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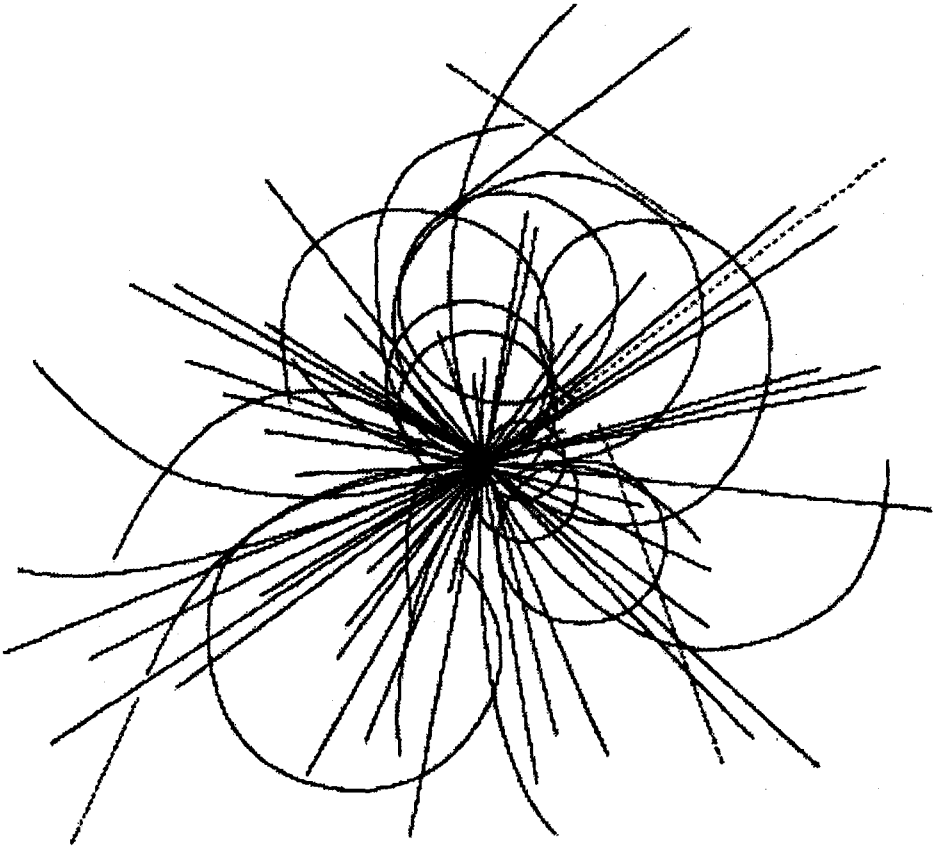

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MAGNETORESISTANCE OF SSC BEAM TUBE SAMPLES

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INTRODUCTION

The beam tube for the Superconducting Super Collider (SSC) is required to have an inner surface of sufficiently high DC electrical conductivity in order to satisfy beam stability requirements. This high conductivity surface will also help to reduce the parasitic heating of the beam tube due to image currents and may have a positive effect on the beam tube cryogenic budget.[1] The SSC specification on beam tube conductivity is related to the inner diameter; for diameters of technical interest the product of DC electrical conductivity and thickness (σt) should be in the range of 1-2 $\times 10^5\ \Omega^{-1}$ under operating conditions which include a transverse magnetic field in the range of 7 T.

A competing factor to be considered is that in case of a dipole quench the collapsing field induces eddy currents in the layer which interact with the collapsing magnetic field, causing large forces and stresses in the beam tube. This requires that the layer be as thin as possible in order to keep the stresses in the beam tube at an acceptable value.

This paper will cover measurements of the DC electrical resistivity with and without transverse magnetic field on samples of stainless steel tubes with inner coatings of copper as well as copper with a thin gold overlay. These samples were produced by different

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vendors by electroplating with some variations in layer thickness, and post-deposition heat treatment.

These measurements are part of an ongoing experimental program to determine the suitability of these copper-lined stainless steel tubes for use as the proton beam chamber in the SSC. Although in the baseline design the beam tube is cooled to 4.2 K by the supercritical helium used to cool the superconducting magnets, an optional design was considered for reasons unrelated to resistivity which required the beam tube to be operated at about 80 K. The 77 K measurements reported here were taken to obtain design data for this option.

EXPERIMENTAL DETAILS

The experiment was performed in two phases. Based on discussions with researchers from the National Institute for Science and Technology (NIST)[2] two sample configurations were identified for magnetoresistance measurements. In phase 1, measurements were performed at 4.2 K to determine which configuration would be a more suitable and cost-effective method for an extensive series of follow-on qualification tests. Table 1 lists the samples used in the phase 1 measurements along with their copper layer thicknesses and post deposition heat treatments.

Table 1. Samples used in phase 1.

Vendor	Sample ID	Cu Layer Thickness	Heat Treatment
A	Cu-SI-0	50 μm	1 hr @190°C
B	Cu-FL-0	38 μm	1 hr @230°C

Figure 1 is a tracing taken from a scanning electron micrograph of a typical elecroplated copper layer. In all cases the stainless steel tube is an austenitic ASTM type XM11 with an inner diameter of 32.3 mm and a wall thickness of 1.2 mm. This material is proposed for use in the collider quadrupole magnets, while the current collider dipole design uses type 304LN steel.

The first sample configuration is a slit tube, in which 5-10 mm wide rings are sliced from the vendor-supplied beam tube by machining in a lathe. A longitudinal slice is then cut in it to allow the current to flow circumferentially around the ring. A four terminal technique was used in the measurements, in which the sample current was introduced and extracted from the ends of the slit ring specimen (100 mm long), and the voltage is LakeShore 120 Current Source, and the voltage was measured using a Hewlett Packard 3458A microvoltmeter.

The second sample configuration was an unslit piece of tube, wherein the current travels axially down the tube. A 35 mm long sample was cut from the vendor-supplied tube by either machining in a lathe or by diamond sawing. A four terminal technique was also used in these measurements. A 12 A current was introduced and extracted from the ends of the 35-mm-long tubular specimen using a Kepco power supply. The voltage was

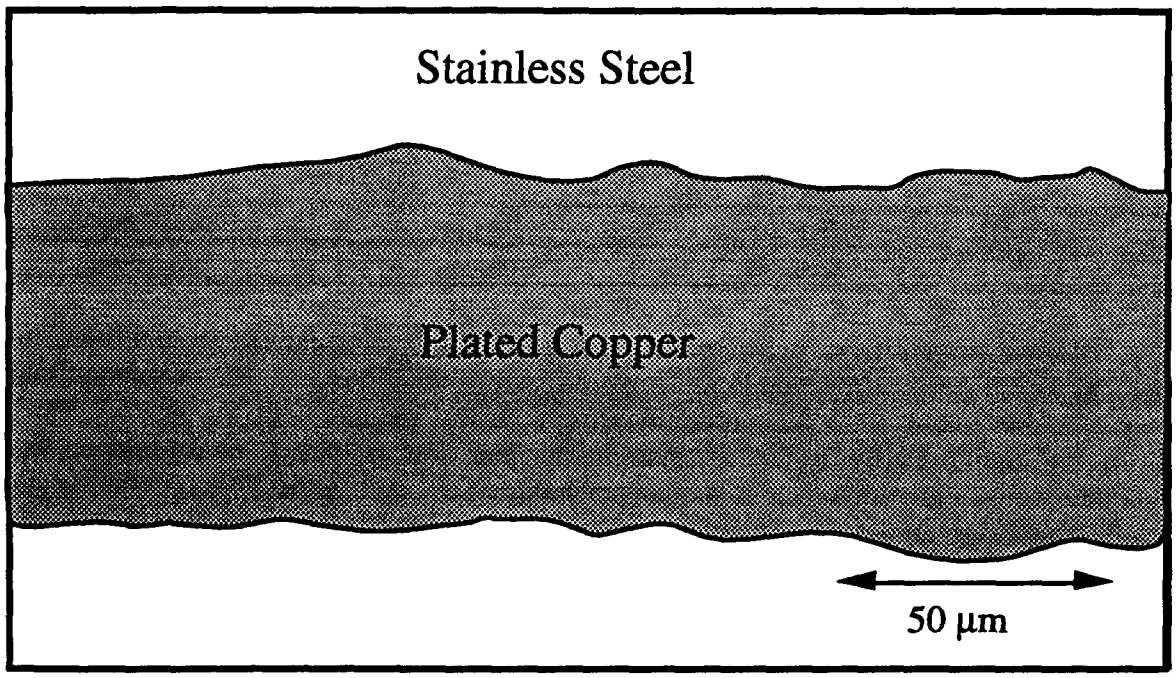


Figure 1. Tracing of a typical copper layer electrodeposited onto a stainless steel beam tube.

measured over a center 20 mm long section using the same Hewlett Packard voltmeter as above. A copper-stabilized NbTi superconductor current lead was soldered around the entire circumference at each end of the tube to provide a uniform current distribution. The voltage taps are 22 gauge copper, soldered circumferentially inboard of the current leads with 60/40 SnPb solder. Polyimide tape was used during the lead attachment to confine the solder.

Phase 2 measurements were carried out at 4.2 and 77 K. For reasons described below only the unslit configuration was used. Again the four terminal technique was used. To enhance the signal-to-noise ratio measurement currents of up to 50 A were supplied using a Hewlett Packard 6031A System power supply. The effect of thermal voltages was eliminated by measuring the voltage drop in both current polarities and averaging the result. A Keithley 182 Sensitive Digital Voltmeter was used to measure the voltage drop. The best results were obtained using a 30 A measurement current and the statistical averaging mode of the Keithley voltmeter. In this mode both the digital and analog intrinsic filters are disabled and a set of 500 voltage readings are stored in a buffer over a period of approximately 30 seconds. The average voltage and standard deviation were recorded. In order to provide equally uniform current distribution for both 4.2 and 77 K measurements a large rectangular cross section MRI-type NbTi monofilamentary conductor was used. This conductor has approximately a 3.75 mm^2 cross section and a Cu:SC ratio of 3.7. The measurement current can then be uniformly distributed by the large copper cross section at 77 K and by the superconductor at 4.2 K. Current was introduced to this superconducting current lead at four equidistant points to further ensure a uniform current distribution. Table 2 lists the samples used in phase 2 along with their copper layer thicknesses and post electrodeposition heat treatments.

Table 2. Samples used in phase 2 measurements.

Vendor	Sample ID	Cu Layer thickness	Heat Treatment
A	Cu-SI-1	109 μm	1 hr @ 260°C
A	CuAu-SI-1	108 μm + 2 μm Au	2x1 hr @ 190°C
A	Cu-SI-2	97 μm	1 hr @ 190°C
B	Cu-FL-0	38 μm	1hr @ 230°C
A	Cu-SI-DD	100 μm	Unknown

All magnetoresistance measurements described above were carried out in a solenoid field up to 8 T with the magnetic field perpendicular to the tube axis. The magnetic field was obtained using a 15 T superconducting solenoid magnet with 64 mm aperture, produced commercially by Oxford Instruments, Inc. For the 4.2 K measurements the samples were simply immersed in the magnet helium bath, and for the 77 K measurements the samples were immersed in a liquid nitrogen bath contained in a vacuum-insulated finger inserted into the magnet bore.

RESULTS AND DISCUSSION

Phase 1 resistance measurements were performed on the tubes listed in Table 1 to assess the differences between the two sample configurations and check out the procedures. A correction for the parallel resistance of the stainless steel was applied to the measured resistance values in order to obtain the contribution due to the copper. This value is significant at room temperature, much less significant at 77 K, and practically negligible at 4.2 K. The measured resistance, R_T, was taken as the resultant of the resistances of the steel tube and the copper coating in parallel. The resistance of the steel, R_{SS}, was calculated using handbook values for austenitic stainless steel resistivity at 273 K (7.4×10^{-7} Ωm) and 77 K (5.3×10^{-7} Ωm), and the resistance of the copper coating, R_{Cu}, calculated using $R_{Cu} = (R_T * R_{SS}) / (R_T - R_{SS})$. For the Cu-FL-0 specimen the measured Residual Resistance Ratio ($RRR = R_{273}/R_{4.2}$) for the slit configuration was lower (RRR = 80) than for the unslit tube (RRR = 160). This is evidence that the machining operations needed to prepare the specimen may result in mechanically deforming a significant volume of copper in the measurement path and thereby underestimating the actual RRR value. In the case of the unslit tube, the material between the electrodes is untouched, so no degradation in apparent RRR value is expected. As a result of these measurements the unslit configuration was adopted for phase 2. The unslit configuration also provides a better approximation to the operating conditions for the collider beam tube since the current is along the tube axis and perpendicular to the magnetic field as is the case with the particle image currents and induced eddy currents in the collider dipoles.

Experimental results for phase 2 magnetoresistance measurements are presented in Table 3. The measurements on several samples were duplicated in order to assess the repeatability of the results. The estimated error in reporting both RRR and $\Delta R/R_0|_{4.2K}$ (ΔR is $R_B - R_0$) is approximately ± 10%. The error is due in part to variations in Cu coating thickness and to the sample geometry which requires high measurement current and yields

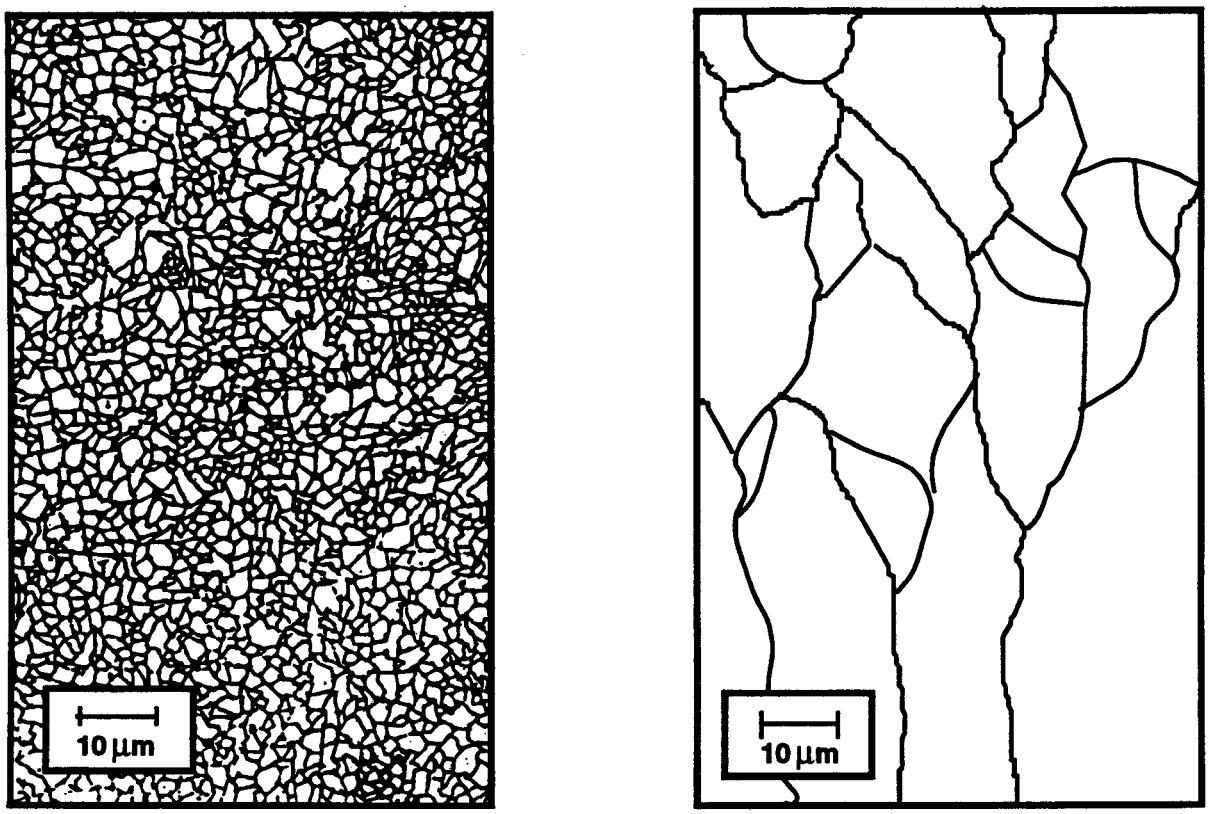
low voltage differences. In addition the calculation of R_{Cu} at 273 K described previously may introduce an error since actual resistivity values may differ from the handbook values or average thicknesses of copper or steel may differ from the measured thicknesses used in the calculations. In general RRR values are consistent with post deposition heat treatment. Samples Cu-SI-1, however, have a range of RRR values which exceed experimental error. The reason for this could be inhomogeneity in the copper deposition process or in the post deposition heat treatment since these three samples were cut from different locations of a single 6m long beam tube. Further study is required to pursue this possibility. The fractional change in resistance, $\Delta R/R_0$, is consistent with RRR data with the exception of sample Cu-SI-1-M3 which shows low $\Delta R/R_0$ and an unrealistically high value of σt.

Tracings of micrographs of polished copper layers of samples taken from beam tubes Cu-SI-2 and Cu-SI-DD are shown in Figure 2. There is an obvious correlation between the RRR values in Table 3 and the microstructures of these samples. The RRR differences are most likely due to the grain size difference. In the case of small heat treatment differences (e.g. samples Cu-SI-1 and Cu-SI-2) there is a less noticeable grain size difference. It is likely that RRR improvement is due primarily to lattice defect annihilation. According to one manufacturer, the heat treatments described in Table 2 were given primarily to drive off hydrogen and other gases that were trapped in the deposited layer. Trapped hydrogen could affect RRR differences if it was incorporated into the crystal lattice during deposition and then escaped during heat treatment. Exact determination of the major factors driving this is out of the scope of the present work and requires further study.

Figure 3 demonstrates the correlation between $\Delta R/R_0$ at 8 Tesla, 4.2 K and RRR of samples measured in phase 2. Data from samples cut from the same tube are represented by a common symbol shape with individual samples differentiated from one another by different symbol fill patterns. The property variations discussed in the previous paragraphs can be seen in Figure 3. This data also shows that the 2 μm thick gold flash of samples CuAu-SI-1 do not degrade the conductivity of the layer. The heat treatment was not sufficient to cause interdiffusion of gold and copper.

The error in RR and $\Delta R/R_0$ at 77 K is of the order of the values calculated. For this reason a cross correlation between RR_{77K} and $\Delta R/R_0|_{77K}$ and 4.2K data cannot be made. The practical result from the 77 K data is that the $\Delta R/R_0$ is no more than about 20%.

The sample designated as Cu-SI-DD in Table 3 is from a beam tube that was placed in a long (17-m) superconducting dipole, designated as DD0028, that was subjected to acomprehensive testing program. The magnet was subjected to twelve cool downs from room temperature to 4.2 K, 81 quench cycles, and 860 power cycles. This represents approximately 10% of the expected lifetime of the magnet. Apparently thermal, quench, and power cycling have little effect on the beam tube RRR. It has been speculated that repeated cool downs may cause thermal strain buildup due to thermal contraction coefficient mismatch between the conducting layer and the substrate, also that the interaction between the quench current induced in the conducting layer and the dipole field may cause large stresses in the beam tube. There is no evidence of stress buildup in either the resistivity or the microstructure (see Figure 2) due to the imposed operational conditions. The results of the measurements at 4.2 K and 77 K and at fields of 1-8 Tesla are presented in the Figure 4, and compared with the upper and lower limits of magnetoresistance data compiled by NIST[3] (solid lines). The logarithmic plot of fractional resistance change, $\Delta R/R_0$, and the



a) Sample Cu-SI-2

b) Sample Cu-SI-DD

Figure 2. Tracings from micrographs of the copper layers of beam tubes having relatively small (Figure 2a, Sample Cu-SI-2) and large (Figure 2b, Sample Cu-SI-DD) RRR values. The Cu-SS interface is in the direction of the top of the page in both tracings.

Table 3. Results of phase 2 beam tube measurements.

Sample ID	RRR	RR (77K)	$\Delta R/R_0$	$\Delta R/R_0$ (7T,77K)	σt, Ω^{-1} (7T,4.2K)
Cu-SI-1-M1	170	6.7	5.7	0.11	1.81E+5
Cu-SI-1-M2	88	6.7	3.4	0.21	1.43E+5
Cu-SI-1-M3	126	7.5	2.3	0.06	2.65E+5
Cu-SI-2-M1	65	7.3	2.4	0.20	1.18E+5
Cu-SI-2-M2	60	6.8	1.8	0.07	1.35E+5
CuAu-SI-1-M1	240	6.7	8.1	0.13	1.87E+5
CuAu-SI-1-M2	207	6.4	8.4	0.14	1.53E+5
Cu-SI-DD	269	6.1	12.0	0.12	1.33E+5

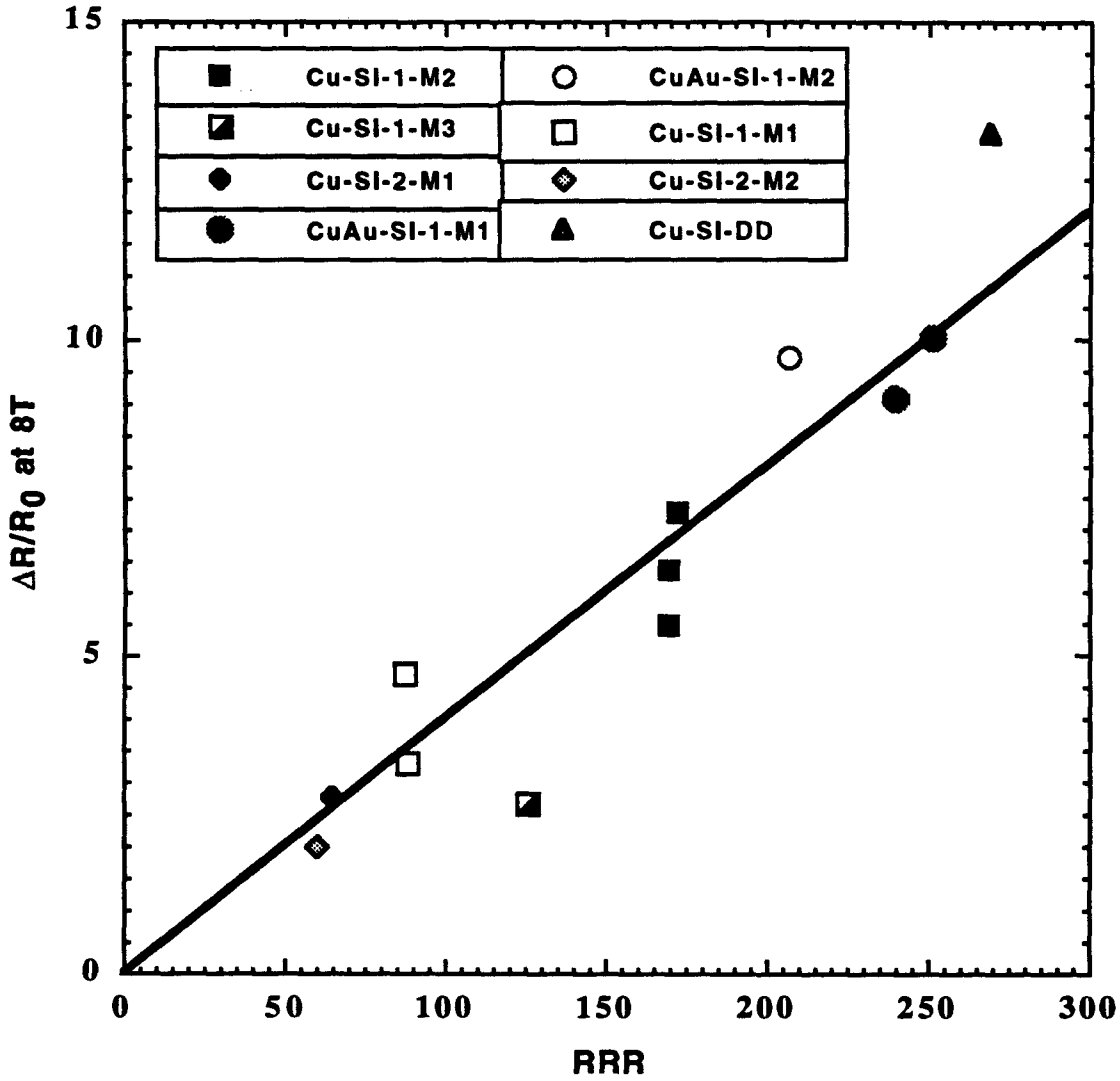


Figure 3. Fractional change in resistance at an applied field of 8 Tesla as a function of RRR for all phase 2 samples at 4.2 K.

RR x B product (in Tesla) is a standard Kohler plot. Our data are in general within the NIST uncertainty band and are in agreement with Kohler's rule. For RR x B values greater than about 30 there is some data slightly above the NIST upper limit.

In Figure 5 the conductivity-thickness product (σt) criterion is plotted as a function of magnetic induction for two samples with different RRR values. As expected, the σt criterion difference at fields above 6 Tesla is rather small. The large RRR does not provide significant enhancement of σt.

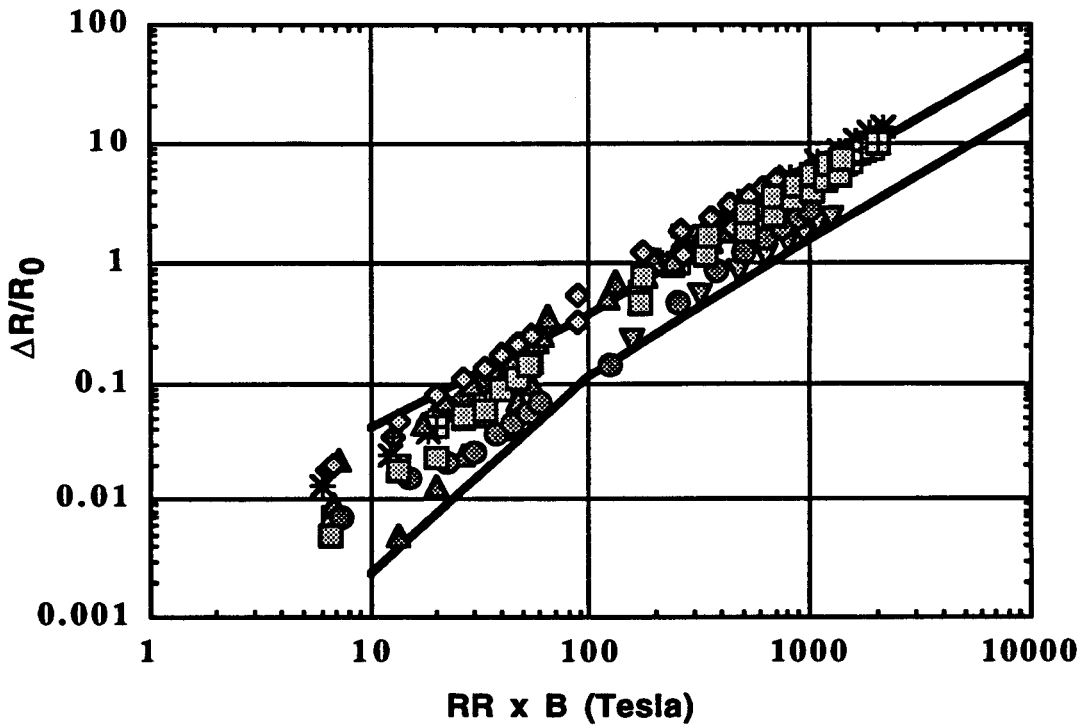


Figure 4. Fractional change in resistance as a function of the product of the residual resistance and magnetic induction (Kohler plot) for all samples measured in phase 2 at 4.2 K and 77 K.

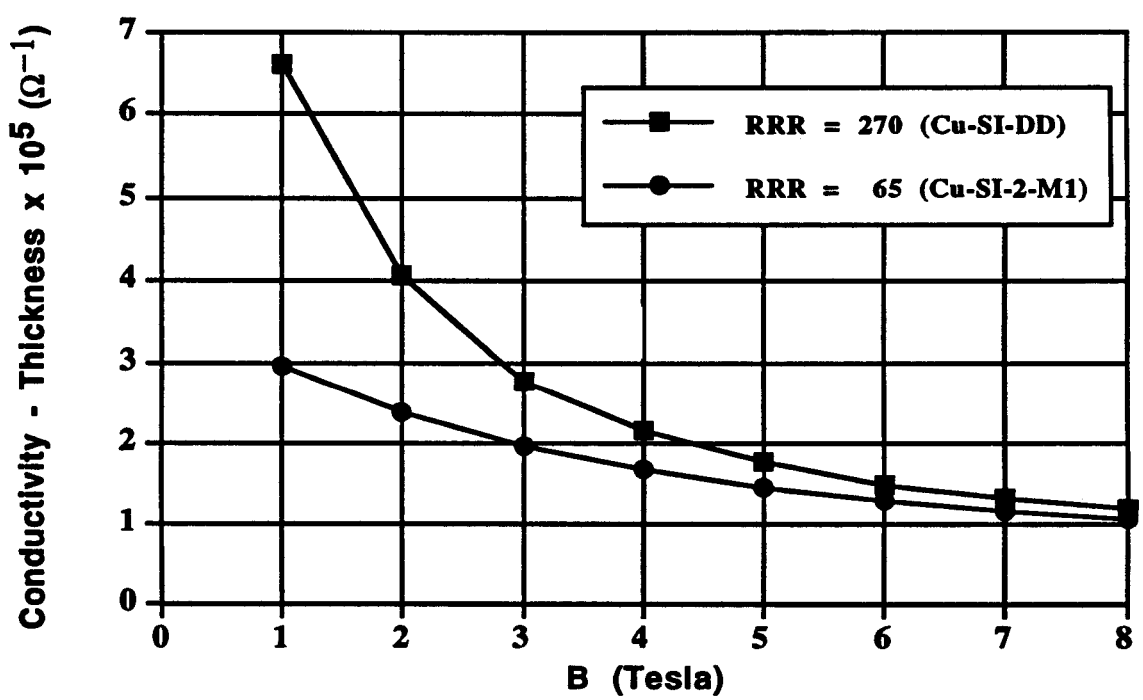


Figure 5. The product of DC conductivity at 4.2 K and copper layer thickness (σt) as a funtion of magnetic induction.

CONCLUSION

It is certain that the deposition technology, the post deposition heat treatment, and thickness can be optimized further to determine the most suitable and cost-effective method for the SSC tube design and production. These measurements show that the enhancement of RRR causes little improvement in σt at the collider operating field of 6.7 Tesla.

Therefore this criterion must be met primarily by adjusting the coating thickness. At 4.2 K copper layer thicknesses of 150 to 200 μm will be appropriate, depending on tube diameter. If an 80 K option for the beam tube is adopted, the only effective variable for meeting the SSC specification will be the copper layer thickness. In this case high RRR material gives no advantage and low RRR material will be sufficient.

The proposed beam tube qualification tests will include about 20 samples from different vendors having different deposition techniques, copper layer thicknesses and post deposition heat treatments. Only a few additional magnetoresistance tests will have to be performed and the majority of the planned testing will be simple thickness and RRR-type measurements.

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