Fabrication, Qualification and Test of High $I_c$ Roebel YBa$_2$Cu$_3$O$_{7-\delta}$ Coated Conductor Cable for HEP magnets

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Abstract — The Roebel concept allows for the cabling of high $I_c$ YBa$_2$Cu$_3$O$_{7-\delta}$ CC tapes which are commercially available in reasonable lengths. This approach to cable design leads to several technological improvements for the manufacture of the next generation of high field magnets. For instance, a reduction in inductance is a key point for the protection of HTS coils generating fields in the range of 40-50 T, such as those needed for the last stage of the cooling channel of a Muon Collider. Here we describe the measurement of the current density uniformity of YBCO coated conductors at 77 K, the manufacture of Roebel cables from these coated conductors at IRL and the measurement of the critical current of the assembled cable in liquid nitrogen. The results compare favorably to the $I_c$ of single tapes, permitting an estimation of the cable $I_c$ at 4.2 K.

Index Terms— 2G HTS YBCO tapes, Roebel cable, critical current 2D homogeneity.

I. INTRODUCTION

The final stage of muon cooling [1-5] in a Muon Collider calls for solenoids generating magnetic fields in the range of 40-50 T. The conceptual design of the new machine relies on the use of high temperature superconductors (HTS) for mainly because of their high irreversibility fields.

Currently, only two high temperature superconductors show the $I_c$ potential for application in the required field range: YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) and Bi$_2$Sr$_2$CaCu$_2$O$_x$ (Bi2212). Bi2212 wires have a round cross section and thus can be formed into Rutherford cables with the same approach used with Nb$_3$Sn and NbTi wires [6]. The technology involved in cabling Bi2212 is currently investigated at Fermilab [7].

Although the Bi2212 conductor doesn’t show anisotropic effects with respect to field orientation, it requires a very precise heat treatment in pure Oxygen after which it becomes extremely brittle and therefore highly strain sensitive. On the other hand, YBCO shows better mechanical properties [7], doesn’t need reaction, but its highly anisotropic behavior needs to be accounted for in magnet design. Nevertheless, the engineering current density $J_c$ of YBCO tapes in unfavorable field direction is still comparable with state of the art Bi2212 wires. YBCO conductors are presently only manufactured as thin tapes, which requires a new approach to cable manufacturing. In the following, the Roebel cabling concept is presented, criteria for tape quality and selection are discussed and test results are presented.

II. CABLE FABRICATION PROCESS

The Roebel cable fabrication entails cutting YBCO tapes into a serpentine shaped conductor that can be used to wind the final cable. This is achieved by mechanically punching the virgin YBCO tape into the desired shape (Fig. 1) which is then fed into an automated winding machine. Any approach based on laser cutting cannot be followed because of the risk of heating the conductor to temperatures above 250° C which might cause degradation.

The conductor chosen for the cable presented in this paper is a commercially available YBa$_2$Cu$_3$O$_{7-\delta}$ tape manufactured by SuperPower. It has a width of 12 mm, an YBCO layer thickness of 1 µm on top of a 50 µm thick Hastelloy substrate and it is completed with two 20 µm layers of copper for electrical stabilization. The details of the conductor are summarized in Table I, while the geometry of the Roebel cable is shown in Fig.2.
Although several cable geometries can be achieved at IRL [9][10], the geometry chosen for this particular cable is a “15/5”, which requires scaling the tape width from the original 12 mm down to 5 mm and using a total of 15 tapes per cable.

Fig. 2. Schematic of Roebel cable and its main geometrical parameters.

Fig. 2 shows a schematic of the cable geometry, whereas in Table II the full set of geometrical parameters for the 15/5 configuration is summarized.

III. QUALIFICATION OF 2G YBCO TAPES FOR CABLEING

Since the process requires reducing the width of the conductor to less than half of its original nominal value, it is extremely important that \( J_c \) is uniform over the entire width and length of the original conductor. One way to address this problem is to measure the field penetration along the width of the tape using several Hall sensors [11] and correlate the obtained curve to the expected field distribution which can be computed via finite element analysis. The correlation factor between measured \( (B_m(x_i)) \) and expected field profile \( (B_e(x_i)) \) was calculated with Eq. 1, where \( x_i \) are the measuring locations across the tape width (at a given longitudinal position). An array of Hall sensors picked up the magnetic field normal to the tape surface at 77 K in a homogeneous applied field in the same direction.

\[
\text{Corr}(B_m, B_e) = \frac{\sum (B_m(x_i) - \bar{B}_m) \cdot (B_e(x_i) - \bar{B}_e)}{\sqrt{\sum (B_m(x_i) - \bar{B}_m)^2} \cdot \sqrt{\sum (B_e(x_i) - \bar{B}_e)^2}} \quad \text{(Eq. 1)}
\]

In Fig. 3 two field profiles are shown. The first one shows an example of a defect-free cross section, resulting in a very high correlation factor. The second one shows some evident divergence from the expected triangle-shaped penetration curve, especially on the right side of the cross-section, resulting in a much lower correlation factor.

For this particular cable, two 50-meter spools were used (called in the following Spool A and Spool B). Measured average critical current and \( n \) values for each spool are summarized in Table III.

The correlation factor, plotted for the whole lengths of available conductors in Figs. 4 and 5, was used to select sections suitable for cabling.
Fig. 5. Correlation between magnetic field penetration data and theoretical model as measured on 50 meters of 12 mm wide YBCO tape (Spool B).

IV. PUNCHED TAPES AND CABLE TESTS

After punching the 15 strands and before proceeding with the actual cabling, the critical current of every single strand was measured at liquid nitrogen temperature in self field. Table IV shows a summary of all measurements, Fig. 6 the complete E-I curves.

<table>
<thead>
<tr>
<th>STRAND# (POOL)</th>
<th>I_c</th>
<th>n</th>
<th>STRAND# (POOL)</th>
<th>I_c</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tape #1 (A)</td>
<td>105.1</td>
<td>32.6</td>
<td>Tape #9 (A)</td>
<td>103.8</td>
<td>34.5</td>
</tr>
<tr>
<td>Tape #2 (A)</td>
<td>103.9</td>
<td>43.7</td>
<td>Tape #10 (A)</td>
<td>105</td>
<td>30.7</td>
</tr>
<tr>
<td>Tape #3 (A)</td>
<td>106.5</td>
<td>34.9</td>
<td>Tape #11 (A)</td>
<td>106.6</td>
<td>33.3</td>
</tr>
<tr>
<td>Tape #4 (A)</td>
<td>108.6</td>
<td>36.1</td>
<td>Tape #12 (A)</td>
<td>105.6</td>
<td>30.1</td>
</tr>
<tr>
<td>Tape #5 (A)</td>
<td>107.4</td>
<td>39.9</td>
<td>Tape #13 (B)</td>
<td>116.6</td>
<td>n/a</td>
</tr>
<tr>
<td>Tape #6 (A)</td>
<td>105.2</td>
<td>34.4</td>
<td>Tape #14 (B)</td>
<td>113.2</td>
<td>n/a</td>
</tr>
<tr>
<td>Tape #7 (A)</td>
<td>104</td>
<td>34.7</td>
<td>Tape #15 (B)</td>
<td>120.7</td>
<td>n/a</td>
</tr>
<tr>
<td>Tape #8 (A)</td>
<td>104.3</td>
<td>32.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Critical current values obtained from punched strands are compatible with the expected scaled values from Table II.

Fig. 6. E-I curves for each punched tape used in the cabling process.

To ensure that no local damage occurred while punching the tapes, several tests have been run on short samples monitoring the voltage across 5 mm of straight section and cross-over section as shown in Fig. 7. \( I_c \) and \( n \) values agree closely.

After testing every single tape individually, an automated winding machine, developed at IRL, assembled the cable. No inter-strand insulation was included for this cable. The completed 3.25 m long cable was wound on a G-10 support and the ends soldered to copper leads as shown in Fig. 8.

Fig. 7. Schematics of voltage taps \( I_c \) measurements on straight and cross-over sections.

Fig. 8. The IRL test setup to measure the critical current in the entire 3.25 m long cable.

The cable was equipped with a total of two pairs of voltage tap pairs. The first one was used to monitor the voltage on the same tape (#5) along the length of the cable covering 2.39 meters of cable, whereas the second one was mounted across two different tapes (#1 and #12) covering 2.61 meters of cable. E-I curves for both taps are shown in Fig. 9. Voltage signals from both channels agree closely.

Table V shows the critical currents and \( n \) values evaluated at 1 \( \mu V/cm \).

Fig. 9. E-I curves for the whole Roebel cable measured at 77 K under self field conditions. Voltage taps along the same tape and on two different tapes agree closely.
TABLE V ROEBEL CABLE TEST RESULTS

<table>
<thead>
<tr>
<th>TAPS ID</th>
<th>DISTANCE</th>
<th>$I_c$</th>
<th>N</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taps #1</td>
<td>2.39 m</td>
<td>1010</td>
<td>28</td>
<td>Voltage taps along strand #5</td>
</tr>
<tr>
<td>Taps #2</td>
<td>2.61 m</td>
<td>1009</td>
<td>28</td>
<td>Voltage taps across strand #1 and #12</td>
</tr>
</tbody>
</table>

The approximately 40% decrease from the sum of the strands’ critical currents to the actually measured $I_c$ of the cable is compatible with the expected reduction caused by the computed self field at this current [12].

V. LOW TEMPERATURE PERFORMANCE ESTIMATION

Although it is very useful to assess Roebel cable performance at nitrogen temperature, high field magnets for HEP application will most likely need to be operated at liquid helium temperature to achieve maximum $J_c$ in the conductor. For a first approximation, Fermilab data [13][14] up to 28 T have been used to estimate design current levels for 15/5 Roebel cables at 4.2 K. The nominal design values plotted in Fig. 10 have been obtained by multiplying short-sample critical current values by the number of strands in the Roebel cable and assuming a linear scaling of the critical current with the width of the tape.

Fig.10. Nominal design current values for a 15/5 Roebel cable in liquid helium under parallel and perpendicular field.

VI. CONCLUSION

Before the assembly at IRL of SuperPower coated conductors into a 15/5 Roebel cable, the 2D $J_c$ uniformity of the entire HTS tapes was scanned and suitable tape sections were selected for cabling. $I_c$ measurements of single strands and the assembled cable in liquid nitrogen showed that the punching and cabling process did not affect the tape performance. The self-field effect explains the reduction of the cable $I_c$ relative to the sum of the strand critical currents. The critical current of the full assembled 15/5 cable will be measured using a superconducting transformer and transverse pressure tests will be run in order to start assessing the performances of the cable at 4.2 K. At this level of development, evaluating both electrical and mechanical characteristics in liquid helium is the next step to assess the viability of this cabling technique in high field/high stress applications.

REFERENCES