VALIDATION OF LOCAL MAGNETIC SHIELDING FOR FRIB USING A PROTOTYPE CRYOMODULE*

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Abstract

The local magnetic shield design and cryogenic magnetic shielding material for the FRIB QWR cryomodule was validated in a two cavity, one solenoid prototype cryomodule. The magnetic fields were measured inside and outside the magnetic shielding before, during, and after operation of an 8 T superconducting solenoid. The effect of demagnetization cycles of the solenoid was also examined.

The magnetic field at the cavity's high RF magnetic field area, inside the magnetic shield and with the solenoid off, was measured using a single-axis fluxgate to be less than 0.3 µT (3 mG) after cool down of the cryomodule. A 3.07 µT (30.7 mG) residual field was observed at high magnetic field area after conclusion of solenoid operation. This was attributed to the persistent currents circulating in the superconducting solenoid. Demagnetization cycles were therefore determined to be unnecessary for FRIB cryomodules, as long as the solenoid is normal conducting when the cavity is cooled through the superconducting critical temperature.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) shall employ local magnetic shielding around the niobium (Nb) superconducting RF (SRF) cavities in its cryomodules (CM). Each CM shall contain at least one 8 T superconducting (SC) solenoid, made of niobium-titanium (NbTi) wire, whose operation could magnetize components in the CM. The quality factors (Q) of the Nb cavities could degrade if they are cooled through the superconducting critical temperature (T_c) in the presence of magnetic fields from either the earth's magnetic field or from magnetized components. To reduce such degradation, FRIB requires the magnetic field at the surface of the SRF cavity to be less than 1.5 µT (15 mG). Historically, demagnetization cycles are performed using the superconducting solenoid to demagnetize components within the CM prior to warming of the CM. If the local magnetic shields used for FRIB are able to attenuate fields from magnetized components, demagnetization cycles will not be required.

The FRIB solenoid design contains bucking coils, beam steering dipole coils, but does not include any iron yoke. The residual magnetic field of the solenoid package, due to hysteresis in the iron, is therefore expected to be small. In addition, the local magnetic shields are expected to attenuate the fields around the cavities further. In the event of a quench of the cavity during solenoid operation, however, the fringe fields of the solenoid may be trapped in the cavity and degrade Q.

Separate cryogenic tests in a vertical Dewar [1] with only the magnetic shields used in this work, without the cavity or any CM components but in the fringe fields of a 2.5 T superconducting solenoid, displayed sufficient shielding of the fringe fields at the quarter wave resonator (QWR) cavity's high RF magnetic field region.

In this work, the magnetic fields before, during, and after operation of a superconducting solenoid at 8 T, inside and outside the 1 mm thick magnetic shielding, within a prototype QWR CM were measured. The effect of demagnetization cycles of the solenoid on the magnetic field distribution were also examined.

PROTOTYPE CRYOMODULE TEST

The Re-Accelerator 6 (ReA6) is a prototype of a FRIB QWR CM, showcasing the bottom-up design and assembly procedure. This CM was populated with two QWR cavities and one superconducting solenoid, with space for six additional cavities and two additional solenoids. The solenoid used in ReA6 is repurposed from the technology demonstration CM (TDCM), and has shielding coils and bucking coils in series with the main coil. In addition, there are horizontal and vertical corrector dipoles, with individual excitation leads. All the coils of the solenoid were manufactured using NbTi wire. The bucking coils operate in series with the main coil of the solenoid, and reduce fringe fields of the main coil in the longitudinal direction. The shielding coils are also in series with the main coil, but help reduce the fringe fields of the main coil in the radial direction. While the TDCM solenoid has the bucking and shielding coils, the FRIB solenoids shall only have bucking coils to limit the fringe fields along the longitudinal direction. The FRIB requirement for the fringe fields of the 25 cm and 50 cm solenoids at the surface of the magnetic shields is to be less than 24 mT (240 G) and 27 mT (270 G), respectively. Due to the differences in the TDCM and FRIB solenoids, there will be some differences in the fringe field distribution in the FRIB CM as compared to the ReA6 CM. These differences will be mainly in the radial direction and should not significantly affect the fringe fields near the cavities.

Solenoid Excitation

The main coil and the corrector dipoles of the solenoid were excited at 4.2 K to 70.4 A (8 T field) at 0.2 A/s and 40 A (0.06 T·m) at 2 A/s, respectively. After several

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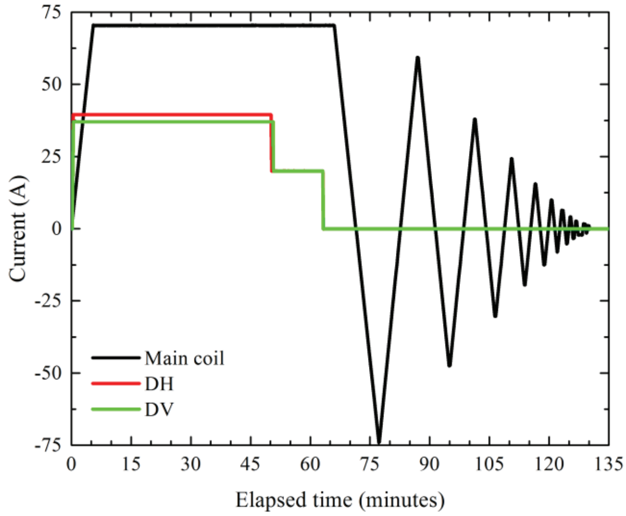

Figure 1: The current profile of the main coil during the 1 h operation with cavities at 2 K (0–65 minutes) and during the degaussing cycle (>65 minutes). The degaussing followed a series of $\boldsymbol{I = (-0.8)^n \times 74}$ A.

initial tests, the solenoid was held at maximum current for 1 h while the cavities were operating at 6.2 MV/m at 2 K. Following the 8 T operation, a demagnetization run was performed. The demagnetization process had 20 steps, following a series of $I = (-0.8)^n \times 74$ A and starting at 74 A, where n was the step number. The current profile of the solenoid coils during the 1 h operation and the demagnetization cycles is illustrated in Figure 1. This process of 8 T operation of the solenoid followed by the degaussing process was performed for a total of three times. The degaussing process using the dipole coils were also performed, but the effect was very small.

Magnetic Field Measurement

One cavity in the ReA6 cryomodule was populated with four single-axis Bartington fluxgates, as illustrated in Figure 2. Two of the fluxgates were type F (0–0.2 μT range) and two were type G (0–2 μT range). One of each type of the fluxgates was placed at the top of the cavity on the side facing the solenoid, near the RF high magnetic field region of the QWR cavity. Another pair was placed near the beam port of the cavity on the side facing away from the solenoid. The type F fluxgates at both locations were placed on the inside of the shield and was mounted to the outside surface of the titanium helium vessel. The type G fluxgates were placed on the outside surface of the magnetic shield, at approximately the same height as the sensors on the inside. The four fluxgates were placed parallel to the vertical axis of the cavity. Since the niobium cavity will expel magnetic field when superconducting, the vertical component of the magnetic field, especially from the solenoid fringe field, is expected to be the greatest component. Therefore, this component was measured.

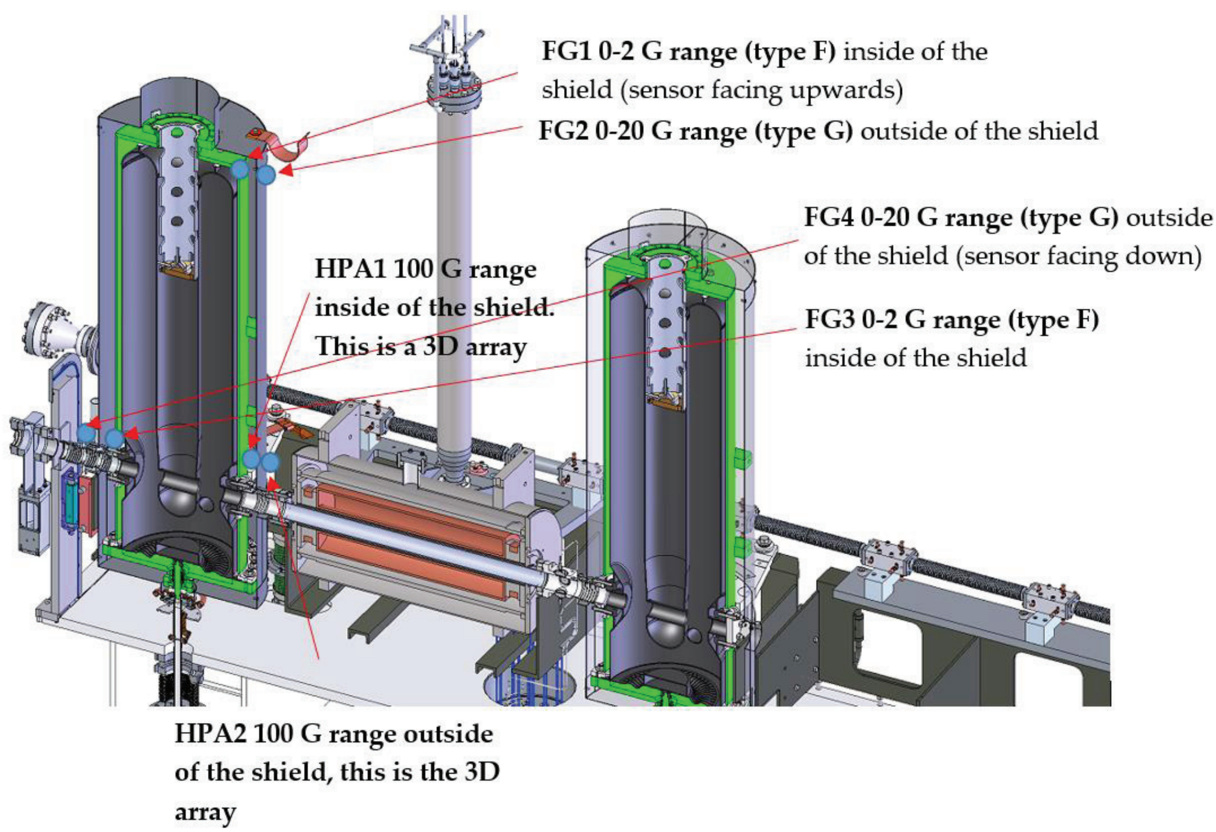

Figure 2: A sectional CAD illustration of the ReA6 CM showing the locations of the fluxgates (FG) and Hall probe sets (HPA) around cavity #1 of the ReA6 cryomodule. The top cover, thermal shields, and cryogenic headers of the CM are hidden for clarity.

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In addition to the fluxgates, six cryogenic axial Hall probes were used. These were arranged to form two sets of three orthogonal sensors. One of the two sets was placed inside the magnetic shield, on the beam port of the cavity facing the solenoid. The second set of 3-D Hall probes was placed outside the magnetic shield, on the beam port of the cavity facing the solenoid. The locations of the described sensors are shown in a sectional CAD illustration of the ReA6 cryomodule in Figure 2. The fluxgates are represented as ‘FG’ and the Hall probe sets as ‘HPA.’ The Hall probes, due to their large range of operation, are not as sensitive as fluxgates in the few µT range. These were therefore used primarily to monitor the fringe fields of the solenoid.

RESULTS

The magnetic fields inside and outside the magnetic shields as measured by the fluxgates before, during, and after operation of the superconducting solenoid package, and after the degaussing processes are tabulated in Table 1. The data are averaged over the three cycles, except for the ‘after cool down’ and ‘after CM warmup’ data. Also tabulated are the magnetic fields after the post-testing warm up of the CM to room temperature.

The measured magnetic fields on the four fluxgates as a function of the degaussing cycle polarity reversal step number is illustrated in Figure 3. The solid symbols represent the fluxgates on the inside of the magnetic shield, while the open symbols represent the fluxgates on the outside of the shield. The fluxgates on the top of the cavity and near the beam port are represented by squares and circles, respectively.

Table 1: The magnetic fields measured by the fluxgates during the different stages of testing. The values, except ‘after cool down’ and ‘after CM warm-up,’ are averaged over three cycles of degaussing.

Process	Magnetic field at fluxgates (µT)			
	Top of cavity		Bottom of cavity	
	In	Out	In	Out
After cool down (shield T=24.5 K)	0.25	0.81	0.30	20.93
During solenoid operation	-16.16 ±0.12	-36.12 ±0.21	165.95 ±2.07	87.20 ±2.02
After solenoid operation	3.07 ±0.06	2.76 ±0.12	1.59 ±0.12	29.09 ±0.03
After full degauss	0.42 ±0.07	0.87 ±0.11	0.05 ±0.17	20.76 ±0.16
After CM warm-up	0 ±0.01	-0.5 ±0.01	0.06 ±0.01	20.50 ±0.01

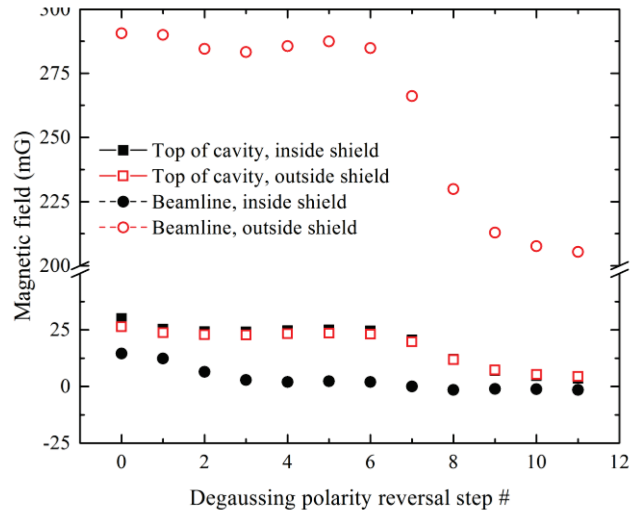

Figure 3: The measured magnetic field as a function of the degaussing cycle steps. The fields were measured using fluxgates on the inside (filled symbols) and outside (open symbols) of the magnetic shield, on the top of cavity #1 facing the solenoid (squares), and on the beamline (circles) port of cavity #1 away from the solenoid.

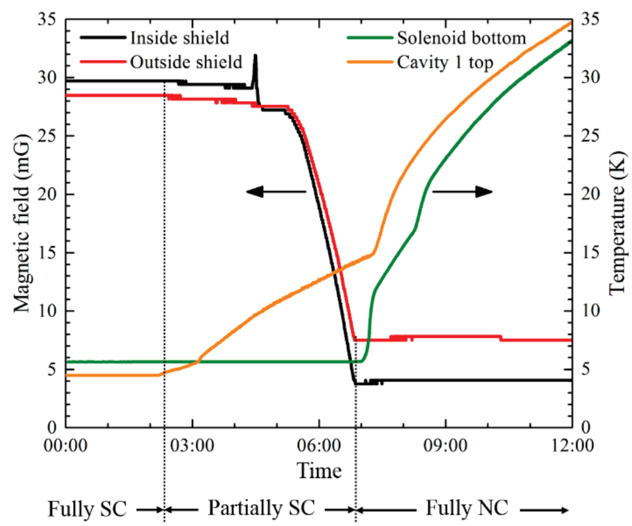

Figure 4: Magnetic field near the cavity high RF magnetic field area and the temperature of the cavity and solenoid helium vessels as a function of time. The deduced state of superconductivity of the solenoid, based on the magnetic field data at the cavity, is also illustrated.

The fields at the cavity high RF magnetic field area, inside and outside the magnetic shield, were measured while the CM was being warmed up to room temperature after the conclusion of testing. The data from the magnetic sensors as a function of time are compared with the temperature of the cavity helium vessel (measured at the top of the cavity) and the solenoid helium vessel (measured at the bottom of the solenoid), and are illustrated in Figure 4. Also illustrated is the deduced state of superconductivity of the solenoid, based on the measured magnetic field data.

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DISCUSSION

The magnetic field data from within the magnetic shielding of cavity 1 of the ReA6 CM indicate that the vertical component of the magnetic field, after cool down of the CM, is less than 0.3 µT (3 mG). Since the earth's magnetic field is angled at 20° from vertical, the vertical component within the magnetic shield is expected to be the greatest. This component is therefore well below the 1.5 µT (15 mG) requirement for FRIB, suggesting that the magnetic shield around the cavities are appropriately designed.

During 8 T operation of the solenoid, the field inside the shield increases to 16.16 µT (161.6 mG). Switching off the solenoid package after the 8 T operation, without degaussing cycles, leads to a residual field of 3.07 µT (30.7 mG). This suggests that either some of the components in the CM have been magnetized, or there are persistent currents circulating in the superconducting solenoid coils.

The degaussing process begins lowering the magnetic field on the inside of the shield especially after the sixth polarity change, and brings it to levels similar to those before the excitation of the solenoid.

Examining the magnetic field data during the warm-up of the cryomodule, illustrated in Figure 4, a significant correlation is seen between the magnetic fields and the temperatures of the cavity and the solenoid. As the cavity transitions through the superconducting critical temperature of niobium, 9.25 K, there is reorganization of the magnetic field profile in the cavity volume. This resulted in the sudden change in the magnetic field, observed only on the inside of the magnetic shield. The change in the magnetic field due to the solenoid transitioning from superconducting to normal conducting state is observed on the inside and outside of the magnetic shield. Since the temperature of the solenoid helium vessel was measured at the bottom of the vessel, an increase in temperature would indicate the absence of liquid helium in the solenoid vessel.

The presence of residual magnetic fields prior to warm up of the CM, of approximately 3 µT (30 mG), on the inside of the magnetic shield is therefore due to the presence of persistent currents in the superconducting solenoid coils. After the solenoid coils are completely normal conducting, the resulting residual magnetic field inside the magnetic shield, near the cavity high RF magnetic shield area, is less than 0.5 µT (5 mG).

Degaussing cycles of the solenoid are therefore not required as long as the solenoid is cycled through its superconducting critical temperature prior to cooling of the cavities to their superconducting state. To be conservative, the solenoid could be required to be normal conducting when the cavities transition from normal to superconducting state.

Although the magnetic shielding for the QWR cavities are validated, these results do not validate the designs for the half wave resonators (HWR). Previous experimental studies using a HWR cavity [2] observed a detectable Q-drop when the cavity quenched in a fringe field of 0.25 mT (2.5 G). Unlike the QWR cavities, the high RF magnetic area of the HWR is very close to the beamline, and therefore close to the solenoid. Further studies are ongoing at FRIB to design effective shielding for the HWR cavities as well.

SUMMARY

The magnetic shielding for FRIB QWR CM was evaluated in the ReA6 prototype CM. Prior to any solenoid operation, the vertical component of the magnetic field at the cavity's high RF magnetic field area, which is expected to be the greatest component, is observed to be no greater than 0.3 µT (3 mG). While the solenoid is operating at its maximum current, the vertical component of the magnetic field at the high RF magnetic field region of the cavity is no greater than 16.16 µT (161.6 mG), which suggests little to no Q-drop if the cavity quenched during the 8 T operation of the solenoid. Residual magnetic fields of 3.07 µT (30.7 mG) were observed at the cavity's high magnetic field area after conclusion of solenoid operation. This residual field was noted to be due to persistent currents in the superconducting solenoid coils, and not due to magnetized components. The demagnetization cycles for FRIB are therefore not required.

REFERENCES

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