CERN-FNAL Collaboration Meeting on DS 11T Dipole grounds – FNAL, Sep. 21-23, 2015

# Conductor and Cable development at FNAL

Emanuela Barzi

September 21, 2015

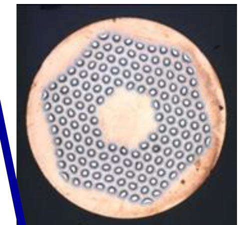
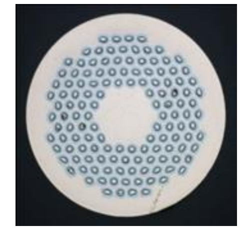
# Outline

- Description of wires used in magnets - Cable specs
- Cable fabrication and quality control, cable expansion
- Uncored and Cored cable development and study
- Cable test
- Summary of cable fabrication

# Wires used in Magnets

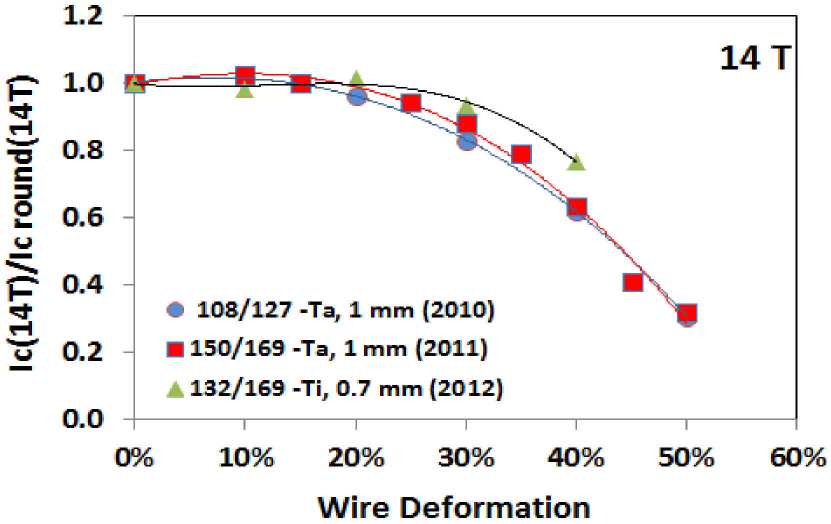
**Advanced strand, to be proven in magnets**

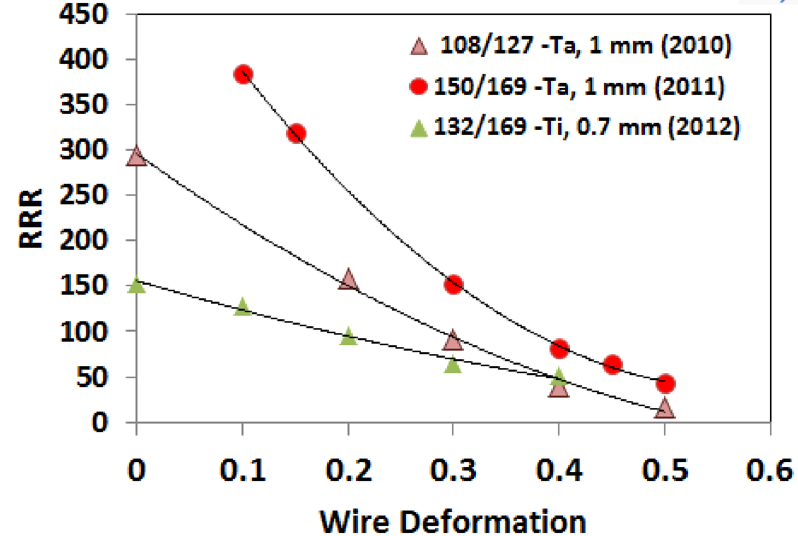
**Baseline strand**

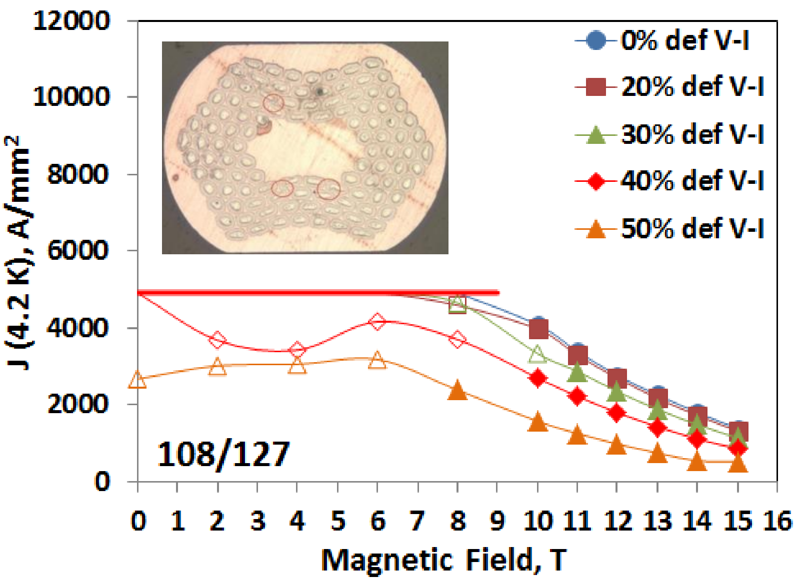




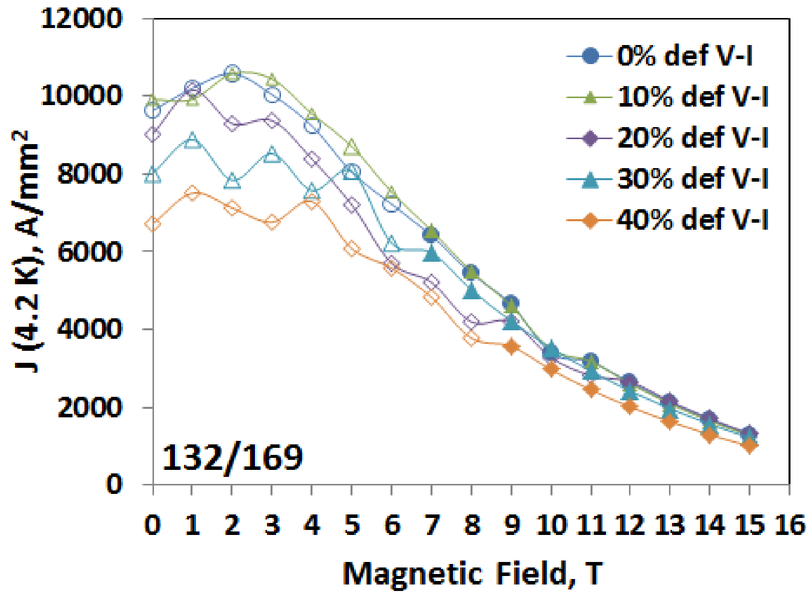
| Strand ID | RRP1 | RRP2 | RRP4 |
|---|---|---|---|
| Stack design | 108/127 | 150/169 | 132/169 |
| Ternary element | Ta | Ta | Ti |
| Used at | FNAL | FNAL | CERN |
| Production year | 2010 | 2011 | 2012 |
| Diameter *d*, mm | 0.7 | 0.7 | 0.7 |
| $I_c$ (4.2K, 12 T), A | 421 | 465 | 449 |
| $J_c$ (4.2K, 12 T), A/mm$^2$ | 2,460 | 2,508 | 2,649 |
| $I_c$ (4.2K, 15 T), A | 201 | 230 | 219 |
| $J_c$ (4.2K, 15 T), A/mm$^2$ | 1176 | 1240 | 1297 |
| $D_S$, μm | 41 | 36 | 36 |
| Twist pitch, mm | 14 | 14 | 13 |
| Cu fraction λ, % | 55.5 | 51.8 | 56.0 |
| RRR | 83-359 | 165 | 153 |
| Final HT step | 640ºC/48h | 665ºC/50h | 640ºC/48h |

# Wires used in Magnets (cont.)



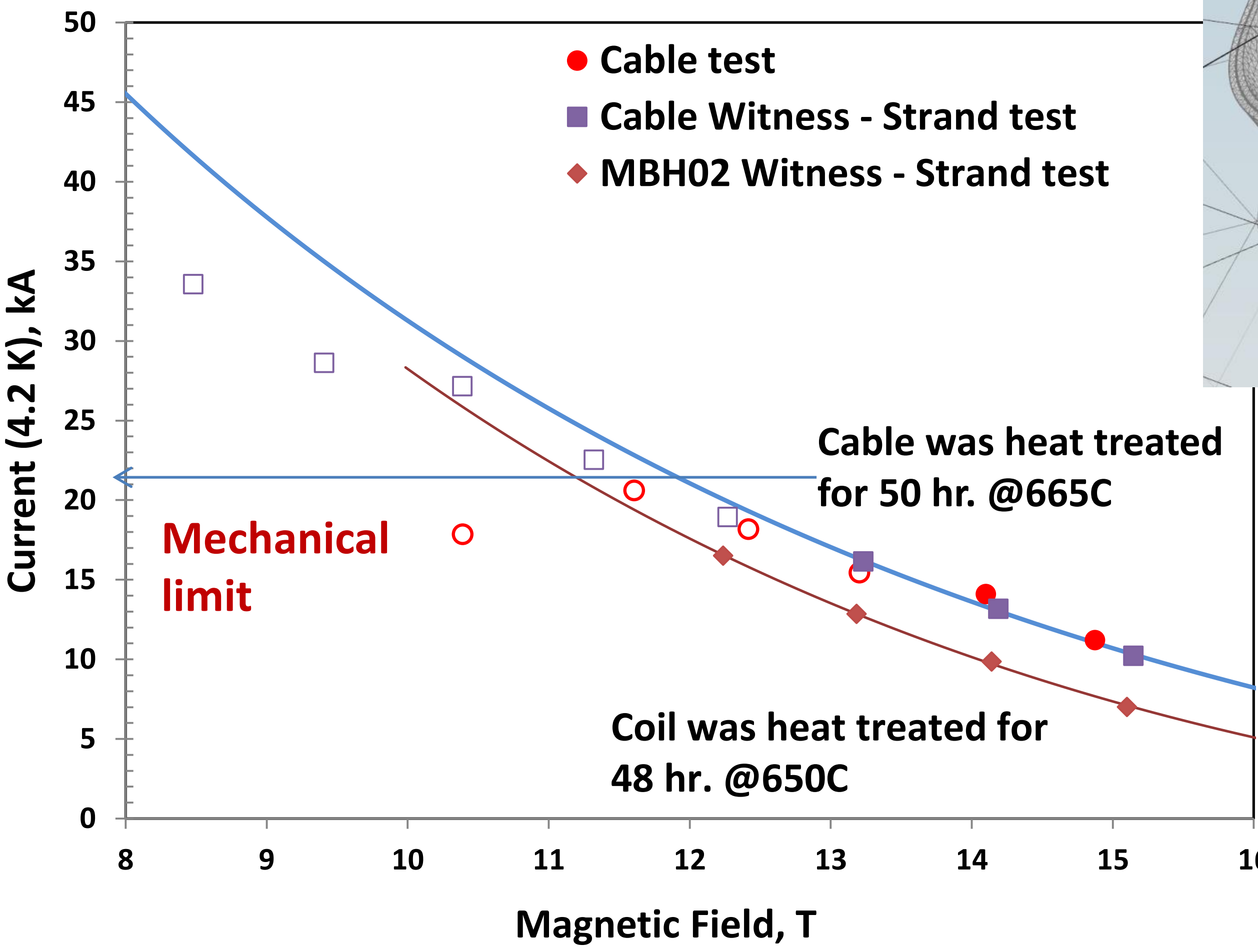



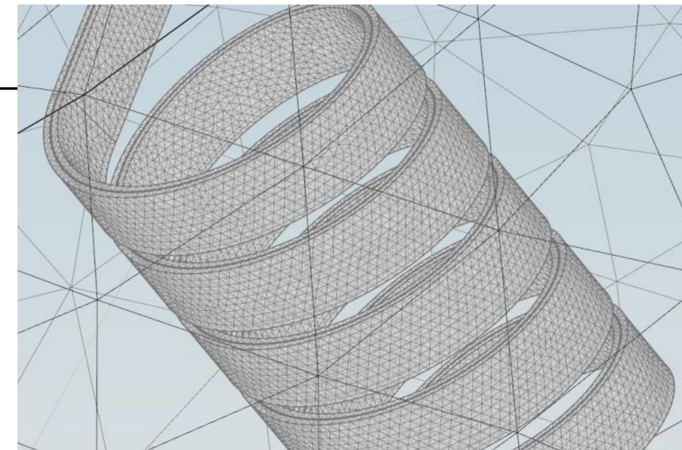




*"Progress in Nb3Sn RRP Strand Studies and Rutherford Cable Development at FNAL", E. Barzi, D. Turrioni and A. V. Zlobin, IEEE Trans. Appl. Sup., article #6000808, V. 24, No. 3 (2014).*

# Test of 108/127 RRP Cable DM-CF-01-0b (MBHSP01) with SC Transformer



## 3D FEM Model

| Cable Parameter | Value |
|---|---|
| Cable thickness | 1.3 mm |
| Cable width | 15.09 mm |
| Bifilar gap | 0.25 mm |

**Self-field correction 0.078 T/kA**

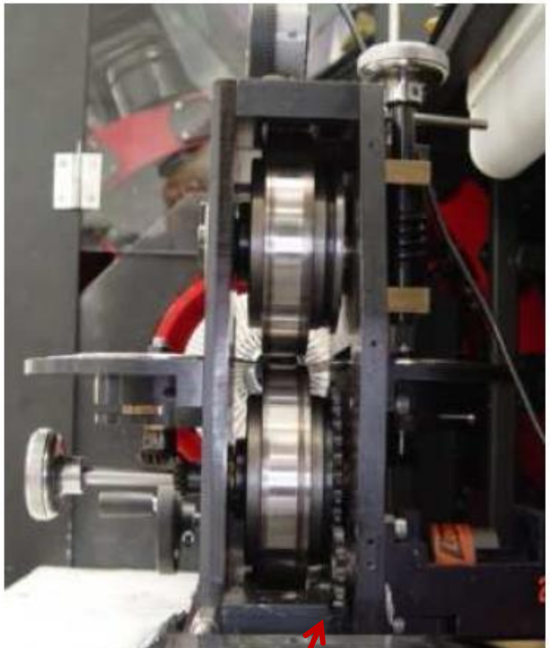
*"Progress in Nb3Sn RRP Strand Studies and Rutherford Cable Development at FNAL", E. Barzi, D. Turrioni and A. V. Zlobin, IEEE Trans. Appl. Sup., article #6000808, V. 24, No. 3 (2014).*

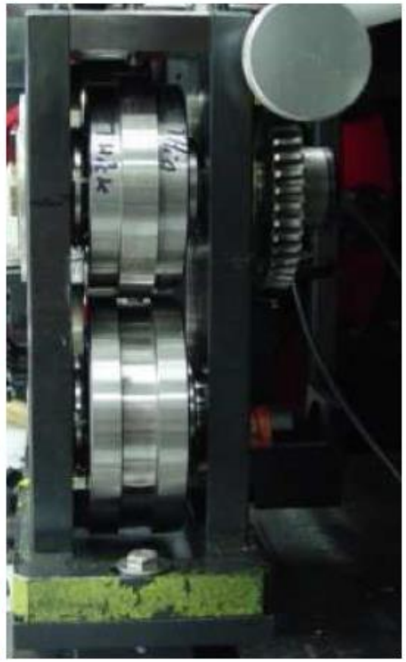
# Cable Requirements

- **Factors used in selecting the initial cable geometry:**
  - **To setup parallel cable fabrication lines at FNAL and at CERN ➔ max. No. strands ≤ 40**
  - **To achieve required magnet transfer function of 11 T at 11.85kA ➔ Strand size ≤ 0.7 mm**
  - **Critical current degradation due to cabling < 10%**

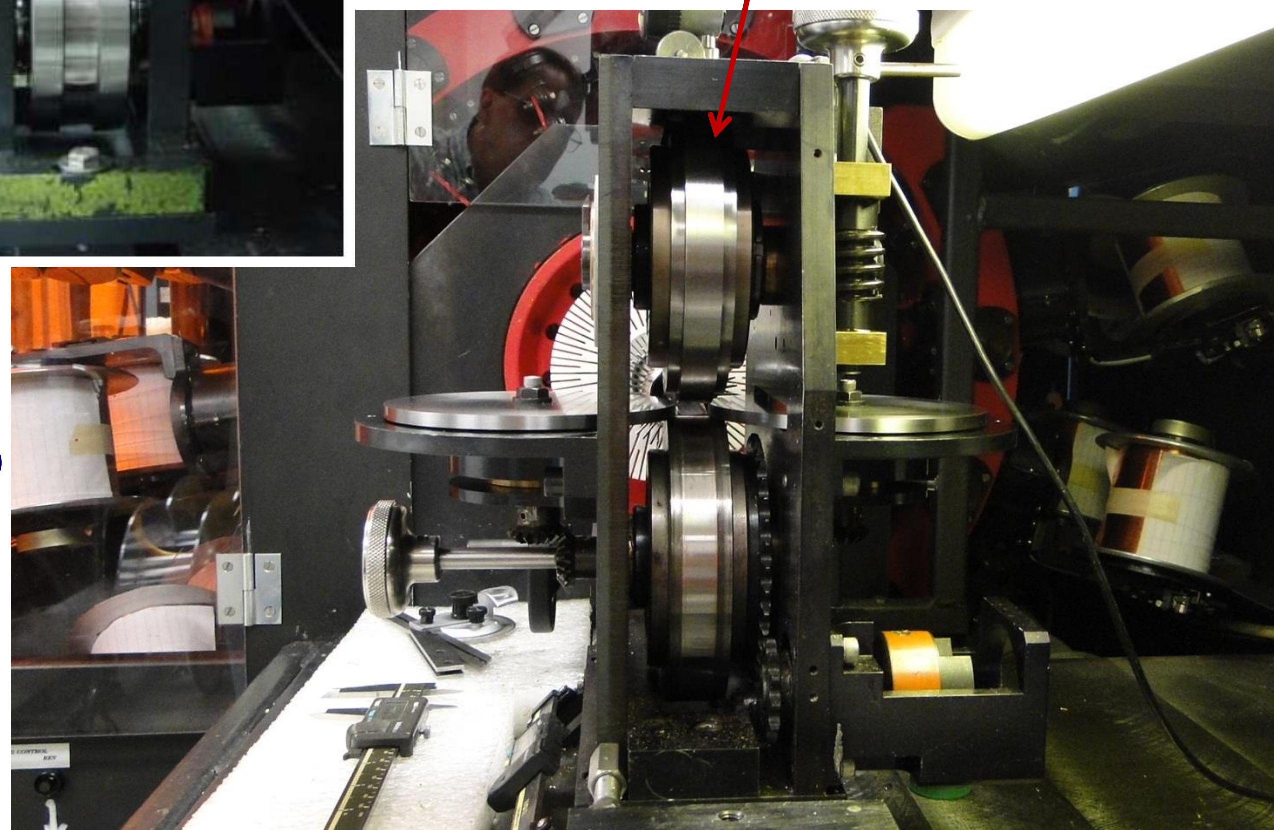
- **Original cables were designed based on:**
  - **Deformation of small edge 1-h/2d ≤ 20%. Large edge compacted by ~2% for mechanical stability.**
  - **Width compaction, i.e. cable width/undeformed width > 1**
  - **Cable packing factor ~ 86% ➔ 1.27 mm mid-thickness**

# Cable Fabrication





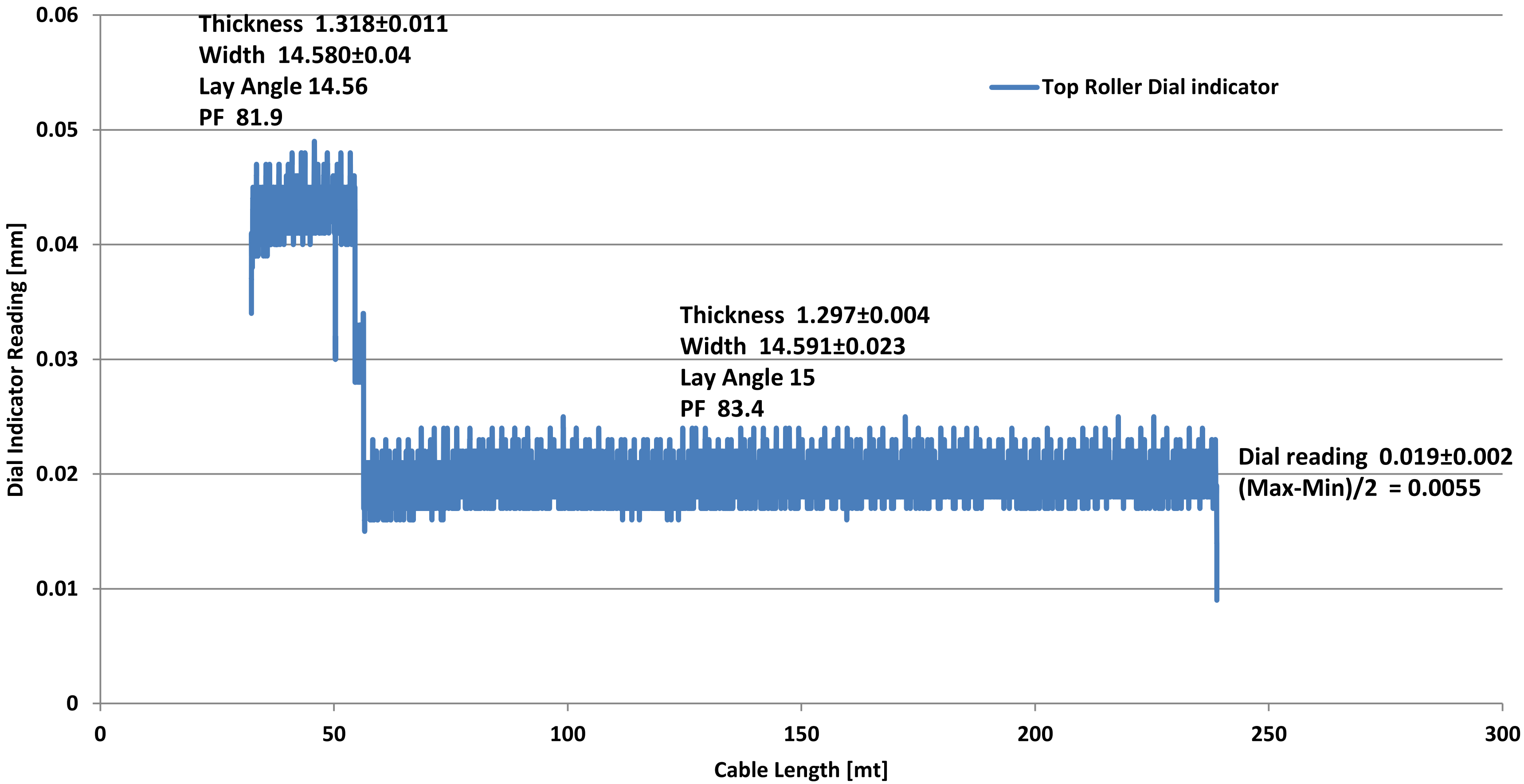
In preparation to coil scale up to 5.5 m long, a new turk-head designed for one-pass cable fabrication was later tested and commissioned.



Original cable was made in two steps using forming fixture and keystoned rollers.

# Example of Cable Measurements

| Traveler | Type | Strand Design | No. strands | Strand size mm | Mandrel width mm | Cable width mm | Cable thickness mm | Lay angle ° | PF % | SS Core | Length m |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R&DT_110420_40_1_0 | R | Cu | 40 | 0.697 | 13.92 | 14.591±0.023 | 1.297±0.004 | 15 | 83.4 | N | 186 |



# Cable Expansion for Tooling Design

- The coil dimensions in the winding and curing tooling are determined by the unreacted cable cross section, whereas the coil dimensions in the reaction and impregnation tooling are based on the reacted cable cross section.
- Experimental data indicate that the $Nb_3Sn$ cable cross section expands anisotropically during reaction. The change in dimensions before and after reaction was measured for five keystoned nominal cables which were stacked on the flat face in a stainless steel straight fixture 1.22 m long. The cables were placed within a groove with enough room for the cables to expand freely in all three directions. Mica layers 0.15 mm thick were placed between the cables:
  - The average width expansion was 2.6% ± 0.2%
  - The average mid-thickness expansion was 3.9% ± 0.5%
  - The average length decrease was 0.3%

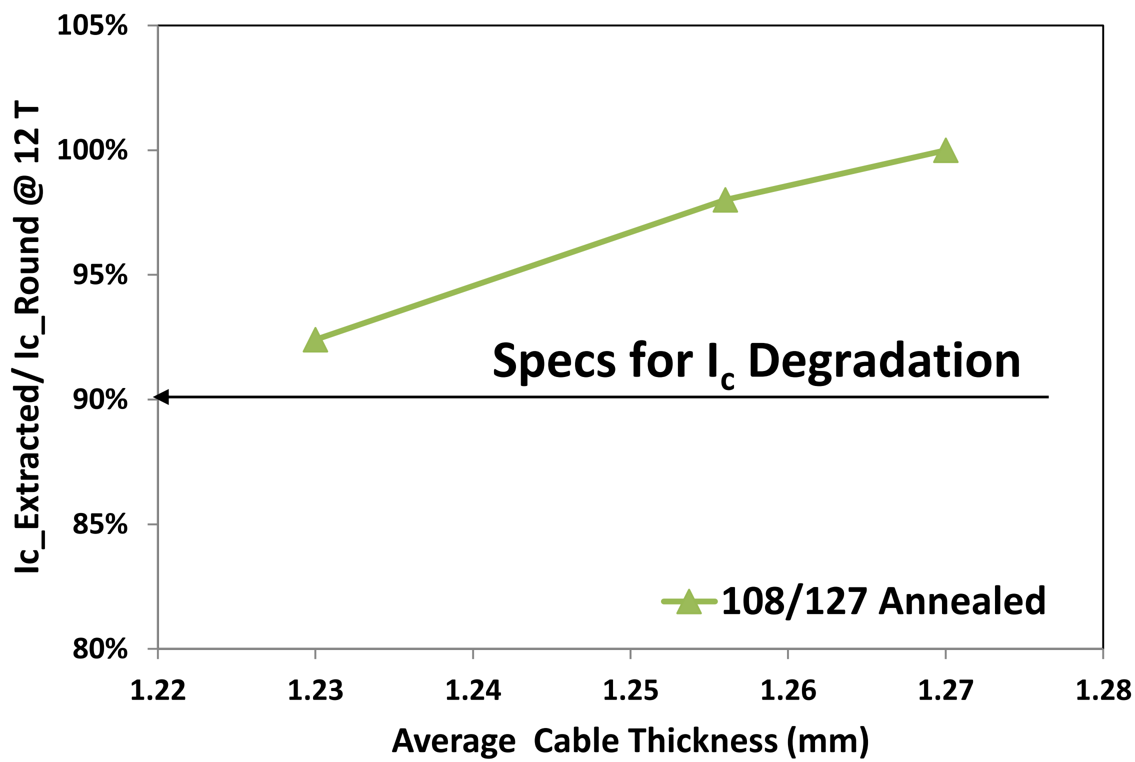
*N. Andreev et al., "Volume expansion of $Nb_3Sn$ strands and cables during heat treatment", Advances in Cryogenic Engineering, V. 48, AIP, V. 614, pp. 941-948 (2002).*

*E. Barzi et al., "Development and Fabrication of $Nb_3Sn$ Rutherford Cable for the 11 T DS Dipole Demonstration Model", IEEE Trans. Appl. Sup., V. 22, No. 3, pp. 6000805 (2012).*

# Development of Cables without Core

- **Post-magnet design R&D was performed to improve cable mechanical stability in the winding process.**
  - **Keystoned cables were made within a range of mid-thicknesses to study sensitivity of electrical properties to compaction.**

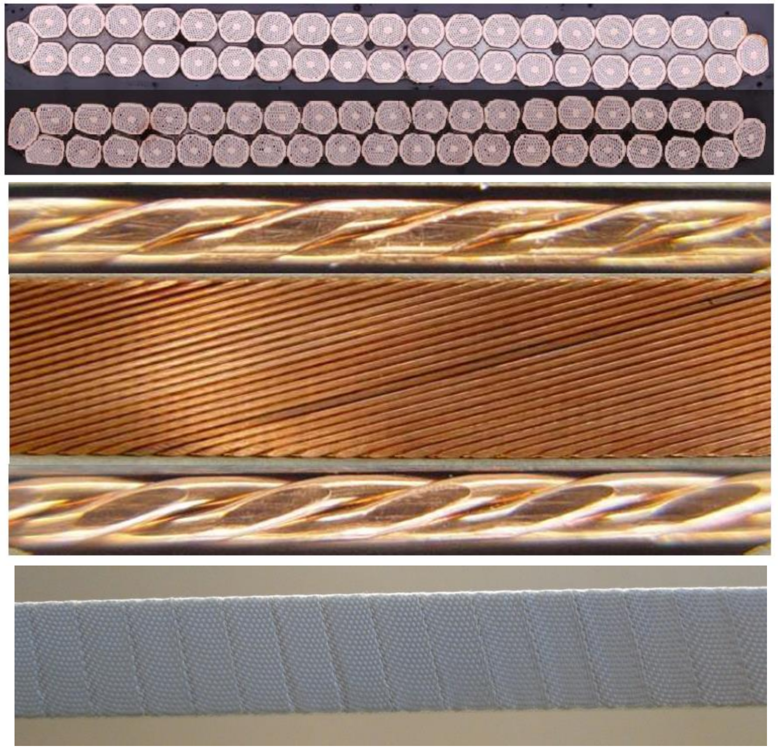
**Reducing keystoned cable thickness of the uncored cable from 1.27 mm to 1.25 mm improved cable mechanical stability and reduces the risk of cable collapsing during fabrication with an $I_c$ degradation still within specs.**




*"Development and Fabrication of $Nb_3Sn$ Rutherford Cable for the 11 T DS Dipole Demonstrator Model", E. Barzi et al., IEEE Trans. Appl. Sup., V. 22, No. 3, pp. 6000805 (2012).*

# Specs v.1 → v.2 for Cable Production

| Parameter | Value | |
|---|---|---|
| | Unreacted | Reacted |
| Cable unit length, m | 210 | |
| Number of strands | 40 | |
| Transposition angle, degree | 15 | |
| Transposition direction | Left-handed | |
| Mid-thickness, mm | **1.25** ← ~~1.269~~ | ~~1.307~~ → **1.27** |
| Thin edge, mm | 1.167 | 1.202 |
| Thick edge, mm | 1.370 | 1.411 |
| Width, mm | 14.70 | 14.847 |
| Key-stone angle, degree | 0.79 | 0.81 |
| Insulation thickness, mm | 0.150 | 0.100 |



**V.2 specs were agreed upon with CERN.**

# Development of Cables with Core

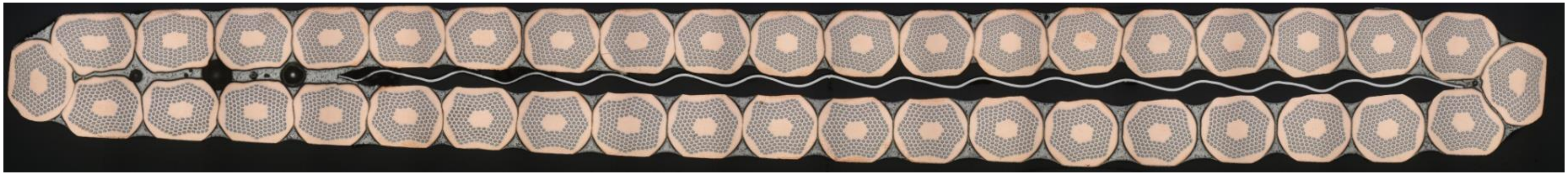
❖ **R&D on cored cable technology to suppress eddy currents was started.**

| Cable ID | Step (No.) | RRP® wire design | Width before/after keystoning (mm) | Mid-thickness before/after keystoning (mm) | *PF* before/after keystoning (%) | Annealing step |
|---|---|---|---|---|---|---|
| 1 | 2 | 150-Ta | 14.48/14.66 | 1.320/1.270 | 84.8/87.1 | No |
| 2 | “ | “ | 14.48/14.66 | 1.320/1.253 | 84.8/88.3 | “ |
| 3 | “ | “ | 14.48/14.68 | 1.320/1.230 | 84.8/89.8 | “ |
| 4 | 2 | 150-Ta | 14.57/14.68 | 1.338/1.270 | 83.4/86.8 | Yes |
| 5 | “ | “ | 14.57/14.68 | 1.338/1.251 | 83.4/88.4 | “ |
| 6 | “ | “ | 14.57/14.69 | 1.338/1.232 | 83.4/89.6 | “ |
| 7 | 2 | 108-Ta | 14.59/14.70 | 1.336/1.270 | 83.0/86.7 | Yes |
| 8 | “ | “ | 14.59/14.70 | 1.336/1.252 | 83.0/87.9 | “ |
| 9 | “ | “ | 14.59/14.71 | 1.336/1.230 | 83.0/89.4 | “ |
| 10 | 1 | 132-Ti | -/ 14.75 | -/ 1.271 | -/ 85.7 | No |
| 11 | “ | “ | -/ 14.71 | -/ 1.250 | -/ 87.4 | “ |
| 12 | “ | “ | -/ 14.73 | -/ 1.230 | -/ 88.8 | “ |

*“Progress in Nb3Sn RRP Strand Studies and Rutherford Cable Development at FNAL”, E. Barzi, D. Turrioni and A. V. Zlobin, IEEE Trans. Appl. Sup., article #6000808, V. 24, No. 3 (2014).*

# Development of Cored Cable Technology

## Better field quality, better ramp rate dependence



40-strand (RRP-150/169) cable with stainless steel core 11 mm wide

### Effect of Annealing

### Rectangular Cable Compaction Study

| Thickness | Width | PF |
|---|---|---|
| mm | mm | % |
| 1.32 | 14.48 | 84.8 |
| 1.3 | 14.5 | 86 |
| 1.28 | 14.55 | 87.1 |
| 1.26 | 14.6 | 88.1 |

No Annealing

### Keystoned Cable Compaction Study

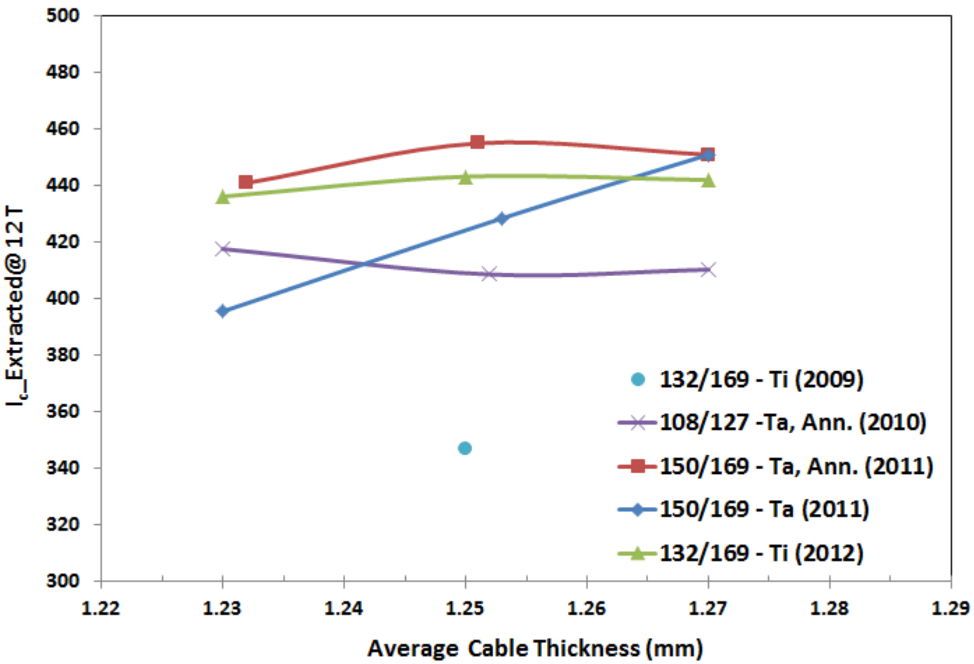
| Mid-thickness | Width | PF |
|---|---|---|
| mm | mm | % |
| 1.27 | 14.66 | 87.1 |
| 1.253 | 14.66 | 88.3 |
| 1.23 | 14.68 | 89.8 |

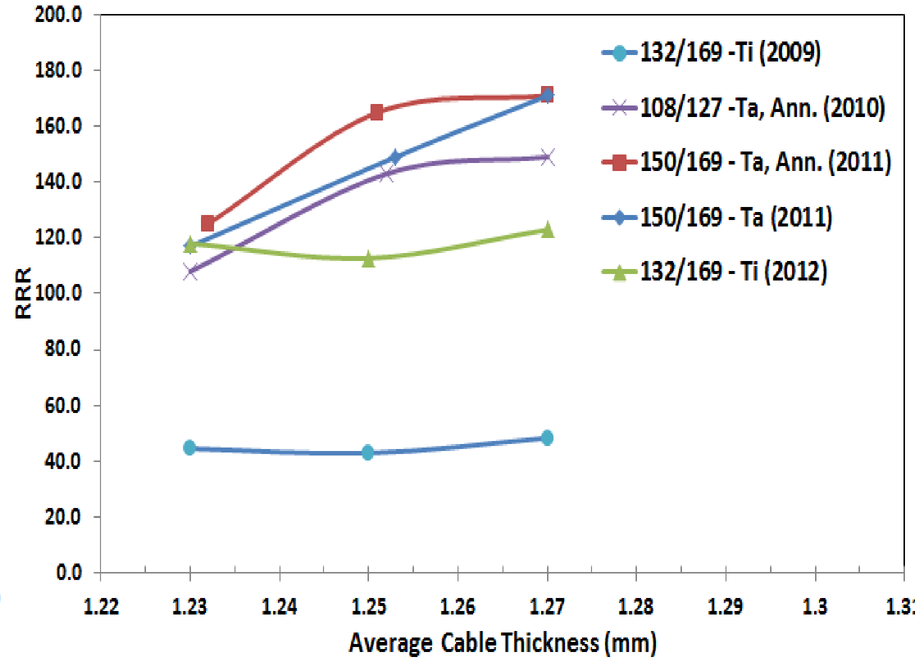
Annealing

### Keystoned Cable Compaction Study

| Mid-thickness | Width | PF |
|---|---|---|
| mm | mm | % |
| 1.27 | 14.68 | 85.7 |
| 1.251 | 14.68 | 87.1 |
| 1.232 | 14.69 | 88.5 |

# Summary of Studies for Cored Cables




- **A mid-thickness spec of 1.25 mm meets the $I_c$ degradation requirements also in the case of a cored cable. This allowed using the same insulation thickness and preserving the same magnet design as when using uncored cable.**
- **TheTi doped wire preserved its current carrying capabilities up to large cable compaction factors, even without any prior annealing. Its maximum Ic degradation at 12 T was ~2% at ~89% cable compaction. Consistently, the only two wires whose RRR values are independent of cable compaction are the Ti-doped.**

# Examples of Collaboration with CERN

- **The Spec v.2 for the cable were discussed and agreed upon during E. Barzi’s visit at CERN in March 2012**
- **CERN produced the cable for the spare coil (MBH04) for the 1-1 demonstrator**
- **Traveler and reporting templates for cable production were discussed and exchanged during Barzi’s visit**
- **To prepare for automated quality control, CERN shipped one of their Inspection Systems following Dan Turrioni’s prior visit**

# Cables used for 1-pass Successful Commissioning

| | R&D_PC_01 | R&D_CF_01_13 | DM_CF_08_01_01 | Cu practice | R&D_CF_03_13 | R&D_CF_02_13 | R&D_CF_04_13 |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| Date | 02.28.13 | 03.04.13 | 03.12.13 | 03.26.13 | 08.30.13 | 09.09.13 | 09.11.13 |
| | | | | | | | |
| Length, m | 20 | 10 | 216 | 10 | 50 | 20 | 600 |
| Finished length, m | | 1.9/1.85/3.45 | 204.3 | 7.65 | 46.14 | 12 | 583.6 |
| Compostion | **Cu** | **Nb3Sn** | **Nb3Sn** | **Cu** | **Cu** | **Nb3Sn** | **Cu** |
| Billet | A101 | 11444/14841-6 | 11444 | A101 | A101 | multiple | A101 |
| Avg. strand dia., mm | 0.699 | 0.701 | 0.701 | 0.699 | 0.7 | 0.702 | 0.7 |
| Core width, mm | 11.00/7.00 | 7 | 9.52 | 11 | 9.52 & 11.00 | 11 | 11 |
| Mandrel ID | 482012B | 482012B | 482012B | 482012B | 482012B | 482012B | 482012B |
| Side roller, mm | 5.52 | 5.52 | 5.52 | 5.52 | 5.52 | 5.52 | 5.52 |
| Turkhead postion, mm | 41.52 | 41.52 | 41.52 | 41.51 | 41.53 | 42.95 | 41.53 |
| Strand tension, lbs | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 |
| Spindle current, uA | 185 | 185 | 185 | 185 | 185 | 185 | 185 |
| Avg. width, mm | 14.76/14.77 | 14.713 | 14.73 | 14.7 | 14.68/14.71/14.69/14.71 | 14.74/14.74/14.75 | 14.71 |
| Avg. thickness, mm | 1.218/1.227 | 1.23/1.25/1.27 | 1.251 | 1.251 | 1.250/1.249/1.251/1.249 | 1.240/1.213/1.289 | 1.25 |
| Packing factor, % | 89.4/89.0 | 88.8/87.4/85.7 | 8780.00% | 8790.00% | 88.1/88.4/88.7/88.9 | 89.5/91.4/85.9 | 88.7 |
| Avg. lay angle, deg | 15/15.5 | 15.6/15.8/15.8d | 15.6 | 14.3 | 15.5/16.5/17/17.5 | 17 | 16.8 |
| Avg. Tension, % | | 99 | 91 | 112 | 111 | 140/181/166 | 122 |

200m+ Superconducting cable with one single b

Relative Rotation Experiment

SC Cable with Multip

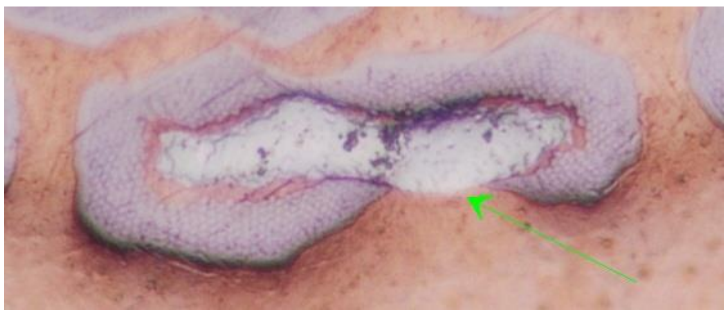
# Summary of Cable Production

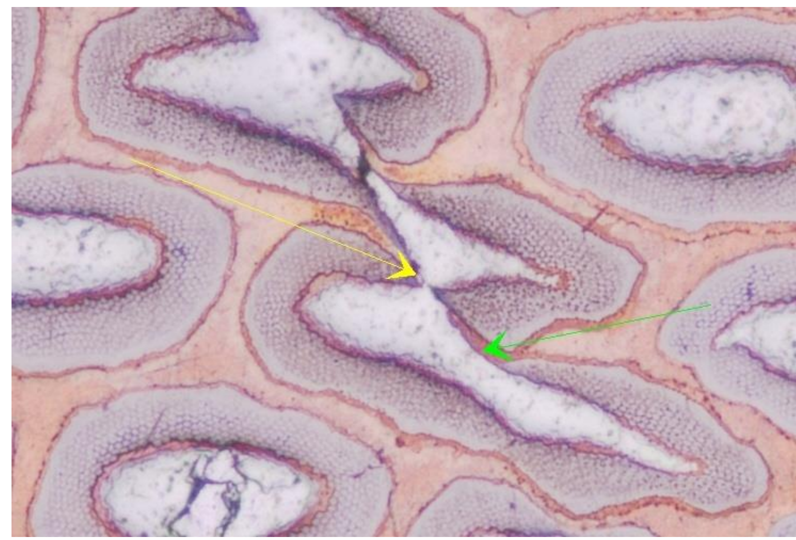
| Coil ID | Cable ID | Billets ID | Nb3Sn Type | Original cable length | Cable geometry | Core geometry | Cable fabrication |
|---|---|---|---|---|---|---|---|
| **MBH02, MBH03** | DM-CF-01-0 | 12292, 12319, 12521-22, 13062-63, 13090 | 108/127 (Ta) | 414 m | 1.251±0.001 x 14.71±0.01 mm2, 15.0 deg | None | Jul. 2011, 2-pass w/intermediate anneal |
| **MBH05, MBH07** | DM-CF-02-0B | 13548, 13613 | 150/169 (Ta) | 120 m, 230 m | 1.251±0.002 x 14.69±0.01 mm2, 15.0 deg | 11.0 mm x 25 μm SS | Sep. 2011, 2-pass w/intermediate anneal |
| **MBH08** | DM-CF-07-03-01 | 14144, 14145, 14194, 14195, 9772 | 108/127 (Ta), 114/127 | 138 m | 1.252±0.004 x 14.71±0.01 mm2, 14.0 deg | 11.7 mm x 25 μm SS | Nov. 2012 1-pass |
| **MBH09** | DM-CF-07-03-01B | 14144, 14145, 14194, 14195, 14700 | 108/127 (Ta) | 180 m | 1.249±0.002 x 14.70±0.01 mm2, 14.8 deg | 11.0 mm x 25 μm SS | Nov. 2012 1-pass |
| **MBH10, MBH11** | DM-CF-07-03-01C | 14144, 14145, 14194, 14195, 14700 | 108/127 (Ta) | 220 m | 1.245 x 14.72 mm2, 15.0 deg | 11.0 mm x 25 μm SS | Nov. 2012 2-pass w/intermediate anneal |
| **1-pass successful commissioning** | DM_CF_08_01 | 11444 | 132/169 (Ti) | 216 m | 1.251 x 14.73 mm2, 15.6 deg | 9.5 mm x 25 μm SS | Mar. 2013 1-pass |
| | R&D_CF_04_13 | A101 | Hard Cu | 600 m | 1.250 x 14.71 mm2, 16.8 deg | 11 mm x 25 μm SS | Oct. 2013 1-pass |
| **MBH12, MBH13, MBH14** | DM-CF-07-13 | 15043, 15044, 15045, 15244, 15245, 15290 | 108/127 (Ti) | 374 m | 1.251±0.001 x 14.71±0.01 mm2, 16.8 deg | 11.0 mm x 25 μm SS | Oct. 2013 1-pass |

# Backup Slides

# RRP Wires

- **The original cable development for the 11 T dipoles was done using $Nb_3Sn$ wires of the Restacked-Rod Process (RRP) type by OST. This technology has a delicate internal structure made of Nb/Sn subelements in a Cu matrix. Subelements are prone to merging together when subject to plastic strain, as during cabling. This phenomenon was taken into account in the cable development.**

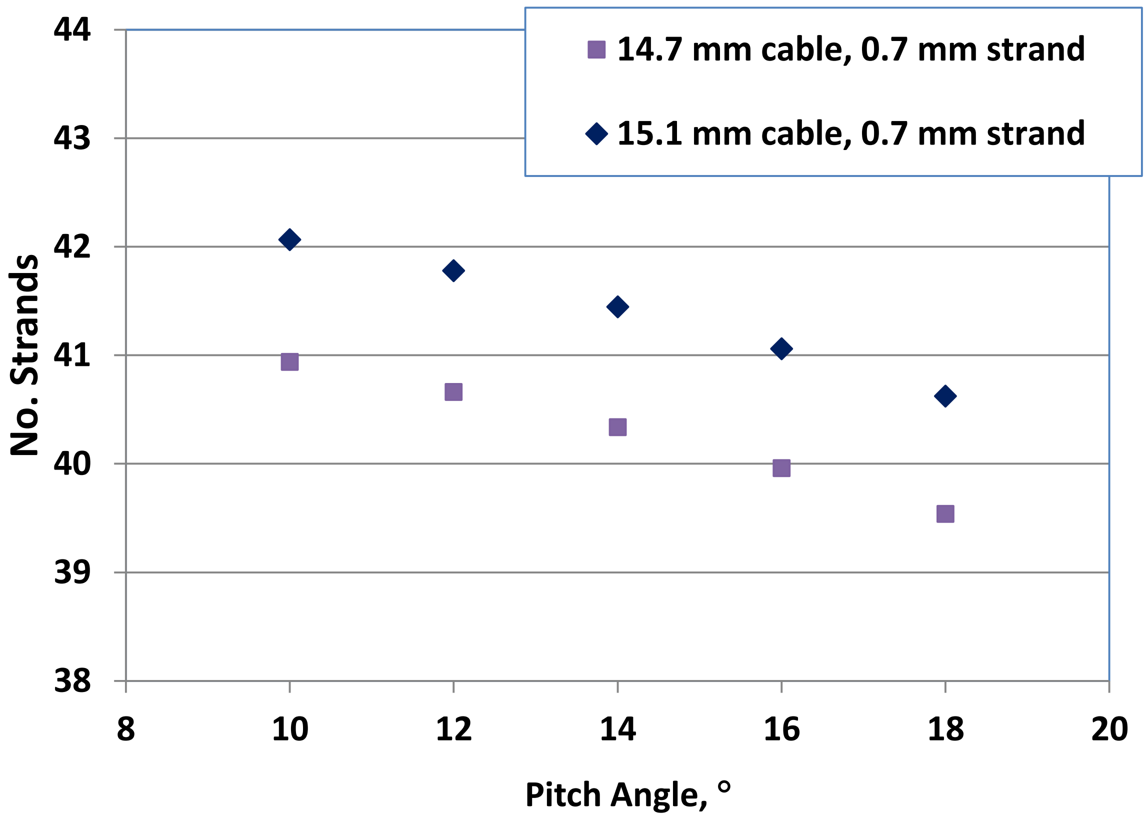




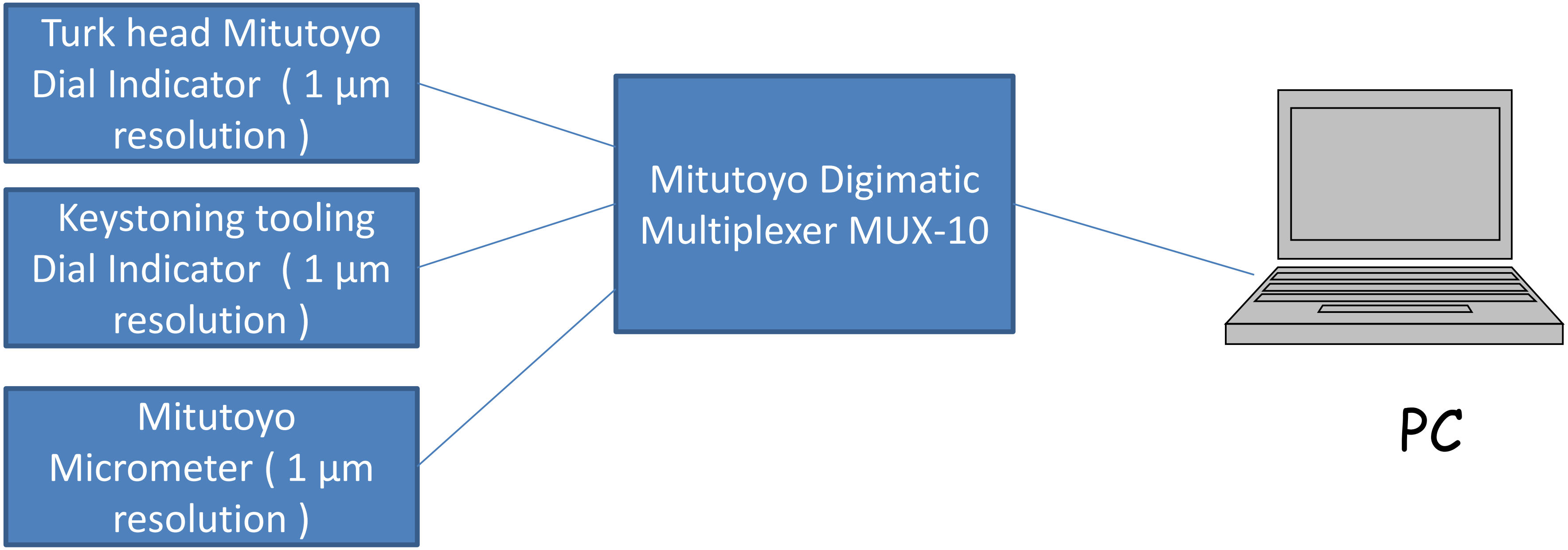
Pictures by Marianne Bossert

# First Cables

- **R&D preliminary to magnet design**
  - **R&D was performed on keystoned cables 14.7 mm and 15.1 mm wide. As expected (see plot), during cabling it was found that 15.1 mm required 41 strands for stability ➔ 14.7 mm width was chosen.**

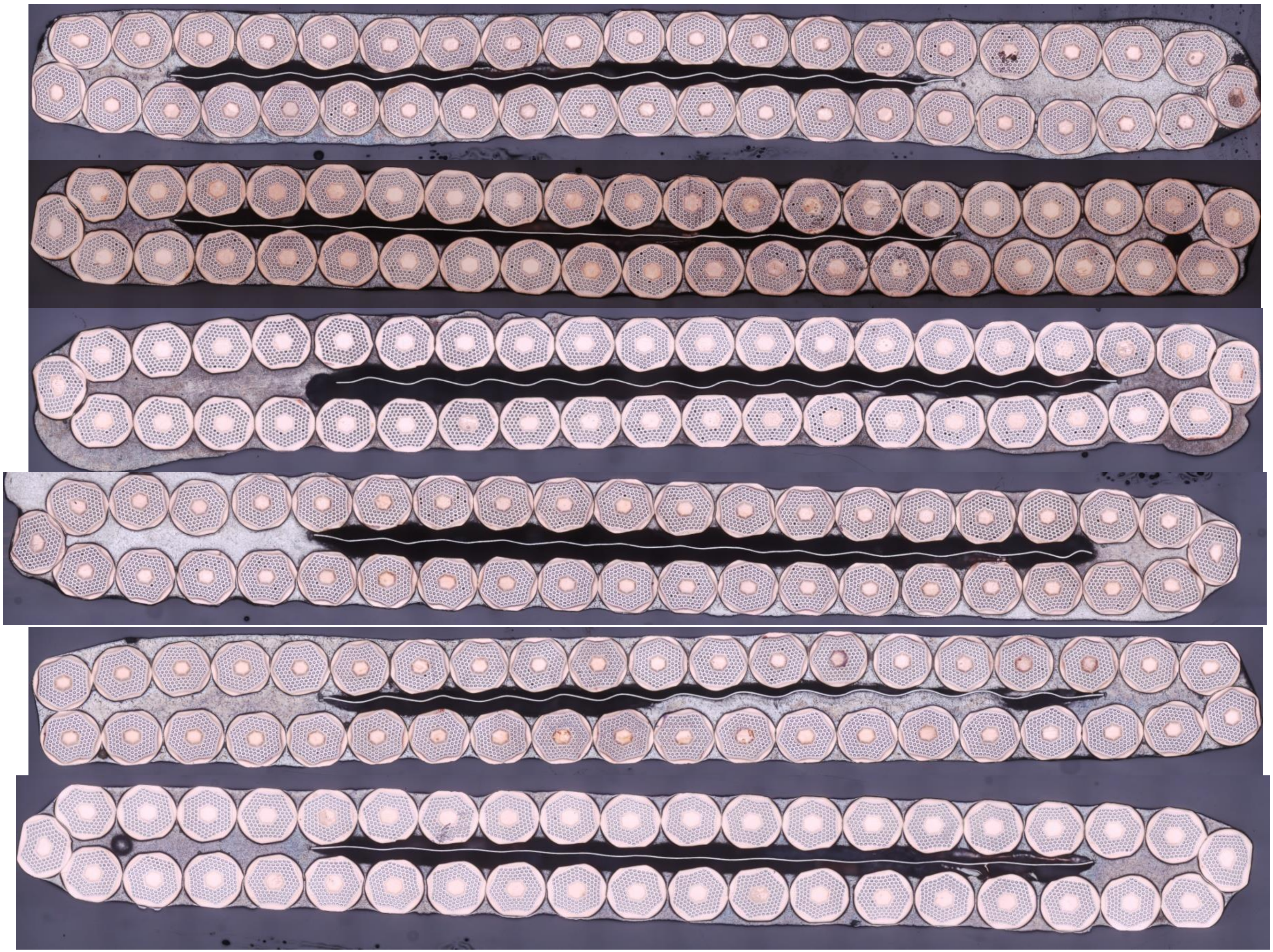


# Data Acquisition




Measurements of the two dial indicators are acquired every 3 cm at 1 m/min of production speed.

# Cable Cross Sections for Microscopic Analysis



CS 1

CS 2

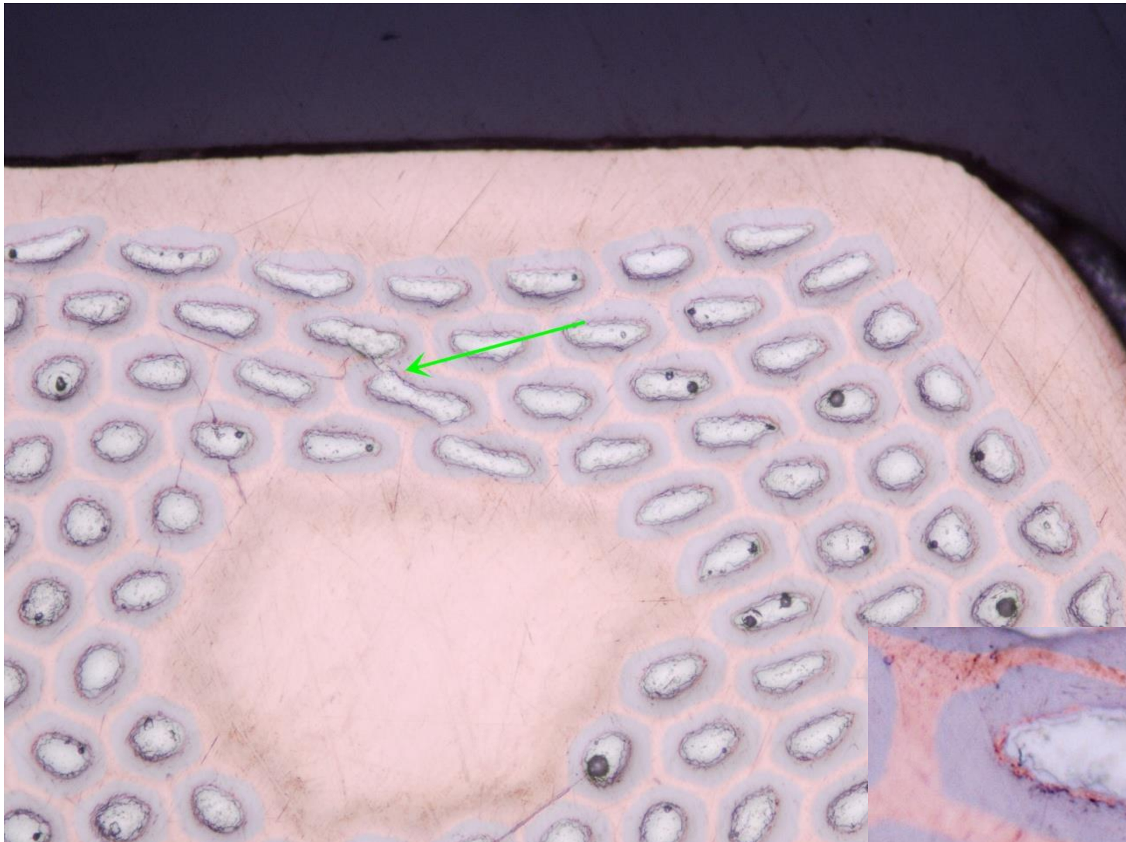
CS 3

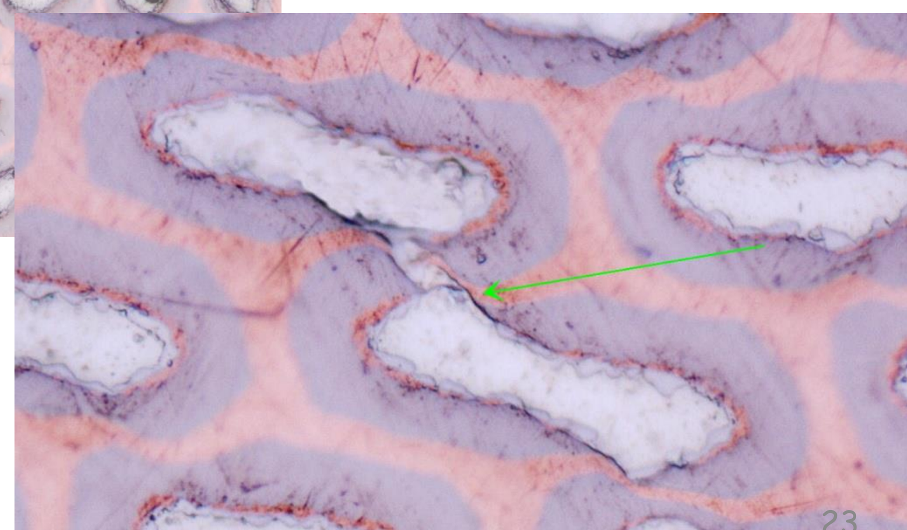
CS 4

CS 5

CS 6

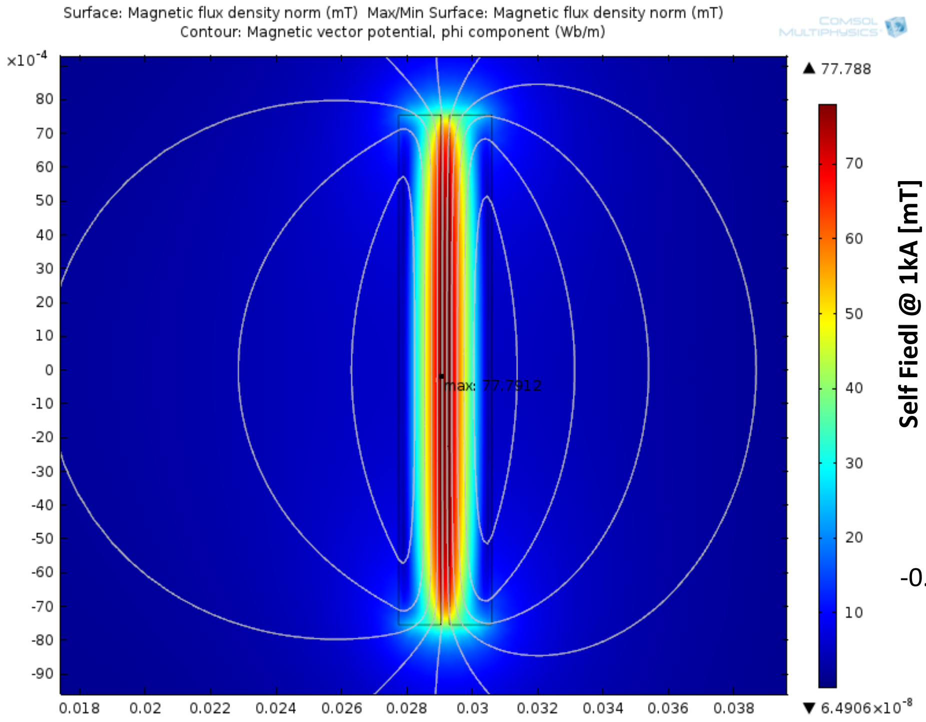
# Example of Analysis

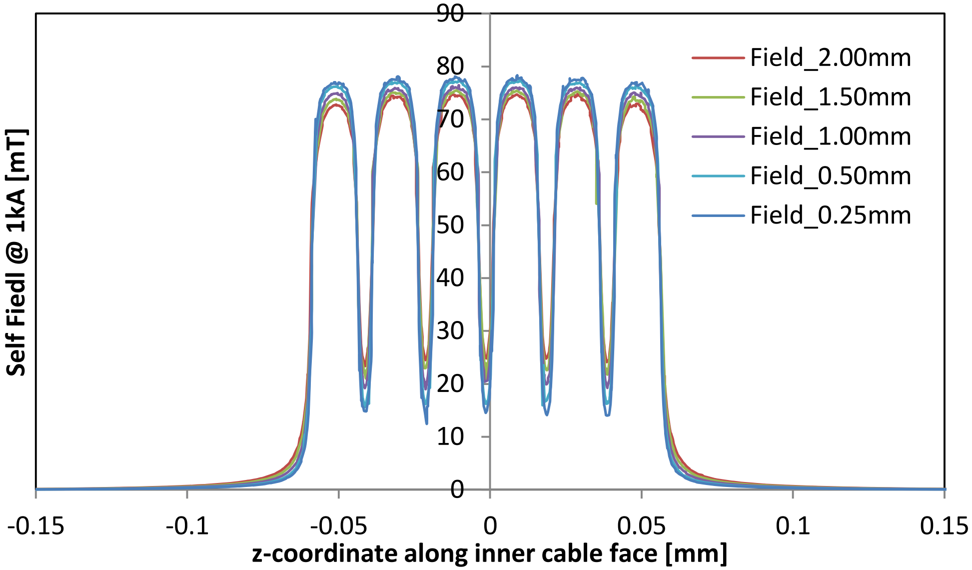


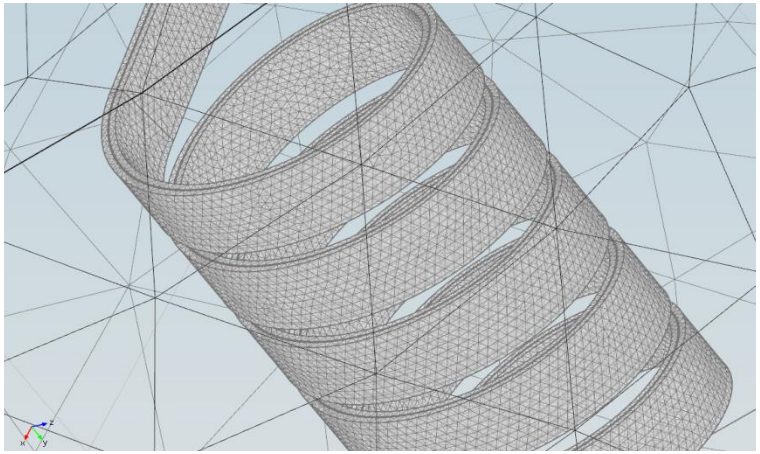


Cross Section 2, Strand 1
of cable R&DT_101109_40_1_1
(with core)

# Self-Field Calculations for Cable Test



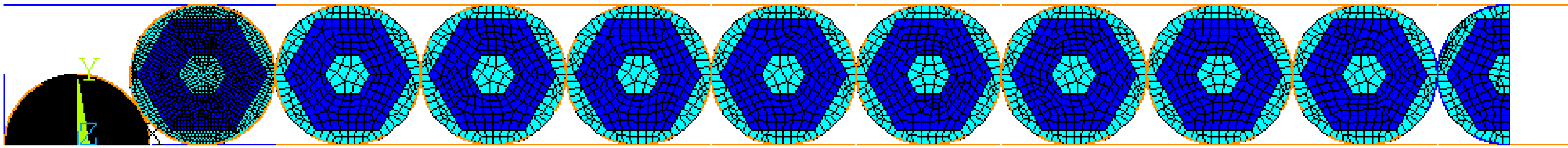



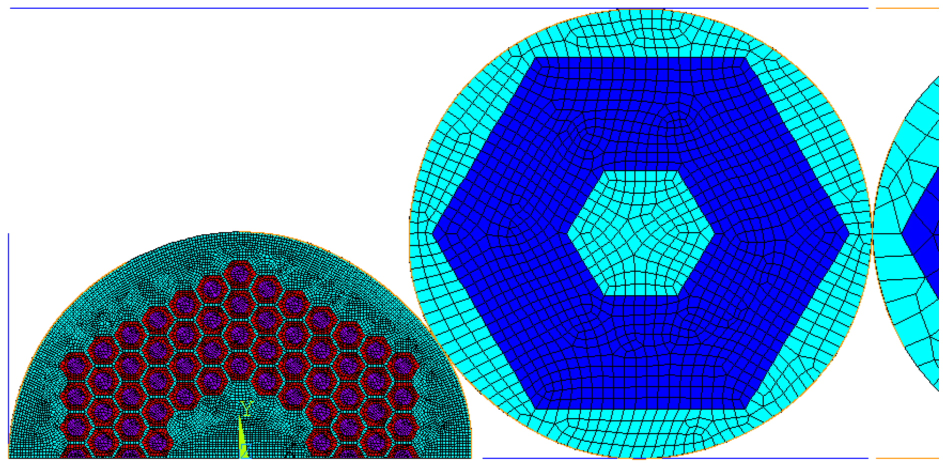
| Cable Parameter | Value |
|---|---|
| Cable thickness | 1.3 mm |
| Cable width | 15.09 mm |
| Cable gap | 0.25 mm |

**Self-field correction 0.078 T/kA**

*"Commissioning of 14T/16T Rutherford Cable Test Facility with Bifilar Sample and Superconducting Transformer", E. Barzi, Vadim Kashikhin, Vito Lombardo, Allen Rusy, Daniele Turrioni, and Alexander Zlobin, AIP Conf. Proc. 1573, 1192 (2014).*

# FEM as Aid in Cable Design (1)





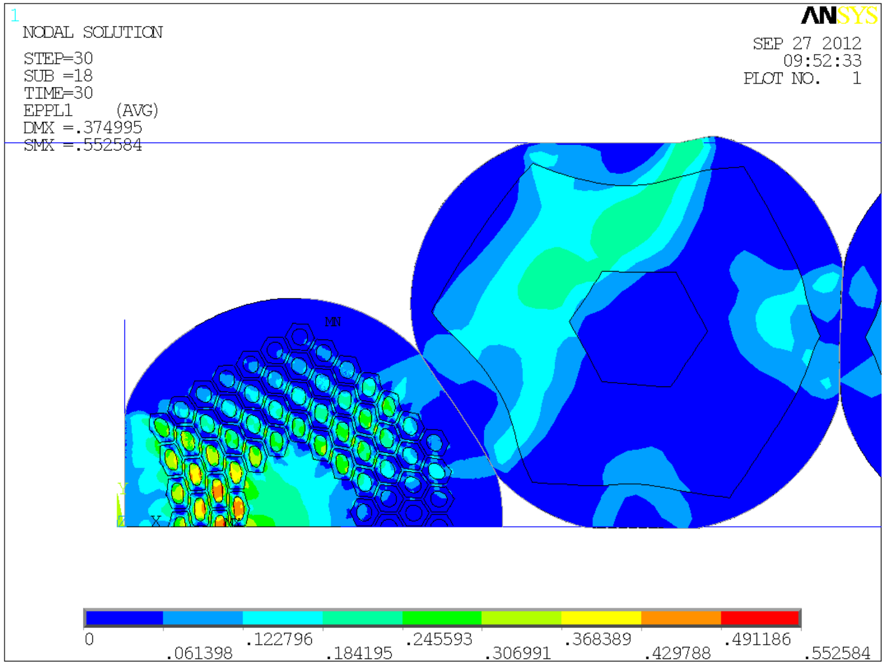
**Purpose of mechanical analyses and experiments is to identify upper limits to plastic deformation to avoid damage, and to understand the influence of the various geometrical parameters in the manufacturing process.**

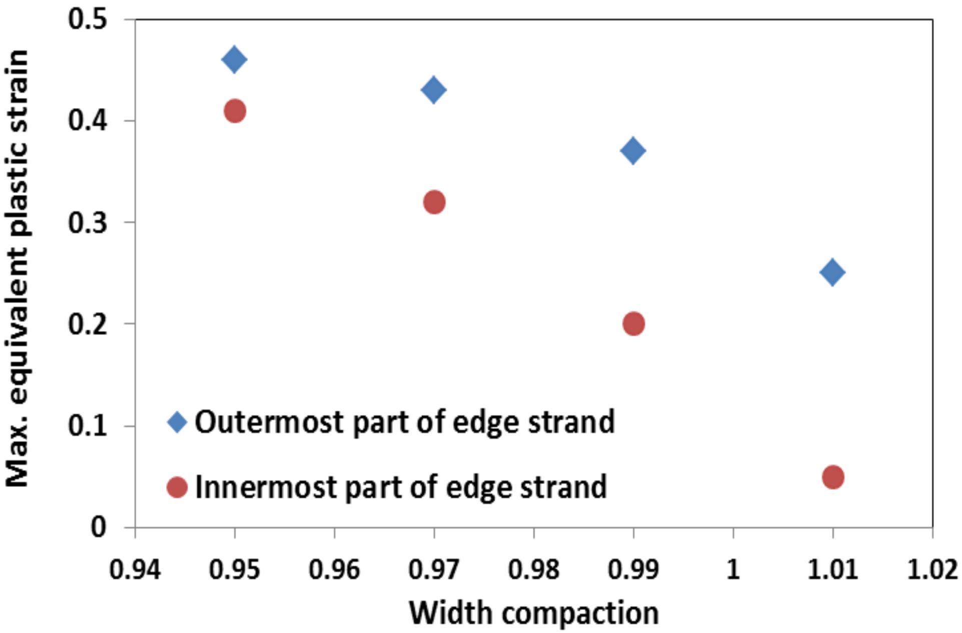
*"FEM Analysis of Nb-Sn Rutherford-type Cables", E. Barzi et al., IEEE Trans. Appl. Sup., V. 22, No. 3, pp. 4903305 (2012).*

*"Superconducting strand and cable development for the LHC upgrades and beyond", E. Barzi et al., IEEE Trans. Appl. Sup., V. 23, No. 3 (2013).*

# FEM as Aid in Cable Design (2)

❖ **Analysis of Strain Sensitivity to Width Compaction $w_C$**

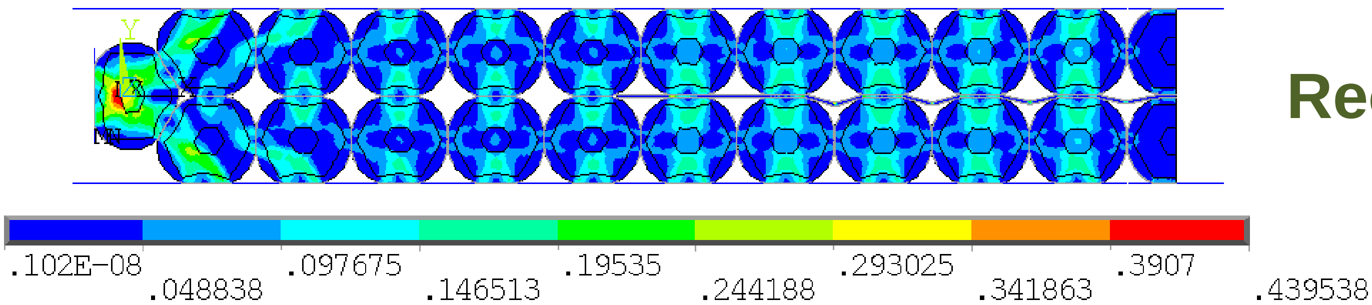


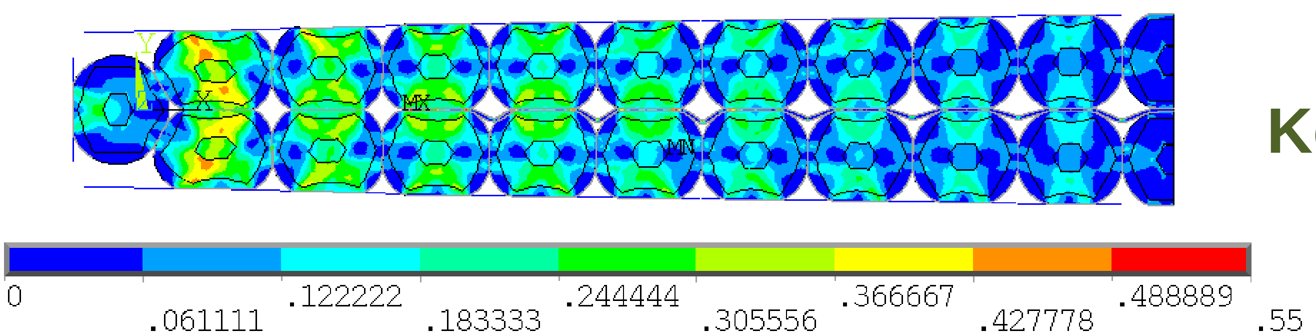

$$w_C = width_{cable} / \, width_{undeformed}$$

# FEM as Aid in Cable Design (3)

## ❖ Modeling of a Core in the Cable




**Rectangular stage**




**Keystoned stage**

**Core assumes a wavy behavior, which is compatible with a non-linear buckling phenomenon**