CRYOGENIC, MAGNETIC AND RF PERFORMANCE OF THE ISAC-II MEDIUM BETA CRYOMODULE AT TRIUMF

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Abstract

The medium beta section of the ISAC-II Heavy Ion Accelerator consists of five cryomodules each containing four quarter wave resonators and one superconducting solenoid. The first cryomodule has been designed, assembled and cold tested at TRIUMF. All cavities have been locked at the ISAC-II frequency and gradient for extended periods. This paper will report the cryogenic and rf test results from the three cold tests. Of note are measurements of the magnetic field in the cryomodule and estimations of changes in the magnetic field during the test due to trapped flux in the solenoid and magnetization of the environment.

INTRODUCTION

TRIUMF is now preparing a new heavy ion superconducting linac as an extension to the ISAC facility [1], to permit acceleration of radioactive ion beams up to energies of at least 6.5 MeV/u. The superconducting linac is composed of two-gap, bulk niobium, quarter wave rf cavities, for acceleration, and superconducting solenoids, for periodic transverse focussing, housed in several cryomodules. The initial stage to be completed in 2005 includes the installation of a transfer line from the ISAC DTL ($E = 1.5$ MeV/u) and the medium beta section to produce 20 MV of accelerating voltage for initial experiments.

MEDIUM BETA CRYOMODULE

The vacuum tank consists of a stainless steel rectangular box and lid. All services and feedthroughs are located on the lid. The entire cold mass is surrounded by a forced flow, liquid nitrogen cooled, thermal shield. The shield consists of several Cu panels riveted together to form a box with 10 mm ID Cu tubing soldered to the panels to form a serial LN2 circuit that also cools the coupling loops. After soldering the panels are nickel plated to improve emissivity. A μ-metal magnetic shield, consisting of 1 mm Conetic panels is attached to the inside of the vacuum tank outside the LN2 shield. A single LN2 panel and μ-metal shield suspended from the lid make up the top thermal and magnetic enclosure respectively. The μ metal is designed to suppress the ambient field by a factor of twenty. Cavities and solenoids are suspended from a common support frame itself suspended from the tank lid (Fig. 1). Each cryomodule has a single vacuum system for thermo-isolation and beam acceleration. The cavities must be aligned to within 0.4 mm and the solenoid to 0.2 mm. A wire position monitor (WPM)[2] system has been developed to monitor the position of the cold mass during thermal cycling.

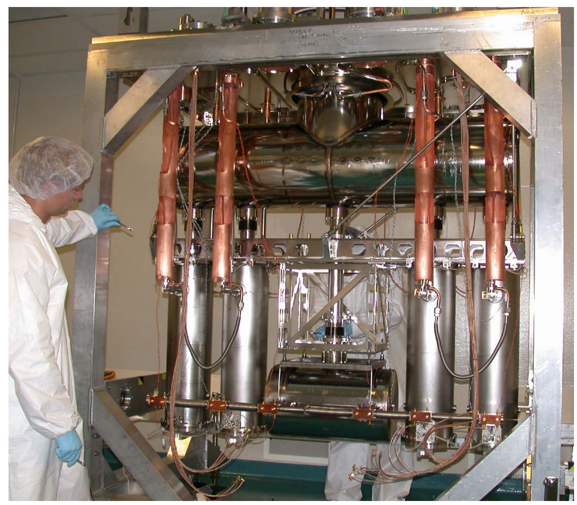

Figure 1: Cryomodule top assembly in the assembly frame prior to the cold test.

The ISAC-II medium beta cavity design goal is to operate up to 6 MV/m across an 18 cm effective length with $P_{\rm cav} \leq 7$ W. The gradient corresponds to an acceleration voltage of 1.1 MV, a challenging peak surface field of $E_p = 30$ MV/m and a stored energy of $U_o = 3.2$ J and is a significant increase over other operating heavy ion facilities. To achieve stable phase and amplitude control the cavity natural bandwidth of $\pm$0.1 Hz is broadened by overcoupling to accomodate detuning by microphonic noise and helium pressure fluctuation. The chosen tuning bandwidth of $\pm$20 Hz demands a cw forward power of $\sim$200 W ($\beta \simeq 200$) and peak power capability of $\sim$400 W to be delivered to the coupling loop. A new coupler has been developed[3] that reduces the helium load to less than 0.5 W at $P_f = 200$ W. The tuning plate on the bottom of the cavity is actuated by a vertically mounted permanent magnet linear servo motor at the top of the cryostat using a 'zero backlash' lever and push rod configuration through a bellows feed-through[4]. The system resolution at the tuner plate center is $\sim 0.055\mu$m (0.3 Hz). The solenoids are equiped with bucking coils to reduce the fringe field in the adjacent cavities to <50 mT.

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CRYOMODULE TESTING

The cryomodule assembly and commissioning tests are conducted in the clean laboratory area in the new ISAC-II building. Single cavity cold tests in a small cryostat confirmed the initial cavity parameters. Three cold tests have been completed. An EPICS based control interface is used to interact remotely with the cryomodule systems during the test.

An initial cold test I in April 2004, without rf ancillaries installed, characterized cryogenic performance and determined the warm off-set required to achieve cold alignment. In cold test II the integrity of the rf and solenoid systems were checked as well as the repeatability of the intial cold alignment. In cold test III the cavities were prepared for final installation with a final high pressure water rinse before reassembly with machined alignment shims. During this third test the cryomodule was outfitted with an alpha source and acceleration was demonstrated for the first time.[5]

Alignment The position of the cold mass as monitored by the WPM at three cold LN2 temperatures is repeatable to within $\pm 50\mu$m vertically and $\pm 100\mu$m horizontally. Due to the different materials involved the solenoid experiences more vertical contraction, with 4.4 mm at LN2 and 5 mm at LHe temperatures while the cavities contract 3.3 mm at LN2 and 3.8 mm at LHe temperatures. For beam dynamics reasons we require the cavity beamport centerline to be 0.75 mm below the beam centerline as defined by the solenoid. Cold tests I and II results show that final alignment is achieved by aligning the cavities while warm to (0,0,0,0) horizontally and (+0.28,+0.38,+0.38,+0.28) vertically with the solenoid at $(x, y) = (0, 0)$. Optical targets are then placed in the upstream and downstream solenoid bore for cold test III. The beam axis is defined by optical targets on the beam aperture of the tank. Adjusters located on the lid are used to align the solenoid targets to the beam axis targets after cooling the cold mass.

Cryogenics The helium transfer line fits to a manifold in the helium space that delivers helium in parallel to a series of 3 mm tubes that are routed to the bottom of each of the cold mass elements. This system works well to efficiently cool the cryomodule. At a total flow of 75 ltr/hr the cavities cool together at a rate of 100°K/hr while the solenoid cools at a rate of 20°K/hr due to its larger mass. The static load on the helium in the three tests is measured to be 11W, 16W and 13W respectively. The differences are due to the variations in the internal cabling and equipment used in each test. The final value of 13 W is representative of the load for the on-line system and compares well to estimates during the design phase. The LN2 flow required to keep the side shield less than 100°K is $\sim 5\ell$/hr matching design estimates.

Cavities and Solenoid The cavities are first baked at $\sim 90^\circ$C for 24 hours. The cold mass is pre-cooled with LN2 to about 200°K before helium transfer. The quality factor of each cavity is determined by measuring the time constant of the field decay in pulsed mode at critical coupling. The Q_0 values for Test II, presented in Table 1, are similar to those measured in the single cavity cryostat indicating that the μ-metal reduces the remnant magnetic field to a sufficient level. In the first rf test (cold test II) the solenoid is ramped up to 9 T with cavity 2 and 3 ON. The cavities remain ON and the measured Q_0 values do not change. The solenoid and cavities are then warmed above transition. After a subsequent cooldown the cavity Q_0 values are again measured. There is no change in the values showing that fields induced by the solenoid in the region of the cavities are tolerably small.

Table 1: Cavity performance during cold test II and III.

Test	Cavity 1 $Q/10^9$	Cavity 2 $Q/10^9$	Cavity 3 $Q/10^9$	cavity 4 $Q/10^9$
II	1.5	1.4	1.5	1.3
III-1	1.25	1.03	1.42	1.13
III-2	0.745	0.89	1.17	0.76
III-3	0.41	0.20	0.19	0.28
III-4	1.12	0.76	1.18	0.75

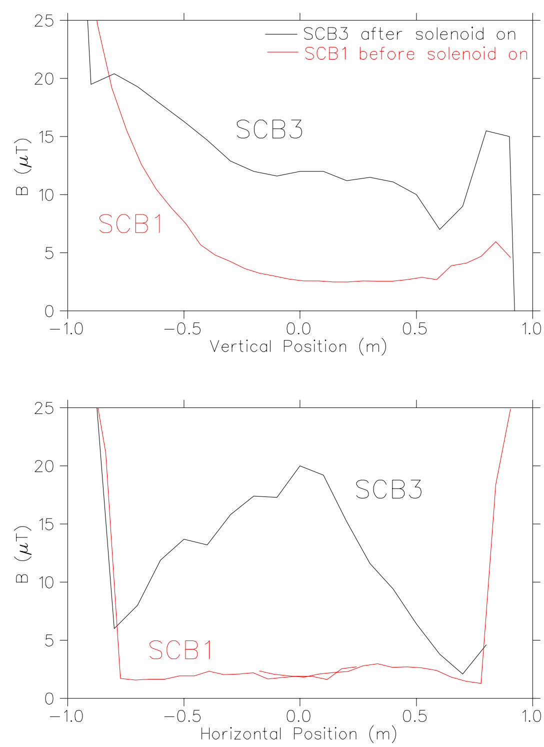

Figure 2: Longitudinal and vertical magnetic field maps inside cryomodule SCB3 (warm) after Test II compared to a mapping on new cryomodule SCB1.

After Test I the cold mass is removed from the cryomodule and the top plate is relaced by sheets of μ metal. The remnant field inside measured longitudinally at the beam axis and vertically in the cryomodule (-1 is at the top) are shown in Fig. 2. Also plotted are values from new cryomodule SCB1 after assembly and before powering the solenoid. Note that the fields in SCB3 are significantly higher especially in the middle of the cryomodule in close proximity to the solenoid. It appears that the solenoid is magnetizing the μ metal enclosure or the nickel in the LN2 sield. In subsequent tests a hysteresis cycling of the cryomodule will be employed to reduce the remnant field. Since $R_s = \Gamma/Q$ and $\Gamma = 19\Omega$ then typical R_s values are in the range of 15-20 nΩ. The magnetic component to the surface resistance is estimated by $R_{\rm mag}({\rm n}\Omega) = 3\sqrt{f({\rm GHz})}B(\mu{\rm T}) \simeq B(\mu{\rm T})$ for 106 MHz. A field higher than 5μT will jeopordize performance.

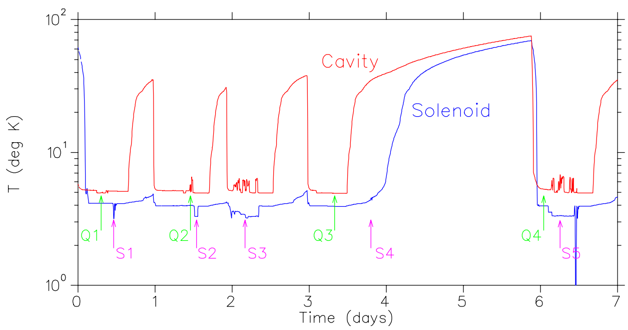

Figure 3: Temperature history of cavities and solenoid during Test-III. Q1-Q4 indicate the time of the Q_0 measurements reported in Table 1 and S1-S5 indicate solenoid 'on' periods.

In test II Q_0 values are taken periodically and the results are reported in Table 1. We attribute the large range in values to trapped flux in the solenoid. Since the modules are filled from dewars the cryomodules are allowed to warm overnight. Fig. 3 gives the temperature of the solenoid and cavities during the test. Labels Q1-Q4 indicate the time of Q measurements corresponding to III-1 to III-4 in Table 1. Labels S1-S5 indicate powering of the solenoid. The cavity temperatures rise above transition during the night but portions of the solenoid remain below tansition. In addition for cases S1, S4 and S5 a hysteresis cycling of the solenoid occurs. For cases S2 and S3 no cycling is done. Taking the Q_0 values for case III-1 as a base and assuming the subsequent reduction in Q_0 is due to an increase in $R_{\rm mag}$ gives an estimate of the magnetic field increase. The resulting estimations are summarized in Fig. 4. Note that the field increase is largest near the solenoid.

RF Control and Tuning A new EPICS GUI interface provided remote tuning control for the four cavities during Test-III. All four cavities were locked at ISAC-II specifications, $f = 106.08$ MHz, $E_a = 6$ MV/m with a coupling $\beta \simeq 200$ for tuning bandwidth. Stable operation was maintained for several hours. Tuner operation is tested by forcing pressure variations in the helium space. The tuner plate position of the four cavities during one perturbation cycle is shown in Fig. 5.

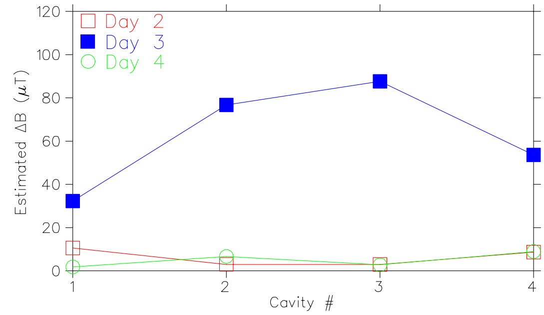

Figure 4: Estimated change in background magnetic field at times corresponding to Q2-Q4 compared to field at Q1.

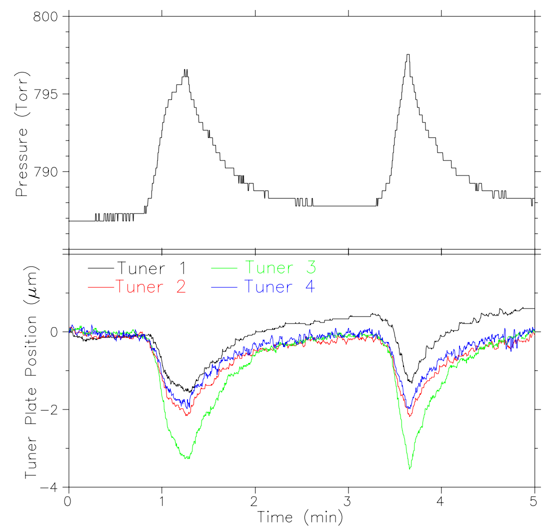

Figure 5: Tuner position response for forced pressure fluctuations in the helium space. The cavity gradient is 6 MV/m with a bandwidth of $\pm$20 Hz.

CONCLUSIONS

SCB3 is now full characterized and the performance is within specification. We will continue to monitor the internal magnetic field of future cryomodules in order to better control remnant field from the solenoid. The rf control systems and tuner are working well to maintain lock on the cavities.

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