Fermi National Accelerator Laboratory

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Superconducting Current Transducer *

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SUPERCONDUCTING CURRENT TRANSDUCER

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Abstract

The construction and performance of an electric current meter that operates in liquid He and mechanically splits apart to permit replacement of the current carrying conductor is described. It permits the measurement of currents induced in a loop of superconducting cable and expeditious exchange of such loops. It is a key component for a short sample cable testing facility that requires no high current power supplies nor high current leads. Its superconducting pickup circuit involves a non-magnetic core toroidal split-coil that surrounds the conductor and a solenoid whose field is sensed by a Hall probe. This toroidal split-coil is potted inside another compensating toroidal split-coil. The C shaped half toroids can be separated and brought precisely together from outside the cryostat. The Hall probe is energized and sensed by a lock-in amplifier whose output drives a bipolar power supply which feeds the compensating coil. The output is the voltage across a resistor in this feedback circuit. Currents of up to 10 kA can be measured with a precision of 150 mA

Introduction

An important step in the quality control of superconducting cables for accelerator magnets is the measurement of their critical current. This is done with short samples of these cables under selected conditions. A typical set of selected conditions is to have the sample at a temperature of 4.2 K in a magnetic field of 5 T perpendicular to its flat side. Such critical currents usually range from 1 to 10 kA, requiring a large power supply and corresponding large power leads. Such costly equipment can be avoided by inducing the current in a superconducting loop made with the sample.[1,2] The measurement of the current then can no longer be made with a shunt at room temperature in series with the sample. An accurate transducer operating at liquid He temperatures is needed.[3] The calibration and installation of such transducers is time consuming and inconsistent with a testing rate of many samples per day.

For the proposed short sample testing facility at Fermilab, which uses many of the ideas developed at University of Twente[1] we have designed, built, and tested a DC transducer containing superconductors that mechanically opens and closes around the sample and should permit a testing rate of many samples per day. We present here a description of this transducer and its performance under test conditions.

Flux Transformer

The sensing component of this transducer, when closed around the sample, can be described as two concentric toroidal coils surrounding the current carrying conductor. The inner toroidal coil is superconducting and it is the pickup part of a superconducting flux transformer whose other part, a short solenoid surrounds a Hall probe. This flux transformer is shown in Fig. 1. The short solenoid (field coil) is enclosed in a superconducting cavity for magnetic background noise shielding.

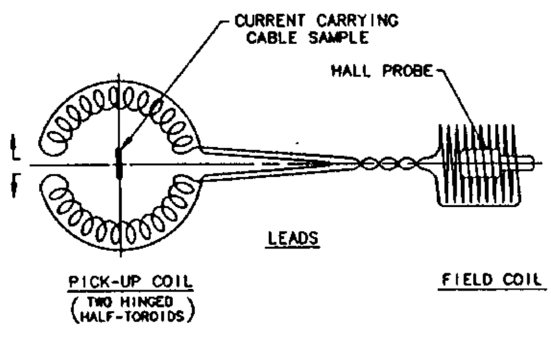

Figure 1. Superconducting Flux Transformer

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The magnetic field due to the current in the sample is prevented from penetrating into the superconducting circuit of the flux transformer by a Lenz law current in this circuit. This Lenz law current produces the magnetic field detected by the Hall probe. The relationship between this magnetic field and the current in the sample depends on the geometry of the pickup, sample, and their relative position. The reproducibility of this geometry is one of the subjects of the tests described below.

Transducer Description

Both concentric toroidal coils are made out of superconducting wire and inserted one inside and the other outside two semicircular (14.69 mm bending radius) brass tubes (5.56 mm O.D., 4.85 mm I.D.). They are then potted or coated with Stycast 2850FT. Two of them were actually built, one potted and one coated. During fabrication this 540 turn 3.18 mm diameter pickup coil was first wound as two solenoids each 53.34 mm long over two Teflon rods using an enamel insulated, copper clad, pure Nb wire of 0.198 mm diameter. Each half of it before insertion in the tube showed an inductance of 25.3 microhenries.

The field coil(5.31 mm I.D., 7.90 mm long, 104 turns, 34 microhenries) is wound with the same wire over a G-10 form. The leads of the pickup extend inside the brass tubes of the moving mechanism (described below) to a brass junction box and from there through the inside of a 61 cm long Pb tube connecting the junction box to the shielded capsule that contains the superconducting cavity. These leads are then joined to the field coil leads by etching and spot welding in one side of the shielded capsule that contains the superconducting cavity. Fig. 2 presents the mechanical details of this capsule .

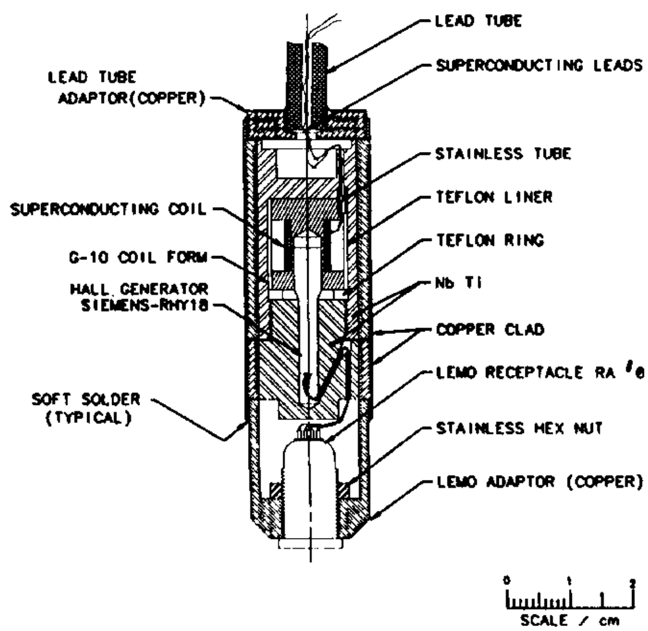

Figure 2. Shielded capsule containing the field coil and the Hall probe in a superconducting cavity.

The cavity itself is machined out of a short piece of Copper clad NbTi cylinder, a sample of the material now used in the early stages of fabrication of multifilamentary superconducting wire.

The second toroidal coil is a compensating coil, part of a feedback loop and for compactness is made also out of superconducting wire. During fabrication this 1000 turn, 6.35 mm diameter coil was first wound as two solenoids, each 44.5 mm long over teflon tubes using an enamel insulated, copper clad NbTi wire of 0.191 mm diameter. Once the teflon tubes were removed, they were inserted over the semicircular brass tubes. The inductance was measured to be 682.0 microhenries.

The mechanism that supports the two halves of the sensing coils (pickup and compensating toroids) is made out of brass tubes forming the sides of a letter "A", and hinged at the top in a brass junction box. The horizontal bar of the "A" can move vertically, changing the separation distance between the two halves. The closing together of the halves is to be effected by the insertion of the sample holder in its measuring position. For the tests presented here, the closing and opening motions were performed from the outside of the test cryostat by manually moving a G-10 rod.

Measuring Circuit

The flux transformer and the Hall probe are used as a null sensing device in a feedback circuit. Fig. 3 presents the circuit, including parts needed for the tests.

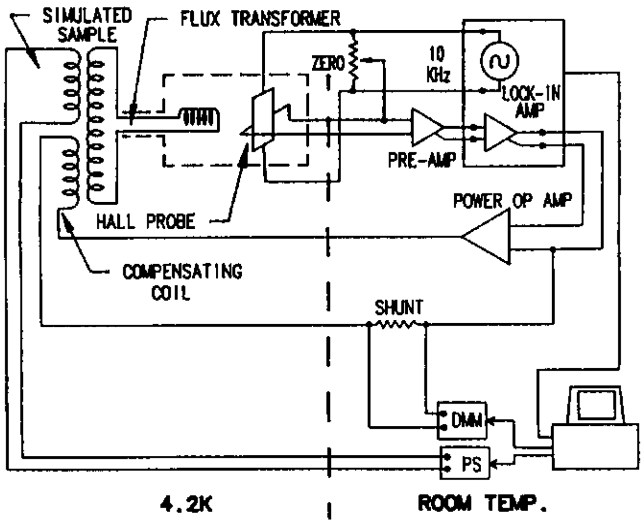

Figure 3. Schematic of the measuring circuit.

A model SR552 differential pre-amplifier and a model SR510 lock-in amplifier (both manufactured by Stanford Research Systems Inc., Sunnyvale, CA 94089) operating at 10 kHz are used to energize the Hall probe and sense the magnetic field in the field coil of the flux transformer. The output of the lock-in is power amplified by a model BOP20-10M Kepco bipolar operational amplifier whose current drives the compensating coil. The output is read across a 0.010 ohm shunt in series with the compensating coil using a model 3457A Hewlett Packard digital multimeter. A voltage divider circuit across the Hall probe current leads is used to zero the output of the Hall probe. This circuit consists of a symmetric arrangement of three linear potentiometers of 50, 5 and 50 kilohms respectively. It is needed not only to balance the natural offset in the Hall sensor chip but also to compensate for trapped flux in the flux transformer loop.

Tests

In order to establish that this cold current meter has the required resolution and reproducibility a test setup was built and several tests were conducted.

The test setup consisted of a simple cryostat in a liquid He dewar. Instead of the actual sample holder with a cable sample requiring currents in the kA range, we used a 1000 turn coil simulating the sample, so that the sample current equivalent is 1000 times the actual current used. Effort was spend in getting the cross section of this sample coil to simulate the cross section of a typical cable and to keep the other side of it far away from the sensing coils. This type of coil wound in an actual sample holder will eventually be used to calibrate the system.

Data acquisition and analysis is performed using a PC (AST-386) running Asyst software and GPIB controlled hardware. This hardware has been described above and is the result of a development program that involved two other power operational amplifiers of lesser current and stability.

In this setup the sensitivity of the system can be measured by the noise in the readings of output voltage. The output voltage as read by the digital multimeter is an average of typically 50 sequential readings and the standard deviation of these readings is taken as the noise. This noise is a function of the sample current and is shown in Fig. 4.

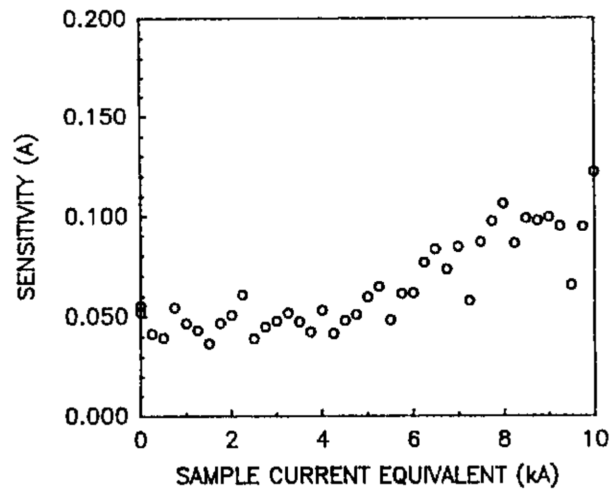

Figure 4. Sensitivity of the latest hardware configuration. It is the standard deviation observed in a set of 50 repeated measurements.

From this data we conclude that 1 kA can be measured with a sensitivity of 50 mA and 10 kA with a sensitivity of 100 mA. Therefore, the current readings have 5 significant digits as far as signal to noise is concerned.

The stability of the current measurements was studied by taking a set of 10 consecutive current measurements separated in time by typically 10 minutes. These measurements were performed using a model BOP36-1M Kepco power operational amplifier and a sample equivalent current of 500 A. The deviation in the set of measurements was on the order of 0.5 A, representing a 0.1% deviation from the average measured current of 486.8 A. The noise limited sensitivity for this set of measurements was 0.13 A, or 0.03%. With this same power operational amplifier in the same current range we carried out a reproducibility study with respect to the opening and closing of the two halves of the sensing coils. In this reproducibility test, a set of 5 measurements were performed consecutively, but the sensing coils were opened and closed between measurements. The deviation in this set of measurements was 0.27 A, representing a 0.06% deviation from the average measured current of 477.7 A. The noise limited sensitivity for this run was 0.15 A, again about 0.03%. From these preliminary measurements we may conclude that any deviation in current measurements due to the opening/closing of the sensing coils is comparable to the deviation observed between successive measurements without opening/closing movements.

The effects of sample location were studied by rotating the sensing coil assembly off-axis with respect to the sample coil. This provided a 10.4 mm shift in the position of the sample relative to the axial center of the sensing coils. The current was measured for three positions of the sample, representing deviations of 0, and $\pm$10.4 mm from the centered position, with a 100 A equivalent current in the sample coil. The average deviation in the measured current at the shifted sample locations was typically 2.8 A, while the measured current with the sample on-center was found to be 90.8 A. This represents a 3% variation from the on-center measurement. To reduce the variation due to sample location deviations to about 0.15 A, the sample position must therefore be constrained to within 0.5 mm. This can be readily achieved through adequate tolerances in the design and manufacture of the sample holder and its locating assembly. To reduce the dependence on the sample position to the sensitivity level of the system using realistic mechanical tolerances we experimented with the placement of superconducting foils between the sample and the pickup. The results were definitely encouraging.

The relationship between the measured current, I_m, and the sample equivalent current, I_s, is expected to be linear, and it is so up to 7.5 kA, but a better representation over the 0 - 10 kA range is given by the following cubic:

$$I_s = 0.0027529\, I_m^3 - 0.033513\, I_m^2 + 1.0985\, I_m - 0.009743\ .$$

The deviation of the data from this expression is less than 0.3%. We do not completely understand the source of this deviation from linearity but it is not inconsistent with flux penetration through the wire of the flux transformer. A more detailed study of it is under way.

The tests so far indicate that this system for measuring the current induced in the short sample cable loop is viable. A more detailed study is intended in the completed facility to establish its accuracy.

Acknowledgments

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