# Cable Insulation Parameters and Dimensional Change in HQ, QXF, and TAMU3

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Workshop series announcement

**$Nb_3Sn$ Rutherford cable characterization for accelerator magnets**

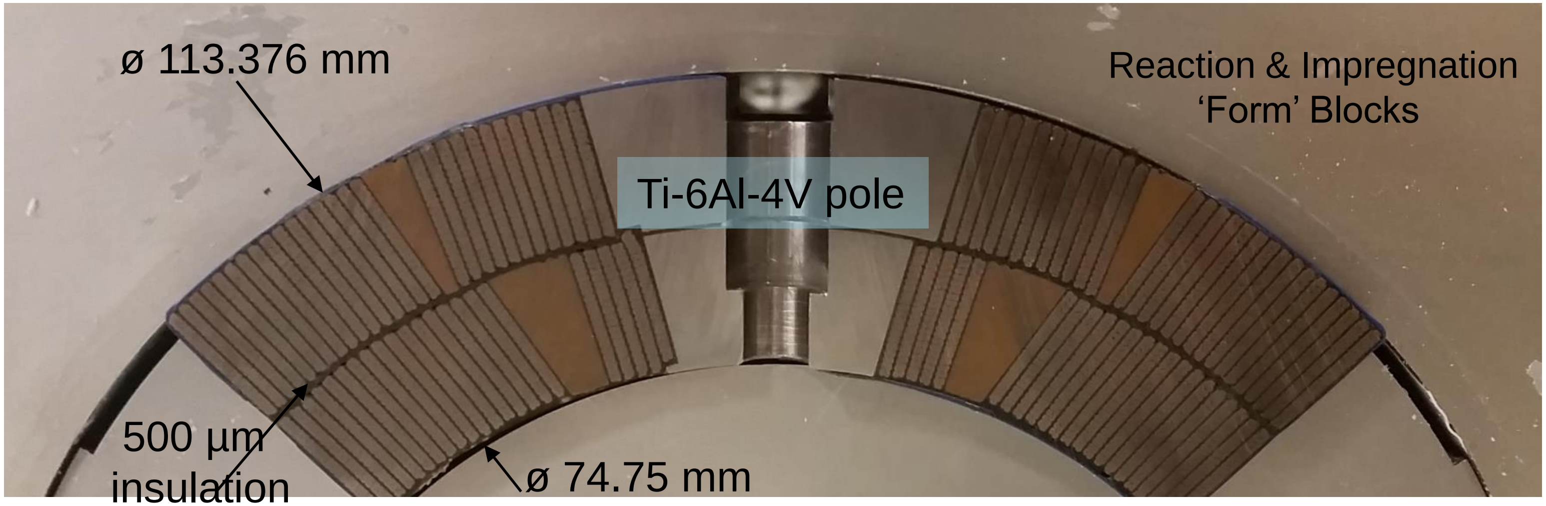
16-17 November 2017

Compatible with HL-LHC collaboration meeting attendance

CIEMAT, Madrid, Spain

# Coil Cross Sections

- QXF design is based on the established 120 mm HQ developed by LARP
  - 2 layer cos(2$\theta$) design with 150 mm aperture




- TAMU3 was 2 racetrack coils that incorporated stress management
  - One quadrant

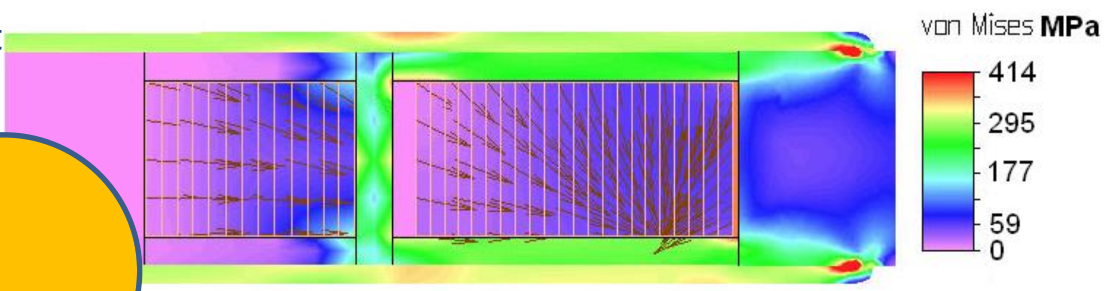
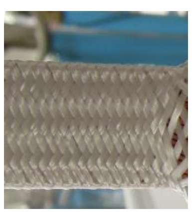



*Photo courtesy of S. Izquierdo Bermudez*

# Superconducting Cables

- Conductor
  - QXF - Ø 0.85 mm, 108/127 RRP (Bruker OST)
  - HQ - Ø 0.788 mm, 108/127 RRP (Bruker OST)
  - TAMU3 - Ø 0.7 mm, 54/61 RRP (Bruker OST)
- Cable
  - QXF - 12 µm thick by 10-12 mm wide SS core
    - 40 strands, 18 mm wide, 2nd gen: 0.40°
  - HQ - 25 µm thick by 8 mm wide SS core
    - 35 strands, 15 mm wide, 0.75° keystone
  - TAMU3 – No core, 34 strands and 13 mm wide
- S-2 Glass sock and braid as insulation,
  - **Braided on** insulation enables long cable lengths
  - Intimately contacts Rutherford cable

*Photo courtesy of P. Ferracin*



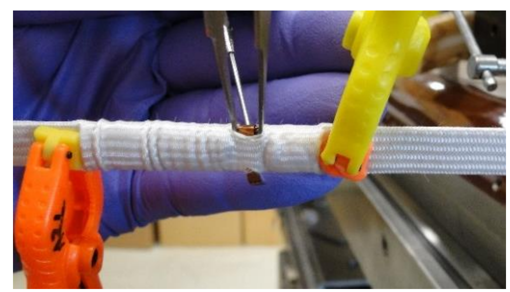
CERN
143 µm

LARP
146 µm

TAMU
70 µm
(5.5 µm filament)

QXF & HQ are
9 µm filament

HQ03
104 µm



Loose TQ Sock



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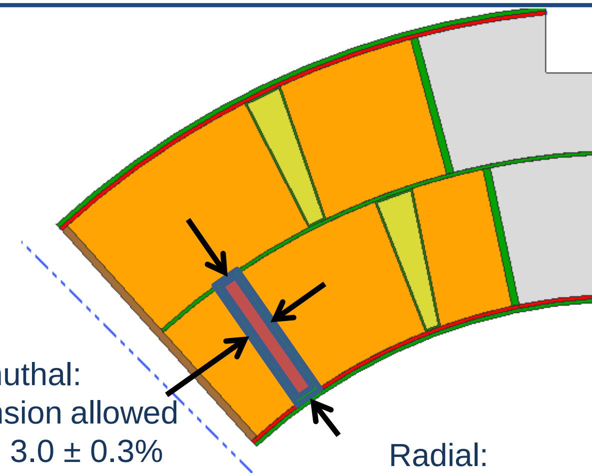
# Pole Gap measurements for QXF

- $Nb_3Sn$ Cable **expands laterally** when heat treated.
- $Nb_3Sn$ Cable **contracts axially** when heat treated.
- Room is left in coil cavity for cable to expand during heat treatment.
- Gaps are left in the pole to allow cable to contract



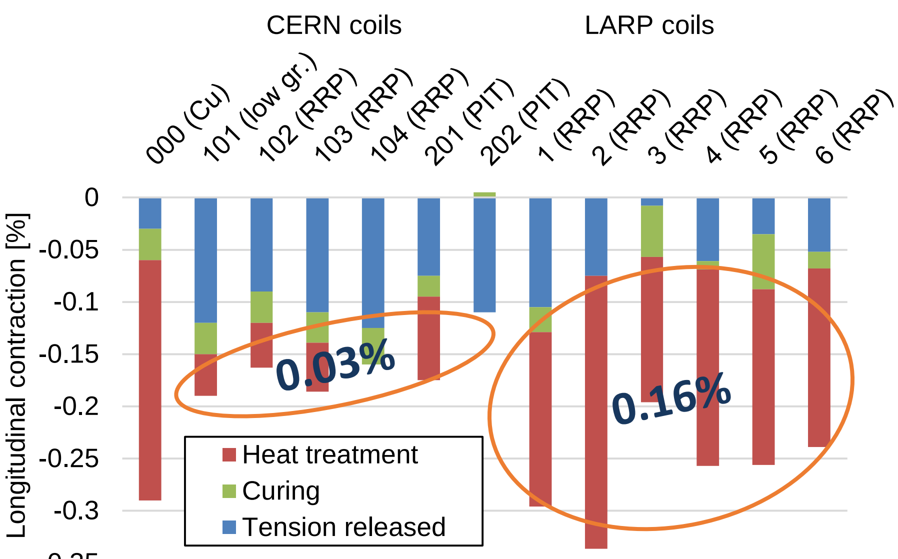




*Figure courtesy of E. Rochepault*


TAMU expansion partially accommodated by means of a laminar spring.

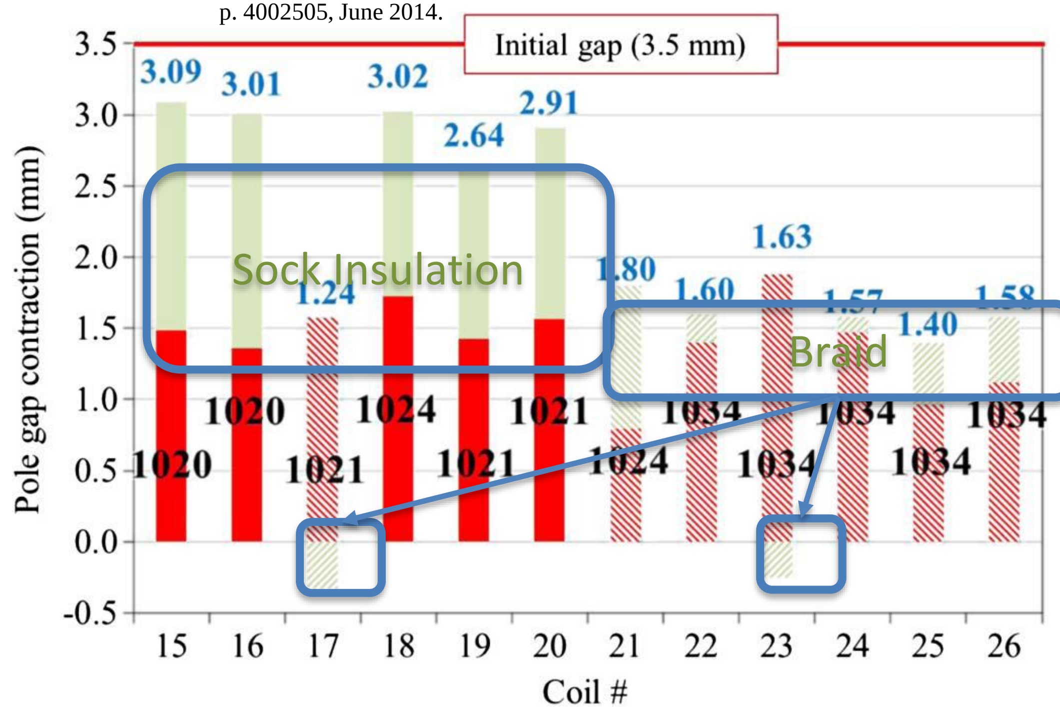
# Pole Gap Measurements from HQ02

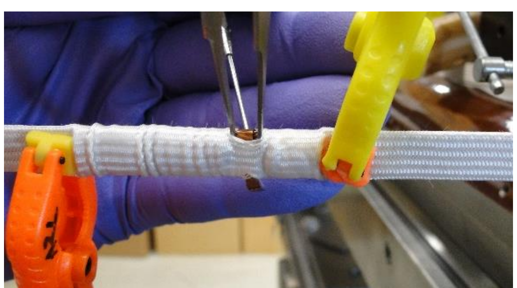
- Pole Gap Closure

From Heat Treatment

From Removing Shims Releasing Tension

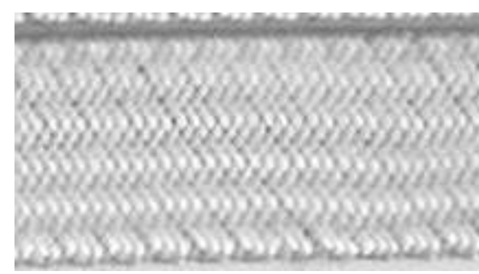
F. Borgnolutti, *et al.*, "Fabrication of a Third Generation of $Nb_3Sn$ Coils for the LARP HQ03 Quadrupole Magnet," *IEEE Trans. App. Supercond.*, vol. 24, no. 3, p. 4002505, June 2014.



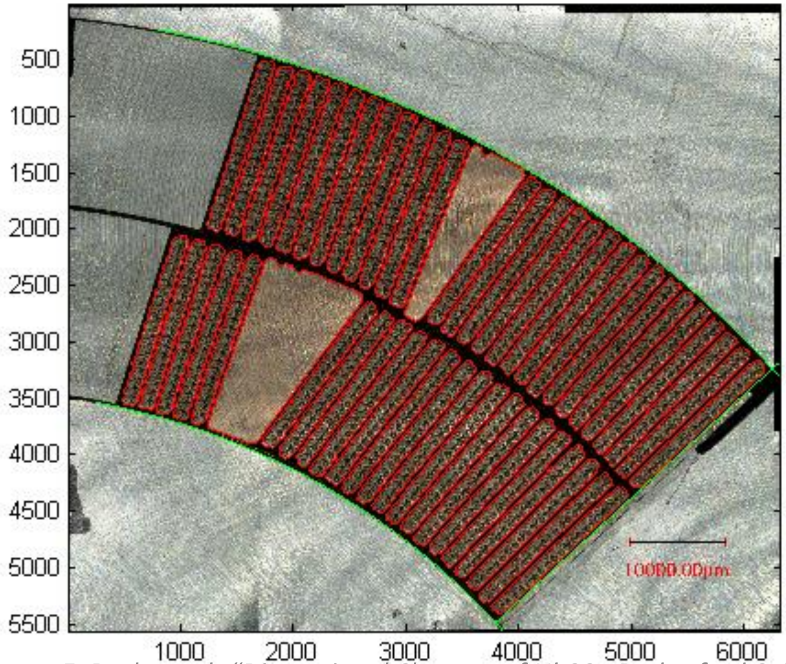



Sock

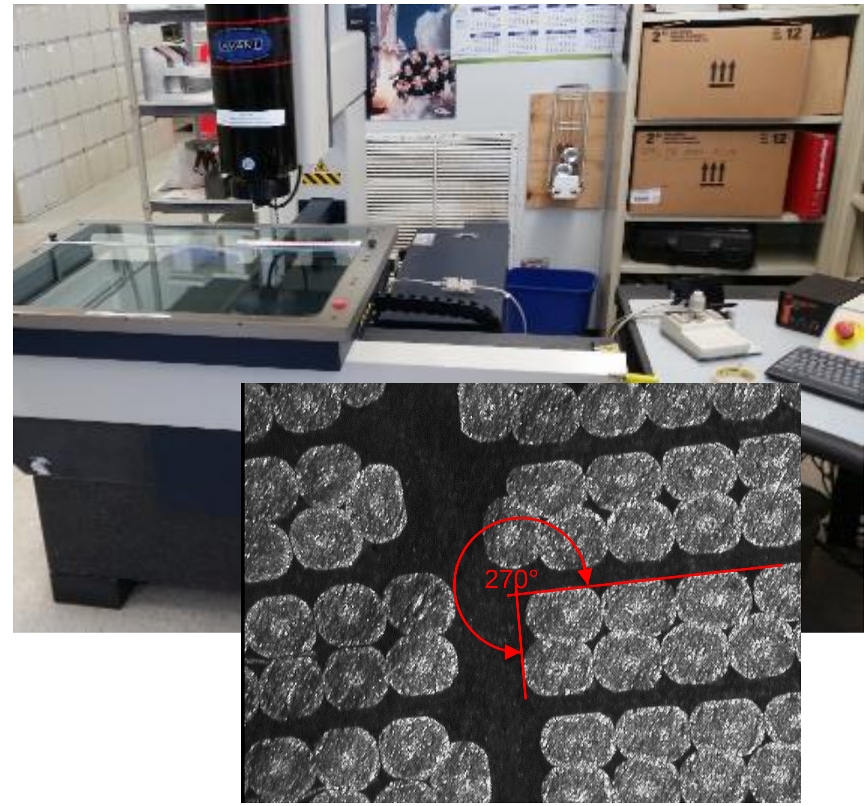
Braid: Enables Long Cable lengths



# Coil Cross Section Analysis



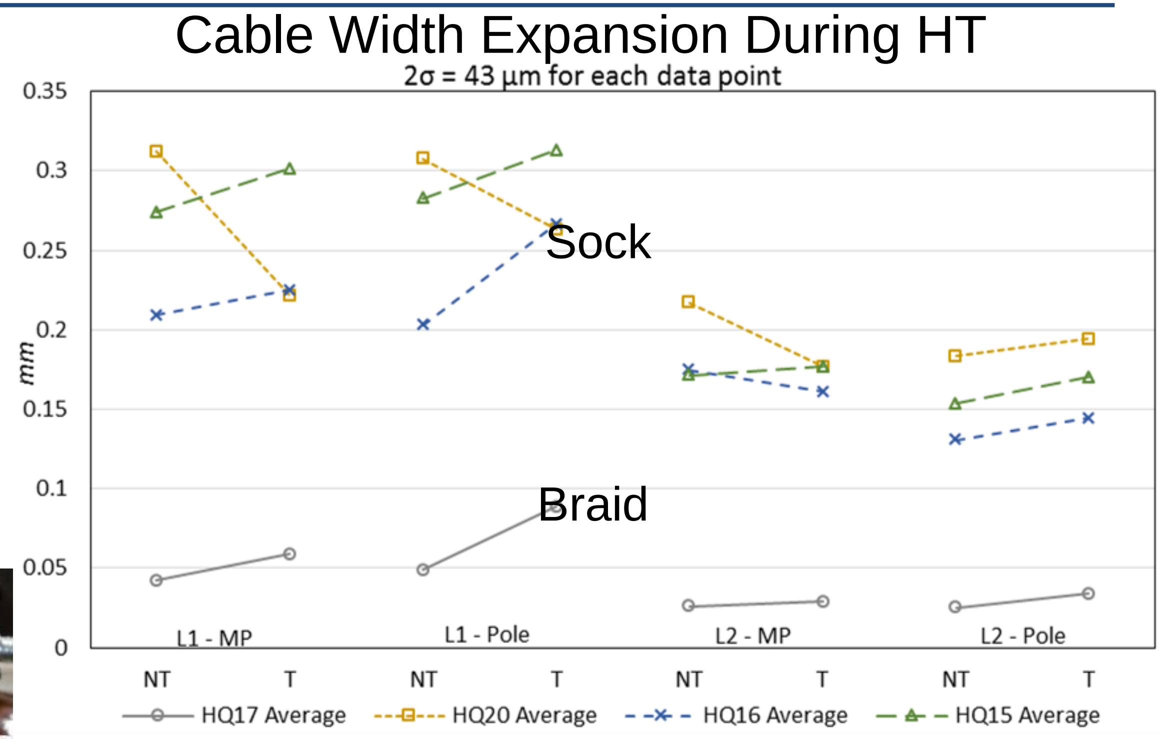

*E. Rochepault "Dimensional Changes of Nb3Sn Rutherford Cables during Heat Treatment" This Conference*

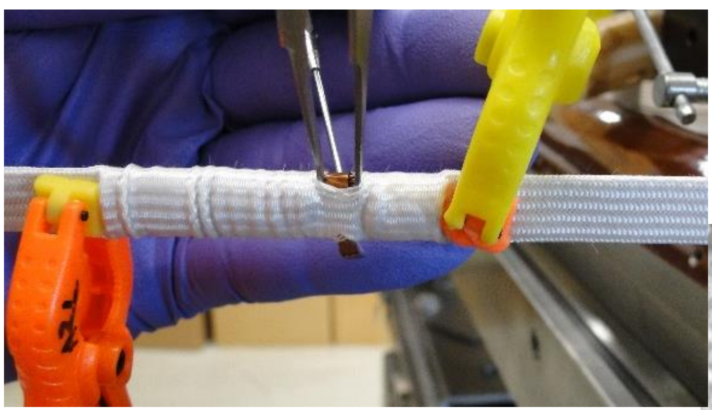



- CERN coil 101, Turn location from Image analysis and edge detection
- LARP coil 1, Turn location from Optical Coordinate Measurement Machine

# HQ02 Cable Width Expansion

- Braided-on insulation constricts cable growth:
  - HQ17 has braided-on type insulation
  - All other coils use sock type insulation



Loose Sock

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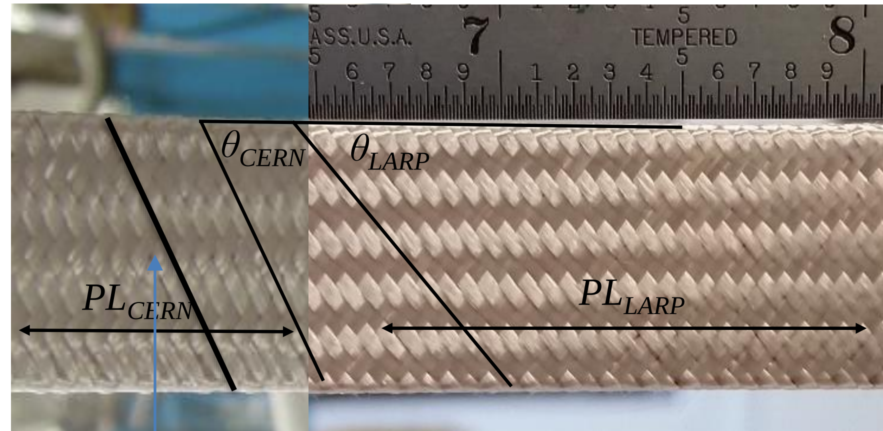
# Insulation and Cable Growth

- Insulation intimately contacts cable

- Thermal Expansion
  - S-2 Glass = ~ 1.5 $10^{-6}$/°C
  - Niobium = ~ 9 $10^{-6}$/°C
  - Copper = ~ 17 $10^{-6}$/°C
- From heat treatment:
  Volumetric expansion of Cable
  (3% – 6%)

- The Insulation applies an axial and transverse pressure on the cable as the cable expands.
- The cable expansion is altered based on the insulation parameters



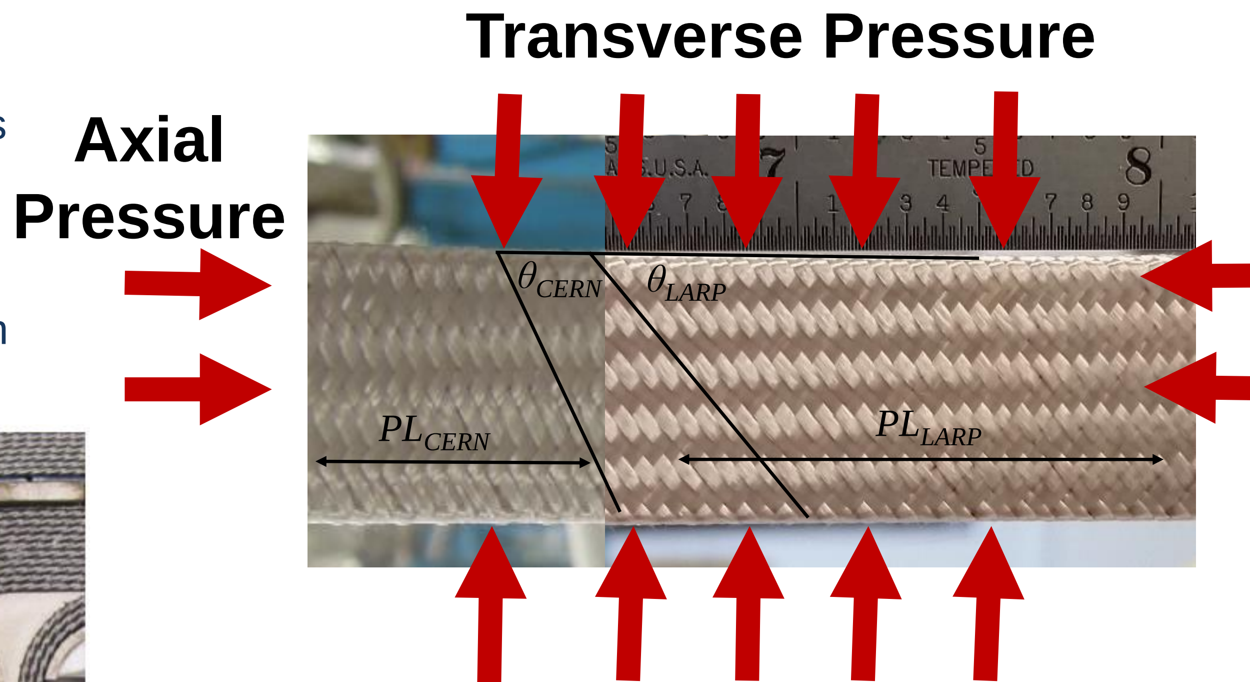

KEY BRAIDED-ON INSULATION PARAMETERS

| Parameter | HQ braid | MQXF LARP | MQXF CERN | units | TAMU3 |
|---|---|---|---|---|---|
| # Carriers | 48 | 48 | 32 | - | 128 |
| Picks per inch (*P/I*) | 28.2 | 18.3 | 21.6 | - | - |
| Pitch Length (*PL*) | 21.7 | 33.4 | 18.8 | mm | - |
| Pitch angle (*PA*) | 56.2° | 49.7° | 64.4° | - | ~CERN |
| Insulation thickness | 0.104 | 0.143 | 0.146 | mm | .070 |
| Width of Cable (*W*) | 14.8 | 18.15 | 18.15 | mm | 13.4 |
| Mid-thickness of Cable (*T*) | 1.375 | 1.525 | 1.525 | mm | 1.25 |
| # Plies / Strand | 1 | 2 | 2 | - | (204 fil/strand) |

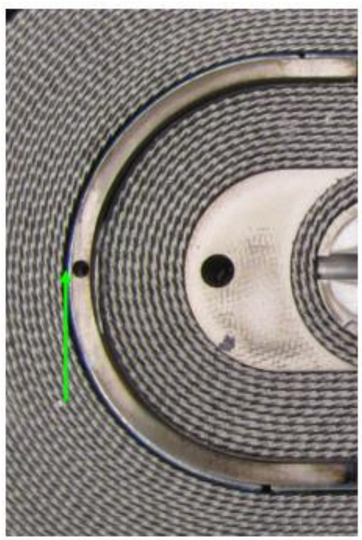
A basket weave of AGY S-2 Glass fibers of 66 TEX with 933 high-temperature silane sizing was used for each type of insulation.

# Insulation and Cable Growth

- CERN Insulation preferentially constricts width growth and thus reduces length contraction
- LARP Insulation with a smaller pitch angle and longer pitch length allows slightly more width growth and more length contraction.

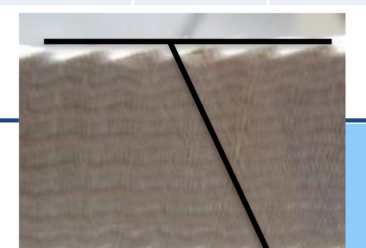



TAMU3 Gap



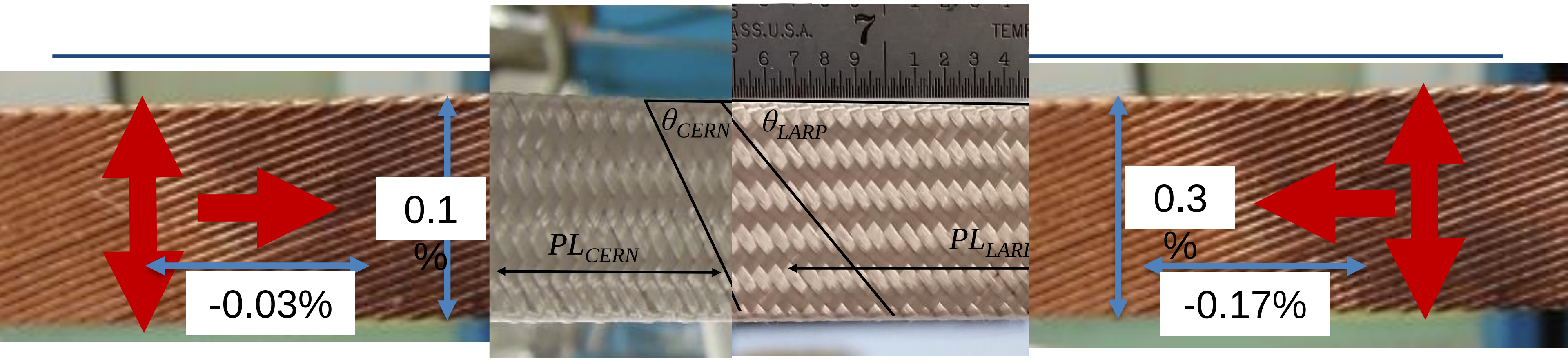
Picture 1: Gap between outer winding and spring of TAMU3b. See green arrow.

| | FREE HQ | Braid HQ | Free MQXF* | LARP MQXF | CERN MQXF | TAMU3 |
|---|---|---|---|---|---|---|
| Avg. Cable Width Expansion | 1.8% | 0.4% | **1.3%** | **0.3%** | **0.1%** | **-** |
| Avg. HT Coil Gap Closure | 0.2% | 0.01% | **0.45%** | **0.16%** | **0.03%** | **-0.3%** |



*From Cable Expansion Experiments (I. Pong, D. Dietderich)*

# How does insulation affect cable growth?




Bare Cable: 1.4% -0.44%

KEY BRAIDED-ON INSULATION PARAMETERS

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|---|---|---|---|---|---|
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| Picks per inch *(P/I)* | 28.2 | 18.3 | 21.6 | - | - |
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| # Plies / Strand | 1 | 2 | 2 | - | (204 fil/strand) |

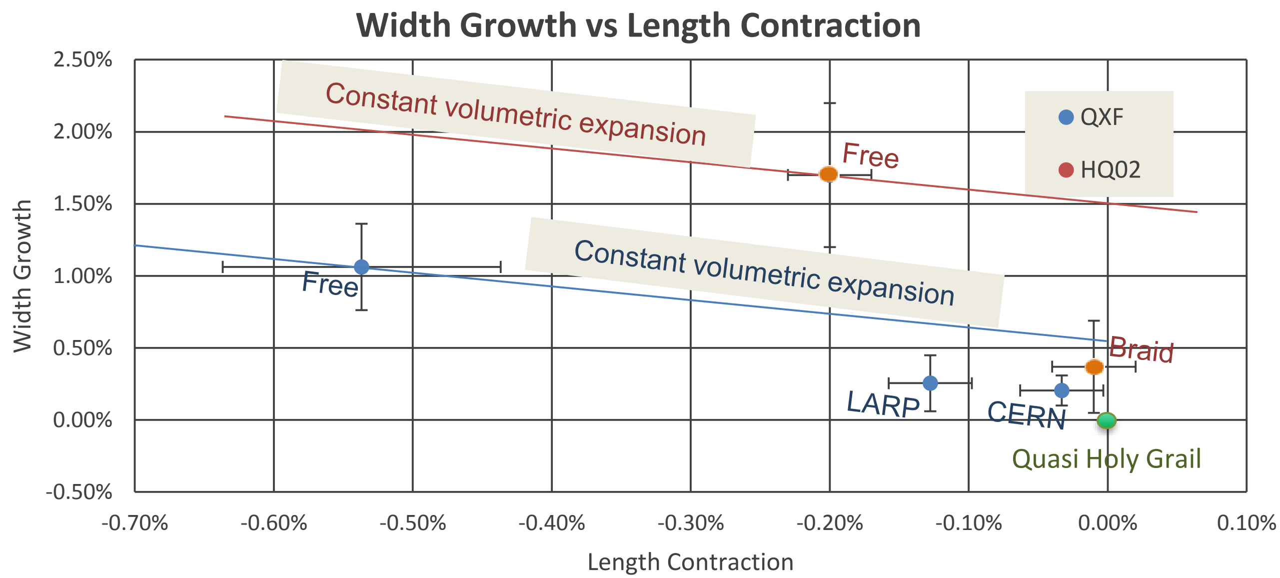
A basket weave of AGY S-2 Glass fibers of 66 TEX with 933 high-temperature silane sizing was used for each type of insulation.

- Cable Width is significantly altered by braided insulation
- Transverse pressure also reduces axial contraction

E. Holik, *et al*., "Fabrication and Analysis of 150-mm-Aperture $Nb_3Sn$ MQXF Coils," *IEEE Trans. App. Supercond.*, vol. 26, no. 4, Jan 2016. *(MT24)*

# Engineering a cable/insulation system

- **A Serendipitous Finding: Braided-on insulation reduces expansion!!!**




TAMU3 out to 0.3%

- **Need to explore parameter space to best exploit insulation parameters in subsequent designs**
  - Volumetric expansion is largely unaffected by insulation
    - Need to verify if insulation increases residual conductor strain
  - Current QXF design is locked for Hi-Lumi LHC despite accommodating more width growth than measured in cross section
    - Would be very risky to change design and reduce assumed expansion

# Conclusions

- **Braided on insulation** constricts cable width growth and reduces length contraction during heat treatment.
  - Likely reduces risk for long length coils! ☺
- Optimizing the insulation system may result in a zero-axial-expansion or zero-width expansion parameter space but not both…