Fermi National Accelerator Laboratory

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Results of Short-Sample Measurements and Their Implications

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I. INTRODUCTION

In order to better understand the optimum copper-to-superconductor ratio in a superconducting dipole cable, I took a trip to Brookhaven National Laboratory in December 1988 and visited the laboratory headed by Sampson, where "short-sample" measurements were performed. In below, I shall present some of the experimental facts that I learned from Garber, Ghosh, and Sampson, together with some of their interpretations as well as mine. Some of these results have been published.[1]

II. CRITICAL CURRENT DENSITY

What I know about superconductor is the phase-transition surface in the 3-dimensional space of temperature T, current density J, and magnetic flux density B as shown in Fig. 1. The superconducting material such as NbTi is in the normal phase when it is above this surface, and in the superconducting phase when it is below. I also know that as the material is crossing the surface from above, the phonon-exchange interaction between two electrons becomes attractive. Thus, every two electrons will bind together to form a bound state called Cooper pair. The Cooper pairs, being bosons, will undergo a Bose-Einstein condensation into a new phase, which is the superconducting phase that we are interested in. In other words, the transition is a phase transition which is a *sudden* change. Therefore, I should expect the critical or thermodynamic surface in Fig. 1 to be a well-defined surface.

I was told that one end point of the surface, the critical temperature T_c is indeed a well-defined point. This is the highest transition temperature, where the magnetic field and the current density approach zero. This temperature has been actively measured by the metallurgists for different materials, hoping to obtain new high-temperature superconductors. At a given bath temperature and given external magnetic field, however, the transition current density J_t is not so well-known. One cannot pass current through a piece of pure superconductor, increase the current slowly, and watch for a transition. This is because, as the superconductor turns normal, it cannot carry so much current, and will therefore melt. Usually this is avoided by drawing the superconductor into fine filaments and have them surrounded by copper. In fact, a dipole cable is typically about 2 mm thick and 1 cm wide, made up of 20 to 40 wires or strands, wound in a spiral pattern as shown in Fig. 2a. An enlarged cross section of a 23-strand cable for the model SSC magnets consisting of over ten thousand NbTi filaments is shown in Fig. 2b. Theoretically, any excess current that the superconductor cannot carry will be spilled over to the surrounding copper. The strand will be heated because copper has a resistivity. A quench will occur only if this heat accumulates and propagates. As a result, the result of measurement will not give the exact value of J_t on the thermodynamic surface. Also, a filament will not have exactly the same diameter along its length; so the amount of current it can carry is *not* equal to J_t multiplied by the *average* cross section. The surfaces between the superconductor and the interfilament copper are complicated. This adds to the uncertainty of J_t in the measurement.

In the actual measurement performed at Brookhaven, the voltage across a length of 70 cm of cable was measured. Such a long length is necessary in order to have good accuracy in the voltage. On the other hand, a longer sample is not suitable because it is hard to maintain a uniform magnetic field for a long length. The result for a typical measurement is shown in Fig. 3. When the current is low, the voltmeter was not sensitive enough to pick up any voltage across the "short-sample." However, at higher current, say above 7 kA, a finite voltage was registered. This voltage increased very rapidly until the cable quenched at about 9 kA. Very clearly, no sudden transition was observed. Empirically, the resistivity ρ of the cable has a power-law relationship with the current I, or

$$\rho = \rho_c \left[\frac{I}{I_c}\right]^n \quad , \tag{2.1}$$

where $n \sim 20$ to 40. The so-called "critical current" I_c is *defined* as the current when the resistivity of the cable reaches $\rho_c = 1 \times 10^{-14}$ Ω-m. The "critical current densities" J_c quoted in all measurements are defined in the same way. As shown in Fig. 3b, the $\log I - \log \rho$ plot does confirm the power-law behavior with $n = 30.4$ and $I_c = 8.377$ kA. There is also a quench current I_q or quench current density J_q, at which the cable quenches. It is clear that both these J_c and J_q are *not* the theoretical transition current density J_t on the thermodynamical surface of Fig. 1. It is also clear that there is no reason to expect measurements of cables with a different copper-to-superconductor ratios will arrive at the same J_c and J_q, although the same superconducting material is used in the fabrication of the cables. However, I was told by Dr. D. Larbalestier that Eq. (2.1) is in fact a good definition, because the J_c of a superconductor determined in this way usually will not vary by more than 5% for cables with different copper-to-superconductor ratios.

III. TRAINING

Four cable samples, one on top of the other as shown in Fig. 4, were actually measured at the same time. The magnetic field was perpendicular to the wide side of the cables and was in such a direction that the peak field was at the thin edge of the cable under test. (The cable was keystoned.) A pressure of 10 kpsi was applied in the direction of the magnetic field. For the sample SC 343, the cable quenched when the current was raised to roughly 7 kA. When the system was cooled down again, the current was again raised gradually. This time a higher current was reached before the cable quenched. During the 5-th quench, the current reached the mathematically defined critical value I_c. This process (Fig. 5) known as training could be continued until the current reached a plateau I_p, which is roughly the quench current I_q. The polarity of the current was reversed, so that the peak field shifted to the thick edge of the cable. The training sequence was repeated. This time, the critical current I_c and plateau current I_p were higher, because usually the thin edge of the cable has a higher self field.

Reversing the polarity again might produce more training, but this would disappear eventually after a number of current reversals, signaling that all factors contributing to the quenches were no longer present.

Such training sequences are highly reproducible. This implies that similar training curves will result if the samples manufactured in the same way is subjected to the same pressure, magnetic field, and the same bath temperature.

A cable that can be trained to the plateau current I_p, which is higher than the defined critical current I_c, is referred to as stable. Usually unstable samples never reach its critical current and train indefinitely.

The quenches that are encountered in the training are usually attributed to the motion of the strands inside the cable. Therefore, the pre-compression pressure is extremely crucial. If this pressure is reduced, a stable cable may become unstable. Figure 6 shows the training quenches of sample SC 351 with a copper-to-superconductor ratio of 1.5 under pressures 11 kpsi, 8 kpsi, and 4 kpsi. It is clear that the sample undergoes more training quenches to reach the plateau current I_p when the pressure is reduced from 11 to 8 kpsi. When the pressure is reduced to 4 kpsi, the sample cannot be trained even to the critical current I_c.

Sample SC 368 having a copper-to-superconductor ratio of 1.2 contains more superconductor than sample SC 351. It can be trained to a much higher plateau current I_p, as indicated in Fig. 7 under a pressure of 11 kpsi. However, when the pressure is reduced to 8 kpsi, it cannot be trained to its I_c. The highest current reached is $\sim$ 8.5 kA, which is much lower the the plateau current $I_p = 9.8$ kA reached by sample SC 351 under the same pressure. For this reason, it is possible that a cable with a higher copper-to-superconductor ratio may carry higher current than one with a lower copper-to-superconductor ratio.

Sampson *et al* soldered together all the strands in a cable and found that the current reached the plateau without training when the pre-compression pressure was high. However, when the pressure was reduced to $\sim$ 5 kpsi, training quenches occurred. This demonstrates that training at high pressure is due to individual strand movement, whereas training at low pressure is due to the bulk movement of the cable. Although a soldered cable is very much more stable, it is not desirable, because most solders traps magnetic field created by eddy currents. As a result, a big sextupole contribution is anticipated.

The number of training steps required to reach 98% of the plateau current I_p can be used as a measure of the cable stability against transient disturbances. Figure 8 is a plot of the number of quenches to reach plateau current for samples with different copper-to-superconductor ratios. All samples are designed for the superconducting supercollider (SSC). The strands in each sample have the same diameter and fabricated with the same NbTi with the exception of the 1.8-ratio one which was made of Hera filaments. All cable samples are stable and are capable of carrying the required current of 6.5 kA and are subjected to the same pressure of about 10 kpsi. According to this plot, it is clear that the higher the copper-to-superconductor ratio, the more stable is the cable. At a bath temperature of $\sim$ 4.3 K and a magnetic flux density of $B \sim 7$ T, using the J_c inferred from sample SC 358A,[2] which has a copper-to-superconductor ratio of 1.3, one cannot go above a copper-to-superconductor ratio of $\sim$ 1.7 in order that the the cable can still carry 6.5 kA.

In my opinion, this measure of stability is not without prejudice. This is because, the current of interest for the SSC dipole is around 6.5 kA. For high copper-to-superconductor ratios like 1.6 to 1.8, I_c is not much bigger than 6.5 kA. But for low copper-to-superconductor ratios like 1.2 and 1.3, I_c is much bigger than 6.5 kA. Therefore, if one wants to train the cables up to 6.5 kA only, the number of training quenches will become much less for the low copper-to-superconductor cables. However, I was told that a low copper-to-superconductor cable may not reach even 6.5 kA if the pre-compression pressure falls. As a result, what is needed is a better definition of stability which takes into account of the effects of pre-compression pressure.

IV. RESISTIVITY OF COPPER

The experiment was performed by Sampson *et al* using two samples SC 368A and SC 368B. These two samples were fabricated exactly in the same way with the exception that the former had been annealed and the latter unannealed. The residual resistivity ratio (RRR) was 125 for the annealed copper and 53 for the unannealed copper. The cable resistances were 0.76 $\mu\Omega$/cm and 0.93 $\mu\Omega$/cm respectively at cryogenic temperature and $B = 5.75$ teslas as indicated in Fig. 9. The training data and the quench wave velocities are plotted in Fig. 10. Essentially, there is no difference between the two samples in the plots. Quench wave velocity is given by

$$v_q = \sqrt{\frac{Pk}{C^2 \Delta T}} \,, \tag{4.1}$$

where P, which is proportional to the copper resistivity ρ, is the power generated per unit volume by the propagating disturbance, k is the thermal conductivity of copper, C is the heat capacity per unit volume of the cable, and ΔT is the temperature difference between the bath and the critical temperature. However, according to the Wiedemann-Franz law, ρk should be roughly a constant. Therefore, the quench-wave-velocity plot may not tell us anything about the dependence of stability on copper resistivity. However, the training data does tell us that copper resistivity may not play a role here. This result is contrary to the usual theory that whether a quench will occur depends on the competition between power generated by the copper according to the resistivity ρ due to the spill-over current from the superconductor filaments and the rate at which heat is conducted away by the copper according to its thermal conductivity. The temperature profile of the disturbance at the balancing point is usually called the minimum propagating zone. A possible explanation is that the heat generated by each movement of a strand may be much larger than the energy of the minimum propagating zone. As a result, the power generated by the copper resistivity always wins so that a small change in the resistivity does not alter the training curve appreciably. In fact, in this experiment, the difference in cable resistances 0.76 $\mu\Omega$/cm and 0.93 $\mu\Omega$/cm is not very large. More experimental measurements are necessary.

V. PLATEAU CURRENT DENSITY VERSUS CRITICAL CURRENT DENSITY

In this section, I want to discuss some properties of the plateau current density J_p and critical current density J_c.

First, I like to argue that J_p is less than the transition current density J_t. If J_p is larger than J_t, all the superconductor filaments will have been saturated with current and there must have been a spill-over current in the copper matrix. Since normal superconductor is so much less conducting than copper at cryogenic temperatures, the resistivity ρ of the cable is given essentially by

$$\rho = \frac{\rho_{cu}}{\lambda_{cu}} , \tag{5.1}$$

where λ_{cu} is the fraction of copper in the strands. At $B = 7$ teslas and residual resistivity ratio (RRR) of 100 for copper, the resistivity of copper is roughly

$$\rho_{cu} = \left(0.0032B + \frac{1}{RRR}\right) \times 1.7 \times 10^{-8}\ \Omega\text{--m} = 5.5 \times 10^{-10}\ \Omega\text{--m} . \tag{5.2}$$

However, from the $\log I - \log\rho$ plot of Fig. 3b, the point with the highest voltage at the plateau corresponds to a cable resistivity of only $\rho = 1.6 \times 10^{-13}\ \Omega$-m, which is at least three orders-of-magnitude less than the prediction of Eq. (5.1). Therefore, there cannot be steady current flowing in all the copper. In other words, the plateau current density must be less than the transition current density. Thus, for a stable cable,

$$J_c < J_p < J_t . \tag{5.3}$$

For this reason, in a computation of something like the minimum propagating zone which involves the transition current density, it appears that the plateau current density I_p should be more appropriate than the mathematically defined I_c.

Then, how does a superconducting cable acquire resistivity? I think this arises from the nonuniformity of the filament cross sectional area. Some of these nonuniformities[3] are shown in Fig. 11. Suppose that the total cross sectional area A of all the filaments is a constant, the phase transition should take place sharply at J_t instead of a power-law behavior. However, at the points of sausaging, pinching, and breaks, the cross sectional area will be less than A, so part of the current flowing across the sausaging, pinching, and breaks will have to go through the surrounding copper instead. This will occur for a fraction ξ of the length of the strands only. Therefore, the effective resistivity of the cable is

$$\rho = \frac{\xi\rho_{cu}}{\lambda_{cu}} , \tag{5.4}$$

where ξ depends strongly on the current density. If ξ is about one-tenth of a percent, the apparent resistivity of the cable at the plateau can be explained.

Experimentally, Sampson *et al* find that the ratio of the plateau current I_p to the critical current I_c, which should be the same as J_p/J_c, increases with the copper-to-superconductor ratio r. The data for nine samples of SSC cables are plotted in Fig. 12. An approximate fit (dashed line) gives

$$\frac{J_p}{J_c} \sim 1 + \alpha(r-1) , \tag{5.5}$$

which holds at least for r from 1.2 to 1.6 with $\alpha \sim 0.2$.

The next question is the dependence of J_p and J_c on the copper-to-superconductor ratio r. If J_p is near to the transition current density J_t and independent of r, data in Fig. 12 will imply that J_c becomes smaller for a higher copper-to-superconductor ratio. This is contrary to the fact that a cable with a higher copper-to-superconductor ratio should be more stable. It is possible that J_c is relatively the same, and J_p increases with r and approaches J_t for large r. It is also possible that J_c increases slightly as r. In any case, for a certain copper-to-superconductor ratio, J_p can be taken as the transition current density with the discrepancy from J_t treated as a degradation.

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2. G. Morgan, SSC Magnet Division Note No. 110-4 (SSC-MD-84), 1984.

3. M. Garber, M. Suenaga, W.B. Sampson, and R.L. Sabatini, Proceed. of 1985 Cryogenic Engineering and International Cryogenic materials Conference, M.I.T., Cambridge, Mass. August 12-16, 1985.

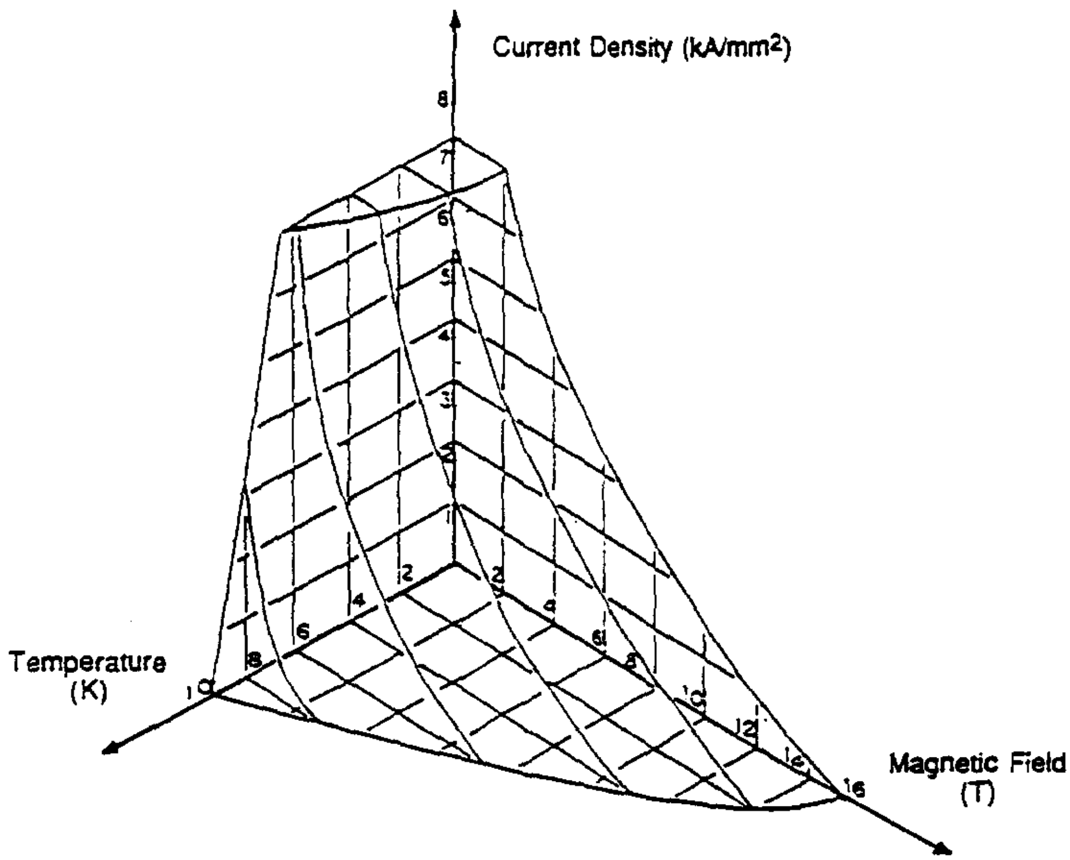
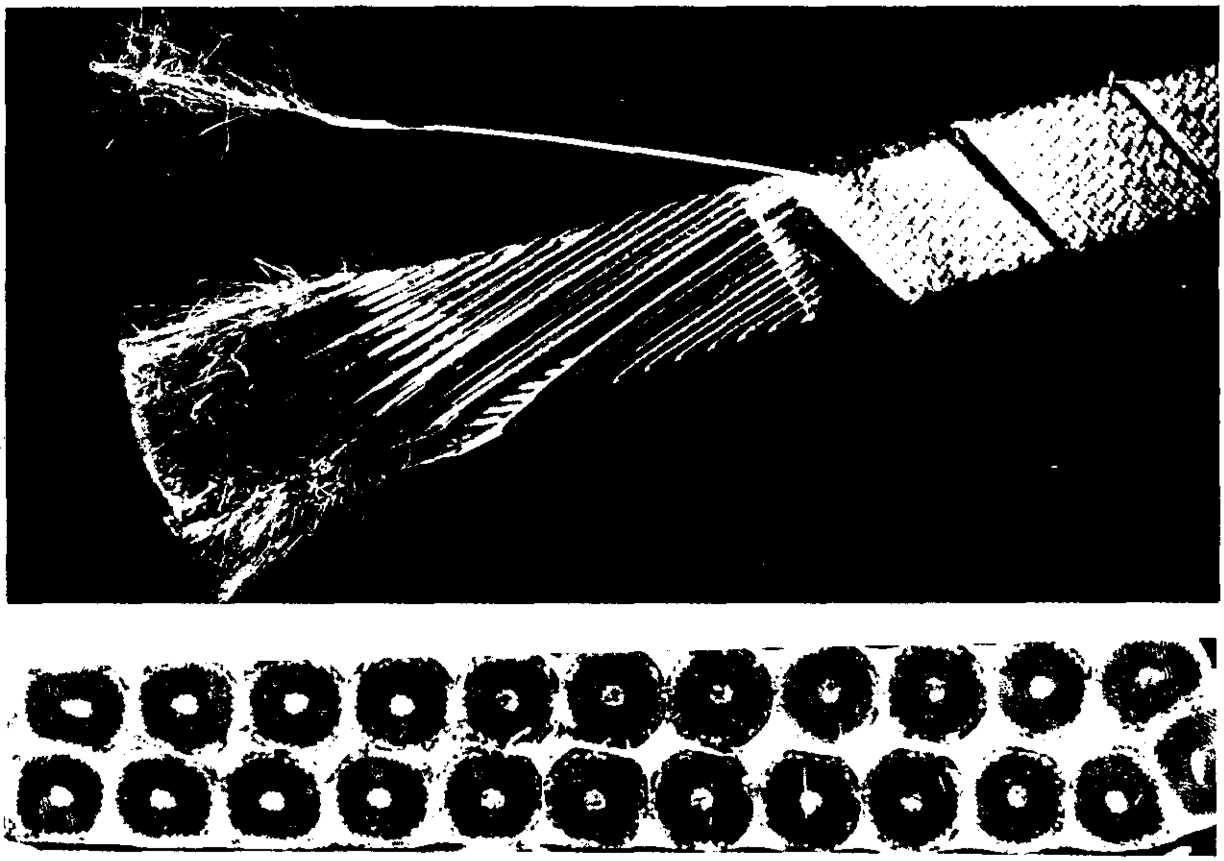


Figure 1. NbTi critical surface.



(a)

(b)

Fig. 2. (a) Spiral wound cable of 30 strands, approximately 1 cm wide, wrapped with insulating tape. The ends of the strands have been etched in acid to remove the copper and reveal the NbTi filaments. (b) Cross sectional view of a 23 strand cable.

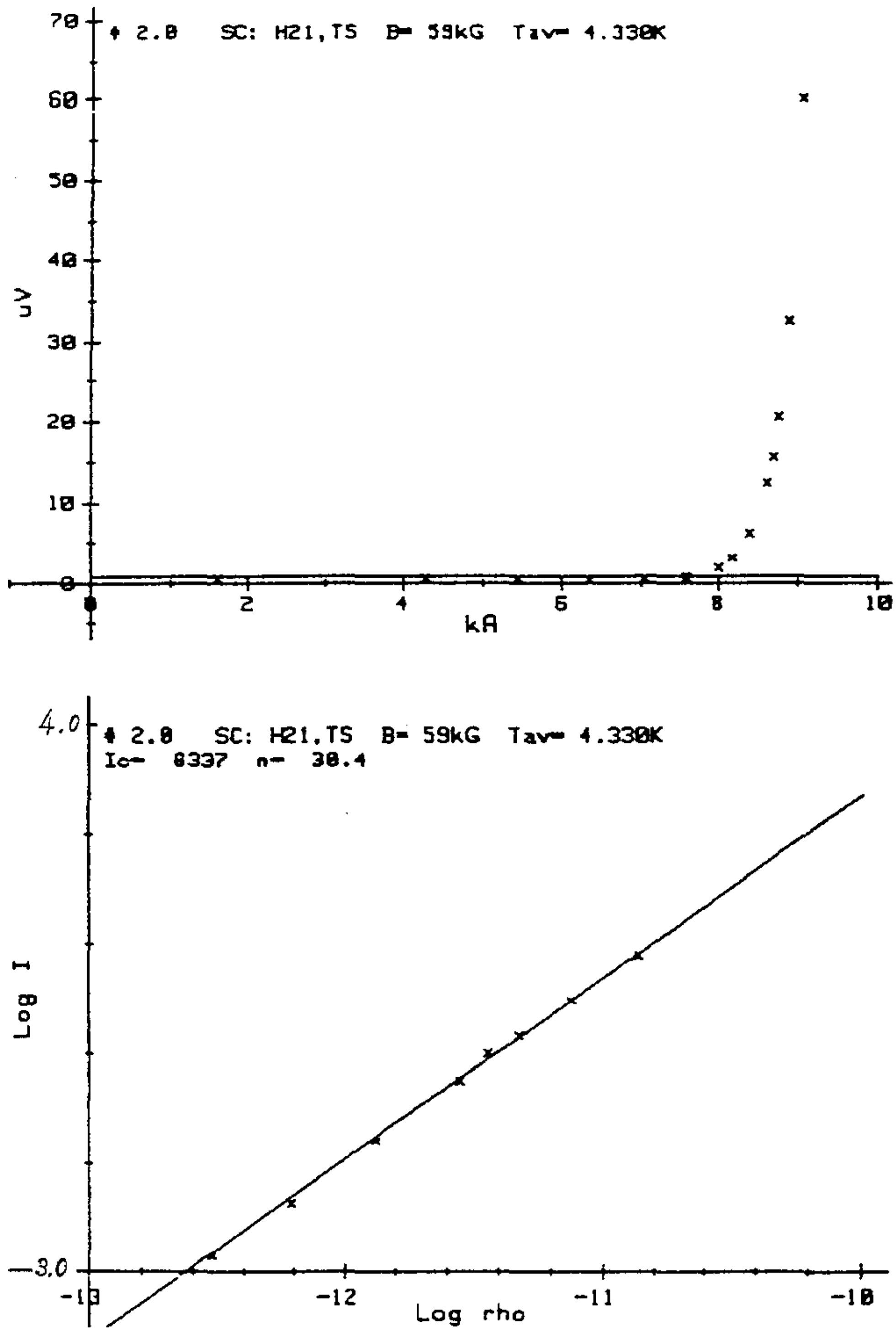
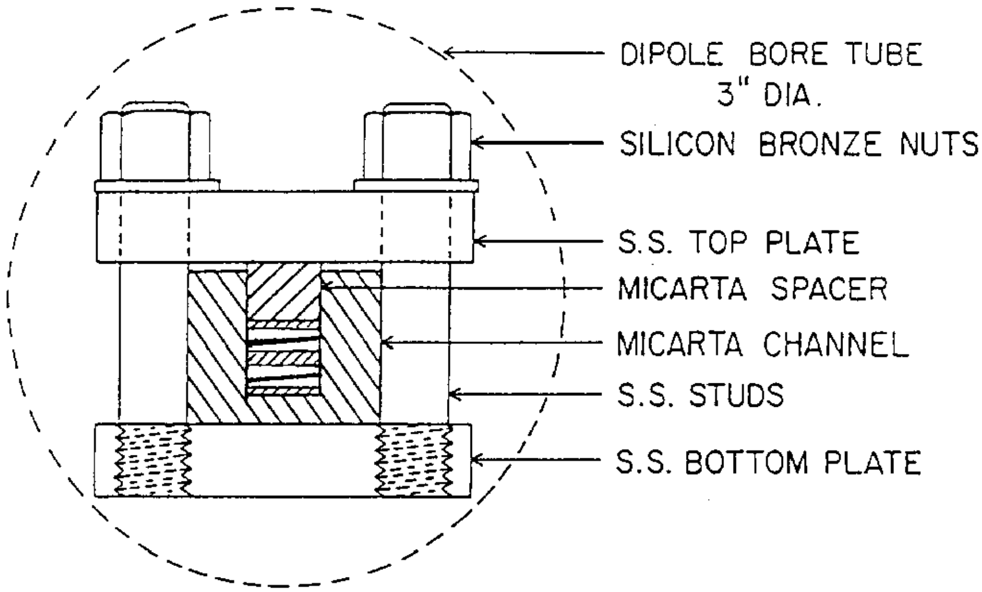


Fig. 3. Upper: the voltage-current relation for a typical accelerator magnet cable. Lower: the $\log I - \log \rho$ plot used to determine the n-value and I_c.



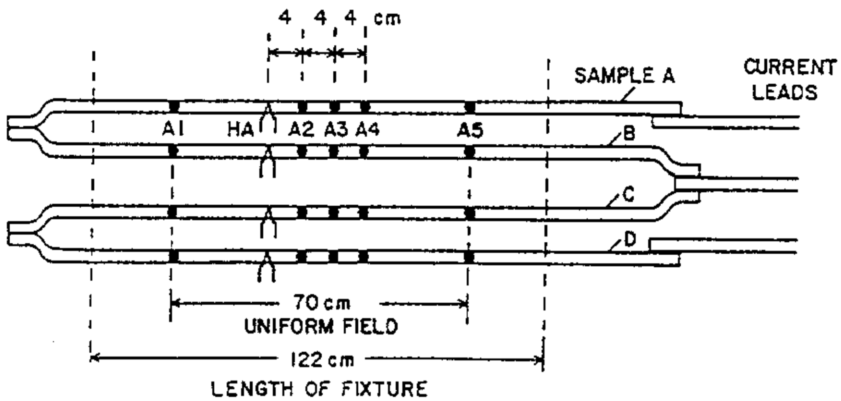


Fig. 4. Setup for short-sample measurement. Four cable samples are clamped together in a micarta channel with compression applied by the bolts which run along each side of the channel. The voltage across each sample can be measured independently. The whole fixture is placed in the bore of a dipole which provides the magnetic field.

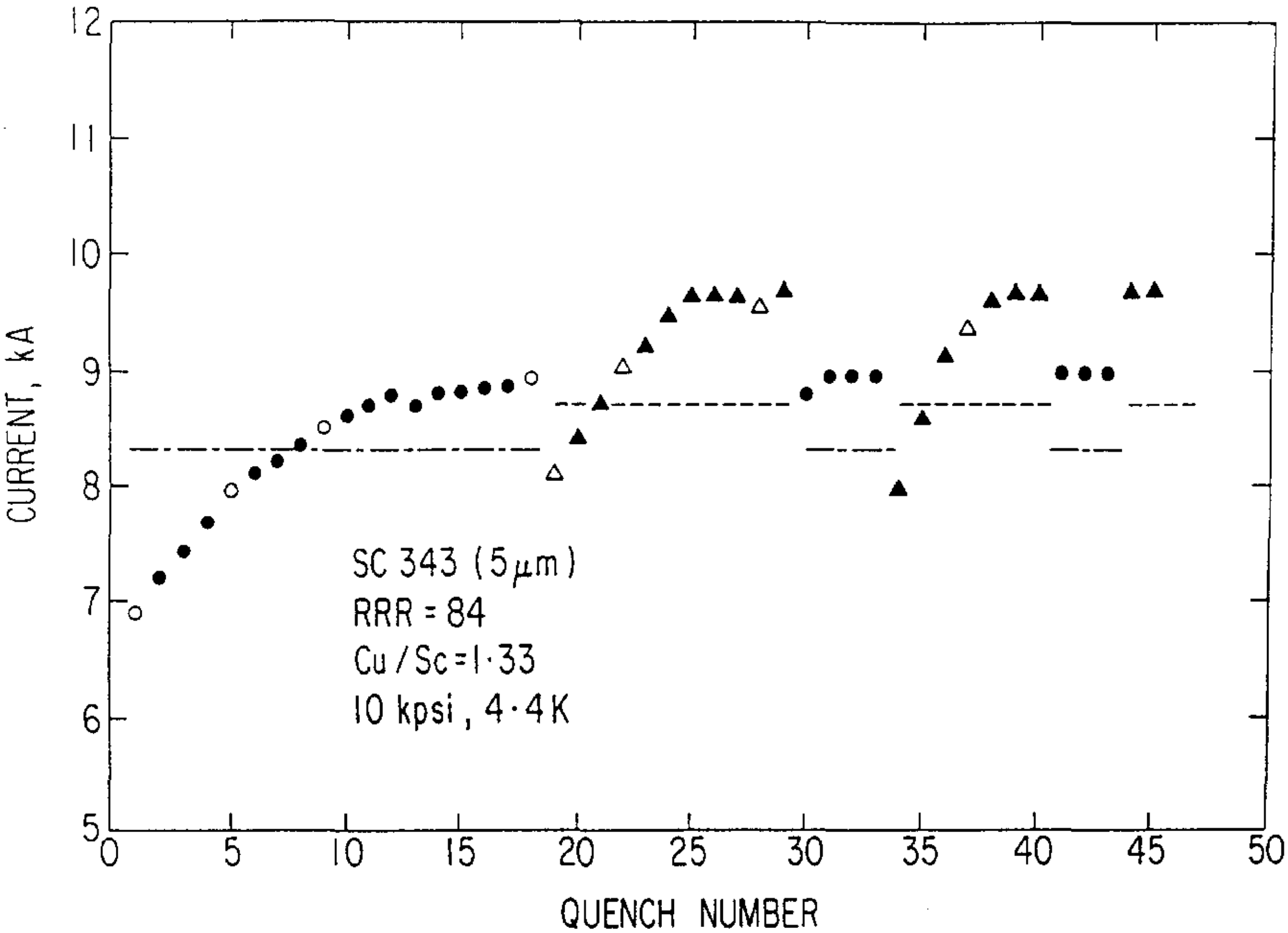


Fig. 5. Training sequence for a SSC inner cable. The circles represent quench currents when the peak field is at the thin edge. The triangles are the currents when the polarity is reversed. The dashed line represents I_c.

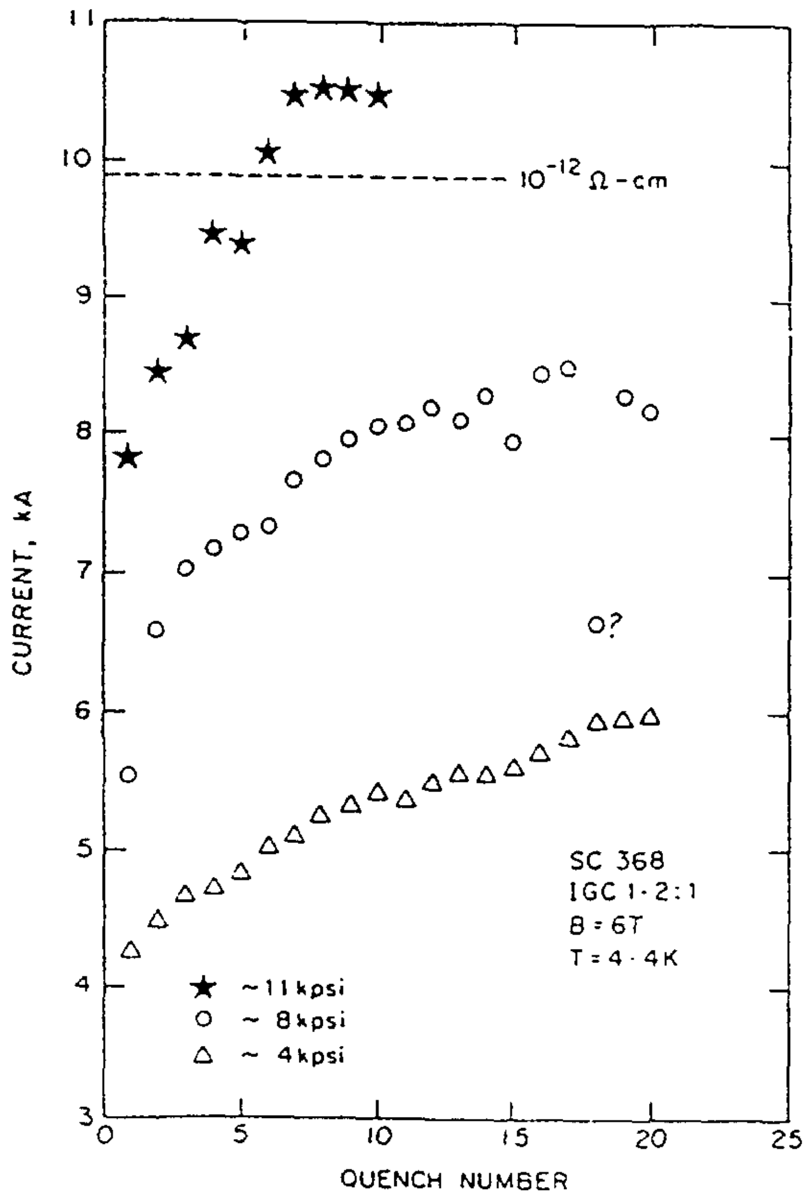


Fig. 6. Quench behavior of sample SC 368 with copper-to-NbTi ratio 1.2 for three levels of pre-compression.

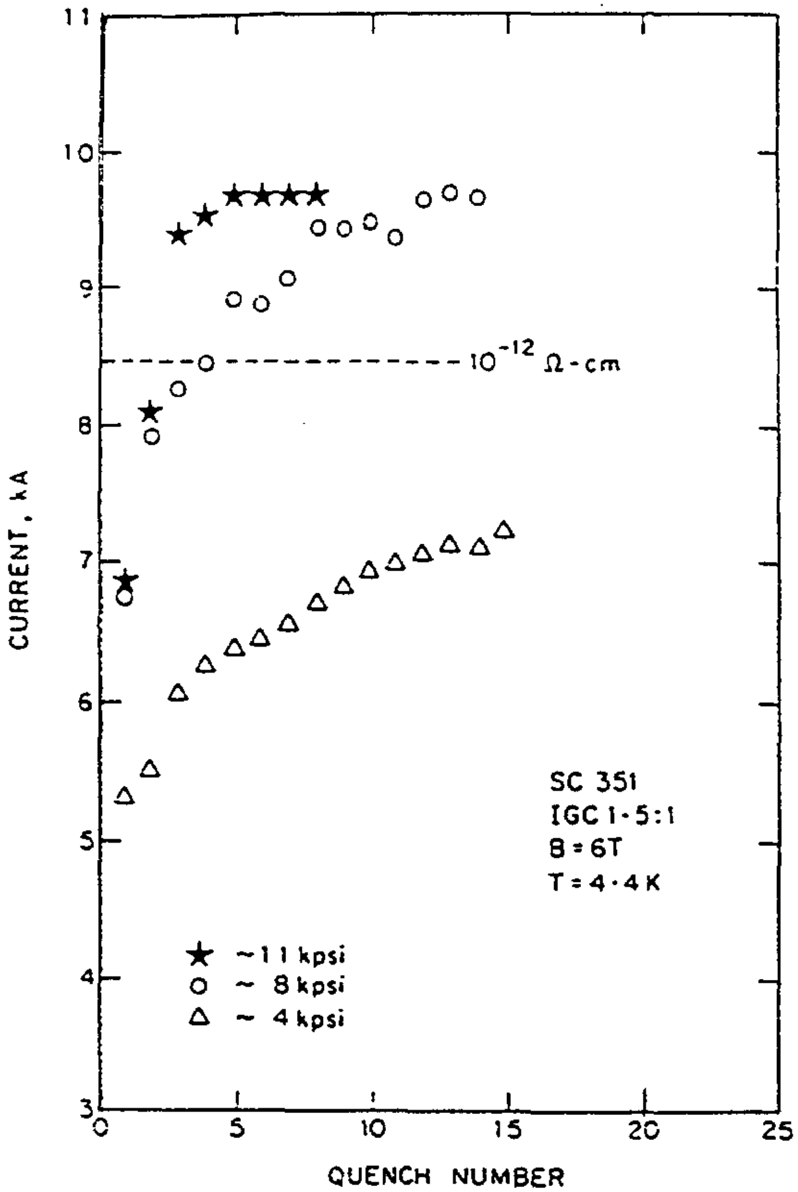


Fig. 7. Quench behavior of sample SC 351 with copper-to-NbTi ratio 1.5 for three levels of pre-compression.

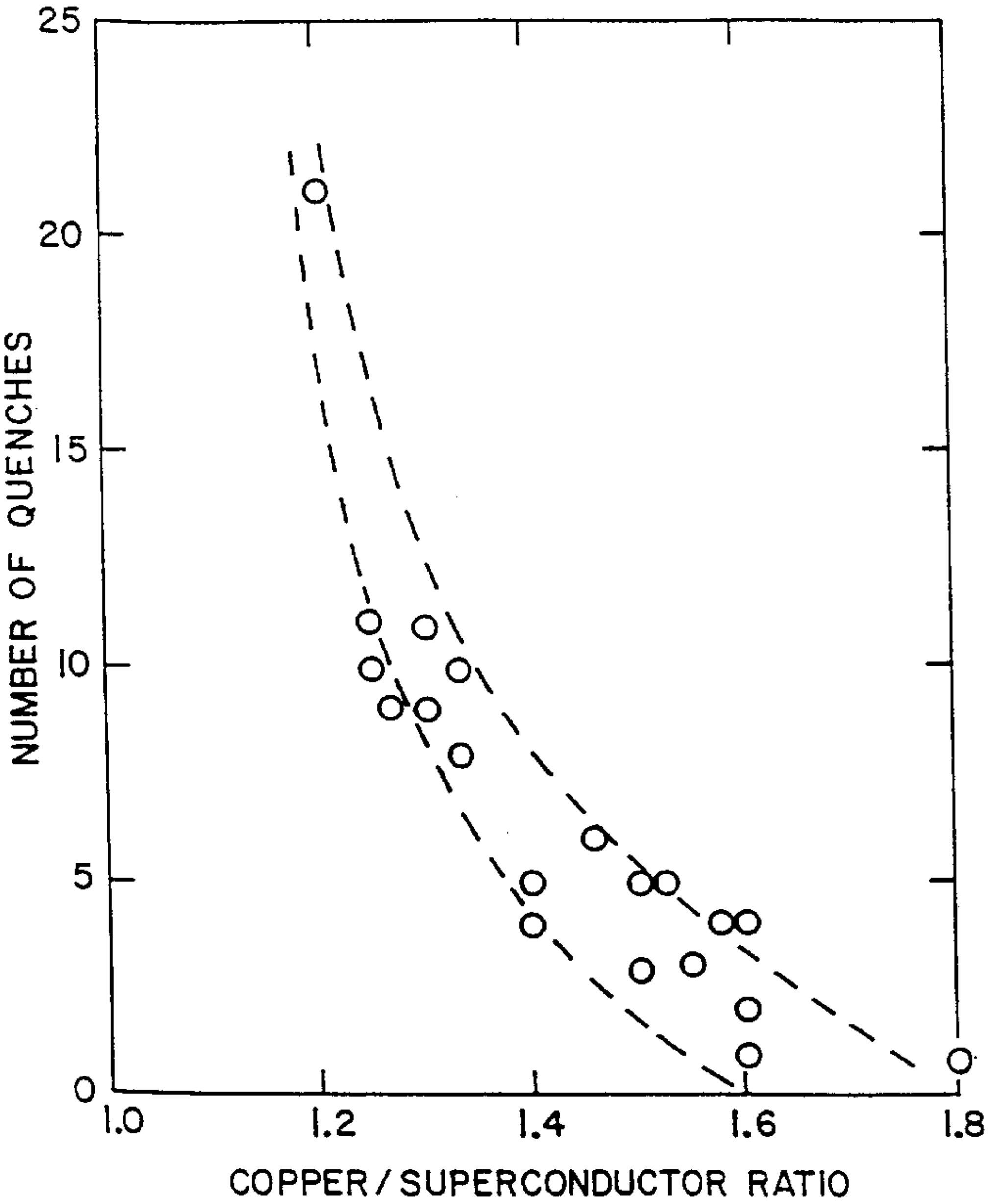


Fig. 8. Plot of number of training quenches versus copper-to-NbTi ratio. All samples are SSC candidates having the same number of strands and same strand diameter. All of them are capable of carrying 6.5 kA.

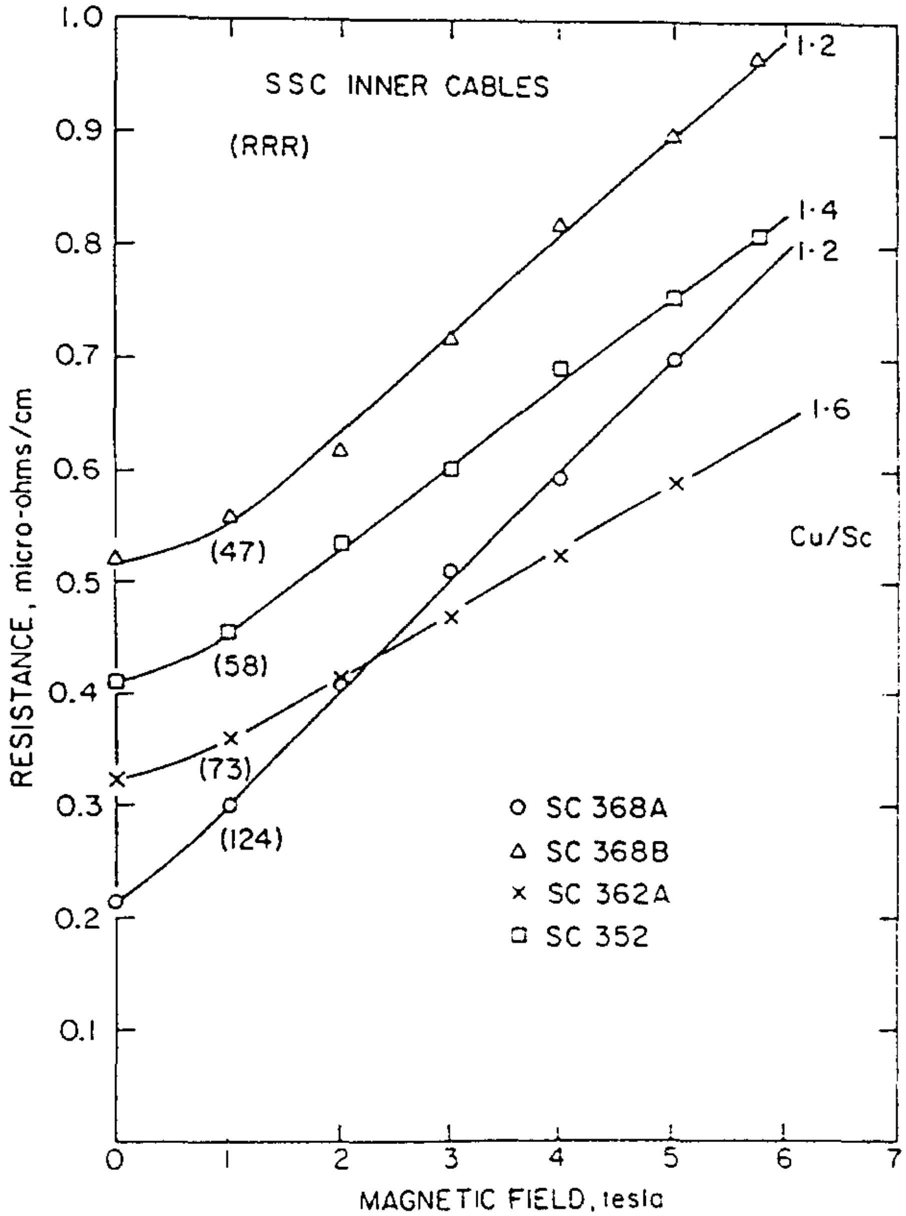


Fig. 9 Resistance per unit length of SSC prototype cables as a function of applied magnetic field.

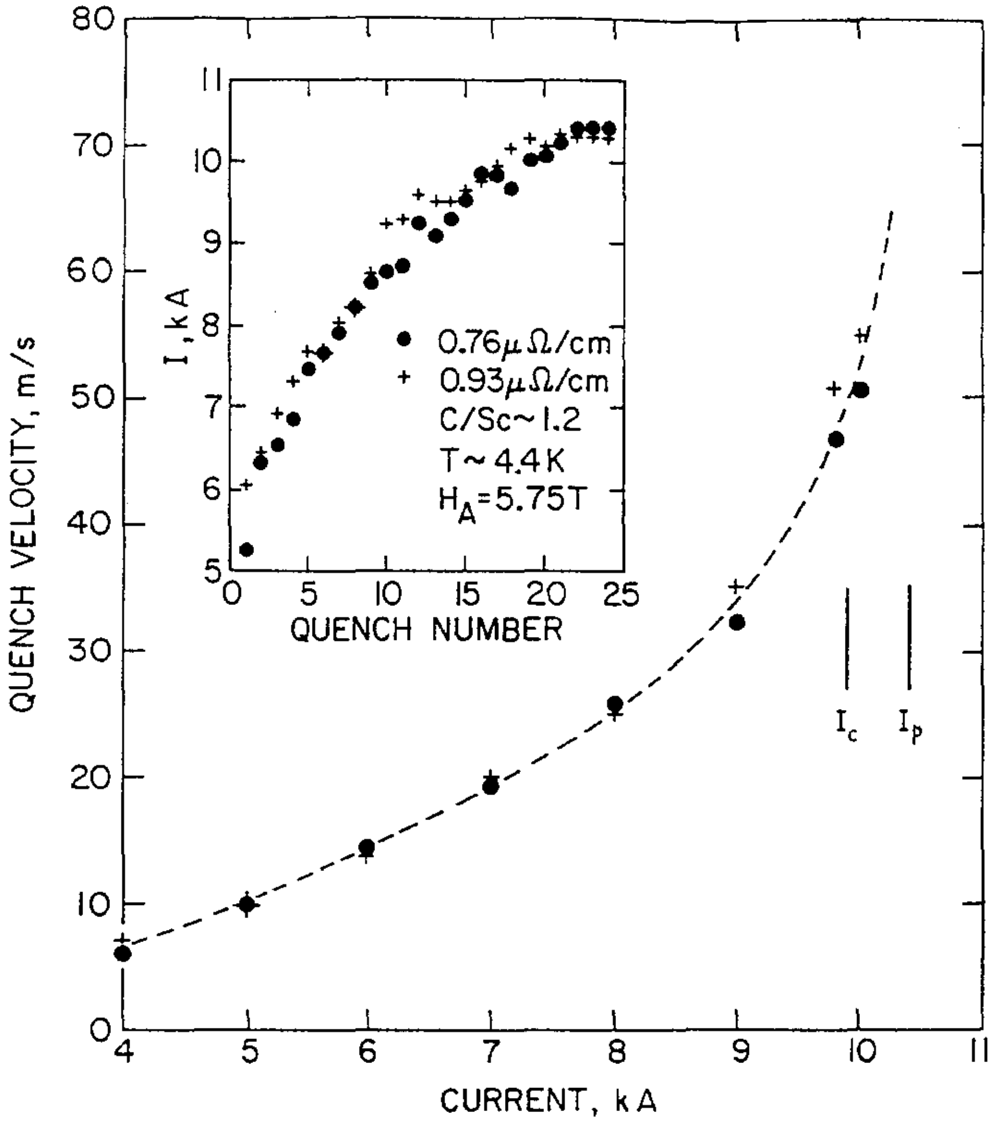
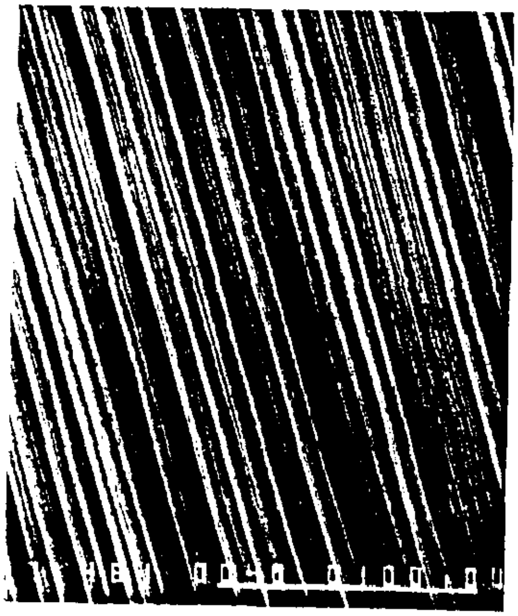
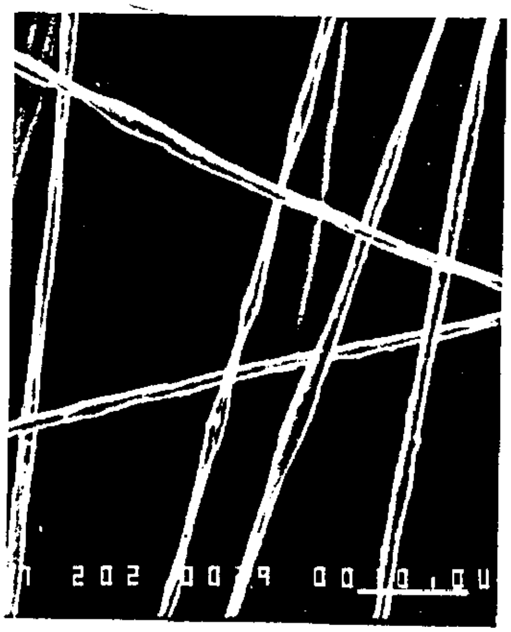


Fig. 10. Training curves and quench wave velocities for sample SC 368A (dots) which has been annealed and sample SC 368B (crosses) which has not been annealed.



(a)



(b)

(c)

Fig. 11. (a) The 9 μm filaments in CBA wire are smooth as shown in the SEM micrograph. (b) Surface imperfections are observied when the filaments are reduced to mean diameter 1.3 μm. (c) SEM micrograph showing filament damage in thin edge region of a cable.

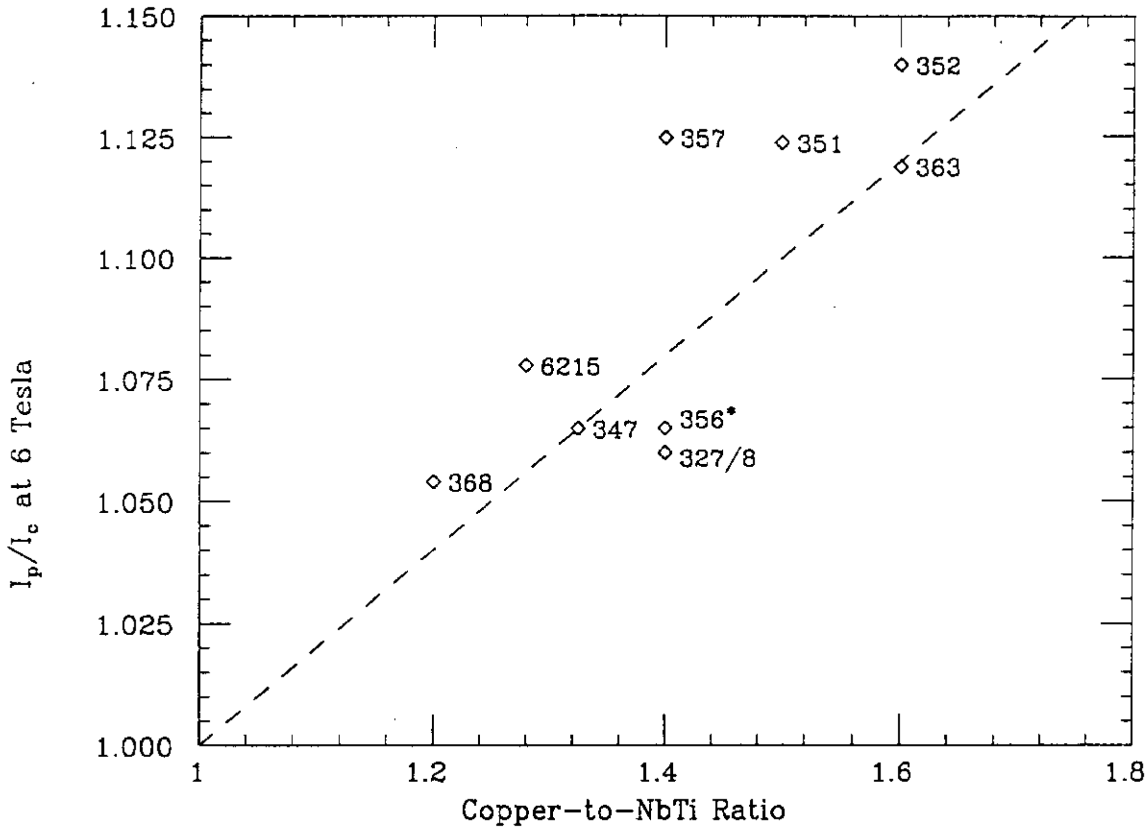


Fig. 12. Plot of ratio of plateau current I_p to critical current I_c versus copper-to-NbTi ratio.