Dimensional Changes of Nb3Sn Cables During Heat Treatment

17/11/17

E. Rochepault (CERN, now CEA Paris-Saclay), on behalf of:

CERN: P. Ferracin, A. Ballarino, A. Bonasia, B. Bordini, L. Garcia Fajardo (now LBNL), S. Izquierdo Bermudez, J.C. Perez,

FNAL: G. Ambrosio, E.F. Holik, M. Yu

LBNL: D. Cheng, D.R. Dietderich, H. Felice (now CEA Paris-Saclay), I. Pong,

BNL: M. Anerella, A. Ghosh, J. Schmalzle,

Context and Motivations

- Early observations at LARP for LQ-HQ:
  - **Radial expansion + longitudinal contraction** observed in coils during Heat treatment at 650°C [1-2].
  - **Residual strain** altering the performances [3].

  → Provide space in the tooling for dimensional changes.

- Collaboration between CERN and LARP for the HiLumi LHC [4]

- Study on strands, single Rutherford cables, cable stacks, and coils:
  - Understand the behavior of **cable dimensions** during heat treatment
  - **Provide estimates** of the space to be accommodated [5]

[1] D. R. Chichili et al., "Fabrication of the Shell-type Nb3Sn Dipole Magnet at Fermilab," IEEE Trans. Appl. Supercond., 2001.
[2] G. Ambrosio et al., "Development and Coil Fabrication for the LARP 3.7-m Long Nb3Sn Quadrupole," IEEE Trans. Appl. Supercond., 2009.
[3] H. Felice et al., "Impact of Coil Compaction on Nb3Sn LARP HQ Magnet," IEEE Trans. Appl. Supercond., 2012.
[4] P. Ferracin et al., "Development of MQXF: The Nb3Sn Low-β Quadrupole for the HiLumi LHC", IEEE Trans. Appl. Supercond., 2016.
[5] S. Izquierdo Bermudez et al., "Second Generation Coil Design of the Nb3Sn low-B Quadrupole for the High Luminosity LHC," IEEE Trans. Appl. Supercond., 2016.

Strand Volume Expansion

- Free bare strands [6]
- Expansion increases with superconductor content [8]
- Thickness growth of rolled wires = up to 2x radius growth of virgin wires [8]
  → stress accumulated during rolling and released during heat treatment

Average Dimensional changes of strands,
*Unavailable data.

Sample	Cu:Sc	Radius/Thick. [%]	Length [%]
MQXF RRP virgin	**1.2**	**1.8**	**-***
MQXF PIT virgin	**1.2**	**1.6**	**-**
RRP virgin [7]	1.15	1.8	0.08
RRP virgin [7]	0.85	2.2	0.04
IT virgin [8]	0.61	1.8	-
PIT virgin [8]	0.83	2.2	-
ITER virgin [8]	1.42	0.9	-
IT rolled [8]	0.61	4.4	-
PIT rolled [8]	0.83	2.3	-
ITER rolled [8]	1.42	1.9	-

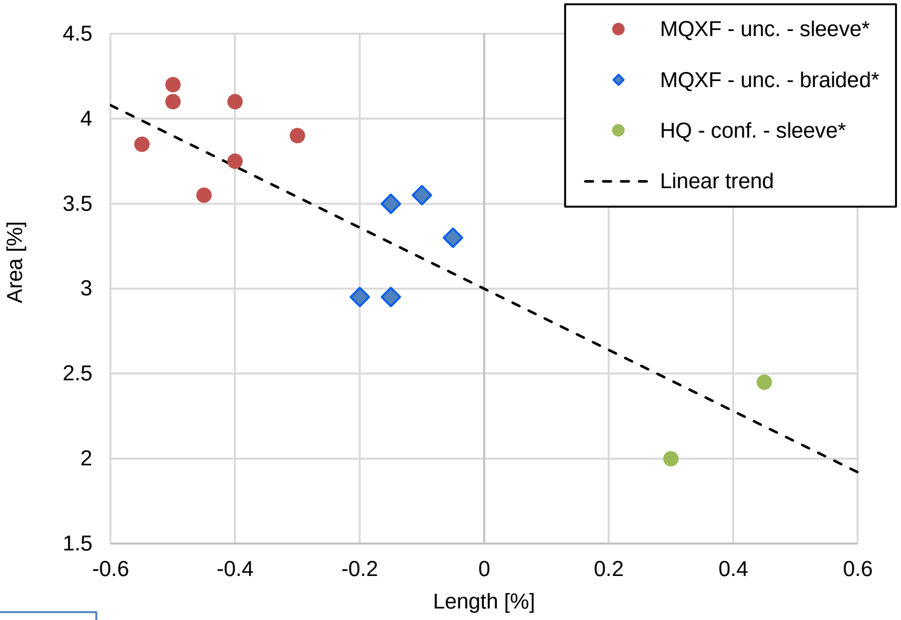
In average:
Radius: +1,7%
Area: +3,4%
Length: +0,1%
Volume: ~+3,5%

[6] E. Rochepault et al. “Dimensional Changes of Nb3Sn Rutherford Cables during Heat Treatment”, IEEE Trans. Appl. Supercond.; 2016
[7] D. Bocian et al., “Measurements of Nb3Sn Conductor Dimension Changes During Heat Treatment.”, AIP Conf. Proc., 2012
[8] N. Andreev et al., "Volume Expansion of Nb-Sn Strands and Cables During Heat Treatment," Adv. in Cryogenic Eng., 2007.

Cable Transverse Expansion

Single cables [9]

- Free cables contract in length (-0.6 to 0 %) → remaining cabling tension or friction between the strands?
- Confined cables:
  - Area: +2.2 %
  - Volume: +2.6 %
- Unconfined cables, braid:
  - Area: +3.4 %
  - Volume: +3.2 %
- Unconfined cables, sleeve:
  - Area: +3.9 %
  - Volume: +3.5 % ≈ free strands

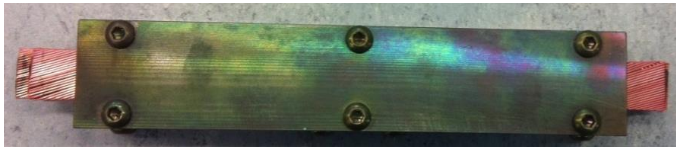


Transverse confinement has a significant impact on dimensional changes.

Area expansion vs. length expansion.
*Courtesy of I. Pong [9]

[9] I. Pong, D. R. Dietderich and A. Gosh, "Dimensional Changes of Nb3Sn Cables during Heat Treatment". Presented at ICMC 2015

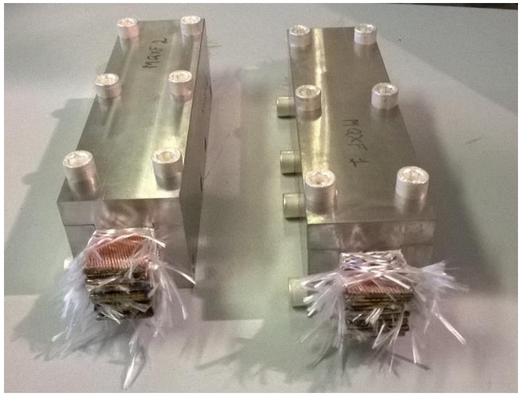
Cable stacks



Bare cable stack

- Stacks reacted in free cavities [6]

- Thickness ≈ rolled wires
- Width ≈ virgin wires



Insulated cable stacks

Sample	Thickness [%]	Width [%]	Length [%]
MQXF RRP bare cable	**2.5**	**1.7**	**-**
MQXF PIT bare cable	**3.0**	**1.5**	**-**
MQXF RRP braided	**2.5**	**-**	**-**
MQXF unconf. sleeve [9]	2.8	1.1	-0.4
MQXF unconf. braided [9]	3.2	0.0	-0.1
HQ conf. sleeve [9]	2.1	0.1	0.4
FRESCA2 RRP 10-stack [10]	3.0	-	-
FRESCA2 PIT 10-stack [10]	3.6	-	-

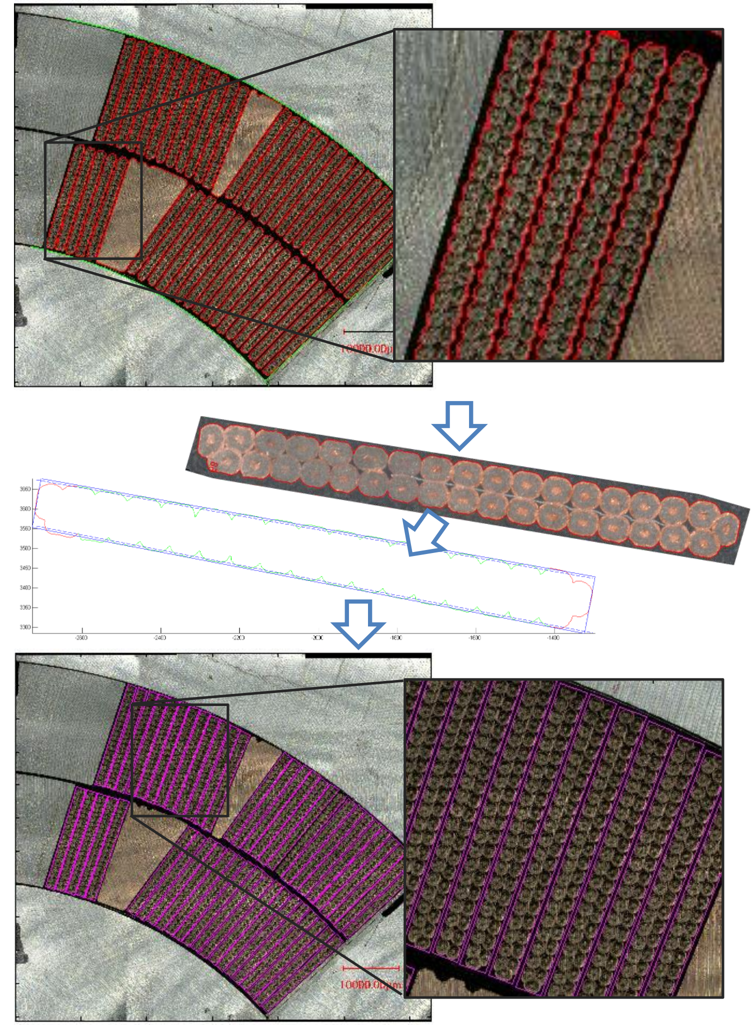
[10] M. Durante et al., " Nb3Sn Rutherford cables geometrical behavior during heat treatment," IEEE Trans. Appl. Supercond., 2016

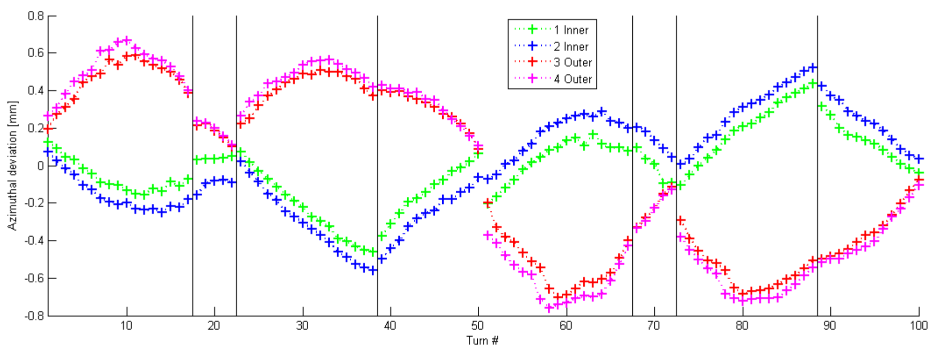
Coil Transverse Expansion

Automated Image Analysis [6]

1. Clean the image
2. Detect the cable contours
3. Fit trapezoids on each contour
4. Post-process: shape, position, size…

- \+ Reliable and reproducible
- \+ Not user-dependent
- \+ Method can be tailored to the needs
- \- Accuracy depends on quality of picture
- \- Relies on accurate definition of the contours





Coil Transverse Expansion

- Room in the heat treatment cavity:
  - TQ/LQ: 1 to 2% in width, ~6% in thickness
  - HQ 1G: 0,8 to 1,3% in width, 1,4 to 1,8% in thick. [3]
  - HQ 2G: 1,4% in width, 3,9% in thick. [11]
  - LARP 1G: 2% in width, 4,5% in thick.
    - Measured: 0 to 0,5% in width, ~3% in thick. [6,12] ≈ braided cables
  - LARP 2G: 1% in width, 3% in thick. [13]

Coil	Method	Thickness [%]	Width [%]
CERN 101	3D measurement machine	3.0 +/- 1.3*	0.14 +/- 0.15
	Automated Image Analysis	2.9 +/- 1.3	0.04 +/- 0.17
LARP 1	Laser confocal scope [12]	3.1 +/- 1.4	0.45 +/- 0.17
	Automated Image Analysis	3.3 +/- 1.3	0.12 +/- 0.16

*standard deviation

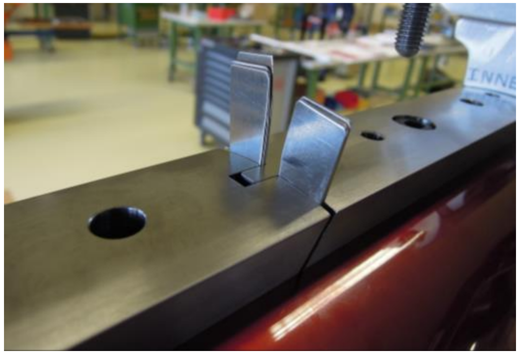
[11] F. Borgnolutti et al., "Fabrication of a Third Generation of Nb3Sn Coils for the LARP HQ03 Quadrupole Magnet," IEEE Trans. Appl. Supercond., 2015
[12] E. Holik et al., "Fabrication and Analysis of 150 mm Aperture Nb3Sn MQXF Coils," IEEE Trans. Appl. Supercond., 2016
[13] S. Izquierdo Bermudez et al., "Second Generation Coil Design of the Nb3Sn low-B Quadrupole for the High Luminosity LHC," IEEE Trans. Appl. Supercond., 2016.

Coil Longitudinal Contraction

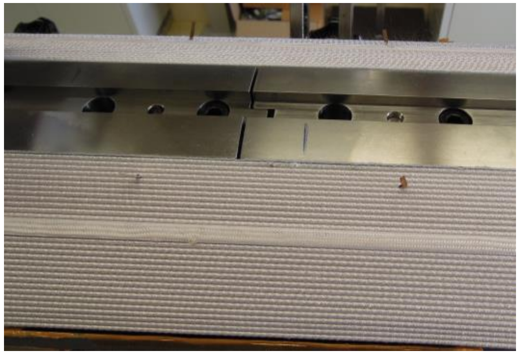
Longitudinal gaps

- HQ: Gaps accommodated in the poles to allow the coils to contract [3]
  Impact of insulation "tightness" [11]:
  - Sleeves: -0,4 to -0,3 % in length (5 coils HQ 2G)
  - Braid: -0,2 % in length (1 coil HQ 2G + 6 coils HQ 3G)

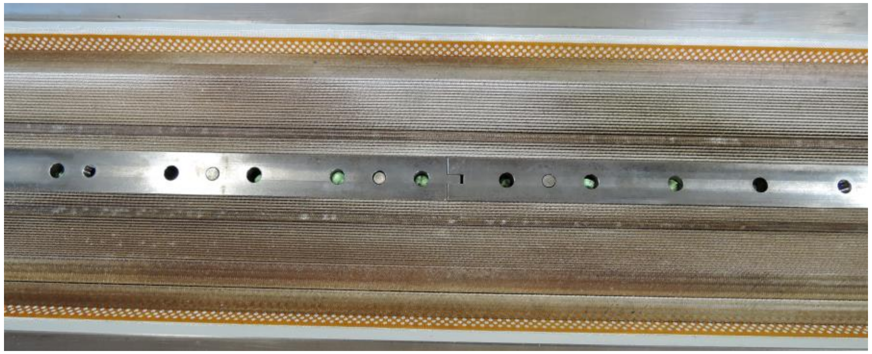
- MQXF: different pole gaps explored [6,12]
  - Braid: -0,4 to -0,1 % in length (40+ coils)



Winding with shims

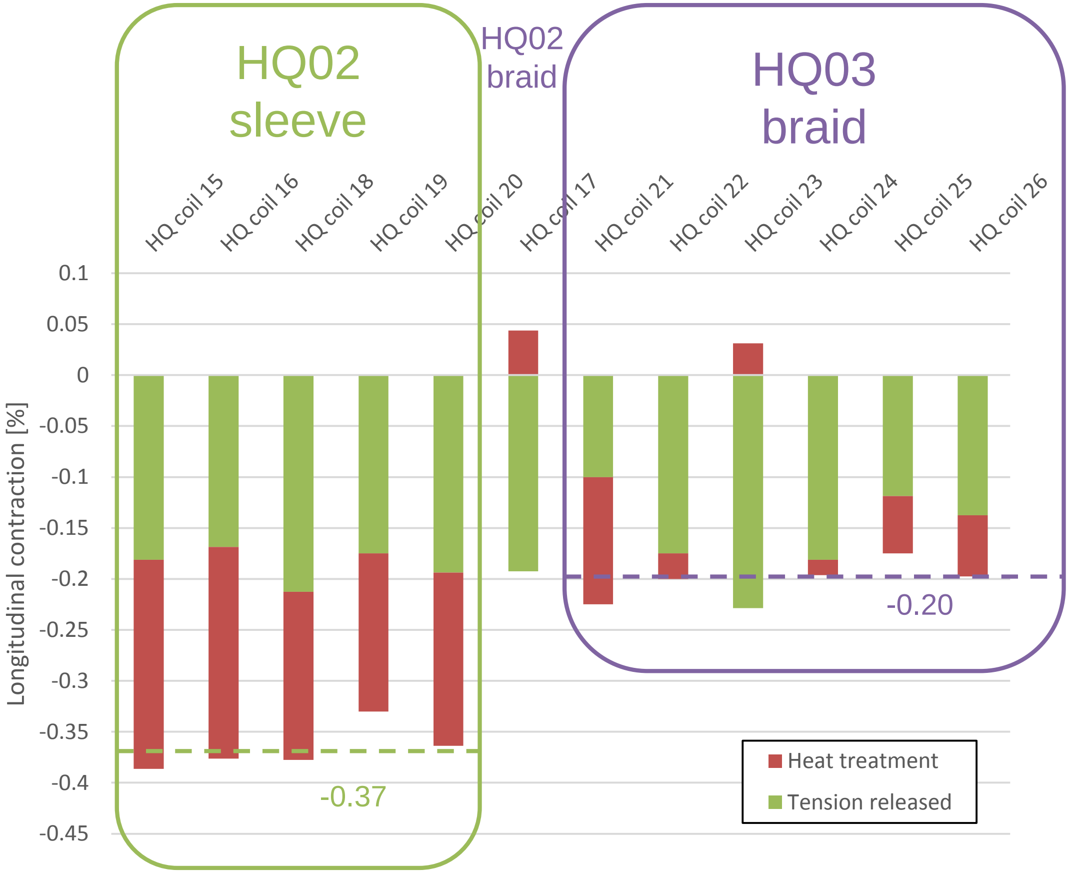


Open gaps after tension release



Closed gaps after heat treatment

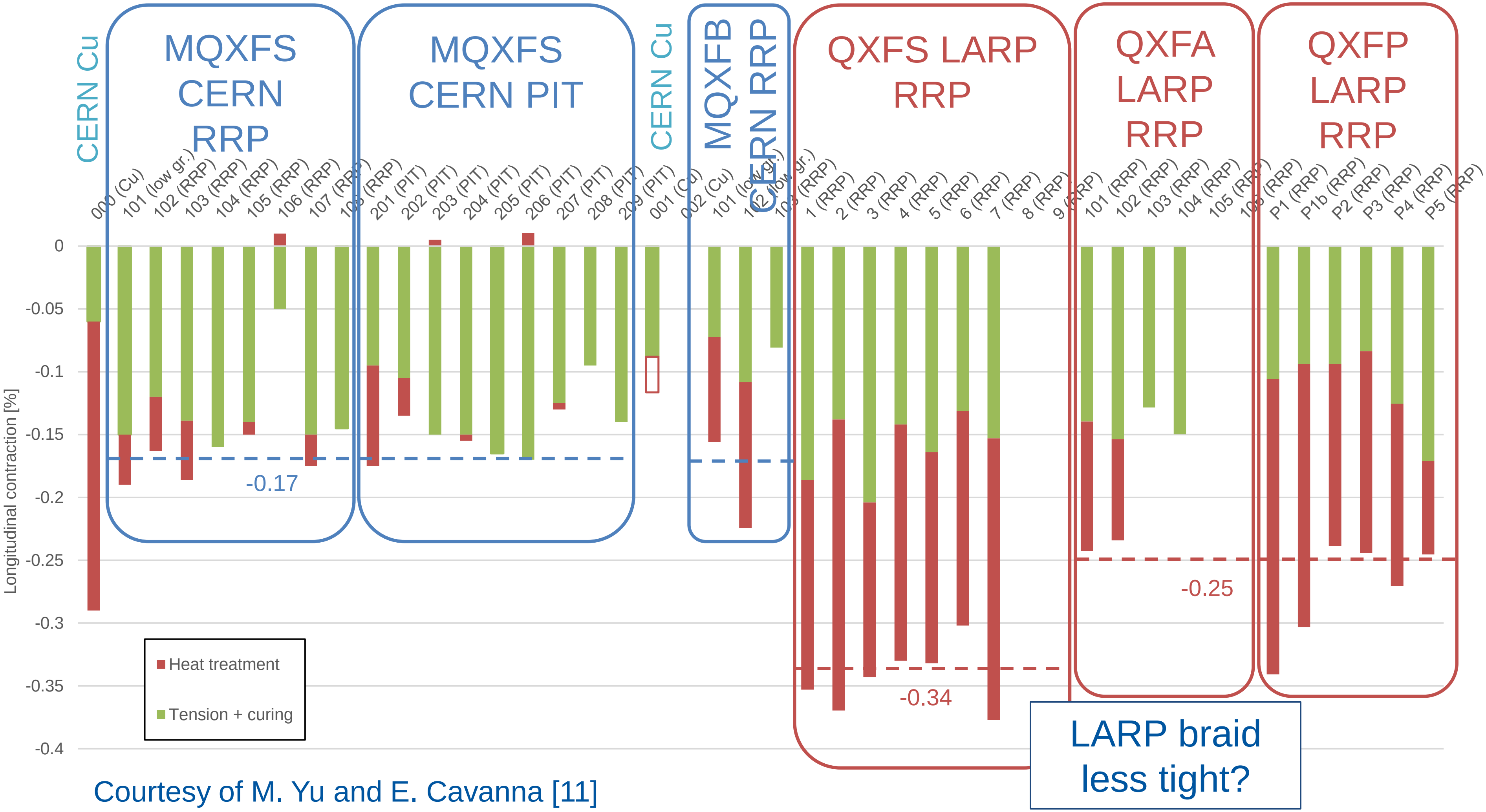
Coil contraction (HQ [11])



Courtesy of F. Borgnolutti [11]

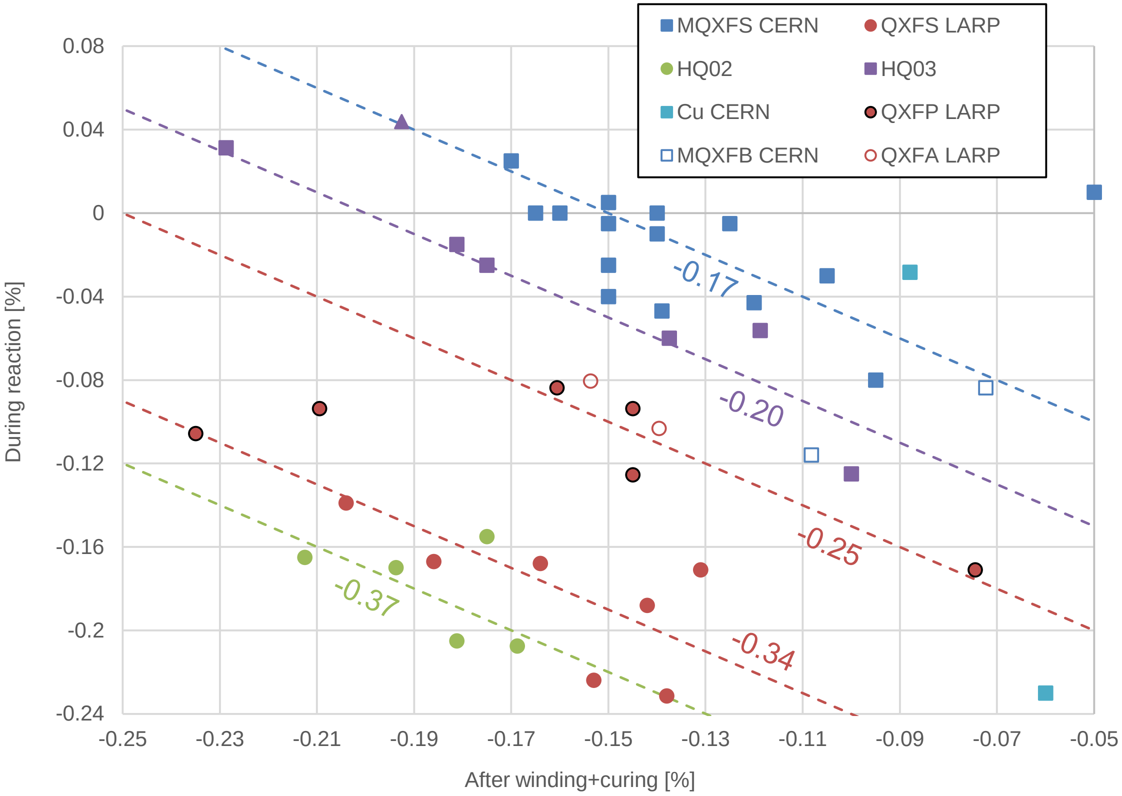
- Coils contract after winding due to tension release
- **Coils with a braided insulation contract less due to a tighter fit around the cable**

Coil contraction (MQXF [6])



Courtesy of M. Yu and E. Cavanna [11]

Coil contraction

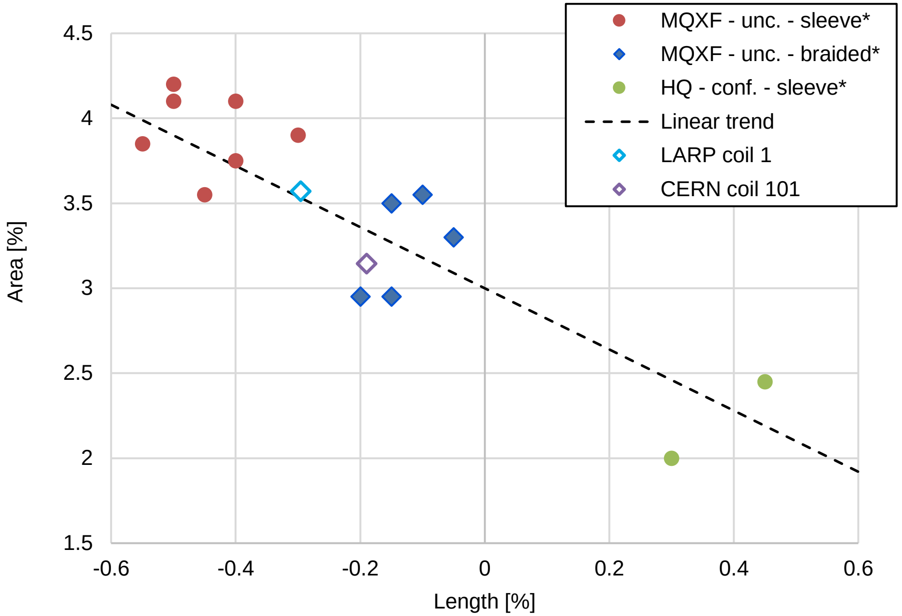


Tight insulation

Loose insulation

- Coil that contract more after winding will contract less during reaction
- **QXF LARP coils contract less suposedly because of less tight braid**

Transverse Vs Longitudinal



Coils/cables with more confinement (tight cavity or insulation):

- **Less transverse expansion**
- **Less longitudinal contraction**

Conclusion

- **Nb_3Sn naturally expands in all directions** during reaction due to phase change → ~3,5 % in volume
- **Cables and coils contract in length**, likely due to stress release
- **A tight insulation (tight braid) may prevent the overall expansion**
- Tooling must: - Provide an adequate space for transverse expansion
  - Allow the longitudinal contraction

	thickness	width	Length	volume
Single strand	+3.4%		+0.1%	+3.5%
Bare cable (or loose insulation)	+3.0%	+1.0%	-0.5%	+3.5%
Braided cable (tight insulation)	+3.0%	0 to +0.5%	-0.2 to 0%	+3.0 to 3.5%

Thank you for your attention,

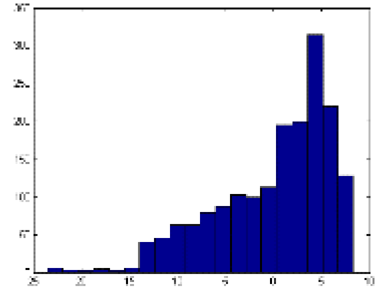
and many thanks to everyone for providing the data and for useful discussions!

Backup slides

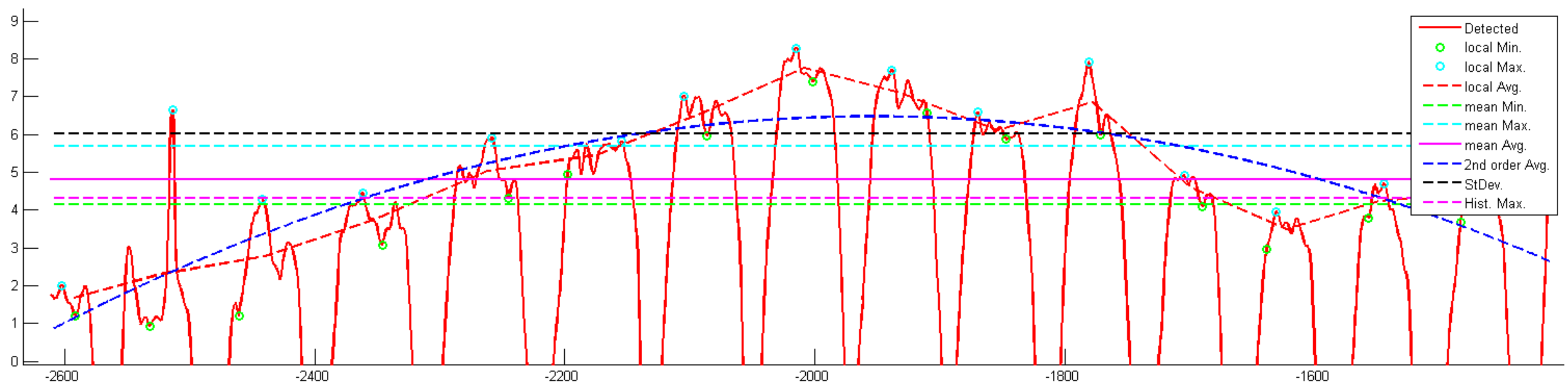
MXQF conductor parameters

Parameter	1st Gen.	2nd Gen.	Unit
Strand Cu:Sc ratio	1.2	1.2	-
Strand diameter	0.85	0.85	mm
Number of strands	40	40	-
Cable twist pitch	109	109	mm
Un-reacted bare cable mid-thickness	1.525	1.525	mm
Un-reacted bare cable width	18.150	18.150	mm
Cable keystone angle	0.550	0.400	°
Cable insulation thickness	0.150	0.145	mm

Trapezoid fits – top face



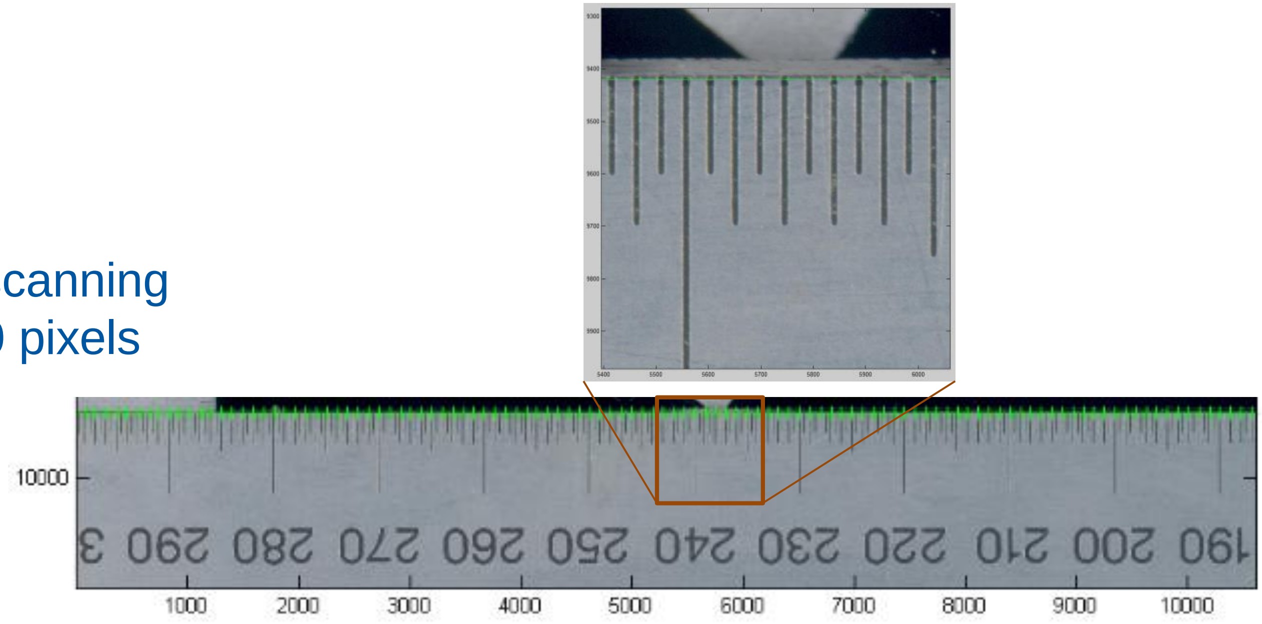
	Local individual strand					2nd order fit on local Avg.		Statistical analysis	
	Mean Min.	Mean Max.	Min. Avg.	**Mean Avg.**	Max. Avg.	Min.	Max.	Stdev.	**Hist. Max.**
Pos [pix]	4.1	5.7	1.7	**4.8**	7.8	0.8	6.5	6.0	**4.3**
Th. [mm]	1.349	1.383	1.299	**1.364**	1.428	1.280	1.400	1.390	1.354
Exp. [%]	-1.9%	0.6%	-5.6%	**-0.8%**	3.8%	-6.9%	1.8%	1.1%	-1.6%



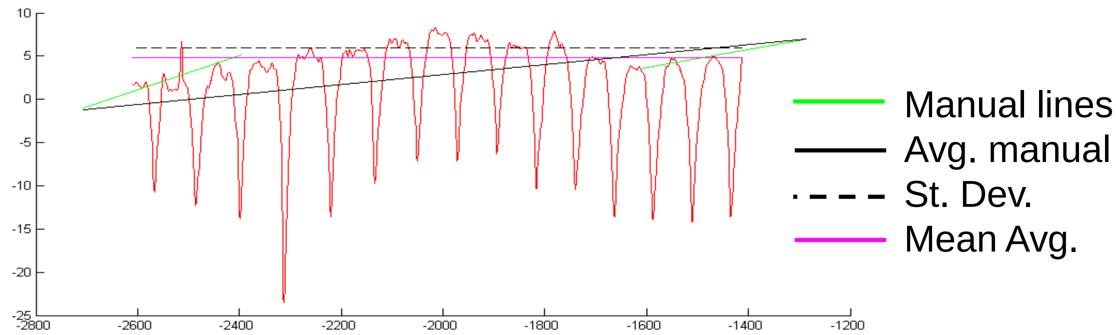
Accuracy

- Using the bottom ruler
- Drift on left ruler due to scanning

Reference = 111 mm/10500 pixels
10 mm = 945.946 pixels
10 pixels = 105.714 µm



- Errors:
  - Due to scaling:
    2 pixels/10500 = $2x10^{-4}$
  - Due to detection:
    2 pixels = 20 µm (depending on image resolution, can be corrected)
  - Due to thickness definition:
    up to 6 pixels = 60 µm
- We would like:
  1% of 1.375 mm
  = 14 µm = 14 pixels



Impact of initial gap