron scattering and synchrotron radiation spectroscopy.
- Development of novel accelerator-based facilities for material characterizations such as Free Electron Lasers and compact accelerator-driven neutron source.
- Provide unique training of world class PhD students and scientists and access to worldwide unique scientific facilities.

What would headlines be in 10 and 20 years that you would want to see about TRIUMF?

- “Research at TRIUMF has clarified how the quantum device works”.
- "New discovery at TRIUMF: how enzyme works in a microscopic level.”
- “Fine control of the probe particles has investigation of interface phenomena possible”.

- “Pump and probe spectroscopy of rare isotope has clarified dynamics of quantum functional molecules”.
- “TRIUMF plays a key role in resolving the long-standing question on the origin of XYZ disease”
- “TRIUMF provides key pieces to understanding toxicity of Cu and Zn in human body”
- “Canada celebrates TRIUMF’s 75th anniversary with an unprecedented investment into fundamental research to further strengthen the laboratory's leadership in accelerator-based science”.
- “Dr. XYZ, outstanding materials scientist in Canada was appointed as the next Director of TRIUMF 2030-2035”.
- “Compact Accelerator based neutron source based in XYZ (Canada) sees first neutrons.”
- Nobel prize in Physics in the development of new quantum materials / new techniques.

How will TRIUMF have contributed to major societal challenges?

- Through identification, understanding and development of new materials necessary for sustainable development goals and future technologies.
- Fostering international collaborations across borders, regardless of nationalities, political affiliations, ethnicities, etc.
- Continues to propel Canada’s role in tackling urgent global issues with innovations in cutting edge fundamental and applied science.
- Education and training of students to drive and adopt to change, to succeed in academia and private sector, and to become future leaders in society.
- Active programs to promote diversity in collaboration with local elementary and high-schools and universities, connecting outreach activities to research at TRIUMF.

What will TRIUMF be doing and what will TRIUMF not be doing anymore?

What will TRIUMF be doing if there were no funding constraints?

Research:

- Increased capabilities of the probe techniques already existing and being operated at TRIUMF.
- Realizations of extreme sample environment (high/low temperatures, high pressure, high magnetic field) together with the unique probes.
- Expansion of the spin polarized rare-isotope facility toward new applications.
- Expansion of in-house sample characterization laboratory equipped with cutting-edge tools.

- Hiring enough personnel to enable the full operation of the existing research facilities, as well as expanding their capability to a full complement.
- Expand the Centre for Molecular and Materials Science (CMMS) to function as a hub of molecular and materials science in Canada, equipped with off-line sample characterization equipment and sample synthesis apparatus.
- Creation of a TRIUMF summer student program with molecular and materials science component built in, to attract excellent students and early career researchers from around the world.
- Creating a competitive joint PhD program with member universities.
- Improvement of TRIUMF measurement facility to be more accessible to a new generation of experimenters with no prior experience.

What are the priorities for TRIUMF activities?

- Maintain and develop the cutting-edge spectroscopy method for biological, medical, molecular and materials science.
- Completion of ARIEL facility and increased availabilities of radioactive beams for material characterizations.
- Develop expertise in the design of accelerator-based material characterization techniques and instruments for technology transfers to other labs or industries.
- International collaboration and openness to international researchers.

What activities capture the interest and imagination of the general public?

- Anything related to “Quantum” and “Life”.
- Radioactive ion beam science and its applications to medicine, (bio)chemistry and molecular and materials science.
- Public lectures / demos like UBC annual Faraday lectures explaining the technologies used at TRIUMF, e.g.: how to build large particle accelerators, superconducting levitation for maglev trains, Li-batteries, UHV vacuum and thin film fabrications, cryogenics, etc.
- Annual TRIUMF open days could allow a stronger connection with local communities through facility tours and presentations/demonstration by scientists as well as online materials like videos to reach remote locations and communities, as well as institutions with no graduate program.

Which program elements or facilities will we have stopped because they have been completed or to make space for new initiatives?

- NONE. All activities about molecular and materials science probes are expanding.

TRIUMF

What will TRIUMF look like?

TRIUMF will continue to be one of the world-leading research facilities, not only in the particle and nuclear physics, but also long-standing molecular and materials science research and more recent biological and medical science research.

What buildings & infrastructures will be on the site?

- A new beamline M9A and M9H are under construction and development.
- High pressure (~GPa) facility will be necessary for the full employment of M9H capability.
- Expansion of polarized rare-isotope capability POLARIS in ISAC-1 hall.
- BL1A renewal and expansion. Possible new muon production target and new beam lines.
- Potentially off-line sample preparation / characterization facilities, e.g. Glovebox for unstable samples, X-ray diffractometer and magnetometer, as well as a lab space for future developments.

Will there be more than one site?

- TRIUMF should actively participate in the accelerator-based neutron facility project, with its 50-year long accumulation of knowledge about proton acceleration and beam delivery. TRIUMF should also be able to contribute to the target design, including the neutron production, transport and shielding simulations.
- TRIUMF is currently accumulating new knowledge of electron linac and target development and operations. This should contribute to the THz generation facility project, even though it may be built off-site from the TRIUMF premises.

What will TRIUMF's organization and its community look like?

- TRIUMF has sustained good and cooperative relationship between the scientific and technical staff. We hope the same attitude stays in the TRIUMF community to realize a more diverse research institute, not only in the background of the staff and the visitors, but also the research goals. It is to be hoped that TRIUMF retains its tradition for flexibility, innovation, commitment from its staff to "get the job done".
- TRIUMF will have ensured its Board Appointment Employees (BAE) retain their independent, externally funded research programs and worked towards providing enriching work environments with positive career development for all its staff. TRIUMF will have maintained its ethos as a research institute.
- Development of a research facility will be best achieved in a good relation to the external experimenter. "Collaborations" and "partnerships" (than "services" or "support") may be the best words describing such relations.

TRIUMF

Accelerator Science and Facilities

Chair: Thomas Planche (TRIUMF)

Working Group Members: Ramona Leewe (TRIUMF), Marco Marchetto (TRIUMF), Angela Lang (TRIUMF), Tobias Junginger (UVic/TRIUMF), Luca Egoriti (UVic), Carla Babcock (TRIUMF), Yuri Bylinsky (TRIUMF), Zhongyuan Yao (TRIUMF), Martin Alcorta (TRIUMF), Gerald Morris (TRIUMF)

Introduction

Our vision for TRIUMF, Canada's particle accelerator centre, is to build on our strengths to serve science, invent life-changing technologies, and build a better world starting here: in Canada. To remain competitive internationally, we will continue to rely on TRIUMF's very own old recipe: we use internal projects and external collaborations as springboards to consolidate and expand our core competencies or acquire new ones. This allows us to gain and maintain a broad expertise within a relatively small laboratory. With our always evolving knowledge and technical expertise TRIUMF will remain a leader in Canada's transformation to a knowledge based economy.

What is TRIUMF today?

TRIUMF has five decades of experience in building a particle accelerator infrastructure that enables cutting-edge research and discovery. Throughout these years, our expertise in accelerator physics and technology is unparalleled in Canada, and envied internationally. The wide variety of accelerator technologies that populate our campus, and the very diverse team of professionals and students who run the place testify to what TRIUMF is today: Canada's particle accelerator center.

What trends and changes will shape TRIUMF's future?

Particle accelerators have first been developed for subatomic research. Nowadays this discipline is dominated by large scale facilities with worldwide collaboration. TRIUMF will be a major contributor in this area using its accelerator expertise but different trends will likely shape the local accelerator infrastructure.

The growing contribution of TRIUMF to life science will undoubtedly shape its future. The construction of IAMI is a clear sign that the wheels are already in motion. The easily quantifiable societal impact of a strong life-science program, and the existing match between nuclear medicine needs and TRIUMF core expertise in accelerator and target technologies will continue to reinforce this trend.

The global environmental crisis, and the growing awareness of the general public to this overarching issue will change the future of nations. It will thereby necessarily guide scientific research and funding policies. Minimizing our impact with energy-saving initiatives is commendable: but is it sufficient? For TRIUMF's research program to be still relevant in 20 years time, we must take the lead on this topic.

Technological breakthroughs will drive the evolution of our facilities. For example: accelerating gradients in superconducting rf technology will continue to increase; very high-gradient accelerator technologies such as laser wakefield may lead to important applications; material science will continue to provide us with better super-conducting materials for magnets and accelerating structures; artificial intelligence will change the way we design and operate particle accelerators. The important point is that our research program will enable some of the breakthroughs which will, in turn, change our future.

What will TRIUMF be?

TRIUMF will remain Canada's particle accelerator centre, with two high-power machines at its center (the 520MeV cyclotron and the ARIEL electron linac) and multiple secondary beamlines and accelerators branching from high power target systems. Particle accelerators are possibly the most complex and discovery-enabling experimental facilities to enable earth-based discovery, as telescopes enable exploration of the cosmos. The real question is, what science are we going to do with particle accelerators in 20 years? It is inherently hard to predict which trend will come to fruition over the next 20 years. Our goal is to remain `on the edge': the best at what we are doing, and strongly connected to our user's communities.

What will TRIUMF have accomplished?

By putting together the resources from many universities across Canada, we will have accomplished what no single university could have achieved alone: to maintain a continuously evolving cutting-edge accelerator facility serving fundamental and applied research. We will have trained a wide diversity of highly qualified people who will have disseminated our competencies, our culture, all across our country and beyond. We will have advanced knowledge in nuclear structure, particle physics and material sciences. We will have transformed the impact of nuclear medicine in Canada, and have saved many lives by doing so.

What will TRIUMF be doing and what will TRIUMF not be doing anymore?

We will remain Canada's center for particle accelerators, but an increasing number of Canadian accelerators will not be on TRIUMF's site. We will centralize the expertise, but not all of the equipment.

In 20 years, accelerator operations will look radically different. We will rely on model based tuning heavily, and put many aspects of operations into the care of artificial intelligence agents. Imagine a control center with technology we have become accustomed to in our daily lives such as Siri or Google Assistant, with an advanced control system like what has so far only been depicted in movies like “2001: A Space Odyssey". This will enable `human' operators to dedicate all their attention to what's most important: ensuring safe operation, and maximizing users' satisfaction.

What will TRIUMF look like?

ARIEL+ISAC will be delivering the most intense and exotic rare isotope beams, as we will have the most powerful and versatile ISOL facility on earth: multiple beams, in parallel, 24-7, year-around. Our post-accelerator complex will continue to lead the world with a major energy upgrade, and a low energy storage ring for neutron capture. The electron linac will produce high-power and high-brightness beams to serve simultaneously ARIEL and a world-class THz light-source. Our contribution to life sciences will have transformed our campus, which will be crowded with accelerators of various sizes to produce medical isotopes and advance research on the clinical isotope front. The major revolution will come from the expansion of TRIUMF outside of its physical boundaries, allowing us to play a key role in the forthcoming knowledge-based economy as the owner of Canada's accelerator-related expertise. With knowledge as our main resource, we will train people, grow accelerator projects in Canada, augmenting and extending our expertise by participating to international big-science projects.

High-Power Drivers

Most experiments carried out on campus depend on the beam from either one of our two high-power drivers: the main cyclotron, and the e-linac. The cyclotron is TRIUMF's original heart since 1974. Like the ship of Theseus, critical systems are continuously upgraded or replaced; the cyclotron of 2021 is quite different from the one of 1974, and so will be the one of 2041. Reliability upgrades will allow reduced maintenance needs, leading to shorter and less frequent shutdowns and increased beam availability. The cyclotron will also reach higher intensity frontiers, delivering more beam to increasing numbers of users.

The e-linac will deliver to ARIEL beam powers to rival that from the cyclotron.

The infrastructure will be expanded to support, in parallel with ARIEL, a science program in the electron hall (FLASH, DarkLight). Beyond that infrastructure upgrades (photo-gun, bunch compression, etc) would support a THz light-source operated as a multi-user facility.

Secondary and Rare Beams

To think about the state of nuclear physics Rare Isotope Beams (RIB) research in 20 years, it is a worthwhile exercise to go look at the state of the RIB program at TRIUMF 20 years ago. The RIB program started as an opportunistic endeavor at a time when the future of TRIUMF was uncertain. The concept was developed organically from a small group of researchers, and eventually evolved into one of the flagship programs at TRIUMF.

The ISAC-II linac was the top performing heavy ion SRF linac in the world at the time of commissioning and first operation in 2004. Its competitive advantage has been gradually eroded as competitors like ISOLDE have added an SRF post-accelerator. With the addition of CANREB and ARIEL new high-mass beams will be available and an increase in ISAC-II final energy with the addition of an after-burner cryomodule plus the refurbishment of the existing linac with modern cavity treatments and infrastructures will allow ISAC-II to regain it's competitive advantage in RIB post acceleration.

Within the current suite of target materials and ion source types, it is becoming a challenge to produce ever more exotic isotopes. Groundbreaking innovations (which are within our reach) are required to meet the demand from experiments for nuclei further from stability. Radioactive molecules are one example where next-generation gas-filled molecular ion sources can produce, on demand, a staggering diversity of new rare molecular beams downstream from ISOL targets. This unique capability building on our RIB infrastructure places TRIUMF in a leadership role, where beyond Standard-Model physics and novel interdisciplinary topics can be studied with new exotic radioactive molecules in compact ultra-high precision experiments.

Similarly, targets capitalizing on new production methods, such as the proton-to-neutron converter target or the ARIEL photofission target, provide an avenue into diversifying our RIB products.

Secondary beams are also used at TRIUMF heavily for material science. Muon beams for spin spectroscopy (muSR) and polarised radioactive ions beams for beta-detected nuclear magnetic resonance (betaNMR) are primarily sensitive to magnetism - and via that coupling - indirectly sensitive to any phenomena that affects the polarisation of the implanted particle. They are probes of choice for a broad range of topics in magnetism, superconductivity, quantum and classical diffusion, etc. Researchers from the accelerator division are using muSR and betaNMR to test materials for superconducting radiofrequency cavities.

Upgrades to cyclotron systems and BL1A that double proton beam current as well as new muon production target technology that could gain a similar factor would enable muSR studies on high quality samples that are often small single crystals, free of backgrounds. Looking at the next large accelerating projects these studies can make an important contribution for the International Linear Collider, especially for potential future energy upgrades which require accelerating gradients beyond current state of the art and therefore new materials and surface treatments which need to be tested on a microscopic level with material science probes such as muSR and betaNMR.

Medical Accelerators

TRIUMF has a spectacular record in developing cutting edge technologies for nuclear medicine. One of them - the cyclotrons for medical isotopes production: TR13, TR19, TR30 have been designed, built and transferred to industry. While the lower energy range (5-70 MeV) cyclotrons nowadays are well represented on the market, the high intensity machines at energies 100-150 MeV are currently not readily available.

This domain would enable production of medical isotopes (therapeutic and diagnostic) with proven commercial demand (82Sr, 68Ge, 224Ra, 211At, 225Ac, 213Bi, 212Pb) as well as new species, that very likely will emerge in the exponentially booming nuclear medicine research. TRIUMF is proposing a high intensity superconducting cyclotron TR100+ in this energy range. In 20 years, TRIUMF lead collaboration will have built a few isotope production facilities based on TR100+ onsite and abroad.

These machines in particular will have fully covered the world-wide demand for Sr-82 that enables virtually all cardiology diagnostic scans, as well as addressing the ever growing medical needs of the ageing population and allowing TRIUMF to maintain and expand a top-notch accelerator physics and technology expertise.

Collaboration on Large-Scale Accelerator Complexes

In today's world, no single institution can afford to embark in a big-science project alone. International collaborations are key to grow the expertise and the visibility of the participating institutions; this is particularly true for small to medium size laboratories, like TRIUMF. Future collaborations are possible with the new electron-ion collider at the Brookhaven National Laboratory (BNL) and, further down the road, with the International Linear Collider (ILC), etc.

TRIUMF aspiration is to collaborate as a contributor by introducing its own original ideas. Our key expertise is both in the theory of beam dynamics and in specialty technical fields such as: superconducting RF technology, accelerating structures, diagnostics, remote handling, magnetic and electrostatic transport systems. Putting this expertise at the service of large-scale

international projects will benefit Canada in several ways: to contribute to the most significant scientific discoveries, attract and train talents, and maintain local cutting-edge expertise.

Superconducting RF technology has become a core expertise of TRIUMF especially coaxial resonators for heavy ion accelerators and crab cavities in high energy accelerators. While an accelerator like the ILC requires thousands of elliptical SRF cavities it only requires a handful of crab cavities. Coaxial cavity technology therefore allows to make a contribution to the biggest upcoming science projects (EIC and ILC) with a relatively small investment. Growing the program around this type of cavities could include exploring new materials such as Nb3Sn. TRIUMF should anticipate to re-establish cavity fabrication in Canada either through qualifying a vendor or further developing in-house capabilities.

Collaborations on Resolving the Environmental Crisis

TRIUMF should leverage its expertise and facilities to support federal and world-wide efforts to reduce human impact on the environment, including our carbon foot-print and pollutant sources. According to Canada's strengthened climate plan “Healthy Environment and a Healthy Economy", one of the objectives towards making clean, affordable transportation and power available in every community is the development of Small Modular Reactors (SMRs). The SMR roadmap has been defined and an action plan has already been released, which specifically calls for universities and colleges, research institutions, and laboratories to provide an essential education and training role, as well as conduct early-stage research and advance international collaboration on topics relevant to the development of advanced SMRs. As an important player in the Canadian nuclear ecosystem, TRIUMF can help the development of these important technologies by supporting the SMR R&D program with its existing accelerator facilities, and expertise in isotope and material science.

In parallel to an SMR program, TRIUMF should look into supporting other nuclear reactor development programs, especially Accelerator-Driven Systems (ADS) for power production and transmutation of nuclear waste. While it is unrealistic that Canada will build an ADS, its SRF expertise and existing partnership with SCK- CEN (he biggest player in the ADS field with their MYRRHA project) provides an excellent starting position for high impact developments. TRIUMF could for example develop double spoke balloon resonators for an ADS project.

In addition to further involvement in the nuclear reactor business, TRIUMF's unique experimental capabilities for probing new energy-storage material properties through betaNMR and muSR will be further expanded in the soon-to-come ARIEL era, and may benefit from continuing upgrades and expansions to support this research which could have a critical impact on the future of the environment.

TRIUMF

TRIUMF Hub

As Canada's center for particle accelerators TRIUMF will assume a leading role in all major endeavors in thisfield in the country. For example, TRIUMF is currently involved with design studies of a compact accelerator-driven neutron source (CANS) as a component of the Canadian Neutron Initiative, under the auspices of the Canadian Institute for Neutron Scattering (CINS) with the eventual goal of constructing a replacement of the NRU facility at Chalk River. Our ambition and mandate is to provide leadership for similar new initiatives across Canada. TRIUMF should capitalize on its broad and deep know-how and unique environment (its large suite of different accelerators, including medical accelerators) and create onsite an accelerator training hub for universities and beyond. Industrial accelerator manufacturing companies and accelerator based medical centers are in great need of such a service, while it is not readily available world-wide. This will position TRIUMF in the forefront of HQP training for society. Personnel in training would also contribute to TRIUMF's operational and development activities, as such helping to address an intrinsic issue with qualified resources shortage. TRIUMF should further strengthen its connection to its partner Universities in the accelerator sciences for graduate and undergraduate education. The creation of a joint position in 2019 with UVic was an important step upon which TRIUMF should further build upon.

TRIUMF

Quantum Technology

Chair: Nigel Hessey (TRIUMF)

Members: John Behr (TRIUMF), Makoto Fujiwara (TRIUMF), Fabrice Retiere (TRIUMF), Thomas Koffas (Carleton), Wolfgang Rau (Queen's), Albert Stolow (U. Ottawa), Andrea Teigelhoefer (TRIUMF)

The Quantum Technology Group has limited expertise in the field of Quantum Technology. However, the members see that this emerging field is clearly of increasing importance, and TRIUMF needs to boldly engage with it. For TRIUMF to play a role in this competitive field, it needs to take on high-risk ambitious ideas. We also discussed other detector technologies, since these were not covered by other groups. There is significant overlap with the AMO, SAP, and Quantum Computing groups. The outcome is summarised below.

What is TRIUMF today?

What does it do?

- Low energy (< 500 MeV hadrons, < 50 MeV electrons) accelerator centre for SAP physics
- National centre for SAP including international projects
- Scientific research in SAP, medical, condensed matter, and accelerator technology

What might be its differentiators ("competitive advantages") in the future?

TRIUMF has several advantages over other Canadian sites, listed below. These should be maintained and developed for future technologies.

- On-site accelerators
- Large body of multi-disciplinary knowledge and experience including engineers, technicians, physicists, admin for big projects
- Theory department supporting nuclear and particle physics
- Expertise in many technologies essential to detector and instrumentation deployment: DAQ, electronics, firmware, cryogenics, vacuum, magnets, beamlines, laser, ...
- Size: can tackle projects too big for individual universities

What trends and changes will shape TRIUMF's future?

- HL-LHC should be shutting down by 2042. HEP will be moving to a new, not yet known, accelerator such as ILC, CLIC, FCC
- Dark Matter searches will be in full flow, ruling out more and more regions, and quite possibly make a discovery
- Cosmology and astrophysics will also continue with great strides, further pinning down DM, Dark Energy and our understanding of the universe
- As project sizes become larger and time scales longer in these fields, there is increasing interest in precision experiments in areas such as symmetry tests and gravity, where emerging novel technologies could be exploited, including Quantum Technologies.
- Detector technologies: the increased scale of some experiments (DM search, neutrino physics, double beta decay, ILC, ...) and requirements of DAQ bandwidth, triggering, radiation hardness will drive detector development. MAPs, 3D integration, novel materials such as GaN, cryogenic detectors, photon detectors, and Noble-gas liquid detectors will all continue to be developed.
- Artificial Intelligence: will allow faster and better tuning of accelerators and DAQ. It will improve analyses, extracting more from our data.

What will TRIUMF be?

- A Canadian centre for SAP physics especially accelerator based but also assisting SNOLAB and other non-accelerator SAP collaborations.
- Canadian centre for accelerator developments for both SAP and commercial/spin- off technologies
- Life Sciences and Condensed Matter will continue to be important
- Quantum Technologies, currently nascent, could grow to take on an important role.

Quantum Computing could enable much better nuclear calculations than current possibilities. Quantum sensing could open up new measurement and discovery possibilities. Condensed matter studies could lead to new quantum materials. New IP developments.

- Canadian hub for Quantum Technologies and AMO techniques, including Quantum Sensing and Metrology for fundamental physics, and possibly for Quantum Information applications
- Increasingly involved in gravitation studies, including LISA and precision studies with atomic fountains including with anti-hydrogen.
- A catalyst for future sensing technology developments, building on its detector expertise and capabilities, partnering with universities, providing unique facilities onsite and fostering the creation of complementary facilities within universities.

Is TRIUMF a site, an idea, a governance model, a network hub?

- All of the above

What role will TRIUMF play in Canada's S&T ecosystem and why?

- TRIUMF will remain central to Canadian SAP, along with SNOLAB.
- Of particular relevance to this group, TRIUMF will continue to support detectors and instrumentation for approved experiments.
- We also see a role for TRIUMF innovating detectors and instrumentation to make new discoveries possible and enable Canadian participation and leadership in future experimental endeavours. We identify the following roles, somewhat weighted to the near term and expected to evolve with time, to remain important, whatever the specific technologies are.
    - Every time-reversal-breaking electric dipole moment proposal has a sensitivity expression improving inversely with the coherence time achieved for each trial-- a quantum state is prepared and allowed to oscillate in time with a known field, with the desired perturbation from new physics measured by the change in phase of a single period of oscillation read out at the very end. This might seem miraculous compared to a decay experiment, which must continuously sample its random decay phenomenon, gaining only with the inverse square root of any counting period. Further holy grails include macroscopic coherence among N atoms, which could improve measurement precision by 1/N^(some power) rather than by 1/sqrt(N). Quantum techniques thus offer brilliant answers in search of interesting questions. Entangled quantized motion of two ions of different isotopes of strontium allows readout of their difference in frequency response to an optical probe with extraordinary common-mode noise rejection [1]. Quantum logic spectroscopy transfers knowledge of a quantum state of a hard-to-probe (and thus well-isolated from environmental decoherence) ion to another ion which can be more conventionally probed [2]. A dark-photon-through-walls experiment harnesses Dicke super-radiance of macroscopic amounts of parahydrogen [3]. Single-photon microwave detection for low-mass dark matter searches has been demonstrated using superconducting qubit-photon quantum non-demolition [4].Traps: It is now possible to string almost any three quantum buzzwords together and find a useful published demo.

- TRIUMF should continue to patiently develop intellectual and technical comparative advantages along with university and NRC partners for precision measurements. Spin-echo techniques are used routinely in muSR and beta NMR. Spukhafte Fernwirkung in neutrino oscillations set a record for long-time nonclassical correlations [5]. Near-future examples include Ramsey fringe experiments for bottled UCN and francium fountain EDM's. Future use likely includes the CFI-approved UBC-TRIUMF hydrogen fountain and interferometer for precision measurements (see below), the Gate 0-approved trapped ion quantum computer project, and the AMO precision centre envisioned in the AMO 20-year section. That AMO precision center must do substantial research with stable isotopes to develop techniques to utilize TRIUMF's comparative advantage in radioactive isotopes. There is no need for quantum cynicism: quantum coherence and entanglement will naturally remain a continually revolutionary research tool, enhancing the long-existent harnessing of quantum effects in semiconductor electronics and tunnel junctions, and there's a reason the concept has captured the public imagination.
- The newly CFI-funded HAICU project, led by UBC and TRIUMF scientists, will have a significant impact on Quantum Technologies. Building upon the recent Canadian-led breakthrough of laser manipulation of antihydrogen, together with a newly proposed concept of magnetically-compressed optical cooling, the project aims to develop quantum sensing techniques for (anti)hydrogen atoms, including (anti)atomic fountain, (anti)atom interferometer, and eventually (anti)molecular quantum logic clocks. While the initial motivation is to apply these techniques to antihydrogen at CERN, they can also push the precision of measurements on atomic hydrogen — a step necessary to achieve ultimate comparisons of hydrogen-antihydrogen properties. The techniques could also be extended to other species that are otherwise difficult to handle, such as cold radioactive atoms or muonium. Success requires several ambitious technology developments, including a cryogenic magnetic compression trap, and single photon detectors at VUV — making this a large-scale project where TRIUMF input will be vital for success.
- Solid state sensors:
  - Silicon-based sensors are undergoing major improvements, with considerable synergy between photon and charged particle variants, and with GaN investigated particularly for extreme radiation hardness. Sub-Kelvin detectors extend detection and energy measurement to very low energy deposits.
  - TRIUMF has groups active in their use and development, and can contribute competitively particularly in the following fields:

- Charged particle detection
  - While silicon strip sensors will still have a role in smaller experiments, developments in pixel sensors are bringing their price per unit area to similar levels as strip detectors; given the better performance, we expect future developments to be in the pixel sector. Depleted-Monolithic Active Pixel Sensor (DMAPS) exploiting standard CMOS fabrication techniques to combine sensor and readout electronics, and Low Gain Avalanche Detectors (LGADs) where excellent time and spatial resolution can be achieved allowing for 4D charged particle track reconstruction are in active development.
  - New sensor materials may be needed for the very high radiation doses expected at future accelerators. If studies of GaN, where Canada has production ability as a competitive advantage, show promise they will remain important for rad-hardness far into the future.
  - These developments are driven by collider experiments, but can have benefits in a much wider field.
- Single photon sensors
  - Relying on avalanche can have wide applications, especially at low temperatures where the dark count rate is reduced. The next frontier is to integrate the read-out with the sensor, allowing 10ps timing resolution. Applications expected in SAP, quantum sensing and communication.
- Electronics integration
  - Relevant to both charged particle and photon detection, 3D integration of electronics allows using the best sensing and electronics technologies, while retaining the tight integration feature that make monolithic sensors so compelling. The facilities in Bromont (QC) within Teledyne DALSA and Sherbrooke's C2MI allow developing this technology in Canada. Possible applications include silicon based Photon to Digital Converter, and combination of a GaN sensor with a CMOS electronics chip.
- Sub-K sensors
  - Cryogenic detectors offer unique opportunities in terms of energy resolution and a large flexibility in terms of absorber materials, making it possible to adopt to a large variety of needs (e.g. single-photon detection with energy resolution for optical photons, IR or UV photons and x- rays, with high efficiency). Due to the existing general expertise in detector technology and the excellent technical and engineering expertise on site, TRIUMF is an ideal place for setting up a cryogenic detector production facility. The respective technologies and expertise could also be used to produce

cryogenic quantum sensors, e.g. based on superconducting tunnel junctions.

- Light management: Light-based quantum technologies are leading to new solutions for producing and transporting photons that can have major impact on particle physics and enable a new generation of experiments. We foresee development of both light sources and photon transport, which are closely allied to photon detection techniques and semi-conductor material development, including GaN.
- Will TRIUMF expand into Quantum Technologies? QT is advancing rapidly, with big funding, and likely to provide useful technologies for us to do fundamental science. Further funding opportunities can arise especially if we work with other groups. Other groups have a lead in some technologies, such as NRC with atomic clocks. We should find the best partners to work with.
    - Whilst we currently have limited QT expertise, we do have expertise in many of the techniques needed: cryogenics, vacuum, lasers, electronics/controls, magnets, electropoles, etc.).
    - We currently have ideas to use QT for both physics measurements (e.g. nEDM, HAICU), and quantum computing for calculations, especially nuclear structure. Over the next 20 years, we could envision things evolving as:
        - Adopt QT techniques (fountains, clocks, quantum computers) and technologies (“quantum scintillators”, low-temperature microcalorimeters, superconducting high coherence platforms/qubits) for our science goals: (antihydrogen, low-energy neutrino searches, axion searches, time reversal symmetry breaking beyond the standard model); join small scale experiments like Gnome for training, outreach; collaborating with other groups including the NRC to learn
        - Adapt: as we learn limitations, we start to improve/tune what we adopted from others to our needs
        - Adept: as we build up expertise, we switch to research into QT itself, developing better tools, both for our own use and use in the wider community.

What will TRIUMF have accomplished?

- TRIUMF will have led or been an important contributor to a Nobel Prize worthy discovery, of e.g. DM, or other physics beyond the SM.
- TRIUMF will have hosted a Nobel Prize winning experiment in some thoughtfully selected niche area (such as UCN, precision measurements, or DarkLight).

What would headlines be in 10 and 20 years that you would want to see about TRIUMF?

- TRIUMF single photon detector in far ultra violet selected for DM experiment
- TRIUMF joins ILC/FCC experimental collaboration to build inner tracker
- TRIUMF atomic fountain delivering results
- TRIUMF develops quantum technologies to manipulate and study antimatter atoms and molecules with unprecedented precision
- Cryogenic detectors developed at TRIUMF open new opportunities

How will TRIUMF have contributed to major societal challenges?

- The main contribution will remain with medical physics.
- Detector systems can be re-purposed for environmental monitoring, with as specific example the ability to monitor forest fires with vuv imaging.
- Medical imaging with TRIUMF detectors reduces radiation exposure of patients
- Radiation-hard semiconductor technologies find a major application in deep space exploration efforts, such as Jovial missions envisioned by ESA and NASA

What will TRIUMF be doing and what will TRIUMF not be doing anymore?

The HL-LHC will be closing down and TRIUMF will be contributing to the accelerator and detector technologies of the next high energy/high luminosity machine that is ramping up.

TRIUMF will host the world's most intense ultra cold neutron source.

Possibly hosting a Canada wide quantum computing facility for academic research.

Measuring atomic systems at unprecedented precision, further constraining physics beyond the standard model or showing deviations from it.

Support cutting-edge experiments at SNOLAB with detector production, electronics and DAQ development.

What activities capture the interest and imagination of the general public?

- Anti-hydrogen
- New semiconductor technologies for wireless communications, deep space exploration

- Quantum computing and artificial intelligence

What will TRIUMF look like?

What buildings and infrastructures will be on the site?

- A new office building
- A new multipurpose lab space

Will there be more than one site?

- That would be a shame, splitting networking, cohesion, and economies of scale

References

1. *T. Manowitz et al. Phys Rev Lett 123 203001 (2019).*
2. *N.-H. Rehbehn et al. Phys Rev A 103 L040801 (2021).*
3. *A. Bhoonah, J. Bramante, and N. Song, Phys Rev D 101 055040 (2020)*
4. *A. Agrawal et al Snowmass 2021 LOI ``Superconducting Qubit Advantage for Dark Matter"*
5. *J.A. Formaggio et al. Phys Rev Lett 117 050402 (2016)*

TRIUMF

Scientific Computing

Chair: Reda Tafirout (TRIUMF)

Members: W. Fedorko (TRIUMF), P. Haljan (SFU), JJ Kavelaars (NRC), A. McCoy (TRIUMF), P. Navratil (TRIUMF), C. Senko (Waterloo), I. Trigger (TRIUMF)

Introduction

Scientific computing at TRIUMF consists of a broad range of activities across the laboratory's domains and research portfolio. These activities play a crucial role in facilitating TRIUMF's mission of discovery and innovation. It is critical that scientific computing keep abreast of technological advances and continue to evolve, so that it can open new pathways and better ways of solving problems. Scientific computing may be considered a third pillar of scientific discovery in its own right, along with theory and experiment.

For the past twenty years, TRIUMF has been a key player both nationally and internationally in all facets of the digital research infrastructure (DRI) ecosystem: advanced research computing, data management, research software and networking. TRIUMF has been at the forefront of technological advances in all these areas, expanding its core competencies and driving innovation. For the past several years, TRUMF has deployed and provided support for several clusters and solutions to meet the needs of large international projects such as the ATLAS and T2K experiments with large-scale and dedicated resources funded by CFI, but also to serve the on-site experimental program, as well as the local theory community engaged in parallel computing applications. TRIUMF has also been involved in research software solutions that benefit not only the TRIUMF community, but also the wider research communities. More recently, new initiatives with respect to machine learning and quantum information systems applications have gained significant traction, and several experimental groups are already benefiting from these advances.

TRIUMF has designed, deployed and operated state-of-the-art advanced research computing facilities and capabilities, most notably the high-profile Canadian ATLAS Tier-1 centre as part of the Worldwide LHC Computing Grid (WLCG), that played a crucial role in the discovery of the Higgs Boson and subsequent Nobel Prize. TRIUMF's participation in WLCG has benefited the wider Canadian research communities, through adoption of innovative solutions by Compute Canada.

Regarding research software, TRIUMF has been part of the GEANT4 collaboration for many years and developed software for simulations of accelerator beams dynamics (ACCSIM) that has been used by international laboratories, as well as the development of the PHYSICA package which is a high-level interactive programming environment with user friendly graphics and sophisticated mathematical analysis capabilities. TRIUMF has also been a key developer and collaborator of the Maximum Integrated Data Acquisition System (MIDAS), which is extensively used by both the TRIUMF on-site experiments and other medium-size experiments around the world. This DAQ expertise dates back to at least the late 1980s, with projects like E787 at Brookhaven National Lab. TRIUMF also has dedicated personnel to handle large-scale FLUKA simulations which are critical for ARIEL shielding design. More recently, TRIUMF has joined the Optimization of Medical Accelerators (OMA) consortium and is performing FLASH studies, a new and promising cancer treatment modality.

Formulating a 20-year vision

Community feedback was solicited via SurveyMonkey and the ThoughtExchange group discussion platform, but unfortunately only a very small number of participants answered (or proposed) questions, directions, or ideas related to scientific computing. To supplement this rather insubstantial community feedback, one-on-one consultations were conducted between the committee members and various experts and key stakeholders. These included representatives of TRIUMF's nuclear physics experiments, and members of the Core Computing and Networking, DAQ, Life Sciences and Accelerator groups for a broad sampling from within the laboratory. We also conducted interviews with individuals in a leadership positions at other physics laboratories, including BNL, CERN, FNAL and JLAB, to gain a better understanding of their strategies and future directions for scientific computing. In Canada, we interviewed representatives of HEPNET/NDRIO and NRC. We also conducted interviews with key researchers from the University of Waterloo, with expertise in quantum information science.

The needs of the particle physics community are laid out in the IPP brief submitted as part of the NSERC Long Range Planning process. We also reviewed various DOE labs' strategies, particularly their initiatives to support and apply artificial intelligence and quantum computing. A literature survey was conducted on modern machine learning applications in particle physics.

Regarding the Canadian Digital Research Infrastructure (DRI) ecosystem strategy in general, we have also reviewed all the relevant White Paper submissions to the newly formed NDRIO. More than 100 papers were submitted, therefore not all of them have been read but only a few considered relevant; the great of the White Papers have been scanned for specific keywords,

such as "Machine Learning" and "Quantum" to gauge the interests of the wider Canadian research community.

We describe below three distinct, although not completely orthogonal, generic areas of activities that TRIUMF should continue to be engaged into and expand upon, as well as new initiatives to remain relevant and competitive for the coming decades. These areas have been identified as those where TRIUMF would play a unique and distinct role, as a national laboratory, with most benefit to its community, while maximizing synergies with other entities, including Universities, NDRIO, CANARIE, industry partners, other national and international laboratories, and virtual organizations.

Scientific Computing Infrastructure

As TRIUMF continues to expand its research portfolio and experimental capabilities, it will require a state-of-the-art on-premises advanced computing infrastructure dedicated solely to research computing. This is completely different from the equally important task of maintaining IT services and related functions solely focused on the business end of TRIUMF's operations (e.g., Mail, Web applications, documentation, training, collaborative tools, etc.), and the two should be kept separate. An adequate organizational structure will be paramount to prevent fragmentation of effort and enhance support for scientific computing with proper resources and focus. The research computing infrastructure should be acquired with minimal total cost of ownership and with varying capabilities and capacities as needed. The main users of the infrastructure would be the local experiments, facilities, and groups, including Theory, who need real-time processing for running experiments, or a fast turnaround time for parallel code development. Large-scale computing resources would still be accessed through a national entity such as NDRIO. Scientific computing techniques, such as machine learning, would also be routinely utilized to improve accelerator operations. Users will be given common tools and services, very similar to cloud computing services, enabling them to deploy their services with dynamic resource allocation. In essence, TRIUMF would provide scientific computing as a common platform and as a service. TRIUMF, perhaps alone among Canadian research institutions, can hire computer physicists with a proven research track record and a deep understanding of experimental challenges and problems, into positions commensurate with their experience, and on long-term or indefinite contracts. This could enable the nurture of a truly first-rate scientific computing group.

TRIUMF must keep abreast of technological advances in the computing industry and be able to evaluate and deploy new technologies and solutions at an early stage to gain a competitive advantage and a head start. For instance, enhanced DAQ capabilities will require the use of FPGAs and utilization of co-processors to enable online data processing chains to do fast real-

time analysis, using machine learning techniques that would reduce the volume of data stored only to be eventually discarded in offline processing. Another example is the utilization of GPU accelerators in large-scale scientific computing. To facilitate this, TRIUMF must put in place a collaboration framework with the computing industry, avoiding the need to strike new agreements and sign new non-disclosure agreements any time a new product or service is available.

TRIUMF must establish itself as complementary to national providers, such as CANARIE and NDRIO, not as a would-be competitor. It is anticipated that NDRIO will remain in place for at least a decade; however, it is not expected that, even in its full maturity, NDRIO will provide Tier-1-like facility services with dedicated personnel on a 24/7 operations model. A Tier-1 facility, such as the one used for ATLAS is effectively an extension of the experiment, with stringent uptime requirements. This is a particular area in which TRIUMF must continue to play a leading role. Collaboration on international projects such as the Worldwide LHC Computing Grid, and the European Grid Infrastructure provides unique opportunities to be involved early on in key developments and innovative technologies, regarding distributed computing, data management, workload management and security frameworks. This ultimately benefits both the overall TRIUMF community and the wider Canadian research communities in various fields of science.

Research Software & Applications

On the timescale of this vision, TRIUMF could establish a centre of excellence in scientific computing. Organization of such a centre could be modelled on existing centres of scientific computing excellence at national labs in the United States and Europe. Such a centre would support research across TRIUMF's science portfolio, fulfil the needs of the TRIUMF community and take global leadership in targeted applications of scientific computing. Fields of research and development supported by the centre must reflect and complement the areas of research pursued experimentally on-site as well as TRIUMF's international partnerships in large science projects.

A clearly identified area where TRIUMF can play a leading role is in development of modeling software frameworks and development of specific models of the passage of particles through matter. Such applications are currently established (GEANT, FLUKA) and are maintained by the user community. Detector simulations are essential across particle, nuclear, accelerator and medical physics, supporting detector design. In life sciences and accelerator physics, simulations are crucial for modelling the targets used in isotope production, and treatment

design. Development of software packages to simulate the passage of particles through material requires dedicated expertise, nurtured over a long period, ideally in the context of a group effort. Hosting of such an effort at TRIUMF would enable partner Universities to enhance their role in future detector developments for instance for efforts such as the International Linear Collider or the Future Circular Collider. Development of this effort is a natural fit for TRIUMF, which has a broad portfolio of on-site and global science applications for such tools and could bring together experts from many of the fields that rely on them. Re-establishing TRIUMF's expertise in modelling the passage of particles through matter within the context of a scientific computing centre of excellence would create efficiencies in terms of shared expertise, create a sustainable effort in this domain, and attract more of the leading experts in the field to TRIUMF.

Advanced research networks (i.e. with complex design topology such as the ones used to handle LHC traffic data) are an area in which it is expected that TRIUMF will continue to play a leading role, in collaboration with national and international projects, alongside with CANARIE. For instance, Software Defined Networks (SDN), which are programmable networks instead of traditional static networks, are a promising area of development as several new projects are coming online that would require a tremendous amount of data to be moved around the globe and analyzed across different network domains. On-demand and dynamic network provisioning would make the most effective use of limited network capacities. For example the Square Kilometre Array (SKA) project will generate vast amount of data at the same time as the HL-HLC which will pose challenges if particularly hosted within the same data centres.

Support for specialized large-scale, parallelized computing is needed by several fields represented at TRIUMF, and efficiencies in support of such activities would be realized by the establishment of the centre. For instance, optimization of parallelized of nuclear theory codes is desired for improving speed and precision of ab initio nuclear structure calculations. Parallelized modelling of commercial cyclotrons and the main cyclotron at TRIUMF would drive detailed understanding of these machines. Specialized software engineering experts would be able to provide expertise in the utilization of modern, heterogenous hardware platforms in applications ranging from nuclear and particle theory (for instance ab initio nuclear theory or lattice gauge theory calculations), modelling of complex phenomena in accelerators as well as large-scale theoretical chemistry calculations. Co-location of advanced experimental facilities – such as the TRIUMF accelerator complex, the IAMI centre and unique experimental facilities (e.g. β-NMR) – with domain and computing talent will provide a unique feedback mechanism that can be efficiently realized within a lab environment. Depending on the current needs of users, experts at the centre will consult on specifications of application-specific, heterogeneous computing hardware. Small-scale development versions of such hardware could be hosted on-site.

Modern Machine Learning (ML) technologies, particularly Deep Learning (DL), have made astounding progress over the past decade, and penetrated many aspects of life and science. In experimental particle physics ML and DL are employed in event reconstruction and analysis, with applications to less obvious tasks such as synthetic data generation or measurement of underlying parton distributions ('unfolding') being developed. In nuclear physics nascent applications are being pursued ranging from data mining to Lattice QCD calculation. In Life and Medical Sciences DL techniques are most prominently in use in diagnostic imagery interpretation, but more advanced applications such as molecular design are on the horizon. Here again, unique interplay between the experimental facilities and computational expertise could be achieved at TRIUMF.

TRIUMF is a recognized centre for detector development and fabrication. AI technologies are likely to be employed in the design of new detectors for future particle and nuclear experiments, and leadership in these new techniques may become essential to maintaining TRIUMF's leadership in detector design. Similarly in accelerator science AI will have a major impact on two aspects: Operational – where AI will be employed for tasks such as machine tuning and predictive maintenance of the facilities – ensuring efficient delivery of beams to experiments; and machine design, based on desired characteristics of the machine to be built.

TRIUMF's needs for ML are unique, but TRIUMF is also exceptionally well placed to enhance scientific output to the fields it supports, because of existing and ongoing specialized expertise at the lab. An ongoing goal for TRIUMF is training highly skilled personnel and preparing them to compete in a knowledge and innovation economy. ML is a very attractive field – currently any position mentioning ML in the job description attracts on the order of 200 applicants, and this trend is expected to continue. Establishment of an excellence centre is particularly well suited for the training of HQP at all professional levels, and this aspect presents an excellent opportunity for TRIUMF to contribute to the establishment of a more equitable society through hiring practices and supervision strategies sensitive to equity, diversity and inclusivity issues. A constant intake of trainees, along with the development of HQP to higher professional levels to maintain a core expert group will ensure the long- term sustainability of the centre.

Quantum Computing User Facility

Quantum Information Science and Quantum Computing have been attracting tremendous interest in recent years, with several public and private billion-dollar-scale initiatives around the world. Several US laboratories are establishing quantum computing initiatives, including user

facilities that provide academic researchers with an alternative to the non-disclosure agreements that often hamper collaboration with industrial partners.

The interest is fueled by the promise of breakthroughs in multiple areas with high societal impact such as molecular structure calculations or machine learning as well as in specific research areas of great interest to TRIUMF, such as nuclear structure and lattice gauge theory calculations. Researchers can now access commercial 10-qubit scale devices with noisy qubits and gates (so called Noisy Intermediate Scale Quantum -NISQ devices). Current research seeks to establish the advantage of these devices for solving practical problems, mainly through the application of hybrid classical-quantum computation.

On the timescale of this vision TRIUMF will become a hub of the pan-Canadian Trapped Ion Quantum Computer (TIQC) network, operating within the scientific computing excellence centre. TRIUMF's main role in the network will be to establish and operate a user facility hosting trapped-ion quantum computers developed at and in collaboration with partner universities across Canada. TRIUMF is well positioned to become a hub in the network exploiting its operational and technical capabilities. Ion- trap-based quantum computers are essentially miniature accelerator systems, which require technical and engineering support analogous to the big accelerators (vacuum, RF systems, cryo systems, controls systems, power supply systems, etc). This mix of accelerator and ion-trapping competencies is unique to TRIUMF in Canada and does not exist at any single partner University.

The construction of a TIQC user facility at TRIUMF will provide access to gate-based quantum computers in Canada to complement commercial or limited public offerings available from vendors of both quantum annealing devices (D-Wave Systems) and gate-based quantum computers (IBM, Rigetti, IonQ, Honeywell). The establishment of the quantum advantage of NISQ devices for solving useful problems is an active area of research with a vibrant community in Canada. Particularly promising in the near term are hybrid algorithms combining a classical computer with a quantum co-processor, with applications in solving molecular and nuclear structure calculations. These applications are of particular interest to TRIUMF and its partners in the context of theoretical nuclear physics research. In the longer term, with large, high-quality quantum processors, quantum chemistry applications are expected to become of practical interest. In this context synergy emerges between facilities such as IAMI, β-NMR and TIQC and the scientific computing excellence centre where multidisciplinary and multimodal research would be accelerated.

Possibilities for quantum-assisted machine learning (QAML) have also recently been suggested. Prospects for quantum machine learning are still speculative for NISQ processors, but given the burgeoning field of big data analytics, realizing a successful application would be of high importance, and could become a key technology for data-intensive sciences (eg. High

Luminosity LHC and future particle physics experiments) critical to TRIUMF's mission. Among TRIUMF's network of member Universities as well as internally there is a strong effort to enhance science outcomes through application of classical machine learning to big data analysis. Initial efforts to do this exist in QAML applications. Primary QAML research is actively pursued in Canada's universities and private institutions, and this community could further expand TRIUMF's user base. Applications of quantum computing to lattice gauge theory simulations are very closely aligned with TRIUMF's mission and have been explored locally in the past. This is an active topic of research at partner Universities. In addition, QC enhancements to research directions such as parton showering and neutrino-nucleus matrix element calculation have been proposed, and expertise exists within the national community to pursue these further. Taken together there is a vast Canadian ecosystem with a high potential to benefit from the establishment of a national quantum computing user facility. TRIUMF would play a central role in making the facility accessible to the national and global users through the development of all levels of the control and software and applications stack.

Summary

Scientific computing includes a number of TRIUMF's historic strengths: data acquisition, simulation of particle transport in materials, and high-throughput computing for very-large-scale collaborations, as well as the new and emerging fields of machine learning and artificial intelligence, and quantum computing. A relatively small core of career computing physicists could form the nucleus of an attractive, innovative group of trainees and collaborators from academia and industry, and provide structure, stability and synergies that would allow TRIUMF to capitalize on its existing leadership in HEP computing. Finally, TRIUMF has the potential to play a significant role in the high-stakes field of quantum computing, where there is an opportunity to contribute local expertise in ion traps and accelerator operation to meet the requirements of Canada's growing quantum computing community.

Site Development

Chair: Anne Louise Aboud (TRIUMF)

Working Group Members: Jens Dilling (TRIUMF), Violeta Toma (TRIUMF), Adrian Lee (TRIUMF), Navid Zolfaghari (TRIUMF), Esther Schirrmacher (TRIUMF), Annika Lennarz (TRIUMF), Dawn-Marie Barreira (TRIUMF), Sean Lee (TRIUMF), Gavin Blackstock (PHSA), Grant Miller (UBC)

What is TRIUMF today?

What does it do?

What might be its differentiators ("unfair advantages") in the future?

Organizational Identity:

TRIUMF was built on the UBC campus in the late 1960s, tucked away in the southwestern corner of the campus. For many years, there was nothing else around surrounded by forest. TRIUMF was likely placed here due to the risk of perception associated with the facility conducting nuclear experimentation, not because of the risk of radiation.

This has influenced the "hidden" culture that TRIUMF has maintained over the years and has created the utilitarian style campus. TRIUMF is physically hidden from the road and its neighbours, and the most fascinating equipment we have is also hidden below concrete blocks.

Science is the core of what TRIUMF does and having the world's largest cyclotron is our differentiator. The site has been developed to facilitate the science, but what is lost in this approach is the how the site design impacts the people. The site and surroundings do not necessarily reflect current the values, the pride and accomplishment that the employees and visitors have in the organization.

Innovation Hub:

TRIUMF is a collaborative hub for researchers from members universities that is known and recognized internationally for its innovation and research.

Design:

The TRIUMF campus has historically followed a utilitarian design, with facilities and building designed for functional purposes. A few of the newer buildings on the campus (ARIEL, Design office and Stores, and IAMI), are more modern, both in esthetics and operations.

Sustainability & Resilience:

TRIUMF has adopted UBC's green building standards and guidelines for the newest buildings on the campus, designed with highly energy efficient building systems. TRIUMF has invested in energy management projects over the last 10 years and is continuing its commitment by supporting the strategic energy management program.

Operational Efficiency:

TRIUMF has a lot of outdated equipment and technology on site and there is significant opportunity to improve operational efficiencies on site.

What trends and changes will shape TRIUMF's future?

Organizational Identity:

TRIUMF's organizational identity will continue to be influenced by the unique research activities in accelerator, physical, and life sciences. Advancements in each of these areas will spur further site development.

Innovation Hub:

As technology advances from fundamental science to commercialization of radioisotopes the role TRIUMF acting as an innovation hub is critical and these opportunities will increase in the future, particularly with academic and industry collaboration.

Design:

Creating and designing space at TRIUMF for industry and academic collaboration will increase innovation and connection.

Sustainability & Resilience:

With climate top of mind for people, universities, and governments, TRIUMF can consider how to quantify and manage its environmental impact.

Operational Efficiency:

Through the pandemic, operational efficiency has increased with the ability to operate remotely, a key step in increasing automation on the site. With an increase in fault detection and diagnostic tools and analysis, TRIUMF could operate remotely, allowing research to be directed from anywhere in the world.

What will TRIUMF be?

Is TRIUMF a site, an idea, a governance model, a network hub?

What role will TRIUMF play in Canada's S&T ecosystem and why?

Organizational Identity:

TRIUMF will be a centre of excellence, a landmark, and an inspiration for people of all ages.

Innovation Hub:

TRIUMF will attract employees and the public from Canada and the world to showcase its diverse, multi- disciplinary program. Opportunities for technology transfer and value-added innovation.

Design:

TRIUMF will be an inviting site that has attractive offices, research and collaboration areas and educational and outreach spaces that represent the culture and history of the site.

Sustainability & Resilience:

TRIUMF will be a leader in managing resources used in operations and its environmental impact enabling more research and discovery in a responsible manner.

Operational Efficiency:

TRIUMF will be a leader in technology and innovation, enabling continuous improvement and optimization of site operations and research.

What will TRIUMF have accomplished?

What achievements will we be proud of within Science & Technology, People Skills, and Innovation & Collaboration?

What would headlines be in 10 and 20 years that you would want to see about TRIUMF?

How will TRIUMF have contributed to major societal challenges?

Organizational Identity:

TRIUMF will be a place that employees are proud to work in and researchers from all over the world will want to visit.

Innovation Hub:

Increasing media exposure and showcasing TRIUMF's involvement in advancing accelerator technology, fundamental and applied physics and life sciences. Building bridges to real-life challenges and problems, including today's and tomorrow's problems and opportunities.

Design:

Further development of TRIUMF's site will consider how to best showcase and increase visibility to the science and research, especially work that may only be done in exclusion areas.

Sustainability and Resilience:

TRIUMF will be a showcase for how innovative research can be done sustainably.

Operational Efficiency:

TRIUMF will be able to operate all year round without a major shutdown and continuously delivering beam to enable more research and experiments.

What will TRIUMF be doing and what will TRIUMF not be doing anymore?

What will TRIUMF be doing if there were no funding constraints?

What are the priorities for TRIUMF activities?

What activities capture the interest and imagination of the general public?

Which program elements or facilities will we have stopped because they have been completed or to make space for new initiatives?

Organizational Identity:

Elevating TRIUMF as a brand and making the site more visible and accessible will inspire future generations of scientists and innovative research. A few key opportunities to showcase our identity are:

- The control room is the nerve centre of TRIUMF, this can be redeveloped to a modern, focal point of the campus.
- Increase use of glass and visuals to help the public understand the work that we do, including inaccessible areas such as the cyclotron, beamlines and counting rooms, building on the virtual tour that has been recently developed by the communications team.
- Create a visitor centre to further engage the public as an outreach and education initiative.

Innovation Hub:

TRIUMF can be a placemaking community, engaging and building relationships with our neighbours. Opportunities for creating an innovation hub and connecting with the community include:

- Create collaboration space for staff, students and visitors to meet and connect.
- Create a maker space and invite people from the community to use our spaces, tools and workshops exposing students, postdocs, technicians and engineers to new technologies, for example 3D printing and fabrication.
- Create an incubation space to support start-ups into commercialization.

Design:

TRIUMF is an anchor tenant of UBC's south campus and can participate in UBC's campus planning, advocating for TRIUMF's vision. The presence and visibility of TRIUMF can be increased from the road, roundabout and from Wesbrook Village by:

- Creating a landmark building that is visible from a distance, optimizing land-use area by considering increasing building height.
- Create a new entrance directly out of the roundabout and that is inviting and welcoming to the community
- Increasing presence of TRIUMF in Wesbrook Village through educational displays, artwork or signage.
- Manage public perceptions and concerns around the proximity to the radiation line through education and knowledge sharing.
- Rethink housing for visiting researchers and what this could look like in the future as south campus continues to expand.
- Improve the working partnership with UBC, collaborating and developing the 30-year plan for the UBC's south campus.
- Build and develop the relationship with the Musqueam Nation through community engagement, incorporating and respecting their interests in our site development and nearby areas of cultural significance.

Sustainability & Resilience:

Post-pandemic stimulus funding from the government will be focused on clean infrastructure building and technology sectors. In considering future growth and site development, opportunities to include sustainability and resiliency are:

- Ensuring that new buildings are highly efficient and building retrofits are to the highest standards, reducing the environmental impact
- Consider the proximity of TRIUMF to Pacific Spirit Park and how the site fits in to the forest.
- Increasing operational efficiencies by reducing resource use in energy, water, and waste materials.
- Partner with UBC to utilize TRIUMF's waste heat as a source of energy in the campus district energy system.

Operational Efficiency:

Increasing operational efficiency will also improve site safety and sustainability performance. Improvements identified to increase operational efficiency are:

- Use robotics in situations and areas that present radiation hazards and are inaccessible during operations.
- Incorporate proven technologies into the operations (such as tools and software) to increase efficiency rather than reinvent the wheel.
- Elevate safety on site from an occupational health and safety using technology and innovation.
- Understand full life cycle costs and impacts of projects during the development stages including energy, maintenance, and other operating costs.

What will TRIUMF look like?

What buildings & infrastructures will be on the site?

Will there be more than one site?

What will TRIUMF's organization and its community look like?

Organizational Identity:

The TRIUMF campus will be upgraded to match the organization's identity, a unique and exciting place of research and technology, and will consider the following:

- There will be spaces indoors and outdoors designed to stimulate collaboration and dialogue between staff, researchers and visitors on site including lecture halls and networking spaces to host colloquium and conferences.
- An outreach and education centre with interactive displays to attract visitors and translate the work that done at TRIUMF to the public.
- Improve staff amenities and facilities to attract and retain top talent such as a fitness centre or daycare promoting a healthy work-life balance and employee wellness.

Innovation Hub:

To support its vision in being an innovation hub and connecting with the community to TRIUMF should consider:

- Creating multi-purpose collaboration spaces, such as a cafeteria and/or coffee shop, and outdoor space with whiteboards.
- Creating publicly accessible space for visitors, site tours and demonstrations deepening the connection with the local, UBC and Greater Vancouver communities.
- Engaging local university, high school and elementary school students to inspire young scientists, encourage them to become more curious, and increase awareness of the work we do.

Design:

As TRIUMF transitions to a have more public presence, the site will need to be inviting. Improving the beauty and esthetics can play a big part, attracting talent and driving performance. Design considerations are as follows:

- A bold landmark that is architecturally unique, interesting, and inviting.
- Focus on the experience as people approach the site as a pedestrian ensuring it is both accessible and approachable.
- Utilize building height to optimize land-use space but also increase the visibility of the site.
- Utilize art or old equipment demonstrations to integrate new modern buildings with the older buildings.
- Improve and optimize the flow of the site to reflect work function and workflow.

- Fit in with the forest, ocean, and mountains around us by incorporate more including green walls and spaces, inside buildings and inside the fence, increase natural lighting in buildings.
- Include WELL standard guidelines in building design, creating a welcoming and comfortable space for staff and visitors.
- Utilize and optimize space between buildings or on building rooftops as meeting space as these can be implemented gradually.
- Bring inside out and outside in.

Sustainability & Resilience:

The TRIUMF campus will need to adapt to local and global impacts of climate change in the future in site development should consider the following:

- Incorporating additional sustainability practices into building design and development, creating showcase buildings for spaces identified for redevelopment.
- Consider construction materials and alternatives to reduce impact.
- Optimize energy and water use at the facility including utilizing waste energy and managing water.
- Advocate for green transportation and increasing accessibility of the site by connecting with UBC on the future Skytrain development, including having a stop on the south campus.

Operational Efficiency:

As the TRIUMF campus involves, future in site development should consider the following improvements for operational efficiency:

- Improve space utilization, through space consolidation, space planning, storage, flexible, multi- use spaces that are bookable.
- Increase in automation and controls of building and process systems.
- Improve safety management on site.
- Improve outdoor landscaping by using drought resistant plants, plants that require low maintenance, and native plants and storm water management drainage by using bioswales.
- Continuous improvement projects that consider project life cycle and impact to minimize operating and maintenance costs to the site.

TRIUMF

People & Skills

Chair: Sean Lee (TRIUMF)

Working Group Members: Kathryn Hayashi (TRIUMF Innovations), Marcello Pavan (TRIUMF), Stephanie Raedel (TRIUMF), Vishnu Vardhan (TRIUMF), Alicia Helde (TRIUMF), Jesse Abney (TRIUMF), Terry Matthews (Waterloo), Tom Roemer (BCIT), Kori Wilson (BCIT)

What is TRIUMF today?

- TRIUMF is Canada's particle accelerator centre – a multidisciplinary laboratory for both fundamental and applied science, and where world class experiments are designed, built, and operated.
- TRIUMF is one of the largest non-university public sector employers of undergraduates and graduates in Canada. TRIUMF trains the next generation of science and technology leaders with highly coveted training programs that attract leading students from across the country.
- TRIUMF is a locally focused centre that supports STEM outreach and increases public awareness of Big Science.
- A "neutral" (connected to but distinct from academia, government, or industry) place to meet for discourse and discussion.

What does it do?

- TRIUMF explores the unknown and the invisible – the world beyond our senses. It pushes the boundaries of physics and questions our models of the world. By exploring abstract theorems through practical observation and novel experimentation, TRIUMF develops new approaches to solving real-world problems.
- TRIUMF is building a diverse and inclusive environment of excellence, where different backgrounds and opinions are leveraged to drive forward world-class research. Equity and inclusion are among TRIUMF's core values, and recent initiatives are small, yet important, steps towards upholding these values.
- TRIUMF is a place where people from different disciplines and backgrounds work together to carry out and advance world-class research. Staff often stay with TRIUMF for their entire careers due to the quality of the science and the work environment. TRIUMF has not had a clear strategy for succession planning.
- In addition to a unique work-integrated learning environment, TRIUMF is beginning to offer professional development, and identifying opportunities to provide compensation

benefits that reduce student attrition; this is a critical component in keeping students involved in the lab throughout their academic lifecycle.
- TRIUMF is a place where top researchers from academia and industry come together to solve important real-world problems and issues. We participate in the global scientific pursuits and work to apply fundamental research to create a better world for all.

What might be its differentiators ("unfair advantages") in the future?

- Multidisciplinarity allows TRIUMF to recruit and attract diverse talent from a wider pool than other research facilities; the laboratory can leverage this to achieve equity, diversity, and inclusion (EDI) across its workforce.
- TRIUMF benefits from its ability to recruit and attract diverse talent from a wider pool through the alumni diaspora tied to its national and international network. TRIUMF's small size also allows it to remain more flexible and nimbler than many of its competitors.
- It offers a unique work-integrated learning environment coupled with a robust professional development program that prepares students for success in academia, business, and industry.
- The lab offers a rich pool of experts-in-residence and can draw on depth and breadth of STEM/STEAM topics to deliver content to educate, as well as to increase national awareness (and appreciation) of science.

What trends and changes will shape TRIUMF's future?

- An enduring commitment to grow EDI through cultivating a critical mass of representation across target groups. TRIUMF must lead by example with a commitment to EDI hard-wired into all laboratory processes; however, in order to accomplish this, resources must be allotted towards EDI efforts, and it must be accepted that challenging and timely decisions will need to be made to make real progress. To maximize results, TRIUMF will also need to partner with key stakeholders and experts to expand TRIUMF's reach and impact on EDI initiatives, committing resources to reach its targets.
- TRIUMF must prepare (and counter) the possibility of the increased turnover of highly skilled staff caused by expansion of choice available to future generations of students and personnel. To this end, TRIUMF must evolve its value proposition for staff, recognizing that it may not always be fully-competitive to industry or academic competitors in pay, ensuring work-life balance must be considered, as should value-added conveniences, such as child care options or on-site recreation facilities.
- Greater student choice in work placements throughout university requires TRIUMF to pivot investments in programs that more directly align with commercial opportunities in

quantum computing, data science, and applied sciences such as medicine and materials. Furthermore, both academia and industry will be demanding students with a stronger set of 'soft skills' who can flourish in collaborative and networked environments.

- To maintain relevance in the knowledge and innovation economy and remain competitive, TRIUMF must pursue tangible real-world impact alongside fundamental discovery.

What will TRIUMF be?

- A world-class laboratory with a focus on the attraction, cultivation, promotion and retention of its diverse and high-performing talent across all levels of the organization.
- TRIUMF will lead a program to develop career paths within and outside of science.
- As a widely known Canadian equivalent to CERN, TRIUMF will be seen as a national hub for outreach and promotion of scientific knowledge and excellence; a Canadian gem that is recognized as a world-class research facility that also actively invests in the promotion of its people and their discoveries.
- TRIUMF will be a partner of choice for key stakeholders in government, academia, civil society, industry. TRIUMF engages the general public to increase understanding and excitement around science and technology.

Is TRIUMF a site, an idea, a governance model, a network hub?

- TRIUMF is emblematic of a Canadian pivot towards strategic investments in science and policy. TRIUMF will exemplify Canada’s commitment to leveraging science and innovation to address broader societal goals and objectives.
- TRIUMF will be a model for ‘EDI done right’ in STEAM.
- A closely knit community working and growing together towards a common purpose.
- TRIUMF is a modern site, as well as a network hub for affiliates and STEAM organizations that benefit from access to our expertise and facilities. It will become a contrast to the academic ivory towers through the embrace of empathy, and human-centered design in outreach.

What role will TRIUMF play in Canada's S&T ecosystem and why?

- TRIUMF will serve as a model for the Canadian science and technology ecosystem where new and bold efforts to promote EDI serve to position the lab as a national/international leader in this area.
- TRIUMF will be a model for training and developing highly skilled multidisciplinary personnel.

- TRIUMF will make ongoing contributions to global collaborations that lead to high-profile success stories and the promotion of the lab's diverse capabilities. Such work provides inspiration and training to the next generation of scientists, technologists, and engineers.
- Delivers a "whoa!" experience and exposes all Canadians – especially marginalized youth – to the fascinating world of science and technology through hands-on programs (both on-site and virtual) that build an early interest and appreciation in the fields.

What will TRIUMF have accomplished?

- Identify and install EDI leaders/champions across the organization. Set clear targets for EDI and put in place mechanisms, including robust data sources and KPIs, to ensure accountability with staff and research teams to strive towards them.
- TRIUMF will have become one of the most desirable places in Canada for students to build valuable skills that will last them their entire careers, also having established a diverse suite of programs to keep students engaged.
- Expansion of the site's facilities to support more programs related to outreach and science promotion, as well as provide space for more national/international collaborations to also take hold.
- TRIUMF's contributions to top-tier national and international collaborations will shine through to the public consciousness, highlighting the laboratory's societal impact and its value to the science and innovation landscape in Canada. With this elevation of the TRIUMF brand, the laboratory will be viewed as a trusted purveyor of scientific data and evidence-based decision-making.

What achievements will we be proud of within Science & Technology, People & Skills, and Innovation & Collaboration?

- TRIUMF will, through a combination of internal and external pipelines, create a critical mass of EDI representation that is self-sustaining. TRIUMF will have also met/exceeded relevant KPIs across all levels of the lab (including leadership), showing a significant movement towards its EDI objectives.
- TRIUMF will maintain high staff retention rates. Those that do leave the organization will remain engaged as alumni grateful for the careers at TRIUMF and will become advocates who have benefited from the lab's ability to support them through all stages of their life while at the lab.
- TRIUMF will be one of Canada's top academic educators and industry employers, boasting an engaged alumni and mentorship network tied to leading positions in academia, business, and industry. TRIUMF will also be widely recognized for training

programs that attract top talent and connect trainees to opportunities in both academia and industry.
- TRIUMF will be a national leader in science outreach and education, leveraging this to attract funding and a steady pipeline of global talent to Canada.

What would headlines be in 10 and 20 years that you would want to see about TRIUMF?

- TRIUMF is recognized in the headlines as leading the effort to grow diversity in Canada's STEM sectors. TRIUMF's diverse personnel are recognized as top tier in awards, publications, and innovative technologies developed and patented.
- TRIUMF will be regarded as one of Canada's top STEAM employers.
- TRIUMF will be recognized as co-op employer of the year by Co-operative Education and Work-Integrated Learning Canada (CEWIL).
- A world-class partner in accelerating discovery in both fundamental and applied research, with TRIUMF being recognized as an anchor in "Canada's isotope valley", which is famous for developing treatment for cancer patients.
- TRIUMF's philanthropic efforts have raised millions for STEAM education via in-house and partner programming.

How will TRIUMF have contributed to major societal challenges?

- Position TRIUMF to be at the centre of a national and international set of EDI best practices in Big Science and research, proactively dismantling systemic barriers and emerging as a standard bearer for EDI leadership.
- TRIUMF will be a model in Canada for supporting students and staff balancing career and family-life responsibilities.
- The laboratory will have leveraged contributions from students and staff to drive forward impactful programs with cross-disciplinary talent and multiple ecosystems to improve human life.

What will TRIUMF be doing and what will TRIUMF not be doing anymore?

- In 20 years, TRIUMF will be a sector champion for EDI, but will no longer be pursing explicit EDI activities, as the principles behind these efforts will be embedded in the culture and values of the organization. While leading by example through their actions, EDI leaders at TRIUMF will no longer need to defend or justify EDI as a priority as the value of these commitments will be self-evident.

- TRIUMF will be developing comprehensive career-pathways for all its staff. The laboratory will have a robust succession planning framework; it will also have a model to balance career and family responsibilities for all its staff.
- TRIUMF will be constantly measuring, evaluating, and improving itself to be the kind of facility it needs to be in the minds of its alumni, its educators, and its student talent pool.
- TRIUMF will be engaging a broad range of people in science and technology experiences, utilizing virtual and novel technologies to reach people in remote regions, underserved communities, and people with mobility issues.

What will TRIUMF be doing if there were no funding constraints?

- TRIUMF would export its EDI model and best practices to other research organizations around the world.
- Provide childcare services for its employees either through an on-site centre or sponsoring space at other centres. More opportunities for all staff (in particular grads and post-docs) to attend more conferences/workshops to develop their networks.
- Increase the number of undergraduate and graduate students to a level aligned with TRIUMF's operational needs and capacity – all supported by a purpose-built work-integrated learning facility.
- Run year-long "camps" (both on-site and virtual) for students of all ages and abilities with specific training program curricula. TRIUMF would hosts world class online-based instructional programs and interactive experiences accessible to all.

What are the priorities for TRIUMF activities?

- Maintaining diversity and representation across all areas of the lab. Fostering and enabling partnerships that support EDI goals and objectives.
- Creating multidisciplinary, public-private collaboration opportunities that address important challenges.
- Be a key player in the promotion of STEAM education and outreach across Canada.

What activities capture the interest and imagination of the general public?

- TRIUMF promotes diversity in its communications and outreach, allowing the public to see people of all types and background playing key roles in science.
- TRIUMF's model for work-life balance is admired in the public sphere.
- Developing alumni who become world leaders in their chosen career field.
- TRIUMF's education programs and general outreach help build awareness in all aspects of the research program but generate specific interest in the practical applicability of result (e.g. medical isotopes, materials science, quantum computing, etc.).

Which program elements or facilities will we have stopped because they have been completed or to make space for new initiatives?

- As noted above, it is envisioned that EDI may no longer need to exist as an explicit program, assuming the values and principles are sufficiently embedded into TRIUMF's everyday practice.

What will TRIUMF look like?

- In the year 2042, TRIUMF's site has expanded with new facilities that include standard office space, laboratory space, auditorium, classroom, and flex spaces. The site is a multi-use community facility able to host outreach and educational events from across the country.
- The campus will be a modern and inclusive facility fitting of the attention it garners from around the world.
- TRIUMF will be the most sought co-op employer in Canada, with applications flowing from all over the world.
- TRIUMF will have a robust online and digital infrastructure allowing staff, users, and the public remotely access and visit the site for both work and educational purposes.

What buildings & infrastructures will be on the site?

- Offices, labs, public and community spaces that create an environment where every member and guest feels welcomed and accounted for.
- Through TRIUMF's 25-year campus vision, ample training centre space is provided for teaching, career-building workshops, maker spaces, and community networking.

Will there be more than one site?

- TRIUMF, seen as a symbol for Canadian excellence, has developed opportunities to co-brand and resource locations throughout the country (and via online platforms) that serve as satellites for research, as well as outreach, events, and education.

What will TRIUMF's organization and its community look like?

- TRIUMF will be a world-class laboratory with a diverse and highly representative community that is a model for other STEAM organizations in Canada and beyond.

- TRIUMF staff and alumni will be a socially active "family" who look out for each other.
- TRIUMF will have an engaged network of alumni graduates and professionals who will be active as a mentor community for students pursuing careers in science, medicine, and business.
- TRIUMF will have a community of sponsors and supporters that have helped build a robust philanthropic program for the laboratory that supports initiatives across the organization.

TRIUMF

Emerging Trends in Convergence Research

Chair: Reiner Kruecken (TRIUMF/ UBC)

Working Group Members: Iain McKenzie (TRIUMF), Caterina Ramodiga (SFU), Rob Thompson (Calgary), Kim Dotto (BCIT), Peggy Schmeisser (U. Saskatchewan), Helen Burt (UBC), Rebecca Lubna (TRIUMF), Jason Chak (TRIUMF), Edward Thomas (McDonald Institute, Queen's)

Introduction

Convergence research is a means of solving vexing research problems, in particular, complex problems focusing on societal needs. It entails integrating knowledge, methods, and expertise from different disciplines and forming novel frameworks to catalyze scientific discovery and innovation.

- The American National Science Foundation

As TRIUMF looks ahead to development of its new 20-year vision, convergence research will open new opportunities to expand the organization's ongoing leadership and contributions in addressing pressing global challenges.

Building on familiar concepts like multi-, inter-, and trans-disciplinary research and scholarship, convergence research offers new models for addressing complex problems through collaboration among multiple stakeholders from across diverse sectors and knowledge systems.

The Canada Foundation for Innovation has encouraged adoption of this new approach to research that is typically "aimed at a specific and compelling problem requiring the deep integration of disciplines, knowledge, theories, methods, data and communities." The collaborative principles informing convergence research approaches will prove critical for the success of Canada's innovation ecosystem and TRIUMF's contributions as a national leader in science and innovation. As CFI emphasizes, "merging ideas, approaches and technologies from widely diverse fields of knowledge at a high level of integration is a crucial strategy for solving complex problems and addressing complex intellectual questions."

Another relevant concept in this context is that of Highly Integrative Basic and Responsive (HIBAR) research which brings together partners with basic research background and experts working outside of basic research who bring leadership skills and deep understanding of a societal problems, jointly driving use-inspired towards solutions-focused innovations.

TRIUMF

What is TRIUMF today?

TRIUMF is Canada's particle accelerator laboratory with a core mission to advance isotope science and technology, both fundamental and applied, to collaborate across communities and disciplines, from nuclear and particle physics to the life and materials sciences, and to discover and innovate, inspire and educate, creating knowledge and opportunity for all.

While the dominant portion of TRIUMF's research is solely curiosity driven, other research as well as technical developments are use-inspired, e.g. the development of radioisotope-based diagnostics and treatments for disease, or materials characterisations motivated by the development of better materials for batteries or quantum computers. TRIUMF facilities are also used for applied research, such as irradiations of electronics components for the aerospace and telecommunications industry.

In recent years, TRIUMF has contributed to various convergence or HIBAR projects:

- Development of cyclotron-based production of radioisotope Tc-99m in a Canada-wide consortium, funded by NRCan ITAP and recently approved by Health Canada.
- MVM Ventilator development as part of international collaboration in response to COVID pandemic with over 6,000 units delivered to the Government of Canada
- Production of alpha-emitting radioisotope Ac-225 to bolster research on Targeted Alpha Therapies (TATs) for cancer and strengthen the development pipeline from lab bench to bedside.
- Development of detector and imaging technology for the mining sector, exploring muon tomography.

Time and again, TRIUMF has demonstrated its ability to contribute to interdisciplinary research projects that involve experts from across various disciplines within TRIUMF and across the broader research community. In fact, TRIUMF has a number of 'unfair' advantages that it can exploit: TRIUMF is nimble and of a size where cross-disciplinary collaboration within the organization is possible. This enables it to leverage its multidisciplinary expertise for a spectrum of projects in its core disciplines and beyond. At the same time TRIUMF can leverage a strong network of national leading Canadian Research Universities as well as international partner organizations. The collaborative, international nature of much of TRIUMF's research has also fostered a culture of teamwork and collaboration across fields that is being utilized for new projects.

However, there are also a number of impediments for TRIUMF and its researchers to contribute to convergence research in a more deliberate way.

- There is a lack of awareness within TRIUMF of the opportunities and challenges to which TRIUMF might be able to contribute and a lack of engagement of TRIUMF in conversations on these topics.
- There is a lack of incentives for TRIUMF researchers and technical staff to pursue research outside of the core mission, since researchers are predominantly focussed on delivering science for their funded projects.
- There is a lack of awareness by external stakeholders that TRIUMF and other Big Science organizations in Canada can contribute to convergence or HIBAR research. When funding schemes are set up to address big societal challenges, there is no strategic consideration to engage Big Science capabilities in the country.
- Lack of strategic vision and discernible decision-making processes to support Big-Science capabilities and potential to contribute to addressing societal challenges; funding incentives primarily foster bottom-up collaboration building instead of building initiatives around existing Big Science capabilities.

What trends and changes will shape TRIUMF's future?

TRIUMF's future will not only be shaped by the evolution of scientific drivers for its core program in nuclear and particle physics as well as accelerator-based life and material sciences. It will also be shaped by the need for TRIUMF to stay relevant to Canada and its society.

Therefore, in the context of convergence or HIBAR research, TRIUMF's future will be shaped by the spectrum of societal grand challenges and governmental priorities spanning from Energy and the Environment (Sustainability, Energy, Climate Change, Natural Resources, Ocean, The North) to Advanced Technologies (Quantum Materials, Quantum Sensors, Quantum Computing, Big Data, AI, Space, Human Technology Frontier) and other important topics of Societal Impact (Personalized Health, Transportation, Border Security, Supply Chain, Food Security, Cultural Heritage, Rebuilding Trust in Science).

There are growing efforts to incentivise interdisciplinary research and cooperation between academia and private sector. Funding programs like CFI IF, CFREF, or NFRF are encouraging interdisciplinary research while the NSERC Alliance grants are encouraging partnerships between academic researchers and industry.

TRIUMF's funding by the federal government relies to a significant level on the alignment of TRIUMF's activities with federal government priorities (e.g. 2014 Federal S&T Strategy, 2017 Innovation and Skills Plan). It can therefore be expected that the Canadian Government will continue to foster innovation and focus on the societal grand challenges.

There is also a growing set of initiatives, like the HIBAR Research Alliance, which is focussed on developing “an improved research and innovation ecosystem that better contributes to solving society’s critical problems” by developing an improved research and innovation ecosystem that expands collaboration on HIBAR Research.

These external trends will have a significant impact on TRIUMF’s role in the national and international science ecosystem and on TRIUMF’s ability to pursue science excellence in its core mission in particle and nuclear physics, accelerator science and accelerator-based life sciences and quantum sciences and associated technologies.

What will TRIUMF be?

Vision: TRIUMF will be a model of collaboration in convergence & HIBAR research, building on its strength across its core disciplines.

Rational: Engaging in convergence & HIBAR research will allow TRIUMF to contribute to the greater good, staying relevant for its funders and other stakeholders. Leveraging and strengthening TRIUMF’s core disciplines has been a model for success in the past and would allow TRIUMF to continue to make leading contributions across its discovery driven research portfolio while demonstrating its importance for the Canadian and international science ecosystem.

Actions needed to achieve this vision:

Build an environment at TRIUMF and exploit our network to foster cross-disciplinary collaboration and use-inspired basic research to contribute to addressing societal and scientific grand challenges.

- Develop mechanisms to identify topics and partners for convergence research
- Generate internal and external dialog around grand challenges. External dialog could be generated by engaging with partner facilities, universities, funders, and policy makers. Internal dialog could be generated by seminar series and workshops focussed on grand challenges and activities to address them that have overlap with TRIUMF’s abilities.
- Develop an environment to incentivise researchers to tackle grand challenges
- Make convergence/HIBAR research part of the TRIUMF mission
- Establish an Innovation Fund for convergence / HIBAR research
- Position TRIUMF in the convergence space and build partnerships
- Develop strategic partnership with academic and non-academic partners on convergence/HIBAR research
- Raise awareness of key influencers of the fact that TRIUMF is a go-to place to help solve challenging problems

- Develop clear ‘front door’ to facilitate engagement w/ TRIUMF in convergence research
- Leverage TRIUMF Innovations to connect industry partners to TRIUMF researchers
- Develop resourced “tickets” for new partners’ “bench time” to provide early-stage access to expertise/facilities
- Facilitate in- and outward mobility across disciplines and institutions
- Establish a Sabbatical & Residence Program for convergence / HIBAR research

Vision: TRIUMF’s brand is synonymous for the value of science and for science communication in Canada

Rational: Building trust in science is foundational to ensure that investment into a research ecosystem has public support, allowing a to enable the long-term convergence and HIBAR research to tackle the grand challenges.

Actions needed to achieve this vision:

Build trust in science and generate access to STEM opportunities for all communities by leveraging TRIUMF’s inspiring story and our nationwide network.

- Extend engagement to communities across Canada
- Leverage TRIUMF’s nationwide network and virtual resources to connect more communities to STEM opportunities.
- Tell our story and engage with the nation’s young and inquiring minds in a variety of ways.
- Expand development opportunities for educators engaged in outreach activities
- Work with established partners in the science communication space to develop a broad portfolio of activities and resources building on their own expertise and life experiences
- Curate outreach resources from and for our members and partners
- Establish a “community of practice” for outreach contacts in member university and other partners
- Build tools and cultivate communications connections that can be leveraged across our network.
- Curate digital communications resources to link our network’s research with its benefits to society.
- Communicate the value of science, technology, and innovation
- Work with stakeholders and partners to celebrate shared successes.
- Emphasizing the role of science, data, and evidence for sound decision making

- Collaborate with member universities, the NRC, granting councils, CFI, international partners, and industry to amplify each other's voices to tell powerful Canadian stories in science, technology, and innovation

Vision: TRIUMF is a cornerstone of Canada's roadmap for large-scale research

Rational: A roadmap for large-scale research is essential for Canada to take full advantage of its investments into major research infrastructures, strategically utilize their complementarity and critical mass to tackle grand challenges, and participate at eye-level in international large scale science.

Actions needed to achieve this vision:

Establish an alliance of major research facilities and partner with universities, agencies, and government to establish a strategic framework for lifecycle support of major research facilities and international big science participation.

- Leverage strategic partnerships to make visible contributions in response to Canada's grand challenges
- Demonstrate how our unique research and technological capabilities as well as our extensive partner network will impact grand challenges in areas relating to Energy, Environment, Health, Quantum Technologies
- Become a major advocate for a Big Science strategy and governance model in Canada
- Engage the other Canadian Big Science Players in gov't relations conversation
- Propose funding schemes that specifically leverage Big Science facilities convergence efforts
- Develop a non-partisan "Big Science" parliamentary caucus
- Create an association of large research facilities as an advocate for Big Science investment and stewardship
- Engage stakeholders in Big Science discussion, e.g. Big Science Round Table

What will TRIUMF have accomplished?

- TRIUMF will have made significant contributions to addressing one or more grand challenges or advanced technologies
    - Examples: Cancer, Batteries, Food security, Quantum Computing, Quantum Sensors, etc.

- TRIUMF will be recognized as a major contributor to rebuilding trust in Science, including increased confidence in its ability to enable Canada and the world to effectively address global challenges.
- TRIUMF will have led the conversation in Canada that has led to a comprehensive stewardship and funding model for Big Science infrastructures across the nation.

What will TRIUMF be doing and what will TRIUMF not be doing anymore?

- TRIUMF will be deliberate and strategic in its approach to contribute to addressing some scientific and societal grand challenges in collaboration across its national and international network.
- TRIUMF has a vibrant convergence research program that attracts collaborators from around the nation and around the world.
- TRIUMF will leverage its eminence in discovery-driven basic research to be a sought-after partner in use-inspired research towards solutions-focused innovations.

What will TRIUMF look like?

- TRIUMF will have maker, laboratory, and interaction space for convergence research visitors.
- The front of the TRIUMF site will include a welcoming science communications and outreach space that highlights the power of collaboration and convergence research
- TRIUMF will have an extensive program for hands-on science experiences as well as interactive in-person and virtual tours.

TRIUMF

Innovation and Collaboration

Chair: Kathryn Hayashi (TRIUMF Innovations)

Working Group Members: Luis Moskven (TRIUMF), Karimah Es Sabar (TI Board), Mike Trinczek (TRIUMF), Keith Ladouceur (TRIUMF Innovations), Martyn Coombs (BWXT), Morgan Dehnel (D-Pace), Paul Cubbon (Creative Destruction Lab), Andrew Robertson (TRIUMF), Sarah Roth (BC Cancer Foundation)

Introduction

Innovation is the practical implementation of ideas that result in the introduction of new or improved goods or services to make a positive impact on society.

Collaboration increases the chances of successful innovation by increasing associations that generate ideas, as well as accelerating of the evolution and adoption of new innovations.

As TRIUMF looks ahead to development of its new 20-year vision, innovation and collaboration will open new opportunities to expand the organization's engagement with a broad community of collaborators, across the spectrum of public and private sector partners, to develop innovations that will make positive impacts on our world.

What is TRIUMF today?

TRIUMF is Canada's particle accelerator laboratory with a core mission to advance isotope science and technology, both fundamental and applied, to collaborate across communities and disciplines, from nuclear and particle physics to the life and materials sciences, and to discover and innovate, inspire and educate, creating knowledge and opportunity for all. TRIUMF is a multidisciplinary lab with a history of successfully applying science to solve difficult problems, making it an excellent breeding ground to advance innovative, convergent ideas into innovative technologies.

Innovation is the application of TRIUMF discoveries and technologies to make a real-world impact. Isotopes researched and manufactured at TRIUMF can be used to diagnose and treat diseases to improve our health, and even save lives. Accelerator-based technologies can help develop the next generation of quantum computers and new batteries for green energy solutions. TRIUMF Innovations is tasked with bringing these innovations into the world.

TRIUMF contributed to solving the problem of an Ontario reactor shutting down that supplied needed medical isotopes for thousands of patients in Canada and around the world, by collaborating with BC Cancer, CPDC, Lawson Health Institute and others to develop a new greener technology that does not require a nuclear reactor to produce imaging isotopes, and gives Canada a path to secure

domestic regionally distributed supply of technetium-99. This technology platform has been licensed to a spinoff company that has successfully raised funds from the private sector to further advance the technology, which can now also be used to make other imaging isotopes for Canadian patients and researchers.

Muon detector technology developed at TRIUMF is the basis of our spinoff, Ideon AI. Ideon has used this TRIUMF technology, miniaturized it and developed proprietary algorithms to use the detector data collected to create a 3-D "X-Ray" image of the earth that extends hundreds a metres from a mining borehole. This can make mining cleaner, greener and more sustainable in the future, making mining excavation more efficient, cost effective and minimizing its environmental impact.

Many early research discoveries lack the expertise, infrastructure, collaborators, and funding to advance them into innovations with impact. Many researchers do not have the resources or incentives to take their early-stage ideas and develop robust proof of concept data packages required to advance innovations through development as they must focus on generating new publications instead of further developing their early discoveries. This results in many early-stage discoveries "dying on the vine". This means that investments made in research projects and research infrastructure are not reaping the full benefit to society. This also means there is a reduced number of innovative technologies in the pipeline for industrial development and commercialization.

Canada has invested billions of dollars in Big Science infrastructure at TRIUMF and other national labs like SNOLAB, CLS, CNL, etc.

What trends and changes will shape TRIUMF's future?

We continue to see the trend of truly innovative technologies coming from areas of scientific and technological convergence and collaboration across scientific disciplines. Innovative Canadian companies like Abcellera have technologies that are positioned at the juncture between scientific disciplines. Abcellera is a $7B company started by a physicist who applied his expertise to solve a biological problem and created a new target discovery platform. Aspect Biosciences is a technology company started by physicists and engineers who applied their expertise to create a 3D tissue printing technology. TRIUMF is working on advances like new conjugated drugs that use medical isotopes coupled with biological targeting vectors, bringing together biology, chemistry, physics, and engineering experts to develop new precision targeted cancer therapeutics and theranostics.

What will TRIUMF be?

TRIUMF will be a collaboration nexus for accelerator-based multidisciplinary science that connects and leverages infrastructure, expertise, talent development, projects, funding and incubation/commercialization to make a global impact.

Vision: Big Science collaborations have real world impact in multiple sectors

Rationale:

Canada's major research facilities must partner with universities, government and industry in collaborative initiatives that leverage Canada's investments into research infrastructure and expertise to focus our resources on challenges that will make an impact on our country and the wider world. During the COVID crisis, the national labs, universities, industry and government worked together to rapidly deploy facilities, expertise and funding to invent, test, certify and manufacture ventilators. This rapid, coordinated deployment of resources can be used for other future challenges.

Actions needed to achieve this vision:

- Create a national Big Science Collaboration Framework that includes researchers, industry partners, government.
- Bring together Big Science organizations and identify key infrastructure, expertise, networks that can be leveraged to address real world challenges
- Connect with industry and government partners to identify challenges that can be impacted by Big Science collaborations
- Develop programs to accelerate and celebrate collaborations that effectively leverage Big Science capacity for real world impact.
-

Vision: Canada has an innovative nuclear medicine ecosystem accelerating research discoveries into treatments for patients

Rationale:

Canada has long "punched above it weight" in medical isotope production and nuclear medicine innovation in the world, due to past infrastructure investments in reactors, accelerators and research facilities. However, many early research discoveries currently "die on the vine" due to lack of infrastructure, expertise and funding and a coordinated, collaborative effort to leverage our assets effectively. This means that there is not a strong pipeline of innovative technologies for development and commercialization as the next generation of novel therapies for patients. Canada must leverage its nuclear medicine strengths: production and R&D infrastructure and expertise to build a strong, innovative and sustainable nuclear medicine ecosystem built on collaboration to effectively leverage our infrastructure, talent, project pipeline, and incubation/commercialization support.

Actions needed to achieve this vision:

Build a national Medical Isotope Innovation Ecosystem that includes researchers, industry partners, government which will:

- Identify and triage early-stage discoveries from nuclear medicine researchers
- Focus and fund, at speed, the most promising discoveries in partnership with private sector and government.
- National and local events to build networks and facilitate collaboration.
- Build a sustainable ecosystem from bench to beside.
- Focus on innovative, impactful new diagnostics and therapies.

Vision: The next generation of innovation leaders is trained in a multidisciplinary collaborative culture

Rationale:

While Canadian produces many top students and trainees, many training programs operate in silos, where physics students work with other physics students and professors on physics projects and have limited opportunities to collaborate outside their core area of study. We know that multidisciplinary collaborations are more likely to lead to innovation and also provide trainees with a broader spectrum of training experience. In addition, industry needs graduates who are more job-ready and trained in real world skills to be globally competitive.

Actions needed to achieve this vision:

Create national programs which provide students with training and role models with high engagement from both industry and academia on collaborative, innovative projects. Leverage the successful TRIUMF training program into a national program that connects top students with innovative multi-disciplinary training opportunities which will:

- Partner with top industry partners to develop training opportunities that provide trainees with hands-on experience and real-world job skills.
- Provide role models/mentors from both academia and industry.
- Focus and incentivize multi-disciplinary, collaborative projects with high innovation potential.

What will TRIUMF have accomplished?

- TRIUMF has worked with government, foundations, and industry to identify and address major societal challenges.
- TRIUMF will lead major global projects for Canada, driven by Canadian advantages in expertise and infrastructure with funding to focus collaborative efforts at speed which bring together researchers, industry, and government to address important challenges.
- TRIUMF is partnered with UBC on a South Campus translational hub with specialized facilities and active innovation programs for translation/collision/collaboration.
- TRIUMF is an “Isotope Valley” hub for nuclear medicine innovation, built upon the foundation of TRIUMF and IAMI that fosters the next generation of innovative companies and trains the next generation of leaders.
- Innovation success means that TRIUMF has contributed to curing cancer (and other diseases) through the development of novel radiotherapeutics and production of medical isotopes.
- TRIUMF has contributed to Canada’s economic development and achieved its own economic sustainability with less reliance on government funding.

What will TRIUMF be doing and what will TRIUMF not be doing anymore?

- TRIUMF will be working on more projects with “real-world” application and impact that are well-aligned with government priorities.
- TRIUMF will have well-maintained, state-of-the-art operating infrastructure.
- TRIUMF will have satellite locations that leverage and contribute to TRIUMF brand of excellence.
- TRIUMF will have active collaboration programs across a spectrum of sectors including electronics, aerospace, semi-conductors, nuclear medicine, climate change, etc.

What will TRIUMF look like?

- The heavy lifting of infrastructure investment is done at TRIUMF site, how can Canada leverage this for maximum impact in terms of outcomes/deliverables?
- TRIUMF site is host to more application/translation/incubation activities. Proximity/clustering are important to advance multidisciplinary cross-cutting innovative technologies.
- Satellite TRIUMF locations across Canada, presence in US, EU, Asia to enable partnerships/collaborations.

- Separate, dedicated research and industrial cyclotrons, so no competition for beam
- TRIUMF will have replaced/renewed cyclotron, efficient and minimized shutdown, multiple smaller cyclotrons, waste handling facilities, emerging biotech companies, robust commercial collaborations, backup production capacity (second site in E Canada?)
- TRIUMF has built out the campus into a world-class facility and grown medical cyclotron research capacity.
- Strong branding and storytelling within in the facility, with physical/visual representations of partnerships including interactive displays/stories.