

Development of YBCO Roebel cables for high current transport and low AC loss applications

N J Long, R A Badcock, K Hamilton, A Wright, Z Jiang, L S Lakshmi

Industrial Research Ltd, PO Box 31-310, Lower Hutt, New Zealand

Email : n.long@irl.cri.nz

Abstract. We discuss production of lengths of up to 27 m of YBCO Roebel cable. Results for 5/2 (5 strands, 2 mm width), 9/2 and 15/5 cables produced from standard 12 mm commercial YBCO wire are presented. We discuss specifications for the input wire and suggest using a statistical correlation function, using data from magnetic field scanning, that is shown to produce high performance strands. We discuss advances in manufacturing techniques including cable insulation processes. Transport and magnetic AC loss data are presented for 5/2 cable which demonstrates the effectiveness of decreased strand width and the transposition of strands. Both losses are predominantly hysteretic in nature. Finally, the cable DC transport is presented and we discuss the possibilities for high current cables in high field applications.

1. Introduction

For high field magnets and large electrical machines it is desirable to have high current cables of several kilo amps capacity. In LTS technology this is usually accomplished by the formation of Rutherford cables. This is accomplished in copper by the formation of Roebel bar or continuously transposed cable (CTC). From a topological point of view this is the same geometry. Both reduce AC losses by fully transposing the component strands. The Roebel geometry can be compared to two stacks of conductors in which the conductor positions are rotated along the length. For HTS coated conductor technology the Roebel geometry is also convenient and the formation of such cables has been demonstrated by a number of groups [1-4]. The Roebel geometry and significant geometrical parameters are shown in figure 1.

In this paper we consider some of the manufacturing issues associated with producing long length Roebel cables from coated conductors including specifying the starting wire and insulation options. We also review our results on AC loss and consider the potential performance of the cables in high field applications.

We label cables using the convention followed for copper CTC: number of strands / strand width in mm, e.g. 15/5 cable has 15 strands of 5mm width. The samples discussed in this paper have all been manufactured from commercially available wire from SuperPower Inc.

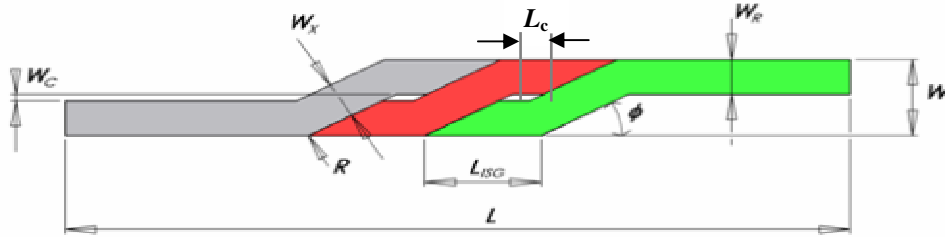


Figure 1. Arrangement of strands in cable and key parameters. L_c is the clearance which must be maintained between strand cross-overs.

2. Quality criteria for wire

A general problem when manufacturing strands for cable is that a satisfactory transport I_c for the starting wire does not guarantee good performance of a strand cut from this wire. This is because a defect which only partially blocks current in a wire can block a substantial fraction or all of the super current in a narrower strand. The Roebel strand also forces current to move at an angle to the longitudinal direction and is sensitive to longitudinal defects, unlike the transport I_c . To overcome this latter problem it is necessary to specify a criteria for 2D uniformity.

Measuring transport currents across the width of wire is not easy to implement but magnetic 2D imaging of wire is commercially available. For example, via the Theva TapeStarTM [5], which can be used to produce a 2D magnetic map of the in plane currents. This maps the magnetic field penetrating a sample at intervals of 1.5mm across the width. Our own remanent field imaging system likewise uses a Hall sensor array with the same resolution [2]. For either penetrative or remanent fields the expected profile for a perfectly uniform wire will follow approximately a triangular profile. Areas of the wire that have regions of poor or zero superconductivity will deviate from this ideal profile. There are many ways to specify acceptable 2D uniformity using this data. For example, one can calculate the gradients, T/m, on each half of the wire using data from a selected number of sensors and stipulate a minimum value. Or, one can compare data directly from sensors placed equidistant from the wire center and stipulate a minimum relative variation.

We have chosen to use a method with focuses solely on the 2D uniformity, weighs data from all sensors equally and provides a single value as a measure of uniformity. To do this we correlate the measured data with the Bean profile, (or if desired a more accurate FEM calculation can be used in the correlation, this is necessary for wire with a weakly magnetic substrate). For equidistant data the Bean profile gives a set of relative field magnitudes $X=\{x_i\}$, the measured data at the same spacing form a set $Y=\{y_i\}$, then the correlation of the two data sets is given by

$$Correl(X, Y) = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}$$

For perfect correlation $Correl = 1$, and for no correlation $Correl = 0$. In figure 2a and 2b we show values of $Correl$ *v* position along two wires. For high quality wire this function can be above 98 % for useful long lengths. Large sections of the wire in figure 2a fall into this category. In figure 2c and 2d we show the magnetic profiles in the regions where the correlation has its lowest value. The transport I_c per width for the starting wires and the punched strand for these wires are shown in Table 1. Both these strands have significantly lower I_c per width than the starting wire and we attribute this to the regions with a lowered correlation. A possible drawback of the correlation and also other methods is that a low value can result from a moderate gradient in J_c across the tape rather than a more serious

defect. This problem can be overcome by testing whether the magnetic profile correlates better with a profile generated from an J_c distribution which includes a gradient.

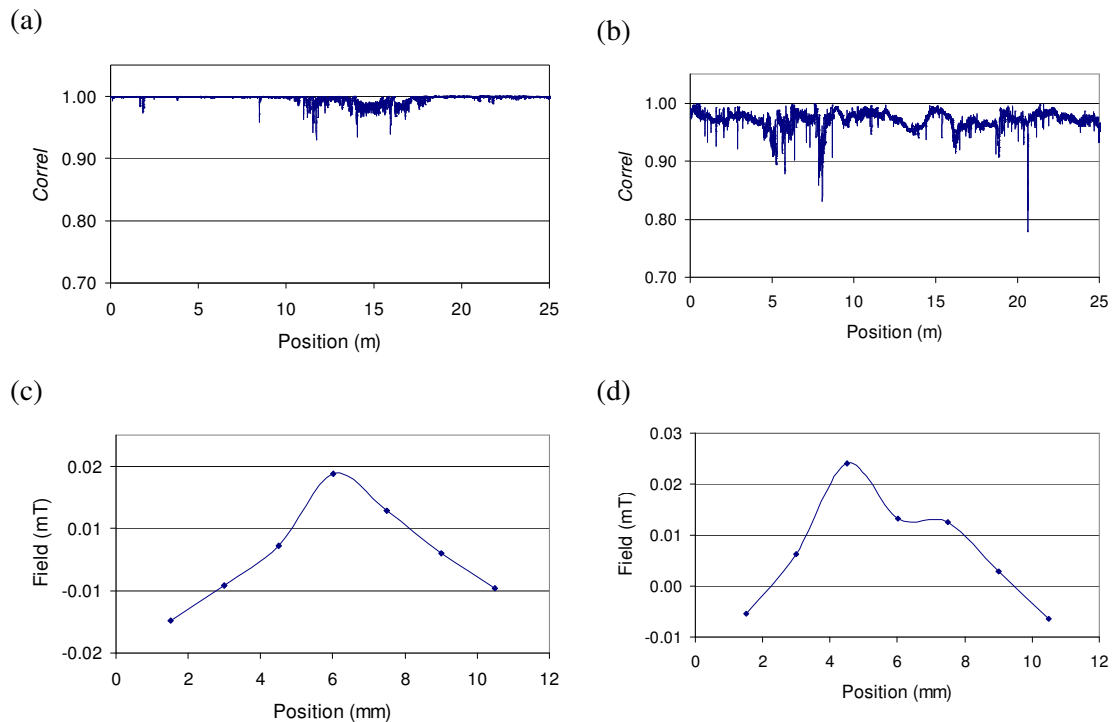


Figure 2. a) Correlation of magnetic scan data with Bean model along tape sample #10, b) *Correl* for tape sample #4, c) Profiles of magnetic field across tape for sample #10, at 14.0 m with *Correl* = 0.94. d) Field profile for tape #4, 20.6 m

In Table 1 we have listed the minimum value of *Correl* as an indication of 2D uniformity. This does not correlate simply to the retained I_c per width or n -value, probably because it does not account for the length of wire which is affected by such poor correlation. To predict precisely the performance of manufactured strands requires more investigation of how this specification should be used.

The magnetic scan methods for 2D uniformity are only useful if the current distributions set up are significantly disturbed by the defects present. Such methods may not be sensitive enough to elongated defects well centered in the wire. There are alternative techniques which can be investigated such as using a magnetic knife [6], or using a second magnet in the system to force currents to close transversely under a sensor array. We believe establishing 2D quality criteria will be essential for manufacturing high quality Roebel cable and expect it will be critical when striating conductors into fine filaments as a means to reduce AC loss.

3. Strand production: 5mm width strand

In this section we give results which show the performance of strands in comparison to the performance of the starting tape. The key point is that we have been able to retain the performance of the wire through the punching process over long lengths. This has also been demonstrated previously over short lengths [1-4]. The strands are punched using an automated punching machine. The machine advances the wire a fixed distance between strokes. Automated payoff and take-up reels control the tension on the strands.

These strands have $W_R = 5$ mm and $W_x = 6$ mm, and $L = 300$ mm. The strand performance is summarized in Table 1. In some cases the strand I_c is higher than the tape I_c , this may be due to the

reduced self field effect of the narrower strand, or we may have punched out on average more low quality material.

Table 1. Example performance of selected wire and 5mm strands

Sample #	Length (m)	Tape transport I_c (A/cm)	Min{Correl}	Strand transport I_c (A/cm)	Strand n -value
1	27	248	0.98	232	21.6
2	27	213	0.89	200	21.2
3	27	213	0.85	239	17.7
4*	27	265	0.94	191	25.4
5	27	263	0.9	236	27.2
6	27	329	0.88	310	33.4
7	27	215	0.9	243	25.0
8	27	322	0.9	309	30.8
9	27	363	0.94	334	19.9
10*	27	400	0.78	307	23.5

* Magnetic data for these strands is shown in figure 2

A key point when cutting long lengths is to maintain the strand registration. The cross-over in adjacent strands will begin to overlap and prevent winding if the length between any two crossovers in one strand, and the length between corresponding crossovers in the adjacent strand, exceeds the clearance between strands. With reference to figure 1 this clearance is $L_c = L_{ISG} - W_x / \sin \varphi$. For our 15/5 cable which has 6 mm width in the crossover regions this clearance between strands is 8 mm. In a cable of total length L_T there are $n = L_T/L$ transposition lengths. In the worst case, the error in length of each transposition could be $\Delta L = L_c / n$ or $\Delta L = L_c L / L_T$. For a 25 m, 15/5 cable, with $L = 300$ mm, this gives approximately $\Delta L = 0.1$ mm. As we have successfully wound 25 m cables the length registration per transposition in our process is at least this accurate. The longer the cable the more accuracy is required in this process.

4. Environmental effects on strands

When strands are punched the cross section of the conductor including the HTS layer is exposed at the edges. We have found during warming from experiments in liquid nitrogen that condensed moisture on the strands will lead to a steady degradation in the transport critical current. This is easily remedied if the strand is kept free from moisture. During experiments this means arranging for the sample to warm in dry nitrogen gas. We have done up to three cycles of measurement involving cooling in liquid nitrogen and warming to room temperature, with no degradation. Strands which have been kept dry (e.g. stored in a bag with desiccant) for up to one year have shown no degradation in properties.

5. Winding methodology

We have constructed two automatic winding machines one dedicated to winding cable with 2mm strands, the other to cable with 5mm strands. Currently the machines are operated at a production speed of about 3 m/min. To test that winding does not cause any damage we have conducted trials winding cables with a single HTS strand and the balance made of copper. The HTS strand is measured before being wound and then after being unwound from the resultant copper cable. The results from one trial are shown in Table 2. The difference in critical currents is within the uncertainties of the measurement.

Table 2. Test of winding effect on strand I_c

	Strand transport I_c	Strand n -value
Before winding into cable	123 ± 1	27 ± 1
After winding into cable	123 ± 1	28 ± 1

6. Insulation of strands

For some applications it is desirable to have insulated individual strands. We have experimented with three methods to achieve this. The first is a roll coating technique which applies a UV cured epoxy acrylate of about 20 μm thickness per pass. Thicker coatings can be built up with multiple passes. A 5/2 cable was assembled and a voltage applied across the strands. The strand-strand break down voltage (BDV) was found to be 500 V for a 50 μm coating. The tape to ground BDV is 350V for a 20 micron coating. No degradation of the coating is seen after 100 thermal cycles between room temperature and 77 K.

The second method is to extrude a coating of PTFE (copolymer of tetrafluoroethylene-hexafluoropropylene). This has been done using a standard wire coating extrusion line. The extruded coating follows the meander of the strand extremely well. The BDV of a 100 μm coating is 2 kV. The disadvantage of this technique is that it is difficult to reduce the thickness below 100 μm . The advantage is that the edge coverage is superior to that of the roll coated strand.

The third technique is to apply a layer of polyimide (KaptonTM) tape to the wire before punching and then punch with the insulating tape in place. This does not give any edge coverage but the insulation still provides a separation between strands. We have wound a 15/5 cable with copper strands covered with a 25 μm thick tape. The strand to strand insulation resistance is > 499 M Ω at 250 V. This cable was also tested when bent around a diameter of 120 mm and the insulation resistance was unchanged.

We are also experimenting with the extrusion technique to insulate the finished cable and developing a wrapping technique which will allow common insulation materials such as Kapton or Nomex paper to be used to insulate the cable.

7. AC loss characterisation

In the following, we briefly discuss the transport and magnetic ac loss characteristics of a 5/2 Roebel cable. We show that geometrical effects such as the width of the strand and cable architecture affect the magnitude of the loss. The important observation is that the loss characteristics are predominantly hysteretic in nature. The magnetic ac loss indicates the presence of a small eddy loss arising from the metallic components, but this is technologically insignificant. Both the transport and the magnetic ac loss measurement establish that coupling losses are not present in these cables.

7.1. Transport AC loss on 5/2 and 9/2 cable

We have recently reported the AC transport loss in a 5/2 cable [7]. In the Norris model [8] it is expected that N conductors which individually have transport loss Q_{t0} , have loss NQ_{t0} per conductor

when bundled together as a single conductor. We have found the averaged transport AC loss per conductor in the 5/2 Roebel cable is 2.9 times the loss in a single strand at $I_t/I_c = 0.85$ as shown in figure 4. The experimental details are reported Ref. 7. In a 9/2 cable the loss per conductor is found to be 8.0 times the loss in a single strand at $I_t/I_c = 0.80$ [9]. There is no observed frequency dependence to the loss showing that the loss is hysteretic in nature and strands are decoupled.

The transport loss depends on the shape of the conductor cross section and for a cable will depend on the detailed architecture. The transposition of the strands within a cable helps equalize the currents and averages the field experienced by each strand. The overall effect of this is to reduce loss, although more work is required to understand how the loss scales with the geometry and number of strands.

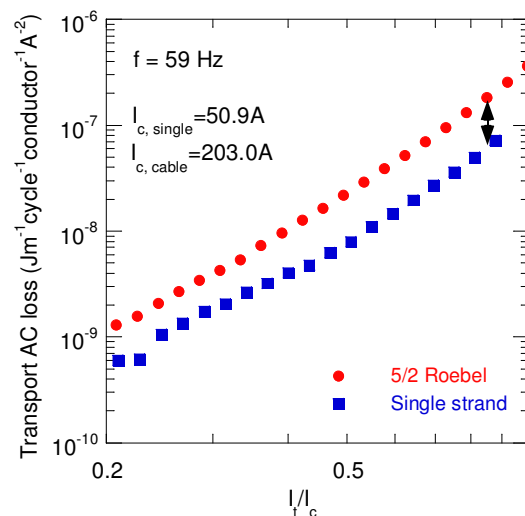


Figure 4. Comparison of normalised transport AC losses in 5/2 cable and single strand. A factor of 2.9 in loss is indicated at $I_t/I_c = 0.85$.

7.2. Magnetisation loss of 5/2 cable

The loss is measured using methods reported elsewhere [10]. Note the strands have not been insulated but the copper surface is oxidized through exposure to the laboratory atmosphere.

We show the loss per strand for a 5/2 cable in figure 5. At high fields (above the penetration field $H_c = j_c/\pi$, where j_c is sheet current density) the loss per strand is equal to the loss in a single isolated strand. At lower fields the screening effect of the HTS reduces the overall loss. We have measured at frequencies from 30Hz to 195Hz. At high fields the loss increases slightly with frequency and at moderate fields the loss decreases slightly with frequency [11]. The small frequency dependence is due to the eddy current loss in the metal components and the intrinsic frequency dependence of the magnetisation loss in the superconductor. Neither are technologically relevant. There is no inter strand coupling loss observable.

The total loss for a cable carrying transport current in an external field is usually larger than the sum of the magnetization loss and the self field transport loss. It is also not easily predicted from these measurements. We are therefore constructing a system to measure total loss for our cables to provide the needed information for engineering design.

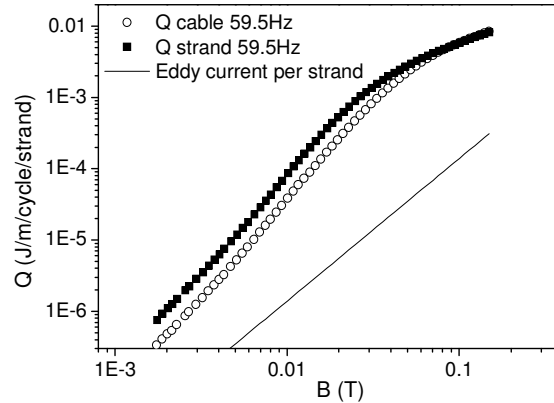


Figure 5. Magnetisation loss for a 5/2 cable and a single strand. The magnitude of the expected eddy current loss in the copper stabiliser is also shown.

8. Cable transport I_c

Cables are generally made with the HTS layers all in the same orientation. Current connections are made by soldering copper or silver foil onto the surface of the cable with a conducting path to the HTS. This usually results in variations in the contact resistance to each strand. For short cables (~ 1 m length) the $I_{\text{cable}}-V_{\text{strand}}$ characteristic is distorted as the current contact acts as a current divider. Even if the contact resistances are equal there is no unique cable I_c due to the variation in strand critical currents and n -values. We define an approximate cable I_c as the average I_c of the strands which is probably sufficient for engineering purposes. For longer cables, greater than a few meters, this problem is not significant.

Table 3 shows representative values of some recent cables and a comparison with the expected I_c . This is calculated using the scaling for self-field suggested by Goldacker et al [3]. The design I_c is the sum of the strands I_c . We discount each strand current according to the experimentally measured $I_c(B_{\text{av}})$ relation, and estimate the average field in the cable from the Biot-Savart law. The resultant scaling for a 15/5 cable at 77K is shown in figure 6.

Table 3. Measured cable I_c

Description	Length	Measured I_c	n -value	Design I_c	Expected I_c
15/5	5m	1100	38	1950	1110
5/2	0.72m	203	-	250.3	205
9/2	0.54m	309	-	427	325

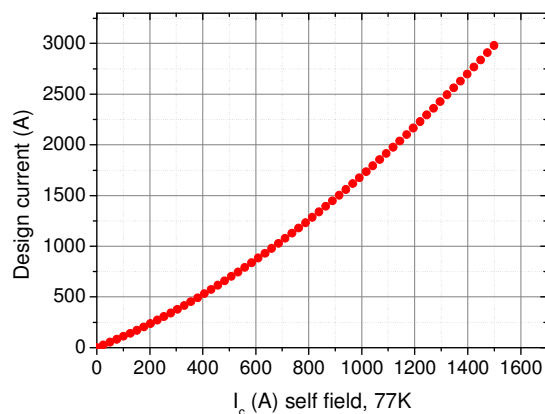


Figure 6. Scaling of design current to the expected self field I_c of a 15/5 cable at 77K.

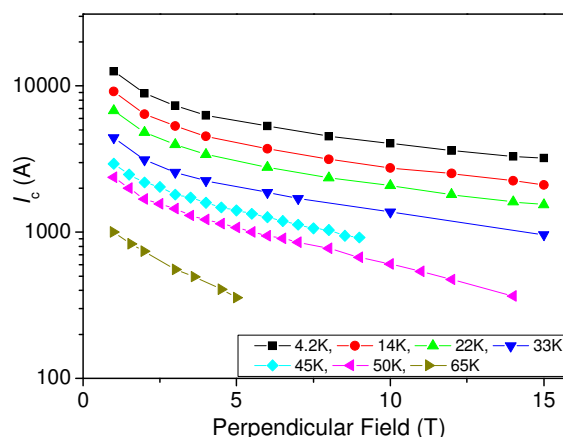


Figure 7. Design currents of a 15/5 cable at higher fields, assuming self-field of 280 A/m.

The effect of self field at 77K is somewhat dramatic. One of the value propositions of YBCO (or REBCO) is the extraordinarily good performance at higher fields and low temperatures. In figure 7 we have taken available performance data for SuperPower wire in perpendicular field [12], and shown how this scales into the performance of a 15/5 cable at higher fields and lower temperatures. Self-field performance of wire is scaled to higher fields and lower temperatures. We have assumed 280A/cm performance of wire at 77K, self field. The expected current capacity will be significantly reduced by the cable self field at fields < 1T. At high fields the expected current should be close to the design current. This figure shows it is possible to construct cables which can carry many thousands of amps in high field applications.

9. Conclusions

The use of CTC and Rutherford cable is well established in conventional electrical machines and LTS magnets respectively. We expect HTS Roebel cables to become just as well established within HTS electrical machines and magnets. We have shown that the same benefits of managing AC losses and achieving high current capacity are achievable with HTS Roebel cable. There are no significant road-blocks to manufacturing long length cables although efficient production of strands places demands on wire manufacturers for material of high 2D uniformity.

References

- [1] Long N J, Badcock R, Beck P, Mulholland M, Ross N, Staines M, Sun H, Hamilton J, Buckley R G 2008 *Journal of Physics: Conference Series* **97** 012280
- [2] Badcock R A, Long N J, Mulholland M, Hellmann S, Wright A, and. Hamilton K A 2009 *IEEE Trans. in Appl. Supercond.* **19** 3 3244
- [3] Goldacker W, Frank A, Kudymow A, Heller R, Kling A, Terzieva S and Schmidt C 2009 *Supercond. Sci. Technol.* **22** 034003
- [4] Lee J K, Park M J, Lee S W, Kim W S, Park C, Lee H, Park S H, Hwang Y I, Byun S B and Choi K 2008 *Physica C* **468** 1727–30
- [5] www.theva.com
- [6] ten Haken B, van Eck H J N and ten Kate H H J 2000 *Physica C* **334** 163
- [7] Jiang Z, Staines M, Badcock R, Long N and Amemiya N 2009 *Supercond. Sci. Technol.* **22** 095002

- [8] Norris W T 1970 *J. Phys. D: Appl. Phys.* **3** 489
- [9] Jiang Z et al, to be published elsewhere
- [10] Lakshmi S, Thakur K P, Staines M, Badcock R, Long N J 2009 *IEEE Trans. in Appl. Supercond.* **19** 3 3361
- [11] Lakshmi et al, to be published elsewhere
- [12] Data courtesy of SuperPower, Inc. 450 Duane Ave. Schenectady, NY 12304 USA, <http://www.superpower-inc.com>