Effects of Core Type, Placement, and Width, on ICR of Nb_3Sn Rutherford Cables

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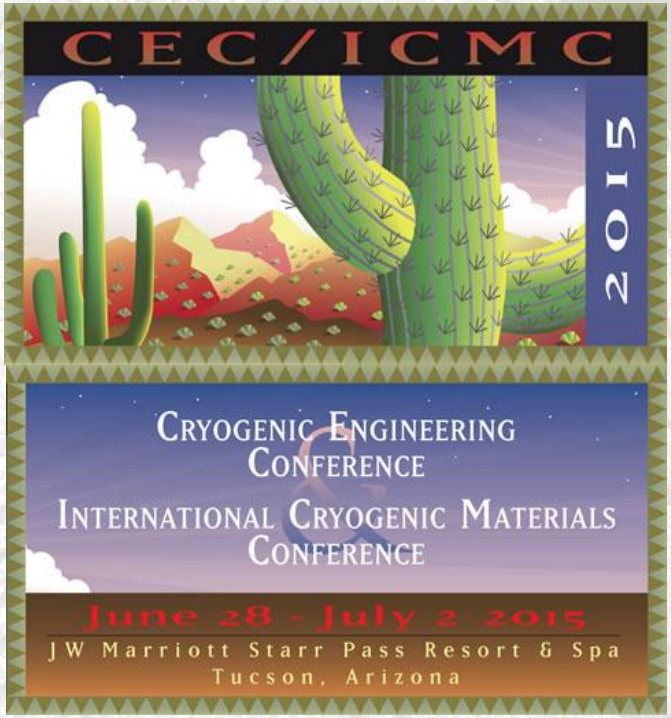

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Magnetization, Error fields, and R_{eff}

$$M_{coup} = \left(\frac{1}{3}\right)\left(\frac{w}{t}\right)L_p\left(\frac{N^2}{20}\right)\left[\frac{1}{R_c}+\frac{20}{N^3R_a}\right]\left(\frac{dB}{dt}\right) \quad \text{A/m (J/m}^3\text{T)}$$

$$M_{coup} = \left(\frac{1}{3}\right)\left(\frac{w}{t}\right)L_p\left(\frac{N^2}{20}\right)\left[\frac{1}{R_{eff}}\right]\left(\frac{dB}{dt}\right) \quad \text{A/m(J/m}^2\text{T)}$$

- The current ramping of LHC magnets produces field errors: (i) in dipoles of about 1 unit of *b1* and less than 0.1 units of *cn*, consistent with *Rc* well above 50 μΩ, (ii) in quadrupoles of about 2 units of *b1* and less than 0.2 units of *cn*, consistent with *Rc* between 100 - 150 μΩ
- This R_c is above the "target" of 15-20 μΩ, and works well
- But, b_3, thus M_{coup}, must be kept down in Nb_3Sn magnets, and R_{eff} tends to be low except with cores, and we will see R_{eff} is a strong function of core width

Introduction -- Experimental

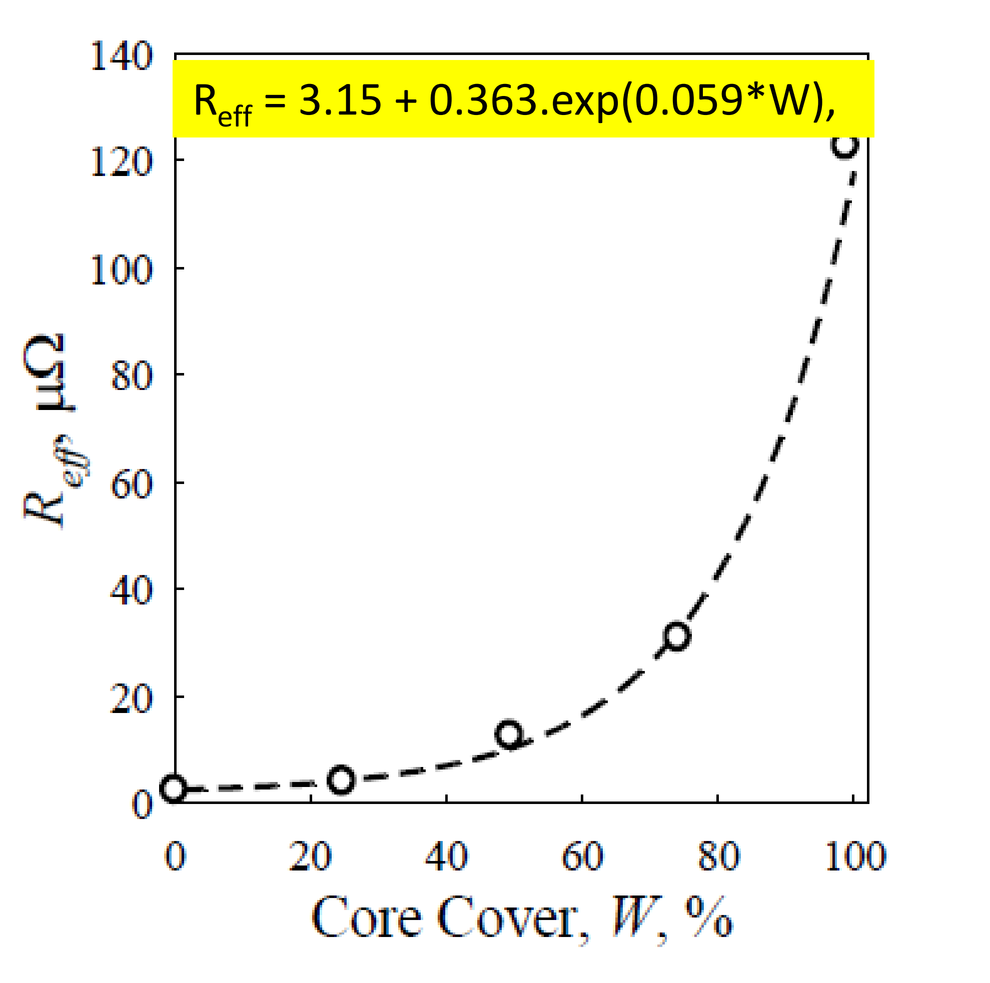
- The coupling magnetization of a Rutherford cable is $\propto 1/R_{eff}$, itself a function of the crossing-strand R_c, and adjacent strand resistance, R_a.
- In cored cables R_{eff} varies continuously with W, the core width
- For a series of stabrite-coated NbTi LHC-inner cables with stainless-steel cores $R_{eff}(W)$ decreased smoothly as W decreased from 100%
- On the other hand, for a set of SS-cored Nb_3Sn cables R_{eff} plummeted abruptly and remained low over most of the range.
- The difference is due to the controlling influence of R_c – 2.5 μΩ for the stabrite/NbTi and 0.26 μΩ for the Nb_3Sn.

Modelling

The experimental behavior was replicated with the program CUDI© which (using the basic parameters of the QXF cable) went on to show that:

- (i) in QXF-type Nb_3Sn cables (R_c = 0.26 μΩ) R_{eff} dropped even more suddenly when the SS core was offset to one edge of the cable
- (ii) R_{eff} decreased more gradually in cables with higher R_cs
- (iii) a suitable R_{eff} for a Nb_3Sn cable can be achieved by inserting a suitably resistive core rather than an insulating (SS) one

R_{eff} vs w for SS-cored Stabrite Rutherford Cables



The fitted *Reff* of 136 μΩ at W = 100% indicates an *Ra* of 0.16 μΩ.

M.D. Sumption, E.W. Collings, R.M. Scanlan, A. Nijhuis, H.H.J. ten Kate,S.W. Kim, M. Wake, T. Shintomi, "Influence of strand surface condition on interstrand contact resistance and coupling loss in NbTi-wound Rutherford cables," *Cryogenics*, vol. 39, pp. 197-208, 1999.

A Compilation of data for Nb_3Sn cables from various experimental campaigns

Data taken by OSU in collaboration with LBNL, FNAL, and the University of Twente

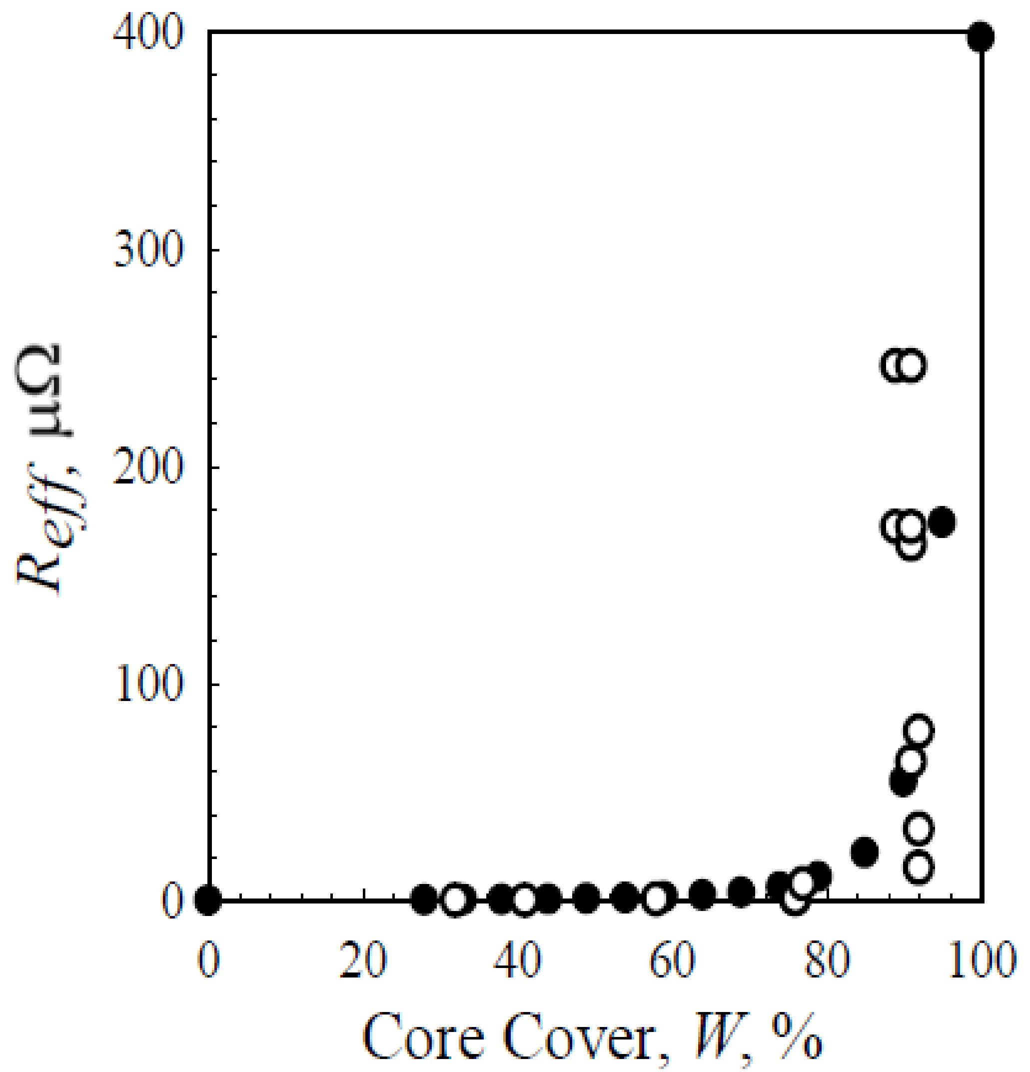
TABLE I. ICR OF THIN-SS-CORED NB_3SN RUTHERFORD CABLES

ICR (μΩ)	Cover, *W*	Ref.	Comments
0.33	41%	[19][25]	Shifted to one side of centerline and curled
0.37	32%	[19][25]	Well centered core
0.9	58%	[28]	Off-center, leaving uncovered 1.5 strands on one side & 5.5 on the other
1.10	76%	[26]	High compaction
1.15	76%	[26]	Standard compaction
1.46	76%	[26]	Low compaction
7.90	77%	[19][25]	Off-center but covering centerline
15.3	92%	[13]	Calorimetric measurement
33	92%	[17]	Calorimetric measurement
64	91%	[20]	Calorimetric measurement
78	92%	[17]	1T applied field
164	91%	[20]	Magnetic measurement
172	89%	[20]	Magnetic measurement
172	91%	[24]	Magnetic measurement
246	89%	[20]	Calorimetric measurement
246	91%	[24]	Calorimetric measurement

Compilation of results for Nb_3Sn cables with cores of various w (closed circles)

Also shown are results of CUDI simulation using a QXF-cable geometry (open symbols)

For the Modelling, the uncored R_c value for Nb_3Sn cables of 0.26 $\mu\Omega$ (established via numerous experiments) was used along with R_a = 0.2 $\mu\Omega$

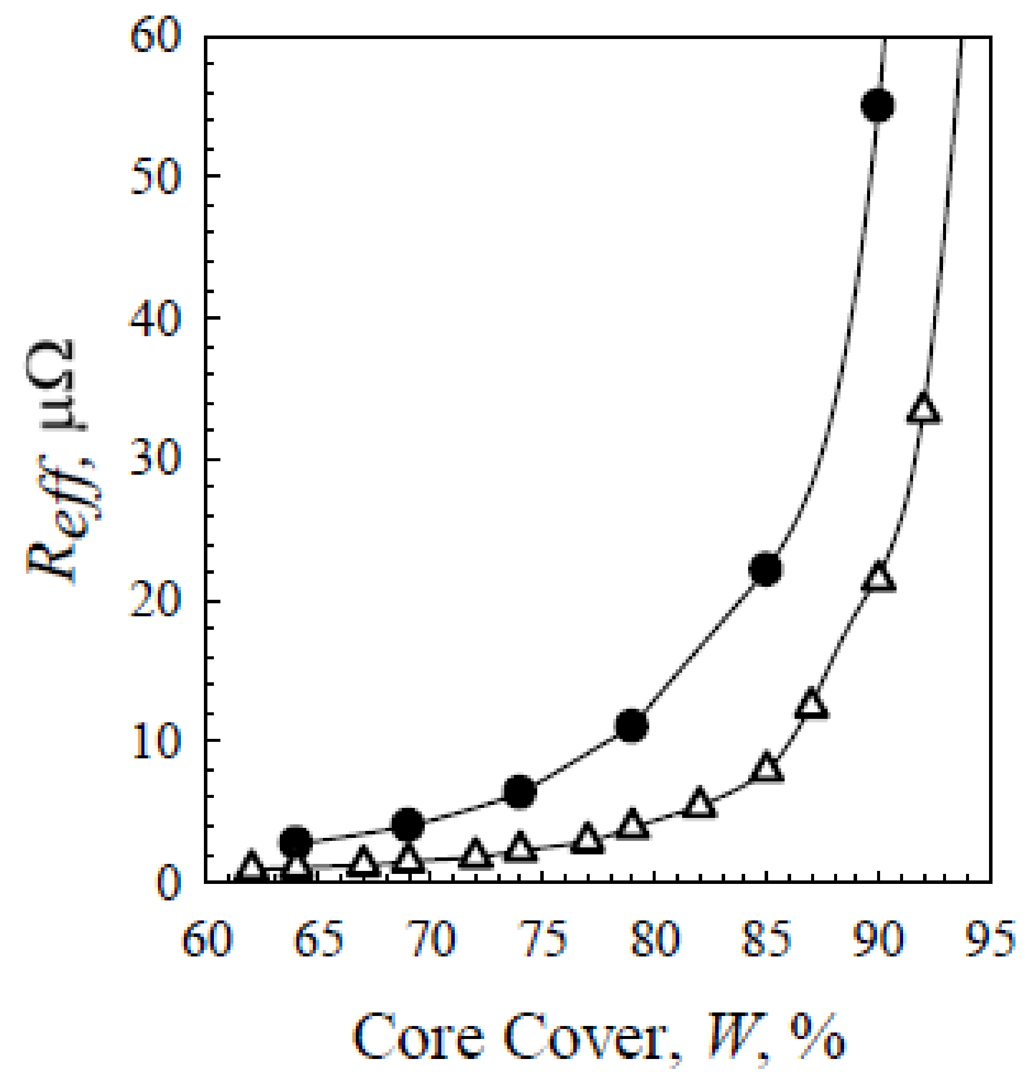


Effect of core biased to cable side

For manufacturing ease, a core shifted to the cable edge (keystoned cables) has been considered

Using CUDI simulations, we show R_{eff} vs w for cores in the middle of the cable (filled circle), and in the case where the core is placed (or drifts) to one side (triangle).

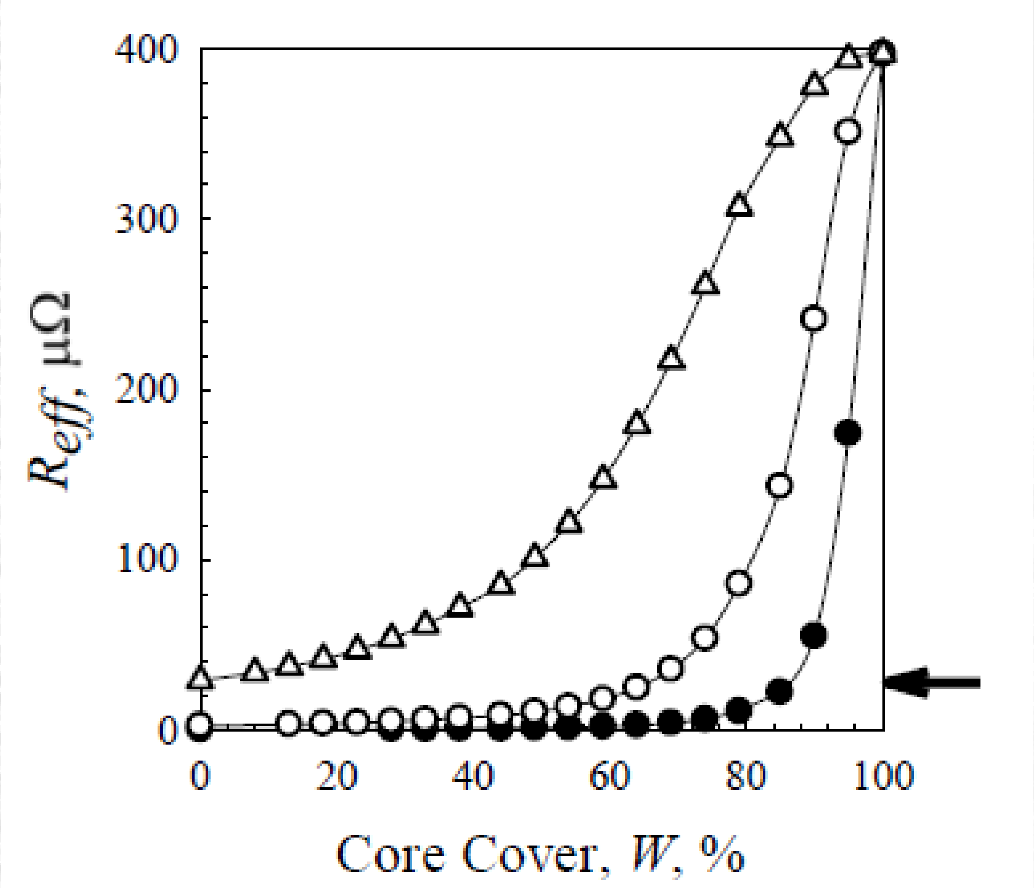
Here R_c = 0.26 $\mu\Omega$, R_{core}=1000 $\mu\Omega$ and a QFX-cable geometry was used



Comparison of insulating Cores with moderate cable R_c, vs low R_c with full width, moderate R_c cores

Shown in curves at right is expected QXF-sytle cable results assuming totally insulating cores of various width and cable (uncored area) R_c values of 0.26 (filled circle), 2.5 (open circle), and 30 $\mu\Omega$ (triangle).

This can be compared to a situation where the core is whole width, but not insulating (say 50 or 100 $\mu\Omega$) This is shown as arrow at right



Conclusions

- Cable coupling magnetization $\propto 1/R_{eff}$
- In uncored cables R_{eff} is primarily controlled by R_c
- Low R_c values for Nb_3Sn cables demands a core
- In cables with insulating cores R_{eff} (a function of both R_c and R_a) increases continuously with W (% core cover), with R_a eventually taking over as the controlling ICR.
- The results of many studies are assembled here for the first time, and show $R_{eff}(W)$ reaching acceptable values only for W ~90%
- These results were compared to modelling results (consistent)

<u>Further application of the program demonstrated that</u>

- R_{eff} decreasing by 2½ times as the cores shifted from center to edge cable
- The sensitivity of R_{eff} to core width and position suggests inclusion of a core, not of SS (which has a stable, insulating oxide surface layer), but of a resistive composite such as Cr-plated SS or Cr-plated Cu.