MAGNETIC SHIELD OPTIMIZATION FOR THE FRIB SUPERCONDUCTING QUARTER-WAVE RESONATOR CRYOMODULE*

Y. Xu#, A. Fox, M. Johnson, M. Leitner, S. Miller, K. Saito, FRIB, East Lansing, MI 48824, USA

Abstract

The Facility for Rare Isotope Beams (FRIB) required 49 cryomodules containing 330 superconducting low-beta resonators, which have to be shielded from the earth magnetic field. Comprehensive magnetic shielding simulations have been conducted for 80.5 MHz β=0.085 cryomodules exposed to earth fields of 0.5 Gauss in different coordinate directions. The magnetic shield has to attenuate the earth magnetic field by a minimum factor of 33 (to less than 15 milli Gauss) in order to limit flux trapping in the resonators during cool-down. In the reported optimization studies, permeability of the magnetic shielding material, shield thickness, and number of magnetic shield layers have been varied. Different design concepts including global and local magnetic shielding have been evaluated. In addition, the design concepts are compared based on the cost of material, fabrication and assembly, the design complexity and compatibility with the overall cryomodule design to obtain an optimum solution.

INTRODUCTION

There are 49 cryomodules that will be built in FRIB: three 80.5 MHz β=0.041 cryomodules, eleven 80.5 MHz β=0.085 cryomodules, two 80.5 MHz β=0.085 matching cryomodules, twelve 322 MHz β=0.29 cryomodules, two 322 MHz β=0.29 matching cryomodules, eighteen 322 MHz β=0.53 cryomodules, and one 322 MHz β=0.53 matching cryomodule.

All cryomodules have to be shielded to attenuate the earth magnetic field in order to limit flux trapping in the cavities during cool-down to less than 15 milli Gauss. Two main different design concepts, room temperature global and low temperature local magnetic shielding as shown in Figure 1, have been compared on 80.5 MHz β=0.085 cryomodule from the attenuation ability, cost of material, fabrication and assembly, to the design and assembly complexity. The global magnetic shield locates between the vacuum vessel and the thermal shield and encompasses the entirety of cold mass, while the local magnetic shield is assembled around the resonators. Two local magnetic shielding designs are compared. One is to shield each resonator with individual shield, the other is to group the nearby resonators as much as possible.

ANSYS Magnetostatic is implemented to study the effects of permeability of material, size of magnetic shield, and the contribution from steel vacuum vessel. The magnetic flux on resonators is obtained to validate the effectiveness of the magnetic shield designs. Finally, Quality Function Deployment (QFD) is applied to compare different design concepts.

*Work supported by US DOE Cooperative Agreement DE-SC0000661
#xut@frib.msu.edu

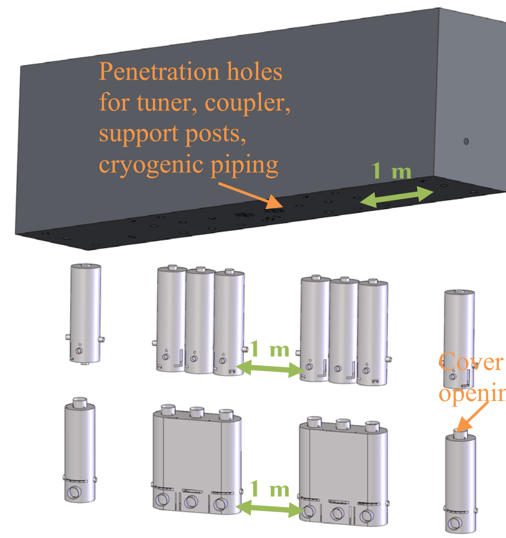

Figure 1: Global shield (top) and local single shield (middle) and local multi shield (bottom).

PERMEABILITY STUDY

The design of the magnetic shield starts with the proper material selection. Magnetic shielding materials should be chosen for their characteristic, usually in respect to permeability and saturation.

Manufacture Data

Amuneal Manufacturing Corporation compares the permeability of two products, Cryoperm 10 and Amumetal, as a function of ambient temperature shown in Figure 2 [1]. Amumetal has the maximum permeability at room temperature and is degraded at cryogenic temperature. Therefore, it is appropriate for the room temperature global magnetic shield. The permeability of Cryoperm 10 reaches its maximum at very low temperature (around 30 K) but is degraded at room temperature. Hence, it is proper for the low temperature local magnetic shield.

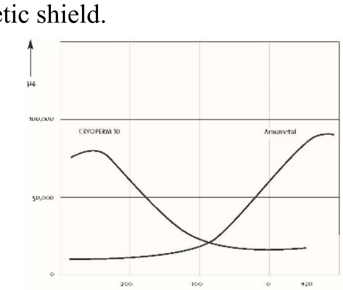

Figure 2: Permeability of Amumetal and Cryoperm 10 versus ambient temperature.

Recently, Amuneal developed a new shielding material Amuneal 4K (A4K) for cryogenic applications. A4K is

ISBN 978-3-95450-138-0

claimed to have higher permeability than Cryoperm 10. Therefore, A4K will be employed in FRIB local magnetic shield design. However, Cryoperm 10 permeability will be utilized in the simulation for the sake of conservativeness.

Table 1 lists the permeability and saturation values of Amumetal and Cryoperm 10. Since a saturated shield is a poor attenuator, the selection of magnetic shield material must have adequate saturation characteristics.

Table 1: Permeability and Saturation

Material	**Saturation (Gauss)**	**Permeability µ Max**	**µ 40**
Amumetal	8,000	400,000	60,000
Cryoperm 10	9,000	250,000	65,000

Measured and Simulation Data

It should be noted that the permeability provided above is the data obtained in the laboratory and has the optimum performance. However, the actual permeability of the shielding material depends on the heat treatment, fabrication and handling process of the material. Studies from CEA show that the actual performance of Cryoperm at low temperature is not as good as the one provided by manufacture. Therefore, simulations on FRIB Cryoperm magnetic shield are conducted at different permeability and compared with the measurement from other labs to determine a practical value of permeability. The comparison is made at the same shield thickness 1 mm.

Simulation of attenuation from FRIB local magnetic shield at different permeability with and without the vacuum vessel, 17500, 32500 and 65000, are displayed in Figure 3. It shows that the attenuation increases as the increase of the permeability. The measurement of CEA provides the attenuation from magnetic shield be 25 and that from both the magnetic shield and vacuum vessel be 100 [2]. In addition, the measurement of FNAL shows that the attenuation from both magnetic shield and vacuum vessel in their cryomodule is 120 [2].

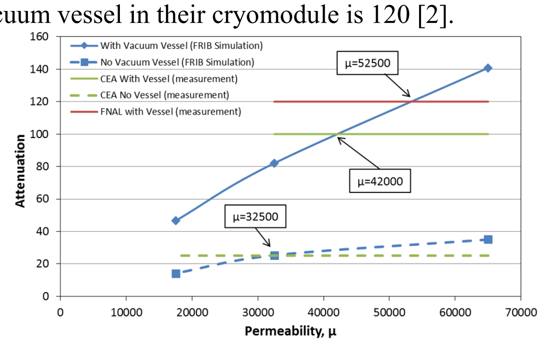

Figure 3: Permeability study.

The length of CEA test magnetic shield is 1.3 m, which is about the same as that of FRIB (1.25 m). Therefore, the performance of CEA and FRIB magnetic shields are similar. Although the permeability is not measured directly, it is reasonable to apply 32500 in the simulation to make direct comparison with the measurement of CEA. The length of FNAL 1.3 GHz cryomodule magnetic shield is 1 m, which is smaller than that of FRIB. Hence, higher attenuation is expected since the smaller the size the better the performance (also explained by Figure 4).

EFFECT OF MAGNETIC SHIELD LENGTH AND THICKNESS

Attenuation simulations on global magnetic shield with full, half, one third and quarter length are conducted and displayed in Figure 4. The shorter the magnetic shield length, the smaller the effective radius of the shield, hence the better its performance. Simulations on thickness 1.6 mm and 3.2 mm shields show that the attenuation increases 1.5 times as the shield thickness doubles. The theoretical study demonstrates that as the decrease of the effective radius of the shield, the attenuation ratio converges to 2 as the shield thickness doubles. For an infinitely large shield, the attenuation converges to 1 and is not affected by the shield thickness and material permeability. Therefore, the attenuation ratio is expected to be between 1 and 2 as the shield thickness doubles.

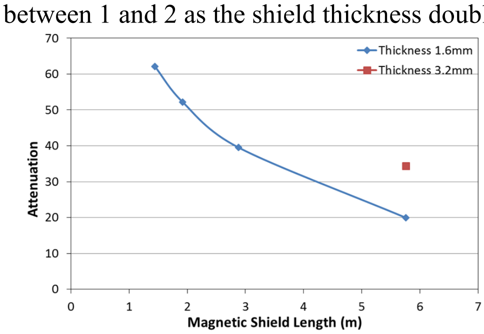

Figure 4: Effect of magnetic shield length and thickness.

STEEL VACUUM VESSEL

The contribution of steel vacuum vessel on the attenuation is displayed in Figure 3. Similar to the magnetic shield, the performance of vacuum vessel also depends on the material permeability, thickness and the vessel size. It can be observed from both the FRIB simulation and the CEA measurement that the contribution from the vacuum vessel is remarkable, especially with thick vessel wall (19 mm for FRIB).

GLOBAL MAGNETIC SHIELD

In the global magnetic shield design, no covers is implemented because of the relative small penetrations. The earth field is 0.5 Gauss in magnitude and varies in different directions for a thorough study. It is found out that the attenuation is the worst when earth field is -30° from the horizontal plane, which is the earth field direction at the FRIB location.

Global magnetic shield simulations are conducted on 1.6 mm, 3.2 mm and two layers of 1.6 mm shields with the contribution of vacuum vessel and the attenuation is 24, 34 and 34, respectively. Two layers of 1.6 mm shield is supposed to have better performance than one layer 3.2 mm shield. However, because of the space limit between the vacuum vessel and thermal shield in FRIB design, the spacing between two layers is very limited. Therefore, the enhancement on performance is not observed.

Since the requirement for magnetic shield is the ability to attenuate the earth field by a minimum factor of 33, single layer of 1.6 mm shield is not appropriate for FRIB QWR cryomodule. The magnetic flux density profile on x-y plane with 3.2 mm magnetic shield is displayed in Figure **5**. Dark blue represents the ***B*** field below 15 milli Gauss. Therefore, 3.2 mm Amumetal global magnetic shield is able to meet the FRIB design requirement.

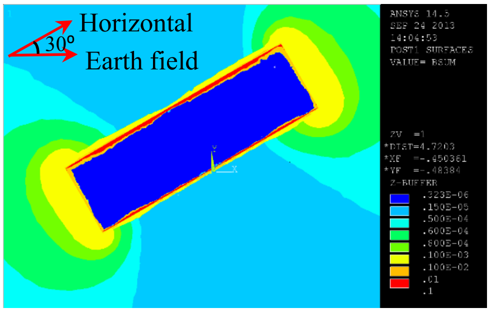

Figure 5: Magnetic flux density with global shield.

LOCAL MAGNETIC SHIELD

The same as the global magnetic shield simulation, the earth field is -30° from the horizontal plane and has magnitude of 0.5 Gauss in both local single shield and combined shield simulations. Tubular covers are necessary for the openings of power coupler, cryogenic supply, beam port and resonator supporting rail penetrations. The height of the cover is proportional to the diameter of the opening since magnetic fields can travel into an opening a distance equal to five times the diameter of the opening.

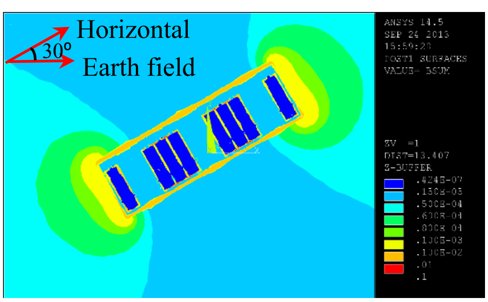

Figure 6: Magnetic flux density with local single shield.

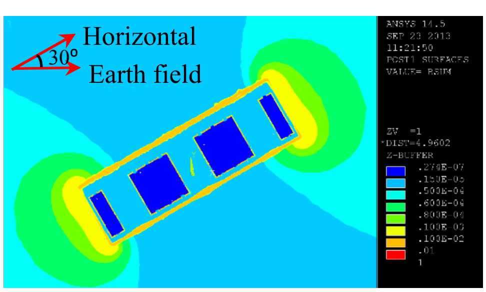

Figure 7: Magnetic flux density with local multi shield.

Simulations on local single shield and local combined shield indicate that the magnetic fields on resonator surfaces in both cases are less than 15 milli gauss (shown in dark blue in Figure 6 and Figure 7).

QFD

Quality function deployment (QFD) is a "method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process." [3] as described by Dr. Yoji Akao, who originally developed QFD in Japan in 1966.

The most important criteria is the inducted field less than 15 milli Gauss at resonator surface. It is shown in Figure 8 that all the designs meet the requirement but with different efforts. Global magnetic shield design requires more effort hence "bad relationship" is specified.

Other important factors include: design, assembly and fabrication complexity; compatibility with design of other systems such as bottom up design, cold mass, thermal shield, vacuum vessel, and cryogenic system; cost including material, fabrication and assembly cost. For example, the cost of 0.125" Amumetal global shield is the highest because of the highest material cost. In addition, the 2 layer 0.062" Amumetal global shield has the lowest compatibility with bottom up design, minimum spacing requirement and post-assembly accessibility to power coupler. In summary, the local A4K magnetic shield is the best design concept, especially with the multi-resonator configuration.

Max Relationship Value in	Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	0.125" Mu-Metal global shield	Single Resonator A4K Shield	Multi-Resonator A4K Shield	2x .062" Mu-Metal shields	0.062" Mu-Metal global shield + A4K local shield
1	3	14.1	10.0	Inducted field is less than 15 mG at resonator surface	▲	O	O	▲	O
2	9	12.7	9.0	Minimal Complexity	Θ	O	O	▲	▲
2	9	11.3	8.0	Cost	▲	Θ	Θ	▲	O
3	9	11.3	8.0	Number of Parts	Θ	O	Θ	▲	O
4	9	12.7	9.0	Compatible with bottom up Design	Θ	Θ	Θ	O	Θ
5	9	12.7	9.0	Accommodates coldmass including FPC & tuner drive penetrations	O	Θ	Θ	O	O
6	9	12.7	9.0	Maintain 1" spacing to the Thermal Shield and 1" Spacing to Vacuum Vessel	O	Θ	Θ	▲	O
7	9	12.7	9.0	Allow for post-assembly access to FPC	O	Θ	Θ	▲	O
				Target or Limit Value					
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	2	3	3	8	5
				Max Relationship Value in Column	9	9	9	3	9
				Weight / Importance	469.0	671.8	739.4	150.7	350.7
				Relative Weight	19.7	28.2	31.0	6.3	14.7

Figure 8: QFD of magnetic shield design concepts (Θ: positive relationship; O: neutral; ▲: bad relationship).

REFERENCES

[1] http://amuneal.com/sites/default/files/AmunealData Sheet2.pdf

[2] FRIB Workshop on Magnetic Shielding for Cryomodules, March 6-7, 2013.

[3] Y. Akao, "Development History of Quality Function Deployment", *The Customer Driven Approach to Quality Planning and Deployment*, Minato, Tokyo 107 Japan: Asian Productivity Organization, pg. 339.

ISBN 978-3-95450-138-0