Fabrication and Performance of Nb_3Sn Rutherford-Type Cable With Cu Added as a Separate Component

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***Abstract*—From the standpoint of overall conductor cost, it is desirable to minimize the amount of Cu that is co-processed with the superconductor during strand fabrication. We are investigating several approaches for fabricating multistrand cables in which the Cu is added at the final, i.e., cabling, stage of manufacture. These include mixed strand Rutherford-type cables with pure Cu strands cabled together with superconductor strands that have a low volume fraction of Cu, Cu added as a core to a Rutherford-type cable, and Cu strip added to the surface of the cable. Results on fabrication of several alternate types of Nb_3Sn cables are presented. The more promising types of mixed strand and cored cables are being evaluated in short sample and small magnet tests. These results will be presented and the performance will be compared with conventional Rutherford cables where the Cu is an integral component of the superconductor strand.**

***Index Terms*—Copper added as a separate component, magnet protection, mixed strand cables, Nb_3Sn, Rutherford-type cables.**

I. Introduction

THE addition of copper as separate strands at the cabling step has been utilized in the past as a method for grading conductors, in order to provide the normal metal shunt path for magnet protection [1]–[3]. Recently, another incentive for utilizing this approach was realized as a result of conductor cost studies performed as part of the HEP Conductor Development Program [4]. The labor cost factor for wire fabrication depends directly on the volume of wire being produced. Thus, if the copper necessary for magnet protection can be added after wire fabrication is complete, wire costs will be reduced significantly.

Several alternative methods have been proposed for adding copper at the cabling stage. These include adding pure Cu strands to the cable, adding Cu as a core in the cable, or wrapping Cu strip around the finished cable. However, a number of questions must be answered before this approach is adopted for use in accelerator magnets. These include manufacturability, effectiveness in magnet protection, and overall conductor cost. These questions are being addressed, and the progress to date will be discussed.

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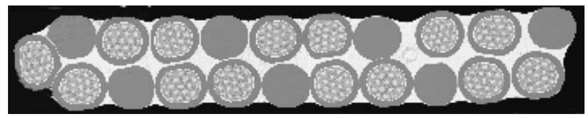

Fig. 1. Cross section of mixed strand cable with 14 superconductor strands (lighter color) and 7 pure Cu strands (darker strands). The superconductor strands contain 30% copper outside the diffusion barrier.

II. Cable Manufacturing Tests

A. Mixed Strand Cables

Two approaches to mixed strand cables are being evaluated. In the first approach, pure copper strands are substituted for superconductor strands in the Rutherford-type cable. In the second approach, pure copper strands are cabled together with fine superconductor strands in a round “first stage” cable; then, strands of this first stage cable are cabled into a Rutherford-type cable. The main difficulty in the first approach is in matching the elongation of the two types of strands which occurs during the compaction of the Rutherford cable. In an attempt to match the elongation properties of the pure Cu strands to the superconductor, a range of Cu tempers, from fully annealed to fully cold worked, were evaluated. None of these cables appeared suitable for magnet winding. An alternative approach of using slightly smaller diameter Cu wires was found to be more successful. In this approach, the pure Cu strands are nested in the cable and experience only a small amount of deformation and elongation (Fig. 1).

The other approach requires the development of fine diameter superconductor wires (typically 0.2–0.3 mm diameter). Several efforts are underway to develop cost-effective fine wires of Nb_3Sn superconductor [5], [6]. As soon as these fine wires are available, this approach will be evaluated as well. One problem that is being addressed with the small amount of fine wire available is the degree that the first level cable can be compacted. Since the overall cable compaction is the product of first stage and second stage compaction, it is important to be able to achieve a high degree of compaction in the first stage, without causing degradation in the strand J_c. An uncompacted, round cable is only about 78% dense. For this approach to be cost-effective, we believe that densities greater than 90% are necessary. This density, together with low J_c degradation, has not yet been achieved.

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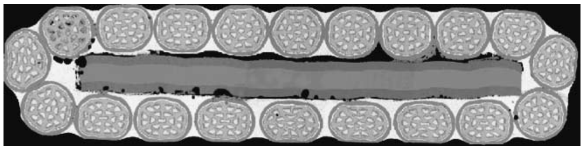

Fig. 2. Cable with core made by an assembly of a stainless steel strip (0.13 mm), a copper strip (0.25 mm) and a stainless steel strip (0.13 mm).

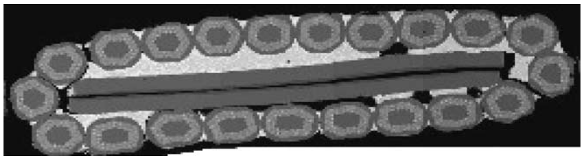

Fig. 3. Cable with core made by an assembly of a copper strip (0. 21 mm), a stainless steel strip (0.044 mm), a stainless steel strip (0.044 mm) and a copper strip (0.21 mm).

B. Cu Added as a Core

Initial tests used pure Cu and, as in the case with pure Cu strands, it was not possible to match the elongation properties of the strands and core to the extent necessary to produce an acceptable cable. However, two alternative designs are promising; both utilize a bimetallic core of copper and stainless steel (SS). The stainless steel serves two purposes, one mechanical and one electrical. It resists elongation and thus improves the mechanical stability of the cable. Also, it provides a high resistance barrier and thus increases the interstrand resistance value for the cable. The first design utilized a SS/Cu/SS bimetallic strip, and a cross section of the cable is shown in Fig. 2.

Although the cable shown in Fig. 2 is acceptable from the mechanical standpoint, a more desirable configuration from the electrical standpoint is to have the Cu component on the outside and the stainless steel component on the inside of the strip (Fig. 3). This arrangement provides a high resistance path between top and bottom strands in the cable, thus reducing eddy currents. However, it provides good coupling between adjacent strands in the cable and is thus effective for magnet protection. Long lengths (40–50 m) have been made for both types of cored cables. Since the mechanical and electrical properties of the Cu/SS/Cu cable are both superior, this version has been selected for evaluation in the small scale coil test program.

C. Cu Added as Wrapped Strip

The third option for adding copper is to wrap the completed cable with Cu strip [7]. In order to evaluate the electrical properties, short lengths of cable have been wrapped with Cu strip and the interstrand resistance measured [8]. Although this approach is satisfactory from the electrical standpoint, several mechanical property issues must be evaluated. First, a technique must be developed to wrap a long length of cable with a tight wrap. Second, the coil winding characteristics and coil impregnation must be evaluated. Finally, the electromagnetic performance in a coil must be tested.

III. Interstrand Resistance Measurements

Interstrand resistance measurements have been made on a prototype mixed strand cable, and on two types of external Cu strip wrapped cables. The complete results are reported in [8], and will be summarized here. The power losses due to field sweep were measured using a calorimetric method (helium boil-off), and compared to the losses of a baseline cable that employed a stainless steel core to reduce interstrand coupling. Compared to the baseline, both mixed strand and Cu-wrapped cables showed higher losses (lower interstrand resistance). However, the values (6.7–8.1 $\mu\Omega$) were still within the acceptable range for accelerator magnets. Also, a direct comparison was made between the mixed strand cable and a control cable made with the same type and same number of strands. The mixed strand cable has shown a lower coupling loss. To justify the measurement result a formula has been taken from the formalism of the Electrodynamics of Superconducting Rutherford Cables [9]:

$$P_c = 8.49 \cdot 10^{-3} \frac{L_{p,s} w^2 \left(N_s^2 - N_s\right)}{R_c} \dot{B}_\perp^2, \tag{1}$$

where P_c is the power loss due to a field sweep $\dot{B}_\perp$ normal to the wide surface of the cable, $L_{p,s}$ is its the half pitch length, w is its width, R_c is the crossover resistance and N_s the number of strands. This formula has been applied for comparison of the two measured cables and redefined as follows [10]:

$$P_c = 8.49 \cdot 10^{-3} \frac{L_{p,s} w^2 \left(N_{s,sc}^2 - N_{s,sc}\right)}{R_c} \dot{B}_\perp^2, \tag{2}$$

where

$$N_s = N_{s,sc} + N_{s,cu}. \tag{3}$$

The mixed strand cable has fewer *diamond* path current loops, because of the fewer superconducting strands. The density of the loops scales with the number of superconductor strands. Thus, if the losses are calculated on the basis of number of superconductor strands (14 in the mixed strand cable vs 21 in the control), the mixed strand results agree with the all superconductor strand control cable. The result of the comparison is

$$\begin{aligned} \frac{P_{c,MC}}{P_{c,TRAD}} &= \frac{\left(N_{s,sc,MC}^2 - N_{s,sc,MC}\right)}{\left(N_{s,sc,TRAD}^2 - N_{s,sc,TRAD}\right)} \\ &= \left(\frac{14^2 - 14}{21^2 - 21}\right) \\ &= 0.44. \end{aligned} \tag{4}$$

This evaluation takes into account the face-on power loss due to crossover resistance only, because it is dominating the losses due to field ramping.

Loss measurements have not yet been made for the cored cables; however, since the *diamond* path loops will be dominated by the high resistance of the stainless steel component, the losses should be comparable to the losses measured for the cable with the thin stainless steel core and are well known to be almost negligible. These losses are well in the acceptable range for accelerator magnet operation.

IV. Magnet Fabrication Results

The mixed strand cable shown in Fig. 1 has been used to wind a coil for evaluation in the Subscale Magnet Test Facility (SMTF) [11]. Such magnets are made of two 30 cm long flat racetrack coils, assembled in a common-coil configuration. Although the cable properties were acceptable immediately after cabling, the properties deteriorated with subsequent handling operations (respooling, cleaning, insulating). The tendency for strands to pop out of the cable required that the coil winding tension be reduced from 18 kg to 9 kg. Even so, it was necessary to reset popped strands occasionally during the coil winding operation. In an attempt to improve cable quality, several additional trials of mixed strand cables were made with increased compaction to help set the strands in the cable. However, as the compaction was increased, the pure Cu strands began to elongate and pop out of the cable. The only advancement in the mechanical quality has been achieved with the insertion of a SS strip as a core in the cable. This cable has been wounded in a coil and tested in the SMTF. The quality of the coil has been certainly better in this second attempt of fabrication, but the magnet performances were not satisfactory as explained in the next paragraph. From these tests, we conclude that the mixed strand cables are not yet acceptable for routine coil fabrication.

Initial tests with the copper/SS cored cables indicate that these cables have improved mechanical properties compared to the mixed strand cables. There is no tendency for popped strands, since the strands have uniform mechanical properties. Also, the core provides additional tensile strength, so that the cored cables can actually withstand higher winding tensions than the standard cables. The only limitation at this time appears to be with the "hard way" bending. The hard way bending is adequate for the flat racetrack coils being fabricated for the SMTF; however, there may be a problem with the cored cables for cosine theta type coils.

V. Magnet Test Results

The first mixed strand coil was tested in the SMTF together with a standard cable coil that had been tested previously to a current of 10 kA. Short sample tests performed on the wires used in this mixed strand cable predicted a magnet current of 9.5 kA at the short sample limit. The first training quench occurred at 3.8 kA. In subsequent ramps, the magnet quench current remained at roughly this level. The current ramp rate was increased from 0.1 A/s to 200 A/s with little change in the quench current. The lack of dependence of the quench current suggested some study and, eventually, a complete inspection of the coil. Analysis of the quench locations indicated that 9 out of a total 10 quenches originated in the mixed strand coil. It was not possible to identify the exact location of these quenches, since the coil was not equipped with multiple voltage taps. However, quench velocities could be measured, and were found to be relatively low. This suggests that the origin of these quenches is a relatively small section of cable, surrounded by undamaged cable with a high current margin.

A full evaluation of the mixed strand cable has not been possible in this degraded coil, so another coil has been wound and tested. The results have been more promising than for the first magnet, but not satisfying if the considerable efforts for the cable design and fabrication are taken into account. In summary the cable had a poor mechanical quality and allowed a diffused epoxy impregnation cracking. The continuation of the studies will therefore move to the option of adding the copper as a core, and delays the study on mixed strand cables to magnet technologies where high field ramp rate is needed.

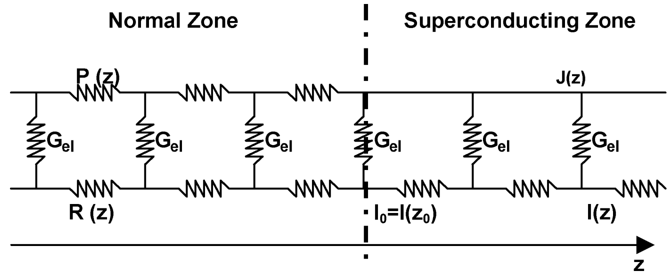

Fig. 4. Simplified version of the resistor network used for computer simulations [13]. The border between the normal and the superconducting regions is at z_0. In the SC region right of z_0 the resistance of the SC strands (P) equals zero, while the resistance of the Cu strands is constant for all temperatures below about 20 K, which is larger than T_c.

VI. Quench Propagation Velocity

A. Current Redistribution Between Added Cu and Sc

Fig. 4 shows the resistor network used as a model to study the current redistribution in cables with Cu added as a separate component [12]. Electrical current can flow from strands with superconductor to the pure Cu elements across the conductors G_{el}, which corresponds to the contact conductance per unit length between these elements. The resistance per unit length of the superconducting (SC) strands is P and the one of the Cu elements R. Both are in principle temperature dependent. In the continuous limit Kirchhoff's laws for the resistor network reduce to the differential equation for the current $I(z)$ in the copper elements

$$(P+R)\cdot I - \frac{1}{G_{el}}\frac{d^2 I}{dz^2} = R\cdot I_{tot} \tag{5}$$

where $I_{tot} = I + J$ is the total current in the cable and I the current in the copper elements. For $I_0 = I(z_0)$ and an infinitely long cable the solution of the differential (5) is

$$I = I_0 e^{-\frac{z}{\lambda}} \quad \text{with} \quad \lambda^{-2} = G_{el}\cdot R, \tag{6}$$

λ is the characteristic length over which, in the SC zone, the current flows from the Cu elements into the SC strands. Exploiting (6) leads to

$$\lambda \propto \sqrt{A_{cu}\cdot \frac{RRR_{cu}}{G_{el}}} \tag{7}$$

where A_{cu} is the added Cu cross section and RRR_{cu} is the purity of the added Cu.

B. Summary of Simulation Results

The thermo-electric model adopted to simulate the quench propagation in a cable made of SC strands and Cu elements is discussed in detail in [13]. Heating created by current in the Cu elements in the SC zone (i.e., where $T < T_c$ and $z > z_0$) enhances significantly the quench propagation velocity, v_q. Fig. 5 shows simulated v_q for a traditional cable constituted only of SC strands and for a cable with the same amount of Cu (4.48 mm^2

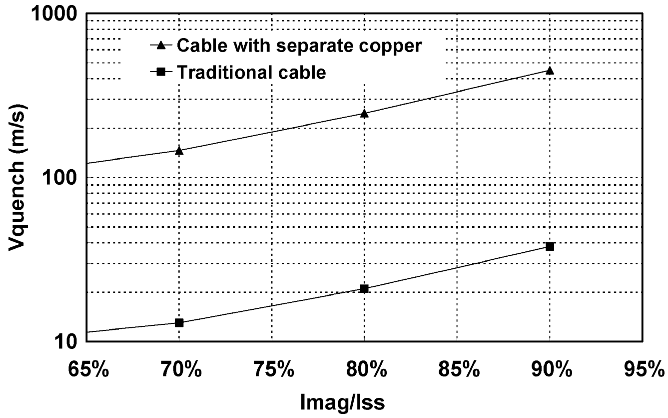

Fig. 5. Simulated quench propagation velocities for conventional cables and for cables with separate copper elements with the same amount of copper and Nb_3Sn. The simulation has been performed for a helium bath temperature of 4.2 K and a transfer function of 1 T/kA. The current (Imag) is normalized with respect to the short sample level (Iss).

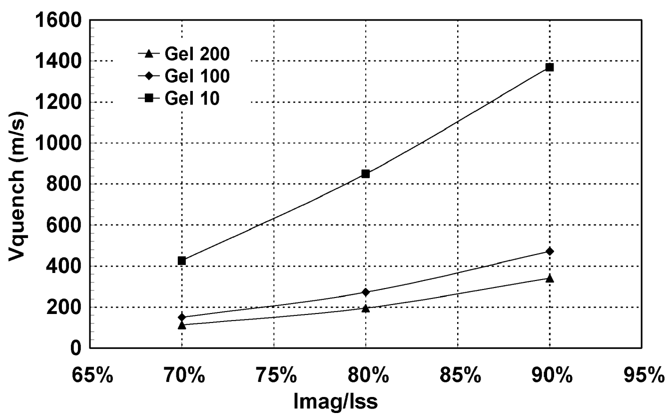

Fig. 6. Simulated quench propagation velocities for three values of G_{el} (kS/m).

cross section) and Nb_3Sn (3.23 mm^2 cross section) but with a fraction of Cu (2.32 mm^2 cross section) added as a separate component and a G_{el} of 100 kS/m.

The simulation results show also that v_q strongly depends on G_{el}. A higher conductance G_{el} leads to a lower velocity (Fig. 6), in agreement with result (7): the longer the length λ for current redistribution, the higher v_q.

C. Advantages of the RRR of the Added Copper

The resistance at low temperatures is an important parameter in view of magnet protection and conductor stability. The proposition of a fraction of the copper added as a separate component at the cabling stage allows more flexible designs. Normally the heat treatment of the Nb_3Sn is a cause of an impure copper stabilizer, thus increasing the resistivity of the strands. This separately added copper is not affected by RRR changes during the superconductor formation and this represents a further degree of freedom in the cable design. Higher RRR may reduce the maximal temperature reached by the superconductor during a quench and it increases also the redistribution length λ which implies higher v_q.

Also, a high RRR, thus a low thermal resistivity at low temperatures, enhances the capability of the cable to dissipate the energy coming from coil motions, epoxy cracking, and beam-related losses.

VII. Conclusion

Several alternative methods for adding Cu to a Rutherford-type superconducting cable have been investigated. This approach may have some cost advantages and some protection advantages related to quench propagation velocity, and a good performance in actual magnet coils. Tests are foreseen in the near future and a more detailed model is being developed.

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References

[1] R. M. Scanlan and W. A. Fietz, "Multifilamentary Nb_3Sn for superconducting generator applications," *IEEE Trans. Magnetics*, vol. MAG-11, pp. 287–290, 1975.

[2] E. Acerbi *et al.*, "The 18 tesla-100 mm 4.2 K free bore solenoid for LASA-milan," *IEEE Trans. Magnetics*, vol. MAG-28, pp. 482–485, 1992.

[3] O. R. Christianson *et al.*, "Stability in the ventilated, cabled superconductor proposed for the navy SMES cable test apparatus," *IEEE Trans. Appl. Supercond.*, vol. 7, no. 2, pp. 946–949, June 1997.

[4] R. M. Scanlan *et al.*, "Development of cost-effective Nb_3Sn conductors for the next generation hadron colliders," *Advances in Cryogenic Engineering (Materials)*, vol. 48B, pp. 949–957, 2001.

[5] B. A. Zeitlin *et al.*, "Continued progress on a low cost high current density mono element internal tin conductor with integral barriers incorporating Ti and Zr additions in the Nb_3Sn," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 3482–3485, June 2003.

[6] S. Pourrahimi *et al.*, "Fabrication and performance of multifilamentary Nb_3Sn wires by the cable-in-tube approach," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 3478–3481, June 2003.

[7] T. Collings, private communication, November 2001.

[8] M. D. Sumption *et al.*, "AC loss of Nb_3Sn-based rutherford cables with internally and externally added Cu," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 2376–2379, June 2003.

[9] A. Verweij, "Electrodynamics of Superconducting Cables in Accelerator Magnets," Ph.D. thesis, University of Twente, Enschede, Holland, 1995.

[10] M. Coccoli, "Design and Measurements of Superconducting Cables and Subscale Magnets for Future High Energy and High Intensity Beam Accelerators," Master's thesis, University of Milan, Italy, 2003.

[11] R. Hafalia *et al.*, "An approach for faster high field magnet technology development," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 1258–1261, June 2003.

[12] R. Herzog, M. Calvi, F. Sonnemann, and J. M. Pelegrin, "Quench propagation in superconducting 6 kA flexible busbars of LHC," in *Proceeding of CEC/ICMC*, Madison, Wisconsin, USA, 2001.

[13] L. Thevenod and M. Calvi, Modeling Quench Phenomenon in LHC Superconducting Dipole Magnets, Grenoble, France, 2003.