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TRAINING IN TEST SAMPLES OF SUPERCONDUCTING CABLES FOR ACCELERATOR MAGNETS*

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Abstract

In the critical current measurement of some high current NbTi cables, the samples have to be "trained" by repeated quenching in order to obtain a usable voltage-current curve for I_c determination. This training behavior is most pronounced when the applied field is perpendicular to the wide face of the conductor and is strongly dependent on the copper-to-superconductor ratio and the clamping pressure. Data are given for SSC prototype cables as well as for HERA production conductors. Although a quantitative understanding of the experimental data is still lacking, some speculations regarding stability are presented.

Introduction

Training is a common problem in superconducting magnets, particularly in accelerator type dipole magnets which are made with high J_c multifilamentary NbTi cables and which have a coil geometry that is difficult to constrain against motion.[1] While measuring short sample critical currents of cables for various accelerator magnet development projects it has been frequently observed that conductors have to be trained by repeated quenching in order to obtain voltage-current data that can be analyzed for the $10^{-12}\,\Omega$-cm resistivity current. Under controlled conditions it is possible to generate training behavior reproducibly and to relate it to certain physical factors. These are the critical current density, J_c, the copper matrix resistivity and amount (in particular, the copper to superconductor ratio), and the constraining pressure. In the design of every device a compromise has to be made between overall current density and stability and these studies lead to certain conclusions about the appropriate copper to superconductor ratio.

Experimental Details

The test samples are mounted on a compression fixture[2] which is illustrated in Fig. 1. The usual test arrangement involves four bare cable samples. As these are keystoned (i.e. they are trapezoidal in cross section), care is taken to alternate thick and thin edges so that pairs of conductors present parallel surfaces to the clamping faces. As indicated in Fig. 1 there are a series of separators 0.8 mm thick G-10 strips which carry the electrical instrumentation described below, and 0.25 mm thick Mylar strips which insulate the adjacent samples of the upper and lower cable pairs.

Compression is applied by the bolts which run along each side of the micarta channel at 38 mm intervals. The usual procedure is to tighten the silicon bronze nuts to 200 inch-pounds of torque resulting in a mean pressure on the sample of approximated 10 kpsi at room temperature. The torque required to produce the necessary pre-compression was calibrated by replacing the samples with an aluminum bar containing a calibrated strain gauge. At a given torque the pressure was found to increase slightly at low temperature.

The sample fixture is supported together with the sample leads from a room temperature flange which may be rotated. The samples are placed in the bore of a 6 tesla dipole which has a uniform field region of 700 mm length. The usual configuration is one in which the applied field is perpendicular to the wide face of the cable. Twisting of the sample fixture relative to the magnet is prevented by means of a locating key on the fixture and a slotted plate on the magnet.

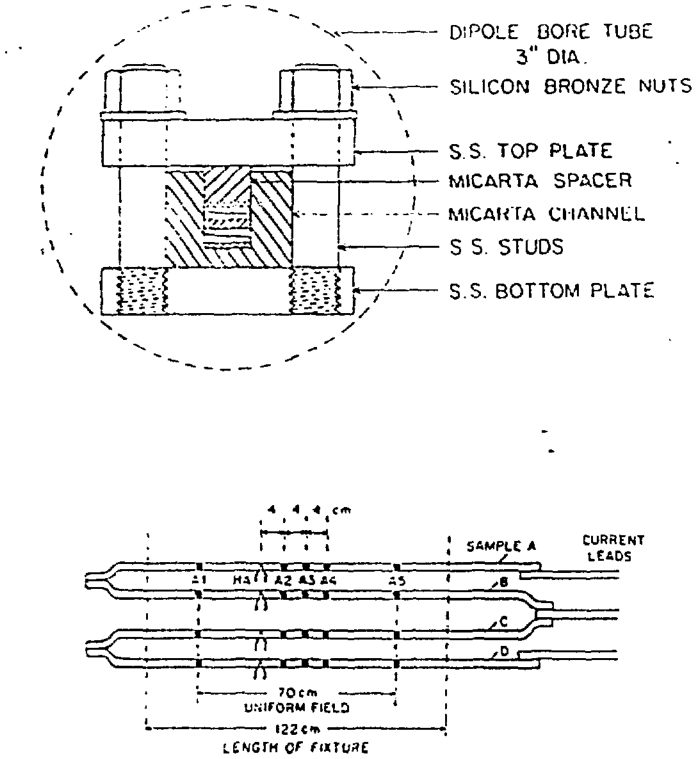

Fig. 1. Schematic of the mechanical assembly and electrical wiring.

Figure 1 shows schematically how the cables are connected to each other and to the gas cooled leads. The connections are made using soft solder over a 4 cm length. A typical joint resistance is about 10^{-9} ohm. The samples are excited in pairs, either A-B or C-D. 5 voltage taps and a thin foil heater element are provided for each sample. These are contained on the G-10 strips. The voltage taps work by pressure contact across the width of the sample. The leads run out through a fine groove in the G-10. The heater element is a strip of 0.013 mm stainless steel contained in a shallow well in the G-10 strip.

In these training experiments, the pair of cables A-B or C-D are test samples from the same piece of cable. This allows the testing of two separate conductors under similar pre-compression and cooling conditions. During a quench, the voltage across the A1 and A5 taps are monitored as a function of time. This allows the determination of which sample of the pair quenched first and also the rate of voltage buildup (dv/dt).

Experimental Results

SSC outer wire cables with a copper-to-superconductor ratio Cu/Sc, of 1.7-1.8 and HERA dipole cables with Cu/Sc of ~ 1.8 usually do not exhibit training at the nominal clamping pressure of 10 kpsi.[3] However prototype SSC inner cables with low Cu/Sc (< 1.6) have to be quenched repeatedly to reach their full operating current. In this section the results of the training experiments are summarized.

Representative Training Sequence

Figure 2 shows the successive quench currents for an SSC inner-cable with a Cu/Sc ratio of 1.3. In the first sequence the current flow in

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the conductor is such that the peak field is at the thin edge.[4] The open and closed circles represent sample A or sample B quenching respectively. The dashed line represents the current I_t, at which the sample resistivity is $10^{-12}\Omega$-cm, at the measurement temperature ~ 4.35 K. Once the current has reached a plateau, the current polarity is reversed, so that now the peak field shifts to the thick edge. Once again the samples are trained up to the plateau. In this configuration the I_t and the plateau currents are higher than the first set because usually the thin edge of the cable has a lower critical current than the thick edge.[4] Reversing the polarity again may produce more training but this eventually disappears after a number of current reversals. At that point all the motion causing the training quenches is over and the samples are fully trained. The plateau quench current is referred to as I_Q. For any given cable the number of training steps to reach 98% of I_Q can be used as a measure of the conductors stability against transient disturbances. Usually unstable samples never reach a plateau and train indefinitely.

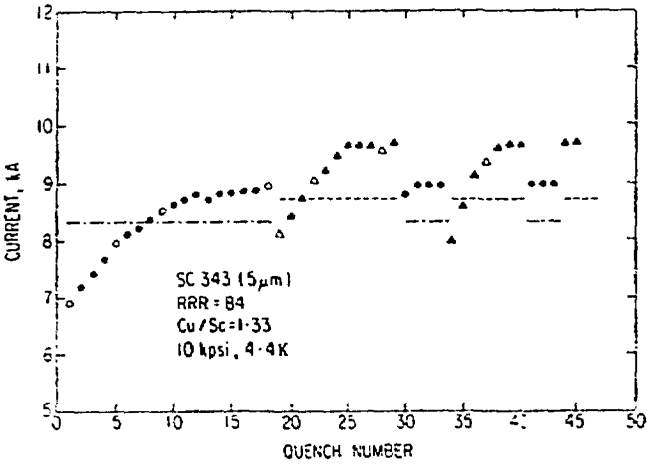

Fig. 2. Training sequence for a SSC inner cable: •,o represent quench currents when the peak field is at the thin edge; ▲,Δ are the currents when the polarity is reversed. The dashed line represents I_t.

During each quench, the initial voltage rise (dv/dt) is recorded. This parameter is a good measure of how far the sample current is from the plateau current which represents the maximum stable operating current at the given field and temperature.[5] At the plateau dv/dt is ~ 100 V/S at which point quenches can be initiated by extremely small disturbances.

In most cases, after the samples have been fully trained, a thermal cycle to room temperature does not cause further training upon recooling to 4.4 K. However if the compression is relaxed to zero and then reapplied then the sample trains up in a manner similar to the initial quench sequence.

Reproducibility

The training behavior of cables with similar Cu/Sc ratios tested under identical conditions is remarkably reproducable. In Fig. 3 the current versus quench number for a series of 4 cables, is shown when tested at the nominal compression of 10 kpsi. Each of these samples represent several thousand feet of cable, which were made from wires from several billets, all having a Cu/Sc ratio ~ 1.26-1.28 and a 5 tesla critical current density, J_c, of ~ 2750 A/mm^2.

Pre-compression and Training

As in magnets, the degree of training seen in test samples depends on the mechanical loading. While the compression on the conductor does not change the potential I_Q, it significantly affects the current that is reached after a given number of quenches. Even conductors like the SSC outer and HERA cables which usually do not exhibit any training at 10 kpsi do train at reduced pressure. However the susceptibility of a conductor to unstable behavior is strongly dependent on the Cu/Sc ratio.

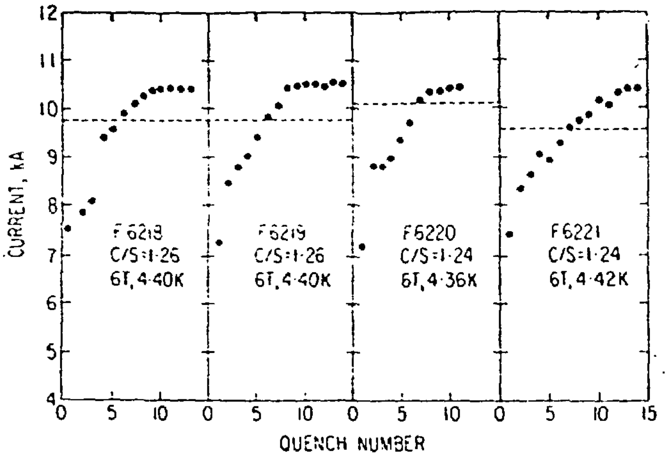

Fig. 3. Training behavior of 4 SSC cables, all of which have the same nominal Cu/Sc.

Figures 4 and 5 show the quench behavior of two conductors, SC368 (Cu/Sc = 1.2) and SC351 (Cu/Sc = 1.5), which were assembled together and tested under identical mechanical loading. At the highest pressure both samples trained up to I_Q in a reasonable number of quenches. I_Q and I_t for SC368 are higher than for SC351 since the former has a higher fraction of NbTi. However, at a reduced pressure of ~ 8 kpsi, SC351 trains up to its potential I_Q whereas SC368 shows erratic quench behavior and is not likely to reach its potential I_Q of ~ 10500 A even after many quenches. Note that after 20 quenches SC368 has only reached about 8000 A whereas SC351 is operating at ~ 9700 A. At an even lower precompression, ~ 4 kpsi, the current in SC351 is still higher than that in SC368. After 20 quenches SC351 is ~ 63% of I_Q whereas SC368 only reached ~ 40% of its potential I_Q.

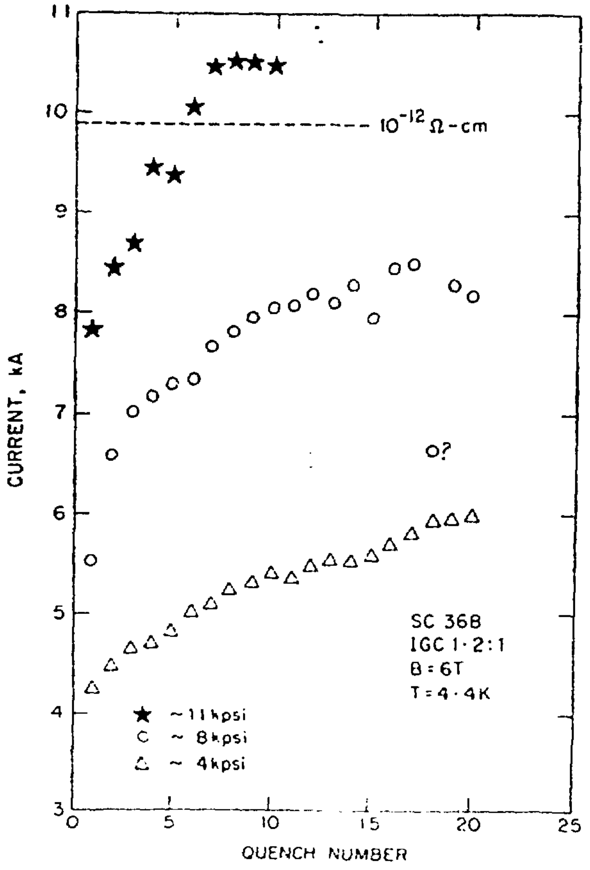

Fig. 4. Quench behavior of SC368 for three levels of precompression.

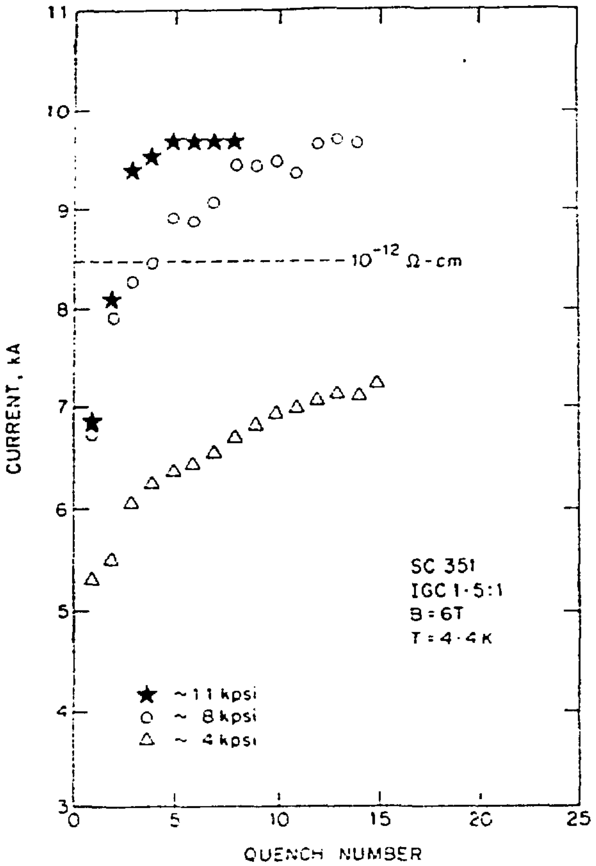

Fig. 5. Quench behavior of SC351 conductors for three levels of pre-compression.

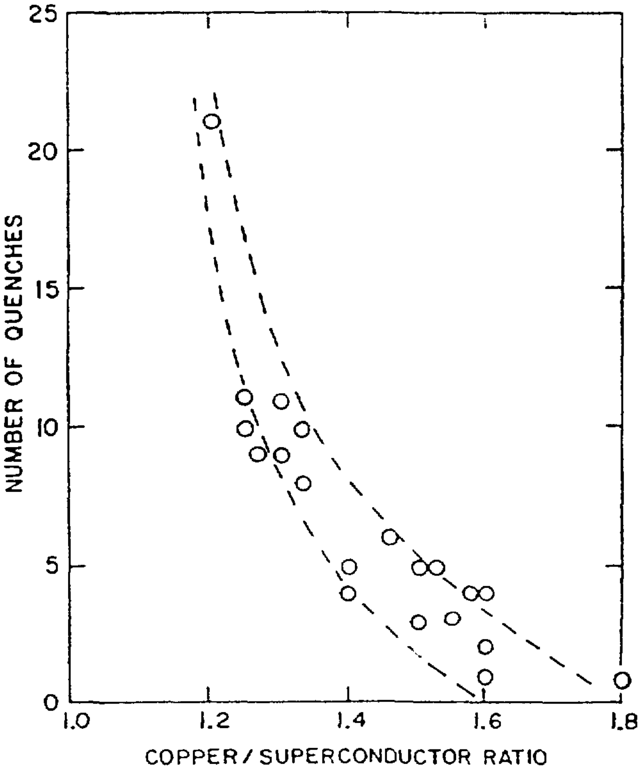

Fig. 6. Plot of number of training quenches versus copper to superconductor ratio.

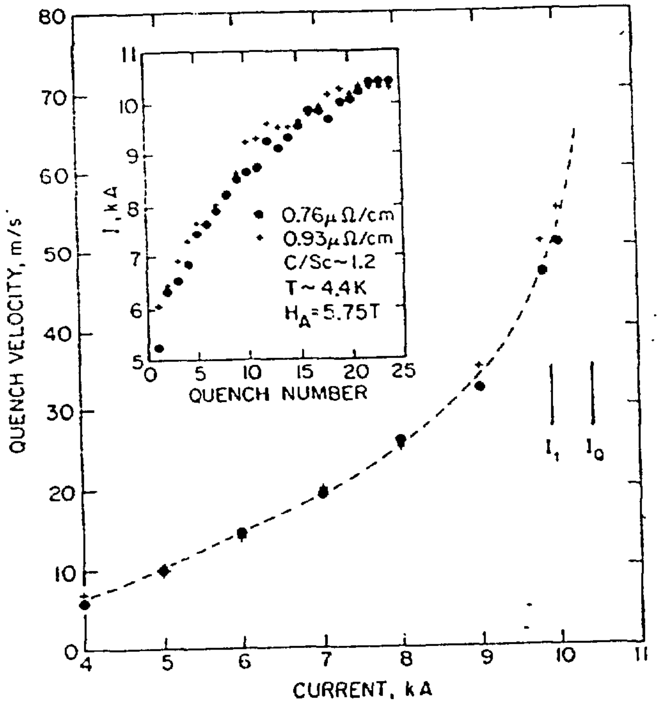

Fig. 7. Quench propagation velocity measurement of two samples with different RRR as a function of current. Inset shows the training behavior of the two samples.

The above experiment establishes that although a conductor with a low Cu/Sc ratio can be made to achieve its potential current, it is more likely to become unstable than one with a higher ratio at low mechanical pre-stress.

Copper to Superconductor Ratio and Stability

A measure of the relative stability of a cable to transient mechanical disturbances can be defined in terms of N, the number of training quenches required to reach its plateau current I_Q. Training experiments on a large number of SSC prototype inner conductors all done in the same fixture under the same mechanical loading (~ 10 kpsi), show that N is strongly dependent on the overall copper to superconductor ratio. This dependence of N on Cu/Sc ratio is shown in Fig. 6. Most of the conductors tested have NbTi filament diameters ~5-6 μm. However a few of the conductors with Cu/Sc >1.5 have filament diameters ranging from 9-20 μm. For a given Cu/Sc ratio the conductor in Fig. 6 which show the most training tend to be of higher J_c and have very closely spaced filaments.

Matrix Resistivity and Training

In order to determine whether the normal state resistance of the conductor affects its performance, the training behavior of two samples of the same conductor (SC368), one of which was annealed, was compared. The residual resistance ratio, RRR, of one cable is 53, the other is 125. At a field of ~6T, the difference in resistance is ~25%. To achieve this large reduction in resistance by simply adding copper instead of annealing would require a Cu/Sc ratio greater than 2.1. The training of these cables at 10 kpsi is shown in the inset of Figure 7. No significant difference is observed. Figure 7 is a plot of the quench propagation velocity, υ, versus currents for these cables. These data were taken by inducing quenches with a heater. The fact that the velocity curves are identical indicates that the product of the matrix resistivity, ρ, and the thermal conductivity, κ is a constant.[5-6] Thus annealing improves both the electrical and thermal conductivities without improving the training behavior of the cable. This remarkable result is easier to understand when the affect on the interfilamentary copper is considered. Because the electronic and thermal mean free paths are limited by the filament spacing they are virtually unchanged by the annealing process.[7]

Discussion

The experimental observations imply that conductor motion is the chief source of the disturbance spectrum responsible for training. Cable FG6220 was also tested after filling with Ag-Sn solder and found to exhibit no training at high pressure but at reduced loading it behaved the same as unfilled conductor. Ths suggests that bulk motion of the cables causes training at low pressure while individual wire motion is responsible at high pressure. When the field is applied parallel to the plane of the cable the magnetic forces add to or subtract from the prestress and do not lead to significant motion. The fact that annealing does not improve the relative stability implies that the interfilamentary spacing is very important in the design of stable conductor i and may impose limits on the spacing and hence the filament size of composites intended for accelerator applications.

There seems to be no conventional theory[8] that predicts a strong dependence of training or stability on Cu/Sc ratio and we do not have an adequate quantative explanation for the experimental observations at this time.

A theory of transient stability must be based on a realistic model that approximates the energy released at the surface of the wire and localized in some small region. Under these conditions the energy required to drive the entire cross-section normal has to be calculated, assuming a longitudinal thermal conductivity consistent with the copper RRR and a much smaller transverse conductivity due to the filament region in the wire cross-section. Calculations along these lines are in progress and will be reported at a later time.

Conclusion

Training has been observed in high current density conductors and the degree of training was found to be dependent on the Cu/Sc ratio, and the amount of compression applied to the conductor. Other factors that might effect the relative stability like the filament size and spacing will be examined in the future.

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