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COMMISSIONING OF THE VECC CRYOMODULE

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Abstract

A quarter-wave resonator (QWR) cryomodule was designed and assembled at TRIUMF for the energy upgrade of the VECC ISOL-RIB facility to boost radioactive isotopes from 1 MeV/u to 2 MeV/u. The top loading cryomodule was chosen based on the ISAC-II low energy section design, consisting of four superconducting QWRs and one superconducting solenoid. The major change from the ISAC-II concept is separating the RF space vacuum from the isolation vacuum. The cryogenic commissioning was recently completed. The cold mass alignments and the cryogenic heat loads were measured. The cavity performance was qualified in both test regime and operating regime. The cavity degradations caused by magnetic pollution from solenoid and the recovery procedure were verified. This paper will report the detailed results of the commissioning.

INTRODUCTION

The radioactive ion beam (RIB) facility at the Variable Energy Cyclotron Centre (VECC) at Kolkata in India uses the isotope separation on-line (ISOL) technique to produce rare isotopes. The post-accelerators consist of a radio frequency quadrupole (RFQ) that accelerates heavy ions with a mass-to-charge ratio of $A/q \leq 14$ to 100 keV/u, and five IH-type linear accelerator (linac) tanks for further acceleration to 1 MeV/u [1]. The energy upgrade of the VECC RIB facility will add two superconducting (SC) heavy ion quarter-wave resonator (QWR) cryomodules (CM) downstream of the IH tank 5 to boost the isotopes with $A/q \leq 7$ to 2 MeV/u. TRIUMF has been in collaboration with VECC to develop the QWR CM.

DESIGN

The VECC CM is a top loading CM based on the ISAC-II low energy section design. The major change from the ISAC-II concept is separating the RF space vacuum from the isolation space. The CM consists of four SC QWRs and one 7 T SC solenoid. The cavity frequency is specified at 113.61 MHz and the cavity geometry β is selected at 5.5% for maximizing the transit time factor (TTF) in the energy range from 1 MeV/u to 2 MeV/u. The general cavity geometry is the same as ISAC-II low β cavity, including a coaxial structure with a diameter ratio of 1/3 and a flat short plate that has been demonstrated to eliminate high level multipacting (MP) barriers (~ 1 MV/m) in ISAC-II [2]. The beam aperture region has been redesigned to accommodate the specified geometry β and to minimize the peak surface field ratio. The iris shape is the axisymmetric nose cone to simplify the manufacture. The vertical steering effect in QWR is to be corrected by aligning the cavity aperture axis below the beam axis by 0.76 mm at 4 K. The resonant frequency is tuned by adjusting the cavity length on the coaxial axis. The distance from the tip of the inner conductor to the tuner plate on the bottom is optimized to achieve the frequency tuning sensitivity at 2.5 kHz/mm. The optimized RF parameters include $E_{peak}/E_{acc} = 4.7$, $B_{peak}/E_{acc} = 8.7$ mT/(MV/m), R/Q = 490 Ω and the geometry factor at 21 Ω. The cavity is specified to operate at 6.6 MV/m and to provide 1 MV effective voltage with < 10 W RF loss. The cavity is made with RRR > 250 niobium, while the helium jacket is made with reactor grade niobium to avoid differential thermal contraction and to act as a Meissner shield at 4 K against the fringe magnetic field from the solenoid. The cavity is mounted on the strong-back and connected to the helium space via the thick stainless-steel top flange that also supports the mechanical damper in the inner conductor to mitigate the microphonics.

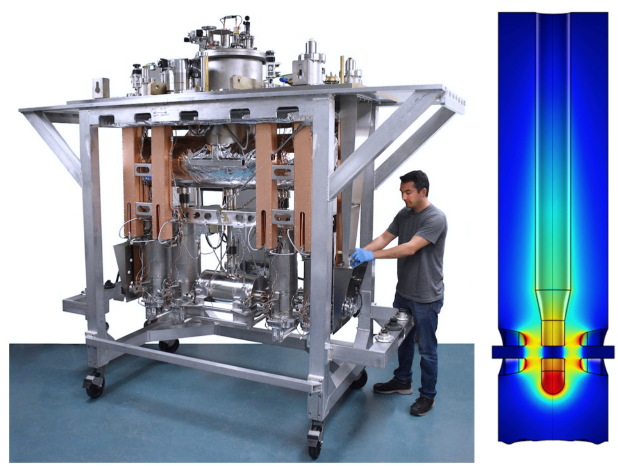

Figure 1: VECC QWR CM in the dirty assembly area (left), and the QWR geometry with the electric field distribution (right).

A few design changes have been developed to accommodate the separated vacuum. Niobium-titanium alloy (NbTi) flanges are added to the beam pipes and the RF ports and are sealed with diamond shaped aluminium gaskets. A set of hermetic variable loop RF coupler and RF pickup has been developed. The cavity bottom assembly is also redesigned. A 1 mm niobium tuning plate is attached the cavity bottom flange as ISAC-II QWR to close the RF volume. A thick stainless-steel flange is sealed with indium to the cavity bottom flange separately to provide the hermetic seal. The tuning plate connects to the tuner lever via the bellow assembly in a small space. The cavity beam port and the tank wall are connected with a warm-cold transition (WCT) with the double-layer bellows and an 80 K intercept with the liquid nitrogen (LN2) shield. The multilayer insulation (MLI) is wrapped on the liquid helium (LHe) reservoir above the strong back, and on both interior

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and exterior surfaces of the LN2 shield. Optical alignment targets are added to the cavities and the solenoids.

Some special features, such as the frame around the solenoid and the block on the side of the cavity bottom assembly shown in Fig. 1, have been added in the consideration of shipping the CM from Vancouver to Kolkata. They will be attached to the vacuum tank through a set of the internal shipping fixtures to stabilize the cold mass. An external double-layer frame with the spring dampers will be assembled to the outer surface of the vacuum tank to mitigate the mechanical shocks in the transportation.

The project launched in 2018 with the cavity and cryomodule design. The QWRs are processed with 120 µm buffer chemical polishing (BCP), high pressure rinsing (HPR) and 48 hours low temperature baking at 120 °C. The cavity performance was qualified in the cryostat tests in 2020. The hermetic string assembly, the lid assembly and the final CM assembly were conducted through 2021. The CM commissioning has been completed in the pit of ISAC-II cleanroom in 2022 to verify the vacuum, diagnostics, alignment, cryogenic and RF performance. The beam commissioning will be performed in VECC.

COMMISSIONING

Cryogenic Performance

Before the CM cooldown, the vacuum in the RF space and the isolation space is established to the acceptance level at room temperature and three pump and purge cycles are completed in the helium space. The LN2 pre-cooling is started 24 hours prior to the LHe cooling. The cavity temperature is above 250 K before LHe. During the LHe cooldown, the cavities experience between 20 minutes and 70 minutes durations in the temperature range from 200 K to 50 K, determined by the helium distribution lines in the CM. The cavities and the solenoid take about 3.5 hours to achieve 4 K. LHe starts accumulating in the helium reservoir after 7 hours. The CM is fully thermalized after 3 days at 4 K. Then the heat loads are measured.

The LN2 supply is controlled by a manual valve in the cleanroom. The valve is adjusted with small steps to reduce the LN2 flow while maintaining the exhaust temperature below 100 K. After thermalization, the LN2 consumption is measured with a gas flow meter at room temperature and under atmosphere pressure on the exhaust side. The gas flow is 1 L/s that is equal to 5.1 L/hour liquid consumption.

The LHe static load is measured by the falling level method. The LHe supply is shut off and after the helium pressure settles the liquid level in the helium reservoir is recorded as a function of time. A calibration with a 12 W heater is performed to crosscheck the vaporization calculation. Both methods result in a 9.3 W static load, which is 30% less than that of the ISAC-II Phase-I CM [3]. The dynamic heat loads are measured in one individual cavity at the operating gradient in both matching regime and over coupling regime. The results are included in the following RF sections.

Alignments

A telescope, installed in the test bunker, is used to check warm and cold alignment after full thermalization. The acceptance was verified by the beam transportation simulation with a beam of A/q = 7 and accelerated at -25° phase in the TRACK code [4]. The emittance growth is around 0.5%, and the beam exits the CM with an angle of 0.5 mrad in the vertical direction and off-axis by 0.4 mm in the horizontal direction. Steerers downstream of the CM will manage the corrections.

Cavity Qualifications

When the cavities are submerged in LHe, the resonant frequency is checked, and the frequency tuning range is defined by setting the positions of the limit switches and the hard stops in the tuner motor assembly. All cavities' frequencies are on target and each cavity has a tuning range of 15 kHz with a ±3 mm movement on the tuner plate. The external Q of the variable loop coupler is verified in the range from 2×10^4 to $> 2 \times 10^9$ to accommodate the conditioning, operation and Q measurement purposes.

The RF tests are preceded by MP conditioning. The coupler is pushed all the way in to maximize the coupling. A few watts forward power is driven to the cavity in continuous wave (CW). Typical barriers occur at gradients of 15 ~ 30 kV/m, ~ 35 kV/m and ~ 100 kV/m, and are fully removed in between 40 minutes and 1 hour.

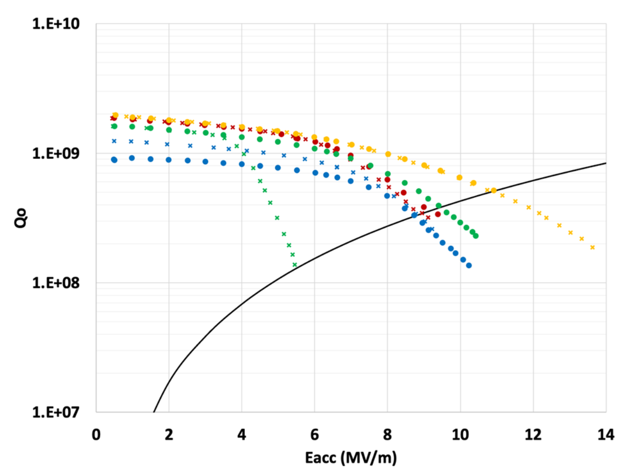

Figure 2: Q_0-E_{acc} curves in CM commissioning. Cavity #1 – #4 are represented in the colour of red, yellow, green and blue respectively.

The variable coupler allows the critical coupling to the cavity and to obtain the Q_0 versus E_{acc} curve in the CM commissioning, shown in Fig. 2. An initial set of measurements is indicated with the cross markers. A second set after helium conditioning is indicated by the circle markers. The base Q_0 of all cavities is $> 1.2 \times 10^9$. Initially cavity #3 had a rigid field emission barrier with an onset level at 3.5 MV/m and a field of 5.4 MV/m at 10 W RF loss. The high-power pulse conditioning could not clean the emitter. Helium is added from vapour boil-off through a leak valve. The helium pressure in the RF space is adjusted to 3×10^{-5} Torr. The cavity is pulse conditioned in helium gas

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with ~ 200 W peak forward power and 5% duty factor. The first field emission barrier was overcome in 30 minutes, then the second barrier was observed and conditioned in another 30 minutes. After the cavity #3 performance was restored, a new field emitter was obtained in the downstream cavity (#4) by means of the vacuum flow. The helium pulse conditioning was also applied to the cavity #4. After conditioning completed, the helium gas was pumped out.

All cavities meet the operating requirement of 6.6 MV/m with < 10 W RF loss. The surface resistance of the cavity #4 in the low field regime increased by 5 nΩ after the helium conditioning, while other cavities maintained the same values. The cause of the base Q change is to be uncovered. Regarding to the high field performance, the cavity #1 in red colour quenches at 9.4 MV/m, but the other three cavities do not quench at the highest gradient points > 10 MV/m.

The dynamic heat load on cavity #2 at the gradient of 6.6 MV/m with the critical coupling is 1.3 W by the falling level method and 1.5 W by RF measurement. The pressure sensitivity and the Lorentz force detuning coefficient are -1 Hz/mbar and -2 Hz/(MV/m)^2 respectively.

In Operating Regime

In the operating regime test, the coupler is used in over coupling regime to broaden the RF bandwidth (~ 20 Hz) for the low-level RF (LLRF) control. The forward power in this regime is adjusted to 200 W, while the RF power loss in the cavity is a few watts. The RF on the cavity drive path is in the full reflection regime. The reverse power is dumped in a dummy load via a RF circulator. The cavity is regulated by the feedback control of LLRF. The amplitude loop and the phase loop are locked to an external 113.61 MHz reference signal for > 30 minutes on each cavity. There was no obvious phase error growth during the tests even without active frequency tuning.

The dynamic heat load on cavity #2 in the operating regime is 1.6 W, compared to 1.3 W in the critical coupling condition. This indicates that the heat load from the coupler in the operating regime is within specification (< 1 W LHe load).

Magnetic Pollution

The SC solenoid achieves 7 T with 79.8 A current with no cavity performance degradation even after cavity quench. The niobium jacket as a Meissner shield against the solenoid fringe field functions as expected.

Thermal cycling tests are done during solenoid testing to determine the level of trapped flux.

In the first thermal cycle, the solenoid was ramped down to 0 A current directly after 7 T operation, the LHe supply was shut off, then the cavities were warmed up above the superconducting transition by the heaters attached to the cavity bottom, while the solenoid was maintained below the critical temperature. After the cavities reached 15 K, the LHe supply was reopened to cool the cavities back to 4 K. There were measurable Q degradations in all cavities after the thermal cycle. The reductions in Q were 18%, 35%, 31% and 11% respectively from the upstream cavity to the downstream one. The magnitudes of the degradations were consistent with the distance of the cavity to the solenoid. It proves that the cavities trap flux due to the magnetic pollution from the solenoid. However, even the degraded cavities still meet the requirement of < 10 W at 6.6 MV/m.

Before the second thermal cycle, the solenoid was powered up to 7 T, then ramped down to 0 A through a degaussing cycle. The supplied current of the solenoid was decreased to 0 A, then increased to 75% of the previous value in the opposite polarity. The cycle was repeated, and the magnitude of the drive current reduced gradually until it converged to 0 A. Then the cavities were thermal cycled again as described above. After the thermal cycle with the degaussed solenoid, the cavities' performances were fully restored to the original values. This 4-hour process is the recommended restoration procedure in case that a cavity is degraded by flux trapping during operation.

CONCLUSION

The VECC QWR CM was developed, produced and recently commissioned at TRIUMF. The CM is vacuum tight both at room temperature and when cooled to 4 K. The static helium loss is 9.3 W. The LN2 usage is consistent with 5.1 L/hour. All cavities' performance exceeded specifications after RF conditioning. Cavities ran in the operating regime for at least 30 minutes without any issue. The solenoid was commissioned up to 7 T. The impact of the solenoid on the cavity Q was measured. With the successful commissioning, the SRF team is in the preparation of shipping the CM to VECC in this year.

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