Single-Strand Excitation Rig for Probing Current Sharing and ICR in Nb_3Sn Rutherford Cable at 4.2K up to 12 Tesla

C.J. Kovacs, M.D. Sumption, E.W. Collings

Center for Superconducting & Magnetic Materials (CSMM), Department of Materials Science & Engineering, The Ohio State University, USA

The Ohio State University
Department of Materials Science & Engineering

ICR in Nb_3Sn Rutherford Cable

Nb3Sn Rutherford cables are the candidate for next generation [1]:

- large-scale high-field applications
- LHC luminosity upgrade

An important parameter for the performance of Nb_3Sn Rutherford Cables is the Interstrand-contact resistance (ICR) as this influences Coupling Currents (CCs) [2]

- Strands adjacent ICR (R_a) should be small but greater than 0.2 μΩ.
- Strands cross-over ICR (R_c) should be 15 ± 5μΩ.
- If these ICRs are too small, there will be high AC-loss, Magnetization
- If these ICRs are too large, there will be low current sharing and lower Mininum Quench Energies (MQE).

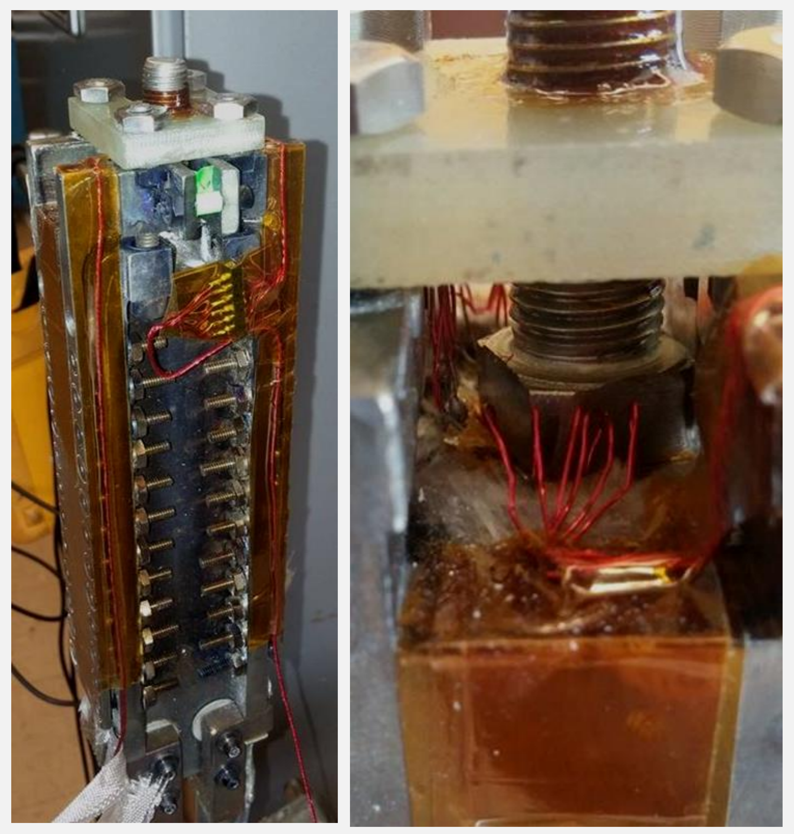
In Rutherford cables, the ratio of applied current to critical current (I/Ic) versus cable stability (determined with MQE experiments) shows two distinct regimes, i.e. a "kink" [3]:

- Current sharing has time to occur (lower I/Ic) which results in higher cable stability (higher MQE).
- Current sharing doesn't have time to occur (higher I/Ic). Psuedo-single-strand behavior is present which results in lower cable stability (lower MQE).

ICR is primarily manipulated by the extent of diffusion bonding of strands within the cable during the heat-treatment and the preservation of these bonds after further processing. Diffusion bonding, is affected by many processing parameters.

Need for small scale, quick turn-around Nb_3Sn Rutherford Cable testing:
Freedom to experiment with newer technologies and different techniques.
Possibility for Nb3Sn Rutherford cable "Vetting Studies" before committing to larger scale measurements.
More chances to experiment for better understanding of variations in parameters which affect ICR.

RC-SSE Probe: Sample and Preparation



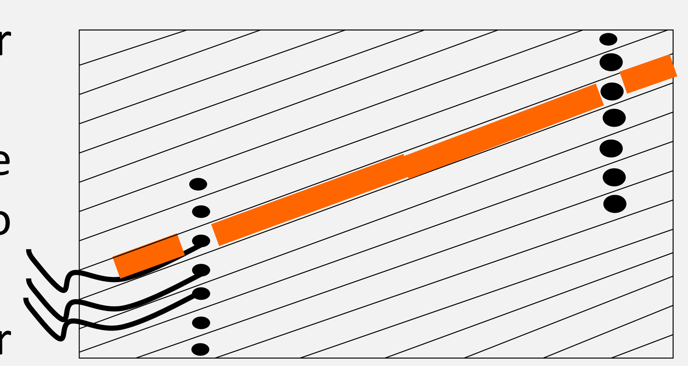
RC-SSE Probe:

- 1000A w/ helium-cooled leads
- Trans Pressure 0-50MPa
- Epoxy Impregnation capability
- Instumentation ports
- Graphite Paste Heaters
- 1-layer Rutherford Cable

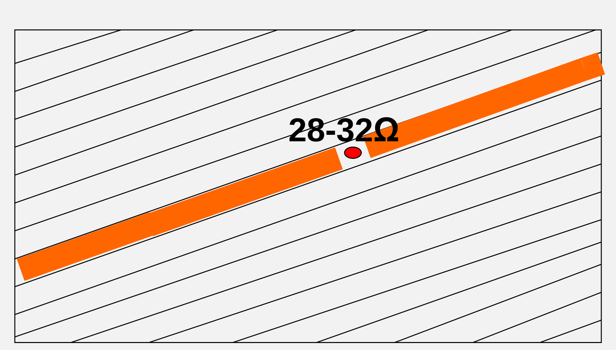
The single-strand excitation of Nb3Sn Rutherford cable probe (RC-SSE) was built to examine interstrand contact resistances (ICR) and current-sharing in a 27-strand Nb3Sn Rutherford Cable. This system was built small-scale and will only consume ~16" of cable per measurement. While other experiments have pressed a multi-stack of cables to more accurately simulate stress conditions within a magnet, only one cable will be pressed in the RC-SSE so the probe can fit in a 60mm bore research magnet and so the (future) Hall-probe array can be as close as possible to the sample under invesitigation [4]. Additionally, the RC-SSE will press the cables onto a U-shaped holder, similar to other probes created for similar purposes [5].

Table: Details of cable sample and sample preparation

Strand	
Type	OST-RRP Billet# 8853-2616
Diam, mm	1.0
Filament count	60/(61)
Filament Diam, μm	110
Cable	
Strand count, #	27
Keystone angle, deg	0.95
Compaction, %	87
Width, mm	14.2
Thickness ave, mm	1.78
Transposition pitch, mm	110.2
Core material	316 S.S.
Core Width, mm	10.8
Core Thickness, μm	25
Sample Prep	
HT/Meas. Pressure, MPa	20
Heat Treatment	210-400-665C for 72-48-50hrs. Under Argon atmosphere in S.S. retort
Epoxy Impregnation	No epoxy



Measurement #1: Voltage was measured along the entire cable length and in between the 1st and 2nd nearest neighbor



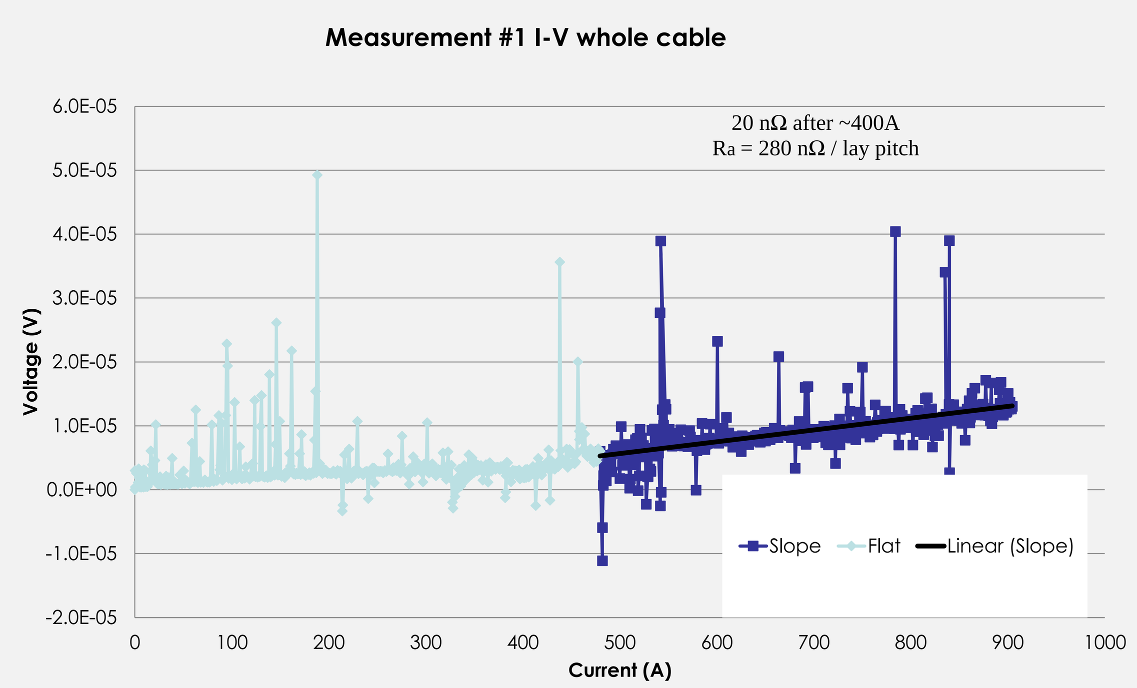
Measurement #2: Voltage was measured along the entire cable at variable I/I_c with heater pulses

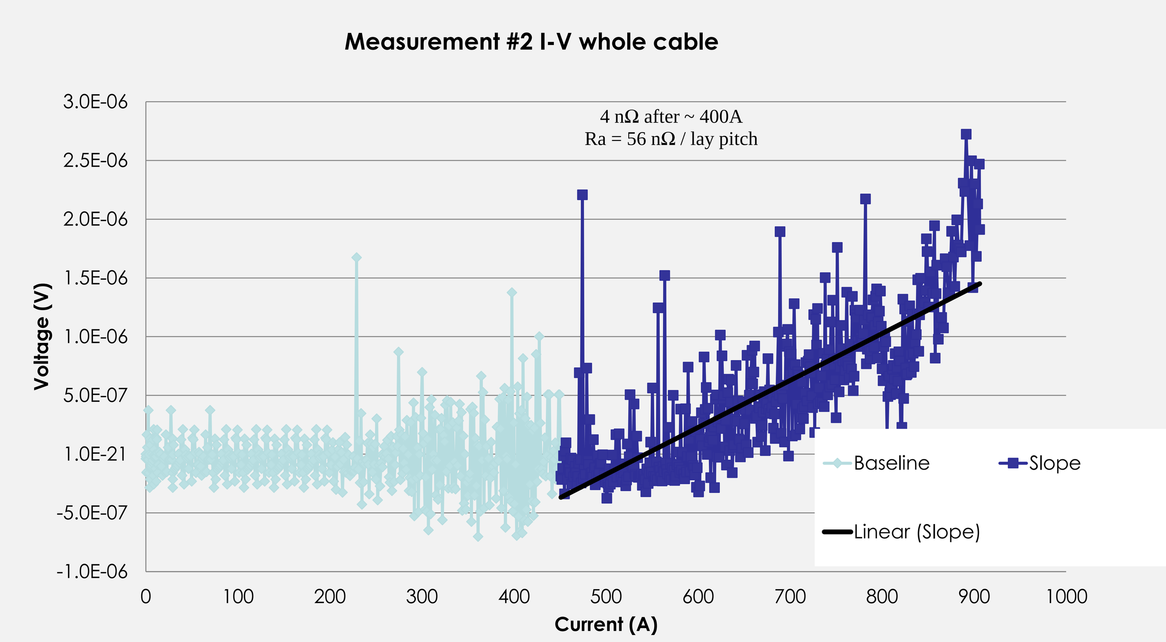
Measurements with the RC-SSE Probe: I=0-900A at 10 Tesla at 4.2 K°

2 different sample measurements were performed at 10 Tesla @ 4.2K°. For the first measurement, the sample was slighty oxidized after heat-treatment. I-V measurements were taken while monitoring the voltage in between the 1st and 2nd nearest neighboring strand. For the second measurement, the sample was less oxidized after heat-treatment, a graphite-epoxy heater was located directly on the single-strand for excitation, and heat pulse measurements were performed with varying power and I/I_c.

For both samples, the transition onset of the single strand was around 400A. After this point, current began to share with the two 1st nearest neighbors. Assuming equal sharing with the two 1st nearest neighbors the adjacent resistance per lay pitch could be calculated.

It was clear from the transverse voltage taps that current sharing was occurring.





I/I_c	Heater (Watts)	Voltage (V)	Res. (Ω)	Neighbors shared with (#)
0.42	3	8.78E-06	4.39E-08	11
0.64	3	1.31E-05	4.37E-08	11
0.84	3	1.70E-05	4.25E-08	11
1.06	3	2.15E-05	4.30E-08	11
1.26	3	2.60E-05	4.33E-08	11
1.26	12	5.10E-05	8.50E-08	22
1.68	12	1.33E-03	1.66E-06	Entire cable
1.90	12	2.10E-03	2.33E-06	Entire cable

$I_c^{est} = 475$ A

$$\#_{neighbors} = \frac{R_{\substack{\text{measured during}\\ \text{heat pulse}}}}{R_{\substack{\text{2 x 1st neighbors}\\ \text{entire cable from I-V}}}}$$

The heat-pulse results could be divided into two sets; ones which could be explained via a stable transverse current sharing covering most of the cable and ones which generated a steady-state normal zone with much larger voltages and are likely due to the entire cable cross section transitioning. These steady-state normal zones are possible because of the large amount of stabilizing copper (i.e. the entire copper cross-section of the Rutherford cable), as well as the fact that the cable wasn't epoxy impregnated (so communication with the LHe would be much higher). Future measurements will utilize a SC-transformer to perform full excitation measurements.

SC-Transformer, in Design phase. Rogowski Coils (w/ amplification & DC integration) and Hall sensors for current determination. Recent Design: 20 kA max

Conclusions and Future Work for the RC-SSE probe

- Designed a fixture and performed single-strand excitation measurements on Nb3Sn Rutherford Cable under magnet relevant conditions.
- Measurements of single-strand excitation were performed at 10 Tesla up to 900A @ 4.2K. Transverse current sharing occurred above 400A and could be initiated using the heater.
- Steady-state normal zones were creased by the heater which covered the entire cable cross section at 1.26 I/Ic with a 3W . After this, the length of the normal zone increased.
- In the future, epoxy impregnated cables will be measured.
- A full-excitation measurement system is being designed to replace the RC-SSE.

References:

1. M.D. Sumption et al. *Cryogenics* 52 91-99 2012
2. Collings et al. "Coupling and Persistent-Current Magnetizations of Nb3Sn Rutherford Cables" *IEEE Trans on App Supercon.* Vol. 1219, pp.191-198 (2010)
3. A. K. Ghosh et al. "Stability measurements on cored cables in normal and superfluid helium" *Physica C* 310 pp. 335-339 (1998)
4. P. Bruzzone et al. "Results of Contact Resistance Distribution in NbTi and Nb3Sn ITER Condutor Termination" *IEEE trans on App. Supercon.* Vol. 17 No. 2 (2007)
5. W. van de Camp "Critical Current versus Transverse Stress and Thermal Stability of a RRP Nb3Sn Rutherford Cable" Thesis, University of Twente (2012)
6. W. M. de Rapper "Critical Current and Stability of High-Jc Nb3Sn Rutherford Cables for Accelerator Magnets" *IEEE Trans on App. Supercon.* Vol. 21 No. 3 (2011)
7. Godeke et al. "A Superconducting Transformer System for High Current Cable Testing" *Review of Sci Instruments* Vol. 81, No. 3 (2010)

This work was supported by the U.S. Department of Energy, Office of Science, Division of High Energy Physics grant DE-SC0010312 and DE-SC0011721

Department of Materials Science & Engineering
Center for Superconducting & Magnetic Materials

MT25
25th International Conference on Magnet Technology
RAI - Amsterdam
August 27 - September 1, 2017