Influence of Reaction Heat Treatment Condition on the Interstrand Contact Resistances of Nb_3Sn Rutherford Cables

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IMPORTANCE OF THE RESEARCH

Rutherford cables wound with Nb_3Sn strands will be used in all the high field superconducting magnets required for upgrades to the large hadron collider:

(1) The high luminosity LHC (High Lumi LHC, HL-LHC, 11 and 12T),
(2) A higher energy LHC (HE-LHC, 16 T),
(3) A very high energy future circular collider (FCC, 16 T).

The numerous planned accelerator applications will demand a continuous supply of Nb_3Sn strand and cables accompanied by vigorous magnet and cable design programs directed towards high field quality magnets.

For this reason we are studying one of the essential components of cable magnetization-- the ramp-rate dependent coupling magnetization, M_{coup},

which is based on the effective interstrand contact resistance, R_{eff}

Measurements

In support of the US LHC Accelerator Research Program (LARP) the magnetizations of eight LARP high gradient quadrupole cables designated HQ and QXF were measured.

The total magnetization losses ($Q_{total} = Q_{coupling} + Q_{persistent\ current}$) of the cable stacks were measured by **pickup coil magnetometry** at 4.2 K in FO fields, B_m, of ±400 mT at frequencies, f, of up to 60 mHz.

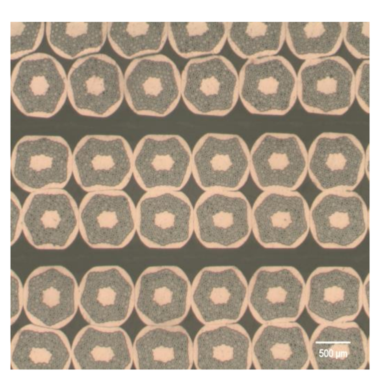
Based on $Q_{total}(f)$ i.e. $Q_{coup}(f)$, the effective interstrand contact resistance, R_{eff}, was derived and presented as a function of core cover, W %.

Strand and Cable Details

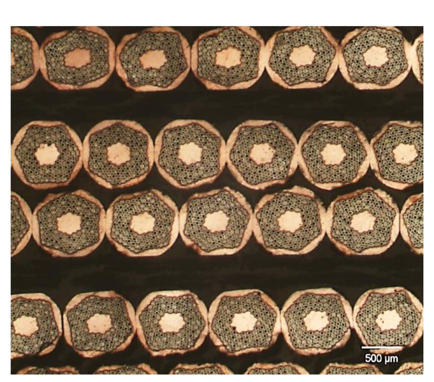
Table 1 ***The Strands***

Cable Type (Table 2)	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. diam., d_{eff}, μm	61.8	72.4

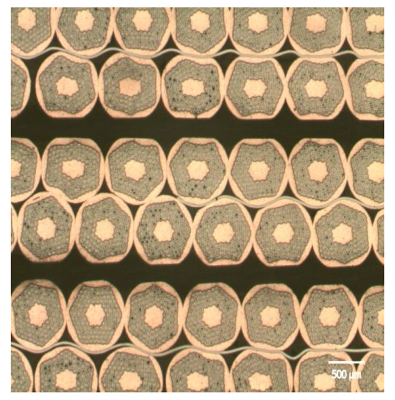
Compacted ***Uncompacted***



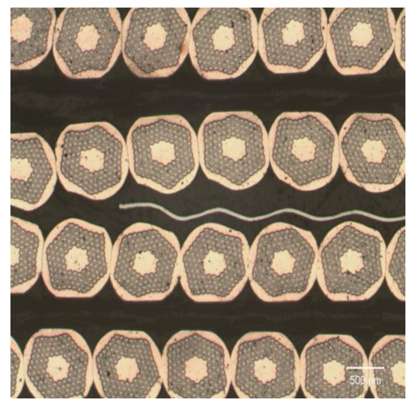
Uncored H1



Uncored Q6



Cored H2



Cored Q5

Table 2 ***The Cables***

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

Data and Analysis for R_{eff} and M_{coup}

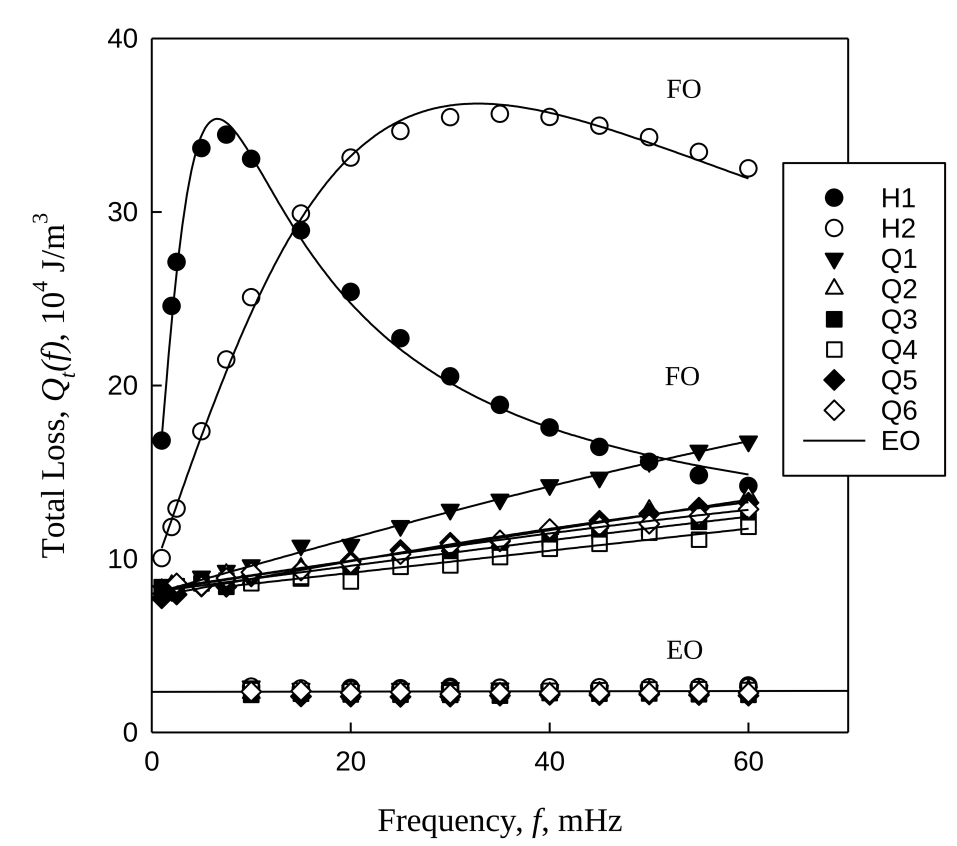


Figure 1: Total magnetization loss, Q_t, as function of frequency, f, for the H series and QXF series cables. The persistent current components, Q_h, are the $f = 0$ intercepts. The EO loss was measured calorimetrically

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

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

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

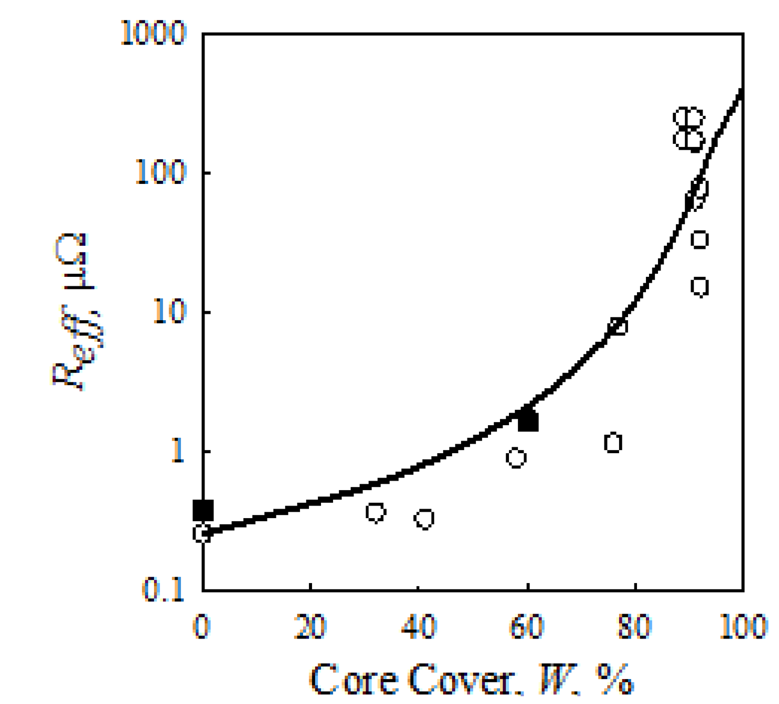
Using Eqn. (3) R_{eff} is obtained from the experimental dQ_{total}/df .

Table 3 **Experimental R_{eff} and derived R_a***

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

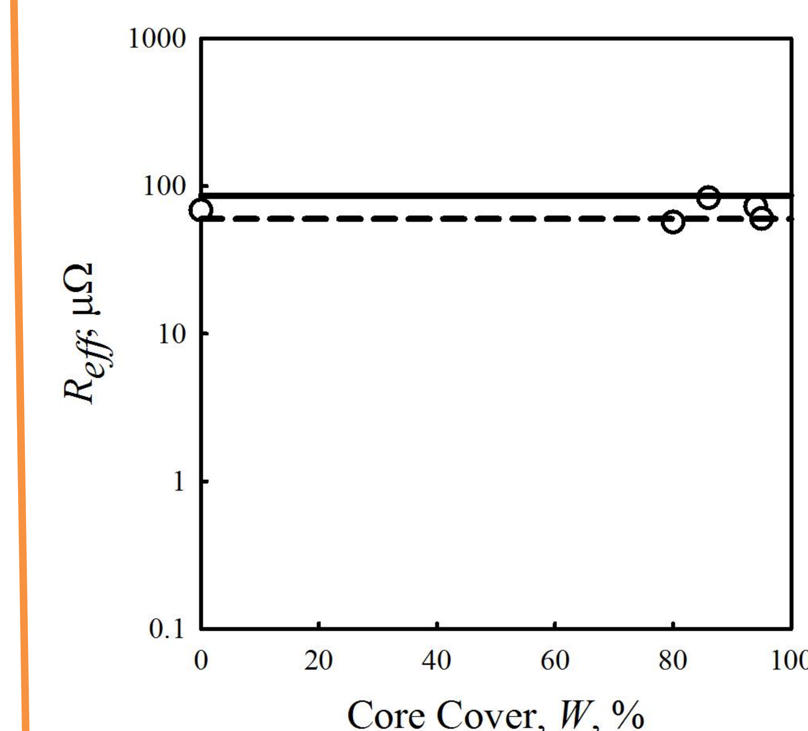
* Based on $R_a = (20/N^3),R_{eff}$ given an "infinite" R_c

CUDI©-calculated plots of R_{eff} versus core-coverage, W %



Compacted Cables

Figure 2: 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 3), and a CUDI© simulation (—) based on R_c = 0.26 μΩ and R_a = 0.2 μΩ



Uncompacted Cables

Figure 3: Experimental R_{eff} versus core cover data for QXF cables Q2-Q6 (o).

The lines are CUDI© simulations based on R_c = 0.1 Ω with R_a = 26 nΩ (—) and 18 nΩ (---); they represent W-independent R_{eff} values of 86 μΩ and 60 μΩ, respectively

Conclusions

Measurements of the LHC NbTi quadrupoles have yielded R_c values around 160 μΩ. To raise the R_c of Nb_3Sn cables to this level from its "compacted value" of 0.26 μΩ would require the insertion of an insulating core. Removing R_c from the equations calls for an R_a = (20/N^3).160 = 50 nΩ, consistent with the present results, **Table 3.**

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_c is essentially "infinite" whether the core is present or not; R_c is independent of core width**, Figure 3**. 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.

Still to be determined are the influences of the above R_c and R_a values on current sharing and stability.

Acknowledgments

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