COMMISSIONING OF THE SRF LINAC FOR ARIEL

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Abstract

This paper is reporting commissioning results for the SRF linac of ARIEL facility at TRIUMF. The paper is focused on the SRF challenges: cavity design and performance, ancillaries design and preparation, cryomodule design and performance, RF system and final beam test results.

INTRODUCTION

The ARIEL project [1] will allow increase in the RIB delivery hours with the addition of a new electron linac driver of 50 MeV (0.5 MW) and new target stations.

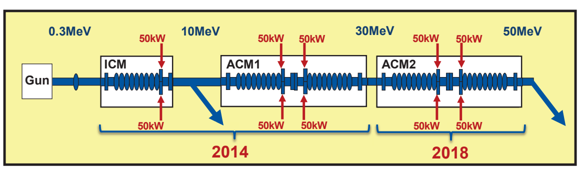

Figure. 1: The stages of the e-Linac project.

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. 10 mA/50 MeV electron beam is required for a goal 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 Fig. 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 contains two 1.3 GHz nine-cell cavities plus associated beamlines is now installed and is in various stages of commissioning. This first phase is designed to accelerate cw up to 10 mA of electrons at 30 MeV but 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.

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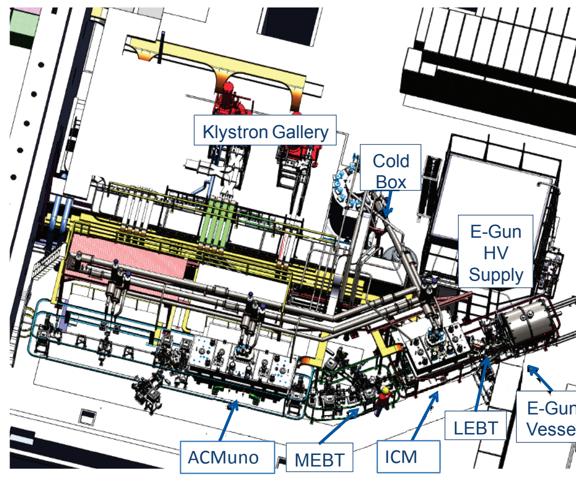

Figure 2: The phase I configuration of the e-Linac.

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 final CW beam power 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 Fig. 2 as it would appear at the end of Phase I.

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 SF_6 filled vessel, and an

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in-air high voltage power supply. The beam is bunched by superimposing a RF modulation to overcome a DC suppression voltage on the grid.

Cavities

The cavity design parameters include f=1.3 GHz, L=1.038 m, R/Q=1000, E_a=10 MV/m [4]. For $Q_o=10^{10}$ 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 Fig. 3.

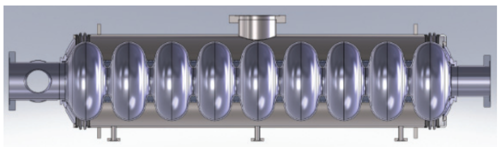

Figure 3: The e-Linac nine cell cavity with jacket.

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/cm^2.

Cryomodules

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

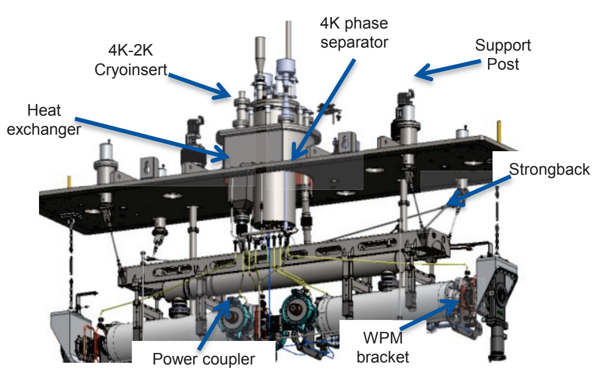

Figure 4: Accelerating cryomodule for ARIEL e-Linac.

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.

Each cryomodule is outfitted with an on-board 4 K to 2 K cryogenics insert. The insert consists of a 4 K phase separator, a 2.5 gm/sec heat exchanger and a JT expansion valve, a 4 K cooldown valve and a 4 K thermal intercept syphon supply and return. During cooldown the 4K valve is used to direct LHe to the bottom of the cold mass until 4 K level is reached. The level in the 4 K reservoir is regulated by the LHe supply valve, the level in the 2 K phase separator is regulated by the JT valve and the 2 K pressure is regulated by the sub-atmospheric line valve. Piping within the module delivers the syphon supply to a number of 4 K thermal intercept points (WCT, ICT and FPC) and then returns the two phase LHe back to the top of the 4 K phase separator.

Cryogenic System

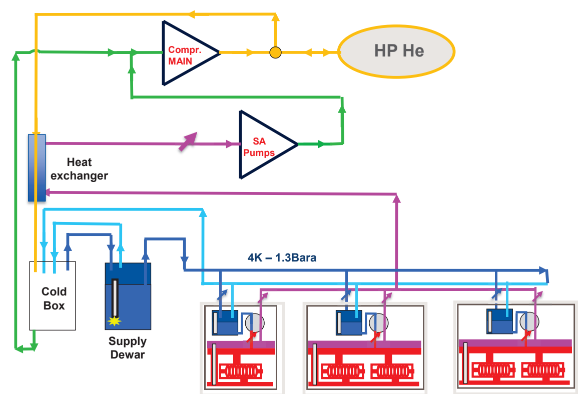

Figure 5: A schematic of the e-Linac cryogenic system.

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 supply side of the trunk to the return side. 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 Fig. 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 (Fig. 6). 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].

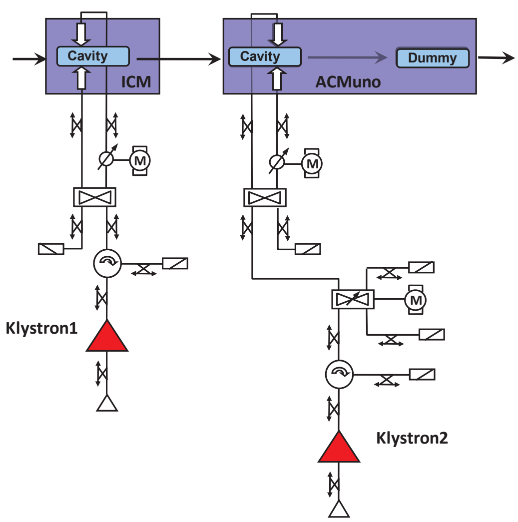

Figure 6: The phase-I RF System: ACMuno is ACM1 with one cavity.

STATUS AND COMMISSIONING

Electron Gun

The system is installed and conditioned to 320 kV with beam extracted at 300 kV up to the full CW intensity of 10mA. RF modulation of the grid voltage is demonstrated over a wide duty factor range from 0.01% to CW. The transverse emittance of the beam measured with an Allison emittance scanner [10-12] for a peak current of 10 mA and 1% duty factor is $\varepsilon_{rms,norm}$ = 7.5 μm. This is above the originally specified value of 5 μm, but still within the acceptance of the planned beamline and accelerator. 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 U_b = -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°.

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 90^0 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 phase space was characterised in a high power Allison scanner capable of accepting beam powers up to 1 kW. The longitudinal phase space was mapped into the transverse space using the dispersion in the analysing 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].

Cryogenics

The ARIEL cryogenic system [13] includes an ALAT LL Cold Box and KAESER FSD571SFC main compressor with a mass flow rating of 112 g/s. In order to arrive at a specification 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. Four Busch Combi DS3010-He sub-atmospheric pumping units rated at 1.4 g/s each are installed. More can be added as the 2 K production increases in Phase II.

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 tests were limited by the available load or circulator – one was operated to 250 kW CW the other to 150 kW CW. Waveguide elements has been installed and tested [14]. The power couplers are conditioned two couplers at once at room temperature in a Power Coupler Test Station (PCTS) using a 30 kW IOT. The couplers are installed on a waveguide box and power is transmitted to a dummy load. Preparation involves extended bakeout (7 days) at 100C with N2 flowing to cover the ceramic and RF surfaces. RF conditioning involved both TW (18 kW CW) and SW mode (10 kW pulsed) with adjustable short for ~5 days [15].

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Cavities

The ARIEL cavities have been fabricated by PAVAC [16]. To date four cavities have been received. The cavities are tuned, degreased then given a 120micron BCP before final tuning. After the initial cold test the 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 $6{\cdot}10^9$ [17]. Since the available cryogenic power is more than enough for Phase I it was decided to accept $Q_0{>}5{\cdot}10^9$ as a Phase I specification to allow moving forward with the cryo-engineering characterization. ARIEL3 is also accepted for jacketing. ARIEL4 cavity is due for completion at the end of 2015. 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.

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 [18] for fast trip of RF drive in case of cavity quench and threshold signals for RF, vacuum and temperature.

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].

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 1g/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.

Table 1: Measured Cryogenics Performance for ICM.

Parameter	Estimate	Measurement
4K static load – no syphon	2W	3W
4K static load with syphon	6W	6.5W
2K static load	5W	5.5W
77K static load	100W	<130W

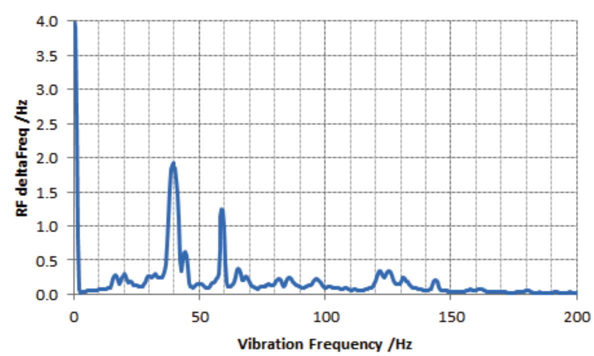

Figure 7: The spectrum of the RF frequency deviation.

RF characterization measurements include 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. The spectrum of RF frequency deviation due to microphonics is shown in Fig. 7.

The phase error signal in the LLRF phase loop was measured by a spectrum analyser, and was calibrated by modulating the RF reference frequency in closed loop operation. Cavity quality factors were estimated based on calorimetric measurements. The performance is presented in Fig. 8 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 E_a=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 $Q_{ext}=7\cdot10^5...3\cdot10^6$. For the initial beam test we set the coupling to the minimum of $Q_{ext}=3\cdot10^6$.

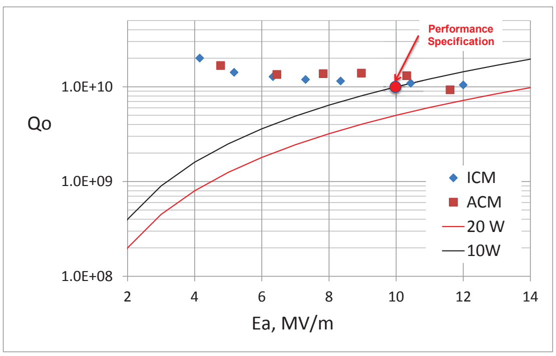

Figure 8: RF characterization of ARIEL1 and ARIEL2 cavities in ICM and ACM cryomodules.

Beam Acceleration 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.

FUTURE PLANS

ICM and ACMuno are assembled, installed and commissioned. Beam acceleration demonstrated that the equipment meets performance goals.

The beam tests will continue through Dec. 2015 at 25 MeV and up to 100 kW. In early 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. The second ACM module is expected for completion in 2018 to complete the e-Linac to its full 50 MeV.

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