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Influence of Compaction During Reaction Heat Treatment on the Interstrand Contact Resistances of Nb_3Sn Rutherford Cables for Accelerator Magnets

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***Abstract*—The high field superconducting magnets required for ongoing and planned upgrades to the large hadron collider (LHC) will be wound with Nb_3Sn Rutherford cables for which reason studies of Nb_3Sn 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, R_c, adjacent strand, R_a, or a combination of them, R_{eff}. Although two decades ago it was agreed that for the LHC R_c should be in the range 10 - 30 μΩ more recent measurements of LHC quadrupoles have revealed R_c 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 R_{eff} 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 R_{eff} 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*— Nb_3Sn accelerator magnets, Nb_3Sn Rutherford cables, Nb_3Sn strands, interstrand contact resistance.**

I. Introduction

RUTHERFORD cables wound with Nb_3Sn 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 Nb_3Sn-wound quadrupoles with peak coil fields of 12 T [2] along with several 11 T 11 m long Nb_3Sn dipoles [3]. A suggested HE-LHC will consist of a ring of about 1280 14 m long 16 T Nb_3Sn dipoles housed in the existing LHC tunnel [4]. The proposed FCC is estimated to require 4578 15 m long 16 T Nb_3Sn dipoles [5] housed in a new 1000 km circumference tunnel. Accordingly a 16 T Nb_3Sn 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 Nb_3Sn for high field magnets [6]. Studies of Nb_3Sn 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 Nb_3Sn 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 Nb_3Sn Rutherford cables.

II. Experimental

A. Preparation of Cables for Measurement

Several meters of stainless steel cored HQ- and QXF-type Nb_3Sn 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 before being sent to LBNL for RHT. After return to CSMM the stacks were wrapped in teflon film, placed in an aluminum mold, uniaxially compressed to 5 MPa, and vacuum impregnated with CTD-101 resin. (2) Six stacks of QXF cable pieces was returned to LBNL for mounting under zero applied pressure and RHT; a similar bolt-down fixture was used but this time adjusted so as to confine the cable stack within a space just large enough to

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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

Cable type	HQ	QXF
Strand source, type	OST-RRP, 108/127	OST-RRP, 108/127
Strand diam, d_s, mm	0.778	0.852
SC filament count	108	108
Filament OD, d_0, μm	51.5	62.2
Eff. fil. OD, d_{eff}, μm	61.8	72.4

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_m = 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_t, 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 $Q_t(f)$. The results of the magnetic loss measurements are presented in Figure 2.

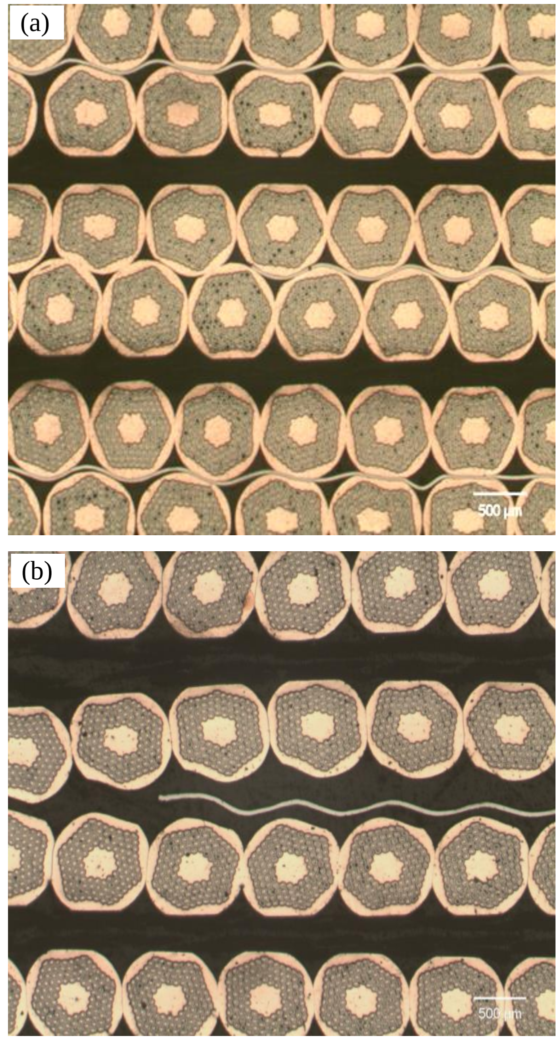

Fig. 1(a) Compacted cored cable H2 (b) uncompacted cored cable Q5.

III. DATA ANALYSIS

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

The total energy dissipated per cycle of a cable exposed to a face-on (FO) alternating field is $Q_t = Q_h + Q_{coup}$ where Q_h is the strand-based persistent current ("hysteretic") 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:

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

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 $(dB/dt) = (\pi^2/2)fB_m$, as explained in [12] we find:

TABLE II CABLE DETAILS

LBNL name	*	HQ1020ZB	HQ1021ZB	QXF 1055z-C	QXF 1055z-K	QXF 1055z-Q	QXF 1055z-O	QXF 1055z-M	QXF 1055z-D
OSU name	**H1**	**H2**		**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**
Strand count	35	35	35	40	40	40	40	40	40
Pack factor**, %	85.54	85.55	85.53	87.04	86.89	87.03	86.98	86.80	87.38
Core width, mm	0	8	--	11.9	15.9	15.4	14.3	13.3	0
Core cover, W, %	0	60	--	72	96	93	86	80	0

* Mixture of 1020 and 1021with cores extracted, ** This is the initial packing factor at the time of cable manufacture.

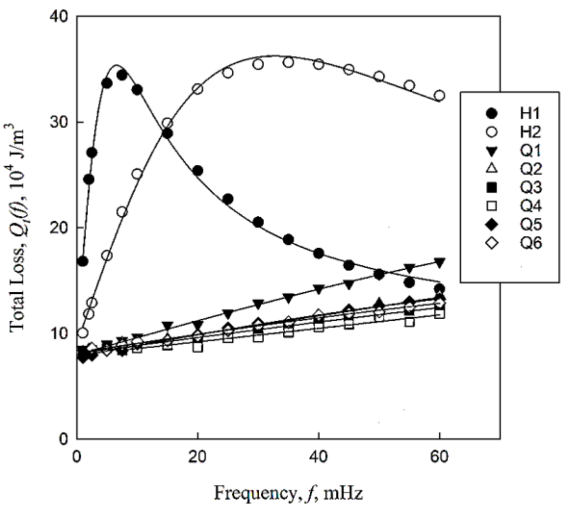

Fig. 2. Total face-on magnetization loss , $Q_t = Q_h + Q_{coup}$, as function of frequency, f, for the H series and QXF series cables. The persistent current components, Q_h, are the $f = 0$ intercepts.

$$Q_{coup(FO)}(f) = \left(\frac{\pi^2}{30}\right)\left(\frac{w}{t}\right)L_p B_m^2 N^2 \left[\frac{1}{R_c} + \frac{20}{N^3 R_a}\right].f \quad (2)$$

$$= \left(\frac{\pi^2}{30}\right)\left(\frac{w}{t}\right)L_p B_m^2 N^2 \left[\frac{1}{R_{eff}}\right].f \quad (3)$$

which indicates that R_{eff} the "effective interstrand contact resistance" defined by $[1/R_c + 20/(N^3R_a)]^{-1}$ can obtained from the initial slope of Q_t versus f. As a final step experimental plots of R_{eff} versus core-coverage, W, can be constructed.

B. CUDI©-Calculated Plots of R_{eff} versus Core-Coverage, W

An expression for coupling power, $P_{coup} = Q_{coup}.f$, starts with Eqn (1), substitutes $f = (dB/dt)(2/\pi^2 B_m)$ [12], and takes the form

$$P_{coup} = \left(\frac{4}{30\pi^2}\right)\left(\frac{w}{t}\right)L_p N^2 \left[\frac{1}{R_{eff}}\right]\left(\frac{dB}{dt}\right)^2 \quad (4)$$

The fortran program CUDI© [13] enables P_{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©-calculated P_{coup} to an R_{eff} which leads to calculated plots of R_{eff} versus W.

IV. Results

A. R_{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_3Sn 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_c of 0.26 μΩ. Then as W increased from 32% to 90% (full width) R_{eff} increased monotonically up to 246 μΩ [7], Figure 3. As expected the data for H1 and H2 are members of this group. Figure 3 also shows the CUDI©-modelled R_{eff}. Selected as inputs to the model are $R_c = 0.26$ μΩ and $R_a = 0.2$ μΩ (following [14] wherein it was recommended that R_a should be small but not less than 0.2 μΩ) 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].

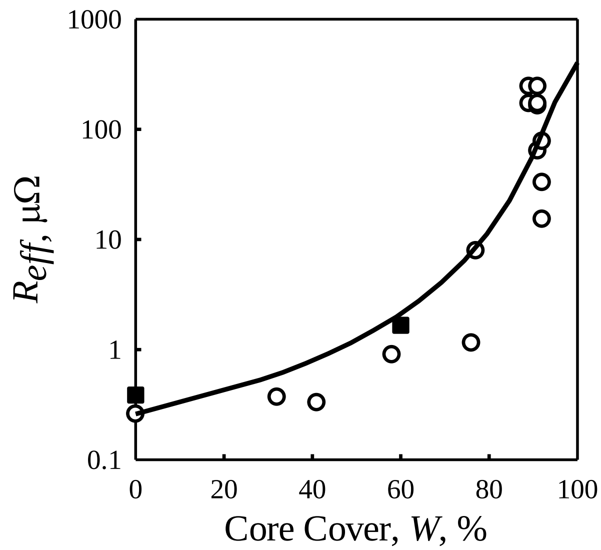

Fig. 3. R_{eff} versus core cover for a previously studied assortment of compacted Nb_3Sn cables (o), the present compacted cables H1 and H2 (■) (see Table III), and a CUDI© simulation based on defined $R_c = 0.26$ μΩ and $R_a = 0.2$ μΩ (—)

B. R_{eff} versus W for Uncompacted QXF-Type Cables

Listed in Table III are the magnetically measured R_{eff} values based on $Q_t(f)$ and Eqn (3)). The low deduced R_a values, in the range of 18-26 nΩ, indicate unexpectedly tight adjacent strand contact ([8], Fig.4). In setting up the CUDI© model we recognize the wide separation between the upper and lower cable layers, Figure 1(b), by assigning a very large value to R_c, viz. 100,000 μΩ. Under this condition R_{eff} turns out to be independent of W. Curves of R_{eff} versus W for $R_a = 26$ nΩ and 18 nΩ are presented in Figure 4. Inserted in the figure are the experimental points for cables Q2 – Q6 (Q1 is neglected as an outlier).

TABLE III Magnetically measured R_{EFF} and the deduced R_A values

Cable Type	HQ		QXF					
Stack name	H1	H2	Q1	Q2	Q3	Q4	Q5	Q6
W, %	0	60	71	95	94	86	80	0
R_{eff}, μΩ	0.39	1.66	31.1	60.3	72.8	83.4	57.1	68.7
R_a, nΩ*			9.7	18.8	22.1	26.1	17.8	21.5

* R_a based on $(20/N^3)R_{eff}$ for the QXF cables

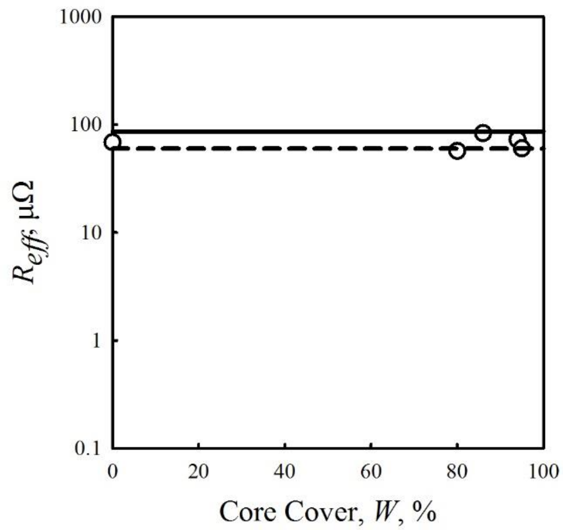

Fig. 4. Experimental R_{eff} versus core cover data for QXF cables Q2-Q6 (o). The lines are CUDI© simulations based on $R_c = 0.1\ \Omega$ with $R_a = 26$ nΩ (—) and 18 nΩ (---); they represent W-independent R_{eff} values of 86 μΩ and 60 μΩ, respectively.

V. Discussion

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

$$M_{coup} = \left(\frac{1}{60}\right)\left(\frac{w}{t}\right)L_p N^2\left[\frac{1}{R_c}+\frac{20}{N^3R_a}\right].\frac{dB}{dt} \tag{5}$$

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 ± 5 μΩ [15] or 20 ± 10 μΩ [16]. The prefactor N^3 allows R_a 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_cs well above 50 μΩ and measurements of quadrupoles using various techniques yielded R_cs 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 $1/R_{eff}$ 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 28^2 with an uncored QXF-type cable, Eqn (6), with parameters 10.1, 54.5 mm, and 40^2 would require R_{eff} (or R_c) to be increased by a factor 2.6.

$$M_{coup,uncore} = \left(\frac{1}{60}\right)\left(\frac{w}{t}\right)L_p N^2\left[\frac{1}{R_c}\right].\frac{dB}{dt} \tag{6}$$

$$M_{coup,core} = \left(\frac{1}{60}\right)\left(\frac{w}{t}\right)L_p N^2\left[\frac{20}{N^3R_a}\right].\frac{dB}{dt} \tag{7}$$

For the uncored cable Eqn (6) shows $M_{coup,uncore}$ to be proportional to $1/R_c$. The introduction of a fully insulating core reduces the proportionality to $20/(N^3R_a)$, 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 $160\text{x}20/N^3 = 50$ nΩ 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 crossing 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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