Nb3Sn cable modelling

CG, 14/11/2023

Update on:

1. Model

2. Experimental activities

Observations on cables & wires

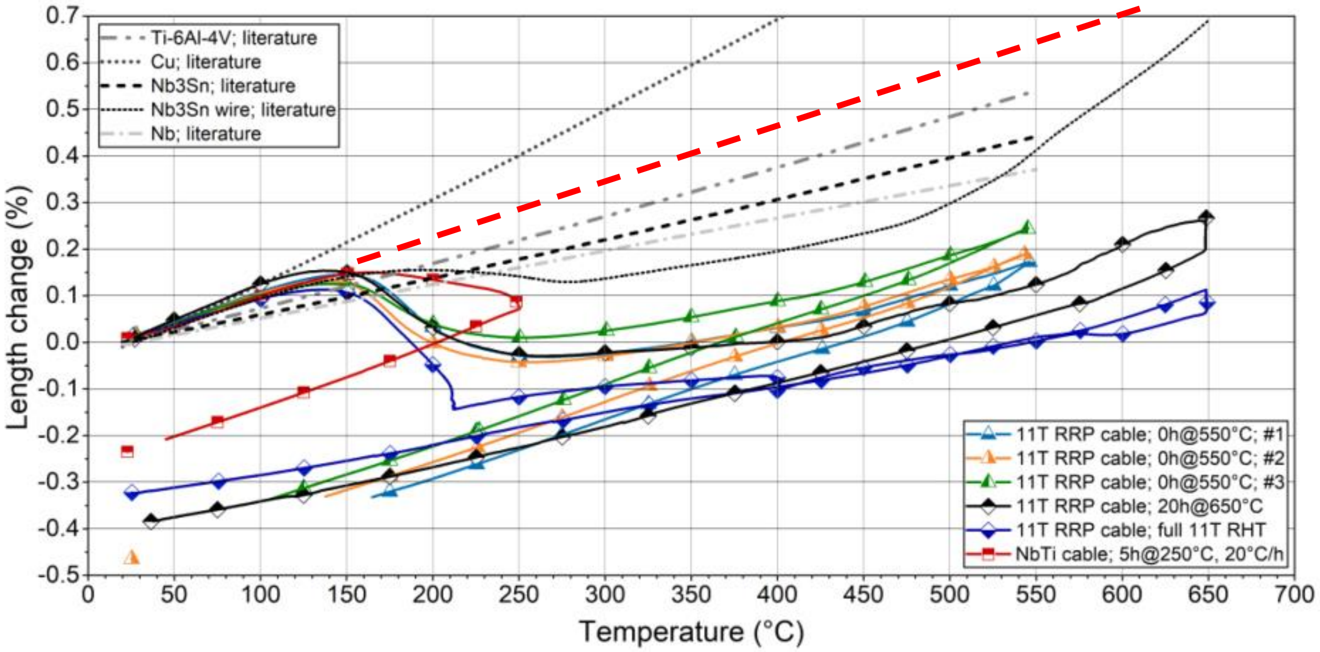
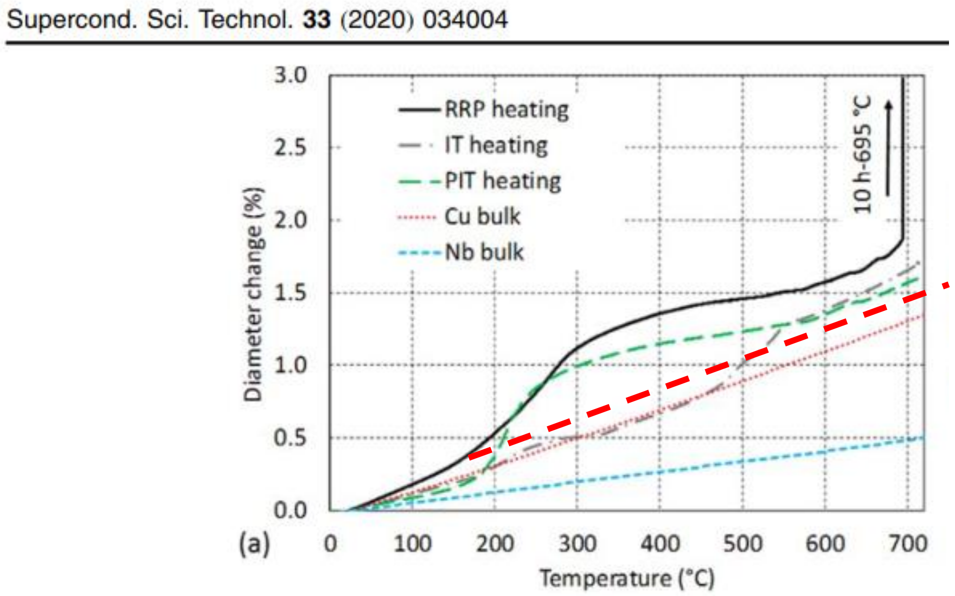
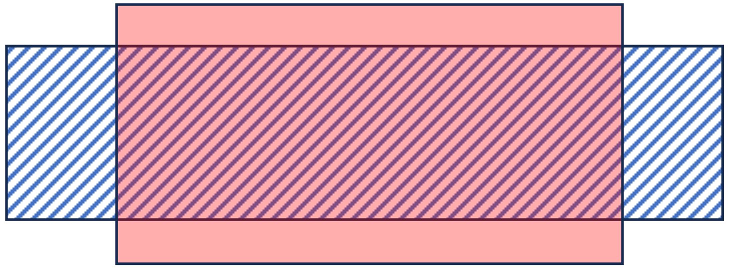


Fig. 5. Comparison of length change behaviour of unreacted Nb_3Sn RRP Rutherford cables (H15OC0220B) with un-annealed Nb-Ti cable and literature values for Ti-6Al-4V [6], Cu [16], Nb [21], bulk Nb_3Sn [16] and Nb_3Sn RRP wires [6].



Axial plastic strain: ~ - 0.004

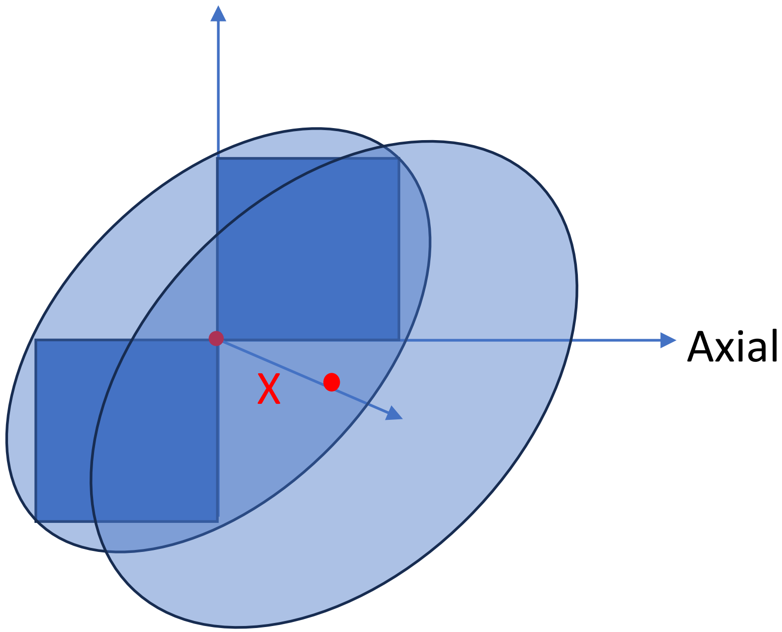
Transversal plastic strain: ~ + 0.005



Yield surface given by Von Mises criterion:

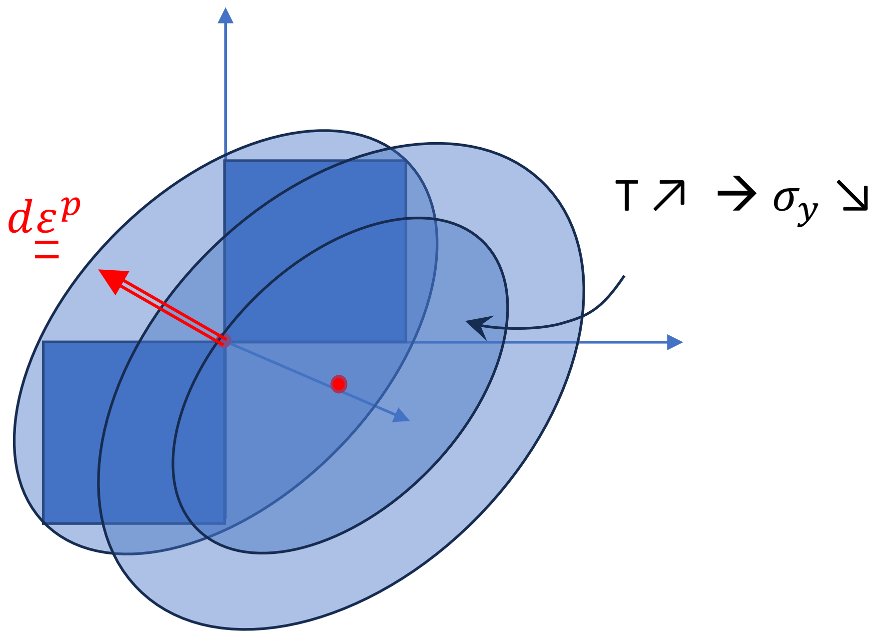
$$f = \sqrt{\frac{3}{2}\left(\underline{\underline{\sigma}}^D - \underline{\underline{X}}\right):\left(\underline{\underline{\sigma}}^D - \underline{\underline{X}}\right)} - R - \sigma_y$$

$$d\underline{\underline{\varepsilon}}^p = d\lambda \frac{\partial f}{\partial \underline{\underline{\sigma}}} \sim d\lambda \frac{\left(\underline{\underline{\sigma}}^D - \underline{\underline{X}}\right)}{\sqrt{\frac{3}{2}\left(\underline{\underline{\sigma}}^D - \underline{\underline{X}}\right):\left(\underline{\underline{\sigma}}^D - \underline{\underline{X}}\right)}}$$



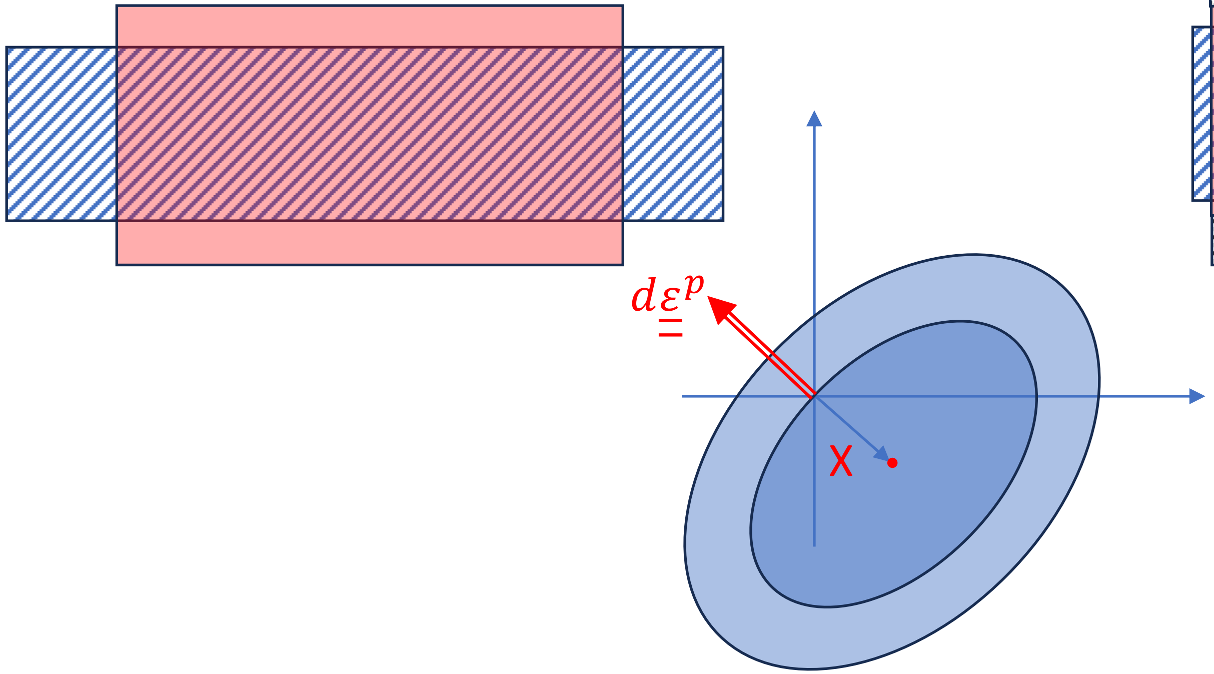
In free state, back stress is mandatory to imply plastic strain.

$$d\underline{\underline{\varepsilon}}^p \sim d\lambda \frac{-\underline{\underline{X}}}{\sqrt{\frac{3}{2}\left(\underline{\underline{\sigma}}^D - \underline{\underline{X}}\right):\left(\underline{\underline{\sigma}}^D - \underline{\underline{X}}\right)}}$$

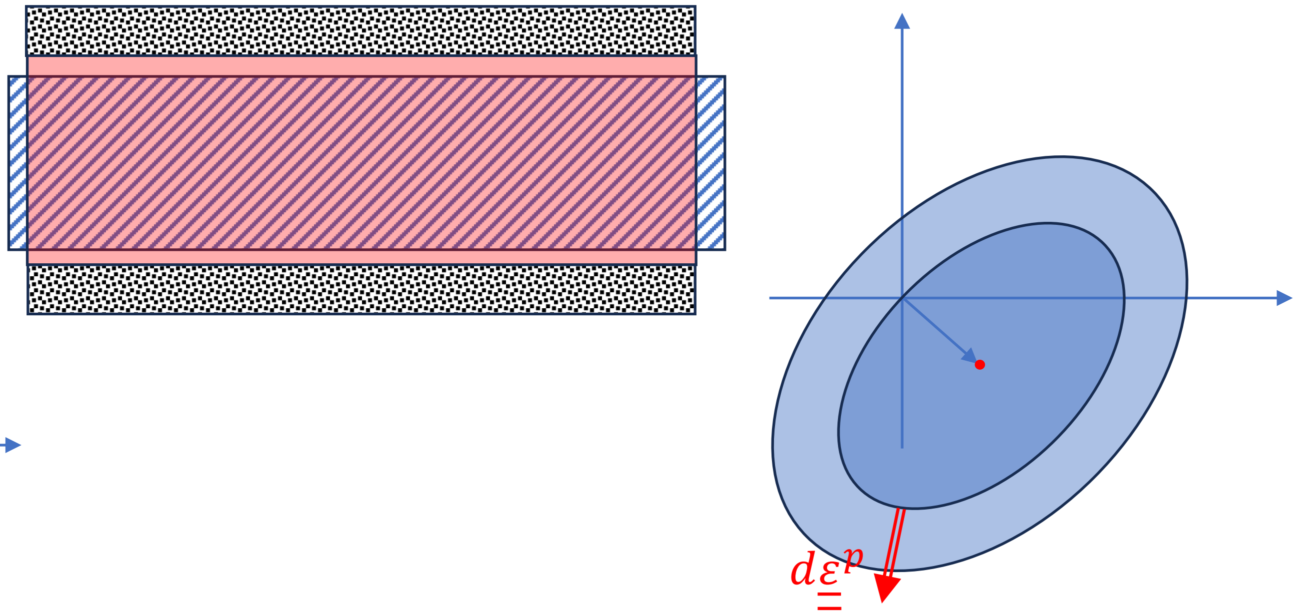


Qualitative behaviour of cables during HT (ramp)

HT in free state

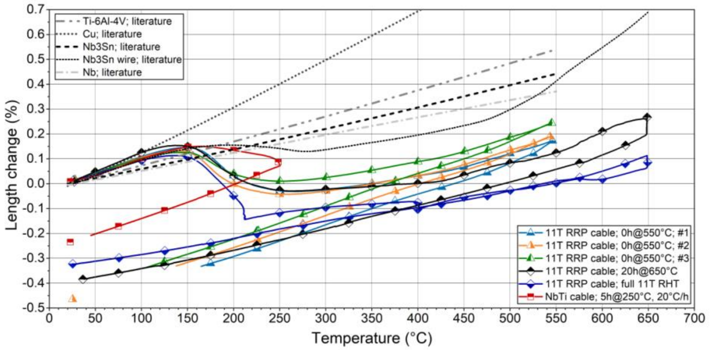


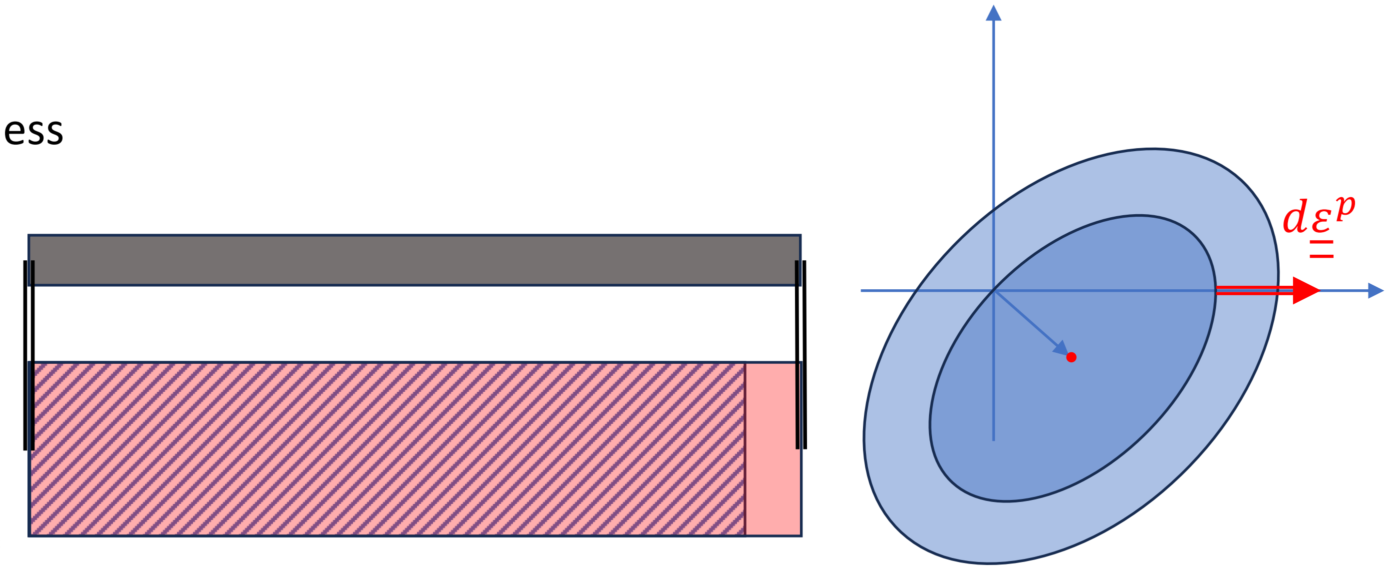
HT of cables (10 stack)with GF braid and/or in stainless steel mold



HT with longitudinal behaviour driven by copper, stainless steel components:

- Wedges
- Loading plates
- Reaction mold





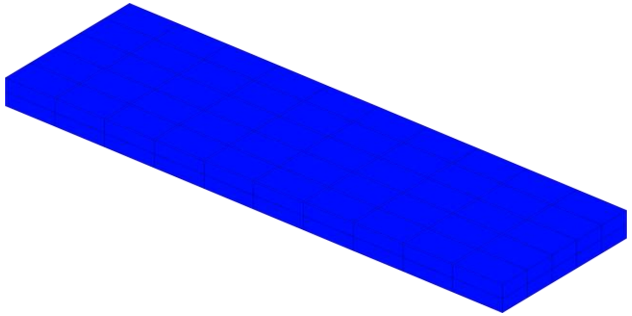
Behavior of the cable during the HT, in particular the temperature ramp, is expected to strongly depend on the boundary conditions.

→ It would be interesting to have an inventory of the different tests and their results.

10 stack samples, free in longitudinal direction, seem, personally, not representative of the real process.

Pending question: with the present configuration, niobium is most likely in tension during the reaction. Is it better, worst or equal compared to a free state?

- Residual stress after cold drawing: ~ Nb +, Cu –
- Cabling: Nb +, Cu +
- Winding: Nb +, Cu +
- Thermal expansion discrepancy (%St. St & Cu): Nb++, Cu 0



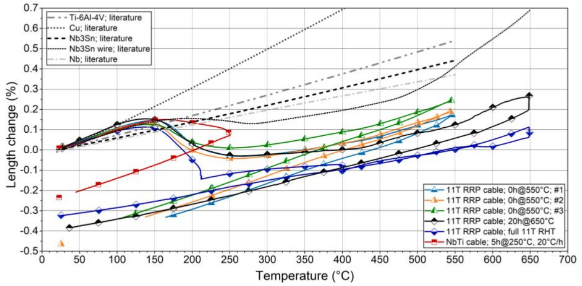
Macroscopic equivalent cable model

$$\underline{\underline{\varepsilon}} = \underline{\underline{\varepsilon}}^{e} + \underline{\underline{\varepsilon}}^{th} + \underline{\underline{\varepsilon}}^{nl}$$

Free state → $\underline{\underline{\varepsilon}}^{e} = 0$

$$\underline{\underline{\varepsilon}}^{th} = \alpha \cdot \Delta T \cdot \underline{\underline{I}}$$

$$\underline{\underline{\varepsilon}}^{nl} = 10^{-3} \cdot \begin{pmatrix} -4 & 0 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & 5 \end{pmatrix}_{(length, width, thickness)}$$



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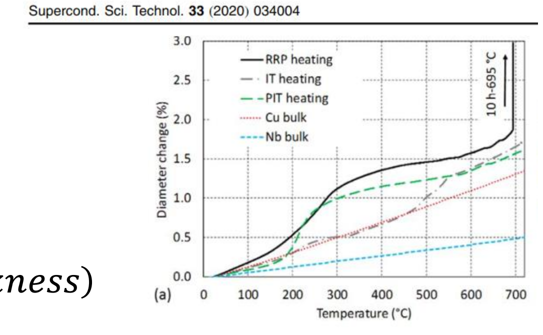
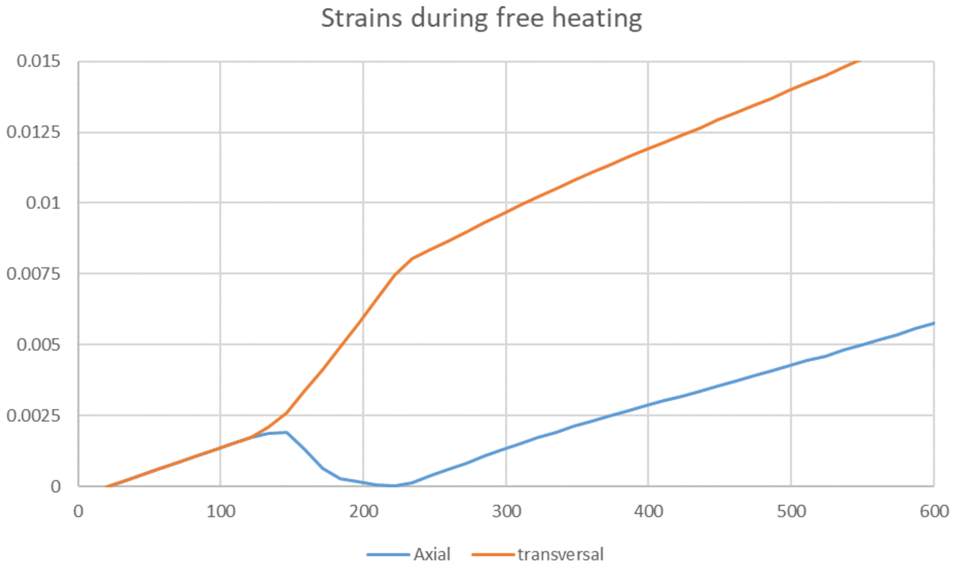


Transversal plastic strain: ~ + 0.005

$\underline{\underline{\varepsilon}}^{nl}$ is not a deviatoric (not coherent with plasticity model) → hydrostatic (change of volume) and plastic parts

$$\underline{\underline{\varepsilon}}^{nl} = \underline{\underline{\varepsilon}}^{h} + \underline{\underline{\varepsilon}}^{p} = \frac{1}{3} \cdot tr\left[\underline{\underline{\varepsilon}}^{nl}\right] \cdot \underline{\underline{I}} + \underline{\underline{\varepsilon}}^{p}$$

$$\underline{\underline{\varepsilon}}^{p} = 10^{-3} \cdot \begin{pmatrix} -6 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 3 \end{pmatrix}_{(lenght, width, thickness)}$$



Model parameters will be identified mainly on free state heat treatment (estimation of $\underline{\underline{\varepsilon}}^{nl}(T)$).

It shall be benchmarked with tests in constrained states.

Next steps:

Measurement of stiffness of cables and of the strain evolutions with temperature in free, force and deformation controlled conditions.

Assessment of the model parameters.

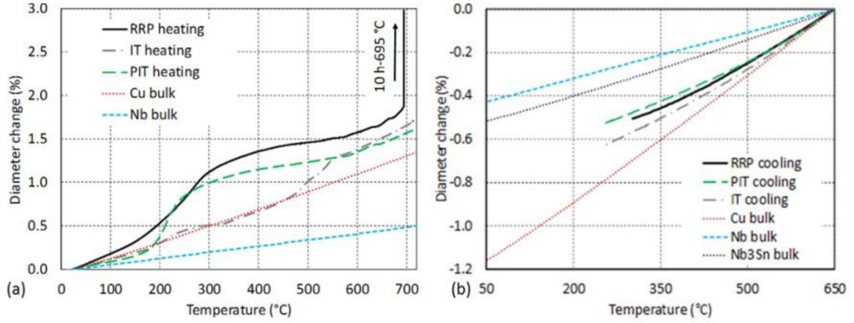


Figure 1. (a) Typical evolution of the RRP, PIT and IT wire diameters as measured by dilation during RHT with a ramp rate of 1.67 °C min^{-1}. (b) Evolution of the reacted RRP, PIT and IT wire diameters during cooling from 650 °C (average of at least two independent measurements). The thermal expansions of Cu, Nb and Nb_3Sn are shown for comparison.

Table 1. Comparison of Nb_3Sn wire diameter and wire and cable length changes before and after RHT. The change to the wire's cross-sectional area was calculated from the diameter change.

	Wire			Cable [11]
	Diameter change (%)	Cross-sectional area change (%)	Length change (%)	Length change (%)
RRP	+2.5	+4.9	−0.07	−0.32
PIT	+1.6	+3.3	−0.15	−0.40
IT	+1.1	+2.3	not measured	not measured

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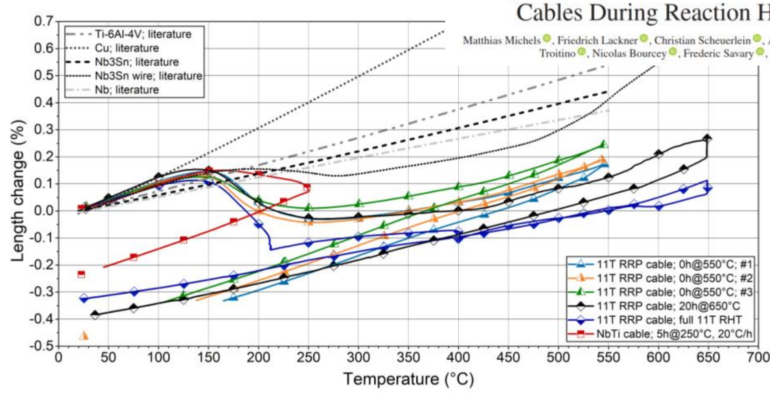
Length Changes of Unconfined Nb_3Sn Rutherford Cables During Reaction Heat Treatment

Matthias Michels, Friedrich Lackner, Christian Scheuerlein, Alejandro Carlon Zurita, Salvador Ferradas Troitino, Nicolas Bourcey, Frederic Savary, and Davide Tommasini



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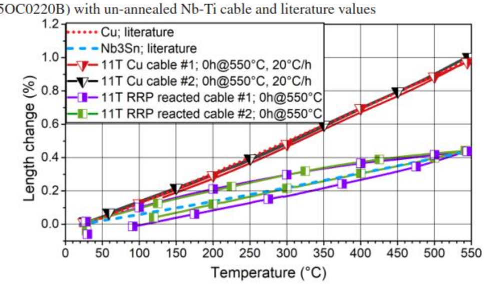

Fig. 6. Relative length changes of un-annealed Cu Rutherford cables and reacted Nb_3Sn RRP Rutherford cables during heat treatment up to 550 °C and comparison with literature values for Cu and Nb_3Sn [16].

Thermomechanical Behavior of the HL-LHC 11 Tesla Nb_3Sn Magnet Coil Constituents during Reaction Heat Treatment

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[1] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[2] Federal Institute for Materials Research and Testing (BAM), Berlin, Germany

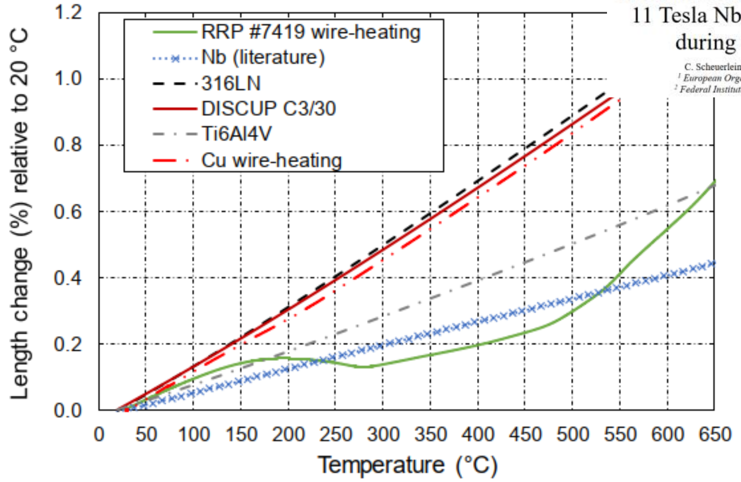
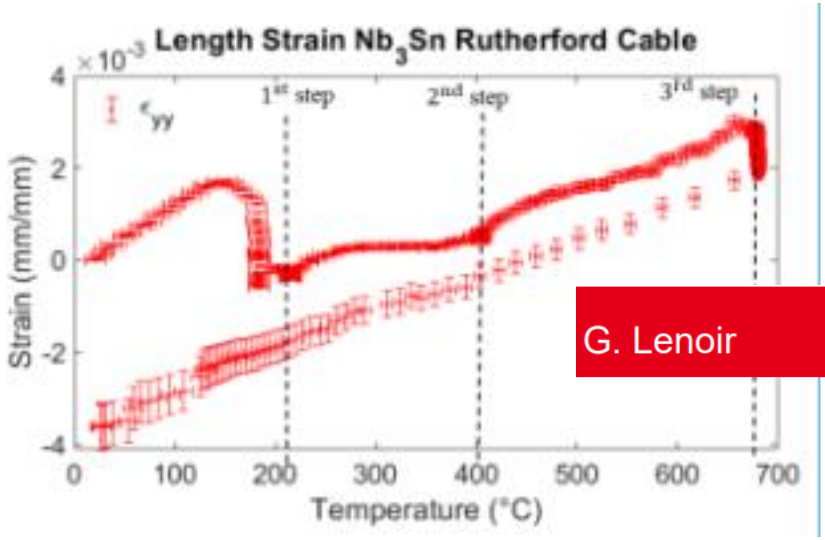


Fig. 10: Comparison of RRP #7419 Nb_3Sn wire axial length change during first heating with that of DISCUP C3/30, Ti6Al4V, and 316LN. The relative length changes of a Cu wire and the Nb thermal expansion from reference [20] are shown for comparison.



Elastic modulus of RRP type Nb_3Sn wire

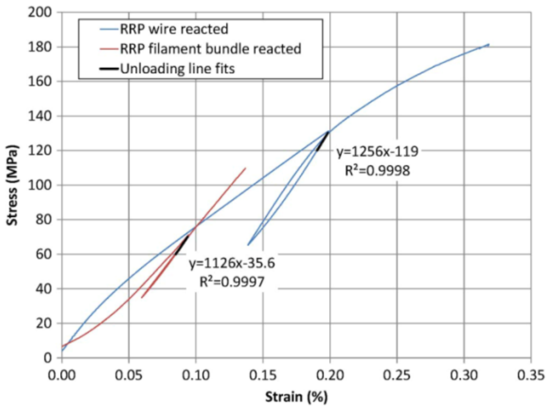


Fig. 3. Stress-strain curves measured at room temperature on a reacted RRP wire and its extracted filaments.

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- E is defined as the initial linear slope of the unloading curve.
- Determined elastic modulus of the reacted RRP wire: **126 GPa**

TABLE II
Nb_3Sn Elastic Moduli in Axial and Transverse Directions Calculated for the RRP and PIT Wires at RT and at 4.2 K

		PIT B215	RRP #7419
RT	E_{axial}	130	140
	E_{trans}	135	129
4.2 K	E_{axial}	106	127
	E_{trans}	116	104

Experimental activities

Mechanical tests with MME:

Nous proposons une matrice d'essais comme suit :

- essais de dilatométrie 20-650-20C sur brins:
  - direction axiale :
    - 3x essai sous faible force
    - 3x essai sous traction a 3 N (Fmax)
    - 3*Essai sous traction a 1.5 N
  - Direction transversale
    - 3x Essai à faible force

- Essais de « traction » de cables sous temperature contrôlée
  - 3x Traction à température ambiante → rigidité et Poissons
  - Cycle 20-650-20C :
    - 3x « 0 » force → déformations axiale et transversales
    - 3x F Force → déformations axiale et transversales
    - 3x X déformation axiale (F=k.X) → force axiale et déformations transversales

Ici nous procèderons comme discuté pour l'arrimage des éprouvettes (collage céramique) sur des inserts consommables. Un approche similaire a été décrit dans la littérature pour les basses températures (brin brassé a l'étain) avec des bonnes résultats. La mesure des déformations transversales reste compliquée, mais je pense que possible avec le système de Corrélation Digitale D'image.

Nous travaillons déjà sur le dessin des outillages. Je contacterai prochainement Hervé Rambeau pour planifier la fabrication (même si je pense que c'est un tout petit truc.).

Au niveau de la production des échantillons, il serait nécessaire de prévoir au moins:
- x15 segments d'au moins 30 mm (dilatometrie)
- x15 segments d'au moins 80 mm (traction)

Comme tu le sais, nous devons facturer no activités. Nous estimons le cout de la campagne en 8000 CHF.

To be added:
- Essais de traction sur brins