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Inter-Strand Resistance Measurements in Cored Nb-Ti Rutherford Cables

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***Abstract*—Cored Nb-Ti Rutherford cables with high crossover resistance R_c are being investigated to minimize ac losses in a set of superconducting dipole magnets for the proposed rapid cycling heavy ion synchrotron facility at the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, Germany. This ring of magnets is based on the Relativistic Heavy Ion Collider (RHIC) design. R_c in cored cables is significantly larger than the contact resistance between adjacent strands R_a. The latter, however, dominates the voltage profile when the interstrand contact resistance is measured via the usual VI technique. This makes the extraction of the magnitude of R_c out of the voltage profile very difficult. Knowledge of R_c is important to predict ac losses, because if R_c and R_a were equal, perpendicular field induced losses due to R_c would be around 50 times greater than those induced by R_a. Because of the importance of the crossover resistance, we have developed a novel measurement technique for R_c in cored Nb-Ti Rutherford cables. The procedure involves removing the edges of the conductors along the region to be measured. We have measured the cables using the new technique and the usual VI technique. We describe the novel measurement technique and present results for cables made with different core materials. While measuring R_c, we found evidence that R_a is non-uniform over the length of a twist pitch and is in fact significantly lower at the cable edge. We report on this as well.**

***Index Terms*— ac loss, crossover resistance, interstrand resistance, Rutherford cable.**

I. Introduction

THE proposal for the heavy ion synchrotron at GSI Darmstadt incorporates a Nb-Ti cosine-theta dipole magnet design that is based on the design of the dipole magnets that are operating in the Relativistic Heavy Ion Collider at Brookhaven National Laboratory (BNL) [1],[2]. However, the proposed GSI accelerator demands a ramp rate of 1 T/s to reach the required beam intensities, whereas the RHIC ramp rate is only 0.042 T/s. Modifications in the RHIC magnet and conductor designs are needed to minimize the ac losses associated with such a rapid ramp [3]. One of the modifications is the introduction of a resistive core into the Rutherford cable to increase R_c. Here we report on the measurement of interstrand contact resistances (ICR) in the cored Rutherford cables. The correlation between the ICR and ac losses is done elsewhere [4].

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II. VI Measurement of Interstrand Resistances

A. Method

The VI method of measuring ICR is described in detail by Verweij [5]. Current is fed into 'opposite' strands (i.e. strands 1 and (N/2)+1 in a N-strand cable) of a length of Rutherford cable that is immersed in boiling liquid helium at 4.2 K. In the experiments described here, the sample length is one twist pitch length. The voltage between strands for a given input current A is then recorded. A profile showing the resistance between strand 1 and strands 2 through (N/2)+1 can then be plotted. From the shape and magnitude of the resulting profile R_c and R_a can (in principle) be extracted. It is well known ([5],[6]) that as the ratio R_c/R_a becomes larger the voltage profile approaches a straight line. Verweij [7] also has developed the computer code VIRCAB that calculates the voltage profile and values for different R_a and R_c values. His program was used to create Fig. 1, which shows the (normalized) voltage versus strand profile for different values of the ratio R_a/R_c. R_a and R_c are assumed to be constant in each of the runs. (VIRCAB allows for variations of the values of R_c and R_a across the width of the cable). The model was run for a 30-strand cable, as the RHIC cables contain 30 strands. The profile is symmetrical about a strand separation of (N/2).

Fig. 2 shows the typical voltage profile for a cored Rutherford cable. The profile is the one we measured for Sample GSI-003-D, as described below. It approaches a straight line, indicating that $R_c >> R_a$ (as is expected for a cored cable). However, it is also seen that the shape is significantly different from the idealized shape shown in Fig. 1, due to local variations in R_a between adjacent strands. Attempting to extract a value for R_c out of this profile is very difficult. We have thus developed the technique described in section III to determine R_c in cored Rutherford cables.

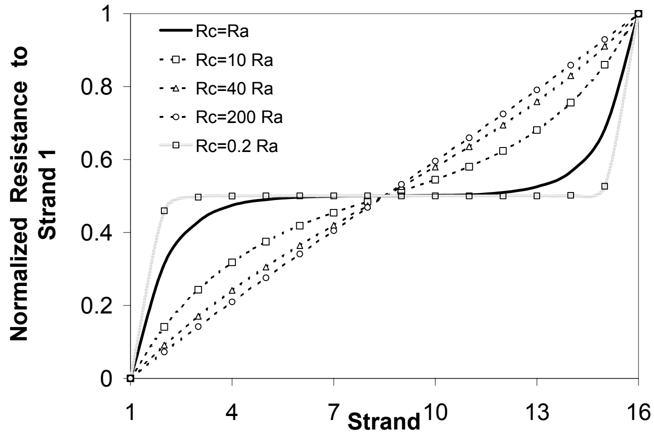

Fig. 1. Computed Voltage Profiles for different Ratios of R_c/R_a.

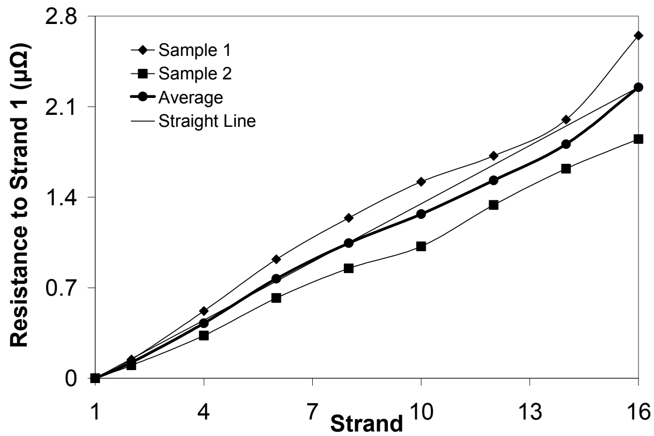

Fig. 2. Voltage Profile for a cored Rutherford Cable (GSI-003-D).

B. Determining R_a from VI profile

In the case of $R_a << R_c$, the VI profile yields a good estimate of R_a when one assumes R_c to be infinite: In the discrete network model, there are *2N* resistances R_a per twist pitch length that connect any strand to its neighboring wire, so that the resistance between two adjacent strands (over one twist pitch length) is $R_a/2N$. There are two parallel current paths between strand 1 and strand (N/2)+1 that contain (N/2) series resistances of $R_a/2N$, so that

where $V_{1\rightarrow N/2+1}$ and $I_{1\rightarrow N/2+1}$ are the voltage and current

$$R_a = 8 \cdot \frac{V_{1\rightarrow (N/2+1)}}{I_{1\rightarrow (N/2+1)}}$$

between strand 1 and strand (N/2)+1, respectively. We have run VIRCAB for several ratios R_c/R_a and found for R_c/R_a =400 that $R_a = 8.036\ (V_{1\rightarrow N/2+1}/I_{1\rightarrow N/2+1})$ and for R_c/R_a = 200 that $R_a = 8.405\ (V_{1\rightarrow N/2+1}/I_{1\rightarrow N/2+1})$. Thus the above formula will underestimate R_a by less than ~ 5 % for R_c/R_a > 200. In the case of the cored cables measured here, we have used the above formula to calculate R_a.

III. Direct Measurement of R_C

To measure R_c directly, we force current through the core and measure the accompanying voltage drop between the top and bottom layers. This gives the sample resistance R_{Sample}. A top view of the upper half of the cable sample setup is given in Fig. 3. The bottom half is set up identically. The voltage is measured at several voltage taps to ensure that the top and bottom layers are equipotentials. The sample length for this test is ~ 2.5 cm, or 1/3 the twist pitch length. We determine the number N_c of crossover resistances R_c that are in the sample. Since they are in parallel, we find $R_c=N_c \cdot R_{sample}$.

To do this measurement, we remove the sides of the superconducting cable to interrupt the current transfer through the wire from the top to the bottom layer. This is done by abrasive cut-off wheels rotating on a shaft that is spun by a vertical mill. The wheels rotate in the plane of the cable, so that there is no smearing of material from the bottom to the top layer and vice versa. We grind until we can clearly see that the bottom and top layers are separated and we can see the foil in the center. Fig. 4 gives a side view of the cable that clearly shows the top and bottom layers as well as the foil in between.

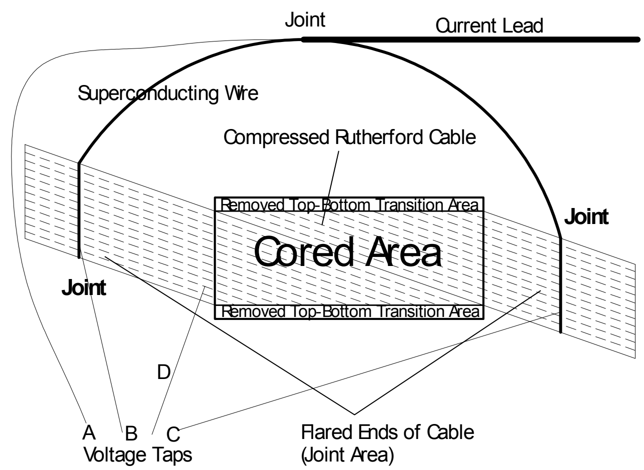

Fig. 3. Top view of experimental setup.

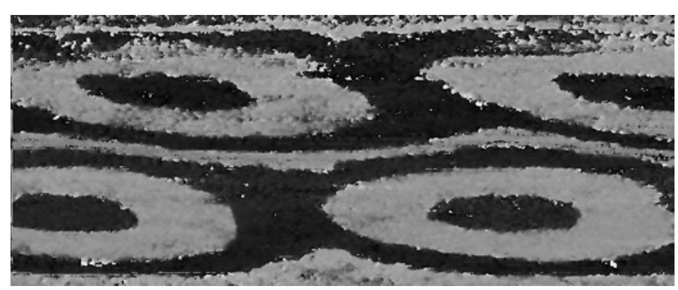

Fig. 4. Side View of separated layers with foil in between.

The sides are ground off while the sample is under full compression (70 MPa) in the fixture in which it is subsequently tested. We monitor the sample temperature while grinding to ensure that the conductors' surface conditions do not change during sample preparation. Pressure relief and subsequent recompression as well as elevated temperatures are known to affect ICR. For the same reason, the grinding is done dry, because cutting fluid (coolant) could have an impact on the surface conditions.

The setup may appear cumbersome in light of the fact that R_a is so much smaller than R_c: One could suggest that in such a case it would be permissible to treat the top and bottom areas of the cable as equipotential surfaces even when the two sides are not connected by a superconducting wire. However, we found evidence (see section VI) that leads us to believe that R_a is very non-uniform across the width of the cable and in fact is significantly higher near the central region than near the edge of the cable, the very area that we have to remove to be able to measure R_c directly. Richter ([6],[8]) has also noted that the interstrand resistance in the cable edge region is a rather complicated issue, without going into further detail.

IV. Cable Sample Preparation

All samples described in this report were formed during the same cabling run (run GSI-003) at New England Electric Wire Corporation (NEEWC) and then insulated at BNL. Unlike the strands in the RHIC magnets, the strands in these cables are coated with staybrite ($Sn_{95\%wt}Ag_{5\%wt}$). For insulation, two 25 µm layers of kapton are wrapped around the cable with a 50 % overlap. The outer wrap is coated on the outside with a polyimide adhesive that bonds the different layers of the cable together after it has been cured. The samples are prepared as ten-stacks: 10 pieces of cable that are stacked on top of each other (with alternating keystones) and then cured. We use four spacer cables above and below the actual sample pieces; only the middle two cable pieces are tested. The 10 cable pieces are stacked into a fixture and cured. The curing cycle is the one used for the RHIC dipole magnets. It can be seen in Fig. 5.

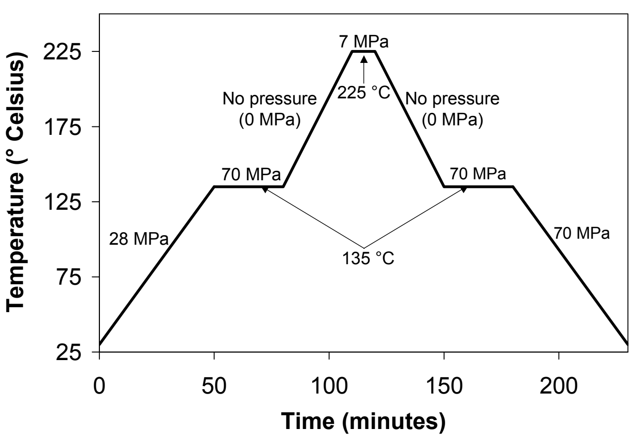

Fig. 5. RHIC coil curing cycle.

Much work has been done at CERN to optimize the coating of the strands in the superconducting dipoles for the Large Hadron Collider (LHC) [6],[8]. As the LHC conductor is also coated with $Sn_{95\%wt}Ag_{5\%wt}$, many of the mechanisms of oxide formation on the strands as described in the LHC references above are likely also at work in the cable described here. It is necessary to point out that, apart from the core, another fundamental difference between the LHC cable and the cable described here is the cable curing method: LHC curing is done with the curing pressure applied throughout. In the RHIC curing cycle, the pressure is completely released as the cable is heated from 135 °C to 225 °C (at which point a rather modest pressure of 7 MPa is applied to aid in the polyimide bonding). The pressure is also completely released as the cable is cooled from 225 °C to 135 °C. Thus oxidation is more likely to occur during this time for the RHIC procedure than for the LHC procedure as oxygen has easier access to the uncompressed wire surfaces than to compressed wire surfaces. Similarly, the work on cored cables described in [9] incorporates a curing cycle in which the samples are pressurized throughout.

V. Results of the ICR Measurements

Each ten-stack contains two test samples; the results presented here are averages of the measured samples. In cases where the two samples in a ten-stack differed significantly, we prepared additional samples to clarify the results.

During the cabling run at NEEWC six different cables were formed: Cables A and B both have a thinner $Sn_{95\%wt}Ag_{5\%wt}$ coating than the other cables, cables A through D have a single 25 µm stainless steel foil, while cable E has two layers of the 25 µm stainless steel foil, and cable F has 1 layer of a 50 µm brass foil. The results are given in Table I. The nominal

Table I: Experimental Results

	Sn-Ag Coating, µm	Cable Thickness, mm	Foil	R_a (µΩ)	R_c (mΩ)
A	0.66	1.138	25 µm SS	**100**	
B	0.66	1.180	25 µm SS	**72**	**14**
C	1.04	1.187	25 µm SS	**28**	
D	1.04	1.202	25 µm SS	**18**	**12.5**
E	1.04	1.173	2·25 µm SS	**21.5**	**62.5**
F	1.04	1.175	50 µm Brass	**8.5**	**0.66**

mid-thickness for the RHIC cables is 1.166 ± 0.006 mm.

All the cored cables show an R_c significantly higher than R_a. In uncored cables, one typically finds $R_c \sim R_a$. The cables with the thinner $Sn_{95\%wt}Ag_{5\%wt}$ coating (A and B) display a higher R_a, which is likely caused by more oxidation due to the thinner coating. Furthermore, we also see that the thinner cables within a given coating thickness (A vs. B and C vs. D) show a higher R_a than the thicker cables. We believe that the reason for this is increased compaction 'damage' to the $Sn_{95\%wt}Ag_{5\%wt}$ coating during cabling, which allows more oxide to form on the 'damaged' areas during the curing cycle. Furthermore, two stainless steel foils (cable E) give higher ICR than one brass foil (cable F) of the same compound thickness. We attribute this to the way brass is 'extruded' during cabling, so that it conforms to the cable strands.

VI. Evidence for the Anisotropy of R_A

As alluded to in describing the setup for the direct R_c measurement, we originally attempted to measure R_c without the superconducting wire that makes top and bottom equipotential layers (see Fig. 3 for a view of the top layer with the superconducting wire). As R_a is significantly smaller than R_c, one would expect the voltage drop across top and bottom layer to be negligible compared to the voltage drop across the core. We monitored the voltage drop across the layers and found a significant voltage drop across both bottom and top layer, much higher than expected given the value of R_a measured previously.

A simple test was devised to clarify this: Sample GSI-003-D had previously been measured and the voltage profile has been given in Fig. 1. We cut the original sample stack in half and cut a sample from either end of it. We then compressed the resulting two samples over 2.3 cm (Sample 1) and 1.2 cm (Sample 2). As this is significantly less than the half-twist pitch of 3.7 cm, some of the wires in the sample are compressed over the cable edge region, while others are compressed only over the central region. We measured another VI profile for each of the samples; these profiles are given below in Figs. 6 and 7. It is immediately obvious that the shape of the profile is very different from the original shape.

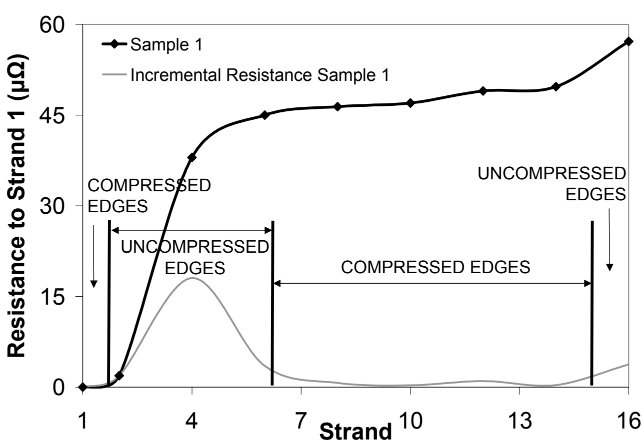

Fig. 6. Voltage Profiles for Sample 1, compressed over only 2.3 cm.

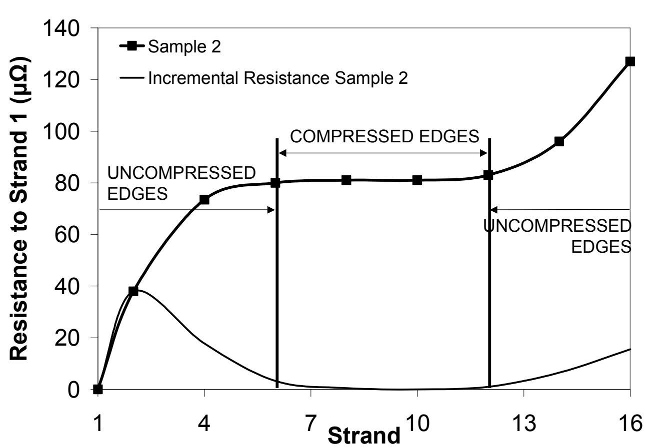

Fig. 7. Voltage Profiles for Sample 2, compressed over only 1.2 cm.

We then traced the wires that were used in measuring the profiles to see whether they had been compressed in the cable edge region. As is indicated in the graphs, adjacent wires that had been compressed in the cable edge region show a significantly lower adjacent resistance than wires that were compressed only over the flat region. The 'incremental resistance' indicated in the graphs clarifies this.

We would like to point out that the absolute values measured here are not representative, as the sample had had its pressure completely relaxed before we undertook this measurement. While this does not change the geometric shape of the measured profile it leads to an increase of the ICR. We conclude from these measurements that R_a is significantly lower in the cable edge region than it is along the flat area.

VII. Conclusion

We have measured interstrand resistances for several cored Rutherford cables under consideration for use in the fast-ramping RHIC-style dipole magnets being developed for the new GSI facility. We developed a new technique to measure R_c in cored Rutherford cables. As expected, the crossover resistance in cored Rutherford cables increases significantly, leading to a dramatic reduction of the associated ac losses. Furthermore, we have found evidence that R_a varies considerably over the length of a twist pitch, being significantly lower in the cable edge region.

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