

Characterization of the magnetically shielded room for
the neutron electric dipole moment experiment at
TRIUMF

by

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Abstract

The motivation to search for the neutron Electric Dipole Moment (nEDM) lies at the interface between particle physics and cosmology. The discovery of a non-zero permanent nEDM by currently planned experiments could provide direct evidence of new physics beyond the Standard Model, motivated by its CP -violating nature. This level of CP violation would help explain the generation of the matter-antimatter asymmetry in the early Universe. The Standard Model (SM) predicts a neutron EDM on the order of $|d_n| \sim 10^{-31} e \cdot \text{cm}$, a value far below current experimental sensitivities. The current experimental upper limit, set by worldwide efforts, is $|d_n| < 1.8 \times 10^{-26} e \cdot \text{cm}$ (90% C.L.). The TRIUMF Ultracold Advanced Neutron (TUCAN) collaboration aims to improve this sensitivity by an order of magnitude, targeting $\sigma(d_n) \leq 10^{-27} e \cdot \text{cm}$.

The typical experimental method to measure the nEDM uses polarized Ultracold Neutron (UCN) and employs the Ramsey method of separated oscillatory fields. Measurement of the spin precession frequency of UCNs requires very homogeneous electric and magnetic fields in space and time over the experimental area. A large multi-layer room called Magnetically Shielded Room (MSR) shields the main precession magnetic field produced by an internal coil from the environmental magnetic fields. In the nEDM measurement, many possible sources of systematic error can manifest as a false EDM signal. Historically, the dominant systematic errors have come from magnetic field inhomogeneities, reducing the statistical precision of the experiment due to its impact on UCNs' relaxation time. Providing a picture of the magnetic field environment within the experiment would help control the system's homogeneity.

This dissertation focuses on the development of the magnetic environment essential for achieving the TUCAN collaboration’s target sensitivity in nEDM measurements, with particular emphasis on the design, characterization, and optimization of the MSR. Initial evaluations of the MSR indicated suboptimal shielding performance, necessitating investigations and targeted optimization efforts.

To enhance the MSR’s shielding factor, a combination of experimental techniques, including magnetic shaking, was implemented. Additionally, residual field mapping was conducted to gain an understanding of the magnetic field environment within the MSR. For this purpose, a custom-built mapping system was developed to analyze residual fields, with its performance simulated to account for systematic errors, such as sensor inaccuracies, positional and rotational offsets, and structural deviations.

The results presented in this work evaluate the MSR’s performance and its suitability for the TUCAN nEDM experiment. Detailed investigations were conducted to identify potential sources of magnetic field contamination and explore strategies for reducing their impact. These efforts contribute to the ongoing preparation of the MSR and support the goal of achieving the target sensitivity for nEDM measurements.

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Dedication

Dedicated to individuals who possessed the passion, curiosity, and potential to become scientists, but whose opportunities were limited for reasons unrelated to their performance or the quality of their work.

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Acronyms

μ -metal mu-metal.

DMM Digital Multi-Meter.

FG Fluxgate.

MSR Magnetically Shielded Room.

nEDM neutron Electric Dipole Moment.

NIDAQ National Instrument's NI USB-6281 data acquisition unit.

RMS Root Mean Square.

SCU1 Bartington Signal Conditioning Unit 1.

SF Shielding Factor.

UCN Ultracold Neutron.

Chapter 1

Introduction

This chapter explains why studying the neutron Electric Dipole Moment (nEDM) is important for understanding fundamental symmetries in the universe. It starts with an introduction to discrete symmetries and how their violations relate to the mystery of baryon asymmetry. The discussion then moves to show the role of the nEDM in solving this imbalance. Next, the experimental techniques used to measure the nEDM, particularly Ramsey’s method of separated oscillating fields, are explained. Finally, the chapter provides an overview of the TUCAN nEDM apparatus, highlighting its design and experimental goals.

1.1 Thesis Outline

This dissertation is organized as follows:

- Chapter 1 explores the physics motivation for nEDM measurements, emphasizing their connection to CP violation and the matter-antimatter asymmetry in the universe.
- Chapter 2 introduces principles of magnetic shielding. The concept of the Shielding Factor (SF) is introduced as a way to quantify a shield’s effectiveness. A review of existing MSRs used in nEDM experiments is also included, along with a description

of the TUCAN MSR, its design, installation, and key features such as the shielding layers and access holes.

- Chapter 3 details the experimental setups and instrumentation used to evaluate the MSR's performance. It covers the different tools used for measurements, such as magnetometers, power amplifiers, and data acquisition systems. It also explains how SF measurement coils and degaussing systems were set up to test the MSR.
- Chapter 4 outlines the approach used to measure the Shielding Factor (SF) without the MSR in place. It explains how the SF is calculated and describes the experimental setup, data collection, and analysis. These results serve as a reference for later comparisons once the MSR is installed.
- Chapter 5 presents post-installation measurements, showing how each layer contributed to improving the SF. Additionally, tests were conducted with the TRIUMF cyclotron field turned on and off to understand its effect on the MSR's shielding ability.
- Chapter 6 discusses the degaussing process used to remove magnetization from the μ -metal. We describe how degaussing cycles were applied to different shielding layers under various conditions, including with the cyclotron field on and off. We also provide the hysteresis loops to discuss magnetic properties and saturation behavior of the MSR's material.
- Chapter 7 presents measurements of the residual field within the MSR, taken through access holes. A custom-built mapping setup was used to measure field strength at different points. These results are important for the MSR characterization as we expected residual field of $< 1\text{nT}$ in the central region of the MSR.
- Chapter 8 investigates potential reasons for lower-than-expected SF and describes several methods tested to improve the shielding. These include measuring material permeability, applying external compensation fields, and using a technique called "magnetic

shaking" to reset localized magnetization.

- Chapter 9 summarizes the findings of the dissertation, reflecting on the challenges faced in optimizing the MSR's shielding performance, and suggests possible improvements for future shielding designs.

1.2 Motivation

The universe we observe today is overwhelmingly composed of matter, with antimatter being exceptionally rare. This asymmetry is inconsistent with the expectation that the universe began with equal amounts of matter and antimatter, which should have annihilated each other completely, leaving behind a universe filled only with photons. Observational evidence, such as the relative abundance of light elements predicted by Big Bang nucleosynthesis, supports the conclusion that baryons outnumbered antibaryons shortly after the Big Bang. It is highly accepted that during a hot early epoch of the Big Bang, matter and antimatter existed as baryonic and leptonic pairs in thermal equilibrium with radiation [1]. As the universe expanded and cooled, these pairs annihilated, but the visible universe—dominated by stars, galaxies, and other matter-rich structures—indicates that symmetry-breaking processes must have favored matter over antimatter.

This observed baryon asymmetry cannot be fully explained within the framework of the Standard Model (SM) of particle physics. Charge-parity (CP) violation, a phenomenon that distinguishes between matter and antimatter, is considered a critical ingredient for explaining this imbalance. Sakharov [2] proposed that CP violation, combined with baryon number violation and a departure from thermal equilibrium, could produce the observed matter-antimatter asymmetry. While CP violation has been observed in certain weak interactions, its magnitude within the SM is insufficient to account for the observed asymmetry, necessitating the search for additional sources of CP violation.

The nEDM offers a promising avenue for discovering new sources of CP violation. Al-

though electrically neutral, the neutron could possess an EDM if its internal positive and negative charge distributions are spatially displaced. Such an EDM would violate both parity (P) and time-reversal (T) symmetries, and by the CPT theorem, this would imply CP violation. Detecting a non-zero nEDM would thus provide direct evidence of physics beyond the Standard Model and illuminate the mechanisms responsible for the baryon asymmetry of the universe.

Despite decades of experimental efforts, as depicted in Figure 1.1, no nEDM has yet been detected. The current best upper limit is $|d_n| < 1.8 \times 10^{-26} e \cdot \text{cm}$ (90% confidence level) [3]. While the SM predicts an nEDM of approximately $10^{-31} e \cdot \text{cm}$ [4], several beyond-Standard-Model theories predict significantly larger values. The TRIUMF Ultracold Advanced Neutron (TUCAN) collaboration aims to improve the sensitivity of nEDM measurements by an order of magnitude, targeting $\sigma(d_n) \leq 10^{-27} e \cdot \text{cm}$.

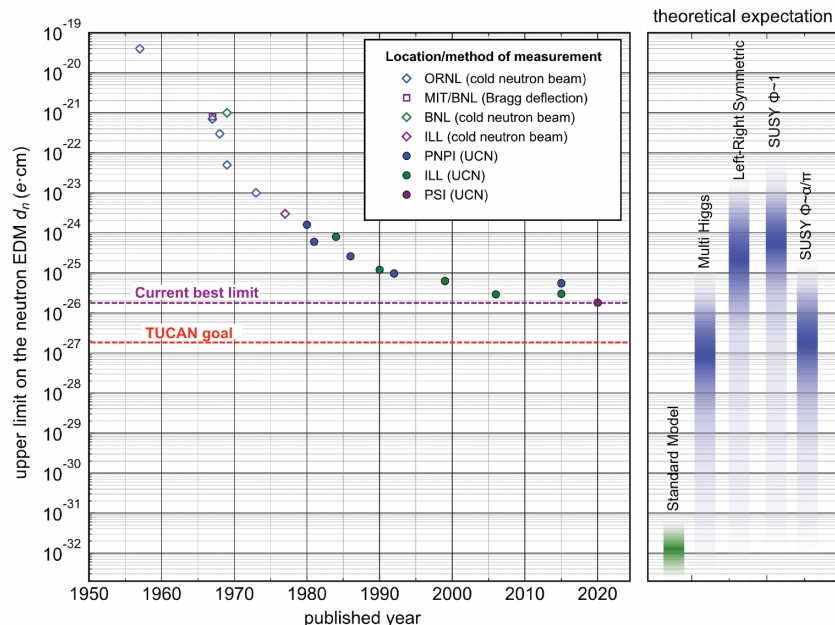


Figure 1.1: The upper limit of the nEDM at 90% confidence level (CL) as a function of time. The figure on the right shows theoretical predictions for the nEDM from the Standard Model and selected beyond-Standard-Model theories, with predicted values from reference [5]. The red line indicates the TUCAN Collaboration’s goal to improve the current upper limit by an order of magnitude. Figure reproduced from [6] by Steve Sidhu [7].

Achieving this ambitious goal requires overcoming significant experimental challenges, particularly in creating stable and homogeneous magnetic environments. Central to the TUCAN experiment is the Magnetically Shielded Room (MSR), a multi-layer enclosure designed to suppress external magnetic fields and create the conditions necessary for precise nEDM measurements. This thesis focuses on characterizing the MSR’s performance, identifying factors such as SF and remanent magnetization, and implementing optimization strategies to improve its performance. By addressing these challenges, this work contributes to the broader effort to achieve the TUCAN collaboration’s ambitious sensitivity target and advance our understanding of the fundamental symmetries of nature.

1.3 Fundamental Symmetries

In exploring the motivations for searching for the neutron electric dipole moment (nEDM), it is essential to begin with a discussion of the fundamental discrete symmetries in physics. The four fundamental forces—gravity, weak, strong, and electromagnetic—are described mathematically, often using Hamiltonian or Lagrangian frameworks. If the physical quantities derived from these models remain unchanged under specific transformations, the theory is considered symmetric with respect to those transformations.

In particle physics, three key discrete symmetries are charge conjugation (C), parity (P), and time-reversal (T). The C transformation replaces every particle with its corresponding antiparticle, the P transformation inverts spatial coordinates, and the T transformation reverses the direction of time. Early theories in particle physics assumed that these fundamental interactions were invariant under such symmetries. However, in 1956, Yang and Lee proposed that parity symmetry might not hold in certain processes, such as K-meson decays [8]. Their hypothesis was soon confirmed, as experiments conducted in 1957 demonstrated the violation of P symmetry in the beta decay of ^{60}Co [9–11]. That same year, Lüders established that in any quantum field theory that respects Lorentz invariance, the

combination of CPT (charge conjugation, parity, and time-reversal) transformations must remain a symmetry [12].

This CPT theorem implies that, although individual symmetries like P may be violated, the combined CPT symmetry must still hold. To date, no experimental evidence has contradicted CPT symmetry. An important consequence of the CPT theorem is that a violation of time-reversal symmetry (T) is directly related to a violation of charge-parity symmetry (CP), making the study of CP violation crucial for understanding certain unsolved problems in physics, such as the baryon asymmetry of the universe.

1.4 Baryon asymmetry and the neutron electric dipole moment

The baryon asymmetry problem refers to the observed discrepancy between the amounts of matter and antimatter in the universe. This difference can be quantified using the asymmetry parameter, defined as

$$\eta = \frac{n_b - \bar{n}_b}{n_\gamma}, \quad (1.1)$$

where n_b represents the number density of baryons, $\bar{n}_b$ is the number density of antibaryons, and n_γ denotes the number density of photons. The Standard Model of particle physics predicts the baryon asymmetry to be around 10^{-18} [13, 14]. In contrast, measurements from the cosmic microwave background indicate a value of $\eta = 6.1^{+0.3}_{-0.2} \times 10^{-10}$ [15], which is eight orders of magnitude greater.

Sakharov proposed three necessary conditions that any theoretical framework must meet to explain this observed baryon asymmetry [2]:

- Violation of baryon number,
- Violation of CP symmetry, and

- A departure from thermal equilibrium.

In 1957, Landau demonstrated that the presence of electric dipole moments (EDMs) in fundamental particles would violate time (T) symmetry [16]. Given that the combined CPT symmetry must be preserved, a finite EDM would imply CP violation. Figure 1.2 provides a conceptual depiction of a fundamental particle undergoing T reversal. The Hamiltonian for this system is expressed as

$$H = -\mu \mathbf{S} \cdot \mathbf{B} - d \mathbf{S} \cdot \mathbf{E} \neq -\mu \mathbf{S} \cdot (-\mathbf{B}) - d \mathbf{S} \cdot \mathbf{E}, \quad (1.2)$$

where $\mathbf{S}$ is the spin vector of the particle. Under a T transformation, the directions of the magnetic field and spin vector are reversed, while the electric field remains unchanged, leading to a difference in energy states. It is noteworthy that the magnetic dipole moment in Equation (1.2) is defined along the direction of the spin vector: $\mu = \mu |\mathbf{S}|$, with a similar representation for the electric dipole moment $d = d |\mathbf{S}|$. The Wigner-Eckhart theorem limits both μ and d to align with the spin vector (see Reference [17] for further details). The magnetic dipole moment of a neutron μ_n has been measured to be $\mu_n = -1.91304273(45)\mu_N$ [18]. The nuclear magneton μ_N is defined as $\mu_N = \frac{e\hbar}{2m_p} = 3.15245125844(96) \times 10^{-14} \text{ MeV/T}$ [19], where e is the elementary charge, $\hbar$ is the reduced Planck's constant, and m_p is the proton's rest mass.

Two sources of CP violation in the Standard Model arise from the CP -violating terms in the CKM (Cabibbo-Kobayashi-Maskawa) matrix and the quantum chromodynamics (QCD) Lagrangian. The CKM matrix contributes to the nEDM predictions, with the Kobayashi-Maskawa (KM) mechanism estimating it to be no greater than $d_n^{KM} \sim 10^{-31} e \cdot \text{cm}$ [4]. The QCD Lagrangian is given by

$$\mathcal{L} = \mathcal{L}_{CP} - \theta \frac{g_s^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad (1.3)$$

where $F_{\mu\nu}$ represents the gluon field strength tensor, $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F^{\mu\nu\alpha\beta}$ is its dual, and

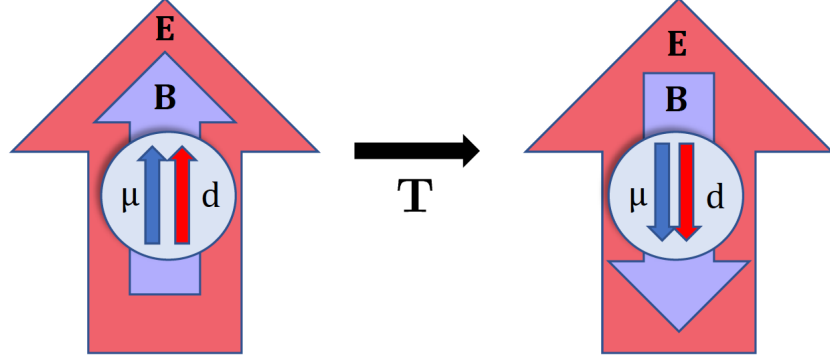


Figure 1.2: A fundamental spin-1/2 particle with both an electric dipole moment (d) and magnetic dipole moment (μ) in the presence of electric ($\mathbf{E}$) and magnetic ($\mathbf{B}$) fields undergoing a time-reversal (T) transformation. The existence of an electric dipole moment in a spin-1/2 particle would indicate a violation of T symmetry, which, by extension, would also violate CP symmetry.

g_s is the strong coupling constant. The term $\mathcal{L}_{CP}$ accounts for the interactions of gluons and quarks. The second term in Equation (1.3) encapsulates the CP -violating interactions of gluons with the vacuum. This parameter is constrained by nEDM measurements to be extremely small: $\theta < 10^{-10}$. Given that θ is dimensionless, a natural expectation would be $\theta \approx 1$. This discrepancy between the measured value and the expected order of unity is termed the "Strong CP problem" and is discussed in references [20, 21].

Furthermore, the Standard Model predicts an EDM for the electron (eEDM) induced by the Kobayashi-Maskawa mechanism, which should not exceed $d_e^{KM} \sim 10^{-38} e \cdot \text{cm}$ [22]. The current upper limit on the eEDM stands at $d_e < 0.41 \times 10^{-29} e \cdot \text{cm}$ at 90% confidence level [23]. Reviews of additional EDM searches can be found in References [24, 25]. Beyond the Standard Model (BSM) theories propose further sources of CP violation, predicting an nEDM in the range of 10^{-32} to $10^{-25} e \cdot \text{cm}$ [4, 24]. Present-day experiments aim to either measure the nEDM as suggested by various BSM theories or impose strict limits on these theories.

1.5 Measurement of an nEDM

1.5.1 Ramsey’s method of separated oscillating fields

To measure the nEDM using UCNs, polarized neutrons are confined in a chamber subjected to both magnetic and electric fields. The interaction between the neutron and these fields is described by the equation on the left-hand side of Equation (1.2). In these experiments, the fields are arranged to be either parallel ($\uparrow\uparrow$) or antiparallel ($\uparrow\downarrow$), ideally as precisely as possible. Under these conditions, the neutron will exhibit precession at frequencies given by

$$\begin{aligned} f_n^{\uparrow\uparrow} &= \frac{2}{\hbar} (\mu_n |\mathbf{B}| + d_n |\mathbf{E}|), \\ f_n^{\uparrow\downarrow} &= \frac{2}{\hbar} (\mu_n |\mathbf{B}| - d_n |\mathbf{E}|). \end{aligned} \tag{1.4}$$

The nEDM is determined from the difference in precession frequencies for the parallel and antiparallel alignments of the fields:

$$d_n = \frac{\hbar(f_n^{\uparrow\uparrow} - f_n^{\uparrow\downarrow})}{2(|\mathbf{E}^{\uparrow\uparrow}| + |\mathbf{E}^{\uparrow\downarrow}|)} + \frac{\mu_n(|\mathbf{B}^{\uparrow\uparrow}| - |\mathbf{B}^{\uparrow\downarrow}|)}{2(|\mathbf{E}^{\uparrow\uparrow}| + |\mathbf{E}^{\uparrow\downarrow}|)}. \tag{1.5}$$

It is critical to maintain a stable magnetic field during these measurements. If the magnetic field strength remains unchanged, the magnetic field terms cancel out, reducing the expression to

$$d_n = \frac{\hbar(f_n^{\uparrow\uparrow} - f_n^{\uparrow\downarrow})}{4E} \tag{1.6}$$

This simplified equation allows direct extraction of d_n . The precession frequency f_n , at which maximal spin-flip occurs, is measured using Ramsey’s method of separated oscillating fields—a technique for which Norman Ramsey received the 1989 Nobel Prize in Physics. The fundamental steps of a full Ramsey cycle are illustrated in Figure 1.3.

At the start of the measurement, polarized neutrons are confined within a storage chamber. Their spins are either aligned parallel N_{up} or antiparallel N_{down} to a static magnetic

holding field, $\mathbf{B}_0$.

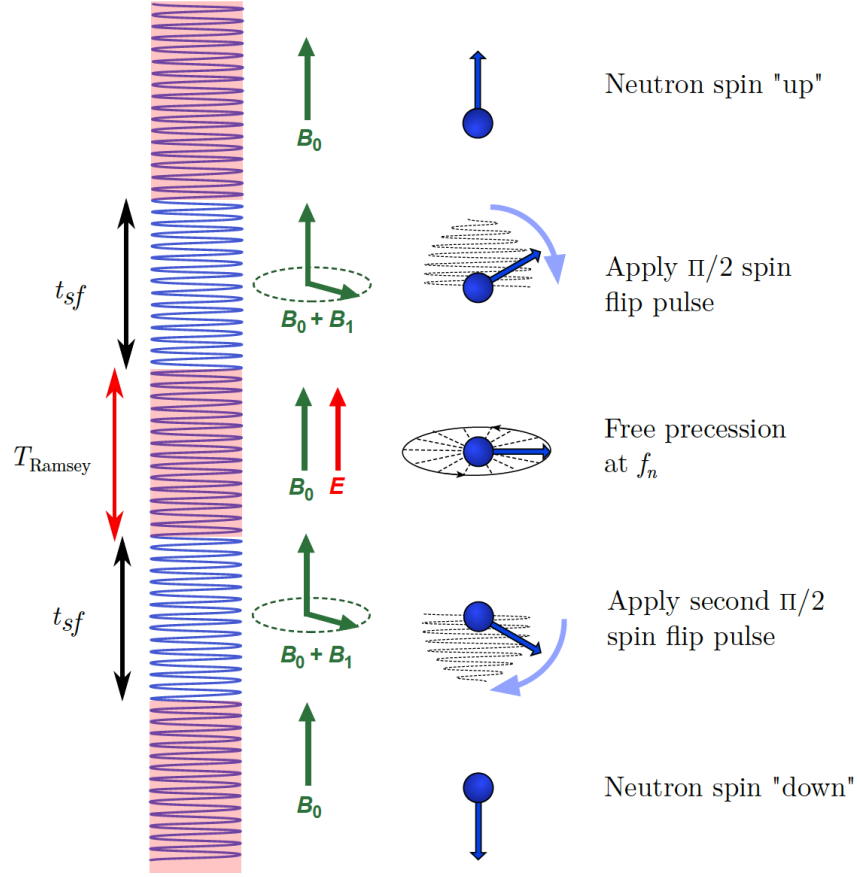


Figure 1.3: Timings and magnetic field configurations during Ramsey's method of separated oscillating fields. The red and black arrows on the left represent the times of spin-flip pulses and free precession intervals, respectively. Green arrows illustrate the magnetic fields active during each phase of the cycle. The blue arrow denotes the direction of the neutron spin vector, initially polarized along the upward direction.

In principle, minimizing the precession frequency contribution from the neutron's magnetic dipole moment, $\mu_n|\mathbf{B}|$, enhances the sensitivity to the nEDM's influence on the precession frequency, $d_n|\mathbf{E}|$. A larger magnetic field $\mathbf{B}_0$ reduces the ratio $d_n|\mathbf{E}|/\mu_n|\mathbf{B}|$, but if $\mathbf{B}_0$ is too weak, external field fluctuations could significantly distort the total magnetic field experienced by the neutrons. A magnetic holding field of $\mathbf{B}_0 = 1\mu T$ is anticipated, consistent with other room-temperature nEDM experiments (see References [26–29]).

A perpendicular spin-flip field is applied briefly for a time t_{sf} at a frequency $f_{\mathbf{B}_1} = f_n$.

The amplitude and duration are selected to rotate the neutrons' spins by $\pi/2$ into the transverse plane, a process referred to as a $\pi/2$ pulse. After free precession for a duration $T_{\text{Ramsey}} \gg t_{\text{sf}}$, another $\pi/2$ pulse, in phase with the first, is applied. Ideally, if the magnetic and electric fields are perfectly tuned, all neutron spins will flip to the opposite orientation from their initial state.

When $f_{\mathbf{B}_1} \neq f_n$, a phase difference accumulates between the neutron spins and $f_{\mathbf{B}_1}$, causing only partial spin reversal and resulting in the interference pattern shown in Figure 1.4. Longer free precession times cause greater phase accumulation, narrowing the interference fringes. By sweeping $f_{\mathbf{B}_1}$, this interference pattern can be mapped, allowing the determination of the central frequency f_n . In practice, four key points on the central fringe (as seen in Figure 1.4) are enough to determine the resonant frequency.

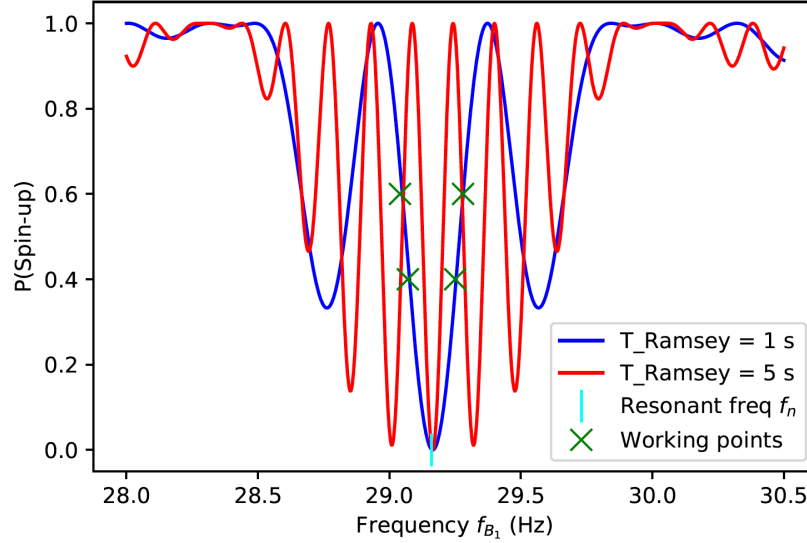


Figure 1.4: Ramsey fringe patterns for free precession times $T_{\text{Ramsey}} = 1$ s and 5 s. The plot assumes an initial magnetic field $B_0 = 10^{-6}$ T, a spin-flip field $B_1 = 15$ nT, and a spin-flip duration $t_{\text{sf}} = 1.143$ s. The horizontal axis represents the frequency of the B_1 spin-flip field [7].

This procedure is repeated for both parallel and antiparallel field alignments, resulting in eight data points per nEDM measurement. A frequency shift observed between the two field configurations gives the value of d_n via Equation (1.6).

To achieve precise nEDM measurements, controlling the magnetic environment is critical. The statistical sensitivity of the Ramsey method for frequency measurement is given by

$$\sigma_\omega = \frac{\sigma_{P_z}}{T}, \quad (1.7)$$

where σ_{P_z} is the uncertainty in the measured spin polarization and T is the precession time. This leads to the statistical sensitivity of the nEDM:

$$\sigma_d = \frac{\hbar}{2\alpha ET\sqrt{N}\sqrt{M}}, \quad (1.8)$$

where N is the total number of neutrons in a cycle, α is the visibility parameter, E is the electric field strength, and M is the number of repeated measurements. These equations rely on the assumption that the magnetic field B remains constant during the measurements of the precession frequencies $\omega_{\uparrow\uparrow}$ and $\omega_{\uparrow\downarrow}$.

However, even slight variations in the magnetic field ΔB between the measurements can introduce a significant false signal in the nEDM. The contribution of this magnetic field change to the measured nEDM is given by

$$\sigma_d(B) = \frac{\mu\Delta B}{2E}, \quad (1.9)$$

where μ is the neutron magnetic moment. For example, with $\mu = 60$ neV/T and an applied electric field $E = 20$ kV/cm, a magnetic field variation ΔB as small as 1 fT would result in a false nEDM signal of

$$d_n = 1.5 \times 10^{-27} e \cdot \text{cm}.$$

Such sensitivity highlights the necessity of maintaining an extremely stable magnetic environment. Without appropriate shielding, external magnetic field fluctuations would dominate the signal, rendering the measurement unreliable. Therefore, a magnetically shielded room is indispensable to suppress ambient magnetic field to the femtotesla level or lower,

ensuring that any observed frequency shift is due to the nEDM and not external field variations. This stringent control of the magnetic field environment is fundamental to achieving the precision required for detecting or setting bounds on the neutron’s electric dipole moment.

1.6 The TUCAN nEDM apparatus

Prior to discussing the TUCAN nEDM apparatus, the objectives of the TUCAN Collaboration should be articulated, as these objectives inform our design decisions. The key aims of the TUCAN Collaboration are the following:

- To construct a high-density ultracold neutron (UCN) source that can accommodate up to two simultaneous experiments. The work in this thesis will not cover UCN source project.
- To conduct a measurement of the neutron electric dipole moment (nEDM) with a statistical sensitivity of $1 \times 10^{-27} e \cdot \text{cm}$ in less than 400 beam-on days at TRIUMF.

The TUCAN nEDM experiment adopts Ramsey’s technique of separated oscillating fields within a double-chamber EDM spectrometer operating at room temperature, as illustrated in Figure 1.5. This methodology aligns with other contemporary EDM investigations. Each EDM cell has a height of 0.16 m and a diameter of 0.5 m, housing polarized UCN. A central high-voltage electrode operating at 200 kV separates the two cells, creating vertical electric fields with average magnitudes of $\pm 12.5 \text{ kV/cm}$.

The insulating walls between the electrodes are fabricated from deuterated polystyrene (dPS), ensuring non-magnetic properties. Non-magnetic, linearly actuated shutters complete the EDM cell design. To maintain a homogeneous and stable magnetic field environment, the setup is enclosed in a magnetically shielded room comprising four layers of μ -metal for direct current (DC) shielding and one layer of copper for alternating current

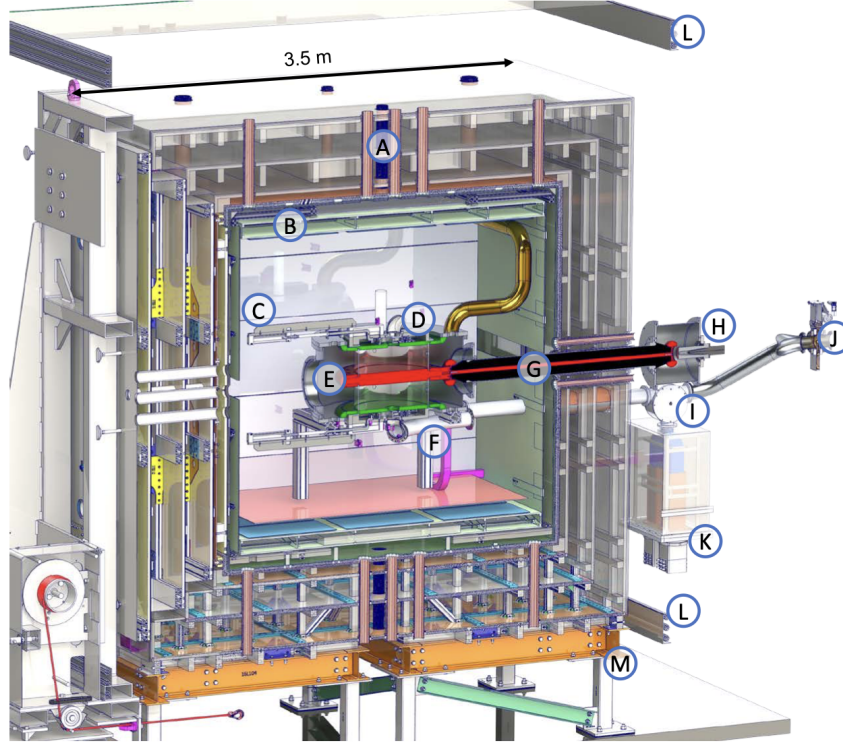


Figure 1.5: Cutaway view of the 3D model for the TUCAN EDM Apparatus. (A) 4-layer magnetically shielded room, (B) Self-shielded B0 coil, (C) EDM cell valve actuation, (D) EDM cell shutter, (E) Central high-voltage electrode, (F) UCN guide, (G) High-voltage feeder, (H) High-voltage vacuum feed through, (I) EDM detector switch, (J) UCN and vacuum valve, (K) Spin analyzers and detectors, (L) Coil compensating the ambient magnetic field, (M) Support structure.

(AC) shielding. The design of the MSR is intended to provide a high level of shielding effectiveness, anticipated to achieve a shielding factor of approximately 10^5 . A self-shielded coil, alongside several shim coils, generates a uniform vertical magnetic field of approximately $1 \mu\text{T}$.

Additionally, polarized mercury vapor will be introduced into the EDM cells to measure the magnetic field within the same volume occupied by the UCN. The necessary $\pi/2$ spin flips for both UCN and mercury are initiated by an oscillating magnetic field of around 10 nT , closely aligned with the Larmor frequencies of both species. Following the Ramsey cycle, neutron counts are recorded by four lithium-glass scintillation detectors, with two

detectors linked to each EDM cell.

The spin analyzers and spin flippers are constructed using magnetized iron films coated onto aluminum foil, strategically placed above each detector. This arrangement prevents low-field seekers from penetrating the iron film due to an increased potential barrier, while high-field seekers can overcome the barrier with careful positioning, ensuring effective detection and analysis of the UCN [30].

As noted earlier, this thesis is focused on magnetic shielding, specifically the characterization and optimization of the MSR (A in Figure 1.5) used in the TUCAN nEDM experiment. Efforts detailed in this work include the evaluation of the MSR’s shielding factor, identification of potential sources of magnetic field contamination, and implementation of techniques to enhance performance.

Chapter 2

Principles of Magnetic Shielding

Magnetic shielding is essential for protecting experimental environments from external magnetic fields that can interfere with sensitive measurements. Various methods exist to inhibit magnetic field penetration, each leveraging different physical principles to achieve this goal. The primary mechanisms include magnetic repulsion, counteraction, and diversion of magnetic fields, each possessing unique advantages and challenges that must be carefully evaluated during the design phase of a magnetic shield.

To effectively assess the performance of a magnetic shield, the shielding factor (SF) is employed, providing a quantitative measure of its effectiveness. The SF is defined as the ratio of the magnetic field intensity measured at a specific location without the shield (B_0) to that measured with the shield in place (B_i):

$$SF(\omega) = \frac{B_0}{B_i}(\omega). \quad (2.1)$$

This factor can vary significantly based on multiple parameters, including the frequency and magnitude of the external field, as well as the specific location of measurement. Understanding these dependencies is crucial for optimizing magnetic shielding strategies in experimental setups.

In the subsequent sections, we will delve deeper into the different shielding mechanisms, exploring their operational principles, applications, and limitations.

2.1 Magnetization and Permeability

To understand the underlying principles of magnetic shielding mechanisms, it is helpful to first examine the magnetic properties of materials. Among these properties, the intensity of magnetization (I) quantifies the extent to which a material becomes magnetized when subjected to an external magnetic field. I is defined as the magnetic moment per unit volume of the material, representing the concentration of magnetic poles within a given region.

In magnetized materials, magnetic induction (B) arises from the combined contributions of the external magnetic field (H) and the material's intensity of magnetization (I). This relationship is expressed as [31]

$$B = H + 4\pi I, \quad (2.2)$$

where H is the applied magnetic field and I is the intensity of magnetization. This addition is vectorial when H and I differ in direction. The factor 4π arises because a unit magnetic pole generates a unit field over the entire surface of a sphere of unit radius enclosing the pole, and the surface area of this sphere is 4π .

When an unmagnetized ferromagnetic material is subjected to a magnetic field, either by being placed near a magnet or influenced by an electric current, it becomes magnetized. The relationship between the induced magnetic induction B and the applied magnetic field strength H is depicted by the magnetization curve. This curve can also represent the intensity of magnetization I as a function of H , and it is commonly used to characterize the magnetic behavior of materials.

The magnetic response of a material can also be described using its permeability curve and hysteresis loop. Permeability, denoted by μ , is defined as the ratio B/H , which indicates

the relative increase in magnetic flux due to the material. The permeability curve is typically plotted as μ against H , B , $B - H$, or I . These curves typically begin at a point above the origin (indicating a non-zero initial permeability), rise to a maximum value (representing maximum permeability), and then decrease, eventually approaching a value of one.

The quantity $B - H = 4\pi I$ reaches a limiting value referred to as the saturation induction, denoted by B_s . When $B - H$ is used as the abscissa in a permeability plot, the curve and the axis terminate at a finite distance from the origin, reflecting the saturation behavior of the material.

If the magnetic field strength is increased from zero to a high value and then subsequently decreased, as shown by the arrows in Figure 2.1, the original curve is not retraced. Instead, the magnetic induction B "lags behind" the applied field H , forming a distinct curve known as the hysteresis loop, indicated by the broken line. This phenomenon, termed hysteresis by Ewing [32], reflects the material's inherent energy loss during the magnetization process.

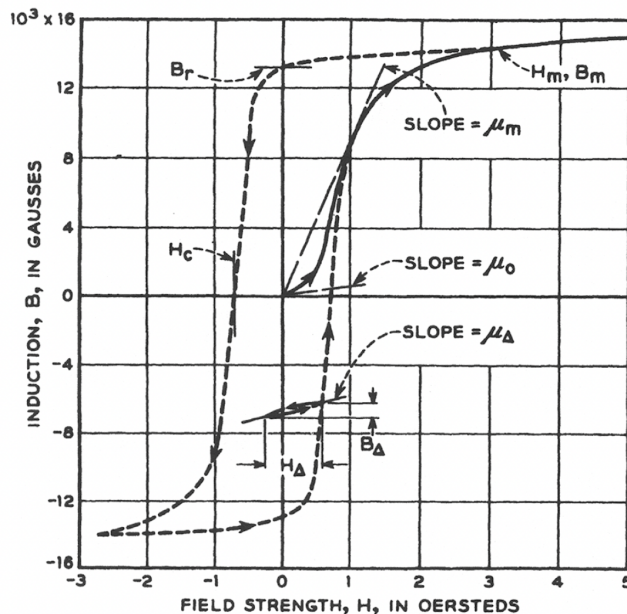


Figure 2.1: Magnetization curve (solid) and hysteresis loop (dotted). Some important magnetic quantities are illustrated [31].

For a hysteresis loop that is symmetrical about the origin, the field strength H at which

$B = 0$ is called the *coercive force*, H_c . The coercive force is often used as an indicator of the material's magnetic quality. Similarly, the value of induction when $H = 0$ is referred to as the *residual induction*, B_r . When the field strength is sufficient to magnetize the material nearly to saturation, the coercive force and residual induction are referred to as the material's coercivity and retentivity, respectively.

The maximum values of H and B at the tips of the hysteresis loop are typically denoted as H_m and B_m . These parameters provide insight into the magnetic behavior and limits of the material.

2.2 Quasi-static ferromagnetic shielding

One effective approach to shield a volume from magnetic fields is to encase it in a material characterized by high magnetic permeability (μ). This method, often referred to as flux-shunting, directs the magnetic field lines within the material, effectively guiding them around the protected volume. This behavior is grounded in Maxwell's equations, particularly through Ampère's Law and Gauss's Law, which stipulate the continuity of the tangential component of the magnetic field intensity (H) and the normal component of the magnetic flux density (B) at the interface between two distinct materials.

As shown in Figure 2.2, in air, the magnetic flux density is defined by $B = \mu_0 H$ with $\mu_1 = 1$, while within a material, it is given by $B = \mu_0 \mu_2 H$. Consequently, when the field lines enter the material, they must change direction sharply, being drawn towards materials with high permeability (μ). This leads to the field lines striking the surface nearly perpendicularly and then bending to travel almost parallel to the surface within the material. As they continue through the material, the field lines effectively circumvent the shielded volume. This flux-shunting effect occurs for both direct current (DC) and alternating current (AC) external fields.

The shielding factor (SF) for this shielding type can be analytically determined for simple

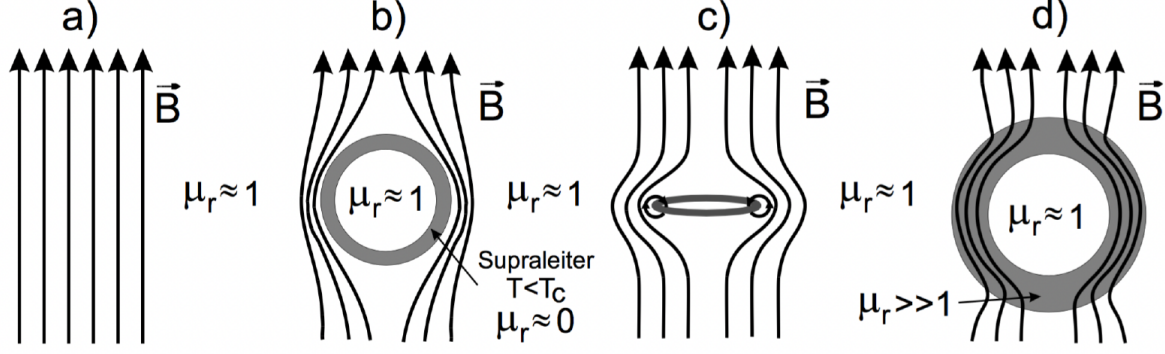


Figure 2.2: Illustration of shielding mechanisms. a) unhindered flux density, b) shielded by repulsion from superconductor, c) counteracting field produced by coil, d) flux-shunting through high permeability material [33].

geometries. For a spherical shield with a diameter D and wall thickness Δ , the shielding factor SF_{sp} is given by [34]

$$SF_{sp} = \frac{2}{3} \frac{\mu_r \Delta}{D} + 1, \quad (2.3)$$

under the conditions that $D \gg \Delta$ and $\mu \gg 1$.

Under the same condition, for an infinite cylindrical shields, the shielding factors are described as follows [35]:

$$SF_{cyl,t} = \frac{\mu_r \Delta}{D} \quad (\text{transverse}) \quad (2.4)$$

$$SF_{cyl,l} = 1 + \frac{N}{\pi} SF_{cyl,t} \quad (\text{longitudinal}), \quad (2.5)$$

where longitudinal refers to the axial direction of the cylinder and transverse indicates the radial direction. Here, N is the demagnetizing factor, which depends solely on the geometry of the system. The demagnetizing factor quantifies the reduction of the magnetic field within the material (H_{in}) compared to that outside it (H_{out}). When a material is magnetized, magnetic poles develop at its boundaries, establishing a counterfield that diminishes the field inside the material.

For cubic shields, the shielding factor is expressed as [36]

$$SF_c = \frac{4}{5} \frac{\mu_r \Delta}{L} + 1, \quad (2.6)$$

where L is the side length of the cube.

An evident strategy to enhance shielding is to increase the thickness of the material layer; however, this approach has practical limitations due to rising material costs. An alternative and often more effective method involves using multiple layers of material with air gaps in between.

The SF of a multi-layer system can be derived using recursive relations that account for the interactions between the layers [37],

$$\begin{aligned} S^T = & 1 + \sum_{i=0}^n S_i^T + \sum_{i=1}^{n-1} \sum_{j>i}^n S_i^T S_j^T \left[1 - \left(\frac{R_i}{R_j} \right)^2 \right] \\ & + \sum_{i=1}^{n-2} \sum_{j>i}^{n-1} \sum_{k>j}^n S_i^T S_j^T S_k^T \left[1 - \left(\frac{R_j}{R_k} \right)^2 \right] \left[1 - \left(\frac{R_i}{R_j} \right)^2 \right] \\ & + \dots + S_1^T S_2^T \dots S_n^T \left[1 - \left(\frac{R_1}{R_2} \right)^2 \right] \dots \left[1 - \left(\frac{R_{n-1}}{R_n} \right)^2 \right]. \end{aligned} \quad (2.7)$$

The individual shielding factors of each layer, denoted as $S_i^T = \frac{\mu_r \Delta}{D}$, depend on the material's relative permeability μ_r , the thickness of the layer Δ , and the diameter D of the shield. The variables R_i represent the radii of the individual layers. When the separation between layers (i.e., the air gap or distance $R_j - R_i$ between adjacent layers) approaches zero, the overall shielding factor simplifies to the sum of the individual shielding factors, effectively behaving as if the layers were merged into a single shield of equivalent total thickness. Conversely, if the layers are spaced far apart, the contribution of the final term becomes significant, causing the overall shielding factor to approach the value

$$S^T = \prod_{i=1}^{n-1} S_n^T S_i^T \left[1 - \left(\frac{R_i}{R_{i+1}} \right)^2 \right], \quad (2.8)$$

where the layers are numbered from the inside to the outside. By forming the derivative of this equation, an optimal layer distance can be calculated. Achieving 90% of the maximum shielding factor is possible with smaller air gaps between layers, which allows for a lighter and more cost-effective shield without a significant loss in performance [38]. Although the optimal gap distance can be analytically determined only for the most basic geometries, empirical formulas provided in [38] offer practical estimates. Figure 2.3 illustrates how the SF varies with the air gap between shielding layers. The comparison includes equal-mass shields—where layers have the same mass but decreasing thickness as their diameter increases—and the more common scenario of equal-thickness shields. For cylindrical equal-thickness shields, the air gap can be reduced from 70% to 40% while still achieving 90% of the maximum SF.

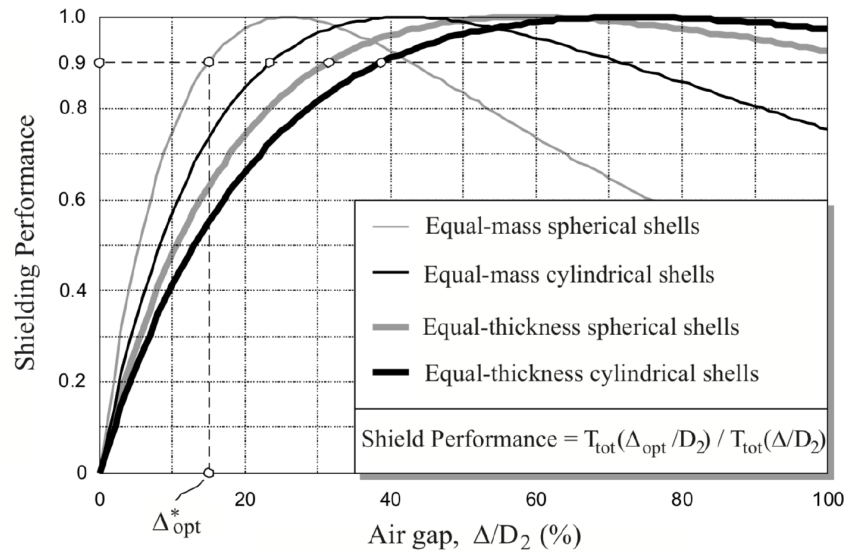


Figure 2.3: The plot shows the effect of the relative air gap Δ/D_2 on the shielding performance of double-shell spherical and cylindrical shields. Equal-mass shields achieve 90% of optimal performance at smaller gaps than equal-thickness shields, but the latter are more practical due to uniform thickness. Adapted from [39].

These SF calculations assume a known and constant permeability, μ , throughout the shield. However, μ can vary within the shielding material due to factors like mechanical stress, welding, or temperature changes. For example, in an 80%-15% nickel-iron alloy, μ

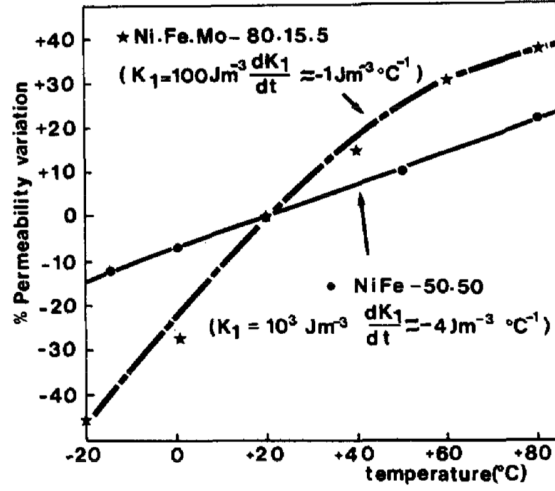


Figure 2.4: Temperature dependence of two different Ni-Fe permalloys in a low field. Picture from [40].

can vary by about 1% per degree Celsius within a 10°C range near room temperature [40], as shown in Figure 2.4. Additionally, the effective μ in a shielding situation depends on the excitation magnitude and is influenced by the material's $B(H)$ hysteresis curve, particularly for ferromagnetic materials where μ can fluctuate significantly. Calculating accurate SFs requires using an effective μ value that accounts for these variations.

The SF's sensitivity to μ is exploited in the magnetic shaking technique, which aims to enhance SF in specific conditions (See Chapter 5). This method involves magnetizing the outermost shield with an alternating current, aligning it on a point of the hysteresis curve where permeability is maximized. This high incremental permeability effectively shields against minor, low-frequency disturbances. However, this approach may introduce additional noise within the shielded environment, presenting a trade-off between shielding effectiveness and internal noise levels.

For alternating external magnetic fields, additional shielding is achieved through eddy current cancellation. When a magnetic field induces an electric field within a conductive material, eddy currents are generated that counteract the incident fields, effectively blocking them from penetrating the shielded area. Both the induced current and the resulting

magnetic flux density decrease exponentially with distance from the material's surface, characterized by the skin depth

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}, \quad (2.9)$$

where ω is the field frequency, μ is the material's permeability, and σ is its conductivity. In this context, the shielding factor becomes a complex quantity, with its phase component reflecting the phase shift between the internal and external fields. For instance, the SF of a spherical shield can be expressed as

$$S = 1 + i\omega\frac{\tau}{3} \quad \text{with} \quad \tau = \mu_0\sigma a\Delta, \quad (2.10)$$

where a is inner radius. This relationship highlights the role of eddy currents in enhancing the shielding performance for alternating magnetic fields [41].

When the skin depth δ is much larger than the shield thickness Δ , the external magnetic field penetrates the shield almost completely, and eddy-current shielding is negligible. In this regime, any induced currents are weak and approximately uniformly distributed across the material, resulting in minimal shielding.

As the frequency or conductivity increases such that $\delta \sim \Delta$, eddy currents become stronger and are distributed across the entire shield thickness. These currents generate induced magnetic fields that oppose the external field, significantly improving the shielding factor (SF), provided the material has sufficient conductivity.

When $\delta \ll \Delta$, the field is confined to a thin surface layer, and strong surface currents flow near the outer boundary of the shield. These surface currents effectively block the penetration of the external field, leading to very high SFs.

Considering both flux shunting and eddy-current cancellation, the shielding factor for a spherical shield is described by Equation (2.9), originally derived by Hoburg [41]. This equation, along with the associated data, was later reproduced by Stefan A. Stuibler [33], and is shown in Figure 2.5. For low conductivities, eddy-current effects are minimal, and

the SF aligns with the DC values given in Equation (2.3). As conductivity increases and the skin depth becomes comparable to or smaller than the shield thickness ($\delta \lesssim \Delta$), eddy currents enhance the shielding performance, consistent with Equation (2.10). In the limit $\delta \ll \Delta$, shielding becomes most effective due to strong surface currents. These factors highlight key aspects of ferromagnetic shielding, which will be further explored in the context of magnetically shielded rooms and the achievement of low residual fields in subsequent chapters.

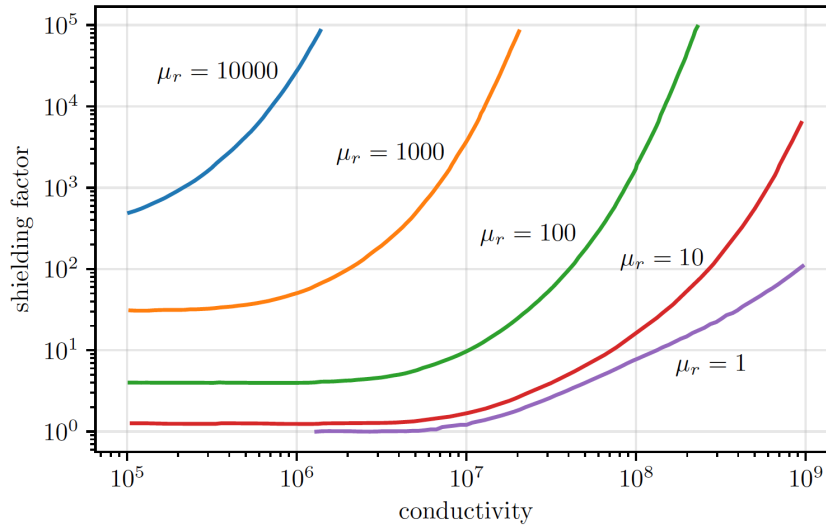


Figure 2.5: Calculated shielding factors (SF) incorporating both eddy-current shielding and flux-shunting effects. The SF is shown as a function of conductivity for various magnetic permeability values (μ/μ_0). The shield parameters are $r = 0.1$ m, $\Delta = 5$ mm, at a frequency of 60 Hz. Data reproduced from Figure 6 in [41] as presented in [33].

2.3 Magnetic Equilibration and Degaussing

While high-permeability materials and layered configurations are highly effective at attenuating external magnetic fields, they naturally retain a finite remanent magnetization due to their microstructural properties. This residual magnetization occurs because magnetic domains within the material, which align under an applied field, do not fully return to their original orientations when the field is removed. As a result, persistent magnetic fields can

exist within the magnetically shielded room, originating from the material itself rather than from external magnetic fields.

In static conditions, where the magnetic field frequency ω is zero, the remanent magnetization of the shielding material becomes the dominant source of residual magnetic fields. These fields originate from the magnetostatic energy within the material and can significantly affect the overall shielding performance if not properly addressed. Techniques such as degaussing or magnetic equilibration are therefore employed to mitigate this effect and enhance the stability of the magnetic environment.

To reduce this remanent magnetization and minimize residual fields, a process known as "degaussing", or "magnetic equilibration", is employed. This process involves generating an alternating magnetic field H using coils wound around the shielding material. The field is produced by applying an alternating current (AC) to the coils, and the amplitude of the current is gradually reduced to zero within these coils. Initially, the alternating H -field saturates the shielding material, inducing a corresponding magnetic flux density B and aligning the magnetic domains within the material. As the H -field amplitude decreases, the material's magnetization cycles through progressively smaller hysteresis loops. This process continues until, ideally, the magnetic flux density B approaches zero, minimizing the remanent magnetization. An illustration of this process is shown in [Figure 2.6](#).

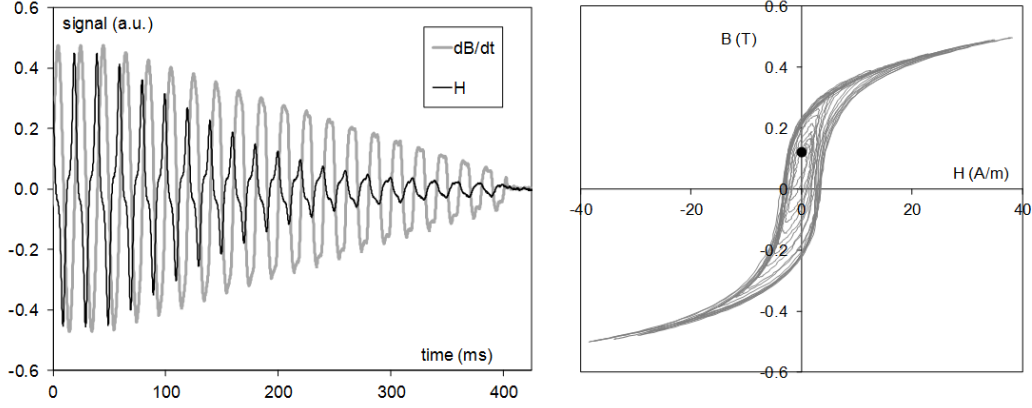


Figure 2.6: Degaussing by applying AC excitation and slowly reducing the amplitude. In this example, the degaussing is incomplete because a residual net magnetization remains (position of the dot in the hysteresis loop graph). This could result from an insufficient initial amplitude or an overly rapid decrease in AC excitation [42].

The term "degaussing" is typically used to describe this procedure; however, it is most accurately applied when the process is performed in a zero magnetic field. In such cases, the material achieves a true degaussed state, where its magnetic domains are randomly oriented and the net magnetization M equals zero. In the presence of an external magnetic field, the term "magnetic equilibration" is more appropriate. Under these conditions, the material reaches a state of equilibrium aligned with the prevailing field, rather than a true demagnetized state. Here, the AC field provides the energy required for magnetic domain walls to overcome pinning sites and realign with the external field, thereby minimizing the overall magnetostatic energy and reducing the residual magnetic field to its lowest possible value.

Degaussing processes have been extensively studied [43–45], with residual magnetic fields in shielded rooms being reduced to the few hundreds of picotesla (pT) level in some cases [46]. Achieving such low residual fields requires high production and manufacturing quality of the shielding material, as imperfections such as granular inconsistencies and mechanical stress often limit the performance [37]. The process typically requires the AC current to have sufficient amplitude to saturate the material's magnetization fully. A continuous path

for magnetic flux within the shielding material is also necessary; otherwise, stray fields can produce localized regions of remanent magnetization.

Although some studies advocate for optimized envelope functions for the decaying amplitude [43], a simple linear reduction has proven effective in other experiments [33, 46]. Nevertheless, the rate at which the amplitude decreases is important toward the end of the equilibration process. During the final half-wave, the H -field provides the least energy for domain walls to overcome pinning sites, which can leave residual magnetization in the material. Larger amplitude steps at this stage deposit more energy into the material, leaving domain walls in higher energy states and thereby increasing the residual field.

To minimize this effect, careful control over the decay progression is necessary, especially in the final stages. High-quality instrumentation, including amplifiers capable of delivering low-noise, low-offset currents and systems with sufficient resolution, is important for gradual and controlled amplitude reductions. These factors significantly impact the effectiveness of magnetic equilibration and minimize residual fields.

2.4 Residual Field

MSRs not only dampen external magnetic disturbances during experiments but also create an environment with ultra-low residual magnetic fields and minimal field gradients. These conditions are necessary for a range of applications, including biomagnetic studies such as magnetocardiography (MCG) and magnetoencephalography (MEG) [47], low and zero-field NMR techniques [48], liquid detection in security settings [49], and fundamental physics experiments, such as tests of the equivalence principle [50] and neutron electric dipole moment (nEDM) measurements [44, 51, 52]. For spin precession experiments, the relaxation times are highly dependent on the field gradients across the sample volume.

Achieving ultra-low residual magnetic fields within an MSR requires careful construction, considering precise door placement, overlaps, and feedthroughs. The shielding material

must be manufactured with care and undergo proper treatment. Additionally, the magnetic equilibration setup and procedures must be optimized specifically for each MSR configuration.

The effectiveness of magnetic equilibration procedures is reflected in the magnitude of the residual fields. If equilibration results in a minimal residual field without any externally applied fields, it indicates that the equilibration field has adequately magnetized the shielding material, aligning it with the prevailing field conditions. This reduces localized magnetization within the material, resulting in minimal fields and gradients inside the shielded volume. When external fields are applied during experiments, successful equilibration adjusts the material to a low-energy state relative to the prevailing magnetic field, ensuring a stable and time-consistent field configuration. In this state, field gradients caused by high-permeability materials are minimized.

However, residual magnetization spots in the MSR walls or gradients in the residual field, coupled with mechanical vibrations of the walls, equipment, or sensors, can introduce magnetic noise. This noise can affect measurements, particularly as it overlaps with the relevant frequency range of neutron and comagnetometer precession frequencies in nEDM experiments.

The residual fields within magnetic shielding rooms are typically on the order of nanoteslas (nT) or lower, making absolute measurements challenging for several reasons. First, the sensors employed must possess sufficient accuracy, and determining the absolute field measurements requires offset corrections to be identified with comparable precision.

A variety of sensor technologies can achieve the necessary sensitivity for these measurements. Optical magnetometers [53], QuSpin Zero-Field Magnetometer (QZFM) [54], and fluxgate magnetometers (Fluxgates (FGs)) [55] are among the options capable of detecting magnetic fields at these low levels.

Optically pumped magnetometers (OPMs) function by measuring the Larmor precession of spin-polarized atoms within a magnetic field. The process involves the use of atomic

vapors, such as cesium (Cs) or mercury (Hg), which are polarized through laser excitation that drives transitions between Zeeman-split energy levels. As these polarized atoms are exposed to a magnetic field, they undergo precession. A secondary laser beam is then directed through the vapor, allowing for the detection of either transmission or Faraday rotation of linearly polarized light. This detection correlates with a frequency measurement of the precession, represented by the equation

$$\omega = -\gamma|B|, \quad (2.11)$$

where ω denotes the precession frequency and γ represents the gyromagnetic ratio. Consequently, OPMs provide scalar measurements of magnetic fields with an impressive sensitivity of $10 \text{ fT}/\sqrt{\text{Hz}}$ [53].

For magnetic fields in the sub-nanotesla range, the resulting precession frequencies are also quite low, approximately $O(1 \text{ Hz})$ for Cs and $O(1 \text{ mHz})$ for Hg. Accurate measurement of these low frequencies typically requires extended integration times. Furthermore, while OPMs can be configured for vector field measurements [56], several challenges limit their applicability for mapping residual fields. For instance, the requirement to direct laser light to the sensor cells complicates the placement of OPMs within a volume of about 1 m^3 . This can necessitate the use of mirrors for free-space operation or lead to strain in fiber-coupled systems, potentially resulting in defects. Additionally, commercially viable OPMs have only recently become accessible.

The QuSpin Zero-Field Magnetometer (QZFM) utilizes zero-field resonance with a single laser beam. A precisely tuned semiconductor laser passes through a glass vapor cell containing rubidium atoms and is detected by a photodetector. In the absence of a magnetic field, the rubidium atoms are mostly transparent. However, a perpendicular magnetic field increases light absorption, allowing the photodetector to generate an electric current proportional to the light transmitted, thus converting a magnetic signal into an electric one.

In a zero-field (ZF) environment [57], applying a perpendicular magnetic field while

sweeping its amplitude reveals that maximum transparency occurs near zero field. The output from the photodetector displays a Lorentzian line shape, referred to as the ZF resonance, with a typical width of around 30 nT. The field value is determined by the deviation from the Lorentzian peak, which can be measured through lock-in detection using a small modulation field at about 1 kHz.

ZF-OPMs require a magnetically shielded environment to function, as they are sensitive to residual fields (usually in the tens of nT) inside magnetically shielded rooms. Instead of relying solely on large offset coils, three-axis orthogonal magnetic coils in each sensor head is employed to locally zero residual fields, compensating up to 50 nT automatically within seconds. This process is repeated whenever significant background field changes occur.

The bandwidth of ZF-OPM is approximately 150 Hz, behaving like a first-order low-pass filter, with a sixth-order hardware digital filter at 500 Hz to eliminate higher-frequency responses. Increasing the bandwidth may compromise sensitivity, as the magnetometer's linearity is influenced by the error signal's non-linearity near zero field. To optimize performance, the vapor cell is heated to about 150°C, increasing vapor density and slightly warming the sensor housing.

Fluxgate sensors operate based on Faraday's law of induction and are primarily composed of a small ferromagnetic core with two coils wound around it. The ferromagnetic core is responsible for collecting the magnetic flux to be measured and directing it through the coils. An oscillating excitation current is applied to one coil, which saturates the magnetic core. The induced voltage generated by the magnetic flux is then measured using the second coil.

In the absence of an additional external magnetic field, the core achieves saturation in a symmetrical manner for both half-waves of the excitation current. However, if an external magnetic field is present, the saturation occurs at different points in time for the two half-waves. This results in a distortion of the induced voltage in the secondary coil, which is utilized to quantify the external magnetic field.

To obtain vector information regarding the magnetic field, a minimum of three fluxgate sensors is required. These sensors are known for their robustness and stability, offering a wide operational range typically spanning from 0.1 nT to 100 μ T, with sensitivities around 6 pT/ $\sqrt{\text{Hz}}$ ¹. Their simplicity of operation is further enhanced by the fact that they only necessitate readout electronics and a power supply. With proper offset calibration, fluxgate sensors can accurately measure absolute magnetic flux density.

While OPMs, QuSpin, and fluxgate sensors each provide valuable magnetic field measurements, understanding the field’s uniformity and overall behavior requires more than just raw data. Analyzing the scalar potential (See Appendix A) helps identify field variations that could impact experimental results. This section focuses on scalar potential decomposition, a key method for evaluating these nonuniformities, especially in nEDM experiments where precise magnetic control is essential.

2.5 Review of MSRs in nEDM Experiments

A range of passive shielding systems has been employed in nEDM experiments to mitigate magnetic field disturbances and improve experimental precision. Over time, different designs and configurations have been implemented across various experimental setups, each addressing unique challenges to optimize shielding performance.

The Institut Laue-Langevin (ILL) experiment initially employed a three-layer cylindrical shield in a vertical orientation, achieving a magnetic shielding factor of approximately 43 [58]. However, this configuration was found to be suboptimal due to the reduced quasi-static shielding factor along the cylinder’s axis of symmetry. To address this limitation, the shield was reconfigured into a horizontal geometry, which increased the shielding factor to 1000 [58, 59]. Further improvements, including the addition of a fourth layer, were projected to increase the shielding factor to as high as 10000 [58, 60]. This upgraded shielding setup

¹Bartington Mag03 specifications

later served as the basis for PSI’s Phase 1 experiment [61].

Similarly, the shielding system used at Gatchina closely mirrors the ILL four-layer cylindrical shield design with the shielding factor of 1000 [62].

For the n2EDM experiment at PSI, a six-layer μ -metal MSR has been constructed, offering significant improvements in shielding efficiency and magnetic stability [28, 61, 63].

The Munich-ILL nEDM experiment represents another development in passive shielding. This effort resulted in the construction of a five-layer MSR at Munich, later utilized in the HeXe-EDM experiment [64]. Initially, only two outer layers were implemented [65], but subsequent enhancements extended the design to include five layers [44]. This system achieved a magnetic field gradient of approximately 3 pT/m and a shielding factor of around 10^6 . Additionally, it demonstrated a magnetic field homogeneity of approximately 200 pT within a cubic meter at the center of the shielded region. Notably, the performance was highly sensitive to the degaussing sequence of the innermost shield layer and the positioning of the access door [44].

Table 2.1: Overview of MSRs in nEDM experiments

Collaboration (Year)	Number of Layers	Shielding Factor at 0.01 Hz	Residual Field (nT)	Field Gradient (pT/m)
ILL - Vertical (1968)	3	43	-	-
ILL - Horizontal (1968)	3	10^3	-	-
Gatchina	4	10^3	-	-
ILL (2000)	4	10^4	-	-
Munich-ILL (2014)	5	10^6	≤ 1	3
PSI (n2EDM) (2019)	6	10^5	≤ 0.1	60
LANL (2022)	4	10^5	≤ 0.5	-

An overview of MSRs employed in nEDM experiments is summarized in Table 2.1.

The importance of degaussing for maintaining magnetic stability was highlighted in studies by Thiel et al. [43] and A. Schnabel [66]. These works showed that the effectiveness of shielding systems depends on how well the degaussing process is performed. Later simulations improved upon their findings, offering better ways to optimize this procedure.

2.6 Description of the MSR for the TUCAN nEDM experiment

The MSR designed for the TUCAN nEDM experiment is a five-layer shielding system constructed to optimize both magnetic and radio-frequency (RF) shielding. Manufactured by Magnetic Shields Limited (MSL), the MSR integrates four layers of high-permeability μ -metal and one layer of conductive copper, achieving a configuration tailored to the experimental requirements.

The μ -metal, used in the MSR fabrication, is an 80% nickel alloy known for its high magnetic permeability, adheres to the ASTM A753 Alloy 4 specification, ensuring consistent magnetic performance. MSL company manufactured the shielding layers, using laser-cut sheets up to 762 mm wide to minimize the number of joints, which are known weak points in large-scale shielding structures.

An important step in achieving high magnetic permeability in μ -metal is heat treatment. This process, carried out by MSL in the UK, involves exposing the μ -metal to a pure dry hydrogen atmosphere, followed by a controlled slow cooling. This ensures optimal magnetic properties. Test tubes accompany each heat treatment cycle for quality verification, with two test samples shipped alongside the panels for additional validation.

The design of the MSR has been developed in collaboration with MSL and Fierlinger Magnetics (FM), with input from TRIUMF engineers to ensure optimal performance for the nEDM experiment. The MSR is expected to reduce the ambient magnetic field by a factor of 100,000 at 0.01 Hz, as effective DC shielding is necessary for holding UCNs in the experiment cell for durations exceeding 100 s. Figure 2.7 shows 3D CAD model of the TUCAN MSR.

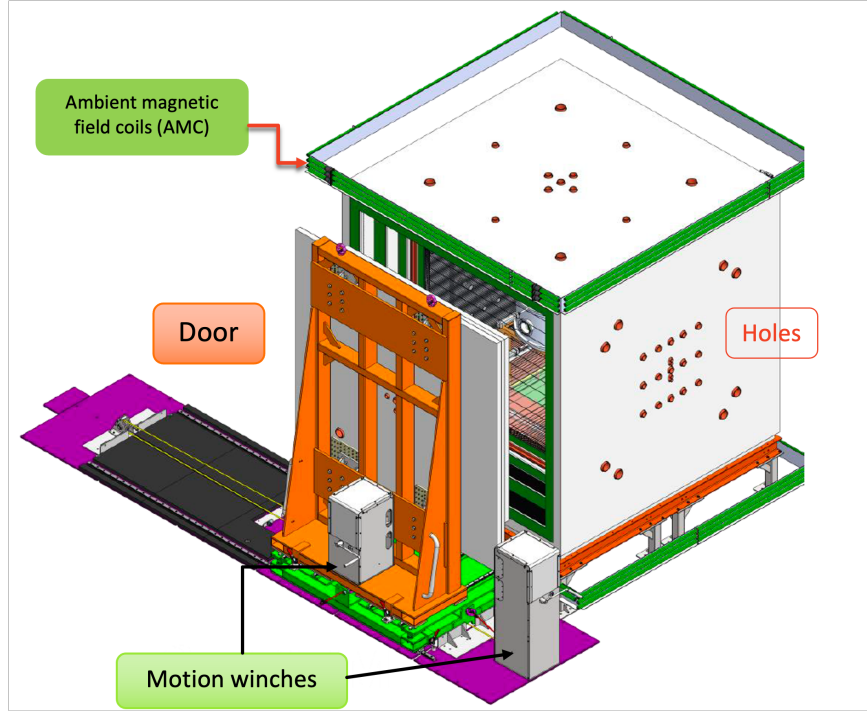


Figure 2.7: 3D CAD model of the TUCAN MSR

Table 2.2: Specifications of the MSR Layers

Layer	Thickness (mm)	Material	External Side Length (m)	Shield Layer (kg)	Shielding Factor* (10 mHz, in-situ)
1 (outer)	4 (2×2 mm)	μ -metal	$3.5 \times 3.5 \times 3.5$	3363	40
2	3 (2×1.5 mm)	μ -metal	$3.0 \times 3.0 \times 3.0$	1853	28
3	3 (2×1.5 mm)	μ -metal	$2.6 \times 2.6 \times 2.6$	1392	13
4	6	Copper	$2.55 \times 2.55 \times 2.55$	3636	1
5 (inner)	2 (2×1 mm)	μ -metal	$2.4 \times 2.4 \times 2.4$	726	7
Total				10970	101920

* Estimations from Fierlinger Magnetics (FM) company.

Table 2.2 describes TUCAN MSR's key specifications for each layer, including thickness, material, and shielding factors. The outermost layer of the MSR, Layer 1, is composed of 2×2 mm thick μ -metal, followed by progressively thinner μ -metal layers as we move inward. The innermost layer, Layer 5, is also made of μ -metal but is thinner than the outer layers. The copper layer, placed between the μ -metal layers, provides RF shielding and improves the MSR's overall shielding performance above 10 Hz.

2.6.1 MSR Door Design and Operation

The MSR door is a specialized five-layer design, consisting of four layers of μ -metal and one layer of copper. Each μ -metal layer is further reinforced with two layers of μ -metal panels and two layers of μ -metal cover strips.

The door is mounted on a stainless-steel framework that provides structural support and facilitates its movement. This framework is attached to a carriage equipped with runners, enabling in/out travel of the door. The in/out motion is controlled manually using a winch system. The carriage is mounted on a rail system that allows for left/right motion of the door, which is also operated via a manual winch.

Locking pins are used to secure the carriage in position at the extreme points of both in/out and left/right travel. The rail system itself is anchored to the concrete floor at TRIUMF. The rail system includes provisions for re-greasing and cleaning to ensure smooth and reliable operation.

To maintain the integrity of the magnetic shielding, the door is equipped with a pneumatic locking system. Each edge of the door features three pneumatic locking points for the outer three layers of the shielding, ensuring a secure seal when the door is closed.

2.6.2 MSR's access holes

The MSR contains a total of 98 holes distributed across its walls, ceiling, floor, and door, each serving specific purposes such as providing access for services, supporting experimental components, or facilitating magnetic field mapping.

The left and right walls each have 8 side holes that are dedicated to services like nEDM cell actuators, internal coil power connections, and vacuum connections. Additionally, the central region of each wall includes 15 holes designed for magnetic field mapping, with 4 smaller central holes specifically allocated for the co-magnetometer.

On the back wall, various components are connected through holes, including a high-voltage feedthrough, vacuum pump access, the UCN guide, 4 holes for Hg fluorescence, and

a Cs fiber hole.

The door includes two holes for Hg fluorescence, positioned at $(0, 140 \text{ mm})$ and $(0, -140 \text{ mm})$, with these positions mirrored on the back wall at corresponding positive and negative coordinates.

On the floor, there are 4 holes for the Hg pre-polarizer, arranged at $(0, \pm 200 \text{ mm})$ and $(\pm 200 \text{ mm}, 0)$, mirroring the arrangement of pre-polarizer holes on the ceiling.

The purpose and placement of the holes on the different walls of the MSR are illustrated in the following CAD models (Figures 2.8 to 2.13).

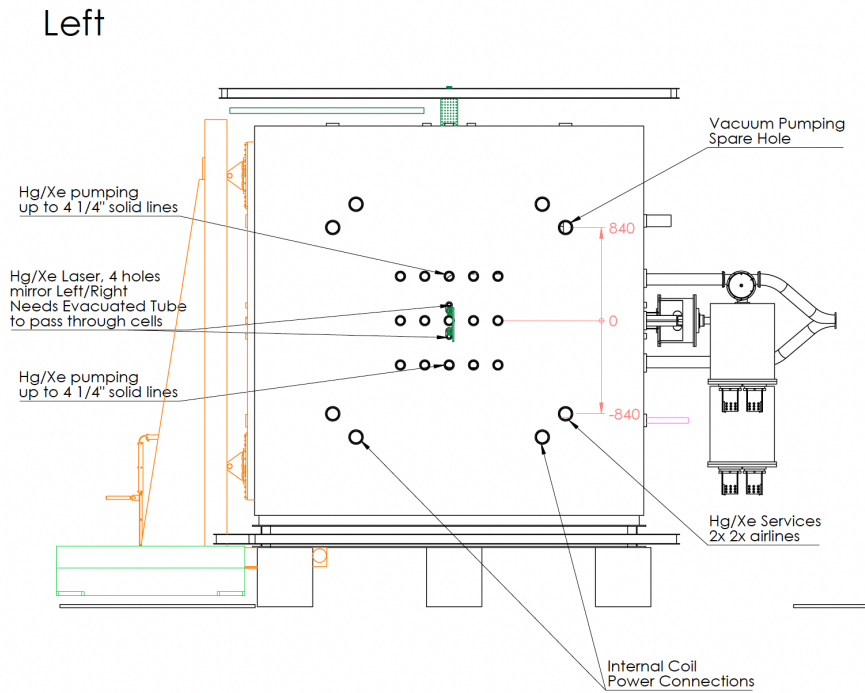


Figure 2.8: Holes on the left wall

Right

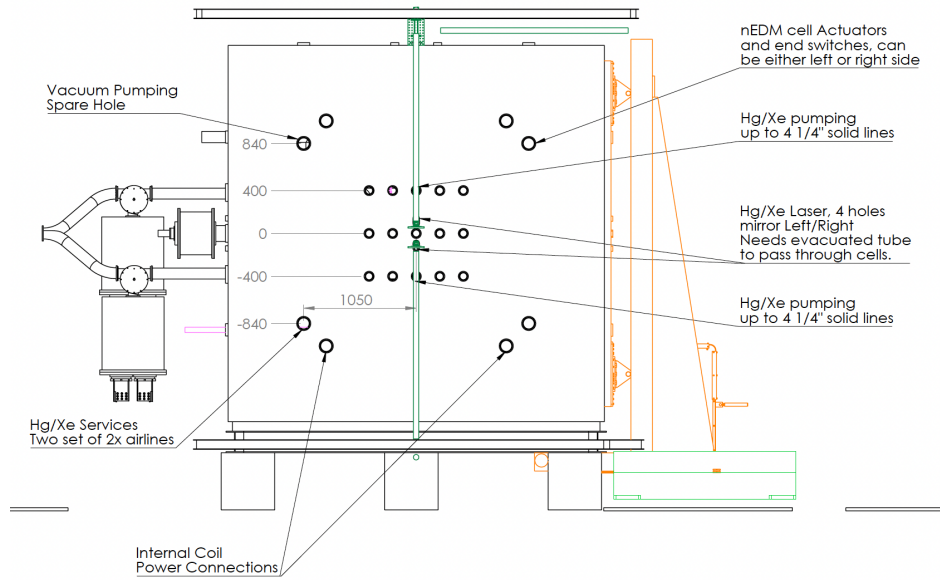


Figure 2.9: Holes on the right wall

Back

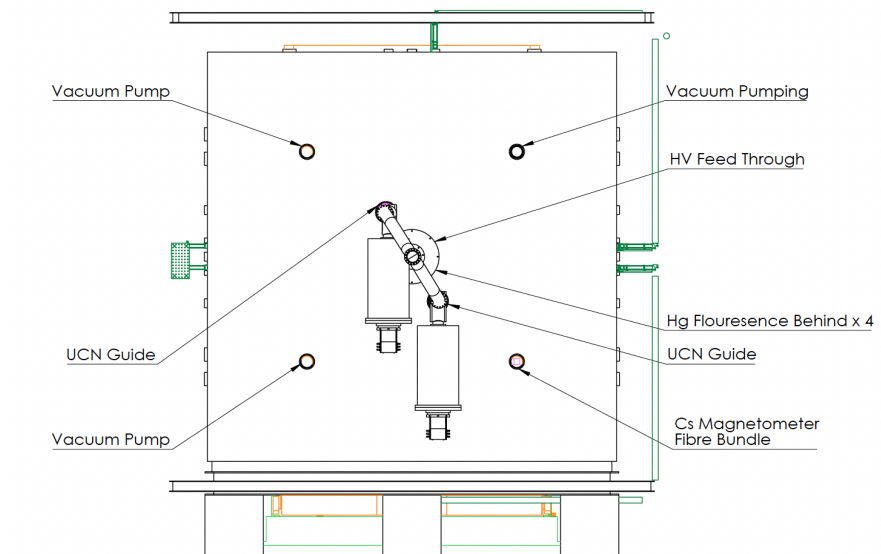


Figure 2.10: Holes on the back wall

Front

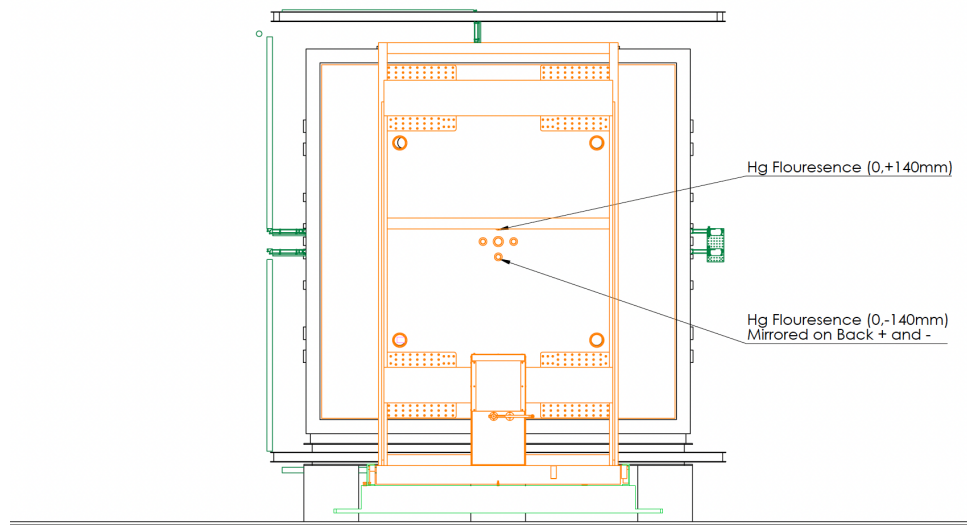


Figure 2.11: Holes on the front wall (door)

Top

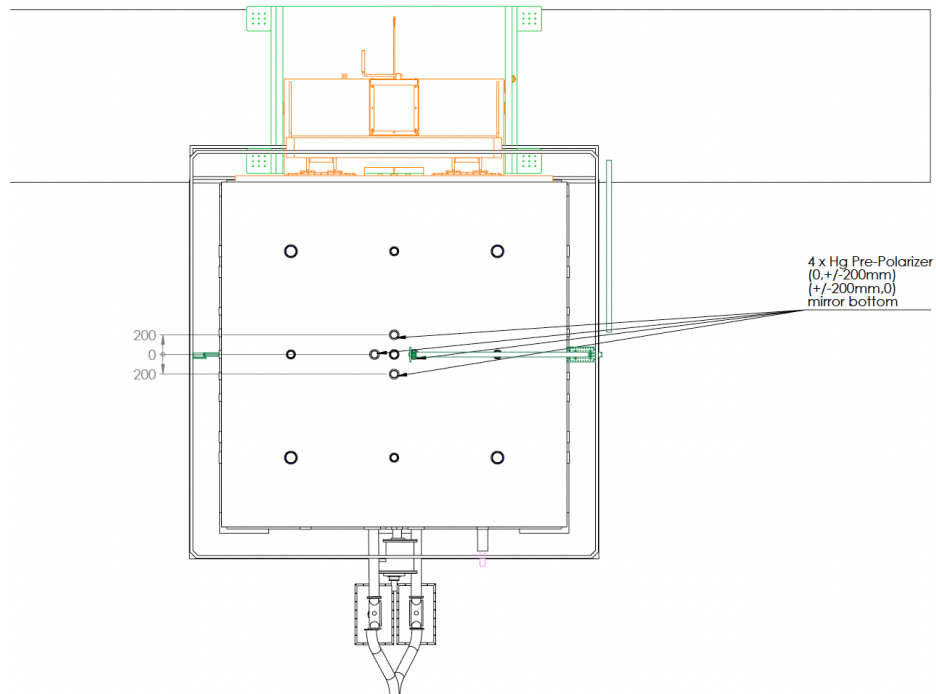


Figure 2.12: Holes on the top wall

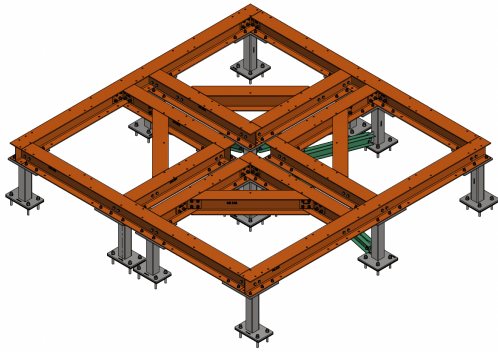


Figure 2.14: MSR's base CAD model.



Figure 2.15: MSR's base with supporting Al extrusion.

The installation began with the construction of the base support (Figures 2.14 and 2.15), an aluminum structure (Figures 2.22 and 2.23) that elevates the entire MSR above the ground. This base provided both stability and clearance for experimental requirements. The base serves as the foundation for all subsequent components, ensuring precise alignment throughout the installation process.

Following the base, the flooring system was installed (Figures 2.16 and 2.17), which included all five shielding layers. The copper layer (Figure 2.18), designed for RF shielding, was integrated into the flooring system to provide a fully enclosed structure. Brass or stainless steel bolts were used to fasten the copper panels, with thorough cleaning of mating surfaces to ensure electrical continuity.

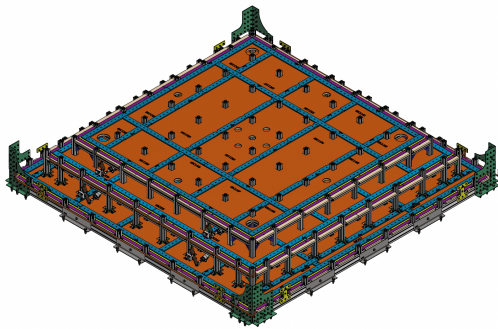


Figure 2.16: MSR's floors CAD model.



Figure 2.17: MSR's floors.

Once the flooring and copper layer were completed, the preassembled MSR door was



Figure 2.18: MSR's copper layer.



Figure 2.19: MSR's door.

installed (Figure 2.19). The door features a five-layer design, including four layers of μ -metal and one layer of copper. It was mounted on a stainless steel framework attached to a rail-and-carriage system for controlled movement. Pneumatic locking points were incorporated to secure the door in its closed position, maintaining the integrity of the shielding.

The shielding layers were assembled next (Figure 2.20), beginning with the innermost Layer 5 and progressing outward to the outermost Layer 1. Each shielding layer was supported by its own aluminum structural framework, designed to securely hold the μ -metal and copper panels while maintaining alignment.

To prevent unwanted magnetic coupling, each layer was electrically and mechanically isolated from the others using non-conductive spacers. Grounding for each layer was ensured through an accessible chain of grounding points, preserving the room's overall shielding effectiveness.

The μ -metal panels were assembled with precision to maintain magnetic integrity, and fixing screws were screened for magnetism. Stainless steel 316 screws were used for mounting,



Figure 2.20: MSR's μ -metal layers.

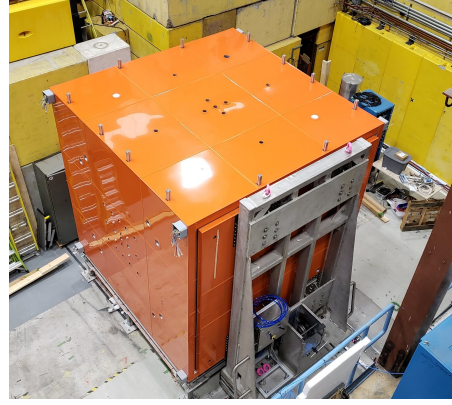


Figure 2.21: MSR's outer cladding.

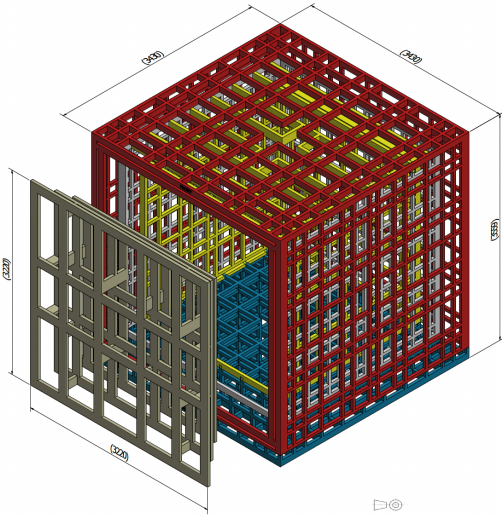


Figure 2.22: MSR's Al frameworks CAD model.

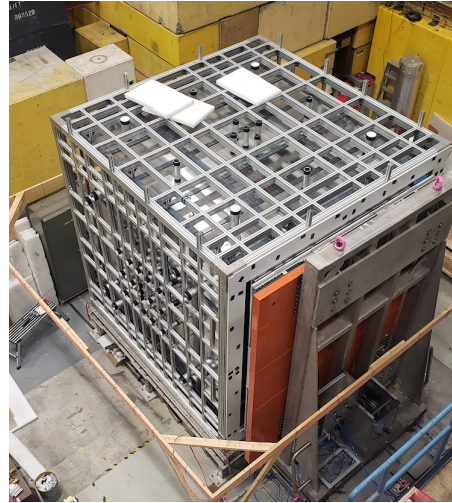


Figure 2.23: MSR's Al frameworks.

with PVC strips placed underneath to distribute the load and prevent deformation of the μ -metal.

To protect the μ -metal layers and enhance durability, PVC cladding (Figure 2.21) was installed on both the outer and inner faces of the MSR. The exposed μ -metal was fully covered with this cladding to shield it from physical damage and environmental factors. On the inner face, a dampening layer was positioned between the μ -metal and the PVC cladding to reduce vibrations and improve structural stability. Additionally, LED lighting was installed inside the MSR to ensure sufficient illumination for experiments and maintenance activities.

During the installation, isolation resistance between layers was tested to ensure a minimum of $30\text{ k}\Omega$. This level of resistance is essential for maintaining the magnetic shielding performance by preventing electrical coupling between layers.

It is important to note that degaussing coils for each layer were wound after the layer was installed.

2.8 Summary

This chapter provided an overview of the principles of magnetic shielding and detailed the design, operation, and installation of the Magnetically Shielded Room (MSR) for the TUCAN nEDM experiment. The discussion covered the fundamental properties of ferromagnetic shielding, the techniques for magnetic equilibration and degaussing, as well as residual field measurements. Additionally, a review of MSRs used in other nEDM experiments highlighted key design considerations.

The next chapter will explore the experimental hardware and instruments used to characterize the TUCAN MSR. By connecting the shielding system to the broader experimental setup, it will provide an overview of the tools and techniques that help achieve the experiment's goals.

Chapter 3

TUCAN MSR Instrumentation

The MSR is an important component of the nEDM experiment, engineered to achieve magnetic shielding requirements necessary for high-precision measurements. Its successful characterization ensures the room achieves the performance needed to suppress external magnetic fields and maintain a stable magnetic environment for the experiment.

This chapter introduces the experimental setups and instrumentation used to evaluate the MSR's performance. It describes the tools and techniques employed to assess the MSR's shielding capabilities, analyze the residual magnetic fields, and implement methods to enhance its performance. By detailing these systems and their integration into the experimental workflow, the chapter provides the foundation for understanding the MSR's role in achieving the precision required for the nEDM experiment.

3.1 Experimental Methods Overview

The characterization of the TUCAN MSR focused on three primary objectives:

1. **Shielding Factor Measurements:** As described in Chapter 2, SF quantifies the MSR's ability to attenuate external magnetic fields. Measurements were performed before, during, and after installation to assess the contribution of each shielding layer.

This evaluation spanned various frequencies to ensure the MSR performs as expected across a broad spectrum.

2. **Residual Field Measurements:** Residual fields within the MSR were analyzed to verify consistency with design specifications and to identify regions requiring further optimization. Mapping techniques were employed to detect magnetic field variations inside the MSR and around its walls.
3. **Degaussing System Setup:** An automated degaussing system was developed to address remanent magnetization in the MSR's μ -metal layers. This system allowed for controlled cycling of the material's magnetization, ensuring that residual fields were minimized and shielding performance was enhanced.

Each method relied on specialized tools and instrumentation that will be described in the following sections.

3.2 Instrumentation

This section provides an overview of the instruments used for shielding factor measurements and residual field assessments, detailing their roles and key specifications.

3.2.1 Magnetometers

Stefan Mayer FLUXMASTER (Three-axis Fluxgate)

Stefan Mayer FLUXMASTER, shown in Figure 3.1, primarily used for quick checks of magnetic fields during the TUCAN MSR characterization. Operating with a range of $\pm 200 \mu\text{T}$, a resolution of 0.1 nT and an accuracy of $0.5\% \pm 5 \text{ nT}$, the device provided a convenient tool for approximate residual field measurements. While not relied upon for high-precision data, its portability and ease of use made it a valuable instrument for initial assessments and field gradient evaluations.

Bartington MAG690

The Bartington MAG690 (Figure 3.2) was employed for shielding factor (SF) measurements inside the MSR to evaluate its capability in suppressing external magnetic fields. This high-precision fluxgate magnetometer features a measuring range of $\pm 500 \mu\text{T}$, enabling accurate measurements of both static and low-frequency magnetic fields. It has a low noise level of $25 \text{ pT}/\sqrt{\text{Hz}}$ at 1 Hz, and a frequency response spanning from DC to 100 Hz. These characteristics made the MAG690 well-suited for capturing SF data across the operational frequency range required for the experiment.



Figure 3.1: Stefan Mayer FLUXMASTER (Three-axis Fluxgate).



Figure 3.2: Bartington MAG690 Fluxgate sensor.

Bartington MAG-03MC

This sensor (Figure 3.3) was employed for mapping the magnetic field inside the TUCAN MSR. This sensor features three flying leads for independent axis measurements, making it particularly suitable for detailed residual field mapping. With a measurement range of $\pm 70 \mu\text{T}$, a noise level of $< 10 \text{ pT}/\sqrt{\text{Hz}}$ at 1 Hz, and a bandwidth of up to 3 kHz, the MAG-03MC enabled accurate characterization of the MSR's magnetic environment during mapping procedures.

Bartington MAG-13MS

The Bartington MAG13 fluxgate magnetometer (Figure 3.4) was used to measure magnetic fields within the TUCAN MSR, particularly for assessing shielding performance. The model we used supports measuring range of $\pm 100 \mu\text{T}$ and has noise levels as low as $5 \text{ pT}/\sqrt{\text{Hz}}$ at 1 Hz. With a bandwidth of up to 3 kHz and protection against electrical interference, the MAG-13MS provided reliable and precise field measurements during the experiment.

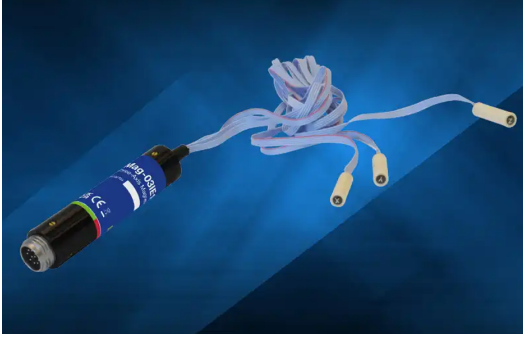


Figure 3.3: Bartington MAG-03MC Fluxgate sensor.



Figure 3.4: Bartington MAG-13MS Fluxgate sensor.

QuSpin Zero-Field Magnetometers (QZFM)

Employed for residual field measurements and mapping due to their ultra-sensitive detection capabilities. These magnetometers (Figure 3.5) operate based on optically pumped magnetometry (OPM) and provide high precision with a noise floor of $< 5 \text{ fT}/\sqrt{\text{Hz}}$ at low frequencies.



Figure 3.5: QuSpin Zero-Field Magnetometers (QZFM).

3.2.2 AE Techron 7224 Power Amplifier

The AE Techron 7224, shown in Figure 3.6, is a high-performance industrial amplifier used in the TUCAN MSR degaussing system, delivering controlled voltage and high-current output essential for magnetic equilibration. It operates on a 120 V, 60 Hz single-phase mains supply and supports both controlled-voltage and controlled-current modes. The amplifier achieves up to 900 W RMS output when driving an $8\ \Omega$ load continuously for one hour, corresponding to 85 V RMS and 10.6 A. For shorter duty cycles or varying load conditions, the output voltage and current scale accordingly, with peak capabilities reaching up to $\pm 158\text{ V}$ and $\pm 50\text{ A}$. The amplifier supports long-term operation at frequencies up to 40 kHz and features a small-signal bandwidth extending to 1 MHz, enabling stable operation across a wide frequency range. In MSR characterization, high-current mode was used. In this mode, the amplifier's internal power supply was configured to maximize current output, ensuring optimal performance for driving the perturbation coil. Safety features include protection against overcurrent, over/under voltage, overheating, and circulating ground currents, ensuring stable and reliable operation during degaussing.



Figure 3.6: AE Techron 7224 Power Amplifier.

3.2.3 Data Acquisition Units (DAQ)

National Instrument USB-6281

The NI USB-6281 data acquisition device (Figure 3.7), used for the TUCAN MSR characterization, offers both analog and digital input/output functionality, enabling signal generation

and data acquisition. Its ADC offers 18-bit resolution at up to 625 kS/s in single-channel mode and 16-bit resolution at 500 kS/s in multi-channel mode, while its DAC delivers flexible and accurate output signals suitable for degaussing procedure. A 10 kHz sampling resolution was employed, ensuring smooth and reliable operation in the experimental setups.

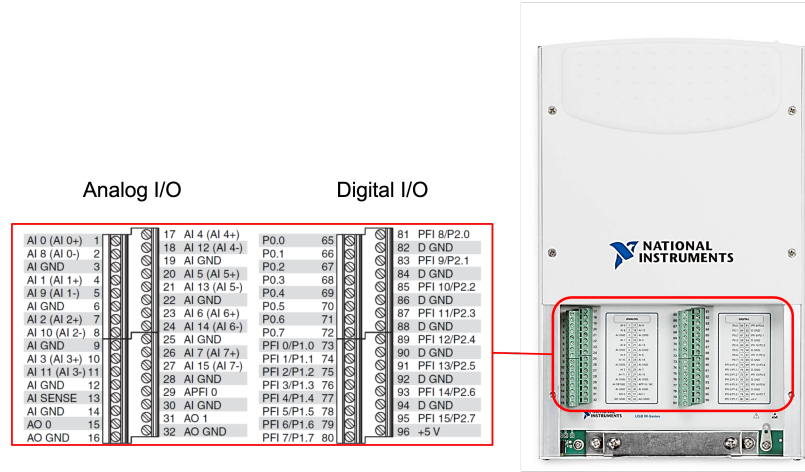


Figure 3.7: National Instrument USB-6281 Data Acquisition Unit.

MCC E-1608 DAQ

The MCC E-1608 (Figure 3.8) is an Ethernet-based data acquisition device employed for field mapping during the TUCAN MSR characterization. It provides 8 single-ended or 4 differential analog input channels with 16-bit resolution and a sampling rate of 250 kS/s, supporting input ranges up to ± 10 V. Additionally, it features two 16-bit analog outputs, eight digital I/O lines, and a 32-bit counter input, making it well-suited for precise data collection and control in the residual field analysis.

3.2.4 SF measurement coils

Perturbation Coil

The external perturbation coil depicted in Figure 3.9a, placed around the MSR with a side length of 5.5 m, was designed to generate a uniform magnetic field of $18 \mu\text{T}$ at frequencies



Figure 3.8: MCC E-1608 Data Acquisition Unit.

from 0.01 Hz to 100 Hz for shielding factor measurements. It consists of three loops of gauge 10 wire and one loop of gauge 14 wire, with a measured resistance of $0.3773(13) \Omega$. The coil's wooden frame included routed grooves to ensure the wire remained straight and the setup was reproducible. The field was driven by the AE Techron 7224 amplifier to achieve the required strengths and frequencies.

Reference Coil

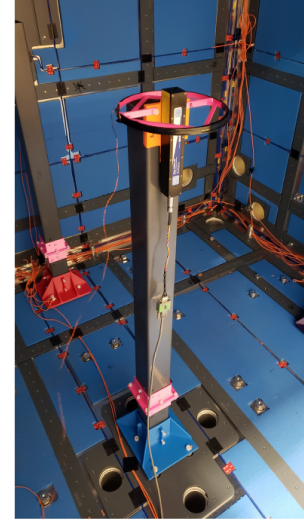
A reference coil (Figure 3.9b) was used to monitor intrinsic variations in the fluxgate magnetometers (FGs) during measurements. Positioned around their respective FGs at the center of the MSR, the coil comprised 15 loops of gauge 26 wire with a measured resistance of $667.016(6) \Omega$. They remained unaffected by external fields by placing within the MSR's shielding. Driven directly by the NI USB-6281 at 8 V, the reference coil generated a low-amplitude field of approximately $1 \mu\text{T}$, operating at a frequency $10\times$ higher than the perturbation coil to avoid signal overlap.

3.2.5 Degaussing/Equilibration Coil Configuration

The processes of degaussing and equilibration, previously discussed in Section 2.3, require specific coil configurations to achieve the desired magnetic shielding performance. The coil



(a) Perturbation coil.



(b) Reference coil.

Figure 3.9: (a) The external perturbation coil is supported on a wooden frame, which will be exterior to the MSR once it is completed. The FG and reference coils are supported by plastic posts and printed parts, which will be inside the MSR. A plywood floor was used to fix the FG positions. (b) Fluxgate setup inside the room, with reference coil.

setup for magnetic equilibration within the MSR consists of 12 coils per layer, positioned along the edges of the cube-shaped structure. These coils are arranged into three distinct configurations: edge coils (Figure 3.10), L-shaped coils (Figure 3.11), and distributed L-shaped coils.

Edge Coils

The edge coils are used for both Layer 1 (outermost) and Layer 5 (innermost) of the MSR. Four coils are connected in series to form a closed loop around one spatial direction. This arrangement generates the magnetic flux for degaussing processes. To facilitate degaussing, five strands of Remington Industries gauge 12 stranded wire are wrapped around each edge of the MSR. Each wire is positioned between Layer 5 and Layer 4 (the copper layer) and left open inside the MSR to maximize flexibility in the degaussing setup.

Four of the wires along each edge were connected in series and linked to three other edges, forming closed-loop flux paths. This arrangement was repeated twice more to create

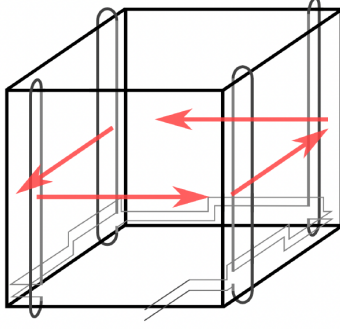


Figure 3.10: The setup of the equilibration coils: Z-direction edge coils with closed-loop flux and current return paths arranged to cancel connecting wire fields [33].

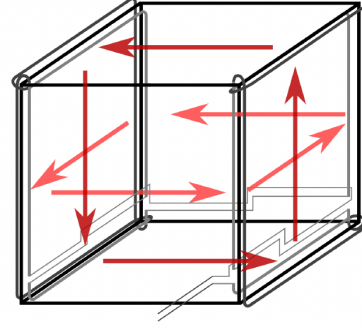


Figure 3.11: The setup of the equilibration coils: L-shaped coils for combined Y and Z-direction equilibration, also forming a closed-loop flux [44].

magnetic flux in Layer 5 along three distinct directions, designated Power 1, Power 2, and Power 3. A pickup loop, created with one leftover wire, measured the induced magnetic flux in each direction, labeled Pickup 1, Pickup 2, and Pickup 3.

The wiring for the edge coils is detailed in Figure 3.12, while Figure 3.13 illustrates the three magnetic flux directions generated by the edge coils in Layer 5. Gauge 12 wire was used for power coils, and gauge 18 wire was used for the pickup coils, with all connections routed outside the MSR via a large side hole. Twisted-pair cables were employed for all supply and return wires to minimize noise.

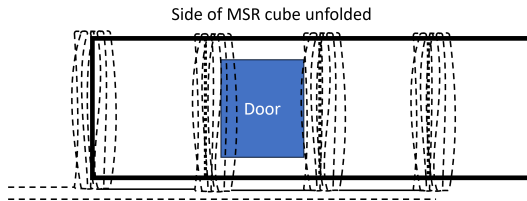


Figure 3.12: Diagram showing how the edge coils were wired up inside the room.

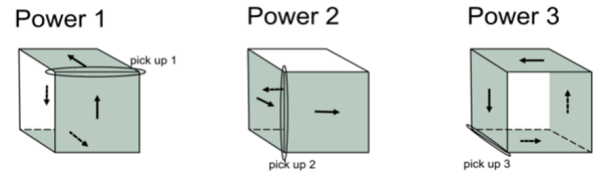


Figure 3.13: Diagram showing the three magnetic flux directions generated by the edge coils of layer 5.

The current in the driving loops for the edge coils was measured and converted to the

applied magnetic H field using the following equation:

$$H = \frac{F_{\text{MM}}}{\ell_{\text{eff}}} = \frac{I_{\text{driving}} N_{\text{driving}}}{\ell_{\text{eff}}}, \quad (3.1)$$

where F_{MM} is the magneto-motive force applied by the driving coil, ℓ_{eff} is the effective path length of the induced flux, I_{driving} is the current in the loop, and N_{driving} is the total number of turns about the μ -metal. For our cubic shield, the flux must travel through the walls. The current varies for each run and is measured accordingly.

The total flux within the metal is determined by integrating the voltage induced in the pickup coils:

$$\Phi = \frac{1}{N_{\text{pickup}}} \int V_{\text{pickup}} dt, \quad (3.2)$$

where Φ represents the total flux in the metal, N_{pickup} denotes the number of loops in the pickup coil, and V_{pickup} is the voltage measured in the pickup coil. The magnetic field is then derived from the total flux and the cross-sectional area through which the flux passes (i.e., the area of the panels):

$$B = \frac{\Phi}{A}. \quad (3.3)$$

L-Shaped Coils

L-shaped coils are configured for Layers 2 and 3 of the MSR. These coils are positioned along two adjoining edges of the shielding structure, allowing them to equilibrate the magnetic field in both the Y and Z spatial directions simultaneously. This configuration reduces equilibration time and ensures a homogeneous flux distribution across the μ -metal layers [43]. The geometry of the "L" coils differs slightly, as shown in Figure 3.14.

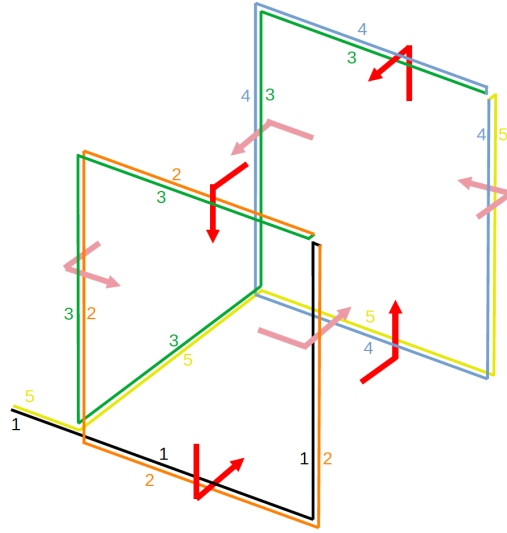


Figure 3.14: L coil configuration. The red arrows are showing the flux lines direction.

To illustrate, Figure 3.15 shows the fields produced by these "L" coils. The two field loops produced by each arm of the "L" coils combine to create a diagonal magnetic flux across two cube faces. This arrangement minimizes the impact of any overlapping flux patterns and ensures smooth, continuous magnetic field lines.

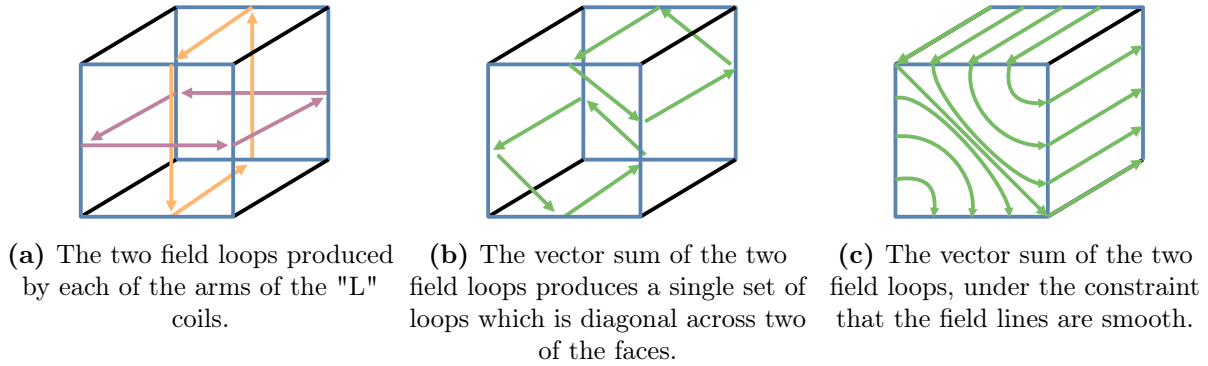


Figure 3.15: Fields produced by the "L" coils. When summed, the fields produce single loops which traverse the diagonal of the front and back. Requiring the loops to be smooth and continuous produces the basketball-like pattern on the diagonal face. The blue edges denote the edges with coils.

A sinusoidal current at 1 Hz is applied during the equilibration process. The timing involves 5 seconds at full amplitude to saturate the μ -metal, followed by a 20-second linear

ramp to zero amplitude, and a subsequent 5-second measurement period at zero amplitude.

For a cube with side length L , the average effective path length for the "L" coils is $\ell = L$ on two faces and $\sqrt{2}x$ on the other two faces, where $x \in [0, L]$. Averaging these lengths yields

$$\langle \ell_{\text{eff}} \rangle = 2L + 2 \frac{1}{L} \int_0^L \sqrt{2}x \, dx = (2 + \sqrt{2}) L. \quad (3.4)$$

Each field line always traverses four coil loops, regardless of configuration. With similar reasoning, the average cross-sectional area is given by

$$\langle A \rangle = \frac{L}{\sqrt{2}} dL. \quad (3.5)$$

Distributed L-Shaped Coils

For Layer 5, a distributed L-shaped coil arrangement is used to enhance flux uniformity. Instead of having only four coils along the edges, 20 coils are evenly distributed over the entire face of the cube. This design reduces the current in each coil by a factor of five, minimizing local magnetic flux density in areas where wires penetrate the walls. The uniform distribution ensures that the magnetic flux is spread more evenly throughout the material, further contributing to homogeneity.

Access ports with detachable screw-on plates are incorporated into the shield design to facilitate coil rewiring during optimization. Spare coils are also installed to mitigate risks of cable damage, ensuring the longevity of the system.

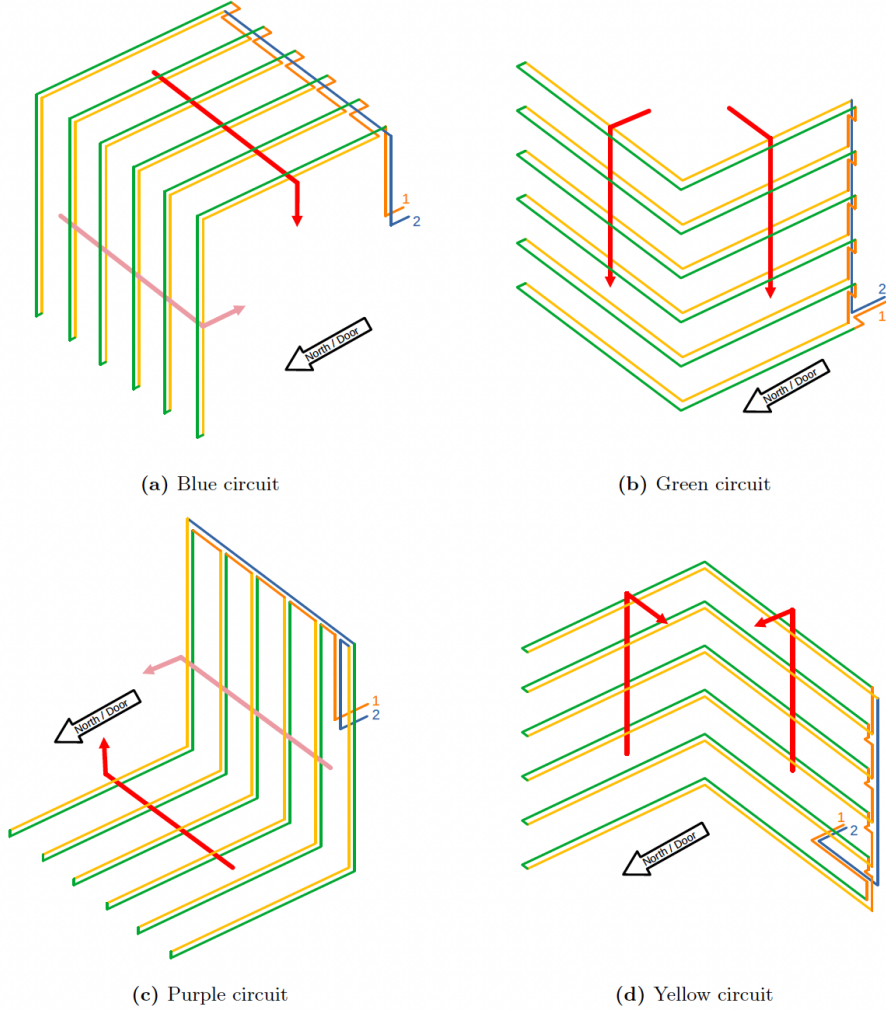


Figure 3.16: Layer 5 distributed L coils. Orange (1) is supply, blue (2) is return. Yellow cables are inside the μ -metal, green are outside. Red arrows indicate the direction of the field.

3.2.6 Relay-Contactor Box

The relay box is a custom designed component in the degaussing procedure, facilitating controlled current distribution to the equilibration coils of the MSR (Figure 3.17). Inside the box, five IEC magnetic contactors are installed, which are rated for 65 A at 120 V AC. These contactors were chosen for their ability to prevent overheating and maintain safe operation under high current loads. Each contactor is connected to a coil set corresponding

to one of the μ -metal layers. These contactors manage the flow of current required to reach magnetic saturation in each layer. The current originates from the NI USB-6281 data acquisition system, where it is output as an analog signal. This signal is amplified using the AE Techron 7224 amplifier before being directed through the contactors to the designated coil set. The NI USB-6281 also controls the contactors using its digital output, determining which contactor should open or close to deliver the current to the desired coil. This dual control helps selective application of the degaussing current, with each layer receiving the appropriate current for effective magnetic equilibration. The relay box was designed to meet CSA safety standards for operation at TRIUMF, with careful selection and approval of components.

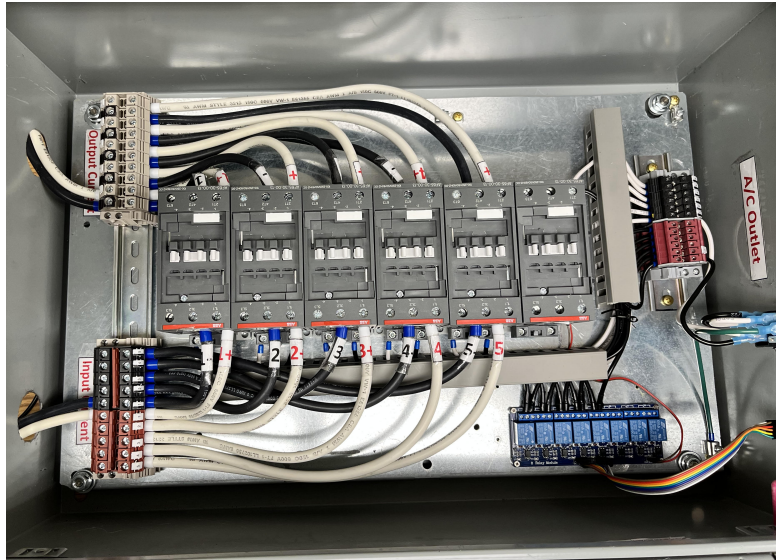


Figure 3.17: Assembled relay box

For more details on IEC contactor, refer to Item #GGE6EAR4, Mfr. Model #6EAR4, UNSPSC #39121529.

3.3 Summary

This chapter provided an overview of the measurement instruments and equipment used for characterizing the TUCAN MSR. The key devices included fluxgate magnetometers, power amplifier, data acquisition systems, and custom-built components such as the relay-contact box and perturbation coils. Each instrument was essential to shielding factor measurements, residual field analysis, and degaussing operations.

By integrating these instruments into the experimental setup, a systematic approach was established for evaluating and improving the MSR's shielding performance. The next chapter builds upon these foundations by presenting different setups and the results obtained from these characterization techniques.

Chapter 4

Pre-Installation MSR Shielding Factor Measurement and Setup

To assess the MSR’s performance, we measured its shielding factor (SF) before and after installation. These tests helped us understand how well the MSR blocks external magnetic fields. The pre-installation measurements captured the unshielded magnetic environment, while comparing them with post-installation results showed the level of shielding improvement. By examining how the ambient field changed across different frequencies, we gained a clearer picture of the MSR’s effectiveness.

This chapter outlines the approach used for the pre-installation SF measurements, starting with how SF is calculated, followed by the testing process, including the experimental setup, signal control, and data collection.

4.1 Shielding Factor Calculation

The shielding factor (SF) quantifies the reduction of an external magnetic field due to the presence of a shield (See Section [2.2](#)). It is defined as the ratio of the magnetic field measured in an unshielded environment to the field measured inside the MSR:

$$SF = \left(\frac{B_{\text{ext}}^u}{B_{\text{ext}}^s} \right) \left(\frac{B_{\text{ref}}^s}{B_{\text{ref}}^u} \right) \left(\frac{K_{\text{ext}}^s}{K_{\text{ext}}^u} \right) \left(\frac{I_{\text{ext}}^s}{I_{\text{ext}}^u} \right) \left(\frac{K_{\text{ref}}^u}{K_{\text{ref}}^s} \right) \left(\frac{I_{\text{ref}}^u}{I_{\text{ref}}^s} \right), \quad (4.1)$$

where B represents the measured magnetic field, I denotes the current applied to the coil, and K is the coil constant, defined as $K = B/I$. Superscripts u and s indicate unshielded and shielded conditions, respectively, while subscripts ext and ref differentiate the external perturbation coil from the reference coil. The term B_{ext} provides a direct measure of the shielding effect, while B_{ref} accounts for potential fluxgate drifts over time. K ratios account for potential changes in coil characteristics, whereas I ratios compensate for fluctuations in driving currents.

The data analysis phase aimed for correction ratios approaching unity, although deviations were expected. Changes in ratios involving certain parameters, such as I_{ref} , enabled the observation of external coil signals within the MSR. While the measurements of K ratios were impractical once the MSR is installed, as the MSR itself will affect the measured value of B , precise preparation sought to minimize discrepancies and ensure ratios remained close to unity.

To determine the SF, measurements must be performed in both unshielded and shielded conditions. The pre-installation phase captures the ambient magnetic field and system response without the MSR, establishing the baseline needed for later comparison. The same measurement process is then repeated post-installation to assess the effectiveness of the shielding. Since the TRIUMF site houses a cyclotron that generates a magnetic field exceeding $350 \mu\text{T}$, we measured the shielding factor both with the cyclotron on and off to evaluate its effect. The pre-installation measurements required for the SF calculation will be discussed in the following sections.

4.2 Pre-Installation Field Measurement Procedure

To measure the shielding factor before the installation of the MSR, a perturbation coil was used to generate a sinusoidal magnetic field with varying frequencies across the intended measurement range. Five fluxgate magnetometers (FGs) were placed in the central region where the MSR would later be installed, positioned at the North, East, West, South, and Center points of this region. These sensors recorded the field response, providing spatially resolved data on the unshielded magnetic environment. A reference coil, positioned around each fluxgate, was used to monitor sensor stability and account for potential drifts over time.

4.2.1 Setup

Before data collection, the perturbation coil, previously described in Section 3.2.4, underwent testing and calibration to establish optimal settings for generating a consistent magnetic field. The perturbation coil was placed around the MSR's intended location and generated a sinusoidal magnetic field of approximately $18\text{ }\mu\text{T}$ at controlled frequencies. It was driven by an AE Techron 7224 amplifier to produce the required field strengths for the shielding factor measurements. A Qingdao Hantek Electronics CC65 AC/DC current probe was used to monitor amplifier output.

The reference coil, also described in Section 3.2.4, positioned around the fluxgate magnetometers at the center of the setup, was used to monitor intrinsic variations in sensor readings. To avoid interference with the perturbation coil's signal, the reference coils operated at a frequency ten times higher than the perturbation coil, generating a low-amplitude field of approximately $1\text{ }\mu\text{T}$. The coils were directly driven by the NIDAQ at 8 V, ensuring stable calibration throughout the measurement process. Figure 4.1 shows field measurement setup before MSR installation. The complete electrical configuration is illustrated in Figure 4.2, and the physical setup and electronic settings used in the reference and perturbation

coils are summarized in Table 4.1.

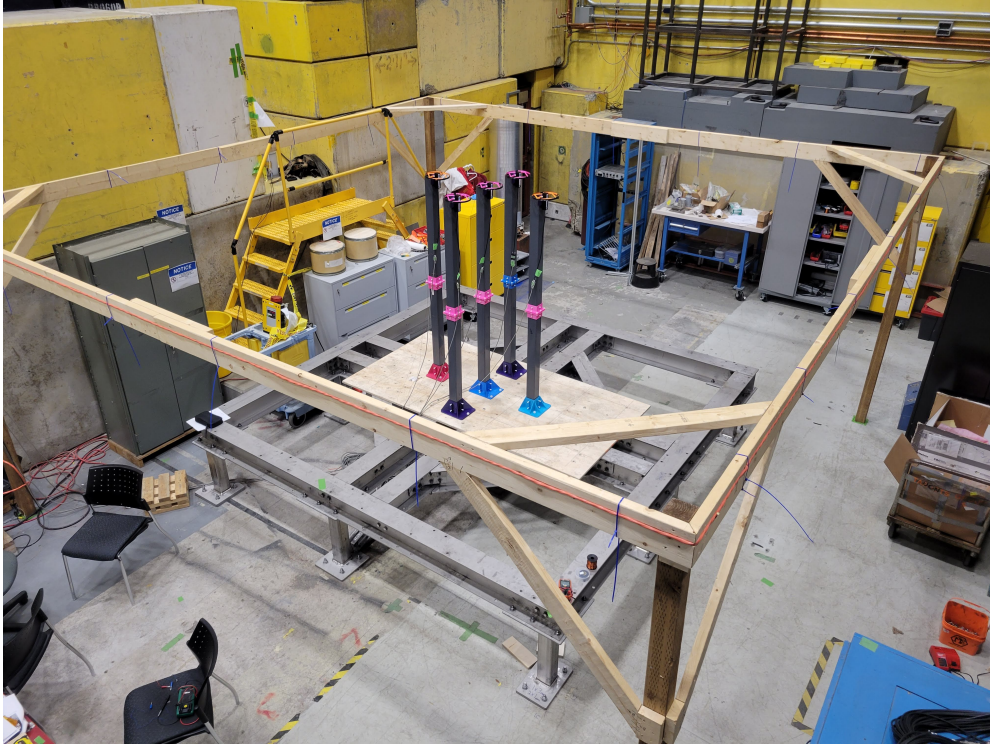


Figure 4.1: Perturbation coil mounted on a wooden post alongside Fluxgates with reference coils positioned at the central region of the designated MSR installation site.

Table 4.1: Summary of the physical setup and electronic settings used in the reference and perturbation coils.

	NIDAQ Voltage	Amp Gain	Number Turns	Resistance
External Perturbation Coil	1 V	60	3× gauge 10, 1× gauge 14	0.3773(13) Ω
Reference Coil	8 V	Bypassed	15× gauge 26	667.016(6) Ω

The FGs used for data collection were initially Bartington Mag690-FL500s. Once the cyclotron magnet was turned off, these were replaced with Bartington Mag-13MS100s and Bartington Mag-03MSL100s to maintain optimal sensitivity. For each fluxgate, measurements were taken with the external coil applying a field at frequencies ranging from 0.01 Hz to 100 Hz, using 50 logarithmically spaced points. The applied field amplitude was approximately 20 μ T. The reference coils operated simultaneously at a significantly lower amplitude

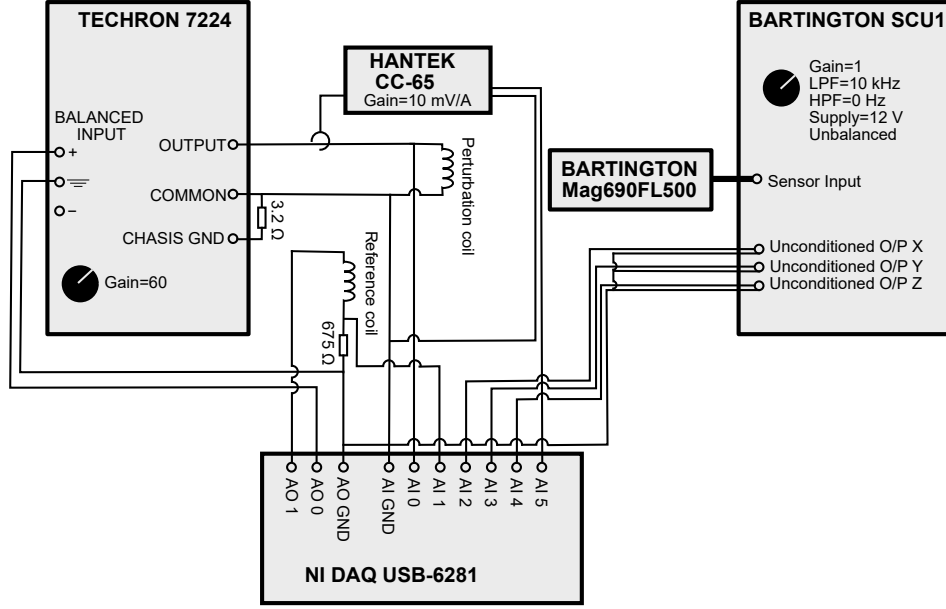


Figure 4.2: Circuit diagram for the SF measurement.

($\sim 1 \mu\text{T}$) and at a frequency ten times higher than that of the perturbation coil, ensuring signal separation.

All signal input and output operations were controlled via NIDAQ using the Python Application programming Interface (API).

Rebinning

During data collection, a challenge emerged from the large file sizes produced by the NIDAQ system, particularly at low frequencies. To address this, a rebinning scheme was implemented. The rebinning process involved averaging successive groups of data points to reduce the overall number of data points written to the file, thereby reducing file size. The rebinning factors were determined based on the frequency range of the measurements and are catalogued in Table 4.2. For frequencies above 10 Hz, no rebinning was necessary, while for lower frequencies, rebinning factors increased to accommodate the longer data collection times required for lower frequencies. This approach significantly reduced the file sizes.

The rebinning process, while necessary, introduced distortions in the sinusoidal fits of the

Table 4.2: Rebinning factors and run durations (in number of cycles) for a given range of frequencies, set to the perturbation coil ($10\times$ lower than that applied to the reference coil).

Range (Hz)	Number of Cycles Collected	Rebinning Factor
Frequency > 10	1000	1
$10 \leq$ Frequency > 1	100	2
$1 \leq$ Frequency	10	100

voltage drop across the reference coils. Specifically, when the rebinning factor was too large for the measured frequency, it affected the amplitude of the recorded signals. To quantify this effect, a correction factor was determined by generating perfect sine waves at the same frequencies and sampling rates (20 kHz) used in the experiment, applying the corresponding rebinning factors, and then fitting the resulting rebinned data with a sine wave.

The correction factor, C_{rebin} , was calculated as the ratio of the amplitude of the best fit of the rebinned data to the original amplitude:

$$C_{\text{rebin}} = \frac{a_{\text{Rebin}}}{a_{\text{True}}}, \quad (4.2)$$

where a_{rebin} is the amplitude after rebinning and a_{true} is the original amplitude. Applying this correction factor to the experimental data allowed for the accurate extraction of the true amplitudes from the rebinned data. Figure 4.3 illustrates the effect of rebinning on both the perturbation and reference coils. It was observed that the impact on the perturbation coil was minimal due to the lower frequencies applied, while the reference coils exhibited more significant distortion due to their higher frequency signals.

By implementing these corrections, the integrity of the experimental data was preserved, ensuring that the measurements accurately reflected the induced magnetic fields despite the necessary data compression.

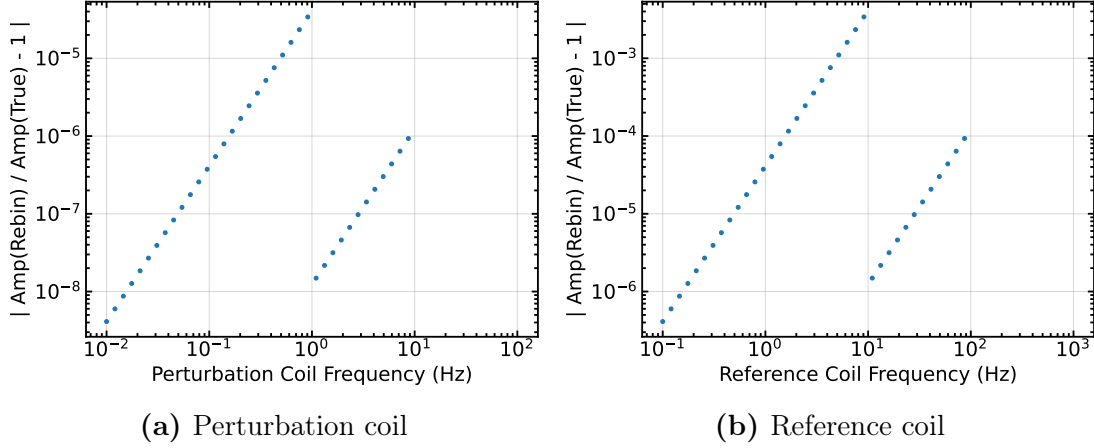


Figure 4.3: Correction factor due to rebinning sinusoidal waves. The factor scales with applied frequency, but appears to be the same otherwise. The effect on the perturbation coil is much less (two orders of magnitude), due to the lower frequencies applied. Shown with one subtracted for clarity. Errors are shown but small (see also Figure 4.4.)

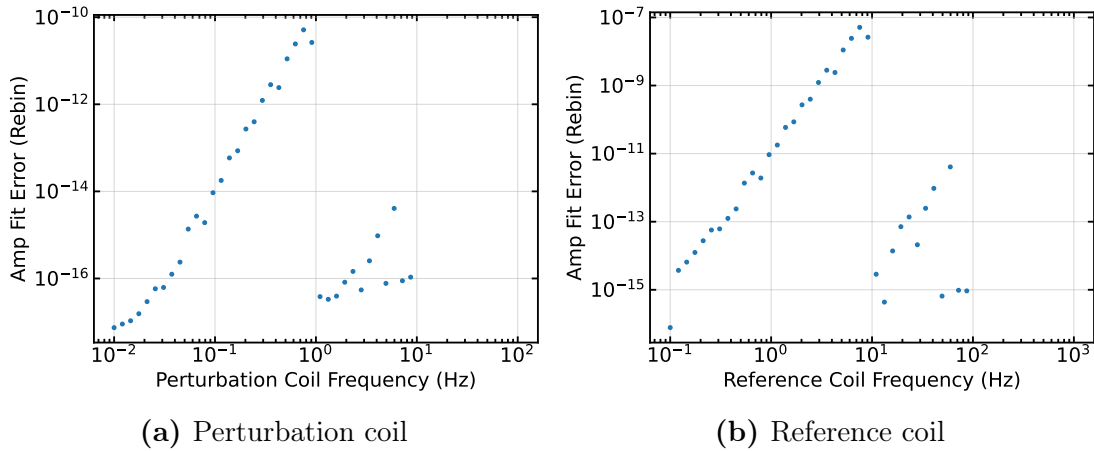


Figure 4.4: The fitting errors corresponding to Figure 4.3, as derived from the Hessian matrix method.

Amplifier Gain Calibration

Since the NIDAQ can only output voltages within ± 10 V, the Techron amplifier gain needed to be carefully chosen to ensure the required voltage drop across the perturbation coil while allowing accurate current measurement using the current probe. Figure 4.5a illustrates the effect of varying the amplifier gain for a NIDAQ output amplitude of 1 V at 1 Hz. Figure 4.5b shows the corresponding voltage drop across the perturbation coil, measured to verify

the applied field. While a higher gain improved the signal-to-noise ratio, it also increased the risk of external offsets driving the B_z signal out of scope. Since the voltage drop across the perturbation coil exceeded ± 10 V (as seen in Figure 4.5a), a gain of 60 was chosen to ensure proper operation.

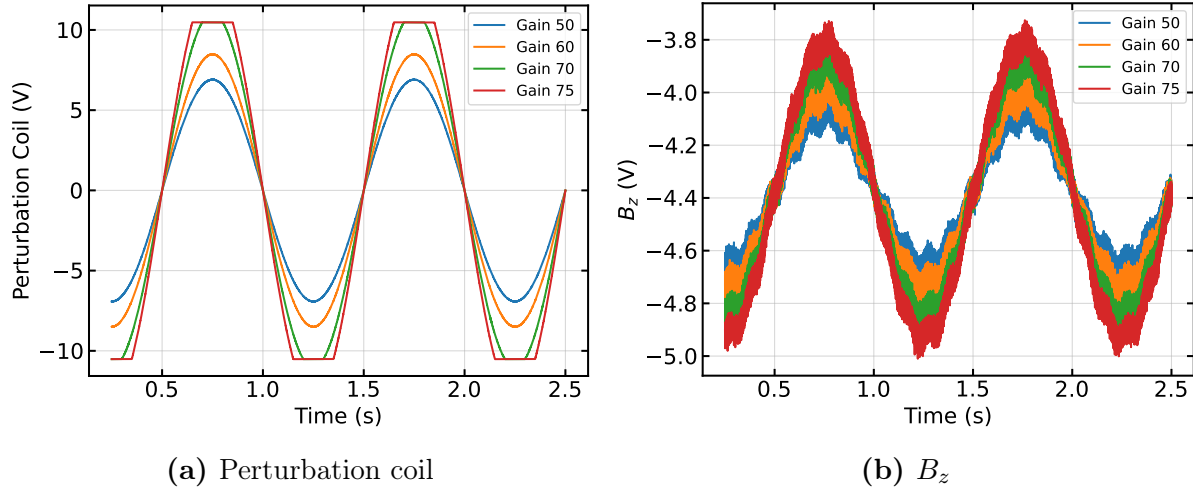


Figure 4.5: Readback for various gain settings on the Techron amplifier. A gain of 60 was chosen as the final best setting.

Perturbation Coil Stabilization

The external perturbation coil requires a period of thermal stabilization, as changes in temperature can affect its resistance and, consequently, the induced magnetic field. To assess this effect, the coil was first left to cool, then operated continuously for 15 minutes to monitor any time-dependent variations in the magnetic field due to heating.

The input voltage frequency was set to 60 Hz, and the amplifier gain was set to 50. Both the voltage drop across the perturbation coil and the voltage across the NIDAQ output were monitored throughout the test. Measurements were recorded at a sampling rate of 20 kHz to capture potential fluctuations in the field. This procedure ensured that any drift in the induced magnetic field due to coil warming was accounted for before subsequent experiments.

The resulting data set was divided into 1-second intervals to express the time-dependent

behavior. It was assumed that 60 cycles were sufficient to obtain an accurate estimate of the fit parameters and that any other time-dependent quantities would vary slowly on the timescale of seconds. Each interval was fitted with a single sine function with the frequency fixed at 60 Hz:

$$f(t; a, b, \phi) = a \sin\left(\frac{2\pi t}{60} + \phi\right) + b, \quad (4.3)$$

where a , b , and ϕ are parameters of best fit corresponding to the amplitude, offset, and phase, respectively. We also attempted fitting with a globally shared phase and offset, as well as fitting with these two parameters fixed to the mean value of the independent fits. Although these methods aimed to eliminate fitting artifacts produced by compensation between correlated fit parameters, any improvement from these more complicated methods was negligible.

The results of this procedure are shown in Figure 4.6. Both the amplitude and the phase data indicate that the coil takes about 10 minutes to warm up to a stable state. The change in phase relative to the baseline was only 0.003%, which is small compared to the change in amplitude (0.04%). This minimal phase change explains why fixing the phase did not significantly affect the amplitude value. The offset appears random over time. Thus, to ensure thermal stability, a warm-up time of 10 minutes was always performed before measurements were taken.

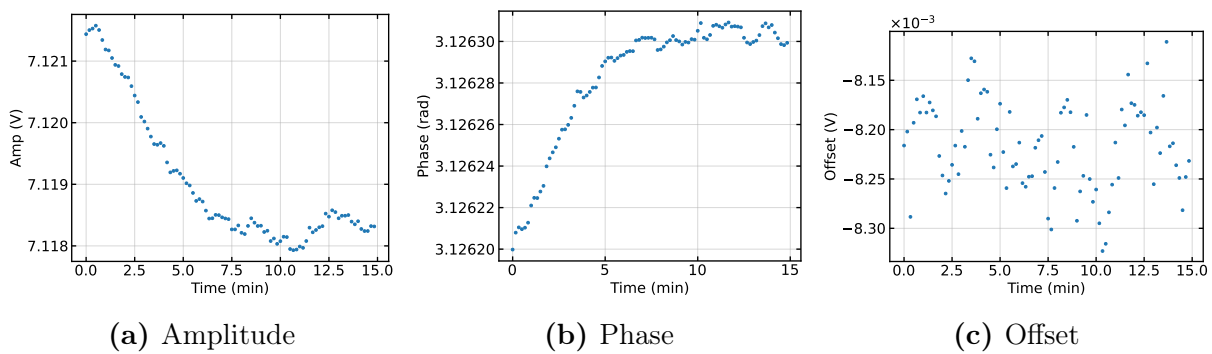


Figure 4.6: Best fit parameters of Equation (4.3) fit to the voltage drop across the external perturbation coil in one second intervals. It's clear that the warm up period is about 10 min. Error bars not shown for clarity.

Impedance and Inductance Measurement

Measuring the impedance in this experiment was essential to accurately determine the current driving through the coil as a function of frequency to calculate SF based on Equation 4.1. We spent a brief period attempting to measure the impedance and resistance of the coils using two different methods. Despite already having resistance values from the Digital Multi-Meter (DMM) ($0.3773(13)\,\Omega$ for the large perturbation coil and an average of $667.016(6)\,\Omega$ for the reference coils), we also employed two LCR meters for additional verification. However, the results from the LCR meters (Table 4.3) showed significant discrepancies when compared to the DMM measurements. Upon comparing the calculated fields to the measurements made by the FGs, the resistance values obtained from the DMM proved to be more accurate than those from the LCR meters, as shown in the later Section 4.2.2. Attempts to include a frequency-dependent impedance did not yield an accurate reflection of the measured amplitudes by the fluxgates. Both the scale of the decrease in the field and the frequency at which the decrease begins to occur were not well predicted by the simple impedance model. This limitation highlighted the need to refine our measurement approach.

Table 4.3: Inductance measurement results using two LCR meters. The user manual of the LCR700 provides a table indicating the recommended frequency range for measurements based on the values of inductance (L), capacitance (C), or resistance (R). For measuring inductance around $100\,\mu\text{H}$, a frequency of $10\,\text{kHz}$ is recommended.

Coil	Keysight				Sanwa LCR700		
	$ Z $ (Ω)	L (μH)	C (μF)	R (Ω)	L (μH)	C (μF)	R (Ω)
Reference coil (100 Hz)	3.23	—	—	3.256	115	—	3.34
Reference coil (1 kHz)	3.41	116	—	—	114	—	3.35
Perturbation coil (100 Hz)	0.44	476	5000	0.288	473	5130	0.41
Perturbation coil (1 kHz)	2.988	473	53.5	0.315	473.2	53.5	0.453

To address this, we used a detailed impedance measurement setup involving the perturbation coil connected to a Bartington Bartington Signal Conditioning Unit 1 (SCU1), Techon 7224 amplifier, and NIDAQ. Figure 4.7 illustrates the circuit diagram for this mea-

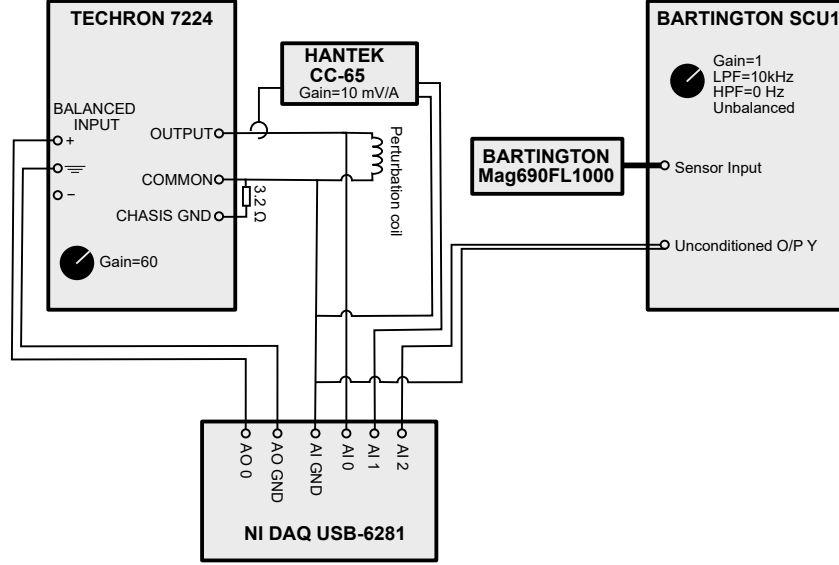


Figure 4.7: Diagram of the circuit used in the impedance measurement.

surement setup. This specific configuration was adopted to minimize noise and external interference, thereby enhancing the accuracy of the measurements. The primary goal was to assess the coil's impedance over a range of frequencies by applying controlled voltage inputs and recording the resulting signals.

4.2.2 Analysis and Results of SF: No MSR

In this section, we analyze the data collected prior to installing the MSR to determine the SF and discuss the results. The fitting of the collected data was a crucial part of this process, as it allowed us to extract meaningful parameters and understand the behavior of the magnetic fields in our setup.

Impedance Analysis

The impedance measurements, described in Section 4.2.1, were conducted with the cyclotron field on, and the FG recorded constant fields: $B_x = 1 \mu\text{T}$, $B_y = 23 \mu\text{T}$, and $B_z = 51 \mu\text{T}$, with B_z oriented vertically down. A script controlled the voltage input to the Techron amplifier,

applying 50 frequencies from 0.01 Hz to 100 Hz. The primary quantity of interest was the amplitude (V_1), obtained by fitting the measured signals with a sinusoidal function:

$$V(t) = V_1 \sin(2\pi\nu t + \phi) + V_0, \quad (4.4)$$

where the frequency, ν , was fixed to the input frequency generated by the NIDAQ, and the remaining fit parameters were free to vary.

In the analysis phase, the initial fit was performed without consideration of fitting errors. To assign a more realistic error estimate, a rolling standard deviation of the residuals was calculated over a window of 10 points, which was then used to assign an error to the central point. Points that could not be windowed were omitted from this error assignment step.

Based on this analysis, we found that the initial fit, while useful, did not provide accurate error estimates due to the lack of measurement error consideration. To improve this, we implemented a refitting procedure:

1. The data were refit using the results of the initial fit as a starting guess.
2. The rolling standard deviation of the residuals was used as the point error.

This iterative method provided more accurate error estimates for the fit parameters, thereby enhancing the reliability of the analysis. Figure 4.8 shows the raw measurement data and its sinusoidal fit at an input frequency of 0.625 Hz, along with the residuals to assess the fit quality.

The results revealed a fluxgate measurement amplitude fit error of 0.003% with a χ^2 value of 1.2. Despite achieving a reasonable fit, the residuals exhibited some structure, indicating that they might not follow a normal distribution. This structural presence in the residuals suggested potential impacts on the accuracy of the standard deviation estimates.

One possible issue with this method is the introduction of correlation between the data errors, which are usually assumed to be independent and normally distributed. As a chi-squared minimizer, we used a python-wrapped `iminuit`. MINOS errors indicated that the

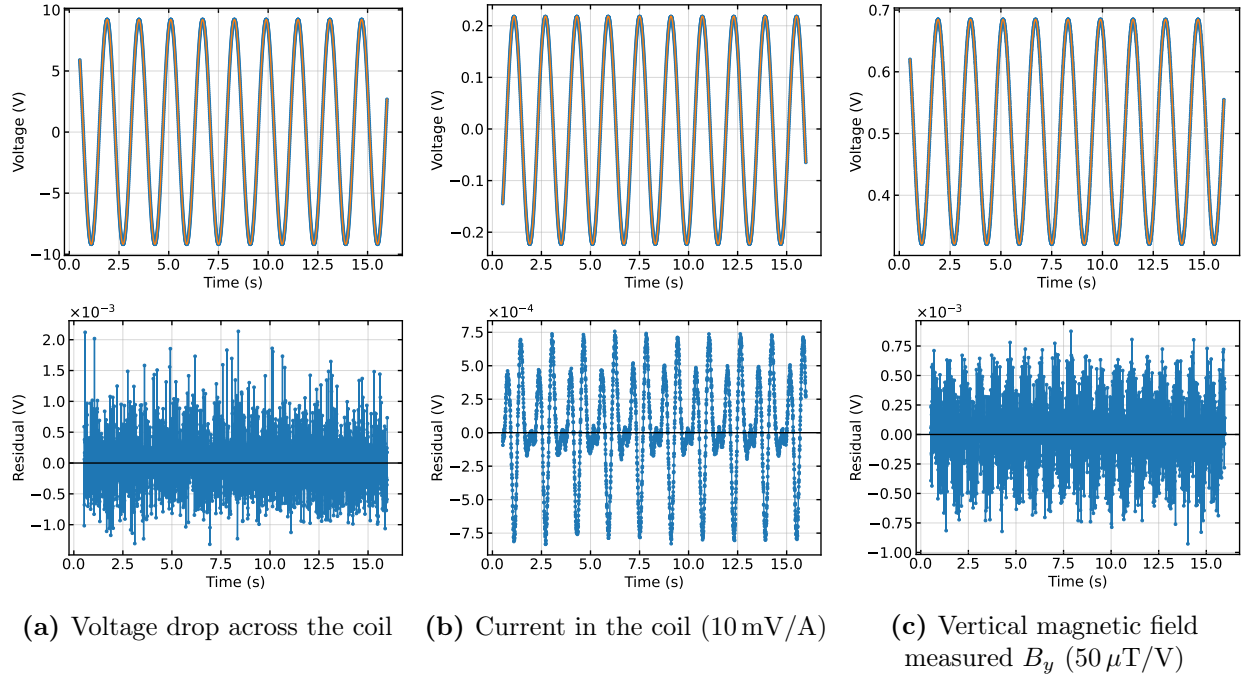


Figure 4.8: Raw data fit with a sine wave (Equation (4.4)) at 0.625 Hz. (*Top*): data (blue) and fit (orange). (*Bottom*): residuals.

HESSE errors were accurate and that the χ^2 was quite symmetric. This suggests that the loss of the independence assumption in the data errors does not significantly affect the fit results.

Another concern is that residuals may not accurately reflect fit errors due to their non-normal distribution. The residuals show substantial structure, indicating potential violations of the Gaussian assumption used for standard deviation estimation, even when considering small windows of 10 data points. Filtering attempts did not improve the signal without distorting the waveform or affecting amplitude, suggesting that the frequency distribution of residual signals is broad and close to the applied frequency.

Figure 4.9 shows fit amplitudes as a function of applied frequency, revealing that fit errors are likely underestimated, particularly at lower frequencies where the response is relatively frequency-independent. Notably, the coil current and measured field are well-correlated, whereas the voltage drop remains constant with some noise.

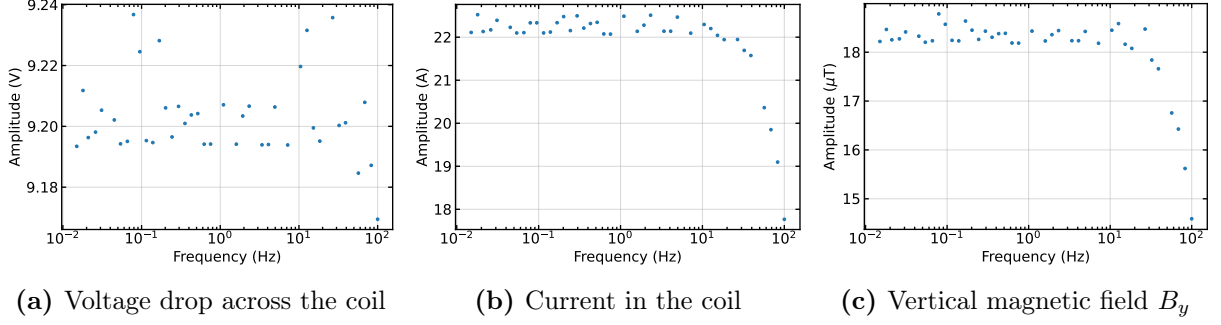


Figure 4.9: Fitted amplitudes as a function of frequency. We observe a relatively constant voltage drop across the coil, and a high degree of comparability between the current and measured field. Fit errors are shown but are clearly well underestimated.

Figure 4.10 illustrates the correlation between current and field, with standard deviation used for error estimation in the current-to-field relationship ($\nu < 10$ Hz). This analysis yields a coil constant of $1.179(37)$ A/ μ T and an offset of $0.60(68)$ A. The coil constant error is about 3 %, which is reasonable, and the offset is statistically negligible.

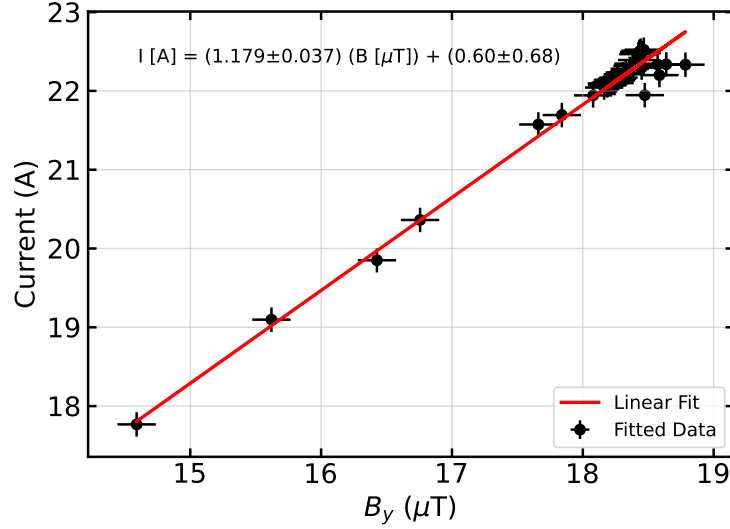


Figure 4.10: Current in the coil, as determined by the field measured by the fluxgate. Data errors are identical, and we use the standard deviation of $\nu < 10$ Hz as this value, given that the errors from the fits are clearly underestimated, as shown in 4.9.

To better estimate fit parameter errors, we developed an improved fitting method. Although it still underestimates errors, using the standard deviation of amplitude for $\nu < 10$ Hz

—where the amplitude is nearly frequency-independent—provides a better uniform estimate.

SF Analysis

To analyze the data for SF measurement, curves were fitted using either a single sinusoidal function, similar to the one used in the warm-up phase (Equation 4.3), or a superposition of two sinusoids when appropriate. The fitting function used for the superposition of two sinusoids is given by

$$f(t; a_{\text{ext}}, a_{\text{ref}}, \phi_{\text{ext}}, \phi_{\text{ref}}, b) = a_{\text{ext}} \sin\left(\frac{2\pi t}{f_{\text{ext}}} + \phi_{\text{ext}}\right) + a_{\text{ref}} \sin\left(\frac{2\pi t}{f_{\text{ref}}} + \phi_{\text{ref}}\right) + b, \quad (4.5)$$

where f_{ext} and f_{ref} were fixed according to the frequencies set by the NIDAQ. The best-fit curves were determined using the iMinuit Python package [67] with least squares cost functions as defined in the bfit package [68]. Errors were reported as HESSE errors since the MINOS algorithm did not provide significantly different values and was slower to converge.¹

During the initial data analysis, we observed that many runs exhibited an "initialization period," where the NIDAQ took some time to stabilize and output a signal. This period was characterized by a series of zeros at the beginning of the run. To address this, up to 10 seconds of data was cropped from the beginning of the time series for long runs. Initial guesses for the amplitude and offset were based on the standard deviation and mean of the data, respectively. For fitting a two-sine function, the initial amplitude for a_{ref} was set to 0.1 V. Examples of these fits are shown in Figure 4.11, where all residuals appear well-distributed over the timescale of the oscillating signal. To ensure the quality of the fits, several automated tests were conducted:

1. Verification that the minimizer returned a valid state, as indicated by a boolean flag written to file.

¹HESSE errors are computed from the inverse Hessian matrix, assuming a Gaussian likelihood near the minimum. MINOS errors, on the other hand, are determined by scanning the likelihood profile and can account for asymmetries. Since MINOS errors were nearly identical to HESSE errors in this case, using MINOS was unnecessary and computationally inefficient.

2. Checking that the mean of the fit residuals was within 1σ of zero.
3. Creating a histogram of the χ^2/DOF to identify outliers, although absolute values were difficult to interpret without errors on the data points.

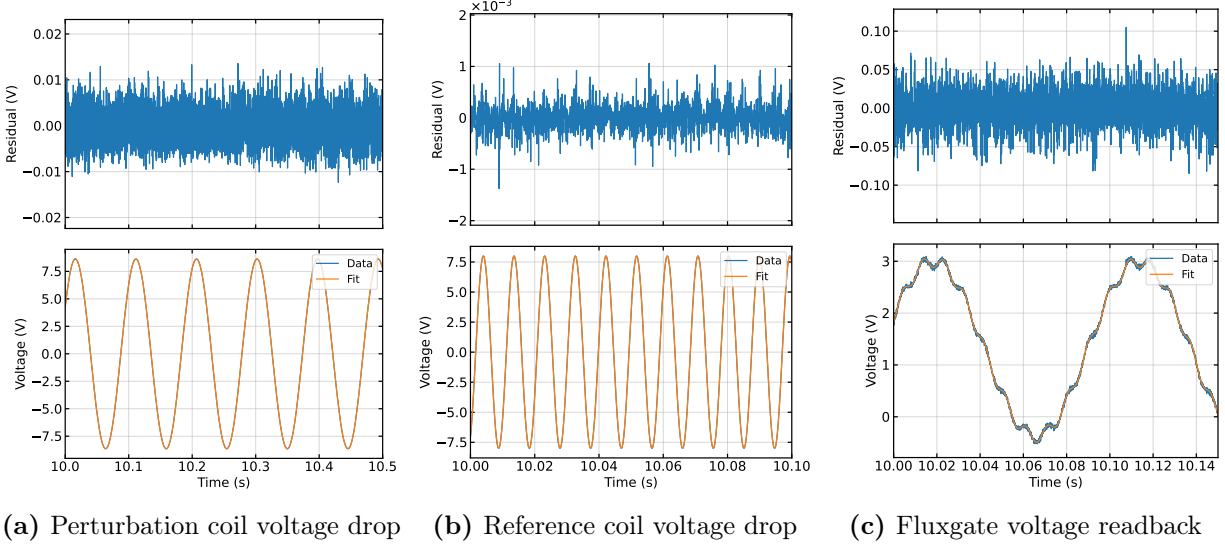


Figure 4.11: Example fits to the recorded signals.

Poor fitting quality was often apparent when plotting the fit parameters as a function of the applied frequency. Initial fitting failures were usually resolved by refining the initial parameter choices. Data that was clearly faulty was omitted from the results. Such faulty data often exhibited discontinuous changes in the otherwise smooth sinusoidal signal, likely due to poor electrical connections or physical disturbances to the connections. In most cases, defective sections of the data could be cropped out, allowing the rest of the signal to be used. However, in a few instances, the entire time series had to be discarded.

The comprehensive analysis and fitting procedures ensured that the data used for determining the SF was accurate and reliable, providing a robust foundation for evaluating the performance of the MSR.

To achieve precise SF measurements of the TUCAN MSR, we analyzed the data under two main scenarios: with the cyclotron magnet turned on and off. Additionally, we utilized different fluxgate magnetometers to measure the fields, examining their performance

under these conditions. The subsequent sections detail our findings from these experiments, focusing on the quality of fit, results, and implications of each configuration.

Cyclotron Field Off (100 μ T Fluxgates)

As described in Section 4.2.1, we installed five FGs in the central region of the MSR. First, a combination of Bartington 100 μ T FGs were used to take data. To assess the quality of fit for the cyclotron field off scenario with 100 μ T FGs, we applied a fitting procedure to the measured data. The fit parameters were optimized to minimize the residuals between the observed and predicted values.

The voltage amplitudes, corrected for rebinning and converted to magnetic fields, were analyzed. For a circular loop with N turns configuration, the field is expressed as

$$B = \frac{\mu_0 NV}{2RZ}, \quad (4.6)$$

where μ_0 is the permeability of free space, V is the voltage amplitude of the sinusoidal signal, and Z was measured to be 667.016(6) Ω (averaged over reference coils). The field due to a square loop of side length L is given by

$$B = \frac{2\sqrt{2}\mu_0 NV}{Z\pi L}, \quad (4.7)$$

where in this case $Z = 0.3773(13) \Omega$ (the external perturbation coil). More simply, the field as measured by both Bartington fluxgates used in this measurement is given by $B = 10 \times V$.

The impact of rebinning on voltage amplitude measurements was significant, particularly affecting error bars by potentially overestimating uncertainties, primarily due to reduced statistical resolution around amplitude peaks. To mitigate this, analysis using standard deviations across fluxgate positions provided a more robust estimate of uncertainty in subsequent magnetic field measurements (Figure 4.12).

Observations from both the external perturbation coil and the calibration coil highlighted

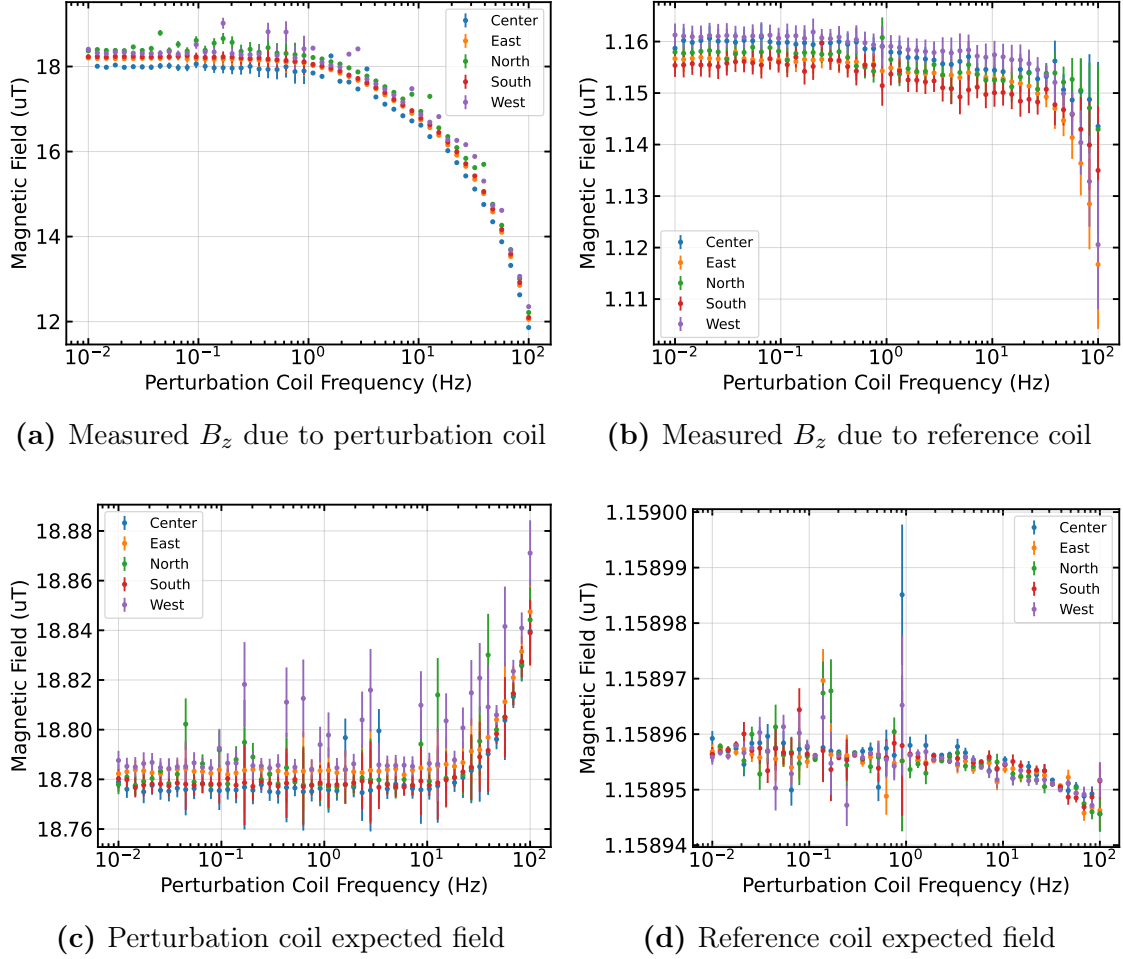


Figure 4.12: Sinusoidal amplitudes (corrected for rebinning and converted to field) as a function of applied frequency of the large external perturbation coil. The small reference coil was applied at a frequency $10\times$ that of the perturbation coil. Figures 4.12b to 4.12d show the standard deviation across fluxgate position as the point error, whereas Figure 4.12a has kept the original minimizer errors. No impedance was accounted for in these calculations.

intriguing frequency-dependent impedance effects. Specifically, discrepancies between expected voltage amplitudes and measured magnetic field strengths were notable, especially in larger coils at higher frequencies. Corrections involving adjustments to impedance characteristics ($Z \rightarrow \sqrt{Z^2 + (\omega L)^2}$) provided approximate scaling but also revealed subtle discrepancies at specific frequency ranges, underscoring the complex interplay between coil size, frequency response, and measurement accuracy.

To assess the accuracy of predicted magnetic fields, a comparison metric resembling this

equation was employed:

$$t = \frac{|B_z - B_{\text{coil}}|}{\sqrt{\sigma_{B_z}^2 + \sigma_{B_{\text{coil}}}^2}}. \quad (4.8)$$

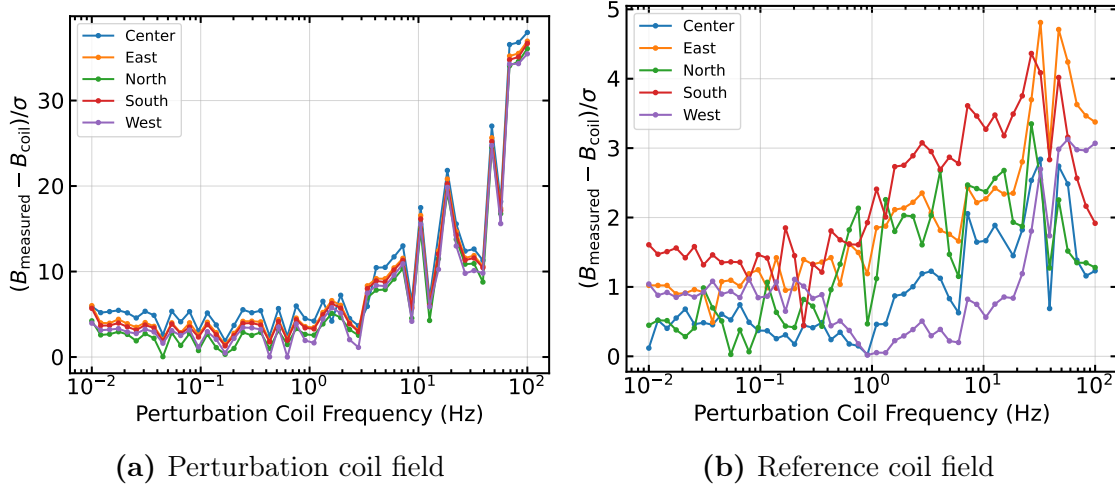
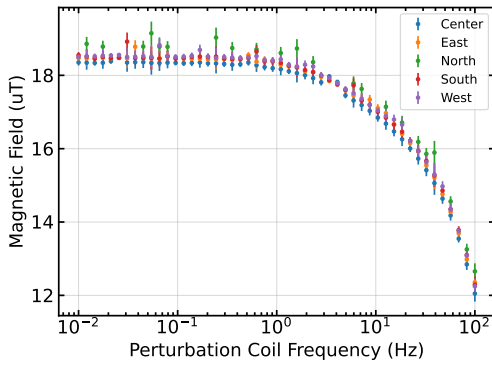


Figure 4.13: A comparison of the expected and measured fields as quantified by Figure 4.8. The reference coil produces a more accurate expected value than the perturbation coil, but in both cases the predicted field calculation suffers from a lack of accounting for the inductive impedance at higher frequencies. Lines are guides to the eye.

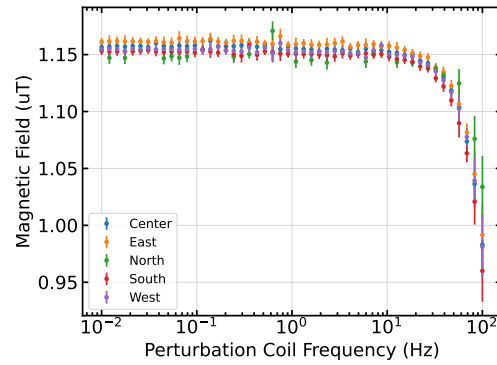
We note that this quantity is only equivalent to the t in cases where B_z and B_{coil} are sample means from populations with identical variances. It can be interpreted as the distance between the difference and zero in units of sigma, serving as a rough measure of similarity between quantities. We calculated the value of Figure 4.8 for each frequency for both the perturbation coil and the reference coil, as shown in Figure 4.13. The interpretation of this quantity depends on both the size of the errors in the compared quantities and their difference. Given that the reference coil has both smaller errors (see Figure 4.12) and a smaller t -value, we conclude that the reference coil field calculation is much more accurate than that of the perturbation coil. At low frequencies, this is almost certainly due to the precision required in measuring the resistance for accurate calculations.

Cyclotron Field Off (500 μ T Fluxgates)

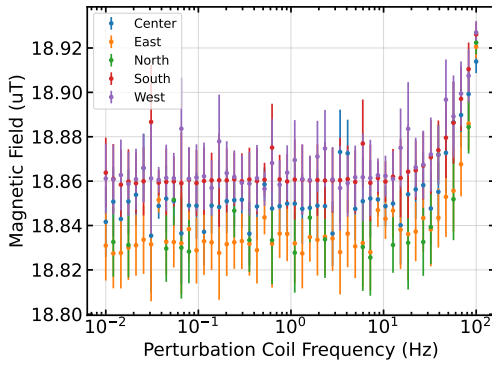
For this measurement, a combination of 500 μ T FGs and one 1000 μ T FG, placed in North position, were used. The amplitudes, corrected for the rebinning factor and converted into the corresponding magnetic field, from the fitting procedure are shown in Figure 4.14. The conversion from voltage amplitude to magnetic field follows the equations provided in Equations 4.6 and 4.7. In this measurement, the 500 μ T FGs had a conversion factor of 50 μ T, while the 1000 μ T FGs had a conversion factor of 100 μ T. Apart from these specific conversion factors, the results and analysis are consistent with those presented in section 4.2.2.



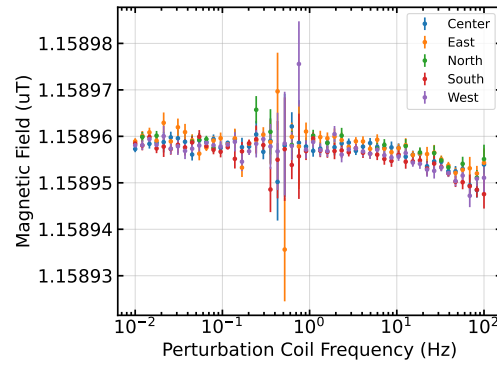
(a) Measured B_z due to perturbation coil



(b) Measured B_z due to reference coil



(c) Perturbation coil expected field



(d) Reference coil expected field

Figure 4.14: Sinusoidal amplitudes (corrected for rebinning and converted to field) as a function of applied frequency of the large external perturbation coil. The small reference coil was applied at a frequency $10\times$ that of the perturbation coil. All of the above show the standard deviation across fluxgate position as the point error.

Cyclotron Field On (500 μ T Fluxgates)

Continuing from the previous section, measurements were conducted using the same setup described in section 4.2.2; however, the cyclotron magnet was activated. All equations, calculations, and methods applied remain consistent with those outlined earlier. Results of these measurements shown in Figure 4.15.

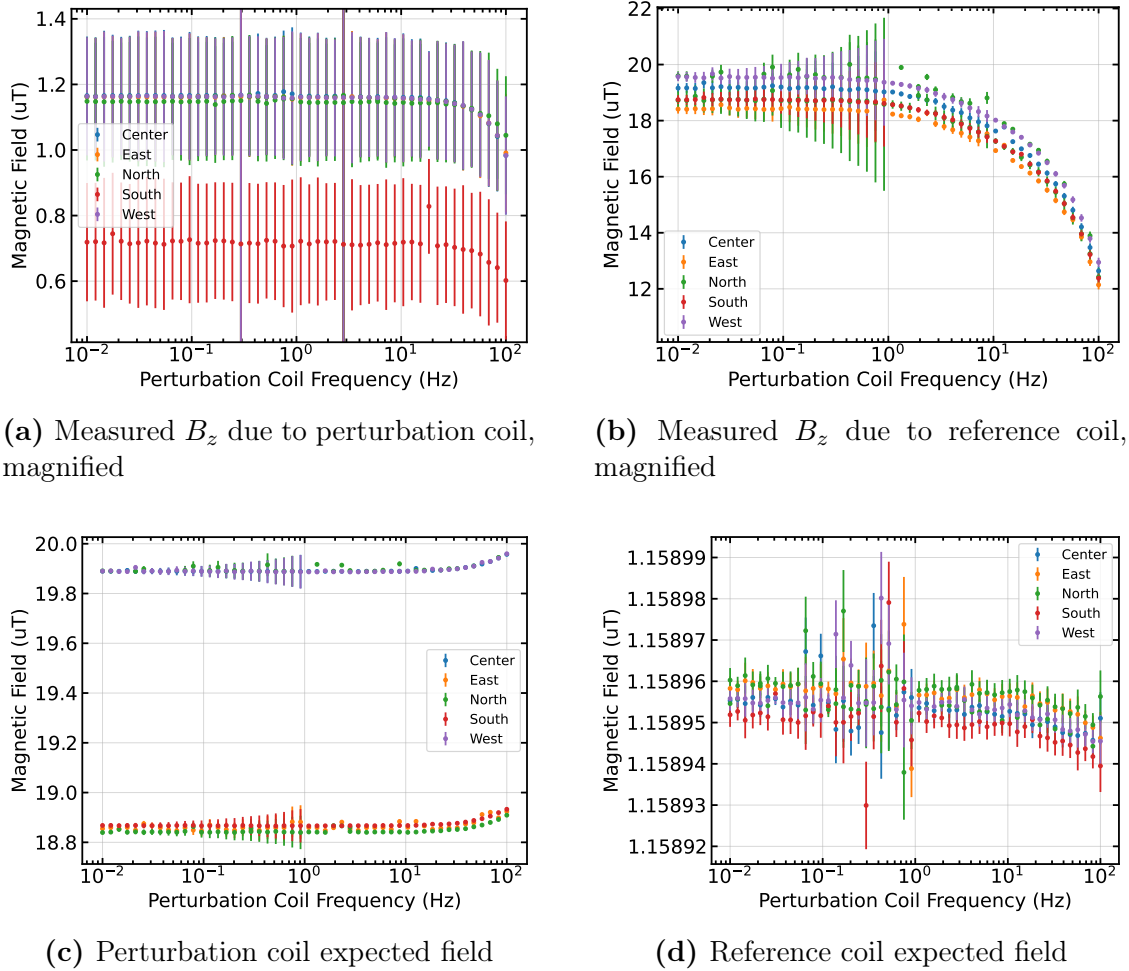


Figure 4.15: Sinusoidal amplitudes (rebinned, field-converted) vs. perturbation coil frequency. The reference coil ran at $10\times$ this frequency. All use minimizer errors except 4.15a, which shows standard deviation errors.

The results of our study, shown in Figure 4.16, demonstrate that turning off the cyclotron field and utilizing more precise FGs significantly reduces magnetic noise. In particular, for the B_x and B_y components, the standard deviation provides a straightforward measure of

noise, as no intentional signals are induced along these axes. For instance, when using the 100 μT FGs with the cyclotron field off, the standard deviation for the B_x component was reduced from 0.45 nT to 0.15 nT, and for the B_y component from 0.50 nT to 0.18 nT. Similarly, the 500 μT FGs showed a reduction from 0.55 nT to 0.20 nT for B_x and from 0.60 nT to 0.22 nT for B_y . Additionally, the B_z component, when analyzed through the Root Mean Square (Root Mean Square (RMS)) of fit residuals, indicates that both the type of fluxgate model and the state of the cyclotron field heavily influence the residual scatter. With the cyclotron field off, the RMS residuals for the 100 μT FGs decreased from 1.25 nT to 0.35 nT. For the 500 μT FGs, the reduction was from 1.50 nT to 0.40 nT. When the cyclotron field was on, the RMS residuals increased by approximately 0.75 nT across all FG models, indicating the cyclotron field's significant impact on measurement accuracy. These findings highlight the importance of optimizing both the environmental conditions and the measurement instruments to achieve accurate magnetic field measurements.

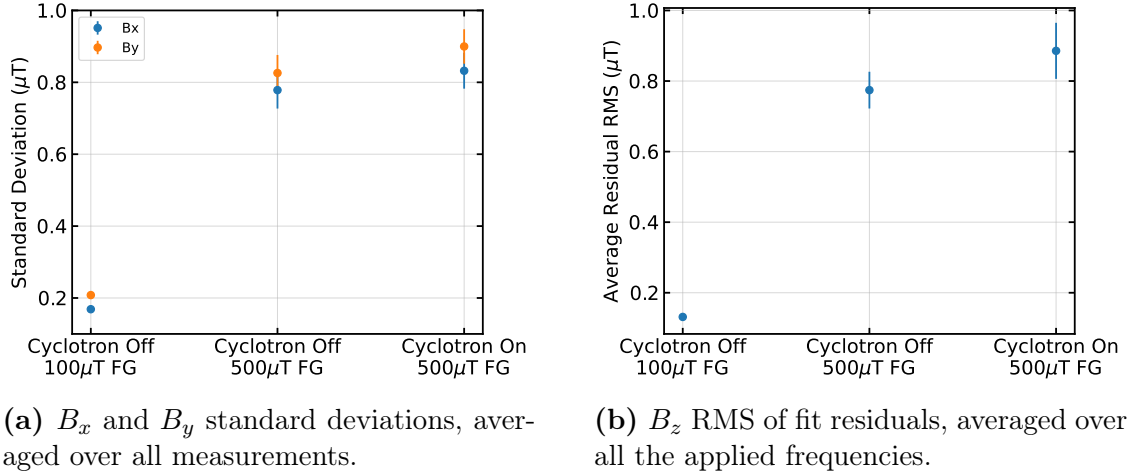


Figure 4.16: Noise in the meson hall. If the fit is accurate, the RMS of residuals in B_z reflects noise along B_z . Residuals from coil voltage drops are independent of the fluxgate model and cyclotron field. In all axes, both factors significantly impact residual scatter.

4.3 Summary

This chapter detailed the pre-installation evaluation of the TUCAN magnetically shielded room (MSR), focusing on shielding factor (SF) measurements and impedance analysis. To characterize the unshielded magnetic environment, we tested various fluxgate magnetometers ($100\text{ }\mu\text{T}$, $500\text{ }\mu\text{T}$, $1000\text{ }\mu\text{T}$) under different conditions, including with and without the cyclotron field active.

Turning off the cyclotron field significantly reduced magnetic noise. The noise in B_x decreased from 0.55 nT to 0.20 nT , while in B_y , it dropped from 0.6 nT to 0.22 nT . The RMS residuals of B_z were reduced from 1.5 nT to 0.4 nT when the cyclotron was off, but when the field was active, the residuals increased by approximately 0.75 nT across all fluxgate models, demonstrating the cyclotron's influence on the magnetic environment.

The shielding factor measurements involved applying a sinusoidal perturbation field of $18\text{ }\mu\text{T}$ using the external coil. The reference coil, positioned around the fluxgate sensors, operated at ten times the perturbation frequency, generating a field of approximately $1\text{ }\mu\text{T}$. The voltage-to-field conversion factors for the fluxgate magnetometers were $10\text{ }\mu\text{T/V}$ for the $100\text{ }\mu\text{T}$ model, $50\text{ }\mu\text{T/V}$ for the $500\text{ }\mu\text{T}$ model, and $100\text{ }\mu\text{T/V}$ for the $1000\text{ }\mu\text{T}$ model. Comparisons between expected and measured fields revealed discrepancies at higher frequencies due to impedance effects, highlighting the need for careful corrections.

The impedance analysis showed that the external perturbation coil had a resistance of $0.3773 \pm 0.0013\Omega$, while the reference coils averaged $667.016 \pm 0.006\Omega$. To ensure measurement accuracy, a 10-minute warm-up period was required for thermal stability. The amplifier gain was set to 60 to achieve the necessary voltage and current output.

These measurements established the unshielded magnetic baseline necessary for evaluating the MSR's performance after installation. The next chapter will examine the shielding factor of the installed MSR and assess its effectiveness in reducing external magnetic disturbances.

Chapter 5

MSR Shielding Factor Measurement and Setup

In the previous chapter we provided magnetic field measurements method and results before installing the MSR necessary for SF measurement. This chapter focuses on the SF measurements after the MSR installation, evaluating how each shielding layer contributes to the overall performance. To evaluate the MSR's ability to suppress magnetic field, we determined the SF after adding each shielding layer. This process helped show how the MSR's performance improved as more layers were added. Additionally, measurements were taken under two conditions—with the cyclotron field on and off—to understand how external magnetic fields influence the shielding. To calculate the SF at each stage, we used the pre-installation measurements from the previous chapter. The results here give a close look at how well the MSR blocks unwanted magnetic fields and how each layer changes its ability to do so.

5.1 MSR Post-Installation Measurement Procedure

Following the installation and setup of the MSR, as outlined in Chapter 2, we systematically measured the SF after each layer was installed. These measurements allowed us to evaluate how each shielding layer enhanced the MSR’s ability to attenuate external magnetic fields. We use the same setup, with most of the same equipment, and largely the same connection scheme for the electronics as was showed in Figure 4.2.

Before each SF measurement, we degaussed the MSR to eliminate any residual magnetization of the μ -metal affecting shielding performance. We will discuss the degaussing process and its role in the next chapter.

In the following sections, we describe the exact setup and equipment used for each SF test, detailing how measurements were performed at each stage of the MSR’s assembly.

5.2 Copper Layer (Layer 4)

As described in Chapter 2, the copper layer was the first completed layer of the MSR. Along with the MSR’s base and door, this provided partial shielding from the ambient magnetic field due to the presence of some μ -metal components. However, at the time of this test, no μ -metal layer was fully complete—only certain sections, such as the floor and door, had been installed.

Following the installation of the copper layer, we measured the shielding factor as a function of frequency. Figure 5.1 shows the partially installed MSR with the perturbation coil setup around. For this test, we used a FG, specifically the Bartington Mag690-FL500, and the exact circuit diagram as shown in Figure 4.2. The post supporting the FG was cut so the FG was at the exact same height above the MSR frame as when the MSR was not present. We ran a similar data collection script as with the no-MSR measurement, including the 15-minute warmup period, with the addition of collecting data from the Hantek current monitor probe. As before, we applied 50 frequencies evenly spaced on a log scale from

0.01 Hz to 100 Hz, but sorted into a random order (each run had a unique random order). The run duration was frequency-dependent, as described in our prior work (Table 4.2).

A $675\,\Omega$ resistor was placed in series with the reference coil. With the coil in the circuit, we measured a resistance of $679\,\Omega$. These measurements were conducted with a multimeter. The impedance of the reference coil and the perturbation coil was measured with a handheld LCR meter, the Sanwa LCR700, as summarized in Table 5.1. Compared to Table 4.3, the results are consistent within the reproducibility limits of the last measurement.

Table 5.1: Inductance measurement results using an LCR meter Sanwa LCR700 and DC multimeter Fluke 75III.

Coil	Sanwa LCR700			Fluke 75III
	$L\,(\mu\text{H})$	$C\,(\mu\text{F})$	$R\,(\Omega)$	$R\,(\Omega)$
Reference coil (DC)	—	—	—	3.3
Reference coil (100 Hz)	114.0	—	3.25	—
Reference coil (120 Hz)	113.0	—	3.25	—
Reference coil (1 kHz)	115.1	—	3.26	—
Reference coil (10 kHz)	115.1	—	3.28	—
Reference coil (100 kHz)	118.7	—	3.76	—
Perturbation coil (DC)	—	—	—	0.7
Perturbation coil (120 Hz)	475	3610	0.44	—
Perturbation coil (1 kHz)	469.4	54.34	0.49	—
Perturbation coil (10 kHz)	455.9	0.5554	0.962	—
Perturbation coil (100 kHz)	628.3	0.00403	15.4	—

5.2.1 Analysis and Results

We used the same fitting procedure as described in subsection 4.2.2, but with the two-sine function we used before (Equation 4.5):

$$f(t; a_{\text{ext}}, a_{\text{ref}}, \phi_{\text{ext}}, \phi_{\text{ref}}, b) = a_{\text{ext}} \sin\left(\frac{2\pi t}{f_{\text{ext}}} + \phi_{\text{ext}}\right) + a_{\text{ref}} \sin\left(\frac{2\pi t}{f_{\text{ref}}} + \phi_{\text{ref}}\right) + b. \quad (5.1)$$

To maintain consistency with the previous analysis, we re-fitted the data from our prior work (Section 4.2.2 using this procedure, including correction factors to account for the

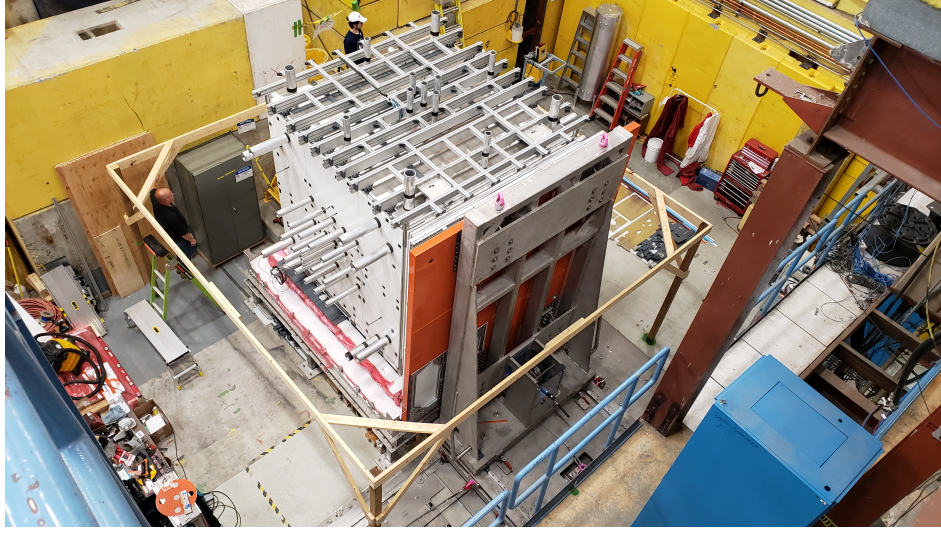


Figure 5.1: Perturbation coil set up around the partially completed MSR.

varying rebinning sizes. An example of this fit is shown in Figure 5.2. Although some residual structure remains in the fit, it is largely due to electronic noise and is unlikely to have significantly impacted the fit quality.

We compare the results from this run with Section 4.2.2, as shown in Figure 5.3. Figures 5.3c and 5.3f present the measured field due to the external perturbation coil. Notably, with the copper layer present, the amplitude is much smaller, and the downturn begins around 0.1 Hz rather than 5 Hz. We expect the current and field from the reference coil to be consistent with and without the MSR since the coil is inside the room.

Based on Figure 4.10, we assume that the current generating the fields in Figure 5.3c is proportional to those fields. However, the current measured with the copper layer present, as shown in Figure 5.3g, exhibits a different frequency dependence compared to the measured field. The same proportionality does not apply with the copper layer.

From Figures 5.3a and 5.3d, we observe that the currents are approximately the same, except for a scaling constant attributed to the difference in measuring resistances ($667\,\Omega$ vs $675\,\Omega$). The observed trend of lower amplitudes near 1 Hz is a known artifact of the data rebinning treatment to conserve storage space.

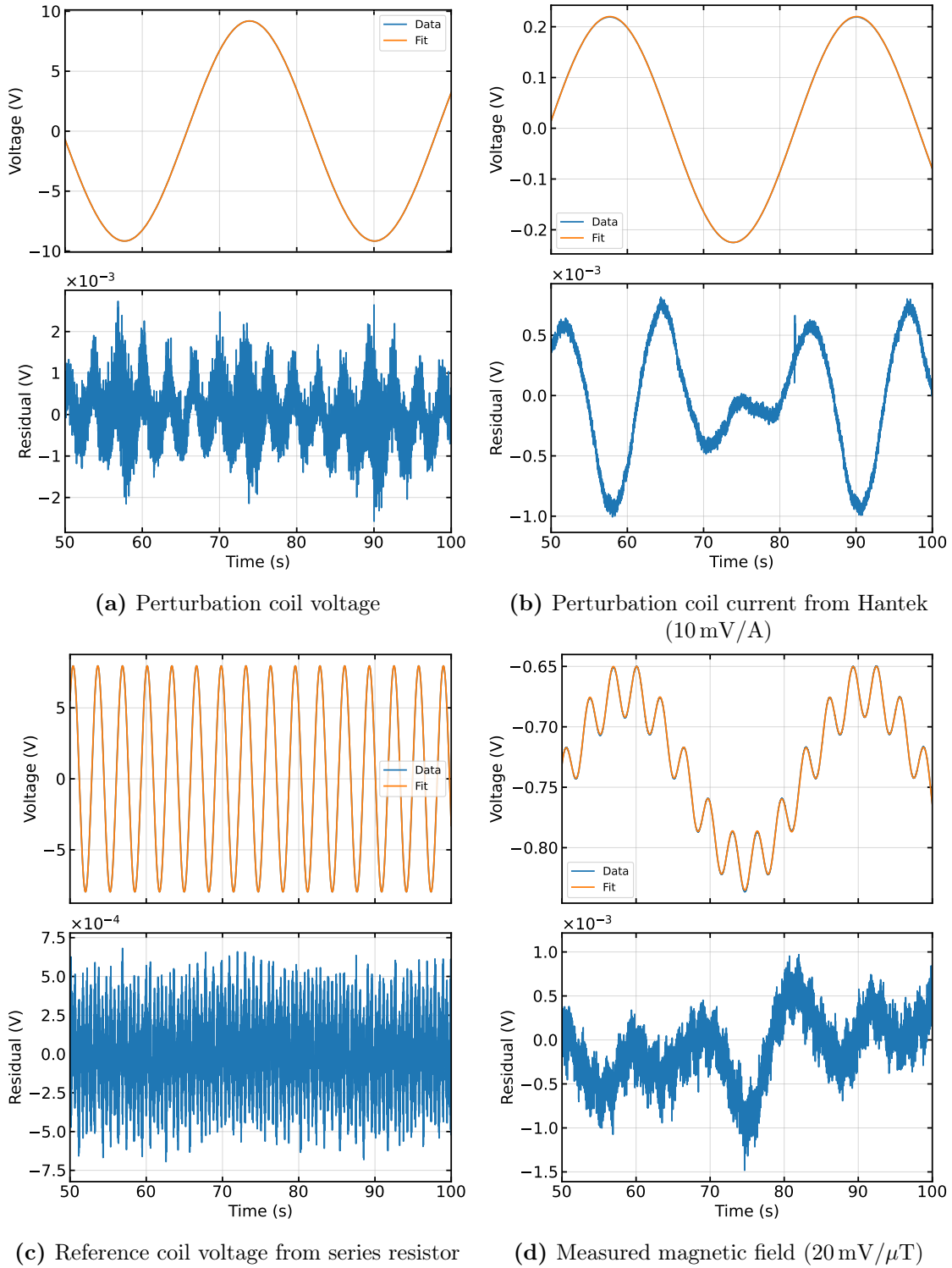


Figure 5.2: Raw data with sinusoidal (Figures 5.2a to 5.2c) or bi-sinusoidal (Figure 5.2d) fits. Data taken with a perturbation coil frequency of 0.03 Hz and a reference coil frequency of 0.3 Hz.

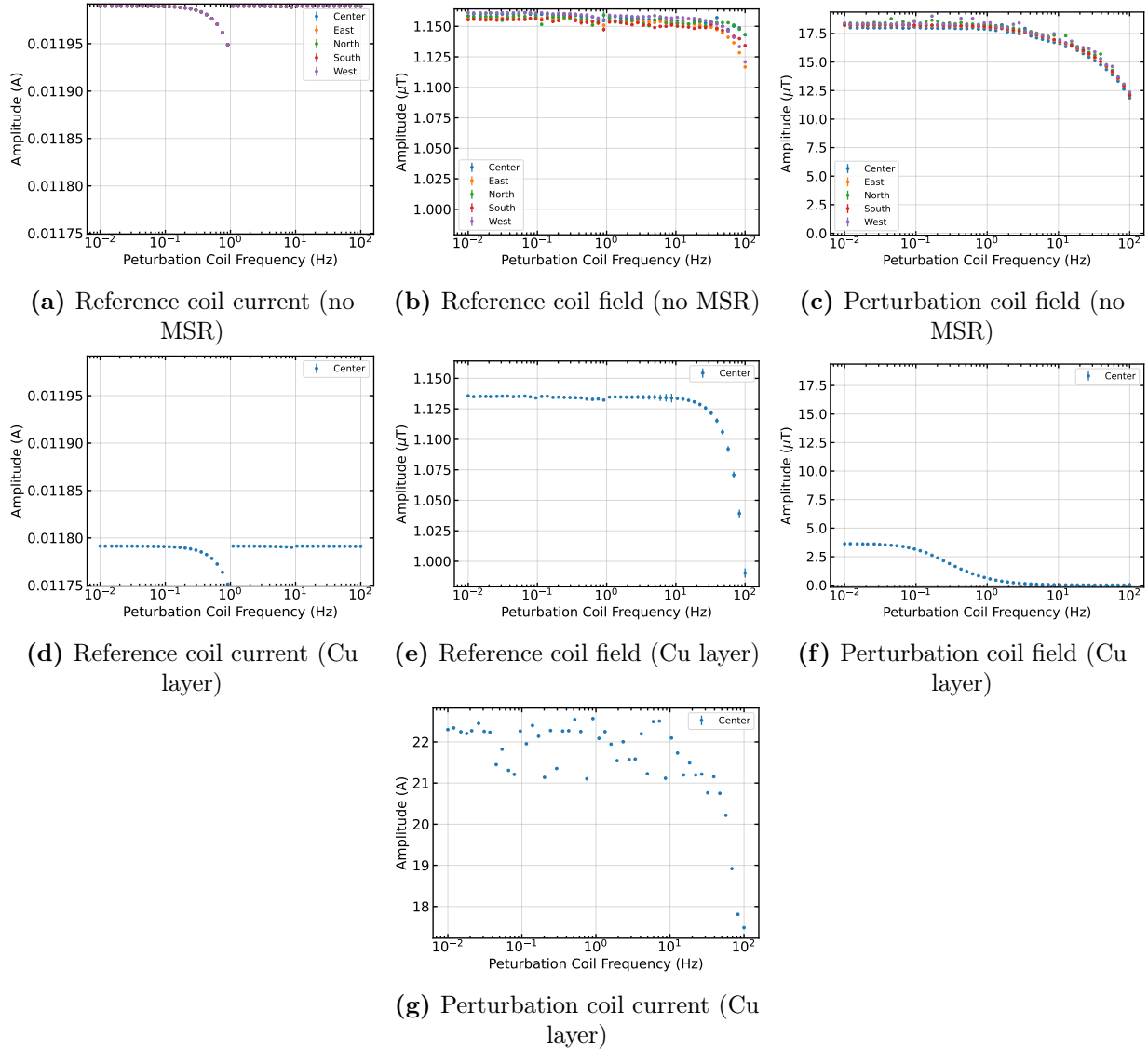


Figure 5.3: Raw fit parameters for both the measurements from this run (copper layer in place) and with no MSR. Note that we did not measure the current with no MSR, the current is estimated from the field measurements in Figure 5.3c.

Using Equation (4.1), assuming the the coil constants K do not change between measurements, we calculate the SF shown in Figure 5.4. Clearly the SF gets larger at high frequency, with a peak near 50 Hz, which be discussed later (see page 100).

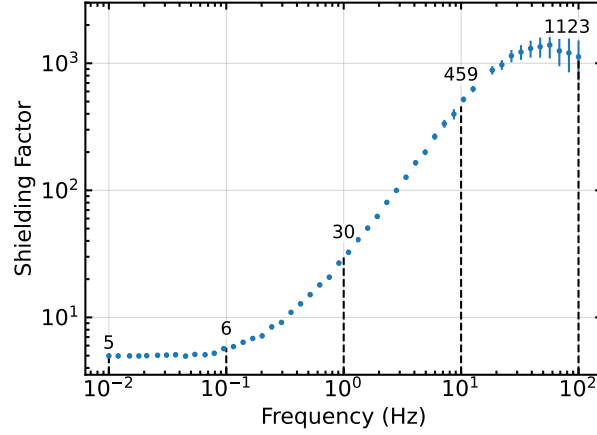


Figure 5.4: SF with only the copper layer and some partial μ -metal layers of the room installed.

5.2.2 Discussion

Comparing the field amplitudes in Figures 5.3c and 5.3f, the increase in static shielding is due to the presence of μ -metal in the area. The change in frequency dependence and high-frequency behavior can be attributed to the RF shielding effect of the copper. There is also likely some change in the coil impedance.

Interestingly, the shape of the measured reference coil field (Figures 5.3b and 5.3e) differs between the two runs. Possible explanations for this include:

1. The two models of FG used (Bartington Mag690-FL500 and Mag13-MSL100), which differ significantly in size, cause the reference coils in the two measurements to have different impedance. This difference would likely appear in the current measurement.
2. The external field to output voltage conversion of the two FGs is different. This could be due to the application of different internal low-pass filters, which seems to be the most likely explanation.

Regardless of the exact cause, the effect appears to be FG-dependent, as shown in Figure 5.5. Here, we compare data from our prior work using a Bartington Mag690-FL500

fluxgate, the same model used in this work. The two figures show that the frequency dependence of the response is much closer than that shown by the Bartington Mag13-MSL100 fluxgate. The effect is only about 15 % at most. If we omit the reference coil field and current from the SF calculation, the results are not significantly affected. The choice of using the Mag13-MSL100 FG to calculate the SFs was motivated by the higher quality of the Mag13 data, despite this small difference in the frequency response of the two FG.

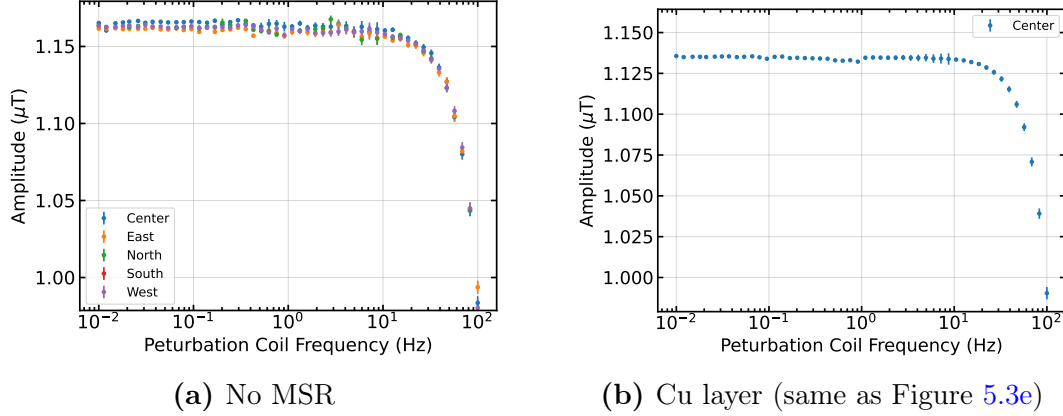


Figure 5.5: Side-by-side comparison of the reference coil fields using the Bartington Mag690-FL500s, the measurement with no MSR taken from the trial when the cyclotron field was on. The high-frequency dependence is much closer than that exhibited by the Bartington Mag13-MSL100 fluxgate used in the no-MSR measurement shown in Figure 5.3b.

Another interesting observation is the large component of the perturbation coil signal in one of the transverse axes, as shown in Figure 5.6. This signal is absent in B_x , which shows only a very small amplitude related to the perturbation coil. The field along $\hat{y}$ is aligned with the path of the UCN coming from the source, perpendicular to the door. There is a significant asymmetry in the amount of μ -metal present in the area. It is likely that the μ -metal in the door redirects field lines into itself, inducing an anisotropy in the $\hat{y}$ direction but not in $\hat{x}$, which remains largely symmetric.

While the FG and the perturbation coil are not perfectly aligned, the misalignment should not be large enough to produce such a significant signal ($\sin(1^\circ) \approx 0.04$). This likely explains the signal present along $\hat{x}$.

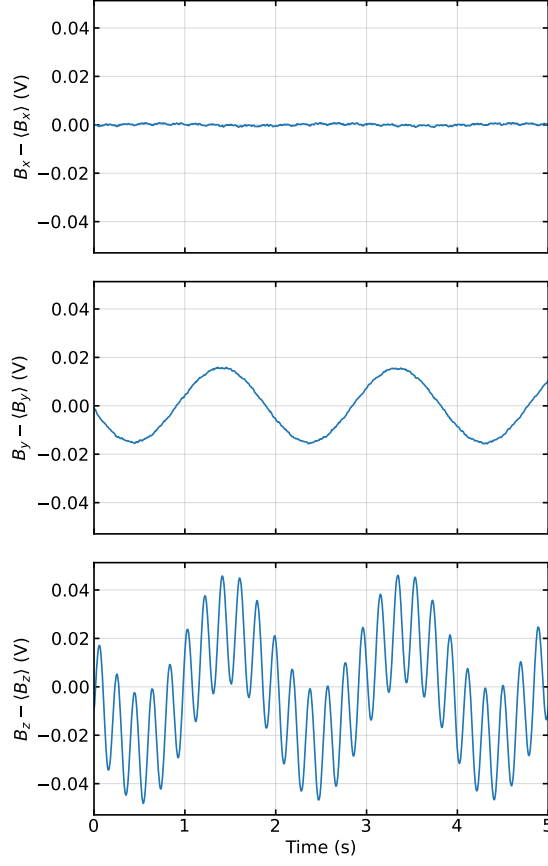


Figure 5.6: Raw measurements from the FG, along all axes for a perturbation frequency of 0.517 947 Hz and a reference frequency of 5.179 47 Hz. We observe a large component of the field in $\hat{y}$ despite a relatively good alignment of the fluxgate and coil. Average values: $\langle B_x \rangle = 3.76 \mu\text{T}$, $\langle B_y \rangle = -10.14 \mu\text{T}$, and $\langle B_z \rangle = -37.06 \mu\text{T}$.

We presume that most of the RF shielding currently provided is due to the copper, as the static SF is attributed to the μ -metal. The performance expectations for the room, as outlined by P. Fierlinger, are summarized in Table 5.2. Qualitatively, the copper layer of the room is meeting expectations, and the μ -metal is performing better than expected. However, this observation is not necessarily significant at this time due to the incomplete state of the MSR.

5.3 The Innermost Layer (Layer 5)

After the completion of the copper layer (Layer 4), the first μ -metal layer, known as the innermost layer (Layer 5), was installed. Both Layers 4 and 5 have been fully completed. All layers have been installed on the door and floor of the room, while the roof has a partially installed Layer 3. The non-door walls of the room currently have only Layers 4 and 5 installed. The setup and equipment used for the measurement are the same as those employed for the SF measurement in copper Layer (Figure 5.7).

We executed a similar data collection script, including a 15 min warm-up period. As before, we applied 50 frequencies evenly spaced on a logarithmic scale from 0.01 Hz to 100 Hz, but sorted into a unique random order for each run. The run duration was frequency-dependent, as described in Section 5.2. Additionally, we conducted reduced point density measurements and extended range measurements, which are summarized in Table 5.3.

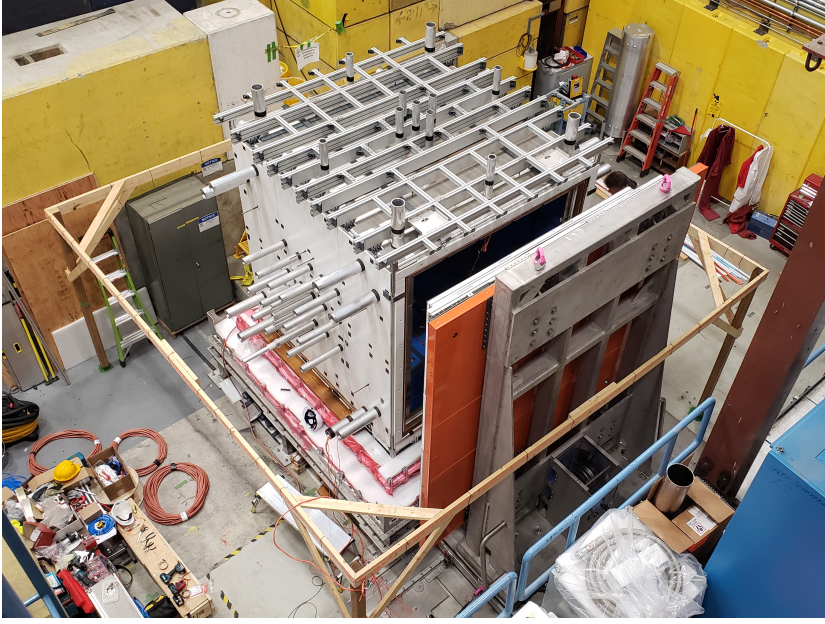
5.3.1 Results and Analysis

We applied the same fitting methodology as described earlier (Section 5.2.1), using the two-sine function:

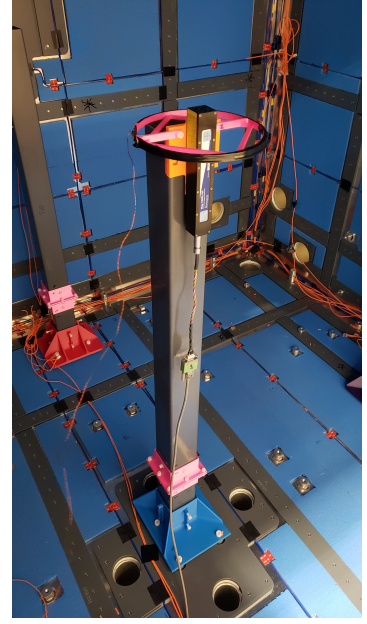
$$f(t; a_{\text{ext}}, a_{\text{ref}}, \phi_{\text{ext}}, \phi_{\text{ref}}, b) = a_{\text{ext}} \sin\left(\frac{2\pi t}{f_{\text{ext}}} + \phi_{\text{ext}}\right) + a_{\text{ref}} \sin\left(\frac{2\pi t}{f_{\text{ref}}} + \phi_{\text{ref}}\right) + b, \quad (5.2)$$

Table 5.2: Expected (by P. Fierlinger) and measured SFs of the MSR given the current state of completion. The MSR is performing as expected.

Frequency (Hz)	Expected Shielding Factor	Measured Shielding Factor
0.01	1	5
0.1	> 2	6
1	> 10	30
10	500	459
100	1000	1123



(a) MSR exterior



(b) MSR interior

Figure 5.7: (*Left*) MSR with door open and enclosed with external perturbation coil. (*Right*) Fluxgate setup inside the room, with reference coil. SF measurements were taken with the door closed, despite the photo.

Table 5.3: Descriptions of the various data collection scripts used. The frequency space was split into two (<1 Hz and ≥ 1 Hz), where the gain on the SCU1, and the amplitude of the reference coil were adjusted such that the signals could be properly measured.

Description	N Points	Range
Normal run mode	50	0.01 Hz to 100 Hz
Extended range	25	10 Hz to 1000 Hz
Reduced point density, low frequency	4	0.01 Hz to 1 Hz
Reduced point density, high frequency	10	1 Hz to 1000 Hz

where f_{ext} and f_{ref} are fixed to the corresponding applied frequencies, and the remaining parameters (a_i, ϕ_i, b for $i \in \{\text{ext, ref}\}$) were allowed to vary within a reasonable range. The resulting fit quality appears largely similar to our prior measurements.

During measurement of the SF with only copper layer, we were unable to confidently track the external coil signal at high frequencies due to the significant increase in the SF with rising frequency. To address this, we now vary the gain on the SCU1 for two different frequency ranges, as summarized in Table 5.4. The reference coil amplitude was also

adjusted to prevent the signal from the reference coil from overshadowing the external field measurement due to varying signal gain. Example fits at the frequency extrema are shown in Figure 5.8.

Table 5.4: Gain and reference coil amplitudes set for the different perturbation coil frequency ranges. This was done to accommodate the large range spanned by the SF.

		<1 Hz	≥ 1 Hz
Techron Gain ≤ 20	SCU1 Gain	100	500
	Reference coil amplitude (V)	0.5	0.025
Techron Gain > 20	SCU1 Gain	100	500
	Reference coil amplitude (V)	0.1	0.01

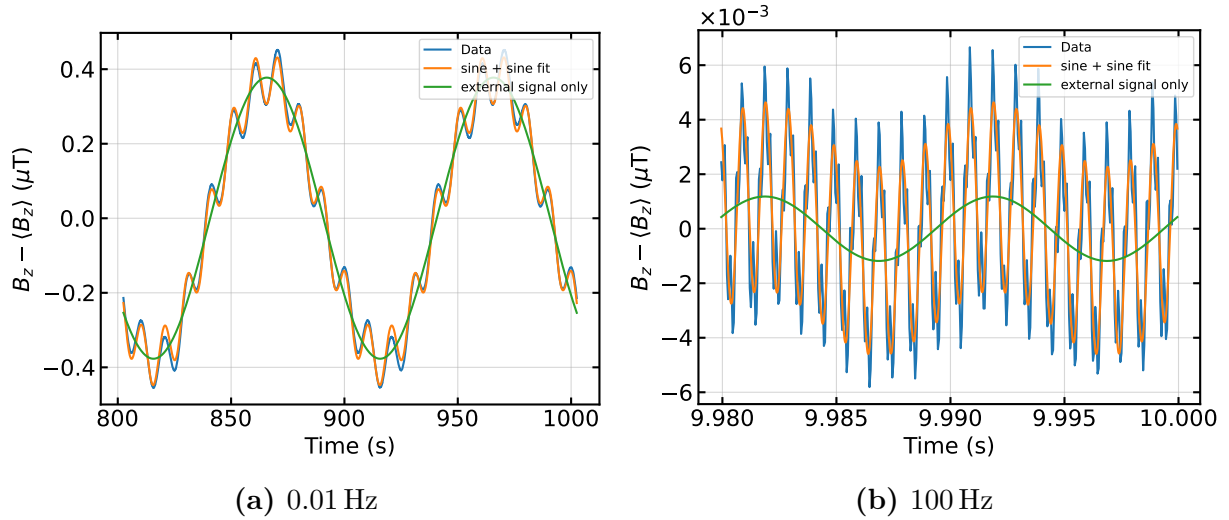


Figure 5.8: Fits of a two-sine wave function to the signal at 0.01 Hz and 100 Hz. Some parts of the 0.01 Hz signal do not fit well to the waveform, though the average fit amplitude appears adequate.

We then examined the effect of the reference coil amplitude. We conducted a set of measurements without the reference coil signal applied and compared them to measurements with the reference coil. In the former, we fit the perturbation coil signal using a single sinusoidal function, while in the latter we used Equation (5.2). Despite setting the Techron gain to 60 for both measurements, possible gain adjustments in between could have resulted in a global offset between the two datasets. As shown in Figure 5.9, there is a substantial

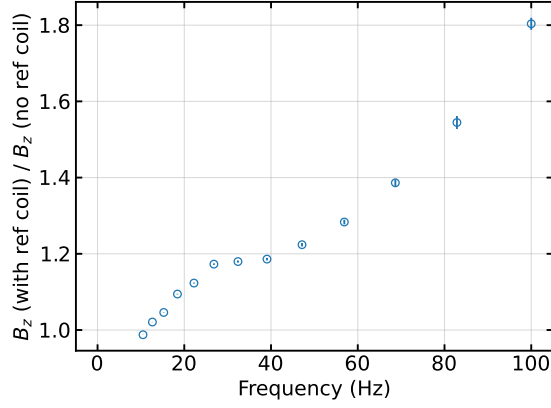


Figure 5.9: Ratio of the external perturbation field amplitude with and without internal reference coil signal applied. Note the significant difference, which varies as a function of frequency.

frequency dependence on the ratio of these two nominally equal signals. At 100 Hz, the measured amplitude with a reference coil is nearly twice as large as the signal without. Despite this, we continue to report SF values uncorrected by this ratio, which should result in the actual SF being larger than reported here. It remains unknown whether this effect is an artifact of the fitting process due to the existence of two signals or is related to the frequency response of the fluxgate or an interaction with the μ -metal of the room.

We now apply Equation (4.1) to determine the shielding factor, as shown in Figure 5.10a. The effect of adding the μ -metal layer to the existing copper layer is shown in Figure 5.10b. Clearly, the SF has increased as a result of the addition of the μ -metal layer. The curve shape is largely the same, with a flat response at low frequency and a plateau forming at high frequency. The increase in SF is not constant and varies non-trivially with frequency. The improvement in SF is shown in Figure 5.11.

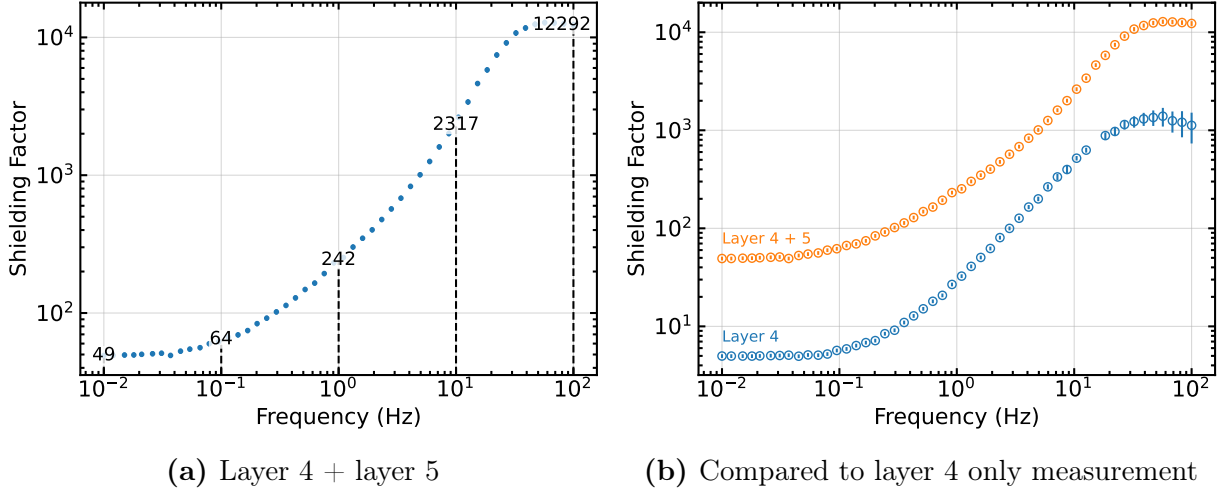


Figure 5.10: Shielding factors at gain 60, cyclotron on. The addition of the μ -metal layer significantly improves the SF.

This figure shows that the μ -metal improves the SF by at most about an order of magnitude, dropping to a minimum of about $5\times$ near 7 Hz. The large error bars near 100 Hz are likely due to errors in the layer 4 SF, which were in turn due to low gain in the SCU1, resulting in an inability to follow the perturbation signal to high SF.

We also investigated the saturation of the MSR from the cyclotron field and the external perturbation coil. To this end, we changed the gain of the Techron amplifier to scan through different amplitudes. If a gain of $60\times$ produces a field amplitude of $\sim 18\mu\text{T}$, then a gain of $40\times$ would produce a field amplitude of $12\mu\text{T}$, and a gain of $20\times$ would result in a field of $6\mu\text{T}$. We repeated the SF measurement at these three gain settings with the cyclotron field both on and off, as shown in Figure 5.12. The SF is clearly affected by

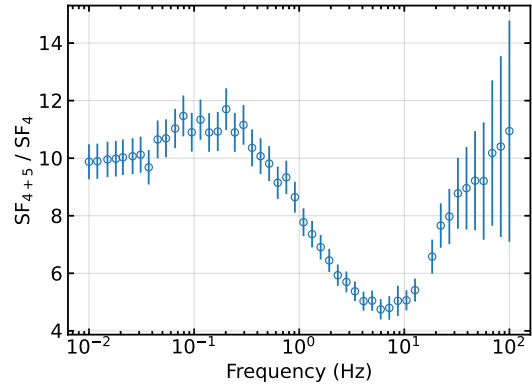


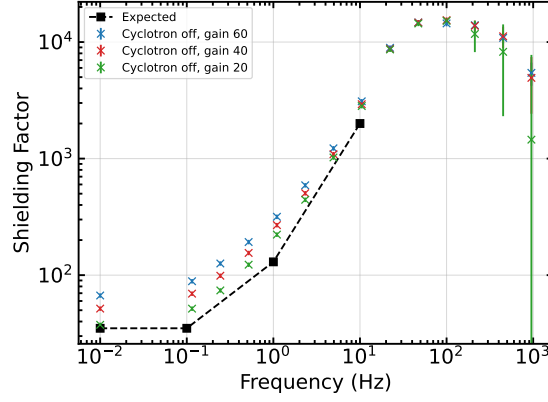
Figure 5.11: Improvement of the SF with the addition of layer 5. Cyclotron on, gain 60. The large error bars near 100 Hz are likely due to errors in the layer 4 SF, which were in turn due to low gain in the SCU1, resulting in an inability to follow the perturbation signal to high SF.

both the perturbation field amplitude and the cyclotron field. In both cyclotron states, a higher gain resulted in a larger SF, whereas the measurements with the cyclotron on resulted in a smaller SF. This result is consistent with our prior measurements and suggests that while the MSR can be improved with the addition of a μ -metal layer, it is still vulnerable to saturation effects.

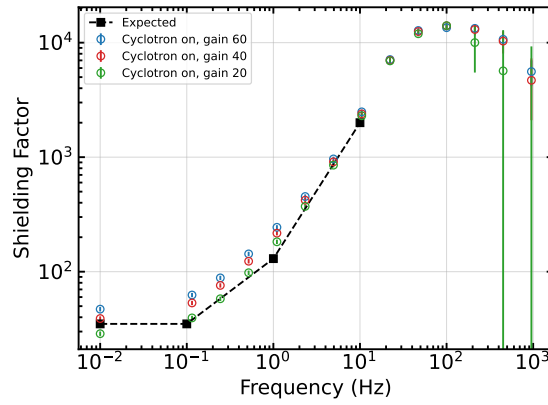
In these measurements, we reduced the point density due to time constraints, however the frequencies which were measured are also found in the no-MSR data set. We also extended our measurement from 100 Hz to 1000 Hz. The no-MSR measurements were also extended by using the current-to-field calibration curve:

$$I = aB + c, \tag{5.3}$$

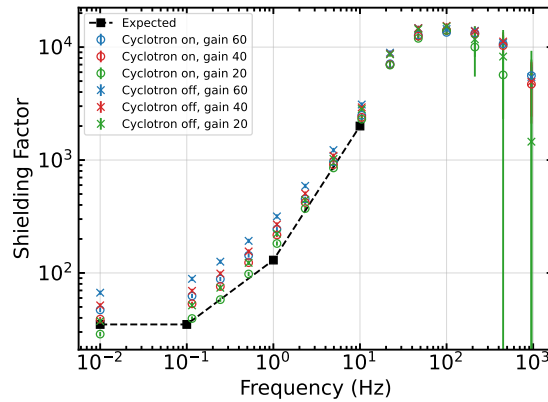
where I is the current in the coil, B is the produced field, and the fit parameters were found to be $a = 1.179(37) \text{ A}/\mu\text{T}$ and $c = 0.60(68) \text{ A}$ (see Figure 4.10). Using this, we can use the measured current from frequencies above 100 Hz to estimate what field would have been produced with no MSR. Since no reference coil measurements exist for these frequencies, we cannot apply this correction factor in Equation (4.1) when calculating the SF. The large error bars in Figure 5.12 reflect the degree to which the linear calibration from Equation (5.3) had to be extrapolated in order to estimate these fields. Thus, these measurements at $>100 \text{ Hz}$ should be considered somewhat unreliable.



(a) Cyclotron Off



(b) Cyclotron On



(c) Figures 5.12a and 5.12b superimposed

Figure 5.12: Shielding factors at various gain settings of the amplifier, for the cyclotron both on and off, in comparison to simulation data from P. Fierlinger. We see that the SF is larger at higher perturbation amplitude, and lower when the cyclotron field is active. SF values for frequencies larger than 100 Hz may be unreliable, due to the need for extrapolated no-MSR field values.

5.3.2 Discussion

The data presented in Figure 5.12, also summarized in Table 5.5, indicates that the MSR is performing as expected according to the SF metric. There are, however, some minor issues that do not significantly affect our conclusions. The additional μ -metal present in the door, floor, and ceiling (layer 3 in the latter) should theoretically increase the SF of the room, making direct comparisons between the simulation and actual measurements challenging. A preliminary simulation conducted by P. Fierlinger estimates a correction factor of 122 % for the simulated values at 10 Hz. This correction factor is likely similar for lower frequencies but may require a new simulation for higher frequencies. These corrected values are shown in Table 5.5. With this correction, the room still meets or exceeds expectations for frequencies below 10 Hz, but falls slightly short at 10 Hz. Given the precision of the simulation, we can reasonably conclude that the room meets expectations.

Table 5.5: Measured and expected (by P. Fierlinger) SF of the MSR given the current state of completion for several frequencies. The expected SF for layers 4 + 5 at 100 Hz was not predicted by simulation, but rather set by P. Fierlinger. The corrected simulation values account for the additional μ -metal (beyond layer 5) in the room. By this metric, the MSR is performing as expected.

Frequency (Hz)	Layer 4	Layers 4 + 5	Expected Layer 4 + 5	Expected Layer 4 + 5 Corrected
0.01	5	49	35	42.7
0.1	6	64	35	42.7
1	30	242	130	158.6
10	459	2317	2000	2440
100	1123	12 292	1000	1220

Regarding findings by P. Fierlinger, the shield’s performance is influenced by a gain factor associated with the distance between the perturbation coil and the shield, shown in Figure 5.13. As the MSR is built outward, it approaches the perturbation coil, but since the MSR is contained within the coil, the applicability of this gain curve is uncertain. For completeness, we present the possibility that it may apply. The maximum shield-to-coil distance would be approximately 1.5 m, given that layer 4 of the MSR has an exterior side length of 2.55 m, and the perturbation coil has a side length of 5.5 m. This results in a SF

gain factor of approximately 1, suggesting our measurements are likely unaffected.

The ratio of field amplitudes shown in Figure 5.9 being frequency-dependent is surprising. One explanation could be that the reference coil signal’s relative size affects the determination of the perturbation coil amplitude, merely as a fitting artifact. At higher frequencies, the SF increases, reducing the amplitude of the exterior field but not the reference coil amplitude. This effect can be simulated to confirm its validity. If true, it suggests that intentional changes to the reference coil amplitude would impact the measured SF (see Table 5.4 for these settings). Unfortunately, no-reference coil data was taken within a single setting of the reference coil measurement, so no discontinuity was observed or expected. Given that the room’s quality is sufficient to continue work and the ratio increases the SF, we can conclude that our measured SFs are lower bounds.

When the cyclotron is turned on, the SF decreases, as seen in Figure 5.12. This is a reasonable response, as the μ -metal becomes more saturated and less effective at absorbing field lines. This underscores the need for ambient magnetic field compensation coils. However, the lower applied amplitude resulting in a lower SF is counter-intuitive. Corrections in Equation (4.1) account for differences in coil current, so the amplitudes of the pre-MSR and post-MSR measurements need not be identical. This result remains puzzling.

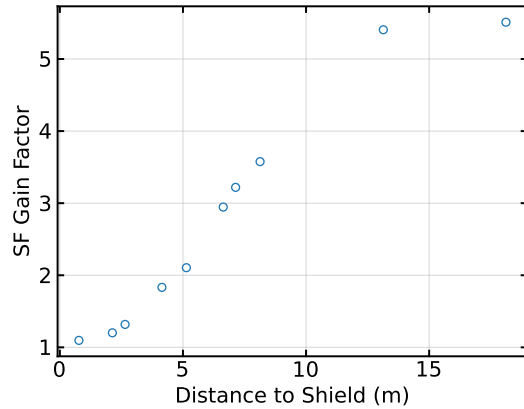


Figure 5.13: Simulated Shielding Factor gain as a result of increasing the distance between the perturbation coil and the MSR.

Extending the frequency range beyond 100 Hz reveals that the SF peaks at this frequency. Despite the uncertainty in the method used to obtain these points, especially in Figure 5.10, there is a plateau near 100 Hz. This phenomenon has been observed before, attributed to defects in the shield from assembly or intentional defects like feedthroughs

for electronics. Efforts to improve electrical contacts between plates in the copper layer of a shield (e.g., through copper soldering or thorough cleaning and including copper tape) removed such peaks, allowing the SF to increase at higher frequencies. Another possibility is the FG’s poor field sensitivity near this frequency, as compared with other FGs. Testing this separately may be difficult due to the need to distinguish the FG’s frequency response from the coil’s frequency-dependent impedance. Another artifact could be the increasing difficulty of measuring the external signal with an increasingly large reference signal masking the external signal, as demonstrated by Figure 5.9.

5.4 Layer 3

Following the installation of layer 3, we began measuring the SF using our established setup (Figure 4.2) and equipment, and we employed the same script for data acquisition. The FG we used in this test, was initially the same as used in previous measurements, but after observing some large offsets in the fluxgate readback, we switched to another Bartington Mag13-MSL100 with different serial number. We will now examine the impact of layer 3 on the room’s behavior.

5.4.1 Results and Analysis

Observed in previous measurements with only layer 5 installed, the shield seemed to require a certain amount of time to equilibrate after each measured frequency. To address this, a delay of 10 s was introduced into the runscript at that time. However, with the addition of layer 3, this effect worsened significantly. We increased the delay between measurements to 30 s, but this still proved insufficient. The relaxation profile is non-linear, appearing exponential at first glance, but transitioning to a quadratic behavior after the initial phase. The analysis script first removes the initial exponential-like period and then adds a quadratic

background term to the usual two-sine function:

$$f(t; a_{\text{ext}}, a_{\text{ref}}, \phi_{\text{ext}}, \phi_{\text{ref}}, b) = a_{\text{ext}} \sin\left(\frac{2\pi t}{f_{\text{ext}}} + \phi_{\text{ext}}\right) + a_{\text{ref}} \sin\left(\frac{2\pi t}{f_{\text{ref}}} + \phi_{\text{ref}}\right) + b + ct + dt^2, \quad (5.4)$$

and fits according to the procedure described in Section 5.2. In Equation (5.4), f_{ext} and f_{ref} are fixed to the corresponding applied frequencies, and the other parameters (a_i , ϕ_i , b , c , d for $i \in \{\text{ext}, \text{ref}\}$) were allowed to vary within a reasonable range. With this background addition, the fitting quality appears largely similar to our prior measurements. An exemplary fit is shown in Figure 5.14. We note that the use of the new fluxgate introduced a clearly-defined 4 kHz component to the signal. To mitigate this issue, all signals were processed through a 6th-order Butterworth bandstop software filter to remove this noise.

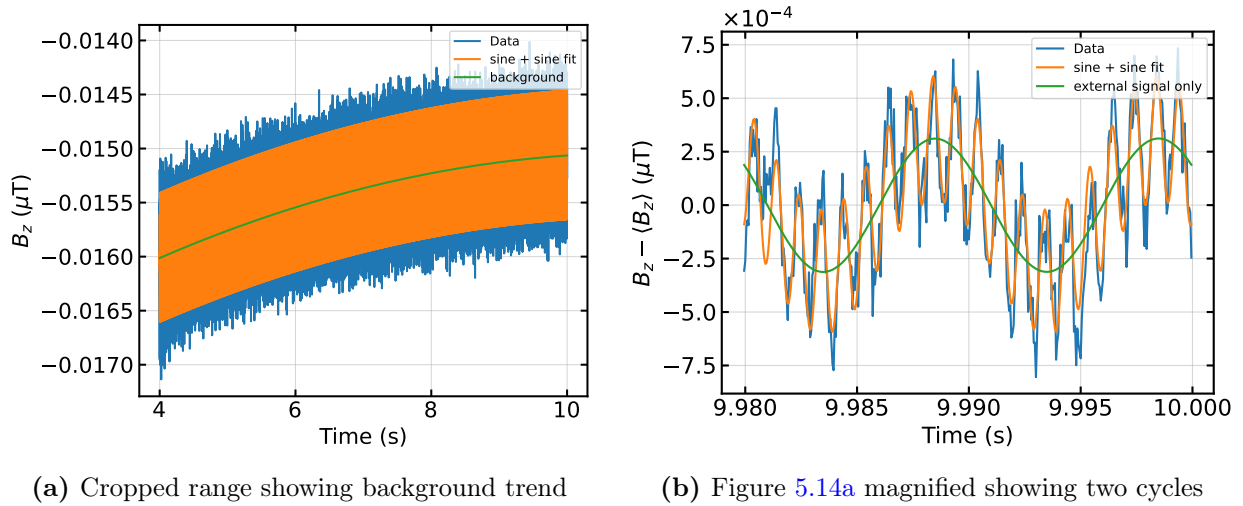


Figure 5.14: Fits of a two-sine wave function with quadratic background to the signal at 100 Hz showing fit quality and background. Data is from cyclotron on, although the effect is present regardless of the cyclotron state.

In our prior work with layer 5 (see Section 5.3.1), we were able to follow the perturbation coil signal to high frequency by adjusting both the SCU1 gain and reference coil amplitude to account for the large range spanned by the SF. We repeated the same procedure for SF measurement with layer 3 installed as summarized in Table 5.6. Unlike the previous set of measurements, the SF was large enough that the lowest frequency resulted in a measured

amplitude within the range of the NIDAQ, if the SCU1 was set to a gain of $1000\times$. Thus, all measurements were taken at a constant gain of $1000\times$.

The SF measured for the inclusion of layer 3 is shown in Figure 5.15, using Equation (4.1). There is a noticeable plateau beginning around 10 Hz. Otherwise, the increase in the SF with frequency is smooth and monotonic. The difference between the two cyclotron-on measurements lies in the modifications made to the door connection. In the second measurement, some brackets that supported the floor of layer 2 were removed. This adjustment was intended to improve the contact between layers 3 and 5 and ensure that the door could close more completely. The implications of this adjustment will be discussed in more detail later (Section 5.4.3).

Table 5.6: Reference coil amplitudes set for the different perturbation coil frequency ranges. This was done to accommodate the large range spanned by the SF.

Frequency Range (Hz)	Reference Coil Amplitude (V)
≤ 0.1	0.03
(0.1, 2]	0.01
(2, 10]	0.005
(10, 100]	0.002

In our earlier work, as detailed in Section 5.3.1, we observed a change in amplitude when comparing measurements with and without the reference coil. In the current analysis, we calculate the SF without applying any reference coil corrections—neither for current nor for field. This calculation is performed on two sets of data: one where the reference coil field was applied, and another where it was not. The results of this comparison are illustrated in Figure 5.16a. Unlike previous data, the reference coil correction here has a minimal effect, causing only a slight decrease in the SF by 2.8(3)%. This result differs from the prior measurement. Specifically, when plotting the equivalent of Figure 5.16b, the ratio of the perturbation coil amplitudes is approximately unity, with a slight drift to a lower ratio observed at higher frequencies.

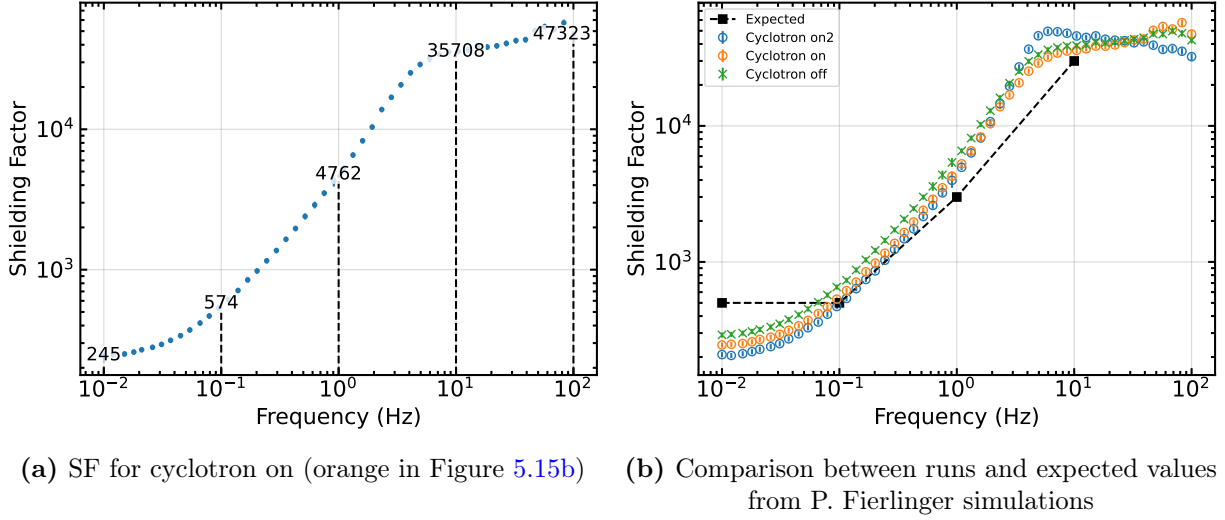


Figure 5.15: Shielding factors at gain 60, cyclotron on, layers 3, 4, and 5 installed. The cyclotron reduces the SF, but the SF also dropped significantly between the two cyclotron on runs. Between these, a panel of layer 2 was removed to move the door closer to being fully closed.

5.4.2 Discussion

Figure 5.17 illustrates the performance enhancement due to the addition of layer 3. While there is a noticeable improvement across all frequencies, the magnitude of this enhancement is insufficient at both low and high frequencies, showing only a five-fold increase in the SF. According to Figure 5.15b and Table 5.7, the expected SF in the low-frequency range is 500, but our measurements show SFs between 200 and 300. Despite our efforts, we have not been able to achieve a higher SF nor identify the clear source of the problem. We tentatively attribute the lack of performance to the following factors:

- Poor mating of the door with the room
- Additional μ -metal associated with layers 1 and 2 in the floor and door of the room

These efforts are detailed further in next section (Section 5.4.3).

Based on the results shown in Figure 5.15b, the measurements taken with layer 5 revealed that the presence of the cyclotron field leads to saturation of the μ -metal, which in turn decreases the SF. Initially, when the cyclotron was turned on, it was noted that the door's

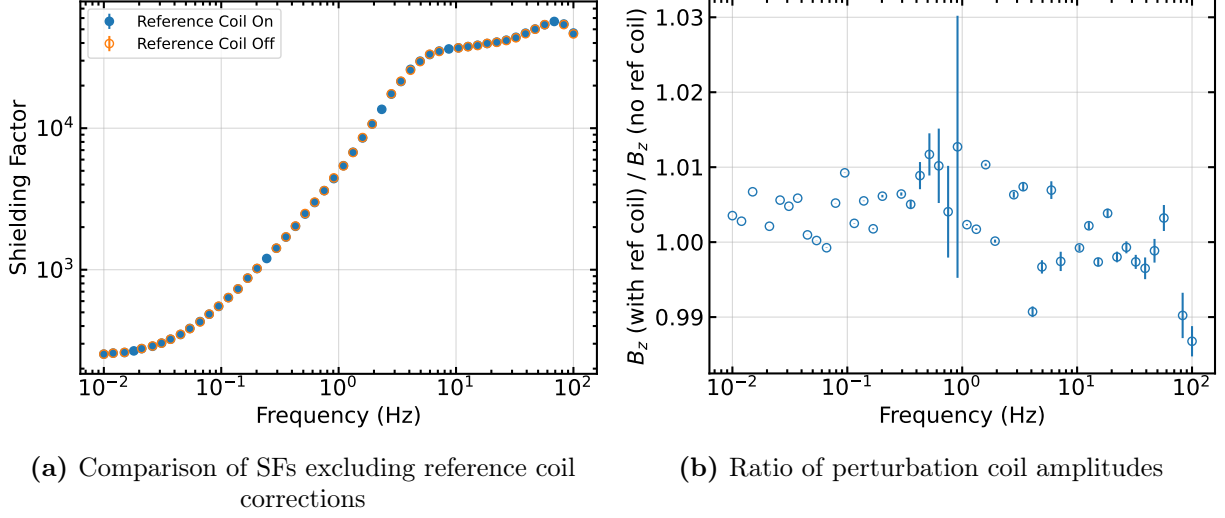


Figure 5.16: A comparison of signals when the reference coil was on and off.

Table 5.7: Measured and expected (by P. Fierlinger) SFs of the MSR given the current state of completion, for several frequencies. By this metric, the MSR is largely performing as expected, with a significant underperformance at frequencies below 0.1 Hz.

Cyclotron Status	Frequency (Hz)	Measured SF			Expected SF
		Off	On	On (2)	
	0.01	291	245	208	500
	0.1	694	574	505	500
	1	5973	4762	4467	3000
	10	38 785	35 708	46 885	30 000
	100	42 677	47 323	32 268	20 000

layer 5 did not fully align with the room's layer 5, leaving a gap of approximately 5 mm. This gap was significant enough to prevent the distributed degaussing cables in layer 5 from forming complete circuits. To address this, the layer 2 μ -metal edge cap on the door was removed, which improved the closure. The resulting data, referred to as "cyclotron on2" in Figure 5.15b, showed a reduction in SF at low frequencies but an improvement around 5 Hz.

The observed changes can be explained by:

- *Improved RF shielding:* The reduced gap in layer 5 enhanced the RF shielding.
- *Reduced low-frequency shielding:* The removal of the layer 2 μ -metal edge cap decreased shielding efficiency at low frequencies.

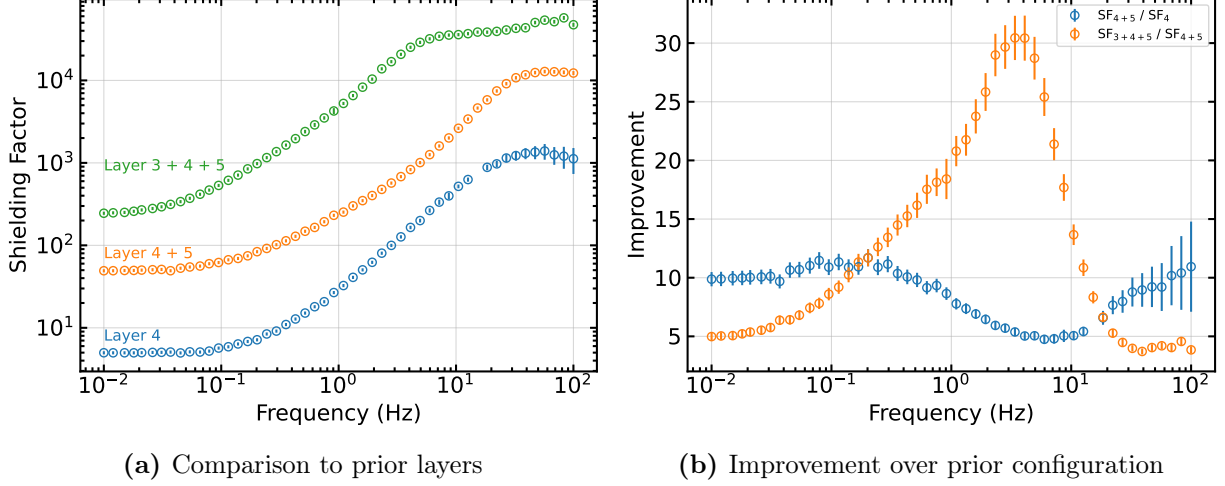


Figure 5.17: Comparison to prior room configurations shows the benefit of layer 3. The improvement over layer 4 + 5 is about a five-fold increase at low frequency, half of the effect due to adding layer 5. The improvement at large frequency is slightly less. The plateau has shifted to about 10 Hz, approximately 40 Hz lower than previous configurations.

If these hypotheses are correct, adding extra μ -metal should theoretically increase the SF. However, factors such as the room-to-coil distance and coil geometry might also influence the SF.

Previous measurements included additional μ -metal, which decreases as more layers are added. This might lead to a more symmetric room setup and alter the SF. Additionally, a $\hat{y}$ component of the perturbation field was detected, likely due to North/South asymmetry in the μ -metal, which affects B_z but does not significantly change the total field magnitude.

During the measurements of layer 5, the absence of a reference coil signal resulted in a smaller measured amplitude. This was attributed to a fitting artifact where a large reference coil amplitude obscured the external oscillating field. For layer 3, the reference coil had minimal impact on the measured amplitude or SF, likely due to improved coil amplitude selection and the addition of a quadratic background to the fitting function.

We also observed an increase in the relaxation time required between measurements for the fluxgate offset to stabilize. This stabilization is crucial for ensuring that the fluxgate signal is within the NIDAQ's range. The relaxation time increased with the addition of

layer 5, from zero seconds to 10 s, and further to 30 s with layer 3. This trend suggests a non-linear increase in SF, as indicated in Figure 5.17a: the SF for a given frequency, such as 3 Hz, increases from about 100 with layer 4, to 600 with layers 4 and 5, and approximately 20,000 with layers 3, 4, and 5. This indicates that the room is much more effective at shielding signals over this timescale than previously.

We propose that this effect is not due to a change in the room’s ability to absorb flux but rather to a characteristic timescale governing how quickly flux is transmitted through the walls. If the flux transit time is long, a fast oscillatory signal will be averaged out, resulting in more effective shielding. Conversely, a slowly varying signal will still be transmitted close to the static SF. Therefore, the observed relaxation between measurements likely reflects the room’s delayed response to an oscillating field applied approximately 30 seconds earlier.

This characteristic time might have a simple relationship with the ideal frequency-dependent SF shown in various figures of this section. The observed plateau in the SF curve, according to P. Fierlinger, could be due to imperfections in the electrical connections in the copper layer. A physical mechanism for this characteristic time could involve the time needed for magnetic domains to escape their local potential wells and reorient to the applied field, potentially through thermal excitation. Higher temperatures would result in faster relaxation rates, thereby lowering the SF at high frequencies. Analytically, a model accounting for this characteristic time could predict the quasi-static to low-frequency SF. At frequencies much higher than approximately 10 Hz, other mechanisms such as eddy currents may dominate, altering the nature of the shielding effect. The slowing of field compensation by the μ -metal might also affect the characteristic relaxation time as additional layers are added, potentially explaining why frequency-dependence does not improve uniformly with each added layer.

5.4.3 Low SF: A Summary of Debugging Attempts

Following the initial SF measurement with the cyclotron on, as depicted in Figure [5.15a](#), we identified and addressed several issues affecting the setup. The primary concern was the door cap, which impeded the door from closing completely. To resolve this, we removed the layer 2 edge caps at the bottom of the room, which were obstructing proper closure. Additionally, we placed cardboard shims under the door's layer 5, reducing the gap to approximately 1 mm to 3 mm. Despite not achieving perfect contact, this adjustment was expected to bring us closer to the optimal configuration observed in earlier layer 5 tests. We also inflated the bladder for layer 3 and wrapped the ends of the grounding cables in electrical tape to prevent unintended contact with the frame. Subsequent observations indicated that layer 2 no longer interfered with the door closure, and the layer 4 (copper) contacts were audibly engaged, suggesting improved door closure (Figures [5.19](#) to [5.21](#)). To verify the contact between layer 3 and the door, modelling putty spheres were used, showing a consistent thickness of 1 mm to 3 mm after compression, indicating good contact when the bladder was inflated (see Figure [5.18](#)). The cardboard shims were inserted deeply, approximating the bladder's position. Most of the distributed coils in layer 5 were now connected, though at least one remained disconnected. Electrical isolation between layers was confirmed using a multimeter, ensuring no electrical contact between them.



(a) Before door close



(b) After door close

Figure 5.18: Modelling clay spheres used to check the contact between the layer 3 door and room after removing the layer 2 edge bracket. The thickness of the squished clay was 1 mm to 3 mm, indicating that the layer 3 door likely makes good contact once the bladder is inflated. Corresponding marks on the door side confirm this contact.



Figure 5.19: Layer 5 distributed degaussing connection not connecting when the door is closed.



Figure 5.20: Layer 5 gap inside the room once the door is closed. The gap is about ~ 5 mm.

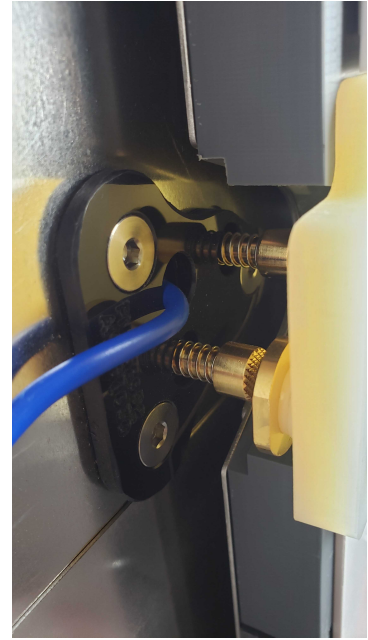


Figure 5.21: Lots of clearance around the black plastic mounting bracket.

Following these changes, we re-ran the degaussing process. Studying the hysteresis loops showed that the performance in layer 5 improved in two orientations, indicating a better door connection. However, the quasi-static SF did not improve and actually worsened after

re-running the measurement referred to as "cyclotron on2" in Figure 5.15b. Although the SF near 5 Hz showed improvement due to the reduced gap, performance at frequencies approaching 100 Hz declined.

To further diagnose the issue, we tested a series of changes while monitoring the 0.01 Hz SF. These changes included uncoiling the signal cable, shifting the input signal phase, adding additional cardboard, switching the FG readback mode, allowing time for adjustments, opening and closing the door, inflating and deflating the layer 3 bladder, and re-degaussing the room. Figure 5.22 presents the 0.01 Hz SF results for these modifications. Only re-degaussing the room produced a minor but persistent increase in the SF, though this increase was statistically insignificant. The residual field was approximately 10 nT or less, suggesting that the static SF should be around 1×10^5 given the cyclotron

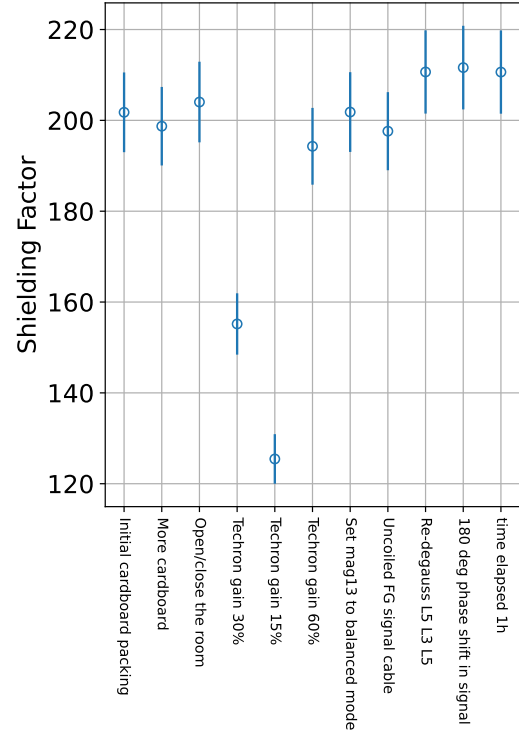
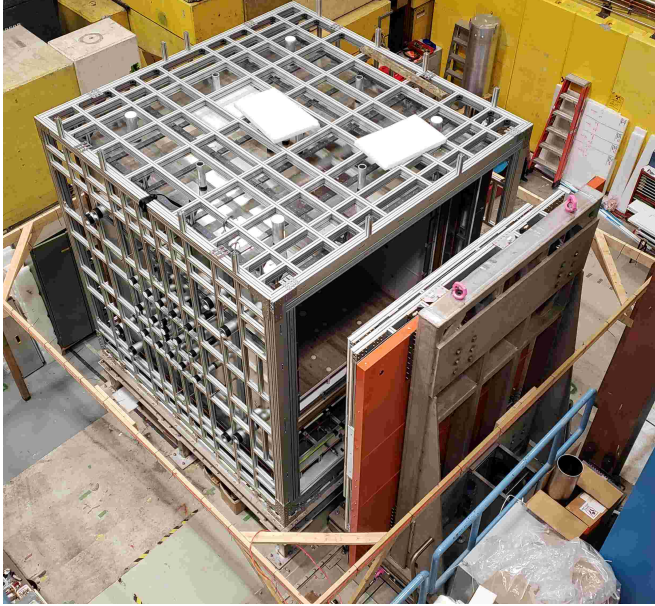


Figure 5.22: The SF measured at 0.01 Hz for various attempted fixes to the room performance.

field of $\sim 100 \mu\text{T}$. We attempted a purely static SF measurement by zeroing the fluxgate and applying a DC field with the perturbation coil. Using the coil constant ($0.85 \mu\text{T/A}$) measured with copper layer, we estimated the field with no MSR to assess the external field. The results were slightly higher than the 0.01 Hz SF measurements but comparable to pre-modification values.

5.5 Layer 2

With the installation of layers 5, 4, 3, and 2 now complete, we proceeded to measure the SF using our established setup (Figure 4.2) with the same equipment and the same data acquisition script. In this section, we will assess how these layers have influenced the room's performance. Figure 5.23 shows the setup for this measurement.



(a) MSR exterior



(b) Fluxgate setup inside

Figure 5.23: (*Left*) MSR with door open and enclosed with external perturbation coil. (*Right*) Fluxgate setup inside the room, with reference coil. SF measurements were taken with the door closed, despite the photo.

5.5.1 Results and Analysis

In our previous measurement before installing layer 2, we extended the delay between measurements from 10s to 30s to allow the room to relax adequately between measurements. Initially, the relaxation profile appeared exponential, but upon closer examination, it was found to follow a quadratic trend after an initial exponential-like phase. With the addition of layer 2, the relaxation period did not increase significantly, and a 30s delay proved sufficient.

As in previous analyses, we cropped out the initial exponential-like phase and fitted the remaining data using a quadratic background term along with a two-sine function, similar to Equation (5.4):

$$f(t; a_{\text{ext}}, a_{\text{ref}}, \phi_{\text{ext}}, \phi_{\text{ref}}, b) = a_{\text{ext}} \sin\left(\frac{2\pi t}{f_{\text{ext}}} + \phi_{\text{ext}}\right) + a_{\text{ref}} \sin\left(\frac{2\pi t}{f_{\text{ref}}} + \phi_{\text{ref}}\right) + b + ct + dt^2, \quad (5.5)$$

Unlike previous analyses, f_{ext} and f_{ref} were rounded to five decimal places rather than using full precision. This adjustment, likely due to the limitations of the function generator, led to improved fitting results. An example of this fit is shown in Figure 5.24.

We also observed high-frequency noise and additional noise up to 60 Hz, likely due to the fluxgate signal cable running parallel to the Techron amplifier power cable. After completing the measurements, repositioning these cables significantly reduced the noise. To mitigate high-frequency interference, all signals were processed through a 6th-order Butterworth 2 kHz low-pass filter, chosen because it is twice the frequency of the highest applied signal (the reference coil operates up to 1 kHz).

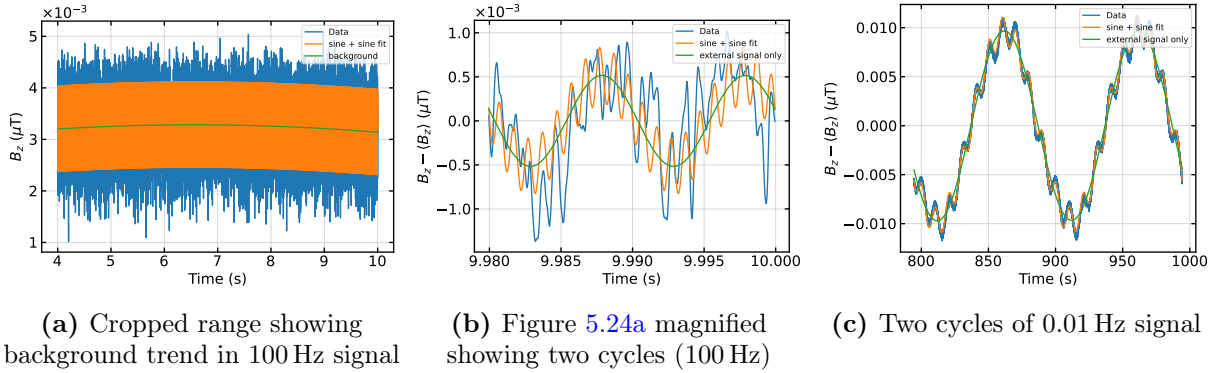


Figure 5.24: Fits of a two-sine wave function with quadratic background to the signal at 100 Hz and 0.01 Hz showing fit quality and background. Data is from cyclotron off, although the effect is present regardless of the cyclotron state. At 100 Hz the reference coil signal is too small to see.

As with the previous set of measurements with layer 3, the shielding factor was sufficiently large that the lowest frequency yielded a measured amplitude within the range of the

NIDAQ when the SCU1 gain was set to $1000\times$. Therefore, all measurements were conducted with a constant gain of $1000\times$.

The SF calculated for the addition of layer 2, using Equation (4.1), is presented in Figure 5.25. Consistent with prior measurements, the SF was slightly lower with the cyclotron field enabled. Additionally, the SF shows an unusual decrease with frequency beyond 2 Hz, differing from previous observations (see Figure 5.27a).

Towards the end of the measurements, while troubleshooting other issues, the NIDAQ unit responsible for all I/O operations began malfunctioning and eventually failed. The specific issues were:

- Distortion in the sinusoidal output waveform, with subsequent cycles starting midway through the current cycle.
- Analog input channels defaulting to approximately -10.5 V regardless of input, even when tested with a known functioning function generator.

This malfunction is unlikely to have caused the observed change in SF, as frequencies were measured in a random sequence. Had the NIDAQ issues impacted the SF, we would expect to see significant random scatter in the SF measurements as a function of frequency, with some discernible trend if plotted chronologically. Any erroneous increase in voltage output by the NIDAQ would be detected by the current meter, and any gain factor affecting the analog input channels would also be corrected by the current and reference coil measurements. If the failing NIDAQ were responsible for the signal changes, it would need to be frequency-dependent and specifically affect only the analog input measuring the fluxgate signal.

As illustrated in Figure 5.25a, there is a noticeable drop in the SF starting around 2 Hz. While one might attribute this to the fluxgate reaching its noise floor, Figure 5.24b shows that even at 100 Hz, the external coil field remains clearly detectable and is well-fitted by Equation (5.5), despite the small amplitude of approximately 0.5 nT . The observed trend of decreasing amplitude with increasing frequency is inconsistent with the expected behavior of a noise floor, which should not exhibit a slope. This decreasing trend is less pronounced

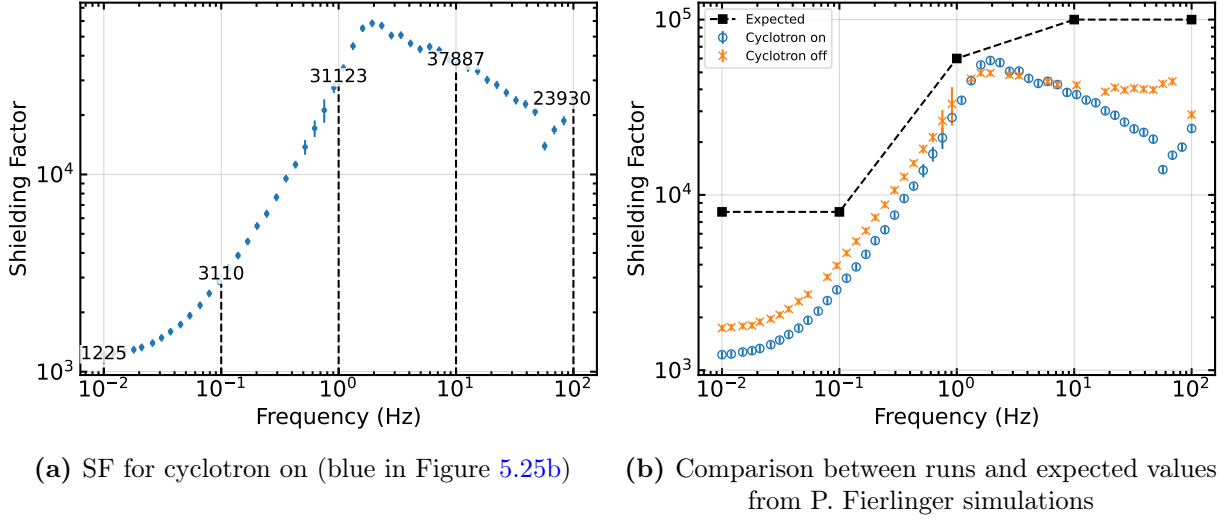


Figure 5.25: Shielding factors at a Techron gain of $60\times$, cyclotron field on, layers 2, 3, 4, and 5 installed. The cyclotron reduces the SF, although the SF is well below expectations at all frequencies.

when the cyclotron field is turned off (Figure 5.25b), suggesting that the effect may be related to the saturation of the μ -metal.

The SF in this frequency range is more dependent on eddy currents in the μ -metal rather than magnetic domains, indicating that the door's connectivity is crucial for effective shielding at higher frequencies.

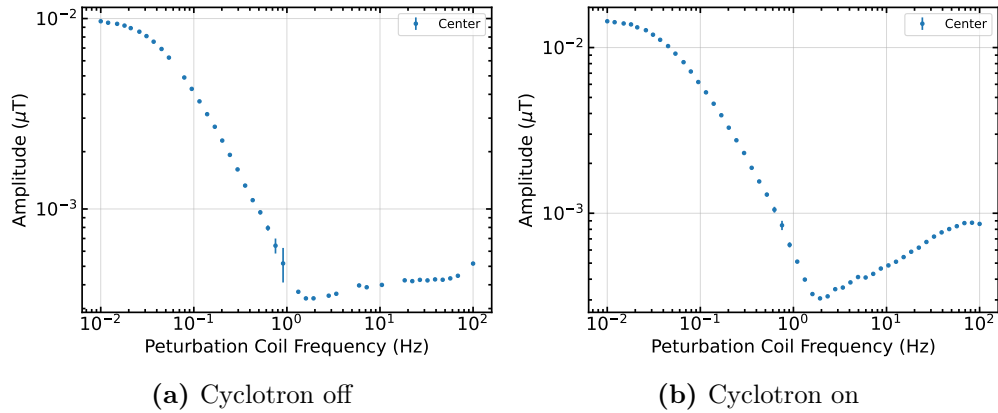


Figure 5.26: Fitted amplitudes for the field generated by the external coil, with adjustments only for SCU1 gain and unit conversion from voltage to field. The close alignment with the slopes of the shielding factor (SF) shown in Figure 5.25 suggests that this behavior is not attributable to the reference coil field or current.

The change in slope is evident in the measured amplitudes of the fields (Figure 5.26), suggesting that the effect primarily arises from the external coil field measurement. The absence of corresponding abrupt changes in the reference coil amplitude, as detailed in Table 5.4, further supports this conclusion, though a single amplitude change to 5 mV at 2 Hz is noted.

Figure 5.27 shows the increase in performance as a result of the addition of layer 2. While performance has clearly improved across the board, as it must, the magnitude of the improvement was lacking at both low and high frequency. Effectively, a mere factor five increase in the SF was present at all frequencies ≤ 2 Hz, with the SF actually getting worse than without layer 2 at frequencies greater than 10 Hz. While a factor of five increase was recorded during the introduction of layer 3 at 0.01 Hz, the improvement was much larger at most other frequencies. It seems odd that the improvement at ≤ 2 Hz is effectively a constant factor, and so small. As with our prior attempts, we have still been unable to measure a SF any larger than that reported here, nor have we found clear evidence for the source of the problem. As is clear from Table 5.8 and fig. 5.25b, the SF is well below expectations given the current state of the room.

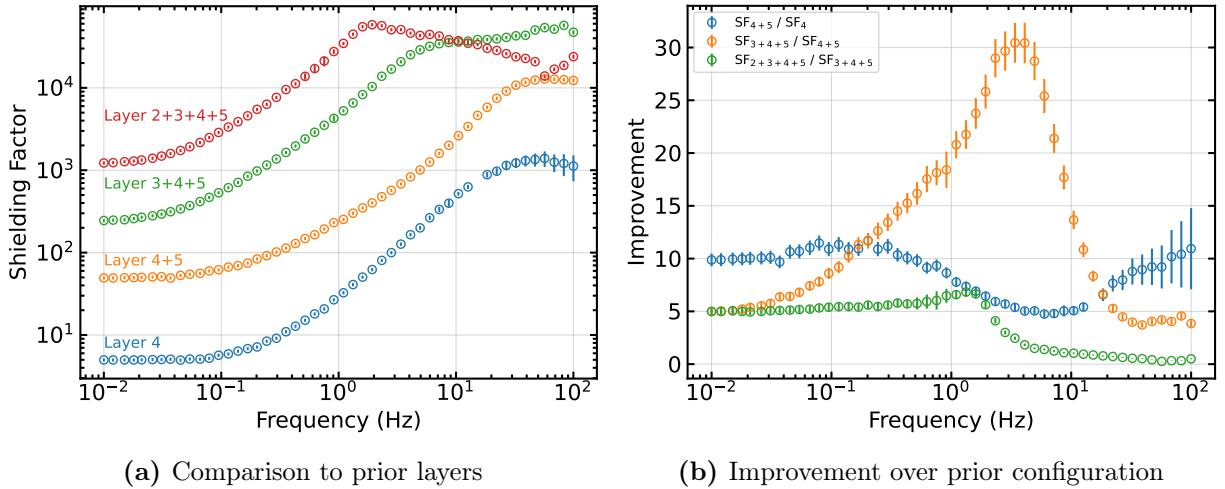


Figure 5.27: Comparison to prior room configurations shows the effect of layer 2. The improvement over layer 3 + 4 + 5 is about a factor five improvement at all frequencies lower than 2 Hz. The improvement at larger frequencies decreases until the SF starts to degrade to be lower than without layer 2.

As a sanity check, we can use the $18\mu\text{T}$ amplitude at 0.01 Hz measured without the MSR and visually estimate the amplitude from the signal in Figure 5.24c to be $0.01\mu\text{T}$. We can then roughly calculate the SF to be $\text{SF} = \frac{18}{0.01} = 1800$, which is much more consistent with our measured values than the estimated 8000 from Table 5.8.

It is noteworthy that the current measured in the external coil remains comparable to the value observed without the MSR, as illustrated in Figure 5.28. Despite the MSR serving as a large core for the coil, which would typically increase the coil's inductance and thus reduce the current for a given driving voltage (subject to minor variations in amplifier gain), no significant decrease in current was observed. This observation is consistent with the measurements taken when only layers 4 and 5 were installed, suggesting that the presence of the MSR does not markedly impact the current.

Table 5.8: Measured and expected (by P.Fierlinger) SFs of the MSR at various frequencies show that the current setup significantly underperforms across all tested frequencies.

Cyclotron Status	Frequency (Hz)	Measured SF		Expected SF
		Off	On	
	0.01	1740	1225	8000
	0.1	4307	3110	8000
	1	39 510	31 123	60 000
	10	42 462	37 887	100 000
	100	28 701	23 930	100 000

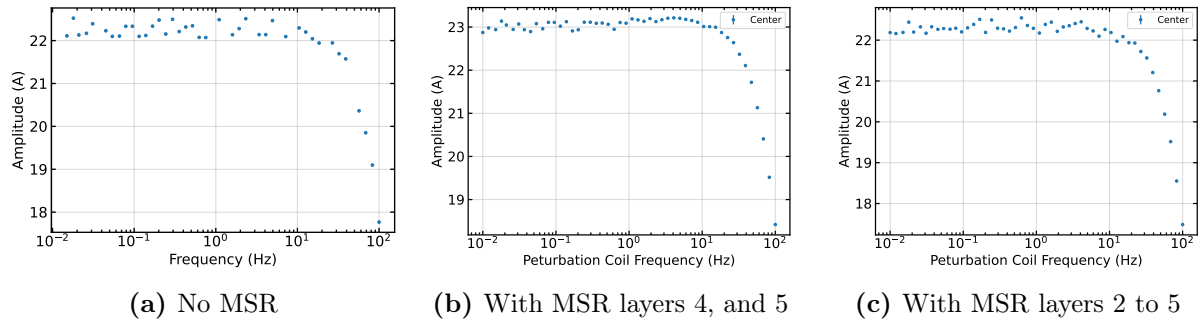
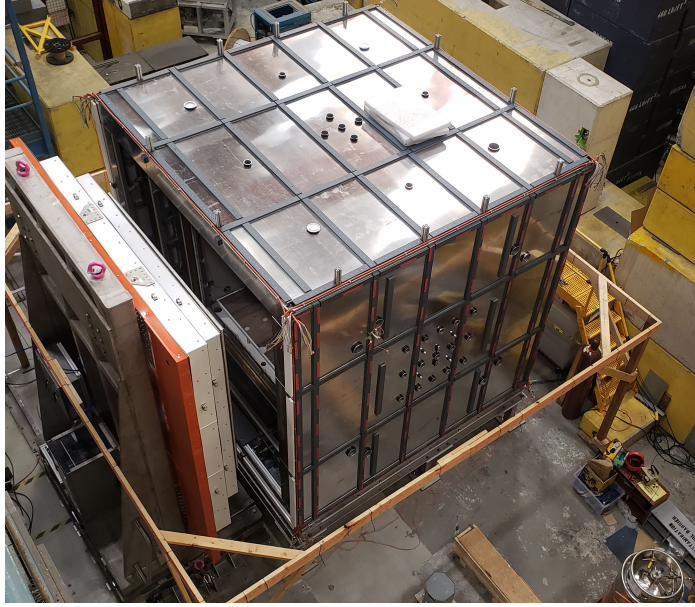


Figure 5.28: The measured current with and without the MSR is nearly identical, despite the MSR being expected to raise inductance and reduce current. The slight baseline shift is likely due to variations in amplifier gain set by an analog dial.

5.6 The Outermost Layer (Layer 1)

Following the full installation of layers 5, 4, 3, 2, and 1 now complete, we conducted SF measurements using our previously established setup (Figure 4.2), maintaining the same equipment and data acquisition script. In this section, we will evaluate the impact of these layers on the room's performance.



(a) MSR exterior



(b) Fluxgate setup inside

Figure 5.29: *(Left)* MSR with the door open, enclosed by the external perturbation coil. *(Right)* Fluxgate setup inside the room, including the reference coil. Note that SF measurements were taken with the door closed, contrary to what the photo indicates.

5.6.1 Results and Analysis

Consistent with previous analyses, we initially exclude the initial exponential-like period and then incorporate a quadratic background term into the standard two-sine function (Equation (5.5)).

As with the previous set of measurements, the SF was sufficiently large that the lowest frequency resulted in an amplitude within the range of the NIDAQ when the SCU1 was set

to a gain of $1000\times$. Consequently, all measurements were performed with a constant gain of $1000\times$.

We performed several measurements to assess the SF. First, we measured the SF with the cyclotron on using an oscilloscope while the NIDAQ was out for repair. Using the middle position post at the center of the room, we applied an external field of $18\mu\text{T}$ at various frequencies with a function generator. The resulting field inside the room was measured with a Bartington Mag13-MS100 fluxgate. The SF for layer 1 was calculated using Equation (4.1) and is illustrated in Figure 5.30a. We observed that the SF decreases with increasing frequency beyond approximately 1 Hz.

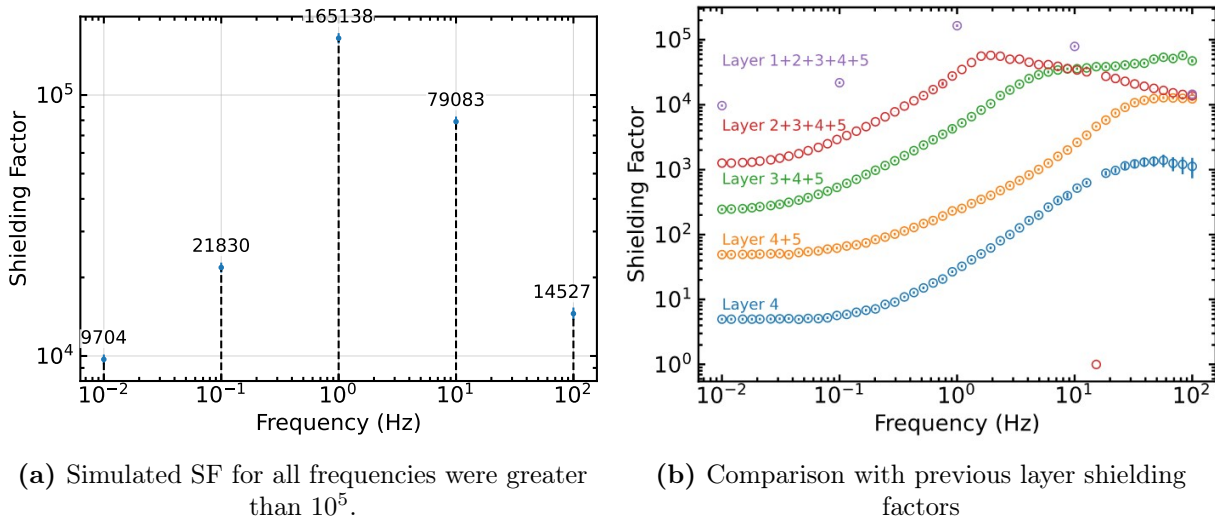


Figure 5.30: Determined SF with the cyclotron on, external field of $18\mu\text{T}$, and measurements taken with the oscilloscope and frequency generator. Simulated SF for all frequencies were greater than 10^5 .

When compared to the SFs of previous layers (Figure 5.30b), the improvement with layer 1 appears modest—slightly better than the additions of layers 2 or 3, but still not sufficient.

We subsequently repeated the frequency dependence measurements using the NIDAQ, applying the standard code and methodology, like before. The fitting was conducted using Equation (5.5), and the SF was calculated with Equation (4.1), as illustrated in Figure 5.31.

Despite no apparent changes to the MSR or measurement conditions, the SF shows

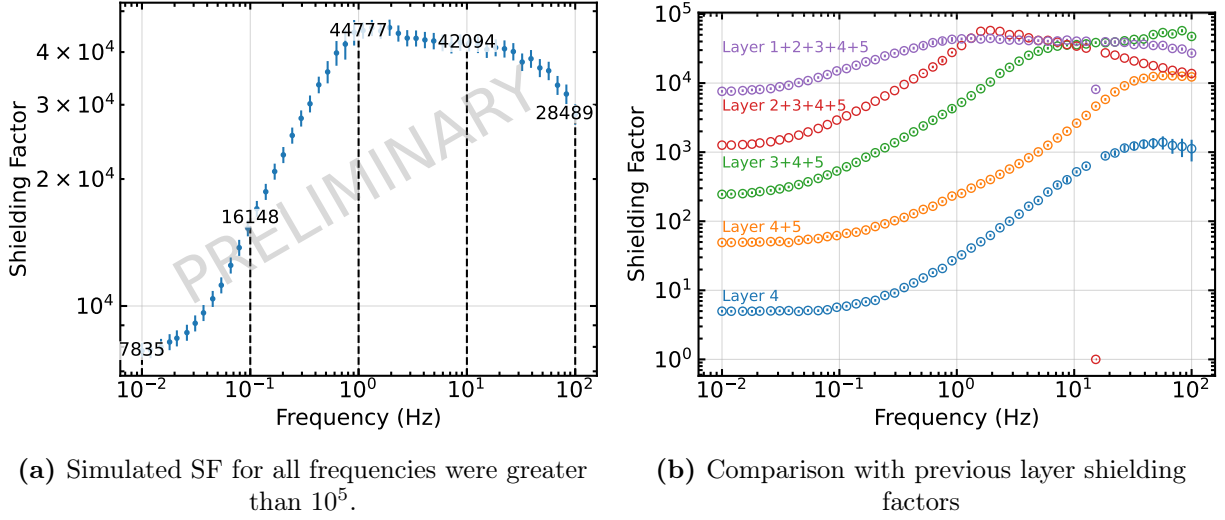


Figure 5.31: SF with the cyclotron on, external field of $18 \mu\text{T}$, and measurements taken with the NIDAQ. Simulated SF for all frequencies were greater than 10^5 .

notable differences, being significantly lower at certain frequencies, especially around 1 Hz, and considerably higher at others (e.g., 100 Hz). The extent of change in the MSR over the two months raises concerns.

The improvement factor for the addition of layer 1 is depicted in Figure 5.32. While the shielding benefit at low frequencies (0.01 Hz) remains consistent across all layers outside the copper layer, there is considerable variation at higher frequencies. Modifications to the door may have affected the SF at intermediate frequencies, as eddy currents likely become the dominant source of magnetic shielding in this frequency range.

We also investigated how the SF depends on the amplitude of the external perturbation coil. This was conducted at 0.01 Hz using a sinusoidal perturbation and the Bartington Mag13-MS100 fluxgate positioned at the center of the room. This measurement is crucial for comparing our results with those from other facilities, such as PSI or LANL, which used external fields in the range of $1 \mu\text{T}$ to $2 \mu\text{T}$. The results show a significant decrease in the SF as the external amplitude is reduced, indicating that our room's performance may be worse than initially estimated.

After a few months with the cyclotron main magnet off, we repeated the SF measurement.

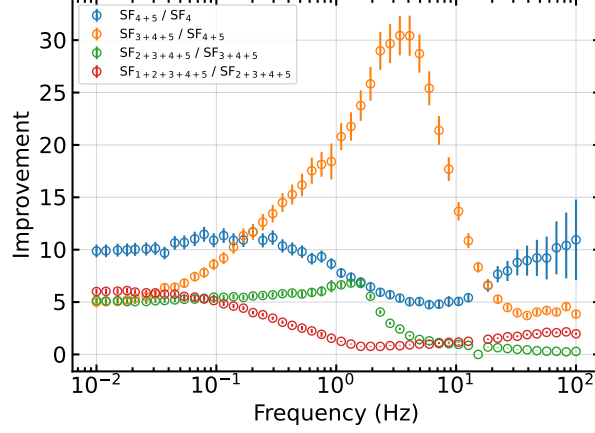


Figure 5.32: SF improvement factor for the addition of layer 1. Cyclotron on, external field of $18 \mu\text{T}$, and measurements taken with the NIDAQ.

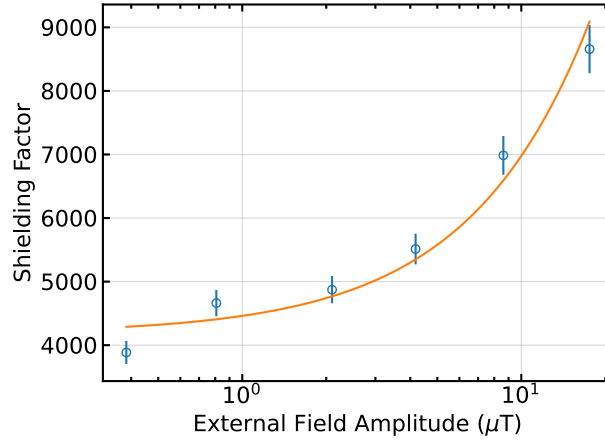


Figure 5.33: The SF at 0.01 Hz exhibits a significant and nearly linear increase with the amplitude of the external field (line represents a linear fit). The relationship is described by $S = [240(1) \mu\text{T}]B + [4627(15)]$.

The setup has changed slightly due to new equipment installed in the MSR, as depicted in Figure 5.34. Notably, we did not use the reference coil for this measurement. The procedure otherwise remained largely the same, with the addition of a 1 kHz low-pass filter applied to the SCU1 to eliminate 4 kHz noise from the sensor.

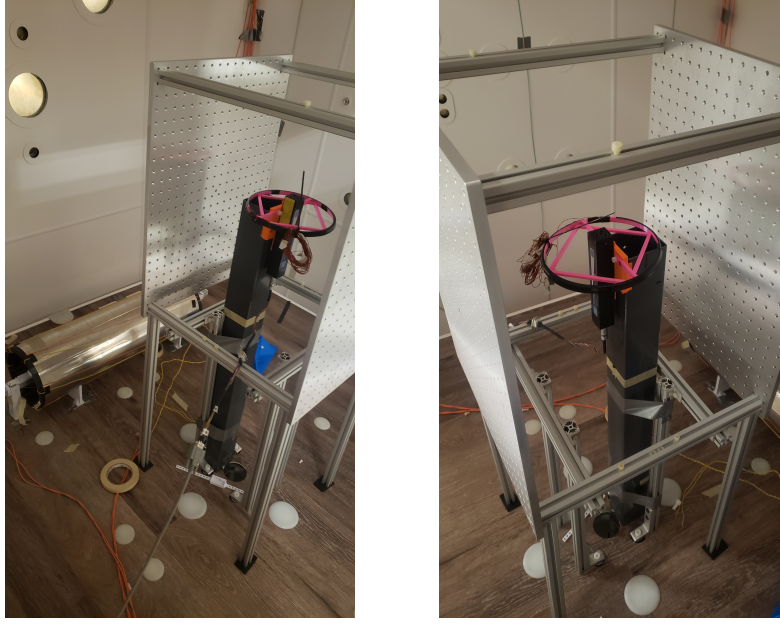


Figure 5.34: Updated setup inside the MSR. The fluxgate’s height remains unchanged, and its horizontal position is nearly identical. The square plastic post is duct-taped to the aluminum frame supporting the Cs magnetometer breadboards. A μ -metal shield from the gradiometer is present behind the setup.

We observed that the SF has improved by approximately a factor of two at low frequencies. The main results are illustrated in Figure 5.35.

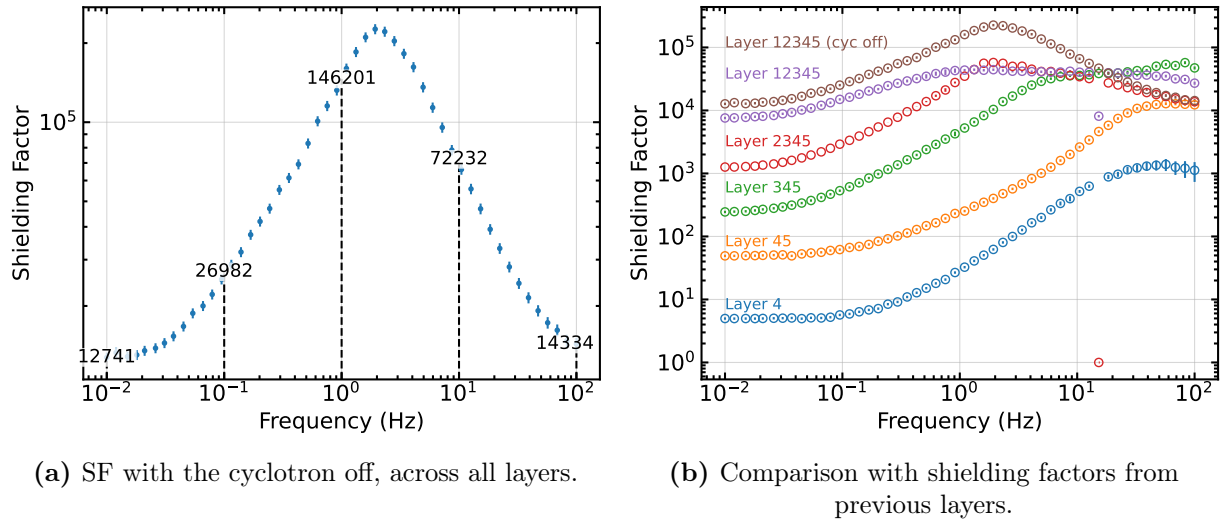
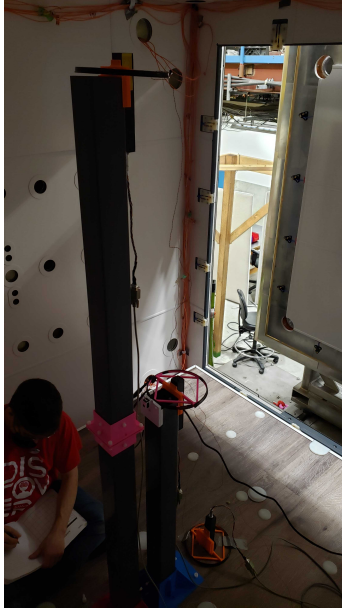
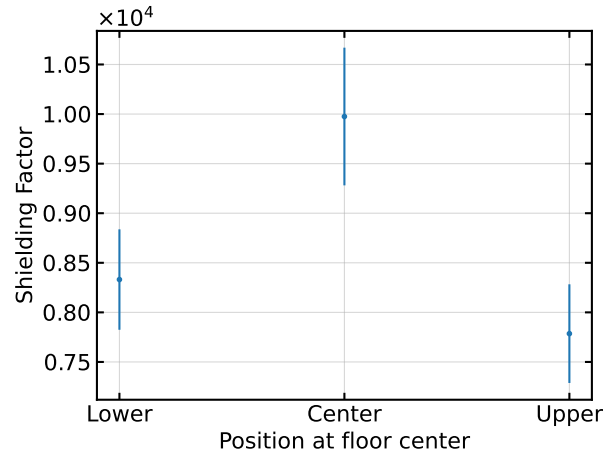


Figure 5.35: SF measurements with the cyclotron off, external field of $18 \mu\text{T}$, and data collected using the NIDAQ. All simulated SF values were greater than 10^5 .

With the cyclotron off, we mapped the MSR using SF as the metric. We set up three posts for mounting the fluxgate, as shown in Figure 5.36a. Initial measurements were taken at the positions indicated, and the results are presented in Figure 5.36b. These measurements reveal no significant first-order vertical gradient in the center column of the room.



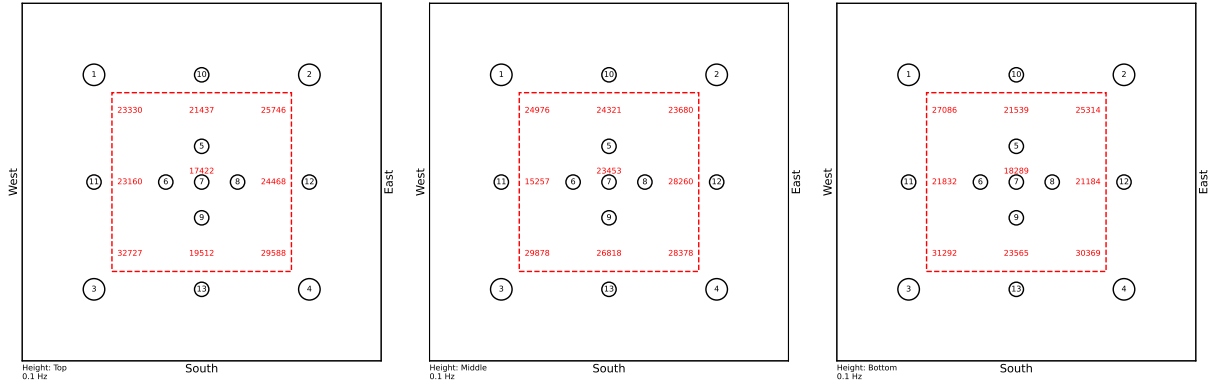
(a) Posts used for positioning the fluxgates.



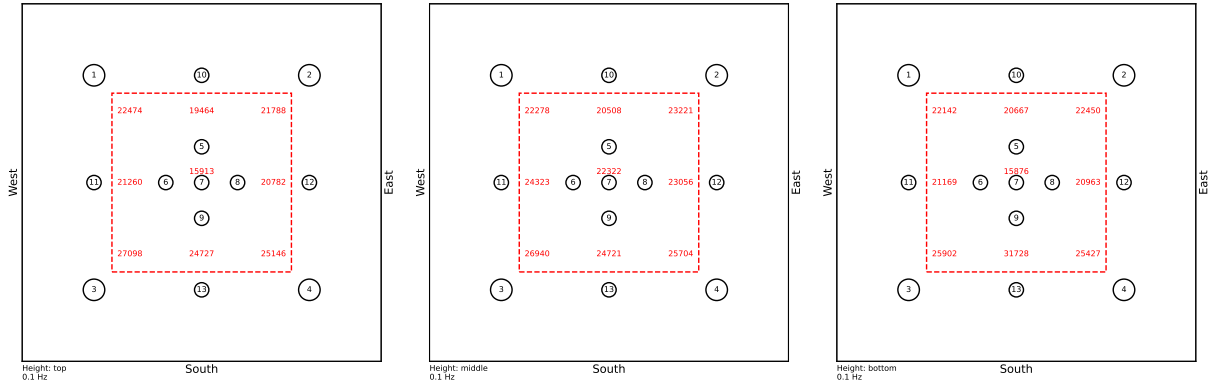
(b) No significant vertical gradient at the room center. Cyclotron off.

Figure 5.36: Mapping the SF at the room center with vertical offsets. The shortest post placed the fluxgate as close to the floor as possible. The external amplitude was $\sim 18 \mu\text{T}$.

We then re-positioned the posts around the room to map the SF at various locations. Measurements were taken at 0.1 Hz with an external field amplitude of $\sim 18 \mu\text{T}$ to increase measurement speed. Each post was held steady by hand during measurements. The resulting maps, shown in Figure 5.37, reveal no obvious trends apart from the typical decrease in SF caused by the cyclotron. Notably, the SF at the room center resembles the pattern observed in Figure 5.36b, both with the cyclotron on and off.



(a) Upper position, cyclotron off (b) Middle position, cyclotron off (c) Lower position, cyclotron off



(d) Upper position, cyclotron on (e) Middle position, cyclotron on (f) Lower position, cyclotron on

Figure 5.37: SF inside the MSR at various heights and positions, with an external field of $18 \mu\text{T}$ at 0.1 Hz . The red dotted line indicates the approximate floor position. The top of the figure represents the door location. No major trends are evident apart from the small negative impact of the cyclotron.

The results of the SF measurements for the completed room, including data across various frequencies and cyclotron status, are summarized in Table 5.9. These results show that the performance of the shielding layers installed in the MSR is below than the expectation.

Table 5.9: Measured and expected (by P. Fierlinger) SFs of the MSR at various frequencies show that the current setup significantly underperforms across all tested frequencies.

Cyclotron Status	Frequency (Hz)	Measured SF		Expected SF
		Off	On	
	0.01	2741	7535	100 000
	0.1	26982	16148	100 000
	1	146 201	44 777	100 000
	10	72 232	42 094	100 000
	100	14 334	28 489	100 000

5.7 Summary

This chapter explored how well the magnetically shielded room (MSR) blocked external magnetic fields as we added each layer. By measuring the shielding factor (SF) at every step, we could see how much each layer improved performance. We also tested the room with the cyclotron field both on and off to check how outside magnetic fields affected the shielding.

With just the copper layer (Layer 4) installed, there was already some shielding because of the mumetal material used in the base of the MSR. At 100 Hz, the SF was about 1123. However, there was an unexpected peak around 50 Hz, possibly due to imperfect electrical connections. When we added the first μ -metal layer (Layer 5), the shielding improved a lot. The SF increased to 242 at 1 Hz and 2317 at 10 Hz.

Adding the next μ -metal layer (Layer 3) made an even bigger difference. The SF reached 4467 at 1 Hz and 46885 at 10 Hz. However, at very low frequencies (<0.1 Hz), the shielding was weaker than expected. Even though everything was installed correctly, something was still limiting the performance.

With the third μ -metal layer (Layer 2), the shielding continued to improve, but not as much as we had hoped. At 0.01 Hz, the SF was 1225 with the cyclotron on and 1740 with it off—much lower than the expected value of 8000. At 100 Hz, it reached 28701 (cyclotron off), but dropped to 23930 when the cyclotron was active.

Finally, we installed the outermost μ -metal layer (Layer 1). At this point, we expected the shielding to go beyond 100 000 at all frequencies. While there was some improvement, the results were still lower than predicted. The highest recorded value was 146201 at 1 Hz (cyclotron off), but at 10 Hz, it was only 72232. Also, at 1 Hz determined SF was 2741 with cyclotron off.

Although each new layer improved the shielding, the final performance was still lower than expected. Something was limiting the MSR, preventing it from reaching the predicted shielding levels. Understanding what caused this shortfall remains an open question, and this will be explored further later in this dissertation.

Chapter 6

MSR Degaussing Procedure

Magnetically shielded rooms (MSRs) are built to lower external magnetic field, but their shield material may retain residual magnetization over time. This residual magnetic field can reduce shield performance as it may cause material saturation. To address this, a degaussing process was utilized to remove the residual field from the material. For the TUCAN MSR, degaussing cycles were run over layers with cyclotron field off and on to examine the saturation impact of the TRIUMF cyclotron.

This chapter details the degaussing procedure and the methods used to demagnetize the MSR after installation.

6.1 Degaussing/Equilibration Setup

To ensure the MSR operated at its full shielding capacity, a degaussing procedure was performed to eliminate residual magnetization from the shielding material. Since the principles and tools used for degaussing were introduced in previous chapters (Section 2.3, Section 3.2), this section focuses on the practical implementation and setup of the degaussing process.

An automated degaussing system was developed to systematically reduce remanent magnetization in the TUCAN MSR. The system generates a controlled alternating magnetic

field with a gradually decreasing amplitude, following the standard degaussing approach discussed earlier (Section 2.3).

The setup, depicted in Figure 6.1, begins with a personal computer (PC) programmed to generate a sinusoidal waveform with a decaying envelope. This signal is converted into an analog voltage by a high-resolution digital-to-analog converter (NI USB-6281) and then amplified using an AE Techron 7224 amplifier to deliver sufficient current for saturating the μ -metal layers.

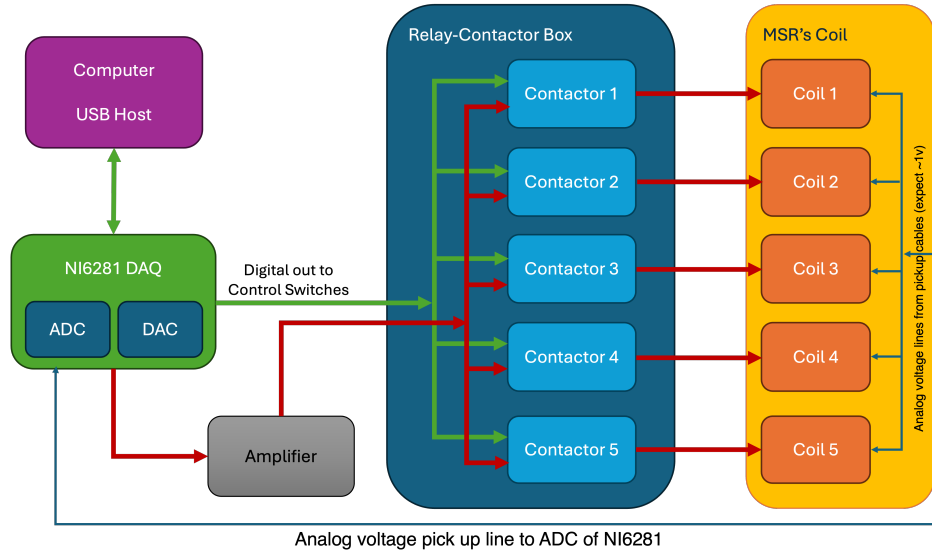


Figure 6.1: Block Diagram Degaussing unit.

Current is distributed to the coils of individual shielding layers via a relay-contactor box, which selects the target layer for degaussing. This modular design enables effective application of the degaussing process across all layers. By combining controlled waveform generation, high-power amplification, and targeted current distribution, the automated system could minimize residual magnetic fields within the MSR.

6.1.1 Degaussing Results and Hysteresis Loops

In this section, the results of hysteresis loop measurements for each of the shielding layers (1 through 5) within the MSR will be presented. Hysteresis loops can help understand the

magnetic properties and saturation behavior of the materials used in our shielding system. This section focuses specifically on the hysteresis characteristics observed in the completed shielding layers.

Layer 5 (Innermost Layer)

To investigate the saturation effects of the TRIUMF cyclotron on Layer 5, the innermost μ -metal layer of the MSR, we conducted degaussing cycles with the cyclotron field both on and off. Hysteresis loops were generated to evaluate the layer's magnetic response. The primary measurements were taken using the "edge coil" installed over Layer 5, but we also tested the distributed "L" coils while the cyclotron was on.

To facilitate degaussing, five strands of Remington Industries gauge 12 stranded wire were wrapped around each edge of the MSR. Each wire was positioned between Layer 5 and Layer 4 (the copper layer) and left open inside the MSR to provide maximum flexibility in arranging the degaussing setup.

Four of the wires along each edge were connected in series and linked to three other edges as illustrated in Figure 3.13. WAGO 221-412 push-in connectors were used for these connections, although they were temporary and will need replacement due to their magnetic properties. This arrangement was replicated two additional times to generate magnetic flux in Layer 5 along three distinct directions, labeled Power 1, Power 2, and Power 3, as shown in Figure 3.12. A pickup loop, created with one leftover wire on an edge, measured the induced magnetic flux in each direction, designated Pickup 1, Pickup 2, and Pickup 3, respectively.

The same gauge 12 wire used for the edge coils was also connected to an amplifier outside the MSR via a large side hole, while gauge 18 wire was used for the pickup coils. Only one loop was used for measurements, with the extra edge wires left open. This setup provided a total of 16 wires generating the H field within the material and one pickup wire measuring the induced flux. Figure 6.2 shows photographs of the setup inside the MSR. To reduce noise, all supply and return wires (both power and pickup) from inside the MSR to outside

were twisted in pairs.

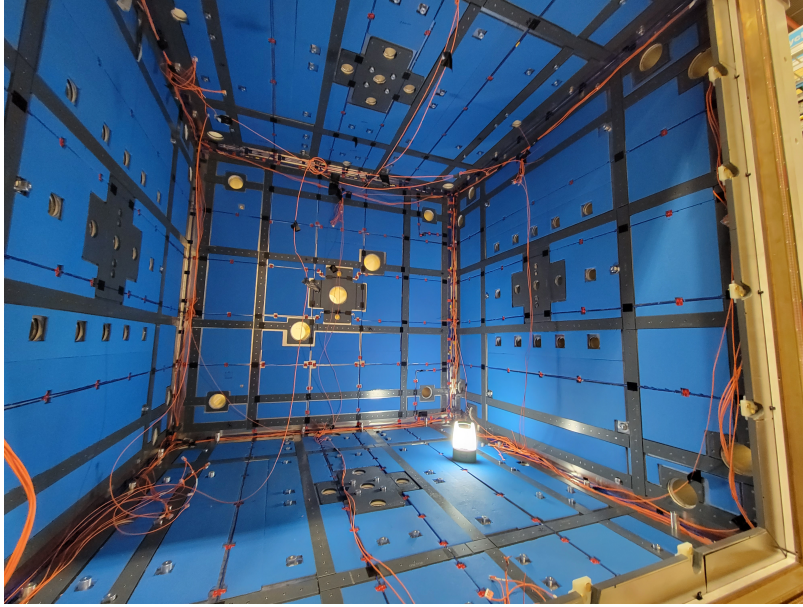


Figure 6.2: Photo of the inside of the MSR from just inside the door. Here one can see the 4 orange loop edge coils wound on each edge.

The NIDAQ was employed to generate the sinusoidal signals necessary for inducing flux in each of the three directions using the edge coils. The NIDAQ outputs the waveform to the AE-Techron 7224, which amplifies the signal and transmits it to the MSR. The waveform consists of a constant amplitude sine wave (1V from the NIDAQ) for 5 seconds, followed by a linearly decaying sine wave over 20 seconds, and concludes with a zero amplitude phase held for 20 seconds. The current was applied to each of the Power 1, 2, and 3 coils separately with AE-Techron gain settings of 60 %, 30 %, and 15 % at frequencies of 1, 3, 5, and 10 Hz. Measurements were taken from all three pickup coils for each configuration. The current in each power coil was recorded using a battery-powered Hantek CC-65 current clamp meter set to 10 mVA. Degaussing coils parameters can be found in Table 6.1.

Starting with the cyclotron off, degaussing cycles were performed on each of the three edge coils individually, with all three pickups recording the induced voltage at three different maximum currents (AE-Techron gain settings) and four frequencies. Figure 6.3 and

Table 6.1: Number of loops and effective path length of edge coils for driving field calculation.

Layer	Setup	Parameter	Value
5	Edge	N_{driving}	4 loops/edge $\times$ 4 edges = 16
		N_{pickup}	1 loops/edge $\times$ 4 edges = 4
		ℓ_{eff}	2.4 m/side $\times$ 4 sides = 9.6 m
		A	2.4 m side $\times$ 0.002 m thickness = 0.048 m ²

Figure 6.4 present typical online plots showing the current measured by the Hantek (AE-Techron gain at 60 % and frequency of 1 Hz) alongside the readings from all three pickup coils over time. The plots reveal the characteristic saturation in pickup coil 3, indicated by the signal approaching 0 V.

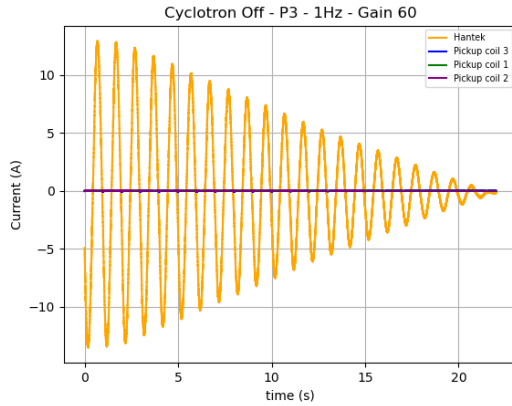


Figure 6.3: Example current signal at 1 Hz used in the degaussing cycle (hysteresis curve generation).

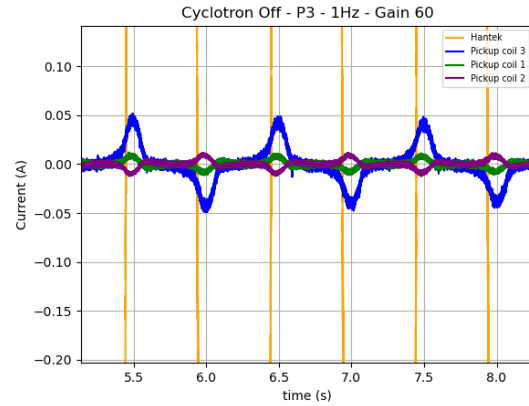


Figure 6.4: Example pickup coil signal (zoom in of Figure 6.3) when using the current configuration.

A total of 36 data sets were obtained, combining the three coils, three maximum currents, and four frequencies. Figure 6.5 shows a typical hysteresis curve obtained with the cyclotron off, displaying saturation around ± 15 A/m and anti-symmetry about $H = 0$ A/m as expected. Figures 6.6 and 6.7 illustrate hysteresis curves at lower maximum H fields where saturation does not occur. These curves will be analyzed further to derive idealized curves.

The results indicate that lower frequency sinusoidal waveforms result in better saturation

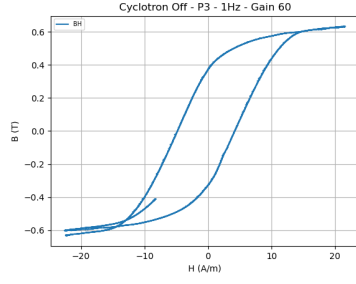


Figure 6.5: Power 3, 1 Hz, Techron 60 %, Pickup coil 3

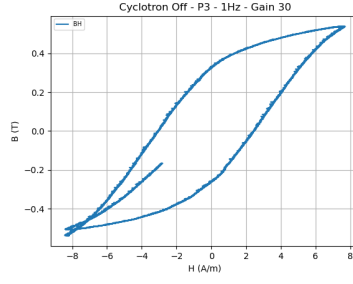


Figure 6.6: Power 3, 1 Hz, Techron 30 %, Pickup coil 3

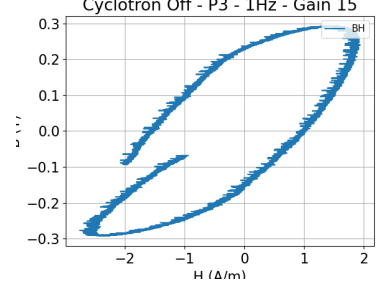


Figure 6.7: Power 3, 1 Hz, Techron 15 %, Pickup coil 3

of layer 5 compared to higher frequencies, as shown in Figures 6.8, 6.9, and 6.10.

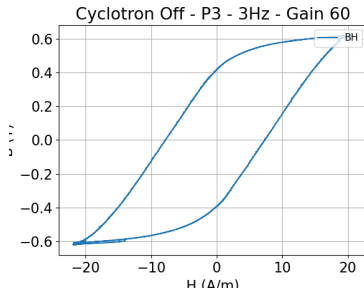


Figure 6.8: Power 3, 3 Hz, Techron 60 %, Pickup coil 3

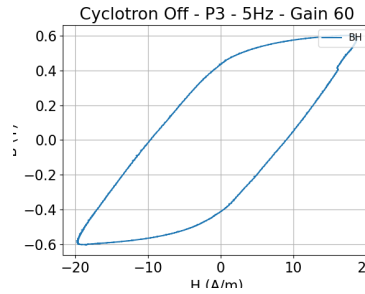


Figure 6.9: Power 3, 5 Hz, Techron 60 %, Pickup coil 3

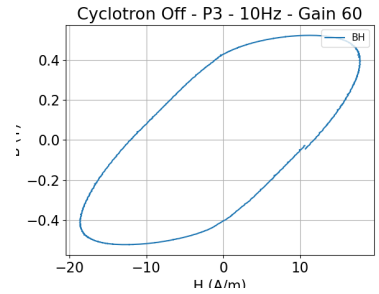


Figure 6.10: Power 3, 10 Hz, Techron 60 %, Pickup coil 3

Examining the signals from other pickup coils reveals flux leakage into non-primary directions. Figure 6.4 shows that while the dominant flux is measured by pickup coil 3, some flux leaks into the other sides of the MSR, particularly into pickup coils 1 and 2. This leakage is attributed to the rectangular geometry and fabrication of the MSR, which includes overlapping edges. This can potentially magnetize the non-degaussed sides of the MSR, leading to increased residual fields and gradients within the MSR.

Figure 6.11 and 6.12 present hysteresis curves for power directions 1 and 2, respectively. Although the magnetization magnitude is minimal, the curves deviate from the expected hysteresis loop, indicating that even when flux in power 3 approaches zero during a degaussing cycle, residual flux may persist in the other power directions.

Therefore, it is optimal to degauss using just enough current and H -field in each of the

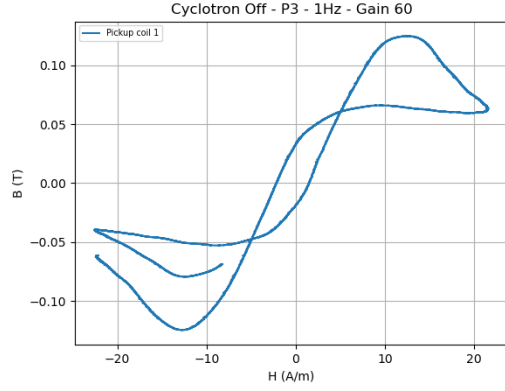


Figure 6.11: Power 3, 1 Hz, Techron 60 % Pickup coil 1

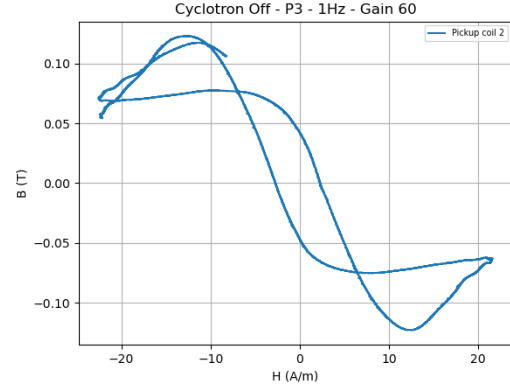


Figure 6.12: Power 3, 1 Hz, Techron 60 % Pickup coil 2

three directions to minimize flux leakage. The maximum current and H -field will be varied as parameters during degaussing optimization tests, which will be conducted once all five MSR layers are installed.

The same degaussing and hysteresis parameter matrix was applied with the cyclotron field turned on. Figures 6.13, 6.14, and 6.15 show the hysteresis curves obtained under these conditions, using the same parameters as before. While the hysteresis curves with the cyclotron on and off appear similar, a difference in the maximum H -field is expected for a given maximum B -field due to the additional starting H -field provided by the cyclotron.

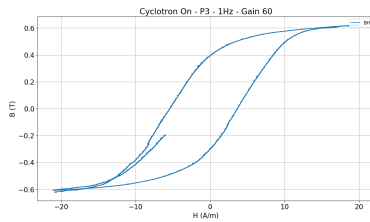


Figure 6.13: Power 3, 1 Hz, Techron 60 % Pickup coil 3

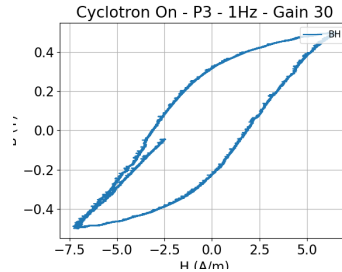


Figure 6.14: Power 3, 1 Hz, Techron 30 % Pickup coil 3

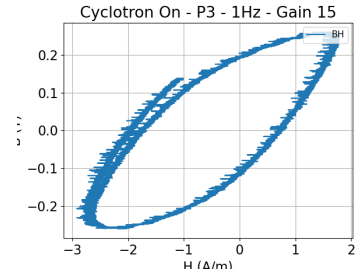


Figure 6.15: Power 3, 1 Hz, Techron 15 % Pickup coil 3

With the cyclotron field on, the distributed L coils for layer 5, with coil configuration shown in Figure 3.16, were operated sequentially with Yellow/Green and then Blue/Purple

in series. During testing, it was observed that when the door bladder pressure was set to 1 bar, the distributed L coils became disconnected (indicated by an infinite resistance). Consequently, tests were conducted with the door bladder pressure reduced to 0.5 bar. Figures 6.16 and 6.17 display the hysteresis curves recorded by all three pickup coils. Notably, the maximum magnetization (B) achieved using this configuration is lower compared to that obtained with the single flux direction edge coil.

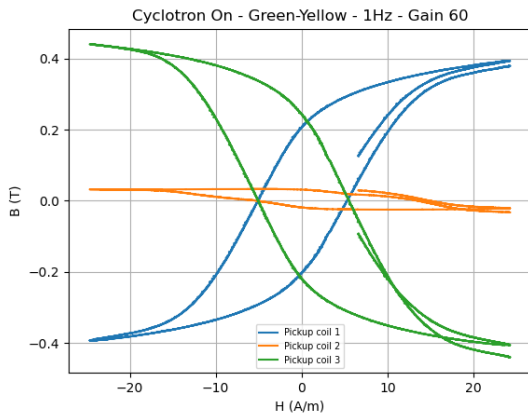


Figure 6.16: Green Yellow “L” Coil

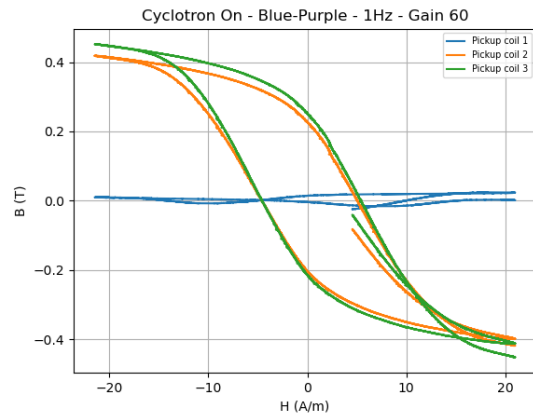


Figure 6.17: Purple Blue “L” Coil

Layer 3

Due to improper connections in the distributed L coils of layer 5, only the edge coils in this layer were utilized. These edge coils are wired similarly to our previous work, but with four pickup loops instead of one. The wiring configuration is detailed in Figure 3.13. The wiring scheme of the L coils for layer 3 is shown in Figure 3.14. A sinusoidal current at 1 Hz is driven with the following timings: 5 seconds at full amplitude to ensure saturation of the μ -metal, followed by a 20-second linear ramp to zero, and then a 5-second measurement period at zero amplitude.

The current in the driving loops for edge coils in layer 5 was measured with the Hantek current meter and converted to the applied magnetic H field using the previous method (Equation (3.1)). The flux in the metal was then calculated using the previously provided

equation (Equation (3.2)), which allowed for the determination of the magnetic field within the metal (Equation (3.3)). As before, for our cubic shield, the flux must travel through the walls.

A summary of values for layer 3 is presented in Table 6.2.

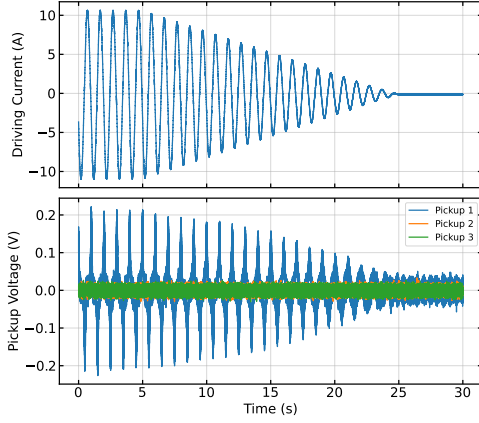
Table 6.2: Number of loops and effective path length for driving field calculations.

Layer	Setup	Parameter	Value
3	L	N_{driving}	1 loop/edge $\times$ 4 edges = 4
		N_{pickup}	4 loops/edge $\times$ 4 edges = 16
		$\langle \ell_{\text{eff}} \rangle$	2.6 m/side $\times$ $(2 + \sqrt{2})$ sides = 8.88 m
		$\langle A \rangle$	2.6 m/ $\sqrt{2}$ side $\times$ 0.003 m thickness = 0.0055 m ²

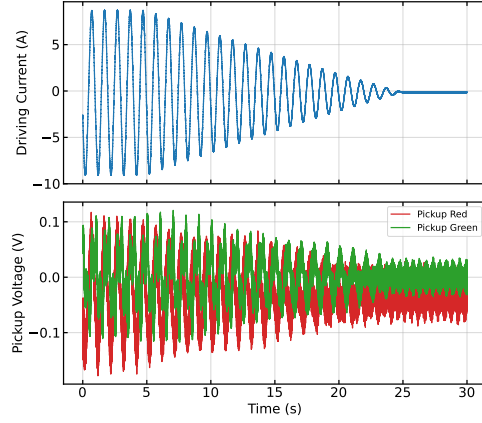
For the measurement, degaussing was carried out both before and after the repairs to the door (see Section 5.4.3 for details). Figure 6.18 presents the driving current and pickup voltages as functions of time. Compared to the layer 5 measurements, the orthogonal edge coils exhibit minimal pickup. In contrast, the pickups in layer 3 produced a substantial signal during the degaussing sequence. Although there is some evidence of phase-lagged edge coil pickup (shown in Figure 6.18c and observed in the green pickup in Figure 6.18d), a significant secondary signal is also present, likely due to the complex geometry of the setup. The current applied to the layer 3 coils was slightly reduced compared to layer 5, by approximately 10 % to 20 %, but the reduction was not substantial. The red pickup demonstrated a nearly sinusoidal signal in phase with the driving current.

Due to some instabilities observed during the initial cycle, the first 1 s of data was excluded from the time series shown in Figure 6.18. The first loop after this exclusion is displayed in Figure 6.19, which was recorded following the door repairs. The hysteresis loops from before the door repairs were largely similar, though they exhibited poorer saturation in the layer 5 loops due to flux passing through the door. It was observed during the second round of degaussing on layer 5 that either the pickups or the driving coil had an incorrect polarity, leading to inversion of these data to align with the first round.

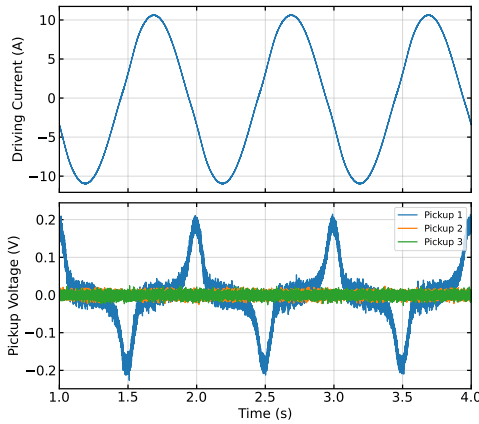
Overall, the results suggest that the door is sufficiently well-connected, as indicated by



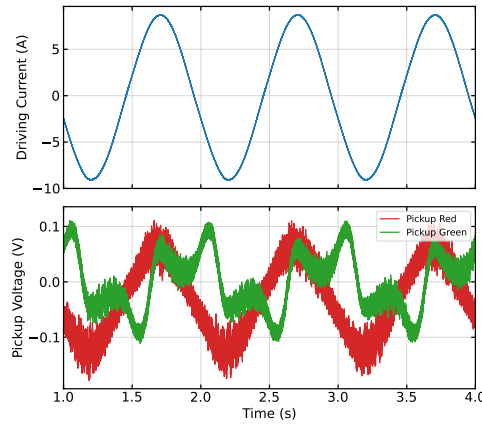
(a) Step 1, layer 5 driving edge coil 1. Techron gain 60 %



(b) Step 2, layer 3 yellow driving L coil. Techron gain 75 %



(c) Magnification of Figure 6.18a



(d) Magnification of Figure 6.18b

Figure 6.18: Driving current and pickup voltages for layer 5 and 3 degaussing sequences. Layer 3 is clearly more complex, with pickup on both coils. The green signal looks like some component of the edge coil signal is present, with the superposition of some additional signal.

the symmetry observed in the layer 5 saturation. If the door were inadequately connected, we would expect the saturation in pickup 3 to differ, since it is the only pickup not affected by flux passing through the door. The observed similarity in saturation levels across pickups indicates that the door connections are relatively uniform and comparable to those in the rest of the room.

We also note minimal to no orthogonal pickup when operating the edge coils, as shown in Figure 6.20, where the saturation in the orthogonal directions is on the order of 0.015 T.

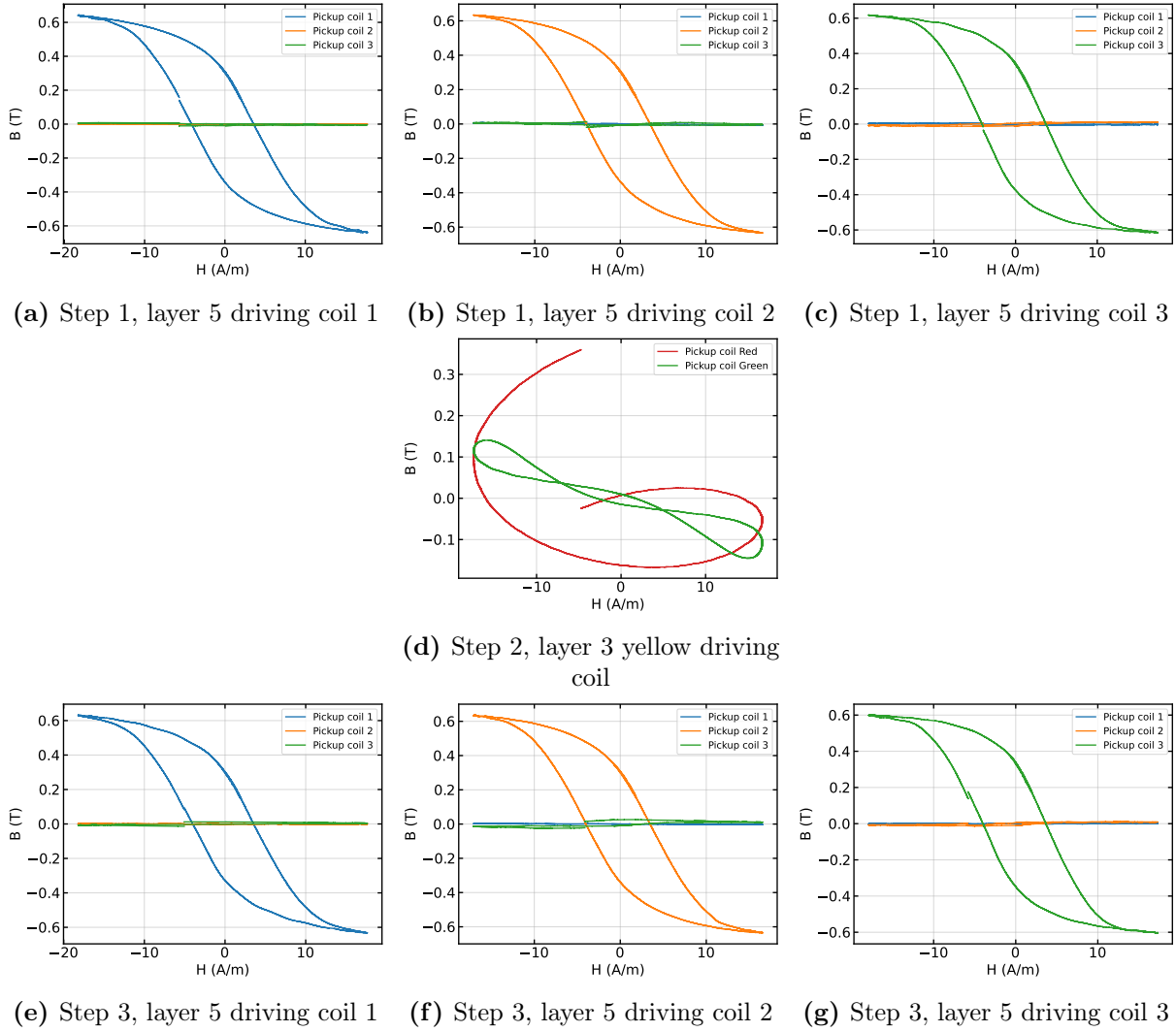
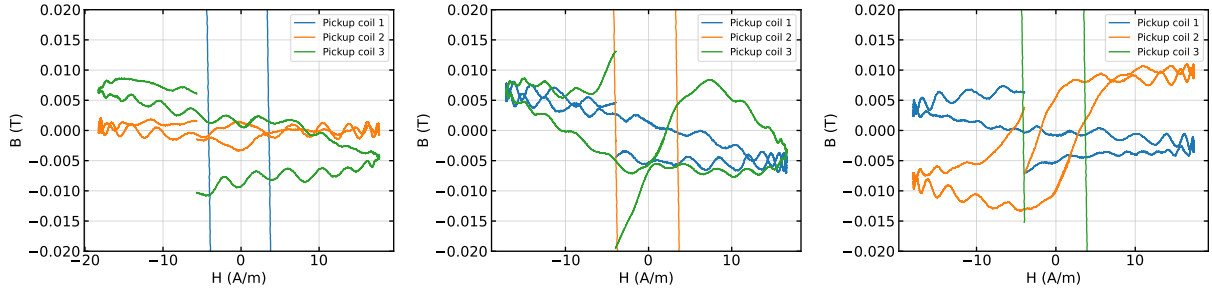


Figure 6.19: Degaussing hysteresis curves from the first cycle for layer 5 (a, b, and c), then layer 3 after layer 5 had been degaussed (d), and layer 5 again after layer 3 had been degaussed (e, f, and g). All layers were degaussed at 1 Hz. Techron gain was set to 60 in all cases except d, where it was 75.

After some investigations, it was found that circuits did not produce clear hysteresis loops due to incorrect wiring.

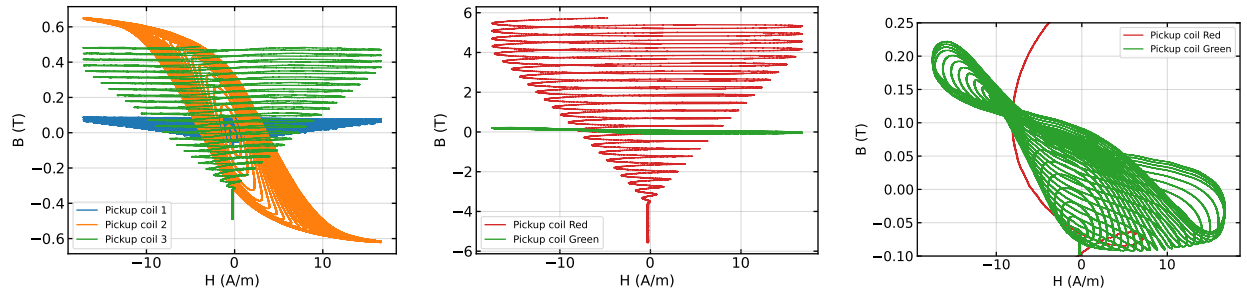
When examining all hysteresis loops, as illustrated in Figure 6.21a, the layer 5 pickup yields a well-defined loop that trends toward a central point, consistent with expectations from the literature [43]. In contrast, the orthogonal loops exhibit a drift in B while oscillating in H , similar to the behavior observed in the layer 3 coils. The green pickup appears to



(a) Magnification of Figure 6.19a (b) Magnification of Figure 6.19b (c) Magnification of Figure 6.19c

Figure 6.20: Some orthogonal signal is seen during the layer 5 degaussing. This is much less than what was observed in our prior measurements for layer 5; which may be attributed to the greater degree of symmetry in the pickup loop arrangement.

be a more reliable source for information on the μ -metal saturation, aligning with our observations from the raw data (Figure 6.18d), where the green pickup resembles the layer 5 pickup more closely. Figure 6.21c presents a magnified view of the layer 3 green pickup, showing a non-trivial loop that is cyclic in B and converges to a single point, similar to the edge coil hysteresis loop.



(a) Step 1, layer 5 driving coil 2. Compare to Figures 6.19b and 6.20b. (b) Step 2, layer 3 driving yellow coil. Compare to Figure 6.19d (c) Magnification of Figure 6.21b

Figure 6.21: Full range hysteresis loops, from which the first loop is presented in Figure 6.19.

Layer 2

With the settings like two other layers shown in Figure 3.13 and Figure 3.14, we degauss the room layer-by-layer at a frequency of 1 Hz in the following sequence: Layer 5 (power 1,

2, then 3), Layer 3, Layer 2, Layer 3 again, and finally Layer 5 (power 1, 2, then 3). We set the Techron amplifier gain to 100 % and adjusted the input voltages to achieve initial amplitudes of 0.6 V, 1.3 V, and 1.4 V for layers 5, 3, and 2, respectively. For layer 5, we used the custom-installed edge coils, with four loops per edge serving as driving coils and one loop per edge as the pickup. For layers 2 and 3, we employed the "L" shape coils, which generates fields across all sides simultaneously, as illustrated in Figure 3.15. The setup depicted in Figure 3.14 features cables bundled into five strands, with four strands connected in series as the driving coil and one strand used as the pickup. To calculate the layer 2 degaussing coils' parameters, we used Equation (3.4) and Equation (3.5). The summary of these parameters is shown in Table 6.3.

Table 6.3: Number of loops and effective path length for driving field calculation.

Layer	Setup	Parameter	Value
2	L	N_{driving}	1 loops/edge $\times$ 4 edges = 4
		N_{pickupo}	4 loops/edge $\times$ 4 edges = 16
		$\langle \ell_{\text{eff}} \rangle$	3 m/side $\times$ $(2 + \sqrt{2})$ sides = 10.24 m
		$\langle A \rangle$	3 m/ $\sqrt{2}$ side $\times$ 0.003 m thickness = 0.0064 m ²

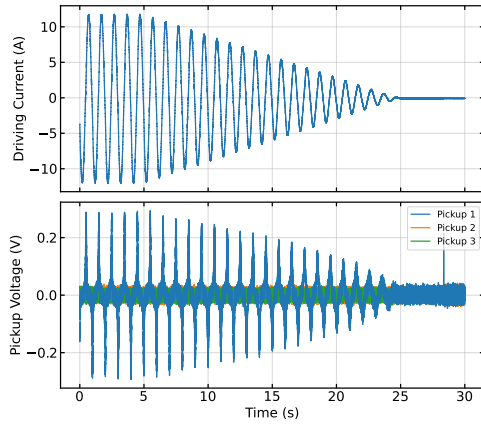
Figure 6.22 presents the driving current and pickup voltages over time. It is evident each layer appears to be reasonably well-saturated, as shown in the figures.

Like previous measurements, due to some instabilities observed in the first cycle, we omit the first 1 s of data from the time series shown in Figure 6.22. We then calculate B and H fields using Equations (3.1) and (3.3) to assess the degree of saturation and hysteresis in the system. The first loop after cropping is shown in Figure 6.23.

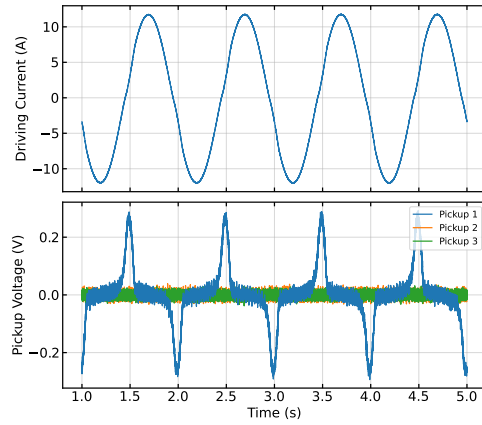
From the figures, the saturation field in layer 5 was consistent across all orientations of the field lines, indicating that the door is well-magnetically connected, at least at the low frequency of 1 Hz.

The edge coils in layer 5 produce a distinct hysteresis loop, as anticipated based on the literature[43]. Compared to our work from measurements with layer 3, the pickup data from the "L" coils is now more meaningful and interpretable, as the wiring connection issues is

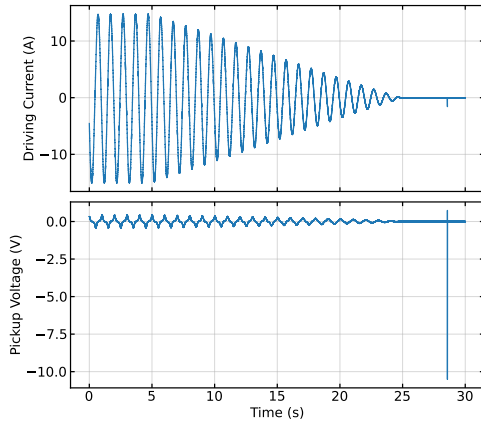
solved. With the current setup, we can confirm that all layers are indeed being saturated.



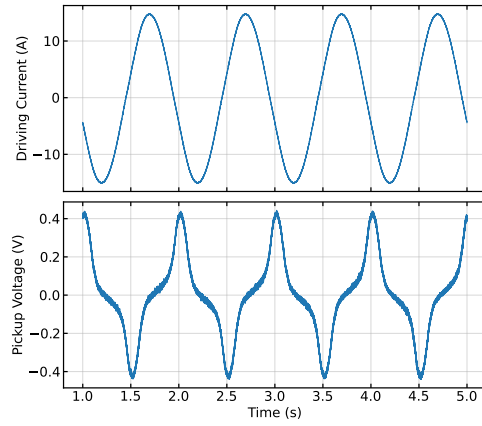
(a) Layer 5 driving edge coil 1



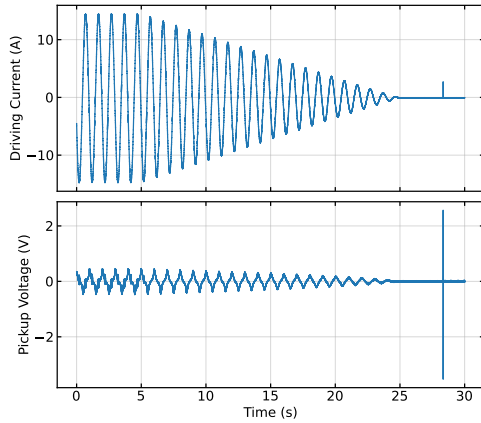
(b) Magnification of Figure 6.22a



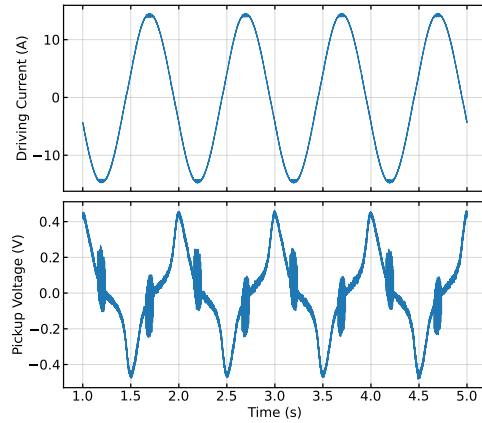
(c) Layer 3 driving L coil



(d) Magnification of Figure 6.22c

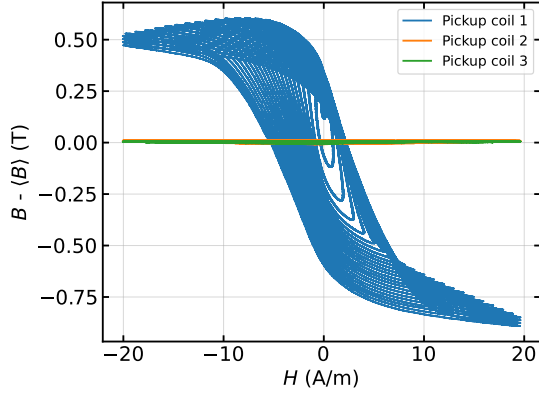


(e) Layer 2 driving L coil

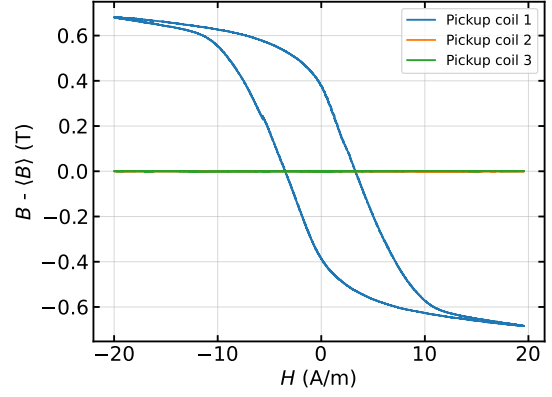


(f) Magnification of Figure 6.22e

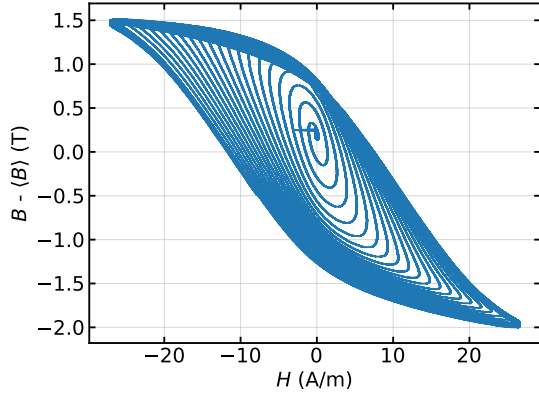
Figure 6.22: Driving current and pickup voltages for layers 2, 3, and 5 during degaussing sequences (cyclotron on). The initial amplitude for layer 2 was slightly excessive, resulting in the amplifier being unable to provide the requested current at the cycle peaks until the linear ramp reduced the peak currents to more manageable levels. Large spikes occurring approximately 2.5s before the end of the sequence indicate the amplifier's disconnection from the circuit via relay.



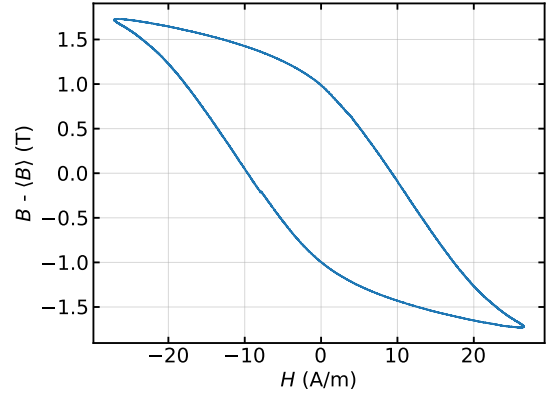
(a) Layer 5 driving edge coil 1



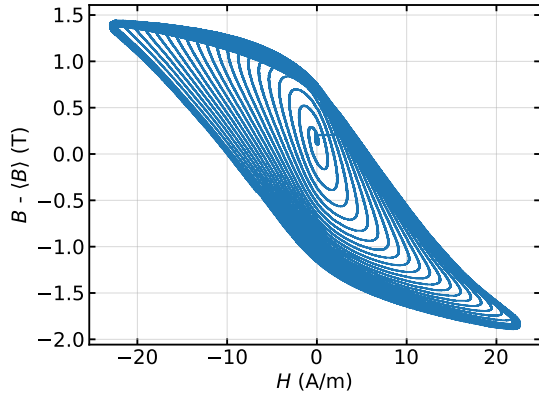
(b) First cycle of Figure 6.23a



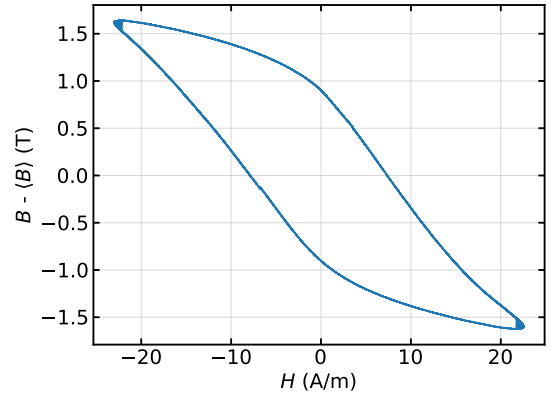
(c) Layer 3 driving L coil



(d) First cycle of Figure 6.23c



(e) Layer 2 driving L coil



(f) First cycle of Figure 6.23e

Figure 6.23: Hysteresis loops from the degaussing sequence (cyclotron on). Layer 5 clearly shows saturation, while layers 2 and 3 are likely saturated sufficiently for the current setup.

Layer 1

By installing Layer 1, the final layer, the MSR setup is complete. We then drive a sinusoidal current signal at 1 Hz for degaussing and to analyze hysteresis loops and saturation. The coils we used to degauss were edge coil for layer 1 (Figure 3.13), L coil for layers 2 and 3 (Figure 3.14), and distributed L coils for layer 5. The timing sequence is as follows: 5 seconds at full amplitude to ensure saturation of the μ -metal, followed by a 20-second linear ramp to zero, and then 5 seconds of measurement at zero amplitude. The degaussing and analysis are performed layer-by-layer in this sequence: Layer 5 (distributed), Layer 3, Layer 2, Layer 1 (power 2), Layer 1 (power 3), Layer 2, Layer 3, and Layer 5 (distributed), all at a frequency of 1 Hz. Calculation of B and H was with using of Equations (3.1) to (3.5) depending on the specific setup.

Starting measurement with cyclotron on, we execute these degaussing loops with 1000 cycles during the ramp-down phase, operating at a frequency of 1 Hz. Figure 6.24 illustrates the driving current and pickup voltage as a function of time. Utilizing the AE Techron 7224 amplifier, we encountered limitations due to its maximum current capacity during the initial cycles, which resulted in less-than-ideal saturation.

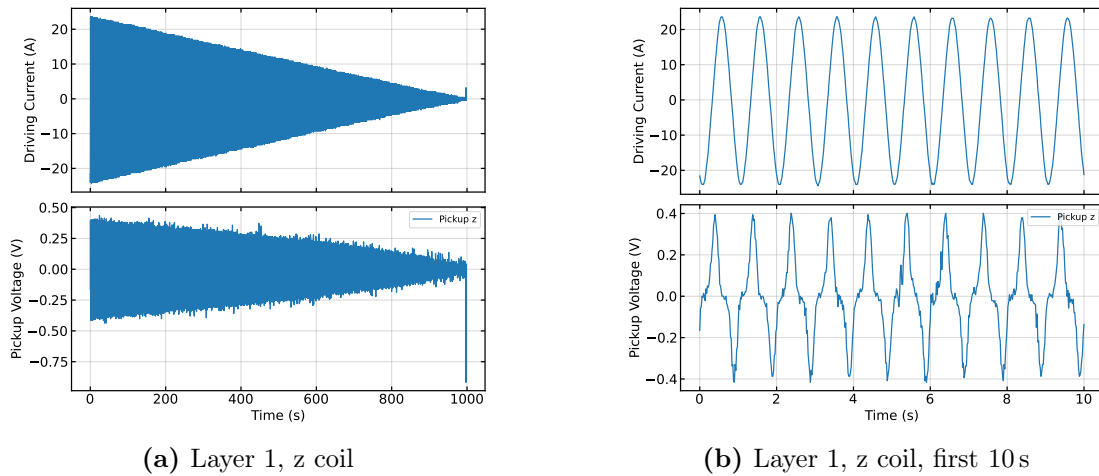


Figure 6.24: Driving current and pickup voltage for the layer 1 degaussing sequence (cyclotron on).

In Figure 6.25, we compare the hysteresis loops for the second cycle across all layers, with the exception of layer 5 where distributed coils were employed. It is evident that there are saturation issues with most layers, particularly layer 1 y (power 3) and layer 2. Notably, the B axis scales for both layer 1 z (power 2) and layer 3 are quite similar, which should provide confidence in the accuracy of the derived corrections for the calculation of B and H for the L coil configurations.

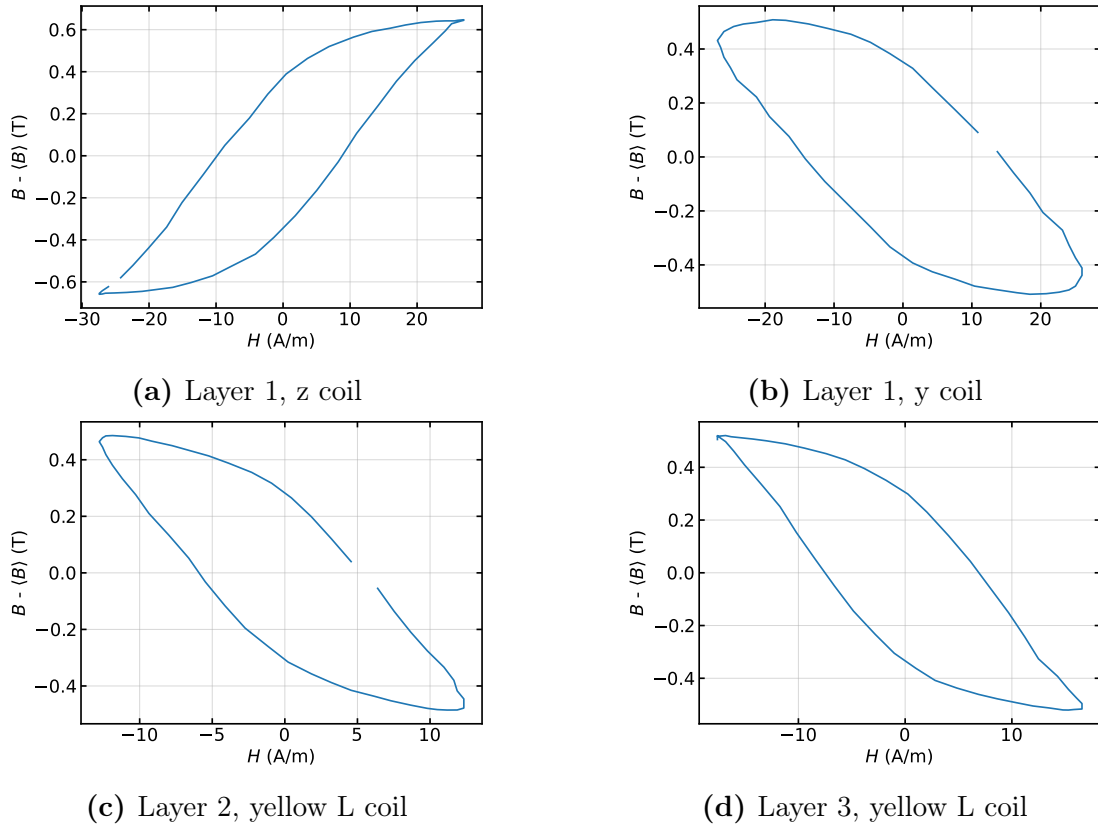


Figure 6.25: BH curves for the all layers, except layer 5 where the distributed coils were used. The axes of Figures 6.25b and 6.25d are inverted due to an inversion of the physical connections to the degaussing loops.

Turning off the cyclotron, we conduct degaussing loops with 20 cycles during the ramp-down period at a frequency of 1 Hz. Figure 6.26 illustrates the driving current and pickup voltage as a function of time. The AE Techron 7224 amplifier was used, and as shown, we remain constrained by its maximum current during the initial cycles, resulting in suboptimal

saturation.

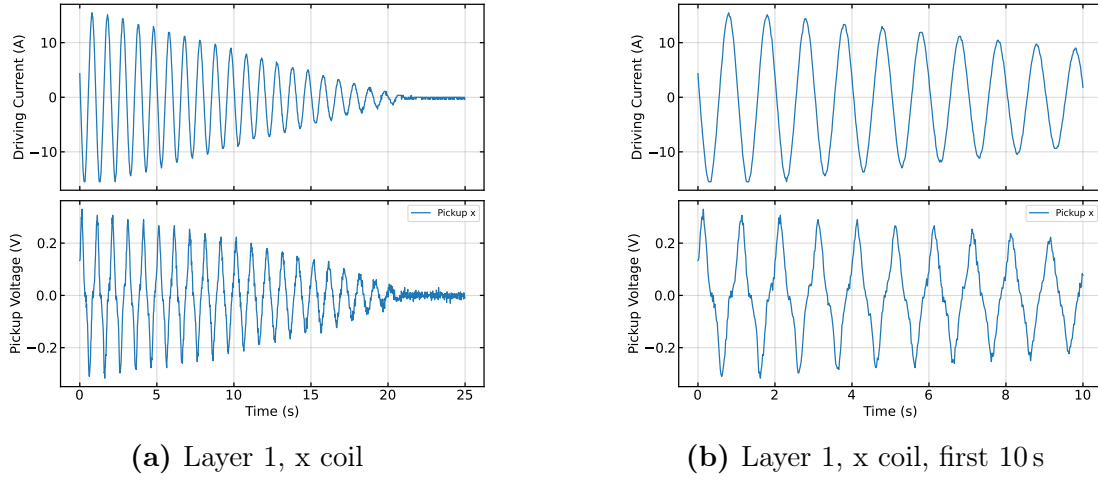


Figure 6.26: Driving current and pickup voltage for the layer 1 degaussing sequence (cyclotron off).

We compare the BH curves for the second cycle of all layers in Figure 6.27, except layer 5 where the distributed coils were used.

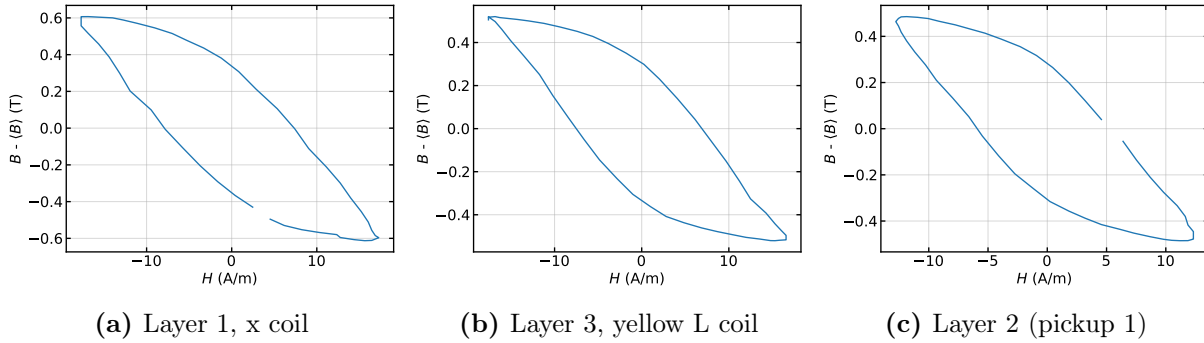


Figure 6.27: Hysteresis loops for the all layers, except layer 5 where the distributed coils were used. As before we used the distributed degaussing loops for layer 5, for which there is no pickup loop.

Based on the provided figures, it is evident that, even with the cyclotron turned off, the MSR is not achieving adequate saturation. This performance shortfall highlights the need for further optimization of the MSR to ensure it meets the specified criteria for magnetic shielding. Additional analysis will be discussed later to address the identified issues and enhance the effectiveness of the MSR in achieving optimal saturation and shielding factor.

6.2 Summary

This chapter outlined the degaussing process used to eliminate remanent magnetization from the MSR's shielding layers. By generating a controlled alternating magnetic field with a gradually decreasing amplitude, the system demagnetized each layer using a relay-based current distribution system.

To check the effectiveness of the degaussing process, hysteresis loop measurements were performed on each shielding layer under different conditions, including the influence of the TRIUMF cyclotron field. The results showed that lower-frequency signals were more effective at driving the shielding material into full saturation.

When the cyclotron field was on, the degaussing current had to be adjusted to compensate for its influence. Although most shielding layers reached saturation, some stayed partly magnetized by external interference or hardware limits.

In summary, the degaussing process significantly reduced unwanted residual magnetic fields, improving the MSR's shielding effectiveness. However, further adjustments such as optimizing waveform parameters, and enhancing electrical connections could improve shielding performance.

Chapter 7

Residual field Inside the TUCAN MSR

Magnetically shielded rooms (MSRs) not only protect experiments from external magnetic fields but also create an environment with extremely low residual fields and gradients. This is very important for the neutron electric dipole moment (nEDM) experiment, which requires precise control of magnetic fields. Based on our MSR specifications, the residual magnetic field at the center of the MSR should be below 1 nT.

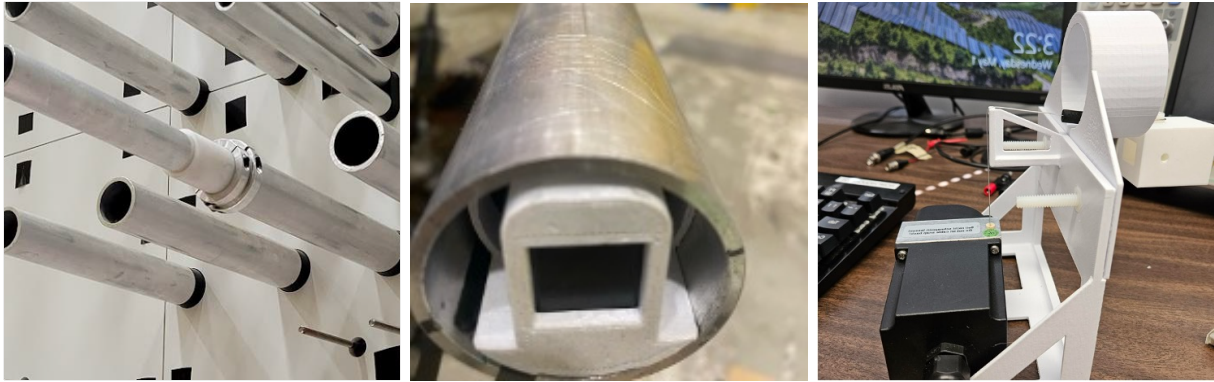
After we found that the shielding factor was lower than expected, we measured the residual field inside the MSR through its access holes, as the strength of the residual field shows how well the degaussing process worked. We designed and built a mapping setup with aluminum tubes and we used various sensors to measure the field. This chapter explains the measuring setup, process next to results that help check the room's shielding performance and find potential leakage.

7.1 Measurement Procedure

We employed various methods for mapping the MSR. We began by using a Stefan Mayer handheld Fluxgate (FLUXMASTER), a single-axis vector magnetometer, to measure the residual field inside the room. The sensor was oriented upwards to capture the vertical field,

resulting in two types of measurements: coarse field maps of the interior volume and field maps obtained through some of the holes in the MSR walls.

To map inside the MSR, we utilized a stick mapper setup that allowed for the attachment of various sensors, including fluxgate and QuSpin sensors, to the end of a stick composed of both aluminum and PVC tubes. These sensors were secured in a 3D-printed holder (Figure 7.1b), with the tube marked at 1 cm intervals. Within each MSR hole, a plastic tube with an outer diameter slightly larger than the inner diameter of the aluminum tube and smaller than the hole’s diameter was inserted to facilitate smooth movement of the stick mapper, effectively acting as a bearing (Figure 7.1a). This configuration enabled precise measurements of the distance from the sensor head to the edge of the aluminum through-tubes. To find the sensor position, a potentiometer (Figure 7.1c) connected to the sensor holder was interfaced with an MCCDAQ data acquisition system. The stick mapper was kept approximately centered in each hole, enabling comprehensive mapping of both the spaces between walls and the interior of the MSR.



(a) Aluminum tube positioned within a hole of the MSR, showing the gap between the mapping tube and the MSR hole.

(b) QuSpin sensor in a 3D printed holder fixed on the stick mapper.

(c) Potentiometer on its holder.

Figure 7.1: Mapping system components.

Briefly, the stick mapper system was employed to collect data on the magnetic field components B_x , B_y , and B_z at various positions within the room as shown in Figure 7.2. To mitigate systematic errors, measurements were taken with the mapper rotated by 180

degrees, allowing for correction of sensor offsets and accurate determination of the magnetic field values using the equations:

$$B_{\text{True}} = \frac{B_{\uparrow\text{meas}} - B_{\downarrow\text{meas}}}{2}, \quad (7.1)$$

$$B_{\text{Offset}} = \frac{B_{\uparrow\text{meas}} + B_{\downarrow\text{meas}}}{2}. \quad (7.2)$$

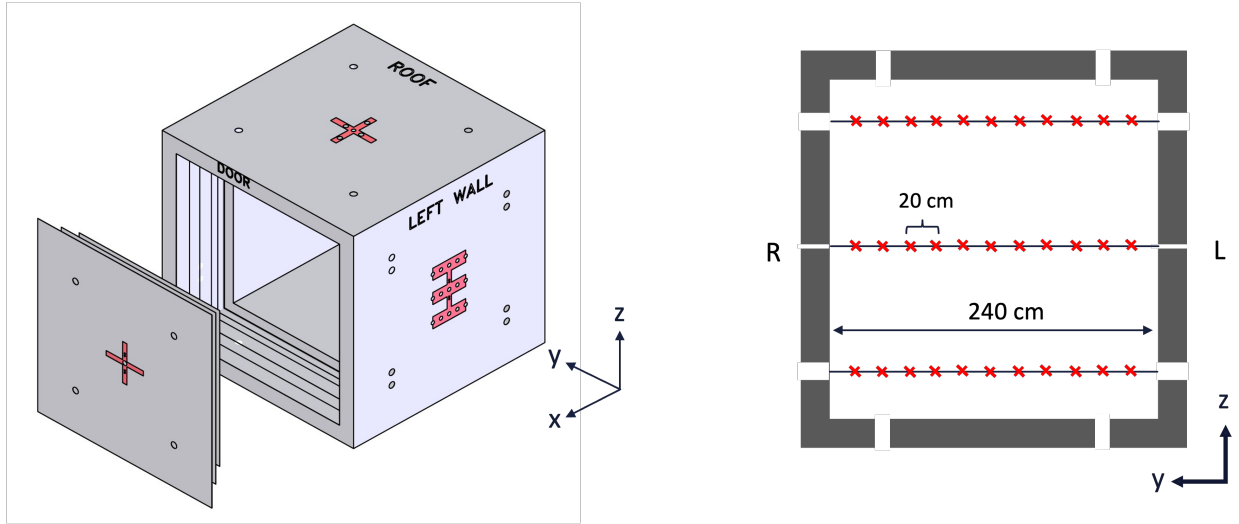


Figure 7.2: Schematic mapping procedure.

7.2 Results

We began with coarse field maps of the MSR's interior. During these measurements, the door was closed with a person inside the room, and degaussing was performed as needed. The maps were acquired without reopening the door. For each measurement, the Stefan Mayer fluxgate sensor was held vertically approximately 5 cm from the μ -metal surface, capturing data from a single point per surface. This method provided an overview of the field gradients present and the residual field at the room's center. Measurements were conducted with Layer 5 installed, with the cyclotron operating and degaussing applied. At

this time, the door pneumatic clamps were not operational, once installed we expect these results to improve. The results from these measurements, focusing solely on the scenario with Layer 5 installed, are presented in Figure 7.3.

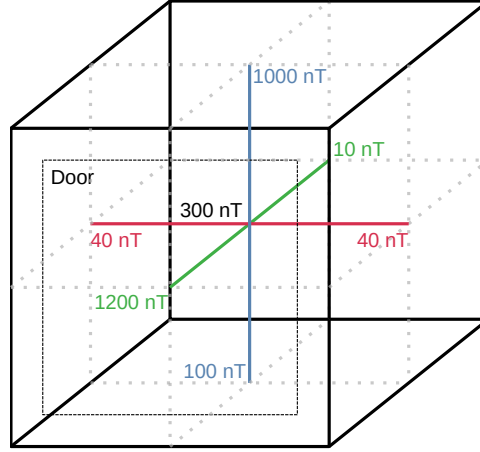


Figure 7.3: Residual field measurements with layer 5 with the cyclotron on, door unpressurized. With the door pressurized, $1200 \text{ nT} \rightarrow 1000 \text{ nT}$, with no other changes. The residual field in the room center was $\sim 300 \text{ nT}$. (Green line is in x axis, red shows y axis, and blue is in z direction).

Later measurements were repeated after installing Layer 3, with the cyclotron both on and off.

Initially, we conducted a mapping after completing Layer 3, as shown in Figure 7.4a. At this stage, no degaussing had been performed on the room. With the cyclotron on and the door bladders depressurized, we observed large residual fields, comparable to the measurements before Layer 3 was installed. The increase in fields, particularly those produced by the μ -metal walls, was notable, although the field measured at the roof was significantly lower than before Layer 3 was installed (previously 1000 nT). This reduction might be unreliable due to considerable fluctuations in the data.

Subsequently, we inflated the Layer 5 bladder to 1 bar despite a known leak, as shown in Figure 7.4b. Although the bladder inflation caused a 1 mm decrease in the spacing between the door and Layer 5, it was insufficient to fully close the gap. The field measurements showed minimal changes compared to the previous map, except for an increase in the roof

value, aligning with observations from layers 4 and 5 alone.

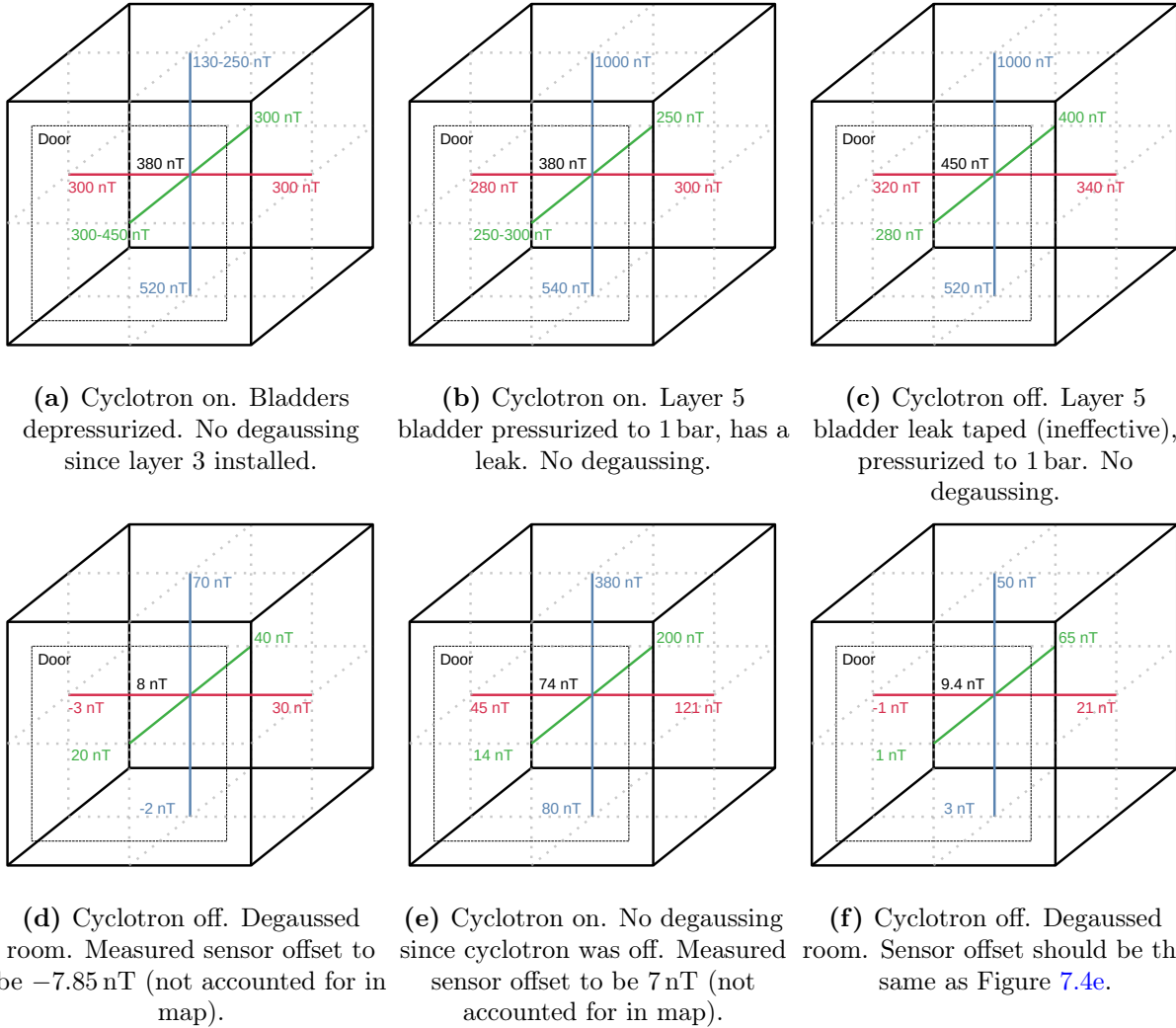


Figure 7.4: Residual fields in MSR for various states of degaussing and cyclotron field status. Maps are presented in chronological order. The field sensor was held vertically about 5 cm from the center of each side of the room, noting that this places the sensor right in front of a hole. Overall, we see a drastic improvement in the residual field after degaussing.

Later, with the cyclotron turned off for maintenance, as depicted in Figure 7.4c, we attempted to address the bladder issue using tape, which proved ineffective. The residual fields remained relatively constant, indicating that the cyclotron’s status had minimal impact on the measurements, suggesting that the fields observed were more likely due to the

state of the Layer 5 μ -metal rather than actual shielding effects.

Afterward, a person was in the room while a degaussing sequence was executed, as illustrated in Figure 7.4d. The sequence involved degaussing Layer 5 first, followed by coils 1, 2, and 3; then Layer 3, with all coils connected in series, potentially leading to counteracting flux and ineffective degaussing; and finally Layer 5 again in the initial order, and a significant improvement in residual fields was observed. By inverting the fluxgate sensor's direction while maintaining its position, we measured an offset of 1.0 nT up and $16.7 \mu\text{T}$ down, concluding an internal sensor offset of $-7.85 \mu\text{T}$. Consequently, the field at the room center was 0.15 nT post-degaussing. However, an observed asymmetry in the East-West fields, which was not present before Layer 3 installation, raises some concern. This asymmetry, potentially due to measurement uncertainty, is also evident in Figure 7.4e and Figure 7.4f.

When the cyclotron field was turned back on, as shown in Figure 7.4e, we took SF measurements. Despite not performing degaussing beforehand, the fields were noticeably large, though not as extreme as those recorded earlier. The largest field was observed near the MSR roof. Sensor offset measurements showed $74.6 \mu\text{T}$ up and $60.5 \mu\text{T}$ down, resulting in a sensor offset of 7 nT, which notably reversed in sign compared to previous measurements.

Finally, measurements were taken after reapplying the degaussing sequence without reopening the room door, including the previously problematic Layer 3 coil configuration, as shown in Figure 7.4f. The residual fields were reduced to values comparable to those in Figure 7.4d, within ~ 20 nT. The gradient orientations were consistent with those observed previously.

Upon completing the setup of the MSR, we proceeded with mapping the central region using the previously described mapper system (page 147). The stick mapper, equipped with a sensor at one end, was inserted into the MSR holes. Data was collected from the sensor at intervals of 20 cm along the length of the mapper to determine the magnetic field components B_x , B_y , and B_z at each position. To account for potential systematic errors, the mapper was

rotated by 180 degrees, allowing us to measure the reversed components $-B_z$ and $-B_x$. The B_y component remained unchanged in this process. By comparing these measurements, we could correct for sensor offsets (Equation (7.2)) and derived accurate magnetic field values (Equation (7.1)). All measurements were conducted with the cyclotron on. We began with the non-degaussed room, mapping it using the Mag-13MS100 Fluxgate, as shown in Figure 7.5. The mapping process proceeded from the west wall, through the central hole in the wall, towards the east (with the room's door located on the north side). Measurements were taken from 120 cm to 240 cm from the outer cladding, covering a central region of 1 meter within the room.

The graph in Figure 7.5a displays the fluxgate readings recorded by SCU1, categorized into two sets: "up" and "down." The "up" set represents measurements obtained when the sensor is positioned in its original orientation, while the "down" set corresponds to measurements taken after the sensor has been rotated 180 degrees. The data includes B_x up, B_y up, and B_z up, which are the magnetic field components in the x , y , and z directions, respectively, measured with the sensor in its initial position. Similarly, B_x down, B_y down, and B_z down represent the magnetic field components measured with the sensor rotated 180 degrees. Notably, the B_y up and B_y down measurements are identical, demonstrating that the y -component of the magnetic field remains constant regardless of the sensor's orientation, indicating its invariance with respect to the flipping. This invariance explains why, in Figure 7.5b, the value of B_y is consistently close to zero.

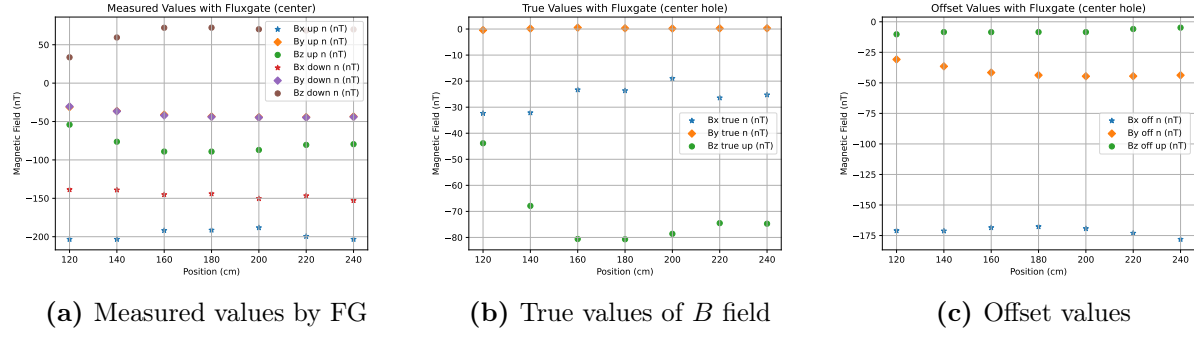


Figure 7.5: Residual magnetic fields in the central region of the undegaussed MSR, mapped from the west wall at 20 cm intervals using a fluxgate.

To determine the true value of B_y , we relocated the mapper to the door side of the room, which is perpendicular to the west wall. This positioning effectively rotates the x and y axes of the sensor, allowing us to measure B_y more accurately, particularly at the center of the room. By aligning the sensor in this new orientation, we obtained a more precise assessment of B_y in the central region. Figure 7.6 displays the measured, true, and offset values of the magnetic field as recorded by the same fluxgate sensor.

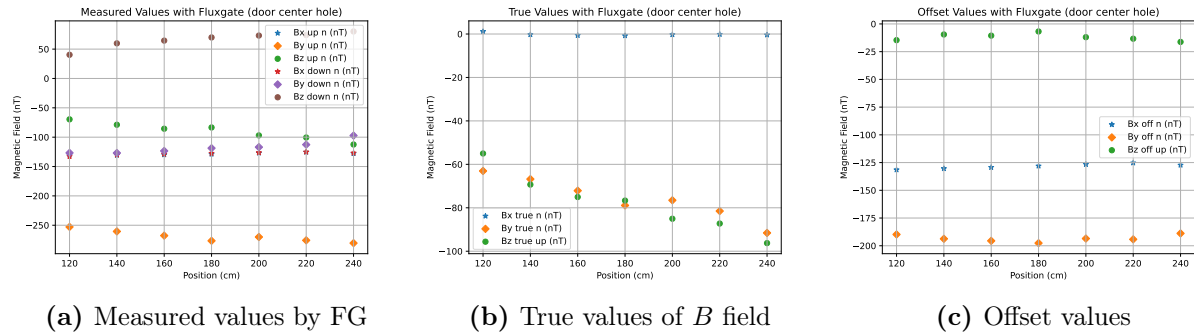


Figure 7.6: Residual magnetic fields in the central region of the undegaussed MSR, mapped from the door side at 20 cm intervals using a fluxgate.

By analyzing Figures 7.5 and 7.6, we obtained the following magnetic field components at position 180 cm that is the center of the room: $B_x = -23 \text{ nT}$, $B_y = -79 \text{ nT}$, and $B_z = -80 \text{ nT}$. These components combine to give a total magnetic field value of 114.8 nT at the center of the MSR.

We repeated the same procedure after degaussing the room. The degaussing procedure in the following layer sequence—Layer 5 (distributed), Layer 3, Layer 2, Layer 1 (power 2), Layer 1 (power 3), Layer 2, Layer 3, and Layer 5 (distributed)—at a frequency of 1 Hz, with a timing sequence of 5 seconds at full amplitude, followed by a 20-second linear ramp to zero, and concluding with 5 seconds of measurement at zero amplitude. Figures 7.7 and 7.8 show the magnetic field measurements within the room post-degaussing. These figures illustrate the updated magnetic field components and provide insight into the effects of degaussing on the room’s magnetic environment.

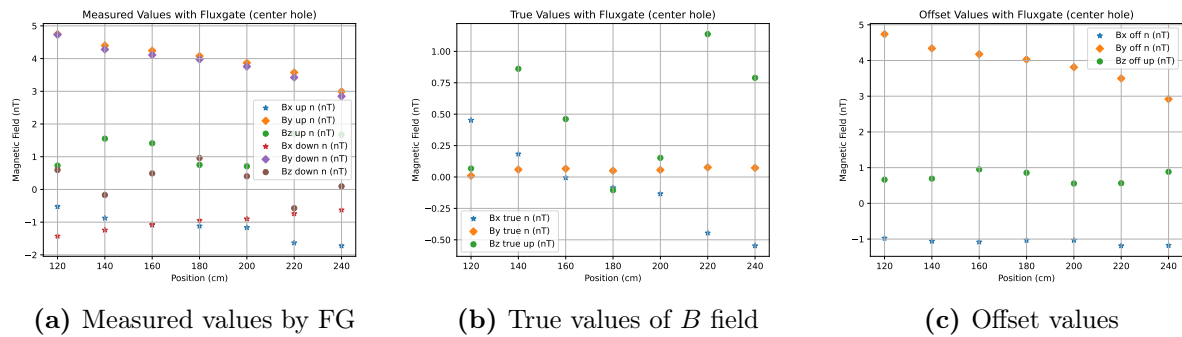


Figure 7.7: Residual magnetic fields in the central region of the degaussed MSR, mapped from the west wall at 20 cm intervals using a fluxgate.

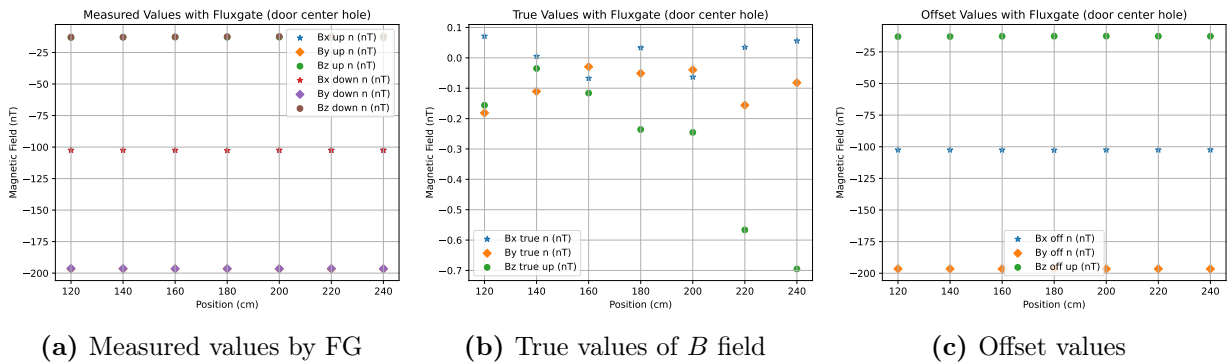


Figure 7.8: Residual magnetic fields in the central region of the degaussed MSR, mapped from the door side at 20 cm intervals using a fluxgate.

Figures 7.7 and 7.8 reveal the magnetic field components at the central position of 180 cm in the degaussed room: $B_x = -0.9$ nT, $B_y = -0.05$ nT, and $B_z = -0.12$ nT. These

measurements result in a total magnetic field of 0.9 nT at this location within the MSR, demonstrating the significant impact of the degaussing process. The magnetic field decreased dramatically from 114.8 nT to 0.9 nT, highlighting the effectiveness of the degaussing procedure.

After obtaining a minimal magnetic field reading at the center of the room, we replaced the fluxgate sensor with a QuSpin sensor for further measurements. We then repeated the entire measurement process with QuSpin, following the same procedures used for the fluxgate. Figure 7.9 displays the results recorded by QuSpin, which was mounted at one end of the aluminum tube while mapping through the central hole of the west wall of the MSR.

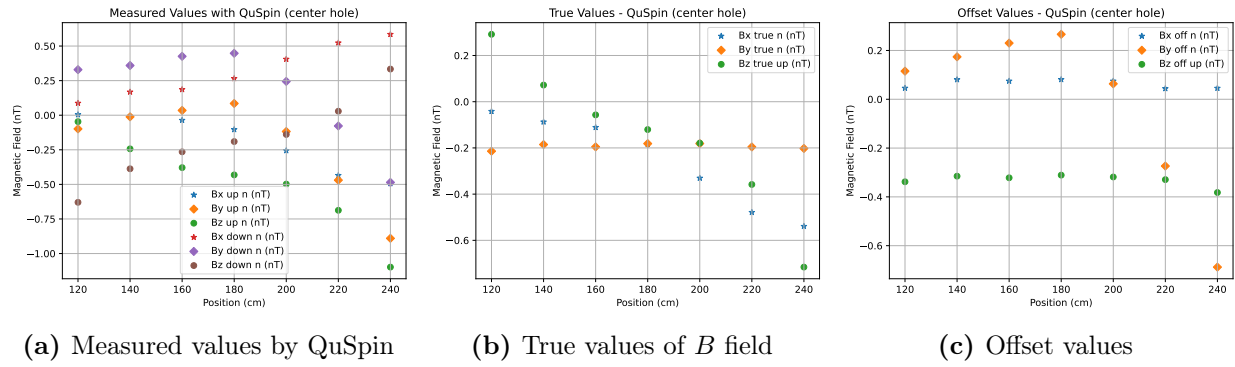


Figure 7.9: Residual magnetic fields in the central region of the degaussed MSR, mapped from the west side at 20 cm intervals using a QuSpin sensor mounted on aluminum tube.

Consistent with previous observations, the y -axis measurements remain unchanged before and after sensor rotation. To accurately determine the true values of B_y , we repositioned the mapper to the door side and performed the mapping through the central hole of the door. This arrangement enabled us to translate the sensor along the x -axis, facilitating precise measurements of B_y within the room.

Analysis of Figures 7.9 and 7.10 shows the magnetic field components at the central position of 180 cm in the degaussed room, with values of $B_x = -0.2$ nT, $B_y = 0.24$ nT, and $B_z = -0.18$ nT. These measurements yield a total magnetic field of 0.4 nT at this location

within the MSR. This value is slightly smaller than the 0.9 nT measured previously with the fluxgate. While the fluxgate measurement is somewhat higher, the close agreement between the two measurements suggests consistency in the magnetic field assessment.

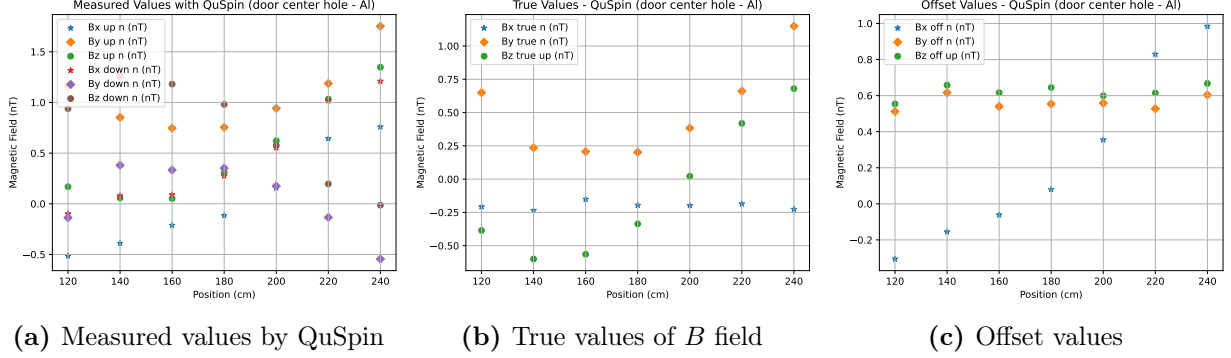


Figure 7.10: Residual magnetic fields in the central region of the degaussed MSR, mapped from the door side at 20 cm intervals using a QuSpin sensor mounted on the aluminum tube.

We were initially skeptical of the results for two reasons: first, the B_y value was not zero in Figure 7.9b, and second, we observed a drift on the scope. When rotating the sensor, we expected the z and x axes to flip, while the y -axis should remain stable. However, we noted instability in the y -axis and observed a drift on the scope, which took several seconds to stabilize. These issues suggested the presence of an additional background field. Upon investigation, we determined that the aluminum tube, being heat conductive, was affecting the magnetic field. Consequently, we replaced the aluminum tube with a PVC tube to eliminate this interference.

Switching to the PVC tube effectively eliminated the drift in y axis field observed on the scope. In Figure 7.11b, the z and x axes are correctly flipped, as shown by the blue and yellow signals, while the y -axis (depicted by the pink signal) remains stable. This contrasts with Figure 7.11a, where the y -axis exhibited significant drift. Figure 7.12 presents measurements from the QuSpin mounted on one end of the PVC tube. Although the PVC tube resolved the drift issue, the data still show some fluctuations. This fluctuation is due to the tube's small diameter, which introduced a gap between the tube and the MSR hole,

and the manual movement of the mapper, which affected measurement stability. It should be noted that the PVC tube was not long enough, resulting in measurements being limited to 200 cm instead of the intended 240 cm.

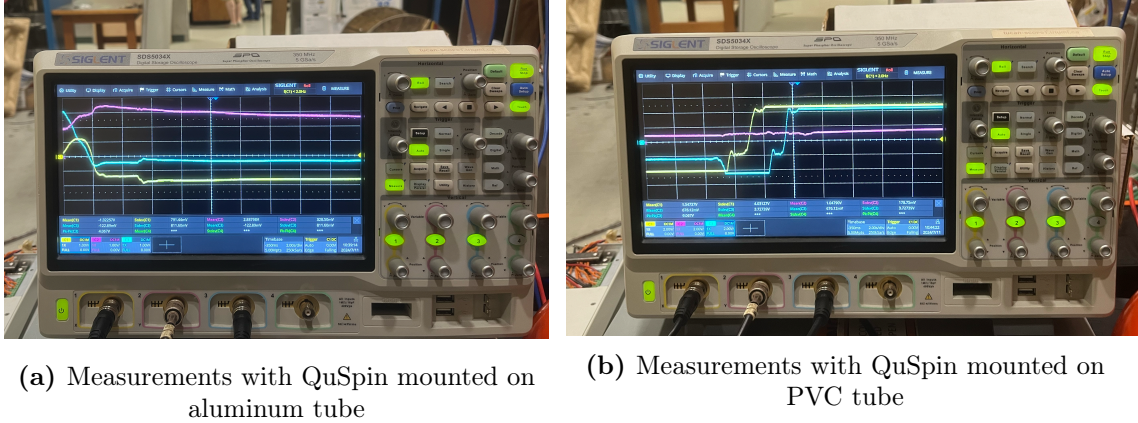


Figure 7.11: Effect of the sensor rotation on the scope.

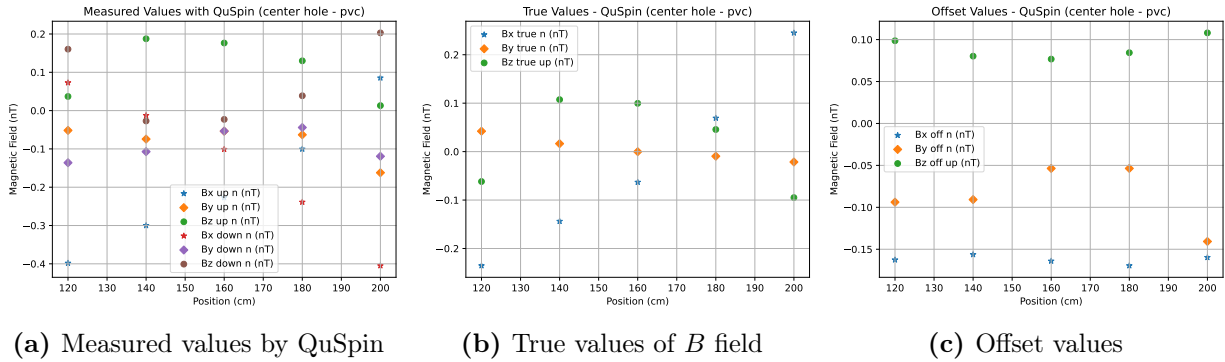


Figure 7.12: Residual magnetic fields in the central region of the degaussed MSR, mapped from the west side at 20 cm intervals using a QuSpin sensor mounted on the PVC tube.

Zhao et al. reported [69] that the QuSpin has an intrinsic offset within ± 3 nT and exhibits stability over extended periods, with a linear response within 2% up to 2 nT_{pp} in the zero-field regime.

In our measurements, we observed the following offsets for the QuSpin under two different configurations:

Our results show that the offsets are consistent with the ± 3 nT range reported by Zhao et

Table 7.1: Measured magnetic offsets for QuSpin in different materials.

Setup	B_x [nT]	B_y [nT]	B_z [nT]
PVC tube	-2.8103	-0.6233	3.30638
Aluminum tube	-2.8024	1.69512	3.40921

al., with slight variations observed between the PVC and aluminum configurations. Specifically, the B_y offset decreased with PVC, indicating improved stability in this direction. It should be mentioned that the aluminum tube replacement with PVC has been done once, and it needs more trials. The overall magnetic stability of the QuSpin was maintained when transitioning from aluminum to PVC, confirming the sensor’s robustness and reliability under different material conditions.

7.3 Summary

This chapter explains the mapping of residual magnetic fields inside the MSR to check its shielding performance. We measured the residual field before and after degaussing procedure. Initial measurements showed the residual field of near 114.8 nT at the room center. After a complete degaussing run on all shielding layers, residual field fell to 0.9 nT measured by the fluxgate sensor and 0.4 nT by the QuSpin sensor. These results confirmed the degaussing procedure has a significant impact on lowering internal field. Pressurizing the MSR door bladder gave slight improvement; the field still stayed above the target.

During the mapping unexpected drifts appeared when using the QuSpin sensor on an aluminum tube. This problem could be because of the thermal and conductive effects from the aluminum, which caused slight interference in the sensor readings. Replacing the aluminum tube with PVC fixed these issues and allowed more stable field measurements.

In summary, while the MSR has successfully achieved a low residual field, which indicates effective shielding, the SF remains below the expected levels. Continued efforts are needed to address the low shielding performance.

Chapter 8

MSR performance improvement attempts

In this chapter, we explore the various methods employed to enhance the shielding factor (SF) of the TUCAN magnetically shielded room (MSR) and investigate the underlying causes of its lower-than-expected performance. The SF is an important parameter in determining the effectiveness of the MSR in attenuating external magnetic fields. Despite extensive efforts during the construction and initial testing phases, the SF has consistently fallen short of the desired benchmarks, necessitating a deeper examination and targeted interventions.

To address these challenges, we implemented a series of methodical approaches designed to both improve the SF and identify potential sources of the discrepancies. First, we measured the permeability (μ) and SF of the MSR while gradually stepping through applied magnetic fields using degaussing coils. This approach allowed us to test whether the outer layer of the MSR had become saturated with magnetic field, which could compromise its shielding effectiveness.

Next, we investigated the possibility of improvement by adjusting the magnetic fields within the μ -metal using different coil configurations. This method was aimed at optimizing

the internal field distribution and enhancing the overall shielding performance.

Lastly, we employed a technique known as "magnetic shaking", where an alternating current (AC) shaking field is applied to increase the initial permeability of the material. This method is intended to disrupt any stable magnetic domains within the shielding layers, potentially resetting localized magnetization and thereby improving the MSR's shielding performance.

Each of these methods provided valuable insights into the behavior of the MSR under varying conditions and contributed to our understanding of the factors influencing its shielding performance. The following sections will detail the procedures, results, and implications of these techniques in the context of optimizing the MSR's shielding capabilities.

8.1 Wall Saturation

To determine whether the outer layer of the MSR had become saturated with a magnetic field, a specialized method was devised. As illustrated in Figure 8.1, magnetic field lines typically enter the μ -metal at right angles as $\mu \rightarrow \infty$. However, as the material approaches saturation, this behavior diminishes, particularly for fields that would otherwise be transverse. To quantify this effect, we introduced the ratio

$$B_{\text{ratio}} = \frac{|B_{\parallel}|}{|B_{\perp}|}, \quad (8.1)$$

where B_{ratio} serves as an indicator of the degree of saturation. When $B_{\text{ratio}} \sim 0$, the parallel component of the magnetic field is small relative to the perpendicular component, suggesting that the μ -metal is either (a) not saturated or (b) the initial field lines were perpendicular to the μ -metal surface. A deviation from this ratio, indicating a larger parallel component, would provide evidence of μ -metal saturation.

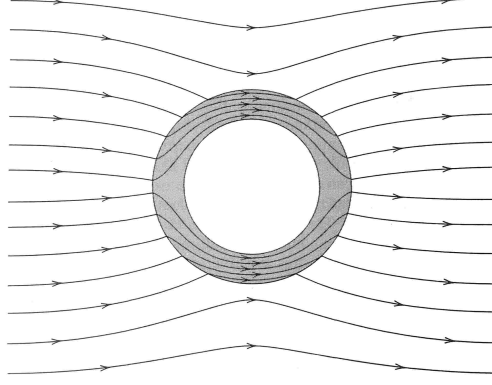


Figure 8.1: Flux lines interacting with a magnetically permeable material [70].

To systematically evaluate this phenomenon, we conducted two distinct types of measurements:

1. *Linear Path Measurement:* In this approach, the fluxgate sensor was employed to measure the magnetic field along a linear path across the μ -metal surface. By pressing the sensor head directly against the μ -metal surface, we tracked changes in the magnetic field's parallel and perpendicular components, which could indicate saturation, allowing us to accurately monitor any deviations in the B_{ratio} .
2. *External Field Application:* In this method, we applied an external magnetic field to the μ -metal, using the fluxgate sensor to monitor the resulting changes in the B_{ratio} . The sensor was instrumental in observing how the magnetic field behaved as the μ -metal transitioned from an unsaturated to a saturated state. By using the fluxgate, we could track the exact point at which the μ -metal began to show signs of saturation, providing critical data for our analysis.

These measurements provided insights into the magnetic behavior of the MSR's outer layer, offering a metric to assess the degree of saturation and its impact on the overall shielding performance.

8.1.1 Linear Path Measurement

For this experiment, we utilized a Bartington Mag690-500 μT fluxgate sensor, powered by an SCU1 power supply. The low-pass filter (LPF) was set to 10 Hz, and the high-pass filter (HPF) was set to 0 Hz. The input mode was configured to be unbalanced, and the unconditioned output was read using an oscilloscope. Data collection involved averaging the readings over one second at each measurement position.

Measurements were conducted along masking tape strips. The positions along each strip were spaced approximately 10 ± 2 cm apart, with the error margin primarily arising from conflicts with overlapping strips and holes. Each measurement was taken with the fluxgate sensor head pressed directly against the μ -metal surface.

The final axis orientations were translated into the following global coordinate system:

+ x : East, + y : North, and + z : Up

The cyclotron was active during the measurements. These readings were taken following a 1000-cycle degaussing procedure, which had been executed four days prior, with the door remaining closed since then. The zero position was defined as the starting point of the tape on each strip, as documented in the accompanying photographs.

Results and Analysis

Throughout the majority of the vertical strip measurements, we observed a zero crossing, indicating a specific point where the magnetic field transitions from positive to negative or vice versa. Notably, this crossing occurs close to the floor near the door and centrally on the south wall. The absence of zero crossings in the horizontal strip measurements suggests a different magnetic behavior in these regions.

On the floor, as shown in Figure 8.2, the measurements show no evidence of saturation, as expected, given that flux lines are anticipated to be predominantly vertical. This observation aligns with our understanding that the floor's magnetic profile may not be as meaningful due to the direction of the flux lines.

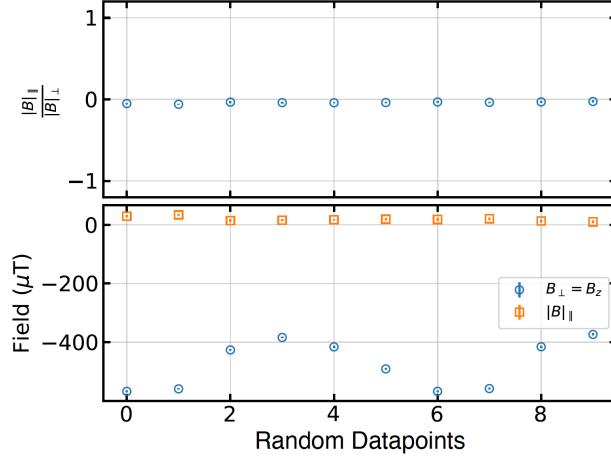


Figure 8.2: Floor, misc points between base frame

Further detailed observations from the vertical strips provide additional insights into the magnetic behavior within the MSR. On the east wall (Figure 8.3), the magnetic field exhibits a notable gradient along the height of the room. Near the top, the field is observed to be entering the μ -metal, while near the bottom, it is being expelled from the room. This behavior suggests varying saturation levels, with a stronger likelihood of saturation occurring near the base of the wall.

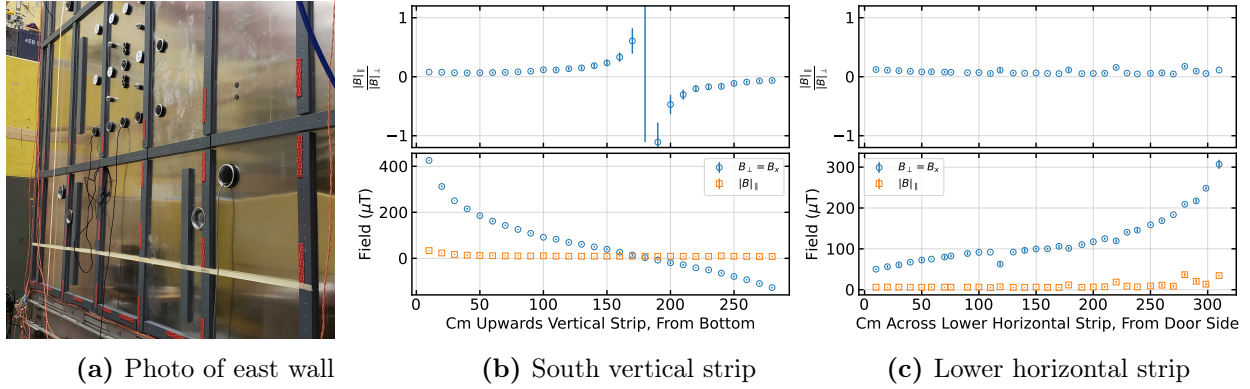


Figure 8.3: East wall: The magnetic field along the vertical strip shows that near the top of the room, the field is entering the μ -metal, while near the bottom, it is being expelled.

On the west wall (Figure 8.4), adjacent to the cyclotron, the magnetic field exhibits a distinct vertical gradient. Near the top of the room, the field exits the μ -metal, indicating

that the material is not fully saturated. Conversely, near the bottom, the field enters the μ -metal, suggesting increased flux line absorption and a possible approach to saturation. This variation highlights the non-uniform magnetic environment influenced by the cyclotron.

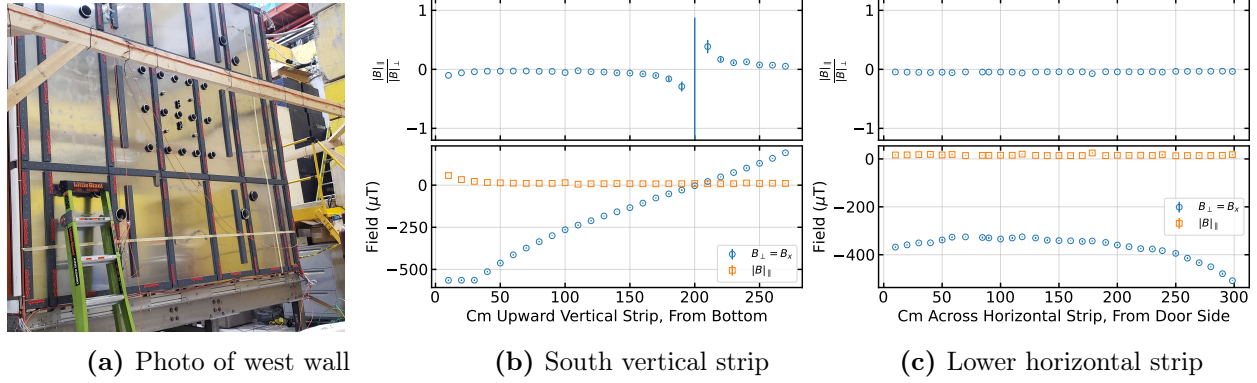


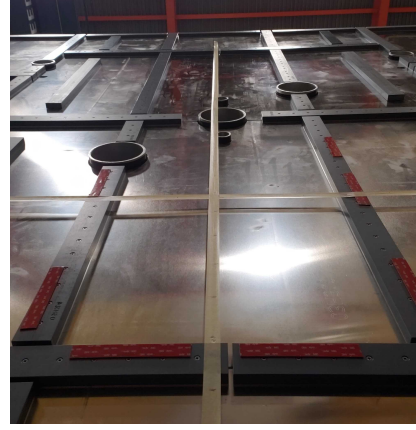
Figure 8.4: West wall (cyclotron side): Along the vertical strip, the magnetic field near the top of the room is exiting the μ -metal, whereas near the bottom, it is entering the μ -metal.

On the south wall, as observed along the vertical strip (Figure 8.5), at the upper region of the room, the field lines are directed into the μ -metal, indicating that the material is absorbing the magnetic flux in this area. Conversely, in the lower region of the room, the field lines are being expelled from the μ -metal, suggesting that the material is unable to retain or absorb the flux at this height.

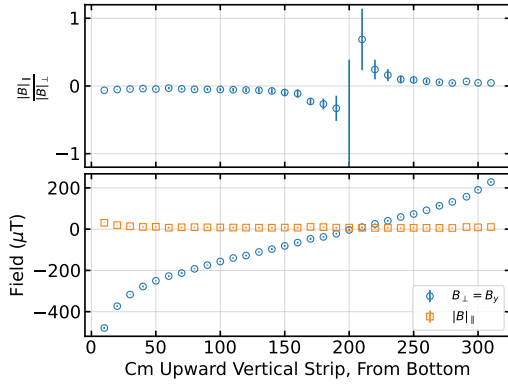
Along the north wall, where the door is positioned (Figure 8.6), the vertical strip measurements reveal that, near the upper part of the room, the magnetic flux enters the μ -metal. In contrast, closer to the bottom, the flux is expelled, indicating a diminished capacity of the material to retain the field in this lower region.



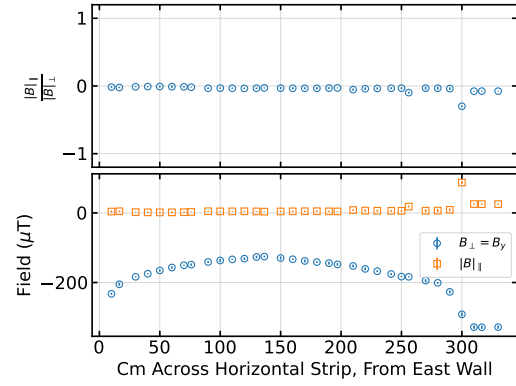
(a) Photo of south wall, vertical strip is centered



(b) Photo of south wall, vertical strip is centered



(c) Center vertical strip

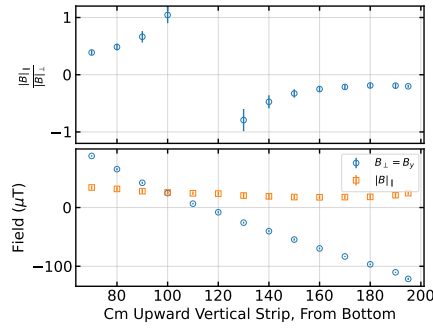


(d) Lower horizontal strip

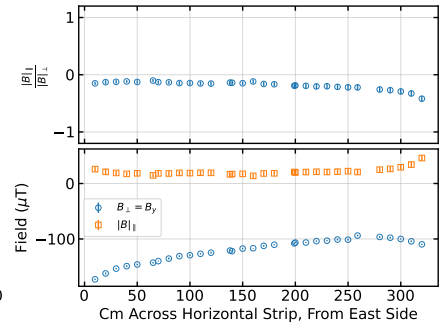
Figure 8.5: South wall: The vertical strip shows that near the top of the room, the magnetic field is entering the μ -metal, while near the bottom, it is being expelled.



(a) North door: vertical strip on west side, closer to the center, horizontal across the face



(b) Vertical on the center-west side



(c) Horizontal

Figure 8.6: North door: Measurements along the vertical strip demonstrate that the magnetic field penetrates the μ -metal near the ceiling, but is forced out closer to the floor.

The pattern of zero crossings hints at the presence of a "waist" in the flux lines, particularly at points where the magnetic flux transitions from entering to exiting the μ -metal. At these transition points, the flux density within the μ -metal is at its peak, leading to the possibility of saturation. This phenomenon is most evident in the south wall, where the "waist" is relatively level and positioned slightly above the midpoint of the wall. Conversely, the "waist" near the door on the north side is angled sharply towards the floor, indicating a potential issue with the magnetic properties of the door.

The east and west walls appear to connect these transition points smoothly, further suggesting that the door may be contributing to an uneven magnetic distribution within the MSR. Our findings emphasize the need for a closer examination of the door's magnetic characteristics, as this could be influencing the overall magnetic environment in the room.

One critical observation is that measurements near the holes in the μ -metal layer did not display significant changes in the magnetic field. This finding suggests that these holes do not create notable disruptions in the field, contrary to what might have been expected.

In summary, while no significant saturation was detected at most ambient field sites, the presence of a magnetic "waist" and the uneven distribution around the room highlight areas for further investigation. Measurements along most vertical strips tend to pass through a zero crossing, with the zero crossing at the door being close to the floor and that on the south wall occurring near the center. In contrast, all horizontal strips do not exhibit zero crossings. These observations emphasize the need for precise control over the degaussing process, as hysteresis observed in some curves suggests that the magnetic field's history influences material response, especially as the field approaches zero.

8.1.2 External Field Application

In this section, we describe the experimental setup used to apply external magnetic fields and measure their effects on the μ -metal within the MSR. The purpose of this setup is to systematically evaluate how the μ -metal responds to various field strengths and orientations.

To ensure accurate and consistent measurements, we position the fluxgate sensor on the μ -metal surface using cover strips. These strips are employed to maintain proper alignment of the sensor with the room's coordinate axes, as illustrated in Figure 8.7. This alignment is important for ensuring that the recorded magnetic field data accurately reflects the orientation of the applied fields.

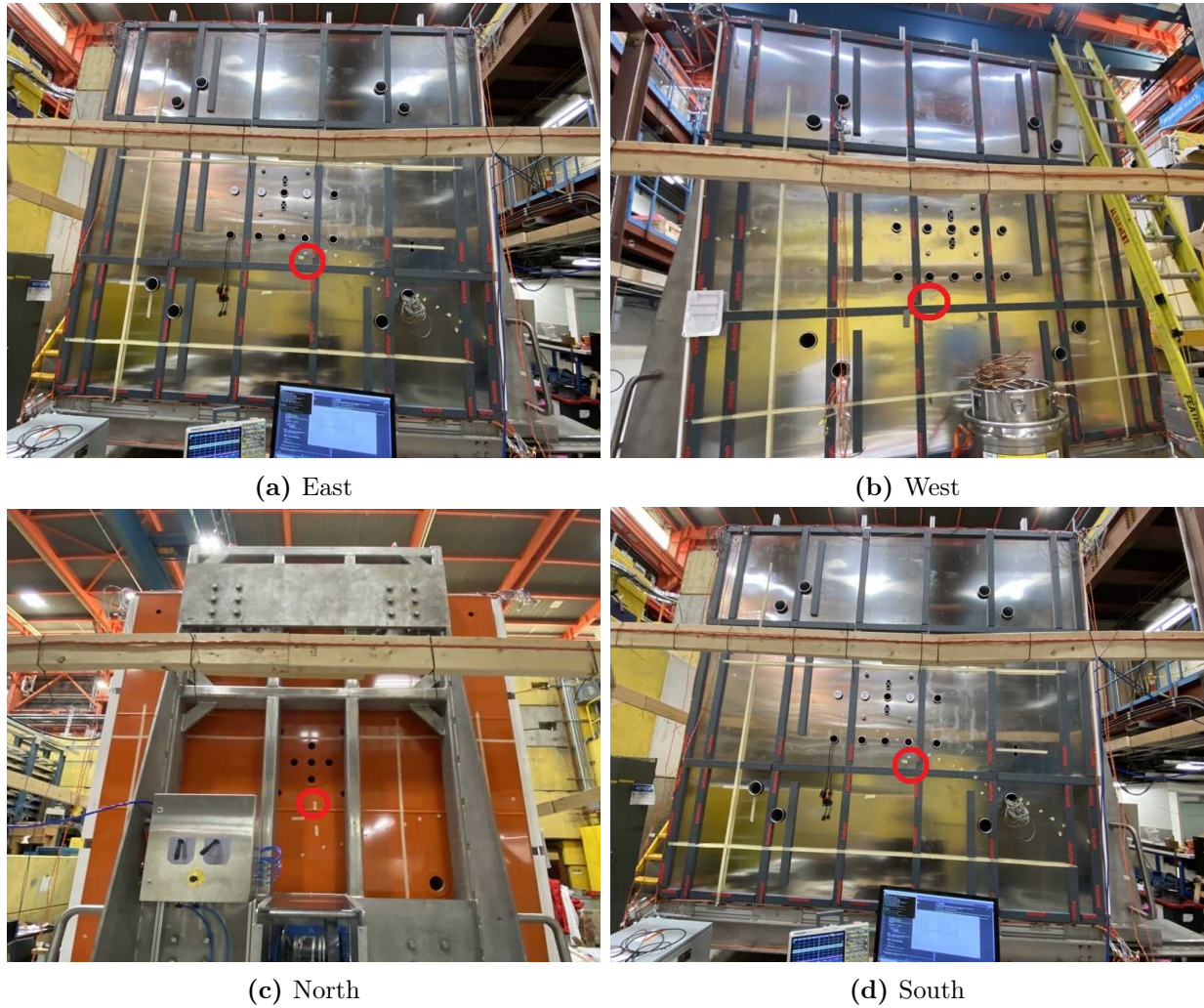


Figure 8.7: Fluxgate position on wall

For the external field application, we utilize the degaussing edge coils installed in Layer 1. These coils are driven at a frequency of 0.1 Hz, which allows us to scan through the magnetic fields applied in both directions—positive and negative. This frequency is chosen to provide

a sufficiently slow sweep, enabling precise measurement of the μ -metal's response to varying field strengths.

Data acquisition is carried out using an oscilloscope to trace the magnetic field variations, while the current supplied to the degaussing coils is measured with a Hantek current meter. It is important to note that some noise may be present in the data due to potential instability in holding the fluxgate sensor in place during measurements.

The global coordinate system is applied throughout this process, with the directions defined as follows: $+\hat{z}$ is oriented upward, $+\hat{x}$ is directed east, and $+\hat{y}$ is aligned north.

The fluxgate sensor is positioned directly on the surface of the μ -metal to measure the magnetic field components, focusing on both the perpendicular and parallel directions. By aligning the sensor with the wall, we aim to locate points where the perpendicular field component is maximized, indicating the strongest inward flux, while the parallel component is minimized, approaching zero. Once the position of maximum perpendicular flux is identified, we apply an external magnetic field, using edge coils, parallel to the surface. This allows us to investigate whether the location of maximum perpendicular flux shifts, which provides insight into the μ -metal's magnetic response.

This approach is particularly important for assessing whether the μ -metal is approaching magnetic saturation. By applying a parallel external field, either horizontally (left to right) or vertically (bottom to top), and observing changes in the perpendicular flux, we can evaluate the degree of saturation. Significant changes in the perpendicular field suggest the material is not fully saturated, while minimal changes may indicate that the μ -metal is nearing or at its saturation limit.

Results and Analysis

The following sections present the results for each face of the MSR, excluding the ceiling. Notably, the data from the south wall (Figure 8.8) appears to represent the most ideal set of curves.

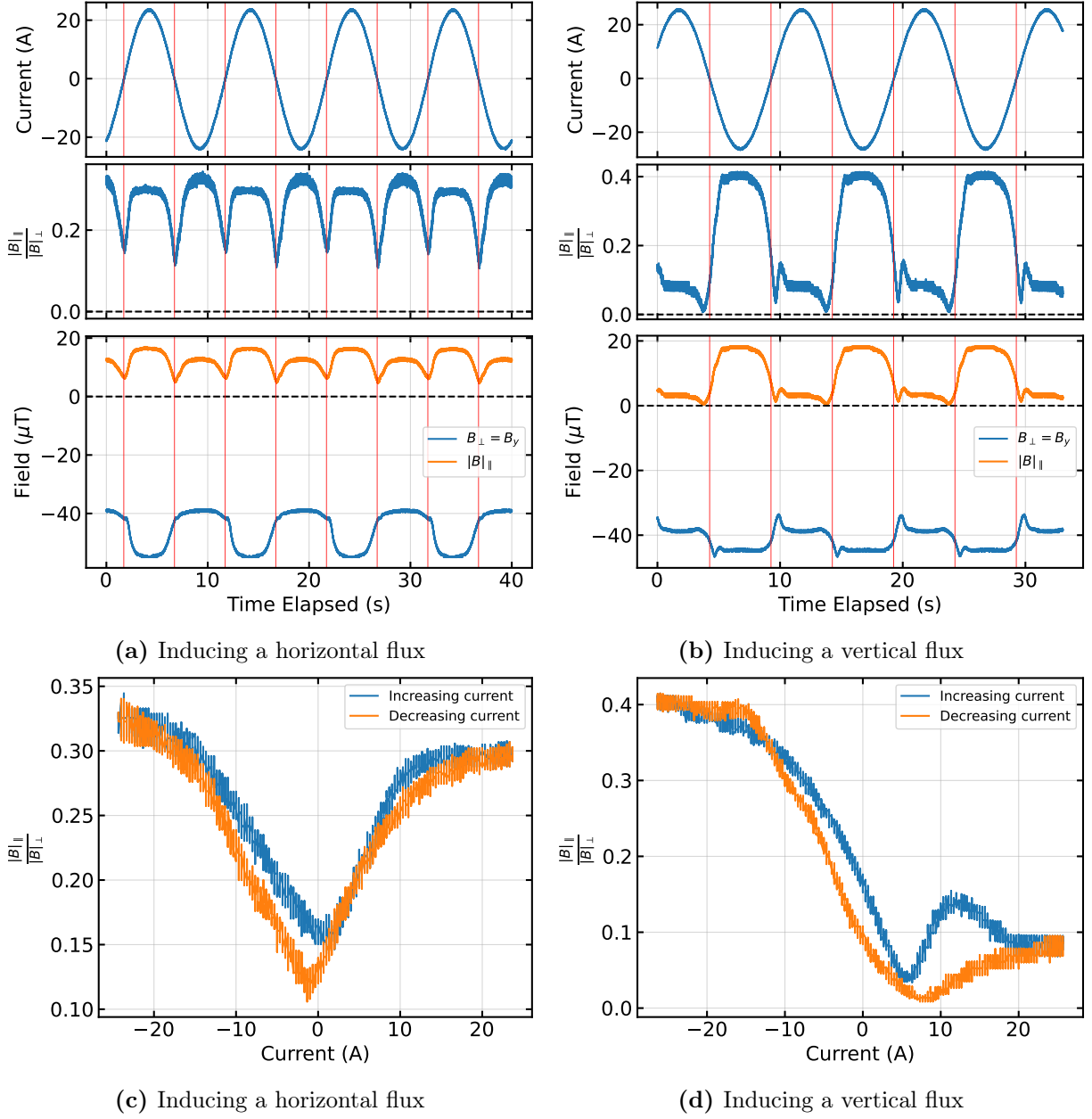


Figure 8.8: South wall

In the case of the horizontal magnetic flux, the response curve exhibits linear behavior for currents $I < 10$ A, with the field ratio being considered in absolute terms. As the current increases beyond this threshold, the curve gradually transitions to a plateau, indicating the onset of magnetic saturation in the μ -metal.

When a vertical field is applied, the behavior of the system changes notably. The minimum of the absolute field ratio shifts toward a positive current, and the slopes on either side of this minimum become asymmetrical, indicating a different magnetic response for increasing and decreasing currents. Additionally, there is evidence of hysteresis between the ramp-up and ramp-down phases, indicating that the μ -metal does not return to its original state immediately and shows a delayed response to changes in the applied magnetic field.

For the East wall (Figure 8.9), applying a horizontal magnetic field with currents below zero, whether increasing or decreasing, does not affect the B_{ratio} , which remains constantly zero. This indicates that the parallel component of the magnetic field remains at zero regardless of the direction or strength of the applied field. In contrast, for positive currents, the B_{ratio} increases exponentially, suggesting that the parallel component of the magnetic field becomes increasingly significant.

The behavior observed with the vertically induced flux is similar to that of the south wall, indicating comparable responses in this direction.

For the north (Figure 8.11), west (Figure 8.10), and bottom floor (Figure 8.12) walls, both increasing and decreasing the horizontal magnetic field lead to an increase in B_{ratio} for currents less than 0 A. As the current decreases below -15 A, B_{ratio} gradually approaches a plateau. In contrast, for positive currents, B_{ratio} reaches the plateau more abruptly with a smaller slope. Notably, the zero of the B_{ratio} shifts towards the positive part of the current range in the horizontal field application.

When a vertical field is applied, the behavior of the system changes notably. The minimum of the absolute B_{ratio} shifts toward a negative current, and the slopes on either side of this minimum become asymmetrical. This asymmetry indicates a different magnetic response for increasing and decreasing currents.

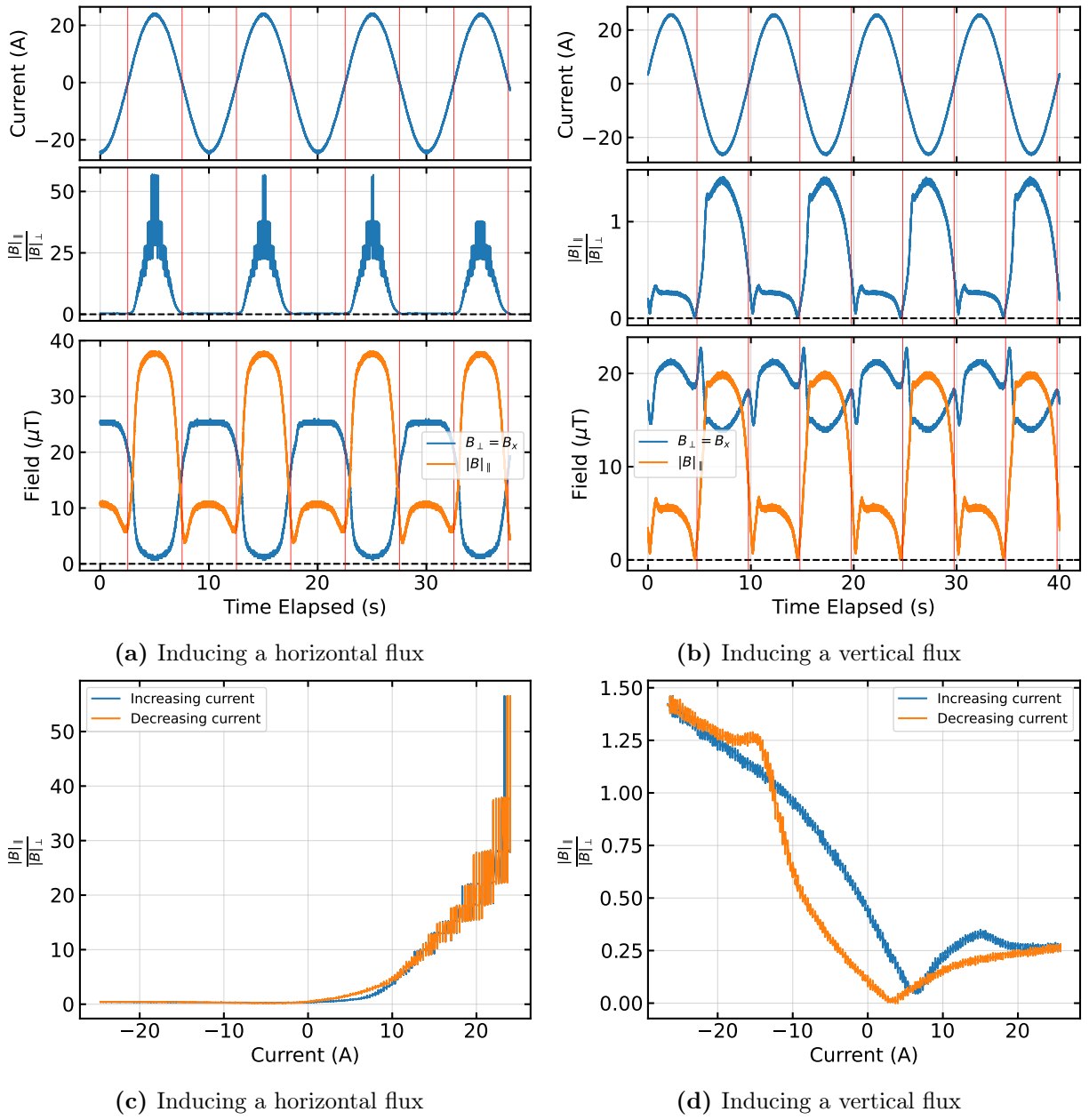


Figure 8.9: East wall

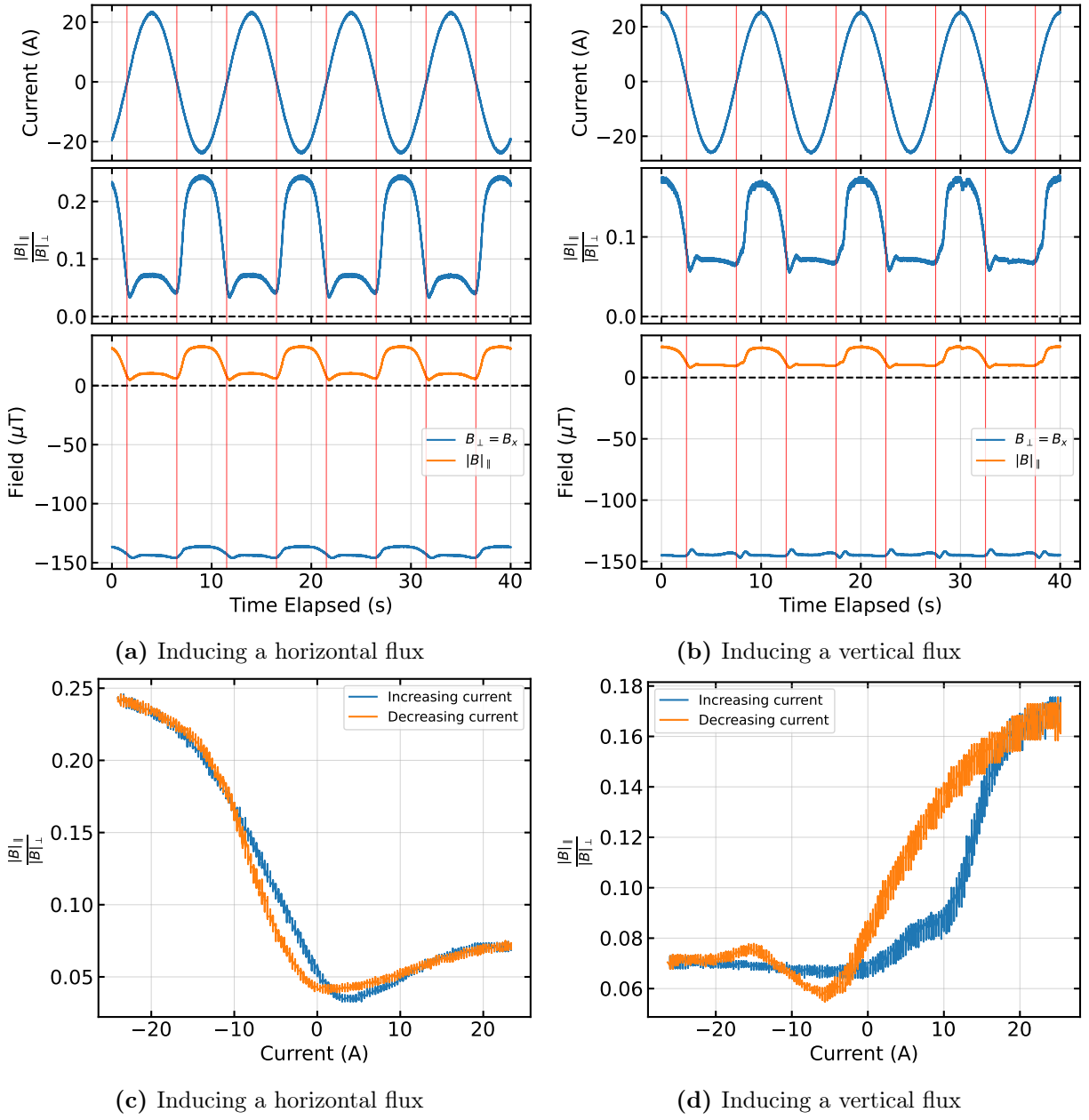


Figure 8.10: West wall

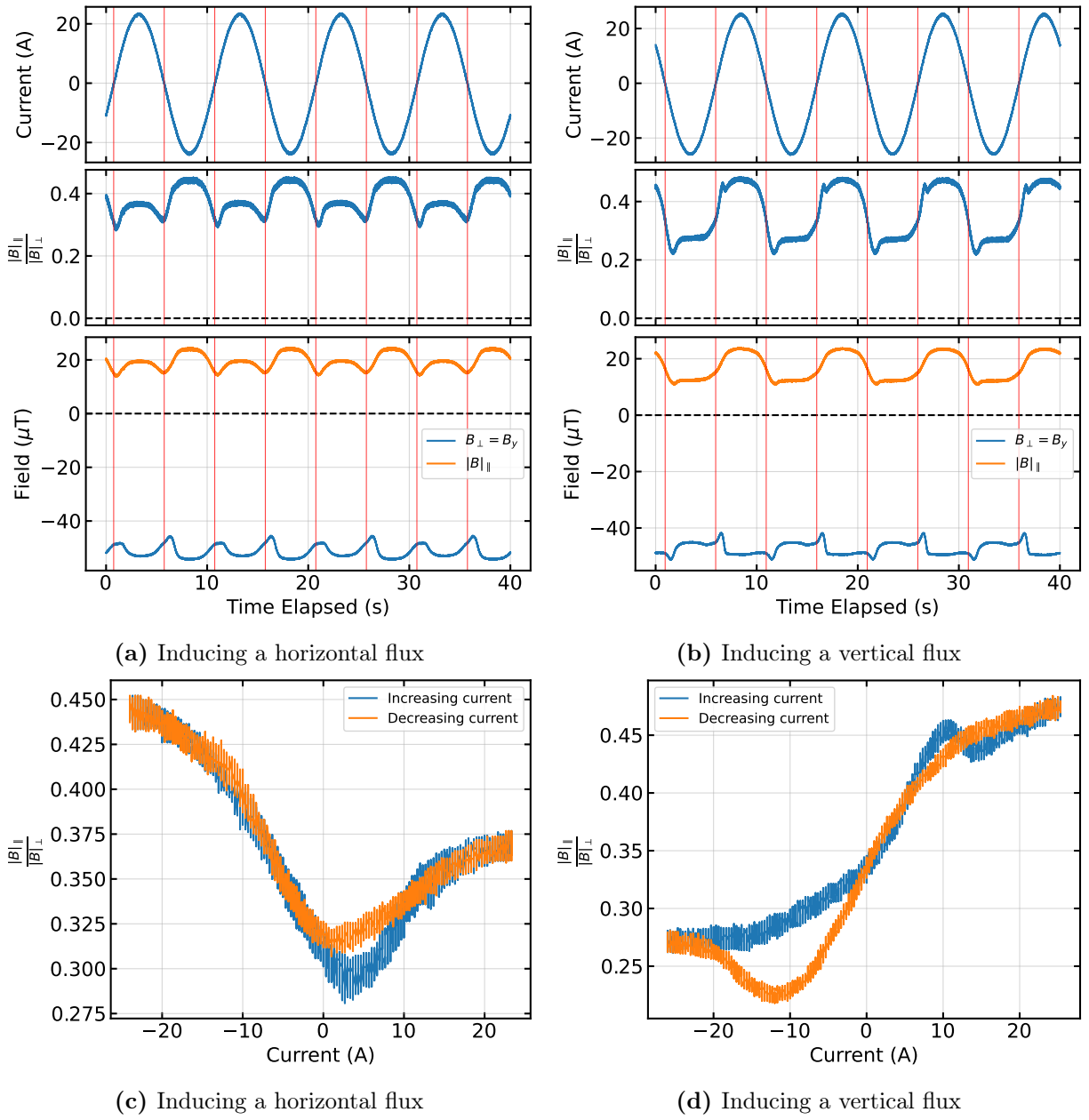


Figure 8.11: North door

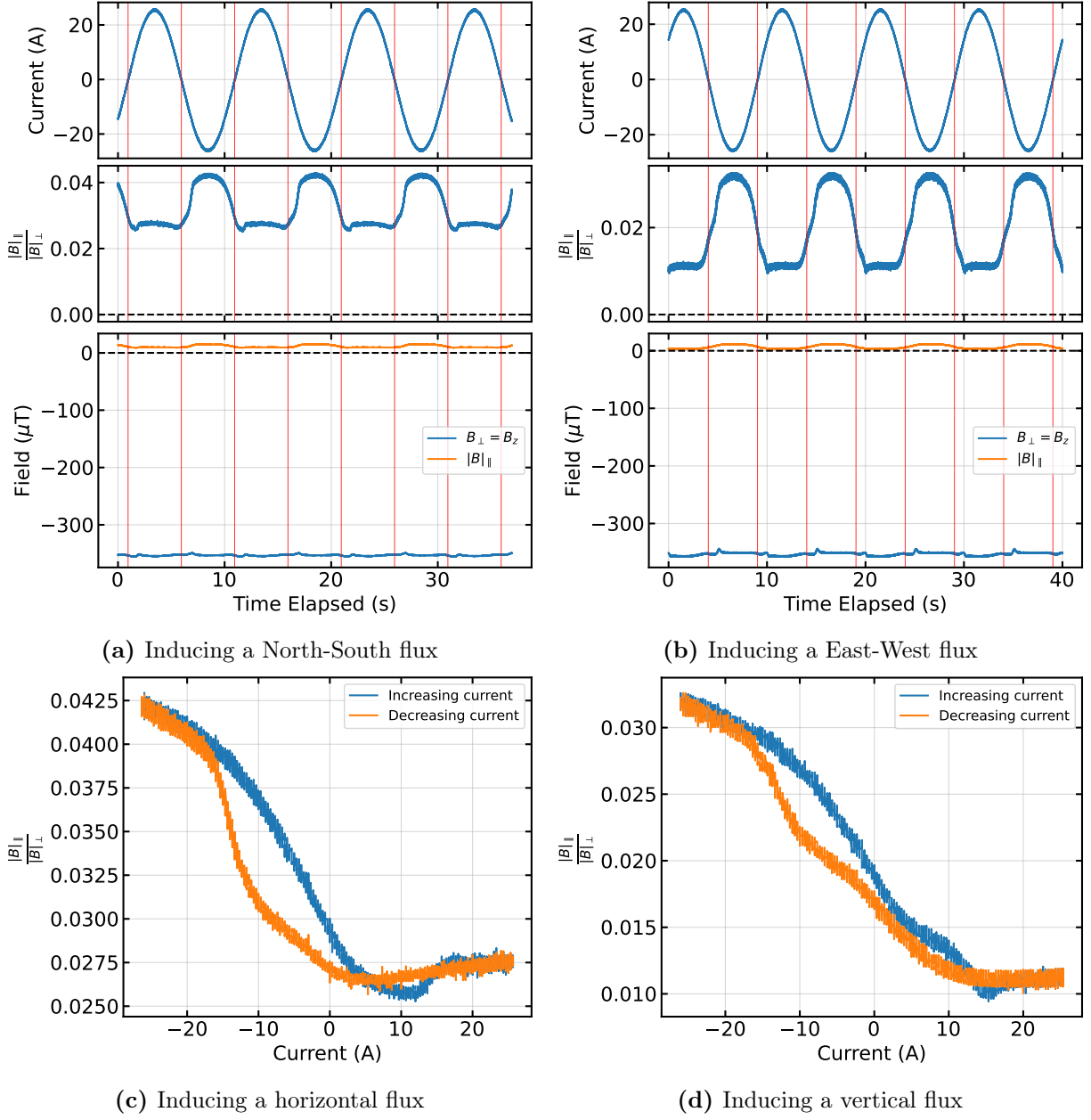


Figure 8.12: Bottom floor

In summary, spot checks of the room and driving a sinusoidal 0.1 Hz signal through the μ -metal to test for saturation revealed no significant signs of saturation in the horizontal direction. However, the results for vertical flux application were inconclusive. There was no large spike in the ratio $B_{||}/B_{\perp}$ to indicate a high degree of saturation, but the minimum

of this ratio was observed at a non-zero current. Additionally, hysteresis was present in the curves, likely due to resistance in aligning the magnetic domains with the applied field, particularly near zero field strength. This suggests that differences might occur depending on the direction of the field (positive or negative) due to the material's magnetic history.

8.2 External field compensation

In this section, we address the application of external fields using the Layer 1 degaussing coils, configured in both a toroidal arrangement and a "magic box" configuration. These coils are used to apply direct current (DC) fields, and the shielding factor inside the MSR is measured at a frequency of 0.1 Hz. The primary objective of this setup is to compensate for any external magnetic fields that could be saturating the outer layer of the μ -metal. Such saturation could lead to a phenomenon often referred to as a "magnetic hole," where external fields penetrate the shielding and enter the MSR. By applying controlled external fields, we aim to neutralize this saturation effect and improve the overall shielding performance.

8.2.1 Experimental Setup

To investigate the external field compensation, we utilize two configurations of the Layer 1 degaussing coils driven by DC power supplies:

1. *Toroidal Configuration:* This setup generates a continuous loop of magnetic flux circulating within the room in one direction. It is the same configuration used during the degaussing process, with flux lines flowing uniformly along a toroidal path around the MSR.
2. *Magic Box Configuration:* In this setup, the flux is generated in opposing walls in the same direction. The resulting magnetic flux on the two perpendicular walls should ideally cancel out, compensating for external fields more effectively along one axis,

but potentially less effective for the perpendicular axes.

The flux line patterns for both configurations are illustrated in Figure 8.13. For positive current, the blue lines correspond to the flux generated by the $+\hat{x}$ coil, the green lines correspond to the $+\hat{y}$ coil, and the red lines represent the $+\hat{z}$ coil. When negative current is applied, the direction of each flux line reverses. The toroidal configuration is specifically used for degaussing, whereas the magic box configuration aims to compensate for external fields along a single axis, possibly at the expense of reduced compensation in the orthogonal directions.

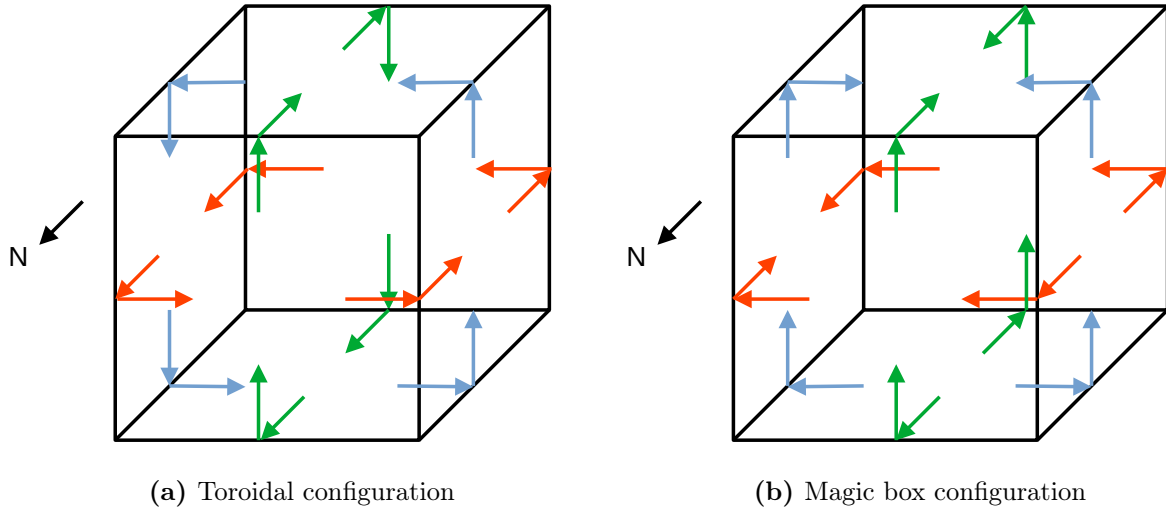


Figure 8.13: Flux lines generated by two different field configurations, as generated by the positive current. For a negative current, flip each arrow. In each configuration, the blue lines are those produced by the $\hat{x}$ coil, the green by the $\hat{y}$ coil, and the red by the $\hat{z}$ coil. This identification comes from the axis about which the toroidal configuration flux lines circulate, in a right-handed coordinate system. The toroidal configuration is that which is using during the degaussing sequence, whereas the magic box can compensate for fields along one axis, possibly at the expense of being unable to compensate anything in the perpendicular axes.

For each applied current, the shielding factor (SF) is measured using the external perturbation coil. The measurement conditions include a frequency of 0.1 Hz, an input peak-to-peak voltage of 2 V, and a Techron amplifier gain of 60. These settings are consistent with those used when the MSR was not present, and under these conditions, the perturbation

coil generates a peak-to-peak field of $36 \mu\text{T}$. The shielding factor is calculated using the following equation:

$$S = \frac{B_{\text{unshielded}}}{B_{\text{shielded}}} = \frac{36 \mu\text{T}}{B_{\text{shielded}}}. \quad (8.2)$$

Correction factors for the applied current or the reference coil, which remained inactive during all measurements, were not yet considered.

To measure the magnetic field at the center of the room, we used a Bartington Mag13-MS100 fluxgate sensor interfaced via a Bartington SCU1. The fluxgate was configured with a low-pass filter set to 10 Hz and a gain of 1000, with conditioned output. The fluxgate readings were recorded using an oscilloscope, which provided peak-to-peak voltage values. The conversion from voltage to magnetic field was then calculated using the relation

$$B = \frac{V}{105}. \quad (8.3)$$

Results

Individual Coil Configuration Testing

The results of applying the toroidal and magic box configurations to the Layer 1 degaussing coils are presented in Figures 8.14a and 8.14b. To analyze the behavior of the magnetic field as a function of applied current, we fit the data using the following absolute value function:

$$B_{\text{pp}}(I) = B_0|I - \phi| + B_1. \quad (8.4)$$

In this fit, the slopes on either side of the minimum are constrained to be equal, allowing us to extract the phase parameter ϕ , which provides an estimate of the optimal current required for the coils. These optimal current values are summarized in Table 8.1. It should be noted that these values do not necessarily sum linearly across configurations, limiting their utility in determining a global minimum for all configurations. Additionally, due to the variability and scatter present in the measurements, these optimal currents are likely

consistent with zero, although we lack a precise estimate of the associated uncertainties.

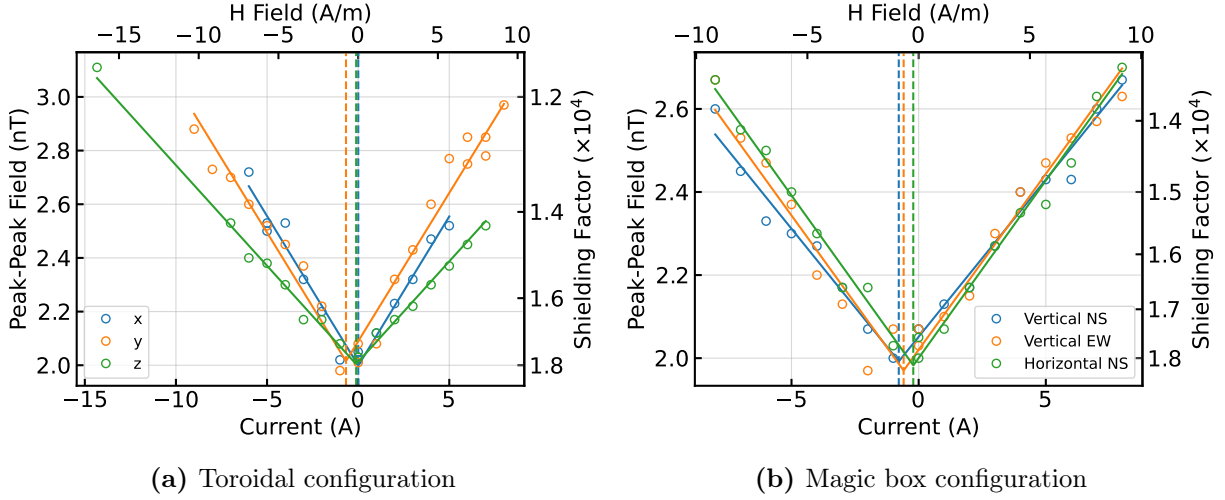


Figure 8.14: Shielding factor and peak-to-peak amplitude of the fluxgate sensor inside the room as a function of applied current, fitted with an absolute value function. Dashed lines indicate the positions of the minimum shielding factor. When one coil set was cycled, the other coils were held at zero current.

Table 8.1: Optimal currents corresponding to the minima in Figure 8.14. All values are near zero, indicating minimal saturation effects.

Coil Set	Toroidal	Magic Box
$\hat{x}$	0.007 A	-0.8 A
$\hat{y}$	-0.7 A	-0.6 A
$\hat{z}$	-0.1 A	-0.2 A

A few important observations can be made from these results. Firstly, the fact that the slopes on either side of the minimum are identical suggests that the system does not experience significant saturation in one direction versus the other. In the presence of a large saturating field, we would expect a notable difference in the currents needed to achieve the same shielding factor on either side of the minimum, corresponding to different levels of internal magnetic field alignment.

Secondly, the minima observed in all configurations are located near zero current, which further indicates that the MSR does not experience substantial saturation. According to the

BH curves for μ -metal, we anticipate saturation to occur around a magnetic field strength of approximately 30 A/m, but this was not observed within the current ranges tested.

Magic Box Configuration: X and Y Coils

When driving the x and y coils simultaneously, the goal is to produce a compensatory vertical field within the walls of the MSR. The behavior of these coils working in tandem is depicted in Figures 8.15 and 8.16. The results reveal an asymmetry in the response, with the field more readily saturating when the generated flux is oriented upwards. This asymmetry suggests a difference in the field behavior depending on the orientation of the applied current.

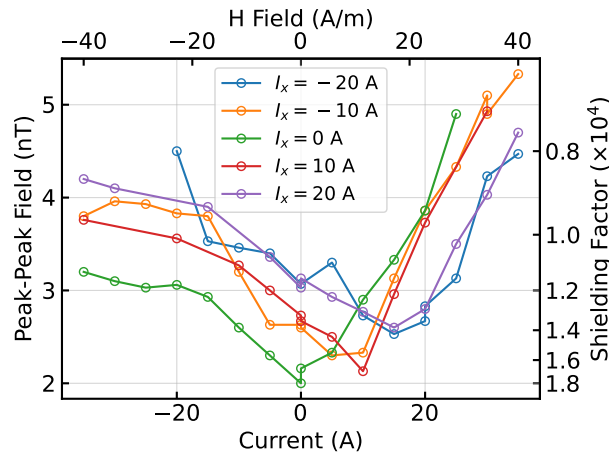


Figure 8.15: Simultaneous driving of x and y coils. The x -axis represents the current applied to the y coil, while the x coil current is indicated in the caption. The asymmetry in the curve indicates that upward flux fields are more easily saturating. The global minimum near zero suggests that the MSR remains unsaturated.

As shown in Figure 8.15, the global minimum trends towards both coils being set to zero, further indicating that the MSR is not in a state of saturation under these conditions. When the currents in the x and y coils are linked, as in Figure 8.16, the global minimum remains centered around zero, albeit mirrored in current. This was confirmed by testing two configurations: one where the coils were connected in series, and another where each coil

was driven by an independent power supply. The consistency of the results suggests that the observed behavior is robust and not due to experimental misconfiguration.

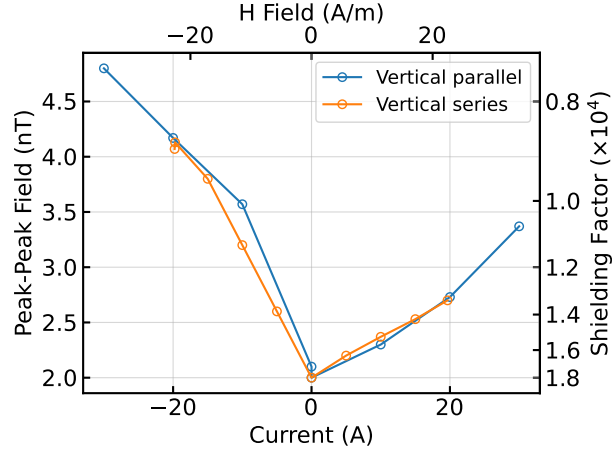


Figure 8.16: Simultaneous driving of x and y coils with identical current in both. The resulting field configuration mirrors the previous result (Figure 8.15), with a global minimum around zero. This was confirmed through repeated tests using both series and independent coil driving methods.

In summary, the experimental results reveal several key insights regarding the magnetic shielding performance of the MSR. The data fitting of the toroidal and magic box configurations indicates that the shielding factor follows a linear relationship with the applied current, with the optimal current values for each configuration being close to zero. This suggests that the MSR does not experience significant saturation within the tested current ranges. Additionally, the symmetry observed in the slopes on either side of the minima for the fitted curves indicates that the material does not exhibit directional saturation effects under these conditions.

When testing the combined x and y coil configurations, an asymmetry was observed, particularly with the upward flux field, which showed a tendency to saturate more easily. Despite this, the global minima for both configurations suggest that the MSR remains unsaturated, as the optimal currents for the x and y coils tend towards zero. These findings are consistent across repeated experiments, confirming the robustness of the results.

8.3 Magnetic Shaking

Magnetic shaking involves applying a high-frequency magnetic field, typically around 100 Hz, within the μ -metal layers of the MSR. The primary objective is to increase the shielding factor by preventing magnetic domains in the shielding material from becoming pinned at lattice defects. By applying a shaking field, these domains are mobilized, allowing for enhanced permeability and, consequently, improved magnetic shielding performance.

The technique was likely first introduced in the 1980s by Kelh  and colleagues [71], who demonstrated its effectiveness using a single-layer square cylinder with open-ended faces and dimensions of $200 \times 200 \times 400$ mm, 1 mm thick. Their study revealed that when biased by Earth’s magnetic field, the shielding factor increased by 7 dB, roughly equivalent to a $5\times$ improvement. Furthermore, they noted that the shaking field’s amplitude and frequency were not particularly critical, as they achieved a $7\times$ increase in the material’s permeability using a 50 Hz shaking field with a field strength of 5 A/m RMS. The coils in their setup were toroidally wound, a configuration they found to minimize disturbance inside the shielded volume.

More recent work by Yang et al. (2023) [72] also applied a magnetic shaking field to the outermost layer of a three-layer cubic magnetic shield. They observed a 77.4% improvement in the quasi-static shielding factor at 0.01 Hz when a 200 Hz shaking field was applied. Additionally, when this technique was applied to a three-layer MSR, the shielding factor increased by a factor of two. Yang’s experiments demonstrated that magnetic shaking has the greatest effect at lower frequencies, particularly below 10 Hz, where eddy currents are less dominant. Their study also found that higher shaking frequencies, up to 300 Hz, resulted in diminishing returns, while a bias in the shaking field could negatively affect the shielding performance. Like Kelh ’s work, Yang’s group employed toroidally wound coils to induce the shaking field.

Yang et al. [72] also measured the interference of the shaking field inside a three-layer room using a QuSpin. They saw a 0.9 nT amplitude in the shield after applying a shaking

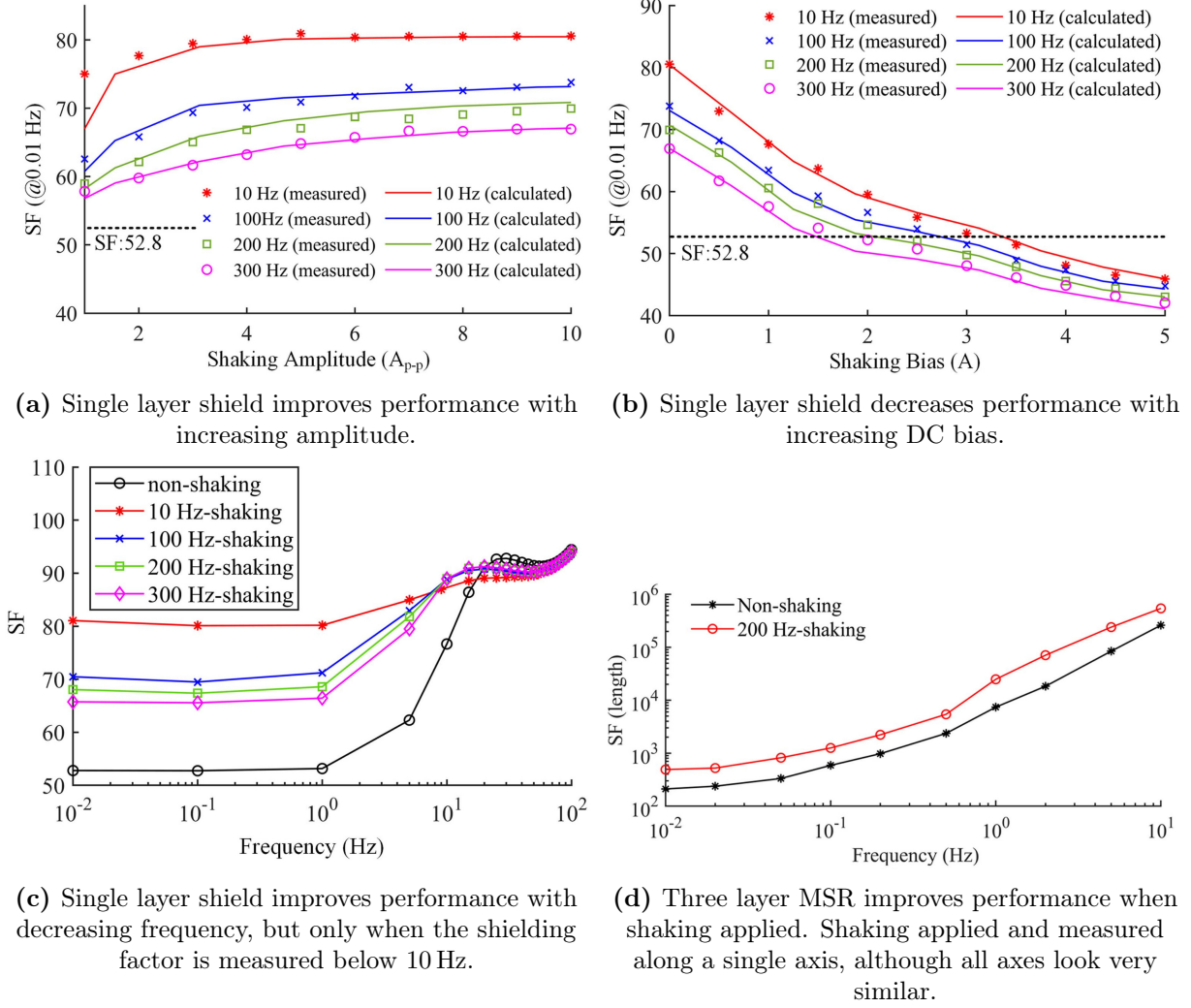


Figure 8.17: Some results reproduced from Yang et al. [72] without permission. Black dashed line indicates shielding factor without shaking.

field of 10 A and 10 Hz. This was reduced to 0.6 nT when the shaking was applied at 200 Hz.

Further studies, such as those conducted by Sasada et al. in 1990 [73], also support the effectiveness of magnetic shaking, though their results are somewhat less clear. They suggested an improvement in magnetic permeability, with a potential factor of two enhancement near 10 Hz, although their data presentation was difficult to interpret.

Together, these studies highlight the potential of magnetic shaking as an effective method for improving the shielding performance of μ -metal, especially at lower frequencies where

domain mobility becomes a limiting factor. We employed the same method to investigate whether magnetic shaking could improve the shielding factor of our MSR. The following sections detail the specific approach we took, along with the results of our investigation.

8.3.1 Setup

In this setup, the sinusoidal shaking field is applied to the outermost layer of the MSR by driving a current through the degaussing coils using a Techtron amplifier. To assess the effect of the shaking field on the shielding factor, an external sinusoidal field of approximately $18\text{ }\mu\text{T}$ is applied to the MSR. This external field is generated and monitored alongside the shaking field to evaluate its interaction with the MSR shielding material.

The external field is measured using a Bartington Mag-13MSL100 fluxgate magnetometer, while the current driving the external perturbation is recorded with a PICO current clamp meter. The current driving the shaking field is monitored separately using a Hantek current clamp meter. Data acquisition is managed by a NIDAQ system, although challenges were encountered when attempting to handle dual output signals. As a result, the external perturbation coils were controlled by a RIGOL function generator, which was set to 1 V and 0.1 Hz for these experiments.

Measurements were primarily conducted at 0.1 Hz to expedite the data collection process, with the assumption that this frequency is sufficiently close to the quasi-static condition of 0.01 Hz to yield meaningful insights into the improvements provided by magnetic shaking. Previous results from Yang et al. [72] suggest that the shielding factor's frequency dependence is minimal below 1 Hz, making 0.1 Hz a reasonable compromise between speed and accuracy.

The layer 1 degaussing cables were tested in an L-shaped configuration (Figure 3.14) to determine the optimal setup for enhancing the shielding factor under the influence of the shaking field. It should be noted using a downsampling rate that is too low can lead to data corruption, causing arbitrary frequency shifts in the measured signals. It was determined

that a sampling rate of 5 kHz produced reliable data. However, removing downsampling altogether resulted in impractically large data files. For pre-filtered data, a 5911 Hz low-pass filter was applied, with the cutoff frequency chosen to be prime to avoid interference.

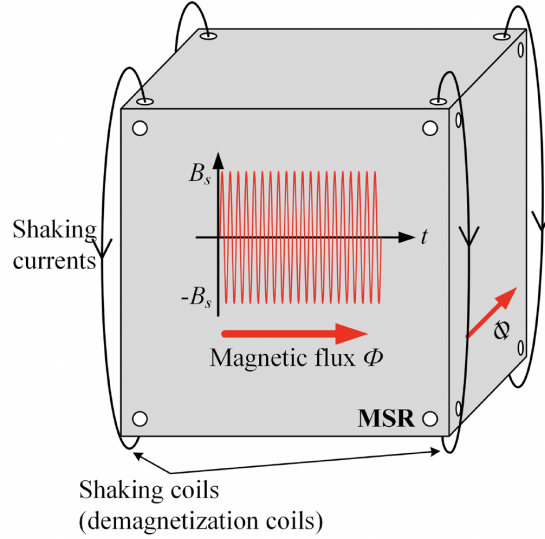


Figure 8.18: Schematic diagram of magnetic shaking for MSR [72].

Analysis

Prior to writing data to the file, the data is downsampled to reduce file sizes and facilitate processing. The downsampling factor varies between runs, typically between factors of 1 and 4, without introducing significant distortion to the recorded signals. The data acquisition system operates at a base read/write frequency of 20 kHz, while the maximum shaking frequency is 500 Hz. This setup ensures that the data is sampled at a minimum rate of 5 kHz, which is sufficient for capturing the key features of the shaking field.

Before extracting signals for analysis, the data undergoes cleaning through filtering and cropping. For the magnetic field readback, a low-pass filter at 10 Hz is applied in software to remove high-frequency noise. The remaining signals, such as the current in the external and shaking coils, are not filtered but are manually cropped to eliminate corrupted data. In particular, the first 20 seconds of each run are omitted due to observed ramp-up behavior

that remains unexplained.

The voltage readback from the shaking field is modeled using the following function to fit the observed time series:

$$V(t) = V_0 \sin(2\pi\nu t + \phi) + V_1 + V_2 t + V_3 t^2, \quad (8.5)$$

where ν represents the frequency of the sinusoidal shaking field, which is fixed for each run, and V_0 , ϕ , and the background coefficients V_1 , V_2 , and V_3 are free parameters. The background is modeled quadratically due to its effective performance in fitting the experimental data.

The resulting fits are illustrated in Figure 8.19, which shows the processed data for various signals, including the fluxgate output, the current in the external coil, and the shaking coil current. In this case, the shaking frequency was set at 500 Hz with an input signal amplitude of 5 V.

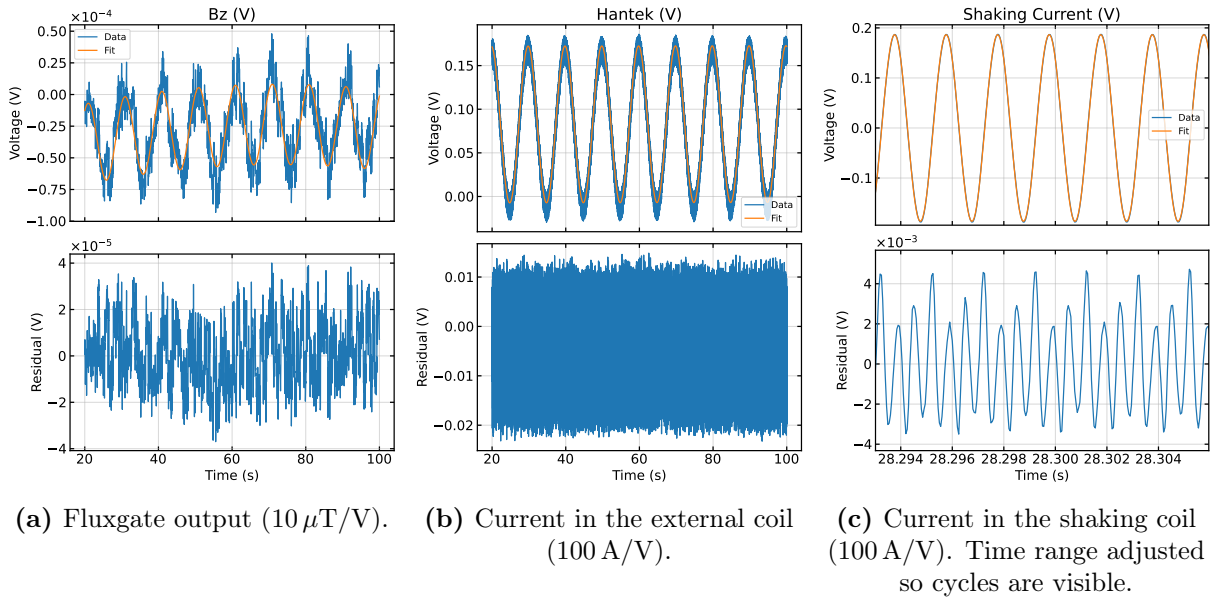


Figure 8.19: Fits to raw data after data processing. Shaking frequency was 500 Hz and the amplitude for the input signal to the amplifier was 5 V.

Once the amplitude of the signals is determined, the shielding factor (S) is calculated

using the following equation:

$$S = \left(\frac{B_{\text{ext}}^u}{B_{\text{ext}}^s} \right) \left(\frac{I_{\text{ext}}^s}{I_{\text{ext}}^u} \right), \quad (8.6)$$

where B represents the magnetic field and I is the current in the external coil. The subscripts u and s indicate unshielded and shielded measurements, respectively. The unshielded data was collected before MSR's installation (see Chapter 4), while the shielded data corresponds to the current experiment.

The shaking field effect is further analyzed using a re-formulation of the Bloch-Siegert shift by Ramsey [74], particularly relevant in the case where $|\omega_0| \ll |\omega_2|$. The shift in the Larmor frequency is given by:

$$\omega'_0 = \omega_0 - \frac{(\gamma B_2)^2}{2\omega_2} + \frac{(\gamma B_2)^2 \omega_0}{2\omega_2^2} \quad (8.7)$$

$$= \omega_0 - \Delta\omega \quad (8.8)$$

$$= \omega_0 - 2\pi\Delta\nu, \quad (8.9)$$

where $\omega_0 = \gamma B_0$ is the unshifted Larmor frequency, B_0 is the static applied magnetic field, B_2 is the oscillating field at frequency ω_2 , and γ is the gyromagnetic ratio. For neutrons, $\gamma = 29.165 \text{ Hz}/\mu\text{T}$ [75].

The neutron electric dipole moment (nEDM) shift due to the shaking field is expressed as:

$$d_n = \frac{\pi\hbar}{2E_0} \left(\nu_0^{\uparrow\downarrow} - \nu_0^{\uparrow\uparrow} \right), \quad (8.10)$$

where $\nu_0^{\uparrow\downarrow} = \nu_0 + \Delta\nu$ and $\nu_0^{\uparrow\uparrow} = \nu_0 - \Delta\nu$, and $\Delta\nu$ is the frequency shift from the shaking field. The maximum nEDM shift is given by

$$d_n = \frac{\pi\hbar}{2E_0} (2\Delta\nu), \quad (8.11)$$

where $\Delta\nu$ is given by Equation (8.9). This shift is maximized when the shaking field

orientation tracks the electric field during field flips. The maximum nEDM shift is illustrated in Figure 8.20, showing the relationship between shaking amplitude, frequency, and the resulting EDM shift.

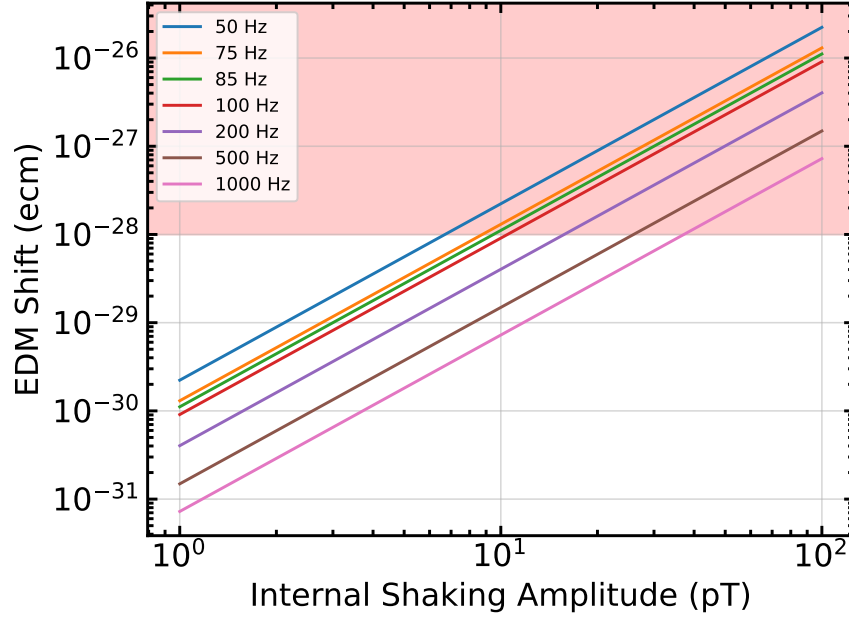


Figure 8.20: Maximum EDM shift by shaking at a given amplitude and frequency, noting that this only applies for when B_0 is flipped. $E_0 = 12.5$ kV/cm.

Results

In this section, we present and analyze two distinct data sets. The first data set, labeled **No Downsampling**, was collected without any downsampling or pre-filtering, and the external coil was positioned off-center. These measurements were conducted overnight. The second data set, **Downsampling**, was downsampled to 5000 Hz and pre-filtered using a low-pass filter with a cutoff frequency of 5911 Hz. In this case, the external coil was centered, and measurements were performed during the day, with external interference from an operational crane.

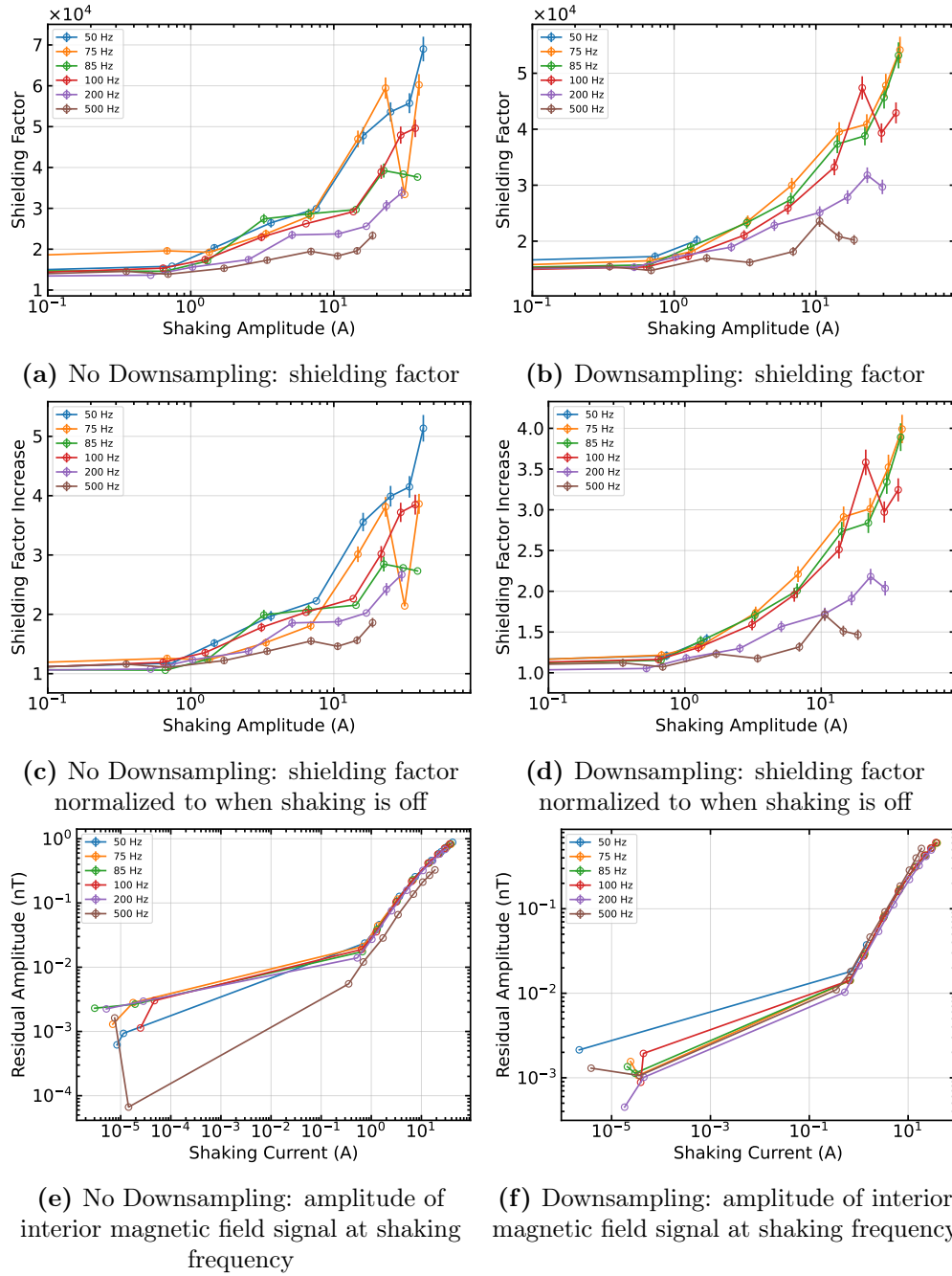


Figure 8.21: Shielding factor, improvement over no shaking, and internal field amplitude due to the shaking as a function of shaking frequency and amplitude.

The results, shown in Figures 8.21 and 8.22, reveal several key findings. First, we observe that the shielding factor increases with the amplitude of the shaking field, while it decreases with increasing shaking frequency. Although the results show qualitative reproducibility,

there is a lack of quantitative consistency between the measurements. Additionally, the amplitude of the magnetic field penetrating the walls of the MSR, which is primarily influenced by the shaking frequency, appears largely independent of the frequency itself.

Interestingly, the residual amplitude of the signal increases with shaking amplitude, but its unexpectedly clean appearance across different frequencies raises questions about its validity. If this signal were real, it would likely exhibit the same level of noise and irregularity as the shielding factor signals. Given that this signal is near the fluxgate's noise floor, further measurements using a more sensitive instrument, such as a QZFM, are recommended to confirm its accuracy.

By averaging the two data sets, clearer trends emerge, but the results would benefit from additional rounds of measurement to improve reliability and uncover any underlying patterns. These findings emphasize the importance of precise measurement conditions and thorough signal validation in magnetic shielding experiments.

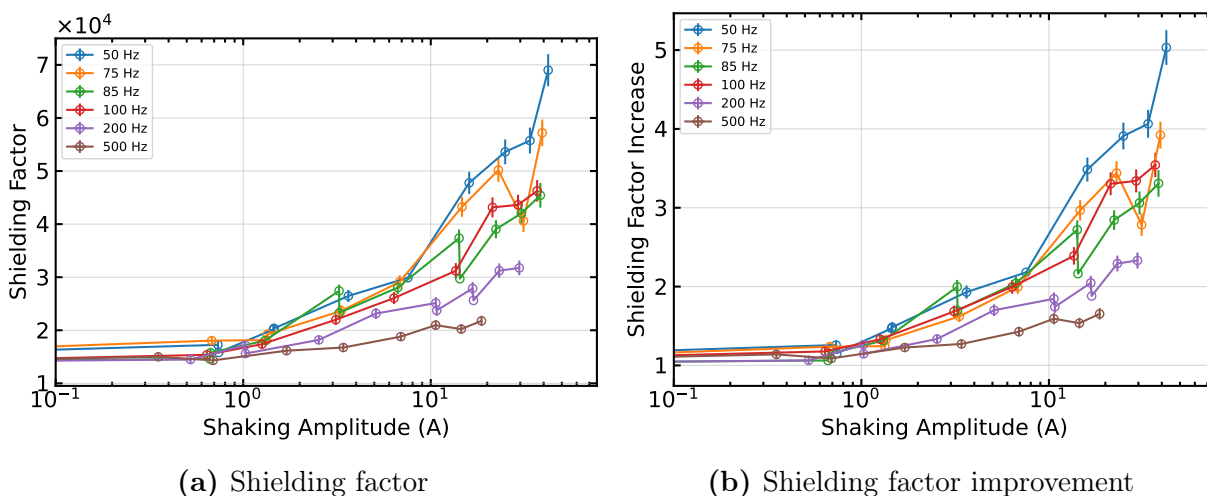


Figure 8.22: Shielding factors and improvement averaged over the two days. We average similar shaking amplitudes, without proper error propagation.

To get a factor of two increase in the shielding factor while shaking at 200 Hz or higher, we should apply at least 20 A of current. This results in about a 0.5 nT amplitude signal inside the room, as measured with the fluxgate.

In summary, using the L-shaped configuration of the layer 1 degaussing cables to evaluate the impact of the shaking field on the magnetic shielding factor revealed that increasing the shaking amplitude led to improvements in the shielding factor, while higher shaking frequencies caused a decline in performance. Although the results were qualitatively consistent, quantitative variations were observed between data sets. Further measurements would be beneficial to refine these findings and confirm the trends observed.

8.4 Analytical Study of Additional Shielding Layers

To address the observed limitations in the SF of the TUCAN MSR, an analytical study was performed to evaluate the potential benefits of adding an additional shielding layer. This study utilized the formalism developed by Bidinosti et al. [76], which provides a method for calculating the SF of multilayer MSRs. The analysis serves as a theoretical tool to explore how additional shielding could improve the performance of the existing design.

8.4.1 Methodology

The theoretical framework for calculating the SF of concentric spherical shields considers the interaction of a general external magnetic field B with spherical shells. The geometry of the system, illustrated in Figure 8.23, defines the conventions for labeling the concentric shielding layers. The m -th shield has an inner radius R_m , an outer radius $R_m + t_m$, a thickness t_m , and a permeability μ_m . For each of the M shielding layers, there are $2M$ bound surface currents to determine.

The i -th surface current K_i is located on the inner surface of the m -th shield if i is odd (i.e., $i = 2m - 1$) and on the outer surface if i is even (i.e., $i = 2m$). The radial position of K_i , denoted r_i , is given by:

$$r_i = \begin{cases} R_m & \text{for } i \text{ odd and } m = \frac{i+1}{2}, \\ R_m + t_m & \text{for } i \text{ even and } m = \frac{i}{2}. \end{cases} \quad (8.12)$$

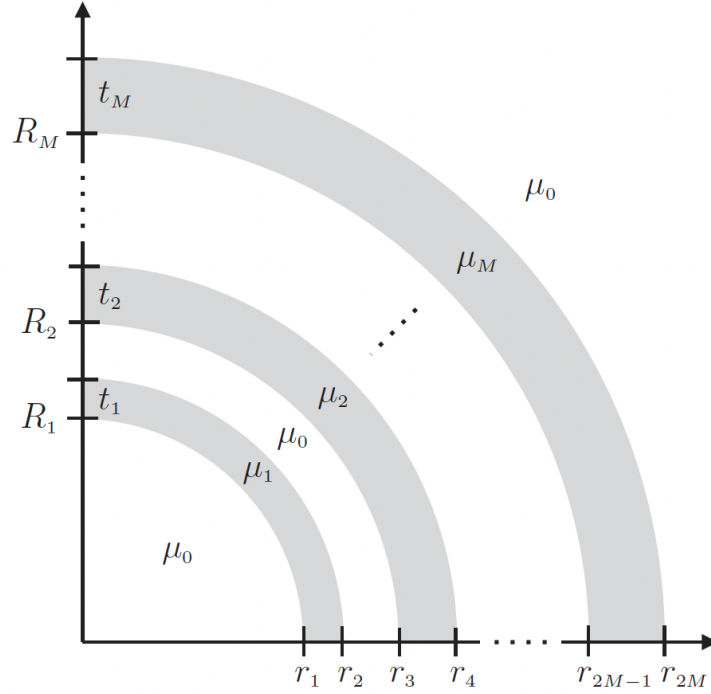


Figure 8.23: Cross-sectional view (first quadrant) of M concentric cylindrical or spherical shields separated by free space. The material boundaries are located at radial positions r_1 through r_{2M} . The inner radius R , thickness t , and permeability μ of each shield is indicated on the drawing [76].

For M concentric spherical shields, the SF is determined using a system of equations:

$$AK = G_n I, \quad (8.13)$$

where:

- A is a $2M \times 2M$ matrix of coefficients dependent on the shield geometry and material properties,
- K is the vector of bound surface currents on the shield surfaces,

- G_n describes the applied external field, and
- I is a vector of unity entries.

The elements of the matrix A for a multilayer spherical shield are defined as follows:

$$a_{ij} = \begin{cases} \frac{n}{n+1} \left(\frac{r_j}{r_i} \right)^{2n+1} & \text{if } j < i, \\ U_m & \text{if } j = i = \text{odd}, m = \frac{i+1}{2}, \\ V_m & \text{if } j = i = \text{even}, m = \frac{i}{2}, \\ -1 & \text{if } j > i, \end{cases} \quad (8.14)$$

where U_m and V_m are given by:

$$U_m = -\frac{(n+1)(\mu_m - \mu_0)}{(n+1)\mu_m + n\mu_0}, \quad (8.15)$$

$$V_m = \frac{n\mu_m + (n+1)\mu_0}{(n+1)(\mu_m - \mu_0)}, \quad (8.16)$$

and r_i and r_j are defined per Equation (8.12). Here, μ_m is the permeability of the m -th shield, μ_0 is the permeability of free space, r_i and r_j are radial positions of the layers, and n refers to the order of the multipole field.

The total SF for the system is expressed as:

$$SF_{\text{tot}} = G_n \left(G_n + \sum_{i=1}^{2M} K_i \right)^{-1}, \quad (8.17)$$

where K_i are the surface currents determined from the system of equations above.

This formalism is particularly effective for analyzing the attenuation properties of multiple shielding layers, as it accounts for both material properties (permeability, thickness) and geometric factors. To implement it, a Python-based analysis was developed to numerically

solve the shielding factor equations. This tool enabled efficient parametric studies, including the examination of various layer configurations and relative permeability values (μ_r). The Python code utilized matrix computations to solve the coupled system of equations defining the SF.

8.4.2 Model Description

Given that the TUCAN MSR is cubic, a spherical approximation was used to apply the above formalism. Two spherical models were considered:

1. **Inscribed Sphere:** A sphere with a radius such that the our TUCAN cubic MSR fits entirely inside the sphere.
2. **Circumscribed Sphere:** A sphere with a radius small enough to be enclosed entirely within the TUCAN cubic MSR.

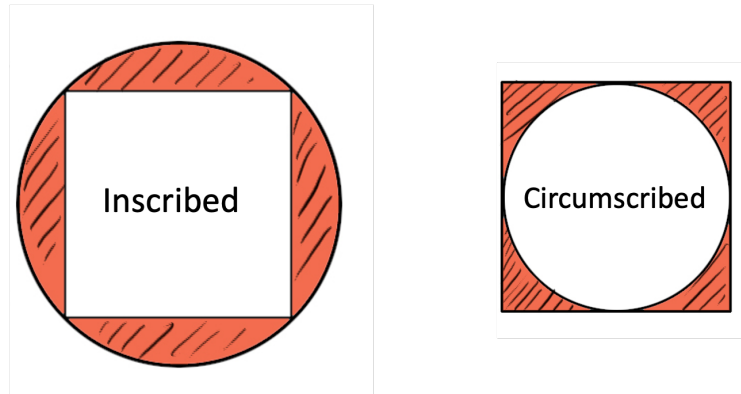


Figure 8.24: Illustration of the inscribed and circumscribed spherical models used in the analytical study. In both case, cubic MSR dimension is the same.

In the actual TUCAN MSR, the proposed shielding improvement involves adding an innermost cubic layer with a side length of 2.26 m. To analyze the effect, a spherical layer with a diameter of 2.26 m was modeled as the innermost layer in both the inscribed and circumscribed configurations.

In addition to the geometric considerations, the analysis examined the effect of varying the relative permeability (μ_r) of the added layer. Values ranging from 20,000 to 45,000 were tested to assess the sensitivity of the shielding factor improvement to material properties.

8.4.3 Results

The results of this study are summarized in Figure 8.25 that shows the shielding factor (SF) as a function of the relative permeability (μ_r) for four configurations:

1. Four-layer shield with an inscribed spherical layer,
2. Five-layer shield with an inscribed spherical layer,
3. Four-layer shield with a circumscribed spherical layer, and
4. Five-layer shield with a circumscribed spherical layer.

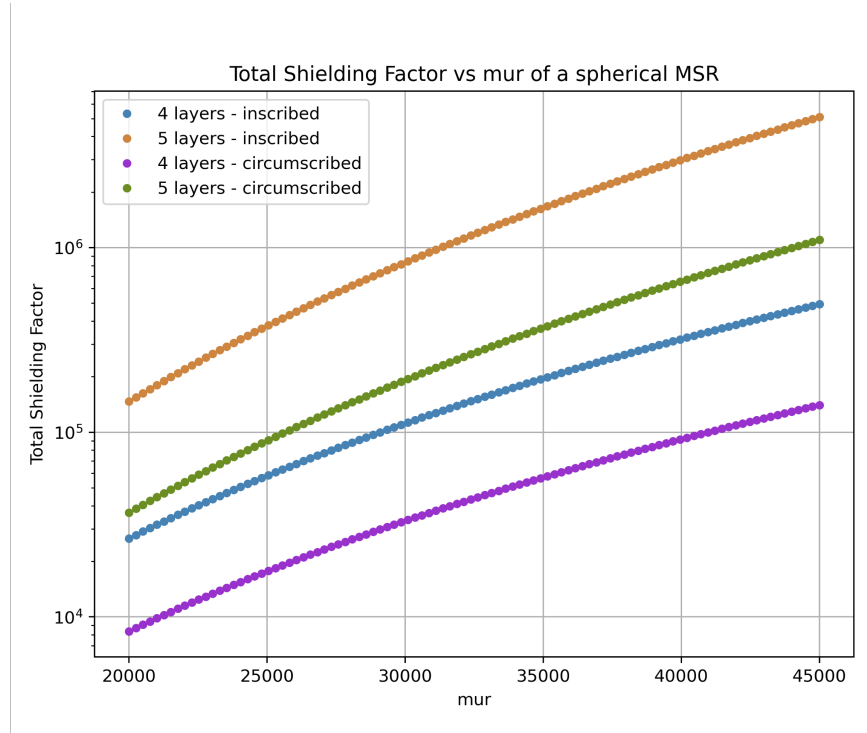


Figure 8.25: Shielding factor (SF) improvement as a function of relative permeability (μ_r) for four configurations, highlighting the impact of adding an additional layer.

The key findings from the analysis are as follows:

1. **Improvement in Shielding Factor:** In both the inscribed and circumscribed scenarios, the addition of a fifth layer improved the overall shielding factor by a factor of ~ 6 , irrespective of the relative permeability. This demonstrates the effectiveness of adding an additional layer in enhancing the MSR's shielding performance.
2. **Dependence on Relative Permeability:** While the total shielding factor increased with higher values of μ_r , the relative improvement brought by the new layer remained approximately constant across the tested range of μ_r . This suggests that the benefit of adding a layer is not diminished at higher permeability.

This analysis, along with simulations conducted by Prof. Peter Fierlinger, indicate how adding another shielding layer could enhance performance. Based on these simulations, Prof. Fierlinger predicted an improvement by a factor of ~ 9 in the shielding factor. These findings helped our collaboration decide to engage with the MSL company to explore the possibility of implementing an additional innermost layer in the TUCAN MSR.

8.5 Summary

This chapter details our efforts to improve the shielding factor (SF) of the TUCAN MSR and understand why it was under-performing.

We first checked if the outermost shielding layer was reaching magnetic saturation by gradually stepping through applied magnetic fields in the MSR layers using the degaussing coils. Measurements of permeability (μ) and SF under applied magnetic fields showed no clear signs of saturation.

Next, we tested external field compensation using DC power supplies to run current through the Layer 1 degaussing coils in toroidal and "magic box" configurations. These tests showed no improvement in SF of the MSR.

We then applied magnetic shaking—an AC field technique designed to increase the material’s initial permeability—using frequencies from 10 Hz to 500 Hz. This method doubled the shielding factor, but required at least 20 A to be effective.

Lastly, an analytical study was conducted to assess the potential benefits of adding an additional shielding layer to the MSR. Using a spherical approximation based on the formalism presented in Reference [76], the study demonstrated that introducing an innermost layer could enhance the SF by a factor of approximately six. This improvement was observed consistently across a range of relative permeabilities, supporting the feasibility of incorporating an extra layer. These findings informed the team’s discussions with the MSL company about the possibility of implementing this enhancement.

Chapter 9

Conclusion

The discovery of the nEDM would help explain the baryon asymmetry of the universe and greatly informs theories beyond the standard model of particle physics. Even setting upper limits on what the nEDM could point to likely candidates for physics beyond the standard model. The TUCAN nEDM experiments will use Rasmeys method of separated oscillatory fields to measure the nEDM, where the magnetic field over the measurement cell needs to be tightly controlled and measured. Thus a magnetic shield is employed over the measurement cell and is usually in the form of a room called the Magnetically Shielded Room (MSR). This dissertation documented the fabrication and characterization of the TUCAN MSR for the TUCAN nEDM experiment.

Chapter 2 lays out the principles of magnetic shielding where the spacing between magnetic shielding layers and thickness of the magnetic shielding are the dominant factors in determining the shielding factor. To reach the SF of most modern nEDM experiments ($\sim 100,000$ SF at DC), several layers of μ -metal material are employed. After shielding factor, residual magnetic field is the next concern, where a highly degaussed/idealized most inner layer of magnetic shielding is required. A well idealized MSR has the lowest residual field and gradients possible for that shield where the TUCAN MSR's needed to have a < 1 nT residual field over the 1 m^3 measurement cell volume.

Chapter 3 introduced the experimental setups, tools, and instrumentation tailored for the MSR’s evaluation. The integration of custom-designed systems, including the relay box, perturbation coil, and reference coil, allowed for accurate measurement of the MSR’s SF and residual fields.

Shielding Factor measurement procedure is explained in Chapter 4 and Chapter 5. Pre-installation measurements provided a baseline for the unshielded magnetic environment. The RMS noise in B_x and B_y was measured at 0.55 nT and 0.6 nT, respectively, while B_z had a higher residual noise of 1.5 nT. When the cyclotron field was turned off, the noise levels dropped significantly to 0.20 nT (B_x), 0.22 nT (B_y), and 0.4 nT (B_z), demonstrating the cyclotron’s impact on the surrounding magnetic field.

Once the MSR was installed, shielding factor measurements were conducted at different stages of assembly. With the copper layer (Layer 4) and the base of the MSR made of μ -metal, at 100 Hz, the SF was 1123. After installing the first μ -metal layer (Layer 5), the SF increased to 242 at 1 Hz and 2317 at 10 Hz, indicating a significant improvement. The SF with the second μ -metal layer (Layer 3) reached 4467 at 1 Hz and 46885 at 10 Hz. However, at very low frequencies (<0.1 Hz), the SF was lower than expected. For the third μ -metal Layer (Layer 2), the SF was 1225 at 0.01 Hz with the cyclotron on and 1740 with it off—well below the expected 8000. At 100 Hz, the SF reached 28701 (cyclotron off) but dropped to 23930 when the cyclotron was on. Final μ -metal Layer (Layer 1) increased the SF to 146201 at 1 Hz (cyclotron off), but at 10 Hz, it remained at 72232—lower than the expected values.

Despite the efforts in designing, constructing, and characterizing the TUCAN MSR, its final shielding performance did not fully meet the expected levels. While each additional shielding layer improved the shielding factor (SF), the overall performance remained lower than anticipated.

The degaussing process and its results are discussed in Chapter 6. Hysteresis loops, which help to study the behavior of the material and the saturation, showed the effectiveness of this process even with cyclotron field on.

To check the residual field inside the MSR, a custom-built mapper was designed and used. Initially, the central residual field was measured at 114.8 nT. After a complete degaussing run across all shielding layers, this was reduced to 0.9 nT with the fluxgate sensor and 0.4 nT with the QuSpin sensor. While these values meet the target of 1 nT, additional pressure applied to the MSR door slightly improved the results, indicating that minor mechanical adjustments could still enhance performance.

One unexpected issue was observed during residual field mapping: the QuSpin sensor exhibited slow drifts when mounted on an aluminum tube. This was likely caused by thermal and conductive effects interfering with sensor readings. Replacing the aluminum tube with a PVC structure eliminated the issue, allowing for more stable and repeatable measurements.

Given that the SF was lower than expected, several additional tests were conducted. We tested MSR's wall saturation and measured SF under varying applied fields to check for signs of saturation. No strong evidence of saturation was found. Next, we tried to compensate external field by using different degaussing coil configurations to see if SF could be improved. The results didn't show any improvements. Magnetic shaking was our next step to improve SF. Applying an AC shaking field at frequencies from 10 Hz to 500 Hz temporarily doubled the SF. However, this effect required sustained currents of at least 20 A, making continuous operation impractical. Additional shielding layer was analyzed using a theoretical study suggesting that adding an extra innermost μ -metal layer could improve SF by a factor of six. This possibility was discussed with the manufacturer (MSL) as a potential future enhancement.

In summary, while the TUCAN MSR has been successfully constructed and characterized, its final SF remains below the expected level. This dissertation has documented the steps taken to investigate and mitigate the observed shortfall. Despite extensive efforts, none of the methods, discussed in this dissertation, provided a significant enough improvement. As a result, the collaboration ultimately decided that adding a fifth μ -metal layer was the best course of action to enhance the shielding factor.

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Appendix A

Stick Mapping Simulation for Magnetic Field Analysis

A.1 Introduction

To map the magnetic field distribution within the TUCAN MSR, a stick mapping technique was developed. This approach utilized the existing access holes in the MSR to insert a magnetometer mounted on a rigid stick. By incrementally moving the sensor through the holes and recording magnetic field measurements, the spatial variation of the field was mapped in three dimensions (See Chapter 7). This appendix outlines the simulation methodology, error considerations, and findings that informed the design and application of the stick mapping technique.

A.2 Scalar potential decomposition of the remanent field

In modern nEDM experiments, a weak and nearly static magnetic field of approximately $B_0 \approx 1 \mu T$ is applied within a large experimental volume, typically about a cubic meter. This field, primarily aligned along the z-axis ($\vec{B}(x, y, z) \approx B_0 \vec{e}_z$), is designed to be highly

uniform; however, minor variations in the field can significantly influence the results. A precise characterization of these nonuniformities is essential for understanding their impact on systematic errors [44]. To address these variations, a multipole decomposition of the magnetic scalar potential using spherical harmonics is performed, which allows the quantification of the strength of each multipole component from field measurements. This method is used to evaluate the influence of different multipoles on systematic errors, and simulations of the field and magnetometer responses provide critical insights for defining the requirements and constraints of the experimental system.

The fundamental equations governing magnetostatics [70] in a vacuum are expressed as follows:

$$\vec{\nabla} \times \mathbf{B} = \mu_0 \vec{J}_f, \quad (\text{A.1})$$

$$\vec{\nabla} \cdot \mathbf{B} = 0. \quad (\text{A.2})$$

Here, $\mathbf{B}$ represents the magnetic field, μ_0 is the permeability of free space, and $\vec{J}_f$ denotes any free current present in the medium. In scenarios devoid of magnetic materials or currents, as is the case by design in this context, the first equation simplifies to $\vec{\nabla} \times \mathbf{B} = 0$. This allows for the expression of the magnetic induction $\mathbf{B}$ as the negative gradient of a magnetic scalar potential Φ :

$$\mathbf{B} = -\vec{\nabla}\Phi. \quad (\text{A.3})$$

Consequently, utilizing equation (A.2), the magnetic scalar potential Φ must satisfy Laplace's equation:

$$\nabla^2 \Phi = 0. \quad (\text{A.4})$$

In spherical coordinates, Laplace's equation has a solution in the form [77]:

$$\Phi = \sum_{l,m} [A_{l,m} r^l + B_{l,m} r^{-(l+1)}] [C_{l,m} \cos(m\phi) + D_{l,m} \sin(m\phi)] [E_{l,m} P_l^m(\cos \theta) + F_{l,m} Q_l^m(\cos \theta)], \quad (\text{A.5})$$

where P_l^m and Q_l^m are the associated Legendre polynomials of the first and second kinds, respectively. The term $r^{-(l+1)}$ diverges at the origin ($r = 0$), which necessitates setting $B_{l,m} = 0$ to avoid singularities. Similarly, since Q_l^m diverges at $\cos \theta = 1$, we also set $F_{l,m} = 0$. The constants $C_{l,m}$ are retained due to their favorable properties concerning the z derivatives of these functions.

The basis, originally presented by [3], is defined as follows:

$$\Phi_{l,m} = C_{l,m}(\phi) r^l P_l^{|m|}(\cos \theta), \quad (\text{A.6})$$

with

$$\begin{aligned} C_{l,m}(\phi) &= \frac{(l-1)!(-2)^{|m|}}{(l+|m|)!} \cos(m\phi) && \text{for } m \geq 0 \\ &= \frac{(l-1)!(-2)^{|m|}}{(l+|m|)!} \sin(|m|\phi) && \text{for } m < 0. \end{aligned} \quad (\text{A.7})$$

The functions $\Phi_{l,m}$ serve as basis functions for the magnetic scalar potential. Utilizing equation (A.3), the corresponding magnetic field basis functions, denoted as $\Pi_{\hat{e}_i,l,m}$, can be expressed as:

$$\Pi_{\hat{e}_i,l,m} = -\partial_{\hat{e}_i} \Phi_{l+1,m}. \quad (\text{A.8})$$

It is noteworthy that the index transition from $l+1$ to l indicates that $G_{1,2}$ constitutes a valid gradient term despite having $m > l$. In this context, l consistently refers to the order of the polynomial in $\Pi_{\hat{e}_i,l,m}$.

The magnetic field at a specific location can be represented as [44]:

$$\mathbf{B}(\vec{r}) = \sum_{l,m} G_{l,m} \begin{pmatrix} \Pi_{x,l,m}(\vec{r}) \cdot \hat{i} \\ \Pi_{y,l,m}(\vec{r}) \cdot \hat{j} \\ \Pi_{z,l,m}(\vec{r}) \cdot \hat{k} \end{pmatrix} \quad (\text{A.9})$$

For multiple positions indexed by n , the expression becomes:

$$\begin{bmatrix} B_x(x_1, y_1, z_1) \\ \vdots \\ B_y(x_1, y_1, z_1) \\ \vdots \\ B_z(x_1, y_1, z_1) \\ \vdots \\ B_z(x_n, y_n, z_n) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & y_1 & 0 & \frac{-1}{2}x_1 & z_1 & x_1 & 2x_1y_1 & 2y_1z_1 \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \\ 1 & 0 & 0 & x_1 & z_1 & \frac{-1}{2}y_1 & 0 & -y_1 & x_1^2 - y_1^2 & 2x_1z_1 \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \\ 0 & 1 & 0 & 0 & y_1 & z_1 & x_1 & 0 & 0 & 2x_1y_1 \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \\ 0 & 1 & 0 & 0 & y_n & z_n & x_n & 0 & 0 & 2x_ny_n \cdots \end{bmatrix} \cdot \begin{bmatrix} G_{0-1} \\ G_{00} \\ G_{01} \\ G_{1-2} \\ G_{1-1} \\ G_{10} \\ G_{11} \\ G_{12} \\ G_{2-2} \\ G_{2-1} \\ \vdots \end{bmatrix} \quad (\text{A.10})$$

In a compact representation, this can also be formulated as:

$$\begin{bmatrix} \vec{B}_x \\ \vec{B}_y \\ \vec{B}_z \end{bmatrix} = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} \cdot \begin{bmatrix} \vec{g} \end{bmatrix}. \quad (\text{A.11})$$

The coefficients $G_{l,m}$, known as gradient terms, quantify the contributions of specific modes to the overall magnetic field structure. In advanced nEDM experiments, this level of generalization is essential for accurately addressing the effects of field nonuniformities. Precise characterization of these gradient terms enables a thorough evaluation of field ir-

regularities and their influence on experimental accuracy. Since even small deviations in field uniformity can introduce significant systematic errors, decomposing the field into its modes helps pinpoint and correct these inconsistencies, thereby optimizing magnetic field configurations to meet the stringent uniformity standards required for precise measurements.

A.3 Simulation Methodology

The stick mapping simulation builds upon the experimental setup discussed in Chapter 7, where the mapping process and its outcomes were detailed. Here, the simulation was designed to evaluate the impact of various errors on the accuracy of magnetic field measurements. By simulating these factors, we aimed to understand how they influence the reliability of the mapping results and determine the feasibility of this approach.

The magnetic field at specific positions within the MSR was computed using the scalar potential decomposition method, which employs gradient coefficients ($G_{l,m}$) to describe the spatial variation of the field.

To define the mapping positions, I started by identifying the holes of the MSR to be used for the measurement. These positions were assigned coordinates (x, y, z) , with z representing the vertical direction and the center of the MSR defined as $(0, 0, 0)$. For each mapping sequence, I simulated the movement of a sensor from one wall of the MSR to the opposite wall, creating a list of evenly spaced positions along the chosen axis. At each position, the scalar potential polynomials, expanded up to the 5th order, were evaluated to compute the corresponding "true" magnetic field components.

To verify the accuracy of the implementation, I first tested the method by using the pseudoinverse approach to check whether the given $G_{l,m}$ could be correctly recovered. The results confirmed that the method was working as expected. Based on this validation, the actual study was conducted using gradient coefficients derived from the Munich MSR model as the initial field conditions.

Table A.1: Values required for each gradient component to generate a field variation of 3 nT/m in a cubic meter centered at the origin [78].

Gradient Component	Value to Produce 3 nT/m Variation
$G_{1,0}$	28 pT/cm
$G_{2,0}$	4×10^{-1} pT/cm
$G_{3,0}$	3×10^{-3} pT/cm
$G_{4,0}$	2×10^{-5} pT/cm
$G_{5,0}$	2×10^{-7} pT/cm

From the given $G_{l,m}$ values, the "true" magnetic field (B_{true}) at each position was computed. Measurement uncertainties were simulated by introducing perturbations either in the magnetic field values or in the sensor positions. A least-squares fitting method was then applied to recover a new set of $G_{l,m}$ based on the perturbed data. These fitted $G_{l,m}$ values were subsequently used to reconstruct the corresponding magnetic field (B_{fitted}). Finally, the residuals were determined by subtracting the fitted field values from the true field values ($B_{\text{true}} - B_{\text{fitted}}$) at their respective positions, enabling an assessment of the impact of various error sources on mapping accuracy.

To assess the impact of measurement uncertainties, different error sources were systematically introduced. These included 1- positional errors, 2- magnetic field perturbations, 3- sensor misalignment due to rotation, and 4- structural deviations such as stick bowing. Each of these factors was individually varied to quantify its influence on the accuracy of the reconstructed magnetic field.

Positional errors were modeled by displacing the sensor randomly within a range of 1 cm to 20 cm, simulating misalignment during data collection. Magnetic field measurement errors were introduced by adding random variations to the true field values, ranging from 0.1 pT to 100 pT, reflecting sensor noise and calibration uncertainties.

Rotation errors were incorporated by tilting the sensor within a range of -15° to 15° , simulating misalignment in sensor orientation. Additionally, structural deviations due to stick bowing were considered by introducing a curvature of 5 cm at the center of the stick,

representing possible mechanical deformations during mapping. The error simulations were repeated up to 2000 times to examine the variability across multiple trials.

A.4 Results

The histogram analysis of all simulated conditions demonstrated a uniform distribution of positional errors, confirming the expected randomness in the applied perturbations. This uniformity was observed consistently across different error magnitudes and repetitions. As an example, Figure A.1 illustrates the residual B_x field when a positional error was introduced a single time. The resulting standard deviation in this case was 0.353 81 pT. This validation of the error distribution ensures that the subsequent analysis reasonably represents the impact of positional uncertainties on the reconstructed magnetic field.

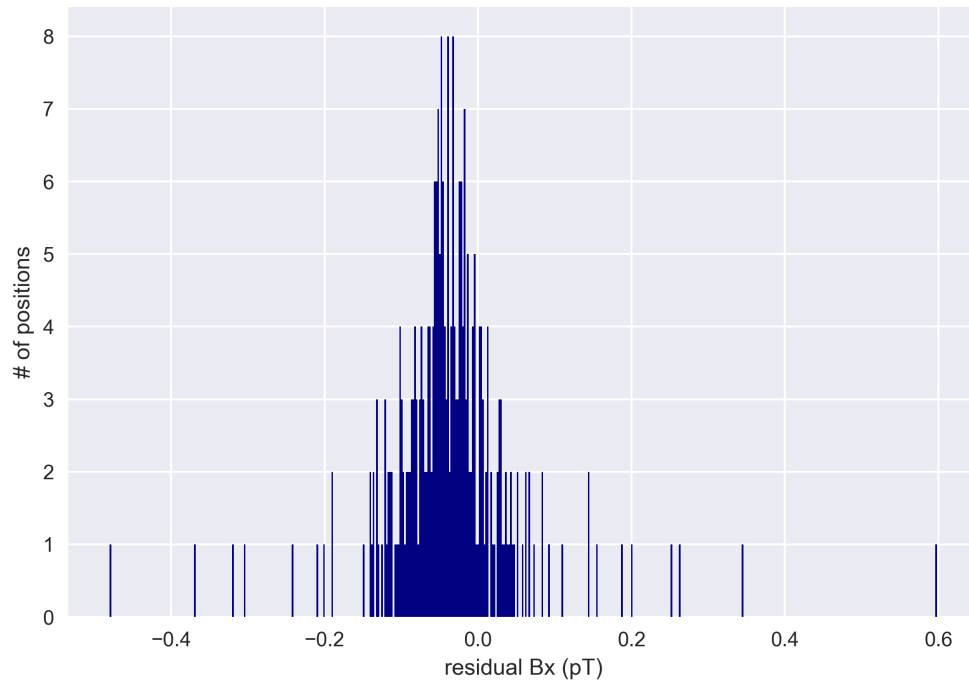


Figure A.1: Histogram of residual B_x field after applying a single instance of positional error, showing a uniform distribution with a standard deviation of 0.353 81 pT.

The relationship between positional and field measurement errors and their impact on

the standard deviation of the reconstructed magnetic field is illustrated in Figure A.2. This heatmap was generated by systematically varying positional errors from 1 cm to 20 cm and magnetic field errors from 0.1 pT to 100 pT. Each condition was simulated 2000 times to capture statistical variations and assess how these uncertainties propagate through the reconstruction process. The results provide insight into the dominant sources of error and their relative contributions to measurement deviations, helping to evaluate the robustness of the mapping technique.

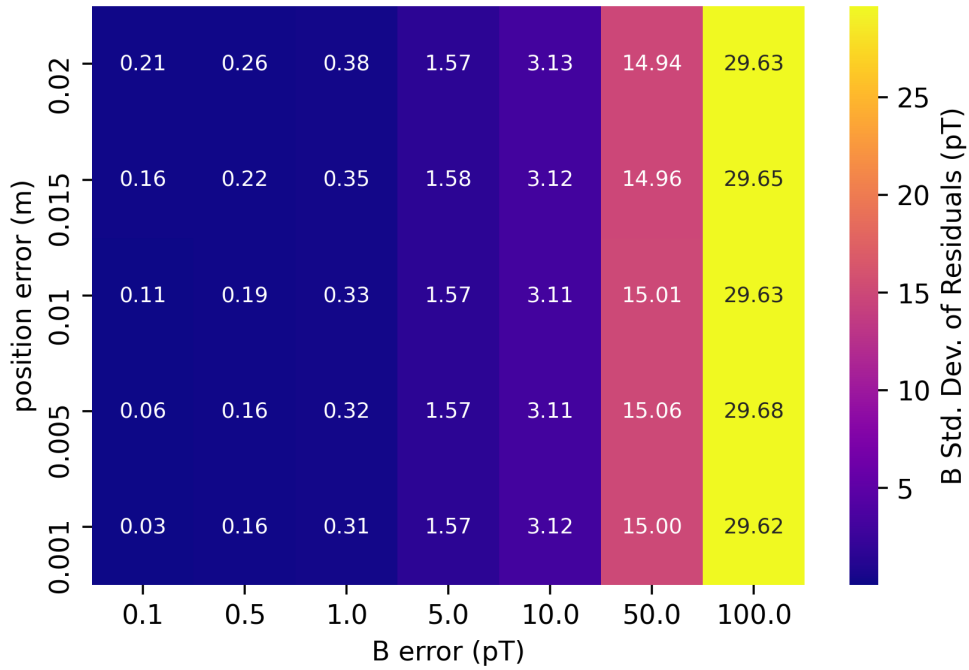


Figure A.2: Heatmap showing the standard deviations of the magnetic field as a function of both positional and field errors.

The analysis of different error sources revealed that the dominant factor affecting the accuracy of the reconstructed magnetic field was the sensor’s intrinsic measurement uncertainty. Specifically, when the magnetic field error was doubled, the standard deviation of the residuals also increased by a factor of two. Additionally, beyond a threshold of 1 pT field error, further increases in positional uncertainty had a negligible effect, indicating that sensor noise became the primary limitation.

Other sources of error, including sensor rotation and stick bowing, had relatively minor effects on the field reconstruction. Rotating the sensor within a range of -15° to 15° resulted in a maximum standard deviation of 1.5 pT, which is same as a 5 cm bowing at the center of the stick led to the standard deviation of 1.5 pT. These results suggest that positional, rotational, and structural deviations in the mapping setup do not significantly impact the overall accuracy of the reconstructed field, reinforcing the robustness of the stick mapping approach.

A.5 Conclusion

This appendix presented a simulation-based evaluation of potential errors affecting the stick mapping procedure used to measure the magnetic field inside the MSR. The study systematically introduced positional errors, field measurement uncertainties, sensor misalignment due to rotation, and structural deviations from stick bowing. By incorporating these perturbations into a Monte-Carlo framework, we assessed their impact on the accuracy of the reconstructed magnetic field.

The results demonstrated that while each error source contributed to deviations in the measured field, their overall influence remained minimal. Histogram analysis confirmed that positional errors followed a uniform distribution, validating the randomness of the simulated perturbations. The heatmap analysis further illustrated that beyond a certain threshold, field measurement errors became the dominant source of uncertainty, while positional errors had a diminishing effect. Sensor rotation and stick bowing introduced deviations on the order of 1.5 pT, indicating that mechanical deformations and misalignment have a limited impact on the overall measurement accuracy.

These findings suggest that the stick mapping method remains a reliable technique for characterizing the residual magnetic field inside the MSR, even in the presence of small errors.