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THE TRIUMF/VECC INJECTOR CRYOMODULE PERFORMANCE

Yanyun Ma†, K. Fong, T. Junginger, D. Kishi, A. Koveshnikov, R.E. Laxdal, N. Muller, R. Nagimov, D.W. Storey, E. Thoeng, Z.Y. Yao, V. Zvyagintsev,
TRIUMF, Vancouver, Canada

U. Bhunia, A. Chakrabarti, S. Dechoudhury, V. Naik, VECC, Kolkata, India

Abstract

The collaboration on superconducting electron Linac for rare ion beam facilities ARIEL (Advanced Rare IsotopE Laboratory) [1-4] and ANURIB [5] (Advanced National facility for Unstable and Rare Isotope Beams) has resulted in production of a superconducting Injector Cryomodule (VECC ICM) at TRIUMF for VECC. The cryomodule design utilizes a unique box cryomodule with a top-loading cold mass. The hermetic unit consists of a niobium cavity which operating at 1.3GHz and connected with two symmetrically opposed couplers which can deliver 100kW RF power to the beam. Liquid helium supplied at 4.4 K is converted to superfluid helium-II through a cryogenic insert on board which includes 4 K phase separator, 4K/2K heat exchanger and Joule-Thompson valve. In 2016, the VECC ICM has been tested at TRIUMF and demonstrated 10.5 MeV acceleration. A summary of the VECC ICM commissioning are presented.

INTRODUCTION

TRIUMF and VECC are developing high intensity electron linac driver to produce RIBs through photo-fission. Final design goals are 50MeV and 10mA/3mA at TRIUMF/VECC respectively [1, 5]. TRIUMF and VECC jointly designed the ICM (termed EINJ in ARIEL). Two injector cryomodules have been fabricated and beam tested at TRIUMF.

A first phase of ARIEL consisting of an ICM, and an accelerating cryomodule with just one accelerating cavity on board plus a `dummy' cavity that occupies the second cavity space in the cryomodule (ACMuno) was installed for initial technical and beam tests up to 23 MeV in 2014 [6]. A completed ACM with two cavities has been installed and is under testing to meet the operational goal of 3mA at 30MeV for first science application from ARIEL ISOL targets (Fig. 1) [3,4]. The 2nd ICM as part of a collaborative agreement with the ANURIB project at VECC [4] has been swapped with the 1st ICM and tested during ACM cryomodule offline. The 2nd phase of ARIEL will add ACM2 module and a ramp up in beam intensity to the full 50 MeV, 0.5 MW capability.

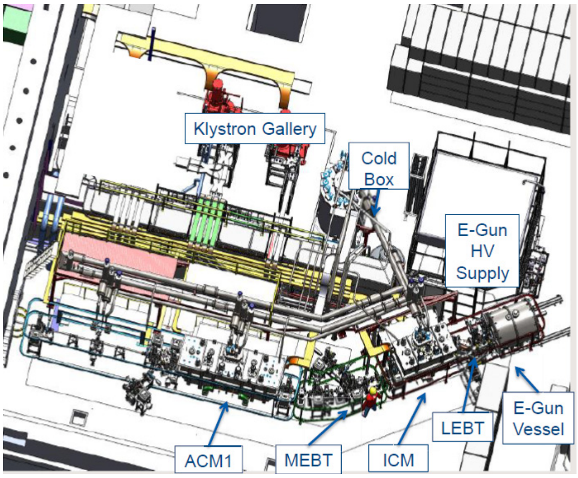

Figure 1: e-Linac layout at TRIUMF.

CRYOMODULE DESIGN

The injector cryomodule design [2], shown in Fig. 2, borrows significantly from the ISAC-II cryomodules.

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, cavity support posts and the cavity hermetic unit. The hermetic unit consists of a niobium cavity, the end assemblies, an inter-cavity transition (ICT) with a stainless steel HOM damper, the fundamental power couplers (FPC) and an RF pick-up. The end assemblies include the warm-cold transition (WCT), HOM damping tubes and beam-line isolation valves.

A scissor jack tuner is attached to cavity's LHe jacket. The custom warm drive system utilizing a servo motor and a resolver placed on top of the cryomodule at atmosphere. The cold mass is surrounded by LN2 cooled thermal isolation box. There are two layers of mu metal, a warm layer just inside the vacuum box and a cold layer surrounding the cavity. A Wire Position Monitor (WPM) alignment monitoring system is installed with the hermetic unit.

In order to be self-reliant to convert 4 K atmospheric LHe into 2 K He-II, the box cryomodule design has sufficient head room that makes possible the addition of a dedicated 4 K/2 K cryo-insert on each module [7].

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† mayanyun@triumf.ca

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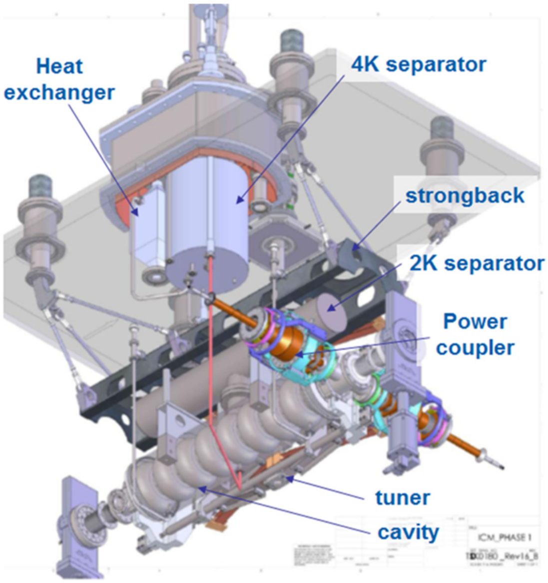


Figure 2: ICM top assembly.

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 circuit in a thermal siphon configuration. During cooldown the 4 K cooldown valve is used to direct LHe to the bottom of the cold mass until 4 K LHe is accumulated in the cavity jacket. Then the cooldown valve is closed, the JT valve is opened and the sub-atmospheric pumps are turned on. 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 siphon supply to a number of 4 K thermal intercept points (WCT, ICT and FPC) and then returns the two phase LHe back to the 4 K phase separator. Depending on the thermal load, the density mismatch between the liquid side (supply side) and the two-phase side (return side) can overcome the head pressure difference between supply and return pipes. In this case a mass flow will be initiated in the siphon loops and convective heat transfer will occur from the load to the helium.

CAVITY

The cavity parameters include rf frequency=1.3 GHz, L=1.038 m, R/Q=1000, E_a=10 MV/m. For Q_o=1e10 the cavity power is P_{cav}=10W [8].

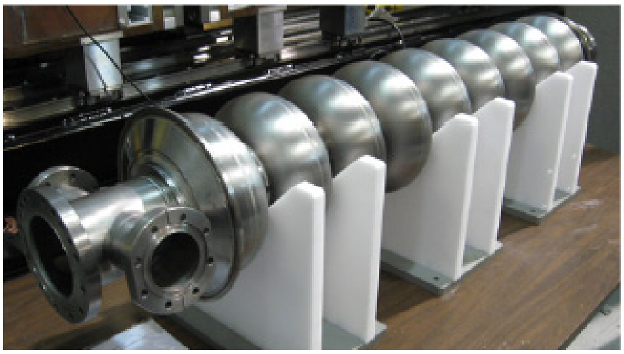


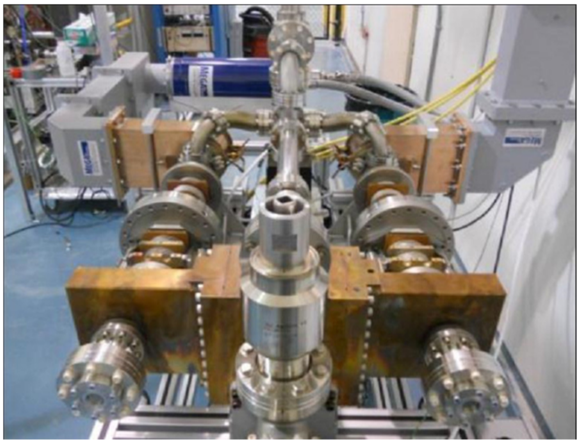
Figure 3: A photo of the unjacketed VECC ICM cavity.

The inner cells take their shape from the TESLA 9-cell cavities but the end groups were modified to accept the two power couplers and to help push HOMs to dampers located on each end as shown in Fig.3. On the power coupler end there is a stainless steel damping tube coaxial with the beam tube and extending into the beam tube by 17 mm. On the opposite end of the cavity a coaxial CESIC tube is used. 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 $R_d/Q*Q_L<10^6$ Ohm. 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 bellows 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. The VECC cavity has been fabricated by PAVAC. The cavity was tuned, degreased, and then given a 120 micron BCP before degassing at 800 °C and final 20 micron etch and tuning.

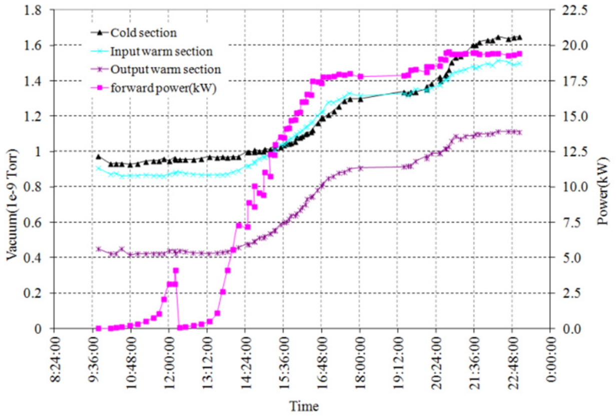
COUPLERS

We employ CPI [9] Power Couplers VWP 3032 [10] capable to deliver up to 75 kW CW RF power at 1.3 GHz to superconducting cavity operating at 2 K temperature of liquid He. Before installing the power couplers with the cavities, they have to be assembled on Power Coupler Test Stand (PCTS) and conditioned with a 30 kW CW Inductive Output Tubes (IOT). We are doing RF conditioning in travelling wave mode with water cooled RF dummy load up to 19.5 kW [11], shown in Fig.4, and in standing wave mode with variable movable short plate up to 9kW with 3 positions based HFSS simulation results to overlap phase of SW from 0 to 90deg: 0, 45 and 90 deg.

The RF power couplers are operating with superconducting cavities in ultra-high vacuum environment, and to avoid contamination with dust, all the inspection, assembling and dissembling operations have to be done in clean room. The 'cold' assemblies were installed on the cavity in class 10 clean room. The 'warm' assemblies were installed in the class 1000 clean room.



(a) Power Coupler Test Stand.



(b) 19.5kW CW travelling wave

Figure 4: Power couplers RF conditioning.

CRYOGENIC TEST RESULTS

The cryomodule static loads are estimated by measuring the rate of falling level in the phase separators coupled with details of the phase separator volume and the heat of vaporization. The falling level measurements are cross-calibrated with additional loads from DC heaters attached to the helium volumes. The tests are completed with the 4 K and 2 K spaces isolated by closing the JT valve, the 4 K cool down valve and the 4 K supply valve. The results of the static load measurements for VECC ICM are shown in Table 1.

Table 1: Measured Cryogenics Performance for ICM

Parameter	Estimated	Measured
4 K static load	6.5	4.55
2 K static load	5.5	5
2K production efficiency	82%	85%
77 K static load	<130	<130

The 77 K static load is measured by noting the warmed GN_2 flow required at the exhaust side in order to keep the LN_2 thermal shield cold. In this case the measurement is an overestimate since it was difficult to regulate the LN_2 at a lower level but the thermal shield was always cold.

The efficiency 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 load plus the vapour lost due to expansion from atmosphere to 31.5 mbar. In order to simulate the dynamic load caused by the RF losses, a series of different heater power are added to the 2 K space. The 2 K production efficiency improves as a function of mass flow as the temperature of the heat exchanger and JT valve decreases. An efficiency of 85% 2 K production efficiency can be achieved for the operating regime as shown in Fig.5.

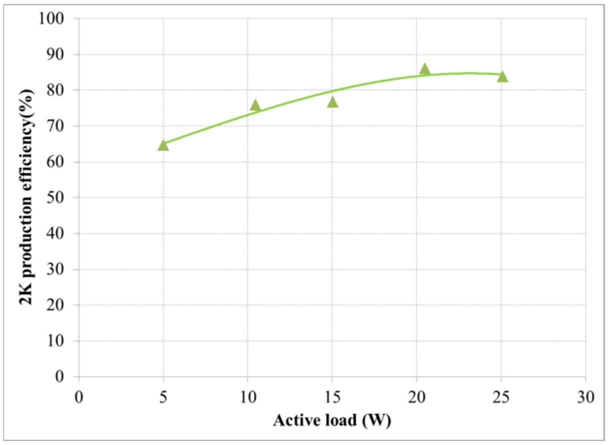


Figure 5: Measurement of the 2 K production efficiency.

RF TEST RESULTS

To perform the test the e-Linac was warmed up and TRIUMF ICM cryomodule was taken off-line and the VECC ICM was installed in its place. Since the TRIUMF ICM and VECC ICM are virtually identical the ICM could be plugged in without any alterations to the installed equipment.

The cavity Q_0 factor is measured by closing the JT valve while running the RF with certain electric field level. In this case the falling level in the 2 K space is a combination of the static loads of the 2 K and RF dynamic load on cavity. The results of on-line Q_0 factor measurements are shown in Fig. 6. After RF conditioning a value of $Q_0=1.03*10^{10}$ was achieved at an acceleration gradient Ea=10 MV/m meeting the design goal. The Q_0 values in the cryomodule are equivalent to the values measured in the vertical test indicating the magnetic shielding is sufficient and the HOM dampers do not load the fundamental mode.

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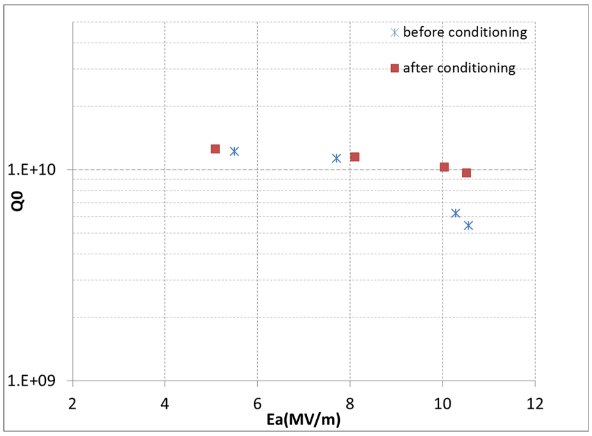

Figure 6: Q_0 measurement results.

The 300 kV e-Gun and LEBT transport were used to inject the beam to the ICM and the downstream 10MeV beam dump is used to calibrate the energy gain. A low intensity beam was used to calibrate the gradient. A final energy of 10.5 MeV was achieved at the beam dump corresponding to a cavity accelerating gradient E_a of more than 11 MV/m.

The cavity design considers the use of two CPI couplers per cavity. This sets a maximum gradient per cavity at 10 MV/m for the design beam intensity. The FPC cold sections are cooled by LN loops, 80 K thermal links and 4 K siphon loops which will intercept the RF dynamic load in the 4K Helium instead of 2 K Helium. During the beam commissioning about 10 kW RF power is delivered through the FPCs in standing wave mode as the beam loading is very weak. The temperature sensors attached to the coupler siphon loops indicate the siphon loops work well.

When VECC ICM runs with about 10 kW RF power, the temperature sensors related to the coupler siphon loops are about 17 K as shown in Fig. 7.

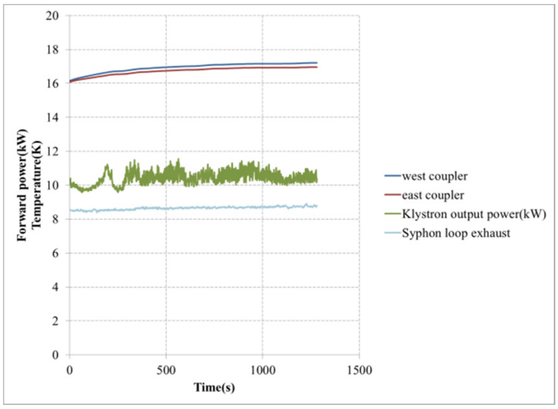

Figure 7: ICM FPC 4 K siphon loops related temperature.

The RF dynamic load to 4 K Helium through FPCs siphon loops has been measured by 4 K Helium falling level test by closing the 4 K supply valve and JT valve and keeping the RF on. The temperature sensors related to the coupler syphon loops indicated that the syphon loops work well. There is ~0.32 W and ~1.2 W RF load to the 4 K reservoir for a total forward power (for 2 FPCs) of 5 kW and 10 kW respectively.

SUMMARY

Early stage commissioning of VECC ICM demonstrates that the cryomodule meets the performance goals. The VECC ICM is now off-line and waiting for deliver to VECC.

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