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Magnetic Materials Characterization and Modeling for the Enhanced Design of Magnetic
Shielding of Cryomodules in Particle Accelerators.

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of
Philosophy in Mechanical and Nuclear Engineering at Virginia Commonwealth University.

By

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May 2016

Dedication

This dissertation is dedicated to my family.

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I would like to express my sincere gratitude to my doctoral committee: Dr. Jayasimha Atulasimha, Dr. Ganapati Rao Myneni, Dr. Sama Bilbao y León, Dr. Afroditi V. Filippas and Dr. Jessika Rojas for supporting me with their expertise and guidance to maneuver through my research project. A special appreciation and thanks to my PhD advisor Dr. Jayasimha Atulasimha for his continued encouragement, advice and guidance for my research and career goals. He is truly an amazing mentor one could wish for. I would also like to thank Dr. Ganapati R. Myeneni for permitting my choice of this project and supporting me in abundance through Jefferson Lab. I would especially like to acknowledge Dr. Sama Bilbao y León for the travel upkeep to attend magnetic shielding workshop at the facility for rare isotope beams. I appreciate her remarkable and thoughtful advice on numerous occasions. I would also like to thank my previous advisor Dr. B. Hinderliter at the University of Minnesota, Duluth, for the earlier discussions regarding my Ph.D. research topic. I would like to acknowledge M. Adolf at Amuneal Corporation for providing me with free Amumetal, A4K samples and for helping with the annealing process. Finally, I would like to acknowledge Nanomaterial Core Characterization at VCU for letting me use VSM. I extend my gratitude to Prof. R. Greene and Dr. S. Saha at the University of Maryland for letting me use SQUID Magnetometer. It is with all this organization and supervision that my project has received its direction and has reached its completion.

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ABSTRACT

Title of the Document: **Magnetic Materials Characterization and Modeling for the Enhanced Design of Magnetic Shielding of Cryomodes in Particle Accelerators.**

Sanjay K. Sah, Doctor of Philosophy, 2016

Directed By: Dr. Jayasimha Atulasimha,
Department of Mechanical and Nuclear Engineering
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Particle accelerators produce beams of high-energy particles, which are used for both fundamental and applied scientific research and are critical to the development of accelerator driven sub-critical reactor systems. An effective magnetic shield is very important to achieve higher quality factor (Q_0) of the cryomodule of a particle accelerator. The allowed value of field inside the cavity due to all external fields (particularly the Earth's magnetic field) is ~15 mG or less. The goal of this PhD dissertation is to comprehensively study the magnetic properties of commonly used magnetic shielding materials at both cryogenic and room temperatures. This knowledge can be used for the enhanced design of magnetic shields of cryomodes (CM) in particle accelerators. To this end, we first studied the temperature dependent magnetization behavior (M-H curves) of Amumetal and A4K under different annealing and deformation conditions. This characterized the effect of stress or deformation induced during the manufacturing processes and subsequent restoration of high permeability with appropriate heat treatment. Next, an energy based stochastic model for temperature dependent anhysteretic magnetization behavior of ferromagnetic materials was proposed and benchmarked against experimental data. We show that this model is able to simulate and explain the magnetic behavior of as rolled, deformed and annealed amumetal and A4K over a large range of temperatures. The experimental results for permeability are then used in a finite element model (FEM) in COMSOL to evaluate the shielding effectiveness of multiple shield designs at room temperature as well as cryogenic temperature. This work could serve as a guideline for future design, development and fabrication of magnetic shields of CMs.

CHAPTER 1. Introduction

This dissertation describes research performed towards the experimental understanding and modeling of the temperature dependent behavior of magnetic shielding materials (Amumetal and A4K, Ni-based ferromagnetic super alloys commonly known as permalloys) under different manufacturing conditions. The experimental data obtained from the characterization of these materials was used for the benchmarking of a model for temperature dependent magnetization model developed by us to account for defects and anisotropies. The experimentally obtained permeability values were used in the finite element analysis using COMSOL for multiple designs of magnetic shields for C-100 cryomodules at Thomas Jefferson National Accelerator Facility. In this section, we will begin with a background on general magnetism, magnetic shielding materials, magnetic permeability, magnetic characterization, stochastic energy based ferromagnetic magnetization model and FEM analysis of magnetic shields using 3-D COMSOL Multiphysics.

1.1 Magnetism and magnetization of ferromagnetic materials and demagnetization

1.1.a Relation between B and H

The relation between the H-field (magnetic field strength, A/m) and the B-field (magnetic flux density, T) in vacuum or free space is defined as [1],

$$B = \mu_o H \quad (1.1.a.1)$$

where, $\mu_o = 4\pi \times 10^{-7} \text{ m kg s}^{-2} \text{ A}^{-2}$ is the permeability of free space. And, the magnetic field applied to an object with permeability μ results in a B given by[1],

$$B = \mu H = \mu_o (H + M) \quad (1.1.a.2)$$

where μ is the magnetic permeability of object subjected to magnetic field and M is the total magnetization measured in A/m. The magnetization is the permanent or induced magnetic dipole moments per unit volume in magnetic material. The permeability measures the degree of magnetization of a material subjected to the applied magnetic field. The ratio of materials permeability and vacuum permeability is defined as relative permeability and is given as[1],

$$\mu_r = \frac{\mu}{\mu_0} = 1 + \chi \quad (1.1.a.3)$$

where, χ is the magnetic susceptibility defined as the ratio of magnetization of material (M) to the applied magnetic field (H).

1.1.b Magnetic Materials

The magnetic materials can be broadly classified into five major types in terms of their magnetic properties. They are diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic and ferrimagnetic. They respond differently to an applied magnetic field and can also be distinguished with their magnetic susceptibility (χ). Materials with no permanent magnetic moments exhibit diamagnetism, materials with magnetic moments that do not interact with each other exhibit paramagnetism and materials with strong interaction between the magnetic moments exhibit ferromagnetism, anti-ferromagnetism, or ferrimagnetism. [1, 3]. The figures 1.1.b.1 to 1.1.b.5 below show magnetic moment alignment and susceptibility associated with these magnetic materials.

Figure 1.1.b.1 Diamagnetic material with no magnetic moment and small and negative susceptibility. Source: [figure reproduced from Harris and Williams, 2009]

Figure 1.1.b.2 Paramagnetic material with randomly oriented magnetic moments and small and positive susceptibility. Source: [figure reproduced from Harris and Williams, 2009]

Figure 1.1.b.3 Ferromagnetic material with parallel aligned magnetic moments and large and positive susceptibility. Source: [figure reproduced from Harris and Williams, 2009]

Figure 1.1.b.4 Antiferromagnetic material with mixed parallel and anti-parallel aligned magnetic moments and small and positive susceptibility. Source: [figure reproduced from Harris and Williams, 2009]

Figure 1.1.b.5 Ferrimagnetic material with anti-parallel aligned magnetic moments and small and positive susceptibility. Source: [figure reproduced from Harris and Williams, 2009]

1.1.c Demagnetization

A demagnetizing field is generated when objects/samples are magnetized with the application of an external magnetic field.

Figure 1.1.c.1 Demagnetizing field and magnetization induced in a magnetic sample due to applied external field. Source: [Chikazumi, 1997]

The intensity of the demagnetizing field is given as [1, 15]

$$H_d = NM \quad (1.1.c.1)$$

where N is called the demagnetizing factor that is influenced by the geometry and material of the sample and M is the magnetization or the magnetic moment per unit volume. As shown in the figure 1.1.c.2 , the shape of the magnetization curve as a function of the applied field (broken line) is sheared when compared with the true magnetization curve (solid line). This is because the actual field in material (H_{in}) is smaller than the applied external field. Thus, to find the effective field inside the sample that produces the moment, the demagnetizing field needs to be subtracted from the applied external field. This is given as, [1, 15]

$$H_{in} = H_{app} - NM \quad (1.1.c.2)$$

Where, H_{in} is the effective magnetic field inside the sample and H_{app} is the applied magnetic field. This correction for converting the sheared magnetization curve to the true curve is called the demagnetizing correction or the shearing correction. As a result of this correction, the magnetization curve has a higher slope, which results in increased magnetic susceptibility and remanence compared to what can be inferred from the raw data.

The summation of demagnetizing factors in x, y and z directions is equal to 1[1].

$$N_x + N_y + N_z = 1 \quad (1.1.c.3)$$

Figure 1.1.c.2 (i) Shearing correction of magnetization curve. Source: [Chikazumi 1997] and (ii.)

Experimental M-H curve and M-H curve corrected for demagnetization.

For the magnetic field applied in a specific direction, the demagnetizing factor (N) in that specific direction can be estimated as:

$$N = \frac{H_{app}}{M} - \frac{H_{in}}{M} \quad (1.1.c.4)$$

H_{in}/M is the inverse of magnetic susceptibility of the material.

$$N = \frac{H_{app}}{M} - \frac{1}{\chi} \quad (1.1.c.5)$$

For the material with very high magnetic susceptibility, $\frac{1}{\chi}$ can be neglected ($\frac{1}{\chi} \approx 0$) as a first approximation and the demagnetizing factor (N) can be directly estimated from the linear region of the experimental data (slope) as:

$$N = \frac{H_{app}}{M} \quad (1.1.c.4)$$

1.2 Overview of magnetic shields

A magnetic shield is used for the reduction of a magnetic field in a prescribed region. The examples of external magnetic field sources are the earth's magnetic field (D.C.), magnetic fields due to power sources and other instruments (A.C. or D.C.). There are two types of magnetic shields, active magnetic shields and passive magnetic shields. Active shielding makes use of the magnetic field produced by a superconducting coil to cancel an external magnetic field. But, the active shield can produce stray magnetic noise as well. A Helmholtz coil is an example of an active shield. Helmholtz coils work as an active magnetic shield by producing uniform homogenous magnetic fields which cancel the outside field.

Figure 1.2.a Schematic drawing of a Helmholtz coil. Source:[Ann Hanks, Magnetic Fields of Coils EX-9931, PASCO.]

A passive shield works by drawing the field into itself, providing a path for the field lines around the shielding volume and minimizing the magnetic field inside the cryomodule. High

permeability ferromagnetic alloys are used as passive shielding materials. Figure 1.2.b below is an example of a cylindrical magnetic field made of soft ferromagnetic material with very high permeability. The effectiveness of this shield (S_f) is also known as the shielding factor and can be described as the ratio of the magnetic field before the shield and the magnetic field after the application of the magnetic shielding:

$$S_f = \frac{B_o}{B_i} \quad (1.2.a)$$

Here, B_o is the outside magnetic field and B_i is the magnetic field in the shielded region.

Figure 1.2.b Example of a Magnetic Shield

Passive magnetic shields can be fabricated in different shapes and sizes depending on the required shielded space. The most common types are spherical, cylindrical, cubical and infinite-plates.

Figure 1.2.c Single layer open cylindrical shield of length L, internal diameter D and thickness t.

The shielding factor or shielding effectiveness of open cylinder (figure 1.2.c) for axial magnetic field is given as:

$$S_{fa} \cong \frac{D}{D+L} \frac{\mu_r t}{D} + 1 \quad (1.2.b)$$

Here, D is the inner diameter, L is length, t is thickness and μ_r is relative permeability of material used for this magnetic shield. And, the shielding factor for the transverse magnetic field for this configuration is given as:

$$S_{ft} \cong \frac{\mu_r}{4} \frac{\left(\frac{D}{2}+t\right)^2 - \left(\frac{D}{2}\right)^2}{\left(\frac{D}{2}+t\right)^2} \quad (1.2.c)$$

The shielding effectiveness of a shield depends on its shape, size, thickness, number of layers and permeability of the material used. Presence of holes in the shields will provide a path for magnetic fields to enter the space to be shielded and ultimately decrease the shielding factor. The analytical expressions for the shielding factors of cubical, spherical and infinite plane can be formulated but for more complex geometries numerical analysis is necessary.

Some common examples of materials used in passive shielding materials are Amumetal, Amumetal 4K (A4K), cryoperm, shielding foils, and ultra-low carbon steel (ULCS). The permeability of materials change with temperature, applied magnetic field, defects in the material, residual stresses and application of stress. The experimental study and modeling of the permeability of passive magnetic shielding materials (Amumetal and A4K) over a large range of temperatures and processing conditions is discussed in detail in chapter 2 and chapter 3. Amumetal and A4K are high content Ni-alloys and are materials of interest for having high permeability values and they are very ideal materials of choice to be used in the cryomodels of particle accelerator as passive magnetic shields.

Figure 1.2.d Schematic of a cryomodule with inner and outer magnetic shields.

Source: [W. J. Schneider, 2001]

1.3 Overview of particle accelerators and magnetic shielding

1.3. a. Particle accelerators

Particle accelerators produce beams of high-energy particles (electrons, protons, heavy ions) based on the interaction of the electric charge with static and dynamic electromagnetic fields. Electrostatic accelerators and oscillating field accelerators are two major groups of accelerators. The Cockcroft-Walton accelerator, Van de Graaff accelerator, linear accelerator, cyclotron, betatron, microtron, synchrocyclotron, synchrotron and storage ring collider are some examples of particle accelerators. Powerful accelerators can produce neutrons by spallation which can potentially be used for the development of accelerator driven systems (ADS) for power generation. Thomas Jefferson National Accelerator Facility (Jefferson Lab) has an electron beam

linear particle accelerator (shown in figure 1.3.a) that produces the electron beam of 12 GeV energy.

Figure 1.3.a Schematic of 12 GeV electron beam linear particle accelerator at Thomas Jefferson Accelerator Facility (Jefferson Lab), Newport News, Virginia.

Source: [R.D. McKeown, 2013]

1.3. b. Importance of magnetic shielding

An effective magnetic shield is very important to achieve high quality factors (Q_0) in the cryomodule of the particle accelerator. This requires enhanced shielding of both the axial and transverse components of the earth's magnetic field. The allowed value for the magnetic field inside the cavity due to external fields is ~ 15 mG or less. A better understanding of the magnetic susceptibility of materials such as Amumetal, Cryoperm and A4K at cryogenic temperatures in

the presence of manufacturing induced stress and defects is beneficial to the design of an effective shield using these materials.

The ultimate goal of the magnetic shield analysis is to provide guidance for the C100 cryomodule (CM) shield design. An important performance index of a CM is its quality factor, Q_o . The quality factor (Q_o) of the CM of the particle accelerator is given as,

$$Q_o = \frac{G}{R_s} \quad (1.3.b.1)$$

Where, G is the geometric factor of the accelerating cavity and R_s is the cavity surface resistance. The cavity surface resistance (R_s) can be divided into contributions from surface magnetic field (R_H) and other components (R_{other}). The R_H can be estimated using the equation (1.3.b.2).

$$R_H = \frac{H_{ext}}{2H_{c2}} R_n \approx 9.49 \times 10^{-12} H_{ext} \sqrt{f} \quad (1.3.b.2)$$

Where, the H_{ext} is the external field that in this case is the earth's magnetic field, f is the fundamental frequency of the Niobium cavity, H_{c2} is the type-II superconductor (Niobium) magnetic quench field and R_n is the normal conducting resistance of niobium. Thus, the earth's magnetic field (~500mG) produces serious surface resistance (R_s) in niobium superconducting radio frequency (SRF) cavities of the CM.

Furthermore, due to Meissner Effect, superconductors will exclude magnetic fields as long as the applied field doesn't exceed their critical magnetic field. Surface defects in Niobium cavities weaken the Meissner state and become a source for pinning centers that trap flux during cooldown in the initial operation of the CM. This trapped flux contributes to the surface resistance (R_s) and can additionally be mitigated by a process called degaussing. Nevertheless, it is beneficial to reduce this trapped flux as well by mitigating the effect of Earth's magnetic field

on cryomodule by using effective passive shielding with optimized magnetic properties. This guides us to look at effective shielding of both axial and transverse components of the earth's magnetic field.

1.4 Magnetic characterization using VSM and SQUID magnetometer

The Quantum Design (QD) Vibrating Sample Magnetometer (VSM) and the superconducting quantum interference device (SQUID) are very sensitive devices used for magnetic materials characterization over a range of temperatures. In VSM, the magnetic material sample to be tested is attached to the end of a sample rod that is driven sinusoidally. Oscillation of the sample starts after the desired field is applied at the desired temperature. Finally, the magnetic moment induced in the sample for a given field is obtained from the induced voltage in a pickup coil. This magnetization (magnetic moment per unit volume) of the sample can be then plotted against the applied field to get the magnetization curve or hysteresis curve. The QD Versalab VSM at Virginia Commonwealth University shown in figure 1.4.a. has magnetization resolution of 10^{-6} emu and can operate between 50 K and 400K.

Figure 1.4.a Quantum Design Versalab VSM at Nanomaterials Core Characterization Facility,
Virginia Commonwealth University

Figure 1.4.b Quantum Design Physical Property Measurement System (PPMS), a
Superconducting quantum interference device (SQUID) at University of Maryland.

Source: [Quantum Design, Inc website.]

In SQUID, a superconducting solenoid produces magnetic fields and the sample to be tested is placed in the center of this solenoid. The space around the sample is filled with helium at very low pressure. There are four windings in the superconducting pick-up coil. The magnetic flux produced in the pick-up coil due to the up and down motion of the sample is recorded by the SQUID antenna and it converts the flux input into voltage output. Finally, the magnetization of the sample is obtained and plotted against the applied field for magnetization curve or hysteresis curve. The system shown in figure 1.4.b has a magnetization resolution of 10^{-8} emu and can operate between 2K and 400K.

Figure 1.4.c Ferromagnetic samples cut using Electrical Discharge Machining (EDM) into 2mm×2mm×1mm samples.

For this dissertation, ferromagnetic samples of size 2mm×2mm×1mm as shown in figure 1.4.c were tested at 5K using the SQUID and at 50K to 300K using the VSM. The magnetization data (raw data) in figure 1.4.d are for as rolled Amumetal sample. These data were obtained using the VSM at temperatures 50K to 300K and are not corrected for demagnetizing field.

Figure 1.4.d Uncorrected magnetization data (M-H) obtained for as rolled Amumetal sample using VSM at temperatures between 50 K and 300K.

1.5 Modeling ferromagnetic behavior (M-H)

There have been many magnetization models for ferromagnetic and magnetostrictive materials such as the Preisach model, the Weiss model, the Stoner-Wolfforth model, the Brown's analysis of thermal fluctuation in single domain particles, the homogenized energy model, the Jiles-Atherton model energy weighted stochastic models, the Globus model other nonlinear constitutive and phase field approaches[46]. While models such as the Preisach model are purely mathematical and do not actually address the underlying physics, later models attempt to incorporate specific exchange coupling, shape anisotropy, magnetoelastic anisotropy magnetocrystalline anisotropy and Zeeman energies in describing the magnetization behavior of bulk samples. The total free energy of the system with the external field H is the sum of all the exchange energy associated with them. That is [1],

$$E = E_{\text{magnetic}} + E_{\text{magnetocrystalline}} + E_{\text{magnetoelastic}}$$

Figure 1.5.a Free-body diagram showing stress (σ), magnetic field (H) and orientation of magnetization (M) in a bulk sample.

This energy associated with the magnetic field, the magnetocrystalline anisotropy and the magnetoelastic effects can be further expanded based on Armstrong model of magnetization. The model is implemented by considering the total energy density for the magnetization orienting in direction $(\alpha_1, \alpha_2, \alpha_3)$ in a cubical anisotropy material due to an applied magnetic field (H) with direction cosine $(\beta_1, \beta_2, \beta_3)$, and stress oriented in direction $(\beta_{1s}, \beta_{2s}, \beta_{3s})$ with respect to the crystallographic axes. For this paper, we only consider the magnetocrystalline energy and Zeeman energy contributions (we note stress anisotropy and other contributions may be added where appropriate):

$$\begin{aligned}
E(\sigma, H) = & K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2) \\
& - \frac{3}{2}\lambda_{100} * \sigma * (\alpha_1^2 \beta_{1s}^2 + \alpha_2^2 \beta_{2s}^2 + \alpha_3^2 \beta_{3s}^2) \\
& - 3\lambda_{111} * \sigma * (\alpha_1\alpha_2\beta_{1s}\beta_{2s} + \alpha_2\alpha_3\beta_{2s}\beta_{3s} + \alpha_3\alpha_1\beta_{3s}\beta_{1s}) \\
& - \mu_0 M_s H(\alpha_1\beta_1 + \alpha_2\beta_2 + \alpha_3\beta_3)
\end{aligned} \tag{1.5.a}$$

Where, K_1 is the fourth order cubical anisotropy constant, K_2 is the second order cubical anisotropy constant, M_s is the saturation magnetization, σ is stress, λ_{111} and λ_{100} are cubic magnetostriction constants. Both of these magnetocrystalline anisotropy constants and M_s are temperature dependent.

Many prior models approximately employ the following approach or some variants thereof to model the magnetization behavior. The total energy *density* (E_i) corresponding to the magnetization orientation along a crystallographic direction (“i”) as shown in figure 1.5.a is evaluated and the probability (p_i) of this state being occupied is calculated as [25-33]:

$$p_i = \frac{e^{-\frac{E_i V}{kT}}}{\sum_i e^{-\frac{E_i V}{kT}}} \tag{1.5.b}$$

Here k denotes the Boltzmann constant, T the temperature and V is nebulous at best for bulk samples and may approximately be assumed to correspond to the average size of a magnetic domain. Some other models consider the effect on inhomogeneities (defects, grain boundaries, polycrystalline texture, etc.) on the possibility of occupation of non-minimum energy states. These models calculate the probability p_i of occupation of state as [28, 29, 32]:

$$p_i = \frac{e^{-\frac{E_i}{\Omega_o}}}{\sum_i e^{-\frac{E_i}{\Omega_o}}} \tag{1.5.c}$$

Here, Ω_0 is the empirical constant. Now, the total magnetization in the z - direction is given as [28,29]:

$$\langle M_z \rangle = \sum M_s \cos\theta P_i \quad (1.5.d)$$

$$M_z = \frac{\iint_{(\theta,\phi)} (M_s(T) \cos\theta) (d\theta d\phi) |\sin\theta| e^{-\frac{E}{\Omega}}}{\iint_{(\theta,\phi)} (d\theta d\phi) |\sin\theta| e^{-\frac{E}{\Omega}}} \quad (1.5.e)$$

Here M_s is the saturation magnetization, θ is the polar angle and ϕ is the azimuthal angle shown in figure above. The equation above can be used to model the ferromagnetic materials for their magnetization which accounts the effect of magnetic field, stress and magnetocrystalline anisotropies. However, equations 1.5.b and 1.5.c can't capture the effects of change in temperature as V and Ω both changes with change in temperature. This dissertation comprehensively finds a framework to capture the effects of temperature on V or Ω to model the magnetization of ferromagnetic materials.

1.6 FEM methods using COMSOL Multiphysics

COMSOL Multiphysics is a finite element modeling (FEM) software package which can be used to solve and simulate different kinds of physics and engineering problems [54]. Specific modules can be used for specific kinds of problems. Multiple modules can be used at the same time depending upon the nature of problem. Here, we describe the use of AC/DC module specially used for solving and simulating magnetostatic problems in this dissertation. This Module contains a set of interfaces adapted to a broad category of electromagnetic simulations and it solves problems in the general areas of electrostatic fields, magnetostatic fields and electrodynamics. The magnetic shielding of cryomodels from the earth's magnetic field is a magnetostatic problem. Thus, we only used the DC features of the module. This interface is

enabled for multiphysics simulations and it can be coupled with any other modules. COMSOL Multiphysics can also be interfaced with MATLAB for input data and scripts required to run certain problems.

The physics interfaces ‘Magnetic Field’ or ‘Magnetic Field, No Currents’ can be used for the magnetostatic problems. The ‘Magnetic Field’ interface (can in general) be used to solve stationary, frequency domain, time dependent, small signal analysis and frequency domain problems. This interface supports the 3D, 2D and 2D asymmetric models for analysis. The ‘Magnetic Field, No Currents’ interface can be used to solve the stationary or time dependent problem. Here we specifically solve only a magnetostatic problem. The magnetic scalar potential is the dependent variable in this interface and can solve for the distribution of magnetic fields.

Figure 1.6.a below shows the setup for ‘Magnetic Field, No Currents’ interface. This setup is used for solving the magnetostatic problems. Here, the desired structure is designed and a static magnetic field is applied to study the field distribution inside the magnetic shield.

Figure 1.6.a: Screen shot of ‘Magnetic Field, No Current’ interface, AC/DC Module, COMSOL Multiphysics version 4.2a

An example of a magnetostatic problem with a cylindrical magnetic shield is shown in figure 1.6.b. An open hollow cylinder made of ferromagnetic material with very high permeability is placed in the magnetic field.

Figure 1.6.b: The multiscale magnetic flux density (T) distribution plot, ‘Magnetic Field, No Current’ interface, AC/DC Module, COMSOL Multiphysics version 4.2a.

The shielding effectiveness is calculated for the static magnetic field applied along the length (axial field) and for the field applied perpendicular to the length of cylinder (transverse field). These results are then compared to analytical results to benchmark the COMSOL Multiphysics solver before further study of magnetic shields for cryomodules. The agreement is found to be good with less than 5% normalized root mean square error. The analytical shielding factor of open cylinder for axial field is:

$$S_{fa} \cong \frac{D}{D+L} \frac{\mu_r t}{D} + 1 \quad (1.6.a)$$

Here, D is the inner diameter, L is length, t is thickness and μ_r is relative permeability. The transverse shielding factor is given as:

$$S_{f_t} \cong \frac{\mu_r \left(\frac{D}{2}+t\right)^2 - \left(\frac{D}{2}\right)^2}{\left(\frac{D}{2}+t\right)^2} \quad (1.6.b)$$

The magnetic shielding factors for the open cylinder of Fig.1 with L=150mm, D=25mm and t=1mm were computed using the FEM and compared with the analytical results as shown in Fig.

2. The applied field was the static magnetic field of 5×10^{-5} T equivalent to earth's magnetic field.

Figure 1.6.c Comparison of axial shielding factors obtained from analytical and FEM results.

Figure 1.6.d Comparison of transverse shielding factors obtained from analytical and FEM results.

CHAPTER 2. Experimental characterization of magnetic shielding materials

The magnetic properties of two important passive magnetic shielding materials (A4K and Amumetal) for accelerator applications, subjected to various processing and heat treatment conditions were studied comprehensively over a wide range of temperatures: from cryogenic to room temperature. In this chapter, we analyze the effect of processing on the extent of degradation of the magnetic properties of both materials and investigate the possibility of restoring these properties by reannealing.

2.1 Introduction

Magnetic shielding is extremely vital for the enhanced performance of cryomodules (CMs) of particle accelerators. This can be understood in terms of the effect of stray magnetic fields on the quality factor (Q_o) of the superconducting radio frequency (SRF) cavity that is given by [4]

$$Q_o = \frac{G}{R_s} \quad (2.1.a)$$

Here, G is the geometric factor of the accelerating cavity and R_s is the cavity surface resistance. The cavity surface resistance (R_s) can be divided into contributions from the surface magnetic field (R_H) and other components (R_{other}). The R_H can be estimated using the equation (2.1.b) as follows [4]

$$R_H = \frac{H_{ext}}{2H_{c2}} R_n \approx 9.49 \times 10^{-12} H_{ext} \sqrt{f} \quad (2.1.b)$$

H_{ext} is the external field that in this case is the Earth's magnetic field ($\sim 50 \mu\text{T}$), f is the fundamental frequency of the Niobium cavity, H_{c2} is the type-II superconductor (Niobium) magnetic quench field and R_n is the normal conducting resistance of niobium. Thus, it is clear that a high stray magnetic field increases the cavity surface resistance, thereby degrading the cavity's quality factor. Furthermore, during quenching, of the SRF cavities, the Nb is not in its superconducting state and therefore magnetic flux can penetrate the cavity.

These issues can be effectively addressed by the appropriate use of magnetic shields [5] that reduce the magnetic field in a prescribed region. The magnetic shielding can be provided by an active shield [6] that uses a magnetic field produced by utilizing a superconducting coil to cancel an external magnetic field or by a passive shield [7] that works by drawing the field onto itself, providing a path for the field lines around the shielding volume and minimizing the magnetic field inside the cryomodule.

Here we studied the magnetic properties of materials used in passive shields that mitigate the effect of the Earth's axial and transverse magnetic field components on cryomodules. Specifically, we focus on the understanding of the manner in which magnetic permeability varies with temperature, applied deformation during manufacturing and heat treatment. While some prior work exists on characterizing the magnetic [5], [7]-[13] properties, a comprehensive study of the effect of deformation during the manufacturing process and annealing on the magnetic permeability of shielding materials over a broad range of temperatures (cryogenic to room temperature) is not available. This research project bridges this gap in knowledge by performing such experimental studies on these magnetic materials.

Mumetal is an important material of interest for magnetic shielding. The specific nominal compositions of two such alloys of the mumetal family are: (i) Amumetal composed of 80% nickel, 4.5% molybdenum and rest iron by weight and (ii) Amumetal 4K (A4K) composed of 81% nickel, 4.5% molybdenum and rest iron by weight. These samples were obtained from Amuneal Manufacturing Corporation [10]. While both materials are high nickel content alloys of the mumetal family we refer to them as Amumetal and A4K henceforth to refer to materials of these specific compositions.

2.2 Experimental methods

2.2.a Sample Preparation

Two mill-annealed sheets of A4K and Amumetal were obtained from Amuneal Manufacturing Corporation with planar dimensions 3'x3' and 1 mm in thickness (figure2.2.a.i). The samples were cut into 2 mm x 2 mm pieces of thickness 1mm (figure2.2.a.ii) using Wire Electrical Discharge Machine (Wire-EDM) at the Jefferson Lab. These cut pieces will be called our regular samples. The Wire-EDM was used so that the external stress induced in the samples during cutting is minimized. The magnetic properties of both un-annealed (regular) samples and those that were hydrogen annealed (pure hydrogen and dry atmosphere) at Amuneal Manufacturing Corporation at 1150°C for four hours were studied. We note that after the anneal process, the cooling rates for Amumetal and A4K were 200°C/h and 50°C/h respectively.

Figure 2.2.a (i.) Amumetal and A4K samples (ii.) Amumetal or A4K sample after EDM cutting, and (iii.) Schematic of Amumetal or A4K Sample with dimension.

Two samples of each metal were then deformed by applying bending stress, which is equivalent to a maximum tensile/compressive stress of 3.18 MPa. The deformation process was designed to produce the typical stress induced in samples by the manufacturing processes while fabricating the shields. *The samples were bent by applying stress and then unbent for the magnetic testing so that demagnetizing factors can be kept constants.* The magnetic properties of the deformed samples were studied to understand the effect of this manufacturing process on permeability.

Finally, these deformed samples were annealed again at Amuneal Corporation and tested to determine if the magnetic properties that were degraded during the deformation process could be restored by appropriate heat treatment.

2.2.b Magnetic testing

The magnetic characterization on the different samples (regular, annealed and deformed) at 50K, 100K, 150K, 200K, 250K and 300K was performed using a Quantum Design Versalab Vibrating Sample Magnetometer (VSM) at the Nanomaterial Core Characterization (NCC) Facility of Virginia Commonwealth University (VCU). The magnetic characterization of the samples annealed after deformation was tested only between 50K and 300K as explained later.

The magnetic moment as a function of magnetic field applied in the Z-direction (axes shown in figure 2.2.a.iii) was collected for each sample at the different temperatures mentioned above. A SQUID (Quantum Design Magnetic Property Measurement System-3) magnetometer at the University of Maryland was used to obtain magnetic moment vs. applied field at a temperature of 5K.

2.2.c Demagnetizing factor

A demagnetizing field is generated when samples are magnetized. This needs to be correctly accounted for while reporting the magnetic moment at a given applied field. The effective field inside the sample that produces the moment is given as [13]-[15],

$$H_{in} = H_{app} - NM, \quad (2.2c)$$

Where, H_{in} is the effective magnetic field inside the sample, H_{app} is the applied magnetic field, N is demagnetizing factor that is influenced by the geometry of the sample and M is the magnetization or the magnetic moment per unit volume.

N is approximately determined from the experimental data using $N \approx H_{\text{app}}/M$ from the linear region of M-H curve where χ is very large. Details of the derivation and when this approximation holds are described in details in Appendix-A of this chapter.

The permeability of the materials tested is computed from the data corrected for demagnetization. The slope of magnetic induction (B) and effective magnetic field (H) curve at the magnetic field of interest gives the incremental relative permeability as calculated in the manner of Ref 13: $\mu_{\Delta} = \frac{1}{\mu_0} \frac{\Delta B}{\Delta H} = \frac{1}{\mu_0} \frac{B_2 - B_1}{H_2 - H_1}$. Similarly the relative permeability at the magnetic field of interest is computed as: $\mu_r = \frac{1}{\mu_0} \frac{B}{H}$. We performed a detailed error analysis on the uncertainty in estimation of μ_{Δ} and μ_r , given the uncertainty in the measurement of magnetization (M) and field (H) are 0.4 A/m and 1.25 A/m respectively. These error estimates are stated in Table I and II. The detailed analysis of error estimates is described in Appendix-B of this chapter.

2.3 Results and analysis

Regular, annealed and deformed samples of Amumetal and A4K were tested at the temperatures of 5K, 50K, 100K, 150K, 200K, 250K and 300K. The plots figures 2.3.a – 2.3.c respectively show the M-H curves of AMU metal without annealing, after annealing and after deformation, while figures 2.3.d -2.3.f respectively show the M-H curves of A4K for the same conditions.

In both materials, irrespective of the processing condition, we note that saturation magnetization (the plots we show are zoomed and saturation magnetization (M_s) is not exactly researched at the highest field shown on the plot $\sim 2 \times 10^4$ A/m, but the trends still stay the same) decreases with

the increase in temperature as expected in any second order system. Also, as expected, deformed samples have the lowest permeability and need high fields to drive them to saturation due to the large number of defects that act as pinning sites and impede the magnetization rotation or movement of magnetic domains walls. The undeformed but unannealed (we henceforth call them “regular”) samples show higher permeability, likely due to lesser defect density while the annealed samples show the best permeability as the annealing process greatly reduces the defects/pinning sites[8,17-19].

The comparative value of the low field permeability (incremental relative permeability at ~ 40 A/m, approximate magnitude of the Earth’s magnetic field) and the intermediate field permeability (incremental relative permeability at $\sim 2 \times 10^4$ A/m and $\sim 4 \times 10^4$ A/m) for two materials (Amumetal and A4K) are tabled at two temperatures: 5K and 300K (in Table I and Table II). These temperatures are of relevance to the inner magnetic shield at cryogenic temperature and the outer magnetic field at room temperature respectively. In addition to confirming that permeability at both temperatures is highest for annealed samples and lowest for deformed samples at low fields, it also shows that the low field permeability of annealed Amumetal and A4K are comparable at 300 K while that of annealed A4K is significantly better than that of annealed Amumetal at Cryogenic temperature (5K). This suggests that A4K is better suited for shielding Earth’s magnetic field at low temperatures and should be the preferred material for design of inner shields.

TABLE 2.3.A
NOMINAL RELATIVE PERMEABILITY AT 5K

Material	Permeability at 5K			
	$\mu_{\Delta} = \frac{1}{\mu_o} \frac{\Delta B}{\Delta H}$ at 0.5Oe (~40 A/m)	$\mu_r = \frac{1}{\mu_o} \frac{B}{H}$ at ~250Oe (~2×10 ⁴ A/m)	$\mu_{\Delta} = \frac{1}{\mu_o} \frac{\Delta B}{\Delta H}$ at ~250 Oe (~2×10 ⁴ A/m)	$\mu_{\Delta} = \frac{1}{\mu_o} \frac{\Delta B}{\Delta H}$ at ~500 Oe (~4×10 ⁴ A/m)
Uncertainty (Higher Bound)	±4%	±0.002%	±4%	±4%
Amumetal-Regular	8700	433	33	22
Amumetal-Annealed	12600	453	31	21
Amumetal-Stressed	3700	375	80	33
A4K-Regular	16700	429	31	21
A4K-Annealed	51900	423	29	21
A4K-Stressed	10100	403	62	28

TABLE 2.3.B
NOMINAL RELATIVE PERMEABILITY AT 300K

Material	Permeability at 300K			
	$\mu_{\Delta} = \frac{1}{\mu_o} \frac{\Delta B}{\Delta H}$ at 0.5Oe (~40 A/m)	$\mu_r = \frac{1}{\mu_o} \frac{B}{H}$ at ~250Oe (~2×10 ⁴ A/m)	$\mu_{\Delta} = \frac{1}{\mu_o} \frac{\Delta B}{\Delta H}$ at ~250 Oe (~2×10 ⁴ A/m)	$\mu_{\Delta} = \frac{1}{\mu_o} \frac{\Delta B}{\Delta H}$ at ~500 Oe (~4×10 ⁴ A/m)
Uncertainty (Higher Bound)	±4%	±0.002%	±4%	±4%
Amumetal-Regular	10300	356	28	20
Amumetal-Annealed	11700	356	28	19
Amumetal-Stressed	8500	329	59	26
A4K-Regular	4100	357	28	20
A4K-Annealed	11700	359	28	19
A4K-Stressed	2800	345	40	22

At intermediate fields (~2×10⁴ A/m) the incremental permeability of the stressed samples is better than that of either the annealed or the regular samples. This is because the annealed (and regular) samples tend to almost reach saturation at low fields; thereafter the increase in magnetization with increasing field is small. In contrast, the stressed samples need a larger field to drive close to saturation and hence they show a higher incremental permeability compared to the annealed (and regular) samples at intermediate fields. This trend is less pronounced at higher field (~4×10⁴ A/m) and it is expected that they would be roughly comparable ($\mu_{\Delta} \sim 1$) at very

high fields as the magnetization in all samples would reach saturation. However, even at intermediate fields ($\sim 2 \times 10^4$ A/m) if one looks at the relative permeability (μ_r) instead of the incremental relative permeability (μ_Δ), at either 0 K or 300K the annealed samples have the highest followed by the regular and the stressed samples have the least permeability (least B or M for a given H).

Figure 2.3.a M-H curves for regular Amumetal sample at various temperatures.

Figure 2.3.b M-H curves for annealed Amumetal sample at various temperatures.

Figure 2.3.c M-H curves for stressed Amumetal sample at various temperatures.

Figure 2.3.d M-H curves for regular A4K sample at various temperatures.

Figure 2.3.e M-H curves for annealed A4K sample at various temperatures.

Figure 2.3.f M-H curves for stressed A4K sample at various temperatures.

Figure 2.3.g M-H curves for all samples at high field and 300K.

Figure 2.3.h M-H curves for all samples at high field and 5K.

Figure 2.3.i M-H curves for all samples at low field and 300K.

Figure 2.3.j M-H curves for all samples at low field and 5K.

Figure 2.3.k M-H curves for an AMU sample at 300K.

Figure 2.3.1 M-H curves for an A4K sample at 300K.

Figure 2.3.m M-H curves for an Amumetal sample at 50K.

Figure 2.3.n M-H curves for an A4K sample at 50K.

We also note that there is some anomalous behavior at the intermediate temperatures 50K-250K in figures 2.3.a-2.3.f. Specifically, it appears that in some cases (see for example, Fig 2.3.a) the 200K and 250 K appears to have lower permeability at low fields compared to 300K followed by a crossover point as they take higher fields for the M-H fields to nearly “flatten out” compared to the 300 K M-H curves. These trends were found to be repeatable across different samples.

Next, the M-H curves at room temperature (300 K) and cryogenic temperature (5K) are plotted for high fields (figure 2.3.g and 2.3.h) and low fields (figure 2.3.i and 2.3.j) for both Amumetal and A4K samples. This again shows the permeability decreases greatly due to deformation. This

effect is particularly large at 5 K as the thermal energy avoided to overcome pinning defects introduced due to the deformation is very small.

2.4 Conclusions

An extensive and detailed magnetic characterization of Amumetal and A4K was performed. The results show, deformation due to the manufacturing process has a significant effect on permeability and can be detrimental to magnetic shielding. For the magnetic shielding at room temperature, either annealed Amumetal or annealed A4K can be used as both have relatively comparable permeability. However, annealed A4K has relatively higher permeability at low-field (~ 40 A/m) and low temperature (~ 5 K) and will be more efficient for shielding at these temperatures compared to annealed Amumetal.

Compared to deformed samples, annealed samples of both A4K and Amumetal show a significant improvement in permeability at low fields (~ 0.5 G) at low temperature (5K) compared to its effect at higher temperature (300K). This is possibly due to the fact that at low temperature there is minimal thermal noise to overcome pinning defects (abundant in deformed samples) which makes it harder to align the magnetization with a small field compared to annealed samples (fewer pinning sites).

Furthermore, the permeability is more or less restored after the stressed samples are annealed again as shown in figure 2.3.j and figure 2.3.k. Since, we found that at 50K- 300K temperatures the magnetic properties of stressed samples were restored upon annealing, we did not repeat the low temperature (5K) magnetic characterization on the stressed samples that were re-annealed as we expect to find that the low temperature magnetic properties will be recovered as well. Microstructure accounts for the arrangement of phases and defects within a material. These

microstructures are generated when both of these materials go through deformation or annealing. After annealing, the equilibrium microstructures are obtained in these materials, resulting in higher magnetic permeability (Appendix 2.C) [57-58].

Finally, the constitutive M-H characteristics obtained in this paper are incorporated in a Finite Element Method (FEM) framework for detailed analysis of magnetic shielding of complex shielding geometries. This is described in details in Chapter 4.

Appendix 2.A – Demagnetizing factors

The effective field inside the sample that induces magnetization in the sample is given as: [10]

$$H_{in} = H_{app} - NM \quad (2.a.a)$$

Figure 2.A Experimental M-H curve and M-H curve corrected for demagnetization.

The demagnetizing factor (N) in equation 3 can be written as:

$$N = \frac{H_{app}}{M} - \frac{H_{in}}{M} \quad (2.a.b)$$

H_{in}/M is the magnetic susceptibility of the material.

$$N = \frac{H_{app}}{M} - \frac{1}{\chi} \quad (2.a.c)$$

$$\frac{1}{\chi} \approx 0$$

Since, the magnetic susceptibility is very high ($\chi \sim 10,000$) for a ferromagnetic material it can be neglected as a first approximation. Hence, the demagnetizing factor (N) can be directly estimated from experimental data as:

$$N = \frac{H_{app}}{M} \quad (2.a.d)$$

The “N” thus determined was used to correctly estimate the H_{in} using equation 3. All M-H curves plotted in this paper employ this correction to plot M vs. the H_{in} , from the measured M vs. H_{app} data in a manner similar to that shown in figure 2.A.

Appendix 2.B – Maximum uncertainties in estimation of permeability

The error analysis is presented below to estimate the uncertainty in the measurement of permeability using QD Versalab VSM. The uncertainty in the measurement of H and M are 0.4 A/m and 1.25 A/m respectively.

Uncertainties in estimation of permeability:

$$H = H \pm \delta H \text{ \& } M = M \pm \delta M$$

$$B = \mu_o(H + M) \pm \mu_o(\delta H + \delta M)$$

$$\Delta B = B_2 - B_1 = \mu_o((H_2 + M_2) - (H_1 + M_1)) \pm 2\mu_o(\delta H + \delta M)$$

$$\Delta H = (H_2 - H_1) = (H_2 - H_1) \pm 2\delta H$$

$$\mu_r = \frac{1}{\mu_o} \frac{B}{H} = \left(\frac{(H + M) \pm (\delta H + \delta M)}{H \pm \delta H} \right) = \frac{(H + M)}{H} \left(1 \pm \left(\frac{\delta H + \delta M}{H + M} + \frac{\delta H}{H} \right) \right)$$

$$\begin{aligned} \mu_\Delta &= \frac{1}{\mu_o} \frac{\Delta B}{\Delta H} = \frac{((H_2 + M_2) - (H_1 + M_1)) \pm 2(\delta H + \delta M)}{(H_2 - H_1) \pm 2\delta H} \\ &= \frac{(H_2 + M_2) - (H_1 + M_1)}{(H_2 - H_1)} \left(1 \pm \left(\frac{2(\delta H + \delta M)}{(H_2 + M_2) - (H_1 + M_1)} + \frac{2\delta H}{(H_2 - H_1)} \right) \right) \end{aligned}$$

Thus, the uncertainties in the measurement of permeabilities are:

$$\text{At 0.5Oe (~40 A/m): } \mu_\Delta \approx 4\%$$

$$\text{At ~250 Oe (~2}\times 10^4 \text{ A/m): } \mu_r \approx 0.002 \%$$

$$\text{At ~250 Oe (~2}\times 10^4 \text{ A/m) : } \mu_\Delta \approx 4\%$$

$$\text{At ~500 Oe (~4}\times 10^4 \text{ A/m): } \mu_\Delta \approx 4\%$$

Appendix 2.C – Effects of microstructures on magnetic property

The microstructure of soft magnetic materials (Ni-Fe Alloys) has a crucial effect on the magnetic properties. Microstructure accounts for the arrangement of phases and defects within a material. These microstructures are generated when both of these materials go through deformation or annealing. After annealing, the equilibrium microstructures are obtained in these materials, resulting in higher magnetic permeability [57-58].

Figure 2.C Effect of sintering temperature on microstructures of Fe-79%Ni-Mo alloy (1) 1240 °C, (b) 1280 °C, (c) 1320 °C , (d) 1360 °C [Source : J. Ma, 2014].

The study [58] shows that the densification and grain size of the alloys increase with increasing sintering temperature and time. This leads to the enhancement of the permeability and saturation and the decrease of the coercivity.

CHAPTER 3. Energy based stochastic magnetic modeling for ferromagnetic materials

In this chapter, an energy based stochastic model for the temperature dependent anhysteretic magnetization curves of ferromagnetic materials is proposed and benchmarked against experimental data. This is based on the calculation of macroscopic magnetic properties by performing an energy weighted average over all possible orientations of the magnetization vector. Most prior approaches that employ this method are unable to independently account for the effect of both inhomogeneity and temperature in performing the averaging necessary to model experimental data. Here we propose a way to account for both effects simultaneously and benchmark the model against experimental data from ~5K to ~300K for two different materials in both annealed (fewer inhomogeneities) and deformed (more inhomogeneities) samples. This demonstrates that the independent accounting for the effect of both inhomogeneity and temperature is necessary to correctly model temperature dependent magnetization behavior.

3.1 Introduction

There have been many magnetization models for ferromagnetic and magnetostrictive materials such as Preisach model [20-21], Weiss model [22], Stoner-Wolfarth model [23], Brown's analysis of thermal fluctuation in single domain particles [24], homogenized energy model [25], Jiles-Atherton model [26-27], energy weighted stochastic models [28-32], Globus model [33] other nonlinear constitutive [34] and phase field approaches [35]. While models such as the Preisach model are purely mathematical and do not actually address the underlying physics, later models attempt to incorporate specific exchange coupling, shape anisotropy, magnetoelastic anisotropy magnetocrystalline anisotropy and Zeeman energies in describing the magnetization behavior of bulk samples. However, the saturation magnetization, magnetocrystalline anisotropy

and average magnetic domain volumes change with a change in temperature. This can present a challenge in modeling temperature dependent magnetization behavior of such materials accurately. In this research project we propose an energy based stochastic approach which can comprehensively model the magnetic behavior of ferromagnetic materials over a range of temperatures by correctly accounting for these temperature effects and benchmark this model against experimental data.

One potential application of the proposed model is to simulate the behavior of passive ferromagnetic shielding materials that are very important for the proper function of cyomodules of particle accelerators [4], sensitive probes and detectors used in satellites and spacecrafts [41], and any other instruments requiring isolation from external magnetic fields. Furthermore, this modeling framework can also be extended to model magnetostriction and would hence be useful for the design of magnetostrictive actuators and sensors that are used over a wide range of temperatures [25-28]. Magnetostrictive actuators, operating over a wide range of temperatures (cryogenic to room temperature), have recently found some niche applications [42-45].

Many prior models approximately employ the following approach [25-33] or some variants thereof to model the magnetization behavior. The total energy density (E_i) corresponding to the magnetization orientation along a crystallographic direction (“i”) as shown in figure 3.2.a is evaluated and the probability (p_i) of this state being occupied is calculated as:

$$p_i = \frac{e^{-\frac{E_i V}{kT}}}{\sum_i e^{-\frac{E_i V}{kT}}} \quad (3.1.a)$$

Here k denotes the Boltzmann constant, T the temperature and V is the volume as discussed below.

However, there are two challenges in applying such models to modeling ferromagnetic behavior over a wide range of temperature, even if these are well below the Curie temperature (T_c): (i) the definition of “V” is nebulous at best for bulk samples and may approximately be assumed to correspond to the average size of a magnetic domain. Even this poses an issue as V may change as domains form, coalesce, etc. during the magnetization process. (ii) At low temperatures (say when $T \sim$ a few Kelvin) this model will only permit the minimum energy states to be occupied that will tend to simulate magnetization curves as shown in figure 3.2.a, which do not model experimental magnetic behavior at low temperatures correctly.

Some models [28, 29, 32] consider the effect on inhomogeneities (defects, grain boundaries, polycrystalline texture, etc.) on the possibility of occupation of non-minimum energy states. This is an important reason for magnetization curves not looking like figure 3.2.a at low temperatures.

These models calculate the probability p_i of occupation of state as:

$$p_i = \frac{e^{-\frac{E_i}{\Omega_0}}}{\sum_i e^{-\frac{E_i}{\Omega_0}}} \quad (3.1.b)$$

Here, they use an empirical term Ω_0 with no temperature dependence. Hence, both models described by (3.1.a) and (3.1.b) do not have a framework to model magnetization over a range of temperatures while comprehensively accounting for the effects of magnetic field, magnetocrystalline anisotropy, stress anisotropy, defects, etc. Therefore, we propose to model both effects simultaneously by defining Ω as follows:

$$\Omega = \Omega_0 + \Omega_1 \left(\frac{T}{T_c} \right) \quad (3.1.c)$$

Hence, there is an explicit dependence of the occupation of non-minimum states on defects and inhomogeneities (through Ω_0) as well as temperature (through $\Omega_1 (T/T_c)$). It is evident that as Ω_0 increases or $\Omega_1 (T/T_c)$ increases, the high energy states are penalized less (larger denominator) and hence have high probability of being occupied. On the contrary, low Ω_0 (less inhomogeneity) and low $\Omega_1 (T/T_c)$ (low temperatures) would penalize the occupation of high energy states more severely.

3.2 Model

The model is implemented by considering the total energy density for the magnetization orienting in a direction $(\alpha_1, \alpha_2, \alpha_3)$ in a cubical anisotropy material due to an applied magnetic field (H) with direction cosine $(\beta_1, \beta_2, \beta_3)$, with respect to crystallographic axes. For this work, we only consider the magnetocrystalline energy and Zeeman energy contributions (we note stress anisotropy and other contributions may be added where appropriate):

$$\begin{aligned}
 E &= E_{\text{magnetocrystalline}} + E_{\text{magnetic}} \\
 &= K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2) \\
 &\quad - \mu_0 M_s H(\alpha_1\beta_1 + \alpha_2\beta_2 + \alpha_3\beta_3)
 \end{aligned} \tag{3.2.a}$$

Where, K_1 is the fourth order cubical anisotropy constant, K_2 is the second order cubical anisotropy constant, and M_s is the saturation magnetization. The shape anisotropy is not included as the experimental data is corrected for the effects of demagnetization (i.e. $H_{\text{Effective}} = H_{\text{External}} - H_{\text{Demagnetization}}$ is used in the experimental data and was estimated in the manner described in detail in Ref. [36]).

The total magnetization in the z - direction is then given as [28, 29]:

$$\langle M_z \rangle = \sum M_s \cos \theta P_i$$

$$M_z = \frac{\iint_{(\theta, \phi)} (M_s(T) \cos \theta) (d\theta d\phi) |\sin \theta| e^{-\frac{E}{k_B T}}}{\iint_{(\theta, \phi)} (d\theta d\phi) |\sin \theta| e^{-\frac{E}{k_B T}}} \quad (3.2.b)$$

Here M_s is the saturation magnetization, θ is the polar angle and ϕ is the azimuthal angle shown in figure 3.2.a.

Likewise, we could model the magnetostrictive behavior by including the magnetoelastic term in equation 4 and calculating the magnetostriction in the manner of Ref 28. However, this is not the focus of this work where we discuss a framework to model a general class of ferromagnetic materials.

The magnetization model (equations 3.1.c, 3.2.a and 3.2.b) only applies to temperatures well below the Curie temperature of the material which is $\sim 400^\circ\text{C}$ [10]. The saturation magnetization (M_s) and magnetocrystalline anisotropy (K_1) both are temperature dependent. Temperature dependence of M_s is described as follows [27]:

$$\frac{M_s(T)}{M_s(T_0)} = \left[\frac{T_c - T}{T_c} \right]^\alpha \quad (3.2.c)$$

Here, $M_s(T_0)$ is magnetization at 0K, T_c is the Curie temperature and α is material dependent critical exponent.

(i.)

(ii.)

Figure 3.2.a (i) Schematic of sample (ii) M-H curve at 5 K of annealed Amumetal sample (at zero and non-zero magneto crystalline anisotropy; with $\Omega_0 = 0$ in both cases).

The temperature dependence of K_1 is described as follows [22]:

$$K_1 = K_1(T_o) * \exp(-\beta T^2) \quad (3.2.d)$$

Here $K_1(T_o)$ is K_1 at 0K and β is material dependent empirical coefficient. Estimation of both α and β is described in the Supplement.

3.3 Discussion and analysis

The magnetic characterization in Ref 18 was carried out using Quantum Design VersaLab and a SQUID magnetometer. We obtained experimental data [36] for two Ni-Cr-Fe alloys (Amumetal and A4K) at different temperatures (5K to 300K). The samples were deformed plastically with the application of bending stress comprising of both tension and compression. The deformed samples were then restored to their original shape before performing magnetic characterization. We note that the “deformed” samples are not characterized under the application of any external stress. The plastic deformation/dislocations induced by the deformation process lead to a magnetic anisotropy in the manner of Ref [37] irrespective of the compressive/tensile nature of stress during the deformation process.

For the annealed sample, we assume we have very low or vanishing cubic anisotropies in the materials [38]. But the cubical anisotropies induced in the deformed samples due to permanent deformation were accounted for with the K_1 term [37].

The following procedure is applied to estimate the model parameters to simulate the behavior of Amumetal and A4K bulk samples. The saturation magnetization (M_s) was obtained from the experimental data for different temperatures. $K_1(T)$ for the annealed samples was assumed to be zero [37]. The texture was not measured for the evaluation of K_1 and all of the samples are

assumed to be random polycrystalline samples. K_2 for all samples at all temperatures was assumed to be zero. For all annealed samples, $\Omega = \Omega_0 + \Omega_1(T/T_c)$ was chosen to give the best fit across all temperatures. For the deformed samples, $\Omega = \Omega_0 + \Omega_1(T/T_c)$ was chosen to give the initial slope of the curve and $K_1(T)$ was chosen to get the overall best fit. A good correlation was obtained with less than 5% normalized root mean square error in each case as can be seen from figures 3.3.a and 3.3.b. The model parameters selected for Amumetal and A4K are summarized in table 3.3.A.

(i)

(ii.)

Figure 3.3.a Comparison between simulated and experimental M-H curves for Amumetal samples at different temperatures (i.) Annealed Amumetal sample with $\Omega = 418 + (0.21 \times T)$ (ii.)

Deformed Amumetal sample with $\Omega = 910 + (0.21 \times T)$ and empirically chosen K_1 . [Curve fit with less than 5% normalized root mean square error.

Table 3.3.A Modeling parameters Ω and K_1

	Undeformed		Deformed	
	K_1 (J/m ³)	Ω (J/m ³) 418	$ K_1 $ (J/m ³)	Ω (J/m ³) 910
Amumetal				
		$+(0.21 \times T)$		$+(0.21 \times T)$
5K	0	419	1.59×10^4	911
50K	0	429	1.51×10^4	921
200K	0	460	1.09×10^4	952
300K	0	481	7.06×10^3	973
A4K		410 $+(0.24 \times T)$		880 $+(0.24 \times T)$
5K	0	411	8.39×10^3	881
50K	0	422	8.18×10^3	892
200K	0	458	5.90×10^3	928
300K	0	482	3.03×10^3	952

(i.)

(ii.)

Figure 3.3.b Comparison between simulated and experimental M-H curves for A4K samples at different temperatures: (i.) Annealed A4K sample with $\Omega = 410 + (0.24 \times T)$, (ii.) Deformed A4K sample with $\Omega = 880 + (0.24 \times T)$ and empirically chosen K_1 . [Curve fit with less than 5% normalized root mean square error.]

Now, we compare the magnetization models using the conventional approach and the new proposed approach for Ω . For the new approach we propose we have:

$$\Omega_i = \Omega_o + \Omega_1 \left(\frac{T}{T_c} \right) \quad (3.3.a)$$

For the old approach we have:

$$\Omega_{ii} = \frac{KT}{V} = \text{Constant} * (T) \quad (3.3.b)$$

For the A4K annealed sample, we compare the results from both approaches and examine the differences. The results for the model using Ω_i are already presented in figure 3. The value of Ω_{ii} is computed at 5K to find the constant term in equation 3.3.b that would best fit the 5K data. Then the value of Ω_{ii} is computed at 300K using the constant term and equation 3.3.b. The results from both the approaches are plotted against experimental data as shown in figure 3.3.c for comparison. While the simulated results from the new approach (equation 3.3.a) give us excellent fit with the experimental results at 5 K and 300K, the conventional method's simulated results completely fail to fit the experimental results at 300K. Likewise, if we had tried to fit the 300K data with the conventional approach, the simulated results for the 5K data would have failed to fit the experimental data.

Figure 3.3c. Comparison of conventional approach and new approach for the simulation of M-H curves of A4K annealed sample at 5K and 300K. This gives the distinct differences between the use of Ω_i (see fit 300K(1)) and Ω_{ii} (see fit 300K(2)). [Curve fit with less than 5% normalized root mean square error]

3.4 Conclusion

In conclusion, we presented a modified energy based stochastic temperature dependent model that could simulate the magnetization of ferromagnetic materials over a range of temperatures by simultaneously incorporating the effect of inhomogeneity and temperature. As expected, Ω_o is smaller for annealed samples than deformed samples as the former have less inhomogeneity than the latter, where defects are induced during the deformation process. $\Omega_T = \Omega_1(T/T_c)$ is independent of the processing (i.e. same for annealed or deformed samples) of a given material. This implies that Ω_T purely models the effect of temperature, independent of the Ω_o term that only

incorporates the effect of inhomogeneity. The K_1 (cubic anisotropy) is induced by deformation and its value decreases with increasing temperature as higher temperatures can quench the anisotropy induced by the deformation [21]. In summary, we propose an approach for modeling temperature dependent magnetic behavior of ferromagnetic materials and show that it can simulate the experimental behavior well.

Appendix 3.A: Temperature dependence of M_s and K_1

The variation of M_s with temperature, $M_s(T)$, was determined by fitting the experimental data to equations 3.2.c as shown in figure 3.A.1.

The variation of K_1 with temperature, $K_1(T)$, was determined by fitting estimates of K_1 at different temperatures to equations 3.2.d as shown in figure 3.A.2. It must be noted the estimates of K_1 at each temperature was obtained to best model the experimental M-H curve at that temperature and hence these estimates are based on experimental data.

Figure 3.A.1 Variation of M_s of Amumetal and A4K as a function of temperature (with $\alpha=0.17$ for Amumetal and $\alpha=0.11$ for A4K).

[Curve fit with less than 5% normalized root mean square error.]

Figure 3.A.2 Variation of K_I of Amumetal and A4K as a function of temperature with $a = -1 \times 10^{-5}$

[Curve fit with less than 5% normalized root mean square error.]

CHAPTER 4. FEM modeling of magnetic shields in C-100 cryomodules

In this chapter, we study the efficacy of magnetic shielding using COMSOL Multiphysics, a finite element modeling (FEM) tool using permeability values estimated from our prior characterization of magnetic shielding materials. We describe a detailed analysis of different magnetic shielding configurations to attenuate Earth's magnetic field. We use the C-100 module's design from Jefferson Lab as a baseline for our FEM studies to find the efficacy of passive magnetic shields. However, the conclusions drawn from this study would apply to other shield designs as well.

4.1 Introduction

Magnetic shielding is vital in a particle accelerator. The superconducting radio frequency (SRF) cavities are required to be shielded from the outer magnetic fields including the earth's magnetic field to ensure they have a high quality factor [1]. The value of earth's magnetic field is $\sim 5 \times 10^{-5}$ T and the magnetic shielding requirement is to reduce this field by about 100 times inside the shielded SRF cavity.

The shielding effectiveness of any magnetic shield is given by the ratio of the magnetic field outside the shield to the magnetic field inside the shield. For example the shielding effectiveness of a cylindrical shield as shown in Fig. 1 is given as [2]:

$$S_f = \frac{H_o}{H_i} \quad (4.1. a)$$

Figure 4.1. Single layer open cylindrical shield of length L , internal diameter D and thickness d .

Passive magnetic shielding is very important and has a wide range of applications beyond particle accelerators as well. Amumetal, A4K and cryoperm are some of the magnetic alloys (permalloys) commonly used as passive shielding materials in particle accelerators. We previously studied Amumetal and A4K for their magnetic permeability over a range of temperature (5K to 300 K) with the effect of deformation and annealing. This study was further extended in developing an energy based stochastic model for the magnetization of these materials. With the applied static magnetic field of ~ 40 A/m (Earth's magnetic field), the relative permeabilities (μ_r) of annealed Amumetal measured experimentally at 5K and 300K are 12600 and 11700 respectively. The relative permeabilities of A4K are 51900 at 5K and 11700 at 300K. These permeability values can approximately be used while studying and evaluating the magnetic shields for cryomodels assuming that the shields have been re-annealed after

transport, handling and manufacturing (bending/forming, etc.) to restore the permeability values that are degraded by process induced dislocations.

COMSOL Mutipysics with AC/DC module is a good tool to study the magnetostatic effects on these magnetic materials. Simple and complex 2D and 3D designs or structures can be studied for the effect of geometric factors and different configurations on the distribution of static magnetic field. The field's distribution data obtained from a detailed FEM study can be used to estimate the shielding effectiveness of the magnetic shields.

4.2 FEM Model

We have used COMSOL Multiphysics as a finite element modeling (FEM) tool to study the shielding effectiveness of the ferromagnetic magnetic shields in C-100 cryomodels at Jefferson Lab. Specifically for the design and optimization of passive magnetic shields discussed in this chapter, COMSOL AC/DC-module (3-D) with static magnetic field interface (magnetic field/no currents) is used. The magnetic shield boundary conditions are applied to the geometry and the efficacy of shielding is evaluated from the distribution of the magnetic field inside and outside the shield.

Figure 4.2.1 Schematic of a cryomodule with inner and outer magnetic shields.

Source: [W. J. Schneider, 2001]

As discussed in the chapter 1(introduction), magneto-static FEM analysis using COMSOL multiphysics was conducted on various dimensions of open cylindrical shields to benchmark these results with established analytical results before applying the same boundary conditions to C-100 magnetic shielding designs. The shielding factors are calculated from the FEM models

Figure 4.2.2. Schematic of C-100 cryomodule with 8-SRF cavities/He-vessels. (Distance in meters.)

The length of the C-100 cryomodule's vacuum vessel at Jefferson lab is 7.68 m and its inner diameter is 0.81m. The cryomodule's large vacuum vessel encloses eight SRF cavities and each of these SRF cavities are enclosed by individual helium vessels. The length and diameter of helium vessels are 0.73 m and .254 m respectively. The SRF cavities are enclosed inside individual He-vessels. The proposed study in this research project is about shielding these SRF cavities from the external Earth's magnetic field. Various designs of magnetic shields can be proposed and fabricated to achieve sufficient shielding to diminish the Earth's field to about 1/100 of its nominal values inside these SRF cavities. Here, we propose five different designs and study them using COMSOL Multiphysics finite element modeling. Combinations of different thicknesses of magnetic shielding materials are used to evaluate the change in shielding effectiveness. A4K has much better permeability at 5K compared to Amumetal while they both have comparable permeability at room temperature. Thus, A4K is used for the cold shielding (inner shielding) around the helium vessel and Amumetal is used everywhere else. The five different designs of magnetic shields proposed for finite element modeling studies are discussed

below in detail. Both outer and inner shields are studied with combinations of thicknesses and results are summarized in next section.

4.2.a Design I

Design I consists of a single cylindrical outer shield and a single cylindrical inner shield without endcaps as shown in figure 4.2.a. The outer shield is made of Amumetal and is placed around the inner side of vacuum vessel. The inner shield is made of A4K and is placed around the helium vessel.

Rationale: The idea is to check a base configuration without end caps

Figure 4.2.a Schematic of magnetic shield design I: one outer shield and one inner shield without endcaps. (Distance in meters.)

4.2.b Design II

Design II consists of a single cylindrical outer shield with endcaps and a single cylindrical inner shield with endcaps as shown in figure 4.2.b. The outer shield is made of Amumetal and is placed around the inner side of vacuum vessel. The inner shield is made of A4K and is placed around the helium vessel. The endcaps for outer shield are made of Amumetal and endcaps for inner shield are made of A4K.

Rationale: The idea is to check a base configuration with end caps

Figure 4.2.b Schematic of magnetic shield design II: one outer shield with endcaps and one inner shield with endcaps. (Distance in meters.)

4.2.c. Design III

Design III consists of a single cylindrical outer shield with endcaps and eight individual cylindrical inner shields for each SRF cavity without endcaps as shown in figure 4.2.c. The outer shield is made of Amumetal and is placed around the inner side of vacuum vessel. The inner shields are made of A4K and are placed around each helium vessels. The endcaps for outer shield are made of Amumetal. There are no endcaps for inner shields in this design.

Rationale: The idea is to see if multiple inner shield modules, one over each SRF cavity rather than one continuous shield encasing all gives better shielding for axial magnetic fields. Here end caps are not included in inner shield modules.

Figure 4.2.c Schematic of magnetic shield design III: one outer shield with endcaps, individual inner shields for each SRF cavities without endcaps. (Distance in meters.)

4.2.d Design IV

Design IV consists of a single cylindrical outer shield with endcaps and eight individual cylindrical inner shields for each SRF cavity with endcaps for each one as shown in figure 4.2.d. The outer shield is made of Amumetal and is placed around the inner side of vacuum vessel. The inner shields are made of A4K and are placed around each helium vessels. The endcaps for outer shield are made of Amumetal and endcaps for inner shield are made of A4K.

Rationale: The idea is to see if multiple inner shield modules with end caps, one over each SRF cavity rather than one continuous shield encasing all gives better shielding for axial magnetic fields.

Figure 4.2.d Schematic of magnetic shield design IV: one outer shield with endcaps, individual inner shields for each SRF cavities with endcaps. (Distance in meters.)

4.2.e. Design V

Design V consists of a single cylindrical outer shield with endcaps, a single cylindrical middle shield (between outer shield and inner shield) without endcaps and eight individual cylindrical inner shields for each SRF cavity with endcaps as shown in figure 4.2.e. The outer shield is made of Amumetal and is placed around the inner side of vacuum vessel. The middle shield is made of Amumetal as well and is placed between outer and inner shields. The inner shields are made of A4K and are placed around each helium vessels. The endcaps for outer shield are made of Amumetal and endcaps for inner shield are made of A4K.

Rationale: The idea is to see if adding a middle shield layer (between the outer and inner shields of configuration IV) further enhances shielding while reducing quantity of shielding material used.

Figure 4.2.e Schematic of magnetic shield design V: one extra layer of shield between outer and inner shield of design IV. (Distance in meters.)

4.3. Results and analysis

The axial shielding effectiveness and transverse shielding effectiveness for all the five proposed designs were studied using COMSOL Multiphysics. The magnetic flux density (T) distribution plots in figure 4.3.1 for magnetic shielding designs I to V shows the distribution of magnetic field in C-100 cryomodule with eight SRF cavities and eight He-vessels. Similarly, figure 4.3.2 shows the distribution of magnetic field along the beam-line of cryomodule with all five magnetic shield designs. For this study, Amumetal is used as the shielding material for outside shield and A4K is used for the inner shield in all designs. For design V, Amumetal is also used for the middle shield. Different combinations of thicknesses of materials are used and are presented in detail in tables 4.3.1.A to 4.3.2.A. The permeability for A4K used for this study at ~5K (cryogenic temperature) is 51900 and permeability of Amumetal at 300K is 11700. These values are based on prior material characterization performed for Amumetal and A4K.

Figure 4.3.1.a The multiscale magnetic flux density (T) distribution plots for *axial magnetic* shielding design I in C-100 cryomodule with 8-SRF cavities/He-vessels

Figure 4.3.1.b The multiscale magnetic flux density (T) distribution plots for *axial magnetic* shielding design II in C-100 cryomodule with 8-SRF cavities/He-vessels

Figure 4.3.1.c The multiscale magnetic flux density (T) distribution plots for *axial magnetic* shielding design III in C-100 cryomodule with 8-SRF cavities/He-vessels

Figure 4.3.1.d The multiscale magnetic flux density (T) distribution plots for *axial magnetic* shielding design IV in C-100 cryomodule with 8-SRF cavities/He-vessels

Figure 4.3.1.e The multiscale magnetic flux density (T) distribution plots for *axial magnetic* shielding design V in C-100 cryomodule with 8-SRF cavities/He-vessels

Figure 4.3.2.a The contour magnetic flux density norm plot and the *axial shielding* effectiveness along the length of C-100 cryomodule with the implementation of magnetic shielding designs I. (Thickness of outer shield = 1.016 mm and thickness of inner shield = 0.508 mm)

Figure 4.3.2.b The contour magnetic flux density norm plot and the *axial shielding* effectiveness along the length of C-100 cryomodule with the implementation of magnetic shielding designs II. (Thickness of outer shield = 1.016 mm and thickness of inner shield = 0.508 mm)

Figure 4.3.2.c The contour magnetic flux density norm plot and the *axial shielding* effectiveness along the length of C-100 cryomodule with the implementation of magnetic shielding designs III. (Thickness of outer shield = 1.016 mm and thickness of inner shield = 0.508 mm)

Figure 4.3.2.d The contour magnetic flux density norm plot and the *axial shielding* effectiveness along the length of C-100 cryomodule with the implementation of magnetic shielding designs IV. (Thickness of outer shield =1.016 mm and thickness of inner shield = 0.508 mm)

Figure 4.3.2.a The contour magnetic flux density norm plot and the *axial shielding* effectiveness along the length of C-100 cryomodule with the implementation of magnetic shielding designs V. (Thickness of outer shield = 1.016 mm, thickness of inner shield = 0.508 mm and thickness of middle shield = 1.016 mm)

The tables I –VI below show the shielding effectiveness at SRF cavities (1 to 4) in a cryomodule with the implementations of all five designs of magnetic shields. The shielding effectiveness $S_{f1} = S_{f8}$, $S_{f2} = S_{f7}$, $S_{f3} = S_{f6}$ and $S_{f4} = S_{f5}$ changes with the change in thicknesses. The increase in thickness, increase in layers of shield and use of endcaps gives enhanced shielding coefficients.

4.3.1 Axial shielding

Axial shielding effectiveness is computed with the application of static magnetic field along the length of cryomodule. The axial shielding results in Tables 4.3.1.A to 4.3.1.E are for five different designs of magnetic shield.

Table 4.3.1.A : Axial shielding effectiveness for design I

Outer Shield thickness (mm)	Inner Shield thickness (mm)	S_{f1}	S_{f2}	S_{f3}	S_{f4}
1.016	0.508	10.84	5.40	4.01	3.57
1.016	1.016	16.36	8.26	6.04	5.33
1.575	0.508	12.68	6.63	4.95	4.40
1.575	1.016	19.04	10.01	7.33	6.46

Table 4.3.1.B: Axial shielding effectiveness for design II

Outer Shield thickness (mm)	Inner Shield thickness (mm)	S_{f1}	S_{f2}	S_{f3}	S_{f4}
1.016	0.508	12.88	5.61	4.11	3.64
1.016	1.016	19.69	8.51	6.16	5.42
1.575	0.508	16.26	7.02	5.11	4.51
1.575	1.016	24.47	10.49	7.55	6.22

Table 4.3.1.C: Axial shielding effectiveness for design III

Outer Shield thickness (mm)	Inner Shield thickness (mm)	S_{f1}	S_{f2}	S_{f3}	S_{f4}
1.016	0.508	105.91	67.44	54.79	50.60
1.016	1.016	181.56	115.39	93.28	86.10
1.575	0.508	152.34	93.12	73.91	67.61
1.575	1.016	264.71	160.76	126.70	115.91

Table 4.3.1.D: Axial shielding effectiveness for design IV

Outer Shield thickness (mm)	Inner Shield thickness (mm)	S_{f1}	S_{f2}	S_{f3}	S_{f4}
1.016	0.508	94.17	64.23	53.54	49.82
1.016	1.016	176.96	121.23	101.08	94.02
1.575	0.508	124.77	84.30	69.52	64.35
1.575	1.016	234.21	159.07	131.22	121.44

Table 4.3.1.E: Axial shielding effectiveness for design V

Outer shield thickness (mm)	Middle shield thickness (mm)	Inner shield thickness (mm)	S_{f1}	S_{f2}	S_{f3}	S_{f4}
1.016	1.016	0.508	97.09	79.69	67.97	63.06
1.016	1.016	1.016	182.83	150.80	128.52	119.23
1.575	1.575	0.508	126.13	108.70	94.38	87.94
1.575	1.575	1.016	236.83	205.25	178.33	166.01

Looking at the results from figures 4.3.1 to 4.3.2 and all of the tables in this section, the axial shielding factors have increased from design I to design V for similar combination of thicknesses of materials. The endcaps provide more efficient path to the magnetic field lines resulting in better shielding in design II compared to design I. Design III results in better shielding effectiveness than design II at the center of each SRF cavities with individual inner shields and lower shielding in-between the SRF cavities. This is because each SRF cavity has an individual shield to provide the path for magnetic lines to propagate through them and no path in between the SRF cavities. As a result, there is concentration of flux at each empty area but much better shielding for the SRF cavity. Again, the use of endcaps in design IV and an extra layer of shield in design V resulted in better shielding effectiveness at each RF cavities along the length of cryomodule.

4.3.2 Transverse shielding

Transverse shielding effectiveness is computed with the application of static magnetic field perpendicular to the length of cryomodule. The results in Table 4.3.2.A are for design I of magnetic shield with outer shield's thickness of 1.016 mm and inner shield's thickness of 0.508 mm. This basic design shows the earth's magnetic field in transverse direction can be attenuated very easily and design-I is more than adequate. Hence transverse shielding does not require further studies with shielding designs II-V. However, in the end, need for effective axial shielding will drive the necessity to find improved designs (such as designs II-V).

Table 4.3.2.A: Transverse shielding effectiveness for design I

Outer Shield thickness (mm)	Inner Shield thickness (mm)	S_{f1}	S_{f2}	S_{f3}	S_{f4}
1.016	0.508	1113.40	1476.35	1506.20	1495.68
1.016	1.016	2168.90	2808.22	2823.04	2955.26
1.575	0.508	1568.13	2150.99	2208.23	2255.53
1.575	1.016	3211.38	4404.48	4563.68	4452.97
3.175	1.016	5283.30	8156.76	8127.80	8767.31

The shielding effectiveness increases with increasing thickness or increasing permeability of the shielding material. It can also be increased with increasing the layers with air gaps in-between

them. Axial shielding factors obtained in each case are lower than transverse shielding factors as explained earlier. The use of end caps would increase the axial shielding factors. Further analysis and optimization of the magnetic shield design is being performed for C-100 cryomodules. In the future study, we will look at both the cryogenic and room temperature shields and their combined effect both for annealed materials and materials whose permeability was degraded by plastic deformations caused by realistic manufacturing and assembly conditions.

4.4. Conclusion

We have successfully studied C-100 magnetic shielding using 3D COMSOL Multiphysics. Here the permeabilities estimated from prior work were used to approximately estimate shielding performance for C-100 cryomodule. The transverse field is found to be easily shielded by the basic configuration presented in design I and results tabulated in Table 4.3.2.a. While the remaining configurations discussed in designs II, III, IV and V show much better transverse shielding effectiveness they are not needed for transverse shielding as design I suffices in meeting the shielding requirement for transverse fields. However, shielding from an axial field requires more design and optimization compared to the designs discussed above because attenuating an axial magnetic field is relatively difficult compared to attenuating a transverse magnetic field. Thus, the comprehensive FEM studies of designs I – V with applied axial field are tabulated in tables 4.3.1.a -4.3.1.e. These estimates of shielding effectiveness with multiple designs and multiple combination of thickness of materials could help us come up with the best possible configuration. The requirement of achieving shielding effectiveness ~ 100 is provided by designs III, IV and V for C-100 module with the thicknesses studied. The optimum design (among those studied) is ~ 1.5 mm thick outer shield and ~ 1 mm thick inner shield in designs III and IV and ~ 1 mm thick outer, middle and inner shields in design V. Hence, we conclude that

the FEM study discussed here can be used to design and optimize passive magnetic shields of different geometries and sizes. In future work, by incorporating details of temperature and processing effects on the permeability of these magnetic shields, integrating the model for permeability as a function of applied field (Chapter 3) with the COMSOL FEM model one can develop a comprehensive method of realistically estimating shielding performance. These analysis can then be coupled with an optimizer to iteratively arrive at the best design (i.e. produces axial shielding factor >100) while consuming the least material or cost. For example a thinner outer shield and thicker inner shield with same performance as thinner inner and thicker outer shield may result in smaller material cost. Similarly, another question is whether the use of the most optimized three layers of shielding (design V) can achieve the same shielding or better shielding efficiency of the most optimized two layer shield (design IV) while needing less shielding material (or costing less when material, manufacturing and installation costs are included). This is beyond the scope of this dissertation.

CHAPTER 5. Conclusions and future work

5.1 Conclusions

In this dissertation, we performed magnetic characterization of magnetic shielding materials (specifically Amumetal and A4K) to address the gap in knowledge of not having sufficient material characterization data for magnetic behavior of such shielding materials over a wide range of temperature and processing conditions (deformation and annealing). This work could potentially help design better magnetic shields for cryomodules. We have explained this experimental data with an energy based stochastic model. Such a model could explain the effects of processing conditions and temperatures on these magnetic shielding materials. Finally, we performed 3-D FEM analysis of the magnetic shielding efficacy of various shield designs for C-100 cryomodules using the magnetic permeability obtained from our experimental characterization. This could help guide future designs with improved shielding from the earth's magnetic field in superconducting radio frequency (SRF) modules in particle accelerators at the Jefferson Lab.

Contributions:

There are three main contributions this dissertation makes to the understanding of magnetic shielding materials and the design of magnetic shields:

1. We performed experimental characterization of Amumetal and A4K samples using a Versalab VSM and SQUID magnetometer. As rolled samples, annealed samples, deformed samples and re-annealed samples were tested in a Versalab VSM at 50K, 100K, 150K, 200K, 250K and 300K to obtain their M-H curves. Similarly, these different samples were tested using SQUID to obtain the M-H curves at 5K. This comprehensive

experimental data obtained for both these important shielding materials over a large range of temperatures and processing conditions is vital for their application in magnetic shielding as previously shielding design was fully dependent on manufacturer provided data and limited studies performed by some other groups[8,9,10,12]. In summary, our work addresses this key gap in knowledge by performing a comprehensive experimental characterization of magnetization data for Amumetal and A4K.

2. This experimental data was explained by developing a stochastic model. This model can be used to simulate and explain the magnetic behavior of these materials at different applied magnetic fields and temperature. This model can be used for similar ferromagnetic and magnetostrictive materials to predict their magnetic behavior as well. While there are others stochastic models for ferromagnetic materials[20-34], this model can comprehensively accommodate and effectively model both the effect of temperature and defects in such materials on their magnetization (M-H) curves. This is the uniqueness of this model compared to other magnetization models for ferromagnetic materials.
3. Finally, we used the experimentally obtained permeabilities to study the effectiveness of a magnetic shield for C-100 cryomodule using five different designs with combination of thicknesses of materials used. This gives us the framework to obtain the best effective shielding coefficient using 3-D models of FEM studies as explained in detail in chapter 4. The methodologies used in this study can be used to develop future designs of magnetic shields very easily using 3-D FEM and we don't have to rely on 2-D symmetric or asymmetric results.

5.2 Future work

While this dissertation has contributed both experimentally and theoretically to the understanding of magnetic materials used for shielding as well as shield designs through comprehensive experimental magnetic characterization, developing an energy based magnetic stochastic model and performing 3-D FEM analysis of magnetic shielding, we believe further studies described below will further strengthen these studies and their application to magnetic shielding of cryomodules.

We have used the experimental data in our FEM analysis in COMSOL. Implementation of the stochastic magnetic model of materials developed in this thesis into COMSOL Multiphysics could not be accomplished within the time constraints. The successful implementation of the M-H model described in chapter 3 could enable us to refine and get better results than predicted here. Also, fabrication and testing of the best possible design from chapter 4 could help us benchmark the 3-D FEM studies using COMSOL Multiphysics with experimental data. This could shed some light on the amount and cost of materials needed for the design and optimization of shields. This could eventually have an application in designing the most effective shield with the least possible material for C-100 cryomodules or other cryomodules.

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2. S. Sah and J. Atulasimha, Energy based stochastic model for temperature dependent behavior of ferromagnetic materials. (Under review, Journal of Magnetism and Magnetic Materials)

3. S. Sah, G. Cheng, G. Myneni and J. Atulasimha, 3D finite element analysis of passive magnetic shielding using COMSOL-Multiphysics (Under preparation)

CONFERENCE PRESENTATIONS

1. S. Sah, G. Myneni and J. Atulasimha, “Magnetic Materials Characterization and Modeling for Magnetic Shielding of Cryomodules in Particle Accelerators”, American Nuclear Society Meeting - 2014 Winter Meeting and Technology Expo, At Disneyland Hotel, Anaheim, CA
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