TRIUMF

Biennial Scientific Report 2013—2015

TRIUMF

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ARIEL–ADVANCED RARE-ISOTOPE LABORATORY

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ARIEL–ADVANCED RARE-ISOTOPE LABORATORY

4.1 INTRODUCTION AND SCIENCE MOTIVATION

In September 2014, TRIUMF completed the first stage of the construction of the Advanced Rare Isotope Laboratory (ARIEL), with the goal to significantly expand TRIUMF's Rare Isotope Beam (RIB) program for Nuclear Physics and Astrophysics, Nuclear Medicine, and Molecular and Materials Science.

Rare isotopes are powerful tools for scientific discovery, such as determining the structure and dynamics of atomic nuclei, understanding the processes by which heavy elements in the Universe were created, and enabling precision tests of fundamental symmetries that may challenge the Standard Model of particle physics. Rare isotopes or "radioisotopes" are also foundational for modern medical imaging techniques like PET and SPECT, and useful for therapeutic purposes, such as the treatment of cancer tumours. They can also serve as unique probes to characterize magnetic and electronic properties at surfaces and interfaces between materials.

At its heart, the full ARIEL project consists of a 500 kW, 50 MeV electron accelerator for isotope production via photo-production and photo-fission as well as a second proton beam line from TRIUMF's 500 MeV cyclotron for isotope production via proton-induced spallation and fission.

The ARIEL scientific program will be implemented in stages beginning with ^{8}Li photo-production for materials science. This stage will be followed by the implementation of the production of neutron-rich fission fragments through photo-fission of uranium with more than 10^{13} fissions per second in the final implementation. Photo-fission will enable the study of the very neutron-rich nuclei involved in the astrophysical r-process responsible for the production of the heavy elements from iron to uranium in supernova explosions or the merger of neutron stars. The new proton beam line (BL4N) will deliver up to 100 microAmp beam onto an additional production target. In conjunction with the e-linac production target TRIUMF will go from the current single ISAC RIB production target to the parallel production of RIBs on three target stations. This new and unique multi-user capability will allow for a much better exploitation of the available forefront experimental facilities at ISAC. Aside from the tremendous gain in available time for the materials science program, other experimental programs that need large amounts of beam time will be enabled by the multi-user capability of ARIEL. In addition, capabilities for the harvesting of medical elements will be implemented.

This first stage of the ARIEL project, which was funded through the Canada Foundation for Innovation and the BC Knowledge and Development Fund and spearheaded by the University of Victoria, comprised the civil construction for the full ARIEL project as well as the development of the new superconducting electron accelerator (e-linac) (see Figure 1).

The subsequent sections will describe the completion of the ARIEL building as well as details on the e-linac accelerator development, construction, and commissioning.

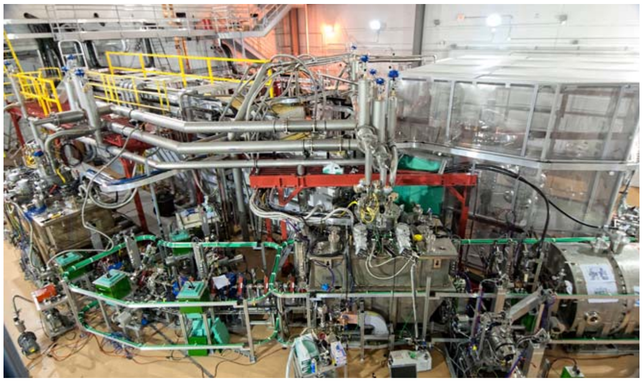


Figure 1. ARIEL electron linear accelerator complex.

4.2 ARIEL CIVIL CONSTRUCTION

R. DAWSON

In June 2010, the Province of British Columbia provided the University of Victoria with $30.7M through the British Columbia Knowledge Development Fund for ARIEL civil construction at TRIUMF. Chernoff-Thompson Architects led the overall architecture and engineering contract, which was awarded in October 2010. The schematic design report was received on March 4, 2011, and the design development report was received on July 4, 2011.

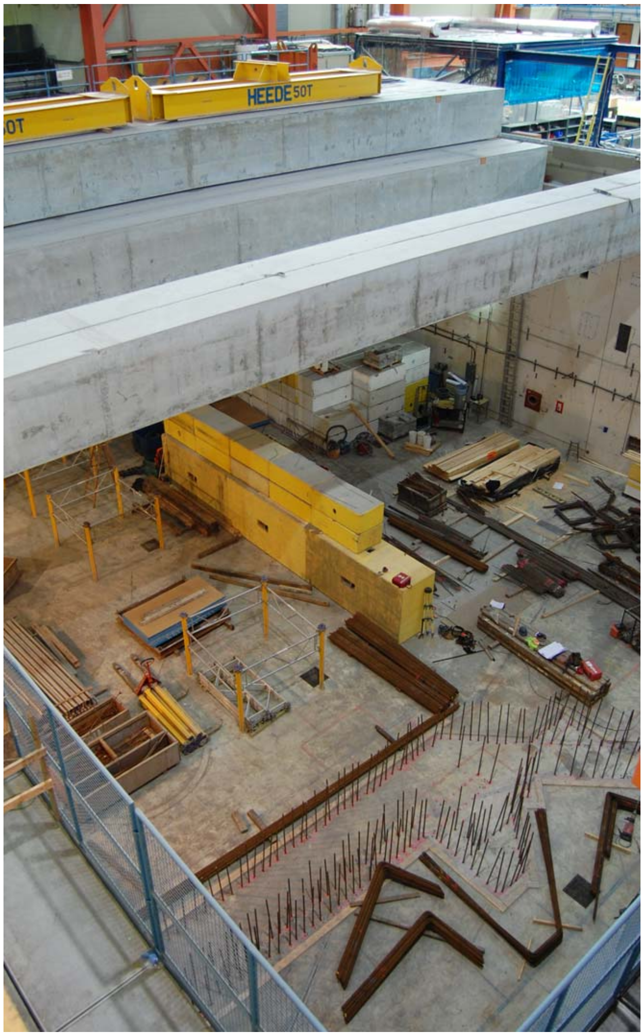


Figure 2. Electron linac hall during rehabilitation

The construction plan consisted of four main components: the demolition of the old Stores building and excavation of the ARIEL building sited; construction of the new Stores building; construction of the new Badge room; and construction of the ARIEL infrastructure, including the main building, the new Helium Compressor Building, and major renovations to transform the former Proton Hall to the new Electron Hall (see Figure 2).

The demolition and excavation contract was awarded and work started on October 17, 2011 and was substantially completed by April 2012. The completion target date of January 20, 2012 was delayed due to unforeseen ground water and soil conditions as well as a water main failure. Construction for the new Stores building and Badge room were completed in 2011. Work on the new Stores building started March 28, 2011 and occupancy was achieved on schedule on September 23, 2011. Construction on the new Badge room started August 3, 2011 and was completed slightly behind scheduled completion on December 10, 2011, primarily because of equipment delivery and coordination logistics (see Figures 3 and 4).

Figure 3. Helium compressor building and storage tank

The construction tender for construction of ARIEL was issued December 14, 2011 and awarded February 9, 2012. The ARIEL main construction contract included work in the Electron Hall, the Helium Compressor Building, and ARIEL building. Both the Electron Hall and the Helium Compressor Building were completed in late 2012. The ARIEL building was substantially completed on September 25, 2013.

In April 2013, the work of engineering consultants Stantee Consulting Ltd. (mechanical), Applied Engineering Solutions Ltd. (electrical), and Bush, Bohman & Partners Ltd. (structural) was recognized with the 2013 Engineering Excellence Award of Merit by the Association of Consulting Engineering Companies of British Columbia. In October 24, at the Vancouver Regional Construction Association's 26th annual Awards of Excellence gala, Ellis Don Corp took home the general contractor award for $15 million to $55 million projects for its work as primary contractor for the ARIEL building project.

Figure 4. New Stores building

4.3 ACCELERATORS AND BEAM LINES

S. KOSCIELNIAK

4.3.1 Introduction

On September 30, 2014, the Advanced Rare IsotopE Laboratory project (ARIEL-I) was complete, and a 23 MeV electron beam was delivered to the EABD beam stop. The second phase, ARIEL-II, will add target stations, mass separators and RIB beam Lines to deliver rare isotopes to the existing ISAC-II experimental facility. The e-linac science infrastructure and all components were funded by the Canadian Foundation for Innovation (CFI). As a contributing development, the electron gun and low-energy beam test stand were prototyped in the ISAC-II building under a collaboration with Variable Energy Cyclotron (VECC) of Kolkata, India.

Gamma-ray induced fission, using copious photons produced from a primary electron beam, is an invented-in-Canada mechanism for RIB production

that is complementary to proton-induced spallation, with the advantages of niche neutron-rich species and lower isobaric contamination. An order of magnitude higher RIB production requires a 50 MeV, 10 mA electron driver beam. Electron beams are easy to produce and are relativistic above 1 MeV, which confers the advantage of compact, constant frequency accelerating structures. L-band (≈ 1GHz) SRF technology has been pursued by the high-energy physics community as an enabling technology for a TeV-scale linear collider since the 1980s and is now considered “mature” for transfer to industry. Efficient operation of these cavities requires immersion in a 2K bath of liquid helium. Niobium SRF cavities have advantages over normal-conducting copper cavities of continuous rather than pulsed operation and much reduced operating costs. The e-linac provides an opportunity for TRIUMF to master this SRF technology and transfer the fabrication know-how to the local Richmond-based company PAVAC Industries Inc.

4.3.2 E-Hall Rehabilitation

The former proton hall was emptied of obsolete science equipment in 2012. Subsequently, the space was taken over by Ellis Don for the pouring of concrete: very massive shielding for BL4N to north, and massive shielding to south to support ERL operation (see Figure 2, p. 108) Occupancy of the e-hall was taken in February 2013 and equipment installations began at that time, starting with the LHe dewar and ALAT cold box.

4.3.3 Accelerators and Beam Lines

The mast head achievements from 2012–14 were: (i) development of two niobium 9-cell elliptical-type cavities both meeting the design specification of bare quality factor $Q=10^{10}$ at an accelerating gradient of 10 MV/m; (ii) acceptance testing of two 1.3 GHz c.w. klystrons to 270 kW each; (iii) acceptance testing of the 4K cryogenic plant beyond the design specification 800 W cooling power at 4.6K and maximum liquefaction rate of 380 l/h; (iv) construction of the e-linac beamlines; (v) integration of all e-linac systems; and (vi) delivery of the 23 MeV electron beam. Progress that led to these achievements is detailed below.

4.3.4 Electron Gun

The electron gun (e-gun) provides up to 10 mA of 300 keV kinetic energy electron beam. The main components are an in-air HV power supply, the gridded thermionic gun electrically isolated in an SF6 filled vessel, and an RF modulation feedthrough. Unique features of the gun are its inverted cathode/anode geometry to reduce dark current, and transmission of the RF modulation through a dielectric (ceramic) waveguide.

The gun interfaces to the waveguide through a shroud and corona domes inside the SF6 tank. The gun cathode, anode and ceramic stand-off were assembled May, 2013. The waveguide, shroud and corona domes were assembled to the gun in September. All e-gun components were installed at the VECC test stand, and the 300keV 10 mA beam demonstrated December 2013. The entire e-gun was moved to the e-hall April 2014 (see Figure 2). The SF6 gas management system will be added in 2015.

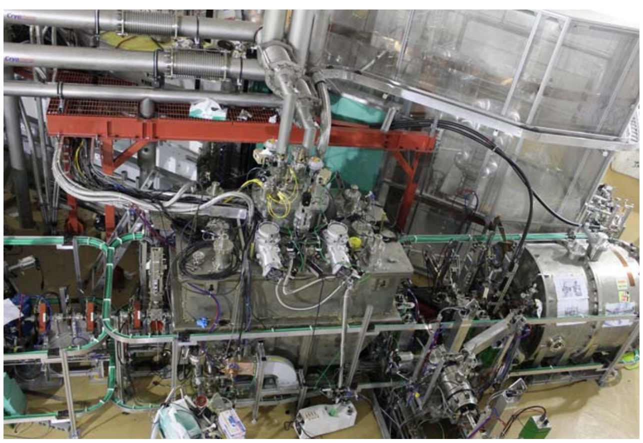


Figure 2. The electron gun and injector cryomodule

4.3.5 (VECC) Injector Test Stand

The purpose of the VECC test stand, initiated 2009, was to jump start the e-linac development activity in advance of the CFI funding. The 2010–12 bi-annual report records the use of a 100 keV prototype gun and testing of beam diagnostic devices, particularly the Allison scanner for transverse emittance measurements, in a low-energy beam transport (ELBT). There is also a momentum analysis stub (ELBD). Subsequently, the buncher RF cavity (in ELBT) and the transverse deflecting cavity (in ELBD) were used to reconstruct the longitudinal phase space in November 2012. This information is useful for matching into the acceptance of the first cell of the injector cryomodule. After the 300 keV gun was installed, many of the beam diagnostic measurements were repeated December, 2013 through January 2014 and more sophisticated algorithms developed for quantifying the strength of optics elements based on beam measurements.

4.3.6 Cryomodules Design

The ARIEL-I e-linac has two cryomodules: the injector cryomodule (EINJ) contains a single 9-cell cavity, and the accelerator cryomodule (EACA) contains two 9-cell cavities; together they can accelerate a beam to 30 MeV. The future ARIEL-II project will add a second accelerator cryomodule (EACB), bringing the beam energy to 50 MeV.

The cyromodules follow a common design that utiliz-esa box-type evacuated cryostat with a top-loading cold mass. To produce 2K helium liquid, a 4K phase separator, 4K/2K heat exchanger, and Joule-Thomson valve are installed in each module. The cold mass is suspended from the lid by mounting posts, struts, and strong back, and is surrounded by a LN2-cooled copper box for thermal isolation. A warm mu-metal shield is fastened to the inside of the vacuum vessel. The cold mass consists of cavity hermetic units, a cold mu metal layer and tuner for each cavity. The tuner cold part is the Jefferson-laboratory scissor type; driven by a long actuator and warm ISAC-II style rotary servo motor mounted on the lid. The hermetic unit includes the cavities, RF power couplers cold parts, rf pick-ups, the warm-cold transitions with higher order mode (HOM) damping material, and warm isolation valves. A silicon carbide material, CESIC, was chosen for the damping material. Tunable coaxial RF couplers of the Cornell design are adopted, and each is capable of transferring 50 kW; the coupler warm parts pass through the cryostat and shields. The coupler cold parts are cooled by 4K intercepts.

4.3.7 SRF Cavity Resonators

A program of single-cell Nb cavity fabrication, surface treatment (buffer chemical polish and high-pressure water rinsing), and cavity quality factor (Q) and accelerating gradient measurements culminated in Q=10^10 at 15 MV/m at 2K in August 2012.

The nine-cell 1.3 GHz elliptical cavity (see Figure 3) borrows the TESLA/ILC type inner cell geometry

but uses modified end groups to accommodate the large power couplers and to mitigate HOMs. A multi-pass beam breakup criterion establishes a limit of $R/Q^*Q_L < 10^7$ Ohm.

Development of multi-cell cavity fabrication techniques began with a 7-cell copper cavity (completed in February 2012), and continued with the first 9-cell Nb cavity delivered by PAVAC in May 2013. The cavity was subsequently etched at TRIUMF, cold tested in August, heat treated at FNAL for hydrogen contamination , and acceptance tested in November 2013; and then sent to PAVAC for cavity jacketing. The first of two EACA 9-cell Nb cavities was cold tested in October 2013, sent to FNAL for degassing, had its second cold test and etch, and after jacketing at PAVAC, was received in May 2014.

4.3.8 Injector Cryomodule

The injector cryomodule (EINJ) raises the beam energy to 10 MeV. The modest accelerating gradient, 10 MeV/m, accommodates the heavy beam loading of the cavity which must transfer up to 100 kW c.w. power to the electron beam. Under the terms of the collaboration agreement, TRIUMF and VECC both contributed engineering resources to the design of the EINJ. By November 2012,

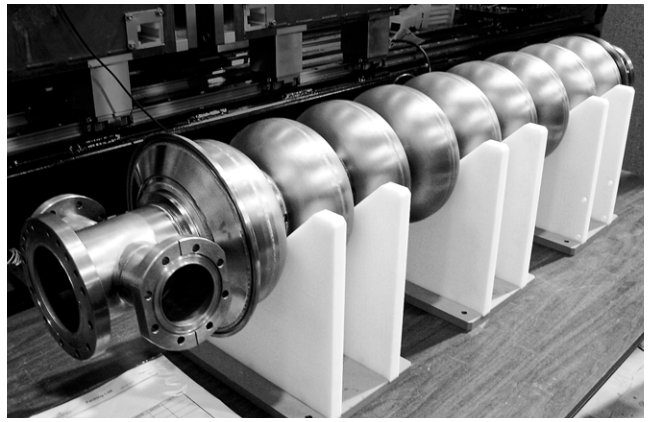


Figure 3. The nine-cell elliptical cavity.

the design was complete and the majority of the components fabricated, with the exception of the 9-cell niobium (Nb) cavity. A mock-up using actual parts, but with the cavity substituted by a dummy, verified the design prior to the final assembly. The jacketed EINJ cavity was received 2014 February. Final assembly followed, which led to the successful cold test of the entire injector cryomodule in April 2014, and subsequent move to the e-hall on May 1 2014.

4.3.9 Accelerator Cryomodule

The first accelerator cryomodule (EACA) raises the beam energy to 30 MeV. The cryomodule design is essentially the union of two back-to-back injector cryomodules (see Figure 4). It was hoped that testing of the EINJ would occur before completion of the design or EACA, so that lessons learnt could be applied to the latter; but this was not to be the case. Although EACA engineering design began in 2011, it did not gain momentum until fall, 2012 through spring 2013, and was finished in October 2013. However, many of the components are shared in common with EINJ, and EACA parts fabrication started June 2013. All sub-assemblies were received by May 2014, and final assembly of the cryomodule was coordinated in readiness for the first EACA SRF cavity. EACA final assembly was completed in July, and the cryomodule delivered to the e-hall in August. Cool down to 2K was achieved August 19, and RF was first applied August 26.

Figure 4. The first EACA raises the beam energy to 30 MeV.

4.3.10 4K/2K Inserts

Whereas the ISAC-II quarter wave cavities, operating at 140 MHz, need a 4K LHe bath, the e-linac elliptical cavities, operating at order 1300 MHz, need a 2K LHe bath to reduce the otherwise higher BCS RF power loss in the superconducting metal.

There is a 4K/2K insert on board each cryomodule, whose main purpose is to generate 2K liquid entering the cavities from 4K liquid entering the cryomodule. 2K liquid is produced by passing 4 liquid through a heat exchanger in counter flow with the returning exhaust gas from the 2K phase separator, and then expanding the gas to 30 mbar through a Joule-Thomson expansion valve. The header pipe above the cavity string acts as a 2K phase separator, and delivers cold gas back through the 4K/2K heat exchanger to the SA pumping system as a liquid load.

Further, a 4K LHe reservoir in each cryomodules acts as a 4K phase separator. Cold gas is returned to a common return trunk and then delivered back to the cold box where it represents a refrigerator load. A siphon circuit from the 4K reservoir cools the 4K intercepts, with vapour returning back to the reservoir. Initial cool down of the cold mass is done by delivering 4K liquid from the 4K phase separator to the bottom of the cold mass through a dedicated cool down valve. The prototype 4K/2K insert underwent preliminary testing at 77K & 4K October to November, and was found to be satisfactory May 2013, after modification of the 4K syphon to reduce convection in the 4K reservoir.

4.3.11 Radio-Frequency Equipment

The purpose of the RF equipment is to energize the cavity resonators with travelling wave electrical fields that accelerate the electrons. When superconducting cavities are used, almost 100% of the incident RF power is transferred to the particle beam.

The 2010–12 bi-annual report records the use of a 30kW Inductive Output Tube (IOT) as the basis for the RF coupler conditioning station. Two couplers at a time are tested/conditioned under either travelling or standing wave conditions ranging from 10 to 40 kW peak power.

The time frame covered by the 2012–14 report concerns the 1.3 GHz high-power RF system that supplies up to 100kW to each of the three SRF cavities. The basic layout is that an RF source (klystron) delivers power via a circulator and waveguide distribution system to the two coaxial input couplers that feed a single SRF cavity. The EACA distribution system must power and phase adjust the RF between the cavities.

A klystron is a very high-gain RF amplifier. The amplification is achieved by modulating a high current (9A) low energy (65 keV) electron beam inside the klystron. 100kW is delivered to EINJ and 200kW to EACA; and each cryomodule is powered by an individual klystron. The RF sources are long lead items. To achieve procurement efficiencies, both klystrons and their high-voltage DC power supplies (HVPS) are identical.

Two custom designed c.w. klystrons were ordered from CPI, USA, in August 2011 as part of a joint venture with Helmholtz Zentrum Berlin. The klystron is specified with a usable linear range up to 270 kW, leaving plenty of margin for transmission loss to the nominal 200kW rated EACA. The first and second were delivered to TRIUMF March 2013 and May 2014 respectively. The 65kV HVPS, rated at 300 kW output power, were procured independently from Ampegon, Switzerland. The HVPS uses IGBT-based, pulse step modulators, and DC/DC convertor to achieve 0.1% low ripple, and low arc energy (so no crowbar is needed).

The order was placed June 2012, and the first HVPS delivered was energized September 2013. The combination of EINJ klystron, HVPS and circulator was acceptance tested to 270 kW at a dummy load April 2014. The second HVPS was energized July 2014. In parallel with sources testing, the waveguide RF distribution systems were installed, with the EINJ and EACA systems ready for operation May and August 2014, respectively.

4.3.12 Cryogenic Equipment

The cryogenic system is tasked with supplying 4K He liquid to and recovering 2K sub-atmospheric (SA) He gas from the cryomodules. There are several cryogenic sub-systems: (i) compressors that provide 12 bar gaseous He to the cold box via the gas management system; (ii) a 4K liquid helium closed (re)-liquefaction/refrigeration loop, that comprises the cold-box, He dewar and 4K He distribution to the cryomodules; (iii) the oil removal and gas management system (OR/GMS) that monitors and purifies the helium, and may also pass He to a 113 m^3 storage tank in the case of a prolonged power outage; (iv) and the SA system, comprising SA pumps and a counter-flow heat exchanger (HX), that returns gaseous helium to the main compressor; and a 77K liquid nitrogen system that pre-cools He entering the cold box, and also cools the thermal shields within the cryomdules. The systems are distributed: the compressors, ORGMS and SA pumps are in the He compressor building; the cold box, dewar, 4K He distribution, 2K SA gas return and HX are all in the e-hall.

Components were delivered by a variety of vendors, and TRIUMF performed the system integration.

The contract for supply of He cryoplant consisting of HELIAL 2000 cold-box, Kaeser main and recovery compressors with OR/GMS, and multi-component purity analyzer was awarded to Air Liquide Advanced Technologies (ALAT), France in October 2011. This machine is class 700 W cooling power at 4.6 K with maximum liquefaction rate of 288 l/h. The SA HX is an innovation that warms the sub-atmospheric return He gas and cools the forward pressurized gas entering the cold box. Use of the SA-HX, which was designed by TRIUMF and Carleton University, increases the overall thermal efficiency, a so-called “green” technology.

The He Compressor building construction formed part of the ARIEL civil construction package awarded to Ellis Don; occupancy was taken December 2012. The helium storage tank delivered in January of 2013.

All ALAT-supplied systems, and the four SA pumps supplied by Busch, were delivered by March. [One SA pump was installed at the VECC test stand and used to support the 2K SRF program.] After installation of the LN2 distribution and GHe distribution to the e-hall, and all connections made, the 4K cold box was successfully acceptance tested in November 2013. The cold box performs at 800W cooling power in refrigeration mode, and 380 litre/hr in liquefaction mode.

The final stage, achieving 2K liquid helium, required progress with several components: LHe-to-cryomodule 4K distribution (vacuum jacketed line); LN2-to-cryomodule distribution line; the SA 2K He return line and HX; and the readiness of the cryomodules in the e-hall to process the cryogens in the 4K/2K inserts. All of these systems, with the exception of final connections to the cryomodules, were completed May 2014. The gaseous He purifier, the subject of a collaboration with FNAL, was delivered in July, but not integrated into the OR/GMS until 2015.

4.3.13 Electrical Infrastructure

A new 5 MW switchgear, connected to the BC Hydro electrical utility and diesel generator, augments the site power for ARIEL. The switchgear will feed: up to 1.5 MW to the klystrons; 2 MW north to the ARIEL building; 1 MW south to the He compressor building; and provide 0.5 MW of emergency power. The Siemens 12.47 kV switchgear was delivered to TRIUMF September 2012 and energized in December.

4.3.14 Beam Lines

Magnetic optics transport electron beam from the source and between the cryomodules, and finally delivers electrons to the converter/target. The beam transport sections are:

- The ELBT low energy (300keV) transport
- The EMBT 10MeV “merger” section, so-called because it could merge the injector beam with the recirculating beam from an Energy Recovery Linac re-configuration of e-linac.
- The EABT 30 MeV transport between two accelerator cryomodules
- The EHAT 50 MeV transport after the future EACB
- The EHDT transport to the 10kW tuning dump
- The EHBT high energy transport through the ARIEL tunnel to the photo-fission target.

Each of these lines forms a point of articulation where the beam may change direction, and is equipped with one or more dipole magnets. The dipoles were designed/procured in batches: 3 specialist magnets for EMBT/D, so-called Y-30 magnets in the EHDT and EHBT horizontal dogleg, and so-called S-34 magnets in the EHBT section leading to the target. The main bends are strong, and must be regulated to 0.01%, otherwise the mis-steering can swamp the correctors. This level of stability is challenging. Magnet current transducers and feedback on the power supply are implemented with controllers supplied by Bira, USA.

Solenoid focusing is used in the ELBT 300keV beam transport. The special “strong” solenoid immediately after the 300keV e-gun was received June 2012 whereas the weaker ELBT/D solenoids were delivered in 2011. The X-Y correction magnets in ELBT are a custom air-cored design that eliminates hysteresis effects; the design recuperates PCB coils and Al heat sinks supplied by RadiaBeam, USA.

From the injector linac onward, magnetic quadrupoles are used for beam transverse focusing. The quads come in three varieties: medium, weak and strong. The beam lines in the e-hall adopt the weak and medium quadrupoles, with integrated strengths up to 0.2 T and 0.7 T respectively. This is easily achieved with the short quadrupoles of aspect ratio 1 and cylindrical poles with spherical faces (see Figure 5). The weak quads are also used for the EHBT periodic section in the tunnel. At highest envisioned energy of 75 MeV, the shortest required focal length is 0.24 m in the EHBT dogleg sections. The required integrated gradient is 1.05 T; this is achieved with a more conventional strong quadrupole design with rectangular cross-section poles and hyperbolic faces. All quadrupoles were provided by Buckley Systems, New Zealand. Prototypes of all 3 types were received February 2013 and all production units were delivered August 2013. The hysteresis curve of all quadrupoles and dipoles were measured, and all were degassed, prior to installation. From the injector onward, the X-Y correction magnets are identical, using a steel core design fabricated by RadiaBeam. All correction magnets use true bi-polar power supplies, whereas the quadrupoles and main dipoles all use uni-polar supplies with polarity switching. Power supplies for all magnets in the e-hall were installed in the e-hall roof beams rack farm by May 2014.

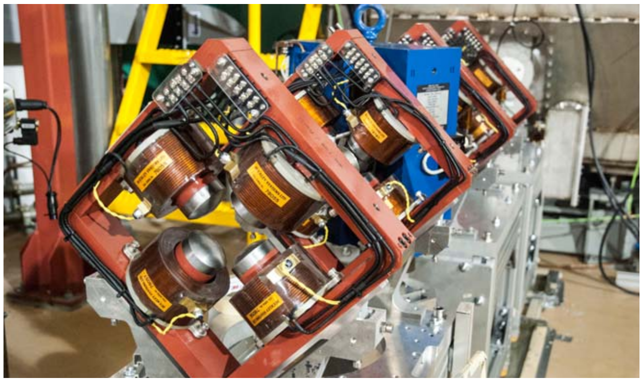


Figure 5. e-linac quadrupoles.

4.3.15 Beam Line Design and Installation

The design, manufacturing, and installation of the electron beam line was very different from any other TRIUMF has installed. New technologies introduced synergizes between three key offices on site: the Design Office, the Machine Shop, and the Beam Lines Group. The equipment stand concept is entirely new: aluminum extrusions for legs, transverse shear plates for torsional rigidity, stiff top plates with a precision milled key way for alignment, and precision machined mounting brackets for magnetic and diagnostic beam line components.

The Design Office modeled the entire beam line in 3D

using SolidWorks. These models produced drawings that went directly to the onsite Machine Shop. The new 3D numerically controlled (CNC) machines tools in the shop were leveraged to manufacture parts with very high precision. Ultimately, these advances changed the method of installation of the beam line. The beam line stands are positioned to sub-millimetre accuracy using the new 3D laser tracker alignment systems. The combination of precision stand alignment and high tolerance parts allowed to assemble quickly the beam line while maintaining accuracy.

The beam optics models were completed in 2012. The stands designs were completed in 2013. Static and dynamic loading of a prototype stand, equipped with

Figure 6. Quadrupoles in ARIEL transfer line tunnel.

quadrupole and diagnostic box and fast wire scanner, October to November 2013 was the gating for commencing mass production. Beam line stands were assembled and grouted in place, beam line equipment such as quadrupole magnets, diagnostic boxes, and vacuum pipes were mounted to support brackets, and beam line sections were aligned in the e-hall and in the periodic section of the ARIEL, all in the space of time between June–September 2014 (see Figure 6)

4.3.16 Beam Diagnostic Equipment

Measurements of beam position, profile and current along the beamline are essential for the beam set-up and for monitoring during the production run. Initial beam threading is performed with view screens, followed by trajectory correction with 4-button type four beam position monitors (BPMs) each measuring in two planes, horizontal and vertical. Electron beam charge is measured by Faraday cups. The view screen effort was led by the University of Victoria. Beam profile measurements can be performed at all energies with view screen systems comprising a thin screen, optical pathway and camera. At low/ high energy, a scintillator/OTR screen is used. An optical pathway transports the light away from the beam line and into a lead-shielded camera box. The camera can be triggered by the output of the electron gun RF signal or through a software interface. Seventeen view screen actuators, foil ladders, optics, cameras and electronics were built; and 16 installed.

There are 54 BPMs at the facility: twenty-two along the e-linac itself and 32 along the high energy beam transfer line, and the majority have been installed. The button pickups are manufactured by Kyocera, and the button bodies/housings by TRIUMF. The BPM signal processing electronics operates in both the pulsed beam tune-up mode and the c.w. beam mode. Electronics consist of analogue front end (AFE) unit and Digital Signal Processor (DSP). Initial prototype and test of the AFE used a commercial Bergoz board customized for 650MHz. Subsequently, the AFE was modified at TRIUMF for higher gain, and the boards manufactured locally.

The view screens are ideal for commissioning, but too fragile for c.w. beam operation. At full power, a Fast Wire Scanner that travels at 3 m/s and intercepts the beam for less than a millisecond must be used. The challenge is to accelerate to that speed while the scanner only travels a few cm, and then returns to rest. A rotary motor turns a drum with a helical slot machined into its surface. A follower rides in the slot and pushes the wire holder fork through the beam. The motion is transferred from the air side to the beam line vacuum via bellows. A first prototype was built and bench tested (including vibration studies) in 2013; it ran consistently at 3 m/s after improvements were applied. The second prototype focuses on providing an increased stroke, more compact dimensions, a stiffer frame, and improved wire fork design, and safety features to protect the scanner were added. The prototype and one production unit were installed in 2014; and another will be added in 2015.

4.3.17 Vacuum Equipment

The electron beam travels in vacuum; if it passed through air, the majority of the beam would be scattered out of the beam pipe in a few meters of length. The e-linac has a challenging vacuum specification: 10^{-9} Torr in ELBT/D, 10^{-8} Torr through the linacs, and 10^{-7} Torr in the high-energy beam lines. These are ultra-high vacuum (UHV) conditions that minimize particulates contamination and migration to the SRF cavities, and minimize electron scattering on residual gas molecules. The cryomodule insulating and coupler vacuums are 10^{-6} Torr. Because of the ionizing radiation present during beam operation, all-metal seals are used throughout. The e-linac and beam lines are divided into a dozen vacuum regions that are pumped out separately. The beam line volumes through the linacs are separated by RF-screened, all metal electro-pneumatic gate valves. The vacuum volumes are evacuated from atmospheric pressure to high vacuum level with turbo-molecular pumps, which are then isolated via gate valves, and the pressure is further lowered by ion pumps.

Beam line stands innovations were not the only contributors to the rapidity of installation and readiness. A cleaning regime was introduced where all beam tube sections (BTS) and diagnostic boxes are UHV cleaned. Boxes and their diagnostics are then assembled and stored under clean room conditions. So carefully were the UHV conditions maintained that no (lengthy) in situ baking was required. All of the BTS were welded in the TRIUMF Machine Shop.

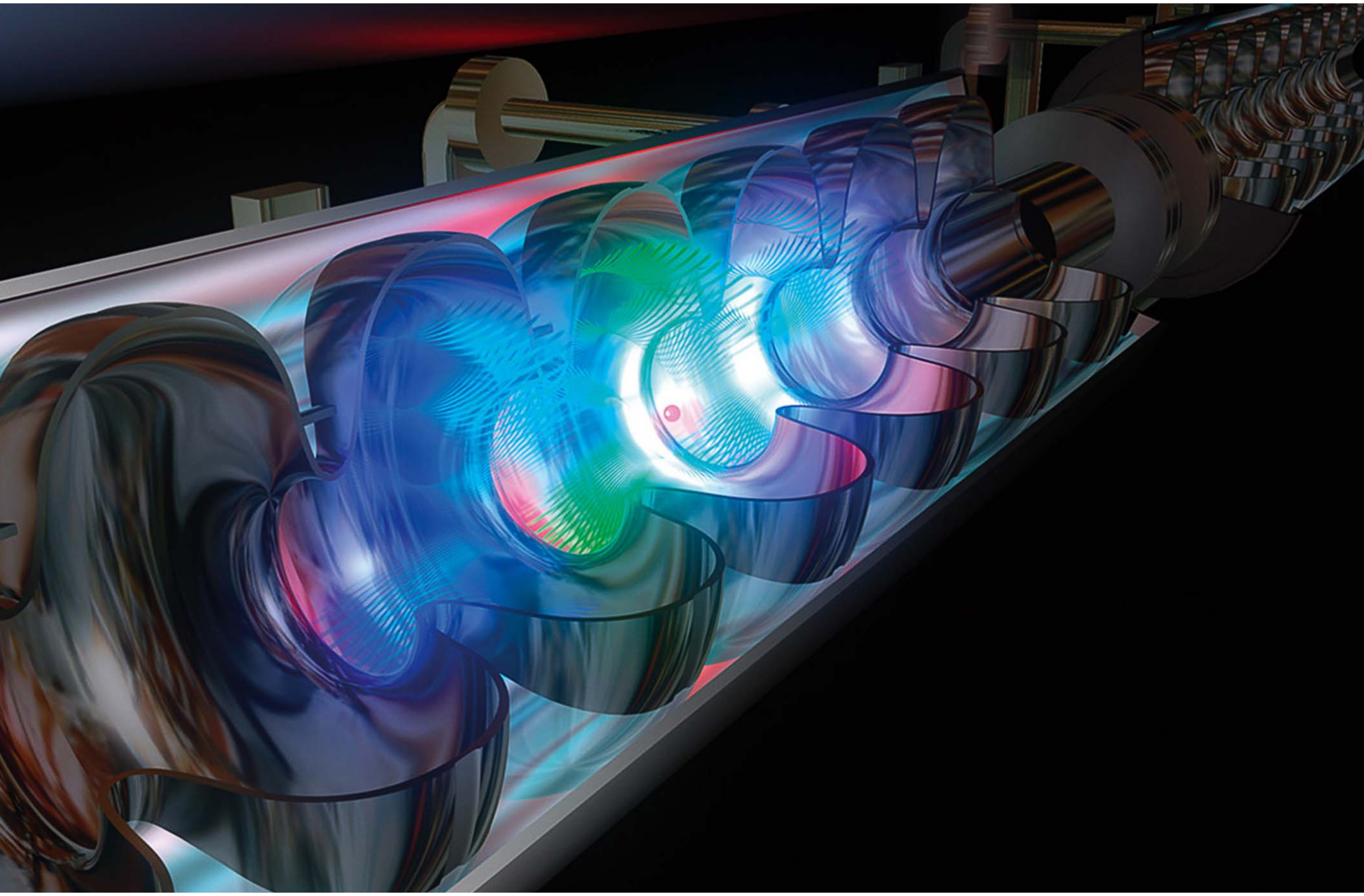
4.3.18 e-linac Beam Demonstration

Room 103-A, in proximity to the cyclotron Main Control Room (MCR) was chosen as the location of the e-linac Control Room (ELCR), for e-linac commissioning purposes, in July 2013. Requirements for the consoles layouts were developed in a workshop in January 2014. Refurbishment of the space took place in March, followed by installation of consoles in April, and integration with EPICS in May. The consoles for the Personnel Radiation Safety system were also installed in May. The e-linac commissioning team took over the ELCR in May and began to re-commission the e-gun and ELBT/D.

The final phase of the e-linac installations and pre-commissioning was fast paced and exhilarating. The 10 MeV injector was moved from the ISAC test stand to the e-hall in May, 2014, and injector services including cryo and RF were connected by June 1st. The 10 MeV medium energy beam transport was installed in June, and the 30 MeV momentum analysis beam line in July. The first accelerated beam, 5.5 MeV from EINJ, was celebrated on July 19.

The transport to the e-hall beam dump and the periodic section in the ARIEL tunnel were both installed in September. The Injector Cryomodule achieved 12 MeV acceleration September 23rd. The accelerator cryomodule, containing one SRF cavity, arrived in the e-hall August 29th. Immediately following, the EACA 4K LHe distribution and 2K SA return and the EACA RF waveguides were connected.

The EACA 4K cool down started September 7th, and the RF input couplers were conditioned to 10 kW level. The combination of EINJ and EACA cryomodules achieved 23 MeV on October 1st, delivered to the Faraday cup downstream of the EABD beam energy analyzer magnet.



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