CERN

Numerical simulation of Nb_3Sn superconductors for accelerator magnets

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TE-MSC-SCD

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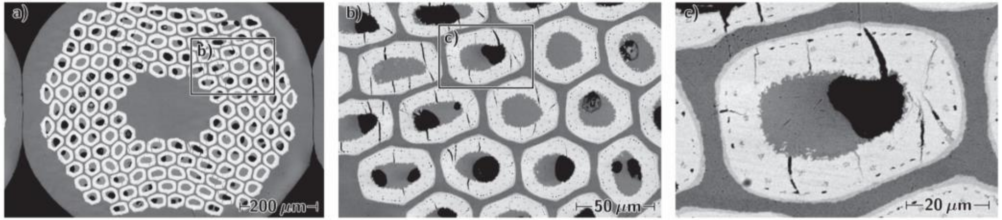
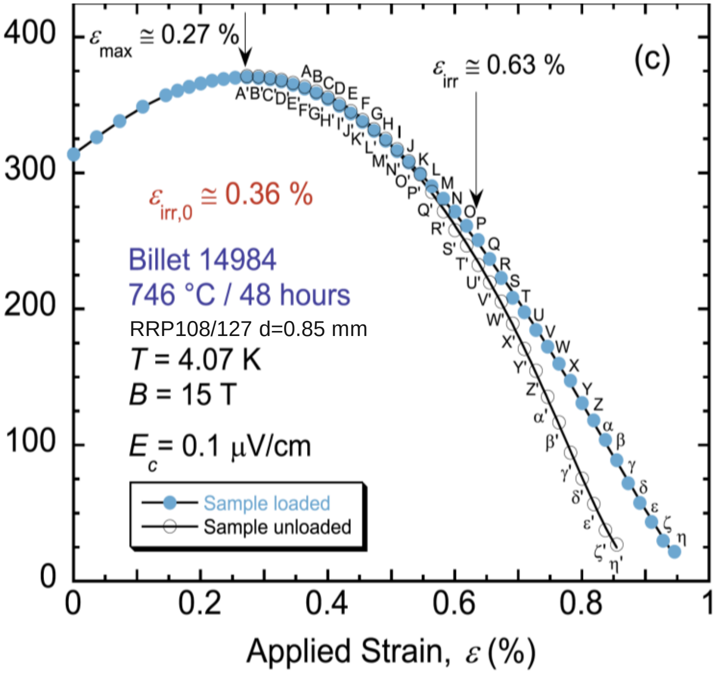
Nb_3Sn: ISSUES AND DIFFICULTIES

- High J_c low temperature superconductor *(>3000 A/mm² @12 T 4.3 K)*
- Brittle composite material (irreversible I_c reduction)
- High strain sensitivity (reversible I_c reduction)

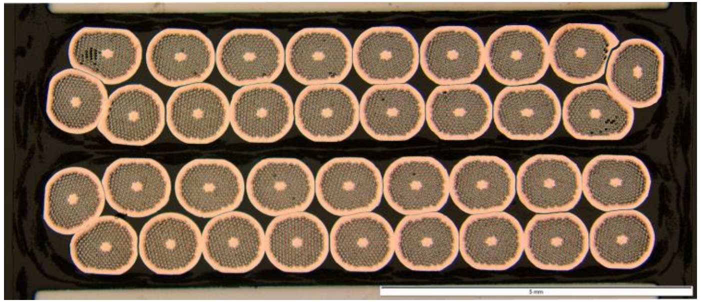


Pictures from Patrick Ebermann et al 2018 Supercond. Sci. Technol. 31 065009



Plot from N. Cheggour et *al.* Scientific Reports (2019)

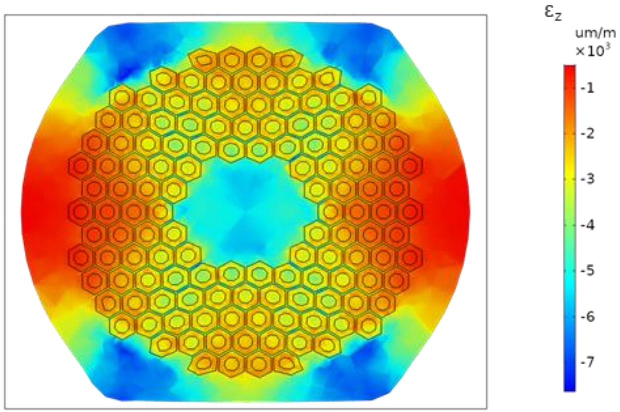
CASE STUDIES TO BE PRESENTED



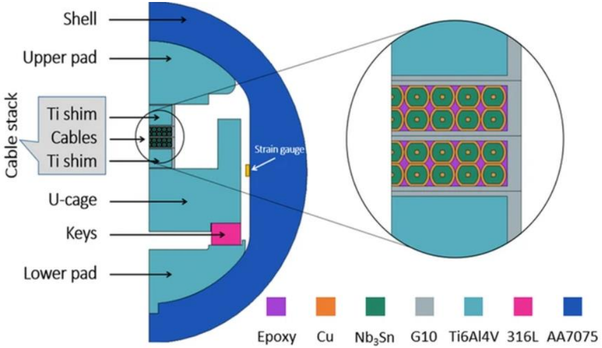
Numerical modelling plays a key role for interpretating the results of experimental campaigns aimed at investigating the strain sensitivity of Nb_3Sn cables and wires.

Some of the most relevant examples of such experiments are:

- Cable under transverse pressure at cold (**FRESCA/CERN**).
- Cable under transverse pressure at cold (**TWENTE**).
- Strand under transverse pressure at cold (**UNIGE**).

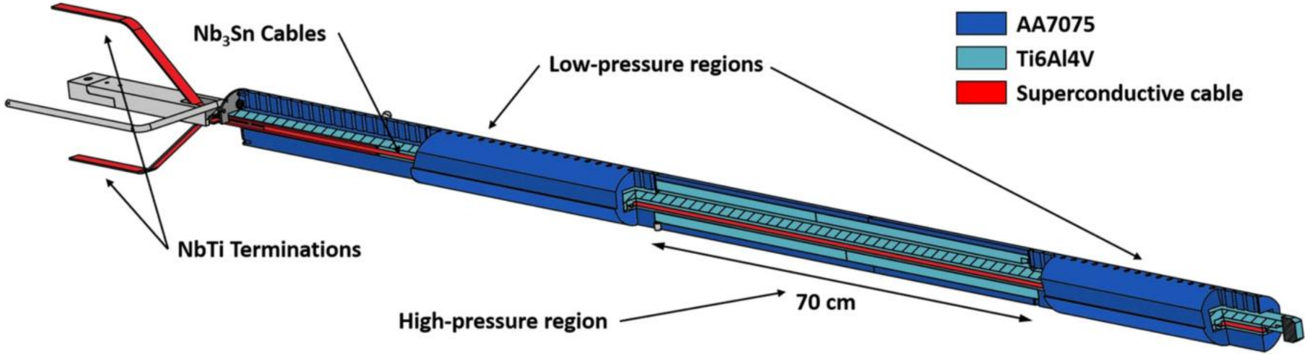


CABLE AT FRESCA - EXPERIMENTAL SET-UP



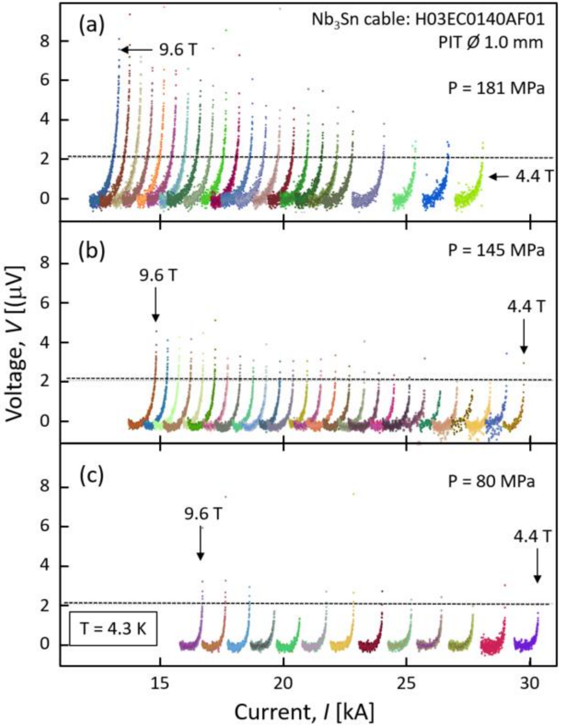
FRESCA test station at **CERN**

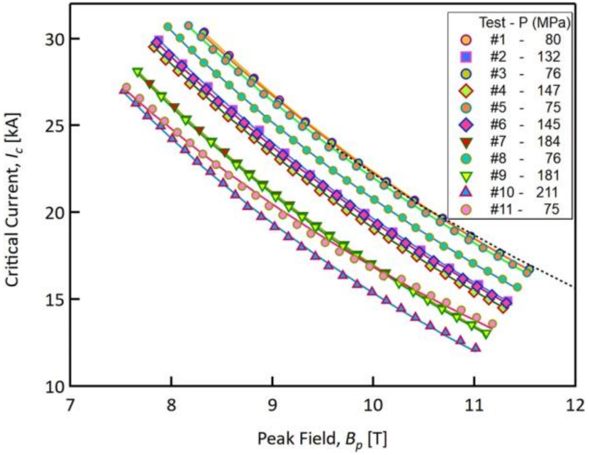
- ➢ B_{app} up to 10 T
- ➢ Transverse pressure up to $2x10^6$ N/m on 70 cm
- ➢ Temperatures 1.9 K & 4.3 K

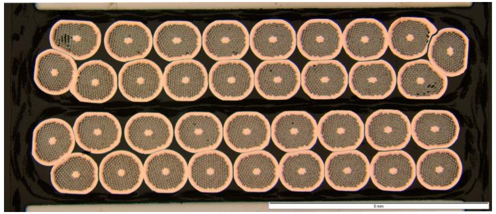


Sketches from: De Marzi, G., Bordini, B. & Baffari, D. *Sci Rep* **11,** 7369 (2021)

CABLE AT FRESCA – WHY FEM MODELLING







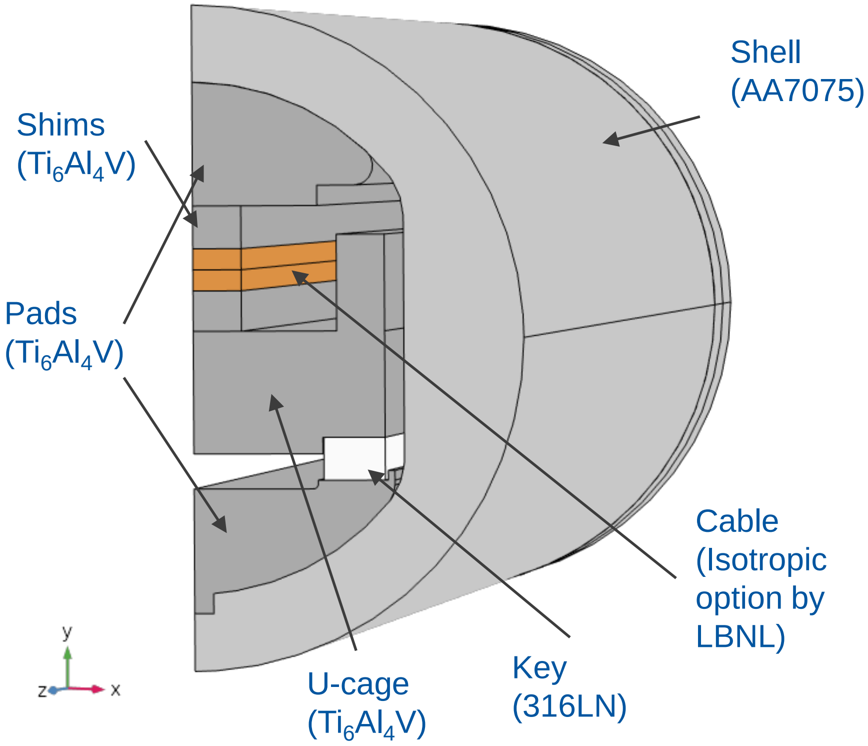
Plots from De Marzi, G., Bordini, B. & Baffari, D. *Sci Rep* **11,** 7369 (2021)

H03RC0140AF01

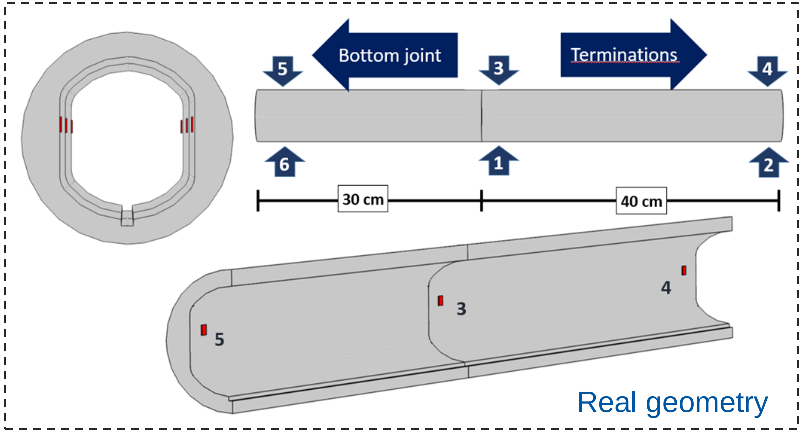
1 mm PIT 192 sub-cable (18 strand, FRESCA2)

- The results shows significant stress sensitivity reversible (up to test#5) and irreversible (from test #7) I_c and B_c reduction.
- To evaluate the level of pressure acting on the cable during the test at cold **FEM simulations** are necessary.

CABLE AT FRESCA – FEM MODEL SET-UP

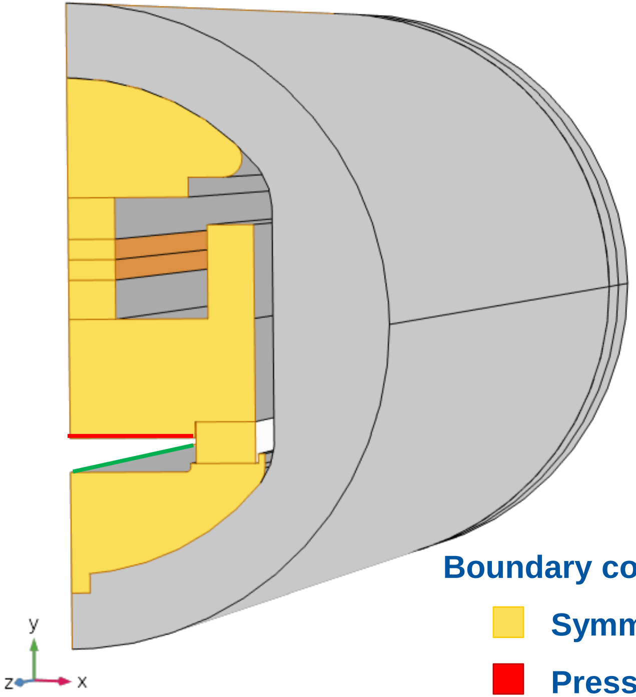


- Simplified model geometry



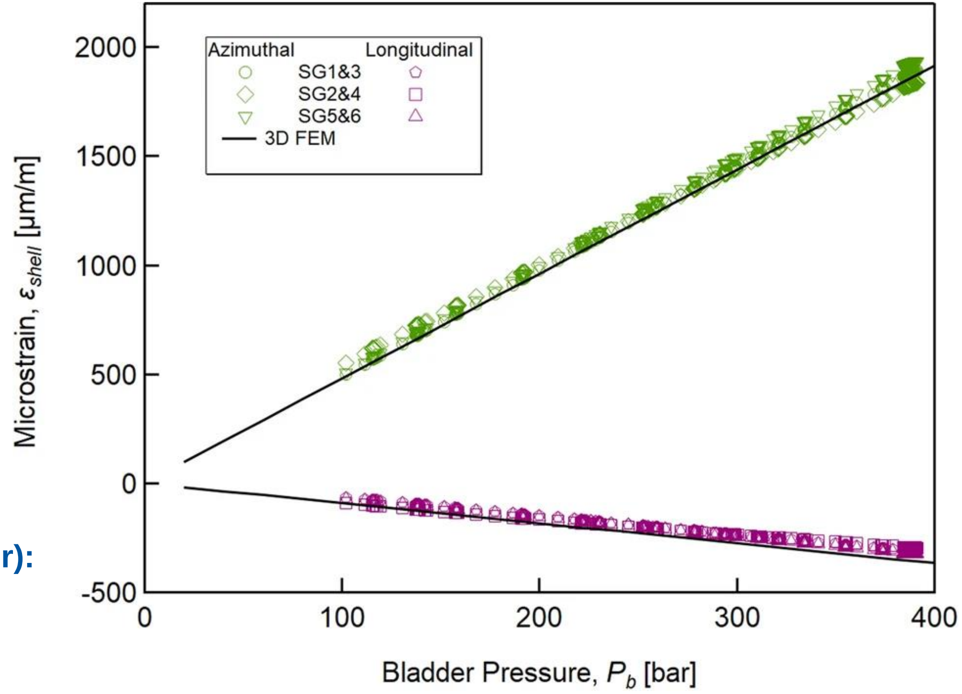
Real geometry

CABLE AT FRESCA - FEM MODEL CALIBRATION



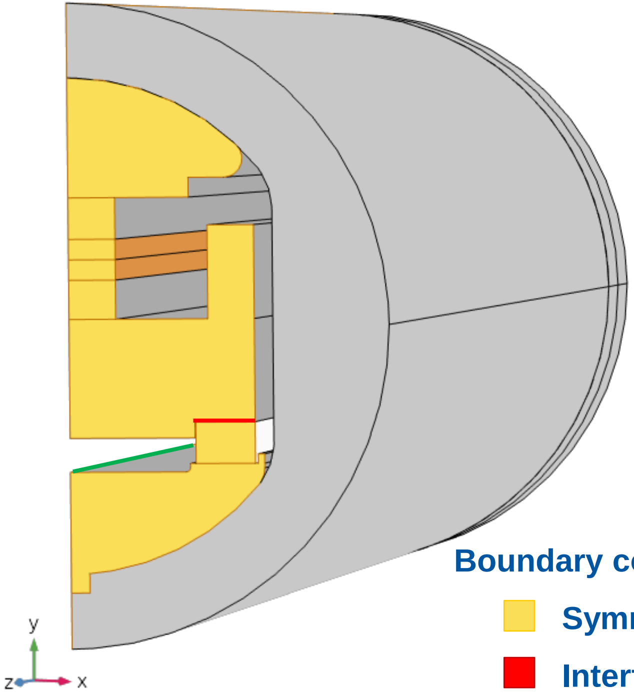
Boundary conditions (Palier):

- 🟨 **Symmetry**
- 🟥 **Pressure**
- 🟩 **y=0**



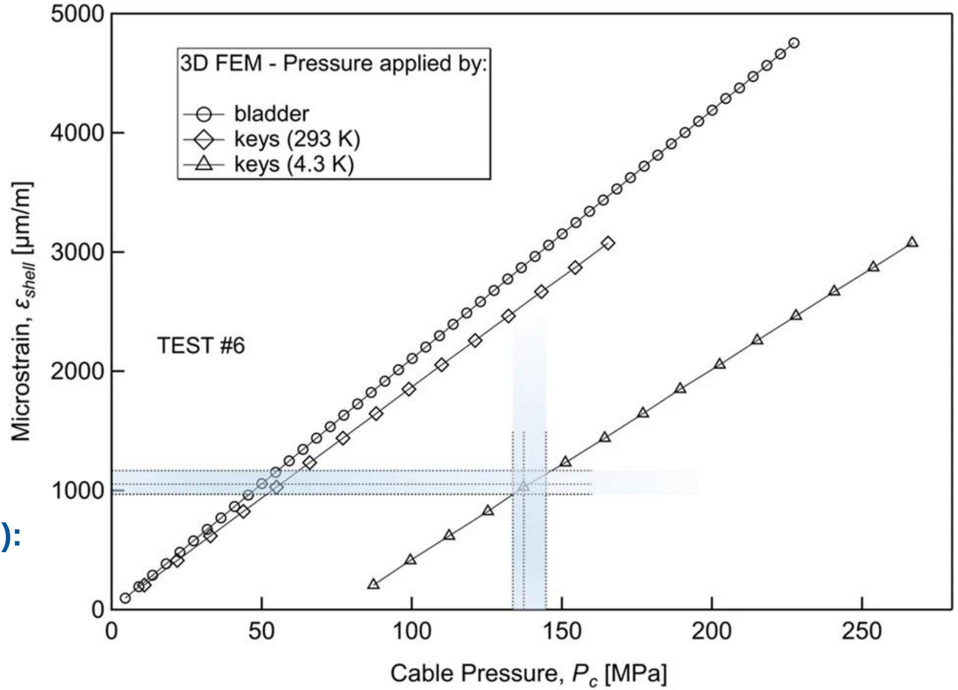
De Marzi, G., Bordini, B. & Baffari, D. *Sci Rep* **11,** 7369 (2021)

CABLE AT FRESCA - FEM MODEL RESULTS



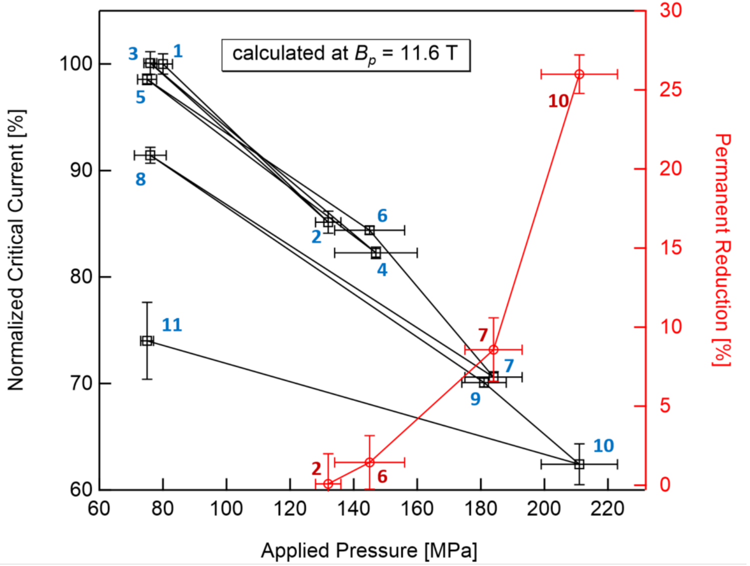
Boundary conditions (keys):

- 🟨 **Symmetry**
- 🟥 **Interference**
- 🟩 **y=0**



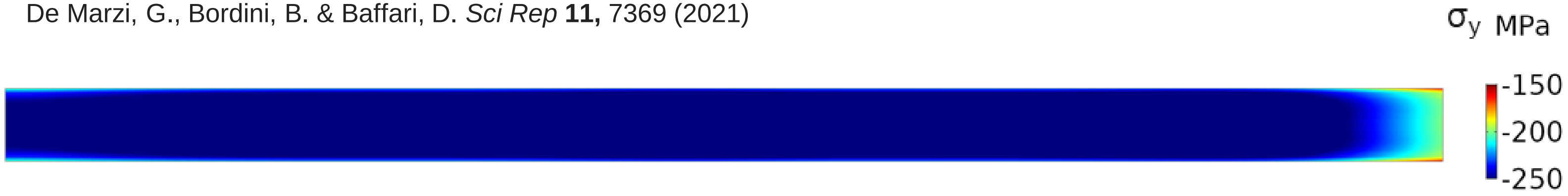
De Marzi, G., Bordini, B. & Baffari, D. *Sci Rep* **11,** 7369 (2021)

CABLE AT FRESCA – CONCLUSIONS



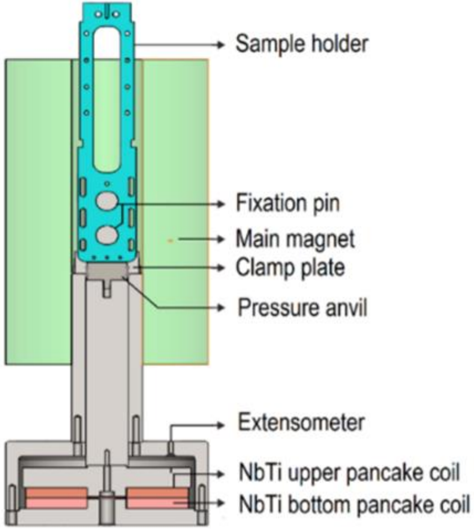
De Marzi, G., Bordini, B. & Baffari, D. *Sci Rep* **11,** 7369 (2021)

- The implemented FEM model is essential to evaluate the pressure level acting on the cable.
- The results show that the pressure is applied at cold uniformly on both longitudinal and transversal direction on the cable surface.
- The combination of experimental data and numerical simulation allowed to evaluate the pressure threshold that triggers permanent critical current reduction.

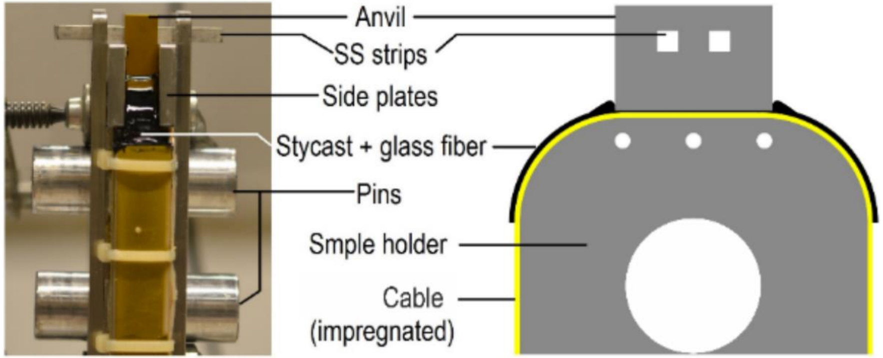


CABLE AT TWENTE – EXPERIMENTAL SET-UP

UNIVERSITY
OF TWENTE.



Pictures and sketches courtesy of M. Dhalle



Cryogenic transverse press

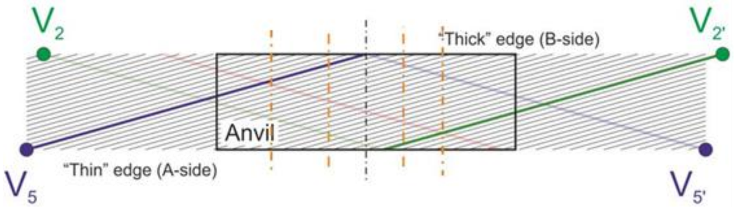
- B_{app} up to 11 T
- Transverse pressure up to 300 MPa on 4.5 cm
- Temperatures 4.3 K

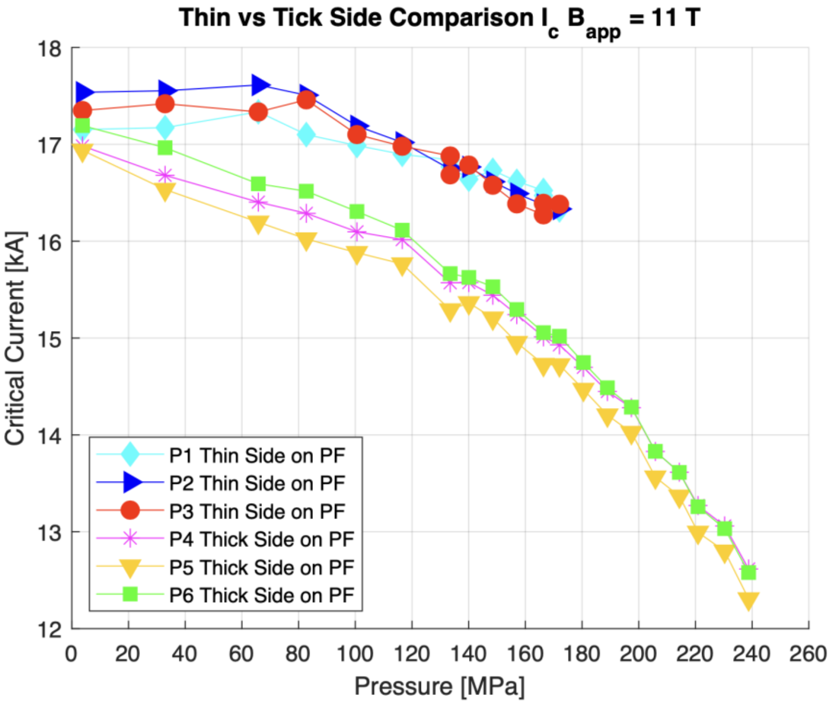
CABLE AT TWENTE – WHY FEM MODELLING

H15OC0239C

0.7 mm RRP 108/127 cable (40 strand, 11T)

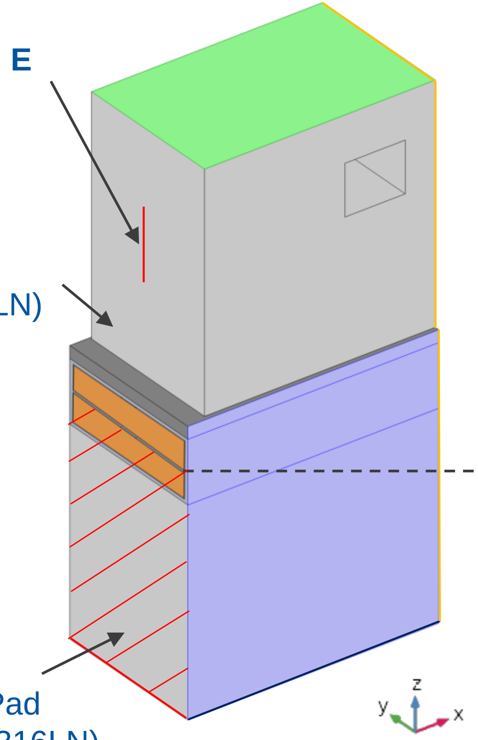
- Large redistribution phenomena
- Average and local pressure acting on cable needs to be evaluated





Measurements and sketch Courtesy of M. Dhalle and S. J. Otten

CABLE AT TWENTE – FEM MODEL SET-UP

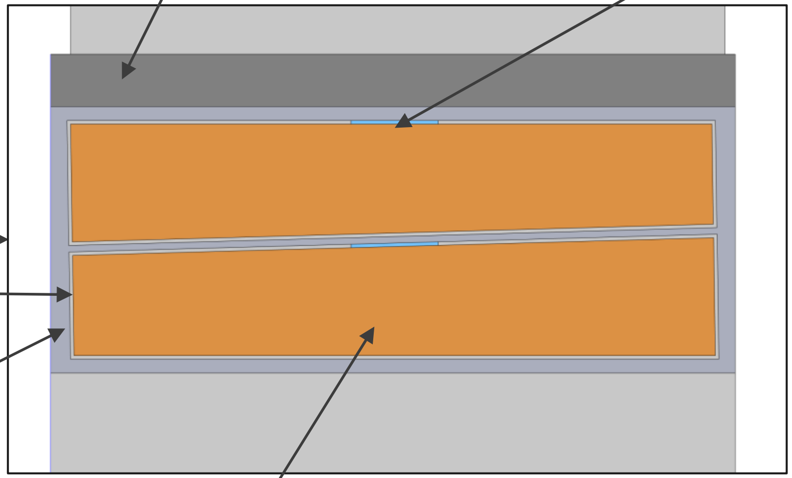


E

Anvil
(316LN)

Pad
(316LN)

- **Boundary conditions:**
  - 🟩 **Displacement control**
  - 🟥 **Fixed**
  - 🟦 **y=0**
  - ▨ **Complanarity**
  - 🟨 **Symmetry**



Epoxy
(Stycast 1266)

Epoxy in the mica gap
(CTD-101K)

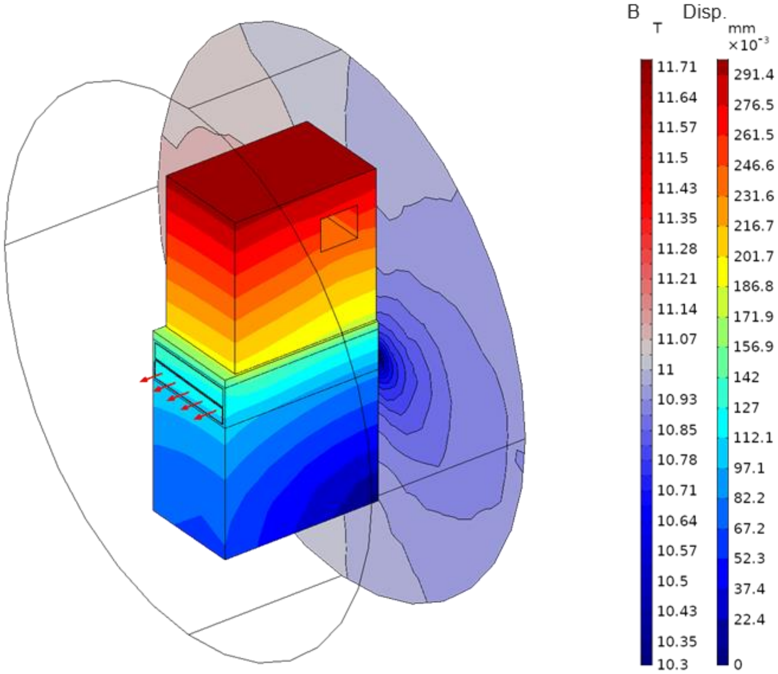
Mica

Impregnated fiberglass
(G10)

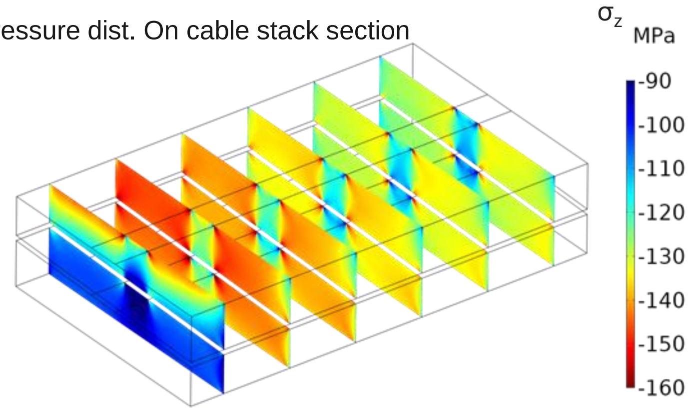
Dummy + Active cable
(CTD-101K impregnated Isotropic model)

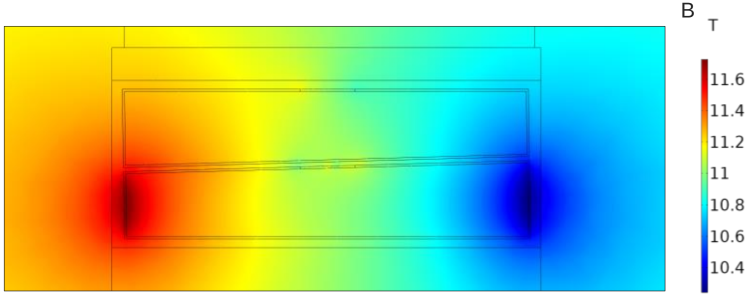
CABLE AT TWENTE – MULTIPHYSICS FEM MODELLING

Displacement and magnetic field, current density.



Pressure dist. On cable stack section

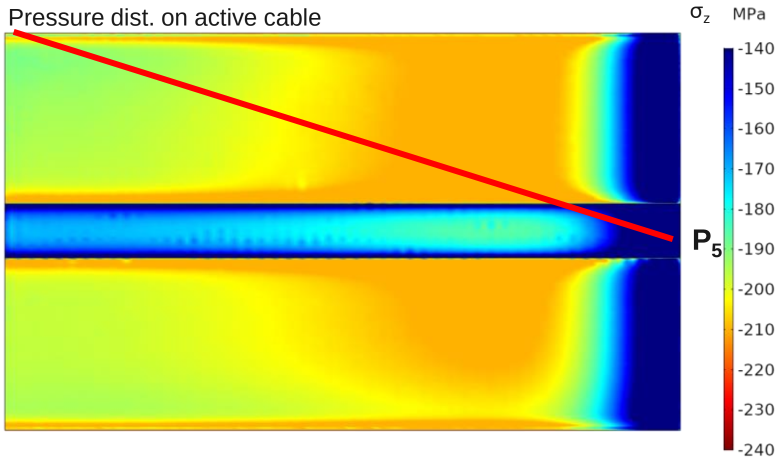




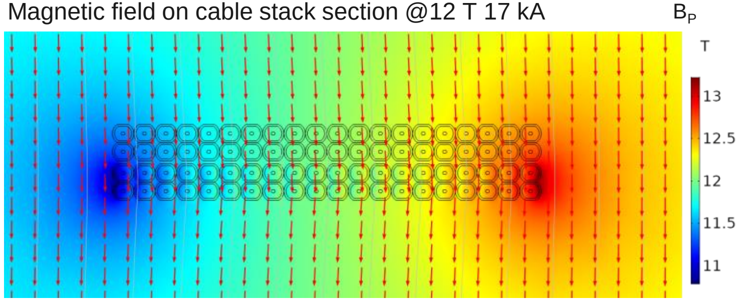
Magnetic field on cable stack section

CABLE AT TWENTE – FEM: PRESSURE DISTRIBUTION

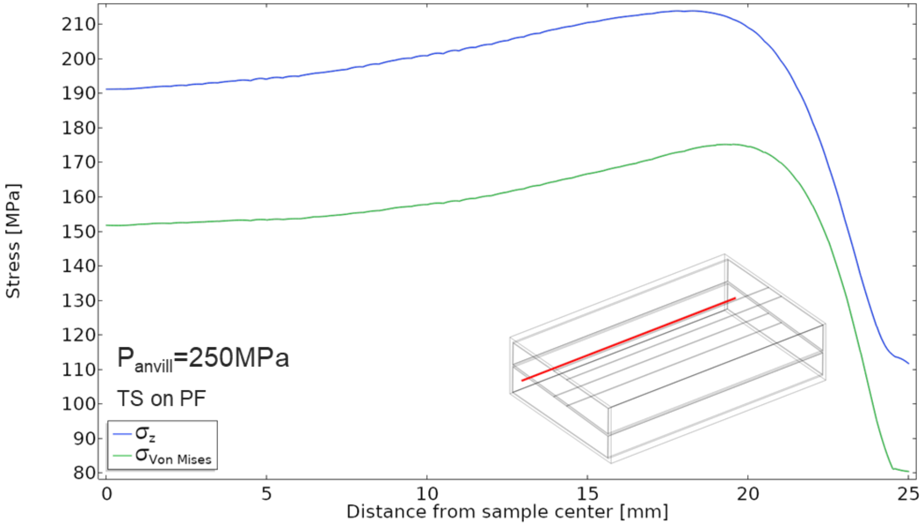
Pressure dist. on active cable



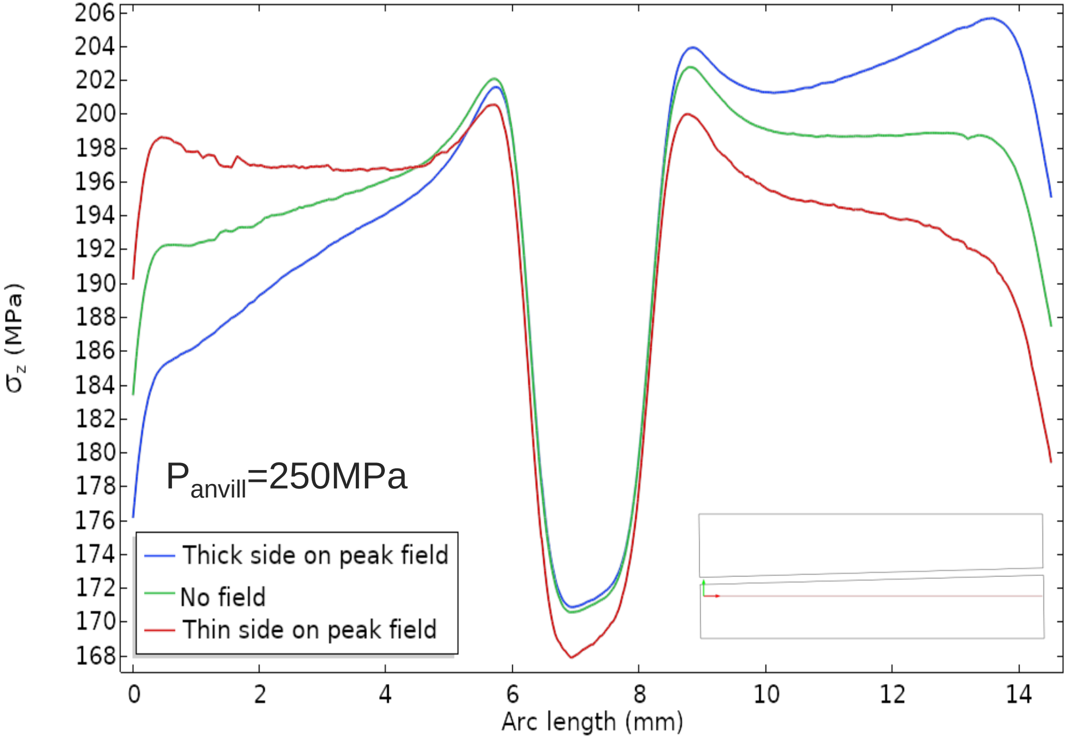
Magnetic field on cable stack section @12 T 17 kA



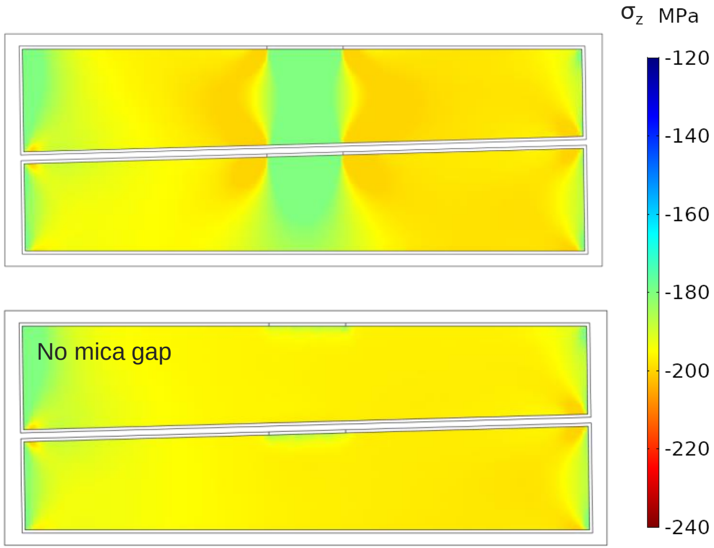
- The FEM results show a non uniform pressure distribution along the cable length (most stressed area is not on peak field for the considered voltage tap).
- The actual pressure acting on the cable is lower that the nominal pressure on the anvil



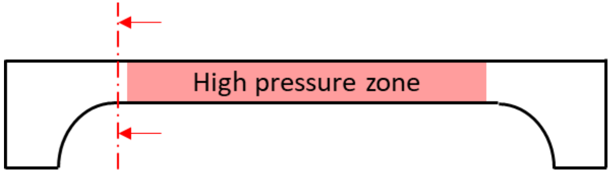
CABLE AT TWENTE – FEM RESULTS: MICA EFFECT



- The central area is characterized by a localized transverse pressure drop. This is due to the mica gap that affect pressure transfer and distribution on the cables.



CABLE AT TWENTE – DAMAGE ANALYSIS: CONTROL

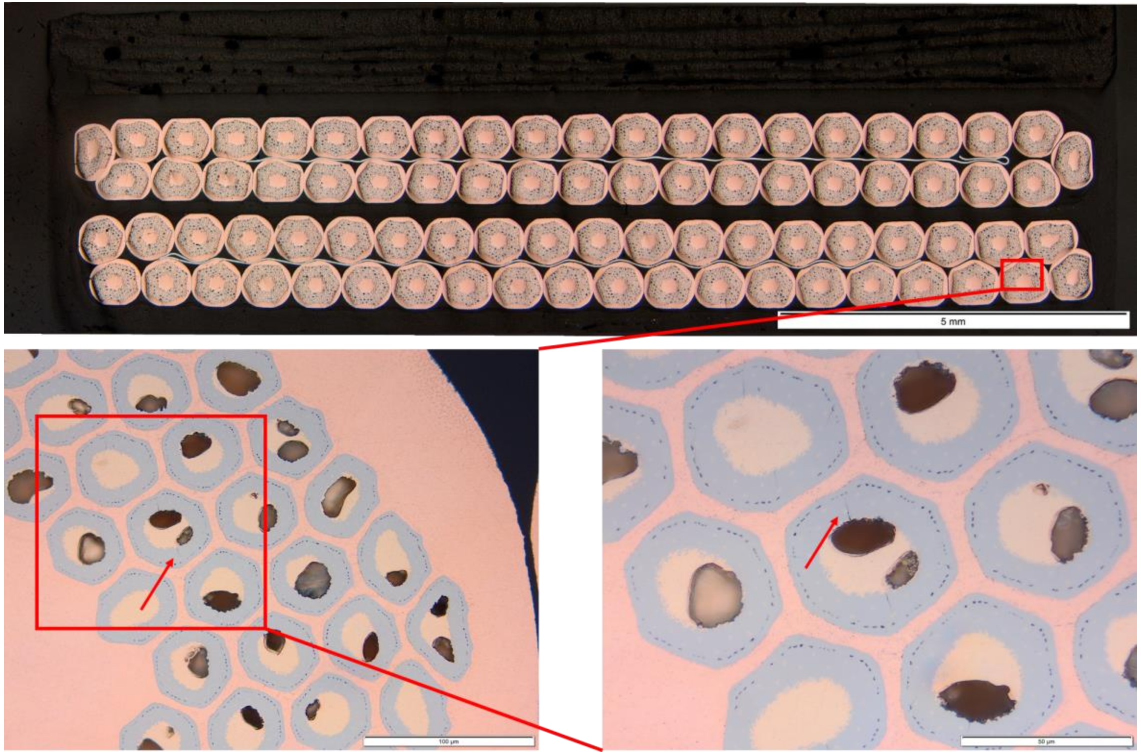


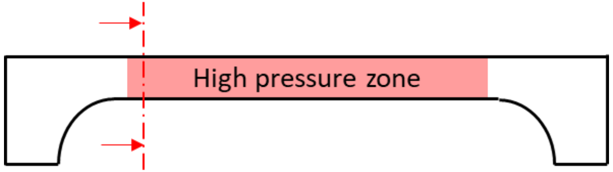
Post-mortem analysis of the sample to confirm FEM results in term of pressure distribution:

- Metallographic preparation of different sections along the sample length.
- Preparation procedure and sample handling qualification on a "control" sound section (no cracks observed through optical analysis).

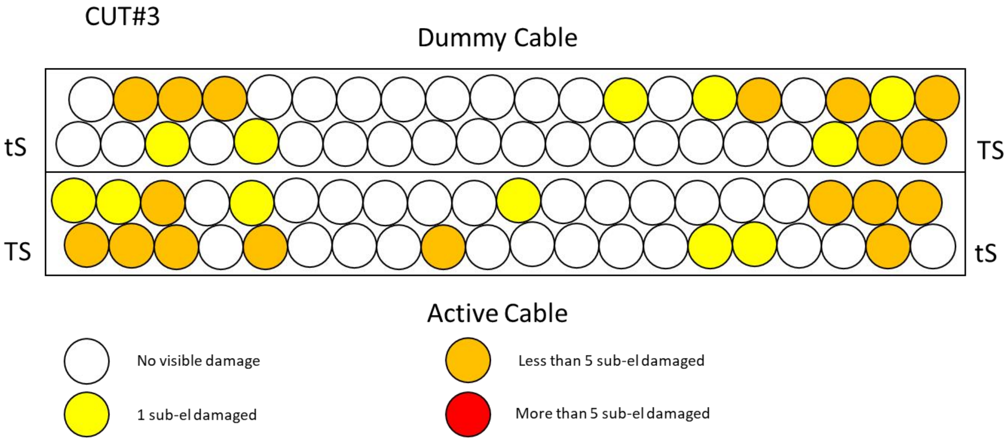
CABLE UNDER PRESSURE AT TWENTE – DAMAGE ANALYSIS

- In the high pressure zone cracks of about 7 µm of length were observed in the A15 of some of the sub elements cross section.
- The numbers of damaged sub elements in each section has been used as an indicator of the local stress level (the high pressure zone was loaded with at least 240 MPa of transverse pressure during the test campaign)



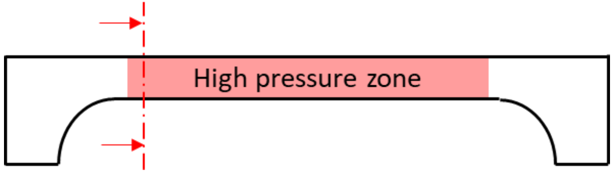


CABLE AT TWENTE – DAMAGE ANALYSIS: SECTION 1

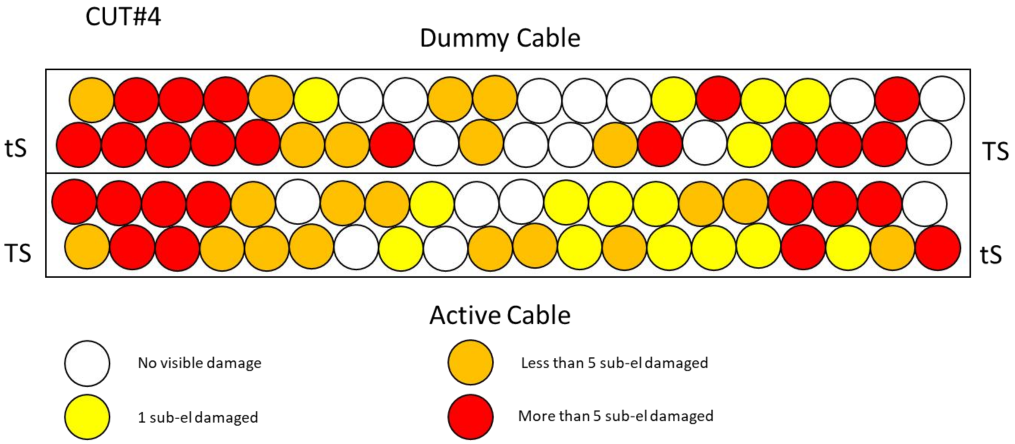


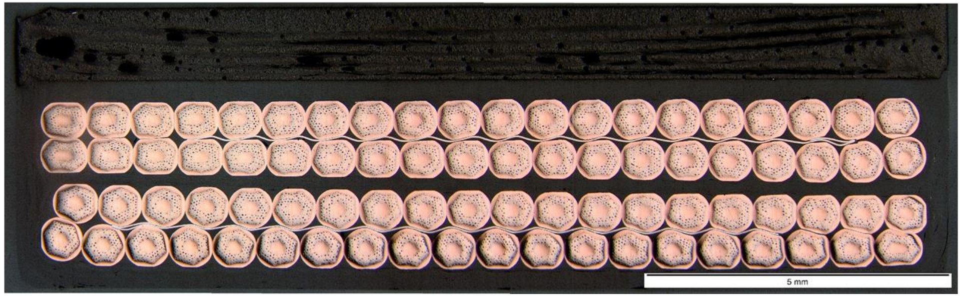
- Each wire has been observed using an optical microscope counting the number of damaged sub elements. Three level of damage has been established.

- Entering the high pressure zone (i.e. under the anvil) some of the wires start to show a moderate damage, concentrated in the cable sides.

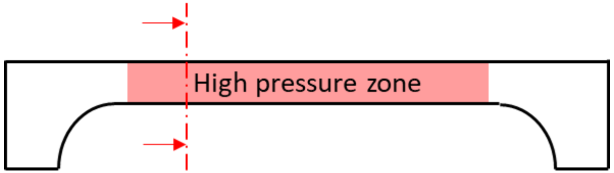


CABLE AT TWENTE – DAMAGE ANALYSIS: SECTION 2

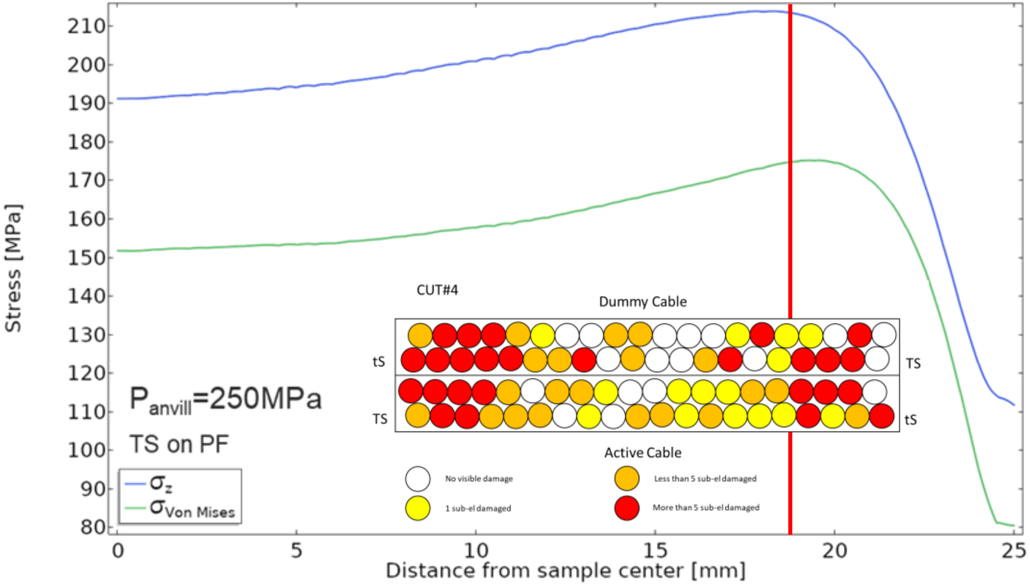


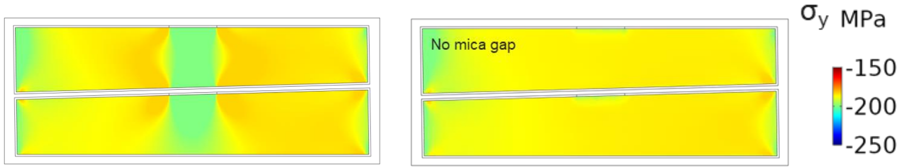


- Moving forward, the level of damage increases, leading to a maximum at about 19 mm from the central section of the sample.
- Moving toward the centre of the sample the damage level slightly decrease, remaining higher in the cables edges for each section.



CABLE AT TWENTE – CONCLUSIONS





- ➢ The implemented model allowed to better investigate the mechanical behaviour of the sample holder and the insulated cable stack during transverse pressure test at cold.

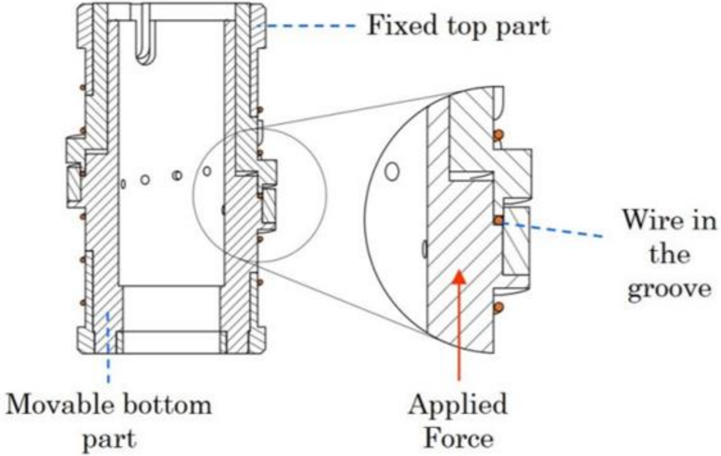
- ➢ The local pressure acting on the peak field area of the cable has been calculated, allowing for better interpretation of the experimental data.

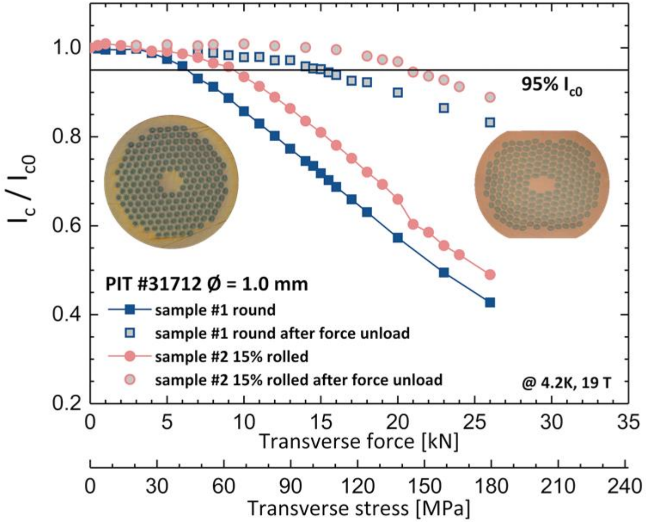
- ➢ The model prediction in term of pressure distribution along the cable length and section have been compared and matched with experimental damage analysis.

- ➢ In the test conditions, the mica gap appear to have a critical influence on stress distribution at the cable level.

STRAND AT UNIGE - EXPERIMENTAL SET-UP

UNIVERSITÉ
DE GENÈVE

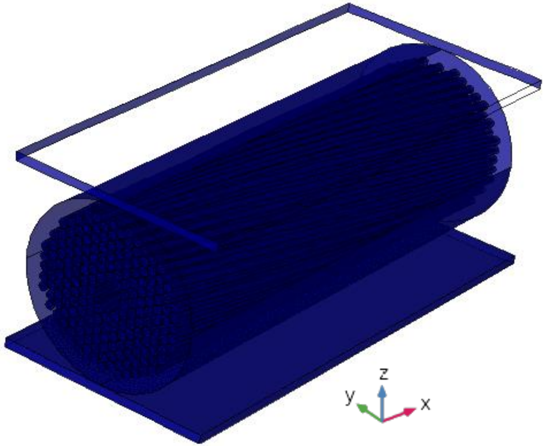


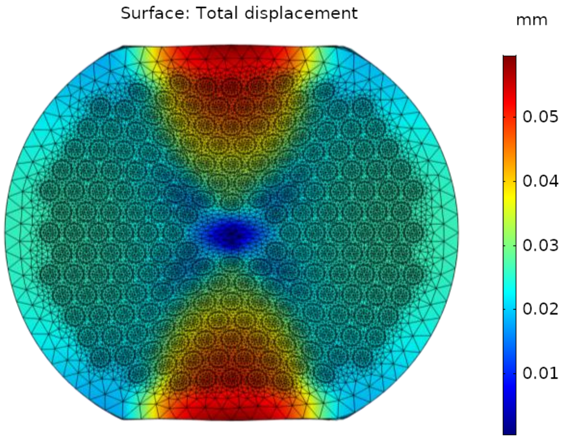


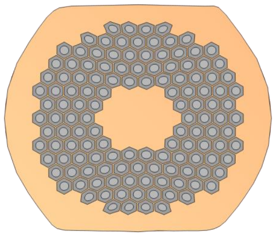
Sketches from: J Ferradas Troitino *et al* 2021 *Supercond. Sci. Technol.* **34** 035008

C. Senatore Indico 896755

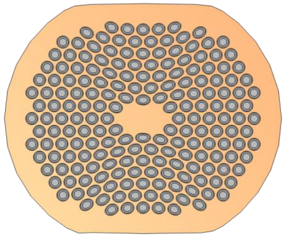
STRAND AT UNIGE - FEM MODEL GEOMETRY



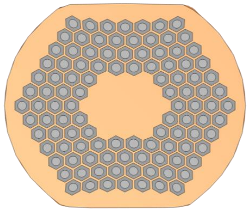




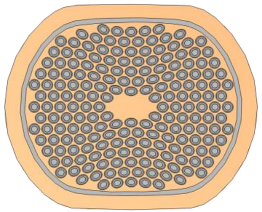
RRP 132/169



PIT 192



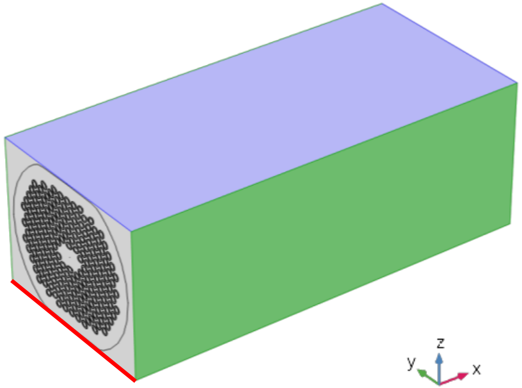
RRP 108/127



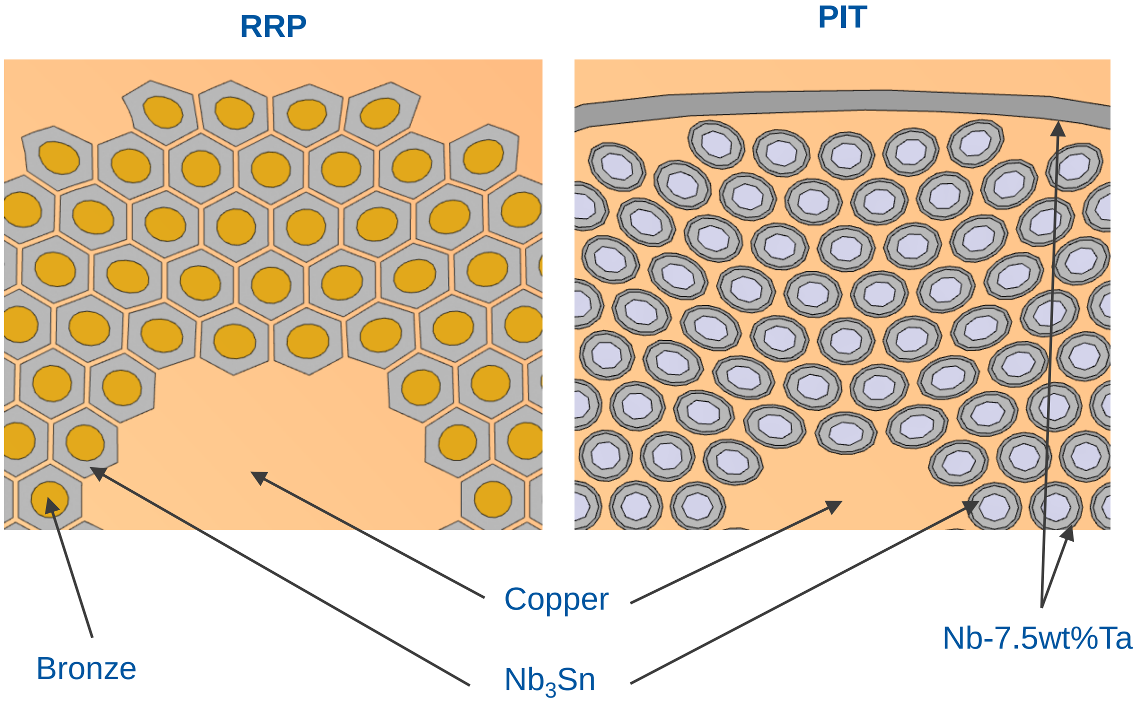
PIT 192 w bb

- In the framework of the HL-LHC project, 15% rolled samples are used to qualify the conductor being procured.
- This deformed configuration is more representative of the strand shape in a Rutherford cable.

STRAND AT UNIGE – FEM MODEL SET-UP



- **Boundary conditions:**
  - 🟪 **Displacement control**
  - 🟥 **w=0**
  - 🟩 **v=0**
  - ⬜ **Continuity (u_1-u_2=0)**


RRP

PIT

Copper

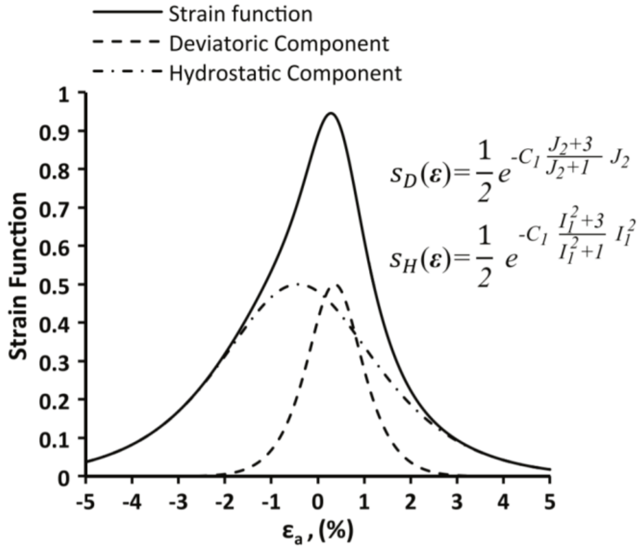
Bronze

Nb_3Sn

Nb-7.5wt%Ta

STRAND AT UNIGE – I_C REDUCTION CALCULATION

- Strain tensor is extracted from the FEM model results and used to compute the I_c reduction thanks to the exponential scaling law proposed by Bordini et al.



Plot from B. Bordini, P. Alknes, L. Bottura, L. Rossi, and D. Valentinis, Supercond. Sci. Technol. (2013)

$$J_c = C_0 s(\boldsymbol{\varepsilon}) h(t) b^{0.5}(1-b)^2 B_p^{-1}$$

$$h(t) = (1-t^2)(1-t^{1.52})$$

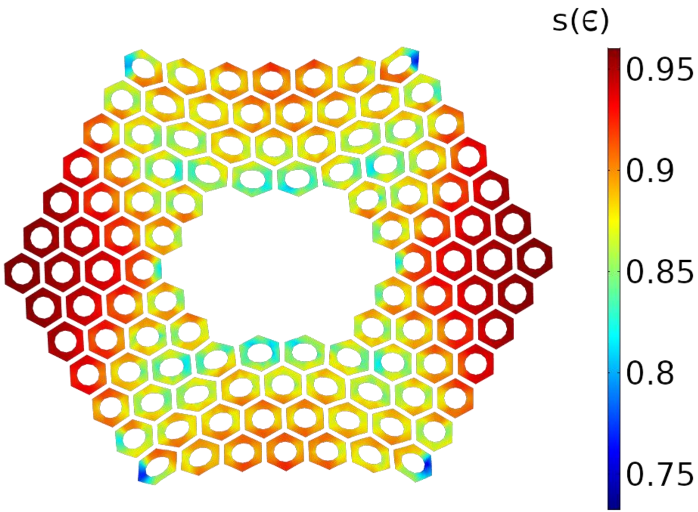
$$b = {B_p}/{B_{c2}(\boldsymbol{\varepsilon},t)} \qquad t = {T}/{T_{c0}(\boldsymbol{\varepsilon})}$$

$$T_{c0}(\boldsymbol{\varepsilon}) = T_{c0}\ s(\boldsymbol{\varepsilon})^{\frac{1}{3}}$$

$$B_{c2}(\boldsymbol{\varepsilon},t) = s(\boldsymbol{\varepsilon}) B_{c20}(1-t^{1.52}) \quad \rightarrow \quad \boxed{s(\varepsilon) = {B_{C2}(\varepsilon, 0\ K)}/{B_{c20}}}$$

STRAND AT UNIGE – EXPONENTIAL SCALING LAW

- Strain tensor is extracted from the FEM model results and used to compute the I_c reduction thanks to the exponential scaling law proposed by Bordini et al.



$$s(\boldsymbol{\varepsilon}) = \frac{1}{2}\left(e^{-C_1\frac{I_1^2+3}{I_1^2+1}I_1^2} + e^{-C_1\frac{J_2+3}{J_2+1}J_2}\right)$$

$$I_1 = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$$

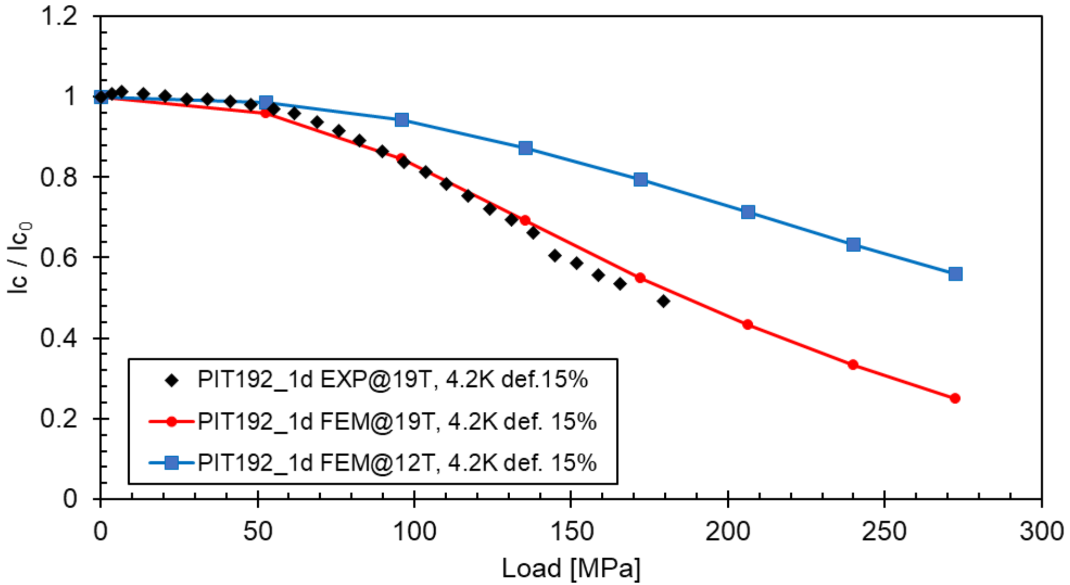
$$J_2 = \frac{1}{6}\left[\left(\varepsilon_{xx} - \varepsilon_{yy}\right)^2 + \left(\varepsilon_{xx} - \varepsilon_{zz}\right)^2 + \left(\varepsilon_{yy} - \varepsilon_{zz}\right)^2\right] + \varepsilon_{xy}^2 + \varepsilon_{xz}^2 + \varepsilon_{yz}^2$$

$$\varepsilon_{xx} = \varepsilon'_{xx} + \varepsilon_l$$
$$\varepsilon_{yy} = \varepsilon'_{yy} - \nu\varepsilon_l + K$$
$$\varepsilon_{zz} = \varepsilon'_{zz} - \nu\varepsilon_l + K$$

B. Bordini, P. Alknes, L. Bottura, L. Rossi, and D. Valentinis, Supercond. Sci. Technol. (2013)

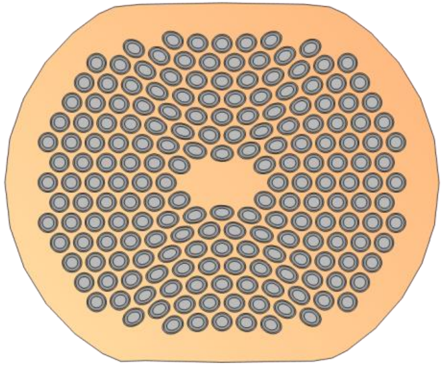
STRAND AT UNIGE – FEM RESULTS: PIT 192

- I_c reduction well match the experimental data from UNIGE. The FEM results at 12T shows the expected reduced strain sensitivity at lower field due to the higher margin on B_{c2}



Simulation data from: A. Cattabiani, D. Baffari and B. Bordini IEEE TAS (2020)

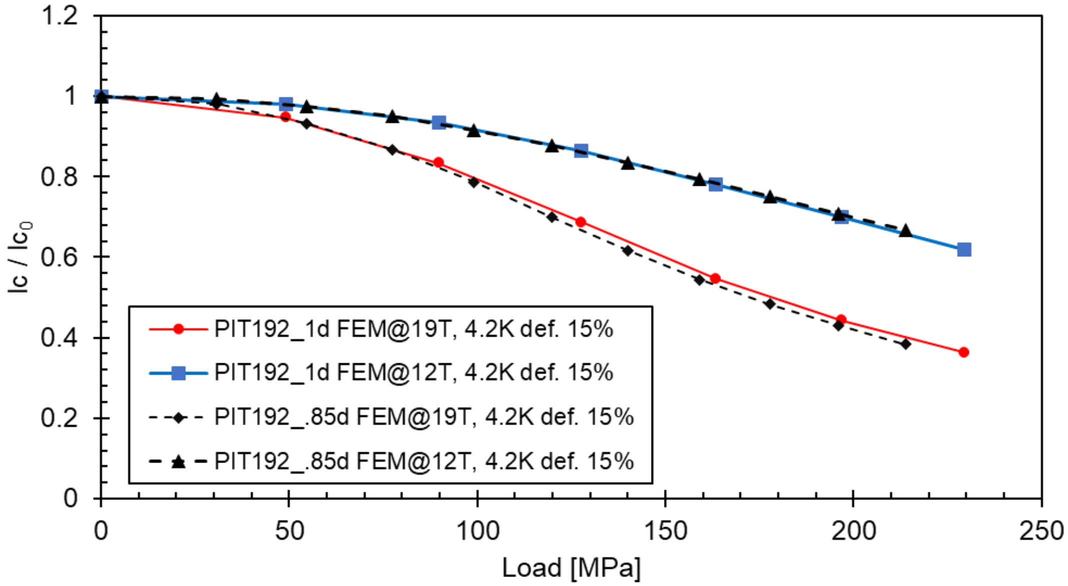
PIT 192
(FRESCA2)
d = 1 mm



Experimental data C. Senatore Indico 896755

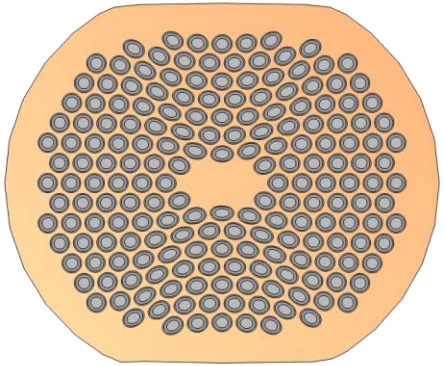
STRAND AT UNIGE – PIT192: DIAMETER INFLUENCE

- FEM results shows a negligible influence of the strand diameter (for given layout) on the critical current reduction.



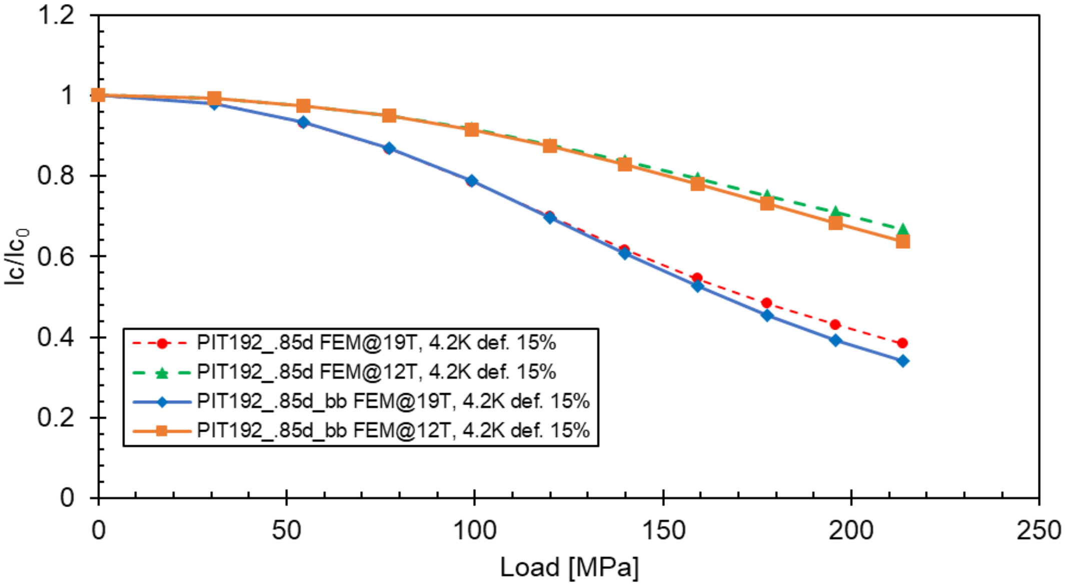
Baffari D., Bordini B., Cattabiani A. Submitted to IEEE TAS MT27 (2021)

PIT 192
(FRESCA2)
d = 1 mm / 0.85 mm



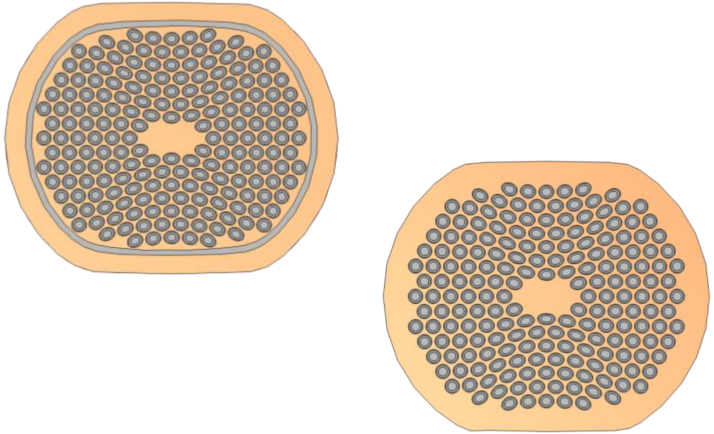
STRAND AT UNIGE – PIT: BUNDLE BARRIER

- The Nb-Ta bundle barrier do not increase the mechanical resistance of the strand. The stress sensitivity is slightly increased, possibly due to some local stress concentration on the sub-elements.



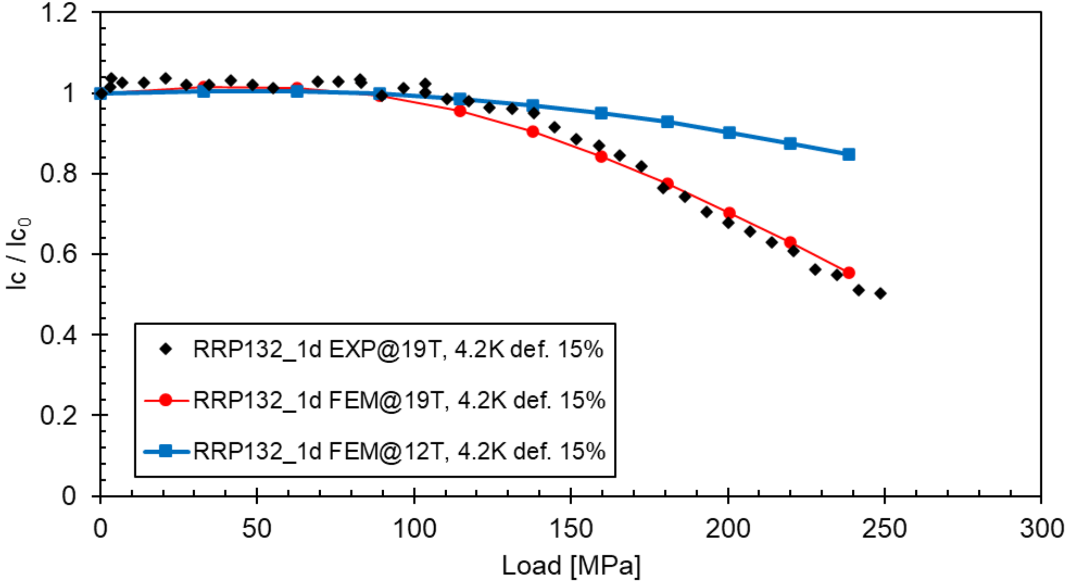
Baffari D., Bordini B., Cattabiani A. Submitted to IEEE TAS MT27 (2021)

PIT 192 w and wo BB
d = 0.85 mm

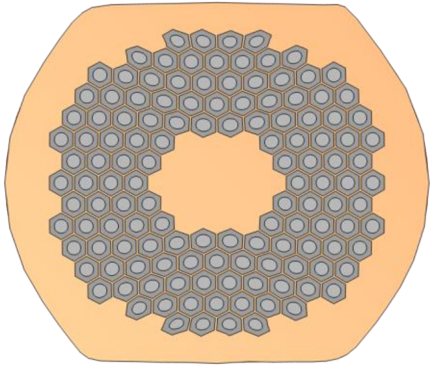


STRAND AT UNIGE – FEM RESULTS: RRP132/169

- The same FEM modelling strategy has been applied to a different wire production technology (RRP) showing good match with the experimental results from UNIGE.



RRP 132/169
(FRESCA2)
d = 1 mm

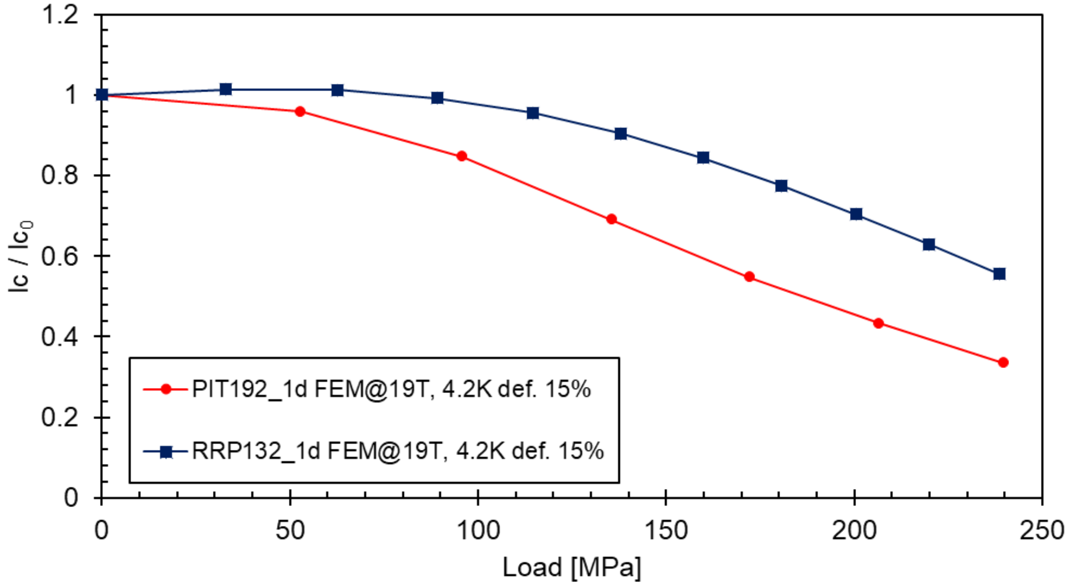


Simulation data from Baffari D., Bordini B., Cattabiani A. Submitted to IEEE TAS MT27 (2021)

Experimental data C. Senatore Indico 896755

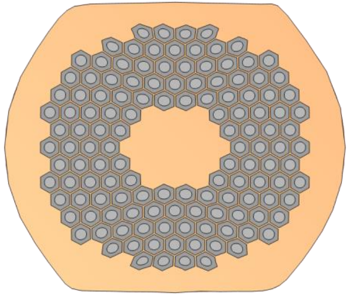
STRAND AT UNIGE – PIT VS RRP COMPARISON

- Comparison between the critical current reduction of two different production technology. The RRP shows, as expected, lower strain sensitivity due to the lower void content and the bronze filling the sub-elements core.

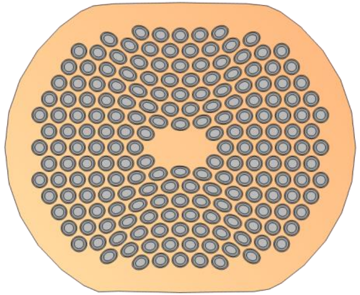


Baffari D., Bordini B., Cattabiani A. Submitted to IEEE TAS MT27 (2021)

RRP 132/169

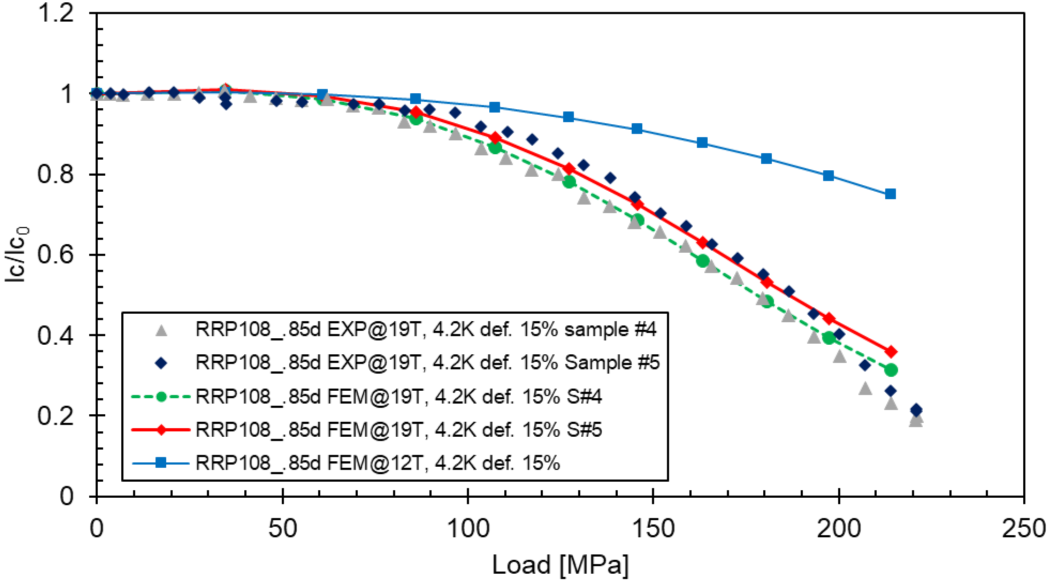


PIT 192



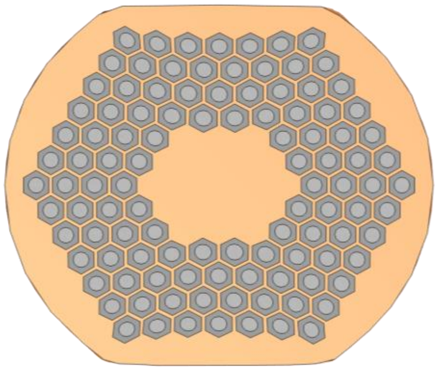
STRAND AT UNIGE – FEM RESULTS: RRP108/127

- The two sets of experimental data refer to samples characterized by different initial strain state that affect the superconductor pre-compression.



Simulation data from Baffari D., Bordini B., Cattabiani A. Submitted to IEEE TAS MT27 (2021)

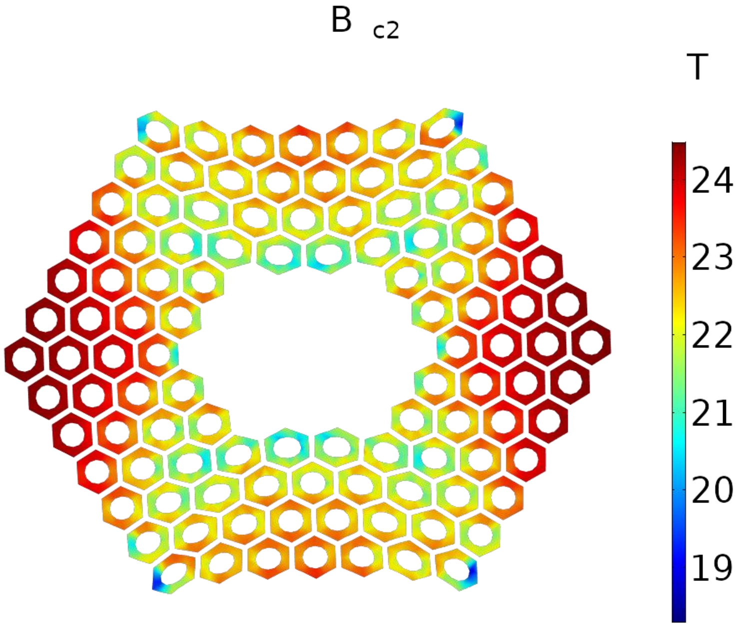
RRP 108/127
(MQXF)
d = 0.85 mm



Experimental data C. Senatore Indico 896755

STRAND AT UNIGE – CONCLUSIONS

- The implemented FEM numerical model is capable of simulating the electromechanical behavior of Nb_3Sn superconductive strands under transverse pressure at cold, predicting the reversible critical current reduction.
- The obtained results well match the experimental data at different field levels and for different strand type.
- The model can be used as an effective tool to predict the behavior of new strand layout and the effect of change of geometry on the superconductive properties.



CONCLUSIONS

- FEM modelling plays a key role at investigating the strain sensitivity of Nb_3Sn cables and wires.
- The data obtained from this kind of numerical simulation can be used as an essential tool to interpreter experimental results and better investigate the macro and micro mechanics involved in the test set-up itself.
- It is important to properly select the “scale” of the simulation, addressing carefully the simplification being added during the modelling (boundary condition, geometry, material, etc.).
- FEM model consolidated on experimental evidence can be used as valuable tool for preliminary investigation of new case studies (i.e. strand layout) preceding the experimental campaigns.

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