COST REDUCTION FOR FRIB MAGNETIC SHIELDING*

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Abstract

Cryogenic magnetic shielding is generally used in SRF cryomodules which is much more expensive than Mu-metal used in room temperature. In order to reduce the cost, FRIB QWR and HWR magnetic shields were redesign to improve the shielding performance so that Mu-metal can be implemented as an alternative shielding material. The magnetic shielding of first FRIB beta=0.085 cryomodule was made up of 50% by cryogenic magnetic shielding and 50 % by mu-metal. Cavities were tested in 4 K and 2 K, the results showed that the Q_O of cavities were similar for both shielding materials, which is a success as a validation test for Mu-metal magnetic shielding.

INTRODUCTION

For superconducting RF cavity, trapped external magnetic field on cavity surface will increase residual surface resistance and reduce cavity Q (unloaded quality factor). In order to lower the residual surface resistance and get a high Q for SRF cavity, magnetic shielding is implemented in the cryomodule. The requirement for FRIB magnetic shielding is to reduce external magnetic field on cavity surface to make $H_{ext\_average}$ smaller than 15 mG. Under this requirement, there are two efforts made for cryomodule magnetic shielding: (1) Reduction of fabrication cost; we simplify FRIB QWR cryomodules' magnetic shielding assemble by eliminating the hats: (2) Reduction of material cost; we optimized shielding structure for implementing Mu-metal as an alternative shielding material. A prototype of new magnetic shielding design with Mu-metal was made and installed in the first FRIB production cryomodule. It is the FRIB QWR085 cryomodule whose magnetic shielding is composed half by cryogenic magnetic shielding and other half by Mu-metal. Cryomodule tested in 2 K showed no difference in cavity Q for both magnetic shielding materials, which is a success as a validation test for new design with Mu-metal. The second section discusses the reduction of fabrication cost by simplify QWR magnetic shielding. The third section introduces the structure optimized for both QWR and HWR magnetic shielding according to EM simulation. The fourth section compares the performance of cryogenic magnetic shielding and Mumetal in FRIB cryomodule test at 2 K.

REDUCTION OF FABRICATION COST

The original magnetic shielding design for FRIB QWR cryomodule is complex, which has six hats around the holes on magnetic shielding to reduce leaking earth magnetic field. Those hats increases fabrication cost and assembling time, also induces a risk of magnetic shielding degradation during assembly. Thus, the elimination of hats is highly desirable. Figure 1 compares the QWR085 original single cavity magnetic shielding design and the hats eliminated new design.

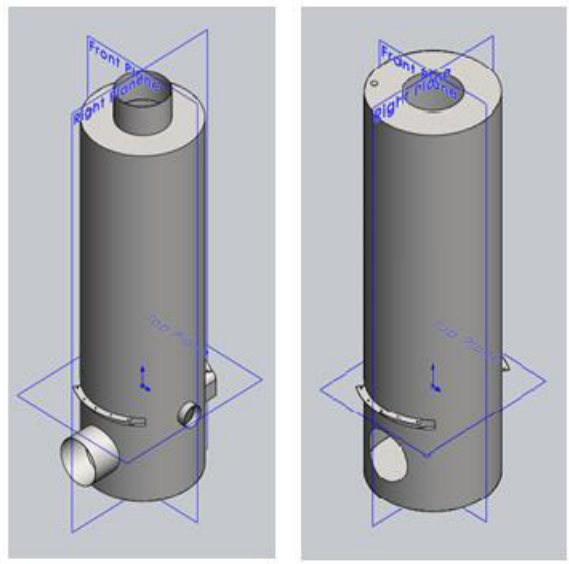

Figure 1: Magnetic shielding with and without hats.

Simulation was done to estimate the Q degradation by earth magnetic field due to elimination of hats. For magnetic shielding with hats, magnetic field on cavity surface are all below 15 mG, while for one without hats, the location near FPC (fundamental power coupler) and Pick-up ports will exceed 15 mG (maximum ≈90 mG, see Fig. 2).

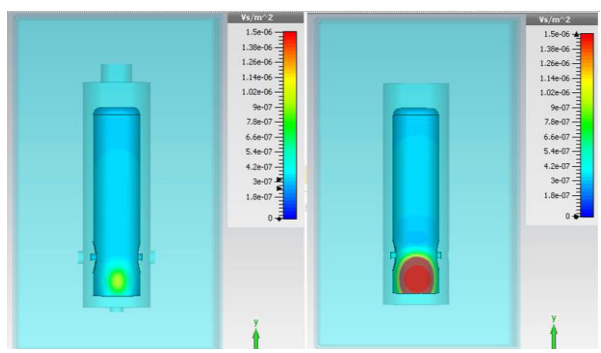

Figure 2: Simulations for shielding with and without hats.

To compare the difference of cavity surface resistance for magnetic shielding with and without hats, we took account the RF H-field distribution inside QWR cavity at nominal gradient. Then, we calculated the additional cavity dissipated power due to earth magnetic field for both magnetic shields by the following equations:

$$R_{res\_mag} = 0.3\ (n\Omega) H_{ext}(mG)\sqrt{f(GHz)} \quad (1)$$

$$P_{loss\_mag} = \frac{1}{2}\int R_{res\_mag}\, H_2 ds \quad (2)$$

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Considering the worst case, P_{loss_mag} with all hats is 67 mW, P_{loss_mag} without hats is 97 mW. Learned from vertical test, the Q_0 of QWR085 at nominal gradient is 6e9, and corresponds to the R_s = 3.7 nΩ, cavity dissipated power P_d is 1.2 W. Taking vertical test as reference and considering the P_{loss_mag}, R_s with hats is 3.9 nΩ, R_s without hats is 4 nΩ. Thus, there is almost no difference in R_s with and without hats.

Based on this analysis, FRIB decided to eliminate all the hats for magnetic shielding of QWR cryomodules.

REDUCTION OF MATERIAL COST

The original material of magnetic shielding FRIB cryomodules is cryogenic magnetic shielding, which is more expensive than common Mu-metal. In order to reduce the material cost, we investigated other potential materials.

A series of simulations were performed with different permeability for QWR085 single magnetic shielding with 1mm thickness, the result is summarized in the Table 1.

Table 1: Simulations of QWR Single Magnetic Shielding

Permeability	$Pd_{\_HEXT}$ [W]	$H_{ext\_average}$ [mG]
2000	1.4	49
4000	0.77	27
8000	0.4	14
32500	0.1	3.5

The equivalent $R_{HEXT\text{-}average}$ and the earth magnetic field $H_{ext\text{-}average}$ was calculated as following:

$$R_{HEXT} = 0.3\,(n\Omega)H_{ext}(mG)\sqrt{f(GHz)} \quad (3)$$

$$P_{d\_HEXT} = \frac{1}{2}\int R_{HEXT}\,H^2 ds \quad (4)$$

$$R_{HEXT\_average} = P_{d\_HEXT}/(\frac{1}{2}\int H^2\,ds) \quad (5)$$

$$H_{ext\_average} = R_{HEXT\_average}/(0.3\,(n\Omega)\sqrt{f(GHz)}) \quad (6)$$

where H_{ext} is earth magnetic field on cavity surface calculated by CST, H is the RF cavity field on the cavity surface calculated by CST, P_{d_HEXT} is the cavity dissipated power due to the residual earth magnetic field.

The requirement of FRIB for $H_{ext\_average}$ is 15 mG, seen in Table 1, in order to meet the FRIB requirement, the minimum permeability for the QWR085 single magnetic shielding is about 8000.

The performance of QWR085 triple magnetic shielding is not as good as single shielding. The minimum permeability required was 16000. An optimization was proposed for the triple shield (Fig. 3), whose required permeability could be decreased to 9000.

New QWR085 shield design meets the FRIB Hext_average requirement (15 mG) by the magnetic shield material with a magnetic permeability >9000.

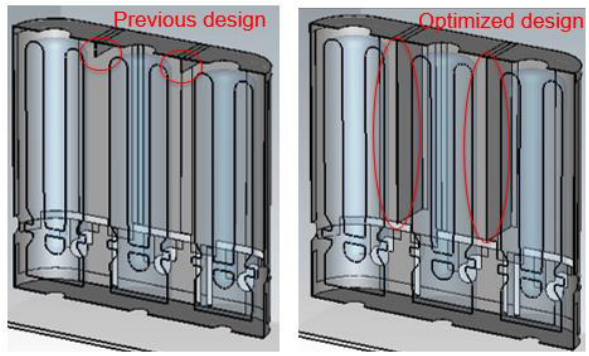

Figure 3: Optimization of triple magnetic shielding for QWRs.

For HWR magnetic shielding (see Fig. 4), similar simulation and analysis was performed.

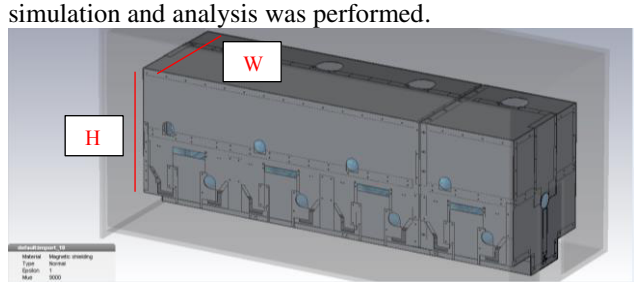

Figure 4: HWR53 magnetic shielding.

Original HWR53 shielding design is 1.5mm thickness, the corresponding minimum permeability required is about 13000.

The performance of single layer cylindrical shielding is well known [1]. Based on it, the magnetic field attenuation of HWR53 shielding (A) was developed as following:

$$A = \frac{\mu\times\Delta}{2\sqrt{W^2+H^2}} + 1 \quad (7)$$

μ is the permeability of the shielding, Δ is the shield thickness, W and H are the shielding dimensions (width and height) shown in Fig. 4.

According to Eq. (7), we need to increase the shielding thickness when we reduced the required minimum permeability for magnetic shielding.

For 2 mm thickness shield (the proximal thickness of Mu-metal shielding provided by vendor), the corresponding critical permeability is 13000 for 1.5 mm and 10000 for 2 mm. To verify this result, a simulation using CST for the shield with 2 mm thick and permeability = 10000 was performed for HWR53 cryomodule magnetic shield (Fig. 5). Though the magnetic field around rising port is higher than 15mG, the $H_{ext\text{-}average}$ is just a little below 15 mG which is consistent with Eq. (7) and also achieves FRIB's requirement.

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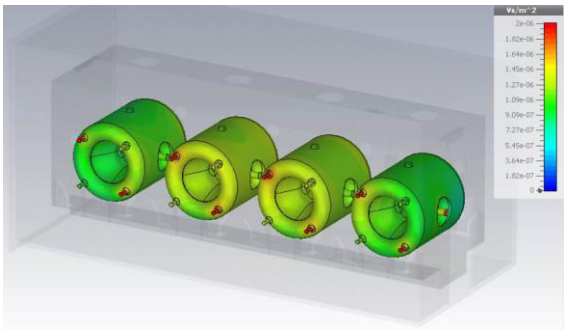

Figure 5: Simulation of HWR53 shielding (2mm thickness with permeability =10000)

Figure 6 shows the KEK's data that the permeability of Mu-metal could be> 10000 at 4 K when the external magnetic field is 500mG. Temperature of the shield is ~ 25 K for the FRIB cryomodule, which expects to improve a little the permeability. In addition FRIB uses a carbon steel vacuum vessel on the cryomodule, which can decrease the external magnetic field to 200~300 mG [2] and the corresponding permeability>15000.

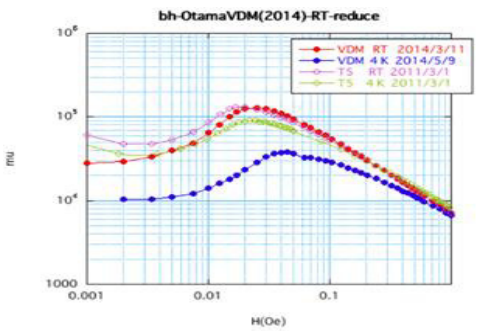

Figure 6: Property of Mu-metal in KEK data [3].

As a conclusion, the magnetic shielding material for FRIB cryomodules should have a permeability > 10000 at ~ 25 K. Since the permeability of Mu-metal can be as high as 15000 with 200~300 mG background field, so it can be an alternative material for FRIB QWR and HWR cryomodules' magnetic shielding.

VALIDATION TEST FOR MU-METAL

In FRIB first production cryomodule (cavity type: QWR085), the magnetic shielding is made up of 50% Mu-metal and 50% cryogenic magnetic shielding (see Fig. 7).

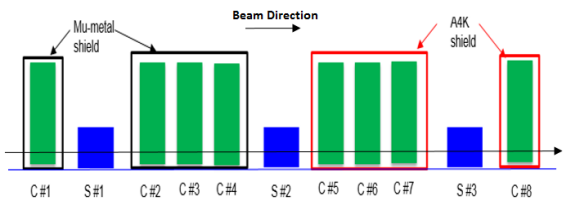

Figure 7: Magnetic shielding distribution in FRIB first production cryomodule.

Cavities were tested at 4 K to validate the cryomodule system including cavities, tuners, couplers, solenoid packages, LLRF control, amplifier and so on. After the success at 4K, it was moved on for 2K test. Cavity dynamic heat load was measured at nominal gradient 5.6 MV/m except for cavity 1 (~7 MV/m) at 2K in Table 2.

Table 2: Cavity Dynamic Heat Load at 2K (C. M. S. = Cryogenic Magnetic Shielding)

Cavity No.	Dynamic Heat Load [W]
1	6.2 (Mu-metal shielded) at 7 MV/m
2	2.4 (Mu-metal shielded) at 5.6 MV/m
3	2.5 (Mu-metal shielded) at 5.6 MV/m
4	1 (Mu-metal shielded) at 5.6 MV/m
5	2.4 (C. M. S. shielded) at 5.6 MV/m
6	2.5 (C. M. S. shielded) at 5.6 MV/m
7	2.4 (C. M. S. shielded) at 5.6 MV/m
8	2.6 (C. M. S. shielded) at 5.6 MV/m

Heat load of cavity 1 was much larger than other cavities. This cavity had a lower Q_0 in the vertical test. In addition cable calibration was wrong in the cryomodule test and we found the operation gradient was ~ 25% higher than other cavities. Mu-metal was applied for cavity 1~4, while cryogenic magnetic shielding is used for cavity 5~8. Known from Table 2, exclude cavity 1, the dynamic heat load of cavities with Mu-metal shielding are almost the same as ones with cryogenic magnetic shielding, which is a success as a validation test for Mu-metal.

CONCLUSION

FRIB QWR magnetic shielding was redesign by eliminating hats to reduce the fabrication cost. New shield designs for both QWR and HWR cryomodules can apply Mu-metal to reduce the material cost. Cavities tested at 2 K on FRIB first production cryomodule showed little difference of cavity Q for cryogenic magnetic shielding and Mu-metal shields. According to the test result, FRIB will use Mu-metal for QWR and HWR magnetic shielding.

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