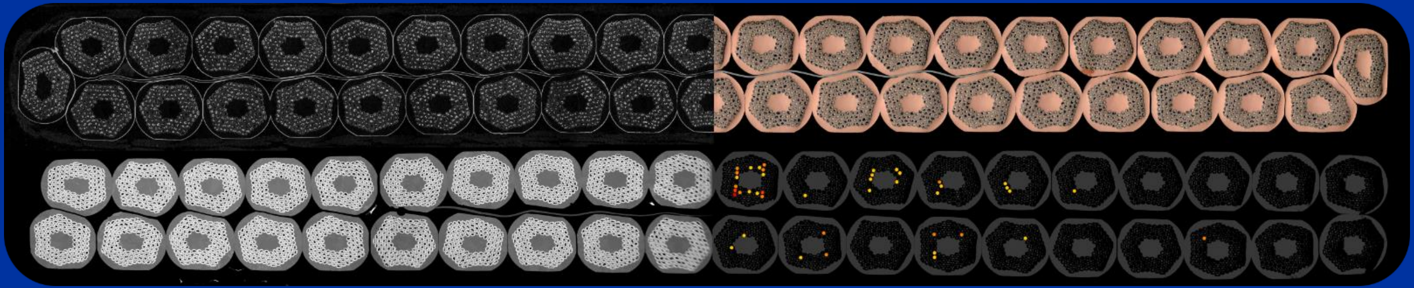
The trade-off between electrical behaviour and mechanical performance under transverse compression of Nb_3Sn conductor by varying heat treatment duration.

Kirtana Puthran

Bentejui M Clavijo, Christian Barth, Tabea Arndt, Amalia Ballarino

ICMC 2024, Geneva.



Karlsruher Institut für Technologie

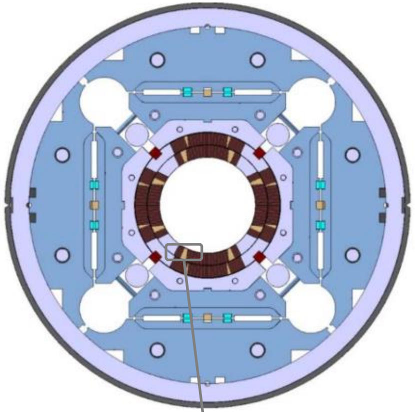
CERN

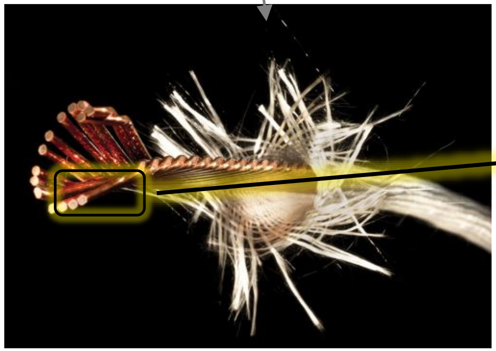
Contents

Introduction

Sub-Scales of a Nb_3Sn Rutherford cable

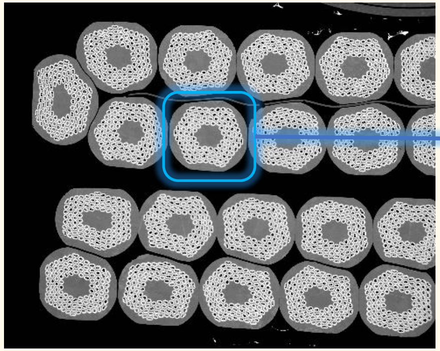
Cross-section of the Nb_3Sn Quadrupole magnet MQXF





Unreacted Nb_3Sn Rutherford cable, with S2 fibre glass insulation

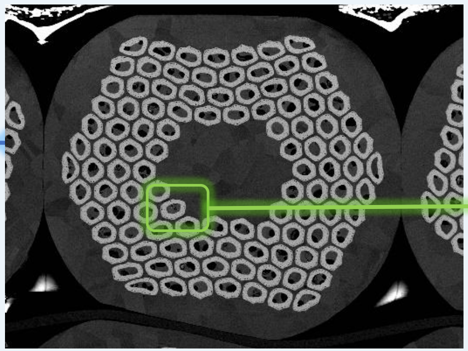
CABLE



Section of reacted double stacked cables

- 18.15 mm x 1.525 mm
- 0.4° keystone angle
- 40x 0.85 mm strands
- 12 mm x 25 µm Stainless steel core
- 145 µm S2-glass sleeve
- Impregnation resin

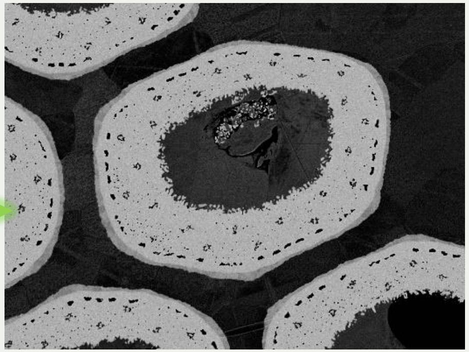
STRAND



Strand/wire in a cable

- 0.85 mm
- RRP® architecture
- 108 subelements
- Cu core
- Cu matrix

SUBELEMENT



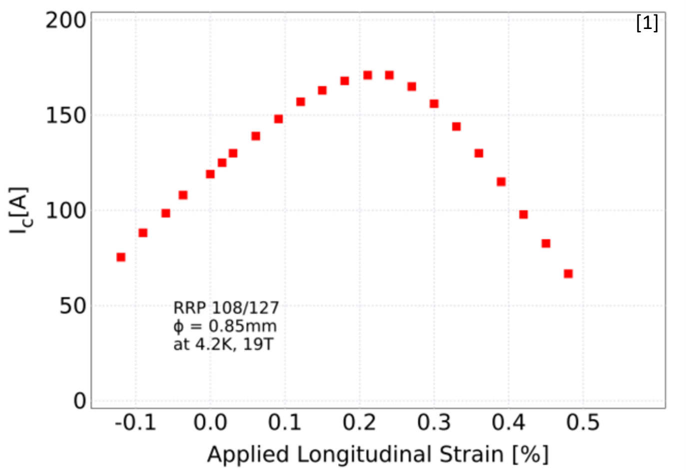
Subelement in a strand

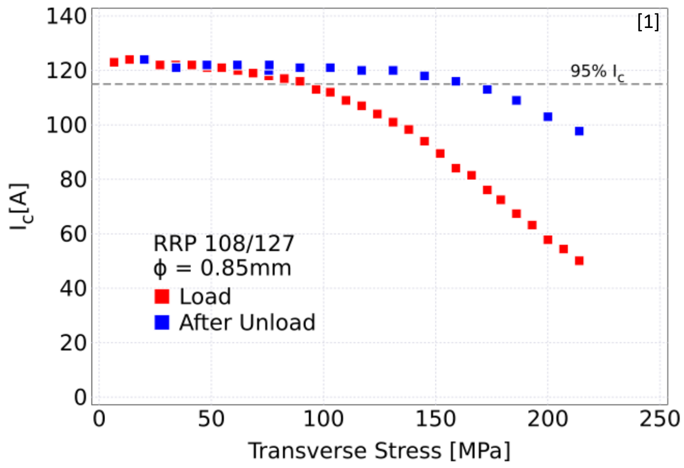
- 0.045 mm
- CuSn core
- Ti doping rods
- **Brittle Nb_3Sn layer**
- Nb barrier
- Voids

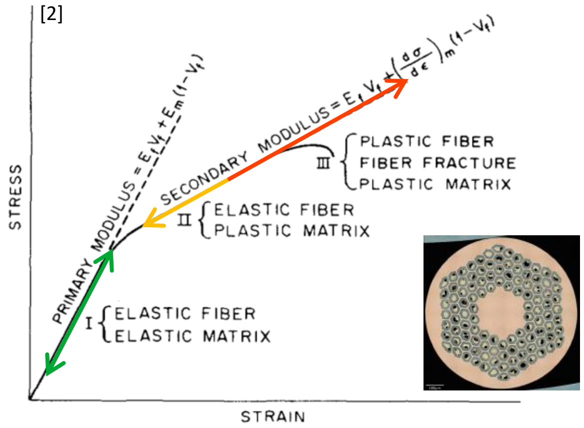
Complex composite structure at different scales

Motivation

- The electrical performance of Nb_3Sn is highly sensitive to stress.







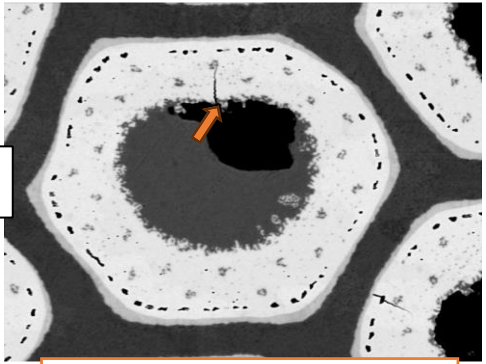
- Transverse compressive stress are the highest loads on the superconductor during operation of large accelerator magnets.

[1] Determination of the electromechanical limits of high-performance Nb3Sn Rutherford cables from a single-wire experiment, https://indico.cern.ch/event/896755/ Carmine Senatore, 30.04.2020
[2] A prediction of the stress state in Nb3Sn superconducting composites, D. S Easton, 1980

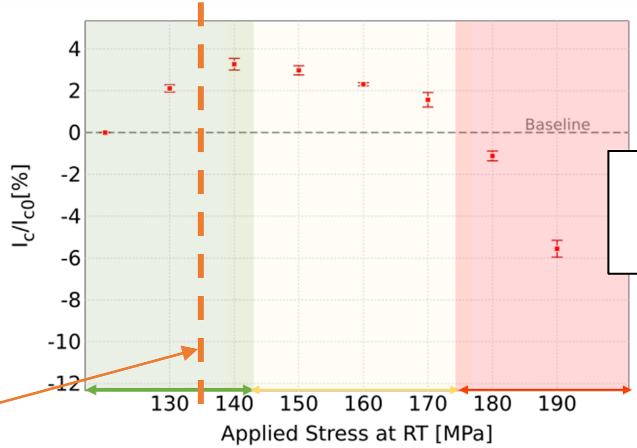
Motivation

- From a previous study[1], it has been shown that mechanical degradation in the superconductor precludes electrical degradation.

Metallography



Crack initiation



Electrical characterization

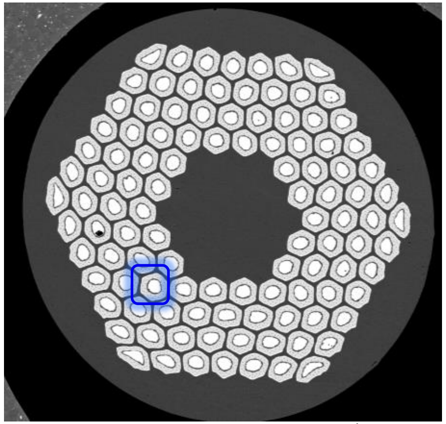
- The over-arching goal of this work is to study and propose a combination of parameters to improve the electro-mechanical robustness of the cables, by a combination in the heat treatment duration and/or impregnation resins for future high field magnets.

- Today's talk : Impact of heat treatment duration.

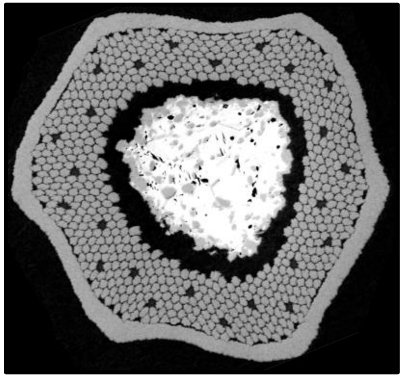
Lenoir, Gilles, et al. "Effect of transverse compressive stress applied at room temperature on Nb3Sn Rutherford cables." Superconductor Science and Technology (2023).

Reaction Heat Treatment Cycle

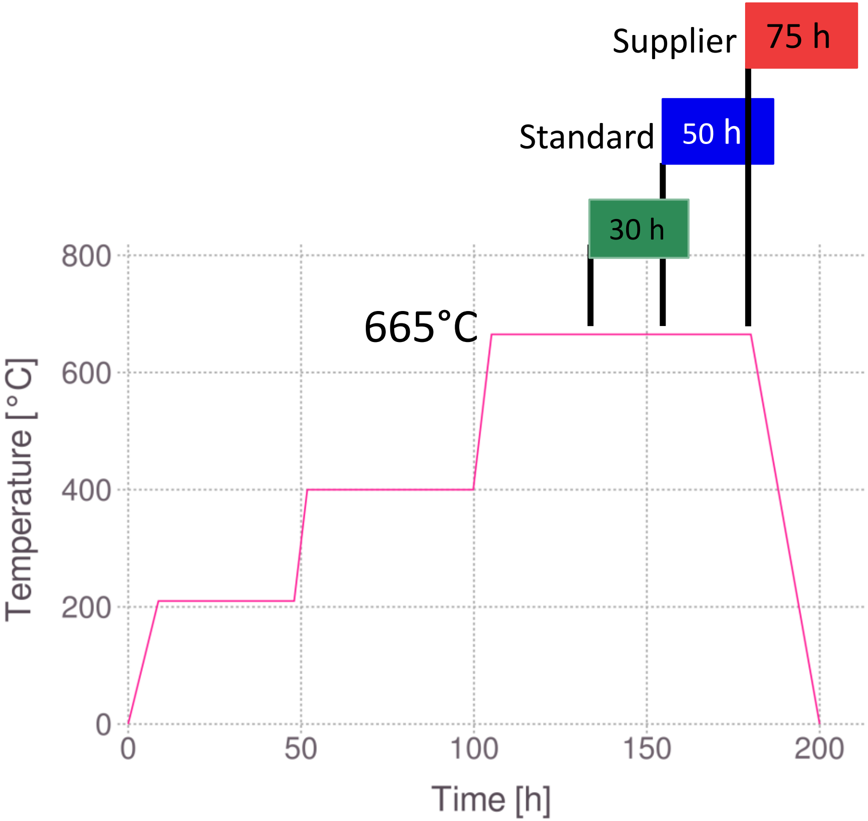
Overview

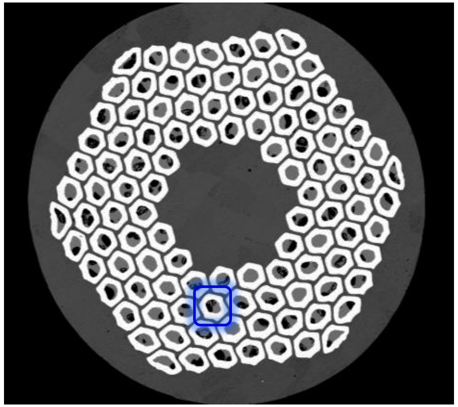


SEM micrograph – virgin RRP® 108/127
0.85 mm unreacted strand

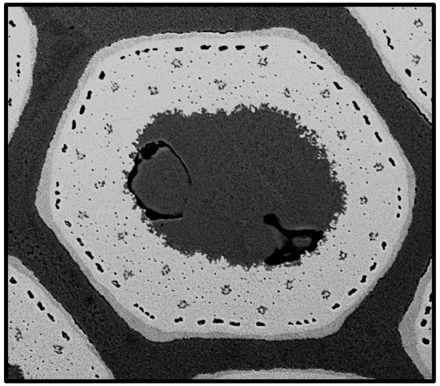


SEM micrograph – RRP® 108/127
unreacted subelement





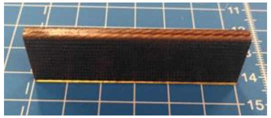
SEM micrograph – virgin RRP® 108/127
0.85 mm reacted strand



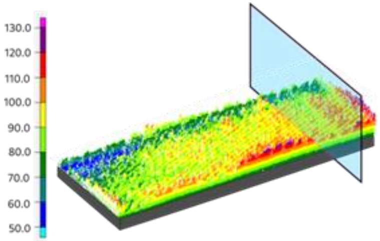
SEM micrograph – RRP® 108/127
reacted subelement

Metallographic characterisation

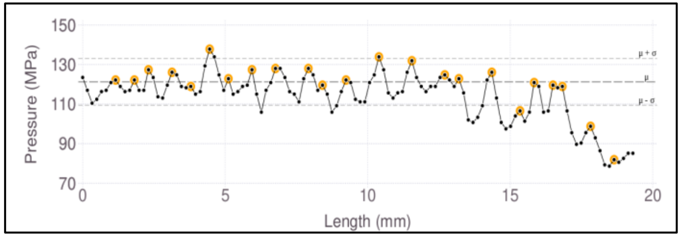
Damage mapping in compressed **double-stack cable** specimens



Double-stack cable sample

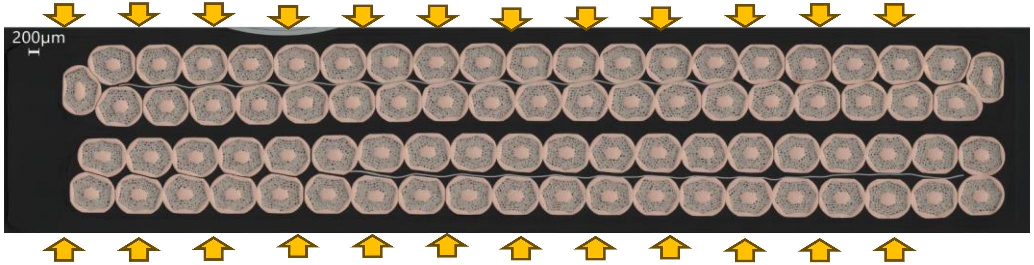


Compression map on surface

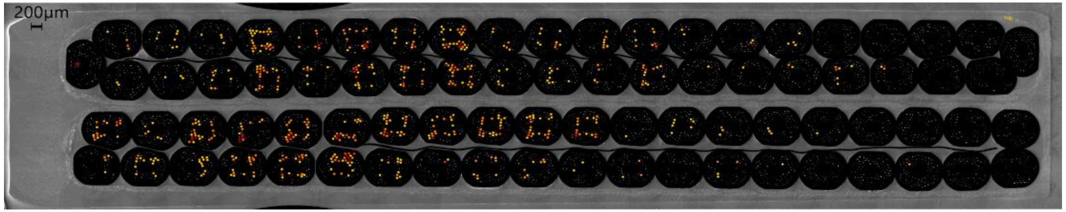


Stress distribution along the cross section.


Embedded _specimens_ – transverse cross sections



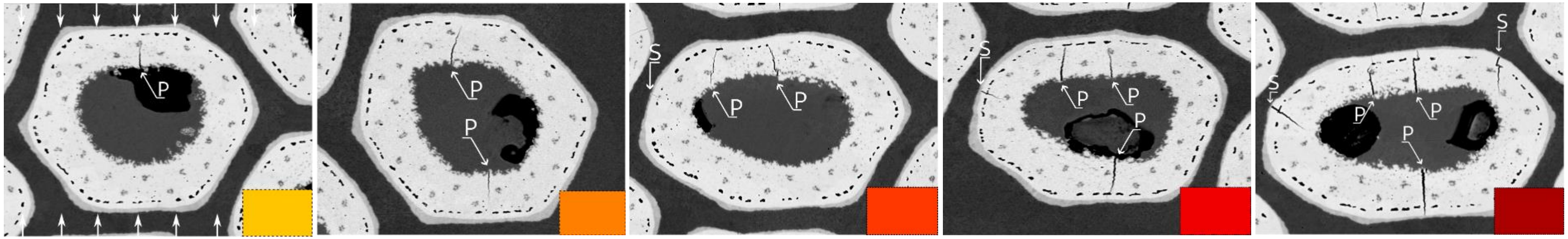
Micrograph of a transverse cross section - with an optical microscope

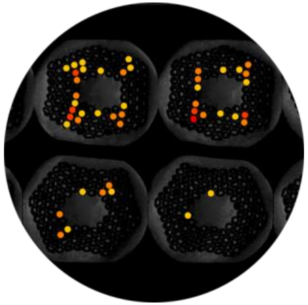


Damage mapping in a compressed double stack cable specimen

SEM Micrographs (75h) :

Increasing damage levels

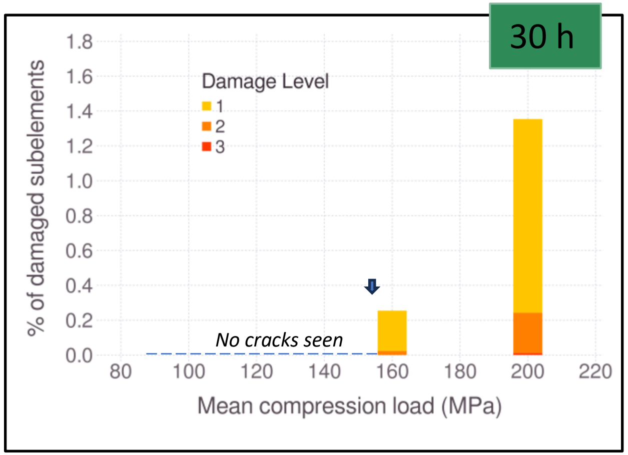


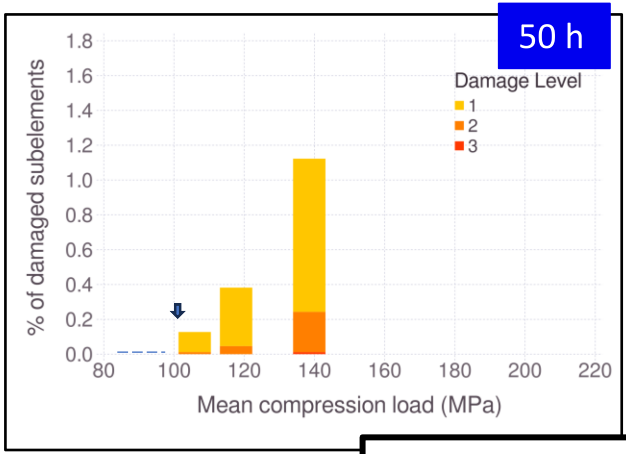


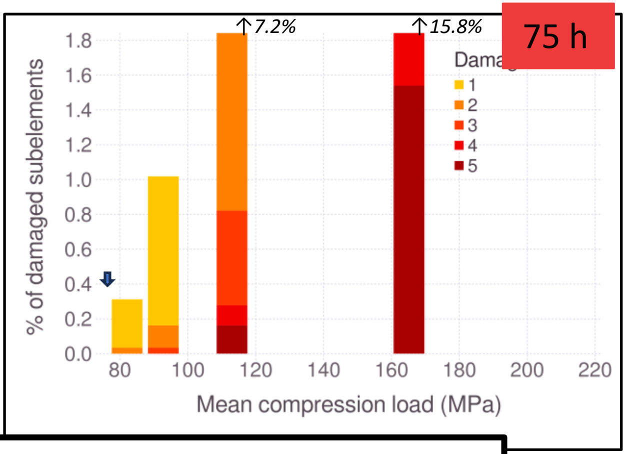
Puthran, K., et al. "Onset of Mechanical Degradation due to Transverse Compressive Stress in Nb 3 Sn Rutherford-Type Cables." IEEE Transactions on Applied Superconductivity 33.5 (2023): 1-6.

Onset and evolution of damage

Damage mapping in compressed **double-stack cable** specimens

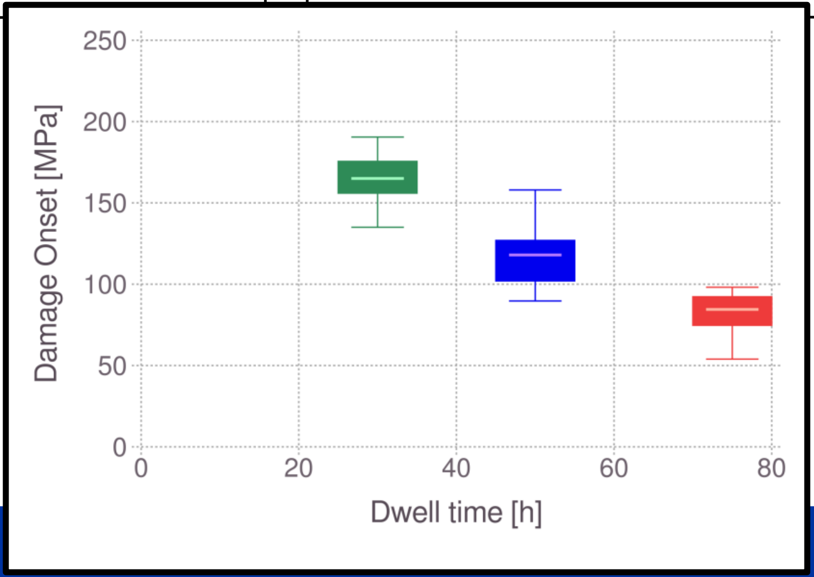






1. Damage onset threshold decreases with longer HT duration.

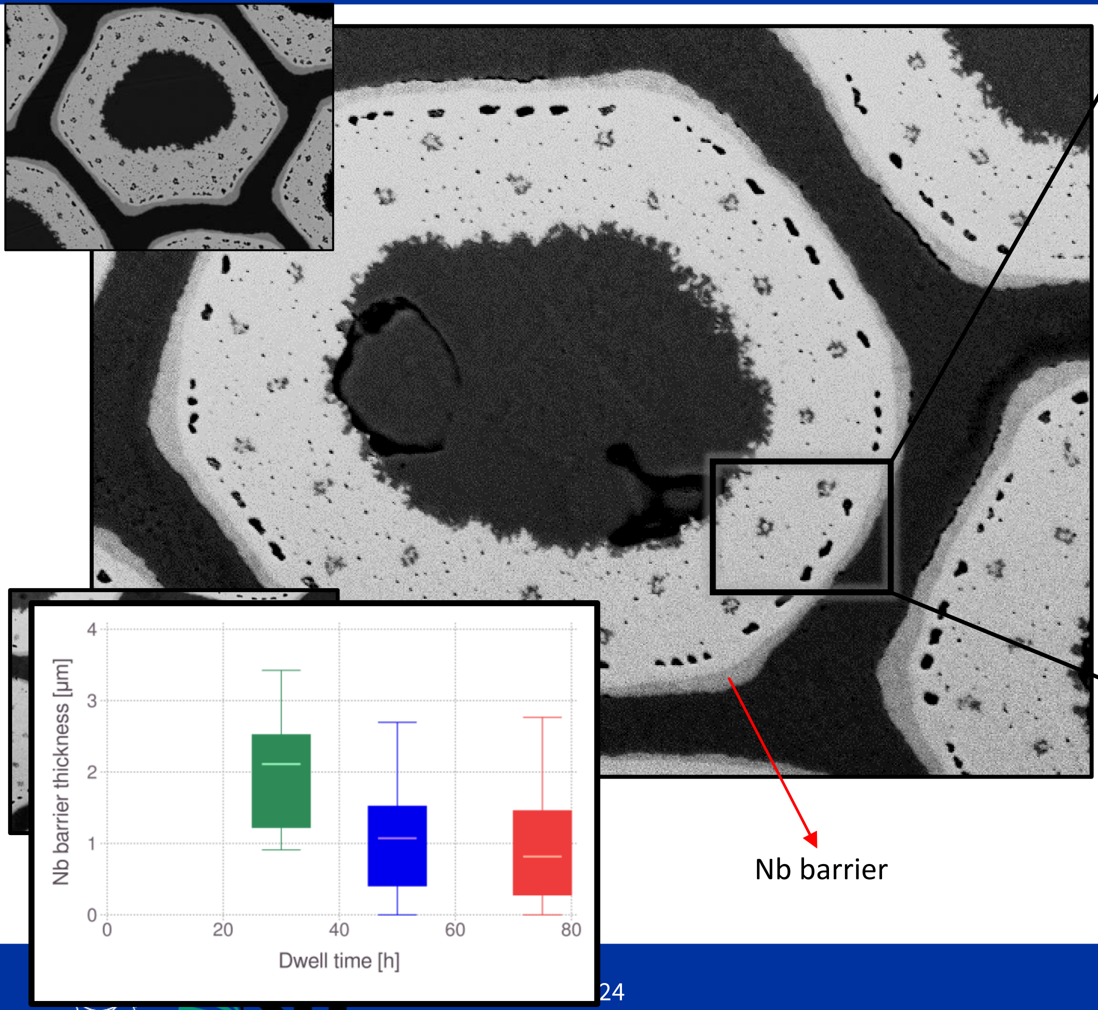
2. Rate of damage evolution is higher for longer heat treatment.



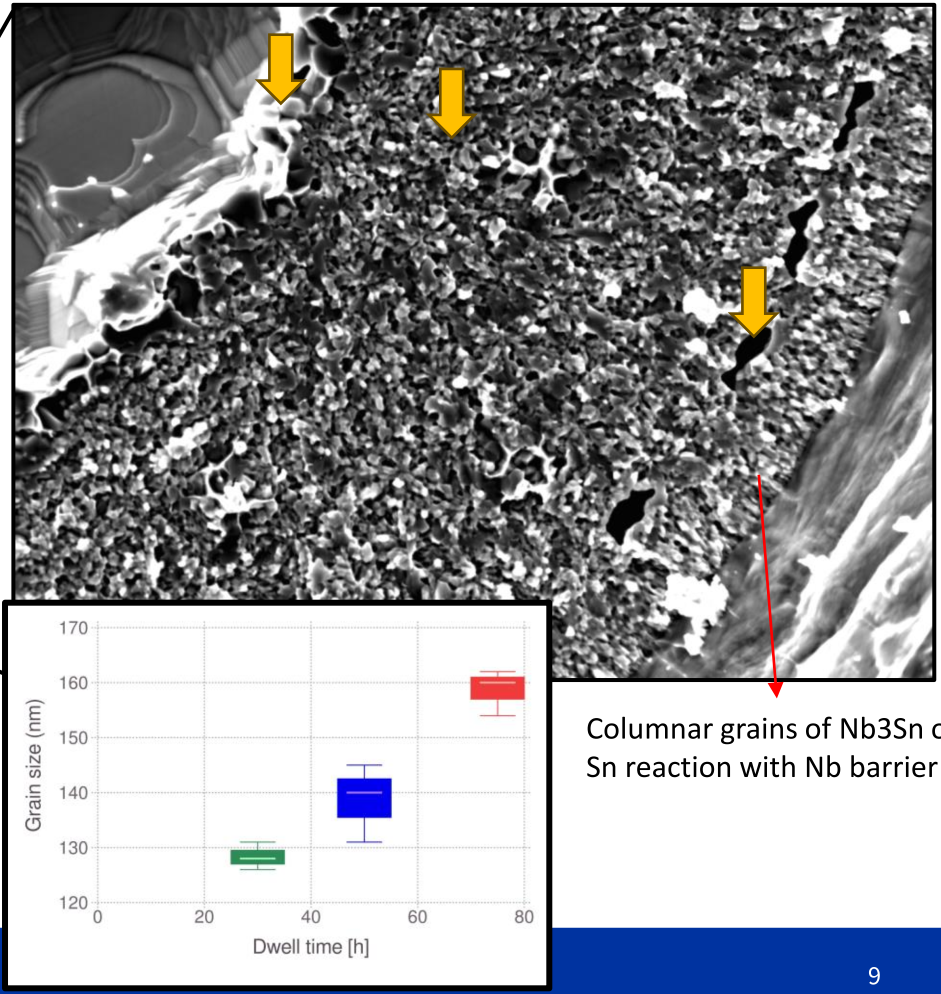
Observations made on over 320 wires (x108 subelements) per HT case

Microstructure

Size of the Niobium barrier and grain size of A15 phase



Nb barrier

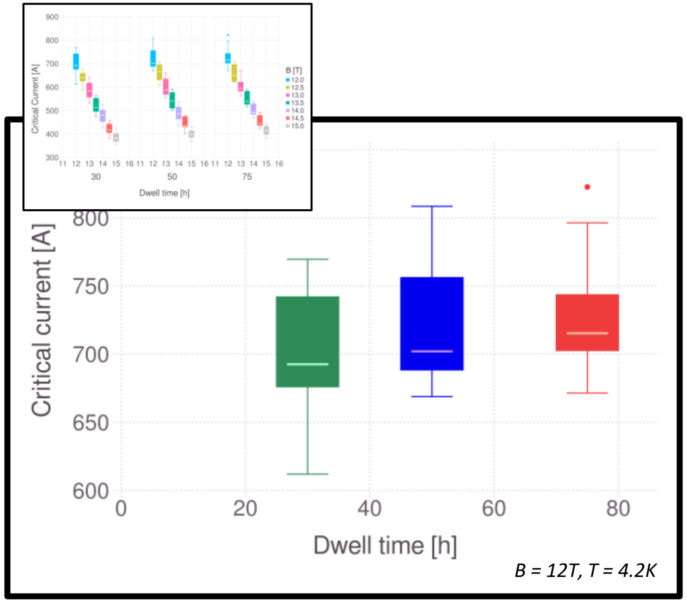


Columnar grains of Nb3Sn of Sn reaction with Nb barrier

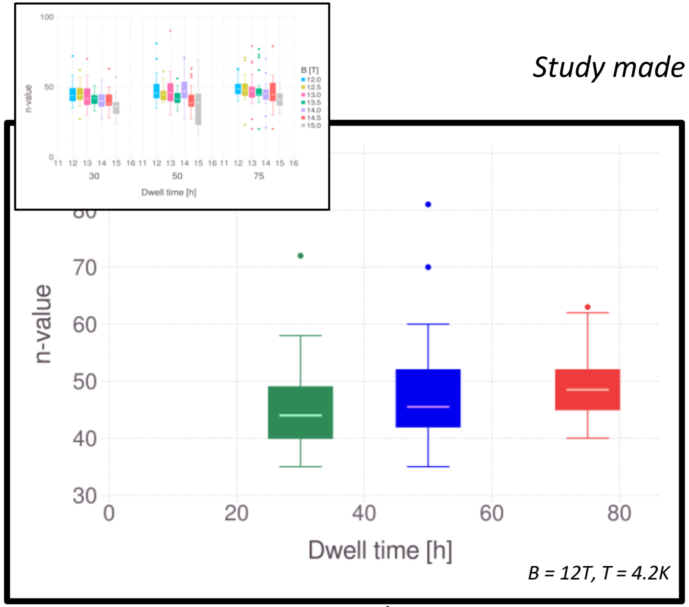
Variation in electrical properties

A small-scale statistical data-set

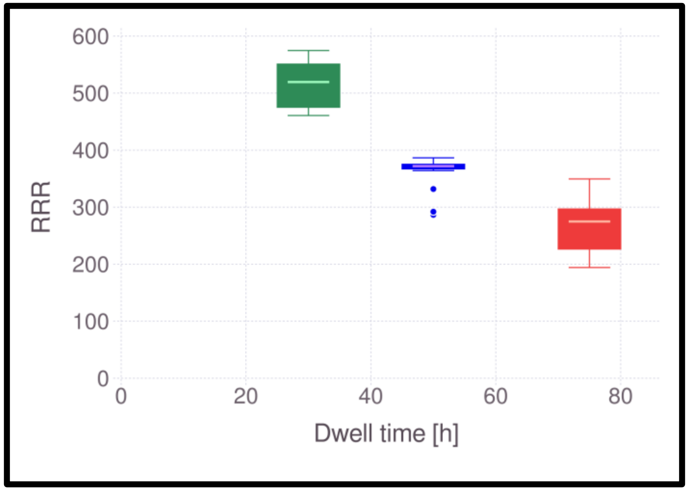
Study made on over 15 wires per HT case



Critical current



n -value



RRR

1. Critical current and n-value increases with longer heat treatment duration, due to consumption of Nb barrier into Nb_3Sn.

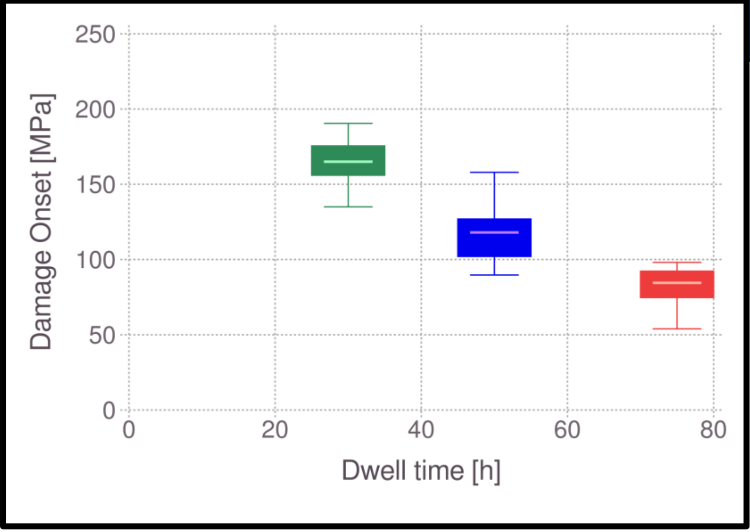
2. RRR or purity of Cu matrix decreases with longer heat treatment duration, due to Sn leakage into Cu matrix.

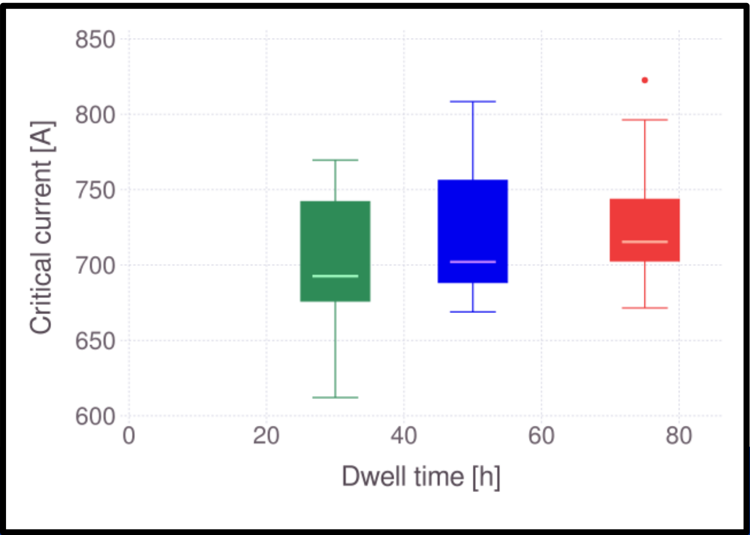
Discussion

Trade-off in the electrical and mechanical properties

*Compared to standard RHT – **50h***

	30h	75h
σ_c	↑ 49%	↓ 33%
I_C (12T)	↓ 1.7%	↑ 1.5%
RRR	↑ 43.3 %	↓ 25%
Gr	↓ 7.4%	↑ 14 %
Nb	↑ 2x	↓ 0.5x





Summary and Outlook

1. HT optimization is fundamental not only for controlling I_c and RRR, but also for mechanical strength.
2. A non-linear trade-off is obtained between the electrical performance and damage threshold due to transverse compressive stress, with a variation in the A15 phase formation dwell time.
3. With a loss in I_c corresponding to 1.7%, a gain of 43% in RRR and 49% in damage threshold in transverse compression may be gained.
4. By reducing the dwell time by ~10h, stronger magnets may be constructed without high compromise on the critical current density.
5. This is essential for future high field [>12T] magnets, where the conductor is exposed to higher transverse stresses.

THANK YOU!