SOLENOID/MAGNETIC SHIELDING TEST RESULTS IN FRIB-1&2 CRYOMODULES*

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Abstract

Recently we tested the first two cryomodules for FRIB, which contain $\beta = 0.085$ superconducting quarter-wave resonators and superconducting solenoid packages. Their performance was successfully validated under realistic conditions. This paper reports the solenoid package tests results.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is under construction on the campus of Michigan State University (MSU) [1]. It is a joint project supported by the US Department of Energy and MSU for cutting-edge research in nuclear physics. FRIB requires a 200 MeV per nucleon driver linac with a total of 332 superconducting radio-frequency (SRF) cavities of 4 different types: $\beta = 0.041$ quarter wave resonators (QWRs, 12 cavities), $\beta = 0.085$ QWRs (100 cavities), $\beta = 0.29$ half wave resonators (HWRs, 72 cavities) and $\beta = 0.53$ HWRs (148 cavities). The cavities are housed in a total of 48 cryomodules, including 4 matching cryomodules [2]. The construction started in early 2014 and is expected to be completed in 2022.

In the FRIB cryomodules, superconducting solenoid packages for transverse focusing and steering are interspersed with the cavities. Because of the close proximity, the influence of the solenoid fringe field on cavity performance is a major concern. An example is shown schematically in Figure 1: the $\beta = 0.085$ QWR cryomodule (CM) contains 8 cavities and 3 superconducting solenoid packages. This cryomodule is similar to the cryomodules fabricated for the MSU re-accelerator, ReA3 [3]. An important feature of the cryomodule design is the local magnetic shielding around the SRF cavities [4]. The shields operate at cryogenic temperature ($\simeq 25$ K).

The cavities and solenoid packages are certified individually via Dewar tests prior to assembly onto the cold mass. After assembly of the cold mass into the cryomodule, the cavities and solenoids are tested again in situ. Two FRIB cryomodules have been tested so far (CM-1, CM-2). For the solenoid packages, the goal is to make sure that all of the coils can reach the FRIB design requirements (Table 1), can operate stably and robustly, and do not adversely impact the SRF cavity performance.

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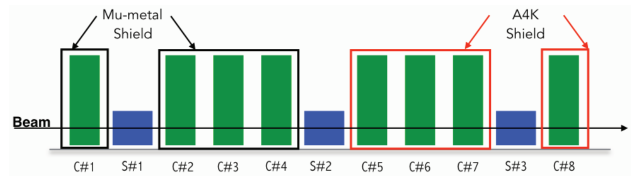

Figure 1: Layout of FRIB-1 Cryomodule (CM-1). C: cavity (green); S: solenoid package (blue). Cavities 1–4 are shielded by mu-metal (black) and Cavities 4–8 are shielded by A4K (red).

Table 1: FRIB 50 cm Solenoid Package Design Requirements. The Fringe Field Requirement Applies at the Magnetic Shield.

Operating temperature	$4.5 + 0.5/ - 0.0$ K
Solenoid nominal current	≤ 90.9 A
$\int B^2 dz$	≥ 13.6 T^2·m
Peak solenoid field on beam axis	≥ 8.0 T
Fringe field	≤ 270 gauss

LOCAL MAGNETIC SHIELD

As discussed above and illustrated in Figure 1, the SRF cavities are enclosed by local magnetic shields. This approach has two benefits: lower material cost for the shields, and better shielding of the cavities from the remnant magnetic field in the cryomodule.

The need to mitigate the fringe field's effect on the SRF cavity performance sets the shield requirements. For the FRIB QWRs, the magnetic field at the cavity must be $\leq$ 15 milligauss. Fringe fields higher than $\simeq 300$ gauss cannot be screened by the shield, hence they will produce a drop in the cavity quality factor after a cavity quench. The magnetic shield requirements are summarized in Table 2.

For the ReA3 cryomodules, the local shields were made of A4K material, with $\mu > 10\,000$ even at cryogenic temperature ($\simeq 25$ K). However, a recent analysis [5] showed that mu-metal of thickness 1 mm with $\mu > 9000$ at $\simeq 25$ K can meet the shielding requirements for the FRIB QWRs. Since cryogenic magnetic shields such as Cryoperm and A4K are very expensive compared to mu-metal, switching to mu-metal is economically advantageous, if mu-metal can provide adequate shielding. To evaluate the shielding perfor-

Table 2: FRIB Magnetic Shield Parameters.

Magnetic permeability μ	$\geq 10\,000$ at 25 K
Thickness	1 mm for QWR

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mance of mu-metal relative to A4K, CM-1 includes shields of both types, as shown in Figure 1.

FRIB SOLENOID PACKAGE

The solenoid package is designed for focussing and steering the beam with fringe field compensation [6]. Figure 2 shows a model of the coils, including the 8 T main solenoid, the two bucking coils for fringe field cancellation, and the two steering dipole coils. The model was made using CST Studio[1]. All of the coils are made of NbTi superconducting wire. The bucking coils are designed to reduce the fringe field to < 270 gauss at the magnetic shield. The bucking coils produce a field of 0.06 T, and are wired in series with the main solenoid, with a nominal current of 90 A [7].

The solenoid packages for CM-1 were fabricated at MSU. CM-2 contains vendor-produced solenoid packages of the same design. The packages have been certified via Dewar tests at MSU.

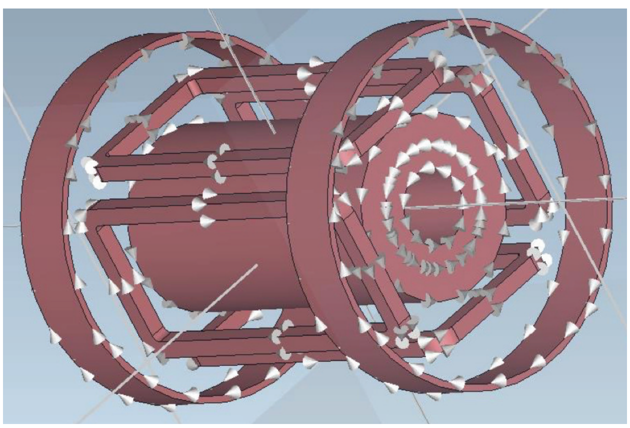

Figure 2: CST Studio model of the 50 cm solenoid package. Inner cylinder: main solenoid; intermediate rectangles: dipoles; outer rings: bucking coils. The diameter is 39 cm.

CRYOMODULE TEST SYSTEM

Figure 3 shows a diagram of the cryogenic circuit for cryomodule testing. The cavities and solenoid packages are cooled via independent supply lines. The cavities are cooled to 2 K and the solenoid packages are cooled to 4.5 K. The current leads for the solenoid and dipoles are made of high-temperature superconductor (HTS) wires, cooled by helium gas from the solenoid header. The helium gas flow rate is controlled with a Proportional-Integral-Derivative (PID) loop based on the measured current lead voltage. As only one set of power supplies is available for the cryomodule test, one solenoid package is energized at a time.

CM-1 SOLENOID PACKAGE TEST

In the CM-1 test, we were able to energize all of the coils in all of the solenoid packages to their operating currents

[1] Computer Simulation Technology AG, Darmstadt, Germany

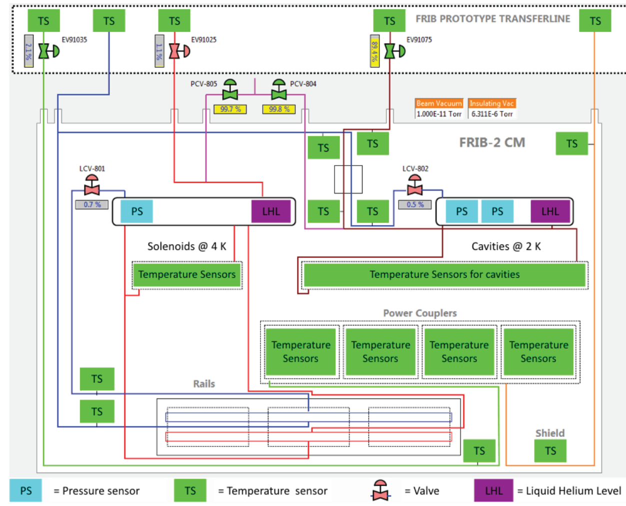

Figure 3: Diagram of the cooling system for cryomodule testing.

(Table 1). The gas cooling of the HTS leads was adequate, with lead voltage drops below 40 mV.

Figure 4 shows the magnet currents as a function of time for one of the solenoid packages during the test. The main solenoid and dipoles were operated individually and collectively. The magnets were ramped to their nominal currents with both polarities (±90 A for the solenoid, ±20 A for the dipoles). Different ramp rates were used, up to 0.5 A/s, to check the PID capability. We observed no magnet quenches during the tests, which indicates that the solenoid packages operate robustly.

The solenoid package and the nearest two cavities were turned on for one hour to test the influence of the solenoid package operation on the cavity performance. This test was repeated for each solenoid package. In all cases, no degradation in cavity performance was observed. This indicates that both mu-metal and A4K provide adequate shielding of

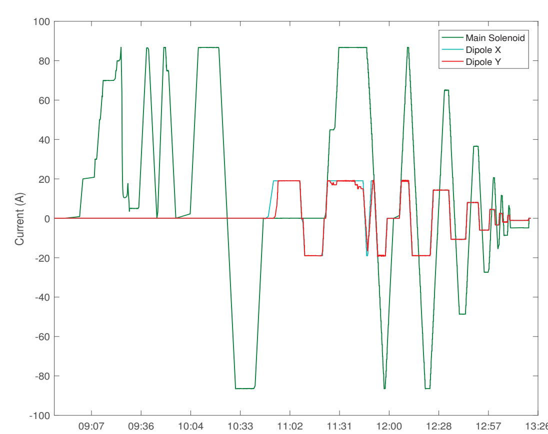

Figure 4: Coil currents as a function of time for part of the solenoid tests in CM-1.

the fringe field. A cavity quench test was not done due to administrative limits on the cavity fields. After the coils were energized, the solenoid package was demagnetized (see the last hour in Figure 4 for an example).

The dynamic heat loads of the cavities at 2 K were measured to evaluate their shielding. The results are summarized in Table 3. No systematic differences were seen between the A4K shields and the mu-metal shields. Thus, the mu-metal shielding of QWRs was successfully validated.

Table 3: Dynamic heat load of CM-1 cavities at 2 K. Measurements were done at the nominal accelerating gradient of 5.6 MV/m (except for C#1, which was at 7 MV/m, having an initially miscalibrated field level).

Cavity	Dynamic heat load (W)	Shielding Material
C#1	6.2	Mu-metal
C#2	2.4	Mu-metal
C#3	2.5	Mu-metal
C#4	1.0	Mu-metal
C#5	2.4	A4K
C#6	2.5	A4K
C#7	2.4	A4K
C#8	2.6	A4K

CM-2 SOLENOID PACKAGE TEST

CM-2 contains the first lot of 50 cm solenoid packages produced from a vendor; all of the cavities are shielded with A4K. The testing procedure for CM-2 was the same as that of CM-1. Figure 5 shows some results from the CM-2 test. All 3 solenoid packages were tested without quenches. The stable and robust operation indicates that the vendor-produced solenoid packages do not affect the cavity performance.

Figure 6 shows an example of the PID control for the He gas flow to cool the current leads as the solenoid is ramped up at 0.3 A/s. The PID control works very well.

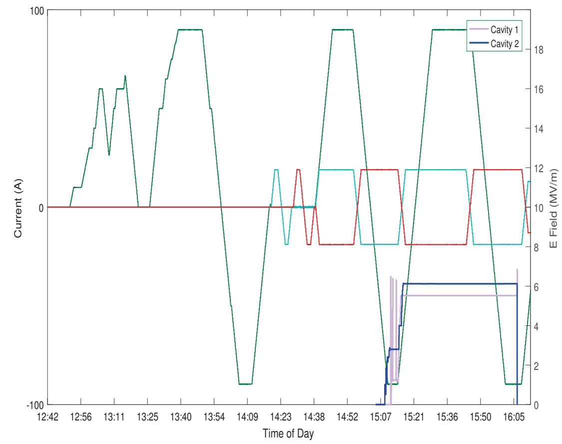

Figure 5: Coil currents as a function of time for part of the solenoid tests in CM-2. The two adjacent cavities were turned on between 15:08 and 16:06.

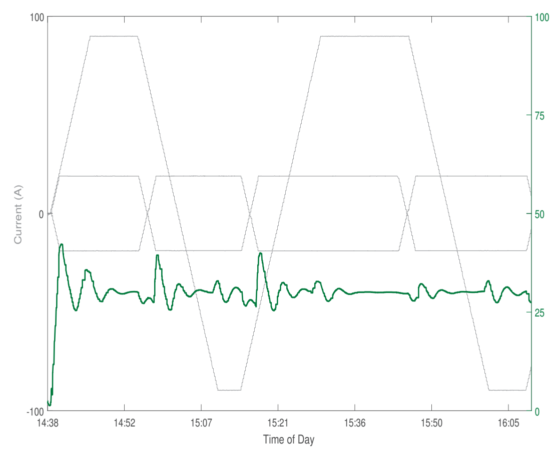

Figure 6: Example of PID control while ramping the solenoid current at 0.3 A/s. The set point is a voltage drop of 30 mV.

CONCLUSION

We successfully tested the solenoid packages in the first two FRIB cryomdules. In the first cryomodule test, we verified that our in-house designed and fabricated solenoid packages meet FRIB specifications for field performance and stable operation. We found that mu-metal is a viable alternative to A4K for local magnetic shielding in FRIB cryomodules. Since the A4K magnetic shields for the FRIB $\beta = 0.085$ cryomodules have already been ordered, we will use mu-metal for other FRIB cryomodules ($\beta = 0.041$, 0.290, and 0.53), which will result in a substantial cost reduction. In the second cryomodule test, we successfully validated the performance and stable operation of vendor-produced solenoid packages.

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