Final Report

Return on Investment in Large Scale Research Infrastructure

Prepared for:
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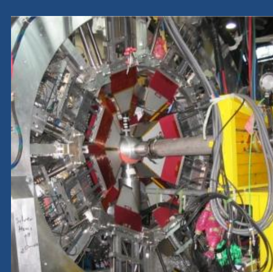

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Executive Summary

This study introduces a systematic approach to evaluating the benefits from investments in large scale research infrastructure that will assist the Government of Canada in identifying, selecting, and managing these facilities to maximize their benefits to Canada.

That approach is illustrated using the example of TRIUMF, Canada's national laboratory for particle and nuclear physics, by performing an analysis of Return on Investment (ROI) over a ten year period (2003-2012) covering a wide range of socio-economic benefits, including training of highly qualified personnel, technology transfer to industry and spillover effects from technology development for the facility, as well as economic benefits attributable to the location of the facility in British Columbia and its impact on the rest of Canada.

The approach has two components: i) a framework that structures a wide range of metrics covering scientific, technical, social, political, economic, and national considerations for the assessment of research infrastructure, and ii) a methodology for the quantification of the economic impact. The approach is suitable for a number of purposes, including the assessment of proposals for the creation of new research infrastructure and the evaluation of the performance and continuing need for existing research infrastructure.

To accommodate the diversity of possible returns and the different decision-making contexts in which projects are assessed (i.e. scientific, political, etc), the Return on Investment Framework has three levels of expected returns as shown in the following table:

Disciplinary Metrics ▶▶▶	Cross-Disciplinary Metrics ▶▶	Strategic Metrics ▶
Scientific Excellence: Does the facility provide an exceptional ability to enable frontier research and education? Is the research impact transformational, with evidence of significant leaps in capabilities, and understanding? Has the facility altered fundamental science or open up significant new lines of enquiry?	**Relative Scientific Impact**: How "transformative" is the facility in comparison to those of other disciplines? What is the international relevance of this facility? Do similar facilities exist in the international research community?	**Scientific Competitiveness:** How important is the facility for: ▪ Maintaining or enhancing scientific competitiveness in the particular research area? ▪ Training, retaining and attracting scientific expertise? Has the facility resulted in greater research output? What are the risks of not meeting these competitiveness objectives?
Technical Excellence: Is the facility pushing the frontier of technology? Are technical risks being thoroughly addressed?	**Impact Across Communities**: Does the facility have cross-disciplinary impact? Is it of interest to more than one stakeholder group?	**Economic Benefits**: What is the economic impact of the facility? Does the facility enhance Canadian R&D and innovation capabilities? What are the risks to not meeting

		the economic objectives?
Community Support: Does the relevant research community consider the facility a high priority? Is the facility accessible to an appropriately broad user community?	**Urgency**: (for proposals) How important is timeliness of the proposal in contrast to other proposals? Is there a window of opportunity? Are there interagency and international commitments that must be met?	**Societal Benefits**: Does the facility have wider societal benefits, including: ▪ Public outreach activities? ▪ Impact on education in schools or of the general public? ▪ Health impacts? What are the risks to not meeting the societal objectives?
Disciplinary Impact: How many researchers, educators, and students does the facility enable?	**Readiness**: (for proposals) Is there a high state of readiness to proceed with development? ▪ Technical / engineering maturity ▪ Partnerships ▪ Facility management ▪ Level of international commitment ▪ Compliance with environmental regulations	**International Leadership**: Does the facility provide international leadership? Does it continue to build on current leadership and expertise? Does the facility bring prestige to Canadians? Is it supported by partnerships that strengthen Canada's standing in the international community? What are the risks of not meeting these leadership objectives?
Partnerships: Are partnership possibilities for development and operation being fully exploited?	**Synergies:** Does the facility benefit from or contribute to coherence and synergies with other Canadian or international programs and investments?	**National Priorities**: Does the facility support current national priorities?

TRIUMF (originally the TRI University Meson Facility) was conceived in the late 1960s to conduct fundamental research in meson and proton physics. The project received final approval in 1968 and the first maximum energy beam was extracted in December, 1974. TRIUMF is now owned and operated by a consortium of 17 Canadian universities: 11 full members and 6 associate members.[1] Since 1995, TRIUMF has been mandated to pursue economic and social returns for Canada from the "vigorous pursuit of technology transfer activities, contracts and procurement policies"[2].

In February 2008, TRIUMF was awarded $14.95 million for a Centre of Excellence for Commercialization and Research (CECR), a program of the Networks of Centres of Excellence (NCE). As a result, TRIUMF incorporated the not-for-profit corporation Advanced Applied Physics Solutions Inc. (AAPS) to receive the CECR funding. The mission of AAPS is to develop technologies emerging from worldwide subatomic physics research, including TRIUMF

[1] Member Universities: University of Alberta, University of British Columbia, Carleton University, University of Guelph, University of Manitoba, Université de Montréal, Simon Fraser University, Queen's University, University of Toronto, University of Victoria, York University; Associate Members: University of Calgary, McMaster University, University of Northern British Columbia, University of Regina, Saint Mary's University, University of Winnipeg.

[2] TRIUMF (2010) Business Development Plan 2006 to 2010, p4.

research. AAPS did not receive additional funding in 2013. AAPS will now become a unit within TRIUMF while continuing to pursue its original mandate.

This study has found that TRIUMF has achieved a wide range of returns on investment for Canada across the metrics contained in the above framework.

For example, TRIUMF has achieved an enviable record of scientific excellence in nuclear physics, particle physics, nuclear medicine, molecular and materials science, and accelerator science. It provides a central resource to a broad community of scientists and students across 17 Canadian universities and industry. It also is responsible for international scientific partnerships with the United States, Germany, Japan, India and others. In particular, TRIUMF coordinated Canada's involvement in the ground-breaking work at the Large Hadron Collider of the European Organization for Nuclear Research (CERN) that recently proved the existence of the Higgs boson. The scientific work of TRIUMF has resulted in the training of a large number of very highly qualified personnel in a variety of disciplines. It has also provided the inspiration for students at the high school level to continue their education in science. And perhaps most importantly, TRIUMF has made significant contributions to medical science in the areas of cancer treatment, medical imaging, and Parkinson's disease research.

Finally, while the primary mandate of TRIUMF is the pursuit of excellence in fundamental research into sub-atomic physics, and not the pursuit of economic impacts, such impacts have been significant, as the results of this study have shown.

TRIUMF has received $630 million over the last ten years, of which $541 million was grants from public sources and $16 million was commercial revenue. The remaining $73 million was flow-through transfers from other organizations. During that time, TRIUMF spent $622.4 million on operating and improving its facilities, realizing an increase to fund balances of $7.3 million. AAPS has received $12.4 million since it was created four years ago[3], of which $11.3 million was grants from public sources, and $1.1 million was commercial revenue. During that time, AAPS spent $11.8 million on its operations, realizing an increase in balances of $0.6 million.

As a result of that investment, TRIUMF and AAPS had a direct GDP impact of $424.9 million for the study period; the total GDP attributable to TRIUMF and AAPS was $941.1 million. British Columbia has received 80% of this total.

The following table summarizes the economic return on investment ratios from a number of points of view:

[3] This figure is the principal and interest drawn down from the CERC endowment of $14.95 million that AAPS received in 2009.

Point of View	Economic Return on Investment Ratio
Return to British Columbia[a]	8.3
Short-Term Return to Canada[b]	1.7
Investment Choice Return[c]	0.77
Long-Run Return to Canada[d]	0.53
Return to Government[e]	0.46

a. GDP increase in BC relative to investments by the BC government
b. GDP increase in Canada relative to public investments
c. Direct GDP increase in Canada relative to public investments
d. GDP increase in Canada after public investments are repaid relative to public investments
e. Tax return increase relative to public investments

While it would be helpful to situate these numbers in a comparative landscape, given the unique nature of TRIUMF, appropriate comparator studies were difficult to obtain. For purposes of context, TRIUMF was positioned on a continuum of investments in innovation stretching from direct funding to industry for immediate impacts to the long-term funding of basic science at the other end – where TRIUMF resides. In this context, TRIUMF compared favourably with at least one case of a technology procurement program.

It is worth repeating that any economic benefit achieved is a bonus on top of TRIUMF's primary mission of scientific research. In fact, TRIUMF is achieving demonstrable social and economic benefits above what might be expected from a scientific research organization.

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1. Introduction

This study introduces a systematic approach to evaluating the benefits from investments in large scale research infrastructure that will assist the Government of Canada in identifying, selecting, and managing these facilities to maximize their benefits to Canada.

That approach is illustrated using the example of TRIUMF, Canada's national laboratory for particle and nuclear physics, by performing an analysis of Return on Investment (ROI) over a ten year period (2003-2012) covering a wide range of socio-economic benefits, including training of highly qualified personnel, technology transfer to industry and spillover effects from technology development for the facility, as well as economic benefits attributable to the location of the facility in British Columbia and its impact on the rest of Canada.

An initial version of the approach has already been applied to Canada's large scale research infrastructure in astronomy. In developing the approach, HAL's 2011 report on the state of astronomy in Canada[4] drew from the criteria used by several other countries, including the US, the UK, and Australia, when assessing major scientific investments.

The approach recognizes that funding for large scale research infrastructure is of a magnitude that such investments must compete for discretionary public funding that is ultimately allocated at the political level, or with political considerations. As a result, these decisions usually take into account a multitude of factors. With scientific excellence being a pre-requisite for consideration at this level, it is often the non-scientific considerations that shape the narrative for the returns that are expected. Alongside scientific excellence, development of talent, leadership, national prestige, economic and societal impacts, and the possibility for partnerships, are all commonly expected returns from an investment. Note that the metrics encompass those of the federal S&T Strategy – the three primary categories being, Entrepreneurial Advantage, People Advantage, and Knowledge Advantage.

A component of the determination of the return on investment for large scale research infrastructure that deserves particular attention is the quantification of the economic returns. Again, the methodology employed in this study was previously applied in the context of astronomy for the calculation of the economic impact of the GEMINI and ALMA telescopes. It considers the contributions of government, industry, and technology users to the current and future impacts of the technology and its spinoffs, including indirect and induced economic impacts.

[4] Hickling Arthurs Low Corporation (2011) *Astronomy in Canada*, prepared for the National Research Council, May.

Information for the analysis of TRIUMF was obtained through a document review and interviews. The document review relied heavily on TRIUMF's business development plans, business development plan annual reports, annual financial reports, and scientific activities reports. Nineteen interviews were conducted with TRIUMF, universities, and industry. The organizations consulted are listed in Appendix A.

This study has provided the opportunity to further refine and prove the approach in its application to TRIUMF. This report is structured as follows:

Chapter 2: Approach – Describes the framework for the determination of the return on investment for research infrastructure, including considerations in the calculation of the economic return.

Chapter 3 TRIUMF Background – Provides an overview of TRIUMF, its research infrastructure, and its economic activities.

Chapter 4: TRIUMF Return on Investment – Applies the framework described in Chapter 2 to the case of the TRIUMF research infrastructure.

Chapter 5: TRIUMF Economic Impact – Calculates the quantifiable economic impact of TRIUMF's activities.

Appendix A: Interviews

Appendix B: Glossary

2. Approach

The approach for the return on investment in large scale research infrastructure described here has two components. Section 2.1 describes the return on investment framework that structures a wide range of metrics covering scientific, technical, social, political, economic, and national considerations for the assessment of research infrastructure. Section 2.2 drills down into the approach for the quantification of the economic impact.

This approach is suitable for a number of purposes, including the assessment of proposals for the creation of new research infrastructure and the evaluation of the performance and continuing need for existing research infrastructure.

2.1 Return on Investment Framework

To accommodate the diversity of possible returns and the different decision-making contexts in which projects are assessed (i.e. scientific, political, etc), the Return on Investment Framework has three levels of expected returns (See Table 1).

The first level (Column 1: Disciplinary Metrics) groups together expected returns that are germane to the discipline from which the proposal is made. Facilities must first meet the standard of true scientific excellence, whereby an investment realizes, or holds the potential for having, a transformational impact in terms of knowledge acquired, and capabilities and concepts developed. Also important is the technological excellence of the facility, especially in consideration of the fact that new scientific facilities normally demand significant technological development at the forefront of current knowledge. This inherently introduces questions of risks and viability which must also be factored into the consideration. Another important metric at the disciplinary level is the extent of the scientific community's support for the facility, as well as its impact in terms of teaching and research opportunities. Given that large scale research investments can be perceived as coming at the expense of more widely distributed investments, the potential for criticism from within the broader research community exists. Finally partnerships, and the extent to which the facility has sought out appropriate partnerships to share the investment risk, is now critical given the associated costs of new investments.

Table 1: Recommended Return on Investment Metrics for Large Scale Research Infrastructure

Disciplinary Metrics ▸▸▸	Cross-Disciplinary Metrics ▸▸	Strategic Metrics ▸
Scientific Excellence: Does the facility provide an exceptional ability to enable frontier research and education? Is the research impact transformational, with evidence of significant leaps in capabilities, and understanding? Has the facility altered fundamental science or open up significant new lines of enquiry?	**Relative Scientific Impact**: How "transformative" is the facility in comparison to those of other disciplines? What is the international relevance of this facility? Do similar facilities exist in the international research community?	**Scientific Competitiveness:** How important is the facility for: ▪ Maintaining or enhancing scientific competitiveness in the particular research area? ▪ Training, retaining and attracting scientific expertise? Has the facility resulted in greater research output? What are the risks of not meeting these competitiveness objectives?
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Partnerships: Are partnership possibilities for development and operation being fully exploited?	**Synergies:** Does the facility benefit from or contribute to coherence and synergies with other Canadian or international programs and investments?	**National Priorities**: Does the facility support current national priorities?

The second level (Column 2: Cross-Disciplinary Metrics) brings to focus more general metrics that are particularly relevant when a facility is being assessed in a multidisciplinary context. The relative scientific impact and the extent to which a facility serves more than one community become important factors in this context. Also, in cases where the framework is being used to assess investment proposals, the urgency of the investment or the window of opportunity to invest, and the overall technological and managerial readiness of a proposal, are relevant. The last metric in this column is that of synergies, which takes into account the extent to which a facility is aligned with, or makes use of, other priorities, investments, or programs.

The third level (Column 3: Strategic Metrics) identifies strategic metrics that correspond to wider considerations of government. The relevance of a facility to the overall scientific competitiveness, its potential for economic or social benefits, its importance to maintaining or developing scientific leadership, and finally, its role in supporting national priorities, are all factors that come to bear on large scale research infrastructure investments.

Related to each of these are questions of risk. What, for example, are the risks should scientific competitiveness not be maintained?

2.2 Economic Impact

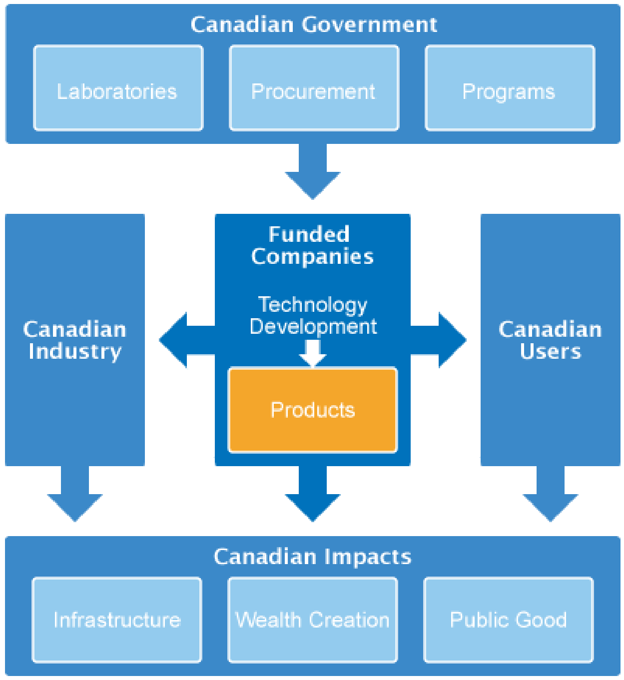
2.2.1 Economic Impact Model

Economic returns from technology result from its commercialization and application, rather than from its development. The immediate return from a million dollars worth of technology development is essentially the same as from a million dollars worth of road building (or any other activity). However, technology development can create greater returns than other activities in the long-term because of its potential for commercialization and application in areas other than that for which it was initially developed. When assessing the potential payoff from technology development, these downstream benefits must be identified and estimated.

Economic impact can be thought of in terms of a framework with five main parts (Figure 1). Central to the framework are companies that undertake technology development, product development, production and marketing activities. Some companies receive funding through projects related to the research infrastructure, and may be influenced and assisted by other government activities, such as the work of government laboratories, and the efforts of other government programs. The Funded Companies, in turn, influence the rest of Canadian industry through the intentional and unintentional diffusion of skills and knowledge to other companies. The Funded Companies also have economic and non-economic impacts through the Canadian users of their goods and services. In the end, the activities of the Funded Companies, Canadian government, Canadian industry, and Canadian users result in impacts on the Canadian economy in the form of infrastructure improvements, wealth creation, and benefits in the public good.

The following sections examine these five parts of the Economic Impact Framework

Figure 1: The Economic Impact Framework



Canadian Government

Government can assist in technology development and commercialization through a number of mechanisms; for example procurement, laboratories, and programs. In the early stages of the technology development cycle, government assistance often plays a major role. The rationale for this assistance is discussed in Section 2.3.

In the later stages of the development cycle, government assistance often involves more general enterprise development. The reasons for government intervention here are generally industrial development, regional development, employment generation, etc. that are consistent with government and social priorities and objectives.

Funded Companies

Spending on research infrastructure and technology development provides some immediate impact; however economic returns from technology come primarily from the commercialization and application of the technology rather than from its development. These longer-term spinoffs result from the increased expertise and experience Funded Companies acquire in undertaking the research infrastructure work. Possession of a skilled and experienced labour force, production facilities, technological and project management expertise, and so on, will make a significant contribution to the future competitiveness of the Funded Company.

Factors that characterize the relationship between the original research and spinoffs include:

- The capability of firms that undertake the contracted activity to pursue commercialization; and
- A long list of product and market development factors (time lags due to certification, registration, patenting, etc., competition from foreign sources, market conditions, business conditions, etc.) that impact whether the resulting product becomes a profitable venture.

Other Canadian Industry

Through diffusion, other companies, which do not have a relationship with the research infrastructure, can gain people, technology, or concepts from Funded Companies that will have a beneficial impact on their own capabilities to develop and commercialize technologies. Diffusion occurs through mechanisms such as strategic partnerships, patenting, published papers, movement of personnel, and reverse engineering.

Canadian Users

There are also potentially economic impacts resulting from the application of related technology by users in the form of improved product quality or lower costs of production that improve the competitiveness of these firms. It is recognized, however, that many such new technologies would likely be eventually available from outside of Canada. Therefore the incremental benefit comes mainly from the advanced timeliness of such developments or the application of technology in manners particularly suited to Canadian conditions, resulting in an accelerated adoption rate and greater penetration for Canadian users.

In addition (unlike the production and sale of products), the use of a technology may also have non-economic benefits for the environment, sovereignty & security, social welfare, health, and the advancement of knowledge. Since these are non-economic by nature, it is not practical to try to reduce them to monetary terms. While they have not been considered here, they are no less important.

To summarize, the impacts from research infrastructure come from three sources:

1. Research and development of related technology,
2. Production and sales of products and services that embody the technology, and
3. Use of the technology (embodied in goods and services).

Traditionally, impacts have been thought of in terms of direct wealth creation - stimulating the economy through the production and sale of tangible goods or services in the economy, usually by the private sector. In addition, we know that technology can enhance the social well-being of a country (the public good), and the infrastructure. Infrastructure improvements, such as faster communications systems, will ultimately contribute to productivity, wealth creation, and the public good. The quantification approach described below only considers wealth creation impacts.

2.2.2 Measures of Economic Return on Investment

First, it must be remembered that the majority of research infrastructure benefits can only be described in qualitative terms (the framework for which was described in Section 2.1) and that this does not make such benefits any less relevant or valuable. For those elements of impact that are amenable to quantification in terms of dollars, impact is often presented as a benefit/cost ratio. There are issues in the calculation of both the numerator and denominator of this ratio.

One problematic measure that is sometimes used for benefits is industry revenues. This measure does not have significant economic meaning because it provides no information on value added. If there is no value added, there is no economic activity and therefore no impact. Large industry revenues may hide very small impacts. For example, if machinery is simply imported by a distributor and sold to Canadian users, the industry revenues of the sale[5] may be very large, but the value added, and therefore economic impact, may be very small because most of the money flows back to the foreign supplier.

However, properly measuring value added is not simple. To the extent that spending on technology development and production occurs in Canada, there will be benefits to Canada. Less obviously, some portion of the work done in Canada will 'leak' out in the form of payments for component parts and services that are not available domestically. A reasonable proxy for economic impact is then, exports plus import substation[6] less imports. This measures the net increase in revenue to the region of study from research infrastructure related activities.

There are a number of factors that need to be considered in calculating the benefits. The first is the time value of money. It is preferable to have a dollar today, rather than a dollar tomorrow. Since the costs of research infrastructure projects are typically borne today, but the benefits often stretch far into the future, they need to be translated into a net present value through discounting. The choice of an appropriate discount factor is a contentious issue. Unfortunately, little guidance is provided by the Government of Canada on what rate to use. A 1998 report from the Treasury Board Secretariat[7] recommends 8% for the time value of money. However, the rate should be altered based on the relative risk inherent in the investment (higher risk should demand a higher return, and therefore a higher rate). Research infrastructure investments are risky, but no guidance is available about how that should be reflected in the rate.

[5] There may be additional impacts from the use of the equipment.

[6] Import substation is when a new Canadian capability permits goods or services to be sourced domestically that otherwise would have been imported.

[7] See, for example, the Treasury Board Secretariat, Benefit Cost Analysis Guide, DRAFT July 1998; www.tbssct.gc.ca/fin/sigs/Revolving_Funds/bcag/BCA2_E.asp. On the other hand, the 2001 report "Research at DOE: Was it Worth it?" from the United States National Research Council suggests a discount rate of 0% and the United States Office of Management and Budget specifies 7%.

The second factor is the dual considerations of incrementality and attribution:

- **Incrementality** refers to the difference in impacts between what would have happened without the supported activity (the funding of research infrastructure) and what did (or will) happen with the activity. If nothing changes as a result of this activity, impacts and effects are the same with and without, and the supported activity is said to have zero incrementality.

- **Attribution** refers to the allocation of benefits among various investments. Even if the supported activity makes incremental differences in impacts, some fraction of the impacts may logically be attributable to other activity, funding sources, organizations or stimulants. To the extent these other sources can be identified, they should share in the allocation of impacts and effects associated with the supported activity. For example, there are substantial efforts and investments in complementary assets (and associated costs) required from companies to commercially exploit technology developed from public research. Thus, even if fully incremental, the benefits attributed to the research funding must be reduced by a factor that takes into account these other investments.

In calculating the cost side of the benefit-cost ratio, there is an additional consideration. This is inefficiencies in the collection and spending of the funds. Government money that is spent on science is obtained from taxes – corporate, personal, and consumption taxes. This process is inefficient and therefore, it costs the nation more than a dollar for every dollar it provides in funding. A recent study[8] calculated the marginal cost of raising revenue from taxes. In summary, it costs approximately $1.26 for the next $1. There are also inefficiencies in the distribution of that money. For example, it costs NSERC approximately 4% to administer the funds that it distributes to researchers. Therefore, at a minimum, $1.30 must be taken from tax payers for every $1.00 that is given to researchers.

This means that, to break even, Canada would need to expect at least a 30% economic return for the cost of money, and additional amounts to account for risk (which is considerable, as discussed earlier), the time value of money (returns will be far in the future from when the funding is provided), and social opportunity costs (there are many other worthy uses for the money). In short, breakeven is not a one-for-one return on funding.

Unfortunately, a benefit cost ratio in isolation provides little guidance without knowing the benefit cost ratios of alternative investments (the opportunity cost of making this investment rather than another). This is a significant difficulty as the benefit-cost of most government investments is rarely calculated (health care, education, social assistance, defence, etc.), and to the extent that such studies exist, differences in the methodologies used mean that comparisons across studies are problematic.

[8] Dahlby, Bev; Ferede, Ergete (2011) 'What Does it Cost Society to Raise a Dollar of Tax Revenue?', C.D. Howe Institute, No. 324, March.

2.2.3 Calculation of Economic Impact

The calculation of the quantifiable economic impact of research infrastructure has three parts:

- Determination of the direct spending related to the infrastructure. This information usually is obtained from the financial records of the organizations involved.
- Determination of the spin-off and diffusion impacts resulting from technology development, if any. Estimates of past and future spin-offs can be obtained from Funded Companies, and can be assisted by appropriate models. Estimates of technology diffusion require appropriate models. An example of a spin-off and diffusion model is the Technology Impact Model maintained by HAL and described below.
- Determination of the economic impact (gross domestic product impacts) of the direct, indirect, and induced economic contributions. This is usually accomplished using econometric models such as Input-Output models or Computational General Equilibrium models.

HAL Technology Impact Model

The HAL Technology Impact Model is concerned with the quantification of the downstream benefits from the public support of R&D and the development of technology.

In the model, we define public support of R&D and technology development as Sponsored Activity. Such Sponsored Activity leads to Spin-Off Activity within the firms or organizations under contract to the sponsoring agency. This Spin-Off Activity results from the expertise and capabilities attained through their involvement in the Sponsored Activity. Possession of a skilled and experienced labour force, production facilities, technological and project management expertise, and so on, will make a significant contribution to the competitiveness of the industrial team in both Canadian and world markets.

Spin-Offs are considered to occur only within a firm that has performed Sponsored Activity. Technology that is developed during this activity, and related technology that is developed by research laboratories, will be diffused throughout the industrial sectors in Canada. Thus, Diffused Technology Activity results in technology-producing firms other than firms who have undertaken Sponsored Activity.

Inputs to the model include:

- Expenditures: Total expenditures of the activity that generate spin-off benefits. This includes both public and private sector investments.

- Type of activity: The nature of the activity funded. Speculative activity with a large research component will have larger spin-offs than a contract for a deliverable (eg. hardware) which requires little or no new technology development.

- Incrementality and attribution: Incrementality refers to the difference in impacts and effects in Canada between what would have happened without the sponsored activity and what did (or will) happen with the activity. An attribution factor determines what portion of the total economic activity is justifiably attributable to the sponsored activity (ie. accounts for the other contributing factors). Only using the incremental and attributable activity to estimate the economic impacts of the sponsored activity results in lower, but more realistic and credible, impact estimates.

- Time: The distribution of benefits over time is important since a benefit is preferred sooner to later. The Time Response component of the model translates the stream of sponsored expenditures into a stream of spin-off and diffused sales so that later benefits can be appropriately discounted in value.

The Model does not account for: Consumer surplus benefits; Benefits to users of new technologies (spin-offs); Induced economic impacts; or Qualitative benefits. These should be taken into account separately.

Input-Output Models

Input-output tables are used to describe the dollar value flows of commodities between industry, persons, government, and foreigners. In the case of regional input-output tables, these flows are extended to include inter-regional flows. An input-output model is developed by converting a set of input-output tables into input-output matrixes and vectors, and then use matrix algebra to define the model's algorithm. The model's vectors are changed (initial shock) and the algorithm will compute the economic impact on industries. An economic impact using an input-output model can be disaggregated into three effects: direct effects, indirect effects, and induced effects.

- Direct Effects – The industrial change that occurs resulting from the initial shock. The initial shock is broken down between the region's production, international imports, taxes, and inter-regional imports.

- Indirect Effects – The resulting industrial change from the increase in inputs required to produce the commodities of the directly affected industries. This is an iterative calculation since each supplying industry will also require inputs, and so on. At each iteration, 'leakages' are removed from the region in the form of taxes and international and inter-regional imports.

- Induced Effects – Direct and indirect effects generate labour income for households (i.e. wages and salaries), which can either be saved or used to purchase consumer products. Saving is a leakage to the flow of income in the economy. Spending this income will create more demand for both domestic and international commodities, which in turn will generate more industrial production and labour income. This cycle continues until the leakages erode the flow of income to zero.

The direct, indirect and induced effects can be translated using fixed ratios into other economic indicators, including: employment, GDP, labour income, and taxes:

- Gross Domestic Product: The value added of the goods and services produced.
- Employment: Results for employment are based on Full-Time Equivalents after adjustments for part-time and seasonal workers.
- Labour Income: Wages and salaries are recorded on a gross basis, before deductions for taxes.
- Taxes: Taxes include components paid to federal, provincial, and municipal levels of government.

2.3 The Economic Argument for Canadian Public Support of Research Infrastructure

Large scale research infrastructure supports basic science, and so it shares with basic science research many of the same benefits, and difficulties in measuring those benefits. Since the end of World War II, when the benefits of investing in scientific research became fully apparent, support for research from governments and the public in Canada and among advanced economies the world over has been remarkably steadfast. The plethora of new knowledge-intensive products, ranging from transistors to magnetic resonance imaging, together with the very significant economic benefits accruing to those companies and countries where such innovations were developed, has only further consolidated support over the decades.

Indeed, despite the difficulties in quantifying the social and economic benefits, the basic policy rationale for supporting research is now effectively beyond political debate, with relevant policy discussions concerned not with whether to fund research, but how best to support research to achieve maximum benefit. What the appropriate balance is between applied and basic research; what the relative benefits are of carrying out research at universities versus government labs; how industry can be encouraged to take advantage of publicly funded research and carry out their own research - these are but some of the policy issues that have emerged recently in Canada.

Growing alongside this support has been a body of literature focused on gaining a better understanding of the various benefits of research and how research supports innovation and economic development. From these extensive studies, it is very clear that research plays a vital social and economic role in advanced economies; more so today than when the value of research was first fully recognized in the post war period. By accessing and expanding the stock of scientific information, firms that invest in the capacity to exploit it are able to advance their technological activities and innovations and stay at the forefront of their often globally competitive industries.

However, this raises an important question: "if fundamental, curiosity-driven, research is economically important, why should it be supported from public, rather than private, funds?"[9] There are a number of classic economic arguments for why government should support basic research, all based on the concept of 'market failure', the idea that the free market, if left to itself, will under-invest in science. These arguments are founded on the belief that science is in the public interest and therefore is deserving of pursuit.

- **Appropriability** – The main cause of market failure in science research is the concept of 'appropriability'; the fact that while basic science is important for society as a whole, it is difficult for any individual investor to profit from the results. This is for a number of reasons: i) the time from discovery to application is typically very long, ii) laws of nature cannot be protected under intellectual property laws, and iii) the cultural and educational benefits that are of value to society do not tend to generate direct profits that can be captured by an individual or company.[10]

- **Risk** – The other cause of market failure is risk. The uncertainty of results, the timeframes necessary to achieve impacts, and the difficulty in reaping any resulting rewards, means that the risks of basic science research are too great for any small group of investors. Governments, through taxation, can increase the number of investors to the population of the country and thereby spread the individual risks and rewards.

Because basic science is in the public interest, and because it is supported by the public, there is a strong rationale for making scientific information freely available. Because no one is excluded from using the information, and it is freely available, scientific information is, in economic terms, a 'public good'[11]. As research moves from basic science towards applied science and its specific application, the appropriability of the results increases, the risks decrease, the resulting information takes on the characteristics of a private good, and support for the research can be increasingly expected from the private sector.

[9] Smith, Llewellyn (1997) "What's the Use of Basic Science?" http://www.jinr.ru/section.asp?sd_id=94
[10] Ibid
[11] A 'pure' public good has very specific characteristics:
- The marginal cost of providing an additional unit is zero;
- Use by one individual does not reduce availability to others ('non-rivalry'); and
- Individuals cannot be excluded from using the good or service ('non-excludibility').

Common examples of public goods include television broadcasts and national defence arrangements. Scientific research results have attributes of public goods in that:
- The marginal cost of supply to an additional person is low, falling close to zero with new technology;
- Use does not deplete the availability to other users; and
- There are potential issues relating to free-riding and to the extraction of revenues.

If there are convincing arguments that science has value, and should be supported, there is still the question of why that support could not be left to others. With the global diffusion of research knowledge, internationalization of economic production and research networks, and mobility of highly skilled individuals, the benefits of research extend well beyond the institution, province, or indeed country, where such activities are originally funded. And as research becomes ever more a global endeavour, this fact is only likely to become more pronounced, particularly as countries such as China and India increasingly invest in research capacity.

This borderless trait of research ultimately raises an important question of whether it is worthwhile for a country such as Canada to invest in its own research, if, as an alternative, it could simply draw from the global stock of knowledge and labour flows to address its knowledge needs. In economics, this is known as the 'free rider' effect – where one party can get a free ride by appropriating the benefits of an investment of another. This is most likely to happen when the investment is made in a commodity that is a 'public good', such as scientific research.

It turns out that, while the results of basic scientific research are generally freely available, highly trained people are needed to assimilate scientific publications and exploit scientific findings. In this sense the results of basic science are not a 'free public good'. Therefore the free-rider effect is mitigated in that the basic science investments of others can only be appropriated if one has the 'absorptive capacity'[12] to understand and implement the results. Knowledge comes in two flavours: i) scientific publications contain 'codified' knowledge; ii) with performance and experience comes 'tacit' knowledge, the elements of knowledge that can only be obtained through learning by doing. Codified and tacit knowledge are inextricably linked and, together with the necessary infrastructure, result in 'absorptive capacity'.

Salter and Martin[13] paraphrase the OECD[14]: "knowledge and information abound, it is the *capacity* to use them in meaningful ways that is in scarce supply." Therefore, as they say: "No nation can 'free-ride' on the world scientific system. In order to participate in the system, a nation or indeed a region or firm, needs the capability to understand the knowledge produced by others and that understanding can only be developed through performing research."

By establishing a research capacity, a region also establishes its receptor capacity, becoming a node of expertise in global knowledge flows and learning that can result in a number of positive regional benefits, including developing a highly qualified labour force, supporting the attraction and creation of new companies, and fostering a stronger learning and innovation environment for local and regional firms. One study in the US, for example, found patents by US companies tend

[12] In an influential study, Cohen and Levinthal (1989) suggest that one can characterize the internal R&D efforts of firms as having two faces: their R&D both allows firms to create new knowledge and enhances their ability to assimilate and exploit external knowledge. They refer to this second dimension as the firm's 'absorptive capacity'.

[13] J. Salter, Ammon; R. Martin, Ben. (2001) "The Economic Benefits of Publicly Funded Basic Research", Research Policy 30 509-532. February

[14] OECD, 1996. Science, Technology and Industry Outlook, p231.

to cite papers produced by local public-sector institutions,[15] while a seminal study of Silicon Valley and Route 128 found that local institutions, including the research infrastructure, can profoundly shape a region's capacity to innovate.[16]

This localization aspect has been explained in part by the fact that knowledge, especially technological, is ultimately embodied in people, the result of which is that face-to-face interactions among researchers, firm staff, and other individuals as they go about developing technology and solving common problems are important. This is also at the core of explanations for why industry clusters can help improve the innovation performance of associated companies: these interactions, which cannot be readily 'traded', help create a social environment that allows and encourages the sharing of ideas, knowledge and learning.

Thus, while publicly funded research does benefit society at large, the regions in which such research is carried out derive additional economic benefits – both directly from the employment of researchers, and from the spillovers of research investments that include the attraction and creation of firms and the deepening of the local labour market.

Another critical aspect of absorptive capacity is the ability of a national innovation system to translate the results of basic science into technological innovations that have economic impact. Japan was particularly adept at this in the 1970s and 80s, but is perhaps less so today. Martin and Irvine[17] comment that during the same period, the prevailing economic and social conditions in the UK were such that potential spin-offs were not translated into actual economic benefits. The innovation system of the US has been, and continues to be, very successful of translating scientific research into innovations and economic impact. Canada is generally considered to have had middling success.

[15] The study found that 27% of 'state-of-the-art' references in patents were linked to research at institutions within the US state in which the patent was taken out. Hicks, D., Olivastro, D., 1998. *Are There Strong In-state Links Between Technology and Scientific Research*. Issue Brief, Division of Science Resources Studies, CHI Research, Cherry Hill.

[16] Saxenian, A., 1994. *Regional Advantage: Industrial Adaptation in Silicon Valley and Route 128*. Harvard Univ. Press, Cambridge

[17] Martin, Ben R.; Irvine, John (1981) Spin-off from basic science: the case of radioastronomy, Phys. Technol. Vo. 12, pp 204-212

3. TRIUMF Background

This chapter provides a brief overview of TRIUMF's history, research infrastructure, and economic activities.

3.1 History

TRIUMF (originally the TRI University Meson Facility) began in the late 1960s as a collaborative effort of three universities: the University of British Columbia, the University of Victoria, and Simon Fraser University. It was conceived to conduct fundamental research in meson and proton physics. The project received final approval in 1968 and the first maximum energy beam was extracted in December, 1974[18]. TRIUMF is now owned and operated by a consortium of 17 Canadian universities: 11 full members and 6 associate members.[19]

TRIUMF's concern with commercial return began with the federal government's 1995 five-year contribution agreement. Section 10 of that agreement identified the requirement for a Small Business Development Plan that would enhance the impact of TRIUMF on the economy of Western Canada. As a result, TRIUMF began to give preference to small Western Canadian suppliers and helped to promote their products and technical abilities to international organizations such as CERN.[20]

In 2000, the next five-year contribution agreement increased the scope of TRIUMF's commercial focus from small business development in Western Canada to business development in general throughout the country. The 2005-2010 five-year agreement also identified the need for economic and social returns to Canada from the "vigorous pursuit of technology transfer activities, contracts and procurement policies"[21]. Those expectations continue to apply under all the current contribution agreement as articulated in its Article 10:

Article 10: Traceable Economic Benefit

10.1 TRIUMF shall exercise commercially reasonable efforts to ensure that during the term of this Agreement, direct and substantial industrial benefits accrue to Canadian companies by

[18] TRIUMF (2003) Business Development Plan Annual Report, p2.

[19] Member Universities: University of Alberta, University of British Columbia, Carleton University, University of Guelph, University of Manitoba, Université de Montréal, Simon Fraser University, Queen's University, University of Toronto, University of Victoria, York University; Associate Members: University of Calgary, McMaster University, University of Northern British Columbia, University of Regina, Saint Mary's University, University of Winnipeg.

[20] CERN (Conseil Européen pour la Recherche Nucléaire) is a fundamental physics research organization in Europe that is home to the Large Hadron Collider (LHC).

[21] TRIUMF (2010) Business Development Plan 2006 to 2010, p4.

> assisting Canadian companies in developing new competence in high technology consistent with TRIUMF's expertise, and in developing products to be demonstrated in international high-technology showcases.
>
> 10.2 TRIUMF shall develop a Business Development Plan to be implemented over the life of this Agreement, which will assist Canadian high technology firms and entrepreneurs to commercialize technology flowing from the Project and to sell the resulting products in the international scientific market. This Plan should outline measurable goals and targets for the commercialization of TRIUMF technology, and contain a procurement strategy and specific steps, such as the use of an 'open bidding system', designed to maximize benefits to Canadian firms. The Plan must be provided to NRC before April 1, 2010. TRIUMF must report regularly on its success in achieving the goals and targets of the Plan.
>
> 10.3 TRIUMF shall encourage Canadian suppliers to develop the necessary capabilities and talents to support the follow-on manufacture in Canada of any products arising from the Project.
>
> 10.4 TRIUMF shall make reasonable efforts to collect data on the industrial benefits traceable to this Agreement, and shall calculate the Canadian and regional content of all its major expenditures funded by this Agreement, in a manner that is auditable and verifiable. TRIUMF shall provide NRC annually with all necessary information to enable NRC to report that data to the Minister of Industry.

As part of its current Five-Year Plan, TRIUMF intends to double its commercial revenues[22]. This is to be achieved through a combination of new business lines; strategic choices about sharing time and resources with the private sector to develop and commercialize technologies; and enhanced efficiency on existing business activities. However, TRIUMF does not measure the success of its commercial activities solely in terms of the revenues it generates. There are many activities that are seen to transcend the requirement for maximizing financial return, particularly in the life sciences, where TRIUMF has been able to assist with the diagnosis and treatment of various diseases.

Indeed, TRIUMF has made the point[23], and it bears repeating, that in considering business development goals it must be remembered that:

- The primary TRIUMF mandate was originally established as, and continues to be, the pursuit of excellence in fundamental research into sub-atomic physics.

[22] TRIUMF (2012) Business Development Plan Annual Report, p14.
[23] TRIUMF (2001) Business Development Plan, p22.

- While TRIUMF may have an economic impact in Canada, it is not by nature an economic engine and cannot sacrifice the pursuit of excellent science for economic effects, although most studies conclude that excellent science ultimately benefits the economy in the long-run.

- By global university and research institution standards, TRIUMF's sponsored research budget is modest, and it would be unrealistic to expect numerous spin-off or spin-out companies, or high numbers of inventions and patents with resultant high royalties.

3.2 TRIUMF Research Infrastructure

The foundation for all of TRIUMF's activities and accomplishments is its research infrastructure, which is summarized in the following sections.

3.2.1 500 MeV Cyclotron

The 500 MeV cyclotron is TRIUMF's primary instrument upon which many other programs and capabilities rely. The cyclotron accelerates negatively charged hydrogen ions (one proton and two electrons) with a high frequency alternating electric field and uses massive magnets to confine the beam in a spiral trajectory. When the beam passes through a very thin graphite foil, the electrons are blocked, while the protons pass through and are directed to a proton beam line. Protons can be provided simultaneously to up to four beam lines. Applications include experiments, medical isotopes, proton irradiation, and proton therapy,

Although the cyclotron is over 30 years old, its capabilities have improved over the years as a result of system upgrades.

3.2.2 ISAC

The TRIUMF Isotope Separator and Accelerator (ISAC) facility uses the cyclotron to produce rare isotope beams for research and development. Applications of ISAC include:

- Measuring the rates of nuclear reactions important in astrophysics,
- Learning about the structure of exotic nuclei and the nuclear reactions that produce the chemical elements in stars and stellar explosions,
- Studying the structure of the atomic nucleus and the forces that hold it together,
- Measuring the mass of short-lived isotopes with high precision,
- Measuring the lifetimes of excited states of nuclei.

3.2.3 Atlas Tier 1 Centre

The ATLAS experiment at CERN's Large Hadron Collider (LHC) is using proton-proton collisions at the highest energy ever achieved to look for the Higgs boson, the particle central to the current model of how subatomic particles attain mass. ATLAS will produce up to 5 petabytes of data per year, and secondary data sets may double that amount. In order to analyze this data, CERN is coordinating an international network of high-performance data centres. The Canadian Tier-1 Data Centre located at TRIUMF is one of eleven in the world.

3.2.4 Nuclear Medicine Laboratories

The TRIUMF nuclear medicine program focuses on PET (Positron Emission Tomography) imaging and the creation of medical isotopes using small cyclotrons.

In PET imaging, radioisotopes are combined with bimolecules and injected into the body. The biomolecules can be traced by imaging the decay products outside of the body. PET is more sensitive than any other human imaging method and is the best method for the detection of cancer.

The PET program facilities at TRIUMF include small cyclotron systems for the production of radioisotopes and chemistry labs for the synthesis of radiopharmaceuticals. The program supports the BC Cancer Association (BCCA) and a joint program with UBC and the Pacific Parkinson's Research Centre for the study of central nervous system disorders such as Parkinson's disease, Alzheimer's disease, and mood disorders. A pneumatic system transports the radiopharmaceuticals directly to the UBC hospital.

The Functional Imaging Program at BCCA is a collaboration with TRIUMF, UBC, and the BC Children's Hospital. TRIUMF supplies 18F.

3.2.5 Centre for Molecular and Materials Science

TRIUMF uses subatomic particles as probes of materials structure at the Centre for Molecular and Materials Science:

μSR uses the muon's spin to examine structural and dynamic processes in bulk materials on an atomic scale, especially the internal magnetic fields of different materials.

β-NMR is a form of Nuclear Magnetic Resonance (NMR) that is about 100 times more sensitive than conventional NMR. It is used to study the magnetic and electronic properties of ultrathin films and nanostructures.

3.2.6 Laboratory for Advanced Detector Development

TRIUMF contributes to the design, development, and construction of advanced detectors for diverse applications beyond particle and nuclear physics to include molecular and materials sciences and nuclear medicine. This work includes an electronic signal processing system for the acquisition of large volumes of data from modern detectors.

3.2.7 Proton and Neutron Irradiation Facilities

TRIUMF beam lines provide low-intensity energetic proton and neutron beams to simulate radiation exposure in space or terrestrial environments. Several minutes of exposure in these beams can provide the equivalent of years of operation for the testing of electronics.

A large fraction of the proton users are Canadian space-related companies, while neutron use is primarily by international companies for avionics, microelectronics and communication equipment.

Each year about 90 users from about 30 companies, laboratories and universities use the test facilities[24]. Commercial users are charged an hourly rate for beam use, while researchers are provided free access.

One of the beam lines is used for the treatment of ocular melanoma, a type of cancer of the eye, at the Proton Therapy Centre which is operated in conjunction with the BC Cancer Agency and the UBC Department of Ophthalmology and treats on average 10 patients a year.

3.2.8 ARIEL

TRIUMF is currently constructing a new facility, the Advanced Rare IsotopE Laboratory (ARIEL). It will use a Canadian high-power superconducting electron accelerator (E-linac).

The primary mission of ARIEL will be to produce rare, short-lived exotic isotopes, and in particular those with extreme neutron excess, to simultaneous and multiple experiments at the existing ISAC accelerator complex. A secondary mission of ARIEL will be to anticipate future uses of E-linac technologies such as free electron lasers, and including commercial uses such as the production of medical isotopes by photo-fission.

3.3 TRIUMF Economic Activities

In addition to its scientific and medical contributions, TRIUMF provides an economic return in a number of different ways:

- By providing medical isotopes.
- By assisting Canadian companies to develop the expertise to build and supply specialized equipment, first to meet TRIUMF's research needs and then to meet the needs of laboratories and businesses world-wide.

[24] TRIUMF (2012) Business Development Plan Annual Report, p5.

- By training people in specialized areas who in turn take their expertise to work in existing companies, or start new companies of their own.
- By supporting related companies, currently through AAPS.
- By providing services such as irradiation services. TRIUMF provides beams of energetic protons and neutrons for testing products and treating cancer.
- By attracting conferences to the Vancouver region.

The following sections look at each of these and provide examples of companies with which TRIUMF works.

3.3.1 Medical Isotopes

TRIUMF works with Nordion, the BC Cancer Agency, the Pacific Parkinson's Research Centre, and Genome BC in the production of isotopes for medical applications.

Nordion

Nordion is a global health science company, headquartered in Ottawa, that provides products used for the prevention, diagnosis and treatment of disease, including targeted therapies, sterilization technologies and medical isotopes. Nordion's customers are some 500 pharmaceutical and biotechnology companies, medical-device manufacturers, hospitals, clinics and research laboratories that use its isotopes for cardiac imaging, targeted cancer treatments and sterilization of medical products[25]. Nordion employs approximately 90 staff at its TRIUMF facility, and exports approximately 95% of its isotope production.[26]

Nordion has a 30-year commercial relationship with TRIUMF that has resulted in a number of pioneering developments in molecular imaging technology and the development of Nordion's commercial radioisotope production facility on the TRIUMF campus, utilizing TRIUMF-designed technology[27]. Products manufactured at this facility assist in the diagnosis and treatment of diseases such as thyroid and prostate cancer, and cardiac and neurological disorders. In addition, Nordion and TRIUMF are conducting collaborative research and development in the areas of radiochemistry and biology that will explore new approaches for imaging, treatment and diagnosis of disease. For example, in April 2009 they announced a study of the feasibility of producing a viable and reliable supply of photo-fission-produced molybdenum-99 (Mo-99) used globally for diagnostic medical imaging.[28] In May 2009 the two organizations announced a

[25] Retrieved February 1, 2013 from Nordion – Our Company: http://www.nordion.com/our_company/about_Nordion.asp
[26] MMK Consulting. (2009). Economic and Social Impacts of TRIUMF. Retrieved February 1, 2013 from Nordion: http://www.triumf.ca/sites/default/files/MMK-EconomicImpact-Study-vFINAL.pdf
[27] Retrieved February 1, 2013 from Nordion – Our Partners: http://www.nordion.com/our_partners/institutional_collaboration.asp
[28] Retrieved February 1, 2013 from TRIUMF News Releases: http://www.triumf.ca/home/press-room/news-releases/moly-99

three-year research and development partnership to pursue the development of new diagnostic imaging agents – medical isotope products using technology based on radiometals and chelates.[29]

BC Cancer Agency

The BC Cancer Agency (BCCA) is an agency of the Provincial Health Services Authority that provides a population-based cancer control program for the residents of British Columbia and the Yukon. The Agency's mandate covers: cancer prevention and screening, diagnosis, treatment and rehabilitation; setting treatment standards, and conducting research into causes of, and cures for, cancer. BCCA's Research Centre includes eight specialty laboratories including the Genome Sciences Centre, and the Terry Fox Laboratory.[30]

BCCA and TRIUMF have a long standing working relationship on the production of medical isotopes and research in oncology related imaging. In November 2009, TRIUMF announced that it had received, together with BCCA and other partners, a $1.3-million grant from the Canadian Institutes of Health Research (CIHR) and the Natural Sciences and Engineering Research Council of Canada (NSERC) to develop an alternative source of medical isotopes. The objective of the two-year research project was to determine if medical isotopes produced from cyclotrons can be a viable alternative to isotopes produced using nuclear reactors.[31] As of September 2010, after years of working alongside TRIUMF experts, BCCA began producing medical isotopes on its own.[32] BCCA also collaborates with TRIUMF and UBC's Eye Care Centre in the Proton Treatment Facility at TRIUMF, which is dedicated to treating a cancerous growth on the back of the eye called choroidal melanomas.[33]

Pacific Parkinson's Research Centre

The Pacific Parkinson's Research Centre (PPRC) acts as a centre of excellence for diagnosis and management of Parkinson's and other related disorders and conducts a strong research program that spans preclinical, clinical and population studies. PPRC's research program focuses on the use of Positron Emission Tomography, and study of the natural history and progression of Parkinson's disease, genetic forms of Parkinson's, the complications of long-term disease and its therapy and the placebo effect.[34]

TRIUMF nuclear medicine group supplies all the PPRC radiotracers. The PPRC program is based on nuclear medicine and thus must have a supply of radiotracers. The C-11 based radiotracers are not possible without TRIUMF because of the short half-life of the isotopes and

[29] Retrieved February 1, 2013 from TRIUMF News Releases: http://www.triumf.ca/home/press-room/news-releases/mds-nordion-triumf-ubc-partnership
[30] Retrieved February 5, 2013 from BC Cancer Agency – About BC Cancer Agency: http://www.bccancer.bc.ca/ABCCA/default.htm
[31] Retrieved February 5, 2013 from TRIUMF – BC Cancer Agency to lead $1.3-million program evaluating medical-isotope alternatives: http://www.triumf.ca/node/2153
[32] Retrieved February 5, 2013 from TRIUMF – BC Cancer Agency producing own isotopes: http://www.triumf.ca/headlines/bc-cancer-agency-producing-own-isotopes
[33] Retrieved February 5, 2013 from TRIUMF – Proton Therapy: http://www.triumf.ca/proton-therapy
[34] Retrieved February 5, 2013 from Pacific Parkinson's Research Centre: http://www.parkinsons.ubc.ca/Research.html

TRIUMF’s proximity to the UBC hospital makes this research possible. TRIUMF produces five radiotracers for studying the brain’s dopamine system Parkinson’s and has recently expanded into serotonin.

Genome BC

Genome BC is a non-profit research organization that invests in and manages large-scale genomics and proteomics research projects and enabling technologies focused on areas such as human health, forestry, fisheries, bioenergy, mining, agriculture and the environment. Established in 2000, it helps to facilitate the translation of genome sciences-based research into practical applications in areas of strategic importance.[35] Genome BC has created sector strategies in consultation with scientists and end-users to predict and quantify the future impact of genome sciences by clearly defining and understanding the challenges facing each sector.

Genome BC has a one-year antisense PET research project with TRIUMF/BCCA/UBC with the goal of imaging gene expression levels related to disease.[36] The TRIUMF nuclear medicine group is also exploring strategic opportunities with Genome BC to develop novel radiotracers for the advancement of oligonucleotide-based radiopharmaceuticals.[37] A joint research project is showcasing TRIUMF’s large molecule radiochemistry expertise by demonstrating the design and production of peptide-PNA tracers to enter, seek, bind, and allow quantification of mRNA within cells.[38]

3.3.2 Equipment Suppliers

In the course of its operations, TRIUMF purchases products and services from a wide range of suppliers. Of particular relevance to its economic impact are the companies that TRIUMF works closely with in the development of new particle accelerator technologies. These companies thus acquire new skills and capabilities which allow them to better compete internationally. Two examples are ACSI and PAVAC.

Advanced Cyclotron Systems Inc. and EBCO Industries

Advanced Cyclotron Systems Inc. (ACSI) is a Richmond-based firm that manufactures, markets, installs, and services TR cyclotrons – complete systems for radioisotope and radiocompound production – using a design originally developed by TRIUMF in the 1980’s. ACSI manufactures and supplies cyclotrons to nuclear medicine markets worldwide, including hospitals, universities, research facilities and commercial distributors of medical isotopes.[39] It also provides services, including site preparations, project scheduling, radiation protection, licensing and other related

[35] Retrieved February 5, 2013 from Genome BC – Research Overview: http://www.genomebc.ca/portfolio/research-overview/
[36] Retrieved February 5, 2013 from TRIUMF: http://www.triumf.ca/sites/default/files/20121101%20NucMed-PPAC1.pdf
[37] TRIUMF. (2011). *Supra* note 10
[38] TRIUMF. (2012). *BeamOn Annual Administrative and Financial Report 2011-2012*. Retrieved February 5, 2013 from TRIUMF: http://www.triumf.ca/sites/default/files/FAR-FY2011-Final.pdf
[39] Retrieved February 1, 2013 from Advanced Cyclotron Systems – About ACSI: http://www.advancedcyclotron.com/about-asci

logistical requirements. ACSI employs approximately 65 employees, and another 45 at EBCO, to manufacture cyclotrons in Richmond, British Columbia.

ACSI's relationship with TRIUMF started some 40 years ago when their affiliated company EBCO was contracted to help build TRIUMF's 500 MeV particle accelerator. Out of that relationship came the transfer and then subsequent commercialization of TRIUMF's technology in 1989, which resulted in ACSI being formed to develop, promote and sell cyclotrons to the medical community.[40] In December 2010, TRIUMF and ACSI announced a new partnership framework to put TRIUMF's intellectual expertise in medical cyclotrons and beam targets behind ACSI's product line.[41] Under a $6 million award received from Natural Resources Canada in January 2011, a TRIUMF-led team is developing and benchmarking the technology for direct production of the medical isotope technetium-99m from cyclotrons instead of the traditional nuclear-reactor route. ASCI and General Electric are partners in this project.[42]

PAVAC Industries Inc.

PAVAC Industries Inc. (PAVAC), a Richmond, BC based manufacturer and service provider for electron beam welding equipment and related technologies, is a world leader with more than 25 years of experience in developing hybrid electron beam products and services. Their electron beam welding, machining, drilling, coating and flue gas technology are based on the patented LASTRON technology, a multi-process system capable, in one setup, of drilling, welding and/or machining.[43] PAVAC employs approximately 55 people in British Columbia, but expects to grow to 200 people within 10 years.[44]

Several years ago PAVAC was selected by TRIUMF as a contractor for the fabrication of specialized solid niobium superconducting cavities. Subsequently, in early 2006 PAVAC began a collaborative development project with TRIUMF to increase heavy ion beam energy levels and prove the reliability of electron beam flue gas treatment (EBFGT) systems to provide multi-pollutant emission reduction for coal-fired power plants. In 2008, a team of scientists and engineers drawn from TRIUMF and PAVAC announced that they had successfully fabricated, assembled, and tested a 'superconducting radio-frequency' (SRF) cavity. These devices can be assembled into modules to form next-generation accelerators with applications in health care, environmental mitigation and remediation, advanced materials science, and high-energy physics.[45] PAVAC has secured orders for cavities from the US. PAVAC has also opened a US facility in Chicago to better penetrate the SRF cavity and electron beam welding markets. In 2012, PAVAC won a contract to develop "spoke" cavities for China in collaboration with

[40] Advanced Cyclotron Systems – About ACSI, *supra* note 11
[41] NSERC Long Range Planning Committee. (2012). *The Subatomic Universe: Putting Canada in the Age of Discovery 2011-16.* Retrieved February 1, 2013 from Subatomic Physics in Canada: http://www.subatomicphysics.ca/documents/SUB_ENG_FINAL_201116.pdf
[42] TRIUMF. (2011). *Supra* note 7
[43] Retrieved February 1, 2013 from PAVAC Industries Inc.: http://pavac.com/technology.html
[44] MMK Consulting. (2009). *supra* note 3
[45] Retrieved February 1, 2013 from TRIUMF – PAVAC Industries, Inc.: http://www.triumf.ca/about-triumf/partners-projects/commercial-partners/pavac-industries

TRIUMF, the only vendor chosen outside of China. TRIUMF's partnership with the VECC laboratory in India on SRF technology introduced PAVAC to Indian markets, resulting in PAVAC selling two of its $3 million electron-welding units to India in 2010.[46]

3.3.3 Spin-Off Companies

D-Pace

Dehnel Particle Accelerator Components and Engineering (D-Pace) is an example of a TRIUMF spin-off company. Based in Nelson, BC, D-Pace supplies both engineering services and beamline and target equipment for use with cyclotrons, linear accelerators and ion implanters. Its primary customer base is the international commercial accelerator industry[47]. In 2009, the company had annual sales in excess of $1 million, and a workforce equivalent to approximately 10 FTE employees.[48] D-Pace staff is hired out to work with engineers and managers of other companies (e.g., in the semiconductor industry for ion implantation, and at institutes for ion source and beamline technologies).

Since 2001 D-Pace has been licensing a group of cyclotron component and ion source technologies from TRIUMF. Since the licensing relationship began, D-Pace staff members have used TRIUMF assembly space for training and have subcontracted TRIUMF when its specialized services were not available elsewhere in Western Canada. D-Pace worked with TRIUMF staff to document much of the lab's know-how into manufacturing drawings and technical manuals, to preserve valuable knowledge for training and future use.[49]

3.3.4 AAPS

In February 2008, TRIUMF was awarded $14.95 million for a Centre of Excellence for Commercialization and Research (CECR), a program of the Networks of Centres of Excellence (NCE). As a result, TRIUMF incorporated the not-for-profit corporation Advanced Applied Physics Solutions Inc. (AAPS) to receive the CECR funding. The mission of AAPS is to develop technologies emerging from worldwide subatomic physics research, including TRIUMF research. AAPS did not receive additional funding in 2013. AAPS will now become a unit within TRIUMF while continuing to pursue its original mandate.

AAPS pursues three independent streams for potential projects: i) Intellectual Property (IP) from TRIUMF, its 11 member and 6 associate member universities and institutions across Canada

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[46] TRIUMF. (2010). *TRIUMF Scientific Activities Report 2008-2010*. Retrieved February 4, 2013 from TRIUMF: http://www.triumf.ca/sites/default/files/TRIUMF-Biannual-Science-Rpt--2008-2010.pdf

[47] Retrieved February 1, 2013 from D-Pace: http://www.d-pace.com/about.html

[48] MMK Consulting. (2009). *supra* note 3

[49] Retrieved February 1, 2013 from TRIUMF – D-Pace: http://www.triumf.ca/about-triumf/partners-projects/commercial-partners/d-pace

including the Canadian Light Source, AECL, and SNOLAB; ii) Local entrepreneurs bringing IP; iii) Building from established private-sector partnerships.[50]

AAPS is working to develop and commercialize technologies that are expected to have an impact in a wide range of areas, including the detection and treatment of disease, natural resource exploration, and border security[51]. The following are examples of current projects.

MICROMATTER

In 2009, AAPS expanded TRIUMF's Foil Lab capabilities by acquiring MICROMATTER, an established niche manufacturer with complementary vapour deposition equipment used to produce thin film X-Ray Fluorescence (XRF) calibration standards[52]. MICROMATTER was originally founded in 1968 to manufacture thin carbon foils for the scientific community. Over the years, the business has expanded to include accelerator target foils and X-ray fluorescence (XRF) calibration standards. MICROMATTER's diamond-like carbon (DLC) foils are manufactured using a proprietary process that makes them useful in a variety of applications: Beam strippers, Particle accelerator targets, X-ray and extreme UV filters, and In-line attenuators[53].

Cosmic Ray Geotomography

Muon geotomography uses the detection of naturally occurring cosmic ray muons to create 3D images of dense mineral deposits, similar to those obtained from CAT scans in medical imaging. AAPS and its collaborating team have demonstrated that muon tomography can successfully identify ore bodies. The technology could increase the success of exploration while making it less expensive and reducing its environmental impact. The project is co-funded by Western Economic Diversification for $1.8 million. The team includes TRIUMF, UB, Geological Survey of Canada, BC Ministry of Energy and Mines, NVI Mining and Bern University. The ultimate objective is to form an independent company to commercialize the technology.[54]

Nuclear Material Detection Technology

AAPS is working with a Canadian team to develop a muon detector designed for use in identifying smuggled nuclear materials at ports and borders. This is the result of a Government of Canada Centre for Security Science award of $2.55 million. The project team includes Defence Research and Development Canada, Carleton University, Atomic Energy of Canada Limited, Canada Border Services Agency, Health Canada, and International Safety Research.

[50] TRIUMF (2012) Business Development Plan Annual Report, p15.
[51] TRIUMF(2010) Business Development Plan Annual Report.
[52] TRIUMF(2010) Business Development Plan Annual Report.
[53] http://www.micromatter.com/company.php
[54] AAPS (2011) Annual Report, p6.

The detector system is now in field trials. AAPS will play the lead role in commercializing the technology.[55]

IKOMED Technologies Inc.

IKOMED Technologies, Inc. (IKOMED) was formed in May 2011 in Vancouver, BC to commercialize and deploy a prototype technology that would autonomously and selectively shutter the x-ray source to reduce exposure to the patient while preserving high-resolution fluoroscopy imaging.[56] This advancement reduces the amount of radiation exposure to the patient and scattered radiation to medical staff. AAPS has been working with the Vancouver-based doctors that developed this technology and with entrepreneurs and private investors to bring it to market.

3.3.5 Irradiation Facilities

The proton and neutron irradiation facilities (PIF and NIF) have seen steadily increasing revenues since they began, with an annual average of approximately $350k for the previous three years (2010/2011) from paying customers and 12 to 16 shifts of beam time for scheduled experiments. In a typical year, about 90 users from about 30 companies in Canada, the US, and Europe make use of TRIUMF's irradiation facilities. Space and avionics companies rely on TRIUMF radiation-effect testing for component selection and to meet contractual requirements.[57]

Examples of Canadian companies that have used the facilities include MDA, Microsat Systems, and Honeywell Canada.

MDA Corporation

Founded in 1969, MDA Corporation (MDA) is a Richmond, BC based global communications and information company providing operational solutions to commercial and government organizations worldwide. MDA's principal lines of business include: Surveillance and Intelligence (information solutions to monitor and manage changes and activities anywhere on the earth); Communication (broadband communication and broadcast solutions); Advanced Technology (customer funded solutions development for various other markets); and Geospatial Services (information products derived from the high-resolution RADARSAT satellites developed by MDA, from commercial optical satellites, and from aerial systems).[58]

[55] AAPS (2011) Annual Report, p8.
[56] Retrieved February 4, 2013 from TRIUMF – AAPS & Partners Launch IKOMED, Inc.: http://www.triumf.ca/headlines/current-events/aaps-partners-launch-ikomed-inc

[57] TRIUMF (2011) Business Development Report, p5.
[58] Retrieved February 4, 2013 from MDA Information Systems: http://is.mdacorporation.com/mdais_canada/

The TRIUMF Proton Irradiation Facility was used by MDA in 2007 to test the "Keep Alive Umbilical System" electronics used for powering the Canadarm 1 extension when it is docked in the International Space Station.[59]

Microsat Systems Canada Inc.

Microsat Systems Canada Inc. (MSCI) is a privately held Canadian corporation applying dynamics and control technology in the space market for reaction wheels, rate measurement units and complete microsatellites. MSCI is a leader in the design, development and delivery of cost-effective, adaptable multi mission microsatellite buses capable of hosting a wide variety of remote sensing, communications, scientific and military payloads.[60]

MSCI used TRIUMF's beam-test services in the proton and neutron irradiation facilities during the 2008-2010 period.[61]

Honeywell Canada

Honeywell is a multinational technology company that invents and manufactures technologies to address challenges linked to global macrotrends such as safety, security, and energy. Its main lines of business include: aerospace (integrated avionics, engines, systems, and service solutions); automation and control solutions (environmental controls, life safety, security, sensing, scanning, and mobility products); performance materials and technologies (to reduce emissions, stop bullets, enable the production of green fuels, increase oil refinery capacity, speed drug discovery, and protect medicines); and transportation systems (turbochargers, brake products such as disc brake pads, drum brake linings and aftermarket brake products, etc.).[62] Honeywell operations in Canada include: design, development, manufacture and aftermarket support of an Electronic Controls and Electric Power Generation, Distribution and Conversion portfolio; design and manufacture of in-flight voice communication and data networking systems; and repair and overhaul support to the aerospace industry.[63]

In December 2005, Honeywell Canada used the neutron beam developed by TRIUMF for testing an aircraft electronic module.[64]

3.3.6 Conferences

Scientific conferences generate economic impacts in a manner similar to general tourism through the spending of delegates on accommodation, food, and other purchases. Conference Economic

[59] Retrieved February 4, 2013 from TRIUMF – MDA Tests Space Shuttle Components at TRIUMF: http://www.triumf.ca/research-highlights/experimental-result/mda-tests-space-shuttle-components-triumf
[60] Retrieved February 4, 2013 from Microsat Systems Canada Inc. – Corporate Profile: http://www.mscinc.ca/about/index.html
[61] TRIUMF. (2010). *Supra* note 17
[62] Retrieved February 5, 2013 from Honeywell – About Honeywell: http://honeywell.com/About/Pages/our-company.aspx
[63] Retrieved February 5, 2013 from Aerospace Industries Association of Canada – Honeywell Canada profile: http://www.aiac.ca/en/member.aspx?id=398
[64] TRIUMF. (2005). Annual Report Scientific Activities 2005. Retrieved February 5, 2013 from TRIUMF: http://publications.triumf.ca/annrep/ar05www/ar05-sci-ef.pdf

Impact is calculated by multiplying the number of people who attended the conference by the number of days the conference was run, and then multiplying by the estimated amount each person spends per day.

4. TRIUMF Return on Investment

This chapter examines TRIUMF according to the criteria laid out in the return on investment framework described in Section 2.1.

4.1 Disciplinary Metrics

4.1.1 Scientific Excellence

TRIUMF pursues science and research outcomes in the following primary areas: nuclear physics, particle physics, nuclear medicine, molecular and materials science, and accelerator science. The following sections provide evidence of the levels of scientific excellence achieved by TRIUMF in each of these areas.

Does the facility provide an exceptional ability to enable frontier research and education?

Is the research impact transformational, with evidence of significant leaps in capabilities, and understanding?

Has the facility altered fundamental science or opened up significant new lines of enquiry?

Nuclear Physics

Nuclear physics is a branch of physics that deals with the study of nucleons (the substructure of protons and neutrons), nuclei (finite nuclear systems), and nuclear matter ("infinite" nuclear systems such as neutron stars). At the TRIUMF-ISAC[65] facility, the intense mass-separated beams and arrays of detectors that are among the most advanced ever applied to nuclear structure studies have been deployed. In addition, at TRIUMF-ISAC highly competitive experimental capabilities for trapping and characterizing rare isotopic species, and for investigating reactions produced by secondary beams of these species, have been built. [66]

TRIUMF's nuclear physics research program is tackling some of the difficult challenges in this field. Examples include:

- The structure of nuclei and nuclear matter
  - ISAC has helped to address the outstanding question of whether and how the excess neutrons in halo nuclei influence the proton distribution by determining the isotope shifts through precision laser spectroscopy in order to extract the charge radii for $^{6\text{-}11}$Li and ^{11,12,14}Be.

[65] Isotope Separator and Accelerator

[66] TRIUMF. (2010). *Five Year Plan 2010-2015 – Chapter 6 The Plan: Pursuing the Vision*. Retrieved February 7, 2013 from TRIUMF – 5YP Document: http://www.triumf.ca/about-triumf/message-director/five-year-plan/5yp-document

- High-precision laser spectroscopy on the light Fr isotopes is facilitating an investigation of the wave function of the valence Neutron.
- One- and two-nucleon transfer reactions are being studied at TRIUMF to determine nuclear orbital occupancies and neutron-neutron correlations in light halo nuclei.
- High-precision mass measurements are being used to determine the binding energies of halo and neutron skin nuclei.
- Experiments are being conducted using all of the available spectroscopic tools at TRIUMF to access shell structure evolution.
- A series of complementary studies are being conducted to map the evolution of single-particle states as a function of neutron excess, establishing ISAC as the world leader in this field.

▪ Nuclear astrophysics with neutron-deficient nuclei
  - The experimental determination of a number of nuclear reaction rates in the Detector of Recoils and Gammas of Nuclear Reactions (DRAGON) program provides one of the links between theory and observation in the field of astrophysics.
  - Direct measurement at the TRIUMF UK Detector Array (TUDA) facility of individual nuclear reactions is being used to constrain models and lead to a proper understanding of the underlying physics of these powerful cosmic events.
  - The DRAGON facility has been involved in the measurement of some of the reactions of quiescent stellar burning and TRIUMF is involved in the measurement of an important reaction for the determination of high-energy neutrino flux from the sun.

Particle Physics

Particle physics is a branch of physics dealing with the constitution, properties, and interactions of elementary particles that are the constituents of what is usually referred to as matter or radiation. The driving motivation behind particle physics research is the desire to uncover the true nature of fundamental forces and particles. While the current Standard Model of particle physics is believed to be an effective theory, the case for physics beyond the standard model is strong. There is no substitute for directly probing the energy regime where the physics lies, so Terascale colliders (i.e., the Large Hadron Collider (LHC) at the CERN laboratory, and the International Linear Collider (ILC)) are a priority in international particle physics.[67]

TRIUMF is contributing to or, in some cases, operating on-site experiments for ATLAS, T2K, ALPHA, DEAP, PIENU and the ultra-cold neutron (UCN) and atom-trap programs seeking

[67] TRIUMF. (2010). *Supra* note 64

electric dipole moments.[68] Examples of TRIUMF's scientific excellence in the particle physics field include:

- ATLAS Physics at the CERN LHC
  - TRIUMF has assembled a critical mass of scientists, faculty, post-docs, and students doing ATLAS physics analysis and is providing office space and conference facilities to accommodate visiting Canadian ATLAS members, enabling a major Canadian impact in the context of a globally distributed effort.
  - The TRIUMF laboratory hosts one of ten ATLAS Tier-1 computing and data analysis centres worldwide for the analysis of several petabytes of data accumulated by ATLAS each year.
  - The LHC experiments ATLAS and CMS have been examining the elementary scalar known as the Higgs Boson (previously predicted in the Standard Model, but not confirmed), which can decay in many different ways, and members of the TRIUMF group are looking at the cases where it decays to two W bosons, or two Z bosons. In July 2012, conclusive evidence for a Higgs-like boson was announced.[69]
- Tokai to Kamioka (T2K) long-baseline neutrino project
  - TRIUMF provides an infrastructure base for Canadians leading T2K physics analysis and is the Tier-1 computing and analysis centre for T2K Canada, storing about 100 terabytes of data. TRIUMF has played a significant role in T2K's data analysis, and hosts the largest analysis group in the collaboration[70].
  - The two main near detector components constructed at TRIUMF, the fine grained detector (FGD) and the time projection chamber, were successfully commissioned and operated throughout the T2K physics data taking period.[71]
  - T2K members ran a dedicated experiment in the M11 beamline at TRIUMF to measure pion scattering parameters relevant for neutrino interaction physics, and are doing optical calibration measurements at TRIUMF for T2K's far detector Super-Kamiokande.[72]
- International neutrino measurements
  - The TITAN facility in ISAC at TRIUMF is being used to support international neutrino measurements. Experiments in Russia and Italy are detecting the low-energy neutrinos

[68] National Research Council. (2012). *Report of the Advisory Committee on TRIUMF Thirty-First Meeting*
[69] *Scientific Activities Report 2010-2012*. Retrieved February 7, 2013 from TRIUMF: http://www.triumf.ca/sites/default/files/TRIUMFBiennialReport2010-2012.pdf
[70] Collaborators include: Japan, Canada, France, Germany, Italy, South Korea, Poland, Russia, Spain, Switzerland, the United States, and the United Kingdom.
[71] TRIUMF. (2012). *TRIUMF Scientific Activities Report 2010-2012*
[72] TRIUMF. (2012). *Supra* note 68

produced by the pp reaction in the sun, and the TITAN collaboration recently carried out the first direct precision Q-value measurement of this reaction.[73]

- SNOLAB
  - TRIUMF is providing engineering and physics design expertise to SNOLAB research projects, which are searching for rare interactions between normal matter and "dark matter", which is hypothesized to be the stuff that shapes the destiny of the universe.
  - With collaborators at UBC and Brookhaven, TRIUMF theorists developed a novel theory of dark matter that realizes the dark matter particles as hidden anti-baryons, and studied ways in which such dark matter particles could be seen in nucleon decay experiments.[74]
- Precise studies of symmetries and their violations
  - An international collaboration[75], FrPNC, has been formed at TRIUMF with the goal of carrying out atomic parity violation experiments with cold, laser-trapped francium isotopes, and the science program will measure hyperfine anomalies (also known as the Bohr-Weisskopf effect) to study the distribution of magnetism inside the nucleus.[76]
  - The goal of the ALPHA experiment, first approved at CERN in 2006, was to develop methods to confine anti-hydrogen in a magnetic minimum trap and study the spectroscopy of these antiatoms with increasing precision. TRIUMF is developing a new anti-atom trap incorporating features required for more precise spectroscopy of anti-hydrogen with very few atoms.[77]
- Weak interaction studies
  - The values obtained by the TRIUMF Weak Interaction Symmetry Test (TWIST) collaboration represent an improvement in precision of approximately one order of magnitude compared to prior experiments, testing the validity of the Standard Model (SM) in a system dominated by leptonic interactions.[78]
  - TRIUMF is also testing lepton universality in pion decays with the PIENU experiment and measuring beta decay correlations and transition rates of short-lived isotopes at the ISAC facility.[79]

[73] TRIUMF. (2012). *Supra* note 68
[74] TRIUMF. (2012). *Supra* note 68
[75] Collaborators are from the United States, Canada, Mexico, Australia, and China.
[76] TRIUMF. (2012). *Supra* note 68
[77] TRIUMF. (2012). *Supra* note 68
[78] TRIUMF. (2012). *Supra* note 68
[79] TRIUMF. (2012). *Supra* note 68

Nuclear Medicine

Nuclear medicine uses radioactive elements or isotopes for diagnosis and treatment of disease. TRIUMF's nuclear medicine program has several unique characteristics, including: the availability of cyclotron physics and chemistry; a well-respected ligand chemistry group; PET scanning and imaging expertise; and established collaborations with programs in neurology at the University of British Columbia (UBC) and oncology at the BC Cancer Agency (BCAA).[80] Accelerator science is the backbone of TRIUMF's nuclear medicine program, which maintains a strong isotope and radiopharmaceutical production capability enabled by four on-site cyclotrons.[81]

Accomplishments of TRIUMF's nuclear medicine research program include:

- Three new tracers have been developed and established for production in the new TRIUMF GMP lab: MRB (methyl reboxetine), a selective norepinephrine transporter (NET) blocker; Yohimbine, to image adrenergic receptors in the brain; and DASB, to assess the serotonin function in the brain.
- Chemists at TRUMF have developed a faster and easier method of producing 18F-containing radiopharmaceuticals, greatly improving the amount of usable 18F (often considered the ideal radionuclide in terms of imaging resolution), which provides a new method should be able to replace the time-consuming multi-step processes otherwise necessary.
- TRIUMF chemists have successfully extended the aqueous 18F labeling technique to "click" chemistry, a labeling procedure via two steps in only one pot, resulting in a very quick and reliable generation of radiopharmaceuticals with high yield.
- A consortium of institutions (TRIUMF, the BCCA, Lawson, and the CPDC) led by TRIUMF has successfully demonstrated the feasibility of producing Tc-99m and Tc-94m using medical cyclotrons.

Molecular and Materials Science

Molecular and materials science involves the study of the physical and chemical properties of materials, and the methods of controlling their deployment in devices. To meet the growing global challenges of overpopulation and overconsumption of resources, development of new technologies to improve efficiency and reduce the production of dangerous by-products are critical. Such technologies will push the limits of our abilities to control materials.[82]

The kinds of challenges that TRIUMF's molecular and materials science research program is tackling in this field include:

[80] TRIUMF. (2010). *Supra* note 64
[81] TRIUMF. (2012). *Supra* note 68
[82] TRIUMF. (2010). *Supra* note 64

- Muon spin rotation (μSR) facility[83]
  - μSR has played a prominent role in our current understanding of high-temperature superconductivity, which has the potential to factor into future energy-saving technologies, with studies at TRIUMF accounting for the recognized μSR contributions to this field.
  - The observation at the TRIUMF μSR facility of superconducting signatures far above T_c raises the prospect of one day creating a room-temperature superconductor.
  - Measurements of kinetic data for hydrogen atom abstraction and electron transfer reactions in sub- and supercritical water have led to an improved model for the reactions of key intermediates involved in the radiolysis of water in the cooling cycle of nuclear reactors and are also relevant to the supercritical water oxidation scheme for the destruction of toxic waste.
  - A new aqua-bridged chain motif discovered by TRIUMF researchers is unique in cyanometallate materials and is rare in aqueous coordination chemistry; such new structural motifs are significant as they form the basis for further modification of polymer properties.
  - Previously undetectable microscopic clouds of magnetization composed of charge carriers and neighbouring magnetic ions, called magnetic polarons, have been detected by TRIUMF researchers; "spintronics", which offers the promise of new technologies for computational devices, is a new discipline exploiting the strong mutual influence of magnetic and electrical properties found in magnetic semiconductors that relies on the magnetic polaron.
  - Research at TRIUMF defines the leading edge of worldwide efforts to understand the phase diagram of NCO and its related compounds with A = Li and K, layered cobalt dioxides that exhibit excellent thermoelectric properties.
- Beta detected NMR (β-NMR) facility
  - Researchers at CMMS used β-NMR to investigate the magnetic properties of single-molecule magnets (SMMs) in a two-dimensional lattice, measuring the temperature dependence of the magnetic moments of a monolayer of the prototypical SMM, $Mn1_2$, grafted to a silicon substrate. Nanoscale magnets have the potential for technological applications such as information storage and quantum computing.
  - β-NMR has been used to monitor the host nuclear spin dynamics (and hence the low energy excitations of the system) under conditions (thin layer, depth-resolved, and small

[83] TRIUMF. (2012). *Supra* note 68

nuclear moments) where conventional NMR is impossible, making absolute measurements of the magnetic penetration depth in superconductors possible.

Accelerator Science

Accelerator science is concerned with designing, building, improving and operating particle accelerators. TRIUMF accelerators are the heart of the Canadian accelerator-based experimental subatomic physics program, and the TRIUMF accelerator complex is the basis for Canadian research in materials science and PET-based nuclear medicine programs. Expansion of programs designed to utilize the accelerator infrastructure and expertise is also planned to establish a strong graduate student program in accelerator physics in collaboration with member universities. [84]

Examples of TRIUMF's achievements in the accelerator science field include:

- TRIUMF developed in collaboration with ACSI a TR-19 medical cyclotron. This was the first in a series of medical cyclotrons sold around the world by ACSI. TRIUMF is recognized by ACSI, GE, IBA, and other cyclotron manufacturers as having a significant concentration of medical cyclotron technology knowledge.
- TRIUMF is recognized for its expertise in high current ion sources, which is now the main product of D-PACE. D-PACE has an exclusive contract with IBA for ion sources for all their medical cyclotrons.
- A new technique was developed to use two independent sets of harmonic coils to suppress the $\nu=3/2$ resonance driven by field imperfection in the cyclotron, resulting in greatly stabilized extracted beam current, and one of the harmonic coils was used in Br mode to correct the vertical position at extraction. These techniques are expected to significantly improve the cyclotron performance.
- TRIUMF is developing an integrated, general purpose optimization software platform, enabling the global optimization of a wide range of beam delivery systems as a unique accelerator design tool.
- TRIUMF's SRF team has gained international recognition by developing and putting into operation a high-gradient, low beam velocity ($\beta = v/c \ll 1$), heavy ion superconducting linac.

4.1.2 Technical Excellence

Since the origins of TRIUMF are in particle and nuclear physics, the lab's key physical resources involve accelerators, beam lines, and detectors. During the most recent reporting period (2010 – 2012), key elements of

Is the facility pushing the frontier of technology?

Are technical risks being thoroughly addressed?

[84] TRIUMF. (2010). *Supra* note 64

TRIUMF's main cyclotron were upgraded.[85] For example, the vertical section of the cyclotron injection beamline was replaced and new beam lines for materials science are being expanded and upgraded. The new M20C/D and M9A beamlines incorporate ultra-fast electrostatic kickers, which allows for a doubling of the time window in which data can be effectively recovered. This capability creates new scientific research possibilities at TRIUMF for the investigation of advanced materials, inclusive of semiconductors, superconductors and, compounds being developed for the next generation of car batteries.

Advances in isotope-production technology were also installed, enabling improved delivery of isotopes to the suite of nuclear physics experiments in ISAC-I and ISAC-II. ISAC is an isotope separation on-line, or ISOL, and rare isotope beam (RIB) facility. Rare isotopes are produced in reactions driven by 480–500 MeV protons from TRIUMF's main cyclotron. The final element of the ISAC accelerator chain, the ISAC-II superconducting linear accelerator, was designed to accelerate beams to energies above the Coulomb barrier over a broad range of masses. Additional upgrades to the beamline infrastructure, including the installation of new dipole and quadrupole power supplies and the fabrication of a Bragg detector for beam characterization, have also been carried out.

The overall performance of ISAC was compromised by a series of equipment failures in 2010, which continued to have an impact in 2011. Of the eight to ten RIB production targets typically used at ISAC in a year, failures of targets, ion sources, or the target modules in which the target and source are housed, cut short four target runs in 2010. Cyclotron vacuum problems compromised an additional target run in May 2010, and problems with the ISAC-II cryogenics systems limited the delivery of high-energy RIB for much of the summer as well. Although performance improved in 2011 and the causes of the problems in 2010 have largely been addressed, further improvements in facility performance are expected with several new planned changes.[86]

TRIUMF achieved several new milestones during the 2010-2012 period with the introduction of actinide targets and improvements to the charge-state booster to enable heavier-mass isotopes to be delivered. Actinide targets are necessary for the production of radioactive isotopes of heavy elements and neutron-rich isotopes from spallation and fission reactions.

TRIUMF's Detector Group has an international reputation for excellence in the design, development and construction of state-of-the-art detectors and new detector technologies. New instruments have been successfully deployed in measurements at TRIUMF and in collaborative projects elsewhere in Canada and abroad, including[87]:

[85] TRIUMF. (2012). *Supra* note 68
[86] TRIUMF. (2012). *Supra* note 68
[87] TRIUMF. (2012). *Supra* note 68

- Leading contributions to the design, construction, installation, and commissioning of the ATLAS liquid argon (LAr) calorimeter system and R&D for new technologies for high-rate calorimetry and high-rate pixel tracking detectors.
- Leading the design of the full set of tooling needed for handling the forward calorimeters for ATLAS upgrade options and completing designs of tooling required to remove the hadronic endcap calorimeters (HEC) for replacement of the electronics mounted on the detectors should that be required.
- Completion of R&D that has been critical to understanding the performance of the Canadian end-cap calorimeter systems at the LHC, and for developing alternative technologies that are better able to cope with the higher luminosities anticipated in the coming years.
- Development of the Silicon Highly-segmented Array for Reactions and Coulex (SHARC), a new silicon-detector array designed for use in reactions with radioactive ion beams in conjunction with the TIGRESS γ-ray spectrometer, and the first upgrade, in which additional detectors were added for improved particle identification.
- Development by TRIUMF in collaboration with Simon Fraser University of the TIGRESS Integrated Plunger (TIP), designed to provide submicron control of distance shifts between thin target and stopper foils while maintaining parallel alignment between the two to achieve picosecond-order lifetime sensitivity.
- HALO, a dedicated detector of neutrinos from galactic supernovae developed by TRIUMF, will not only provide an early warning supernova signal for optical telescopes, but will elucidate how the immense electron and neutrino densities in the proto-neutron star cause neutrinos to change from one flavour to another.

New laboratories with hot cells and chemistry suites were developed for nuclear-medicine, underground pneumatic pipeline connections between the TRIUMF production labs and laboratories at UBC were upgraded, and designs for an expansion were completed. For example:[88]

- The TR13 cyclotron produces isotopes that are primarily used for the production of medical-isotope tracers, mainly supporting the Pacific Parkinson Research Centre and the BC Cancer Agency programs.
- A Good Manufacturing Practices Laboratory (GMP) containing three new hot cells for the production of radiopharmaceuticals for human use was completed. This area is used by TRIUMF with partners at UBC to produce PET radiopharmaceuticals for use in Parkinson's and Alzheimer's research.

[88] TRIUMF. (2012). *Supra* note 68

- The new joint TRIUMF/Nordion lab contains four new hot cells for radiochemistry research, which will be used to add value to their growing line of Nuclear Medicine radiometals, plus the production of Tc-99m using accelerators.

TRIUMF's stewardship of the Canadian ATLAS Tier-1 Data Centre expanded simultaneously with an upgrade of the lab's core network fabric. TRIUMF increased its connectivity to the Research Network from 1 Gbps to 10 Gbps to handle the significant increase in the utilization of its network due to the LHC moving into a production phase. TRIUMF has also added 400 TB of storage for access via grid-enabled services to T2K collaborators worldwide. To meet the demands of the Theory group for a high-performance computing facility for developing and debugging new codes and partially running the less demanding jobs for production, the TRIUMF Core Computing and Networking Centre established a 288 processor-core cluster.[89]

TRIUMF is a founding member and a lead contributor in the collaborative effort to develop and improve GEANT-4, an object-oriented toolkit for large-scale, accurate, and comprehensive simulations of particle detectors. TRIUMF's unique contributions are in the simulation domain of modeling the optics of scintillation and Cherenkov detectors and their associated light guides.

Construction is well underway on the Advanced Rare Isotope Laboratory (ARIEL) at TRIUMF. The primary mission of ARIEL is to deliver rare, short-lived exotic isotopes, in particular those with extreme neutron excess, to simultaneous and multiple experiments at the ISAC accelerator complex. A secondary mission of ARIEL is to anticipate future uses of e-linac technologies such as free electron lasers, and including commercial uses such as the production of medical isotopes by photo-fission.[90] When operational in 2013, ARIEL will increase TRIUMF's scientific productivity by up to three times its current level by providing two additional beams of rare isotopes to augment the existing single beam line. The project is developing an electron accelerator capable of saving electricity by approximately a factor of five, as compared to conventional technology.

4.1.3 Community Support

> **Does the relevant research community consider the facility a high priority?**
>
> **Is the facility accessible to an appropriately broad user community?**

As a joint venture of 11 Canadian universities with another six universities as Associate Members, TRIUMF provides a unique set of centralized resources to a broad group of researchers and students. Strong evidence of the community support for TRIUMF is provided by the extent of funding obtained for the facility by external organizations. For example, university-based research collaborations accessed more than $100 million investment in experimental facilities at TRIUMF from NSERC up until 2010.[91] In addition, CFI funding has been obtained by universities for investment at TRIUMF in two categories: enhancements to the existing TRIUMF facility that provide new research capabilities; and the development of new detector facilities.

[89] TRIUMF. (2012). *Supra* note 68
[90] TRIUMF. (2012). *Supra* note 68
[91] TRIUMF. (2010). *Supra* note 64

The fact that the majority of graduate students at TRIUMF come from foreign countries is a hallmark of a laboratory with an international reputation for excellence in both science and educational opportunities.[92]

Another measure of the importance of the facility to the relevant research community is the international demand for involvement of TRIUMF staff in high profile international collaborative projects. For example, at CERN in Geneva TRIUMF physicists, engineers, and technicians have contributed to the construction of magnets, kickers, and control systems for the Large Hadron Collider accelerator system, and high power beam monitoring systems have been provided by TRIUMF to J-PARC in Japan.[93]

4.1.4 Disciplinary Impact

How many researchers, educators, and students does the facility enable?

TRIUMF is home to some 350 staff, the majority of whom are scientists, engineers and technologists. Approximately 20% of the scientific staff and one third of the engineering staff are resident at Canadian universities, strengthening both TRIUMF's and the universities' intellectual and scientific abilities. TRIUMF attracts talent from around the globe to Canada: more than 500 top graduate students, post-doctoral fellows, and researchers perform research at TRIUMF each year.[94]

During the period 2003-2008, the number of graduate students who completed theses based completely or partially on research performed at TRIUMF is summarized in Table 2. While some of the graduate students at TRIUMF come from Canadian universities, the majority come from international universities and laboratories that use the research facilities of TRIUMF.[95] During the same period, TRIUMF was also host to 88 post-doctoral fellows and research associates. In addition, TRIUMF annually hosts the TRIUMF Summer Institute, which is designed to provide graduate students and young researchers with an in-depth course covering one of the areas of research pursued at TRIUMF and annually attracts about 40 students.

Table 2: Graduate students at TRIUMF from 2003-2008 by area of study

Area	Ph.D	Masters
Subatomic Physics	65	126
Molecular & Materials Sciences	32	69
Accelerator Technology	1	3
Life Sciences	6	25
Total	104	223

[92] TRIUMF. (2010). *Five Year Plan 2010-2015 – Chapter 2 Successes: Impacts 2003-2008*. Retrieved March 22, 2013 from TRIUMF – 5YP Document: http://www.triumf.ca/sites/default/files/TRIUMF.5YP.Chpt4_.pdf
[93] TRIUMF. (2010). *Five Year Plan 2010-2015 – Chapter5 Assets: Physical and Intellectual Capital*. Retrieved March 22, 2013 from TRIUMF – 5YP Document: http://www.triumf.ca/sites/default/files/TRIUMF.5YP.Chpt5_.pdf
[94] TRIUMF. (2010). *Supra* note 89
[95] TRIUMF. (2010). *Supra* note 89

4.1.5 Partnerships

Are partnership possibilities for development and operation being fully exploited?

The broad range of partnerships that TRIUMF has developed and cultivated have been one of the keys to their success. These partnerships span the spectrum of stakeholders in nuclear physics, particle physics, nuclear medicine, molecular and materials science, and accelerator science research and development, including universities, hospitals, companies, not-for-profit organizations and other research institutions. Key national and international partnership examples are briefly discussed in the following sections.

National

University Collaborations Exploiting ISAC's Rare-Isotope Beams: *TIGRESS* – TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) is a state-of-the-art γ-ray escape suppressed spectrometer developed for use at the ISAC-II facility. TRIUMF's partners in this collaborative effort included eight universities.[96]

TRIUMF Advanced Rare Isotope Laboratory (ARIEL) / electron linear accelerator (e-linac) – This joint initiative between the University of Victoria and TRIUMF brings together accelerator technology expertise from British Columbia and India with the participation of the following Canadian universities in the e-linac[97]: University of British Columbia, Simon Fraser University, University of Alberta, University of Saskatchewan and Canadian Light Source, University of Regina, University of Guelph, McMaster University, University of Toronto, Carleton University, Université de Montréal, Laval University and Saint Mary's University.

Pan-Canadian Network for Production of Radiotracers – Co-led by TRIUMF and the University of British Columbia, this initiative brought together the following partners[98]:

- Active cyclotron-based programs (BC Cancer Agency, St Joseph's Health Care London, McMaster University, Cross Cancer Institute, Montreal Neurological Institute, Ottawa Heart Institute and Université de Sherbrooke)
- Emerging cyclotron-based programs (BC Cancer Agency, Sunnybrook Hospital, University Health Network, University of Calgary, Dalhousie University, University of Saskatchewan, University of Manitoba and Université de Montréal)
- Private-sector companies (Nordion, Siemens Medical, GE Healthcare and Edmonton Radiopharmacy Centre)

[96] Retrieved February 12, 2013 from TRIUMF – Canadian University Partners & Owners: http://www.triumf.ca/about-triumf/partners-projects/canadian-university-partners
[97] Retrieved February 12, 2013 from TRIUMF ARIEL Partners: http://www.triumf.ca/ariel/partners
[98] TRIUMF. (2010). *Supra* note 64

- Terry Fox Research Institute
- Advanced Applied Physics Solutions, Inc.
- Centre for Drug Research and Development
- The Prostate Centre's Translational Research Initiative for Accelerated Discovery and Development
- Centre for Probe Development and Commercialization

Ultra-Cold Neutron Source (UCN) – Led by researchers at the University of Winnipeg and University of Manitoba, partners in this project include[99]: TRIUMF, University of Northern British Columbia, Simon Fraser University, the Research Center for Nuclear Physics (RCNP, Osaka), Osaka University and University of Tokyo, North Carolina State University, Oak Ridge National Laboratory, Caltech, Los Alamos National Laboratory and University of Kentucky.

Gamma-Ray Infrastructure for Fundamental Investigations of Nuclei (GRIFFIN) – The GRIFFIN project is led by University of Guelph and the partners include[100]: TRIUMF, Simon Fraser University, Saint Mary's University, Université de Montréal, Laval University, McMaster University and University of Toronto.

ISAC Charged Particle Spectroscopy Station (IRIS) – Led by Saint Mary's University, the partners in this project are: TRIUMF, McMaster University, Osaka University, Simon Fraser University and University of Guelph.

β-detected Nuclear Magnetic Resonance (β-NMR) Facility – This facility uses a low-energy ISAC-I radioactive ion beam as a novel depth-resolved local probe of the properties of thin films and heterostructures. It was developed through a partnership among TRIUMF, University of British Columbia and University of Alberta.[101]

TRIUMF/UBC PET Centre – This joint TRIUMF-University of British Columbia partnership studies the origins, progression, and treatment of Parkinson's disease and other neurological diseases such as Alzheimer's. The PET Centre also dedicates substantial resources to basic research in psychiatry, the genetic causes of neurodegeneration, and diabetes. Another partnership initiative, the **Centre of Excellence for Functional Cancer Imaging** jointly established by the TRIUMF-UBC PET Centre, the British Columbia Cancer Agency (BCCA) and the Vancouver Hospital and Health Sciences Centre, works to improve cancer diagnosis and treatment for patients, build research programs for the discovery, development, and application

[99] TRIUMF. (2010). *Supra* note 64
[100] TRIUMF. (2010). *Supra* note 64
[101] TRIUMF. (2010). *Five Year Plan 2010-2015 – Chapter 3 Partnerships: TRIUMF, Canada and the World*. Retrieved February 12, 2013 from TRIUMF – 5YP Document: http://www.triumf.ca/about-triumf/message-director/five-year-plan/5yp-document

of new radiotracers, and promote collaboration with a national and international network of functional imaging programs.[102]

International

The TITAN Facility – TRIUMF partnered with the Max-Planck Institute for Nuclear Physics (MPI-K) in Heidelberg, Germany on the development of this facility, with TRIUMF providing expertise for coupling trap systems to an accelerator-based beam line, and MPI-K contributing its unique electron beam ion trap (EBIT) expertise.[103]

The ATLAS Experiment – Under this partnership, TRIUMF accelerator physicists contributed unique expertise for the design and construction of critical parts of the accelerator (the Large Hadron Collider-LHC) at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland. TRIUMF is also home to the ATLAS-Canada Data Centre, which pre-processes the raw data from the experiment prior to analysis by Canadian and foreign researchers, and provides domestic detector experts access to raw data for detailed calibration and monitoring.[104]

T2K (Tokai to Kamioka) Long Baseline Neutrino – TRIUMF and Japanese scientists initiated the project in 2000, which has since grown into an international collaboration of 12 countries from Europe, Asia, and North America, including all the G8 nations. TRIUMF provided input to the neutrino beam line design and contributed to the design and construction of the remote handling mechanism in the target station. In addition, TRIUMF and Canadian industry contractors contributed detector expertise to the construction, such as precision machining of the large TPC, development of scintillator extrusion techniques and fabrication of readout electronics.[105]

Collaboration with the Variable Energy Cyclotron Centre (VECC) in India – The initial goal of the VECC-TRIUMF partnership is to develop and build jointly two single cavity horizontal test cryomodules – one for VECC and the other for TRIUMF. The cavities will be constructed by PAVAC, a Canadian company, thereby bringing industrial activity and expertise to Canada. TRIUMF and VECC will fully develop all aspects of cavity production. Scientific and engineering staff of VECC and TRIUMF will collaborate to develop the design and subsequently to build the required infrastructure.[106]

[102] TRIUMF. (2010). *Supra* note 97
[103] Retrieved February 12, 2013 from TRIUMF – Examples of International Partnerships: http://www.triumf.ca/node/14756
[104] *Supra* note 99
[105] *Supra* note 99
[106] *Supra* note 99

4.2 Cross-Disciplinary Metrics

4.2.1 Relative Scientific Impact

> **How "transformative" is the facility in comparison to those of other disciplines?**
>
> **What is the international relevance of this facility?**
>
> **Do similar facilities exist in the international research community?**

TRIUMF has been the source of a number of research findings that have had transformative impacts. For example, the TRIUMF ATLAS group has made contributions to the search for the Higgs boson, with a major impact on the Canadian physics effort at the Large Hadron Collider. TRIUMF has led the collaborative research team that has successfully demonstrated the feasibility of producing Tc-99m and Tc-94m using medical cyclotrons. Research is continuing to demonstrate the feasibility of large scale commercial production of these isotopes, urgently required to replace isotopes currently being produced with the Chalk River nuclear reactor, whose licence will be reviewed in 2016.

As has been noted previously, TRIUMF has an international reputation and its participation has been sought in international collaborative initiatives such as the ATLAS experiment at CERN in Switzerland, the T2K Long Baseline Neutrino project in Japan, the TITAN Facility at the Max-Planck Institute for Nuclear Physics (MPI-K) in Germany and the development of horizontal test cryomodules with the Variable Energy Cyclotron Centre in India.

While TRIUMF is unique in Canada, the international research community has access to several similar facilities in other countries. Major physics research facilities include:

- **European Organization for Nuclear Research (CERN)**, located on the Franco-Swiss border near Geneva, Switzerland, is an international organization whose purpose is to operate the world's largest particle physics laboratory, the main function of which is to provide the particle accelerators and other infrastructure needed for high-energy physics research. Purpose-built particle accelerators and detectors are used for research at CERN covering topics from kaons to cosmic rays, and from the Standard Model to supersymmety.[107]
- **Fermi National Accelerator Laboratory** (**Fermilab**), located near Chicago, USA, is a US Department of Energy national laboratory specializing in high-energy particle physics. Fermilab's mission is to advance the understanding of the fundamental nature of matter and energy. Scientific achievements at Fermilab have included discovery of the top quark and determination of top quark and W boson masses to high precision, discovery of the bottom quark and subsequent studies of its properties, discovery of a quasar at a distance of 27 billion light years, and calculation of the strong coupling constant using supercomputers.[108]

[107] See http://home.web.cern.ch/about
[108] See http://www.fnal.gov/pub/inquiring/physics/discoveries/index.html

- **Oak Ridge National Laboratory** (**ORNL**), located near Knoxville, USA, is a multiprogram science and technology national laboratory managed for the US Department of Energy (DOE) by University of Tennessee-Battelle. The laboratory's nuclear medicine research is focused on the development of improved reactor production and processing methods to provide medical radioisotopes, the development of new radionuclide generator systems, the design and evaluation of new radiopharmaceuticals for applications in nuclear medicine and oncology. Physics research at ORNL is focused primarily on studies of the fundamental properties of matter at the atomic, nuclear, and subnuclear levels and the development of experimental devices in support of these studies.[109]
- **Los Alamos National Laboratory** (**LANL**), one of the largest science and technology institutions in the world, conducts multidisciplinary research in fields such as national security, space exploration, renewable energy, medicine, nanotechnology, and supercomputing. The basic and applied R&D programs have a primary focus on energy but also encompass medical, biotechnology, high-energy physics, and advanced scientific computing programs.[110]
- **Max Planck Institute for Nuclear Physics (MPI-K)**, located in Heidelberg, Germany, is a research institute with a focus on the crossroads of particle physics and astrophysics (astroparticle physics) and many-body dynamics of atoms and molecules (quantum dynamics). MPI-K's research addresses such matters as: What cosmic objects are sources of high energy gamma radiation? Why is the universe made of matter and not antimatter? What is dark matter and how can it be found?[111]
- **Variable Energy Cyclotron Centre (VECC),** located in Calcutta, India, is a research and development unit of the Indian Department of Atomic Energy that performs research in basic and applied nuclear sciences. The Centre houses cyclotrons that provide proton, deuteron, alpha particle and heavy ion beams of various energies to other institutions. Accelerator related R&D programmes and activities primarily focus on their two cyclotrons (K130 cyclotron and K500 superconducting cyclotron). VECC also provides cyclotron related computational support in beam dynamics, beam optics, magnet design and cryogenics.[112]

4.2.2 Impact across Communities

While the principal focus of TRIUMF initially was particle and nuclear physics, its impact has spread, with the most significant cross-disciplinary impacts occurring in the medical and materials science fields, as discussed in the following sections.

[109] See http://www.ornl.gov/
[110] See http://www.lanl.gov/science-innovation/science-programs/index.php
[111] See http://www.mpi-hd.mpg.de/mpi/start/
[112] See http://www.vecc.gov.in/index.php

Nuclear Medicine

Does the facility have cross-disciplinary impact?

Is it of interest to more than one stakeholder group?

As shown in Section 4.1.1, TRIUMF has made considerable contributions to the field of nuclear medicine. The core of the TRIUMF nuclear medicine program is positron-emission tomography (PET) imaging, a technique whereby radioisotopes are combined with certain biomolecules and injected into the body and allowing them to be traced. Advances in the understanding of the molecular basis for many diseases allow the design of targeted functional imaging agents that will improve the specificity/selectivity of disease diagnosis and therapeutic interventions. TRIUMF's direct contributions to human health include[113]:

- Daily supply of a critical diagnostic imaging drug (FDG) to BC Cancer Agency (BCCA) to diagnose cancer, determine treatment regimes, and follow treatment efficacy.
- Successful treatment and cure, by the proton irradiation facility at TRIUMF, of a hundred patients annually suffering from ocular melanoma.
- Development of PET radiopharmaceuticals to follow the course of enzyme replacement therapy used in rare children's diseases such as Gaucher's disease.
- Development of radiometal-based radiopharmaceuticals for potential use as possible cancer imaging and therapy agents.
- All isotopes used by the Pacific Parkinson's Research Centre.
- Provision of expertise and advice to other PET centres across Canada.

Molecular and Materials Science

Section 4.1.1 also summarizes some of the key contributions made by TRIUMF researchers to the materials science field. TRIUMF's materials science research program utilizes muon spin rotation, relaxation and resonance (μSR) techniques based on the capability of the positive muon (μ+) to detect the magnetic field at its microscopic location. μSR has been applied at TRIUMF to the study of magnetism, superconductivity, semiconductors and semi-metals, quantum diffusion, molecular bonding states, and fundamental and complex chemical reactions.[114] In addition, TRIUMF operates a proton & neutron irradiation facility (PIF & NIF) containing several beam lines that provide low-intensity, energetic proton and neutron beams to simulate radiation exposures either in space or terrestrial environments. Annually some 100 users from

[113] Retrieved February 12, 2013 from TRIUMF – Nuclear Medicine: http://www.triumf.ca/research/research-topics/nuclear-medicine

[114] Retrieved February 12, 2013 from TRIUMF – Molecular & Materials Science: http://www.triumf.ca/research/research-topics/molecular-materials-science

approximately 30 companies, laboratories and universities test electronics or materials with the TRIUMF beams.[115]

4.2.3 Urgency

Urgency is not an applicable criterion in the context of TRIUMF, which is an existing infrastructure.

How important is timeliness of the proposal in contrast to other proposals?

Is there a window of opportunity?

Are there interagency and international commitments that must be met?

4.2.4 Readiness

Urgency is not an applicable criterion in the context of TRIUMF, which is an existing infrastructure.

Is there a high state of readiness to proceed with development?

- **Technical / engineering maturity**
- **Partnerships**
- **Facility management**
- **Level of international commitment**
- **Compliance with environmental regulations**

4.2.5 Synergies

Does the facility benefit from or contribute to coherence and synergies with other Canadian or international programs and investments?

As referenced in previous sections, TRIUMF has created synergies with a broad range of other Canadian and international research programs and investments in the fields of nuclear physics, particle physics, nuclear medicine, molecular and materials science, and accelerator science. TRIUMF was originally created in recognition of the need for a national nuclear physics laboratory to work closely with the university community and draw together the strengths and capabilities of many institutions. This need applies equally to the other fields in which TRIUMF has expanded its research work.

TRIUMF's research efforts are closely linked with those of universities, and particularly the eleven Member Universities and six Associate Members of the Canadian consortium that owns and operates the laboratory. TRIUMF's unique mix of human and technological resources makes it an ideal partner for researchers who do not have access to similar resources in their own universities, and enables it to foster collaborative partnerships among Canadian researchers and between Canadian researchers and their international colleagues. The synergies with Canadian

[115] Retrieved February 12, 2013 from TRIUMF – PIF & NIF: http://www.triumf.ca/pif-nif

universities also allow TRIUMF to benefit from CFI funding, which is only accessible to university researchers but can be applied to projects based at the laboratory.[116]

As indicated in Section 4.1.5, TRIUMF has developed synergies with a range of universities internationally as well. Canada's world-leading expertise in key TRIUMF areas of focus makes it a welcome member of international scientific collaborations. For example, TRIUMF has memoranda of understanding with 32 foreign institutions in 16 different countries and has played a key role in Canadian involvement in international projects in Europe, Japan, and the United States. Foreign collaborators are also attracted to TRIUMF by its facilities and expertise. These visitors include senior scientists, post-doctoral fellows, students and technical experts, who bring equipment or materials, as well as knowledge or expertise that strengthens Canada's scientific community. Developing such synergies with international research programs is a priority for TRIUMF's Board of Management, which has developed a Board policy, under which the laboratory has developed a three-pronged approach: [117]

- *Scientific* – Once individual scientists identify common work, TRIUMF negotiates a formal lab-to-lab Memorandum of Understanding, which usually covers exchanges and sharing of personnel and equipment on an in-kind (rarely cash) basis.
- *Diplomatic* – Once scientific connections are established and working well, TRIUMF seeks to brief the respective embassies, with the objective of having diplomatic staff support the future of the partnership and guide future initiatives and visits.
- *Business* – Once regular scientific and diplomatic relations are established, efforts are directed towards connecting Canadian suppliers or industrial partners with counterparts and customers in the foreign country.

In a 2009 letter from the Director General of one of its most important partners in the nuclear research area, CERN, the important role that TRIUMF is playing in creating synergies was acknowledged:[118]

> "We at CERN know all about TRIUMF's engagement to partnership between labs through the LHC. Working with TRIUMF has also helped to reinforce my view that the world's particle physics labs should come even closer together, exploiting the undoubted synergies that exist between our unique, yet complementary facilities. CERN's ISOLDE and many of the facilities at TRIUMF, for example, are world-class in their own right, but together they're even stronger."

[116] *Supra* note 89
[117] Retrieved February 13, 2013 from TRIUMF – International Partnerships: http://www.triumf.ca/about-triumf/partners-projects/international-partners
[118] Retrieved February 13, 2013 from TRIUMF – Guest Column: CERN's Director General: http://www.triumf.ca/about-triumf/message-director/message-cerns-director-general

4.3 Strategic Metrics

4.3.1 Scientific Competitiveness

> **How important is the facility for:**
> - **Maintaining or enhancing scientific competitiveness in the particular research area?**
> - **Training, retaining and attracting scientific expertise?**
>
> **Has the facility resulted in greater research output?**
>
> **What are the risks of not meeting these competitiveness objectives?**

Previous sections of this report have provided evidence of the importance of the TRIUMF facility for maintaining and enhancing Canada's scientific competitiveness in subatomic physics and related areas of research. In particular, the organization's record of success in creating research partnerships with a broad range of Canadian and external organizations demonstrates the competitiveness of its human and physical resources. TRIUMF's core expertise in nuclear, particle, and accelerator physics has been leveraged to expand into key niche areas in life sciences and molecular and materials science. The organization is recognized for its scientific excellence in three key areas[119]:

- The design, operation, and use of particle accelerators and related beam lines – The associated facilities include the cyclotron itself, the additional accelerators, the beam transport lines, targets for producing secondary beams, and high-power beam tuning stations.
- The production, isolation, and use of rare isotopes – TRIUMF is one of a few organizations in the world with the skill and expertise to provide comprehensive training in nuclear science and engineering, medical isotopes, and related areas.
- The expertise required to build and operate detector facilities – state-of-the-art facilities that are essential for all of TRIUMF's scientific activities: ISAC, CMMS, ATLAS, T2K, and life sciences.

As a national and international laboratory, TRIUMF is in a unique position to attract scientific expertise through the provision of research facilities and educational opportunities that no single university can provide. One of TRIUMF's priorities is to help train the scientific leaders of the future, with student programs targeting high-school students, undergraduate, and graduate students, as well as post-doctoral and research assistant positions. Students working on their Masters and Ph.D. degrees gain hands-on research experience at TRIUMF and learn to work in teams as part of a research group, a learning experience that may not be available at their university. For example, between 2003 and 2008 some 220 Masters and 100 PhD students completed theses based on research performed completely or partially at TRIUMF.[120] Approximately 45% of these students came from outside of Canada. In addition, during this period TRIUMF was host to 88 Post-Doctoral Fellows (PDFs) and Research Associates (RAs). Many PDFs and RAs work full time at TRIUMF, while others come to TRIUMF only for limited

[119] TRIUMF. (2010). *Supra* note 81
[120] TRIUMF. (2010). *Supra* note 81

periods of time (e.g., to use allocated experimental beam time or build or prepare experimental equipment).

4.3.2 Economic Benefits

TRIUMF's economic benefits are examined in detail in Chapter 5.

What is the economic impact of the facility?

Does the facility enhance Canadian R&D and innovation capabilities?

What are the risks of not meeting the economic objectives?

4.3.3 Societal Benefits

TRIUMF has designed a formal outreach program to promote science and research in the public arena and to tell Canadian students, teachers, and the public about the excitement of curiosity-driven research and about how a laboratory like TRIUMF adds value to Canada in new technologies, medical applications, and highly qualified people. Through its programs to stimulate the interest of students in the physical sciences, and to support science teachers, TRIUMF is inspiring a new generation of scientists. Key outreach programs include[121]:

Does the facility have wider societal benefits, including:

- **Public outreach activities?**
- **Impact on education in schools or of the general public?**
- **Health impacts?**

Has the facility resulted in greater research output?

What are the risks of not meeting the societal objectives?

- Teacher Programs
  - Physics in Action animated physics education videos for schools
  - Fall Professional Development Day at TRIUMF, a full day of tours, talks, and hands-on physics demonstrations for science teachers
  - Internship program that offers high-school educators a three- to seven-day research experience working as part of an experimental research team
  - Participation in the Alberta Large-area Time-Coincidence Array and QuarkNet programs, which bring into schools compact cosmic-ray detector equipment that can be operated and maintained by teachers and students
- Student Programs

[121] TRIUMF. (2010). *Supra* note 81

- Field trips for high-school science classes
- A High-School Fellowship program that offers high-school science students a hands-on, six-week research experience as a participating member of a research team

▪ General Public Programs

- Monthly Saturday Morning Lecture Series, featuring talks by scientists from TRIUMF, the University of British Columbia, Simon Fraser University, the National Research Council's Fuel Cell Program and other notable visitors to TRIUMF
- Support of the science promotion community (e.g., Scientists in Schools program at Telus World of Science in Vancouver, the Regional Science Fair, the Canadian Journal of High School Science, etc.)

As discussed previously, TRIUMF has made a number of important contributions that have positively impacted the health of Canadians. Most notable is its work with partners in the experimental development of medical isotopes produced from cyclotrons as a viable alternative to isotopes produced using nuclear reactors. Key goals in 2013 are to change the global perception of ^{99m}Tc production by cyclotron and to help formulate Government of Canada policy on ^{99}Mo/^{99m}Tc medical isotope production.[122] TRIUMF plans to optimize the production process in 2013, be in routine production in 2014 and enter clinical trials in 2015.

In its work with the BC Cancer Agency, the laboratory has been directly involved in the treatment of patients with a type of eye cancer, ocular melanoma using the Proton Treatment Facility at TRIUMF. With the Pacific Parkinson's Research Centre, TRIUMF is working to better understand causes of Parkinson's Disease (PD) and the mechanisms of disease complications/ treatment and to use PD to understand neurobiology of the brain.[123] Under a Strategic Opportunities Fund award from GenomeBC, TRIUMF is working on antisense Positron Emission Tomography (PET) imaging to develop a new class of molecular-imaging agents for diagnosis and characterization of disease.[124]

TRIUMF has a number of other goals in 2013 for its nuclear medicine program that will have wider public health benefits, including:[125]

▪ The use of 18F production technology with metal salt in solution to allow cyclotron centres to obtain radiometal isotopes without substantial infrastructure upgrades
▪ The use of radiochemistry to image gene expression levels related to breast cancer
▪ Microfluidics research involving 18F microdroplet radiolabeling on a model compound
▪ Oxidive stress imaging research to produce 11C and 18F amino acid analogues

[122] TRIUMF. (2012). *Nuclear Medicine Divisional Report*.
[123] TRIUMF. (2012). *Supra* note 109
[124] Delanoë, D. (2012). *NRC and TRIUMF*
[125] TRIUMF. (2012). *Supra* note 109

- The use of acyclic chelates for imaging with radiometals to enable radiometal incorporation onto large molecular weight radiotracers

4.3.4 International Leadership

Does the facility provide international leadership?

Does it continue to build on current leadership and expertise?

Does the facility bring prestige to Canadians?

Is it supported by partnerships that strengthen Canada's standing in the international community?

What are the risks of not meeting these leadership objectives?

TRIUMF has an international reputation as a leader in particle and nuclear physics and is gaining recognition in its more recent fields of endeavour – nuclear medicine and molecular and materials science. Its strong participation in the work of two major international scientific endeavours – the ATLAS experiment at CERN and the neutrino T2K experiment in Japan – is evidence of the leadership role that it plays. Examples of areas in which TRIUMF has achieved international leadership recognition include:

- The DRAGON facility is an excellent instrument for experiments that will advance the understanding of astrophysics of neutron-deficient nuclei.[126]
- TRIUMF is playing a leadership role in the international collaboration of the experimental physics and industrial control system (EPICS).[127]
- The TRIUMF Tier 1 data center is the most reliable among the more than ten Tier 1 data centers maintained by the ATLAS collaboration.[128]
- The TRIUMF ATLAS group has had a major impact on the Canadian physics effort at the LHC through their contributions to the search for the Higgs boson, and for new physics in channels including lepton-MET, dilepton and multi-lepton final states.[129]
- Canadian groups have made contributions to the design, construction, installation, and commissioning of the ATLAS liquid argon (LAr) calorimeter system, with leadership from the TRIUMF laboratory and the support of TRIUMF infrastructure for the contributions made from Canadian university groups.[130]
- TRIUMF scientist Michel Vetterli, project leader for the ATLAS Canadian Tier-1 Data Analysis Centre, was appointed deputy chair of the ATLAS Publications Committee and a member of the Executive Board in March 2012.[131]

[126] TRIUMF. (2010). *Supra* note 68
[127] TRIUMF. (2010). *Supra* note 68
[128] National Research Council. (2012). *Report of the Advisory Committee on TRIUMF Thirty-First Meeting*
[129] National Research Council. (2012). *Supra* note 115
[130] TRIUMF. (2012). *TRIUMF Scientific Activities Report 2010-2012*
[131] Retrieved February 15, 2013 from: TRIUMF – SFU/TRIUMF Physicist Selected for ATLAS Leadership Role: http://www.triumf.ca/headlines/awards-honours/sfutriumf-physicist-selected-for-atlas-leadership-role

- TRIUMF is responsible for the design of the atom trap cryostat, the key part of ALPHA-2 (which will allow laser spectroscopy of anti-hydrogen atoms), and is also contributing to its fabrication.[132]
- Under the leadership of TRIUMF, Canadian researchers contributed to the successful creation and capture of antihydrogen in November 2010; the results were published in the journal *Nature* and were cited as the top physics result of 2010.[133]

4.3.5 National Priorities

Does the facility support current national priorities?

TRIUMF's research program is well aligned with the national S&T priorities outlined in *Mobilizing Science and Technology to Canada's Advantage*, released in 2007. The following paragraphs outline this alignment with the S&T's core principles and advantages.[134]

Principle: Promoting World-Class Excellence

TRIUMF attracts hundreds of top international researchers to Canada to use the laboratory's ISAC rare-isotope beams, and enables Canadian scientists to play leading roles in breakthrough projects abroad such as the ATLAS project at CERN, the largest scientific undertaking in history, or the J-PARC neutrino project in Japan. TRIUMF also supports Canadian researchers who are designing and building state-of-the-art experiments for SNOLAB.

Principle: Focusing on Priorities

TRIUMF's review process ensures that priority is given to key projects that will have the most significant national and international impact. TRIUMF has also worked with the university community to develop the NSERC Subatomic Physics Long-Range Planning Committee report and is using the resulting plan in setting TRIUMF's own priorities.

Principle: Encouraging Partnerships

TRIUMF exists because of the formation of a partnership among several Canadian universities. As discussed in Section 4.5.5, TRIUMF has had a long track record of successful partnerships with other high-energy physics research labs, universities, government organizations and companies, both in Canada and internationally.

[132] TRIUMF. (2012). *TRIUMF Financial Statement and Project Activities, April – July 2012*
[133] TRIUMF. (2012). *BeamOn Annual Administrative and Financial Report 2010-2011*. Retrieved February 15, 2013 from TRIUMF: http://www.triumf.ca/sites/default/files/annual_financial_admin2010_0.pdf
[134] TRIUMF. (2010). *Five Year Plan 2010-2015 – Chapter 2 The Vision: Giving Canada the Advantage. 2010-2015*. Retrieved March 22, 2013 from TRIUMF – 5YP Document: http://www.triumf.ca/sites/default/files/TRIUMF.5YP.Chpt2_.pdf

Principle: Enhancing Accountability

TRIUMF's progress and accomplishments are carefully monitored by three oversight committees:

- The Advisory Committee on TRIUMF;
- The multi-Agency Committee on TRIUMF, which is chaired by the President of the National Research Council, and on which both the President of NSERC and the Deputy Minister of Industry Canada sit; and
- The TRIUMF Board of Management, which represents the university joint venture.

Advantage: Global Excellence in Research

TRIUMF's research thrusts are drawn from such sources as the NSERC Long-Range Plan for subatomic physics, the community-based decadal plan for condensed matter and materials science, and the research statement of the Michael Smith Foundation grant for research at the Pacific Parkinson's Research Centre. Such research is contributing to the knowledge base for next-generation nuclear reactors, helping to understand the behaviour of advanced materials under extreme conditions, and training people for the nuclear industry. By connecting subatomic physics with research in other areas, TRIUMF is developing and contributing to research in materials and to a life sciences program that utilizes medical isotopes combined with positron emission tomography (PET) detectors. TRIUMF's experimental facilities and particle and nuclear physics scientific programs are finding new applications in the studies of molecular and materials science, as well as nuclear medicine.

Advantage: Enabling and Equipping the Next Generation of Leaders

As discussed in Sections 4.5.4 and 4.7.1, TRIUMF has an important impact on training the next generation of scientific leaders at both the secondary school and post-secondary education levels. It attracts students to Canada to learn from the best, with more than 50 students per year participating in onsite internships and co-op programs. The laboratory is a common destination for graduating engineers and technicians because the challenging technical environment ensures competitive training. These highly skilled personnel then move on to successful careers in other sectors of business. In addition, TRIUMF's programs in modern GRID computing for the LHC and nuclear science will prepare personnel for leadership roles in information and communication technologies and nuclear power and engineering.

Advantage: Bridging the Academic and Commercial Sectors

TRIUMF innovations have provided new commercial opportunities for several Canadian companies, including MDS Nordion, D-Pace, ACSI, and PAVAC.

5. TRIUMF Economic Impact

Table 5 shows TRIUMF's financial information for the past decade. The information covers TRIUMF's public funding and other revenue, and TRIUMF's expenditures. In summary, TRIUMF has received $630 million over the last ten years, of which $541 million was grants from public sources and $16 million was commercial revenue. The remaining $73 million was flow-through transfers from other organizations. During that time, TRIUMF spent $622.4 million on operating and improving its facilities, realizing an increase in fund balances of $7.3 million

Table 6 shows similar information for AAPS. In summary, AAPS has received $12.4 million since it was created four years ago[135], of which $11.3 million was grants from public sources, and $1.1 million was commercial revenue. During that time, AAPS spent $11.8 million on its operations, realizing an increase in balances of $0.6 million.

5.1 Economic Activity

The quantifiable economic impact of TRIUMF comes from the following sources:

- Expenditures by TRIUMF and AAPS in Canada
- Revenue by Canadian businesses attributable to their relationship with TRIUMF
- Spending by delegates to conferences located in Canada as a result of TRIUMF

These three sources of impacts are discussed in the following sections. However, we first examine some of the TRIUMF benefits that have not been quantified in this analysis:

- Medical Benefits – TRIUMF is a significant contributor to nuclear medicine in Canada through its production of medical isotopes and its relationships with organizations such as the BC Cancer Agency, the Pacific Parkinson's Research Centre, Genome BC, Lawson Health, and the Centre for Probe Development. These efforts are undeniably improving the health of Canadians today and the research has excellent potential for further improvements in the future. However, no attempt has been made here to quantify the economic impact of those health improvements beyond the value of the services and products provided due to the difficulty in attributing economic value to improvements in health.

- Future Business Revenues – TRUMF has a portfolio of business development projects that it is pursuing. These include using muons to detect ore deposits for mineral exploration,

[135] This figure is the principal and interest drawn down from the CERC endowment of $14.95 million that AAPS received in 2009.

detecting nuclear materials for security screening, developing a non-nuclear process for producing Tc99m, and a method for decreasing the radiation dose received by patients and doctors involved in medical imaging. Given the uncertainty of the return from these projects, no attempt has been made to quantify their future economic impact.

- Past Business Revenues – This analysis considers the investments, and resulting benefits, from the past decade. Economic impacts that were realized before that period have not been considered.

- Consumer Surplus Benefits – TRIUMF performs fee-for-service activities in the area of proton and neutron irradiation. The access convenience and specific technical attributes of the TRIUMF facility may have benefits to clients that exceed what they pay for the service (i.e. consumer surplus). However, similar facilities are available in other places in the world. Therefore, consideration of the economic impact of the PIF/NIF has been limited to the value of the services provided.

- Technology Diffusion Benefits – TRIUMF is involved in the development of very specialized technologies. The science involved will undoubtedly have long-term benefits to the Canadian economy, but the linkage between TRIUMF and the rest of the Canadian economy beyond the companies with which TRIUMF is currently working comes primarily through the movement of personnel and the results are difficult to measure. No attempt was made to quantify the economic impact of the diffusion component of TRIUMF technology development due to the lack of data on those personnel movements.

- Skills Improvement Benefits – The skills developed when companies work on projects that push their capabilities often can be transferred to other components of their business, making them more competitive. This has an economic benefit to Canada when the improved skills result in increased exports or the provision of domestic goods or services that otherwise would have been imported. Such benefits are captured in this analysis for the four companies that have been included. While many other companies have provided goods and services to TRIUMF over the last decade, the project team is not aware of any significant capacity improvements that resulted for those companies.

5.1.1 TRIUMF Expenditures

While TRIUMF expenditures totaled $622.4 million over the last ten years, the economic impact of those expenditures is lessened in two ways. First, $78.8 million was spent outside of Canada for specialized products not available here, and therefore lost to the Canadian economy. Second, $9.6 million was put into a site decommissioning fund and that money will have no economic impact until it is spent. Therefore, TRIUMF expenditures with a Canadian economic impact totaled $534.0 million.

The nature of AAPS expenditures, on the other hand, was such that the majority remained in Canada. Thus, AAPS expenditures with a Canadian economic impact totaled $11.8 million.

However, $5.8 million of this was paid to TRIUMF for reimbursement of expenses paid on behalf of AAPS and is included with their numbers.

TRIUMF and AAPS expenditures were for a wide variety of goods and services such as: salaries, building construction and maintenance, electrical power, equipment, supplies, and computers.

5.1.2 Business Enterprise Revenue

Four Canadian businesses have significant revenues that are attributable to their relationship with TRIUMF: Nordion, ACSI, D-Pace, and PAVAC. The value of these revenues has been adjusted to prevent double counting by accounting for royalties paid to TRIUMF, contracts with TRIUMF, and fees for services from TRIUMF. The adjusted total of these revenues is $249.7 million over the last decade.

5.1.3 Conference Spending

TRIUMF actively encourages organizers of conferences related to particle physics to consider the Vancouver area for their venue. This has had a high degree of success given the international scientific reputation of TRIUMF and the desirability of Vancouver as a tourist destination.

Given that most people attending such international conferences are from outside of Canada, the money they spend on food, lodging, and other purchases is an economic benefit to the region and to Canada.

TRIUMF has tracked the number of delegates that have attended these conferences over the years, and the time they have spent in Vancouver. This analysis has assumed that on average they spend $250 per person night.[136] The total value of such spending over the last decade totals $9.8 million.

Tables 6, 7 and 8 summarize these figures. Table 6 shows public funding over time, Table 7 shows the business enterprise revenue before adjustments for royalties, contracts and fees paid to TRIUMF, and Table 8 shows the direct effects on the economy as they were entered into the Input-Output model.

5.2 Economic Contribution

Table 10 to Table 14 show the results of the Input-Output modelling of the economic contribution made by TRIUMF over the last decade in British Columbia and the rest of Canada.

[136] The figure of $250 per person night has been estimated by the Canadian Tourism Commission for ‘Meetings Conventions and Incentive Travel’ (MC&IT). See: http://en-corporate.canada.travel/sites/default/files/pdf/Research/Stats-figures/Year-in-review-facts-figures/Tourism%20Snapshot%20-%20Year%20in%20review/2011_year-in-review_en.pdf This figure is considerable lower that the $450 per person night that has been used in TRIUMF’s publications.

Table 10 presents the gross output results. The direct gross output is equal to the sum of the TRIUMF expenditures, business enterprise revenue and conference spending discussed in the previous section, which are the model inputs. Direct, indirect and induced gross output attributable to TRIUMF totals $1.8 billion for the study period. However, this figure is misleading as it does not account for leakage from the economy through imports, and it double-counts the value of products as they move through the value chain. Gross output is used as the input to the calculation of gross domestic product, discussed next.

The most accurate measure of economic contribution is Gross Domestic Product (GDP), shown in Table 11. The direct GDP was $424.9 million for the study period; the total GDP attributable to TRIUMF was $940.9 million. British Columbia has received 80% of this total.

Figure 2 shows the distribution of the total GDP among the direct (45%), indirect (19%), and induced (36%) components.

Figure 2: Distribution of Total GDP – Direct, Indirect, Induced

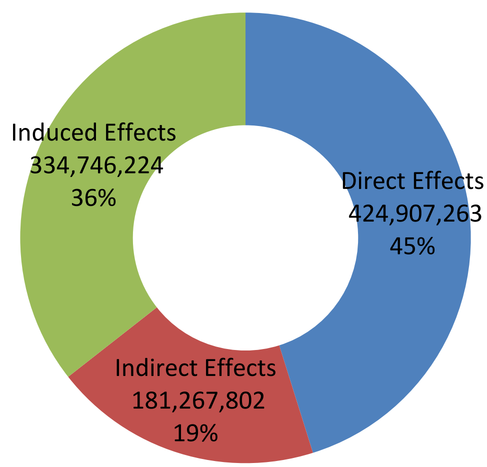

Figure 3 shows the distribution of the total GDP among British Columbia (80%) and the rest of Canada (20%).

Figure 3: Distribution of Total GDP – British Columbia, Rest of Canada

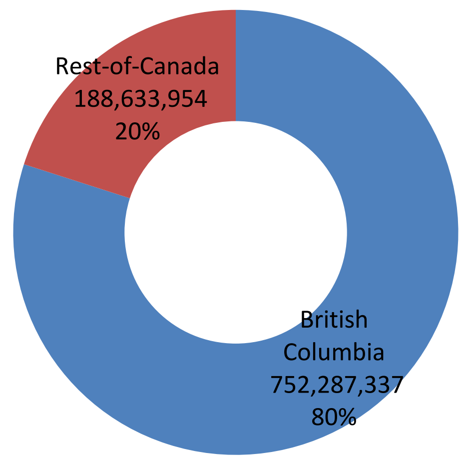

Figure 4 shows the distribution of the total GDP over time from the year ending 2003 to 2012. Note the significant increase over the last four years. This was partially due to increases in funding, but there was also a significant increase in business enterprise revenue.

Figure 4: Distribution of Total GDP by Year

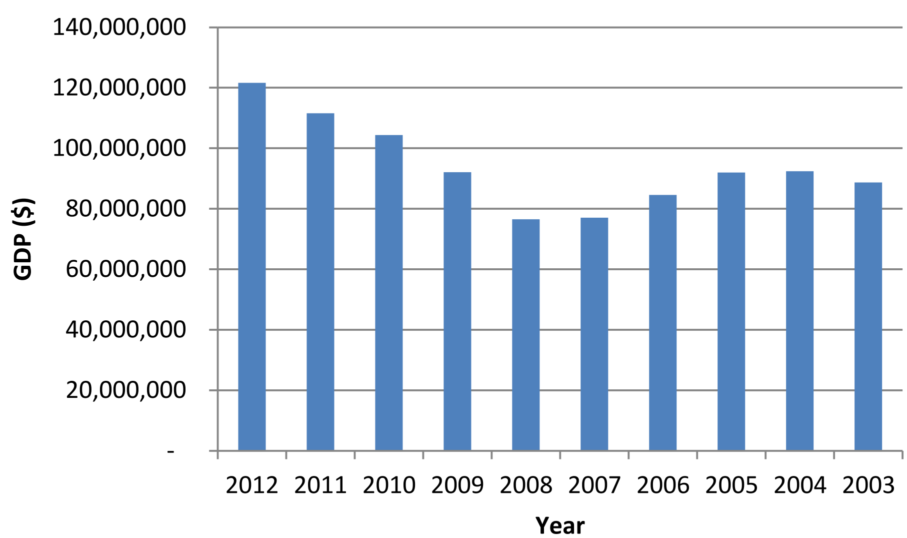

Table 12 shows how TRIUMF's contribution to GDP would nominally be translated into full time equivalent jobs. The total impact for Canada over the last ten years was 11,733 person-years of employment. About 82% of this was in British Columbia and 45% was a direct effect.

Table 13 shows the labour income earned as a result of that employment. The total was $586.3 million during the study period.

Finally, Table 14 shows the tax revenue, which totaled $252.3 million.

5.3 Economic Return on Investment

Assessing a project's return on investment depends critically on one's point of view. This section examines TRIUMF's return on investment from five perspectives: the return to British Columbia, the short-term return to Canada, an investment choice decision, the long-run return to Canada, and the return to government.[137]

5.3.1 Return to British Columbia

All but $27.3 million of $552.2 million, or 95%, of public funding of TRIUMF and AAPS has come from federal sources. Given that British Columbia's GDP is about 12% of the Canadian total, BC's total contribution to TRIUMF can be estimated at $90.3 million, with the remainder coming from the rest of Canada. For this, they received an increase in their GDP of $752.3 million; a return of 8.3 times their investment.

5.3.2 Short-Term Return to Canada

In the short-term, public spending on TRIUMF is a stimulant to economic activity. The $552.2 million of public spending resulted in an increase of $940.9 million in the country's total GDP for a return of 1.7 times the investment.

5.3.3 Investment Choice Return

While investment in TRIUMF creates indirect and induced economic impacts, so would most other investments of public money. Therefore, the indirect and induced impacts are irrelevant and it is the direct impacts that should be used to compare investment choices. From this point of view, the $552.2 million of public spending resulted in an increase of $424.9 million in direct GDP for a return of 0.77 times the investment.

5.3.4 Long-Run Return to Canada

Public spending on TRIUMF contributes to the nation's debt, which in the long-run must be paid back. From this point of view, the public expenditures should not be considered as contributing to the benefit. This leaves $291.1 million of the increase in the country's total GDP for a return of 0.53 times the investment.

[137] The calculations presented here were performed using constant dollars. The calculations were also done taking into account inflation and adjusting for time using a discount rate of 8%. Because the expenditures and benefits occur more or less in synchronization, these adjustments have little impact on the ratios obtained.

5.3.5 Return to Government

From the narrow view of government, the return on investment in TRIUMF comes from the increase in taxes generated. From this perspective, the $552.2 million investment of public money resulted in an increase of $252.3 million in tax revenues for a return of 0.46 times the investment.

These results are summarized in Table 3.

Table 3: Return on Investment Results Summary

Point of View	Economic Return on Investment Ratio
Return to British Columbia[a]	8.3
Short-Term Return to Canada[b]	1.7
Investment Choice Return[c]	0.77
Long-Run Return to Canada[d]	0.53
Return to Government[e]	0.46

a. GDP increase in BC relative to investments by the BC government
b. GDP increase in Canada relative to public investments
c. Direct GDP increase in Canada relative to public investments
d. GDP increase in Canada after public investments are repaid relative to public investments
e. Tax return increase relative to public investments

5.4 Interpretation of the Economic Results

What is the significance of the economic return on investment that TRIUMF has achieved? Unfortunately, we are not aware of any similar economic studies of research infrastructure with which TRIUMF's performance can be compared. However, TRIUMF can be positioned on a continuum of investments in innovation that stretches from direct funding of industry for short-term impacts at one extreme and long-term funding of basic science at the other (where TRIUMF resides) and compared with other investments on that basis.

A recent report from the Council of Canadian Academies (CCA), "Innovation Impacts: Measurement and Assessment", provides a framework for assessing the likelihood of impact from innovation investment programs along such a continuum (Table 4). On the vertical axis are different types of investments; on the horizontal axis are different types of impacts; within the body of the table are relative likelihoods of impact. In the table have been located TRIUMF and two other investment examples for which economic impacts have been calculated in previous studies:

- TRIUMF – a public research organization for fundamental science research.

- Technology Partnerships Canada (TPC) – a direct business support program primarily for the aerospace industry.[138]
- RADARSAT – a public procurement program for an earth observation satellite.[139]

Technology Partnerships Canada (TPC) provided funding support for strategic research and development, and demonstration projects that would produce economic, social and environmental benefits for Canadians. TPC's focus was on key technology areas such as environmental technologies, aerospace and defence technologies, and enabling technologies, which included biotechnology, advanced materials, advanced manufacturing, and information and communications technologies. TPC had two main delivery mechanisms: TPC R&D, delivered directly by TPC, which was targeted at larger firms, and TPC IRAP, delivered by the National Research Council Industrial Research Assistance Program, which supported small to medium-sized enterprises (SMEs) with projects valued under $3 million. The study covered some 693 projects that received $2,797,845,062 in funding.

The RADARSAT-1 satellite earth observation program was originally initiated to improve Canada's management of its natural resources and the monitoring of its extensive landmass, coastal zones (particularly the Arctic), and offshore regions. The program was also seen as a stimulus to Canadian technology development in the space and ground segments and in furthering the applications of the RADARASAT-1 images. RADARSAT-1 operated for 18 years (1995-2013), well beyond its five year design life.

RADARSAT-1 costs were of three types:

- Capital costs associated with the design, construction, launch, and commissioning of the satellite and associated infrastructure. These costs were about $762 M, of which $578.4 M was from the federal government, $56M from the provinces, $28 M from industry, and $100 M was provided by the United States.
- Operating costs associated with the ongoing mission control and tasking of the satellite. These costs averaged about $11 M per year and have been partially offset by data royalties of on average about $2.5 M per year. The total operating costs to 2006 were $98.2 M, offset by $25.3 M in royalties.
- Support costs associated with programs that have developed applications and promoted the use of Radarsat data. These costs totaled about $127.7 M to 2006.

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[138] Hickling Arthurs Low Corporation (2005) "Valuation of Technology Partnerships Canada Benefits", prepared for Industry Canada.

[139] Hickling Arthurs Low Corporation (1999) "RADARSAT Program Economic Assessment", prepared for the Canadian Space Agency.
Hickling Arthurs Low Corporation (2007) "RADARSAT-1 Canadian User Benefits Assessment", prepared for the Canadian Space Agency.

In terms of economic impacts (labeled 'GDP/Output' in the table), the CCA report predicts that TRIUMF will be 'Low' (although 'High' for 'Knowledge Generation'), and TPC and RADARSAT will be 'Moderate' and 'High' respectively.

The following are the benefit/cost ratios actually obtained for the three initiatives:

- TRIUMF 1.7
- RADARSAT 1.4
- TPC 8.6

However, it is worth underlining the point made in Chapter 3 that the primary purpose of TRIUMF is not economic return. As was discussed in Chapter 4, TRIUMF has achieved an enviable record of scientific excellence in nuclear physics, particle physics, nuclear medicine, molecular and materials science, and accelerator science. It provides a central resource to a broad community of scientists and students across 17 Canadian universities and industry. It also is responsible for international scientific partnerships with the United States, Germany, Japan, India and others. In particular, TRIUMF coordinated Canada's involvement in the ground-breaking work at the Large Hadron Collider of the European Organization for Nuclear Research (CERN) that recently proved the existence of the Higgs boson. The scientific work of TRIUMF has resulted in the training of a large number of very highly trained personnel in a variety of disciplines. It has also provided the inspiration for students at the high school level to continue their education in science. And perhaps most importantly, TRIUMF has made signification contributions to medical science in the areas of cancer treatment, medical imaging, and Parkinson's disease research.

In that light, any economic benefit achieved is a bonus on top of TRIUMF's primary mission of scientific research. And while caution should be exercised in comparing disparate studies across time and subject matter, TRIUMF can be seen to be comparable with at least one case of a technology procurement program. In fact, TRIUMF is achieving demonstrable social and economic benefits above what might be expected from a scientific research organization.

Table 4: Likelihood of Innovation Investment Program Impacts

Program Type:	Knowledge Generation	Creation of New Ventures	Access to Capital	Employment	GDP/Output	Taxes	Social
Types of Impact	**Likelihood of Impact**						
Direct Academic Support	High	Low	n/a	Moderate	Low	Low	Moderate
Public Research Organizations **[TRIUMF]**	High	Low	n/a	Moderate	Low	Low	Moderate
Innovation Intermediaries	Low	Moderate	Moderate	Moderate	Low	Low	Low
Direct Business Support **[TPC]**	Moderate	High	High	High	Moderate	Moderate	Moderate
Indirect Business Support	Moderate	Moderate	Moderate	High	Moderate	Moderate	Moderate
Public Procurement **[RADARSAT]**	Low	Low	n/a	High	High	High	High

Source: Council of Canadian Academies

Table 5: TRIUMF Financial Information

Year Ending:	Total	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
Public Funding											
NRC	**438,500,000**	44,000,000	45,000,000	44,000,000	43,500,000	51,500,000	45,500,000	44,000,000	40,000,000	40,000,000	41,000,000
NSERC	**58,597,682**	6,316,503	6,309,557	6,587,586	5,970,896	6,374,929	5,266,630	4,688,242	5,300,363	5,704,966	6,078,010
BCKDF/BCBF	**13,458,892**	4,877,723	632,024								7,949,145
CFI	**27,733,790**	10,196,335	5,580,147	1,946,096	1,114,884	1,867,939	2,406,137	1,923,525	1,203,511	1,495,216	
NRCan	**1,744,226**	1,043,988	700,238								
WD	**918,964**			918,964							
Other Revenue											
Nordion	**41,811,343**	4,190,636	4,219,420	4,350,138	4,370,636	3,938,506	3,771,760	4,523,406	4,299,391	3,727,465	4,419,985
AAPS	**5,761,335**	1,806,141	1,754,608	1,166,618	1,033,968						
Affiliated Institutions	**17,373,673**	2,207,629	2,110,304	2,191,470	2,092,220	1,815,124	1,084,050	1,083,601	1,249,940	1,391,060	2,148,275
Commercial Revenue	**16,152,204**	1,441,927	2,628,668	2,338,207	1,529,721	1,711,706	1,486,266	1,728,178	1,433,679	1,048,967	804,885
General Fund	**2,053,584**	200,258	98,063	60,947	175,071	461,169	417,161	250,428	140,701	120,281	129,505
Intramural Accounts	**5,635,332**	1,116,365	1,275,087	1,442,797	1,801,083						
Total	**629,741,025**	77,397,505	70,308,116	65,002,823	61,588,479	67,669,373	59,932,004	58,197,380	53,627,585	53,487,955	62,529,805
Expenditures											
Buildings and Improvements	**23,859,563**	6,387,794	847,283	334,315	1,176,123	505,470	586,523	379,467	3,088,368	1,642,048	8,912,172
Communications	**1,760,646**	216,387	190,173	245,542	158,169	144,872	157,995	204,282	122,442	157,365	163,419
Computer	**12,756,754**	1,241,276	2,049,025	1,203,207	903,876	1,022,417	1,435,878	1,248,930	1,168,475	1,063,457	1,420,213
Consulting	**8,461,207**	3,374,520	2,390,710	1,347,242	1,348,735						
Equipment	**66,678,756**	6,662,677	5,251,722	4,342,100	4,116,790	6,834,656	6,428,809	8,213,429	6,563,773	8,478,874	9,785,926
Power	**21,537,886**	2,370,483	2,608,866	2,551,233	2,343,671	1,905,098	2,192,484	1,889,040	1,890,107	1,843,775	1,943,129
Salaries and Benefits	**357,053,808**	40,588,275	40,281,034	40,102,553	36,638,698	35,794,712	34,138,291	34,355,746	33,014,827	31,760,528	30,379,144
Supplies and Other Expenses	**113,162,757**	13,710,207	10,720,245	11,527,208	13,763,186	12,953,653	13,052,245	12,065,206	8,997,681	7,867,075	8,506,051
Travel	**7,550,238**	1,949,168	1,847,246	1,833,428	1,920,396						
Facility Conformity Costs	**9,600,000**			1,000,000	1,000,000	7,200,000	400,000				
Total	**622,421,615**	76,500,787	66,186,304	64,486,828	63,369,644	66,360,878	58,392,225	58,356,100	54,845,673	52,813,122	61,110,054
Increase (Decrease) to Fund Balances	7,319,410	896,718	4,121,812	515,995	(1,781,165)	1,308,495	1,539,779	(158,720)	(1,218,088)	674,833	1,419,751

Table 6: AAPS Financial Information

Year Ending:	Total	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
Public Funding											
CECR	**8,780,049**	2,192,145	3,018,545	2,506,991	1,062,368	-	-	-	-	-	-
Interest	**706,831**	122,678	126,353	114,419	343,381	-	-	-	-	-	-
Other Funding	**1,801,271**	1,603,016	181,720	13,698	2,837	-	-	-	-	-	-
Other Revenue											
AAPS Commercial Revenue	**1,105,104**	444,841	272,099	266,667	121,497	-	-	-	-	-	-
Total	**12,393,255**	4,362,680	3,598,717	2,901,775	1,530,083	-	-	-	-	-	-
Expenditures											
Operating Costs	**5,346,082**	2,113,957	1,370,049	1,333,028	529,048	-	-	-	-	-	-
Salary Costs	**4,959,276**	1,654,786	1,717,986	1,090,217	496,287	-	-	-	-	-	-
Knowledge Dissemination Costs	**324,364**	64,550	116,071	73,112	70,631	-	-	-	-	-	-
Commercialization Costs	**693,002**	190,946	172,705	91,790	237,561	-	-	-	-	-	-
Other Expenses	**451,191**	334,710	43,412	28,377	44,692	-	-	-	-	-	-
Total	**11,773,915**	4,358,949	3,420,223	2,616,524	1,378,219	-	-	-	-	-	-
Increases in Balances	**619,340**	3,731	178,494	285,251	151,864	-	-	-	-	-	-

Table 7: Public Funding

Year Ending:	Total	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
TRIUMF	**540,953,554**	66,434,549	58,221,966	53,452,646	50,585,780	59,742,868	53,172,767	50,611,767	46,503,874	47,200,182	55,027,155
AAPS	**11,288,151**	3,917,839	3,326,618	2,635,108	1,408,586	-	-	-	-	-	-
Total	**552,241,705**	70,352,388	61,548,584	56,087,754	51,994,366	59,742,868	53,172,767	50,611,767	46,503,874	47,200,182	55,027,155

Table 8: Attributable Business Enterprise Revenue

Year Ending:	Total	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
Business Enterprise Revenue	**266,927,238**	35,757,376	35,729,029	32,477,017	25,257,685	14,214,895	15,330,787	21,062,724	32,542,775	34,869,090	19,685,861

Table 9: Direct Effects

Year Ending:	Total	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
TRIUMF Canadian Expenditures	**534,062,671**	65,295,240	57,056,034	54,999,468	54,029,959	51,159,585	51,581,707	52,716,381	46,644,459	45,497,480	55,082,359
AAPS Expenditures	**11,773,915**	4,358,949	3,420,223	2,616,524	1,378,219	-	-	-	-	-	-
Business Enterprise Revenue	**249,669,930**	33,870,608	32,828,262	29,872,143	23,606,467	12,503,189	13,844,521	19,334,546	31,109,096	33,820,123	18,880,976
Conference Spending	**9,824,250**	560,500	1,559,750	1,846,500	1,363,750	1,100,000	688,000	1,056,000	698,500	305,500	645,750
Total	**805,330,767**	104,085,297	94,864,269	89,334,634	80,378,395	64,762,774	66,114,228	73,106,927	78,452,055	79,623,103	74,609,085

Table 10: Gross Output

Year Ending:	Total	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
British Columbia											
Direct Effects	799,569,434	102,279,158	93,109,659	88,168,019	79,344,427	64,762,774	66,114,229	73,106,925	78,452,056	79,623,102	74,609,085
Indirect Effects	265,138,073	35,083,080	31,405,076	29,048,420	26,330,942	20,979,299	21,614,521	24,066,491	25,734,416	25,994,146	24,881,680
Induced Effects	351,323,145	45,692,876	41,714,321	38,822,207	34,320,201	29,210,404	29,185,761	31,652,250	33,928,206	33,685,011	33,111,909
Total Impact	1,416,030,653	183,055,114	166,229,056	156,038,645	139,995,569	114,952,476	116,914,511	128,825,671	138,114,677	139,302,260	132,602,675
Rest-of-Canada											
Direct Effects	-	-	-	-	-	-	-	-	-	-	-
Indirect Effects	167,854,530	22,110,870	19,559,614	18,190,156	16,527,363	12,747,015	13,319,210	15,319,199	16,790,122	17,229,589	16,061,392
Induced Effects	251,099,583	32,714,268	29,721,172	27,652,243	24,544,250	20,577,077	20,705,758	22,673,842	24,405,538	24,378,794	23,726,640
Total Impact	418,954,113	54,825,138	49,280,786	45,842,399	41,071,613	33,324,092	34,024,969	37,993,041	41,195,661	41,608,383	39,788,032
Canada Total											
Direct Effects	799,569,434	102,279,158	93,109,659	88,168,019	79,344,427	64,762,774	66,114,229	73,106,925	78,452,056	79,623,102	74,609,085
Indirect Effects	432,992,603	57,193,950	50,964,690	47,238,576	42,858,305	33,726,313	34,933,732	39,385,690	42,524,538	43,223,736	40,943,072
Induced Effects	602,422,728	78,407,144	71,435,493	66,474,449	58,864,451	49,787,481	49,891,519	54,326,093	58,333,744	58,063,805	56,838,550
Total Impact	**1,834,984,767**	**237,880,252**	**215,509,842**	**201,881,044**	**181,067,181**	**148,276,568**	**150,939,479**	**166,818,712**	**179,310,338**	**180,910,643**	**172,390,707**

Table 11: Gross Domestic Product

Year Ending:	Total	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
British Columbia											
Direct Effects	424,907,263	54,166,676	50,503,378	47,591,084	41,369,609	34,743,807	34,684,170	37,939,131	41,792,211	42,060,261	40,056,937
Indirect Effects	114,241,035	15,107,865	13,565,553	12,566,583	11,391,488	8,917,725	9,231,657	10,331,826	11,117,282	11,274,003	10,737,052
Induced Effects	213,139,037	27,720,538	25,307,369	23,552,802	20,821,163	17,722,277	17,706,815	19,202,456	20,582,855	20,434,800	20,087,962
Total Impact	752,287,337	96,995,078	89,376,300	83,710,467	73,582,260	61,383,809	61,622,644	67,473,416	73,492,349	73,769,064	70,881,951
Rest-of-Canada											
Direct Effects	-	-	-	-	-	-	-	-	-	-	-
Indirect Effects	67,026,767	8,828,068	7,837,565	7,259,364	6,602,536	5,146,417	5,378,970	6,142,602	6,658,075	6,816,445	6,356,727
Induced Effects	121,607,187	15,847,699	14,386,953	13,384,833	11,887,849	9,942,966	10,016,238	10,984,742	11,831,262	11,829,320	11,495,325
Total Impact	188,633,954	24,675,767	22,224,518	20,644,198	18,490,385	15,089,383	15,395,208	17,127,344	18,489,336	18,645,765	17,852,052
Canada Total											
Direct Effects	424,907,263	54,166,676	50,503,378	47,591,084	41,369,609	34,743,807	34,684,170	37,939,131	41,792,211	42,060,261	40,056,937
Indirect Effects	181,267,802	23,935,933	21,403,118	19,825,947	17,994,024	14,064,142	14,610,627	16,474,428	17,775,357	18,090,448	17,093,779
Induced Effects	334,746,224	43,568,236	39,694,322	36,937,635	32,709,013	27,665,243	27,723,054	30,187,198	32,414,117	32,264,120	31,583,287
Total Impact	**940,921,291**	**121,670,845**	**111,600,818**	**104,354,665**	**92,072,645**	**76,473,191**	**77,017,852**	**84,600,759**	**91,981,685**	**92,414,828**	**88,734,003**

Table 12: Employment (Full Time Equivalent)

Year Ending:	Total	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
British Columbia											
Direct Effects	5,311	690	622	581	512	441	436	473	518	501	538
Indirect Effects	1,466	192	174	163	148	117	119	132	142	143	137
Induced Effects	2,826	367	335	312	276	235	235	255	273	271	266
Total Impact	9,602	1,249	1,131	1,056	936	793	790	859	932	914	941
Rest-of-Canada											
Direct Effects	-	-	-	-	-	-	-	-	-	-	-
Indirect Effects	616	81	72	67	61	47	49	57	61	63	58
Induced Effects	1,515	197	179	167	148	124	125	137	147	147	143
Total Impact	2,131	278	251	233	209	171	174	194	209	210	202
Canada Total											
Direct Effects	5,311	690	622	581	512	441	436	473	518	501	538
Indirect Effects	2,082	273	245	230	208	164	169	189	203	205	195
Induced Effects	4,340	565	515	479	424	359	359	391	420	418	410
Total Impact	**11,733**	**1,527**	**1,382**	**1,290**	**1,145**	**964**	**964**	**1,053**	**1,141**	**1,124**	**1,143**

Table 13: Labour Income

Year Ending:	Total	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
British Columbia											
Direct Effects	325,088,731	41,772,842	38,676,150	36,105,511	31,688,096	27,607,737	27,364,769	29,456,630	31,275,779	30,980,044	30,161,172
Indirect Effects	69,061,382	9,126,368	8,211,131	7,603,052	6,870,130	5,359,488	5,553,251	6,235,664	6,748,381	6,870,102	6,483,815
Induced Effects	95,953,445	12,479,799	11,392,773	10,602,873	9,373,580	7,977,142	7,970,806	8,645,006	9,266,899	9,200,873	9,043,695
Total Impact	490,103,557	63,379,010	58,280,053	54,311,436	47,931,806	40,944,368	40,888,825	44,337,300	47,291,058	47,051,019	45,688,681
Rest-of-Canada											
Direct Effects	-	-	-	-	-	-	-	-	-	-	-
Indirect Effects	34,716,527	4,565,834	4,043,929	3,751,972	3,400,962	2,629,901	2,753,914	3,173,474	3,486,071	3,588,008	3,322,461
Induced Effects	61,514,365	8,015,114	7,279,814	6,772,942	6,013,051	5,036,852	5,070,383	5,555,339	5,981,010	5,976,476	5,813,384
Total Impact	96,230,891	12,580,948	11,323,743	10,524,914	9,414,013	7,666,753	7,824,296	8,728,813	9,467,082	9,564,484	9,135,845
Canada Total											
Direct Effects	325,088,731	41,772,842	38,676,150	36,105,511	31,688,096	27,607,737	27,364,769	29,456,630	31,275,779	30,980,044	30,161,172
Indirect Effects	103,777,908	13,692,203	12,255,060	11,355,024	10,271,092	7,989,389	8,307,165	9,409,138	10,234,452	10,458,110	9,806,276
Induced Effects	157,467,810	20,494,913	18,672,587	17,375,815	15,386,631	13,013,994	13,041,188	14,200,345	15,247,909	15,177,349	14,857,079
Total Impact	**586,334,449**	**75,959,958**	**69,603,796**	**64,836,350**	**57,345,820**	**48,611,121**	**48,713,121**	**53,066,114**	**56,758,139**	**56,615,503**	**54,824,526**

Table 14: Tax Revenue

Year Ending:	Total	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
British Columbia											
Direct Effects	88,872,009	11,450,627	10,551,745	9,920,474	8,688,889	7,351,933	7,307,031	7,928,353	8,639,660	8,588,491	8,444,806
Indirect Effects	51,830,558	6,803,782	6,160,137	5,720,192	5,115,000	4,185,550	4,245,425	4,668,676	5,018,334	5,025,787	4,887,679
Induced Effects	61,477,851	7,995,708	7,299,673	6,793,586	6,005,657	5,111,854	5,107,376	5,538,753	5,936,902	5,894,178	5,794,167
Total Impact	202,180,416	26,250,116	24,011,554	22,434,252	19,809,546	16,649,337	16,659,831	18,135,780	19,594,896	19,508,454	19,126,650
Rest-of-Canada											
Direct Effects	-	-	-	-	-	-	-	-	-	-	-
Indirect Effects	16,785,825	2,211,046	1,961,248	1,815,539	1,650,247	1,284,756	1,343,757	1,538,731	1,671,694	1,713,318	1,595,488
Induced Effects	33,294,885	4,339,499	3,938,101	3,663,712	3,254,923	2,719,357	2,740,846	3,008,017	3,240,811	3,241,716	3,147,903
Total Impact	50,080,711	6,550,545	5,899,350	5,479,252	4,905,171	4,004,113	4,084,603	4,546,749	4,912,506	4,955,034	4,743,391
Canada Total											
Direct Effects	88,872,009	11,450,627	10,551,745	9,920,474	8,688,889	7,351,933	7,307,031	7,928,353	8,639,660	8,588,491	8,444,806
Indirect Effects	68,616,384	9,014,828	8,121,385	7,535,731	6,765,247	5,470,306	5,589,182	6,207,407	6,690,028	6,739,104	6,483,166
Induced Effects	94,772,736	12,335,207	11,237,774	10,457,298	9,260,580	7,831,211	7,848,222	8,546,770	9,177,713	9,135,893	8,942,070
Total Impact	**252,261,127**	**32,800,661**	**29,910,904**	**27,913,504**	**24,714,717**	**20,653,450**	**20,744,434**	**22,682,529**	**24,507,402**	**24,463,488**	**23,870,041**

A. Interviews

A total of 19 interviews were conducted in support of this study. Representatives of the following organizations were interviewed:

- AAPS
- ABB
- ACSI
- AECOM
- Bubble Technologies
- D-Pace
- General Electric
- IKOMED
- Lawson Health
- Nordion
- Pacific Parkinson's
- PAVAC
- Queen's University
- Toyota
- TRIUMF
- TRIUMF PIF/NIF
- UBC Campus Planning
- University of Toronto
- Westport Innovation

B. Glossary

11C	Carbone 11
18F	Fludeoxyglucose
AAPS	Advanced Applied Physics Solutions Inc. (AAPS), a wholly owned, not-for-profit company positioned as the development arm of TRIUMF
ACSI	Advanced Cyclotron Systems Incorporated
ALMA	Atacama Large Millimeter/submillimeter Array, an international telescope located in Chile.
ALPHA	An international collaboration based at CERN, whose aim is stable trapping of antihydrogen atoms
ARIEL	Advanced Rare IsotopE Laboratory
ATLAS	One of two major international collaborations operating a high-energy collider detector on the LHC at CERN
BCCA	British Columbia Cancer Agency.
β-NMR	Nuclear Magnetic Resonance with radioactive nuclei
Br	Bromine
CECR	Centres of Excellence for Commercialization and Research
CERN	Centre for Nuclear and Particle Physics, a major international laboratory for nuclear and particle physics located in Geneva, Switzerland
CFI	Canada Foundation for Innovation
CIHR	Canadian Institutes of Health Research
CMMS	Centre for Molecular and Materials Science at TRIUMF
CMS	Compact Muon Solenoid
CPDC	Centre for Probe Development and Commercialization
DEAP	Dark Matter Experiment using Argon Pulse-shape discrimination.
DLC	Diamond-like Carbon
DOE	US Department of Energy
D-Pace	Dehnel Particle Accelerator Components and Engineering, a private firm
DRAGON	Detector of Recoils and Gamma Rays for Nuclear Astrophysics

DRDC	Defence Research and Development Canada
e-Linac	Superconducting Electron Linear Accelerator.
EBFGT	Electron beam flue gas treatment
EBIT	Electron Beam Ion Trap.
EPICS	Experimental Physics and Industrial Control System
Fermilab	Fermi National Accelerator Laboratory in Illinois
FDG	Fluorodeoxyglucose
FGD	Fine Grained Detector
FLUKA	(FLUktuierende KAskade) is a fully integrated Monte Carlo simulation package for the interaction and transport of particles and nuclei in matter
FrPNC	Francium parity non-conservation
GEANT4	GEometry ANd Tracking,a toolkit for the simulation of the passage of particles through matter
Gemini	An International partnership comprised of two 8.1-meter telescopes located in Hawaii and Chile.
GMP	Good manufacturing practice
GRIFFIN	Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei.
HALO	Helium and Lead Observatory for Supernova Neutrinos
ILC	International Linear Collider
IRIS	ISAC Charged Particles Spectroscopy Station.
ISAC	Isotope Separator and Accelerator
J-PARC	Japan Proton Accelerator Research Complex, a nuclear and particle physics laboratory located in Tokai, Japan
LANL	Los Alamos National Laboratory
LAr	Liquid argon
LHC	Large Hadron Collider at CERN, the world's highest energy proton-proton collider
µSR	Muon spin rotation
MPI-K	Max Planck Institute for Nuclear Physics in Heidelberg, Germany.
MRB	Methylreboxetine
mRNA	messenger RNA
NCE	Network of Centres of Excellence

NCO	NaxCoO2 System
NET	Norepinephrine transporter
NIF	Neutron irradiation facility
NMR	Nuclear Magnetic Resonance
NRC	National Research Council Canada
NSERC	Natural Sciences and Engineering Research Council
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory, a multidisciplinary laboratory in Oak Ridge, Tennessee.
PAVAC	PAVAC Industries, a BC firm.
PD	Parkinson's Disease
PDF	Post-Doctoral Fellow
PET	Positron Emission Tomography
PIENU	A collaborative experiment designed to make a precision measurement of the pion decay rate to an electron and neutrino.
PIF	Proton irradiation facility
PNA	Peptide nucleic acid
PPRC	Pacific Parkinson's Research Centre.
RA	Research Associate
RCNP	Research Center for Nuclear Physics (Osaka)
RIB	Radioactive Ion Beam.
SHARC	Silicon Highly-segmented Array for Reactions and Coulex
SM	Standard Model
SMMS	Single-molecule magnets
SNO	Sudbury Neutrino Observatory
SNOLAB	International Facility for Underground Science at Sudbury
SRF	Superconducting radio frequency
T2K	Next-generation long baseline neutrino oscillation experiment in Japan
TIGRESS	TRIUMF ISAC Gamma Ray Escape Suppressed Spectrometer
TIP	TIGRESS Integrated Plunger.
TITAN	TRIUMF Ion Trap for Atomic and Nuclear Science.

TRIUMF	Canada's national laboratory for particle and nuclear physics
TUDA	TRIUMF UK Detector Array.
TWIST	TRIUMF Weak Interaction Symmetry Test
UBC	University of British Columbia
UCN	Ultra cold neutron
VECC	Variable Energy Cyclotron Centre, India.
WED	Western Economic Diversification
XRF	X-Ray Fluorescence

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