Large Hadron Collider
Accelerator
Research
Program

BROOKHAVEN NATIONAL LABORATORY

BERKELEY LAB Lawrence Berkeley National Laboratory

Dimensional Changes of Nb_3Sn Cables during Heat Treatment

LBNL: Ian Pong (ipong@lbl.gov), Dan Dietderich
BNL: Arup Ghosh

* This work was supported by the Director, Office of Science, High Energy Physics, U.S. Department of Energy under contract Nos. DE-AC02-05CH11231 and DE-AC02-98CH10886

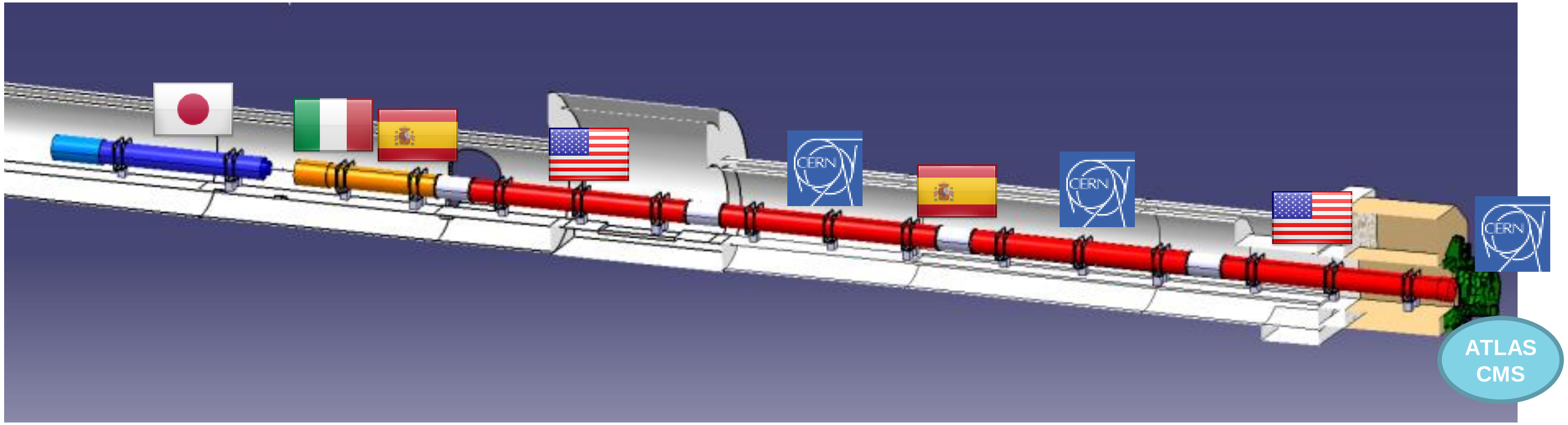
Large Hadron Collider
Accelerator
Research
Program

Outline

- Introduction
- Motivation
- Experiments
- Results
- Conclusion
- Acknowledgement: Hugh Higley (LBNL), LARP, GARD, Toohig Fellowship

Introduction

- The LHC-Accelerator Research Program (LARP) has been designing and fabricating R&D magnets for the High Luminosity Upgrade for over ten years
- Inner triplet quadrupoles using Nb_3Sn. US in-kind contribution.
- "MQXF"



Large Hadron Collider
Accelerator
Research
Program

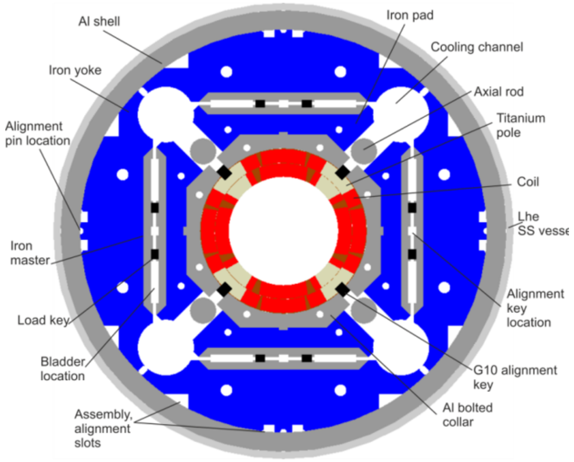
MQXF - Magnet

High Luminosity LHC

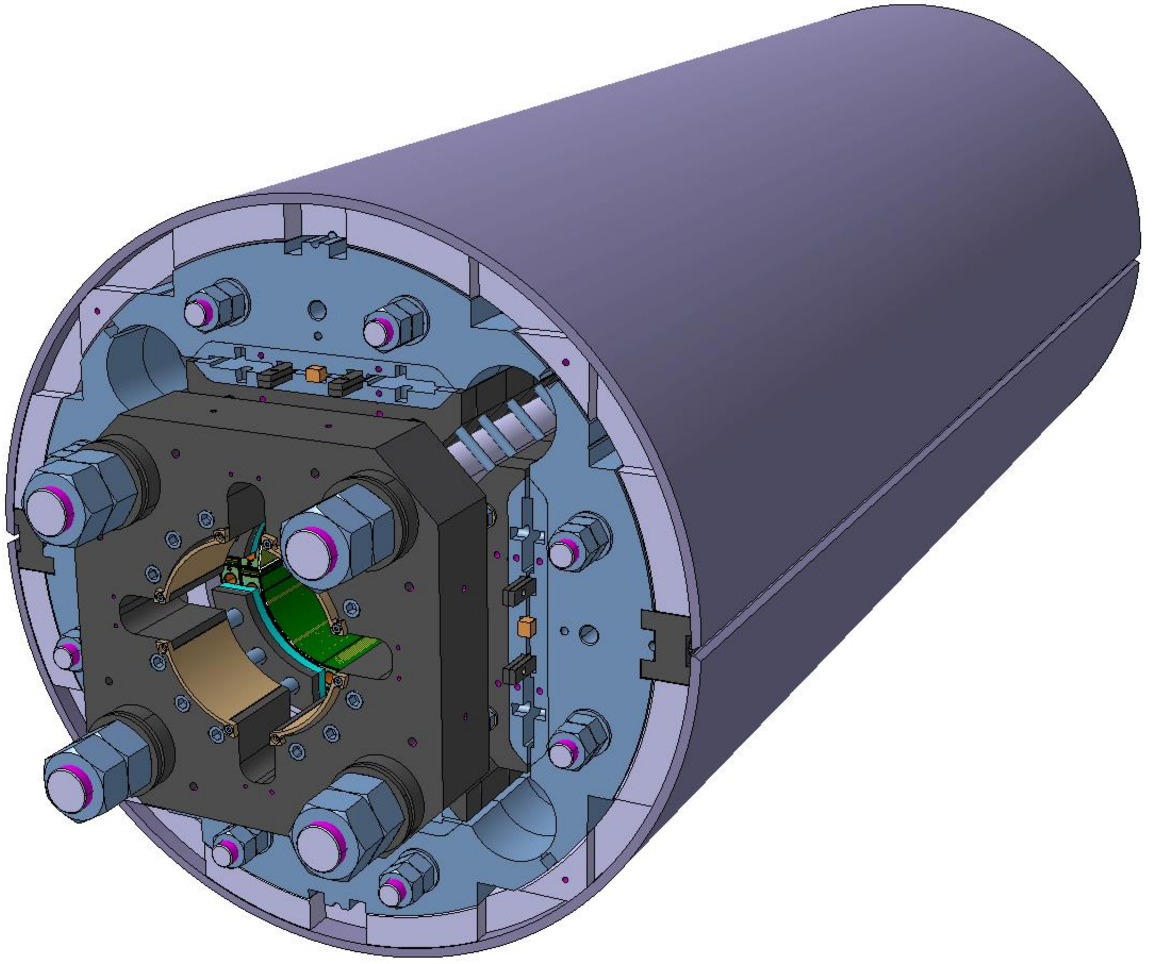
THE TRIPLET

LARP

- Main parameters [LHC today]
  - Aperture 150 mm [70 mm]
  - Gradient 140 T/m [200 T/m]
  - Lengths 8.0 m/6.8 m [6.2/5.5 m]
  - Peak field 12.1 T [8.6/7.7 T]
  - Current 17.45 kA [7.2 kA/12 kA]
  - 80% on the loadline [80%, 84%]
  - To be installed in '23-'24 [2007-8]
  - Temp margin ~4.5 K [1.5-2.0 K]



QXF cross-section [G. Ambrosio, P. Ferracin]

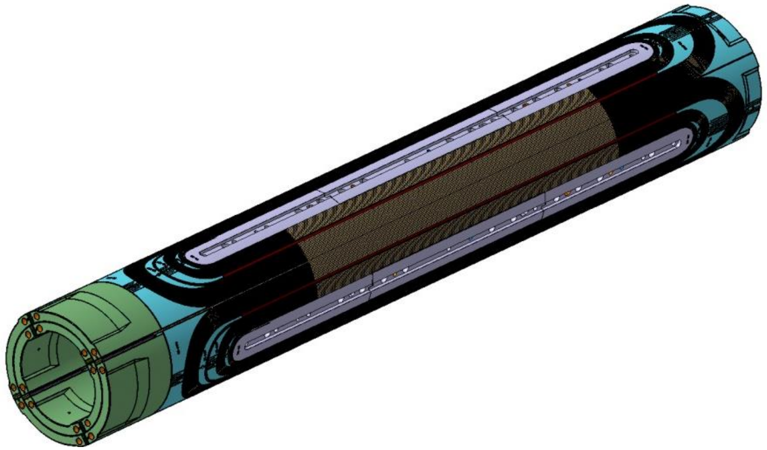


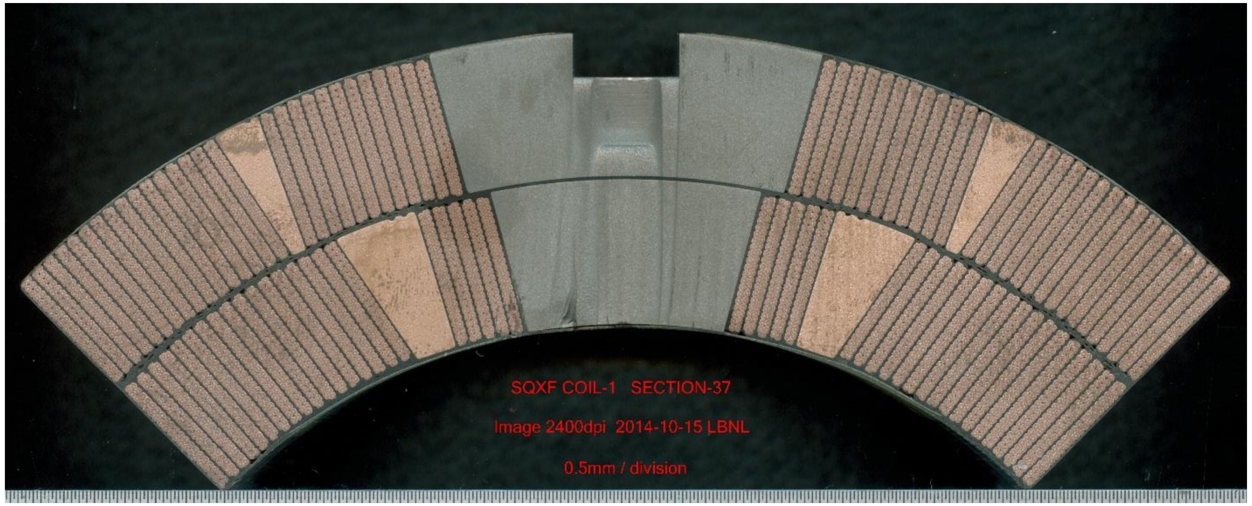
  - $j_{overall}$ ~500 A/mm^2 [380-420 / 480-590 A/mm^2]
  - j_{sc} ~1600 A/mm^2 [800-1600 / 1000-1500 A/mm^2]
  - 16 units needed (IR1 and IR5) plus spares [we do not touch IR2 and IR8]

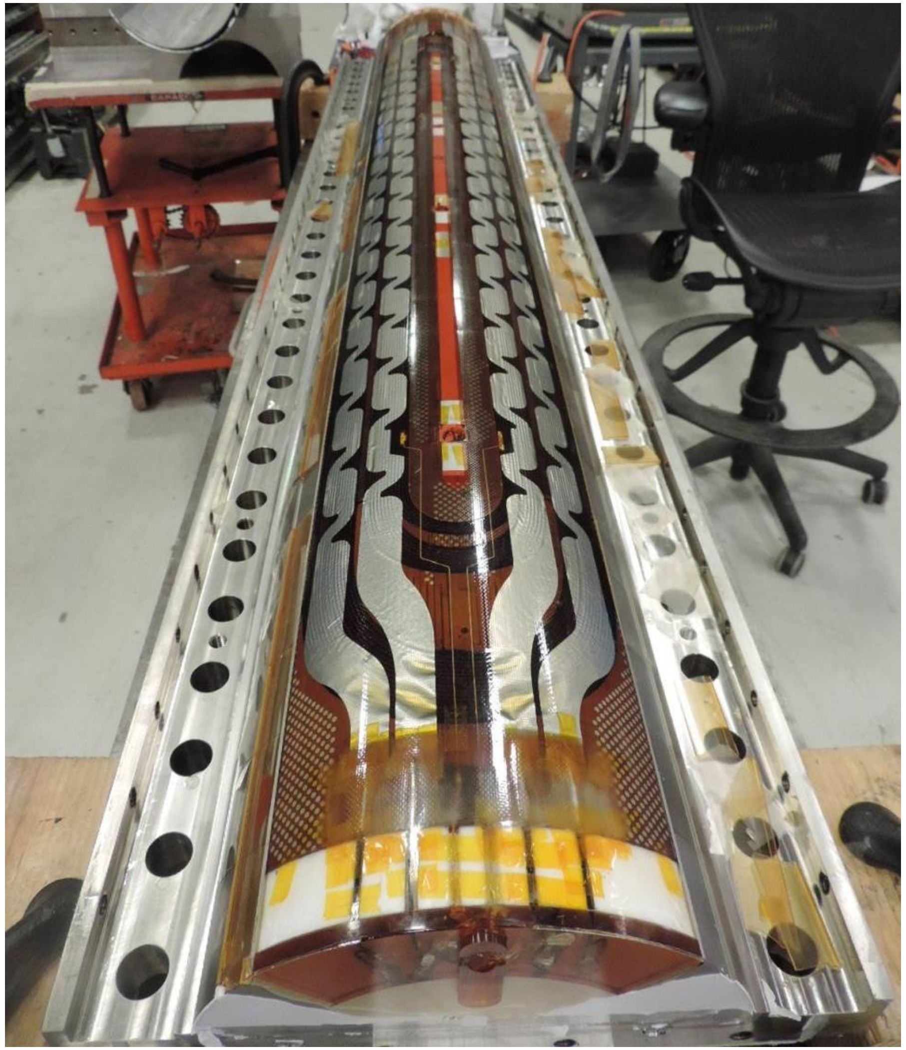
E. Todesco

MQXF - Coil

- Two layers
- Four blocks
- No grading







Large Hadron Collider
Accelerator
Research
Program

MQXF Conductor

- 108/127 stack Nb_3Sn wires
  - – 0.850 mm diameter, uncoated
- 40-strand cable UL ~500 m
  - – 18.15 mm wide
  - – 1.525 mm thick
  - – 0.40° keystone ("2nd generation")
  - – With stainless steel core
  - – Unannealed strands

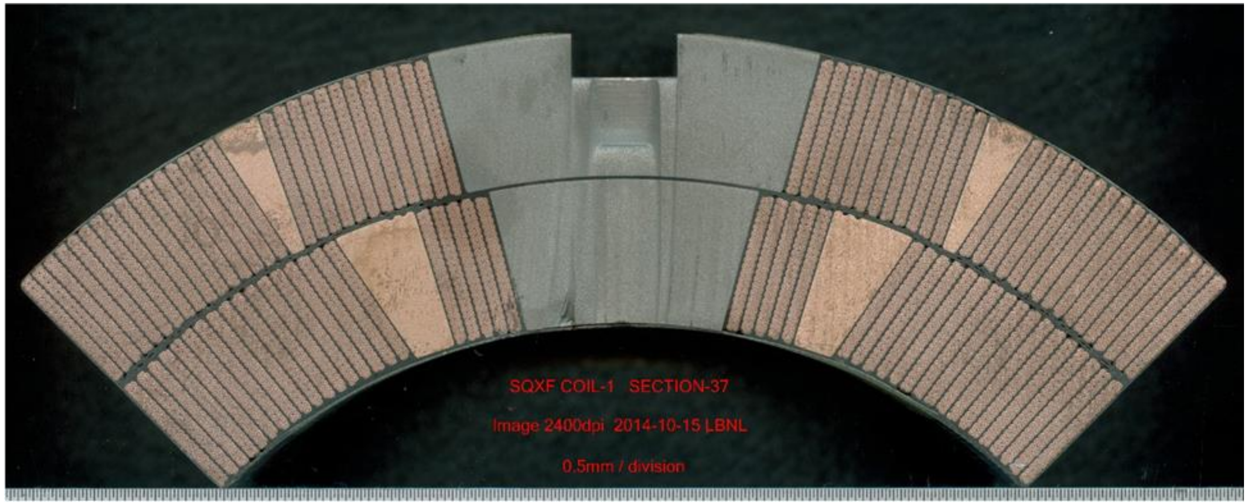
ANNEX – SUMMARY OF PERFORMANCE REQUIREMENTS

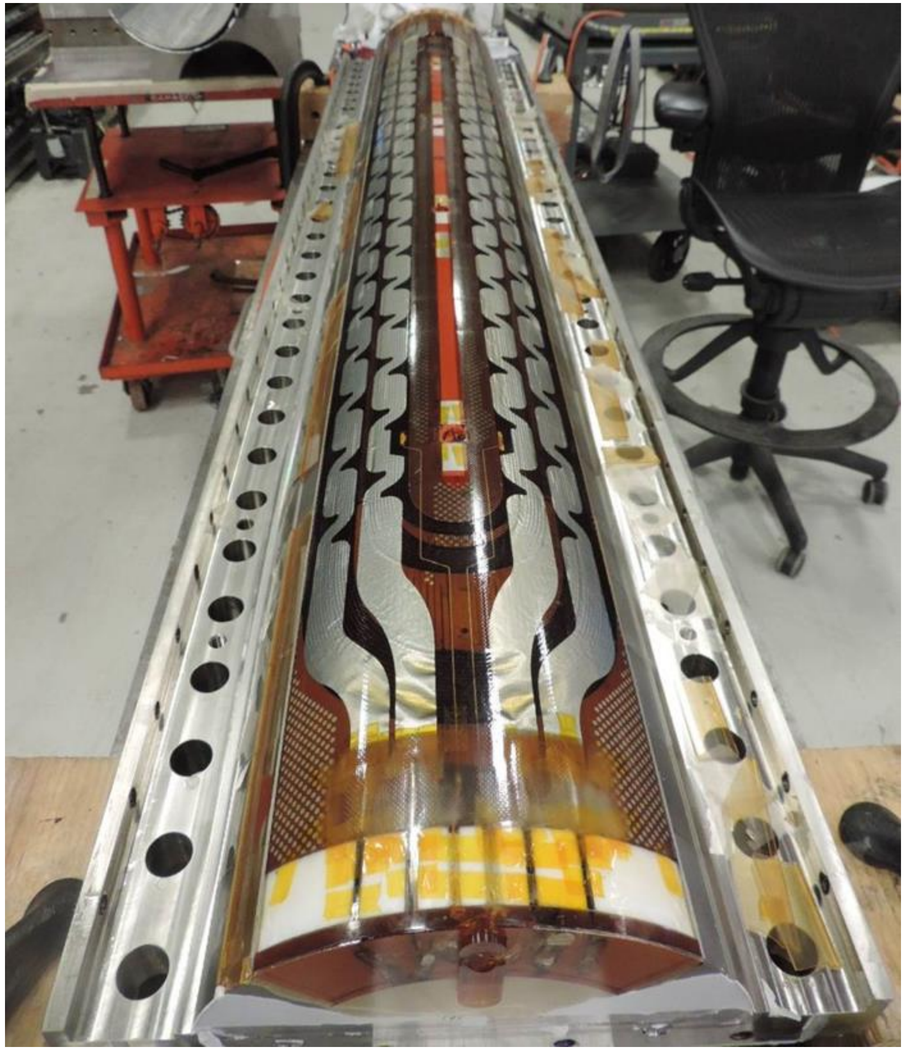
Parameter or characteristic	Value	Unit
Superconductor composition	Ti-alloyed Nb_3Sn	
Strand Diameter	0.850 ± 0.003	mm
Critical current at 4.2 K and 12 T	> 632	A
Critical current at 4.2 K and 15 T	> 331	A
n-value at 15 T	> 30	
Count of sub-elements (Equivalent sub-element diameter)	≥ 108 (< 55)	 (μm)
Cu : Non-Cu volume Ratio Variation around mean	≥ 1.2 ± 0.1	
Residual Resistance Ratio *RRR* for reacted final-size strand	≥ 150	
Magnetization* at 3 T, 4.2 K	< 240 (< 300)	kA m^{-1} (mT)
Twist Pitch	19.0 ± 3.0	mm
Twist Direction	Right-hand screw	
Strand Spring Back	< 720	arc degrees
Minimum piece length	550	m
High temperature HT duration	≥ 40	Hours
Total heat treatment duration from start of ramp to power off and furnace cool	≤ 240	Hours
Heat treatment heating ramp rate	≤ 50	°C per hour
Rolled strand (0.72 mm thk.) critical current at 4.2 K and 12 T	> 600	A
Rolled strand *RRR* after reaction	> 100	

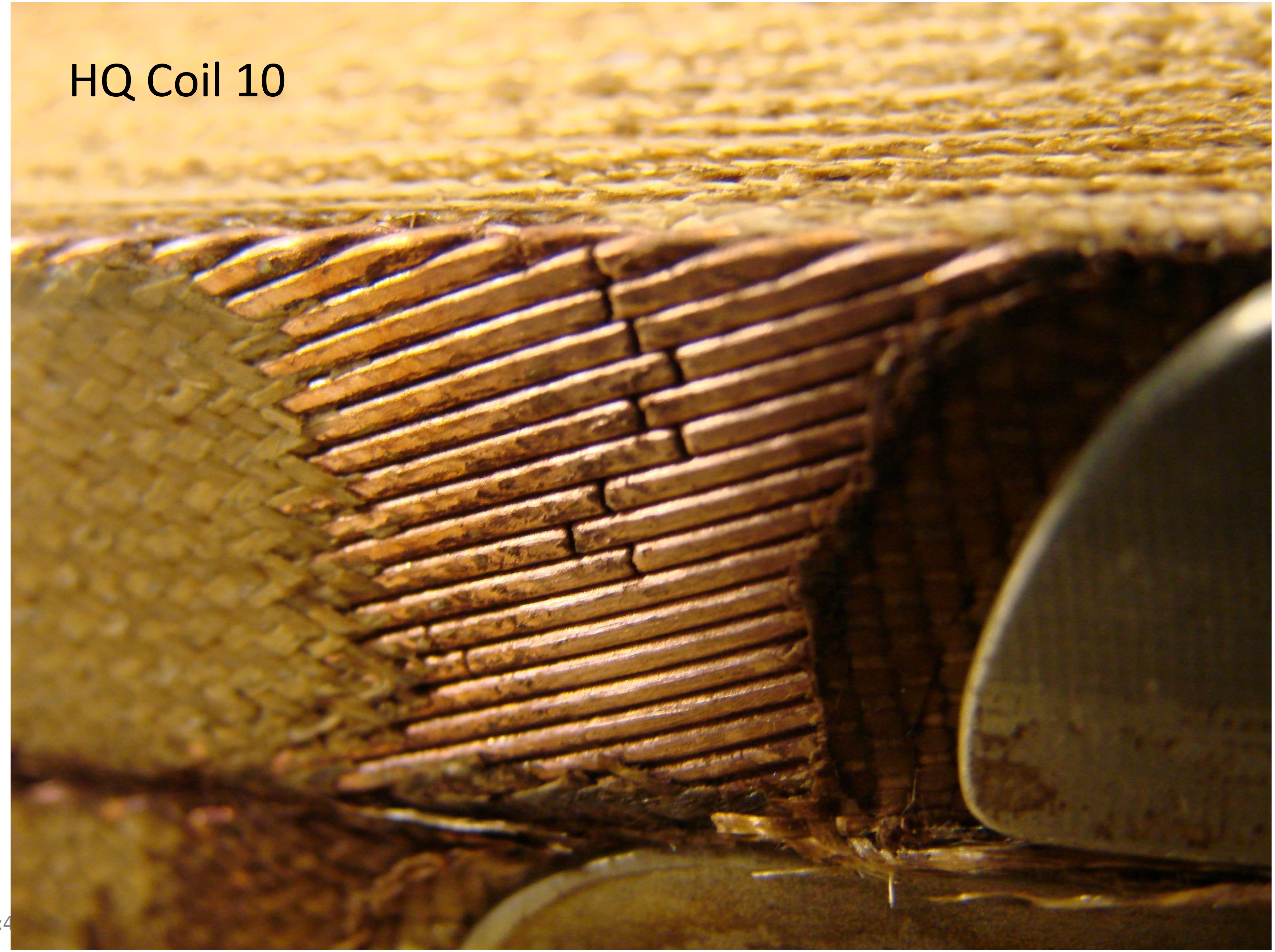
*Magnetic moment (A m^2) divided by the volume (m^3) of a strand piece in transverse magnetic field, without removing copper

Motivation

- Nb_3Sn: wind & react → impact on coil due to cable dimension change during heat treatment, esp. length, width, and thickness?






HQ Coil 10

Complication

Cable insulation

- AGY S2-glass fibers 66 tex with 933 silane sizing
- 32 (CERN, CGP) or 48 (LARP, NEW) coils (bobbins)
  - Variables: # of yarn per coil and of picks/inch
- Target: ≤ 150 μm per side (145 ±5 μm) at 5 MPa, average 3 cycles

Cable insulation changes cable behaviour!
LBNL experience shows that dimension change is different between confined and unconfined cables

Past Experience

- Unconfined cables
  - Cables are free to expand or contract in width, thickness, and length
- Confined cables
  - Width and thickness defined by tooling that is bolted together
    - Cable width and thickness are determined by CME at 17 MPa
    - Insulation thickness are determined at a reference pressure
  - Length is not confined.

Unconfined Cables

Figure 7: a) Measuring cable length, b) in the unconfined case, the cables are placed between siderails, top & bottom plates are tied together

Large Hadron Collider
Accelerator
Research
Program

Confined Cables

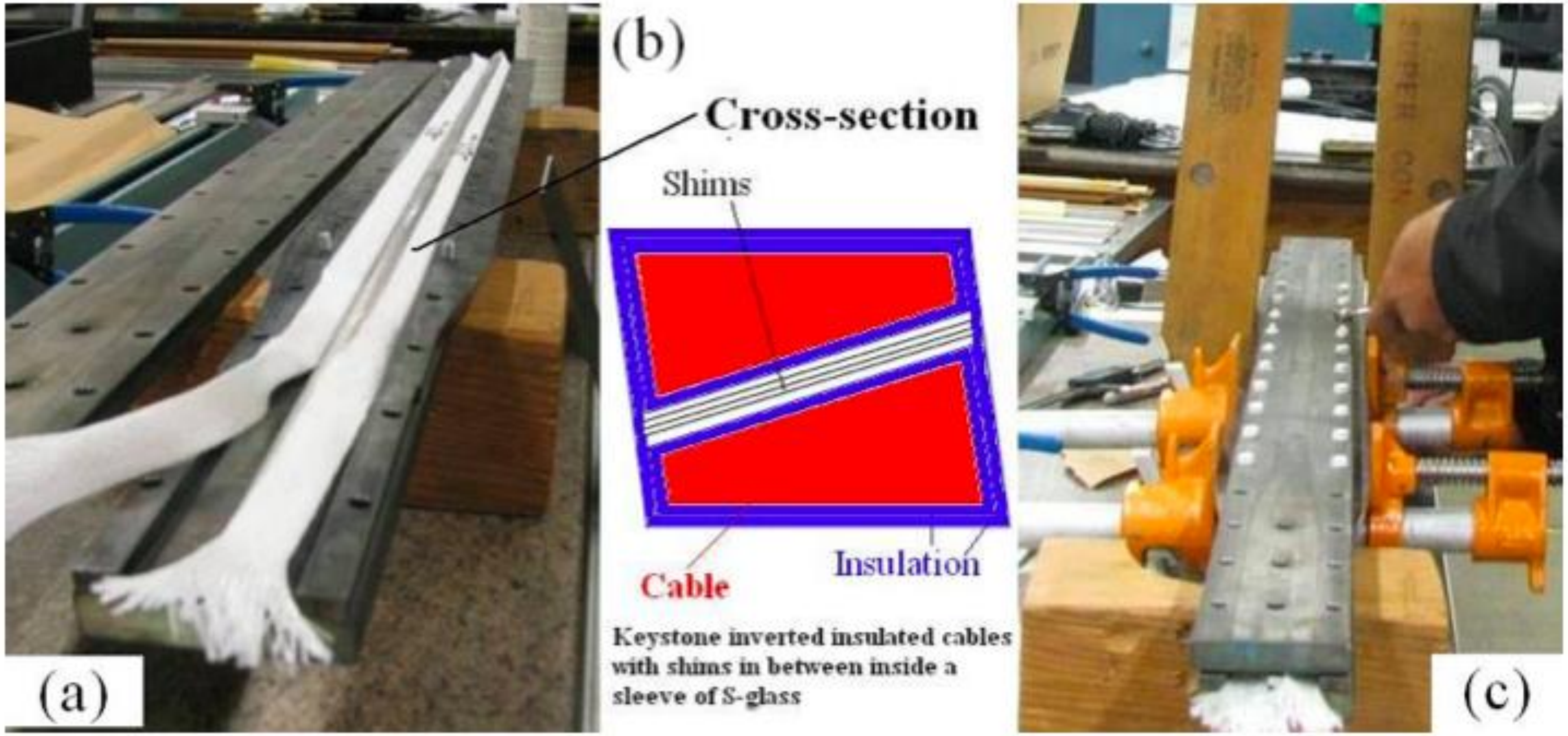
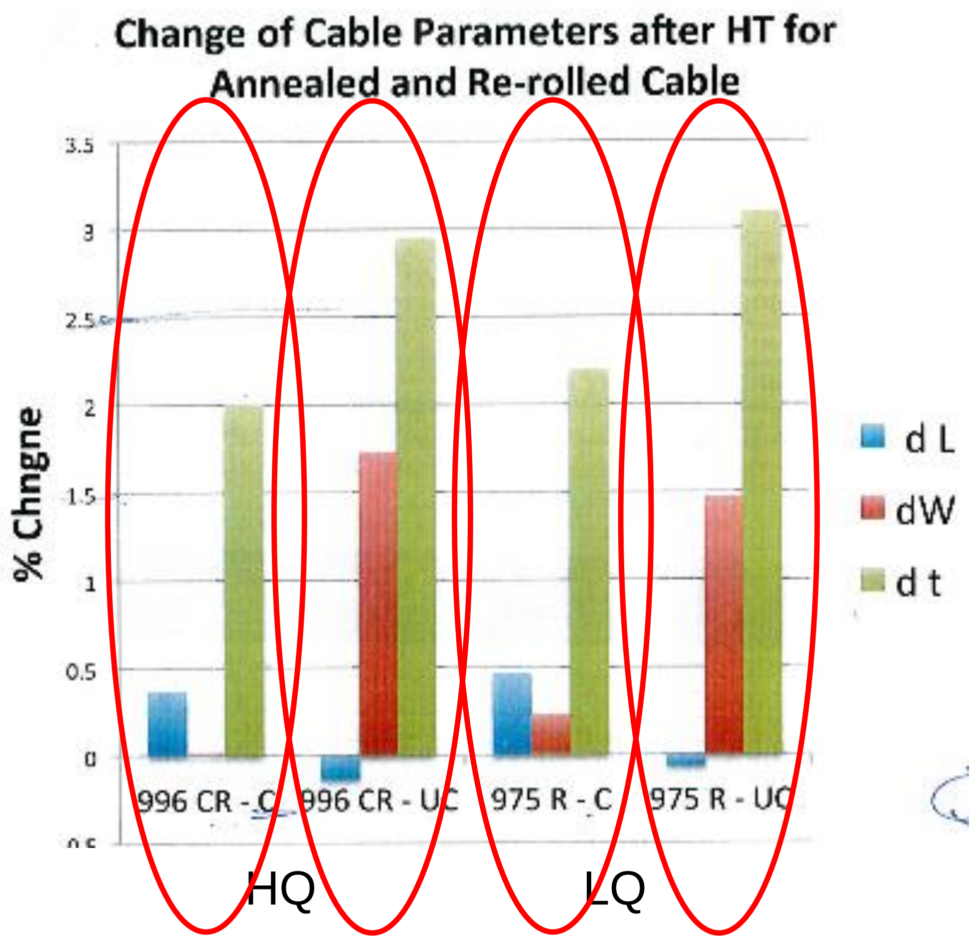


Figure 6: a) & b) The cables in the tooling, c) top plate is bolted on while the width is maintained by wooden blocks

Large Hadron Collider
Accelerator
Research
Program

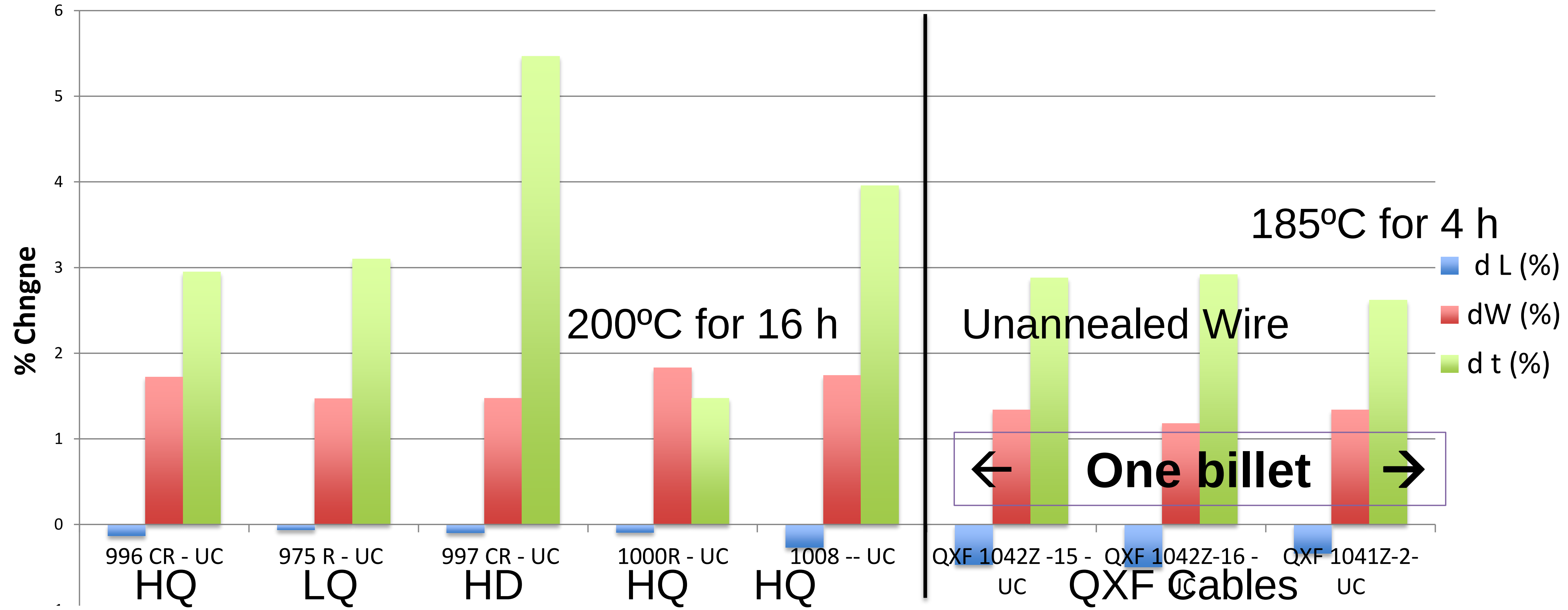
Confined vs. Unconfined Cables



Large Hadron Collider
Accelerator
Research
Program

Unconfined Cables

Change of Cable Parameters after HT for Annealed and Re-rolled Cable + QXF Cables with Annealed and Un-annealed



Large Hadron Collider
Accelerator
Research
Program

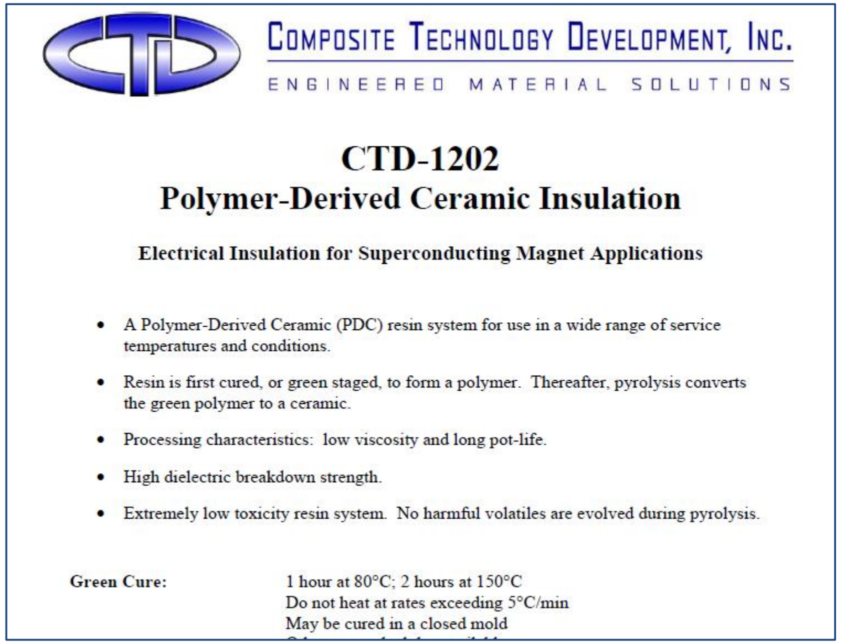
Materials

Cable Samples ("1st Generation")	**Details**
SQXF03 Inner - P33OL1053CB(70)B*	108/127, Ti-doped, reduced-Sn, 0.55° KS; annealed prior to cabling
SQXF-PC01b - P35OL1056AB(70)B	132/169, Ti-doped, Standard-Sn, 0.55° KS; annealed prior to cabling
SQXF04 Inner - P33OL1057AA(00)B	108/127, Ti-doped, reduced-Sn, 0.55° KS; annealed prior to cabling
SQXF05 Outer - P33OL1057AD(40)B	108/127, Ti-doped, reduced-Sn, 0.55° KS; annealed prior to cabling

* This cable was test-wound on a Selva winder and subsequently straightened.
It had matrix painted on the insulation every ~24" in 6 to 12" painted sections.

Reaction Method

- S2-glass Sleeve
- S2-glass Braid
- S2-glass Braid + CTD-1202 Matrix



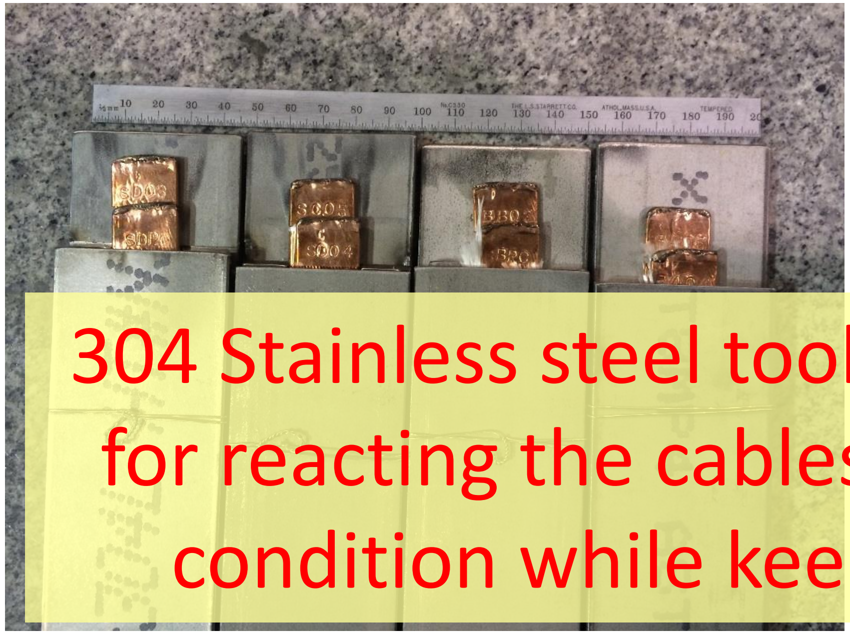
COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
ENGINEERED MATERIAL SOLUTIONS

CTD-1202
Polymer-Derived Ceramic Insulation

Electrical Insulation for Superconducting Magnet Applications

- A Polymer-Derived Ceramic (PDC) resin system for use in a wide range of service temperatures and conditions.
- Resin is first cured, or green staged, to form a polymer. Thereafter, pyrolysis converts the green polymer to a ceramic.
- Processing characteristics: low viscosity and long pot-life.
- High dielectric breakdown strength.
- Extremely low toxicity resin system. No harmful volatiles are evolved during pyrolysis.

Green Cure: 1 hour at 80°C; 2 hours at 150°C
Do not heat at rates exceeding 5°C/min
May be cured in a closed mold



304 Stainless steel tooling held by wire wrap for reacting the cables in the "unconfined" condition while keeping them straight.

Large Hadron Collider
Accelerator
Research
Program

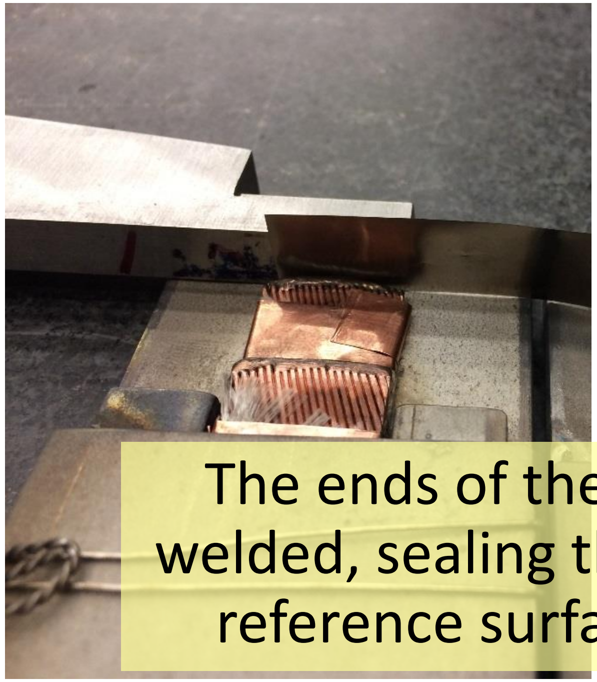
Heat Treatment

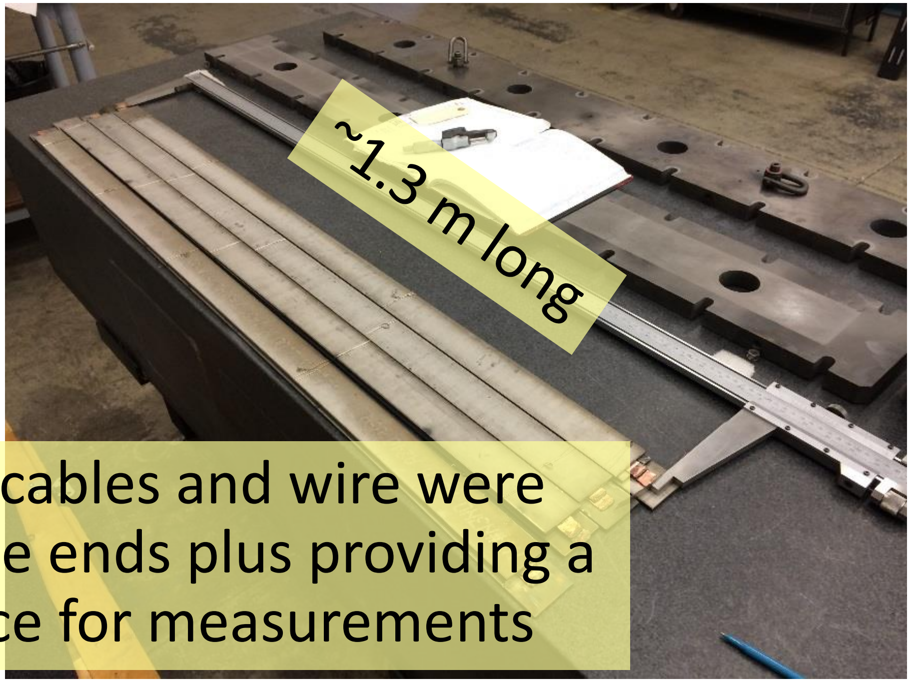
- 210°C for 72h + 405°C for 50h + 654°C for 50h and furnace cooled
- ± 5°C and ± 5 h at dwell; under flowing Ar

Large Hadron Collider
Accelerator
Research
Program

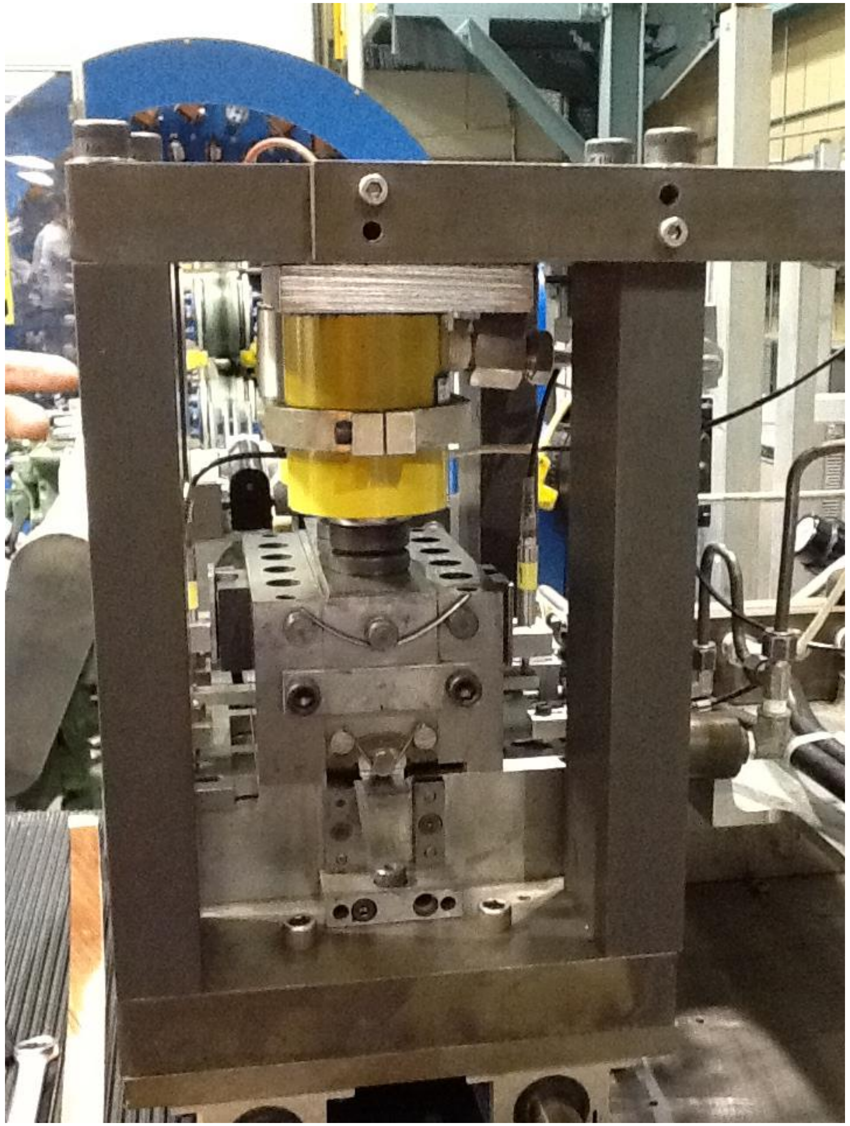
Measurement Methods

- Length measured with a caliper (±0.002”)
- Mid-thickness, width, and keystone angle measured by CME (17 MPa)

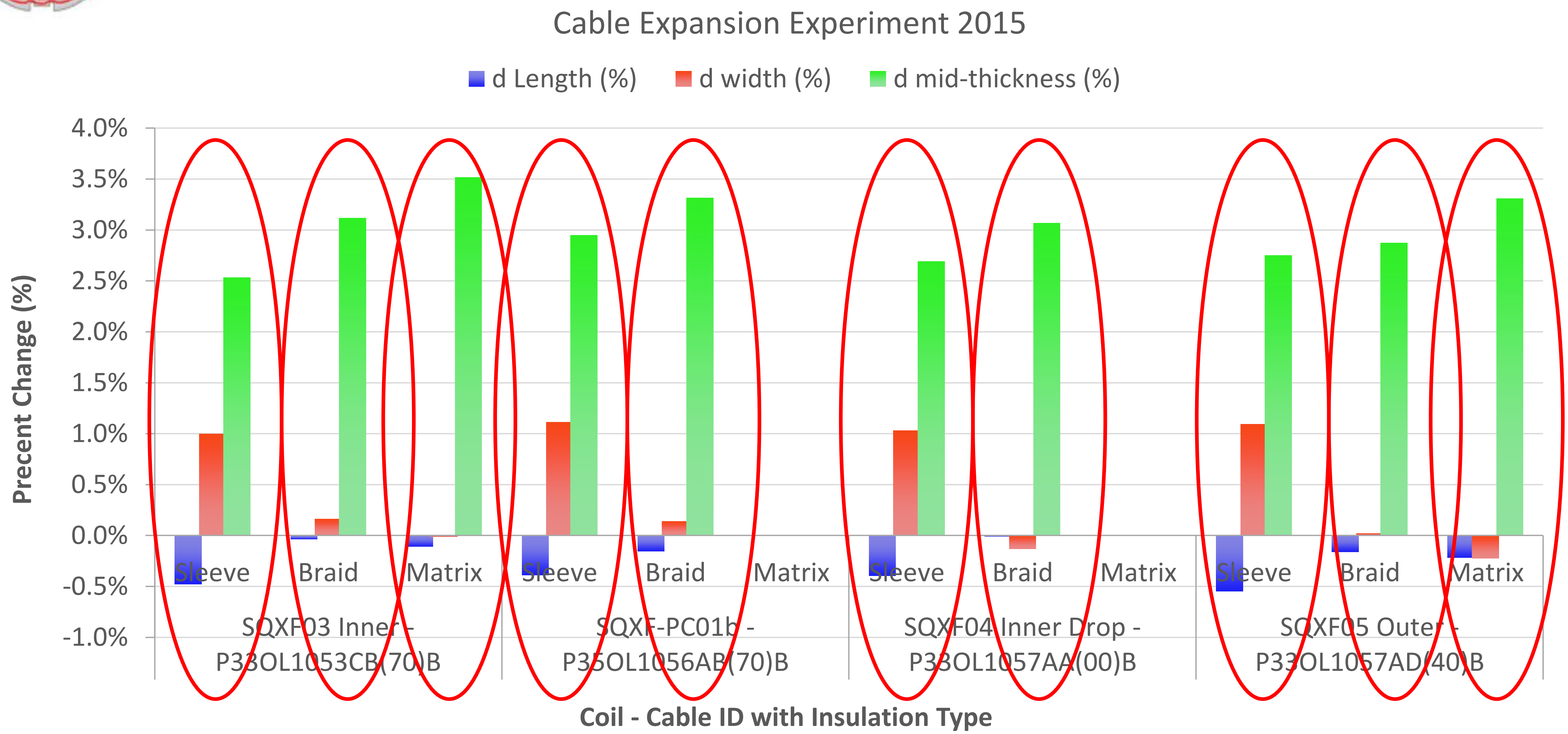


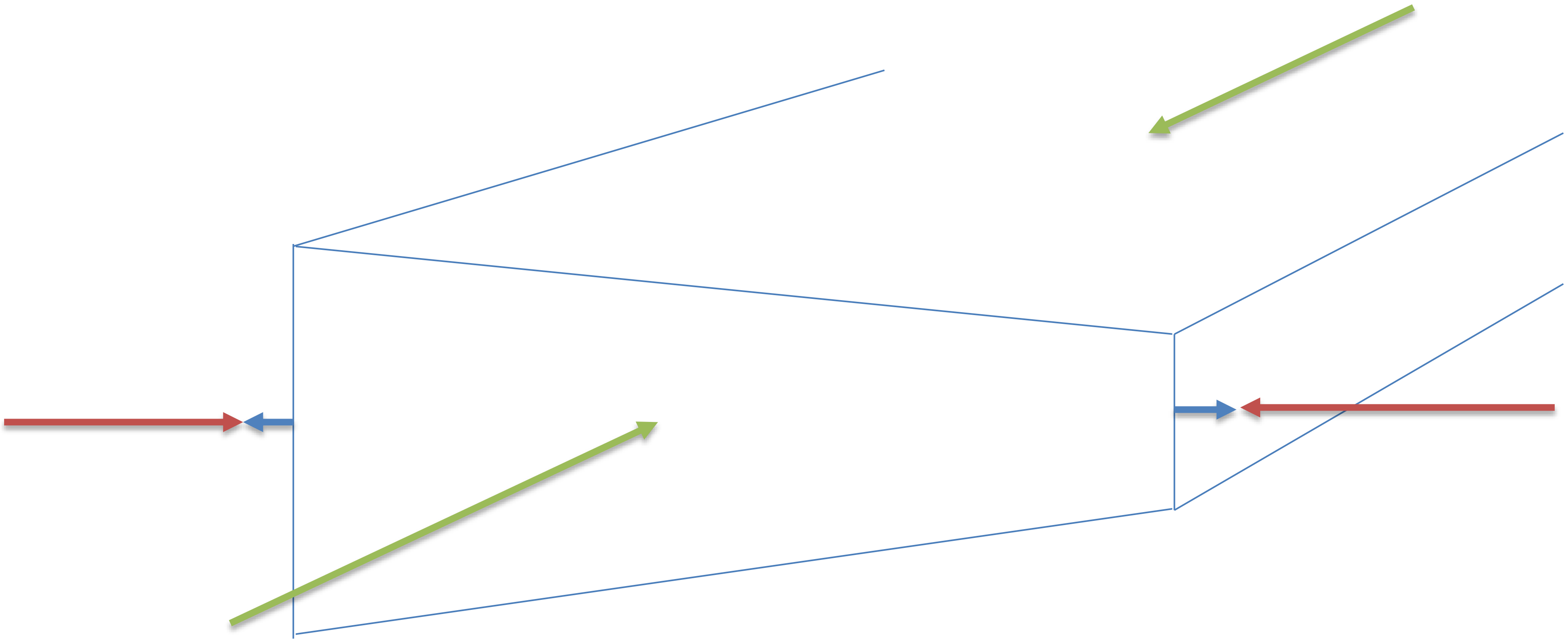


The ends of the cables and wire were welded, sealing the ends plus providing a reference surface for measurements



Results


Cable Expansion Experiment 2015
d Length (%)
d width (%)
d mid-thickness (%)
4.0%
3.5%
3.0%
2.5%
2.0%
1.5%
1.0%
0.5%
0.0%
-0.5%
-1.0%
Precent Change (%)
Sleeve
Braid
Matrix
Sleeve
Braid
Matrix
Sleeve
Braid
Matrix
Sleeve
Braid
Matrix
SQXF03 Inner - P33OL1053CB(70)B
SQXF-PC01b - P35OL1056AB(70)B
SQXF04 Inner Drop - P33OL1057AA(00)B
SQXF05 Outer - P33OL1057AD(40)B
Coil - Cable ID with Insulation Type

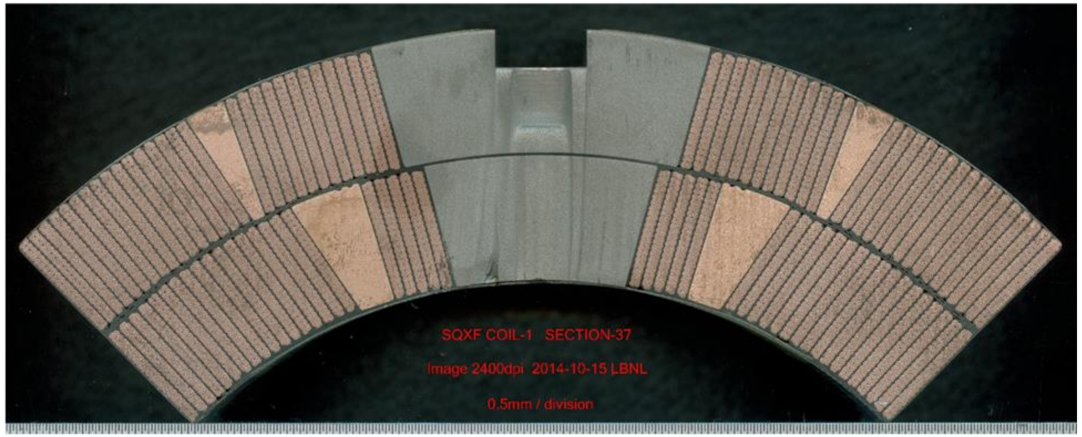


Conclusion

- Confined and unconfined cables behave differently
  - Length shrinks with greater width and thickness increase when unconfined; whereas cable elongates when confined
- Braid and sleeve have different effect on cable dimension change during heat treatment → impact of insulation
  - braid is like a cable with width and thickness confined
  - Slight length shrinkage and slightly larger thickness increase than C
- "Matrix material" degrades the braid but the effect on cable dimension change is similar: ~3% increase in mid-thickness

Coil Cross Section Analysis

- Direct coil cross section analysis comparison is difficult due to many reasons
  - Cable parameter definitions
  - Thickness variation
  - Core folding
  - etc. etc.



- Future papers:
  - MT24 (abstract 0101OP0696 by Holik et al.)
  - EuCAS (abstract A51662EH by Pong et al.)