Measurement Techniques for Longitudinal Dimensional Changes of Nb_3Sn Conductor due to the Reaction Heat Treatment

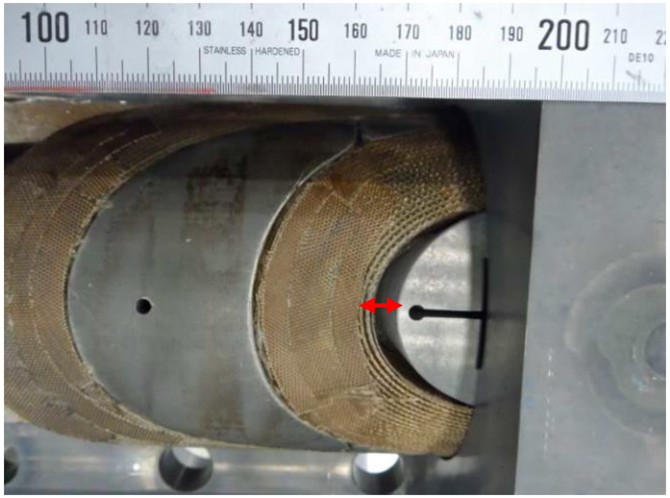
M. Michels, C. Scheuerlein, F. Lackner

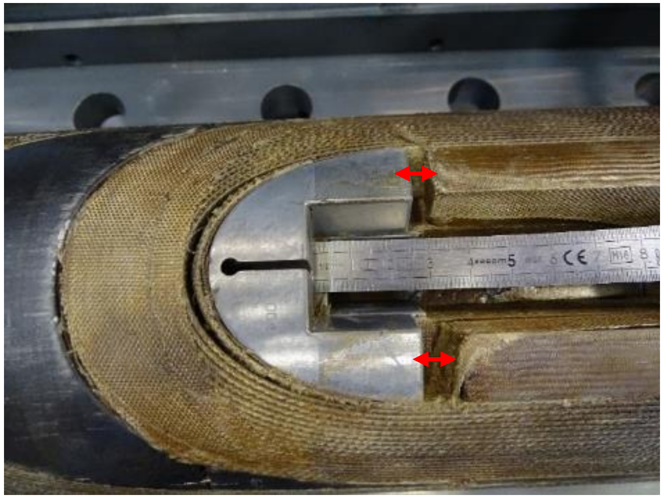
Outline

1. Introduction
2. Length changes of Nb_3Sn RRP wires
3. Length changes of Nb_3Sn Rutherford Cables
4. Conclusion
5. Outlook

Introduction

Why measuring the longitudinal dimensional changes of Nb_3Sn conductor?





Gaps observed between wedges and end spacers after opening of the reaction mold on 11T dipole prototypes.

- Coil dimensional changes due to the Reaction Heat Treatment (RHT) are not well understood.
- The knowledge of the dimensional changes of different cable types might help to predict the coil behaviour during RHT in advance.

Why does the Nb_3Sn volume increase due to the RHT?

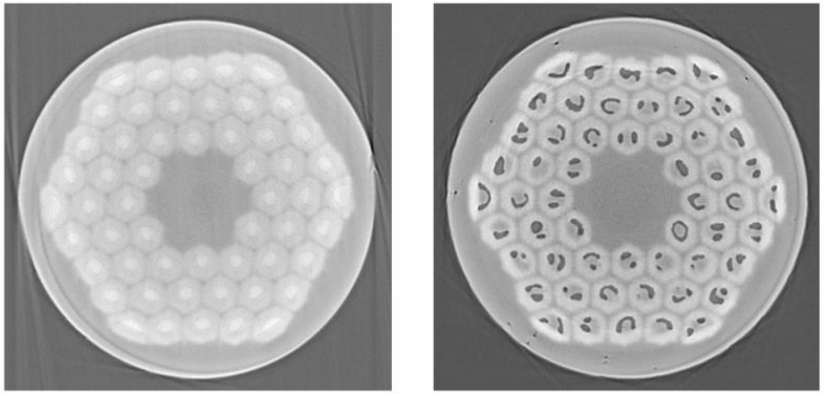


Fig. 6. OI-ST RRP strand cross section before HT (left) and after 17-h 695 °C HT (right), obtained by synchrotron microtomography. The total void cross section is 0.027 mm^2, which corresponds with 5.0% of the total strand cross section.

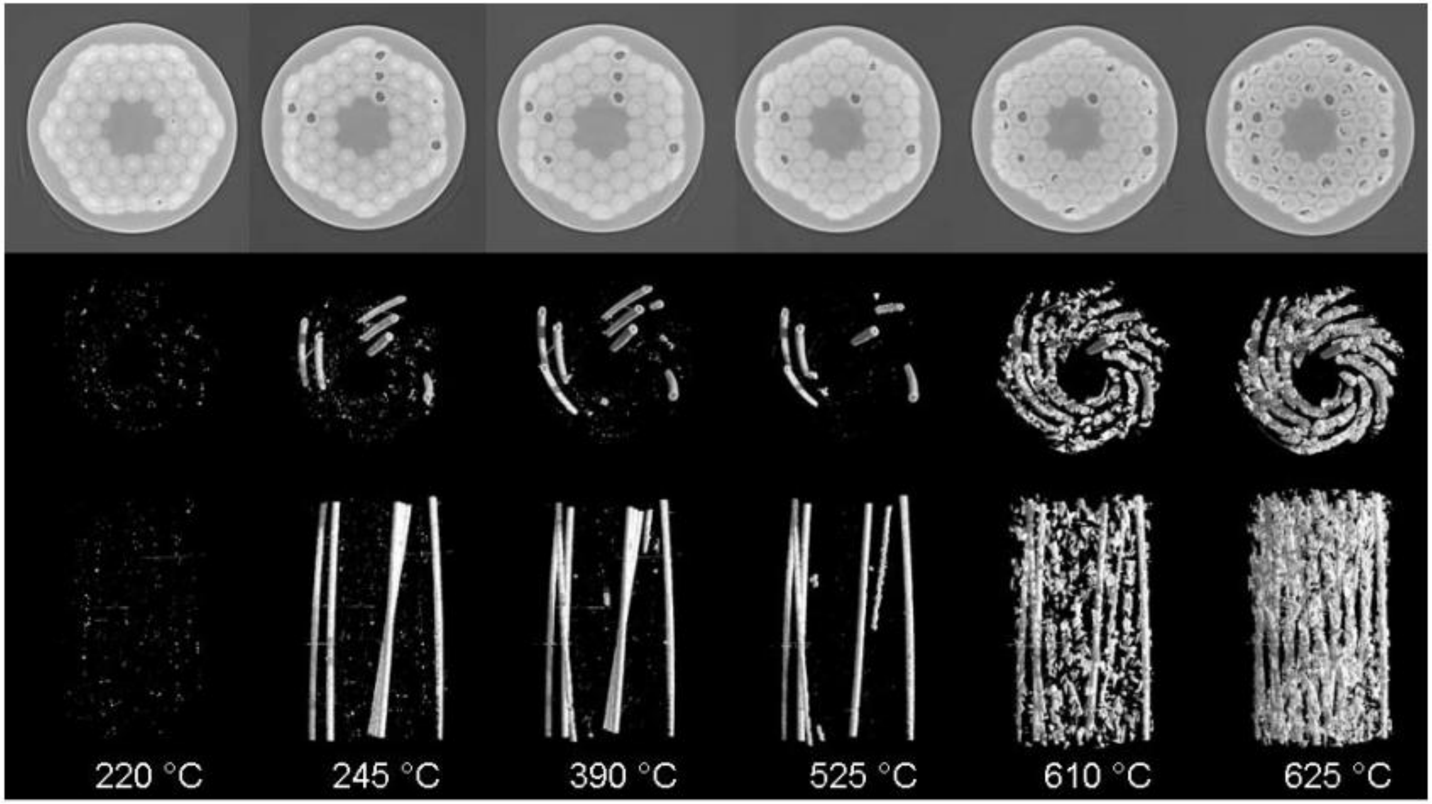
The volume increase of the unconstraint RRP wire corresponds approximately with the void volume after the reaction.

Wire volume shrinks if reaction is performed under high pressure (2000 bar) and no voids are formed.

	Diameter (µm)	*Strand cross section (mm^2)*	*Pore cross section (mm^2)*	**Length (mm)**
Before HT	803±1.7	0.507	0	304.2
After HT	823±1.2 (+2.5%)	0.532 (+4.9%)	0.0267	304.0 (-0.07%)

„Phase Transformations During the Reaction Heat Treatment of Internal Tin Nb_3Sn Strands With High Sn Content", C. Scheuerlein et al., IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 18, NO. 4, DECEMBER 2008

In situ observation of void formation during RHT



Porosity evolution inside a RRP wire as observed by synchrotron microtomography.

„Phase Transformations During the Reaction Heat Treatment of Internal Tin Nb_3Sn Strands With High Sn Content", C. Scheuerlein et al., IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 18, NO. 4, DECEMBER 2008

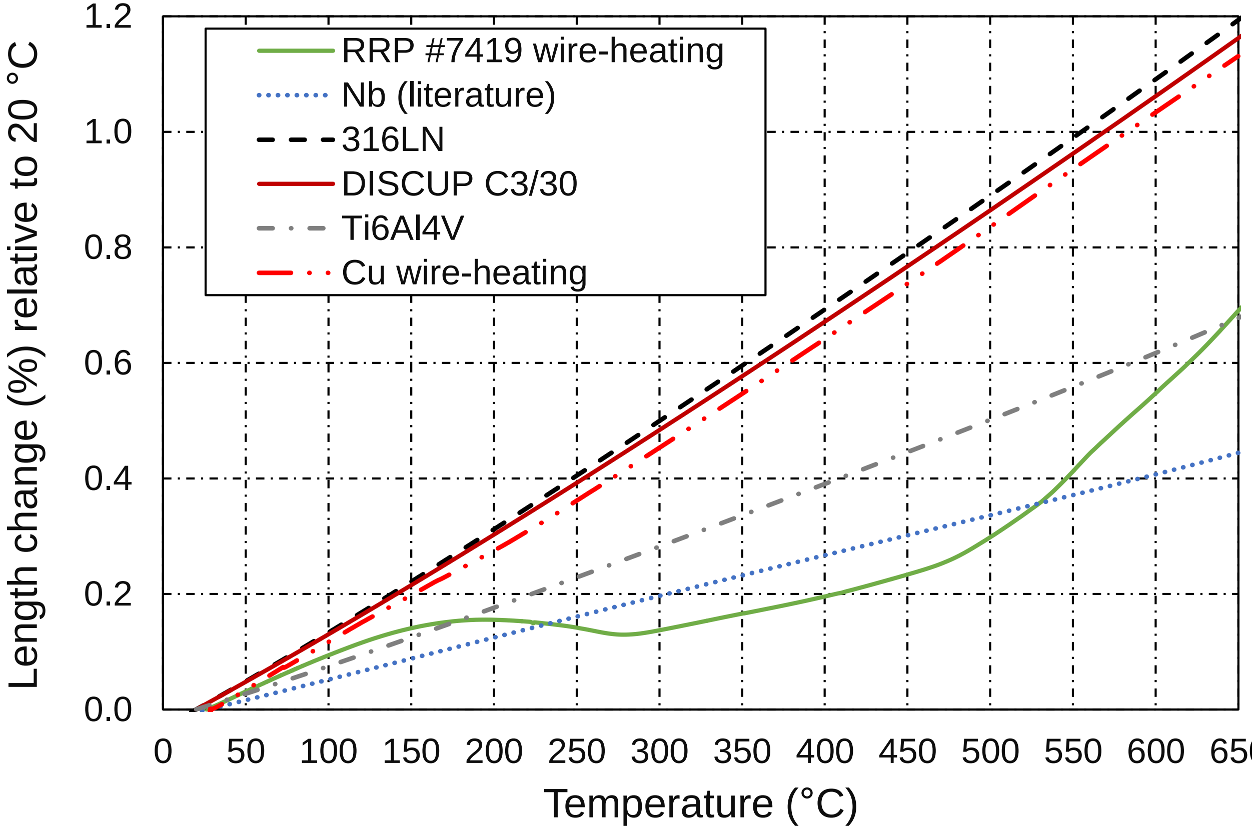
Length changes of Nb_3Sn wires

RRP wire length change measurements during the RHT with a dilatometer

- Wire samples are not well suited for dilatation measurements (slightly bent wire, internal stresses and end modifications during RHT)
- Dilation results are qualitative results showing the overall wire expansion behaviour
- Experimental set-up: Netzsch 402E high temperature dilatometer
  inert atmosphere
  heating rate 5 °C/min
- Sample: 10 mm freestanding
  OI-ST RRP wire
  Ø 0.8 mm

Measurements conducted by Federal Institute for Materials Research and Testing (BAM), Berlin, Germany

Wire length change measurements during the RHT (warm up)

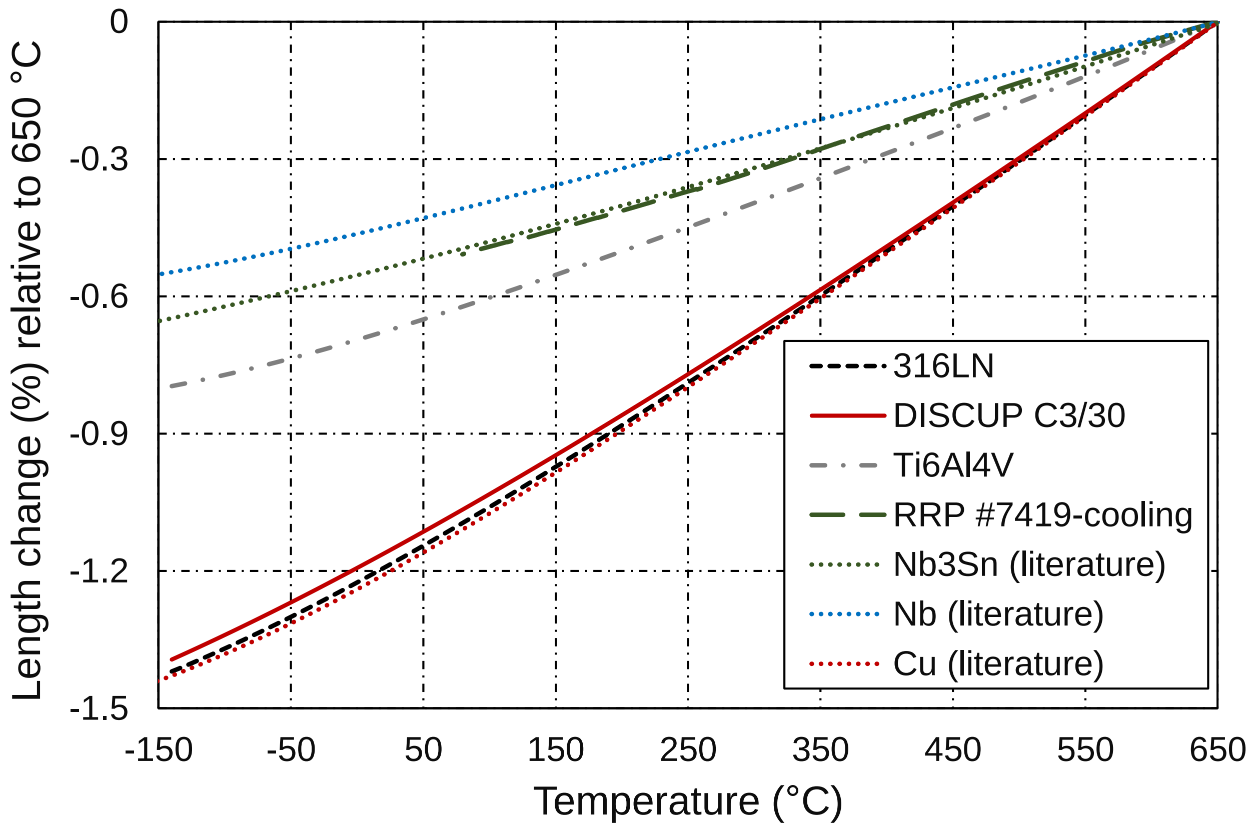


Wire length changes determined by coefficients of thermal expansion (CTE), phase transformations and stress states of constituents.

Unusual behaviour during warming up compared to homegeneous materials.

„Thermomechanical Behaviour of the HL-LHC 11 Tesla Nb_3Sn Magnet Coil Constituents during Reaction Heat Treatment", C. Scheuerlein et al.

Wire length change measurements during the cool down



Wire length changes determined by coefficients of thermal expansion (CTE).

Reacted wire length changes show similar behaviour as bulk Nb_3Sn (literature).

„Thermomechanical Behaviour of the HL-LHC 11 Tesla Nb_3Sn Magnet Coil Constituents during Reaction Heat Treatment", C. Scheuerlein et al.

Summary: Nb_3Sn wire volume changes

- Unusual Nb_3Sn RRP wire expansion behaviour during RHT compared to homogeneous materials.
- Wire volume increase during RHT correlates to formation of voids inside the subelements.
- Wire volume changes continue during isothermal holding steps (no thermal expansion of other coil constituents that constrain the conductor).
- Steel mould, Ti6Al4V and DISCUP wedges thermal expansion behaviour is likely influencing conductor volume changes in a magnet coil.
- During cooling the wire length contraction is similar to bulk Nb_3Sn.

Length changes of Nb_3Sn Rutherford cables

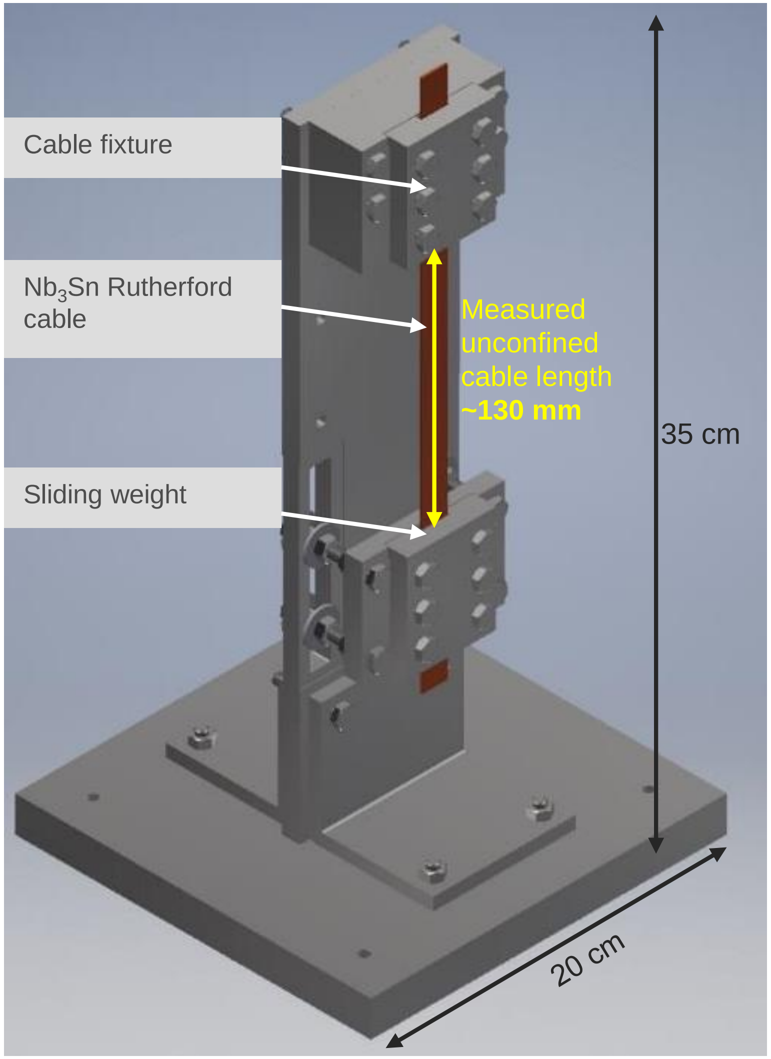
Vertical testing device

- Cable sample length is unconfined to avoid friction

- Typical free cable length: 130 mm

- Constant uniaxial tensile load (sliding weight):
  - Mass: 734 g → 0.5 MPa
    (cable cross-section of 15.4 mm² and zero friction assumed)
  - For maintaining cable straightness, no creep expected
  - Rotation angles restricted to 1.6 °
    → Limited cable torsion

- Specified length measurement resolution: 50 µm
  (about 10% of typical contraction of 0.5 mm)



Room temperature cable length measurement methods (before and after RHT)



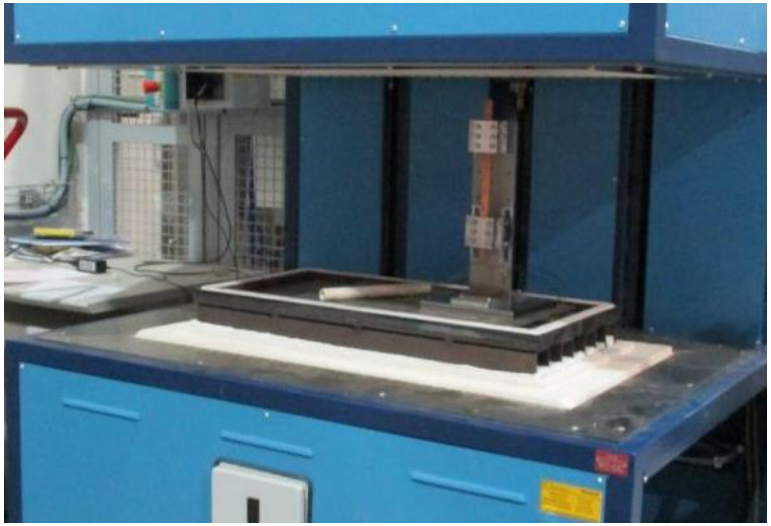
	Calliper	Faro Probe	Faro Laser
Dimensions	Length	Length	Length, cable deformation
Method	Invasive	Invasive	Non-invasive
Repeatability	100 µm	29 µm	25 µm
Absolute Accuracy	± 30 µm	± 41 µm*	± 41 + 10 µm*

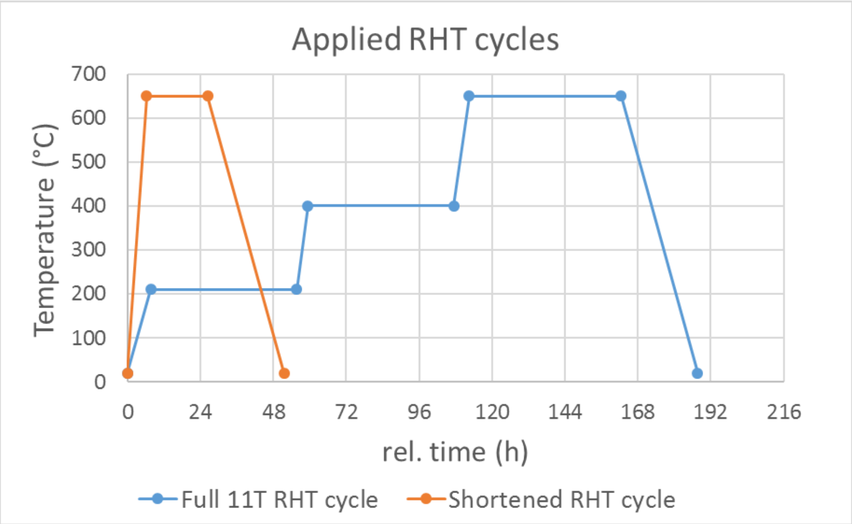
*over full FaroArm measurement radius of 2.7 m

M. Michels, CERN
C. Scheuerlein, CERN
F. Lackner, CERN

Experimental conditions

- RHT performed in hood furnace in Argon atmosphere.
- First RHT performed with full cycle (48 h@210 °C, 48 h@400 °C, 50 h@650 °C ~ 9 days).
- Later RHT performed with shortened cycle (20 h@650°C, 100°C/h ramp rate ~ 3 days).
- Preliminary result: No measureable influence of the accelerated RHT on the cable length results.





Thanks for the RHT to N. Bourcey, CERN, TE-MSC-MDT

Preliminary cable length change results (before and after RHT)

#	Cable	RHT cycle	Measurement method	length before (mm)	length after (mm)	length change %
1	bare 11T low grade cable: H15OC0180A	full 11T	Calliper	122.91	122.27	-0.52
2	bare 11T low grade cable: H15OC0180A	short (100°C/h, 20 h at 650°C)	Calliper	140.08	139.27	-0.58
3	bare 11T high grade cable: H15OC0194A	short (100°C/h, 20 h at 650°C)	Faro (laser)	146.09	145.45	-0.44
4	braided 11T high grade cable: H15OC0194A	short (100°C/h, 20 h at 650°C)	Faro (laser)	130.79	130.12	-0.51
5	bare 11T high grade cable: H15OC0194A	short (100°C/h, 20 h at 650°C)	Faro (laser)	127.05	126.41	-0.50
6	bare 11T high grade cable: H15OC0194A	short (100°C/h, 20 h at 650°C)	Faro (laser)	140.81	140.21	-0.42
7	bare 11T high grade cable: H15OC0194A	short* (100°C/h, 96 h at 650°C)	Faro (laser)	140.86	140.52	-0.24

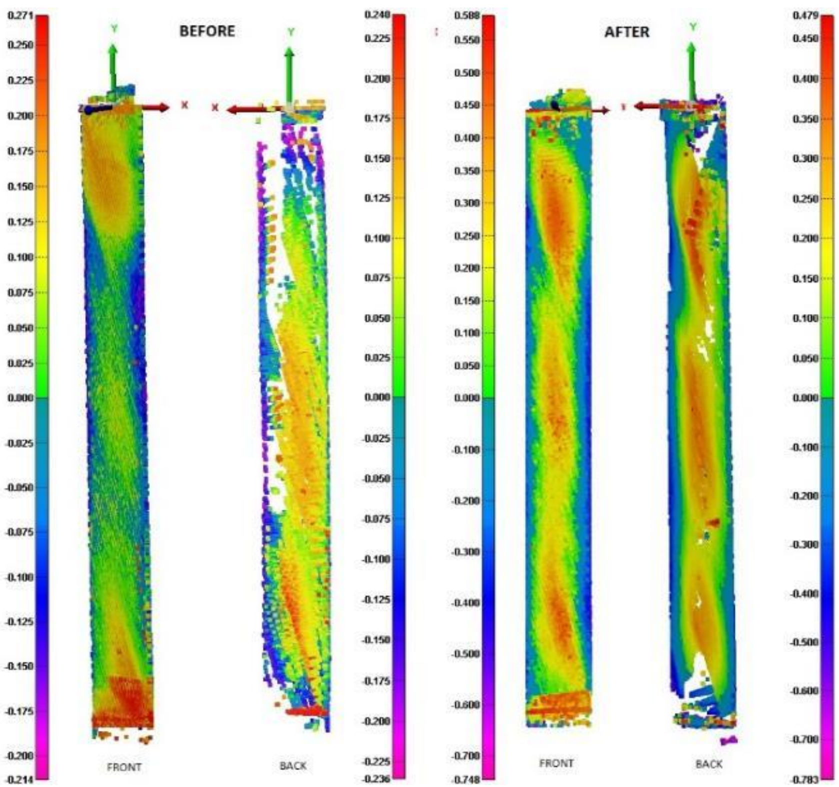
Preliminary result for bare 11T dipole high grade cable, H15OC0194A

Length change: -0.46%

Standard deviation: 0.043%

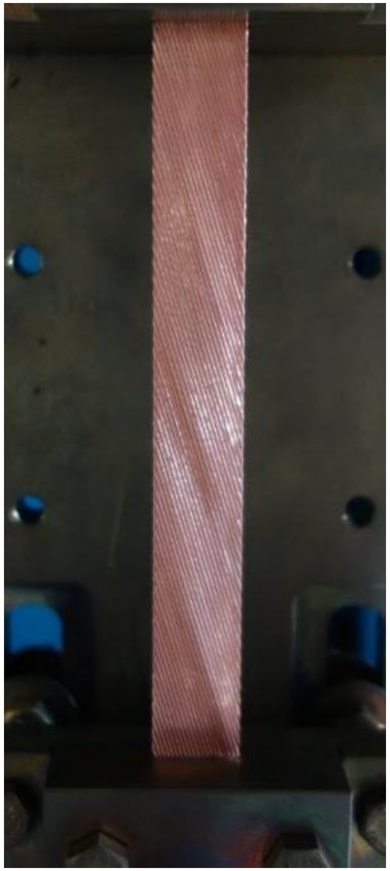
Cable deformations due to RHT

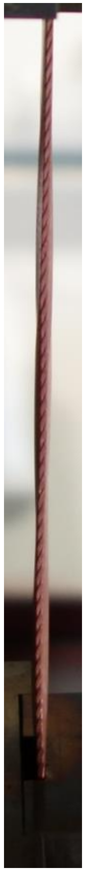
- Influencing parameters:
- Initial plastic deformation and stresses after cabling and spooling
- Dimensional changes of wires due to RHT



FaroArm laser scan:

Deviation from rectangular cross section with 15 x 1.5 mm

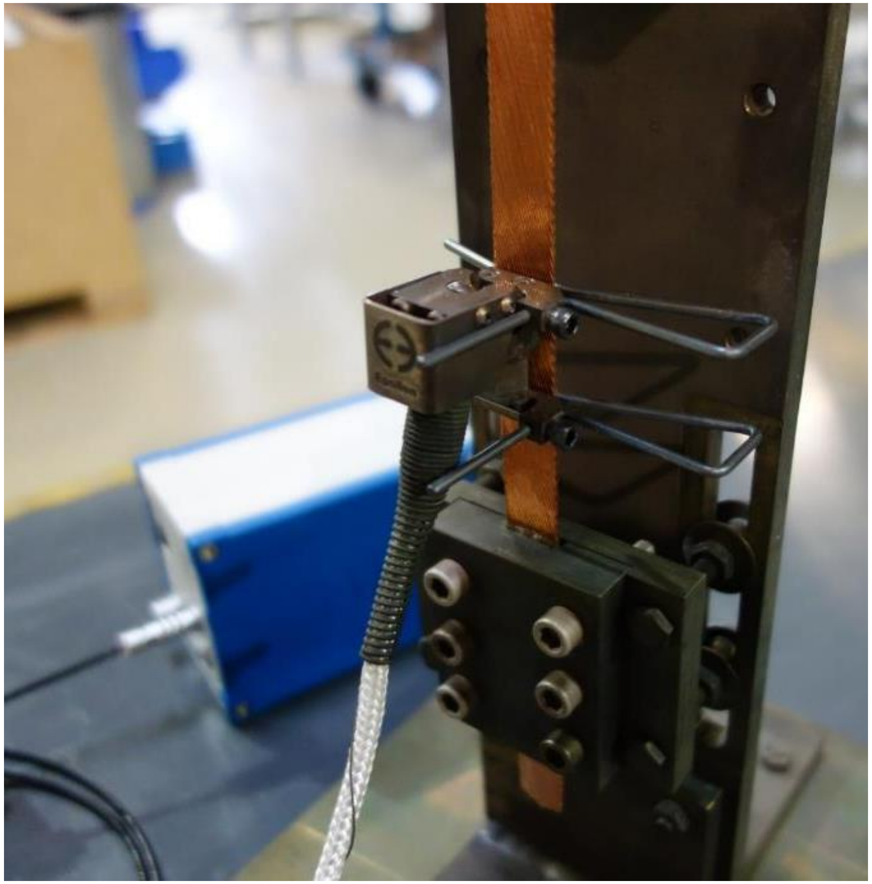




Thanks for Faro measurements to Alejandro Carlon Zurita, CERN, TE-MSC-MDT

Nb_3Sn cable length change measurements during RHT with an extensometer (outlook)

- Goal: Measurement of cable length during the RHT (warming and cooling).
- Compatible with the vertical testing device.
- For use in the reaction furnaces a non-cooled high temperature extensometer is used.
- Operational range: RT to 700 °C
- Grips are at the same temperature as the cable → no temperature gradient
- Gauge length: 25 mm
  Measuring range: +2.5/-0.5 mm



Clip on extensometer (Epsilon 7642) mounted on 11 T dipole Nb_3Sn Rutherford cable

Conclusion

- A comparison of the Nb_3Sn RRP wire length changes throughout the RHT and cool down with that of 316LN, Ti6Al4V and DISCUP shows the different thermal expansion behaviour of the 11 T dipole coil constituent materials and reaction tooling.
- A vertical testing device for the measurement of unconfined Rutherford cable relative length changes before and after RHT was built and commissioned.
- Preliminary results for the length change of bare 11T dipole cable have been presented.
- Cable topography changes during the RHT have been observed that affect the length change results.

Outlook

- For high throughput of samples 4 set-ups have been assembled. They can be used simultaneously in parasitic mode during HL-LHC coil reaction RHTs, or in dedicated RHT in a smaller hood furnace.

- Cable surface laser scans can be used to analyse the effect of cable deformation on cable length changes.

- An extensometer for continuous Nb_3Sn Rutherford cable length measurements during RHT up to 700 °C has been procured and is being commissioned.

Acknowledgement

This work has been conducted in the framework of the FCC 16 T Technology Programme, Task 2: Wound Conductor Test Facilities.

Annex

Experimental results

Number	Date	Cable	RHT cycle	Measurement method	length before (mm)	length after (mm)	length change %	Comments
1	11/07/2017	bare 11T low grade cable: H15OC0180A, CR000001	full 11T	manually (caliper)	122,91	122,27	-0,52	Cable soldered to clamp (no Mica insulation)
2	31/07/2017	bare 11T low grade cable: H15OC0180A, CR000001	short (100°C/h, 20 h at 650°C)	manually (caliper)	140,08	139,27	-0,58	With U-shape Mica 0.08 mm thickness, partially soldered
3	04/08/2017	bare 11T high grade cable: H15OC0194A, CR000004	short (100°C/h, 20 h at 650°C)	manually (caliper)	145,92	145,23	-0,47	With 0.125 mm Mica Foil
				Faro (probe)	145,88	145,36	-0,36	
				Faro (laser)	146,09	145,45	-0,44	
4	15/08/2017	braided 11T high grade cable: H15OC0194A, CR000004	short (100°C/h, 20 h at 650°C)	manually (caliper)	130,73	129,93	-0,61	With 0.125 mm Mica Foil
				Faro (probe)	130,70	130,04	-0,50	
				Faro (laser)	130,79	130,12	-0,51	
5	29/08/2017	bare 11T high grade cable: H15OC0194A, CR000004	short (100°C/h, 20 h at 650°C)	manually (caliper)	127,10	126,36	-0,58	With 0.125 mm Mica Foil
				Faro (probe)	126,92	126,52	-0,32	
				Faro (laser)	127,05	126,41	-0,50	
6	27/09/2017	bare 11T high grade cable: H15OC0194A , CR000004	short (100°C/h, 20 h at 650°C)	manually (caliper)	140.84	140.18	-0.47	With 0.125 mm Mica Foil
				Faro (probe)	140.85	140.23	-0.44	
				Faro (laser)	140.81	140.21	-0.42	
7	10/10/2017	bare 11T high grade cable: H15OC0194A , CR000004	short* (100°C/h, 96 h at 650°C)	manually (caliper)	140.86	140.52	-0.24	With 0.125 mm Mica Foil, non-conform RHT
				Faro (probe)	140.95	140.57	-0.27	
				Faro (laser)	140.86	140.52	-0.24	

Preliminary results for bare 11T high grade cable H15OC0194A

Measurement method	Mean length change (%)	Standard Deviation (%)
Calliper	-0.51	0.064
Probe	-0.37	0.063
Laser	-0.46	0.043

Comparision with results reported elsewhere

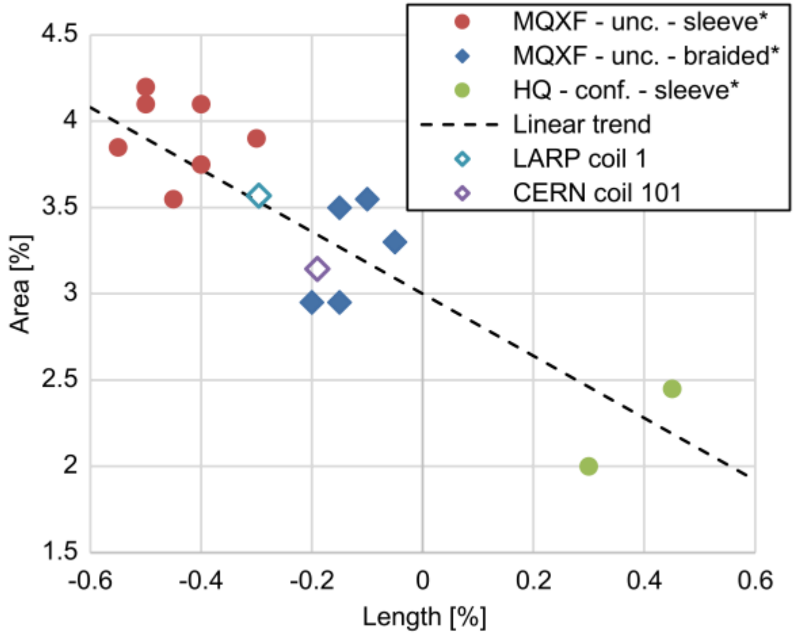


Fig. 2. Area expansion versus length expansion for cables using sleeves or braided insulation. "Conf." stands for confined cables, and "Unc." stands for unconfined cables. The values of two MQXF coils using braid are plotted with open markers for comparison (see Section V for more details). *Data from [8].

[8] I. Pong, D. R. Dietderich, and A. Gosh, "Dimensional changes of Nb_3Sn cables during heat treatment," presented at the Int. Cryogenic Materials Conf., Tucson, AZ, USA, 2015, Paper C2OrF.

SUMMARY OF AVERAGE DIMENSIONAL CHANGES FOR CABLES AND COILS

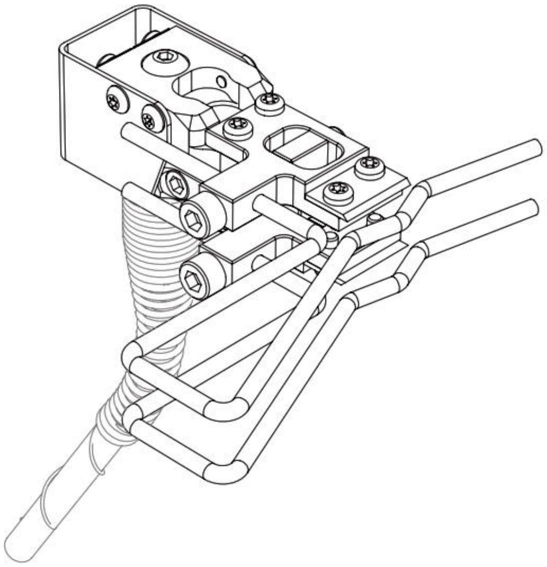
Conductor	Insula -tion	Thick. [%]	Width [%]	Length [%]	Area [%]	Vol. [%]
MQXF cable	Sleeve	2.8	1.1	-0.4	3.9	3.5
	Braid	3.2	0.0	-0.1	3.2	3.1
CERN 101	Braid	3.0	0.1	-0.04	3.1	3.0
LARP 1	Braid	3.1	0.5	-0.2	3.6	3.4

E. Rochepault et al., Dimensional Changes of Nb_3Sn Rutherford Cables During Heat Treatment, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 26, NO. 4, JUNE 2016

Epsilon 7642-025M-025M HT extensometer

SPECIFICATIONS

Analog Output:	User specified, +/-5 VDC or +/-10VDC typical, ±10.8VDC rail
Digital Output:	24 bit high speed Ethernet output with built-in web interface
Linearity:	11 point linearization, ≤0.1% FS typical linearity
Resolution:	<55 PPM (0.006%FS) RMS @4 kHz, <6 PPM (0.0006%FS) @100 Hz
Cyclic Testing:	>25 Hz typical, up to 100 Hz with small travel units, @0.5 mm travel
Analog Filter:	Selectable 100 Hz analog and 2 Hz - 3 kHz digital filters
Temperature Range:	Ambient to 700°C (1300°F). Use up to 800 °C is possible – contact Epsilon for details. Wire forms may require periodic adjustment or replacement after long-term testing above ~600 °C.
Temperature Sensitivity (Gain):	<100 PPM/°C (0.01%FS/°C) typical
Temperature Sensitivity (Offset):	20 PPM/°C (0.002%FS/°C) typical
Sensor Cable:	0.7 m (2.5 ft) tri-axial high temperature cable, plus 1.5 m (5 ft) room temperature extension cable
Standard Quick Attach Kit:	Fits round samples up to Ø15 mm (0.60"). Fits flat samples up to 50 mm (2.0") wide with thicknesses up to 6.35 mm (0.25"), and up to 19 mm (0.75") wide with thicknesses from 6.35 mm to 12.5 mm (0.25" to 0.50")
Operating Force:	<100 g typical
Environment:	Recommended for elevated temperature testing in dry air, inert / non-corrosive gases, or vacuum
Power:	Includes power supply for your country (specify)



"High Temp Un-cooled Extensometers - Model Series 7642" Data Sheet, Epsilon technology corp