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Influence of Compaction During Reaction Heat Treatment on the Interstrand Contact Resistances of Nb₃Sn Rutherford Cables for Accelerator Magnets

E.W. Collings, M.D. Sumption, M. Majoros, X. Wang, D.R. Dietderich, K. Yagotyntsev, and A. Nijhuis

Abstract—The high field superconducting magnets required for ongoing and planned upgrades to the large hadron collider (LHC) will be wound with Nb₃Sn Rutherford cables for which reason studies of Nb₃Sn strand, cable, and magnet properties will continue to be needed. Of particular importance is field quality. The amplitudes of multipoles in the bore fields of dipole and quadrupole magnets, induced by ramp-rate-dependent coupling currents, are under the control of the interstrand contact resistances—crossing-strand, Rₓ, adjacent strand, Rᵧ, or a combination of them, Rₓᵧ. Although two decades ago it was argued that for the LHC Rₓ should be in the range 10 - 30 μΩ more recent measurements of LHC quadrupoles have revealed Rₓ values ranging from 95 μΩ to 230 μΩ. The present paper discusses ways in which these values can be achieved. In a heavily compacted cable Rₓᵧ can be tuned to some predictable value by varying the width of an included stainless steel (effectively “insulating”) core. But cables are no longer heavily compacted with the result that the crossing strands of the impregnated cable are separated by a thick epoxy layer which behaves like an insulating core. If a stainless steel core is actually present Rₓᵧ must be independent of core width. Since there is no guarantee that a fixed pre-determined amount of interlayer separation could be reproduced from winding to winding it would be advisable to include a full width core.

Index Terms—Nb₃Sn accelerator magnets, Nb₃Sn Rutherford cables, Nb₃Sn strands, interstrand contact resistance.

I. INTRODUCTION

Rutherford cables wound with Nb₃Sn strands will be used in all the high field superconducting magnets required for ongoing and planned upgrades to the large hadron collider (LHC): the high luminosity LHC (High Lumi LHC, HL-LHC, 11 and 12 T), a higher energy LHC (HE-LHC, 16 T), and a very high energy future circular collider (FCC, 16 T) [1]. The HL-LHC upgrade project [2] will involve four pairs of Nb₃Sn-wound quadrupoles with peak coil fields of 12 T [2] along with several 11 T 11 m long Nb₃Sn dipoles [3]. A suggested HE-LHC will consist of a ring of about 1280 14 m long 16 T Nb₃Sn dipoles housed in the existing LHC tunnel [4]. The proposed FCC is estimated to require 4578 15 m long 16 T Nb₃Sn dipoles [5] housed in a new 1000 km circumference tunnel. Accordingly a 16 T Nb₃Sn dipole will be developed to satisfy the requirements of both the FCC and the HE-LHC. In contributing to that development, the US Magnet Development Program will be exploring the limits of applicability of Nb₃Sn for high field magnets [6]. Studies of Nb₃Sn cable and strand properties will continue to be needed. Reported elsewhere are the effects of core type, placement, and width and heat treatment condition on interstrand coupling properties of Nb₃Sn cables [7][8][9]. Magnetization due to ramp-rate-dependent interstrand coupling currents in cables induces multipoles in the bore fields of dipole and quadrupole magnets [10][11]. As a contribution to this topic, and indirectly to the US LHC Accelerator Research Program (LARP), we report on the influence of reaction heat treatment conditions on the interstrand contact resistances of Nb₃Sn Rutherford cables.

II. EXPERIMENTAL

A. Preparation of Cables for Measurement

Several meters of stainless steel cored HQ- and QXF-type Nb₃Sn Rutherford cables, wound at the Lawrence Berkeley National Laboratory (LBNL), were provided to Ohio State University’s Center for Superconducting and Magnetic Materials (OSU-CSMM). Strand and cable details are given in Table I, Table II, and reference [8]. In preparation for measurement cable samples were cut to length (50 cm) insulated, reaction heat treated (RHT) and epoxy impregnated. Two different procedures were applied: (1) Two stacks of HQ cable were uniaxially compressed to 20 MPa at CSMM in a bolt down fixture [2] along with several 11 T 11 m long Nb₃Sn dipoles [3]. A suggested HE-LHC will consist of a ring of about 1280 14 m long 16 T Nb₃Sn dipoles housed in the existing LHC tunnel [4]. The proposed FCC is estimated to require 4578 15 m long 16 T Nb₃Sn dipoles [5] housed in a new 1000 km circumference tunnel. Accordingly a 16 T Nb₃Sn dipole will be developed to satisfy the requirements of both the FCC and the HE-LHC. In contributing to that development, the US Magnet Development Program will be exploring the limits of applicability of Nb₃Sn for high field magnets [6]. Studies of Nb₃Sn cable and strand properties will continue to be needed. Reported elsewhere are the effects of core type, placement, and width and heat treatment condition on interstrand coupling properties of Nb₃Sn cables [7][8][9]. Magnetization due to ramp-rate-dependent interstrand coupling currents in cables induces multipoles in the bore fields of dipole and quadrupole magnets [10][11]. As a contribution to this topic, and indirectly to the US LHC Accelerator Research Program (LARP), we report on the influence of reaction heat treatment conditions on the interstrand contact resistances of Nb₃Sn Rutherford cables.

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let it freely expand 1.5% in width and 4.5% in thickness. The final impregnation also took place under zero applied pressure.

Figure 1 illustrates the pronounced effect of uniaxial pressure on the compaction of the cable stack during reaction and epoxy impregnation. As a result of compaction the upper and lower cable layers are tightly squeezed together; in the absence of compaction they can become widely separated. This can modify the strand packing density from the as manufactured cable packing factor of Table II.

### TABLE I STRAND DETAILS

<table>
<thead>
<tr>
<th>Cable type</th>
<th>HQ</th>
<th>QXF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand source, type</td>
<td>OST-RRP, 108/127</td>
<td>OST-RRP, 108/127</td>
</tr>
<tr>
<td>Strand diam, d, mm</td>
<td>0.778</td>
<td>0.852</td>
</tr>
<tr>
<td>SC filament count</td>
<td>108</td>
<td>108</td>
</tr>
<tr>
<td>Filament OD, d_s, μm</td>
<td>51.5</td>
<td>62.2</td>
</tr>
<tr>
<td>Eff. fil. OD, d_eff, μm</td>
<td>61.8</td>
<td>72.4</td>
</tr>
</tbody>
</table>

**B. Measurement of Interstrand Contact Resistance**

The interstrand contact resistances (ICR) were derived from the results of AC loss measurement using equipment located in the Energy, Materials, and Systems Laboratory of the University of Twente. The cable stacks to be measured were exposed to transverse AC fields of amplitude $B_{ac} = 400$ mT and frequencies, $f$, of up to 60 mHz applied perpendicular to the broad faces of the cables (the “face-on, FO, orientation). Total loss, $Q$, could be measured both by He-boil-off calorimetry [8] and pick-up coil magnetometry. The calorimeter was calibrated against ohmic loss of a 25 Ω resistor; the magnetometer was calibrated against the calorimetric loss of cable stack H2 near its maximum $Q(f)$. The results of the magnetic loss measurements are presented in Figure 2.

III. DATA ANALYSIS

**A. $R_{eff}$ versus Core-Coverage, W, from the Magnetic $Q(f)$ or $Q_{coup}(f)$ Data**

The total energy dissipated per cycle of a cable exposed to a face-on (FO) alternating field is $Q = Q_h + Q_{coup}$ where $Q_h$ is the strand-based persistent current (“hysteresis”) loss and $Q_{coup}$ is the interstrand coupling loss. As explained in [8] the coupling loss per cycle per m$^3$ of cable (width, $w$, thickness, $t$, strand count, $N$, transposition pitch, $2L_p$) exposed to an FO field linearly ramping at a rate $dB/dt$ is given by:

$$Q_{coup(FO)} = \left(\frac{4}{3}\left(\frac{w}{t}\right)\right) L_p B_m \left(\frac{N}{20}\right) - \frac{1}{R_c} + \frac{20}{N^2 R_a} \left(\frac{dB}{dt}\right)$$

where $R_c$ and $R_a$ are the cable’s crossover and adjacent ICRs.

Then after transforming $dB/dt$ to a sinusoidal frequency, $f$, according to $(dB/dt) = (\pi^2 f)B_{ac}$, as explained in [12] we find:

### TABLE II CABLE DETAILS

<table>
<thead>
<tr>
<th>LBNL name</th>
<th>*</th>
<th>HQ1020ZB</th>
<th>HQ1021ZB</th>
<th>QXF 1055z-C</th>
<th>QXF 1055z-K</th>
<th>QXF 1055z-Q</th>
<th>QXF 1055z-O</th>
<th>QXF 1055z-M</th>
<th>QXF 1055z-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSU name</td>
<td>H1</td>
<td>H2</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q5</td>
<td>Q6</td>
<td></td>
</tr>
<tr>
<td>Strand count, %</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Core width, mm</td>
<td>0</td>
<td>8</td>
<td>--</td>
<td>11.9</td>
<td>15.9</td>
<td>15.4</td>
<td>14.3</td>
<td>13.3</td>
<td>0</td>
</tr>
<tr>
<td>Core cover, W, %</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>72</td>
<td>96</td>
<td>93</td>
<td>86</td>
<td>80</td>
<td>0</td>
</tr>
</tbody>
</table>

* Mixture of 1020 and 1021 with cores extracted. ** This is the initial packing factor at the time of cable manufacture.
A. \( R_{\text{eff}} \) versus \( W \) for Compacted HQ-Type Cables

Since 2008 this group has conducted about 17 AC-loss-based ICR measurements of uncored and cored Nb:Sn Rutherford cables that had been compacted to 20 MPa uniaxial pressure before and during RHT [7]. As a result of crossover interstrand sintering the uncored cables exhibited an average \( R_{\text{eff}} \) of 0.26 \( \mu \Omega \). Then as \( W \) increased from 32\% to 90\% (full width) \( R_{\text{eff}} \) increased monotonically up to 246 \( \mu \Omega \) [7], Figure 3. As expected the data for H1 and H2 are members of this group. Figure 3 also shows the CUDI\( ^0 \)-modelled \( R_{\text{eff}} \). Selected as inputs to the model are \( R_{\text{c}} = 0.26 \mu \Omega \) and \( R_{a} = 0.2 \mu \Omega \) (following [14] wherein it was recommended that \( R_{a} \) should be small but not less than 0.2 \( \mu \Omega \)) and the core is assumed to be centered. Many of the experimental points lie below the model curve indicating that for those cables the cores were biased to one edge [7].

B. CUDI\( ^0 \)-Calculated Plots of \( R_{\text{eff}} \) versus Core-Coverage, \( W \)

An expression for coupling power, \( P_{\text{coup}} = Q_{\text{coup}} f \), starts with Eqn (1), substitutes \( f = \frac{1}{R_{\text{eff}}} + \frac{20}{(N^2 R_{a})} \) [12], and takes the form

\[
P_{\text{coup}} = \left( \frac{4}{30 \pi^2} \right) \frac{w}{f} L_p B_m^2 N^2 \left( \frac{1}{1} \frac{1}{R_{\text{eff}}} \right) f
\]

The fortran program CUDI\( ^0 \) [13] enables \( P_{\text{coup}} \) to be calculated as function of \( W \) for a set of Rutherford cables with insulating cores of various widths and positions within the cable. Then as explained elsewhere [7][8] Eqn (4) enables the conversion of the CUDI\( ^0 \)-calculated \( P_{\text{coup}} \) to an \( R_{\text{eff}} \) which leads to calculated plots of \( R_{\text{eff}} \) versus \( W \).

IV. RESULTS

A. \( R_{\text{eff}} \) versus \( W \) for Compacted HQ-Type Cables

Since 2008 this group has conducted about 17 AC-loss-based ICR measurements of uncored and cored Nb:Sn Rutherford cables that had been compacted to 20 MPa uniaxial pressure before and during RHT [7]. As a result of crossover interstrand sintering the uncored cables exhibited an average \( R_{\text{eff}} \) of 0.26 \( \mu \Omega \). Then as \( W \) increased from 32\% to 90\% (full width) \( R_{\text{eff}} \) increased monotonically up to 246 \( \mu \Omega \) [7], Figure 3. As expected the data for H1 and H2 are members of this group. Figure 3 also shows the CUDI\( ^0 \)-modelled \( R_{\text{eff}} \). Selected as inputs to the model are \( R_{\text{c}} = 0.26 \mu \Omega \) and \( R_{a} = 0.2 \mu \Omega \) (following [14] wherein it was recommended that \( R_{a} \) should be small but not less than 0.2 \( \mu \Omega \)) and the core is assumed to be centered. Many of the experimental points lie below the model curve indicating that for those cables the cores were biased to one edge [7].
Presented here. The compacted cable needs a full width core, be agreed that for the LHC w/t w/td, heat measurements of LHC dipoles reveal a value of $R_c$ needed would be 160x20 = 3200 μΩ a value consistent with the results presented here. The compacted cable needs a full core to remove $R_c$ from the equation. Since in the uncompacted case the screening strands are separated by a thick epoxy layer, $R_{eff}$ is essentially “infinite” whether the core is present or not; i.e. $R_{eff}$ is independent of core width as illustrated in Figure 4. Since there is no guarantee that such a condition could be reproduced from winding to winding it would be advisable to include a full width core.

V. DISCUSSION

The true index of field error is the coupling magnetization, $M_{coup}$, which based on Eqn. (1) is given in general by

$$M_{coup} = \left( \frac{1}{60} \right) \left( \frac{w}{t} \right) L_p N^2 \left[ \frac{1}{R_c} + \frac{20}{N^3 R_s} \right] dB/dt$$

Large values of $R_c$ clearly favour small $M_{coup}$ but in the interests of current sharing and stability some compromises have been sought. Some two decades ago it was agreed that for the LHC $R_c$ should be in the range $15 \pm 5$ μΩ [15] or $20 \pm 10$ μΩ [16]. The prefactor $N^3$ allows $R_c$ itself to be small although it was recommended to be no smaller than 0.2 μΩ [14]. As pointed out recently [8] with reference to [7] and [17] numerous measurements of LHC dipoles and quadrupoles have revealed $R_c$ values very much larger than the 20 μΩ “target”. Measurements of dipoles yielded $R_c$ s well above 50 μΩ and measurements of quadrupoles using various techniques yielded $R_c$ s ranging from 95 μΩ to 230 μΩ for an approximate average value (based on [7]) of 160 μΩ.

When translating these results into other cables it must be recognized that $M_{coup}$ is proportional not just to $1/R_c$ but also to the other cable design parameters ($w/t, L_p$, and $N^2$). So to preserve the same $M_{coup}$ when replacing an LHC-inner cable with design parameters 7.94, 55 mm, and 282 with an uncored QXF-type cable, Eqn (6), with parameters 10.1, 54.5 mm, and 402 would require $R_{eff}$ (or $R_c$) to be increased by a factor 2.6.

$$M_{coup,core} = \left( \frac{1}{60} \right) \left( \frac{w}{t} \right) L_p N^2 \left[ \frac{1}{R_c} + \frac{20}{N^3 R_s} \right] dB/dt$$

For the uncored cable Eqn (6) shows $M_{coup,core}$ to be proportional to $1/R_c$. The introduction of a fully insulating core reduces the proportionality to $20/(N^2 R_c)$, Eqn (7). So not only is $M_{coup,core}$ reduced by a huge factor, further decreases would accompany increases in $N$.

Measurements of LHC quadrupoles have revealed $R_c$ values around 160 μΩ which at an LHC ramp-rate of 7.5 mT/s leads, via Eqn (6), to an $M_{coup}$ around 0.8 kA/m. To raise $R_c$ from its “compacted value” of 0.26 μΩ would require the insertion of an insulating core in which case $M_{coup}$ would depend on $R_a$. Comparing Eqns (6) and (7) to keep $M_{coup}$ fixed the value of $R_a$ needed would be $160x20/N^2 = 50$ μΩ a value consistent with the results presented here. The compacted cable needs a full core to remove $R_c$ from the equation. Since in the uncompacted case the screening strands are separated by a thick epoxy layer, $R_{eff}$ is essentially “infinite” whether the core is present or not; i.e. $R_{eff}$ is independent of core width as illustrated in Figure 4. Since there is no guarantee that such a condition could be reproduced from winding to winding it would be advisable to include a full width core.

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REFERENCES


