The 1.3 GHz SRF Injector Cryomodule for VECC – designed and manufactured at TRIUMF

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Abstract. The combined R&D efforts of engineers and scientists from both TRIUMF and VECC have resulted in production of a superconducting Injector Cryomodule operating at 1.3 GHz. The design utilizes a unique box cryomodule with a top-loading cold mass. Liquid helium supplied at 4.4 K is converted to superfluid helium-II on board the cryomodule. A 4 K phase separator, 4 K / 2 K heat exchanger and Joule-Thompson valve are installed on the cryomodule to produce 2 K liquid helium. Two identical (by their parameters) cryomodules have been manufactured at TRIUMF. The Injector Cryomodule (ICM) has been tested and commissioned in June of 2014 and is the first cryomodule for the ARIEL e-linac at TRIUMF. The Injector Cryomodule for VECC (VECC ICM) is currently at the finishing stage of its assembly and will undergo cryogenic tests in Q1 of 2016 followed by RF and beam tests at TRIUMF before being shipped to India. The particularities of the design as well as results of the cryogenic and RF performance are presented in this paper.

1. Introduction
TRIUMF is now finishing the commissioning of Phase-I of the high intensity superconducting electron linear accelerator (e-linac), as a key element of the ARIEL project [1]. The e-linac is specified to produce 10 mA of 50 MeV electrons in continuous wave (CW) mode as a powerful 0.5 MW photo-fission driver to add a complimentary second source of radioactive ion beams for the existing ISAC experimental facility. Similar requirements are set for the RIB facility at VECC, ANURIB, where a photo-fission driver is planned to produce a 50 MeV, 0.1 MW electron beam [2]. Owing to converging goals, TRIUMF and VECC agreed to join efforts in order to design and manufacture the injector cryomodule. Two identical cryomodules were fabricated at TRIUMF with one cryomodule beam-commissioned in 2014 [3] and the second is undergoing commissioning tests at TRIUMF.

2. Design
Typically cryomodules for 1.3 GHz elliptical cavities utilize round vacuum chambers with end loaded cold mass assemblies. However, in order to take advantage of TRIUMF experience with the design and production of ISAC-II top-loaded cryomodules [4], it has been decided to produce e-linac cryomodules in a similar top-loaded box design [5].
The existing TRIUMF infrastructure for assembly and test of top-loaded cryomodules [6], as well as experience with the operation of the ISAC-II accelerator allowed significant savings in design and production of cryomodules. Due to the top-load design (Fig. 1), cryomodules have sufficient head room that allows the addition of a dedicated 4 K / 2 K cryogenic insert on each module, thus, providing the capability to convert liquid helium-I at 1 bar to superfluid helium-II on-board each cryomodule [7]. The cold mass is suspended from the top 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 cavity, the end assemblies, the power couplers and an RF pick-up. The end assemblies include the warm-cold transition, higher-order mode damping tubes on each end and beam-line isolation valves. Among other features there is a scissor jack tuner with a warm motor, liquid nitrogen cooled thermal isolation box, two layers of mu metal, and a wire position monitor diagnostic system intended for alignment monitoring. The assembly of the hermetic unit takes place in a class-10 clean room. The hermetic unit is filled with filtered dry nitrogen gas with a slight over pressure before installation in the cryomodule.

The cavities are operated at a temperature of 2 K to meet the unloaded Q factor specification of $1 \times 10^{10}$. Liquid helium is distributed in parallel to each module at a temperature close to 4.4 K and pressure 1.3 bar. Each cryomodule is equipped with a cryogenic insert on board that allows the conversion of 4.4 K liquid helium into 2 K. The insert contains a 4 K phase separator, heat exchanger with specified mass flow <2.5 g/s, JT expansion valve, 4 K cooldown valve and 4 K thermal intercept siphon supply and return. During cooldown the 4 K cooldown valve is used to direct liquid helium to the bottom reservoir until the level is reached. The level in the 4 K reservoir is regulated by the 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. The cryogenic unit is identical for both ICM and VECC ICM. The design of the cryogenic insert is compatible with an existing TRIUMF cryostat.

The 300 K to 4 K connections at the beam pipe and at the power couplers are intercepted at both 77 K and 4 K. The 4 K intercepts are fed via syphon loop from the 4 K phase separator. Two-phase helium is then returned back to the 4 K phase separator. Siphon loops were designed, tested and optimized at TRIUMF during the development of the 4 K / 2 K cryogenic insert and the directly on the cryomodule.
Figure 2. 4 K / 2 K cryoinsert test cryostat (left) and 9-cell cavity prepped for cold cavity RF test (right)

3. Cryogenic Tests

Cryogenics tests have been conducted using the cryoinsert connected to a dummy load (Fig. 2) in a vertical cryostat and in situ in the cryomodule. In both cases the cryogenic insert was equipped with temperature sensors, liquid helium level probes, gaseous helium flow meter and pressure transducers. Heaters located on each of the reservoirs are used to boil-off helium when required to provide a calibrated heat load for the system.

Figure 3. The difference in measured heat loads between configurations a, b and c (shown on Figure 4)

The liquid helium siphon circuit was tested applying various thermal loads to the bottom of the loop using an electrical heater and measuring the rate of falling level in the 4 K reservoir with the JT-valve closed. When the applied heat load is large enough, the density mismatch between the liquid side and the two-phase side overcomes the head pressure between supply and return pipes. This drives the siphon loop circulation, and initiates increased heat transfer due to a convection caused by siphon loop flow.
Results from syphon loop studies are summarized in Fig. 3. The initial configuration with the syphon loop returning to a side port in the 4 K reservoir (Fig. 4a) produced a high heat load (20 W for 2 W of added heat and 2 W of static load) due to introducing convection in the 4 K reservoir. The siphon loop return was modified (Fig. 4b) inside the 4 K phase separator to limit the convection reducing the measured heat load to 5 W (for 2 W of static load and 2 W of added heat) [7]. In a third variant the syphon return line was routed through the bottom of the vessel through the LHe to the vapor region (Fig. 4c). This variant was tested in the cryomodule and produced excellent performance with a linear increase in measured load as the additional heat was turned on.

The performance of the cavities for ICM and ACM are measured using calometric techniques. The measurements show that the performance specification of 10 MV/m at $1 \times 10^{10}$ is met for both installed cavities (Fig. 5).
4. Commissioning
Due to a distributed 4 K to 2 K liquid helium production, the standard 0.7 kW class 4 K helium liquefier has been installed and commissioned in TRIUMF in order to provide liquid helium to the cryomodules during both commissioning stage and beam operation [8]. The distribution system delivers 4 K liquid helium utilizing a common delivery trunk with parallel feeds to each cryomodule. In order to reduce the cryomodule installation and replacement time, helium cryogenic connections are designed as serviceable in-situ assemblies. Figure 6 shows the overall layout of liquid helium distribution to cryomodules, as well as the location of serviceable joints and cryogenic valves.

Table 1. Measured cryogenic performance of ICM

| Parameter                           | Estimate | Measured |
|-------------------------------------|----------|----------|
| 4 K static heat load (no RF applied) | 6 W      | 6.5 W    |
| 2 K static heat load (no RF applied) | 5 W      | 5.5 W    |
| 2 K production efficiency           | 82%      | 86%      |
| 70 K static heat load (no RF applied) | 100 W    | < 130 W  |

Four warm subatmospheric pumping units were installed to provide the necessary pumping capacity for 4 K to 2 K conversion stages of each cryomodule [9]. Two commissioning runs of the ICM have been successfully finished in Q4 2014, confirming both cryogenic and accelerating performance requirements [10] (Table 1).

Commissioning of VECC ICM is scheduled for Q1-Q2 of 2016 after the technical maintenance shutdown dedicated to a set of upgrades, including upgrade of the cryogenics control system. The cryomodule is currently fully assembled and goes through vacuum leaks checks for isolation vacuum and helium volumes. The first cooldown is scheduled in mid-March.

The cryogenic performance test of the VECC ICM cryomodule is going to be performed utilizing existing diagnostics and instrumentation equipment of the cryomodule (Fig. 1). Measurement of falling liquid helium level in the 4 K and 2 K spaces of cryomodule should confirm that the cryomodule meets the requirements for cryogenic performance. VECC ICM is to be transported to VECC from TRIUMF after the end of commissioning tests.
5. Conclusion
As a part of collaboration between VECC and TRIUMF two injector cryomodules for similar RIB projects were successfully designed and manufactured at TRIUMF. The VECC ICM is been assembled and ready to move to SRF clean room for the cold test. After passing the cold test, ICM will be moved to ARIEL e-linac facility in order to follow with RF and beam tests.

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