Magnetic Field Studies in the ISAC-II Cryomodule

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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 bulk niobium resonators and one superconducting solenoid. The 9 T solenoid is not shielded but is equipped with bucking coils to reduce the magnetic field in the neighbouring rf cavities. A prototype cryomodule has been designed and assembled at TRIUMF. The cryomodule vacuum space shares the cavity vacuum and contains a mu-metal shield, an LN2 cooled, copper, thermal shield, plus the cold mass and support system. Several cold tests have been done to characterize the cryomodule. Early operating experience with a high field solenoid inside a cryomodule containing SRF cavities will be given. The results include measurements of the passive magnetic field in the cryomodule. We also estimate changes in the magnetic field during the test due to trapped flux in the solenoid. Residual field reduction due to hysteresis cycling of the solenoid has been demonstrated.

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 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 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.

The magnetic shield will suppress the local background field inside the module. However the solenoid is a source of strong magnetic field inside the cryomodule. A development study was undertaken to measure the effects of the solenoid operation on the cavity performance.

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

ISAC-II CAVITIES

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 peak surface field of $E_p = 30$ MV/m, a stored energy of $U_o = 3.2$ J and an operating Q of $\sim 5\times10^8$. Since $R_s = \Gamma/Q$ and $\Gamma = 19\Omega$ then typical R_s values are in the range of $\sim 25\ n\Omega$. The magnetic component to the surface resistance is estimated by $R_{\rm mag}({\rm n}\Omega) = 3\sqrt{f({\rm GHz})}B(\mu{\rm T}) \simeq B(\mu{\rm T})$[2]. For 106 MHz, a field higher than 5μT will jeopardize performance. Since typical environmental fields are in the range of 50μT the μmetal was specified to reduce the field by a factor of 20.

SUPERCONDUCTING SOLENOIDS

Besides the external environmental field the cryomodules are also equipped with superconducting solenoids located in the center of the cryomodule. Focussing in the medium beta section is provided by 9 T, 26 mm diameter bore SC solenoids. The solenoids have an effective length of 340 mm and a mechanical length of 540 mm. The magnets are mounted in a liquid Helium vessel fed from the common helium header. Due to the close packing of the lattice the solenoids are equipped with bucking coils to actively limit the fringe field in the adjacent cavity to prevent reduction in cavity performance. The axial field map of the solenoid is shown in Fig. 2 with the fringe field strength highlighted. The map indicates that the fringe field in the cavity region is less than 40 mT.

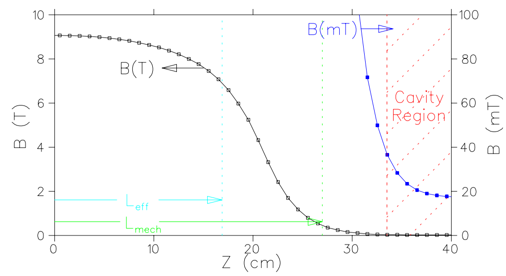

Figure 2: ISAC-II solenoid axial field map showing fringe field in the cavity region.

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. Two cryomodules have been tested so far. Cryomodule SCB3 underwent three cold tests while SCB1 has received one test thus far. Another cold test is scheduled for later this summer. An EPICS based control interface is used to interact remotely with the cryomodule systems during the test.

Cryomodule Magnetic Field

The 1 mm Conetic panels form a box between the outer vacuum vessel and the LN2 cooled thermal shield. The panels are thermally connected to the vacuum vessel to enhance the magnetic suppression. Three dimensional modeling studies predict that the panels should reduce the environmental field by at least a factor of twenty. Field mapping studies are done on the cryomodule with and without the cold mass. When the cold mass is removed the top plate is replaced by sheets of μ metal to form a magnetic box. Measurements with the cold mass in the volume are consistent with cold mass out mappings except for small local magnetic hot spots caused by some fasteners. The empty cryomodule results are reported here. The field measurements are done with a Fluxgate Magnetometer device that measures down to 1μT.

Mappings for three different cases are summarized in Fig. 3. In each case the remnant field is measured longitudinally at the beam axis and vertically in the cryomodule (-1 is at the top). In the first mapping (a) cryomodule SCB3 is measured after the solenoid is ramped up to 9 T then ramped directly to zero before warming. In (b) cryomodule SCB1 is measured after assembly and before powering the solenoid. In (c) SCB1 is measured after the first cooldown where the solenoid was ramped to 9 T followed by a hysteresis cycling procedure to zero before warming. The hysteresis cycle involved driving the solenoid to zero, reversing the polarity and driving the solenoid to half the previous value. This continues until a solenoid current of 1% the original is reached. Note that the fields in SCB3 with no hysteresis cycling are significantly higher especially in the middle of the cryomodule in close proximity to the solenoid. The solenoid is magnetizing the μ metal enclosure or the nickel in the LN2 shield. The hysteresis cycling has effectively reduced the effect of the magnetization.

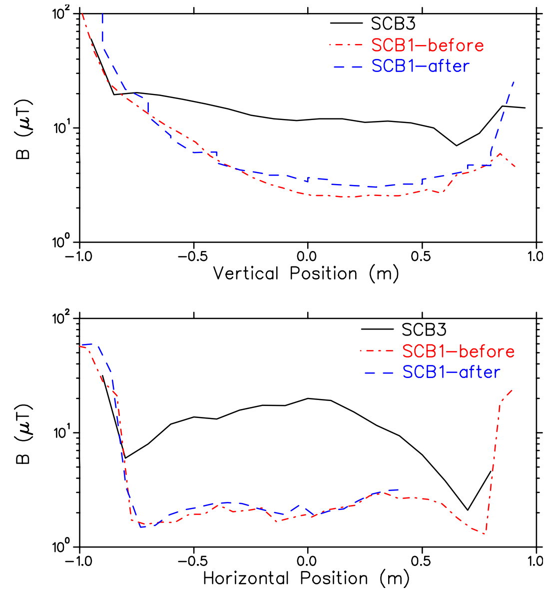

Figure 3: Warm longitudinal and vertical magnetic field maps (a) for SCB3 after solenoid excitation and no hysteresis cycle, (b) for SCB1 before solenoid excitation, and (c) for SCB1 after excitation including a hysteresis cycle.

Cavities with Solenoid

Rf tests on SCB3 were done during the second and third cooldown cycles (Test II and III). The initial Q_0 values of the four cavities measured in Test II are presented in Table 1. They are similar to the values measured in the single cavity cryostat indicating that the μ-metal reduces the remnant magnetic field to a sufficient level. In the first SCB3 rf test 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.

In test III 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. 4 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 the solenoid remain below transition. In addition for cases S1,

Table 1: Cavity performance during SCB3 cold test II and III (see text for explanation).

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

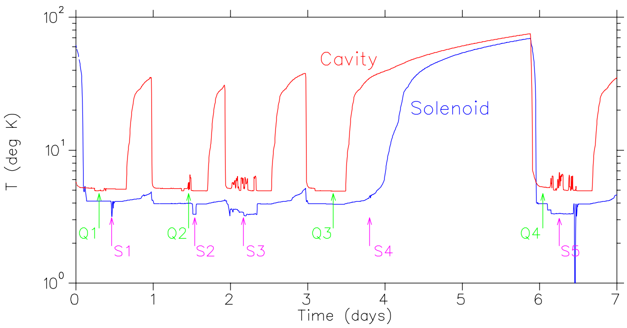

Figure 4: Temperature history of cavities and solenoid during Test-III. Q1-Q4 indicate the time of the Q_0 measurements reported in Table 1 and S1-S5 indicate solenoid 'on' periods.

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_{mag} gives an estimate of the magnetic field increase. The resulting estimations are summarized in Fig. 5. Note that the field increase is largest near the solenoid.

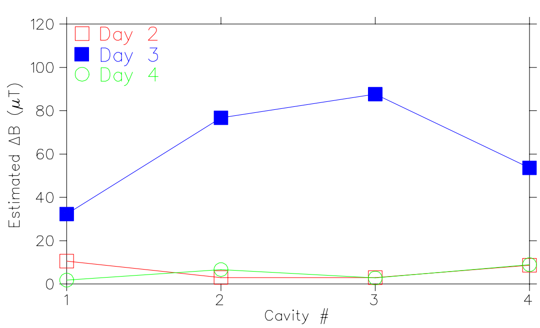

Figure 5: Estimated change in background magnetic field at times corresponding to Q2-Q4 compared to field at Q1.

An independent study confirms the arguments above. During field mapping [3] the on-axis residual field in the solenoid, plotted in Fig. 6 is measured along the axis with a hall probe for three different conditions. In the first the solenoid is powered to 9T then turned off. In the second the solenoid is powered to 9T then turned off after a hysteresis cycle and in the third the magnet is powered to 9T, hysteresis cycled to off and subsequently warmed above transition. Note that while the magnet is cold and off frozen flux adds to the remnant field. The level of frozen flux is reduced through hysteresis cycling but is only canceled with warming above transition.

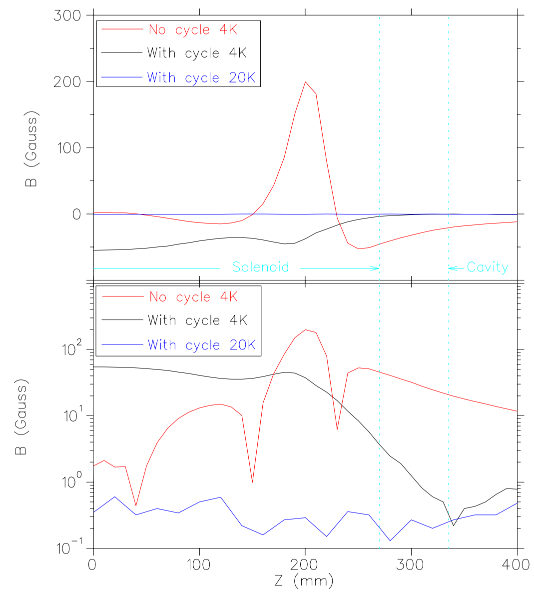

Figure 6: Mapped solenoid residual field for three cases. In (a) the solenoid is powered to 9T then turned off, in (b) the solenoid is powered to 9T then turned off after a hysteresis cycle and in (c) the magnet is powered to 9T, hysteresis cycled to off and subsequently warmed above transition.

CONCLUSIONS

Both warm and cold tests of SCB3 and SCB1 have characterized the performance of the cryomodule magnetic suppression and clarified complications due to operating a solenoid in close proximity to the cavities. The bucking coils reduce the fringe field in the cavity region sufficiently small to operate the cavities even at peak solenoid field without quenching. The solenoid does magnetize the environment when powered however the magnetization can be canceled as long as a hysteresis cycling can be employed. The solenoid is susceptible to frozen flux that can only be canceled if the solenoid is warmed above transition. In such cases where the cavities are warmed above transition and the solenoid remains below transition a hysteresis cycling can render the field in the cavity region sufficiently low to minimize degradation of the cavity Q.

REFERENCES

[1] P. Schmor, et al, "Development and Future Plans at ISAC", LINAC2004.

[2] H. Padamsee, et al, "RF Superconductivity for Accelerators", John Wiley and Sons, 1998, p. 174.

[3] ACCEL, Private communication.