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Experimental Investigation of High Temperature Superconducting Imaging Surface Magnetometry*

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Abstract—The behavior of high temperature superconducting quantum interference devices (SQUIDs) in the presence of high temperature superconducting surfaces has been investigated. When current sources are placed close to a superconducting imaging surface (SIS) an image current is produced due to the Meissner effect. When a SQUID magnetometer is placed near such a surface it will perform in a gradiometric fashion provided the SQUID and source distances to the SIS are much less than the size of the SIS. We present the first ever experimental verification of this effect for a high temperature SIS. Results are presented for two SQUID-SIS configurations, using a 100 mm diameter $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ disc as the SIS. These results indicate that when the current source and sensor coil (SQUID) are close to the SIS, the behavior is that of a first-order gradiometer. The results are compared to analytic solutions as well as the theoretical predictions of a finite element model.

I. INTRODUCTION

The theoretical basis of superconducting imaging surface (SIS) magnetometry was introduced by van Hulsteyn *et al.* in [1]. The primary concept is that a single coil detector located in the vicinity of a superconducting surface can be made to act like a first-order gradiometer. Conceptually, one can think of the SIS as acting as a mirror to the magnetic sources in its vicinity. A single coil detector (i.e. SQUID) placed close to the SIS would see a signal from both the source and the image of the source. This leads to "gradiometer-like" behavior.

It is important to note, however, that unless the SIS is infinite it cannot mirror all the flux lines from the source to create a complete image. For any finite-sized SIS the device is not a true gradiometer. Thus, uniform magnetic fields (or fields from very far placed sources) are not completely canceled out. However, when the sensor coil and current source distances to the SIS are much less than the size of the SIS, the behavior is essentially that of a gradiometer.

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Two biomagnetic systems using low temperature SQUIDs and lead surfaces have been developed at Los Alamos National Laboratory. These systems take advantage of the built-in shielding and easily adjustable baseline provided by the SIS. One system uses a flat 25 cm diameter lead plate and 12 SQUID magnetometers. The other is a magnetoencephalography system using 155 SQUID magnetometers and a lead hemispherical SIS of radius 11 cm. Tests of these systems indicated that when the SQUIDs were near the center of the SIS they did behave primarily as gradiometers [2].

This paper presents the first results investigating SIS magnetometry with high temperature superconducting (HTS) materials. Planar $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ discs were used as the SIS. Although the SIS magnetometry theory is not specific to superconductor type, our investigation of the use of HTS material was motivated for two reasons. First, because it was not clear that HTS material could be obtained of sufficient quality to perform as an SIS. Second, to investigate whether the SIS technique would provide a useful alternative to HTS SQUID gradiometry. The SIS technique has the advantage of a very easily adjustable baseline (move the disc) which could be especially appealing when building HTS SQUID gradiometer arrays.

We designed two experiments to explore the behavior of magnetic field sources near a 100 mm diameter YBCO surface. HTS SQUID magnetometers were used as the magnetic sensing coil. The second section of this paper presents the results for the case with a current loop as the source and the SQUID normal oriented orthogonally to the disc. Magnetometer data (no disc) were also taken. These data are compared to analytic solutions as well as the theoretical predictions of a finite element model [3]. The third section of this paper presents the shielding factor for the disc. The fourth section presents the results of an experiment with a long straight wire as the field source and the SQUID normal oriented tangentially to the disc. These data are presented and compared to the finite element model.

II. MEASUREMENTS WITH A CURRENT LOOP

Our first experiment used a 3-turn 2.5 mm radius coil as the source. The current to the loop was provided by a func-

tion generator at 70 Hz. The loop produced a magnetic dipole that was oriented parallel to the z -axis. The normal of the YBCO disc was also along this axis. A SQUID magnetometer was located between the current loop and the disc and oriented orthogonally, to measure the z component of the magnetic field. The SQUID was a bare Conductus Mr. SQUIDTM, with $70 \mu\text{m} \times 70 \mu\text{m}$ area and $700\text{nT}/\Phi_0$, positioned such that the distance from the SQUID to the plate was about 2.2 mm. The baseline of the "gradiometer" is twice this distance. The disc consisted of a 100 mm diameter substrate with a YBCO layer $\text{\AA}2000$ thick. The SQUID remained fixed above the YBCO disc while the current loop was moved upward along the z -axis.

The upper panel of Fig. 1 shows the results for both the magnetometer (triangles) without the YBCO disc, and gradiometer (diamonds) with the YBCO disc. The magnetometer data were fit (solid line) to the analytic form

$$Bz = \frac{\alpha a^2}{(a^2 + (z + \beta)^2)^{\frac{3}{2}}} \quad (1)$$

where the terms allowed to vary were α , a normalization factor, and β , which allowed for any error in z . The best fit to the magnetometer data was with $\alpha=76877.2$ a.u.mm and $\beta=0.01$ mm. The dashed line is the result the finite element model. The gradiometer data were fit (solid line) to the analytic form

$$Bz = \frac{\alpha a^2}{(a^2 + (z + \beta)^2)^{\frac{3}{2}}} - \frac{\alpha a^2}{(a^2 + (b + z + \beta)^2)^{\frac{3}{2}}} \quad (2)$$

where α and β were constrained to the values for the magnetometer fit and the baseline b was allowed to vary. The best fit to the gradiometer data was with $b=2.06$ mm. The dashed line is the prediction of the finite element model, where b was taken to be 2.15 mm.

The lower panel of Fig. 1 shows the ratio of the magnetometer to gradiometer data (diamonds). The solid line is a best fit to the ratio of equation 2 to equation 1

$$\frac{Bz(\text{grad})}{Bz(\text{mag})} = 1 - \frac{(a^2 + (z + \beta)^2)^{\frac{3}{2}}}{(a^2 + (b + z + \beta)^2)^{\frac{3}{2}}} \quad (3)$$

where β was constrained to the value from the magnetometer fit but baseline b was allowed to vary. The best fit the the ratio was found to be $b=2.23$ mm and is shown as a solid line. The dashed line is the ratio of the values from the finite element models. Both models are in excellent agreement with the data for all z values. The disc is large enough that it is a good approximation to an infinite disc and the gradiometry is nearly exact.

III. SHIELDING FACTOR

The SIS is not a true gradiometer. For example, magnetic fields from very distant sources are not completely

Figure 1: Upper panel: Magnetometer (triangles) and gradiometer (diamonds) data. Lower panel: Ratio of the magnetometer to gradiometer data (diamonds). The solid lines are a fit to the analytic forms (see text). The dashed lines are from the finite element models.

canceled out. However, the SIS does provide some magnetic shielding. To test this we placed the SQUID sensor in a uniform magnetic field from a Helmholtz coil both with and without the YBCO disc. The ratio of the value with the disc to that without the disc is what we call the shielding factor.

Fig. 2 presents shielding factor, S , as a function of the distance, b , from the YBCO disc to the SQUID sensor. The solid line shows a fit to the function

$$S = k \left(\frac{R}{b} \right)^p \approx \frac{R}{b} \quad (4)$$

where k is a normalization factor, R is the radius of the disc, b is the distance from SQUID-to-disc, and p is the exponential power. The best fit values were $k=0.90$ and $p=0.92$.

IV. MEASUREMENTS WITH A LONG WIRE

These experiments used a long straight wire that ran parallel to the surface of the 100 mm diameter YBCO disc, along the x -axis. The normal of the YBCO disc was along the z -axis and the SQUID was tangentially oriented to detect the y component of the magnetic field. The wire was 100 mm in length and the current was provided by a function generator at 70 Hz. The same SQUID was used as with the current loop experiments. The wire was moved both along the y -axis as well as the z -axis.

Figure 2: Shielding factor vs. distance.

Figure 3 shows the y component of the magnetic field B plotted as a function of z for both the magnetometer (triangles) and gradiometer (diamonds), for various wire positions along the y axis. The dashed lines are the result of the finite element model. For the magnetometer, the model was of a single long wire. For the gradiometer, the model was of a single long wire and a superconducting disc of 100 mm radius. The solid line fit to the gradiometer data was the result of the finite element code using two long wires with currents in the opposite direction as source and its magnetic image. The finite element data was normalized to fit the data.

The single wire model is in good agreement with the magnetometer data. For the gradiometer data, both the wire-and-disc model and the two-wires model are similar. Neither of these models takes into account the finite wire length or the return leads. We have to note that the gradiometer values are actually *larger* than the magnetometer values. This is because when the SQUID is located between the source wire and its image, as in our case, the y component of the magnetic fields have the same sign and are summed. Thus, the plate does not produce the equivalent of a gradiometer, but rather simulates the case of two coils wound in the same direction.

V. DISCUSSION

A 100 mm diameter $\text{\AA}2000$ YBCO disc was used as a superconducting imaging surface. A HTS SQUID magnetometer placed close to the disc acted as a first-order gradiometer both orthogonally when the source was a current loop. When the SQUID was oriented tangentially and the

Figure 3: Magnetic field plotted vs. z for both the magnetometer (triangles) and gradiometer (diamonds), for various wire positions along the y axis. The dashed and solid lines are the result of finite element models (see text).

source was a long straight wire, the SIS produced the effect of two coils wound in the same direction. Either behavior was true as long as the SQUID and source current were at distances from the disc much less than the disc's radius. The shielding factor in a uniform magnetic field was about 16 when the SQUID was 2 mm from the disc. HTS SIS gradiometry could prove a useful alternative to other HTS gradiometry techniques, particularly in cases where an easily adjustable baseline is desired.

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