ELECTRON LINAC PHOTO-FISSION DRIVER FOR THE RARE ISOTOPE PROGRAM AT TRIUMF*

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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 will follow in 2013. TRIUMF is embarking on major equipment purchases and has signed contracts for 4K cryogenic plant, a 290kW c.w. klystron, and four 1.3 GHz niobium 9-cell cavities from a local Canadian supplier. Moreover, the low energy beam transport is under construction; and detailing of the intra-cryomodule beam transport has begun. Procurements are anticipated in mid 2012 for (i) the entire facility quadrupole magnets, and (ii) the klystron's 600kW HV power supply.

CONVENTIONAL INFRASTRUCTURE

The ARIEL project is described in Reference[1].The conventional infrastructure consists of four main contracts: the main ARIEL construction, demolition and excavation, the Stores building, and Badge building. The latter are necessitated by the ARIEL 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 construction is complete, and occupancy was achieved Sept 2011. The Badge building construction is complete, and occupancy taken Dec 2011.

The demolition and excavation work started October 2011, and completed April 2012. The ARIEL main construction package was awarded Feb 2012; the foundations are well advanced. The CB foundations and services roughing-in are complete. In the E-hall, the south wall shielding upgrade is complete, and the north wall shielding (that will protect the E-hall from the future BL4N proton beam) is near complete. Services and a 10T crane will be installed before the roof beams are sealed and e-hall occupancy taken in October 2012.

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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, in-air HV power supply, and RF modulation feed through. 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 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 100kV 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 cycle from 99.9% down to 0.1%. The lowest duty factor 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. The SF6 vessel will be fabricated in the fall 2012, and components assembly and integration follow thereafter.

Figure 1: ARIEL construction site, view north.

INJECTOR TEST FACILITY

The Injector test facility, under collaboration between TRIUMF and VECC of Kolkata, India, provides an ideal proving ground for e-linac design and operation strategies. It duplicates the e-linac up to the exit of the injector cryo-module with enhanced diagnostic capability for benchmarking the performance of the gun, various diagnostic devices and procedures, and demonstrating sustained operation under the parameter envelope as designed. Commissioning this facility began Nov 2011. Stable beam delivery from the gun to various diagnostic devices over 1.2 m portion of beam line was proven. The following summarizes 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 RF, as well as phase lock to the gun grid, was demonstrated. (iii) The beam horizontal emittance was measured directly with an Allison type scanner, and indirectly with scintillator screen and solenoid scan. Both methods confirmed the Gaussian distribution from the gun, and will be used to benchmark the simulation model of the gun currently being refined. (iv) BPM, Faraday cups, slit scanner, two types of scintillator screens[3] (chromox and YAG), capacitive pickup, PMT based loss monitor, and Allison scanner were tested[4] and areas for improvement identified. Two additional solenoids and diagnostic boxes have been installed for the phase-two test under way. An RF deflecting cavity will be installed for measurement of longitudinal parameters in the phase-three test.

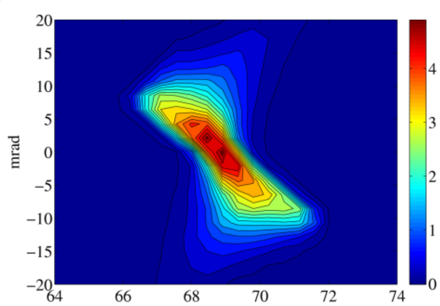

Figure 2: Phase space as mapped by the Allison emittance scanner, for a 60 keV, 10 mA peak electron beam. The normalized r.m.s. emittance is 4.6 microns.

BEAM LINES

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. Thus, a theoretical study was undertaken to arrive at optimal pole shape for short quadrupoles whose length is comparable to or shorter than the aperture. Conventional 2-D treatment and fabrication practice assuming sufficiently large pole length break down in such cases. We have derived[4] analytically a new 3D shape, and demonstrated that this shape yields smaller aberrations. Though the exact shape is impractical, for short quads it can be approximated with a simple spherical pole provided the sphere radius is precisely 1.65 times the quadrupole aperture radius.

The beam transport sections are (1) the EMBT "Merger" section, so named because in Phase 2B, it will merge the injector beam with the recirculating beam from the ERL; (2) the EHDT section to a low power beam dump, and (3) the EHBT which transports to the photofission target. The EHBT 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, and the EHBT two doglegs and a bend section to target. All insertions are achromatic.

At highest envisioned energy of 75 MeV, the shortest required focal length is 0.24 m in the dogleg section. The required integrated gradient is 1.05 T. This is easily achieved with the short quadrupoles of aspect ratio 1. There will thus be only one pole-shape design; the stronger quads will be water-cooled and the weaker ones air-cooled. In total, there are 77 quadrupoles. All have aperture diameter and yoke length equal to 52.0mm.

CRYOMODULES AND CAVITIES

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 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 1mm 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 layer and the tuner. The tuner cold part is the J-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 1.3GHz and 80K of 2200Si/m.

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 30 mbar through

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a JT expansion valve. The header pipe above the cavity string acts as a 2 K phase separator, and delivers cold gas back through the 4K/2K heat exchanger to the sub-atmospheric pumping system as a liquid load. 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 4K liquid from the 4K phase separator to the bottom of the cold mass through a dedicated cool down valve.

The nine-cell 1.3GHz 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 48mm and 39 are used for the power coupler and RF pick-up end, respectively.

The 4K/2K cryo-insert is being built and tested as a separate package. The size of the unit is chosen to be compatible with pre-testing in an existing cryostat, at least in the prototyping phase. 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 with an estimated capacity of 2.5 gm/sec. All components plus fabricated parts are now being assembled for cold test in July 2012. The lid, support posts, strong back and cavity support detailing is complete. Tank and LN2 shield detailing are in progress. The niobium cavity is being fabricated at PAVAC Industries of Richmond Canada. A 7-cell cavity in copper was completed to test all fabrication procedures and manufacturing jigs.

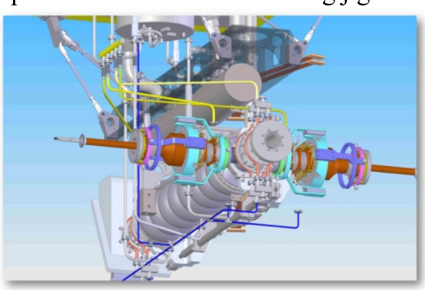

Figure 3: Injector cryomodule internal assembly.

CRYOGENIC EQUIPMENT

Since the project start, June 2010, the e-linac cryogenic system 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 design 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 700W cooling power at 4.6K machine with maximum liquefaction rate of 288 l/h. The cryoplant final design was recently approved, and will move to production; concluding in delivery the second quarter of 2013. The contract for helium gas storage was awarded with delivery scheduled Jan 2013.

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 will be located outside the e-hall in separate compressor building.

Activity is presently, focused on design of the liquid helium distribution system, and imminent tendering of sub-atmospheric helium pumps. Further development is related to helium sub-atmospheric and LN2 system design and manufacturing, installation of services and auxiliaries, instrumentation.

RADIO-FREQUENCY EQUIPMENT

The e-linac 1.3GHz 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. Each cavity is equipped with two 50 kW c.w. couplers.

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 200kW 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 review is scheduled June 2012. The klystron is expected to be factory tested in Nov 2012 prior to shipment to TRIUMF.

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 tendered March 2012, and a vendor will soon be selected.

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