ARIEL SUPERCONDUCTING ELECTRON LINAC

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Abstract

The TRIUMF Advanced Rare Isotope Laboratory (ARIEL) is funded since 2010 June by federal and BC Provincial governments. In collaboration with the University of Victoria, TRIUMF is proceeding with construction of a new target building, connecting tunnel, rehabilitation of an existing vault to contain the electron linear accelerator, and a cryogenic compressor building. TRIUMF starts construction of a 300 keV thermionic gun, and 10 MeV Injector cryomodule (EINJ) in 2012; the designs being complete. The 25 MeV Accelerator Cryomodule (EACA) follows in autumn 2013. TRIUMF is embarking on major equipment purchases and has signed contracts for 4K cryogenic plant and four sub-atmospheric pumps, a 290 kW c.w. klystron and high-voltage power supply, 80 quadrupole magnets, EINJ tank and lid, and four 1.3 GHz niobium 9-cell cavities from a local Canadian supplier. The low energy beam transport and beam diagnotics are being installed at the ISAC-II/VECC test facility. Procurement is anticipated October 2012 for the liquid He distribution system.

CONVENTIONAL INFRASTRUCTURE

The ARIEL project is described in Refs. [1,4]. The conventional infrastructure consists of four contracts: the main ARIEL construction, demolition and excavation, and the Stores and Badge buildings replacements. The latter are necessitated by site congestion. The new Compressor Building (CB), for gaseous helium management, forms part of the ARIEL package. In addition there are major renovations that will transform the former Proton Hall to the Electron Hall (e-hall).

Chernoff-Thompson Architects led a successful bid for the overall architecture and engineering contract, awarded October 2010. The Stores and Badge building construction is complete and occupancy was taken Sept 2011 and Dec 2011, respectively.

The demolition and excavation work started October 2011, and completed April 2012. The ARIEL main construction package was awarded Feb 2012. There is substantial completion of the tunnel and B2 level of the actinide target preparation labs, target hall and Rare Isotope Beams annexe. The annexe will contain mass separators and front-end accelerators. The CB is well advanced: roofing and envelope cladding, mechanical and electrical rough-in, are all proceeding on-track for occupancy in December 2012.

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The e-hall was emptied of legacy proton spectrometers in March 2012. The e-hall shielding, south wall upgrade and new north wall (that will protect e-hall from the future BL4N proton beam), is complete. The 10T full-coverage crane, and egress stairway are installed. Sealing of the concrete roof beams is pending final shield block moves. E-hall occupancy is anticipated October 2012.

Figure 1: ARIEL construction site, view north.

To accommodate the power requirements of e-linac systems a new 12.5 kV, 5 MW switchgear will be installed atop the e-hall roof. The gear will be close to the klystron power supplies and other local loads including a 0.5 MW emergency power bus. Further, the gear will feed north to the ARIEL building (2 MW) and south to the He CB (1 MW) housing the compressors and SA pumps.

The contract was awarded to Siemens Electric Canada April 2012. Fabrication is complete, and factory tests satisfactory. Delivery and installation will occur Sept-December, followed by connection to the TRIUMF grid, commissioning and energization.

ELECTRON GUN

The thermionic gun provides 300 keV kinetic energy electron bunches with charge up to 16 pC at a repetition frequency of 650 MHz. Aspects of the gun design were reported [2] previously. The main components are a gridded gun in a 2 bar SF6 filled vessel, and in-air HV power supply. Unique features of the gun are its inverted cathode/anode geometry to reduce dark current, and transmission of RF modulation via a dielectric (ceramic) waveguide and chokes through the SF6. The latter obviates the need for an HV platform inside the vessel to carry the RF transmitter, and results in a significantly smaller/simpler vessel. The modulation is applied to a CPI Y-845 gridded dispenser cathode via a stepped

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coaxial line impedance matching section from the RF-collecting choke. The gun bias and heater power are applied through an isolation transformer.

The grid biasing and modulation is tested on a 100 kV prototype source; a conductance angle ±16° at 650 MHz is inferred from the transconductance. The same source confirmed the beam intensity can be varied by applying a macro pulse structure (over the RF) with a variable duty factor from 99.9% down to 0.1%; the lowest value is essential for intercepting profile monitors. The RF waveguide was subject to bench testing on scale models and extensive simulation and optimization with HFSS, and has been ordered from Kyocera. The gun electrodes, the vessel internal corona domes and shroud, were subject to extensive 3D electrostatic modelling and optimization. The electrodes are fabricated, ready for polishing. The gun ceramic, anode-tube internal steering coil, gun solenoid, isolation transformer, conditioning resistors and 350kV Glassman HV power supply are all delivered. Detailing of the gun support struts, HV shroud SF6 vessel is complete; and will be fabricated in autumn 2012, and components assembly and integration follow thereafter.

INJECTOR TEST FACILITY

The VLBT test facility at ISAC-II, under collaboration between TRIUMF and VECC of Kolkata, India, provides an ideal proving ground for e-linac design and operation strategies. It prototypes the injector up to the exit of the cryomodule with enhanced diagnostic capability for benchmarking the performance of the gun, various diagnostic devices and procedures, and demonstrating sustained operation at the design parameters. Refs. [8,9] detail recent beam dynamics simulations and beam tests.

The extant part of the ELBT, Fig. 2, comprises the sequence: box DB1A after 1st solenoid, DB1B after buncher cavity, DB3 after 3rd solenoid, all in the mainline; and MB0 dipole, RF deflector cavity, DB0 in the analyzer stub. Button BPMs are installed between the first and second solenoids. View screens VS1A, VS1B, VS3 are installed and tested at each of the diagnostic boxes (DB). An Allison type emittance scanner [3], a wideband capacitive pickup (a.k.a non-intercepting monitor, NIM) and fast Faraday cup are moveable.

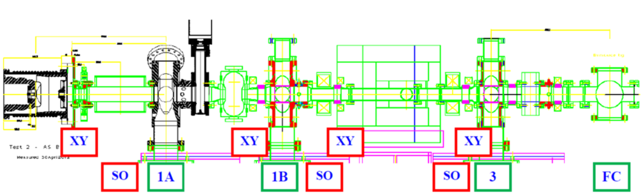

Figure 2: ELBT mainline major components.

Do date there have been two rounds of beam tests: phase (i) to DB1B; and phase (ii) transport to DB3 and DB0 is underway. In the intervening period, a crane was installed for shielding block lifts and moves; and shielding (for an eventual 25 kW beam test) is configured.

The outcome of the phase-one test: (i) The solenoid and correctors successfully controlled beam trajectory and shape as designed. (ii) Low level control of buncher cavity, and phase lock to the gun grid, was demonstrated. (iii) The beam horizontal emittance was measured directly with the Allison scanner, and indirectly with scintillator screen and solenoid scan. Both methods confirmed the Gaussian distribution from the gun. (iv) BPM, Faraday cups, slit scanner, chromox and YAG scintillator screens, capacitive pickup, PMT based loss monitor, were tested [5] and areas for improvement identified. The time structure of the electron source was measured with the NIM. The measured bunch length of 200 ps agrees with beam dynamics simulations.

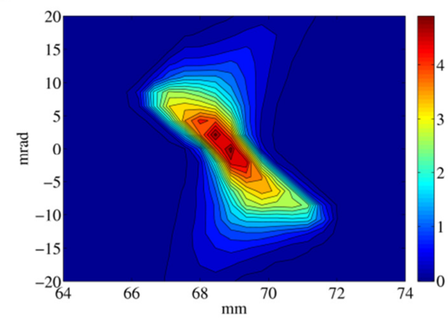

Figure 3: Phase space as mapped by the Allison emittance scanner, for a 60 keV, 10 mA peak electron beam. The normalized r.m.s. emittance is 4.6 microns.

For the phase-two test under way, two solenoids and diagnostic boxes were added; and the Allison rig and FC reinstalled after DB3. The analyzer magnet MB0 and deflecting cavity are now installed for measurement of longitudinal parameters. The 1.3 GHz deflector LLRF is synchronized with the gun modulation; and electron beam deflections are recently demonstrated in a RF phase scan.

BEAM DIAGNOSTICS

Status of diagnostic devices is reported in Refs. [5,10]. Initial beam threading will be with view screens, followed by orbit correction with 4-button type BPMs each measuring in two planes H &V. Sixty button electrodes were delivered by Kyocera Corp; all were inspected and verified to be within tolerance of 0.05 mm. The position sensitivity is 1.4dB/mm between opposite pickups. The signal power of -27dBm was measured at VLBT with the beam current of 10 mA (peak), and agrees well with the expected value of -30dBm. About 140 more buttons are still to be procured and tested. The prototype of the stripline BPM is being manufactured for test at VLBT.

The BPM electronics design is complete; a prototype unit has been successfully tested in the laboratory. This consists of a commercially available, *Bergoz*, analog front-end (AFE) customized for 650 MHz and a TRIUMF developed intermediate frequency (IF) processing unit based on a 125 MHz 14-bit ADC and Spartan-6 FPGA. The output bandwidth is around 1 MHz.

Preliminary design of the fast wire scanner, speed goal of 3 m/s, was completed. The prototype unit is presently being fabricated at TRIUMF for test at VLBT.

A *Bergoz* DC current transformer is housed in a magnetic and vibration shielded and temperature stabilized enclosure. Initial bench tests reveal a drift of ~ 40 uA over 48 hours; the cause is being investigated.

BEAM LINES

The beam line sections are: ELBT, the 300 keV transport; EMBT 5-10 MeV transfer between EINJ and EACA; EABT 25 MeV transfer to future EACB; EHAT 25-50 MeV transport downstream of the cryomodules to a switching magnet; EHDT leading to a 100 kW beam dump; and EHBT 25-75 MeV transport to the photo-fission targets. The EMBT layout anticipates a "Merger" section in a future scenario that will merge the injector beam with a recirculating beam to provide RLA and/or ERL functionality. The EHBT, in the tunnel, consists mainly of a periodic section consisting of six 90^o FODO cells, each 4m in length. The EMBT contains a 36^o bend section, the EHDT, a 90-degree section formed of four bends, and the EHBT two doglegs and bend sections to the west and east targets. All insertions are achromatic.

Quadrupoles

From the Injector linac onward, the most convenient focusing device is the magnetic quadrupole. However, at lowest envisioned beam energy of 5 MeV, the focal power required is rather small. This forces us to shortest possible quadrupoles, else the fields are too low compared with expected remanent field of low-carbon steel. A theoretical study was made to derive the optimal pole shape for short quadrupoles whose length is comparable to or smaller than the aperture. Conventional 2-D treatment and fabrication practice, assuming sufficiently large pole length, break down in such cases. We have derived [6] analytically a new 3D shape, and demonstrated that it yields smaller aberrations. For short quads it is well approximated by a simple spherical pole provided the sphere radius is 1.65 times the quadrupole aperture radius.

The beamlines in the e-hall adopt 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. The weak quads are also used for the 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 will be achieved with a more conventional strong quadrupole design with rectangular cross-section poles and hyperbolic faces. The strong quads will be water-cooled, the weaker ones air-cooled, and the medium ones indirectly cooled. All have aperture diameter equal to 52.0 mm. In total, there are 80 quadrupoles; the contract for their manufacture was awarded to Buckley Systems Ltd., New Zealand, August 2012 with delivery scheduled January to March 2013.

Dipoles

The different beam lines contain a total of fifteen dipoles, which have been divided into four groups, depending on their required integrated field and field quality. for the purpose of design and procurement. Longitudinal space constraints in the beamline layout, particularly in “Merger” and doglegs, lead us to design the magnets as small as possible. Thus, many of these dipoles are short compared with their aperture leading to low strength because the field does not “plateau” inside the magnet. Proximity of other magnets implies also the use of field clamps to contain the field fall-off. These features combine to make essential their modeling with a 3D finite element code such as OPERA. Moreover, one must ensure that the second order aberrations (sextapole) will causes negligible emittance growth (<0.01% per dipole). To study the non-linear optical properties of our models, we used the differential algebra and particle tracking code COSY INFINITY with field maps imported from OPERA. Satisfactory pole, field clamp and yoke geometries were obtained (0.1% fringe field at 10cm from magnet edge) and are being used as the basis for tender. The first dipole, the EMBT momentum analyzer, contract was awarded to Alpha Magnetic Inc. August 2012.

Vacuum

ARIEL e-linac has 13 vacuum volumes with requirements ranging from 10^{-10} Torr in the gun, 10^{-9} in ELBT, 10^{-8} in EMBT and EABT, to 10^{-7} in EHAT, EHDT and EHBT when the beam is present. The limits arising from residual gas (Rutherford) scattering and ion neutralization are an order of magnitude relaxed compared with these values. The pipes inside the cryomodules will naturally cryopump to 10^{-11}Torr, and the issue there is of cleanliness and particulates free. The insulating and coupler vacuums are 10^{-6} Torr. The beam line volumes 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 also used during the in-situ bake out. After the bake out is completed, the turbo-pumps are isolated via gate valves and the pressure is further lowered by ion pumps. The ion gauges are used only during the initial evacuation and bake out. Once the ion pumps are turned on, the ion gauges are turned off. The pressure is observed on the cryo-pumps controllers.

CRYOMODULES

Due to heavy beam loading, five 9-cell cavities at 100kW/cavity are required to reach the 0.5 MW beam power. The injector cryomodule (EINJ) contains a single 9-cell cavity, and is designed [11] and constructed in collaboration with VECC. The accelerator cryomodules (EACA,B) each house two 9-cell cavities.

The cryomodule design utilizes a box vessel with a top-loading cold mass. A 4 K phase separator, 4K/2K heat exchanger and Joule-Thomson valve are installed within each module to produce 2 K liquid. The cold mass is suspended from the lid with mounting posts, struts and strong back; and is surrounded by a LN2-cooled copper box for thermal isolation. A 1 mm warm mu-metal shield is fastened to the inside of the vacuum vessel. The cold mass consists of the cavity hermetic unit, a cold mu metal

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layer and the tuner. The tuner cold part is the Jefferson-lab style scissor type; and is followed by a long actuator and warm ISAC-II style rotary servo motor mounted on the lid. The hermetic unit includes the cavity(s), power couplers, RF pick-up(s), the warm-cold transitions with HOM damping material and warm isolation valves. A carbon fibre reinforced silicon carbide material CESIC is chosen for the damping material with measured conductance at 1.3 GHz and 80 K of 2200 Si/m.

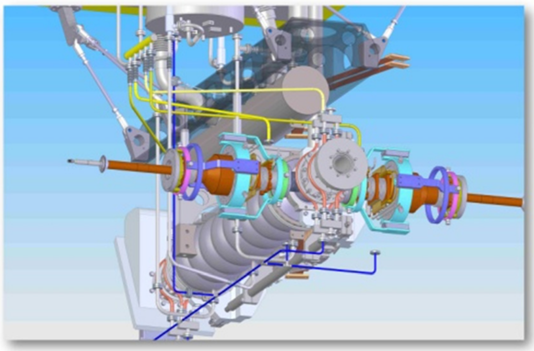

Figure 4: Injector cryomodule internal assembly.

The e-linac cryogenic distribution is based on a parallel feed of atmospheric LHe from a main trunk to each cryomodule. The LHe is drawn from a main dewar supplied from the 4 K cold box. A LHe reservoir in each cryomodule acts as a phase separator. Cold gas returns in parallel back to a common return trunk and is delivered back to the cold box where it represents a refrigerator load. 2 K liquid is produced in each cryomodule by passing the 4 K liquid through a heat exchanger in counter flow with the returning exhaust gas from the 2 K phase separator and expanding the gas to 31 mbar through a JT expansion valve. The header pipe above the cavity string acts as a 2 K phase separator. The cold helium gas passes through 4K/2K heat exchanger; and then, after warming up to ambient temperature, reaches the warm sub-atmospheric pumping system. This fraction constitutes a liquefaction load to the He cryoplant. A siphon circuit from the 4 K reservoir is used to cool the 4 K intercepts, with vapour return back to the reservoir. Initial cool down is done by delivering 4 K liquid from the 4 K phase separator to the bottom of the cold mass through a dedicated cool down valve.

The 4K/2K cryo-insert is being built and tested as a separate package. The insert includes a 4 K phase separator, 4K/2K heat exchanger, JT expansion valve, 4 K cool down valve plus siphon circuit for intercept cooling. The prototype heat exchanger is from DATE, France, with an estimated capacity of 2.5 gm/sec. All components plus fabricated parts are now being assembled for cold test in October 2012. The lid, tank, support posts, strong back and cavity support detailing is complete. LN2 shield detailing is in progress. Manufacture of the tank and lid was awarded August 2012.

SRF Cavities

The nine-cell 1.3 GHz elliptical cavity 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 break up (BBU) criterion establishes a limit of $R_d/Q*Q_L < 1e7$ Ohm. End group beam tubes of inner radius 48 mm and 39 are used for the power coupler and RF pick-up end, respectively.

The first of four niobium cavities is presently being fabricated at PAVAC Industries of Richmond Canada. A 7-cell cavity in copper was completed Feb 2012 to test all fabrication procedures and manufacturing jigs; lessons learnt are now applied to the Nb cavity production to improve quality assurance.

Processes have been developed at PAVAC that will expedite the fabrication of future cells and cavities – in terms of reproducibility, true to shape and frequency. A main study was on forming. The original dies produced cells too short at the equator - causing material stress and some multipacting. PAVAC developed a forming tool with male die against a plastic that becomes almost fluid at high pressure and “hydroforms” - all cells formed since then are exceptionally reproducible. Next the fixturing during welding of half cells became an issue. Our equator weld set-up initially was a butt weld of two identical ½ cells. During forming and machining, and due to grain structure, the niobium ½ cells can go slightly out of a true circle. The question became how to hold them nicely true to a circle while not touching the newly etched weld zone. A self-fixturing solution is adopted: an interleaving feature is machined into the equator of unique male and female half-cells so they fit together and ‘self-fixture’ during welding. Two Nb cells have been prepared in this way, and frequency is very repeatable. Success at equator suggested we prepare the iris in the same way to better control weld and reduce centroid drift over multi-cell length. All cell parts are coming out very true and the self fixturing is better suited for production. The near term milestone is to have a complete Nb 9-cell cavity in November 2012.

CRYOGENIC EQUIPMENT

Since the project start, June 2010, the e-linac cryogenic system 13], Fig. 5, has moved from conceptual design phase to the engineering design and procurement stages. Conceptual design of e-linac cryomodules and cryogenic system went through external reviews Sept 2010 and March 2011, respectively. In parallel with SRF cavity and injector cryomodule engineering design, the helium refrigerator-liquefier specification was produced and tendered June 2011. The contract for supplying He cryoplant consisting of HELIAL 2000 cold-box, main and recovery compressors with oil removal and gas management systems (OR/GMS), and multi-component purity analyzer was awarded to Air Liquide Advanced Technologies (France). This is class 700 W cooling power at 4.6 K machine with maximum liquefaction rate of 288 l/h. The final design was approved June 2012, and the cryoplant has moved to the production phase; concluding in delivery the second quarter of 2013. The contract for helium gas storage was awarded May 2012 with delivery scheduled January 2013.

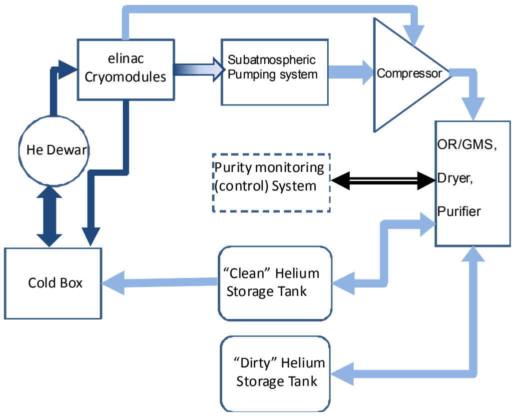

Figure 5: e-linac cryogenic system overview.

The cold-box with 1000 litre liquid helium storage dewar are positioned in the immediate vicinity of the e-linac cryomodules in order to minimize losses associated with LHe transfer. The warm part of installation, including two Kaeser He compressors, OR/GMS, and sub-atmospheric helium pumps, will be located outside the e-hall in the separate compressor building.

Recent activity has focused on design and tender of the liquid helium distribution system, and procurement of SA pump units. Further development is related to SA helium and LN2 system design and manufacturing, installation of services and auxiliaries, instrumentation.

The sub-atmospheric units will pump continuously on He gas to maintain a suction pressure within 24-28 mbar measured at the pumps inlet. The exhausting clean He gas is sent to a helium compressor at 1.05–1.1 Bara. A modular design is adopted with 4 units for EINJ and EACA having a combined through-put totalling 5.6 gm/sec, and 6 units totalling 9.3 gm/sec after the addition of EACB. The contract for supply of four sub-atmospheric helium pumps, type DS3010-B, was awarded to Busch Vacuum Technics Inc. in August 2012; and delivery is scheduled first quarter 2013.

RADIO-FREQUENCY EQUIPMENT

The e-linac 1.3 GHz high power RF system will be installed in stages: in the first, to be completed in 2014, the injector cryomodule (EINJ) is fed by a 30 kW c.w. Inductive Output Tube (IOT); and the first accelerator cryomodule (EACA), will be powered by a high power c.w. klystron and power divider. At a later stage, EINJ is upgraded to 100 kW, and a second accelerator cryomodule (EACB) is added along with another klystron and power supply. EINJ and EACA contain one, and two, SRF cavities respectively. Each cavity is equipped with two 50 kW c.w. input couplers – manufactured by CPI following the Cornell (ERL injector prototype) design. Ref. [12] details the coupler conditioning station.

The IOT with solenoid and trolley is purchased from CPI, USA, and its HV power supply and drive amplifier from Bruker BioSpin, France. The system is installed and tested to the maximum rated output power of 30 kW on a water cooled load, and can now be run routinely.

The c.w. klystron is specified with a saturated power of 290 kW and usable linear range (incremental gain of 0.5 dB/dB) up to 270 kW, leaving plenty of margin for transmission loss to the 200 kW nominal rated EACA. After a tender process, coordinated as a joint venture with Helmholtz Zentrum Berlin, orders were placed with CPI, USA: one for TRIUMF and 3 units for HZB. The klystron is a factory-tuned multi-cavity, high efficiency, high gain, broadband, water cooled tube. The final design was complete August 2012. The klystron is to be factory tested January 2013 prior to shipment to TRIUMF.

The contract for the klystron high voltage power supply, rated at 65 kV 8.65 A, and focus, filament and vacuum ion pump power supplies, and trunk RF distribution system including all control, interlocks and protection and integration of the klystron was awarded to Thomson Broadcast June 2012. The power supply is based on a voltage controlled power module type *PM-14-10-VR-1* derived from the modulator PSM12-2400 for DESY. A description of this technology and its advantages is provided in Ref. [7]. The 300 kW c.w. circulator and loads are subcontracted to AFT Microwave.

CONCLUSION

The ARIEL e-linac project has witnessed outstanding progress across all areas. The building's construction is on schedule for completion 2013 April. Beamlines, cryogenic and high-power RF equipment design and procurements are on schedule. The facility two key milestones, the Injector Cryomodule beam test in 2013 March and Accelerator Cryomodule initial beam test in 2014 June, are on track.

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