EXPERIMENTALLY MEASURED MINIMUM QUENCH ENERGIES OF LHC CABLES

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Abstract

The stability of superconducting cables may be characterized by their minimum quench energy (MQE), i.e. the minimum energy pulse (of small extent and short duration) needed to trigger a quench. This report describes a series of MQE measurements on LHC cables, made at the superconductor test facility of Brookhaven National Laboratory during the period February'95 to July'96. We find great differences between the cables tested. An unexpected finding has been that there are even substantial differences between different types of regular LHC cable, which superficially appear to be very similar. Heat transfer to the helium plays a key role. Partial soldering of the cable brings a small improvement in stability, but soldering with porous metal brings a very large improvement, producing cables of much higher stability than any other.

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1. Introduction

Premature quenching and 'training' in superconducting magnets are generally thought to be caused by energy releases within the windings caused by frictional movement of conductors under the electromagnetic forces. In superconducting accelerator magnets, these energy releases may come from motion of the Rutherford cable as a whole or from motion of individual wires within the cable. There are some grounds for believing that the latter is more important.

Stability of a conductor may be defined in general terms as the ability of that conductor to withstand a given release of energy without quenching. The energy released may be sufficient to drive some parts of the conductor into the resistive state but, if the heat can be removed quickly, via conduction to other parts of the conductor or heat transfer to the liquid helium, it is possible for the conductor to recover from the disturbance and return to a fully superconducting state. In Rutherford cables, an additional stabilizing mechanism is provided by the ability of currents to switch between strands and thereby avoid resistive regions.

It is difficult to make a general definition of conductor stability because of the very wide range of possible energy releases within a magnet. Wipf [1] has postulated the idea of a 'disturbance spectrum' encompassing disturbances which range in time from the abrupt to the continuous and in space from a single point to the whole volume. To define stability, we must first define the disturbance. For this series of measurements, we have decided on a point disturbance of infinitely short duration. The energy of such a disturbance which is just sufficient to quench the cable is known as the minimum quench energy MQE. Although this choice of disturbance is somewhat arbitrary, there are at least three arguments in support of it:

a) Measurements on magnets show that the 'spikes' which initiate quenching are of short duration ~100 μs and there are some reasons for believing that they afflict rather small volumes

b) The MQE as defined above is the smallest number of Joules to trigger a quench; disturbances which last for a long time or affect a large volume always need more Joules. It seems likely that, in a magnet, the mechanism requiring the smallest number of Joules will usually be the first one to trigger a quench.

c) The MQE provides a uniquely defined number, independent of the measuring method, which should enable different conductors to be compared in a quantitative way.

This report describes a series of MQE measurements on LHC cables, made at the superconductor test facility of Brookhaven National Laboratory during the period February '95 to July '96.

Theoretical investigations described in [2] and [3] show that, as the size and duration of the disturbance is reduced, the quench energy tends to a constant value - the MQE. For the LHC cables, these calculations show that the MQE will be estimated to an accuracy of a few percent if the disturbance is restricted to less than ~1mm of a single wire in the cable and has a duration < 50 μs. The MQEs reported here are accordingly measured using heaters of length 1 mm attached to a single strand in the cable and energized with a pulse of 45 μs duration. Past attempts to measure MQE by using resistive heaters which are insulated from the strand have always yielded high values since the thermal time constant of the heater-wire system is usually large and not well controlled. More recently, a technique developed by Seo et al.[4] and Kimura et al.[5] of using graphite paste heaters attached directly on the strand have proven to be effective in reducing the time constant and has yielded MQE values for single strands that are of the same order as theoretical calculations.
Measurements so far have been restricted to cables for the inner LHC dipole coil, partly because these cables are more stressed in the magnet, but also because it is easier to attach heaters to wires of larger diameter. However, measurements on dipole outer cables are planned for the future.

Initial measurements were concerned with investigating the effect of interstrand resistance on stability. Regular LHC cables were compared with the same cable in which the strands were soldered together by a ‘partial soldering’ process which ensures a very low contact resistance between strands at all points where they touch, but still allows helium to permeate the interstices of the cable. Closely linked with the idea of partial soldering is the use of resistive core foils in the cable, which allow the strands to be soldered without causing unacceptable coupling errors when the cable is exposed to changing fields. Finally, the effects of enhanced cooling have been investigated by filling the cable voids with various kinds of porous metal.

A totally unexpected finding of the measurements has been that there are great differences between the MQEs of regular (unsoldered) LHC cables, which superficially appear to be very similar. This effect, which is not yet fully understood, is thought to be caused by differences in the internal cooling, probably coming from differences in the voidage and cooled surface of the wires.

All tests so far have been done in boiling helium at ~4.5K, usually at a field of 7T or 7.2T, which is the maximum capability of the BNL magnet. Of course these conditions are quite different from the LHC dipoles at 8.4T and 1.9K, but a recent measurement at CERN [6] seems to indicate that, for the particular sample tested, the behaviour in boiling and superfluid helium is rather similar. For the time being therefore, we may take the 4.5K measurements as a reasonable basis for comparing different cables.

This report is essentially an expanded version of a recent paper at the Applied Superconductivity Conference [7]. In what follows, Chapter 2 describes the experimental techniques, Chapter 3 presents details of all results obtained so far, Chapter 4 uses data averaged from these detailed results to discuss trends and differences between the cables, and Chapter 5 presents some conclusions.
2 The Experiments

2.1 Test Facility

Cables were measured in the BNL Test Facility [8], for which a schematic is shown in Fig 1. Note that samples are tested in two pairs of 2 and that, because they are powered in series, they should preferably have the same critical current. For this reason, each leg of a pair is usually made from the same cable. Maximum field is set at 7.2T by the capability of the magnet. The helium temperature depends on back pressure generated in the current leads and recovery line, it is usually ~4.5K and may vary during the course of a measurement. Orientation of the samples may be adjusted such that the field is either perpendicular or parallel to the broad face of the cable, and this has substantial effects on the self field.

2.2 Training

Training quenches are observed in these tests, particularly if the sample is not clamped tightly enough. Fig. 2 shows examples of training by two different LHC cables which were clamped at 23 MPa, about half the normal working pressure. The first sample ‘unsoldered B1/2’ is a regular LHC cable ALS83. The second sample is exactly the same cable, but partially soldered as described above. It may be seen that the partially soldered cable needs far fewer training quenches than the ‘bare’ cable to reach a final current which is actually higher than the bare cable, although both cables are exactly the same material. It would seems that soldering the cable has either:

a) made it more stable against energy released by motion under the field forces or

b) reduced the likelihood of such motion

Although the training of short samples is very suggestive of training in magnets, unfortunately we do not yet have much of a correlation between training behaviour of a given cable in short sample tests and in magnets. However, one earlier result [9] does shed some light on the energy release mechanism in short samples. If, after training to full current, the current (and hence the electromagnetic force) is reversed, the cable trains again, but not so much. After several reversals, a state is reached where no more training occurs in either direction. If the training were caused by movement of the cable en masse, one would expect the movement, and hence the training, to be the same at each reversal. But the training stops after a few reversals, hence it seems likely that it was caused by movements of strands within the cable, which eventually settle down.

2.3 Heaters

As noted above, the practical measurement of MQEs only became possible with the invention of carbon paste heaters which, because they are so thin ~100 μm and so well bonded to the wire, have a very rapid thermal response. The layout of our heaters on the wide face of the cable is shown schematically in Fig. 3. To simulate the thermal environment of the magnet winding, all cables have been tested in the insulated state, so a special technique had to be developed for heaters in this situation. First of all, a 1 mm square cutout is made in the insulation layer exactly above the selected wire in the centre of the broad face of the cable. This hole is then filled with a small amount of the graphite paste, after which a 25μm thick, 2mm wide copper foil current lead is placed over the heater as shown in the figure and is held down by a layer of self adhesive Kapton. Usually about 6 heaters are installed, spaced ~ 4-5 wires apart in order to give a representative coverage of all strands in the cable. After all the heaters are assembled, they are allowed to cure at room temperature under moderate pressure. Initially, heaters were made with the graphite paste ‘Leit C’ which is intended for
earthing samples in electron microscopy, but these heaters had a variable resistance and were rather fragile. Later, we found that heaters made with the graphite based electrically conductive epoxy ECOBOND 60L [10] are more robust and give a reproducible resistance in the range of 1 to 5 ohms. The heater resistance can be controlled by the pressure applied during the curing of the epoxy.

Heaters were always placed on top of either cable as it was placed into the test fixture. As shown in Table 3 this arranged gives two possible locations of the heater with respect to the self field of the samples.

Energy is deposited on the strand by passing a current pulse through the heater via the copper foil current lead, using the superconducting strand as the current return path. This heater current is always small compared to the strand current. Rectangular current pulses of variable duration of 20-500 μs are produced by an audio-amplifier driven by a pulse generator. For most experiments a 45 μs pulse is taken as standard. Many of the early experiments showed a puzzling time dependence of the MQE. If the sample was left for a long time at current before applying the heater pulse, the MQE was reduced. After much investigation and several exotic theories about time dependent current distributions, the problem was traced to a small leakage of the main cable current to earth via the heater, thereby providing a small dc pre-heating of that region of the cable. To block these leakage currents, a Zener diode is now placed in the heater current circuit.

Current and voltage waveforms during are digitized in a transient recorder and the energy dissipated is calculated by integrating V x I over the pulse duration. MQE's are established by repeatedly testing with different pulse energies, each time choosing a new energy midway between the last pulses which either quenched or did not quench the sample. It has been found that the application of a pulse which is insufficient to trigger a quench can substantially change the MQE as measured by a following pulse. In fact the MQE can be increased by factors of 2-5 by a process of repeatedly applying pulses of increasing size which are always less than required to trigger a quench. The reasons for this effect are not hard to find; the sub-quenching heater pulse reduces the current in that particular strand so that the strand is less sensitive to the pulses that follow. To avoid this effect and obtain reproducible results, the cable is always quenched after each test pulse and then ramped up to current for the next pulse.

2.4 Critical Current

All samples are measured for critical current in situ at the start of each experiment. Following the usual convention, critical current is defined as an effective resistivity of 10^-14 Ωm. Initially this resistivity was defined on the special CERN standard as measured over the area of the filaments, but later the definition was changed to the more usual one where the area is taken over the entire metal cross section. Thus some of the raw data is presented in terms of Ic(CERN) and some is Ic(RoW) - rest of world but, for this report, all data has been plotted in terms of Ic(RoW).

To measure Ic, the current is ramped up at a constant rate of ~ 165 A/s. Voltage is measured via taps on the conductor spaced 61cm apart and the standard BNL routines are used to fit this data to a critical current Ic and a power law index ‘n’. These taps are also used to record the voltage signature across the cable at each heater pulse, although the presence of noise from the current supply makes it difficult to glean much information from these signals.
2.5 Field Orientation

At currents of more than 10 kA, self field can have a significant effect on the results [11]. Initially, all measurements were made with the external field perpendicular to the broad face of the cable. The field pattern is shown in Fig 4 and the field values are given in Table 3. It may be seen that the field at either heater location is only \(-1\%\) greater than the external field and this difference has been ignored in presenting the results. On the other hand, an external field parallel to the broad face of the cable can either produce a peak field in between the two cables or on their outer face, as shown in Fig.5 and Table 3. Depending on whether the heaters are located inside or outside, this can either produce a high or low field point at the heater. All the later measurements were actually made with inside heaters at the high field point, thereby ensuring that \(I_c\) in the \(I/I_c\) factor applies to the actual heater location. A self field correction was applied to the calculated \(I_c\).

Although the parallel field arrangement does at first sight appear to be to most logical, theoretical predictions for bare unsoldered cables [2] [3] show that the temperature disturbance can grow to a size of \(\pm20\text{mm}\) and the current disturbance to a size of \(\pm50\text{mm}\) before the quench/recovery is determined. In this situation the appropriate critical current ranges from that at the cable edge to the centre. It may therefore be better to use the original perpendicular configuration which puts all parts of the cable in roughly the same field. An additional factor to consider is the reduction in \(I_c\) at the narrow edge of the cable, coming from the heavy compaction in this region. Thus, it may be impossible to achieve the 'ideal' situation of uniform \(I/I_c\) over the normal zone, which is what has been assumed in all the theoretical simulations. As noted in the Conclusions, more work is needed to determine the optimum field orientation.
3. The Measurements

3.1 Presentation of the Results

In this chapter, the measurements are presented in chronological order. The measurements are each identified by a run number, usually corresponding to a particular week during which MNW visited BNL, and an experiment number, corresponding to the experiment during that week. In additional, each experiment is given a BNL test number. The cables tested were each given a sample identifier, and these are summarized in tables 1 and 2.

A standard format is used to present the results in terms of MQE in $\mu$J versus $I/I_c$, the current as a fraction of critical current at the appropriate temperature and field. Because the cryostat pressure can vary during an experiment, the temperature is measured at each MQE measurement and used to correct $I_c$. Thus different measurements at the same current will usually appear on the standard plot with different values of $I/I_c$.

For all experiments, the field was left at a fixed value throughout and the current was ramped up to the chosen level, usually at a rate of 500 A/sec. As noted earlier, all measurements were done on samples in the 'virgin' state, i.e., the cable was always quenched before ramping up the current.

Results for all heaters are presented on the plots for each experiment. In addition, the results are summarized by a 'smoothed mean' line, which will then be used to compare and contrast the results in Chapter 4.

MQEs have also been measured for single wires as described in [7][12]. These measurements are presented on some of the charts for comparison with the cable values but not described in detail.

3.2 Results

As noted above, early results were afflicted by a problem of earth leakage currents flowing through the heater, which gave a dc pre-heating effect and thereby reduced the measured MQE. The whole of runs 1 and 2 suffered from this problem and the first result for which we are reasonably confident in the measured MQE is 3-1, shown in Fig 6. This cable is a partially soldered version of cable ALS83, for which the bare unsoldered version was measured extensively in runs 1 and 2, but registered a low MQE because of earth leakage pre-heating, thereby giving a false impression of the benefit of partial soldering. Better results for the bare ALS83 were finally obtained in run 7-1.

Note that the MQEs for all heaters in Fig 6 are very close to each other, a characteristic of all soldered cables. Fig 7 shows a cross section of the unsoldered ALS83.

Figs 8 and 9 show different heaters from run 4-6, which measured LBL533, the first cored cable made at Lawrence Berkeley Lab, using Staybrite coated wire. Note the very strong 'kink' which, as discussed in [3], is thought to indicate the boundary between a regime where cable quenching is triggered by a single wire and where many strands must quench to trigger the whole cable. Also shown is a measurement of MQE on a single ALS wire, which is not actually the wire used in that cable, but is the closest single wire result we have. It may be seen that the MQE at high currents comes very close to the single wire, as predicted by the theory [3]. Note also that the kink occurs at different currents for different heaters. We believe this effect is comes from strands in the cable carrying different currents. It is not surprising that bare cables show the effect and soldered cables do not. Computer simulations show that soldered cables tend to behave as one single large strand whereas the strands in bare cables can behave quite independently. Thus we believe that soldered cables probably have an equally non-uniform current distribution, but that the energy of the heat
pulse is spread over many strands so that the MQE does not depend on which particular strand is heated.

Also shown in Fig 10 is the strange result for one heater on LBL533 which showed a time dependence of MQE, i.e., the MQE was reduced if, after ramping the current up to the chosen level, one waited for 30 seconds before pulsing the heater. Similar behaviour had been observed in runs 1 and 2, when the heaters had earth leakage problems. We do not think there was any earth leakage in this run however and can offer no explanation for the effect.

Because the results of run 4-6 are so different, we represent it by 2 smoothed means, as shown on Figs 8 and 9.

Fig 11 shows the MFISC result, which is surprising for an unsoldered cable in that the MQEs are much higher and there is no kink. Furthermore, results for all heaters are rather similar. There is no reason to assume that the current distribution in this cable is any more uniform than any other, so we may perhaps take this similarity to indicate a regime of cooperative behaviour between all strands. As discussed in [3], one possibility is that the cable, which has a somewhat higher voidage than ALS83, is so well cooled that the kink has effectively been pushed above Ic. Fig 12 shows the cross section, which may be compared with Fig 7. Unfortunately no single wire data is available for this cable.

Fig 13 shows another unsoldered AgSn coated cable ALS89B. More differences between heaters are seen and there seems to be the beginnings of a kink just about at Ic. Here again, the single wire data is the closest we have and not actually from the cable material.

Fig 14 shows the second cored cable made at LBL, this time with an oxidized stainless core. Also shown is the MQE measured for a single strand of the wire used to make this cable. It may be seen that the kink is quite pronounced, but that the MQE above the kink is still about 3 x higher than a single strand. A cross section of the partially soldered version is shown in Fig 15. Partial soldering straightens out the kink as shown in Fig 16, but does not increase the MQE much at high currents. Measurements of coupling for both the soldered and unsoldered version of this cable were made at University of Twente, using an ac loss technique [13].

Fig 17 shows the first test of Vac 43, in the bare unsoldered state. This cable, which was a first trial at Brugg Cable Co, is made from a scrap Vac wire originally intended for SSC. Because it was readily available, it has been used a lot in these tests. The cross section in Fig 18 shows the unusual design of wires, consisting of a large central copper core with filaments located right up to the outer boundary. From the appearance of Fig 18, it also seems likely that there is more voidage in this cable, but a definite answer on this point must await more accurate density measurements.

The first attempt at porous metal filling was tested as sample 6f shown in Fig 19. Almost certainly this filling was not porous because it contained too much solder and should rather be regarded as a bulky solid solder fill with some voids.

Fig 20 shows the repeated run on bare unsoldered ALS83. During this run, several new things were tried. Firstly the new epoxy heaters were put on cable B2 and compared with the original Leit C heaters on cable B1 (B1 and B2 were identical). From Fig 20 it may be seen that, in general, the epoxy heaters registered a somewhat higher MQE than the old heaters. We are not sure whether this is a real effect or just a random fluctuation. The single wire plot is actually for a strand from this cable and is quite close to the cable MQE above the kink.

Effects of field direction were tried in run 7-3. Heater 1 on B2 was at the inner location as defined in Table 3. Fig 21 shows the MQE for this heater with a 7T field perpendicular or 6.4T and 7.2T
parallel, aiding the self field at the heater. The self field is quite strong, changing $I_c$ at the heater from 9522A to 12481A. However, when $I_e/I_c$ is expressed in terms of the calculated $I_c$ at the heater, all three curves are brought quite close together. Even closer correspondence is shown in Fig 22, which plots heater 2 located at the outer position on cable B1. In this case, the heaters are in the outer position where the self field is much lower.

Fig 23 shows the first real porous metal cable, filled with a sponge of silver flakes. The lower curve shows the first result, obtained in boiling liquid helium, but much higher MQEs were then obtained by pressurizing the liquid so that it was subcooled. The explanation seems clear: boiling liquid does not fill the pores of the metal sponge, but subcooled helium is forced into every void. Of course one would expect similar behaviour in LHC conditions. Fig 24 shows that all heaters register very similar MQEs. Fig 25 shows that copper pormet, made from spheroidal powder of sphere diameter 25-36 μm, gives very similar MQEs. Fig 26 shows the cross section of a cable filled with porous metal made from spheroidal metal powder. Details of the manufacturing process are described in [13].

In an attempt to maximize helium percolation of the two pormet cables, they were insulated with a barber pole wrap (50μm thick Kapton of width 10 mm and pitch 12mm, i.e with a 2mm gap) against the metal. This first layer was then covered with an outer wrap of double overlap 25 μm thick Kapton. The remaining runs were devoted to an exploration of the effects of barber pole wrap, all using Vac 43 cable, which was bare, partially soldered or with pormet. In each case, the cables were tested with either barber pole wrap or solid wrap, consisting of two layers of double overlapped 25μm Kapton, i.e a cover of 4 thicknesses.

Fig 27 shows the partially soldered cable with solid insulation and Fig 30 shows it with a barber pole wrap. Fig 28 shows the bare cable with a barber pole wrap and Figs 29 and 32 show it with solid insulation. Fig 31 shows pormet with solid insulation.
4 Comparisons of the Results

In the following, smoothed means taken from each of the plots in Chapter 3 are used to compare and contrast the stability of different cables.

4.1 Soldered and Bare

Fig 33 plots results for bare and soldered ALS83, showing ‘classical’ kink behaviour with the bare MQEs tending towards single wire values at high current. Soldering straightens out the kink, as expected from the theory, but also makes the MQE higher than unsoldered cable at low currents - not expected from the theory. Run 3-1 was a very early result and may perhaps be in error, but there is nothing obviously wrong with it and, as may be seen in Fig 6, all heaters were in excellent agreement.

Fig 34 shows a similar plot for the cored cables LBL533 and LBL 558. Here again, the kink is very much as expected and tends to single wire values. Soldering straightens out the kink, but does not increase MQE much at high currents. Perhaps this because the core foil ensures a large (thermal and electrical) crossover resistance, even though the adjacent resistance is greatly reduced.

Fig 35 compares partially soldered cables - on this plot also, ALS83 looks a bit high. Run 6-4 has been included here because, as noted earlier, the voids of the porous metal were clogged with excess solder, so it should be regarded as a soldered cable with less voidage than usual. For this reason, it is not surprising that the ‘solid pormet’ lies below the same cable with partial soldering.

4.2 Heat Transfer and Voidage

Fig 36 compares all the uncored bare cables. Also shown is the single wire ALS202328 result, which only really applies to ALS83, but is a reasonable approximation to all others except MFISC (which had larger strands). It may be seen that all cables tend to similar limiting lines above and below the kink, i.e. in the ‘single wire’ or ‘cooperative’ regimes. However, the kink occurs at very different currents. Indeed, for MFISC, it seems to have been pushed above Ic, Remarkably similar behaviour has been seen in the computer simulations, where it was produced by varying the heat transfer - both cooled area and volume of liquid helium contained in the voids of the cable. From the appearance of Figs 7 and 12, one might estimate that MFISC has more internal cooling than ALS 83, particularly at the narrow edge. However, the difference is much smaller than the factor ~2 needed to produce such effects in the computer simulations.

Fig 37 explores some other effects of heat transfer. As noted above, the ‘solid pormet’ of VAC 43 is lower than the partially soldered version, probably because there is less voidage and thus less internal heat transfer. Both these cables had ‘solid’ insulation consisting of two layers of double overlapped 25µm Kapton, ie 4 thicknesses in total. Also shown is a partially soldered cable with barber pole insulation, which increases cooling on the outside of the cable.

4.3 Porous metal

The extreme case of good heat transfer is, of course, the porous metal. Fig 38 summarizes the three runs on two types of pormet. Here again, it would appear that the barber pole insulation has brought some benefits.
4.4 An Anomaly

All results so far have been fairly understandable in terms of the theoretical simulations and a general physics intuition, but Fig 39 shows a set of results that are not. All curves are for bare Vac 43 cable; the sample used for the upper three curves is actually different from that used for the lower one, but they are exactly the same cable. It may be seen that insulation, ie barber pole or not, has made no detectable difference to the upper curves. Furthermore, as may be seen from Figs 28, 29 and 32, the results from different heaters are not so different. Nevertheless, the MQE measured in Run 6-3 is very much smaller. At present we have no explanation for this effect. One obvious difference is that the upper curves were measured in parallel fields and the lower one was in perpendicular but, as shown by Figs, we did not see any strong effect of field orientation on ALS83. Neither did we see any strong differences between the samples of LBL tested in perpendicular field at BNL and in parallel field at Twente and CERN- if anything, the Twente results in parallel field results had kinks at lower currents than the BNL results in perpendicular field.

One possible explanation may come from the observation (Fig 40) that cable samples, particularly Vac 43, prepared for micrographs usually have perpendicular and parallel gaps between the strands unless the samples are pressed on both the broad and narrow faces. In the BNL test fixture, considerable pressure is applied to the broad faces, but not to the sides. Thus it is quite possible that the vertical gaps shown in Fig 40 remain open. In the perpendicular field configuration, magnetic forces will push the cables towards the sides and may tend to close the gaps, but in parallel field there is no sideways force and the gaps will remain open. The cooling, and hence the stability may thus be better in parallel field. However, this idea is purely hypothetical and more experiments are needed to find the true cause of the anomaly.
5 Conclusions

5.1 Comments on the results

a) Cables have very different MQEs. As shown in Fig 41, the mean MQEs at I = Ic can vary from 65 µJ to 1250 µJ. In fact the individual heaters range from 35 µJ to 1500 µJ. Although we still have no experimental data on magnets, it would be surprising if this wide range of stability did not have some effect on magnet performance.

b) The kink is an important aspect of MQE behaviour in standard LHC cables. Theoretical simulations lead one to believe that, at currents above the kink, the whole cable can be quenched by quenching of a single strand. This must be dangerous for magnets, particularly in situations where the current is not shared equally between strands.

c) Heat transfer plays a key role. We have direct experimental evidence that pormet cables behave differently in subcooled or boiling helium and that some cables are improved by barber pole insulation.

d) Computer simulations seem to show that increased heat transfer can shift the kink to higher currents, even above Ic. It therefore seems likely that the different behaviours of bare cables can be explained in terms of different internal heat transfer, i.e. different voidages, but this hypothesis is not yet proven.

e) Preliminary results at Twente and CERN [6] on the same cable in boiling 4.2K or subcooled 1.9K helium show that the overall behaviour is not much different. It follows that the results reported here can be used to make reasonable comparisons between the likely behaviour of cables at 1.9K.

f) Cable filled with pormet are clearly the most stable. Partially soldered are is less erratic than the same cable unsoldered and generally have a higher MQE at high currents, but lower at low currents. If either pormet or partially soldering are to be used in an accelerator magnet, a core foil is needed in the centre of the cable to suppress coupling currents.

g) The behaviour of regular (unsoldered) LHC cables is very variable. At Ic, there is factor ~7 in MQE between the best and the worst.

h) The effect of field orientation not yet understood.

5.2 Recommendations for Work in the Near Future

a) The new LBL cables (series 583) with different voidages should be tested for MQE and measured for density, starting with the most and least compacted. If an effect is found, the whole range of density should be measured to see if the dependence on compaction is progressive or abrupt.

b) The effect of field orientation should be cleared up - starting with the two samples of Vac 43 unsoldered, then the Vac 43 pormet, followed by a representative number of all the other samples tested so far. New samples should be measured in both field orientations until the effect is fully understood.
c) For preference, all new samples should be tested in superfluid, but cryogenic problems should not be allowed to delay testing unduly. If there are problem with superfluid, samples should continue to be measured at ~4.5K.

d) A 1 metre test magnet should be made with pomet cable as soon as possible. Because pomet cable has such a high MQE, this test should establish (for the first time ever) whether cable stability has any effect on magnet training.

e) If tests (a) give a positive result, a 1 metre test magnet should be made using cable with a voidage which has been found to give the optimum MQE. Results from this test could have a real impact on the performance of LHC dipoles and therefore have implications for the forthcoming conductor specification.

Acknowledgements

Many people have contributed to the work described here. Some of the cables tested were made at Lawrence Berkeley Lab by H. Higley, A.D. McInturff and R.M. Scanlan. Our only comparison between 4.2K and 1.9K helium was made in tests at Twente University and CERN by B. Ten Haken and S. Jongeleen. D.E. Bayham of Rutherford Appleton Lab made some helpful contributions to the debate, particularly on porous metal. Members of the Superconducting Cable Section at CERN, under the leadership of D Leroy have helped in many discussions about the general stability problem and the manufacture of special samples, measurement, calibration etc, notably D.Adam, C.H. Dennarie, L. Oberli, D Richter, and R Wolf.

M.N.W. is grateful to CERN for this opportunity to spend 2 very interesting years working on this problem and wishes to thank in particular L. Evans for the initial invitation and R. Perin for the suggestion that he should work in this area.
REFERENCES


6. Jongeleen


Table 1: First Series of Samples Measured for Stability at BNL

<table>
<thead>
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<th>cable name</th>
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<th>B2</th>
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<th>5a</th>
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<td>LBL 558</td>
<td>Vac 43</td>
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<td>Vac 43</td>
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<td>11599</td>
<td>17076</td>
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<td>12066</td>
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Solder types

P1 Original effort using soldering iron in air, lots of solder and some oxide
6b Sn/Ag paste under argon - good quality
6e Mixture of Sn/Ag paste and <50 mm copper powder under argon. Poor quality, too much inside not enough outside, too much solder and Cu dust
Table 2: Pormet Cable Samples

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<td>Vac 43</td>
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<td>I</td>
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Table 3: Contribution of Self Fields for Double Cable samples

External field = 7.0T
Sample current = 10 kA

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<th>Field at inner heater</th>
<th>Peak field</th>
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<td>parallel high</td>
<td>6.930 T</td>
<td>7.764 T</td>
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Fig 1: The Brookhaven Cable Test Facility

Samples are immersed in the field of dipole magnet, producing a transverse field of up to 7T, contained in a vertical dewar. Their orientation may be adjusted such that the field is either perpendicular or parallel to the broad face of the cable. The 4 samples are tested in 2 pairs, with current passing either through sample A and B or, using the third current lead, through samples C and D. Stainless steel bolts are used to apply a pre-load the cables similar to that found in magnets.
Fig 2: Training of Bare and Partially Soldered Cables

Run 1-5  Sample ALS 83  27 Feb 95
Field = 7.29 T  Temp = 4.47 K  Ic = 11600  pressure = 23 MPa

![Graph showing the comparison between Unsoldered B1/2 and Partially soldered P1/2.]
Fig 3. Schematic of the heater location on certain strands in the cable.
Fig 4: Field Pattern of double cable sample in Perpendicular External Field

(computed by M Garber)
Fig 5: Field Pattern of double cable sample in Parallel External Field

(computed by M Garber)
Fig 6: ALS83 (sample P1) partially soldered, solid insulation

Run 3-1 BNL test #3766  May 96  Ext field 7.0 T  perpendicular
Ic = 11569 A  at temp 4.475 K
Fig 7: Cross sections of ALS83, unsoldered
Fig 8: LBL 533 AgSn coated, 25 μm stainless core, unsoldered

Run 4-6 BNL test#3772 19 Jun 95
Ext Field = 7.0 T perpendicular
Ic = 11599 A at temp 4.475 K (from 28 * 522 @ 4.2K)

- - htr #4 zero wait
- - htr #4 30 sec wait
--- smoothed mean
- + single wire ALS 6/20328 Run#1581

MQE, micro joules

I / It cern
Fig 9: LBL 533 AgSn coated, 25 µm stainless core, unsoldered

Run 4-6 BNL test#3772 19 Jun 95
Ext Field = 7 T perpendicular
Ic = 11599 A at temp 4.475 K (from 28 * 522 @ 4.2K)
Fig 10: LBL 533 AgSn coated, 25 μm stainless core, unsoldered

Run 4-6 BNL test #3772 19 Jun 95
Field = 7 T perpendicular
Ic = 11599 A at temp 4.475 K
Fig 11: ALS80 (MFISC inner) AgSn coated, unsoldered

Run 5-1  BNL test #3788  6 Nov 95
Ext Field = 7.2 T perpendicular
Ic = 13036 A  at temp 4.493 K
Fig 12: Cross section of ALS80 (MFISC)
Fig 13: ALS 89B AgSn coated, unsoldered, solid insulation

Run 5-2 BNL test #3782 5 Dec 95
Ext Field = 7.2 T perpendicular
Ic = 11900 A at temp 4.50 K
Fig 14: LBL 558 bare Cu with 12 μm stainless core, (sample 6a) unsoldered, solid insulation

Run 6 - 2 BNL test #3794 23 Jan 96
Ext Field 7.2 T perpendicular Ic = 12066 at temp 4.454 K
Fig 15: Cross section of LBL 558 soldered
Fig 16: LBL 558 bare Cu, 12 µm stainless core, part soldered, solid insulation

Run 6-1 BNL test #3793      22 Jan 96
Ext Field = 7.2 T perpendicular
Ic = 12184      at temp 4.454 K
Fig 17: Vac 43 (sample 6c) bare Cu, unsoldered, solid insulation

Run 6-3b  BNL test #3795  25 Jan 96
Ext field = 7.2 T perpendicular
Ic ~11900 A  at temp 4.509 K
Fig 18: Cross section of Vac 43 bare
Fig 19: Vac 43 (sample 6f) bare Cu, soldered with solid pormet, solid insulation

Run 6 - 4 BNL test # 3796  25 Jan 96
Ext field = 7.2 T perpendicular
Ic = 11900  at temp  4.509 K

10000
1000
100

MOE µJ

I / Ic

--- htr # 1  6-4
--- htr # 3  6-4
--- htr#2  6-4
--- htr#4  6-4
--- htr#5  6-4
--- smoothed means
Fig 20: ALS83 (samples B1/B2) bare Cu, unsoldered, solid insulation

Run 7-1   BNL test #3799      16 Feb 96
Ext field 7.0 T perpendicular
Ic = 11065 A      at temp 4.50K

\[ \text{MQE} \mu \text{J} \]

- B2 epoxy htr #1
- B2 epoxy htr #3
- B2 epoxy htr #4
- B1 old htr #3
- B1 old htr #4
- B1 old htr #2
- B2 epoxy htr 1

smoothed mean

- X single wire ALS
  6/20328 Run#1581

\[ \frac{I}{Ic} \]

4.0  5.0  6.0  7.0  8.0  9.0  1.0  1.1
Fig 21: ALS83 (sample B2) bare Cu, unsoldered, solid insulation

Run 7-3  BNL test #3799  16 Feb 96
Ext field = 7.2 T or 6.4 parallel or 7.0T perpendicular

Ic = 9522A, 12481A or 11065A at 4.50K
Fig 22: ALS83 (sample B2) bare Cu, unsoldered, solid insulation

Run 7-3  BNL test #3799  16 Feb 96
Ext field 7.2 T perpendicular or 7.0T perpendicular
Ic = 12577A or 11065A  at 4.50K

---

I/It

10000

1000

100

10

0.4  0.5  0.6  0.7  0.8  0.9  1.0  1.1

MOE, µJ

---

- - B1 htr 2, field parallel low B=7.2T

- - B1 htr 2 field 7.0 T perpendicular run 7-1
Fig 23  Vac 43 Pommet (silver) PMC4, barber pole insulation

Run 8-1 BNL test #3810    13 May 96
Ext field = 7 T parallel   Self field = 0.764 T at 10 kA
Ic = 10780 A    at temp 4.508K

\[ MQE \text{ mJ} \]

\[ 10000 \]

\[ 1000\]

\[ 100 \]

\[ 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1 \]

\[ I / I_c \]

- - Htr # 1

\[ \square \] boiling at 17 psi

\[ \cdot \cdot \cdot \triangle \cdot \cdot \cdot \] Htr #1 subcooled
Fig 24 Vac 43 Pormet (silver) PMC4, barber pole insulation

Runs 8-1 to 8-3  BNL tests #3810    13 May 96
Ext field = 7 T parallel high    Self field = 0.764 T at 10 kA
Ic = 10780 A    at temp  4.508K
Fig 25 Vac 43 Pormet (copper) PMC3, barber pole insulation

Runs 8-4 to 8-5  BNL test #3811  16 May 96
Ext field = 7 T parallel high  Self field = 0.764 T at 10 kA
Ic = 11176 A  at temp 4.498K
Fig 26 Two views of a cable filled with porous metal

Mixture comprises 75% spheroidal silver powder of particle diameter 25-36 µm and 25% SnAg solder powder of particle diameter < 45µm. Flux used in the process was Alpha Metals RMA
Fig 27 VAC-43 (sample 6d) partially soldered, solid insulation

Run 9-1 BNL test #3822, 11 Jun 96
Ext field = 7 T parallel Self field = 0.751 T at 10 kA
Ic = 11374 at temp 4.498 K
Fig 28  VAC-43 (sample 6c) bare Cu, barber pole insulation

Run 9-2 BNL test #3821,  12 Jun 96
Ext field = 7 T parallel    Self field = 0.751 T at 10 kA
Ic = 11374        at temp 4.497 K
Fig 29  VAC-43 (sample 6c) bare Cu, solid insulation

Run 10-1 BNL test #3830, 10 Jul 96
Ext field = 7 T parallel  Self field = 0.764 T at 10 kA
Ic = 11273  at temp 4.50 K
Fig 30  VAC-43 (sample 6d) partially soldered, barber pole insulation

Run 10-2  BNL test #3830,  10 Jul 96
Ext field = 7 T parallel   Self field = 0.751 T at 10 kA
Ic = 11367   at temp 4.4.493 K
Fig 31  VAC-43 Pormet copper (sample PMC3), solid insulation

Run 11-1  BNL test #3837,  10 Jul 96
Ext field = 7 T parallel    Self field = 0.764 T at 10 kA
Ic = 11367   at temp 4.490 K
Fig 32 VAC-43 bare copper (sample 6c), solid insulation

Run 11-2 BNL test #3838, 30 Jul 96
Ext field = 7 T parallel  Self field = 0.764 T at 10 kA
Ic = 11316 at temp 4.499 K
Fig 33 Summary of smoothed means for ALS83
Bare, part soldered and single wire

Runs 3-1 and 7-1 Ext field = 7 T perpendicular
Fig 34  Summary of smoothed means for Cored Cables
Bare, part soldered and single wire

Runs 4-6, 6-1 and 6-2  Ext field = 7 T perpendicular
Fig 35 Comparison of smoothed means for partially soldered cables

Ext field = 7 T perpendicular
Runs 5-1, 5-2, 6-3b and 7-1
Fig 36  Comparison of smoothed means for unsoldered cables
bare and SnAg coated

Ext field = 7 T perpendicular    Runs 5-1, 5-2, 6-3b and 7-1
Fig 37 Comparison of smoothed means for partially soldered VAC-43 different voidage and external cooling

Runs 9-1 and 10-2 Ext field = 7 T parallel
and Run 6-4b ext field 7.2T perpendicular
Fig 38 Comparison of smoothed means for poromet cables also showing effect of barber pole insulation

Runs 8-1,2,3 8-4,5 and 11-1 Ext field = 7 T parallel
Fig 39 Comparison of smoothed means for bar Vac 43
lower curve in perpendicular field, upper curves in parallel

Runs 9-2, 10-1, 11-2, Ext field = 7 T parallel
and Run 6-3b ext field 7.2T perpendicular
Fig 40  Sample of Vac 43 cable prepared without sideways pressure

Note that vertical gaps between strands as indicated by the arrows
Fig 41 Global comparison of different cable types

Runs 3-1 and 7-1 Ext field = 7T perpendicular Run 5-1 7.2T perpendicular
Run 8-3 Ext filed = 7 T par