THE CRYOGENIC PERFORMANCE OF THE ARIEL E-LINAC CRYOMODULES

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Abstract

The Advanced Rare Isotope Laboratory (ARIEL) project at TRIUMF requires a 50 MeV superconducting electron Linac consisting of five nine cell 1.3 GHz cavities divided into three cryomodules with one, two and two cavities in each module respectively. The cryomodule design utilizes an unique box cryomodule with a top-loading cold mass. LHe is distributed in parallel to each cryomodule at 4 K and at ~1.2 bar. Each cryomodule has a cryogenic insert on board that receives the 4 K liquid and produces 2 K liquid into a cavity phase separator. In the cryomodules the natural two-phase convection loops, i.e. siphon loop, are installed which supply 4 K liquid to thermal intercepts and return the vaporized liquid to the 4 K reservoir as a refrigerator load. The design of the cryomodule, the simulation results with Ansys Fluent and the results of the cold tests will be presented.

INTRODUCTION

The ARIEL [1] is an on-going project at TRIUMF which will triple TRIUMF's capability of rare isotope production over the next ten years for the needs of the international scientific community. ARIEL uses a 50 MeV, 10 mA continuous-wave (CW) electron linear accelerator (e-Linac) as a driver accelerator utilizing superconducting bulk niobium technology at 1.3 GHz. The accelerator is divided into three cryomodules [2] including a single cavity injector cryomodule (ICM) and two accelerating cryomodules (ACM) with two cavities each as shown in Fig. 1.

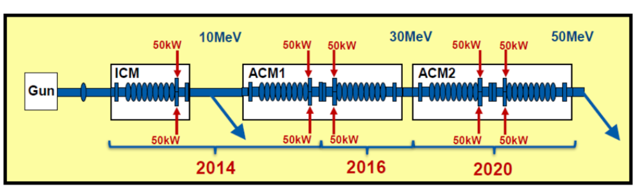
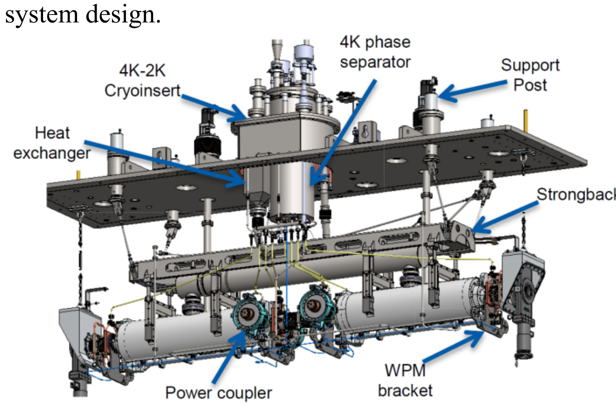


Figure 1: A schematic of the e-linac showing the installation stages.

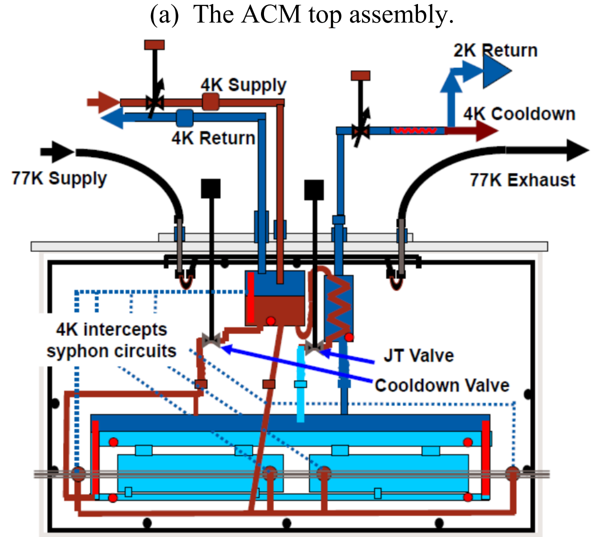
A first phase consisting of an ICM, and an accelerating cryomodule with just one accelerating cavity on board plus a `dummy' cavity that occupies the second cavity space in the cryomodule (ACMuno) was installed for initial technical and beam tests to 23 MeV in 2014 [3]. The ACMuno configuration allows a full cryo-engineering characterization of the cryomodule. An upgrade that will add a second 1.3 GHz nine-cell cavity to ACM1 is in progress. A 2nd ICM as part of a collaborative agreement with the ANU-RIB project at VECC [4] is under testing. The 2nd phase will add ACM2 module and a ramp up in beam intensity to the full 50 MeV, 0.5 MW capability.

CRYOMODULE DESIGN

The ARIEL cryomodule design [5], shown in Fig. 2, borrows significantly from the ISAC-II cryomodules. The modular and staged testing/installation sequence of the e-linac suggests that each cryomodule be self-reliant to convert 4 K atmospheric LHe into 2 K He-II. To this end 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. Incorporating features of the ISAC-II design reduced the engineering design load within TRIUMF and takes best advantage of the existing infrastructure. This finds important savings in both the cryomodule design, fabrication and testing but also in the cryogenic system design.



(a) The ACM top assembly.



(b) The ACM cryogenic piping schematic.

Figure 2: ACM top assembly and piping schematic.

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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 the niobium cavities, 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), CESIC or stainless 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, 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.

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 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.

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 vapourization. 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 1st ICM and ACMuno in 2014 and 2nd ICM are shown in Table 1.

Table 1: Static Load

Load(W)	1st ICM	ACMuno	2nd ICM
4 K static load	6.5	6.25	4.55
2 K static load	5.5	6.9	5
77 K static load	<130	<130	<130

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.

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 86% 2 K production efficiency can be achieved for the operating regime with a mass flow of 1.5 gm/sec for both the ICM and ACMuno which shown in Fig. 3.

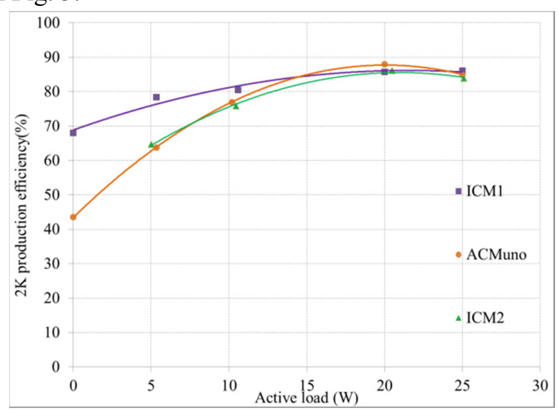

Figure 3: Measurement of the 2 K production efficiency.

The cryo-insert was initially tested in a vertical cryostat with a `dummy' 2 K volume and variable thermal intercept loads. The tests gave early experience with the thermal siphon circuit [6]. In particular the study showed that the design of the siphon return is important. A schematic of various return methods for the siphon circuit are shown in Fig. 4.

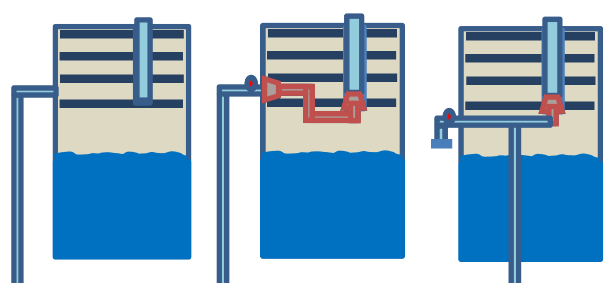

Figure 4: (a) the initial return loop in 4K/2K insert test; (b) modified return loop with funnel (c) return loop pass through reservoir bottom.

In variant (a) the returning 2-phase flow can cause a high heat load in the 4 K phase separator if allowed to cause convective mixing in the vapour space while in (b) this mixing is minimized by funnelling the returning vapour to the helium return stinger. A third variant (c) passes the return vapour through the 4 K bath and a lower exhaust position than (a) and (b). The siphon circuit in the cryomodule is tested by applying various heater levels to the siphon

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loads and measuring the rate of falling level in the 4 K reservoir with the J-T valve closed. Temperature sensors have been installed to monitor the siphon circuit mass flow in (b) and (c), shown in Fig. 4 as a red point. Both variants (b) and (c) have been used with (c) exhibiting favourable performance.

CFD simulations of mass and heat transfer and the 2-phase flow in the ICM siphon circuit has been done with ANSYS-Fluent [7]. In this study hexahedral mesh with 5 layers insulation on the tube wall and Multiphase-Mixture method have been applied to the model. Based on the simulation results the Max. Mass flow rate is about 3gm/s as shown in Fig. 5.

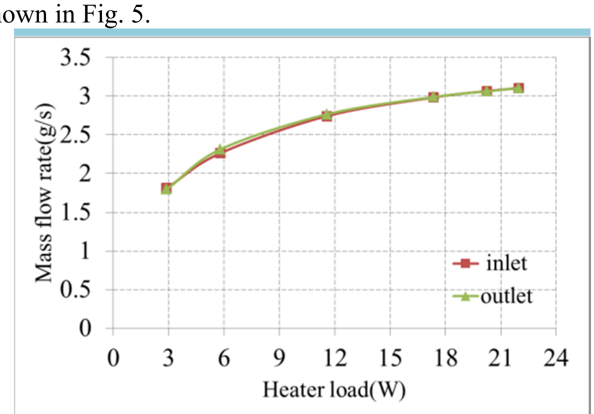

Figure 5: ICM Ansys-fluent simulation results.

RF TEST RESULTS

The 1st ICM and ACMuno have been tested in 2014 [3]. Now the 2nd ICM for VECC[4] has been installed into the beam line and the test is in process.

The cavity design considers the use of two CPI couplers per cavity delivering a total of 100 kW of beam loaded RF power. This sets a maximum gradient per cavity at 10 MV/m for the maximum beam intensity of 10 mA. 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 12~15 kW RF power is delivered through the FPCs in standing wave mode as the beam loading is very weak. The temperature sensors related to the coupler siphon loops are which indicates the siphon loops work well.

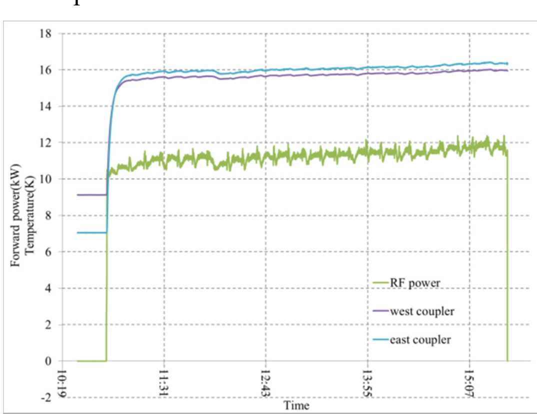

Figure 6: ICM FPC 4 K siphon loops related temperature.

When 1st ICM run with 10 MV/m with about 12 kW RF power, the temperature sensors related to the coupler siphon loops are about 16 K as shown in Fig. 6.

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. It is about 1.2 W with 10 kW standing wave RF forward power for 2 FPCs.

The cavities Q0 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 Q0 factor measurements are shown in Fig. 7. All the cavities meet specifications in terms of quality factor at the operating gradient.

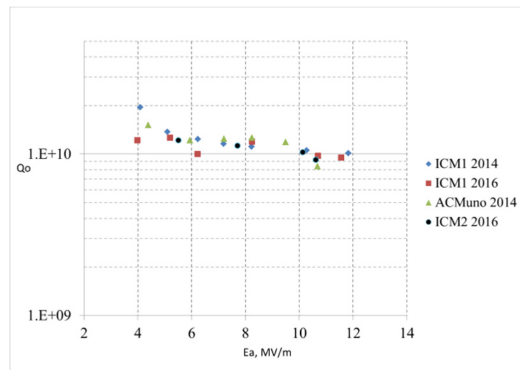

Figure 7: Q_0 measurement results.

SUMMARY

The top loading cryomodules for 1.3 GHz Nb cavities have been developed and 2 ICM cryomodules and 1st ACMuno have been tested in TRIUMF. Early stage of commissioning with ICM and ACMuno demonstrates the cryomodules meet the performance goals.

REFERENCES

[1] S.R. Koscielniak, *et al.,* “e-Linac photo-fission driver for the Rare Isotope Program at TRIUMF”, Presented at PAC2011, New York, USA, April 2011.

[2] R.E. Laxdal, *et al*, “The Injector Cryomodule for e-Linac at TRIUMF”, AIP Conf. Proc. 1434, 969 (2012); http://dx.doi.org/10.1063/1.4707014

[3] M. Marchetto, *et al.*, “Commissioning and operation of the ARIEL electron LINAC at TRIUMF”, in *Proc. IPAC2015*, Richmond, VA, USA, paper WEYC3, pp. 2444–2449.

[4] A. Chakrabarti, *et al.*, “The ANURIB project at VECC – Plans and preparations”, *Nucl. Instr. Meth., vol. 317, Part B*, pp. 253–256, 2013.

[5] R.E. Laxdal, *et al.*, “The injector cryomodule for the ARIEL e-linac at TRIUMF”, in *Proc. LINAC2012*, Tel-Aviv, Israel, paper MOPB091, pp. 389–391.

[6] R.E. Laxdal, *et al.*, “Cryogenic test of the 4 K/2 K insert for the ARIEL e-linac cryomodule”, AIP Conf. Proc. 1573, 1184 (2014), http://dx.doi.org/10.1063/1.4860840

[7] ANSYS Inc., “Fluent Help” (2015).

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