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Cryogenic Current Comparator Measurements at 77 K Using Thallium-2223 Thick-Film Shields

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***Abstract*— Several different magnetic shield geometries were used to study cryogenic current comparator (CCC) operation with thallium-based thick film superconducting shields at 77 K. These shields are found to have good magnetic shielding properties and to support low-level persistent currents. This study investigates geometric properties of the magnetic coupling between the CCC and one type of superconducting quantum interference device (SQUID) sensor. The sensitivity of the SQUID and its coupling to the shielding currents limit ten-to-one CCC resistance ratio measurements to approximately 0.2 $\mu\Omega/\Omega$ in relative uncertainty.**

***Index Terms*—Cryogenic current comparators, high temperature superconductors, resistance measurement, superconducting shielding.**

I. INTRODUCTION

An earlier paper [1] outlined plans for the construction of a CCC device using high-temperature superconductor (HTS) magnetic shield components including $YBa_2Cu_3O_7$ (YBCO). Unfortunately, manufacturers were unsuccessful in producing large YBCO pieces of sufficiently high density to withstand machining into tube-shaped shields. Shields based on HTS thick films, of nominal composition $Tl_2Ba_2Ca_2Cu_3O_x$ (Tl-2223), were obtained and these shields have provided good magnetic shielding and allowed greater latitude in design than bulk YBCO material. Experiments were conducted with CCC devices made from these commercially fabricated HTS shield assemblies.

The magnetic flux is completely expelled from bulk HTS materials if the field near the HTS surface is below the Josephson lower critical field, which is determined by the coupling strength between superconducting grains. CCC devices rely on persistent shielding currents, thus, the magnetic field from the CCC windings should be below that which causes the circulating current to exceed the bulk critical current at the surface in the thick film of Tl-2223. This field is of order 10 A/m at 77 K [2], while in typical Tl-2223 crystalline grains, the penetration depth is of order 0.6 μm [3] and the critical field is about 12 000 A/m. Crystal grains in Tl-2223 may be in the form of overlapping flat plates, which may increase the field needed to break the Josephson coupling. The bulk polycrystalline characteristics determine the shielding attenuation of the walls of our HTS magnetic shields, consisting of 0.1 mm to 0.3 mm thick films.

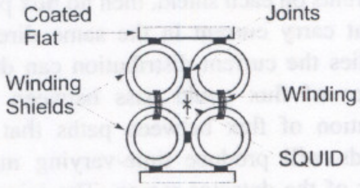

Fig. 1. Joined four-tube CCC assembly with windings and SQUID detector. The length of the tubes and flats is 20 cm into the page, and the tubes are about 1.5 cm in diameter.

A slurry of the HTS precursor compound was first coated on MgO tubes and flats in a commercial process and then heat treated and annealed. Tubes were coated on both the interior and exterior surfaces. Some of these pieces were subsequently bonded together as shown in Fig. 1 to form sets of parallel tubes with superconducting joints based on Tl 2223. One outer cylindrical HTS shield was used in all of the experiments to exclude external and end-effect magnetic fields from the detector region.

YBCO rf-SQUID detectors with a flux-loop area of 0.1 mm × 0.1 mm were commercially supplied with a 1.4 mm × 1.4 mm flux-focusing washer, resulting in a field sensitivity of about 2 pT/$\sqrt{\text{Hz}}$. The SQUID flux noise level is specified to be $\leq 2.5 \times 10^{-4}\ \phi_0/\sqrt{\text{Hz}}$ for frequencies above 5 Hz. These sensors were used in 4.0 mm diameter probes with thin copper covers. A 4 mm × 7 mm washer was used with one similar SQUID system in a 6.0 mm diameter probe with no cover.

II. SHIELD ASSEMBLIES

Three CCC assemblies were constructed. The first CCC was made with winding shields in which the substrates were machined from a solid MgO cylinder. This design is based on the shields machined from bulk HTS material described in [1]. Two holes for the windings were drilled in a 37 mm diameter MgO cylinder parallel to the axis and the cylinder was then split parallel to the axis. This separated the cylinder into two unequal parts, each containing one of the holes. Finally, before the coating process, an aperture for the SQUID was machined across the full width of the flat surface of the larger half, near the midpoint. This aperture was about 5 mm deep and wide.

Two other CCC assembly designs are conceptually closer to Harvey's original CCC devices [4]. Both of these designs used sets of four adjacent, parallel tubes to shield the ratio windings. The four tubes are used to shield two sets of windings, which typically are identical in the number of turns in both sets.

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In one type of assembly, the four tubes are separated by thin insulators. The second design has a superconducting joint along the entire length of pairs of shields which carry the windings in the same direction, as shown in Fig. 1. This joint prevents magnetic flux from passing between the joined tubes.

The purpose of the joined shield design is to eliminate lines of flux that encircle only one current-carrying tube. Electromagnetic field simulations show that when shields in the four-tube geometry carry equal magnitude, symmetrically distributed currents on each shield, then no flux passes between the shields that carry current in the same direction. In real shield assemblies the current distribution can differ from the ideal, and lines of flux could pass between such shields. Any redistribution of flux between paths that encircle one and two shields will produce time-varying magnetic noise near the center of the detector region. The joined-tube shield design limits the path of the lines of flux and should improve the accuracy and stability of the shield assembly as a flux transformer.

III. CCC SENSITIVITY

Calculations of the signal flux can be used to determine approximately a coupling coefficient γ that depends on the geometrical form of the shield. If the current is uniformly distributed on the surfaces then the calculated flux density for the four-tube CCC assemblies is given by

$$B = \gamma(\mu_0 I/\pi r) \tag{1}$$

where μ_0 is the magnetic permeability constant, I is the net signal current on the shields, and r is the distance from the tube axis to the detector. In our four-tube geometries, the calculated value of γ for nonsuperconducting tubes is 0.71. The effect of superconducting shields should be to increase the flux density in the SQUID region and to increase the coefficient γ.

The transverse-aperture CCC geometrical factor is derived differently from that of the parallel tubes. The signal flux is generated by (approximately circular) current loops on the inner surface of the aperture. The flux density is given by (1), where r is now the distance from the aperture surface to the detector. If the current is uniformly distributed on the surfaces, then for this geometry only about $2/\pi$ of the net current flows in these loops and generates a signal. For a normal conductor γ is $(\kappa^2+1)^{-1/2}$ where κ is the outer radius of the shield set divided by the radius of the aperture, and the geometrical factor γ is calculated to be 0.11. However, γ should be approximately 1.0 for a superconducting aperture, where the flux from the current loops is excluded at the surface, and where all flux encircles the body of the superconducting shield.

Values of the CCC sensitivity were measured for each of the three CCC devices using similar standard commercial SQUID's. Using the signal in units of the flux quantum ϕ_0 $(=h/2e)$ produced by passing a known current through a winding, it is possible to determine an effective SQUID flux-sensing area for each CCC from (1). Since the SQUID detectors are very similar and all have 1.4 mm × 1.4 mm washers, each should have roughly the same degree of coupling to the magnetic flux. As shown in Table I, all three CCC devices give consistent results if the same geometric factor (here, $\gamma = 1$) is used to calculate each detector flux-sensing area. The values in Table I indicate that if γ is of order 1, the SQUID senses less than 0.2% of the flux passing through the aperture. Signal coupled into the HTS SQUID is then less than 1 percent of that obtained with niobium-based SQUID's that are used with multi-turn flux transformers.

An outer HTS shield tube of inner diameter 63 mm and length 150 mm was used to reduce stray fields in each of the CCC devices. Measured CCC sensitivity was not changed by a significant amount when this shield was removed from the transverse-aperture CCC, which has an outer diameter of 37 mm. Any change in sensitivity due to the large outer shield should be negligible in the smaller-diameter CCC devices constructed from tubes.

TABLE I
COMPARISON OF SENSITIVITIES AND CALCULATED EFFECTIVE FLUX-SENSING AREA OF THE SQUID FOR THREE CCC GEOMETRIES. THE DISTANCE r FOR EACH TYPE OF CCC IS EXPLAINED IN THE TEXT

CCC type	Distance, r	Sensitivity, $\mu A/\phi_0$	Flux-sensing area ($\gamma = 1$)
Transverse-aperture	2.2 mm	495 ± 15 μA	$2.30 \pm 0.1 \times 10^{-8}$ m^2
Separate four-tube	7.6 mm	1740 ± 50 μA	$2.26 \pm 0.1 \times 10^{-8}$ m^2
Joined four-tube	10.8 mm	2460 ± 75 μA	$2.27 \pm 0.1 \times 10^{-8}$ m^2

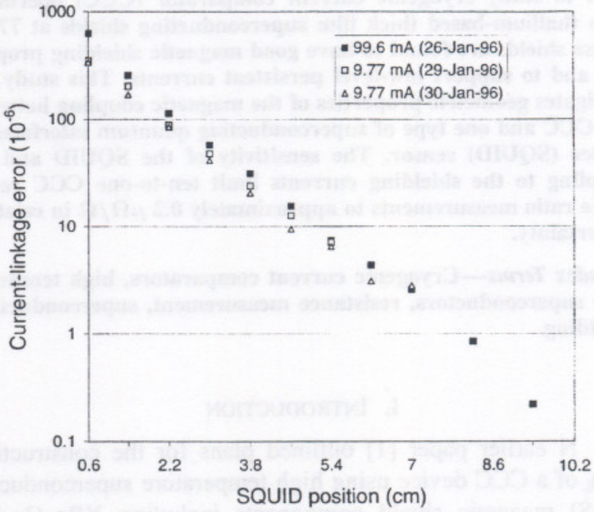

Fig. 2. HTS attenuation of magnetic fields between one end and the midpoint of the separate four-tube CCC. The data represents 1:1 cancellation errors as a function of the SQUID displacement along the axis for currents in opposing 20-turn windings. Three sets of data are shown: 0 cm represents the end of the shields and 10 cm is the approximate midpoint of the shields.

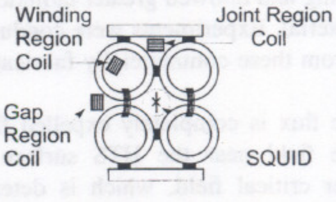

Fig. 3. Configuration of the joined four-tube CCC for measurements of attenuation of magnetic fields, viewed end-on. The positions of three small copper windings used for these measurements are indicated by arrows.

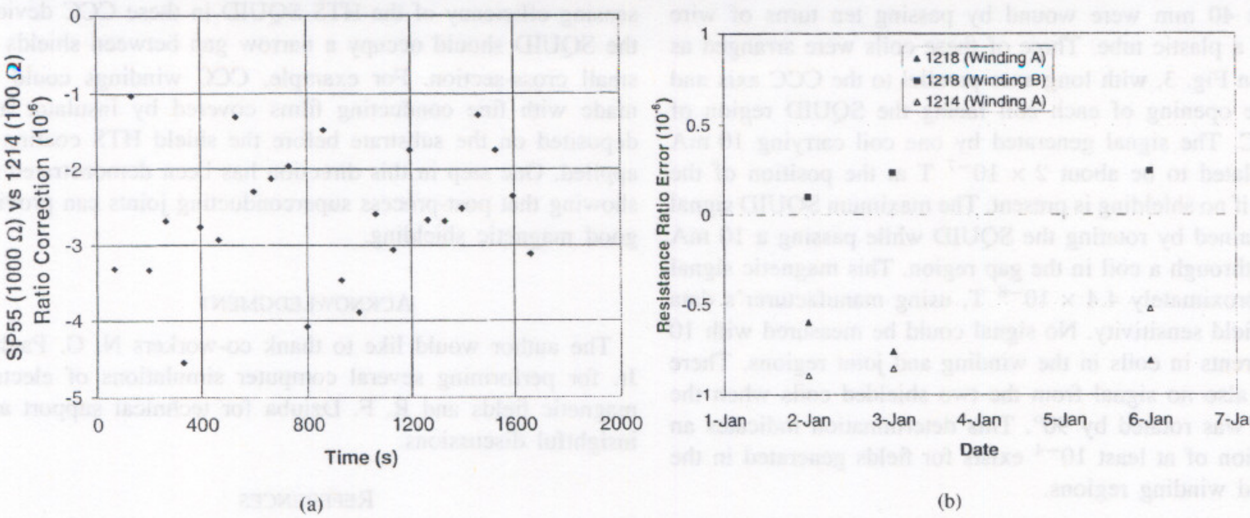

Fig. 4. Resistance ratio comparisons using the joined shield CCC with a 6 mm diameter SQUID probe, 4 mm × 7 mm SQUID flux-focusing washer, and 320 to 32 turn ratio windings in a single set of tubes. The CCC sensitivity is approximately 780 $\mu A/\Phi_0$ in this configuration. (a) A sequence of data for a 10:1 ratio measured by the CCC. Each ratio consists of six direct current measurements totaling about 20 s, with a current-reversal frequency of about 0.09 Hz. (b) Resistance ratio error determined for two different sets of 32 windings in the CCC, measured over a period of several days. Two different 100 Ω resistors were used. The Type A component of uncertainty for each point is 0.2×10^{-6}.

HTS SQUID measurements are sensitive to environmental magnetic fields in two ways. First, the SQUID senses fluctuations in background magnetic fields, and this study indicates that thick-film HTS shields can be highly effective for shielding magnetic fluctuations. The second effect of background magnetic field is due to the static field. Static-field-induced $1/f$ noise is more important in HTS SQUID's than in niobium-based SQUID's. Even for SQUID's cooled in background fields below the geomagnetic field level, magnetic vortices are trapped in the superconducting region of the HTS detector and can hop between pinning sites causing $1/f$ noise [5]. Appropriate design of the SQUID system, such as reducing the width of HTS films by patterning of the washer [6], may help to eliminate the increase in $1/f$ noise due to static fields.

IV. CCC CANCELLATION AND ATTENUATION MEASUREMENTS

The transverse-aperture CCC windings were constructed from 14 turns of 19-conductor copper cable passed through the two longitudinal holes. The length of these shields is 150 mm and the average separation of the windings is 15 mm. The effect of unshielded winding currents was relatively large in unity-ratio (1:1) cancellation measurements. Each of four individual windings was measured in opposition to one other winding, and the magnitudes of the relative current-linkage errors averaged 7×10^{-6} times the total measurement current. It is not possible to change the position of the SQUID sensor relative to the shields in this CCC design.

The CCC with four separate shields was constructed from approximately 10.6 mm diameter, 200 mm long HTS-coated tubes arranged with axes at the corners of a square, creating an internal space of approximately 4.3 mm diameter in which a 4.0 mm SQUID probe was placed. The interior dimensions of the tubes limited the number of windings, which consisted of four turns of 19-conductor cable, passed through both pairs of shields. The SQUID detector sampled the magnetic flux that passed between the tubes containing opposing windings, and was rotated to find the maximum CCC signal. The SQUID detector could also be moved parallel to the axis and positioned near the midpoint of the shields.

Current-linkage error in the four-tube CCC was measured as a function of SQUID position (see Fig. 2). Currents of 9.77 mA or 99.6 mA in opposing windings provided a partially canceling signal. Each winding consisted of five 4-turn windings and produced a total signal of either 0.195 ampere turns or 1.992 ampere turns. Ratio error was observed to increase exponentially as the SQUID was moved from the midpoint toward the upper end of the shielded region provided by the external HTS shield. Ideally, the strength of a magnetic field inside a superconducting tube of radius R falls off as $\exp[-c(Z/R)]$ where Z is the distance within the tube as measured along the axis [7]. The constant c is 3.83 for an axially-directed external field, and 1.84 for a uniform external field directed at a right angle to the tube axis. Fields originating within the tube fall off at least as fast as $c = 1.84$. The constant $c = 2.6$ was determined from a fit to the data of Fig. 2, and indicates a high level of attenuation within the central region. The current-linkage error passed through zero and reversed sign at the midpoint for all those windings tested. This indicates that dominant errors from the unshielded windings at the two ends have opposite signs.

Dominant end-effect errors of the joined four-tube assembly were attenuated exponentially with about the same rate as those in Fig. 2. The sign of the error for displacement in either axial direction was the same, however. For all sets of windings tested, nearly constant ratio error was observed over a region of ±20 mm near the midpoint. Thus, the axial position of the SQUID was relatively unimportant in the joined shield CCC. In this central region, the typical magnitude of the 1:1 current-linkage error was less than 1×10^{-6}.

The joined-tube CCC shields allowed tests of magnetic attenuation in a region enclosed between HTS joints made of Tl-2223. Narrow copper wire coils of approximate dimensions

2 mm × 40 mm were wound by passing ten turns of wire through a plastic tube. Three of these coils were arranged as shown in Fig. 3, with long axes parallel to the CCC axis and with the opening of each coil facing the SQUID region of the CCC. The signal generated by one coil carrying 10 mA is calculated to be about 2×10^{-7} T at the position of the SQUID if no shielding is present. The maximum SQUID signal was obtained by rotating the SQUID while passing a 10 mA current through a coil in the gap region. This magnetic signal was approximately 4.4×10^{-8} T, using manufacturer's data on the field sensitivity. No signal could be measured with 10 mA currents in coils in the winding and joint regions. There was no also no signal from the two shielded coils when the SQUID was rotated by 90°. This determination indicates an attenuation of at least 10^{-4} exists for fields generated in the joint and winding regions.

V. THE 10:1 CCC RESISTANCE RATIOS

The 1000 Ω to 100 Ω ratio CCC bridge measurements were made for the joined four-tube CCC assembly. These ratios were measured for one 1000 Ω and several 100 Ω resistors, compared at 1 V. The measurements were made using an RF SQUID magnetometer that consists of a YBCO SQUID with a loop area of about 1×10^{-8} m^2, with a 4 mm × 7 mm washer providing about a factor of three enhancement in flux sensitivity over the 1.4 mm × 1.4 mm standard flux-focusing washer. The stability of the measured ratios was consistent with the standard deviation of short-period measurements. The typical level of short-term and long-term stability obtained with the joined-tube CCC is shown by Fig. 4(a) and (b). The relative Type A uncertainty in these CCC ratios is about 2.0×10^{-7} for a 30 minute measurement. Current-linkage error contributed by individual windings was the largest source of uncertainty.

VI. CONCLUSION

CCC devices working in liquid nitrogen at 77 K have been constructed with shields made of HTS thick films. At signal levels up to at least 1.99 ampere turns and for flux densities of about 2×10^{-7} T, the shielding of magnetic flux generated well inside the HTS shield tubes is essentially complete. Signal flux at the detector for parallel-tube CCC shield assemblies scales with the inverse of the distance between the detector and the axes of the tubes. This suggests that much better CCC devices could be constructed by reducing the transverse dimensions of the shields and windings. In order to overcome the low flux-sensing efficiency of the HTS SQUID in these CCC devices the SQUID should occupy a narrow gap between shields of small cross-section. For example, CCC windings could be made with fine conducting films covered by insulator and deposited on the substrate before the shield HTS coating is applied. One step in this direction has been demonstrated by showing that post-process superconducting joints can provide good magnetic shielding.

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