TRIUMF

TRIUMF is Canada's National Laboratory for Particle and Nuclear Physics

TRIUMF
4004 Wesbrook Mall
Vancouver, B.C.
V6T 2A3 Canada
Tel: 604 222-1047
Fax: 604 222-1074
www.triumf.ca

Annual Financial & Administrative Report

2006-2007

The wonder of science and the splendor of nature come together at TRIUMF. The laboratory is located on the campus of the University of British Columbia, next to Pacific Spirit Regional Park.

TRIUMF is Canada's national laboratory for particle and nuclear physics. It is owned and operated as a joint venture by a consortium of Canadian universities via a contribution from the Government of Canada through the National Research Council of Canada.

The Province of British Columbia provides capital funding for the construction of buildings for the TRIUMF laboratory.

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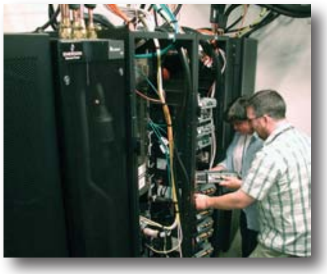

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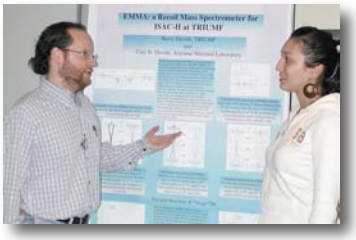

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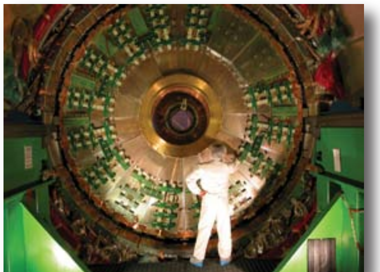
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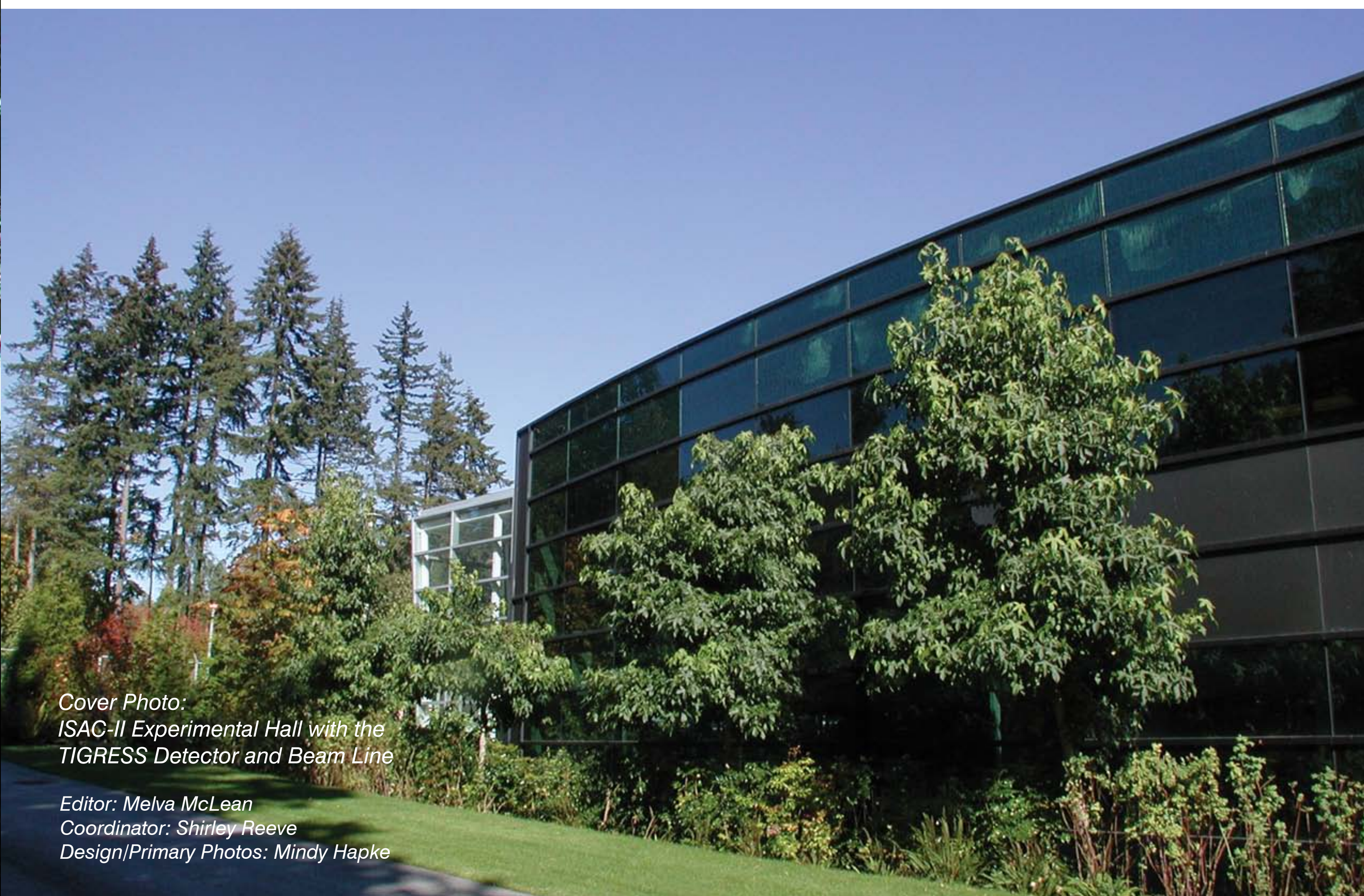


Cover Photo:
ISAC-II Experimental Hall with the TIGRESS Detector and Beam Line

Editor: Melva McLean
Coordinator: Shirley Reeve
Design/Primary Photos: Mindy Hapke

One of the highlights of the 2006/2007 fiscal year was the completion of the first phase of the ISAC-II accelerator. Designed and built at TRIUMF, this accelerator is based on a technology that requires the accelerating components to be cooled to an extremely low temperature of about -268˚C. However, before any new accelerator can be connected to a scientific experiment, it must undergo a rigorous commissioning stage to ensure that the accelerator performs to its design specification and that the radiation fields generated by the accelerator are well within prescribed safety limits. This commissioning process must be undertaken before the Canadian Nuclear Safety Commission (CNSC) will issue a running license to perform scientific experiments.

TRIUMF Director
Alan Shotter

The regulatory license allowing the ISAC-II accelerator to send a radioactive beam to an experiment was received at the beginning of January, so the annual three-month shutdown period for laboratory infrastructure maintenance was delayed to the fourth week of January. This delay enabled a two-week running period for MAYA, ISAC-II's first experiment. This experiment involved the production of ^{11}Li by the 500 MeV proton beam and acceleration of the lithium beam through the ISAC-I and ISAC-II accelerator complex before injection into the MAYA apparatus, which had been brought to TRIUMF from the GANIL laboratory in France.

The new ISAC-II accelerator worked superbly during the experiment, and exciting new data from the reaction ^{11}Li(p,t) ^{9}Li was obtained. The data is sensitive enough to distinguish between the various models that have been proposed to describe the neutron halo nature of this exotic nucleus. MAYA was an excellent start to ISAC-II operations, and I would like to pay a special tribute to Bob Laxdal and his team for their work in bringing the first phase of the ISAC-II accelerator to such a successful conclusion.

Preparations for the installation of the TIGRESS detector array in the ISAC-II experimental hall are well advanced; the first experiment is scheduled for the summer of 2007. A recent Canada Foundation for Innovation (CFI) award to construct a neutron wall to be used with TIGRESS for ISAC-II experiments is most welcome news. Congratulations to the University of Guelph for this award!

The precision isotope mass measuring system, TITAN, is now entering its final commissioning phase with first measurements scheduled for the summer of 2007.

Recent developments during the year on the FEBIAD ion source, and the relocation of the driver lasers for the laser ion source, should lead to a significant improvement in isotope variety and intensity for RIB experiments in the coming year.

The µSR program is a very significant component of the TRIUMF research portfolio and has remained competitive over the years due to the continuing innovation of experimental technologies; this year's investigations of microscopic behaviour of materials under high pressure are a good illustration. The quest for continuing improvement of the µSR program received a major boost with the announcement of a major CFI award to significantly enhance the experimental capabilities of one of the muon beam lines. This, together with the current upgrades on another muon beam line, should provide the basis for µSR innovation for several years to come. Simon Fraser University (SFU) is the lead university for this CFI award, but 15 other Canadian universities are also associated with it.

The data taking phase of the TWIST experiment, a precision measurement of the muon decay parameters, will be completed in 2007. The expectation is that all the goals of this challenging experiment will be achieved. This is excellent news because the team has worked very hard to achieve this result. The outcome is also a fitting tribute to the initial leader of the project, Nate Rodning, who tragically died during its early stages. Nate was a fine scientist as well as a wonderful person to know.

The use of radioisotopes produced at TRIUMF continues to be of great value across a range of scientific disciplines, with the life sciences being a dominant component. This year TRIUMF was able to supply a steady stream of the radioisotope ^{18}F to the BC Cancer Agency (BCCA) to enable an early start-up of their new PET facility, which will provide treatment to cancer patients. So far, several thousand patients have benefited from this TRIUMF/BCCA collaboration.

TRIUMF has campaigned for some time to establish the Canadian Tier 1 data centre at TRIUMF for the analysis of data that will soon stream from the Linear Hadron Collider at CERN. I am pleased to report that the funds to establish this 23M$ data hub are now in place. (see page 4) TRIUMF wishes to thank both the BC Provincial Government and CFI for generously supporting this important project. The lead university for the CFI component is SFU together with nine other collaborating universities.

Canada, through TRIUMF, is also making a significant contribution to the Tokai to Kamioka (T2K) experiment at J-PARC, an international laboratory in Japan. These activities heavily involve TRIUMF expertise in detector technology and high-powered targets. The T2K experiment is a natural extension of the SNO experiment at Sudbury which has been so successful in revealing clues to the enigmatic nature of the neutrino.

This year, TRIUMF applied to the CNSC for renewal of its operating license for another five years, beginning April 2007. I am pleased to report the license was awarded.

TRIUMF's current funding cycle extends to 2010, and the laboratory has started planning for the funding period 2010 to 2015. Groups of scientists have been meeting since the summer of 2006 to propose how different science areas in the laboratory should develop over this period.

This is a time for reflection and forward vision, and it is in this vein that I warmly welcome Nigel Lockyer, TRIUMF's new director. My term as TRIUMF's Director ends April 30, 2007, and my parting wish is for Nigel and TRIUMF to flourish for many years to come.

The ATLAS Tier 1 Computing Centre at TRIUMF

by Rèda Tafirout & Isabel Trigger

Deep below the vineyards and farmlands of the French-Swiss border, members of the ATLAS collaboration are racing to complete the assembly of the largest and most complex particle detector ever built. ATLAS is a colossal endeavour. Forty-six metres long, twenty-five metres in diameter, and weighing about 7,000 tonnes, ATLAS is the bigger of the two general-purpose detectors at the Large Hadron Collider (LHC) at the CERN laboratory near Geneva. Its final assembly, in a cavern a hundred metres underground, is like putting together a giant jigsaw puzzle. About 1,500 physicists from more than 150 universities and laboratories in 35 countries are working on the project. Liquid argon hadron calorimeters, comprising hundreds of tonnes of precisely machined copper plates and sandwiching delicate readout electronics, which were designed and assembled at TRIUMF, are set to take their place in the puzzle.

ATLAS will deal with huge energies and extremely high data rates. The LHC will collide bunches of about 100 billion protons, 40 million times every second. Each proton will have a kinetic energy of 7 TeV, the energy that an electron would have after moving through a potential difference of 7 trillion volts. Each beam will store 362 Megajoules of energy, enough to melt about 400 kg of copper. Although ATLAS is big, many of its components must be aligned within tens of microns, literally a hair's breadth. Thousands of sensors will track the movements of everything from huge metallic masses to tiny silicon wafers, and their output will be recorded in databases.

Forty million times a second, twenty or more individual pairs of protons will collide and interact. Only a small fraction of the interactions will be "interesting" ones in which most of the kinetic energy of the colliding protons is converted into new, much more massive particles. These could be Z and W gauge bosons or top and bottom quarks, particles which have been produced at other accelerators, but which will be made more copiously at the LHC. More excitingly, some collisions could release enough energy to produce the elusive and much sought-after Higgs boson (the key to why matter has mass), or perhaps other new particles predicted by models which invoke supersymmetry or gravity propagating in additional dimensions.

To avoid multiple occupancy, where ionization charges from several particles in this high-rate environment hit the same wire or calorimeter cell at the same time and send overlapping signals, ATLAS has a very fine granularity, with millions of electronics channels. It is impossible, however, to analyze millions of channels 40 million times a second, so a complex trigger system looks for specific features, or "signatures," and throws away most of the uninteresting data. After all filtering, ATLAS will still produce about 320 Megabytes of raw data every second (27 Terabytes per day). As a comparison, if a year's data were stored on double-density DVDs, even without cases, the stack of DVDs would be as tall as the CN Tower.

This is where the LHC Tier 1 centres enter the picture. It is not practical to create a giant computing centre at CERN to store all the data and run all the analysis jobs. Instead, data will be distributed to ten Tier 1 centres around the world, using the Worldwide LHC Computing Grid (WLCG).

A Grid connects computers in different places, running different hardware, different software, different security systems, and using different methods of storage access without requiring individual users to have accounts on all the systems involved. This connectivity is achieved by running so-called "Middleware" (which, despite its intriguing name, has nothing at all to do with corsets and cummerbunds) on all of the individual nodes that make up the Grid. Middleware provides a convenient way to distribute large tasks to geographically distributed, heterogeneous systems.

As part of the world's most advanced network and computing Grid, TRIUMF is hosting Canada's Tier 1 computing centre for the ATLAS experiment. Funds for the centre in the amount of \$10.5M (\$8.0M in capital, \$2.5M in operating) have been secured by a consortium of Canadian universities from the Canada Foundation for Innovation (CFI) through its Exceptional Opportunities Fund program. An additional \$4.0M grant has been secured from the BC Knowledge Development Fund. There will also be a very important contribution from the computing industry in the form of discounts on hardware purchases, equivalent to several million dollars.

Each Tier 1 centre will be coupled to a set of Tier 2 centres, which are based primarily at participating universities and which will produce the simulated datasets required to understand ATLAS data. The simulated data will be uploaded to the Tier 1. User analysis will also be done at the Tier 2 centres. In Canada, by Rèda Tafirout & Isabel Trigger

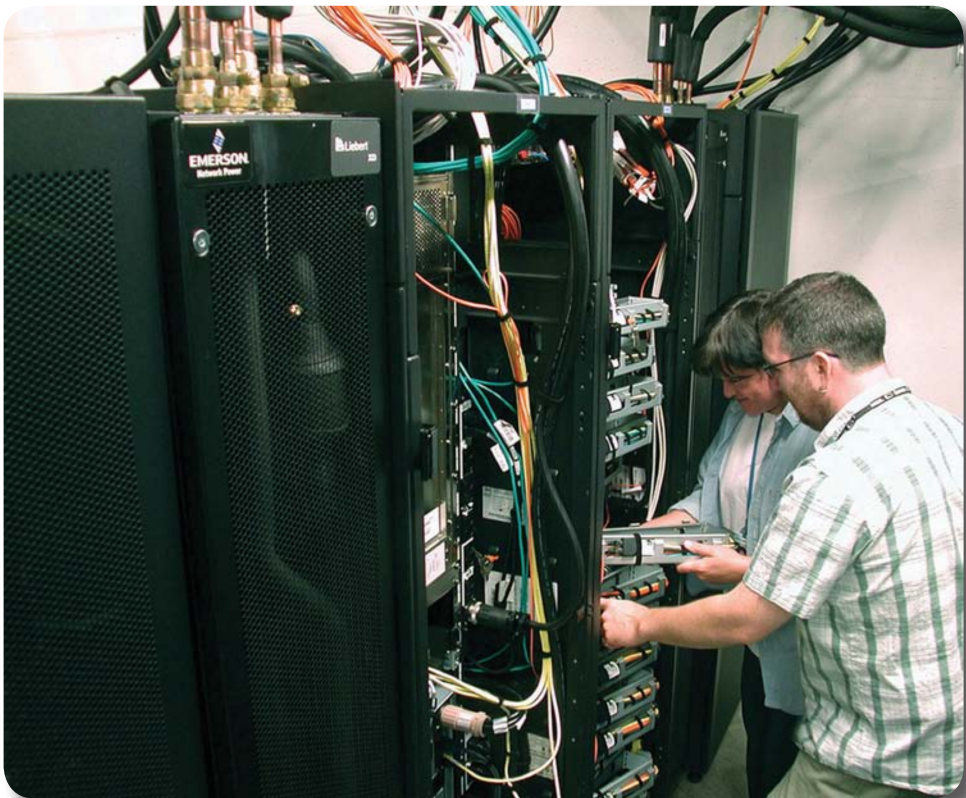
the two federated Tier 2 centres, one in the East and one in the West, will be "virtual" facilities pulling together resources located at participating universities. Canada's Tier 2 centres will share equipment and resources with other research clients of the high-performance computing consortia collectively known as Compute Canada. Funding for these shared resources is secured through CFI's National Platform Fund program.

Managing the Centre

In early 2006, the TRIUMF centre moved from being a Tier 1 prototype to a fully functional system providing production-quality service for ATLAS on a continuous, around-the-clock basis.

The main missions of the TRIUMF Tier 1 centre are to receive, store and perform the final-pass reconstruction of real data from the Tier 0 centre at CERN, and to receive and store simulated data from the Tier 2 centres. Freshly reconstructed data from the ATLAS detector at CERN are copied to TRIUMF, and the reconstruction may be re-done at the Tier 1 if new calibrations need to be applied. If the load on the Tier 0 is too heavy, some of the first-pass reconstruction may also be done at TRIUMF. In either case, final reconstruction of the Analysis Object Data, which physicists ultimately analyze, is done at the Tier 1 centres. Meanwhile, sets of simulated data produced at the Canadian Tier 2 sites are also sent to TRIUMF, where they are catalogued and copied to sites around the world.

To accomplish all this, the Tier 1 runs various Grid services which provide access to the Centre's resources. A Compute Element distributes tasks to hundreds of CPUs. The Storage Resource Manager allocates Terabytes (and, in the future, Petabytes) of disk and tape storage. A File Transfer Service controls data movement channels between LCG sites. An LCG File Catalog contains information about the locations of millions of files, and the metadata needed to organize them and prevent unnecessary duplications and file transfers. An ATLAS Virtual Organization service handles datasets and file subscription, determining who orders what to be copied where and when. The Tier 1 also provides a critical database service using an Oracle Real Application Cluster, which was deployed as part of the LCG Distributed Database Deployment project. The database will hold ATLAS conditions data, including readings from all the thousands of temperature sensors, alignment monitors and gas purity gauges, which determine the calibration and alignment constants, as well as event summary data suitable for quickly selecting events of interest in a particular analysis.



Lead system administrator Denice Deatrich and networking administrator Chris Payne examine the dCache servers.

The challenge is therefore to build, maintain and operate a large-scale data-intensive analysis facility for 24/7 operations. Compliance with the WLCG Memorandum of Understanding, which was signed by TRIUMF in October of 2006, allows for a maximum integrated downtime of just one week per calendar year. Carefully planned interruptions for system maintenance, improvements and expansion will be necessary, but the rest of the time, all Grid services must be available and reliable. The system is therefore designed to be highly fault tolerant and scalable for smooth growth so that each year more computing resources may be deployed to the experiment.

The ATLAS Tier 1 Computing Centre at TRIUMF

by Rèda Tafirout & Isabel Trigger

To test the LHC experiments' computing models, several Service Challenge phases have been planned. The Service Challenges are meant to test the robustness of Grid Middleware services, storage access and networking at several sites to ensure readiness for LHC start-up in 2007. In early 2006, a test of file transfers between CERN and several Tier 1 sites, including TRIUMF, achieved an aggregate rate of one gigabyte per second throughput — a major success. Imagine copying a typical six-gigabyte movie from Switzerland to sites around the world in just six seconds and sustaining that transfer rate for days on end! (Note that this is the aggregate rate for transfers to all sites; the rate to TRIUMF alone is about one tenth of that, so if we wanted the whole movie in our example at TRIUMF, it would take about a minute to get here.)

Data movements among the Tiers are a fundamental component of the ATLAS computing model. They require high-speed dedicated networks connecting the various Tier layers. In November of 2006, a five-gigabit/s CERN TRIUMF link was commissioned in accordance with a Memorandum of Understanding among HEPNET, CANARIE and TRIUMF to establish the proper Tier 1 connectivity as part of the LHC Optical Private Network. Two dedicated one-gigabit/s lightpaths were established in 2006 to connect TRIUMF to the Canadian Tier 2 resources at the University of Victoria and the University of Toronto, and more recently a dedicated link was established between TRIUMF and McGill University. Connections to Simon Fraser University and to the University of Alberta currently use the one-gigabit/s WestGrid link but will have dedicated links in the future.

The data centre is housed in the ISAC-II building and has required important infrastructure work to bring in power, cooling and networking. The available floor space is less than a hundred square metres, so the cluster design has been carefully optimized for the space limitations. The current estimates for power consumption are 175 kW for the computing nodes (CPU), 75 kW for the disk storage system and 25 kW for the remaining components (tape library and drives, network switches, Grid services and RAC system). Think about the air conditioning you would need in a typical two-bedroom apartment illuminated by three thousand 100-Watt light bulbs. The Tier 1 air conditioning/cooling system will use about 130 kW of power at full capacity. Its design is critical for the centre, and various options have been explored. A solution using liquid-cooled heat exchangers was selected due to the very high heat density.

All personnel for the system administration and operational aspects of the Tier 1 centre were hired by the end of 2006, including a lead system administrator, and experts in Grid computing, storage, databases and networking. While each staff member has a specific area of expertise, all must be knowledgeable about other operational aspects of the Tier 1 centre to provide backup when the expert is away. Some of the Tier 1 personnel are required to travel frequently to CERN to represent the TRIUMF centre at meetings and workshops.

ATLAS-Canada Reaping the Benefits

When an individual Canadian physicist sits down at her computer to analyze ATLAS data, how does having a Tier 1 centre at TRIUMF benefit her? The beauty of Grid computing is that no matter where she is in the world, our ATLAS physicist can submit an analysis job to the LCG and tell it what data she wants to analyze. Grid tools then figure out where the data are stored and what nearest available processors are available. The tools can decide whether it is more efficient to copy the data to sites with free processors or to wait for resident processors. The highly refined and fully reconstructed Analysis Object Data (AOD) files, and the processors that will be available for user analysis jobs, will be at Tier 2 centres. It might therefore seem irrelevant to our physicist whether the nearest Tier 1 is in Vancouver or in Amsterdam. Indeed, as long as working on an analysis only requires access to the standard set of AOD files, it *should* be irrelevant on a day-to-day basis. On the other hand, the first few years of a particle physics experiment are usually eventful ones. The detector is new and has to be completely understood before subtle analyses can provide conclusive answers. Calibration and alignment data change rapidly. These are ingredients which feed into the final AOD production.

What then if our physicist is a calorimetry expert and his job is to calibrate the hadron calorimeters? He can't run on the AOD because his job requires access to the more detailed information only found on the Event Summary Data (ESD) stored at the Tier 1. Or perhaps he is performing a new analysis with a signal that requires special AOD files, which nobody else in ATLAS is using, or takes advantage of information which is only recorded at the ESD level.

by Rèda Tafirout & Isabel Trigger

In practice, there will be some additional resources at the TRIUMF Tier 1 over and above the Canadian share of LCG requirements, which will be dedicated to Canadian research activities. A Canadian "Virtual Organization" (VO) has been set up as a sub-group of the ATLAS VO in the LCG, so that priority queues can be set aside for Canadian users. This may be used, for example, to perform tasks like calorimeter calibration which require access to the ESD at the Tier 1.

Subtler advantages of having a Tier 1 centre in Canada come from the creation of a concentration of computing expertise. The 24/7/365 schedule of a Tier 1 requires that there be abundant local expertise in all fields necessary for operating the facility, as well as dedicated user-support personnel. Having these experts in one place ensures that they constantly exchange ideas and provide a pool of expertise that is a valuable resource for the Tier 2 centres.

Isabel Trigger and Rèda Tafirout with one of the control stations for the Tier 1.

Students at Canadian universities can apply for the appropriate Grid certificates and VO memberships. They can then plug in their laptops and run a few scripts to set up user interfaces to submit analysis jobs to the Grid. Jobs could now run anywhere on the LCG, but with priority access to Canadian processors, jobs will probably run faster if they run in Canada and copy the output back to Canadian storage elements. If students have difficulties with the software, they can ask for help from local experts. If they are in any doubt, they can consult Tier 2 personnel who, in turn, can refer them to Tier 1 personnel.

Having a Tier 1 centre gives Canada a higher profile within ATLAS and the LHC computing community and demonstrates our leadership in the field. TRIUMF will continue to attract top-quality post-doctoral fellows and computer scientists, who will transfer Grid computing expertise back into the larger community, where it will benefit Canadian high-tech industries. As computing becomes ever more critical to the field of subatomic physics, it is appropriate that Canada's national laboratory for subatomic physics should be home to a world-class computing facility.

The ATLAS Tier 1 centre at TRIUMF opens many doors: between the LCG and the heterogeneous Grid computing resources in Canada; between fundamental research and high-tech industry; between TRIUMF and our consortium of universities; between ATLAS and TRIUMF; between Canada and the world. Now is our chance to step through as many of those doors as possible, as TRIUMF and Canada join in the incredible voyage of discovery that is ATLAS.

Isabel Trigger is a TRIUMF Research Scientist with the ATLAS Group at TRIUMF.

Rèda Tafirout is a TRIUMF Research Scientist and the ATLAS Tier 1 Data Centre Manager.

ISAC-II Science with MAYA & EMMA

by Barry Davids

Thermonuclear fusion reactions power the stars and produce the chemical elements of which the Earth and its inhabitants are made. Many of the atomic nuclei that participate in these reactions are both rare and radioactive and therefore have not been studied in the laboratory. Nevertheless, because they play an important role in stellar energy generation and the synthesis of the chemical elements, the properties of these nuclei must be understood. With the completion of the initial configuration of ISAC-II, TRIUMF's new radioactive ion beam accelerator, the laboratory is now able to accelerate the world's most intense, high quality radioactive ion beams to energies high enough to allow detailed studies of the structure of these nuclei and the reactions they undergo. When the accelerator is complete in 2010, the final energies of these beams will depend on the specific nuclei being accelerated, but maximum speeds will exceed 10% of the speed of light throughout the operating range of the accelerator. The installation of a charge state booster in 2008 to strip additional electrons from the ions will extend the range of accessible nuclei to include those as heavy as 150 atomic mass units.

Several experimental set-ups will allow scientists from Canada and abroad to take advantage of the beams from the new accelerator. All of the experiments will scatter a beam of radioactive ions from a target and detect the outgoing nuclei and/or gamma radiation. A different detection apparatus is optimized for each task. The TIGRESS gamma ray spectrometer, a state-of-the-art device with a high efficiency for detecting gamma rays emitted in the decay of nuclei produced in these reactions, is being assembled and has already been used in a successful measurement at ISAC-I. (See Annual Financial and Administrative Report 2005/06). The HERACLES detector will be used for charged particle detection, as will EMMA, which is covered in more detail below. The first experiment at ISAC-II employed MAYA, a detector imported from the French national laboratory GANIL to take advantage of the world's leading ^{11}Li beam intensity and quality provided by ISAC-II. By studying the reactions ^{11}Li undergoes, we can learn about its exotic halo structure. (see Fig. 1)

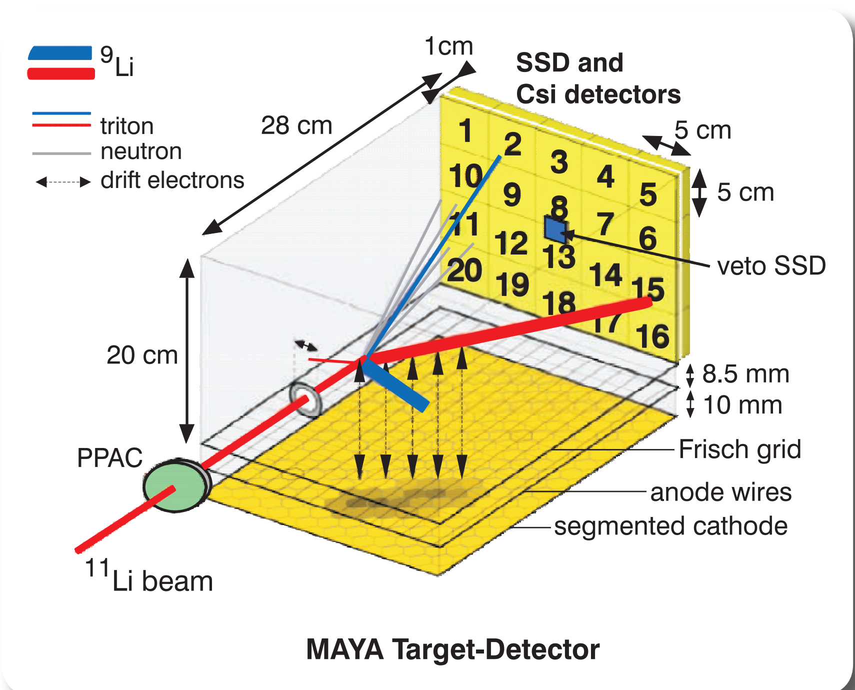


Fig. 1: Schematic of the MAYA target and detector array used in the first ISAC-II experiment.

MAYA

Nuclear physicists often picture ^{11}Li as being made up of ^{9}Li and two neutrons. The structure of ^{11}Li is particularly interesting because it is a halo nucleus in which these two neutrons occupy orbits that extend significantly beyond the ^{9}Li core, forming a neutron halo. It turns out that neither of the two-body subsystems, ^{9}Li + a neutron and the subsystem consisting of two neutrons, is bound. Rather, these subsystems fall apart spontaneously. Hence, only when the two neutrons are combined together with ^{9}Li can a bound state be formed. By studying the $^{11}\text{Li} + {}^{1}\text{H} \rightarrow {}^{9}\text{Li} + {}^{3}\text{H}$ reaction, we can learn about how the two neutrons are bound together to the ^{9}Li core to make ^{11}Li. (see Fig. 2) We are particularly interested in learning the answer to the fundamental question of whether the neutrons move independently, or exhibit correlated orbits, thereby elucidating the structure of this diffuse form of matter.

Although the ^{11}Li beams at ISAC-II are the world's most intense and highest quality at this energy, they are still relatively weak compared to the stable beam experiments nuclear physicists have been performing for decades. For this reason, new, highly sensitive detectors are needed to ensure that every single event of interest is recorded by the detectors and none are missed. In the case of MAYA, the detector is a gas-filled wire chamber in which the path of the beam and the trajectories of any nuclei formed in reactions with the beam are measured and recorded. The amount of energy deposited by the beam by Barry Davids

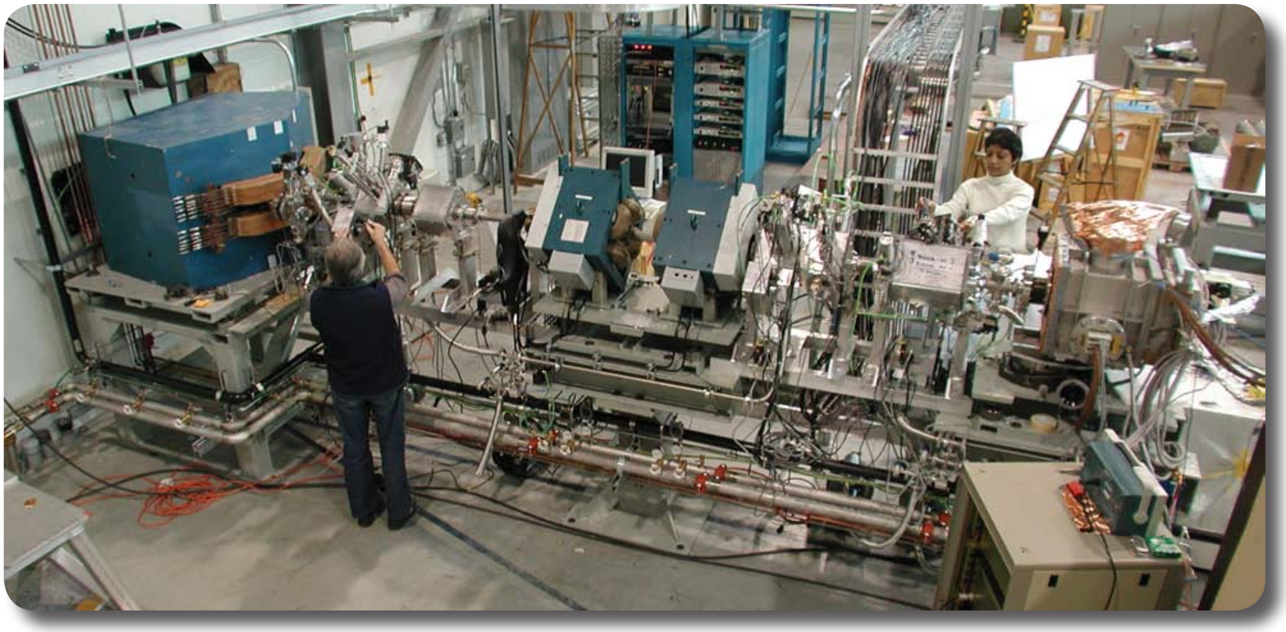


Fig. 3: Setting of the MAYA target and detector in the ISAC-II experimental hall.

and any nuclei formed in reactions are recorded by the wire chamber and, for those particles not stopped in the gas volume, by a wall consisting of silicon strip detectors and cesium iodide detectors. The silicon detectors are also position sensitive, providing additional trajectory information for nuclei that strike them.

MAYA is a very special instrument because the detector gas C_4H_{10} that is ionized by charged particles and that allows trajectory reconstruction also serves as the target for the nuclear reaction, which in this case is protons. This unique arrangement allows for simultaneous measurements of the reaction over a range of different beam energies, since the beam loses energy in the gas before it reacts. The first experiment at ISAC-II using

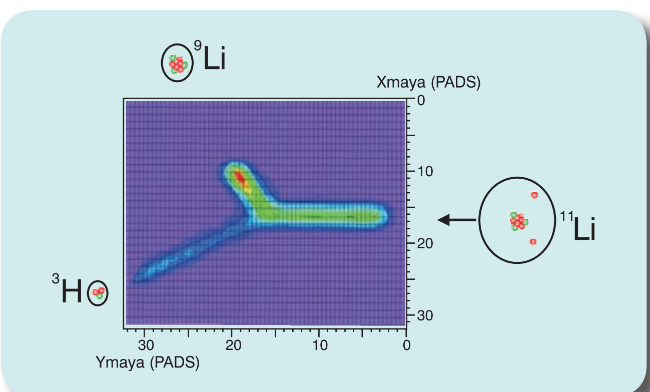


Fig. 2: The first $^{11}Li+^1H\rightarrow{}^9Li+^3H$ event recorded by MAYA in January 2007. A ^{11}Li nucleus came in from the right and reacted with a proton, which captured the two weakly bound neutrons from the ^{11}Li, leaving the more tightly bound ^9Li core and forming ^3H.

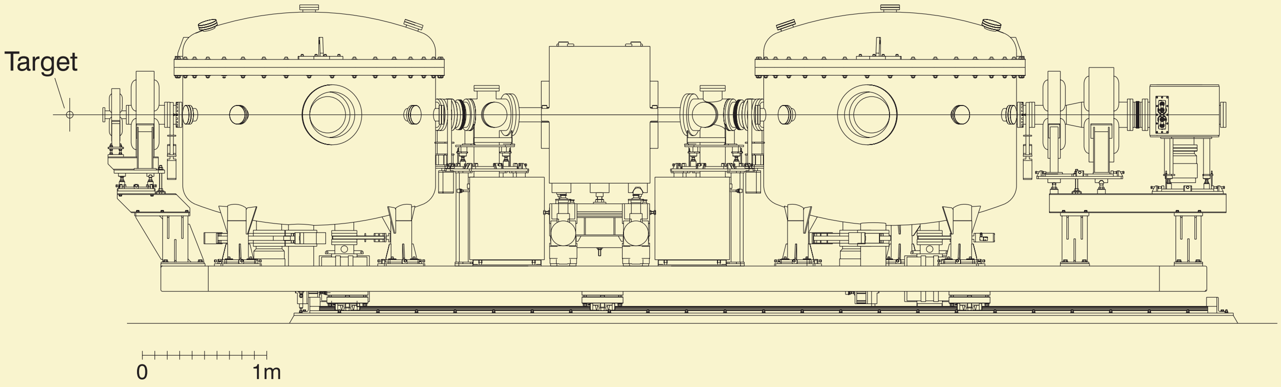
MAYA, led by I. Tanihata and H. Savajols, was an unqualified success, demonstrating simultaneously the power of the new accelerator and the active target.

EMMA

Active targets such as MAYA are very effective when the beam intensity is low. For some experiments that require higher beam currents, another type of detector, the electromagnetic spectrometer, is essential. EMMA, TRIUMF's ElectroMagnetic Mass Analyser, is a recently funded recoil mass spectrometer for ISAC-II. At the beam energies that can be reached by ISAC-II, different types of nuclear reactions can be studied to learn about the structure of exotic nuclei. These include transfer reactions, which typically involve the pickup or removal of one or several protons or neutrons from the projectile, and fusion-evaporation reactions, in which the projectile and target fuse into a single, heavy, excited system that subsequently evaporates a small number of protons or neutrons. Some transfer reactions are interesting because they occur in the stars, and others because they can tell us about the nature of nuclei near the limits of stability, advancing our knowledge of the structure of matter and the character of the force that holds the nucleus together. Fusion-evaporation reactions are useful because they allow us to make and study new, exotic nuclei that have never before been studied in the laboratory.

ISAC-II Science with MAYA and EMMA

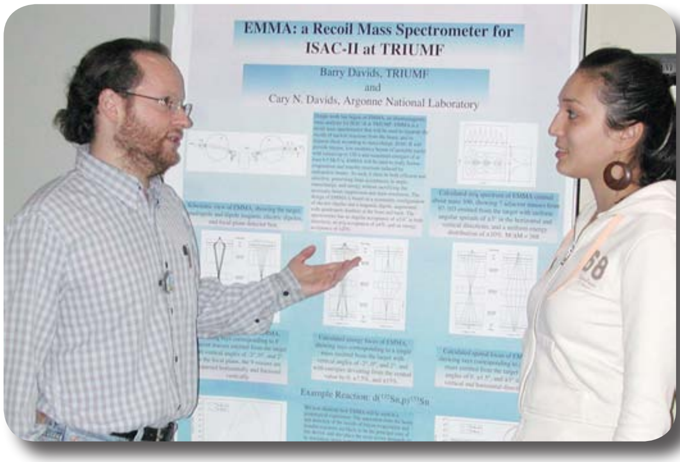
by Barry Davids



Schematic view of EMMA

To learn about the properties of the rare nuclei formed in transfer and fusion-evaporation reactions, as well as measure the rates of reactions that produce the chemical elements in stars, it is first necessary to identify the products of these reactions. An atomic nucleus can be uniquely identified by measuring its charge and its mass. The charge of a nucleus is simply the number of protons it contains, while its mass is the sum of the number of neutrons and protons that make it up.

How can one measure the mass and charge of a nucleus? The trajectories of nuclei in magnetic fields are bent according to their momentum and charge, while in electric fields the trajectories depend on the energies and charges of the nuclei. By combining electric and magnetic fields in a particular way, one can cancel the energy and momentum dependence of the trajectories and bend them according to their masses and charges alone. Hence, a device that combines electric and magnetic fields can be used to separate one nucleus produced in a nuclear reaction from all of the other nuclei produced in different nuclear reactions and from the beam used to initiate the reactions. When additional focusing elements are used, the nuclei passing through the separator can be focused in different positions according to their mass and charge. These devices are called recoil mass spectrometers because they analyze the products of nuclear reactions, called recoils, dispersing them according to their mass and charge. When it is completed, EMMA will be one of the world's most advanced recoil mass spectrometers, boasting significant advantages over its competitors. (see Fig. 3)



EMMA's operation is explained to a PhD student.

A proposal to build EMMA was submitted to Canada's Natural Sciences and Engineering Research Council (NSERC), and was funded in 2006 at the $2.085 million level, with the understanding that TRIUMF would contribute the additional $1 million needed to complete the spectrometer. Tender requests for the large electromagnetic components have been issued, and the spectrometer is expected to be completed in time for its first experiments to be performed in 2010.

ISAC-II produces the world's most intense beams of accelerated radioactive ions and is the world leader in radioactive ion beam physics. Unique and specialized detectors such as MAYA, TIGRESS, HERACLES and EMMA provide scientists with specialized tools to probe the properties of exotic nuclei far from the valley of stability. These properties are important to our understanding of the origin of the elements in the universe and the nature of the nuclear force for weakly bound systems. For further information, see http://davids.triumf.ca/emma.htm

Barry Davids is a TRIUMF Research Scientist.

The TRIUMF Theory Group

by Byron Jennings & Achim Schwenk

The Theory Group plays an important role by contributing to the intellectual leadership of TRIUMF, by guiding the experimental program, and by providing a focus and theoretical resource centre for Canadian university theorists and experimentalists.

At the present time, the group includes four research scientists, seven research associates, and two students. Our scientists and research associates are involved in collaborations with researchers from universities and laboratories in Canada and the United States and from around the world, in such countries as Denmark, France, Germany, Israel, Italy, Norway, Japan, South Korea and Taiwan. The majority of our former research associates hold faculty positions across Canada, in the United States, Europe and Asia. The Theory Group also plays an active role in the TRIUMF Co-Op Undergraduate Program. In fact, this summer more students had applied for the Theory Group position than any other at the laboratory. Every year, the group hosts a number of visiting scientists who interact with TRIUMF's experimental and theoretical physicists.

The group's research interests cover nuclear theory, particle phenomenology, nuclear and particle astrophysics, and neutrino physics. This article will highlight the recent developments in nuclear theory, with brief descriptions of the other areas of our program.

Nuclear physics, at ISAC and many new facilities worldwide, concerns the understanding of strongly interacting matter in the cosmos and in novel laboratory experiments. Nuclear theory explores matter over tremendous extremes. These range from the nuclei we are made of (a millionth the size of nano-particles) to neutron stars (giant "nuclei" in the universe, the size of greater Vancouver). A central goal of nuclear theory is to understand and predict the changes from strongly interacting matter on Earth, with an almost equal number of protons and neutrons, to the new phenomena in systems with a large neutron-to-proton imbalance. These conditions are reached in the formation of the elements and are at the heart of our existence. In addition, nuclear theory is crucial for the processes in explosive astrophysics events, in novae, supernovae and X-ray bursts, with the highest temperatures in nature since the Big Bang. These novel conditions can only be re-created and investigated at facilities such as ISAC. This puts TRIUMF and our Theory Group at the forefront of an exciting theoretical and experimental synergy.

Over the last five years, there have been substantial advances on three coherent fronts that connect the interactions of neutrons and protons in nuclei and in astrophysics to the fundamental theory of quarks and gluons (the constituents of neutrons and protons) called Quantum Chromodynamics.

First is the development of effective field theories (EFT) for nuclear forces. EFT is based on the separation of long-distance properties from complicated details at short distances. As an analogy, if we take an electric charge distribution on a complicated surface for a neutron, and another complicated charged object for a proton, then at long distances, the details of the surfaces are blurry, and we can replace the forces between neutrons and protons by simpler interactions of two electrically charged blobs. This, in simple terms, is how EFT works. The advantage of EFT is that it is systematic (and based on the long-distance properties of the fundamental theory) and enables us to make predictions to a given accuracy, for instance, as desired by a potential experiment.

Fig. 1: Achim Schwenk with Theory Group students.

Second are the continuous advances in giant computer simulations of QCD on a discrete space-time lattice (“lattice QCD”) for systems with, at present, one or two neutrons/protons. Lattice QCD can be used to constrain EFT interactions and their dependence on the fundamental constants of nature, as well as to extract physical properties of systems that are nearly impossible to create experimentally, such as the interactions of three isolated neutrons. Our group, in collaboration with Simon Fraser University and the University of Regina, is involved in lattice QCD calculations of similar properties.

Third is the application of the Renormalization Group (RG) to nuclear forces. The RG is a powerful method to vary the resolution scale at which one is looking at the interactions of neutrons and protons. The RG evolution of EFT interactions to lower resolution leads to low-momentum interactions, generically known as “$V_{\text{low }k}$”, which show great promise and improved convergence in few- and many-body calculations. The resulting interaction matrices are much sparser, which makes it possible to solve complicated strong interaction problems. There are many on-going developments, including exact calculations of light nuclei, studies of superfluidity in nuclei and neutron stars, and improving global predictions of nuclear masses. Novel trends in nuclear masses can be directly tested with the TITAN facility at TRIUMF (See the article on “TITAN” in the 2005-2006 Annual Financial and Administrative Report [http://admin.triumf.ca/docs/reports/annual_finacial_admin2006/].

In March 2007, the Theory Group organized a key workshop, “3N Interactions from Few-to Many-Body Systems” at TRIUMF. Three-nucleon (3N) interactions (for example, between two neutrons and a proton) are a frontier in nuclear physics. An important theoretical development is that low-momentum 3N interactions are weaker than conventional 3N interactions and thus computationally tractable. Recent studies of the coupled-cluster method (one of the most powerful techniques of quantum chemistry) show direct convergence and enable us to perform the very first calculations of intermediate-mass nuclei with 3N interactions.

Nuclei are complicated many-body systems of strongly interacting neutrons and protons. They exhibit fascinating phenomena ranging from collective to superfluid and to chaotic characteristics. One of the central challenges is to reach a universal description of nuclear systems based on EFT and low-momentum interactions. This is an ambitious goal and requires input from new experiments and exchange of ideas with experimentalists. At TRIUMF, the TIGRESS facility provides new access to the properties of nuclei with state-of-the-art techniques. (See the article on “TIGRESS” in the 2005-2006 Annual Financial and Administrative Report [http://admin.triumf.ca/docs/reports/annual_financial_admin2006/].

In addition to such nuclear structure studies, our group is carrying out a program to predict the nuclear equation of state for astrophysics. This is a key input for simulations of core-collapse supernova explosions, for neutron star mergers (an important source of gravitational waves) and for the structure and cooling of neutron stars. The theoretical developments will enable controlled extrapolations to the extreme conditions of nuclear physics in the universe. (see Fig. 3)

New phenomena develop in weakly bound nuclei due to the large scattering lengths between neutrons and protons. Large scattering lengths correspond to systems of two particles that are fragilely bound or nearly bound. In three-body systems, large scattering lengths lead to trail-blazing “Borromean states.” These are quantum three-body bound states where all two-body subsystems are unbound, such as the ^{6}He and ^{11}Li halo nuclei (composed of ^{4}He and ^{9}Li with two neutron halos respectively). This leads to gaps for the existence of bound nuclei (^{5}He and ^{10}Li are unbound). These mass

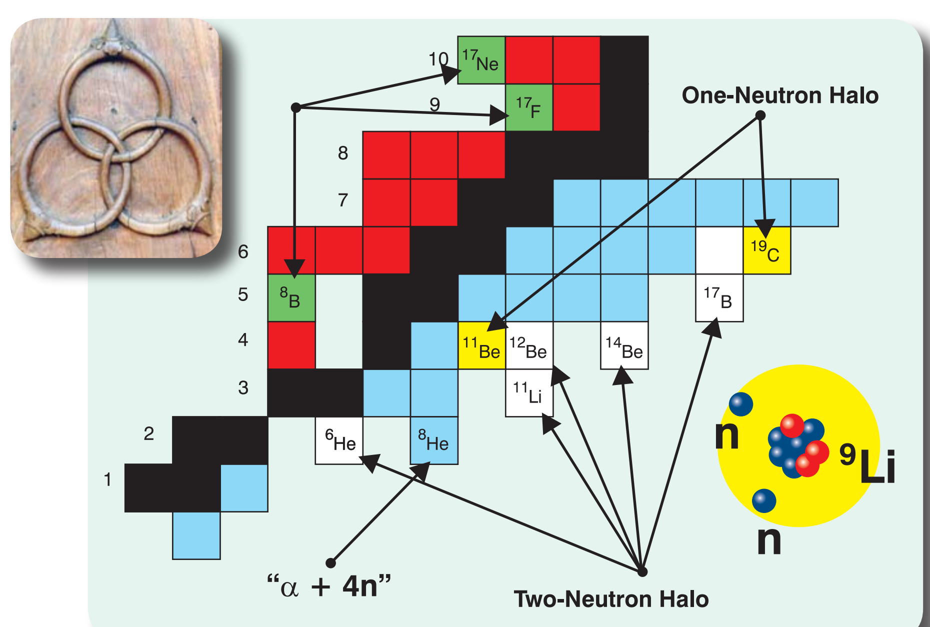


Fig. 2: Borromean two-neutron halo and other exotic quantum systems that are only known in nature at the limits of existence. The name “Borromean” comes from the symbol of the Borromeo family of northern Italy: three entangled rings which would fall apart if any one ring is removed. (see upper left)

by Byron Jennings & Achim Schwenk

gaps have important consequences for the creation of the elements. At TRIUMF, we have the most intense beams of ^{11}Li halo nuclei in the world and are in a unique position to explore how these Borromean systems arise. (see Fig. 2)

While many nuclear scattering lengths are large in nature, it is possible to experimentally tune the scattering lengths in trapped ultracold atoms by means of magnetic fields. The intersections of large-scattering-length problems in nuclear and astrophysics with ultracold atoms are very fruitful.

The same trapping and cooling techniques are used for the most precise fundamental symmetry tests at TRIUMF. Exotic nuclei provide access to new tests, for instance for parity non-conservation and for searches of permanent electric dipole moments. Nuclear theory impacts many of these experiments by providing the fundamental interactions inside nuclei and the information necessary for the analysis of the observed signatures. The initial impact of the new theoretical developments is very promising, and we expect significant improvements for the studies of fundamental symmetries over the next decade.

Over the next ten years, particle physics will enter a decisive stage when the Large Hadron Collider (LHC) at CERN in Geneva directly probes the nature of electroweak symmetry breaking and the origin of mass. TRIUMF is playing a lead role in the ATLAS experiment at the LHC, which will provide the most severe tests for the Standard Model. This unprecedented task requires close collaboration between experimental and theoretical particle physicists at TRIUMF. Our group has most recently investigated a shadow model, where the new physics sector is hidden and couples to the Standard Model of particle physics. We have made predictions for the signals of a new "shadow" Z-boson at the LHC.

Nuclear and particle theory are central to astrophysics, for instance in core-collapse supernovae. Supernovae are giant stellar explosions of massive stars, which emit 99.9% of the energy in neutrinos, the lightest elementary particles in nature. The interactions of neutrinos with nucleonic matter drive the energy transport of the explosion, and after neutrinos leave the supernova, they can be detected on Earth. The next generation neutrino detectors are planned for the underground SNO laboratory in Sudbury, Ontario. We have studied the

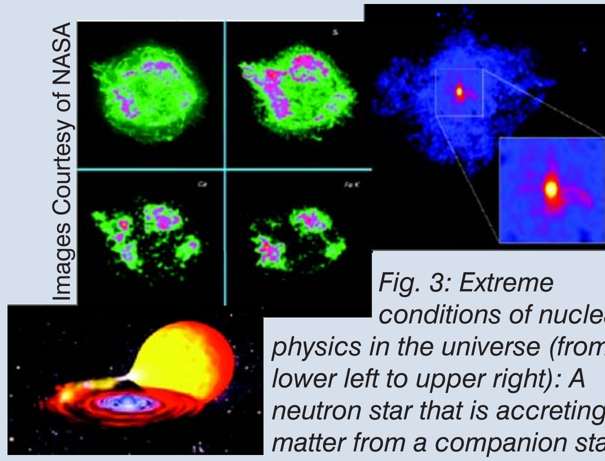


Fig. 3: Extreme conditions of nuclear physics in the universe (from lower left to upper right): A neutron star that is accreting matter from a companion star in low-mass X-ray binaries; chemical elements (silicon, calcium and iron) in the supernova remnant Cassiopeia A; the cooling of the densest matter in the interior of the isolated neutron star in 3C58.

properties of neutrino interactions with low-density nuclear matter near the neutrino-sphere, the surface of last scattering of neutrinos (before they free-stream). We have found that neutrinos are energetic enough to break up loosely bound nuclei, which can provide an additional source of heating.

The Theory Group will continue to be active in the organization of topical workshops at TRIUMF and other institutes, to connect to the Canadian and international subatomic theory community and to bring their broad expertise to TRIUMF. In addition to the workshop on 3N interactions, we co-organized the "Experiment-theory intersections in modern nuclear structure" workshop at ECT, the European Center for Theoretical Studies in Nuclear Physics and Related Areas, in Trento, Italy, in April, 2007. Several workshops are being planned, one of them with the Joint Institute for Nuclear Astrophysics. The dates and locations for these workshops are available on the TRIUMF Theory Group web site.

The TRIUMF Theory Group is an active and vibrant component of the physics community in Canada and worldwide. To learn more about the group's members and about the possibilities of joining as a student, research associate, or visitor, visit our web site at [http://trshare.triumf.ca/~theoryweb/]

Byron Jennings is a Theorist and Group Leader for the TRIUMF Theory Group.

Achim Schwenk is a Theorist and Deputy Group Leader for the TRIUMF Theory Group.

A Productive Collaboration: TRIUMF & The University of Victoria

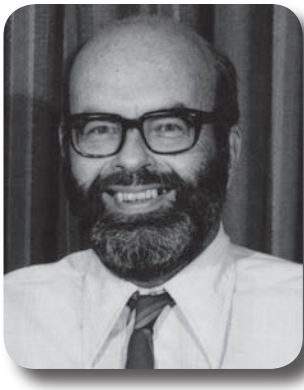
by Richard Keeler

TRIUMF and the Department of Physics and Astronomy at the University of Victoria (UVic) share a common history and a long and productive collaboration. Shortly after the founding of UVic in 1963, the Department began hiring nuclear physicists. Two years later, they began writing a proposal for an accelerator laboratory, and in 1968, UVic became a founding member of the TRIUMF joint venture.

The team at UVic took responsibility for the design of TRIUMF's beam line optics. The original meson production target as well as the first temporary beam dump were both designed and constructed in Victoria and then transported to Vancouver. At TRIUMF, the M9 muon beam line, which initiated the molecular and materials science studies that are now an important research component of TRIUMF, was developed with significant input from UVic. The design of the M8 medical channel and the first design of the M11 septum magnet were also done at Victoria.

As the initial construction work at TRIUMF proceeded, scientists in the UVic group began planning and building physics experiments of international scope to exploit TRIUMF's unique features, including the latest in its instrumentation technologies and high-performance computing. The BASQUE experiment, the first experiment in the then new TRIUMF Proton Hall, was a collaboration among the University of Victoria, the University of British Columbia (UBC) and AERE Harwell, the University of Surrey, Queen Mary College and Bedford College in the UK. This collaboration used TRIUMF's cyclotron to accelerate polarized protons to produce record intensity polarized proton beams. The UVic group contributed a liquid deuterium target capable of producing polarized neutrons and intense unpolarized intermediate energy neutron beams while surviving the high-radiation environment and a large deposited heat load. Nucleon-nucleon cross sections and spin dependent measurements published by the BASQUE collaboration in 1983 established unambiguous phase shifts for kinetic energies up to 500 MeV. (see Fig.1)

The second focus of the UVic group was on the "other side" of the cyclotron, using low energy pions. Dr. Michael Pearce started and led a productive program of mesic and muonic X-ray physics. His untimely death was a severe blow to this work and a sad personal loss to those who knew him. The University created a named professorship in his memory and, in 1983, Dr. Alan Astbury became the first holder of the Pearce Chair of Physics. His appointment changed the main focus of the UVic group towards particle physics.



Dr. Michael Pearce

In the early 1980s, TRIUMF, with the UVic group, built one of the world's first operating time projection chambers (TPC) to make precision measurements of pion decay modes to establish stringent limits on lepton universality, a key component of modern particle theory. The collaboration was also actively involved in calculating the correction needed to understand the new high-precision data. In 1983, an important review article was published in *The Review of Modern Physics* (50:11-21) on double beta decay as well as calculations of branching ratios, radiative corrections and strong interaction effects. A second group unraveled the subtle and complex atomic and molecular interactions involved in muon catalyzed fusion.

Two years later, in 1985, TRIUMF proposed building a Kaon Factory. Alan Astbury was the Kaon Factory

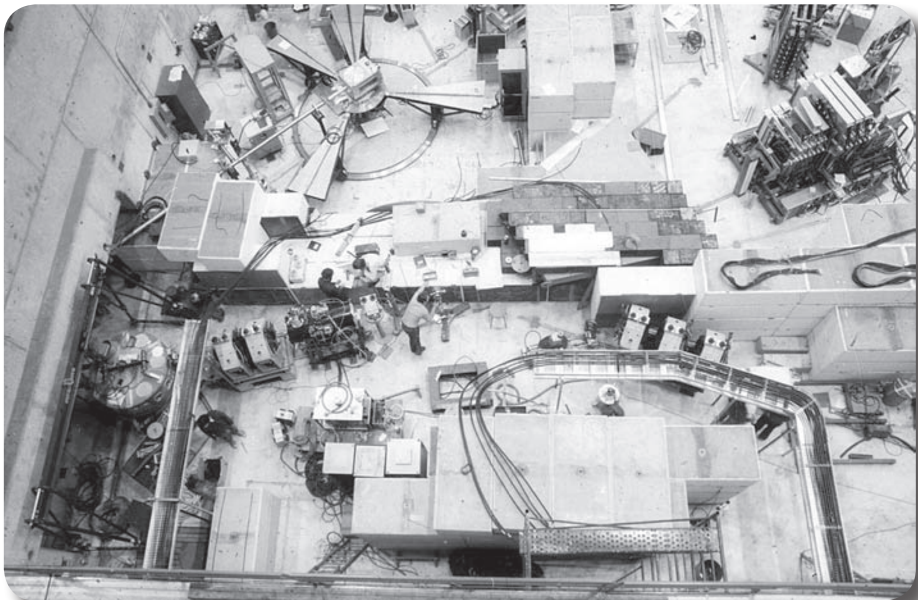


Fig. 1: Aligning the Basque experiment beam line.

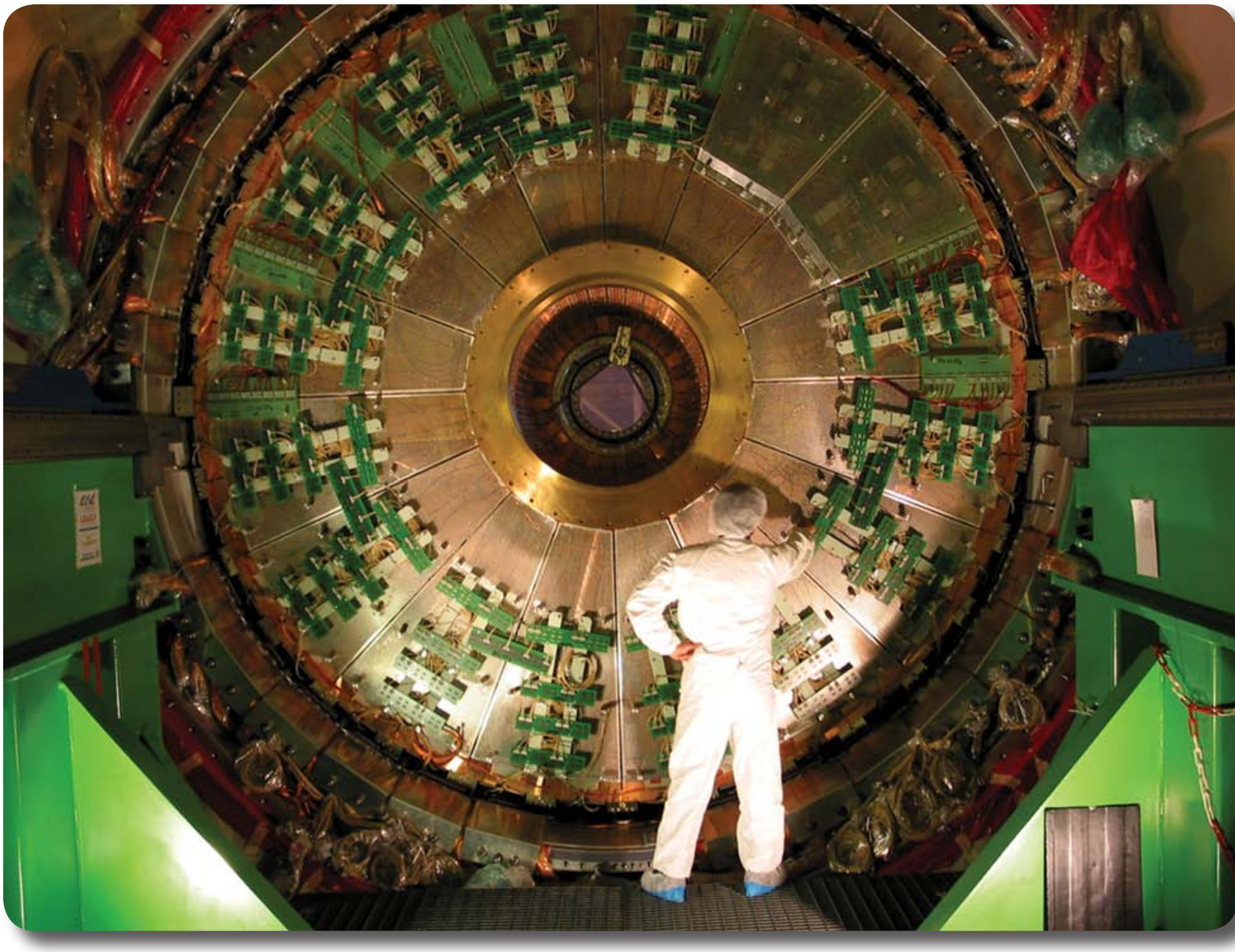


Fig. 2: Rear view of ATLAS Hadronic End Cap.

Definition Study Director, and the UVic group became involved in several critical design components. The Kaon Factory was not to be, but the innovative work done by TRIUMF and UVic as one of the partners was not completely lost. University of Victoria and TRIUMF scientists began work on rare kaon physics at the Brookhaven National Laboratory in the USA, and the Victoria targets group designed a new target for the Alternating Gradient Synchrotron (AGS) that enhanced the kaon beam used in the observation of the ultra rare decay of a charged kaon into a charged pion and two neutrinos. Ultimately, a project with many of the same goals as the TRIUMF Kaon Factory was proposed and is being built in Tokai Japan. It is an interesting coincidence that the present Pearce Professor of Physics, Dr. Dean Karlen, is playing a leading role with the Tokai to Kamioka (T2K) neutrino experiment.

In the late 1980s, the University of Victoria joined the SLD experiment at the Stanford Linear Accelerator (SLAC). TRIUMF and Victoria were responsible for the mechanical design of the liquid argon calorimeter and half of the modules of the electromagnetic section were built at TRIUMF. A very nice engineering project involved designing and testing earthquake protection, called snubbers. In operation, the hydraulic liquid changed phase and was supersonic; not a textbook problem by any means. It is a credit to the advanced engineering skills of the TRIUMF-UVic group that the snubbers actually worked as predicted and prevented any significant damage from occurring to the SLD detector as a result of the hugely destructive 1989 San Francisco earthquake.

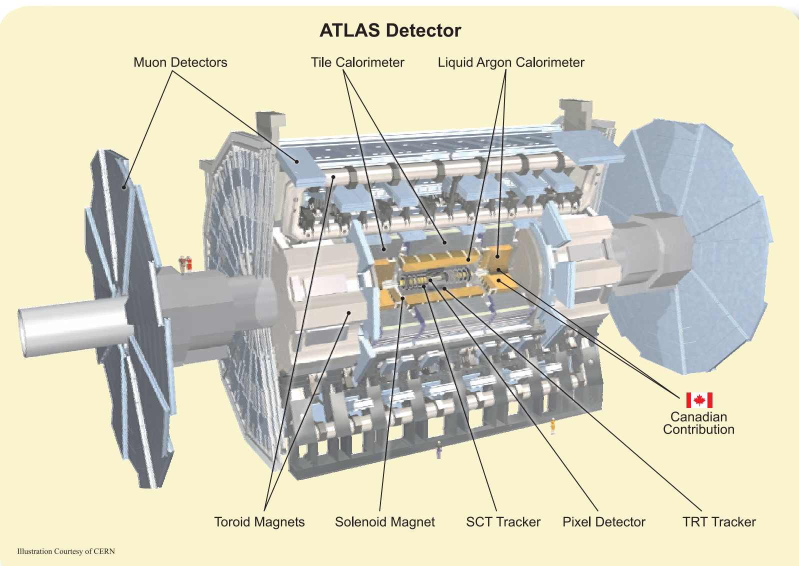
In 1991, TRIUMF and UVic scientists joined the OPAL collaboration at CERN, where they played a leading role in designing and building an advanced silicon micro-vertex detector that led to the world's best measurements of B meson and tau lepton lifetimes. TRIUMF-UVic's detector expertise was on the international stage again in 1997 when the large drift chamber at the heart of the BaBar experiment was assembled at TRIUMF. The detector was instrumental in the discovery of CP violation in B mesons.

A Productive Collaboration: TRIUMF & The University of Victoria

by Richard Keeler

Virtually every particle physics laboratory in the world has been called upon to make contributions to the Large Hadron Collider and the associated detectors soon to be complete at CERN in Geneva. The University of Victoria founded ATLAS Canada, the Canadian collaboration that now has approximately 40 leading scientists from across Canada. UVic and TRIUMF worked with the University of Alberta, UBC, Carleton University and collaborators in Europe to design, construct and install the liquid argon hadronic calorimeters in the end cap region of the detector. (see Fig. 2) A member of the TRIUMF-UVic group was the chief mechanical engineer for this project and played a critical role as a member of the ATLAS cryogenics steering committee. In collaboration with the Brookhaven National Laboratory, the TRIUMF-UVic engineering group also designed, built, tested and installed advanced high-density cryogenic feedthroughs. TRIUMF personnel were responsible for managing the installation of the calorimeters and feedthroughs at CERN.

In 1994, Alan Astbury temporarily left Victoria to become the Director of TRIUMF. Under his direction, the laboratory redirected its efforts to design and build the world's most powerful isotope separator and accelerator (ISAC). The initial thermal calculations for the ISAC target were done in Victoria, and the beam dump module was designed by the Victoria target group.



The ATLAS detector at CERN.

ISAC-I Opening: Dr. Alan Astbury and The Honorable John Manley.

Dr. Alan Shotter replaced Dr. Alan Astbury as TRIUMF's Director in 2001, and the relationship and collaboration between TRIUMF and UVIC continued to be strong. The ATLAS Tier 1 Data Centre (see page 4) was secured for the Canadian ATLAS collaboration in 2006, and the TRIUMF-UVic collaboration on T2K expanded as UVic and Canada's interest in the proposed experiment grew. Advanced engineering by UVic for targets at ISAC and for the TRIUMF beam lines is continuing as well. More recent efforts include studies and measurements to help develop targets capable of taking higher beam power, effusion oven designs and prototypes, heat shield analysis and forced electron beam induced arc discharge (FEBIAD) ion source development.

The 37 years that the University of Victoria and TRIUMF have collaborated have been wonderful years of discovery and invention. At the present time, significant engineering and detector development is in progress for the T2K neutrino oscillation experiment. Thermal analysis of electronic crates and research and development in advanced TPC detectors is also ongoing with design and manufacture of prototypes moving into full-scale production. And the future looks just as bright: for ISAC-II experiments, ATLAS and the LHC, as well as TRIUMF-UVic research and development on gas detector systems for a future International Linear Collider.

Richard Keeler is a Professor of Physics at the University of Victoria and member of the TRIUMF Board of Management.

Radiation Testing at TRIUMF

by Ewart Blackmore

What do companies such as Cisco Systems, who produce routers for the internet, Philips Medical Systems, who produce MRIs for medical imaging, and MacDonald Dettwiler and Associates (MDA), who develop robotics equipment for the International Space Station, have in common? All of these companies have products that can be affected by the natural background radiation present in the environment where their equipment is designed to work, whether that be in orbit around the earth or on it at ground level. The other thing these companies have in common is that they come to TRIUMF frequently to determine how their equipment responds to radiation.

The most common type of radiation problem is called a Single Event Effect (SEE), which is a problem caused by a single energetic particle interacting in the silicon device rather than a cumulative effect of a lot of radiation. Highly ionizing particles can directly deposit enough charge locally in the silicon to disturb the function of an electronic circuit, while protons and neutrons can cause nuclear interactions within the component itself to generate ionizing recoils that deposit sufficient charge locally to disturb the correct function. A Single Event Upset means that the deposited charge is sufficient to cause a bit flip in a memory circuit. This is called a soft error in that nothing is damaged, but the memory has to be rebooted to correct the problem. There are more serious types of SEEs such as latchups, where the electronic circuit has to be powered off and on to correct the problem when it occurs, or burnout, where a power transistor can fail catastrophically.

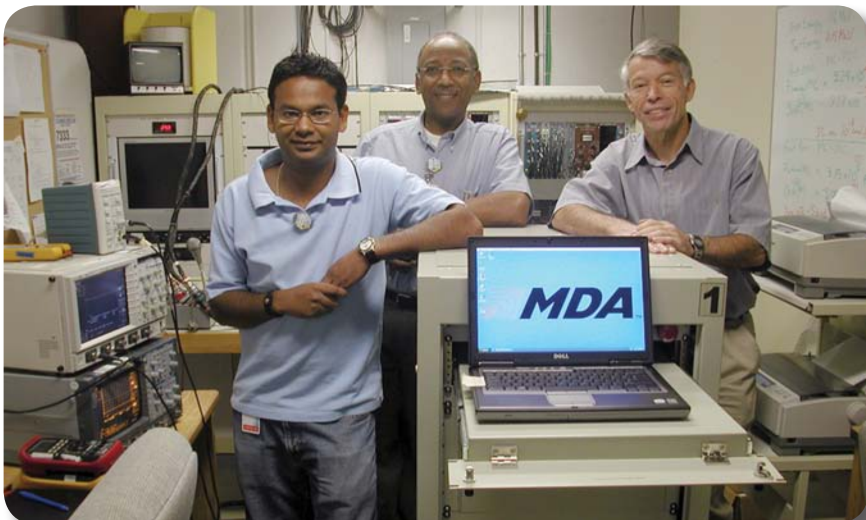


Fig. 1: MDA engineers with PIF coordinator Ewart Blackmore during a recent test of Space Shuttle components at TRIUMF.

A company like Cisco Systems wants to ensure that their routers, which contain vast amounts of processing power and memory, are immune to these SEEs as well as how often a latchup, which would cause downtime to their users, might occur. Soft errors will occur, but the question is whether their error detection and correction methods can keep the systems running in all cases.

Philips Medical Systems found that there were rare but still troubling failures of the MOSFETs (metal oxide silicon field effect transistors) in the power converters driving the magnet coils in their MRIs, and these failures were caused by high-energy neutrons present at ground level. Philips is trying to design power converters that are more immune to burnout.

All space equipment is subject to much higher fluxes of protons and cosmic rays than at ground level, and any computers, cameras, lasers, motor controllers, etc., must be checked for sensitivity to radiation. In space, other effects, such as total dose damage due to the accumulation of radiation, can be a serious problem. For these reasons, radiation testing is routinely required to qualify electronic systems for the environments in which they may be exposed to radiation. These environments can be in space, where the radiation belts surrounding the earth can cause very serious problems; at aircraft altitudes, at ground level, where the radiation is much lower but still present; and, for the special case of particle physics detectors, in the region around colliding beam accelerators.

There are a number of different types of radiation: gamma rays, electrons, protons, neutrons and heavy ions, and in many cases electronics will respond differently to each type. TRIUMF has developed a unique facility for radiation testing of electronic devices and components with protons and neutrons. The energy range of the TRIUMF 20-500 MeV H-cyclotron matches the proton energies that are of most concern for electronics used in space, and this range of energies is not available at any other single accelerator laboratory.

At sea level, and at altitudes up to 20 km, the main radiation component that can disrupt electronics is neutrons produced by spallation and other nuclear reactions of energetic protons and light ions in the gases in the upper atmosphere. These neutrons have an energy spectrum which drops as 1/E, where E is the neutron energy, from energies below 1 MeV to about 1000 MeV. The sea level flux of neutrons is about 10-20 neutrons/cm^2 hour with an energy above 10 MeV and depends on latitude and solar activity. For terrestrial and aircraft altitude radiation effect studies, there is a requirement for testing directly with neutron beams because neutrons, being neutral, are not as easily shielded as protons.

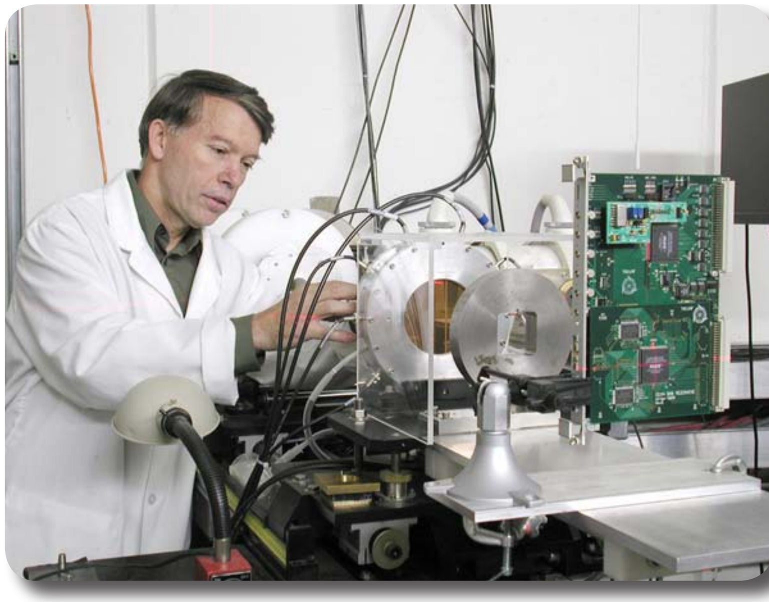


Fig. 2: An electronic test card being aligned in the proton beam line.

The Proton Irradiation Facility (PIF) at TRIUMF makes use of two beam lines, BL2C and BL1B, which enter the same test area, one covering the energy range from 65 MeV to 116 MeV and the other from 180 to 500 MeV. Lower energies can be obtained by using variable thickness plastic degraders. Protons extracted at 74 MeV in BL2C are used on a regularly scheduled basis in collaboration with the BC Cancer Agency for treatment of patients with ocular melanoma.

The testing facility was originally designed for SEE testing of memory and similar devices for space applications. Typically, the ten-year dose for the International Space Station can be delivered in ten minutes, or more slowly, if desired. This test facility has also been used in qualifying electronics used for the ATLAS experiment at CERN, where the dose levels are much higher than in space. On both beam lines, higher fluxes can be obtained over smaller areas at a front test location. This rate is useful for displacement damage and total ionizing dose testing. Figure 2 shows the beam line with an electronic test card being aligned.

Doses (rads or Gy) and fluences (protons cm^{-2}) can be measured to an absolute accuracy of better than 5% with the reproducibility for a given geometry and energy better than 1%. The transverse uniformity of the beam is measured using radiochromic film or by scanning a silicon diode across the beam using an X-Y scanner. For proton rates below 10^5 protons cm^{-2}s^{-1}, the fluence can be measured directly by counting individual protons using a scintillation counter with a known area.

At TRIUMF, the high power 500 MeV proton beam from BL1A is stopped in an aluminum plate beam dump surrounded by cooling water. Several neutron channels were designed into this beam dump to extract a neutron beam with energies from thermal to about 400 MeV. As this neutron beam is produced via spallation reactions on aluminum and water, the resulting neutron spectrum is very similar to that observed inside spacecraft where there is reasonably thick shielding. It is also similar to the neutron spectra at aircraft altitudes and ground levels where the cosmic ray protons are stopped in the upper atmosphere.

The neutron flux and energy spectrum in one of the channels has been well characterized using a series of activation foils and neutron monitors. The neutron rate in the energy range 1-400 MeV is 5 x 10^6 neutrons cm^{-2}s^{-1} at the normal operating proton current of 120 μA. This flux is a factor 2-5 higher than that available at the LANSCE test facility at Los Alamos, the only other neutron facility with an atmospheric neutron spectrum operating in North America. A unique feature of the TRIUMF beam is that thermal neutrons are present at a rate of about 20% of the >10 MeV neutron rate due to the presence of the water, which acts as a moderator. The sensitivity of electronic devices to SEE from thermal neutrons can be determined by measuring the SEE rate with and without a cadmium absorber. Many electronic devices contain boron, and the reaction of neutrons on boron produces alpha particles that can cause single event upsets.

This facility is very good for testing small devices or circuits that can fit into the 5 cm x 15 cm aperture of the vertical access hole but is not suitable for testing larger systems. For these larger systems, a neutron beam can be produced in the PIF test area by stopping a high-by Ewart Blackmore

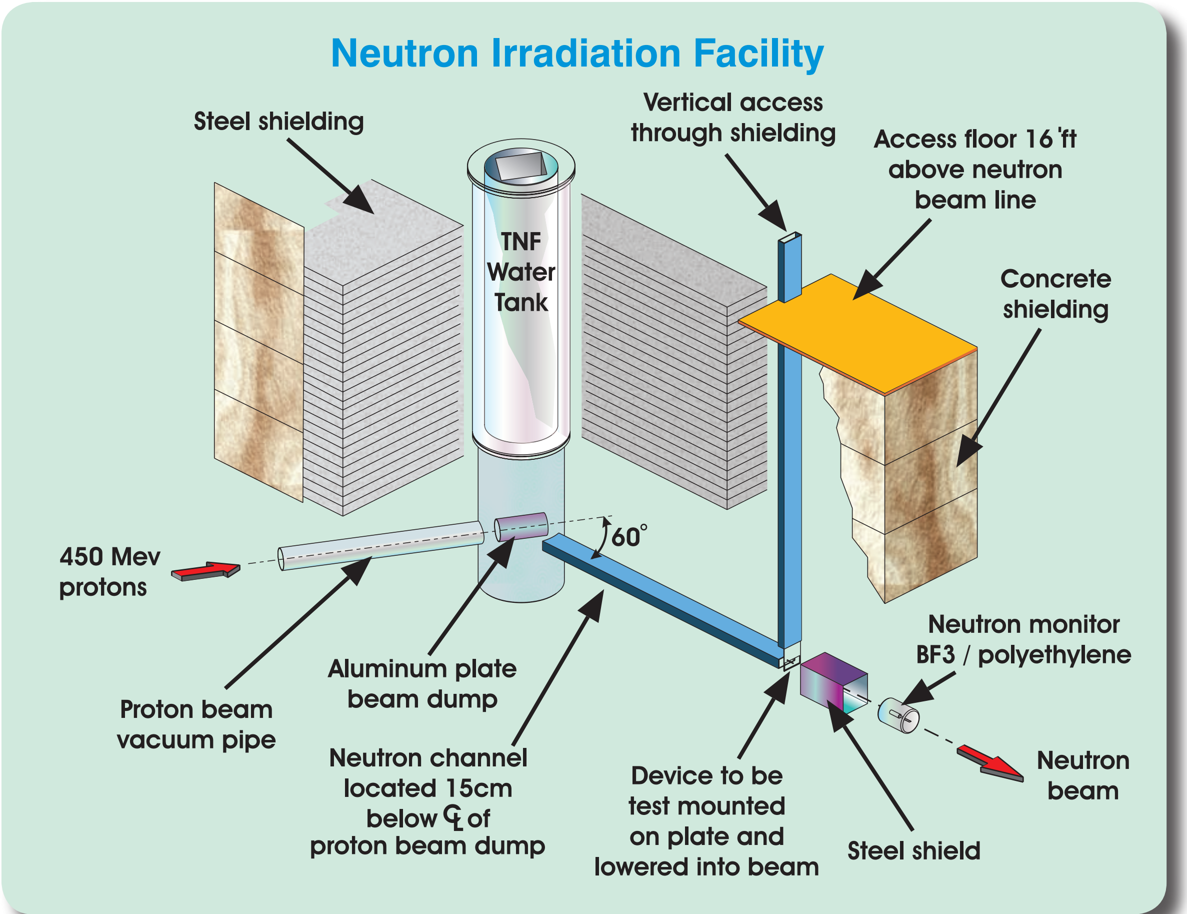


Fig 3: A schematic view of the neutron test facility located at the end of the high-intensity proton beam line.

energy proton beam in a lead absorber and carrying out the test in the cone of forward going neutrons. The flux of 10 MeV or greater neutrons, although about a factor 100 below the TNF flux, is still about a factor 10^7 higher than the sea level flux. An hour in this beam corresponds to many years at aircraft altitudes and much longer at ground level. The neutron beam is uniform to about 80% over transverse dimensions of 80 cm x 80 cm at a distance of 200 cm from the lead absorber.

There is an hourly charge for beam time to commercial users, and most of the users are repeat customers. The proton beams have been used since 1996, and the neutron beams were developed in 2003. There is increasing demand for beam time with more requests than can be satisfied. In 2006, there were 64 users of the test beams from 21 companies, many from the United States and Europe. The testing programs have included SEEs in memories and FPGAs (Field-Programmable Gate Arrays), displacement and other damage on optoelectronic devices and in new semiconductor materials such as gallium nitride (GaN), and total dose effects on various components such as CCD and CMOS cameras, power supplies and motor drivers for space applications. Neutrons have been used to test MOSFET burnout in ground-based power supplies and to measure SEEs and transistor gain degradation. Some proton and neutron dosimetry and biological studies relevant to space applications have also been carried out.

For the past six years, a collaboration among Sandia National Laboratory in Albuquerque, CEA Bruyère Le Chatel in France, and TRIUMF has researched the basic mechanisms of radiation damage using beams from TRIUMF. This group was awarded the Outstanding Conference Paper Award at both the 2005 and 2006 Nuclear and Space Radiation Effects Conferences.

Ewart Blackmore is Head of TRIUMF's Engineering Division and International Projects Division.

AUDITORS' REPORT

To the Joint Venturers of TRIUMF

The accompanying summarized statements of financial position and combined statement of funding/income and expenditures and changes in fund balances are derived from the complete financial statements of TRIUMF as at March 31, 2007 and for the year then ended on which we expressed an opinion without reservation in our report dated July 11, 2007 (except for note 12, which is as of October 12, 2007). Those financial statements were prepared to comply with section 7 of the TRIUMF joint venture agreement and the contribution agreement with the National Research Council of Canada, and are prepared using the basis of accounting as referred to in note 2 to the accompanying financial statements. The fair summarization of the complete financial statements is the responsibility of management. Our responsibility, in accordance with the application Assurance Guideline of the Canadian Institute of Chartered Accountants, is to report on the summarized financial statements.

In our opinion, the accompanying financial statements fairly summarize, in all material respects, the related complete financial statements of TRIUMF in accordance with the criteria described in the Guideline referred to above.

The summarized financial statements, which have not been, and were not intended to be, prepared in accordance with Canadian generally accepted accounting principles, are intended for the information and use of the Joint Venturers and the National Research Council of Canada. Furthermore, the summarized financial statements do not contain all the disclosures required by Canadian generally accepted accounting principles. Readers are cautioned that these financial statements may not be appropriate for their purposes. For more information on TRIUMF's financial positions, results of operations and changes in fund balances, reference should be made to the related complete financial statements.

PricewaterhouseCoopers LLP

Chartered Accountants
Vancouver, B.C.
July 11, 2007

TRIUMF
Statement of Combined Funding/Income and Expenditures
As at March 31, 2007

	2007 $	2006 $
Assets		
Cash	7,451,031	5,102,209
Decommissioning Fund	401,074	-
Due from Joint Venturers	410,884	24,723
Funding receivable (note 3)	868,968	956,356
	9,131,957	6,083,288
Liabilities		
Accounts payable	1,127,071	564,408
Funds received in advance (note 4)	2,864,306	2,025,816
Decommissioning Fund	401,074	-
Bank loan (note 7)	906,658	1,199,995
	5,299,109	3,790,219
Fund Balances		
Restricted		
Natural Sciences and Engineering Research Council Fund (note 5)	2,773,941	2,240,299
MDS NORDION Inc. Fund	100,000	100,000
Canada Foundation for Innovation	(241,404)	(170,975)
	2,632,537	2,169,324
Other		
Commercial Revenue Fund	1,084,788	979,935
General Fund	31,512	16,465
TRIUMF House Building Fund (note 6(c))	(1,328,298)	(1,934,789)
Intramural Accounts Fund	1,412,309	1,062,134
	1,200,311	123,745
	3,832,848	2,293,069
Total liabilities and fund balances	9,131,957	6,058,565

Encumbrances and commitments (note 6)

Economic dependence (note 10)

TRIUMF
Statement of Financial Position
As at March 31, 2007

	2007 $	2006 $
Funding/income		
National Research Council Fund	45,500,000	44,000,000
Natural Sciences and Engineering Research Council Fund	5,266,630	4,688,242
MDS NORDION Inc. Fund	3,771,760	4,523,406
Canada Foundation for Innovation	2,406,137	1,923,525
Affiliated Institutions Fund	1,084,050	1,083,601
Commercial Revenue Fund	1,486,266	1,728,178
General Fund	417,161	250,428
	59,932,004	58,197,380
Expenditures		
Buildings and improvements	586,523	379,467
Communications	157,995	204,282
Computer	1,435,878	1,248,930
Equipment	6,428,809	8,213,429
Power	2,192,484	1,889,040
Salaries and benefits	34,138,291	34,355,746
Supplies and other expenses	13,452,245	12,065,206
	58,392,225	58,356,100
Surplus (Deficit) of funding over expenditures for the year	1,539,779	(158,720)
Fund balances - Beginning of year	2,293,069	2,451,789
Fund balances - End of year	3,832,848	2,293,069

TRIUMF

Notes to Financial Statements

1 Nature of operations

TRIUMF is Canada's national laboratory for particle and nuclear physics, owned and operated as a joint venture by the University of Alberta, Carleton University, the University of Victoria, Simon Fraser University, the University of British Columbia and the University of Toronto, under a contribution from the National Research Council of Canada. As a registered charity, TRIUMF is not subject to income tax.

Each university owns an undivided 16.7% interest in all the assets and is responsible for 16.7% of all liabilities and obligations of TRIUMF, except for the land and buildings occupied by TRIUMF, which are owned by the University of British Columbia. On April 1, 2007, L' Université de Montréal became a joint venture member; each venturer's interest is now 14.3%.

These financial statements include only the assets, liabilities, funding and expenditures of the activities carried on under the control of TRIUMF and do not include the other assets, liabilities, revenues and expenditures of the individual joint venturers.

Sources of funding include grants and contributions from the National Research Council of Canada, the Natural Sciences and Engineering Research Council, and governments; advances and reimbursements from other sources; royalty income; and investment income. TRIUMF has established a number of separate funds to account for the various funding sources. The sources and purposes of these funds are:

National Research Council Fund (NRC)

Funding of operations, improvements and development; expansion of technical facilities (buildings excluded); and general support for experiments.

Natural Sciences and Engineering Research Council Fund (NSERC)

Funding to grantees for experiments related to TRIUMF activities. These funds are administered by TRIUMF on behalf of the grantees.

MDS NORDION Inc. Fund

Advances and reimbursements from MDS NORDIAN Inc. for expenditures undertaken at its TRIUMF site.

Canada Foundation for Innovation (CFI)

Funding to grantees for capital projects related to TRIUMF activities. These funds are administered by TRIUMF on behalf of the grantees.

Affiliated Institutions Fund

Advances and reimbursements for expenditures undertaken on behalf of various institutions from Canada and abroad for scientific projects and experiments carried out at TRIUMF.

Commercial Revenue Fund

Royalties, revenue and expenditures relating to commercial activities and technology transfer.

General Fund

Investment income for discretionary expenditures incurred by TRIUMF.

TRIUMF House Building Fund

Contributions from unrestricted funds and expenditures for the construction of TRIUMF House.

Intramural Accounts Fund

Net recoveries for internal projects and services. The recoveries of expenditures are charged to the appropriate TRIUMF funding source by

Intramural Accounts.

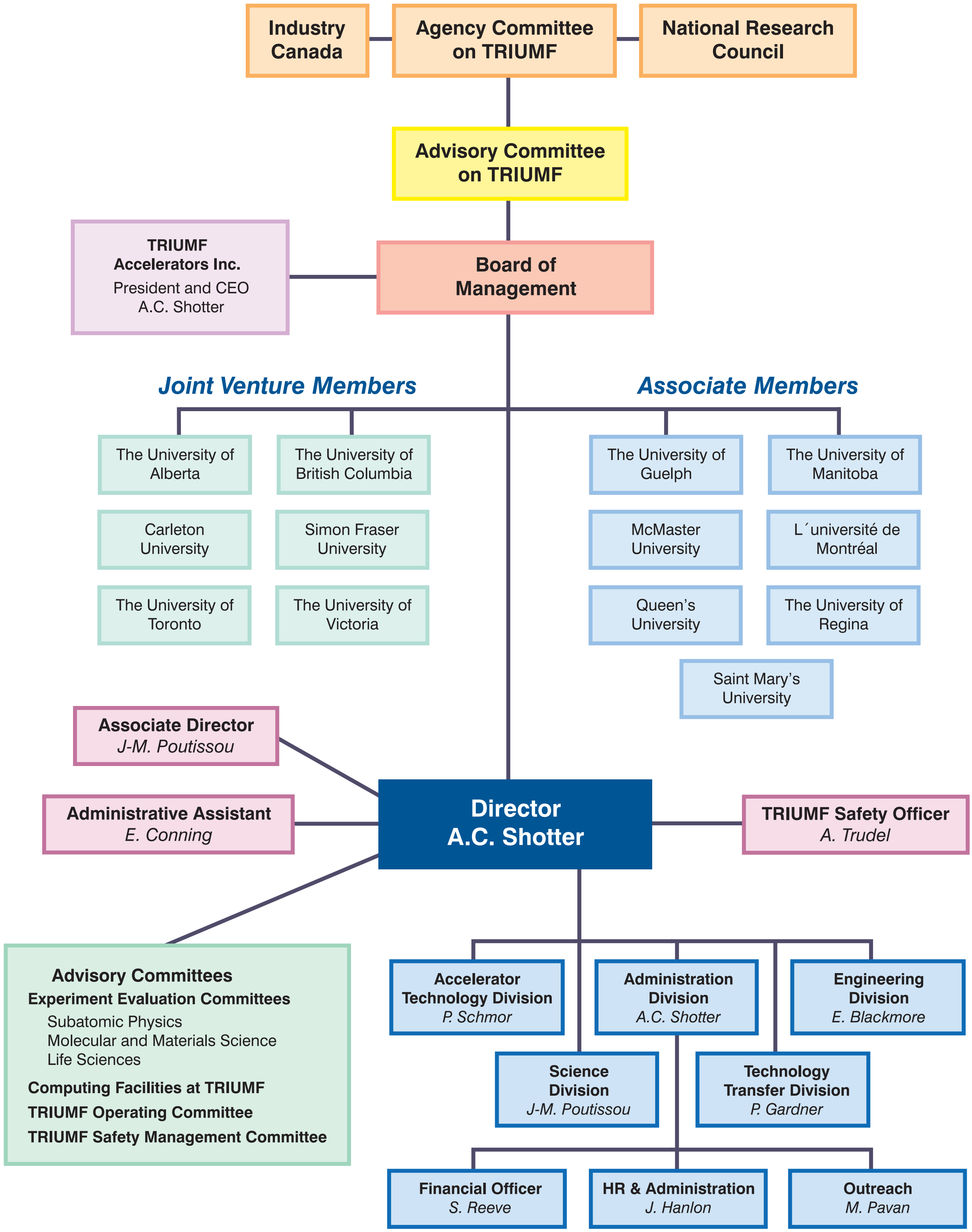
Net recoveries for internal projects and services. The recoveries of expenditures are charged to the appropriate TRIUMF funding source by Intramural Accounts.

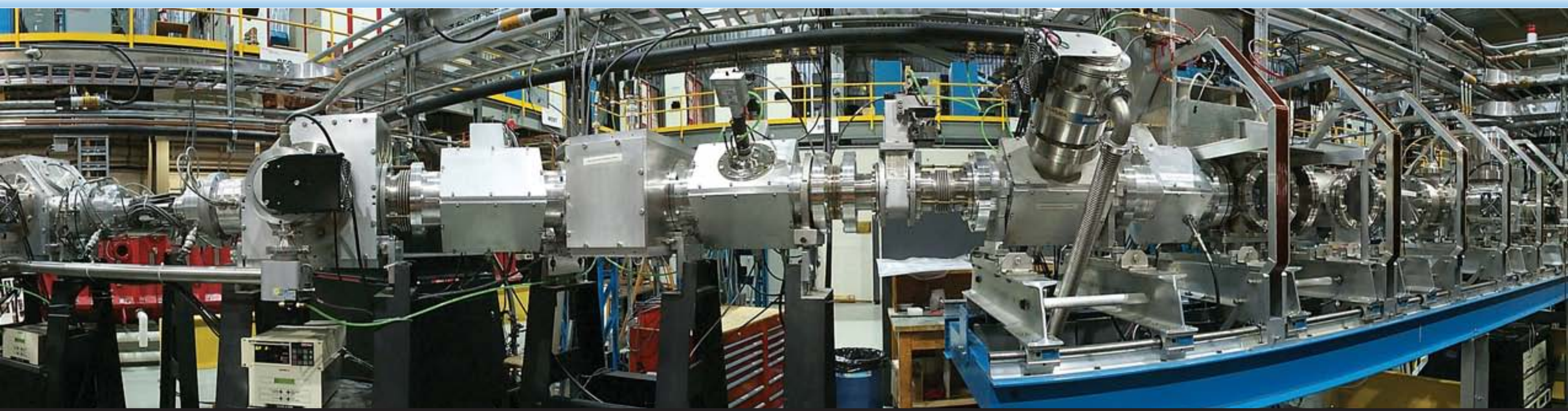
2. Significant accounting policies

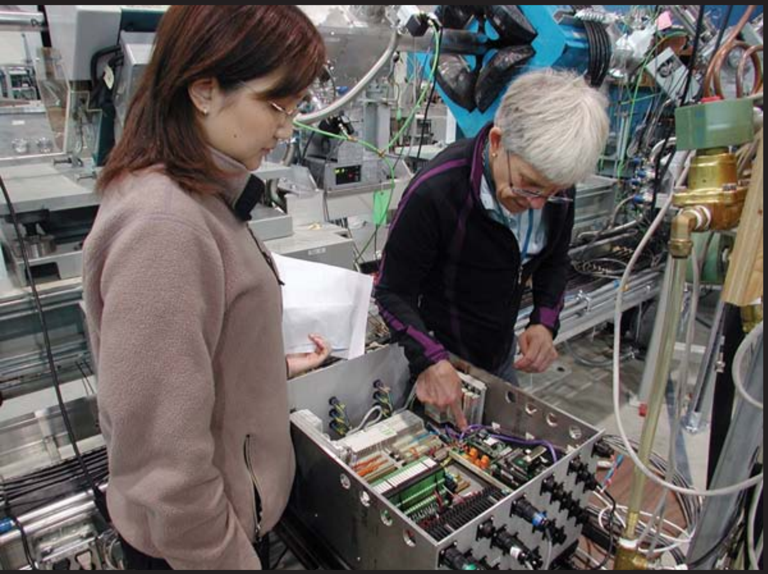
Basis of presentation

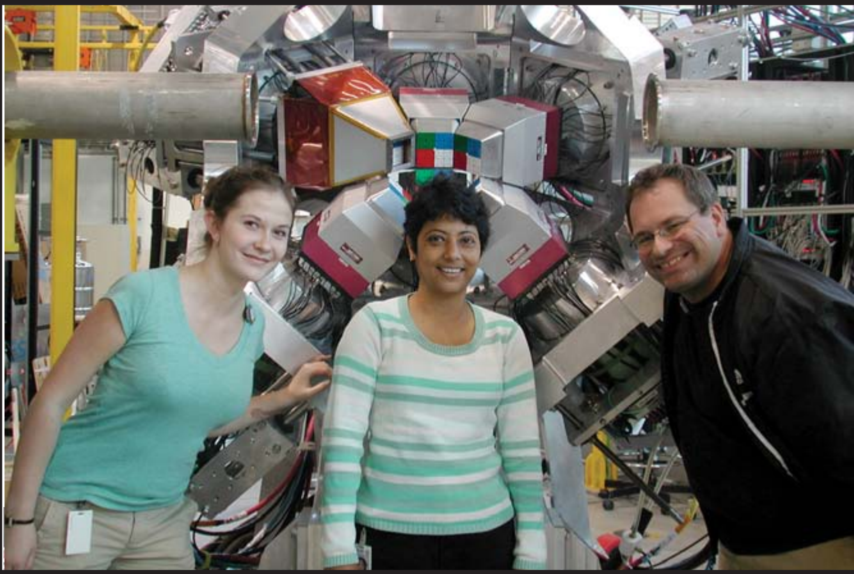
These financial statements have been prepared in accordance with section 7 of the TRIUMF joint venture agreement (note 1) and the contribution agreement with the National Research Council of Canada, and follow Canadian generally accepted accounting principles for not-for-profit organizations as referred to in the Canadian Institute of Chartered Accountants (CICA) Handbook, except that all property, plant and equipment purchased or constructed for use at TRIUMF and related decommissioning costs (if any) are expensed in the period in which the costs are incurred.

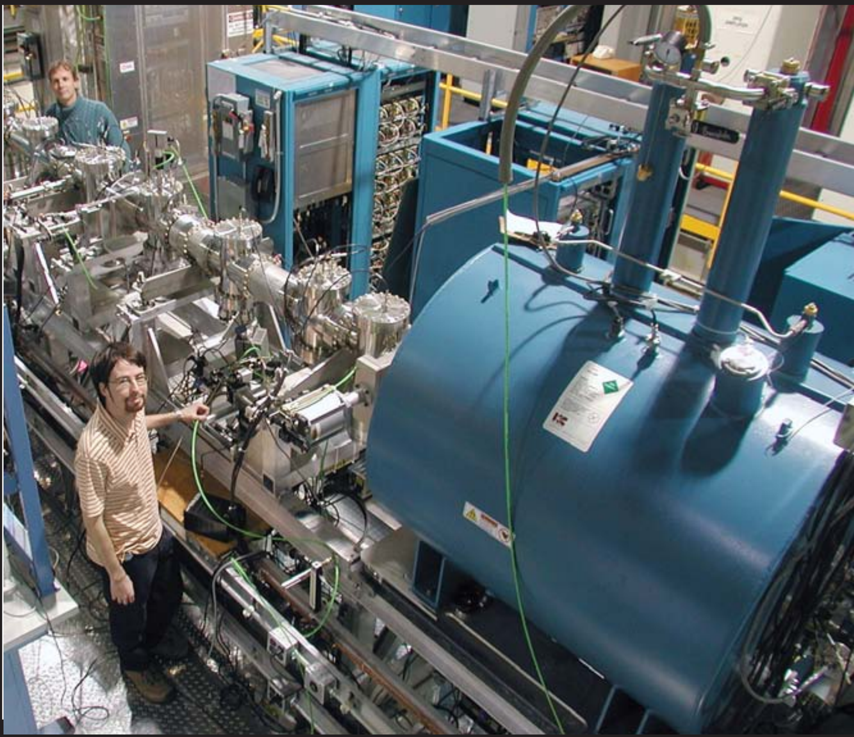
Organization Chart











TRIUMF provides educational and training opportunities for approximately 200 graduate and postgraduate students and 80 undergraduate students each year.