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FAINT MAGNETIC FIELD SHIELD USING THE MEISSNER EFFECT*

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Abstract

Magnetic fields play an important role in many physical phenomena, and many meaperrements in physics experiments require the control of small magnetic fields. Superconducting (Sc) accelerator cavities can generate high electric fields with low power, but the material Nb is a type II superconductor, and when exposed to a magnetic field during the Sc transition, it captures surrounding magnetic flux, leading to increased losses when feeding high frequency power. Therefore, micro-magnetic shielding is essential. Recent improvements in the performance of Sc cavities have reduced power consumption, further increasing the importance of magnetic shielding. Enhancement of micro magnetic shielding is essential. We are therefore conducting research on the shielding effect of faint magnetic fields based on the Meissner effect of Sc materials, which are perfect diamagnetic materials. We have established a system capable of measuring magnetic field distributions on sc sheets at extremely low temperatures, enabling observation of the underlying processes. Preliminary results indicate that the amount of flux rejection generally increases monotonically with temperature gradients.

INTRODUCTION

Superconducting (Sc) accelerator cavities have been gaining popularity recently due to their low RF power consumption. Most of these cavities are made of Nb, a type II superconductor, which captures environmental magnetic flux during the Sc transition. When the captured magnetic flux oscillates in the RF electromagnetic field on the cavity walls, heat is generated, increasing the power load on the cryogenic system. This effect becomes more pronounced as the Q-value of the cavity increases, but even weak magnetic fields can have a significant impact, making shielding essential. However, high-permeability magnetic materials for cryogenic applications are expensive, mechanically sensitive, and difficult to handle [1]. Additionally, their permeability decreases at cryogenic temperatures and in extremely low magnetic fields. On the other hand, Sc materials exhibit perfect diamagnetism and complement magnetic shielding using high permeability materials. Nb has the highest transition temperature among pure metals (see Table 1). Lead has the second-highest transition temperature, but obtaining sufficiently high-purity material is difficult, and lead is a regulated substance under RoHS (Restriction of Hazardous Substances) and other regulations. Given these circumstances, Nb is the top candidate for shielding material, except for its potential to trap flux.

Table 1: Sc Transition Temperature of Pure Metals

Material	**Nb**	**Pb**	**La**	**V**	**Ta**	**Hg**
Temperature[K]	9.2	7.2	5.9	5.3	4.5	4.2
Type	II	I	?	II	I	I

MAGNETIC SHIELDING USING SUPERCONDUCTING MATERIALS

Recently, it has been shown that magnetic flux exclusion occurs during the Sc transition under a temperature gradient in Sc cavities [2-6]. If the cavity can be cooled with a sufficient temperature gradient before reaching the transition temperature, it may function as a faint magnetic field shield to complement conventional high-permeability shielding materials [5]. To achieve this, it is essential to induce the Sc transition in the shielding material before the cavity itself during cooling. The cavity walls have a thickness of approximately 3 mm to ensure mechanical strength. For example, if a thin Nb sheet of approximately 0.5 mm is used, it would have a smaller thermal capacity compared to the cavity walls, making it easier to cool it first [7,8].

Figure 1 shows a conceptual view of flux ejection during cooling. When cooling from one side, flux is emitted from the material. On the other hand, when the normal-conducting region is surrounded by the superconducting region, the magnetic flux is confined.

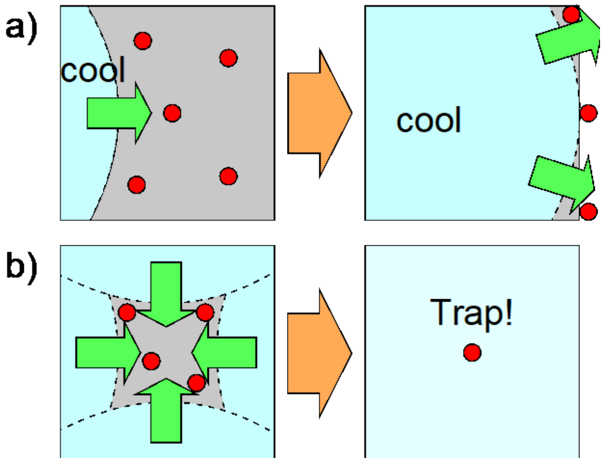

Figure 1: Rough images of flux ejection during cooling.
a) When cooled from one side, flux is ejected from the material.
b) When the normal-conducting region is surrounded by the Sc region, the flux will be significantly trapped.

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EXPERIMENT

An experiment was conducted using a device as shown in Fig. 2. An AMR (Anisotropic-Magneto-Resistive) type 3-axis sensor was selected, and five 3-axis sensors (HMC1053) were mounted on a sensor printed circuit board. Two reset coils within each of the five chips were connected in parallel, and the five chips were connected in series and driven by the driver MCP1406/MCP1407 (High-Speed Power MOSFET Drivers) mounted on the control board. The 15 sensor bridges are sequentially driven with +5 V through an analog multiplexer 74HC4067, and the bridge differential signals are extracted to the room temperature side using two 74HC4067 multiplexers. The analog multiplexers are driven by the 74HC393, with the clock signal supplied from the room temperature side. All these circuits operate at cryogenic temperatures. The signal was multiplexed and successfully brought to the room temperature side via nine cables, including the power supply. At room temperature, the difference between the bridge differential signals is taken, oversampled using a 12-bit ADC, and the average value is obtained, achieving a resolution equivalent to 16 bits or more. The FluxGate sensor is placed directly above the sensor board, and the magnetic field around it is set using a coil placed on the crogenic temperature side. The output of the FluxGate sensor is compared to obtain calibration values (Fig. 3).

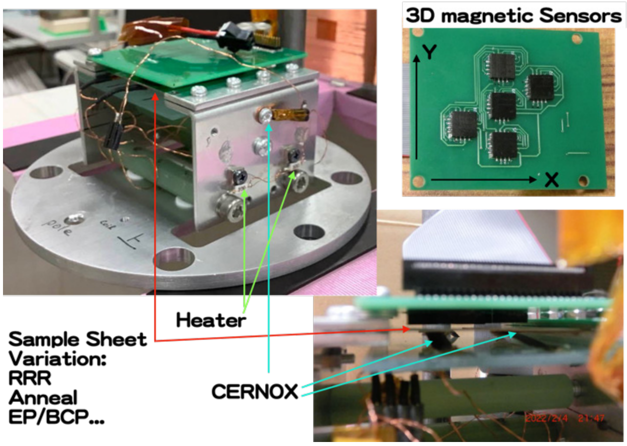

Figure 2: Setup for experiment of flux expulsion.

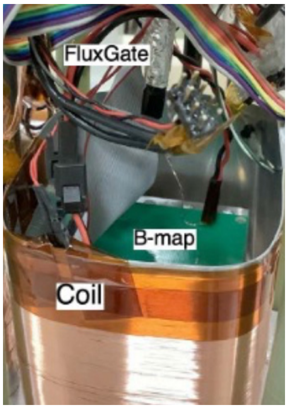

Figure 3: Coil and Flux Gate for calibration.

The sample is clamped at both ends with aluminum fixtures, and each aluminum fixture extends a tab downward, which is immersed in liquid helium for cooling. The sample is then heated with a heater to control the temperature. While maintaining a temperature gradient between the two ends, the temperature is gradually lowered, and the changes in the magnetic field of the 15 sensors are measured. The relative positions of the magnetic field sensors, CERNOX, and the sample are shown in Fig. 4. The five magnetic field sensors are arranged in a staggered pattern, and if there is not much change in the X direction, the magnetic field distribution should represent evenly spaced ones in the Y direction. Figure 5 shows typical data obtained. The upper panel shows the temperatures at C2 and C3, and the middle panel plots the difference between them. The lower panel shows the magnetic flux changes at the center, where a jump is visible. The sensor temperatures appear to lag behind the actual sample temperature changes by about 5 seconds. This is likely due to the temperature response delay of the sensors themselves and the temperature readout system. Figure 6 shows the vector plots of the Bz and By components at this time. As the temperature decreases, the direction of the magnetic field in the central region changes, which is thought to indicate magnetic flux repulsion. At the point where the temperature has dropped to its lowest, the absolute value of the magnetic field decreases. Preliminary results of the temperature gradient and magnetic flux changes are shown in Figure 7. Although these are preliminary results, they show a monotonic change in the temperature gradient. We plan to collect more detailed data in the future.

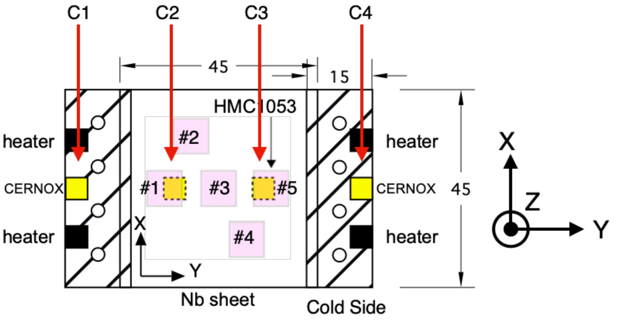

Figure 4: Layout of magnetic sensors and CERNOX.

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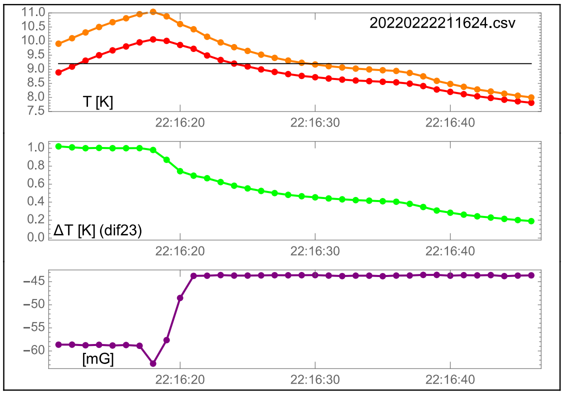

Figure 5: Typical data for temperature changes and magnetic field jump. Top figure shows temperatures at C2 and C3. Center figure shows the difference. Bottom figure shows the magnetic field of #3.

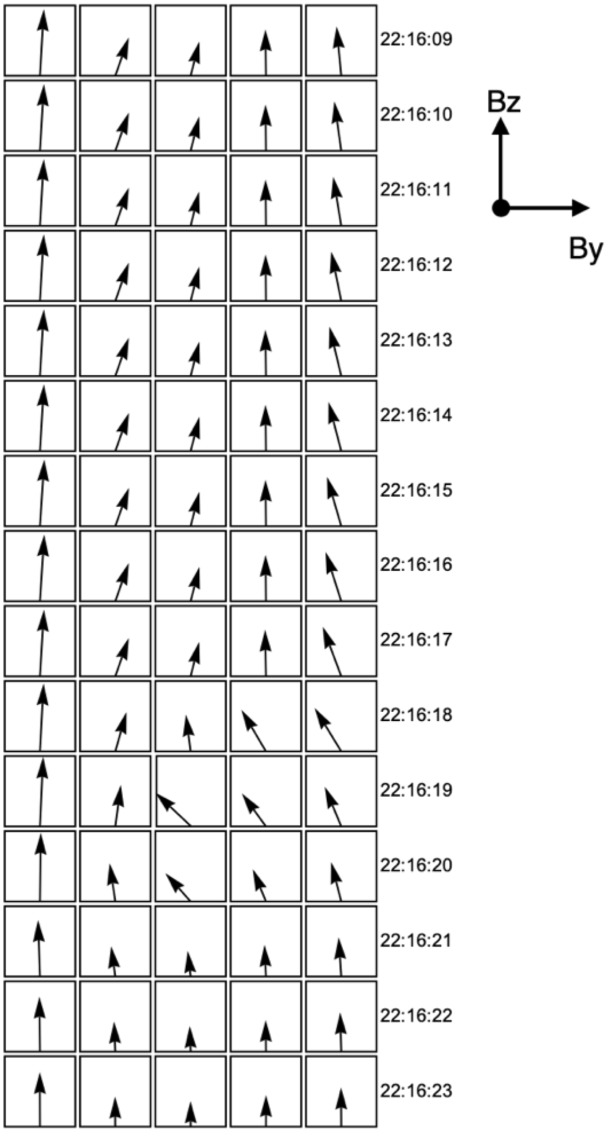

Figure 6: Vector plot of magnetic component Bz and By.

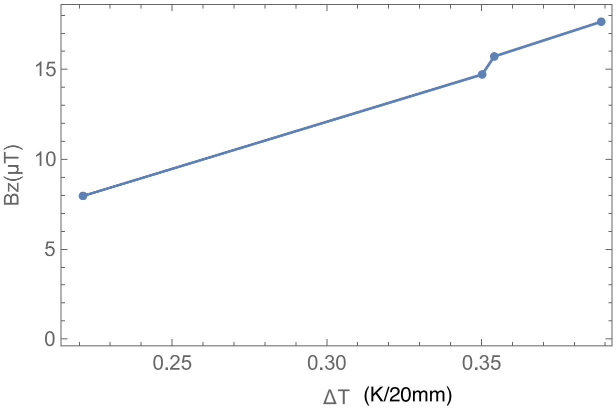

Figure 7: Field jump as a function of temperature gradient.

CONCLUSION

Nb (Type-II Sc) can trap magnetic flux during cooling, degrading the Q0 of Sc cavities if sufficient magnetic shielding is not provided. Especially in Hi-Q cavities, the effect of Q0 degradation becomes more pronounced, and it is necessary to shield the weak magnetic field. Conventional magnetic shielding has a lower permeability at cryogenic temperatures, is expensive, and is sensitive to mechanical distortion, making it delicate to handle.

Now, Type-I sc materials should exhibit perfect diamagnetism (Meissner effect), but tests with commercially available materials show that they do not behave as expected. On the other hand, even Type-II materials can be expected to exhibit a flux exclusion effect if a Sc transition is induced with a temperature gradient. In this regard, preliminary experiments have yielded promising results. Since the heat capacity of a thin Sc sheet is smaller than that of a thick Nb-walled cavity, it may be possible to cool it faster by using pre-cooling pipes.

Hybrid magnetic shields combining highly permeable and fully antimagnetic materials may be useful for further shielding against low magnetic fields.

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