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ELECTRICAL RESISTANCE OF SUPERCONDUCTING CABLE SPLICES

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ABSTRACT

The electrical resistance of superconducting cable splices is known to be in the 10^{-9} Ω range which to be measured conventionally would require the use of a micro voltmeter with a power supply capable of generating kilo Amperes plus a liquid helium cryostat with large power leads. Here we present a system for carrying on such measurements that requires besides the microvoltmeter a power supply capable of generating only up to 35 A and a 152 mm diameter neck helium dewar using less than 25 liters per day after initial cool down. In this paper we describe the apparatus and present the data taken with it in its first use which for data acquisition used just a chart recorder. The method is based in making the splice in a loop of cable, inducing a current in it and measuring its decay time constant. Generating high currents in superconductors by induction is not a new technique but the use of the decay constant of currents generated this way for the determination of minute electrical resistance seems novel to the author. Unexpected details in the results will be discussed.

INTRODUCTION

The quantitative knowledge of the heat generated in a cable splice is required early in the design of accelerator superconducting magnets. The decision of whether the splice can be incorporated in the body of the coil winding of an interaction region quadrupole or has to be placed away from it suggested these measurements to confirm calculations[1]. The heat generated at the splice is due to eddy currents and ohmic resistance to the transport current. Here we address the latter which is due to the current having to traverse the copper matrix of the strands of the cable ends being joined. The method used has the economic advantage of requiring modest hardware and liquid helium consumption compared to what is usual in this field. After describing the method and going through an analysis of it we give the construction details of the superconducting coil and heater that had to be fabricated specially for this project. The data collected is then presented and discussed.

METHOD

The method is based in making the splice in a loop of cable, inducing a current in it and measuring its decay time constant τ. Generating high currents in superconductors by induction is not a new technique[2], it is a method that has been used both for the short sample testing of cable for large bubble chambers[3] and for cable in conduit like the one for the Elmo Bumpy Torus[4]. A good review of the subject is presented by Mulder et al.[5] and a recent use has been described by Ohira et al.[6]. The use of the decay constant of currents generated this way for the determination of minute resistances as well as the use of primary circuit as pick up coil seem novel to the author.

The resistance R in question is obtained from the expression $\tau = L/R$ where L is the self inductance of the loop of cable, which depends only on its geometry (since no magnetic material is involved) and can be calculated and/or measured at room temperature. Figure 1 presents the electrical schematic of the arrangement. The costliest component in this circuit is the coil with inductance L'. It was built on a G10 frame in a racetrack shape in order to provide the largest area that would fit through the neck of the dewar.

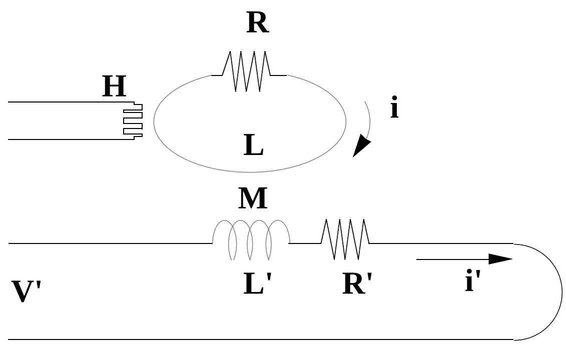

Figure 1. Electrical circuit

The loop of superconductor cable L with its splice R fits tightly over it in order to maximize their mutual inductance M. A special notch is cut out from its frame in order to facilitate the installation of a heater H over a spot on the cable with the appropriate thermal insulation to keep liquid helium out from this region.

The coil L' has 440 turns of superconducting wire and is used both as the primary of this transformer in order to energize the loop L with current i and as a pickup coil to detect the decay of this current due to the splice resistance R. The expressions for the voltage in the primary and secondary circuits are respectively:

$$V' = L' \cdot \frac{di'}{dt} - M \cdot \frac{di}{dt} + R' \cdot i' \tag{1}$$

$$0 = L \cdot \frac{di}{dt} - M \cdot \frac{di'}{dt} + R \cdot i \tag{2}$$

By replacing the expression for di/dt from the second equation into the first one gets:

$$V' = \left(L' - \frac{M^2}{L} \right) \cdot \frac{di'}{dt} + \left(M \cdot \frac{R}{L} \right) \cdot i + R' \cdot i' . \tag{3}$$

Therefore, an instrument measuring the inductance of the coil before the cable loop is installed will read L' and after the loop is installed will read $L_{eff} = L' - M^2/L$; so that

$$\frac{M^2}{L} = \left(L' - L_{eff} \right) \quad . \tag{4}$$

The repulsive forces between the cable loop and the coil can be destructively large if both of them are superconducting during energizing. In a very crude approximation the current in the loop will be 440 times larger and in the opposite direction to the current through the coil due to the external DC power supply. To reduce this danger and to end up with an electrically quiet situation for the data acquisition the heater is first turned on to dissipate the current induced in the loop preventing it from building up while the power supply is ramped up. Once the desired current in the coil, i'_{max}, is reached, the heater is turned off and the loop is given time to cool and superconduct. The power supply current is then ramped down and when it reaches zero Amperes, the loop current reaches its extreme value, i_o. The coil leads are then moved from the power supply to the microvoltmeter. Just prior to the ramp down the magnetic field flux established by the primary coil, $\Phi' = L' \cdot i'_{max}$, is not totally trapped in the now superconducting cable loop since some flux lines return in the narrow space between the coil and the cable loop. The trapped flux, $\Phi = M \cdot i'_{max}$, is kept essentially constant by Lenz Law during the ramp-down by the increasing superconducting current in the cable loop such that at the end: $\Phi = L \cdot i_o$. Therefore $i_o = M \cdot i'_{max} / L$. Following this current transfer from the coil to the loop no current now flows in the coil and we have:

$$0 = L \cdot \frac{di}{dt} + R \cdot i \tag{5}$$

$$V' = -M \cdot \frac{di}{dt} \tag{6}$$

The solution is:

$$i = i_0 \cdot e^{-\frac{t}{\tau}} \quad \text{with} \quad \tau = \frac{L}{R} \tag{7}$$

$$V' = -\left(\left(\frac{M^2}{L}\right) \cdot \frac{i'_{max}}{\tau}\right) \cdot e^{-\frac{t}{\tau}}. \tag{8}$$

In a linear-log plot V' vs. t is a strait line from which τ can be determined. The resistance of the splice is then given by

$$R = \frac{L}{\tau}. \tag{9}$$

The value of L can be calculated from the known geometry of the coil form or it can be obtained after the experiment by the destructively sawing the splice in place on the coil form and measuring its inductance. Future splices with the same cable might then use this value of L.

The ratio, α, between the initial decay voltage,

$$V'_0 = -\left(\frac{M^2}{L}\right) \cdot \frac{i'_{max}}{\tau} \tag{10}$$

and the maximum coil current, i'_{max}, can be experimentally determined by repeating the procedure for several i'_{max} and extracting the slope $\alpha = V'_o / i'_{max}$ that allow us to write

$$-\frac{M^2}{L} = \alpha \cdot \tau \tag{11}$$

as another measurement for M^2/L permitting a self consistency check with Eq. (4).

HARDWARE

Primary coil

The fiberglass-epoxy (G10) frame for this coil was machined out of a 2.54 cm thick plate in the racetrack shape indicated in figure 2. The reason for this shape is that it is simple, allows for large immersed inductance (area) and fits through the dewar neck. The coil fills a 19.2 mm wide by 6.9 mm deep groove along its outer perimeter. It was designed to use some[7] available insulated multifilamentary NbTi wire with 0.46 mm diameter and 0.231 Ω/m at room temperature.

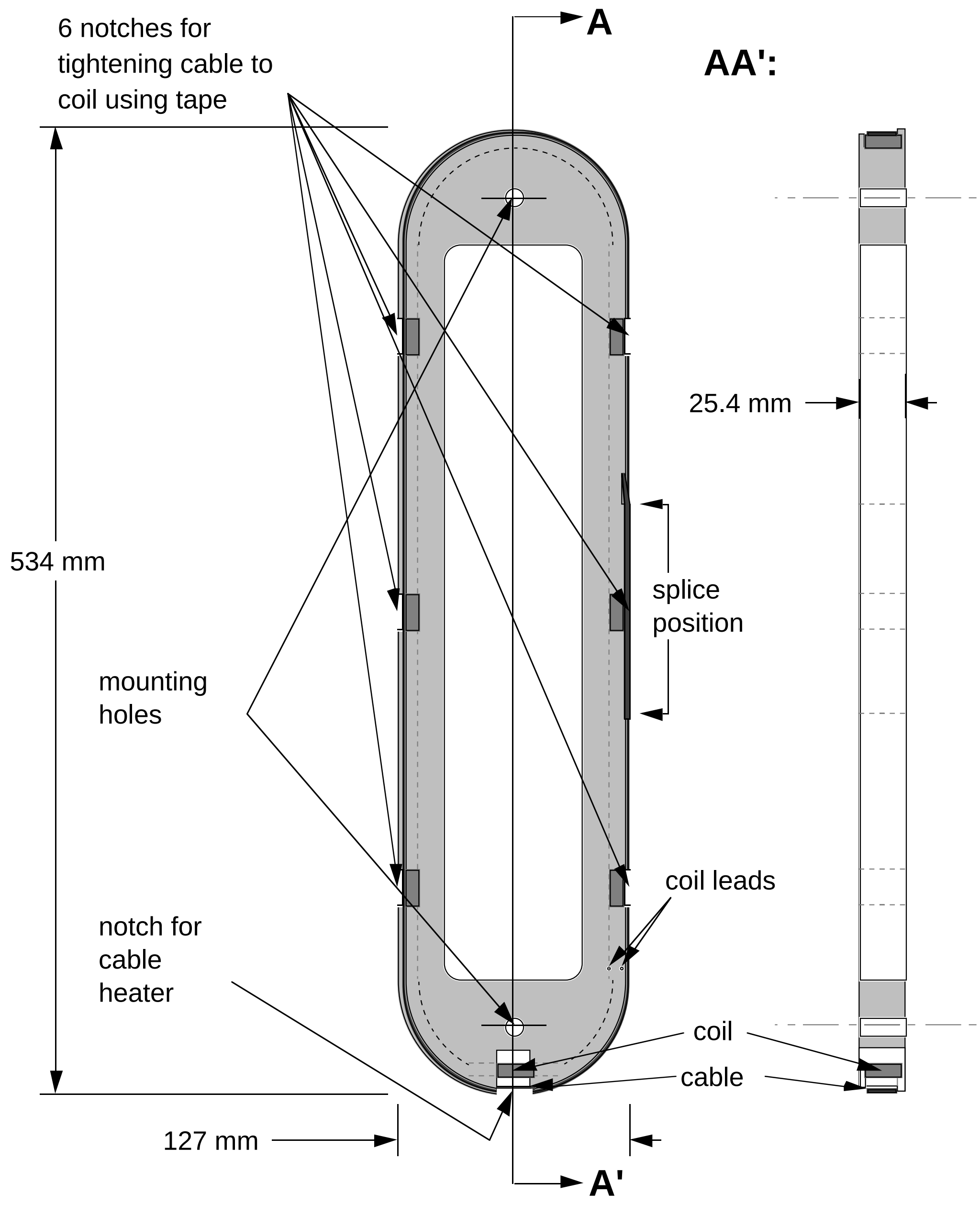

Figure 2. Mechanical drawing of the G10 coil form

The winding parameters are 40 turns per layer, 11 layers tightly and uniformly wounded with a 0.17 mm thick Kapton (with adhesive) tape between the layers. One extra layer of fiberglass based electric tape covers the coil and the flush groove side. Over it goes the cable loop with the splice to be studied. The resistance of this coil at room temperature is 109.6 Ω.

Cable, splice and heater

The Rutherford type cable used consists of 38 strands of multifilamentary NbTi composite with 114 mm transposition pitch turksheaded to a 15.0 mm x 1.5 mm cross section. This is the cable intended for the inner triplet quadrupoles of the Large Hadron Collider interaction regions.

The splice was made by soft-soldering an overlapping length of 112 mm. The cable length used was 1326 mm. The solder used (60Sn/40Pb ersin multicore) was applied using a large soldering iron heated to 588 K while the splice was pressed between two Teflon blocks in a bench vise.

In the notch of the frame a heater was installed surrounding the cable. This heater consisted of two strain gauges[8], one on each side of the cable connected in series-parallel to form a total resistance of 120 Ω, 1 W (assuming each section capable of handling 0.25 W in air). The original Kapton wrap of the cable was not disturbed. The strain gauges were mounted in a folded tab of 0.23 mm thick G-10 covered by 0.08 mm thick copper foil to spread the heat. The whole arrangement was insulated and sealed from the liquid helium by means of Teflon in the form of Gore-Tex joint sealant and plumbers tape. Immersed in liquid helium this heater performed satisfactorily with 18 V and 0.14 A for periods as long as 3 minutes.

MEASUREMENTS

Decay time measurements in this first run of the apparatus were obtained by recording the analog output of the microvoltmeter[9] with a chart recorder[10], manually digitizing it into an Excel spreadsheet for plotting and manually extracting the slope.

The opposite sign relationship between V'_o and i'_{max} predicted by Eq. (10) is observed on the data but for the purpose of plotting in a logarithmic scale only their absolute values are used.

Figure 3 presents the plots of several of these decays. Decays from i'_{max} = 30 A are not shown to prevent crowding of the figure. Because the microvoltmeter has a zero offset, partially due to thermal emf on the leads, the signal is the result of the pickup voltage minus an artificial bias selected to make the signal of the last point to be 1 μV. So the slope touching the bottom edge of the plot is to be definitely disregarded and some caution is require when trying to interpret the slopes with signal less than 100 μV specially if the data covers less than 10,000 s of acquisition time.

Some of the fine structure might be related to artifacts due to the change of scales in the chart recorder and the manual digitization (which will be eliminated in future runs). Other contribution to the fine structure might come from the solder in the splice which is a superconductor with low critical field[1]. Although one can see fine structures, that might have interesting origins, there is the clear predominance of one slope. Neglecting the decays from runs of i'_{max} less than 20 A this slope correspond to a decay constant τ = 810 s and is independent of i'_{max}.

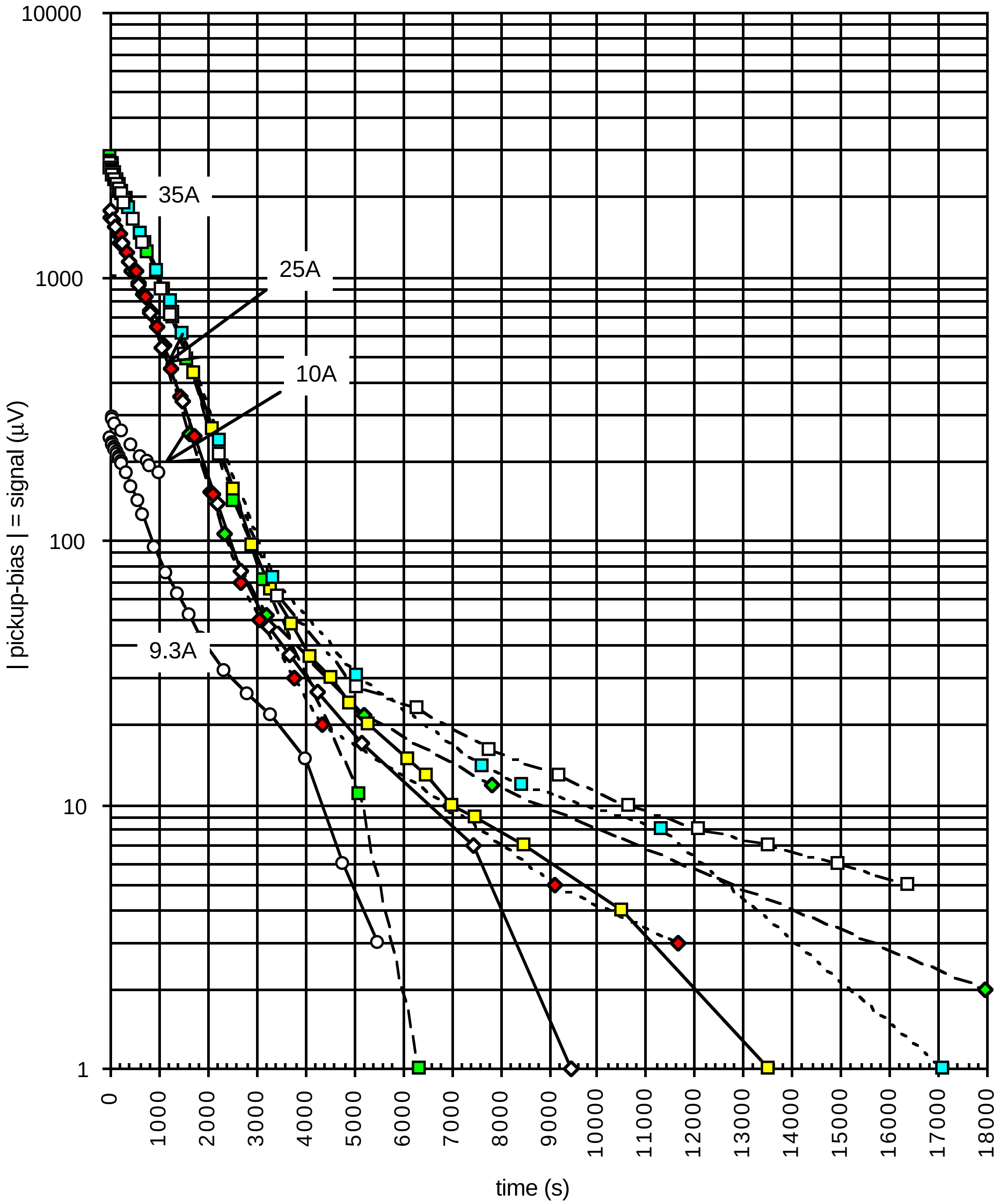

Figure 3. Decay curves from several excitation currents

Extrapolating these decaying voltages to time $t = 0$ and plotting them with respect to their i'_{max} we get figure 4, in which we see a clear linear behavior for i'_{max} larger than 10 A. The slope in this case is -94.7 µV/A. Deviation is expected for smaller i'_{max} since this line is expected to go through the origin.

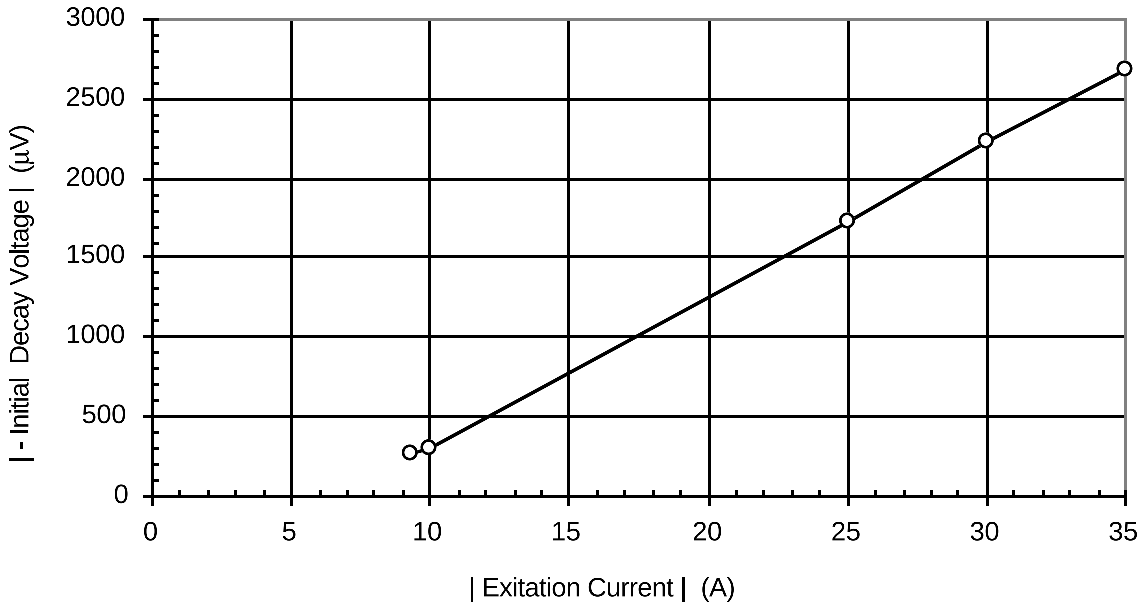

Figure 4. Relation between primary excitation current and initial decay signal

Self inductances were measured with a Sencore Model LC77 Auto-Z meter with an accuracy of 3%. The self inductance of the coil before installation of the spliced cable loop was L' = 126.8 mH. The installation of the spliced cable loop over the coil changes the self inductance to an effective inductance of L_{eff} = 57.5 mH. This effective inductance is a function of temperature. At 4.2 K its value is 31.5 mH. It is speculated that this temperature dependence comes from two sources: 1) the Meissner effect; 2) the differential thermal expansion between the cable loop and the coil frame which strongly tightens the coupling (increasing the mutual inductance M). The repulsion forces between the coil and the loop when both are carrying current should also affect this coupling but in the measuring condition this force is zero since i' is zero. After the decay time measurements described above, the splice was sawed in place to allow for the measurement of its self inductance, L = 0.20 µH±8% and again for the measurement of L' which turned out to be 130.5 mH at room temperature and 115.8 mH at 4.2 K.

RESULT

The quality of the data and self-consistency of the method can be quantified by the agreement between the two ways of measuring M^2/L:

from Eq. (4) using the 4.2 K values: $M^2/L = 115.8 - 31.5 = 84 \pm 4.4$ mH

and from Eq. (11): $-M^2/L = -94.7\times10^{-6} \,.\, 810. = 77 \pm 4.6$ mH.

The error bars are calculated using error propagation and result from the 3% accuracy of the inductance measurements and the same error being attributed to the values of α and τ.

The resistance of the splice according to the Eq. (9) and its error bar similarly calculated is:

$$R = 0.2\ \mu\text{H} / 810.\ \text{s} = 0.25 \pm 0.027\ \text{n}\Omega$$

a value that has been compared[11] to and found consistent with other samples measured with kiloamperes, microvolts and Ohm's Law.

In conclusion: the resistance of a splices in a loop of superconducting cable can be measured rather economically from the decay time of an induced current . We unexpectedly observed a second decay constant explainable as a change in the splice resistance. As the self field of the induced current decays the solder goes through its superconducting transition lengthening the decay time constant.

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