History of TRIUMF's transformation into a Rare Isotope Laboratory

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For over 50 years, the TRIUMF cyclotron has spurred the growth of a diverse and multidisciplinary community whose ideas continue to coax new uses from the decades-old accelerator. These new applications served to continuously redefine TRIUMF as a laboratory, from its roots in the 1970s as a nuclear and low-energy particle physics lab utilizing mesons and protons, to a more multidisciplinary laboratory in the 1980s by adding molecular and material science with muons and then life sciences with radioisotopes. At each stage the inherent flexibility of the cyclotron's design and the management philosophy has allowed TRIUMF to overcome challenges and exploit new opportunities as they arose. Today, TRIUMF has transformed into a world-leading rare isotope factory utilizing a unique suite of particle accelerators to create isotopes for science, medicine, and business.

TRIUMF's transformation into a rare-isotope facility began soon after the cyclotron turned on in the early 1970s, though it was nowhere near apparent at the time. In those days there were a number of ISOL (**I**sotope **S**eparator **O**n-**L**ine) facilities in the world, including the ISOLDE facility at CERN in Geneva. ISOL is a method to create beams of rare isotopes: a solid target is bombarded with a driver beam (protons, neutrons, etc.), which creates an array of rare isotopes through fission, spallation, or fragmentation that escape the very hot target through diffusion and effusion for later ionization and mass separation. In 1975-76, SFU professor John D'Auria went on sabbatical to ISOLDE, where he became interested in the ISOL technology and its potential at TRIUMF. John brought his trademark enthusiasm back to TRIUMF and began a two-decade long campaign to realize an ISOL facility at the lab. The concept was met favourably at TRIUMF and ultimately a small group generated a proposal in the late 1970s for a facility similar to that at ISOLDE. But with TRIUMF in full swing exploiting the nuclear and particle physics capabilities of the lab, this was viewed as a niche project and placed on the back burner.

Summary

A brief account of the people and events that led TRIUMF's transformation from a meson factory into a rare isotope laboratory.

But by the 1980s, the TRIUMF research community was looking for new opportunities. Planning had begun on the much more ambitious KAON project, which would have seen the cyclotron become the injector for a new 30 GeV synchrotron complex. This was a huge effort led by then TRIUMF Director Erich Vogt as the project soaked up most of the resources at the lab throughout the 80s. Nevertheless, with support from the TRIUMF Cyclotron and Experimental Facilities Divisions, led by Gerardo Dutto and Ewart Blackmore, respectively, a small group with modest funding and much resourcefulness continued work on an ISOL proposal, which included rare isotope post-acceleration, a unique proposition for the time. TRIUMF's transformation into a premiere radioactive isotope beam facility can be traced to a pivotal workshop in Mont Gabriel, Quebec in June 1984. Workshop participants concluded that there was a strong scientific case for a next-generation ISOL facility at TRIUMF and recommended construction of a test facility (**T**RIUMF **ISOL** or TISOL). A second workshop at Parksville, British Columbia in September 1985 focused on nuclear astrophysics applications using rare isotope beams. This led to an internal report for an ISAC (**I**sotope **S**eparation and **Ac**celeration) facility, coupling an ISOL target with post-acceleration in the proton hall at TRIUMF.

These background efforts led to a proposal before the TRIUMF Board of Management in 1985 which recommended post-accelerated rare isotope beams (RIB's) up to energies <1.5 MeV/A (see Fig. 1) to induce nuclear reactions for nuclear astrophysics experiments, as well as standard experimental stations for stopped rare isotope beam studies. The TISOL test facility went ahead quickly after TRIUMF approval. It was built at the end of the BL4A proton beam line (see Fig. 2) over a five-year period by a very creative and experienced group of scientists and engineers, largely using equipment repurposed from other laboratories and TRIUMF experiments. At TISOL, targets were irradiated with a 1 μA 200-500 MeV proton beam, producing a wide range of short-lived (milliseconds to seconds) rare isotopes. TISOL became operational in 1986 and ran until 1999. It was originally envisioned to be a low-power test area to gain R&D and operational experience for a more complete ISAC facility, but with target and ion source advancements, a science program

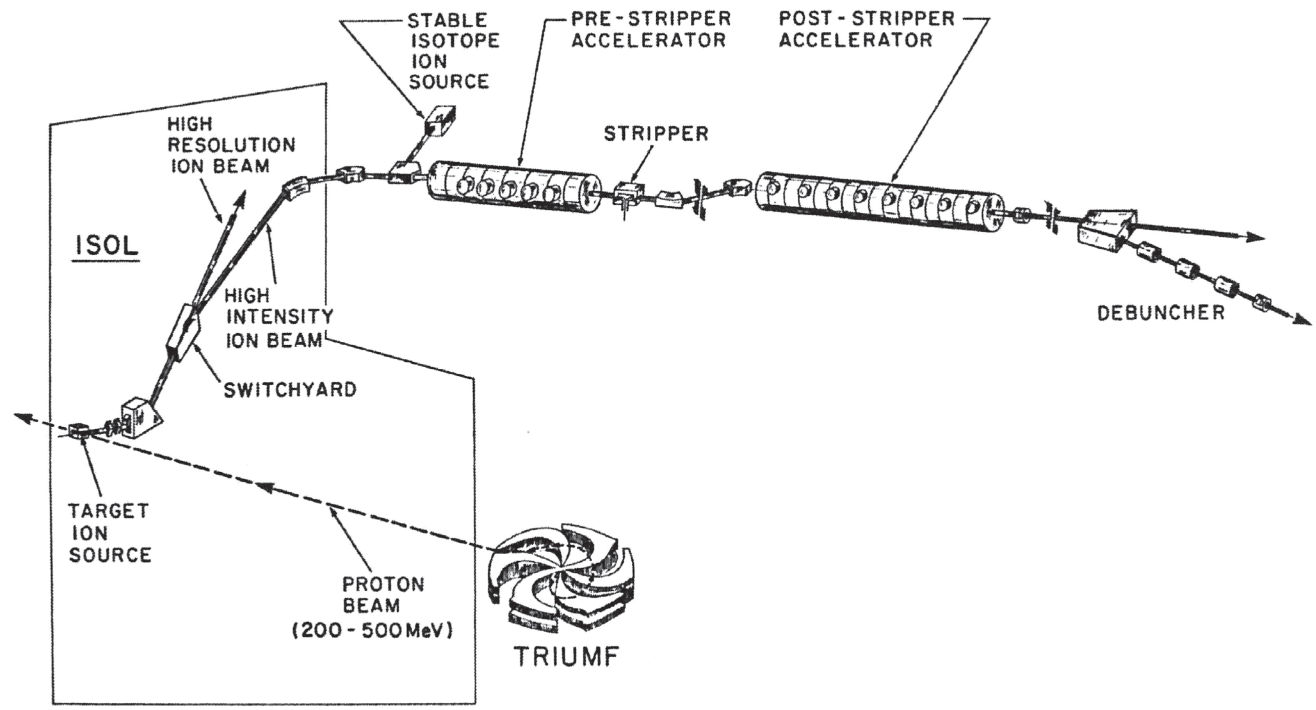

Fig. 1 From the 1985 Annual report, an early conceptual design for a TRIUMF-ISOL facility in the TRIUMF Proton Hall west of the main cyclotron, a decade before ISAC.

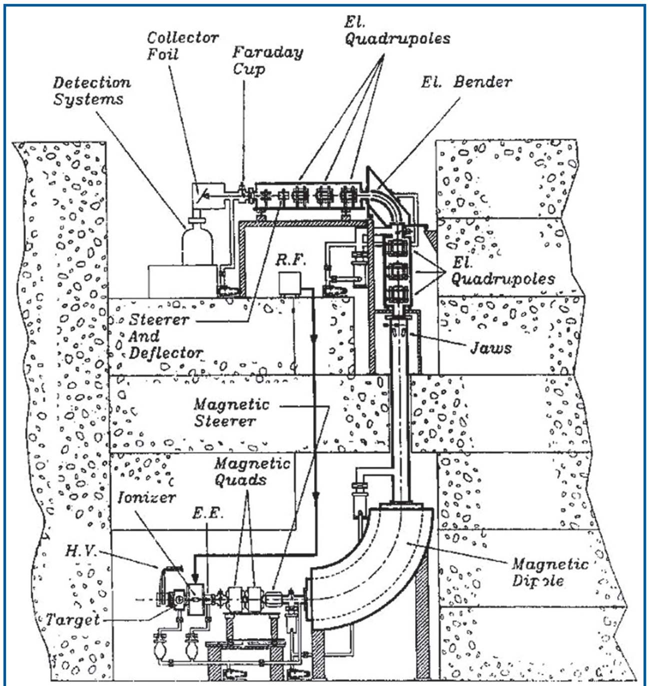

Fig. 2 An elevation view of the TISOL test facility *circa* 1987.

developed that made important contributions to nuclear astrophysics and fundamental symmetries.

TISOL's scientific impact is best illustrated by a key experiment and a ground-breaking facility. In 1992 scientists undertook an indirect measurement of the ^{12}C(alpha, gamma)^{16}O reaction, which is believed to be the mechanism for creating oxygen from carbon and helium in red giant stars. In fact, this "Red Giant" experiment studied the reaction in reverse, where the unstable isotope ^{16}N (1.6 second half life) was produced in TISOL, which then decayed to ^{16}O, and in a miniscule fraction of the time, followed by a decay into an alpha particle (helium) and ^{12}C. The experiment successfully threw light on the origin of the carbon to oxygen elemental abundance ratio observed throughout the universe.

In the early 1990s, Simon Fraser University professor Otto Hausser led the development of a magneto-optical trap for neutral atoms that would exploit the novel properties of rare isotopes produced at TISOL. The facility was envisioned initially to study atomic parity violation, which is greatly enhanced in high-Z rare isotopes (like Francium), and new classes of beta decay correlation measurements. The effort bore fruit in 1997 with a measurement of the optical isotopic shifts and nuclear radii differences between the radioactive isotopes ^{37}K and ^{38m}K. The success of Red Giant and TRINAT gave TRIUMF confidence in its ability to develop a world-class rare isotope program.

Background work on the TRIUMF ISAC proposal continued during the end stages of the KAON proposal in the early 1990s. In 1993, when it was becoming clear that the KAON proposal might not be approved, efforts redoubled on developing the ISAC proposal, which included recruiting a dedicated development team pursuing target and accelerator technology. These efforts led to a number of submissions to the TRIUMF Long Range Planning Committee meeting in summer 1993, and to the creation of an ISAC Steering Committee in September 1993, chaired by (then) Science Director Jean-Michel Poutissou.

The wisdom of pursuing the TISOL programme and the parallel ISAC study became evident in February 1994, when the federal government chose not to pursue the KAON proposal. From then events moved very quickly — University of Victoria professor Alan Astbury was appointed to succeed Erich Vogt as TRIUMF Director in April 1994, with the task of mapping out TRIUMF's future. Initial plans called for an upgraded TISOL facility in the Proton Hall area, but feedback from the nuclear physics community called for a facility with post-acceleration, so Astbury took the courageous decision to pursue the more expensive ISAC option, leading to the submission of TRIUMF's first Five-Year Plan (5YP) in July 1994. Work on the detailed ISAC design began immediately. The proposal to government envisioned a modest ISAC facility where TISOL was located, but after more detailed studies the location was moved to the present site as it offered better opportunities for future expansion, a decision that would become prescient. The breakneck effort was rewarded in June 1995, when the federal government awarded TRIUMF funding over five years, including ~\$18M for a new ISAC facility. In March 1996, the Province of British Columbia followed with funds for new civil construction. The period between the 5YP submission and the budget approval was a time of great uncertainty at TRIUMF, but the time allowed for careful planning which has since served the lab well. Thus dawned the isotope era at TRIUMF.

Work soon began under the project leadership of TRIUMF scientist Paul Schmor. It included provisions for facilities for modular ISOL targets, stopped rare-isotope beams, and one 1.5 MeV/A accelerated beam (up to $A = 30$) utilizing a radiofrequency quadrupole (RFQ) and drift tube linac (DTL) linear accelerator chain. The lab's existing expertise in remote handling of high-current production targets facilitated development of a modular target system able to withstand 100 μA of proton beam, advances which were unique to TRIUMF. The accelerators also were designed at TRIUMF from scratch and were unique in the world at that time. TRIUMF had excellent contacts with the Vancouver construction community as a result of KAON, so design and construction proceeded rapidly and was completed on budget and on schedule. The building permit was received in September 1996, and by 1998 the ISAC building, isotope production target, transport beam line, and mass separation components were completed (see Fig. 3). The first radioactive beam (^{38m}K) was delivered to TRINAT, now relocated to the new ISAC building, in November 1998. This was followed by the first physics with unaccelerated beam for a precision measurement of the ^{74}Rb lifetime, in 2000, the same year that the facility was declared commissioned by federal Industry Minister John Manley in an on-site ceremony. The linear post-accelerator chain also became operational by 2000, and the first accelerated beam, ^{21}Na, was delivered to the DRAGON and TUDA nuclear astrophysics experiments in 2001. In 2002 two other key facilities became operational: (1) the 8π spectrometer (built in 1985 by a Canadian consortium for in-beam reaction studies at Chalk River) was relocated from Lawrence Berkeley Laboratory and reconfigured for use with stopped radioactive beams; and (2) the beta-NMR facility for material science studies. In 2003, funding was announced for the TITAN facility for precision isotope mass measurement, and in 2004, the laser ion source became operational, allowing a wide array of rare isotopes to become available for ISAC experiments. So in just under a decade, ISAC went from an idea to a fully operational facility doing world-class science in nuclear astrophysics, nuclear structure, fundamental symmetries, and materials science, remarkably transforming TRIUMF into an isotope science laboratory.

At the outset, ISAC-I was purposely overdesigned to permit upgrades and future expansion. Soon after construction on ISAC-I started, thoughts turned toward preparing a proposal for an upgrade. At the Dunsmuir Workshop in February 1998, discussion swirled around "doing ISAC properly" to put "TRIUMF on the international map". These efforts culminated in the ISAC-II proposal, which planned for an increase in beam energy from 1.5 MeV/A in ISAC up to 6.5 MeV/A for masses up to $A = 150$, opening up new capabilities in nuclear structure research. The ISAC-II proposal was included in the 2000-2005 5YP, which was funded by the federal government in February 2000, with additional funding for civil construction released by the Province of British Columbia in June 2001. A key feature of the ISAC-II proposal was a third stage of isotope post acceleration utilizing superconducting radio-frequency (SRF) cavities, developed with a laboratory in Legnaro, Italy and sourced from Italian Industry with cryomodules and cryogenics systems designed and built at TRIUMF.

Federal funds allowed work to begin on the first of three planned SRF accelerator sections, with support for completing a second ISAC-II SRF accelerator section and the high-energy experimental beamlines being received in the 2005-2010 5YP budget. The ISAC-II building was completed in 2003, and by 2005 SRF module acceleration was demonstrated with a beam of $^{4}He^{2+}$. In April 2006, a $^{40}Ca^{10+}$ beam was accelerated through both ISAC-I linear accelerators and the first ISAC-II superconducting section to a final energy of 220 MeV (5.5 MeV/A). The second section featuring 'Made In Canada' SRF cavities was completed in 2010. The experimental facilities were to be anchored by two flagship facilities for nuclear reaction studies: TIGRESS, a gamma-ray detection array with provision for auxiliary detection of charged particles and neutrons, and EMMA, a next-generation mass analyzer designed to be used stand-alone or in conjunction with TIGRESS. The ISAC-II era began in earnest when the first production radioactive ion beam (^{11}Li) was

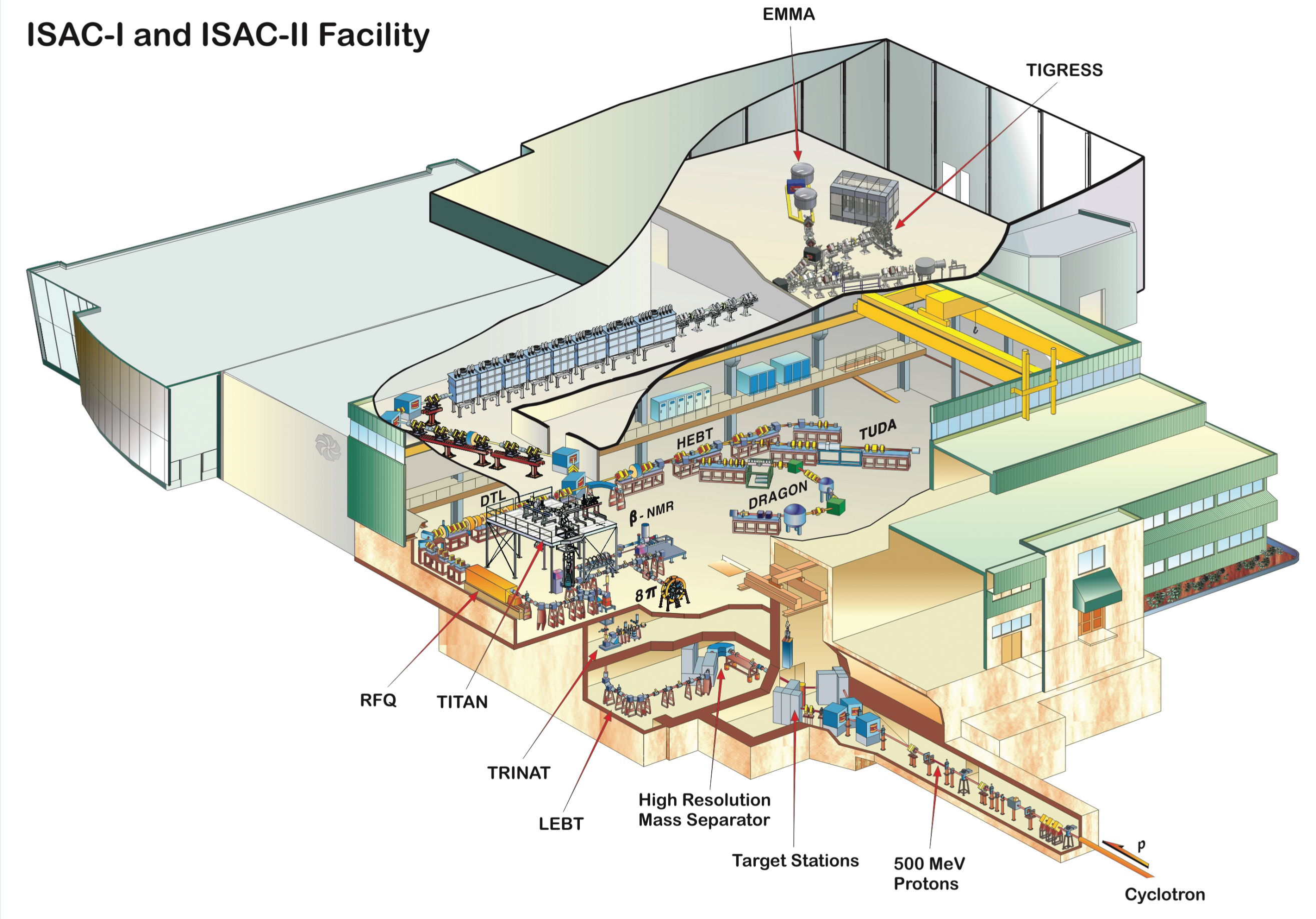

Fig. 3 Cutaway graphic of the ISAC I and II facilities as they appeared in March 2012. These purpose-built buildings are located north of the main cyclotron.

delivered to the MAYA experiment (from GANIL in France) in the ISAC-II experimental hall on January 05, 2007.

ISAC's success did not satiate TRIUMF's ambitions to become a truly multi-user RIB "factory". There were plans extant to provide additional "driver" beams for isotope production in addition to the single proton beam line from the main cyclotron, and the decisive step was taken by (then) TRIUMF Director Nigel Lockyer in 2008 to pursue the ARIEL project (**A**dvanced **R**are **I**sotop**e** **L**aboratory). The centrepiece of ARIEL is a new superconducting electron linear accelerator (e-linac) for isotope production via photoproduction and photofission which promise a complementary class of neutron-rich isotopes created completely independently of the main cyclotron. The proposal also envisioned a second proton beam line from the cyclotron, resulting in ultimately three independent rare isotope beams into the ISAC I and II experimental facilities, thereby tripling the scientific output potential.

ARIEL was the centrepiece of the 2010-15 5YP, with construction beginning in March 2011. In contrast to the way ISAC was funded, ARIEL funding has come in stages from a combination of Canadian Foundation for Innovation (CFI), provincial, and TRIUMF federal operating funding. The University of Victoria is the primary CFI stakeholder for the e-linac, with professor Dean Karlen as principal investigator for two successive CFI projects. The e-linac, developed at TRIUMF in partnership with local industry, demonstrated electron acceleration in September 2014. The first stage of ARIEL, which included the building and e-linac, was declared completed in November 2014 (see Fig. 4). The second stage, which includes completion of the beam transport lines, target hall, ion sources, and second proton beamline, received funding in June 2017. At time of writing, TRIUMF is working with great effort on ARIEL, with first post-accelerated beams utilizing the new ARIEL CANREB charge-breeding facility (itself a CFI project) anticipated in 2020. Beams utilizing the e-linac and second proton beamline drivers are anticipated in 2023 and 2026, respectively. Ultimately, ARIEL will deliver three independently produced rare radioisotope beams to the many experimental facilities at ISAC I and II, strengthening and growing research programs in nuclear structure, nuclear

Fig. 4 Drone's-eye view of the present TRIUMF site, with the ARIEL building (orange trim) visible in the centre, and the ISAC-I and II buildings in behind it. The long main cyclotron building is visible on the right.

astrophysics, fundamental symmetries, materials science, as well as the life sciences.

While TRIUMF began as a "meson factory" primarily for nuclear and particle physics, the laboratory has transitioned over the last 30 years into a laboratory where rare radioisotopes have taken centre stage. This transition was set in motion with the construction of the TISOL facility in the 1980s, which led in turn to ISAC I and II. The new ARIEL facility will greatly augment the capabilities of both these facilities.

The visionary design of the TRIUMF cyclotron, and in particular the (up to) four simultaneously available very intense proton beams at energies up to 500 MeV, has ensured that the laboratory, as a world-class facility, could transition smoothly into this new role. That a cyclotron designed in 1967 could have such an exciting and forefront future in international science 50 years later is a testament to the laboratory Directors and the scientists, engineers, and technical and support staff who have contributed over the years to this continuing development.

MORE INFORMATION

For more information on the facilities and experimental program developed to exploit the rare isotope beams at ISAC and ARIEL, as well as the many talented people who worked on the projects, please refer to the following publication and presentations:

"Canada's Radioactive Beam Facility – At the Nexus of Past and Future Triumphs", John D'Auria, Jens Dilling, Paul Schmor, *Nuclear Physics News*, **20**, 2010.

ISAC and ARIEL: The TRIUMF Radioactive Beam Facilities and the Scientific Program, ed. J. Dilling, R. Kruecken, L. Merminga, *Hyperfine Interactions*, **225**, 1-282, 2014.

G.C. Ball, G. Hackman, R. Kruecken, *Physica Scripta*, **91**(2016), 093002.

Presentation on the 10th Anniversary of ISAC, by John D'Auria, https://www.triumf.ca/sites/default/files/TRIUMF_ISAC_10th_jd'auria.pdf.

Presentation on the 20th Annivesary of ISAC, by Gordon Ball, https://meetings.triumf.ca/indico/event/75/session/2/contribution/2/material/slides/0.pdf.