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Stability Measurements on Cored Cables in Normal and Superfluid Helium

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Abstract

The relative stability of LHC type cables has been measured by the direct heating of one of the individual strands with a short duration current pulse. The minimum energy required to initiate a quench has been determined for a number of cables which have a central core to increase the effective inter-strand cross-over resistance. Experiments were performed in both normal helium at 4.4 K and superfluid at 1.9 K. Conductors in general are less stable at the lower temperature when measured at the same fraction of critical current. Results show that the cored-cables, even when partially filled with solder or with a "porous-metal" filler exhibit a relatively low stability at currents close to the critical current. It is speculated that the high inter-strand electrical and thermal resistance inherent in these cables may effect the stability at high currents.
Keywords: Nb-Ti Rutherford cables with core, stability , "porous-metal" filling

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1. Introduction

In the construction of high field superconducting dipole magnets, much effort is devoted to containing the electromagnetic forces on the conductor. Improvements in the support structure reduce the occurrence of energy release at the superconductor due to either gross motion of the cable or the strands within the insulated conductor. The level to which the cable can absorb these energy releases without quenching is one measure of the stability of the cable. To study this stability to transient energy release for different cables, we define stability as the minimum energy of short duration applied to a small volume of one strand in a cable which is sufficient to initiate a quench of the entire conductor. This is referred in the text as the MQE. Such measurements on single strands have yielded MQE values that are comparable to theoretical calculation [1]. For Rutherford cables however a wide variety of behavior was observed that is much more complicated, both experimentally and theoretically [1,2].

Another issue for cables used in accelerator dipole magnets is that of the field errors which arise during current ramping and are caused by coupling currents flowing between the strands [3]. This is controlled by the inter-strand cross-over resistance, Rc, which if sufficiently high will suppress this eddy-current contribution to the field errors.

One way to increase Rc is by introducing a resistive core into the center of the cable as detailed by Adam et al. [4]. Several studies have shown that eddy-current suppression is indeed quite significant in such cored-cables made with either uncoated or Sn-Ag solder coated strands [4,5].

In this paper we examine the stability of cored-cables in various states, and compare the results with other similar non-cored cables.

2. Experimental Details

MQE values for several LHC type cables (28 strands, 1.065 mm diameter) have been measured at the cable test facility at BNL. For these tests the cable samples which are ~ 1.5 m long are fully insulated with two layers of 25 μm thick kapton film. A 1-mm square cutout in the insulation layer is covered with a small amount of graphite epoxy paste, which contacts a single strand in the cable. A 25 μm thick, 2 mm wide copper strip is placed over the paste and held down by a layer of 25 μm adhesive backed Kapton tape. Pressure is applied during the curing of the epoxy. The graphite forms a contact heater, such that energy can be deposited on the strand by passing a current pulse through the heater using the superconducting strand as the return path. Typically heaters were placed on five strands well separated within one lay pitch of the cable. The layout of the heater positions on the wide face of the cable is shown in Fig. 1. A pair of cables is assembled in the test fixture similar to the one described in reference [6], with transverse compression on the sample of ~ 50 MPa. Pulse widths were generally 45 μs long and the MQE was established by repeatedly testing with different pulse energies. Because the application of a pulse that is insufficient to trigger a quench can actually change the distribution of current among the strands in a cable, the conductor was quenched after each test pulse and then ramped up to current for the next pulse. Measurements at 4.4 K were made in "pool-boiling' helium in a background field of 7 T and those at 1.9 K were in one-atmosphere superfluid helium and in a field of 8.7 T.

All samples are measured for critical current (I_c) at the start of each experiment. Following the usual convention, I_c is defined at an effective resistivity of 10^{-14} Ω-m where the area is taken as the total strand cross-section in the cable. In this determination, the self-field produced by the high currents in the cable has to be taken into account in determining the field at various points in the cable cross-section [7]. As with I_c measurements, the MQE of a conductor at a given field and current depends on the cable orientation relative to the applied field. Initially, measurements were made with the external field perpendicular to the wide face of the cable. In this case the field at the heater location is ~ 2% lower than the peak field which is at the edge of the cable. Most of the data shown here were taken with the field parallel to the wide face of the cable, such that the peak field is at the heater site, thereby assuring that the I_c in the reduced current factor I/I_c applies to the actual heater location. The results are presented in terms of the MQE in μJ plotted against I/I_c, the current as a fraction of the critical current at the appropriate field and temperature.

The cored cables for this study were fabricated at the Experimental Cabling Facility at LBNL. Details of the cable fabrication are given in reference [4]. The core in this cable is a 12-μm thick oxidized austenetic stainless steel. The best feature of cored cables is that they allow the use of various strategies for improving the stability without increasing the eddy-current coupling. The simplest way is to solder adjacent strands together, thereby creating a mechanically rigid conductor, with less energy release due to inter-strand motion. For non-cored cables made with uncoated strands, partial soldering increases the stability as shown in earlier experiment [2].

Much greater improvements in stability can be achieved by adding metal spheres ~ 25 μm to the solder filling, thereby making the filler between the strands fairly porous with fine interstices that can fill up with helium and enhance the heat transfer by increasing the effective surface area [4,8]. The "porous metal" filling was achieved by mixing metal particles with a proprietary solder cream such as *ESP Solder Plus.* A typical mix contains by volume: 50% flux, 40% metal powder and 10% solder. This paste when heated to ~30°C above the melting point of the solder in an inert atmosphere produced a good sponge between the strands. At CERN a continuous process has been developed to fabricate long lengths of cable with this treatment. The cable is first injected with the paste and then passes into an oven with inert gas, which fuses the solder and the metal particles. While the solder is still molten, the cable passes through a cooled die, which presses the cable to the correct size while the solder solidifies. A brief description is given in reference [4] with more details available in a CERN report [9].

3. Results

In this section, the MQE measurements on prototype LHC inner cables with a stainless steel core are described. These include the following: a) a sample "as-cabled" with un-coated strands and a typical inter-strand resistance ,Rc, of ~ 700 μΩ [4], (b) the same cable "partially soldered" which is assumed to have a similar Rc but with adjacent strand resistance of ~ 0.1 μΩ [4], (c) a cable with the "porous-metal" treatment using the continuous process, with copper powder ~ 45 μm mixed with lead/tin solder paste and the oven temperature set at 600°C, and (d) another cable without a core that was manually treated with the "porous-metal" filling process, and which has a Rc value of ~ 3.5 μΩ [10].

Fig. 2 shows the MQE for the "as-cabled" and "partially soldered" samples measured at 4.4 k and 7.2 T in the perpendicular orientation. As predicted by theory [2], a "kink' is observed in the as-cabled conductor, which separates the regime where cable quenching is triggered by a single wire from that where many strands must be driven normal before the whole cable is quenched. Similar behaviour is observed for non-cored cables made with un-coated strands which have Rc values ~ 100 μΩ [1]. Note also that the "kink" occurs at different currents for the three different heaters, shown in Fig. 2. Partial soldering straightens out the kink, but does not increase the MQE at high currents. Also, the results for the different heaters are almost identical so that the average is plotted in the figure to highlight the variation in the un-soldered case. It is not clear whether the scatter observed is caused by local variations in stability or by a non-uniform current distribution among the strands. The factors that effect the location of the kink are the thermal conductance between the strands and the volume of liquid helium within the insulation and the cable. These parameters may vary along the length of the cable, giving rise to the observed variation. Above the kink, the MQE for the different heaters is very similar indicating that the current distribution at these levels is uniform among the strands.

Fig. 3 summarizes the MQE for the as-cabled and the "porous-metal" filled cable sample, where now the data were taken in the parallel orientation as described earlier. For the as-cabled sample, a typical result is shown both at 4.4 K and at 1.9 K, solid triangular points for 4.4K and open points for 1.9 K. Also shown are the ranges of values measured for the filled cable sample at both temperatures, (solid diamond points for the maximum and solid squares for the minimum at 4.4 K and open points for 1.9 K). Note that for this cable the variation in MQE below the kink is even more pronounced than the as-cabled sample, however, above the kink the MQE variation is small both in normal and superfluid helium. Also plotted in the figure is the MQE measurement taken at 1.9 K for a single strand that is used to fabricate the cored-cable. For either conductor, the stability at 1.9 K is considerably reduced for I/Ic greater than ~ 0.8.

For comparison, the MQE for a non-cored cable with good porous-metal filling is shown in Fig. 4. In this case the kink has been pushed far beyond I_c at 4.4 K, and is probably near I_c at 1.9 K. For this cable the variation in MQE for different heaters is small. Again, this could be a reflection of the fact that below the kink the cable behaves as one large strand so that MQE does not depend on which particular strand is being heated.

4. Conclusions

The few samples of cored-cables measured to date show that the stability of such conductors is not significantly higher than single strands for currents close to the critical current. And at 1.9 K, the MQE is considerably lower than at 4.4 K. This seems to be the case even for porous-metal filled cable with a core. However, an SEM examination of the cable surface and the cross-section show that the filling is not very uniform and that there is no filler inside the cable on the underside of the strand [8]. This could account for the lack of enhancement of the MQE over the unsoldered cable. Future measurements will be done on a well-filled porous-metal cables to see whether such cored cables can indeed have stability comparable to that shown for the non-cored cable. It is also possible that the low MQE at high currents that have so far been observed for the core-cables may be due to the presence of the foil which ensures a large thermal and electrical cross-over resistance, even when the adjacent resistance is greatly reduced. The role of Rc in determining the stability of cables, especially at 1.9 K, needs further examination.

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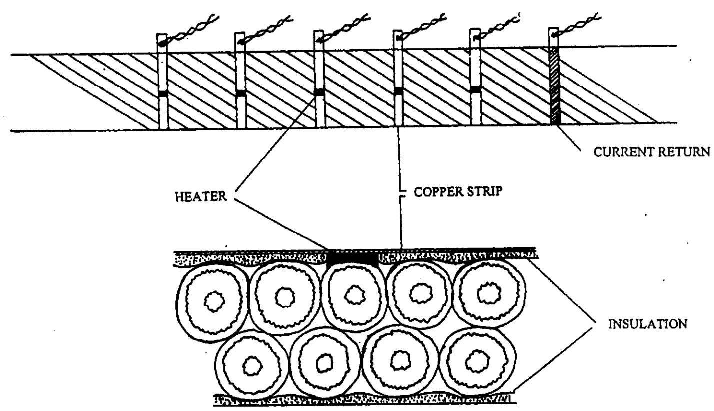

Figure 1. Schematic of the heater layout at the center of the wide face of the cable.

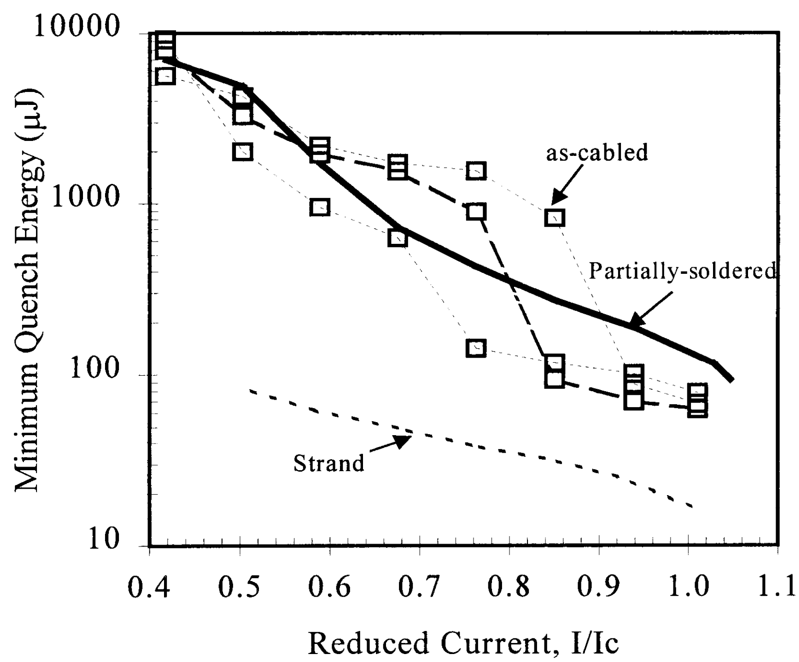

Figure 2. MQE vs. I/Ic for the cored cable in the "as-cabled" and "partially-filled" state. External field of 7.2T is perpendicular to the wide face of the cable. For the "as-cabled" conductor, the "kink" occurs at different currents for the three heaters. For the "partially-filled" case, the results for the different heaters are similar so that the average is plotted. The strand data at 4.2K are shown for comparison.

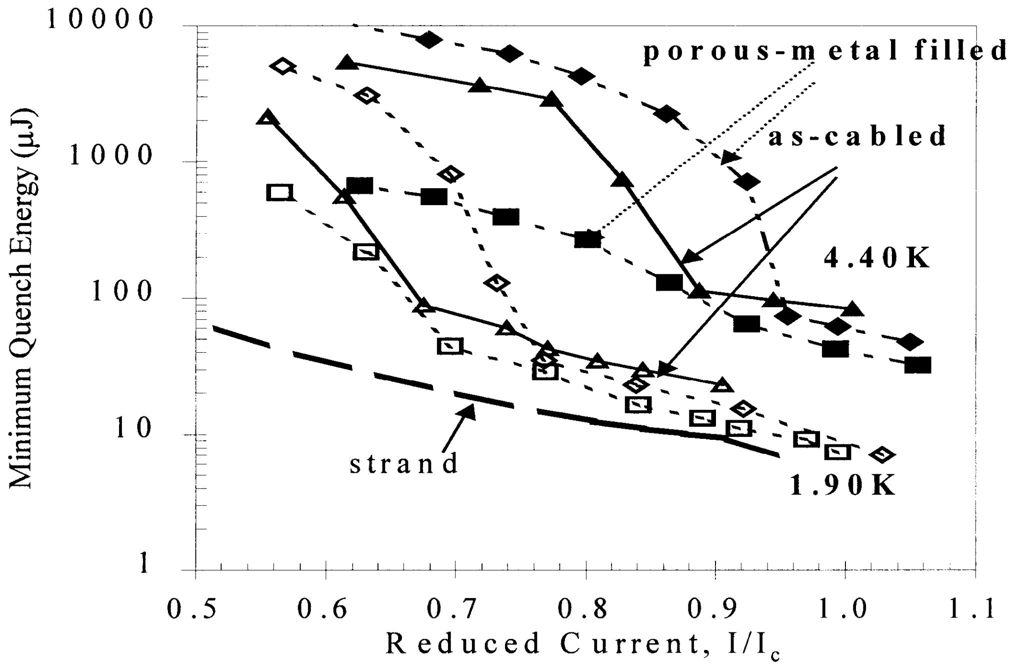

Figure 3. MQE vs. I/Ic of the cored cable in the "as-cabled" and "porous-metal" filled state. For the filled case the range of variation with different heaters is shown, solid diamond points for the maximum and solid squares for the minimum at 4.4 K and open points for 1.9 K. For the "as-cabled" sample a typical result is shown at 4.4 K (solid triangles) and at 1.9 K (open triangles). The strand measurements at 1.9 K are shown for comparison.

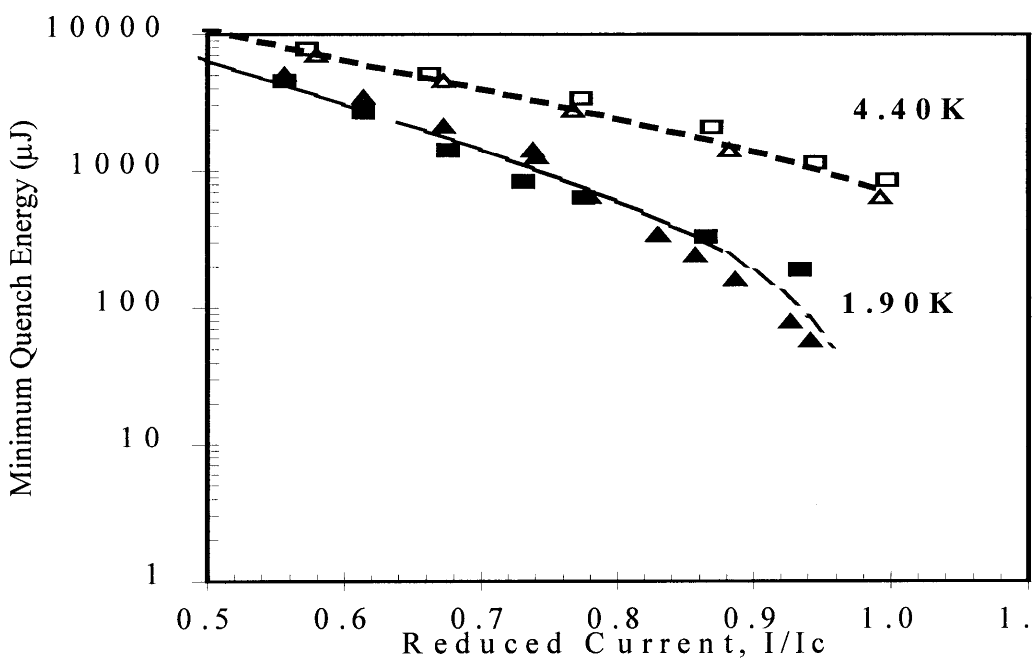

Figure 4. MQE vs. I/Ic of a "porous-metal" filled cable without a core. Data for two heaters are shown. Open symbols are for 4.4 K data, and closed ones for 1.90 K.