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RUTHERFORD CABLES WITH ANISOTROPIC TRANSVERSE RESISTANCE

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Rutherford Cables with Anisotropic Transverse Resistance

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I. INTRODUCTION

Coupling currents flowing between the strands of Rutherford cables can cause substantial errors in the field quality of accelerator magnets during ramping. They are much larger than the inter-filament currents within each strand, because the twist pitch of the cable is much larger than that of a strand. To control the inter-strand currents, it is necessary to make the effective resistivity across the cable much larger than that of copper. This increase is usually obtained via a surface coating on the strand:- natural oxide, artificially enhanced oxide such as 'Ebonol', solder coatings, metal plating etc. All these coatings produce a roughly isotropic increase in contact resistance, ie. the resistance R_a at adjacent contacts is the same as R_c at crossover contacts (see fig 1). As discussed in section IV however, to control the coupling, it is usually only necessary to increase the crossover resistance R_c, not the adjacent resistance R_a. This increase may conveniently be achieved by putting a resistive core into the center of the cable as shown in Fig.1.

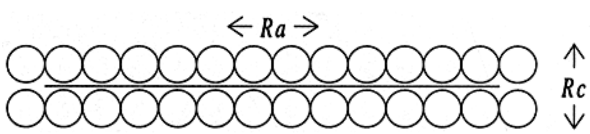

fig. 1 Cable with resistive core in the center to increase crossover resistance R_c

The resistance obtained via cores is more reproducible than surface layers and is not susceptible to being changed by heating or applied pressure during coil fabrication. In addition, it offers the possibility of improving stability, by soldering or adding porous metal, without greatly increasing the coupling.

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II. CABLE MANUFACTURE

A series of cables for this study were fabricated at the Experimental Cabling Facility at LBNL. This facility is equipped with a number of features that are valuable in fabricating experimental cables, including large strand number (up to 60), good strand tension control (less than 0.5 kg), powered turkshead (so that cable tension can be reduced), good dimensional measurement and control (to 5 μm). The twisting area of this machine is shown in Fig. 2, and a complete description can be found in [1].

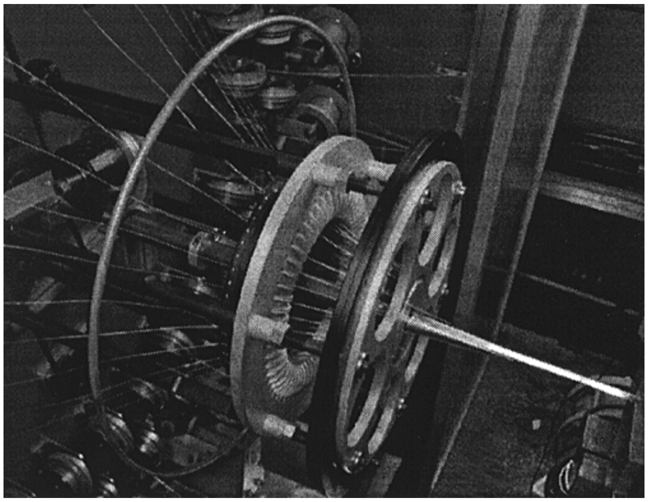

Fig. 2 Twisting head and mandrel of the LBL cabling facility

In addition, the machine has provision for introducing a core into the cable at the point of closing the strands. Two different methods for introducing cores have been explored. In the first method, first introduced by [2], a spool containing the core material was mounted at the end of the cabling machine and the core was fed through a hollow tube and into a hollow mandrel so that it could be introduced at the point where the strands came together just before entering the turkshead rollers. This method suffered from the following problems: (a) the hollow mandrel was costly and difficult to fabricate; (b) the hollow mandrel was easily damaged when the cable is being started and strand crossovers occur, resulting in the thin mandrel tip being crushed; and (c) the core must be fed from the end of the cabling machine to the mandrel, a distance of several meters.

A new method for introducing the core has been developed, and it has proven to be much superior to the first. This new installation (see Fig 3.) consists of (a) a mandrel with a groove machined in one of the flat surfaces of it, instead of a hollow core; and (b) the payoff spool for the core mounted in close proximity to the mandrel so that the core material is easily threaded into the mandrel.

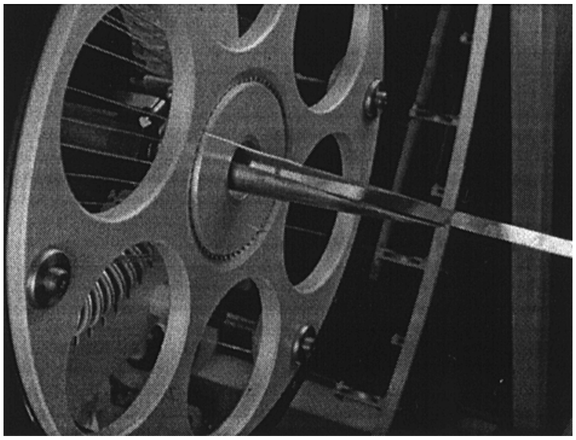

Fig.3 View of the mandrel with core foil in place

It has proven to be fast and straightforward to make cored cable with this installation, and a large number of parameters have been explored. Cables with as few as 10 strands and as many as 36 strands have been produced. A wide range of core materials, including polyimide, pure Ti, TiA1V alloy, and several stainless steel compositions were used. The stainless steel composition was chosen based on availability and stability of the austenitic phase, since it is not desirable to introduce magnetic material into the cables. Core thicknesses from 12 μm to 50 μm were investigated. In addition to the measurements of magnetization reported here, several other studies have been published, including the effect of various core materials [3], different core thicknesses [4], and different amount of compaction [4] on the interstrand resistance values.

The parameters investigated in the present study included the thickness and anneal condition of the stainless steel, the core thickness, and long length fabricability. The initial experiments were performed using 25 μm thick stainless steel cores, and this core produced a cable with a high interstrand resistance and good fabricability. In order to reduce the volume of core, a series of experiments was performed with 12 μm thick cores with cold worked, annealed, and oxidized strips. At the 12 μm thickness, the cores were unstable, with a tendency to migrate to one edge of the cable and then either fold over or tear. After several attempts to rectify this problem by adjusting the strip tension and alignment, the 12 μm thick core material was replaced with the 25 μm thickness. Subsequent cable runs of several hundred meters were made with no problems of core folds or breaks. The 25 μm thick cores still show the tendency to migrate to one side of the cable, but the 25 μm core has adequate strength and rigidity to prevent the folding and breakage problems experienced with the 12 μm cores. The cores still experience significant deformation during the cabling process and are embossed with a diamond pattern where the wires on opposite sides of the cable are crossing. It remains to be seen in magnet fabrication and magnet tests whether this core will cause problems in coil winding or in cable stability. However, from the point of cable manufacture, it now appears that a core of 25 μm thickness can be added to a Rutherford type cable without causing fabrication problems.

III. Soldering and Porous Metal

Our main interest in cored cable is that it allows us to use various strategies for improving stability, without incurring the penalty of increased coupling. The simplest way of increasing stability is to solder the strands together. By increasing the mechanical rigidity of the cable, it can reduce the incidence of mechanical energy releases within the cable. As described in [5] [6], soldering can also increase the minimum quench energy MQE at currents near to critical. However, the MQE will only be increased if good heat transfer is maintained to the helium in the interstices of the cable. In other words, we need to solder the strands together where they touch, but leave the voids open to liquid. We call this partial soldering and have found that it may conveniently be done using a proprietary solder cream such as *ESP Solder Plus.* These creams, which are widely used in the electronics industry, are a mixture of flux and spheroidal solder powder of ~ 30 μm particle size. After cleaning the cable, we fill the outer grooves with solder paste, wiping off any excess. The cable is then heated in an inert atmosphere to ~ 30°C above the melting point of the solder. Provided the cable is clean, the solder runs into all the capillaries between strands. Typically, we find that the method adds ~2% of solder, so for a cable starting at 90% density, the voidage remaining after soldering is ~8%. Fig. 4 shows a cross section of a partially soldered cable.

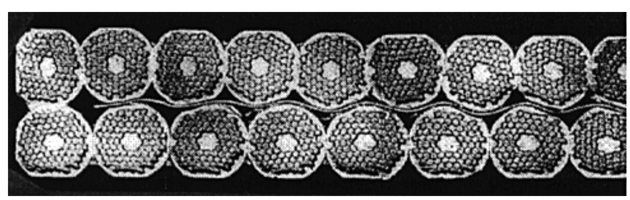

Fig. 4 Cross section of part of a partially soldered cable.

Much greater improvements in stability can be achieved by adding porous metal to the cable [6] [7]. To make the porous metal, we use a development of the solder cream process, in which metal particles and additional flux are mixed in with the solder cream. A typical mix contains by volume: 50% flux, 40% metal powder and 10% solder powder. On heating, the solder coats all the metal particles and also bonds them to the surrounding wires. Regular 63%Pb37%Sn solder wets copper powder very well and produces a good sponge, but it is superconducting at 4.2K, which would give errors in the magnet field shape. Our preferred solder is therefore 96.5%Sn 3.5%Ag because it is not superconducting at 4.2K and only weakly superconducting at l.9K. Unfortunately 96.5%Sn 3.5%Ag does not wet particles of copper well enough and so far we have only had success with silver powder. Fig 5 shows a cable filled with a metal sponge consisting of ~25% solder (96.5Sn3.5Ag) and 75% silver grains of diameter <25μm. Measurements on the stability of this type of cable are reported in [6]. Because silver powder is rather expensive, we are also experimenting with a process for silver plating the particles of copper powder, using the product *Alpha Level* which is used industrially for plating printed circuit boards prior to soldering.

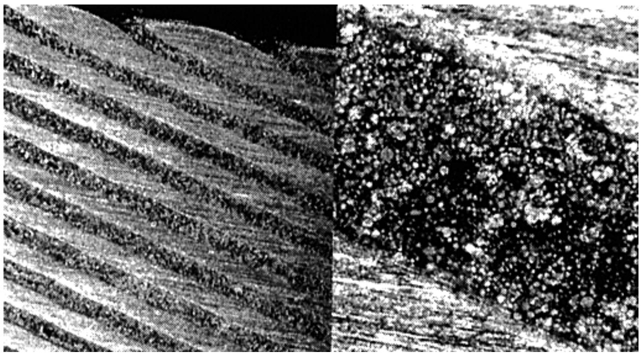

Fig 5. General/magnified view of LHC cable filled with porous metal sponge comprising 25% solder and 75% spheroidal silver particles of size 15 - 25 μm.

As may be seen from Fig. 4, the voidage in Rutherford cables is distributed roughly 50/50 between the outer grooves and the inner spaces. For the best heat transfer we want to fill both these spaces, but it is clearly more difficult to fill the inside than the outside. All the samples tested so far have been made by hand, opening the cable at ~lcm intervals and injecting the metal/solder cream into the center using a syringe. For continuous production, our original idea was to inject paste during the cabling process, but this idea is not popular with cable producers who, quite rightly, worry about the damaging effects of abrasive paste on the precision machined rollers of the turkshead die.

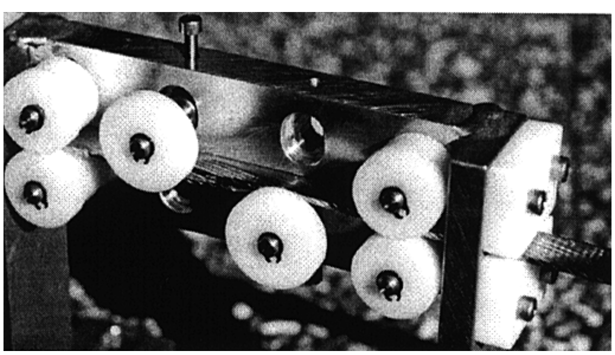

Fig. 6 Mechanism for continuously opening and closing cable so that metal/solder cream may be injected into the interior.

We have therefore developed a continuous version of the manual process which uses rollers to open up one edge of the cable and then close it again; in keystoned cables, we open up the thick edge. Early attempts suffered from occasional problems of wires crossing over, leading us to develop the arrangement shown in Fig. 6, in which the narrow edge of the cable is constrained throughout in a tightly fitting groove, while the thick edge is successively opened and closed by rollers.

The mechanism shown in Fig. 6 is fitted inside an extrusion vessel which the cable enters and leaves via closely fitting dies. Metal/solder cream is pumped into the vessel at a pressure of a few bars as the cable is pulled through. Work here has only just started, but first results are very promising, indicating that it should be possible to fill both the inner and outer spaces of the cable in a single continuous process. After filling, the cable will pass through an oven under inert gas to fuse the solder. While the solder is still molten, the cable will then pass through a cooled die which presses the cable to size while the solder solidifies. In this way we hope to make sufficient cable for a small test dipole.

IV. COUPLING

Strongest coupling occurs when the changing field is normal to the broad face of the cable; there are two patterns of current flow between strands.

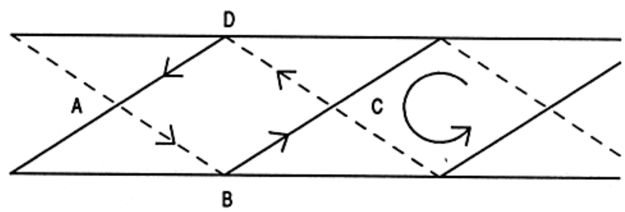

Fig.7 Diamond pattern of coupling current flow, top face shown as solid lines, bottom face shown dashed.

As shown in Fig. 7, currents in the diamond pattern flow on the bottom face from A to B and the top face from B to C. At C they cross over to the bottom face and flow to D and then to A, where they again cross over to the bottom face. By integrating over all possible diamond shapes, the magnetization due these coupling currents may be shown to be [8]:

$$M_c = \frac{\mu_0}{240} \cdot \frac{w^2 L^2}{d.r_c} \cdot \dot{B} \qquad (1)$$

where w is the cable width, L twist pitch, d wire diameter and r_c is the crossover resistance per unit area.

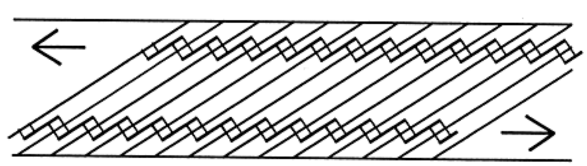

Fig. 8 Coupling currents flowing between adjacent strands.

As shown in Fig.8, the other type of current flow is where the coupling currents flow along each side of the cable between adjacent strands. In this case, there is no interaction between top and bottom face of the cable and the magnetization is:

$$M_c = \frac{\mu_0}{48} \cdot \frac{dL^2}{Cos^2\theta.r_s} \cdot \dot{B} \qquad (2)$$

where r_a is the adjacent resistance per unit area and θ is the angle between strands and longitudinal direction *(cos θ ~1)*. The ratio between these magnetizations is thus

$$\frac{M_c}{M_a} = \frac{1}{5}.\frac{r_a}{r_c}.\left(\frac{w.Cos\theta}{d}\right)^2 = \frac{4}{5}.\alpha^2.Cos^2\theta.\frac{r_a}{r_c} : \quad (3)$$

where α is the aspect ratio of the cable. For LHC inner cable, the factor $0.80\alpha^2 Cos^2\theta = 47$, implying that the adjacent resistance can be 1/47 the crossover resistance for the same magnetization.

For a cable parallel to the changing field, the coupling currents also flow longitudinally between adjacent strands, to give a magnetization:

$$M_{ap} = \frac{\mu_0}{16}.\frac{d^3 L^2}{w^2 Cos^2\theta.r_s}.\dot{B} \quad (4)$$

To check whether this theory applies to cables with strongly anisotropic resistance, we have measured the magnetization of two sample cables with an oxidized stainless steel core, one sample unsoldered and the other partially soldered in a way which joins the strands together where they touch, but leaves the interior porous to liquid. Magnetization was measured in perpendicular and parallel fields via a calorimetric ac loss experiment [9] where the field was ramped in a triangular waveform of ±0.4T at rates between $0.032T.s^{-1}$ and $0.32\ s^{-1}$. At low $\dot{B}$ the losses per cycle may be approximated by a simple straight line fit.

$$Q = C + g.\dot{B} \quad (5)$$

where C is the hysteresis loss and $g.\dot{B}$ *is* the coupling loss. Table 1 lists the parameters derived from these measurements. In listing the resistances, we use the commonly used resistance per crossover $R_c = r_c/A_c$ where A_c is the area of a crossover. = $1.9mm^2$, and also use $R_a = R_a/A_c$.

For measurement b), eq (4) predicts such a low coupling loss that we may assume all of g to come from interfilament coupling and subtract this component from each of the other measurements. In calculating R_a from (c) and (2), we assume that R_c *is* the same in soldered and unsoldered cables. The result, $R_a = 8.9x10^{-8}\ \Omega$, is somewhat less than the $R_a = 1.4x10^{-7}\ \Omega$ found from a separate *VI* measurement. It is possible that the soldering process has reduced R_c, particularly in this cable where the foil had some small punctures and was crumpled in places so that it did not reach right to the edge. From (d) and (4), we find an even smaller $R_a = 4.5x10^{-8}\ \Omega$, we do not understand this low value.

TABLE 1

MEASUREMENTS OF AC LOSS

	C $J.m^{-3}$	g $J.m^{-3}T^{-1}s$	R_c μΩ	R_a μΩ
a) unsoldered transverse	$22x10^3$	$51x10^3$	784	
b) unsoldered parallel	$20x10^3$	$39x10^3$		*(assume large)*
c) soldered transverse	$21x10^3$	$2672x10^3$	*(assume) 784*	0.089
d) soldered parallel	$21x10^3$	$111x10^3$		0.045

Finally we note that the magnetization c), if measured in a cable with isotropic resistance, ie no foil, would indicate an R_c of 3.6μΩ – a value which is too small for LHC. However our *VI* measurements on porous metal show a contact resistance some 10-20 times higher than partial soldering, indicating that the coupling in cored cables filled with porous metal will be comfortably below the acceptance level.

V CONCLUDING REMARKS

Cored cables can be made reliably in a large scale process. Porous metal has been added to short samples of uncored cable and tests on the continuous processing of cored cable are just starting. AC loss measurements are in reasonable agreement with theory; they indicate that the coupling magnetization in cored cable filled with porous metal will be acceptably low. The next stage in our programme is to make cored cable filled with porous metal, in a sufficiently long length to wind a 1 metre LHC test dipole.

REFERENCES

[1] J. M. Royet and R. M. Scanlan, "Development of Scaling Rules for Rutherford Type Superconducting Cables", IEEE Trans. on Magnetics 27, No.2 March 1991, pp 1807-1808.

[2] R. F. Meserve, U.S. Patent 4,439,256.

[3] E. W. Collings et.al., "Magnetic Studies of AC Loss in Pressurized Rutherford Cables with Coated Strands and Resistive Cores", Adv. in Cryogenic Engineering (Materials) (1996) 42 in press.

[4] E. W. Collings et.al., "Suppression of Eddy Current Loss in Bare-Copper Rutherford Cables Using Stainless Steel Cores of Various Thicknesses", Sixteenth ICEC/ ICMC Conf., Kitakyshu, Japan, May 1996.

[5] M. N. Wilson, R.Wolf, "Calculation of Minimum Quench Energies in Rutherford Cables", paper LT-6 at this conference

[6] A.K.Ghosh, W.B.Sampson, M.N.Wilson, "Minimum quench energies of Rutherford cables and single wires" paper LT-7 at this conference

[7] D. E. Baynham, V. W. Edwards M. N. Wilson "Transient stability of high current density superconducting wires," IEEE Trans MAG-17 Nol pp 732.

[8] A.P. Verweij, A. den Ouden, B. Sachse, H.H.J. ten Kate 'The effect of transverse pressure on the interstrand coupling loss of Rutherford type of cables', Adv. Cryo. Eng., Vol. 40 A,1994, pp. 521-527.