ADVANCES IN LOW LOSS NBTI STRAND AND CABLE

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Abstract

The new fast ramping accelerators will require NbTi conductors with lower ac losses than hitherto. Finer filaments will be needed, which will demand significant improvements in the double stack production process. Eddy current coupling between filaments within the wire must be reduced by increasing the transverse resistivity across the matrix, but this increase must be achieved without increasing the longitudinal resistivity too much. Coupling within cables must be reduced without impeding current sharing between strands. Cored cables offer the best way of achieving this compromise.

INTRODUCTION

Early work on superconducting particle accelerators was directed towards a fast ramping fixed target machine, where ac loss in the superconductor is a major design problem. Wires containing many fine filaments separated by resistive barriers and cables with a substantial resistance between the strands were all developed at this time. Subsequently however the emphasis in accelerators shifted to storage rings, where much slower ramp times were acceptable. Fine filaments were still needed to achieve the required field quality, but the other features needed for low ac loss were no longer required and the pace of development slowed somewhat.

With the arrival of the Facility for Antiproton and Ion Research FAIR at GSI [1] and the possibility of a new fast cycling injector for the LHC at CERN, interest in fast ramping NbTi conductors has resurfaced. It is time to dust off the old work and push it further.

Much of subject matter of this paper, presented as a talk at WAMSDO, is about to be published as part of a broader review [2], so this paper will not repeat every detail of the talk, but will concentrate on the main points and recommendations for future work.

For ramped accelerator magnets, achieving an economic refrigeration load and reaching the desired maximum field without performance loss due to overheating depends on keeping the ac losses within bounds. There are three main sources of loss in the superconductor when a magnet is ramped up to field:

(i) hysteresis losses within the filaments of NbTi.

(ii) eddy current coupling losses between filaments in the wire.

(iii) eddy current coupling losses between wires in the cable.

The following sections will treat each of these loss components in turn.

HYSTERESIS LOSS

The hysteresis loss power in a single filament of superconductor exposed to a changing field is

$$P = \dot{B}\,\frac{2}{3\pi}\,J_c(B)\,d_f \qquad (1)$$

where d_f is the filament diameter. Clearly, low loss demands fine filaments, which implies many filaments in the wire. Present generation accelerator magnets use wires with ~ 7 μm diameter filaments, but finer sizes of 2-3 μm are needed for the new fast ramping machines.

Wire Manufacture

Multifilamentary wires are made by cladding rods of NbTi in copper, drawing them to a hexagonal cross section and stacking them in an extrusion container. The best quality wires are made using a single stack process as illustrated in Fig 1.

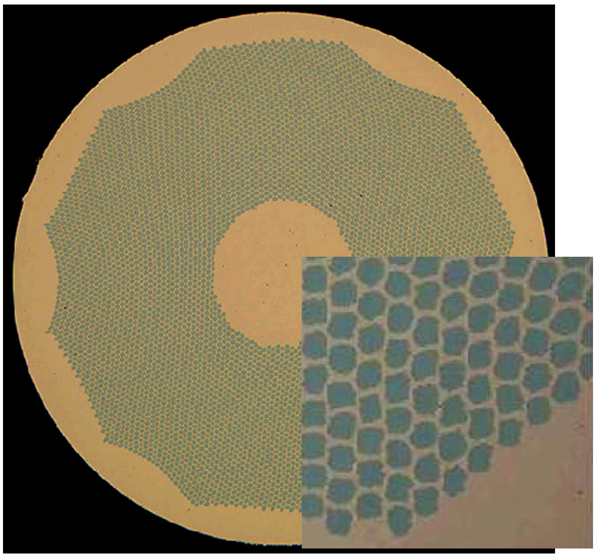

Fig 1: A single stack wire with 6264 filaments (photo courtesy of European Advanced Superconductors)

Practical considerations limit the number of rods which can be stacked to about 15,000, although a single stack of 38,000 filaments has been made using a technique in which the rods are grouped into clusters surrounded by a thin shell [3]. In general however, more filaments require a double stack process in which bundles of filaments are drawn hexagonal and then re-stacked for a second extrusion to produce wires like the one shown in Fig 2.

During the pre-heating needed for extrusion, there is a danger that the titanium will react with the copper to form hard particles of an intermetallic compound. These particles do no reduce in size as the wire is drawn down and are likely to cause breakage when the filaments reach a similar size. To guard against this problem, the NbTi rods are wrapped in a thin niobium diffusion barrier.

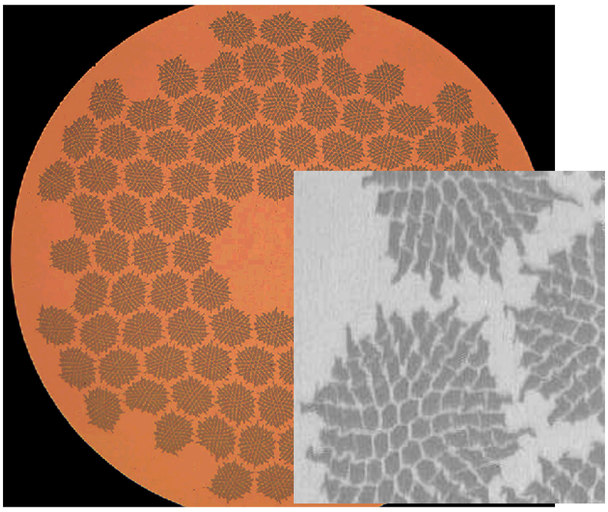

Fig 2: A double stack wire with 102 × 85 filaments (photo courtesy of European Advanced Superconductors)

Filament Uniformity.

As wires are drawn down to finer filament diameters, J_c as measured from the transport current decreases, but the inherent J_c, as measured from magnetization, remains the same. On closer examination, it turns out that n reduces with filament size, where n is the exponent in the following empirical expression for the growth of resistivity with increasing current.

$$\rho(J) = \rho_o \left\{ \frac{J}{J_o} \right\}^n \qquad (2)$$

Part of this resistive transition is ascribed to flux flow resistance in the NbTi, but the major part is thought to be caused by non uniformities in the longitudinal direction or 'sausaging' of the filaments. This is a fabrication problem and more work is needed here if 2-3μm filaments are to be produced with a good current density.

As may be seen in Fig 2, filaments also become distorted in cross section and this has negative consequences for the losses because the d_f in (1) refers to the largest dimension perpendicular to the field. Table 1 presents some measurements made for FAIR of the ratio between J_c measured by magnetization and by transport current. For the best magnet performance, we clearly want to minimize this ratio, ie get minimum loss for maximum transport current.

Table 1: J_c from magnetization and transport current

stack	single	double Cu	double CuMn	double sector
J_{cmag}/J_{ctrans}	0.94	1.40	1.23	1.10

It may be seen that the single stack wire is much better in this respect. The double stack is worse – not surprisingly in view of the obvious distortion of the filaments shown in Fig 2. The third wire is of similar construction, but with CuMn alloy next to the filament. This alloy is somewhat harder than pure Cu and therefore closer to the filaments in mechanical properties, so it presumably gives them better support during wire drawing. Finally, the innovative 'sector' geometry shown in Fig 3 groups the filaments into bundles that fit together more naturally at the second stage extrusion and therefore produces less distortion of filaments at the edge of the bundles. It gives the best result so far for double stacked wires.

Fig 3: Double stack wire with innovative sector geometry (photo courtesy of European Advanced Superconductors)

LHC conductors have ~8000 filaments of ~7 μm size in a wire of ~1 mm diameter. Future fast ramping machines might require filaments as small as 2μm, which would demand ~90,000 filaments in a 1mm diameter wire – clearly beyond the possibility of single stacking. So these future machines are going to demand some improvements in the process techniques of double stacking.

Proximity Coupling

Eq (1) predicts a linear decrease in loss with reducing filament size but in practice we find that, below a size of ~3μm, the loss starts to increase again [4]. The problem is caused by proximity coupling, an effect whereby the copper between the filaments becomes weakly superconducting when its thickness falls below ~ ½ μm. Collings [5] has shown that the effect can be suppressed by adding ~ ½ wt% of manganese to the copper. As noted above, this may also reduce filament distortion by hardening the copper.

Sumption [6] finds that the niobium barrier, which is put around fine filaments to suppress intermetallic formation, may be responsible for launching the Cooper pairs across the copper. So an alternative way of avoiding proximity coupling might be to miss out the barrier and avoid the intermetallic by extrusion at low temperature or by adding silicon to the copper [7].

COUPLING BETWEEN THE FILAMENTS

In changing fields the filaments of a multifilamentary wire are coupled together by eddy currents which cross the matrix. These eddy currents increase the loss by:

$$P_e = \frac{\dot{B}_i^2}{\mu_o} 2\tau = \frac{\dot{B}_i^2}{\rho_{et}} \left(\frac{p}{2\pi} \right)^2 \qquad (3)$$

where τ is the decay time of the eddy currents, ρ_{et} is the effective transverse resistivity across the matrix and p is the twist pitch. Fig 4 shows some experimental values of ρ_{et} for two wires, obtained by measuring magnetization as a function of ramp rate. Also shown are values of ρ_{et} calculated using the methods of [8]. Note the effect of magnetoresistance in the copper.

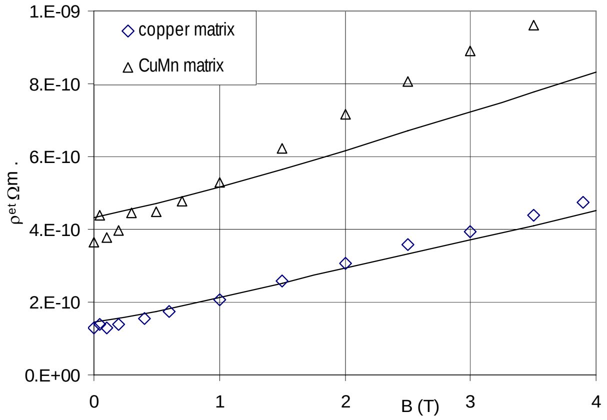

Fig 4: Measured and calculated values of effective transverse resistivity for two wires.

The lower curve of Fig 4 is for a wire with pure copper matrix, as used in all superconducting accelerators built so far. This level of ρ_{et} has been quite adequate to control the losses in storage rings with ramp times of 100 to 1000 sec, but the faster ramps of the new accelerators need more resistance. The upper curve of Fig 4 is for a wire in which the matrix immediately surrounding the filaments is CuMn, with the rest of the wire pure Cu. As already noted, in addition to its higher resistivity, CuMn brings the benefits of suppressed proximity coupling and improved processing. However, ρ_{et} for this wire is increased by only a factor 3, although the CuMn alloy has ~100× the resistivity of pure copper at 4K. The reason for this is that ρ_{et} comprises many parallel paths and it necessary to block all of them if the resulting resistivity is to be increased. The simplest way would be to make the whole matrix from resistive alloy, but this would bring problems of stability and quench protection.

On stability, it was a matter of early experience that even the smallest coils made from wires with a resistive matrix suffered severe training problems. The effect may be quantified roughly in terms of minimum quench energy MQE, defined as the smallest pulse of heat (on a short length of wire for a short time) needed to trigger a quench. Fig 5 plots the MQE computed for a typical accelerator magnet wire as a function of matrix resistivity in the longitudinal direction. It may be seen that there is almost a linear dependency and that the energy needed to trigger a quench with CuMn is ~100 times less than with pure Cu. The result will inevitably be less reliable magnet performance and more training.

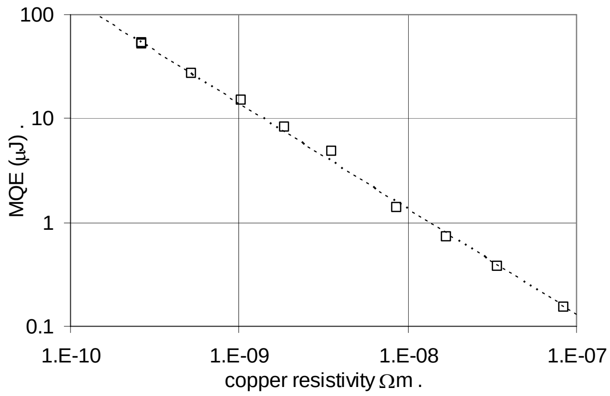

Fig 5: Computed MQE versus matrix resistivity for a typical accelerator wire (0.85mm dia, 50% of I_c at 4.5T)

The challenge therefore is to design a matrix with anisotropic resistivity: large in the transverse direction to control losses and small in the longitudinal direction for large MQE and therefore good stability. Fig 6 shows an early attempt to reach this goal; it had a strongly anisotropic resistivity, but was very difficult to manufacture. There is scope for future innovation in this direction.

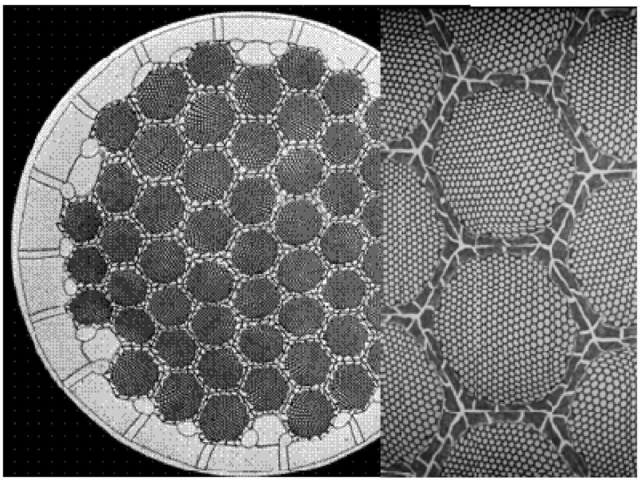

Fig 6: Composite wire with CuNi barriers to produce highly anisotropic resistivity [9]

CABLES

All accelerator magnets to date have been made from Rutherford cable. For reasons of stability and current sharing, the strands are never insulated from each other. Electrical contact between the strands enables eddy currents to flow in changing field, which produces more ac loss. Not surprisingly, these losses are greatest when the field is perpendicular to the broad face of the cable, but there are also different loss mechanisms depending on how the currents flow [2]. As sketched in Fig 7, the contact resistance between strands is of two types: crossover resistance R_c and adjacent resistance R_a. Losses from crossover resistance $Q`_{tc}$ are much greater than adjacent losses $Q`_{ta}$,

$$\frac{\dot{Q}_{tc}}{\dot{Q}_{ta}} = \frac{R_a}{R_c}\frac{N(N-1)}{20} \qquad (4)$$

where N is the number of strands in the cable, usually ~30-40. Because the rolling process produces greater contact areas for R_c, it has been found that $R_c \sim R_a / 7$. The crossover loss is thus ~ 400× the adjacent loss.

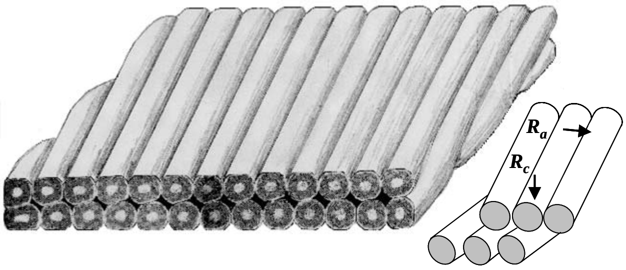

Fig 7: Rutherford cable showing the two types of inter-strand contact resistance.

To control losses in a fast ramped magnet, it is necessary to increase the contact resistance, but this makes it more difficult for the currents to share evenly – so the resistance should not be increased any more than necessary. From (4) it is clear that the best way of reducing loss without impairing the current sharing too much is to increase R_c while keeping R_a low. The traditional method of increasing contact resistance by oxidizing the wire surface won't work because it increases R_c and R_a by about the same factor. A better way is to make a 'cored cable' with a thin resistive foil on its mid plane, which can produce a factor of up to 1000 in anisotropy between R_c and R_a [10].

Inter–strand resistance can also affect the stability of the cable against external disturbances. Fig. 8 shows some measurements of MQE made by applying heat pulses to one strand of a cored cable [11]. It may be seen that smaller values of R_a move the MQE from the lower branch corresponding to the MQE of a single wire, to the upper branch where the whole cable is involved. It is worth remembering that 100 μJ is the energy released by dropping a pin just 100 mm. Clearly the upper branch and lower R_a is preferred!

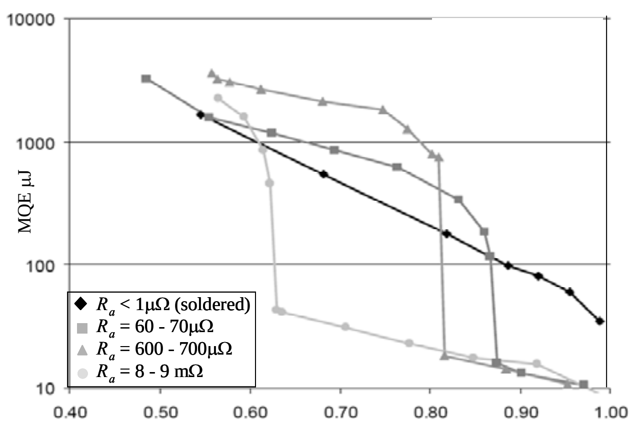

Fig 8: MQE measured for cored cables with different R_a

CONCLUSIONS & RECOMMENDATIONS

Although it cannot match the critical field or temperature of the newer superconductors, NbTi is still the best for pulsed applications because it offers the finest filaments in precise geometries and the ability to produce anisotropic resistivity in the matrix by the use of resistive barriers. To produce the 2-3 μm diameter filaments needed for the next generation of fast ramping accelerators, double stacking will be needed. Further development is needed here to keep all the filament cross sections round so that losses will not be increased by shape effects. Possible strategies are the use of novel geometries and/or CuMn next to the filaments, which will also suppress proximity coupling.

For coupling losses, both between filaments in the wire and between wires in the cable, there is a trade-off between loss and stability. The essence of good design is to control the losses without compromising stability too much. Minimum quench energy MQE is a simple unique number for a given conductor under given conditions and gives a fair measure of stability. It is strongly recommended as a criterion for deciding on whether a chosen configuration of resistive barriers will reduce the wire performance significantly. It may also be a help in those difficult judgements about matrix: superconductor ratio, temperature margin etc for a new magnet if there is available a body of experience on the MQE and performance of existing magnets.

Coupling losses within the wires must be controlled by using resistive barriers. There is scope for innovation in designing new geometries which increase ρ_{et} without increasing the MQE too much and which can be fabricated in long lengths. For cables it seems that cores offer the best prospects for reducing loss while retaining a reasonable inter-strand contact for stability and current sharing.

Although NbTi has been around for as long time, there is still lots of work to do.

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