MAGNETIC MATERIAL CHARACTERIZATION & SC SOLENOID COIL PACKAGE DESIGN FOR FRIB*

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Abstract

To date SRF technology is extending to large scale heavy ion LINACs, where SRF cavities accelerate beams from very low energy to high energy. In this application, superconducting (SC) solenoids are installed inside the cryomodule to provide strong beam focusing with enhanced space efficiency. FRIB will use local magnetic shielding, where magnetic shielding by Cryoperm or A4K is located close to the cavity at 2K. In this scheme rather strong magnetic fringe fields from the SC solenoid expose the shielding material and will magnetize it. An efficient degaussing process is required as a cure for such magnetization. Magnetic material characterization of magnetic shielding is very important to identify effective degaussing procedures. FRIB is designing SC solenoids to optimize for cost, reliability, and robust long-term operation. In this paper the magnetic shielding investigation and SC solenoid design are reported.

CONCERNED ISSUES

When a solenoid is located close to a SRF cavity, several issues are to be considered. In general: 1) how to attenuate not only the earth's magnetic field but also fringe fields from the solenoid on the cavity wall, 2) what kind of magnetic shielding material is best to get good attenuation, 3) how much residual magnetic field strength is allowable for healthy cavity operation, 4) magnetization of component by the fringe field, 5) demagnetization, and so on [1].

FRIB has chosen local shielding scheme because of benefits of reliability in shielding and cheaper shielding material cost. In this scheme, magnetic shielding is located in the vicinity of the cavity and is exposed to cryogenic temperatures. Cryogenic magnetic shielding material like Cryoperm or A4K should be used. To get high Q, the earth's magnetic field must be attenuated to less than 15mG
around the cavity wall before the cavity gets into Meissener state. Local shield allows this using 1.0mm thick cryo-magnetic shielding compared with 3.2mm thick μ-metal global shielding [2], which results in cost reduction.

At the cold cryomodule operation, solenoid is energized to 8T (FRIB) after cavity gets into Meissen state. By FRIB current solenoid package design which includes a main solenoid coil, X-Y dipole SC steering coils, and iron yoke, the fringe field from the solenoid is estimated to be about 130 G on the cavity wall at beam axis under 8 T operation as shown in Table 1 [3].

Table 1: Fringe Field in Various Schemes with FRIB CM

Solenoid Model	Bucking coil	Iron Yoke	Fringe field By at z* = 27cm	Fringe field By at y = 30cm
A	NO	NO	~900G	~ 220G
B	YES	NO	~ 70G	~ 35G
C	NO	YES	~ 130G	~ 45G

*z is defined as beam axis direction, the numbers were calculated for 9 T in [2] and scaled for 8T in this table.

Annealing Effect

Q drop by exposing cavity to a fringe field does not occur up to 2500G if cavity has not quenched [4]. On the other hand, when a cavity quenches under a fringe field, Q drop occurs. The degree of this Q drop depends on the fringe field strength. However, it can be recovered by performing quench processing without solenoid field, so called annealing effect [5]. This effect has been confirmed in MSU with β=0.53 HWR up to 50G of fringe field, maybe possible up to 100G or more. If this effect is available up to more than 130G, cavity handling will be easy in recovering Q drop by cavity quench under operation, any warm up is not needed for the cavity.

FRIB Concerns

FRIB concerns are: 1) how much magnetization in the magnetic shield after the solenoid is energized to 8 T, 2) can fringe fields be attenuated sufficiently by local shielding so as to not have significant Q drop. 3) Magnetization of components in the vicinity of the cavity and their demagnetization. To answer these questions, we have started a magnetic shielding material characterization program, whose details are in the next section.

MAGNETIC SHIELD MATERIAL CHARACTERIZATION

B-H Curve Measurement

AC B-H curve measurements were performed on three magnetic shielding materials: μ-metal, Cryoperm and A4K. Figure 1 shows the room temperature measurement setup. The data acquisition system is fully computerized.

The AC B-H curve measurement method conformed to

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the ASTM (American Standard Testing Materials) code [6]. This method is showed in Figure 2. The applied AC field H[Oe] can be calculated by the equation (1), where N_1 is the number of turns of excitation coil, I_{rms} is the AC root mean square current, and ℓ[cm] is the average length of the excitation coil. The induced AC magnetic flux density B[G] is calculated by equation (2), where V_{avg} [V] is the AC average voltage, N_2 is the number of turns on the pickup coil, f[Hz] the frequency of the current, and A[cm^2] the cross-sectional area of the sample. Table 2 shows the parameters used in this measurement.

$$H = \frac{0.4\pi\sqrt{2}N_1 I_{rms}}{l} \quad (1)$$

$$B = \frac{10^8 V_{avg}}{4fN_2A} \quad (2)$$

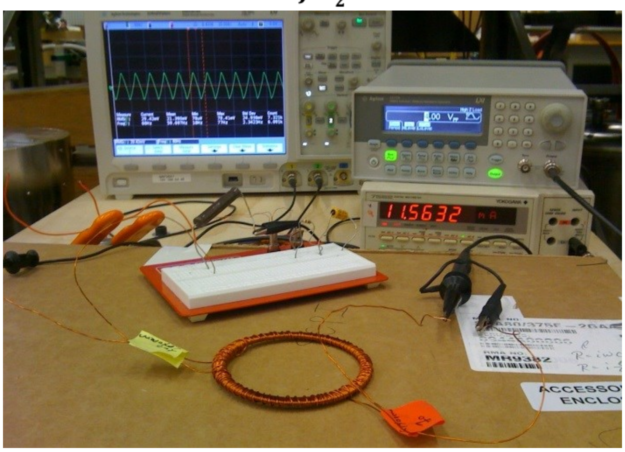

Figure 1: B-H curve measurement system at room temperature.

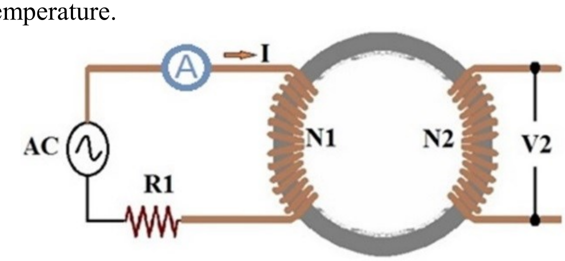

Figure 2: B-H curve measurement method by ASTM.

Table 2: B-H Curve Measurement Parameters

Shape	Circular Ring
Thickness of sample [mm]	1.0
Inner Radius of the sample[mm]	33.0
Outer Radios of the sample [mm]	37.0
N_1[Turns]	320
N_2 [Turns]	335
ℓ [cm]	22.0
Cross-section A [cm^2]	0.04
R_1 [Ω]	50

Figure 3 shows the AC B-H curve measurement at room temperature, 77 K and 4.2 K for A4K material. Current (I) is limited in this measurement by the safety regulation in MSU. As a result, H was measured up to 1.7 Oe The permeability is defined at 4.5 mOe applied magnetic field, which is followed to the company definition (Amuneal Manufacturing Co.) to compare the result easily.

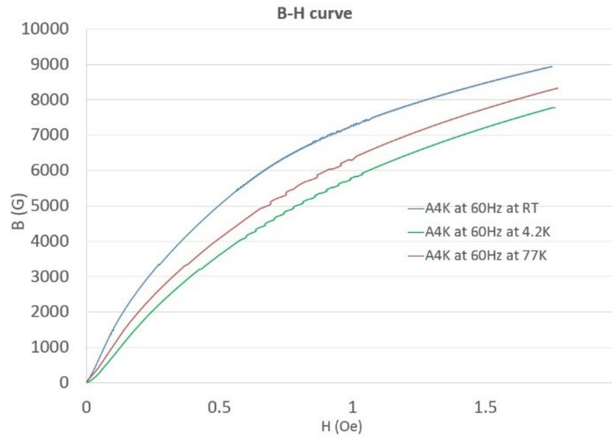

Figure 3: B-H curve at RT, 77 K, and 4.2 K for A4K material.

DC Magnetic Permeability

In cryomodule, the solenoid operates in DC mode. To evaluate the DC magnetic permeability, frequency dependence of the AC magnetic permeability was measured at below 70Hz as seen Figure 4, which is for A4k at RT, 77 K, 10 K, and 4.2 K.

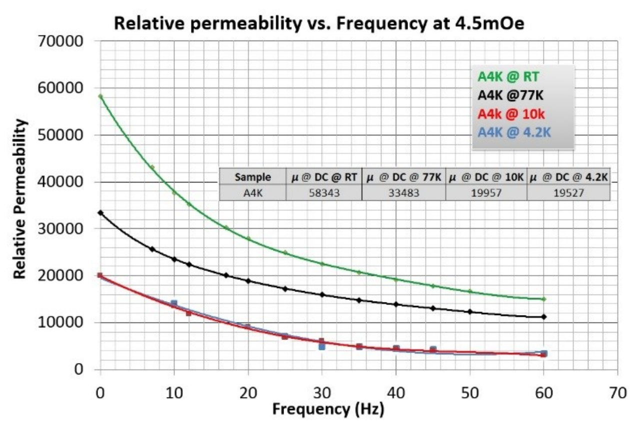

Figure 4: Frequency dependence of relative permeability (μ) at 4.5mOe for A4K material at RT, 77K, 10K, and 4.2K.

DC permeability was calculated by curve fitting the data in this graph and extrapolating to zero frequency. The temperature dependence of the relative permeability (μ) is presented in Figure 5 for A4K. Vendor provided values for μ displayed enhancement of μ at cryogenic temperatures [7]. This is not the case for this sample. Cryogenic magnetic shielding material property is sensitive to annealing history. The sample measured in this work might not have the same processing history as the one used to determine Vendor values. Efforts are being made to contact the Vendor to gather more information about the annealing history. Additional samples with the best processing history will be measured in the future.

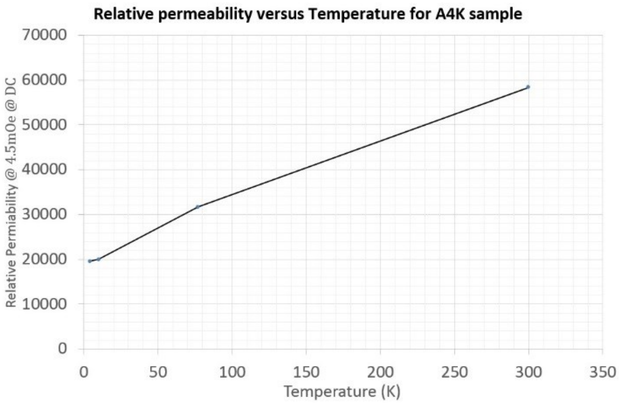

Figure 5: Temperature dependence of μ at 4.5 mOe with A4K material.

MAGNETIC SHIELDING TEST

Magnetic Shield Attenuation Test at Room Temperature

Direct magnetic field attenuation measurements are planned both for room and cryogenic temperatures. Figure 6 shows a solenoid coil, capable of producing a fringe field of several hundred Gauss at room temperature. A real cavity magnetic shield will be exposed to the fringe fields at various strengths and the field attenuation will be measured. The fixture to map the fields using flux gauges is currently being fabricated. The measurements are estimated to begin in October 2013.

Figure 6: Magnetic shielding test at room temperature.

Magnetic Shield Attenuation Test at Cryogenic Temperature

Figure 7 shows an insert for magnetic field attenuation measurement at cryogenic temperature. The magnetic shielding seen in this figure is the same one used for ReA acceleration QWRs, which is made of Cryoperm. A 2kGauss SC solenoid has been already fabricated, which will be put alongside the shield (blue area in the figure). Several magnetic flux gauges will be attached to the outside and inside of the shield to compare the magnetic field strength by exciting the solenoid at cryogenic temperatures. We are preparing the experimental space for this experiment. This experiment will start from middle of October 2013.

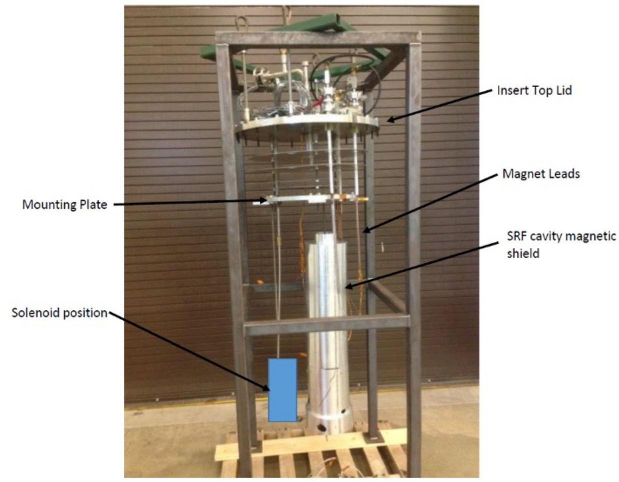

Figure 7: A magnetic shielding insert for magnetic attenuation measurement at cryo-temperatures.

8T SC SOLENOID

We are prototyping an 8T SC solenoid in parallel to the magnetic shield material investigation. 9T solenoids were to be used in FRIB original linac optics design, but it is too critical on the current density limit for NbTi wire in 4.5 K operation, with very little margin (0.1 K). The design has been reconsidered and changed to 8 T applying constant beam size optics [8].

FRIB cryomodule needs 6 pieces of 8T SC 25 cm solenoid packages for low β=0.041 section and 63 pieces of 8T SC 50cm solenoid packages for high β=0.085-0.53 sections [8]. These solenoid packages consist of an 8T main solenoid, two corrector dipole coils for X-Y directions, and iron yoke inside the helium vessel.

8T Main Solenoid Design

In order to estimate the cost of the FRIB solenoid packages with high accuracy, solenoid prototyping has been started under MSU/KEK collaboration. 8T 25cm SC solenoid cold mass is being designed, which includes an 8T SC 25cm solenoid with bobbin (Figure 8) and two SC

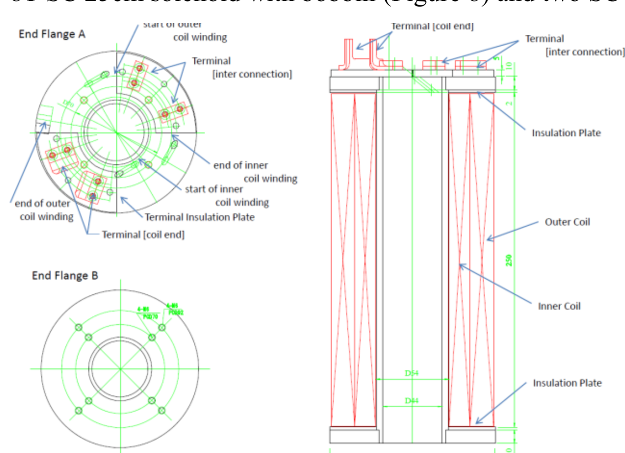

Figure 8: 8 T SC 25 cm main solenoid design.

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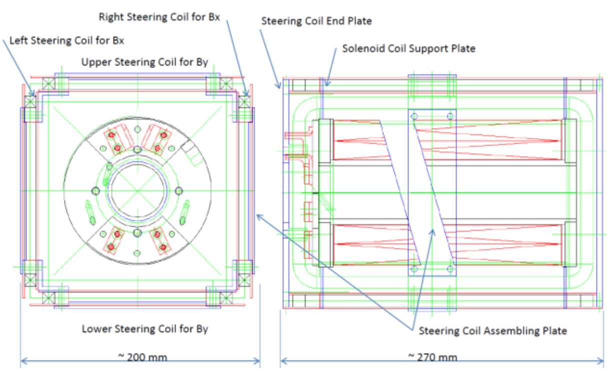

Figure 9: 8 T 25 cm solenoid cold mass with steering dipole coils.

25cm dipole coils (Figure 9). The bobbin has been completed and fit checked at KEK (Figure 10).The solenoid design is summarized in Table 2.

Status of Prototyping

8 T 25 cm solenoid prototyping is starting at KEK. Solenoid bobbin parts were already fabricated and fitting check was completed on the winding machine. Solenoid winding work and cold test of the main solenoid itself is planned in October 2013.

Table 2: 8T SC Solenoid Design Parameter

Operation Temperature (K)	4.5
SC Wire	NbTi
Number of different wire for grading	2
Solenoid coil length(cm)	25/50
Core Diameter (mm)	46
B_{max} (T)	8.13
B_O (T)*	8.10
Integrated B2 (T^2m)	
Solenoid operation current (A)	100
Operation temperature margin (K)	0.3
Correction dipole field (T)	0.6
Correction dipole current (A)	40

* Defined as maximum field on beam axis

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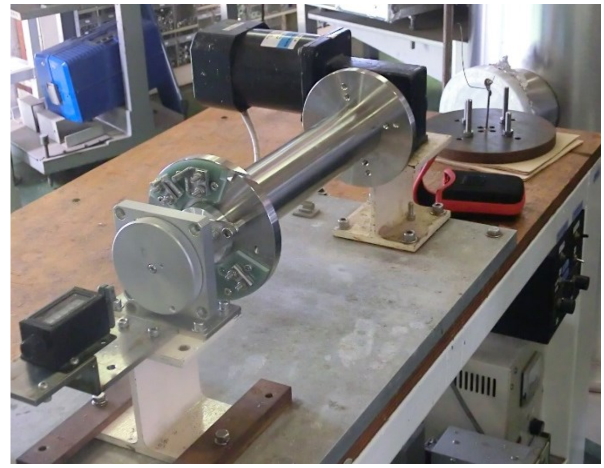

Figure 10: Completed bobbin for 8 T 25 cm main solenoid.

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