ARIEL e-LINAC: Commissioning and Development

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Abstract. A superconducting electron Linac (e-Linac) will be a part of the ARIEL facility for the production of radioactive ion beams (RIB) at TRIUMF. The e-Linac will consist of five 1.3GHz 9-cell cavities in three cryomodules delivering a 50MeV 10mA beam. The baseline operation will be single pass but a re-circulating ring is planned to allow either energy boost or energy recovery operation. The first stage of the accelerator which consists of two cryomodules has been successfully commissioned in 2014. The paper will discuss the superconducting radio-frequency (SRF) challenges of the accelerator. Cavities, cryomodules and RF system design, preparation, and performance will be presented.

1. Introduction

The ARIEL project [1] will allow an increase in the radioactive ion beam (RIB) hours with the addition of a new electron linac driver of 50 MeV (0.5 MW), a new proton line from the 500MeV cyclotron and new production target stations.

Figure 1. The stages of the e-Linac project.

Accelerated electrons can be used to generate RIBs via the photo-fission process [2]. The electrons are stopped in a converter to generate bremsstrahlung photons for fission in actinide target material. An electron beam intensity and energy of 10 mA and 50 MeV is required for a fission rate of $10^{13}$ fissions/sec.

The electron linac is housed in a pre-existing shielded experimental hall adjacent to the TRIUMF 500 MeV cyclotron that has been re-purposed as an accelerator vault. The e-linac is being installed in a phased way with stages shown schematically in figure 1.

A first phase consisting of a 300 kV 16 mA electron gun, an injector cryomodule, ICM, containing one 1.3 GHz nine-cell cavity and an accelerating cryomodule, ACM1, that now contains one 1.3 GHz

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nine-cell cavity (and eventually two cavities) plus associated beamlines is now installed and is being commissioned. This first phase is designed to accelerate cw up to 10 mA of electrons at 30 MeV. The initial beam dumps and production targets will only be compatible with 100 kW operation. A second phase, dependent on funding, will see the addition of a second accelerating module, ACM2, and a ramp up in beam intensity to the full capability of 50 MeV 0.5 MW.

2. ARIEL e-Linac Design

An RF frequency for accelerating cavities of 1.3 GHz is chosen to take advantage of the considerable global design effort at this frequency both for pulsed machines (ILC) but also for CW ERL applications (KEK, Cornell, BerlinPro). The linac architecture was determined by the final CW beam power of 500 kW (10 mA/50 MeV electron beam) and the available commercial CW RF couplers at 1.3 GHz. The CPI produced coupler, VWP3032, developed with Cornell for the ERL injector cryomodule is capable of operation up to 75 kW CW. In order to provide reliable operation it was decided to set a safety factor for power of 1.5 that is 50 kW CW RF power per coupler. To deliver 500 kW of RF power to the beam requires 10 such couplers. The cavity design allows two couplers per cavity arranged symmetrically around one end delivering a total of 100 kW of beam loaded power. This sets the number of cavities at 5 with a maximum gradient per cavity of 10 MV/m. It is our intention to install a future ERL ring with injection and extraction between 5-10 MeV and so a single cavity off-line injector cryomodule was chosen plus two 2-cavity accelerating modules. The electron hall is shown in figure 2 as it would appear at the end of Phase I.

![Figure 2](image.png)

Figure 2. The phase I configuration of the E-Linac

2.1. Electron Gun

The electron source [3] provides electron bunches with charge up to 15.4 pC at a repetition frequency of 650 MHz. The main components of the source are a gridded dispenser cathode in a SF6 filled vessel, and an in-air high voltage power supply. The beam is bunched by superimposing a RF modulation to overcome a DC suppression voltage on the grid.

2.2. Cavities

The cavity design parameters include f=1.3 GHz, L=1.038 m, R/Q=1000, Ea=10 MV/m [4]. For Qo=1x10^{10} the cavity power is P_{cav}=10 W at 2 K that sets the active load requirement for the cryogenics system. A rendering of the jacketed cavity is shown in figure 3.
The inner cells take their shape from the Tesla nine cell cavities but the end groups are modified to accept the two power couplers and to help push HOMs to dampers located on each end. On the power coupler end there is a stainless steel damping tube coaxial with the beam tube and extending into the beam pipe. On the opposite end of the cavity a coaxial CESIC tube is used [5]. Each tube is thermally anchored at 77 K and thermally isolated from the cavity by a thin walled stainless steel bellows. The dampers are sufficient to reduce the HOMs to meet the BBU criterion of \( R_d/Q\cdot Q_L < 10^7 \). The beam tube diameters on the coupler end and opposite end are 96 mm and 78 mm respectively. The vacuum jacket is made from Ti with a machined two convolution flexure on either end. A single 90 mm diameter chimney allows for large CW RF loads of up to 60 W per cavity assuming a conservative heat transfer of 1 W/cm².

2.3. Cryomodules

A rendering of the ACM module is presented in figure 4.

The cryomodule design has been reported elsewhere [6, 7]. In brief the module is a top-loading box-like structure with a stainless steel vacuum chamber. The cold mass is suspended from the lid and includes a stainless steel strongback, a 2 K phase separator pipe, cavity support posts and the cavity hermetic unit. The hermetic unit consists of the niobium cavities, the end assemblies, an inter-cavity transition (ICT) with a stainless steel HOM damper, the power couplers (FPC) and an rf pick-up. The end assemblies include the warm-cold transition (WCT), CESIC HOM damping tubes and beam-line isolation valves. Other features include a scissor jack tuner and warm motor, LN2 cooled thermal isolation box and two layers of mu metal and alignment monitoring via a WPM diagnostic system.

![Figure 3. The e-Linac nine cell cavity with jacket.](image)

![Figure 4. Accelerating cryomodule for ARIEL e-Linac](image)
2.4. Cryogenics System

The design of the cryomodules allows a simplified cryogenics system. A standard commercial 4 K cold box is employed delivering 4 K liquid to a supply dewar near atmosphere. The LHe in the dewar is pushed through the cold distribution with slight overpressure (1.3 Bar) and delivered to the cryomodule 4 K reservoir with parallel feed from a common distribution trunk and cold return back from each cryomodule to the exhaust side of the trunk. The distribution has a ‘keep cold’ return pipe that joins the each cryomodule has an associated variable LHe supply valve. The 4 K supply and return operates as a refrigerator load. The sub-atmospheric system is independent from the cold box and operates as a liquefaction load. Each cryomodule is pumped in parallel from a common pump line while a variable valve controls the pressure. A common pump line leads between the cryomodules and the sub-atmospheric pumps in a separate building. A common valve near the sub-atmospheric pumps optimizes the operating pressure at the pumps for a given mass-flow. The return 2 K exhaust is warmed passively in a counter flow heat exchanger by thermal exchange with the helium high pressure stream going to the cold box. A simplified schematic of the system is shown in figure 5.

![Figure 5](image-url)

**Figure 5.** A schematic of the e-Linac cryogenic system

2.5. RF System

The RF system includes one high power rf source for each cryomodule [8]. In Phase I each cryomodule is driven by a dedicated 290 kW CW 1.3 GHz klystron, CPI VKL7967A (figure 6).
Figure 6. The phase-I RF System: ACMuno is ACM1 with one cavity

For Phase II one of these klystrons will drive ACM2 while the ICM will be driven by a 150 kW power source to be determined. The ACM RF power feed is split to feed each of the cavities equally. A further splitting is required to feed each of the power couplers while phase shifters in each leg are used to achieve the proper phase conditions. One LLRF system is used for each cryomodule with a vector sum compensation of voltage and phase drifts in the ACM [9].

3. Status and Commissioning

The first stage of the accelerator has been built and commissioned at TRIUMF. The progress has been reported elsewhere [10-13].

3.1. Electron Gun

The system is installed and conditioned to 320 kV with beam extracted at 300 kV up to the full CW intensity of 10 mA. RF modulation of the grid voltage is demonstrated over a wide duty factor range from 0.01% to CW. The bunch length as measured with an RF deflecting cavity in the LEBT analyzing leg at a peak current of 1.75 mA and a grid bias voltage of Ub = -160 V is ±12.3° with an energy spread of ΔE = ±500 eV. Estimates based on the measured transconductance (g_{21} = 23 mA/V) result in a pulse length of φ = ±10°.

3.2. LEBT

The LEBT straight section contains three solenoids to provide transverse matching and transportation. A 1.3 GHz room temperature buncher provides longitudinal matching to the ICM. A diagnostic line includes a 90° bending spectrometer, diagnostic boxes and a 1.3 GHz TM011 mode RF deflector for bunch length measurements. In an initial configuration the LEBT allowed a full 3-D characterization of the beam phase spaces. The transverse emittance of the beam was measured with an Allison emittance scanner [10-12] for a peak current of 10 mA and a 1% duty factor to be ε_{rms,norm} = 7.5 μm. The longitudinal phase space was mapped into the transverse space using the dispersion in the analyzing magnet to map energy spread into the horizontal plane and the vertically deflecting RF device to map time spread into the vertical plane. The LEBT is now installed and commissioned [10-12].
3.3. Cryogenics

The ARIEL cryogenic system [14] includes an ALAT LL Cold Box and KAESER FSD571SFC main compressor with a mass flow rating of 112 g/s. In order to specify the required performance the estimated static loads from the distribution and the cryomodules were multiplied by 1.5 while the active load was doubled assuming that either the $Q_0$ would be lower by a factor of two or the gradient would be increased to 14 MV/m in some modes. This resulted in a mixed mode set point with a refrigeration load of 128 W and a liquefaction load of 220 l/hr (7.6 g/s). Considering these requirements a specification of a pure refrigeration performance of 600 W and a pure liquefaction performance of 280 l/h was defined. The final commissioning produced a pure refrigeration performance of 837 W and a pure liquefaction performance of 367 l/h comfortably above the criteria. More can be added as the 2 K production increases in Phase II.

3.4. RF System

Two CPI VKL7967A 290 kW CW 1.3 GHz klystrons and two 600 kW 65 kV klystron power supplies from AMPEGON are now installed [8]. Each klystron reached the goal specification at the factory. At TRIUMF RF tests were limited by the available power range of RF loads and RF circulators – one was operated to 250 kW CW and the other to 150 kW CW. Waveguide elements has been installed and tested [15]. The power couplers have been conditioned by two couplers at once at room temperature in a Power Coupler Test Station (PCTS) using a 30 kW IOT. Preparation procedure involved an extended bakeout (7 days) at 100°C with N2 flowing to cover the ceramic and RF surfaces. RF conditioning employed both TW (up to 18 kW CW) mode with RF waveguide dummy load and SW mode (up to 10 kW in 1 ms pulse and 1% of duty cycle) with adjustable short for ~5 days [16].

3.5. Cavities

The ARIEL cavities have been fabricated by PAVAC [17]. To date four cavities have been received. The cavities are tuned, degreased then given a 120 μm BCP before final tuning. After the initial cold test ARIEL1 and ARIEL2 were each degassed at FNAL at 800 C for four hours. Both cavities exhibit similar test results. The cavities reach, during vertical tests, the specified gradient of 10 MV/m but at a $Q_0$ of $6\times10^9$ [18]. Since the available cryogenic power is more than enough for Phase I it was decided to accept $Q_0>5\times10^9$ as a Phase I specification to allow moving forward with the cryo-engineering characterization. ARIEL3 is also jacketed and ready for installation in cryomodule. ARIEL4 cavity is ready for jacketing. Cavity jacketing is done at PAVAC. Due to problems with Ti-bellows from the sub-contractor PAVAC proposed to machine Ti flexures into the jacket. These work well with no significant increase to the cavity stiffness of 1800 N/mm.

3.6. Cryomodules

The cryomodule test strategy utilizes the ARIEL1 and ARIEL2 cavities to qualify the two cryomodule types. ARIEL1 is chosen for ICM production while ARIEL2 is chosen for ACM1 installation along with a ‘dummy’ cavity that occupies the second cavity space in the cryomodule and the RF System was adapted accordingly (Fig. 6). The ‘dummy’ cavity contains all the interfaces to the helium system so that all helium piping surrounding the dummy will be final. In addition the ‘dummy’ cavity is installed with a DC heater to replicate cavity active loads and WPM brackets to permit alignment studies. The one cavity ACM variant we term ‘ACMuno’. This configuration allows a full cryo-engineering characterization of the cryomodule. The ICM and ACM preparations each consist of the hermetic unit assembly in the clean room, top down assembly in the ISAC beam assembly area and installation in the vacuum tank. The ICM assembly was completed and full cold test was done in the ISAC-II clean room before installation in the e-hall. Due to the size of the ACM it was delivered direct to the e-hall after the top plate was installed and the warm couplers were added there. Both cryomodules are equipped with protection systems developed and fabricated at TRIUMF [19] for fast trip of RF drive in case of cavity quench and threshold signals for RF power, vacuum and temperature.
3.7. 23 MeV Beam Test

A ‘23 MeV Beam Test’ of the front end unit is a project milestone to validate cryogenics, HLRF, LLRF, e-Gun operation, LEBT, ICM, ACMuno engineering and overall synchronization [12].

| Parameter                        | Estimate | Measurement |
|----------------------------------|----------|-------------|
| 4 K static load without syphon   | 2 W      | 3 W         |
| 4 K static load with syphon      | 6 W      | 6.5 W       |
| 2 K static load                   | 5 W      | 5.5 W       |
| 77 K static load                  | 100 W    | <130 W      |

3.7.1. Cryogenics characterization.Cooldown to 4 K and production of 2 K was straightforward. The static heat loads are measured by observing the rate of falling LHe level after the supply valves are closed to the volume and noting the volume change of LHe per unit time and the heat of vaporization. The rate of 2 K production is measured by closing the 4 K supply valve while regulating the JT valve to keep the level constant in the 2 K space. In this case the falling level in the 4 K space is a combination of the static loads of the 4 K and 2 K space plus the vapour lost due to expansion from atmosphere to 31.5 mbar. The 77 K static load is measured by noting the warmed GN2 flow required at the exhaust side in order to keep the LN2 thermal shield cold. In this case the measurement is an overestimate since it was difficult to regulate the LN2 at a lower level but the thermal shield was always cold. Measured values for the ICM are shown in Table 1 compared to estimates made during the engineering phase. The 2 K production efficiency improves as a function of mass flow as the temperature of the heat exchanger and JT valve decreases. Values are 70% at 0.5 g/s, 80% at 1 g/s and 86% at 1.5 g/s. The ACMuno cryogenics test with one cavity and one ‘dummy’ show 6.4 W of static load for 4 K and 6.5 W of static load for 2 K.

3.7.2. RF characterization. The test includes cavity turn on and phase/amplitude lock, tuner frequency range and tuner lock, microphonics measurements and beam acceleration. The tuner range was measured at +400 kHz – the tuner motion was very stable and the cavity frequency could be stepped very precisely over this range. Due to the excellent frequency stability and broad bandwidth phase lock could be obtained with stable forward power even without the tuner but the tuner lock was easily achieved in any case. Cavity quality factors were estimated based on calorimetric measurements. The performance is presented in figure 7 showing RF characterization results of ARIEL1 and ARIEL2 cavities installed in ICM and ACMuno cryomodules. The $Q_0$ values in the cryomodules are higher than the values measured in the vertical test. This can be due to an additional BCP of 20 μm that each cavity received after vertical test or an improved magnetic environment or both. The cavities meet ARIEL specifications of $Q_0=10^{10}$ corresponding to power dissipation of 10 W at 2 K for Ea=10 MV/m. The results indicate that the magnetic shielding is sufficient and that the HOM dampers do not load the fundamental mode. The ideal RF coupling for ARIEL cavities for 10 mA/10 MV performance at $Q_0=10^{10}$ is $Q_{ext}=10^6$. The coupling adjustment is in the range of $Q_{ext}=7\times10^5...3\times10^6$. For the initial beam test we set the coupling to the minimum of $Q_{ext}=3\times10^6$. 
3.7.3. Beam Acceleration Test. The beam tests were completed using the MEBT analysing leg as a beam dump. The beam energy was estimated based on the dipole setting at the maximum current intensity into the dump Faraday cup. A low duty factor unbunched beam was first aligned in the LEBT and drifted through the ICM. The ICM cavity was turned on at modest gradient and the phase scanned to achieve a good beam spot on a downstream screen. The analysing leg was then turned on and scanned until the beam was seen on the dump FC. The phase of the cavity was optimized to achieve the maximum energy for the particular cavity gradient while the buncher and optics were used to optimize the transmission. Beam simulations were done to calculate the final energy assuming a certain cavity gradient. For the beam tests a gradient of 12 MV/m is achieved for the ICM and 11 MV/m for the ACM cavity. The required forward powers are 18 kW and 14 kW CW respectively.

4. Conclusions
The ICM and ACMuno are assembled, installed and commissioned. Beam acceleration demonstrated that the equipment meets the performance goals. The project has now received the license to commission to higher beam intensities and the commissioning is on-going.
In spring 2016 a second ICM prepared for VECC in Kolkata will be installed and tested with beam. At the same time ACMuno will be removed and completed with the ARIEL4 cavity for re-installation in mid 2016. If funding is available a second ACM module is planned for completion in 2018 to complete the e-Linac to its full 50 MeV.

References
[1] L Merminga, et al., “ARIEL: TRIUMF’s Advanced Rare Isotope Laboratory”, WEOBA001, IPAC 2011.
[2] W T Diamond NIM-A 432 (1999) pp 471-482.
[3] F Ames, et al., “The TRIUMF ARIEL RF Modulated Thermionic Electron Source WECF1133, EIC2014.
[4] V Zvyagintsev, et al., “Nine-cell Elliptical Cavity Development at TRIUMF”, MOPO020, SRF2011.
[5] P Kolb, et al., “Cold Tests of HOM Absorber Material for the ARIEL eLINAC at TRIUMF”, http://dx.doi.org/10.1016/j.nima.2013.05.031.
[6] R E Laxdal, et al., “The Injector Cryomodule for the ARIEL e-Linac at TRIUMF”, MOPB091,
[7] N Muller, et al., “ARIEL e-Linac Cryomodule - Design and Performance”, THPB115, SRF2015, Whistler, Canada.
[8] A Mitra, et al., “High Power RF System for E-Linac for TRIUMF”, Proc. of PAC’13, WEPHO01.
[9] Q Zheng, et al., “LLRF System for TRIUMF 1.3 GHz SRF E-Linac”, LLRF Workshop 2013
[10] R E Laxdal, et al., “TRIUMF/VECC e-Linac Injector Beam test”, MOPB026, LINAC12, Tel Aviv, Israel.
[11] R E Laxdal, et al., “Status of Superconducting Electron Linac Driver for Rare Ion Beam Production at TRIUMF”, MOIOC01, LINAC 2014, Geneva, Switzerland.
[12] M Marchetto et al., “Commissioning and Operation of the ARIEL Electron Linac at TRIUMF”, WEYC3, IPAC2015, Richmond, USA.
[13] V Zvyagintsev, et al., “Commissioning of the SRF Linac for ARIEL”, TUAA02, SRF2015, Whistler, Canada
[14] A Koveshnikov, et al., “Integration and Commissioning of the ARIEL e-Linac Cryogenic System at TRIUMF”, ICEC-ICMC2014
[15] Z T Ang, et al., "HPRF Waveguide Elements Study and Distributions in TRIUMF Electron Linac System", TUPB011, SRF2015, Whistler, Canada.
[16] Y Ma, et al., “High Power Coupler Test for Ariel SC Cavities”, THPB103, SRF2015, Whistler, Canada.
[17] V Zvyagintsev, et al., “Production of a 1.3GHz Niobium 9-cell TRIUMF-PAVAC Cavity for the ARIEL Project”, THP035, SRF2013, Paris.
[18] P Kolb, et al., “1.3 GHz Cavity Test Program for ARIEL”, MOPB089, SRF2015, Whistler, Canada.
[19] Z Y Yao, et al., "Cryomodule Protection for ARIEL e-Linac", TUPB103, proc. SRF2015, Whistler, Canada.