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Le Palace

Future Circular Collider Conference

Electro-mechanical properties of Nb_3Sn conductors for application to high-field magnets

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WRITING the FUTURE

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Outline

- Introduction
- Critical Current Measurements of Cables under Transverse Load
- Computational Modeling
- Conclusions

Introduction

Strain dependence of Nb_3Sn

- Superconducting **performance** of Nb_3Sn are strongly dependent on the superconductor **strain state**
- In the case of **applied axial strain**, with a good approximation we can write

$$B_{c2}(T, \varepsilon) = B_{c2}(T, 0)\, s(\varepsilon)$$

Where $s(\varepsilon)$ is the *strain function* that ranges between 0 and 1

$$J_c(B, T, \varepsilon) = C(T)\; b^{-0.5}(1-b)^2$$

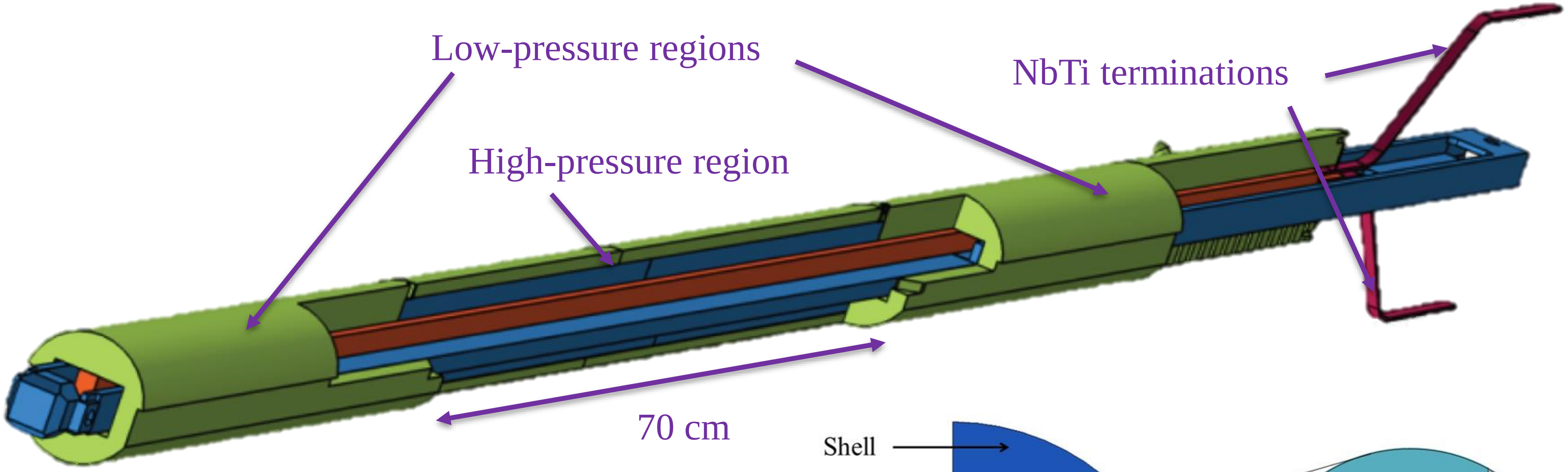
Where: $b = \dfrac{B}{B_{c2}(T, \varepsilon)}$

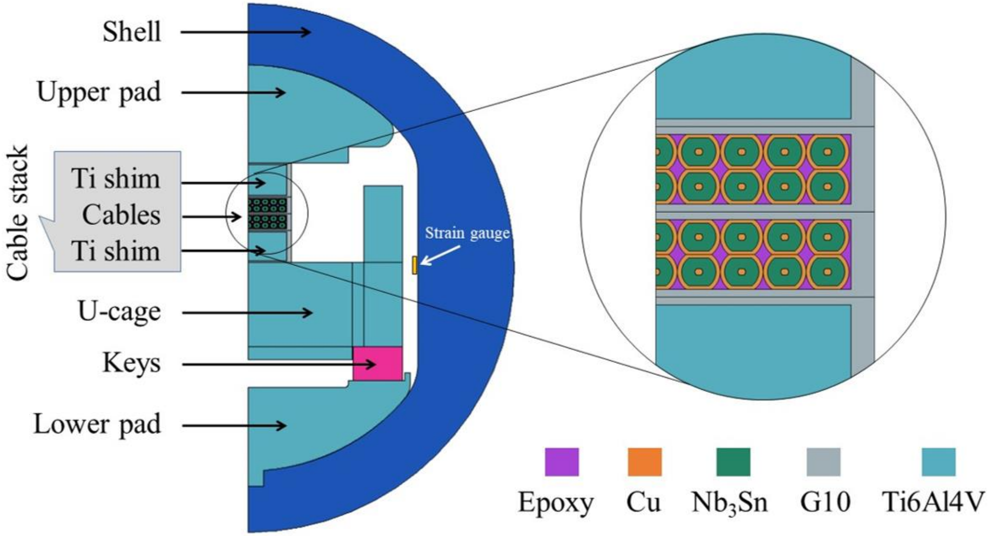
- Before cracking the filaments, the same equation proved to be valid also in the case of transverse loads

Critical Current vs Transverse Load

CERN cable sample holder

Max transverse force: **1750 kN**



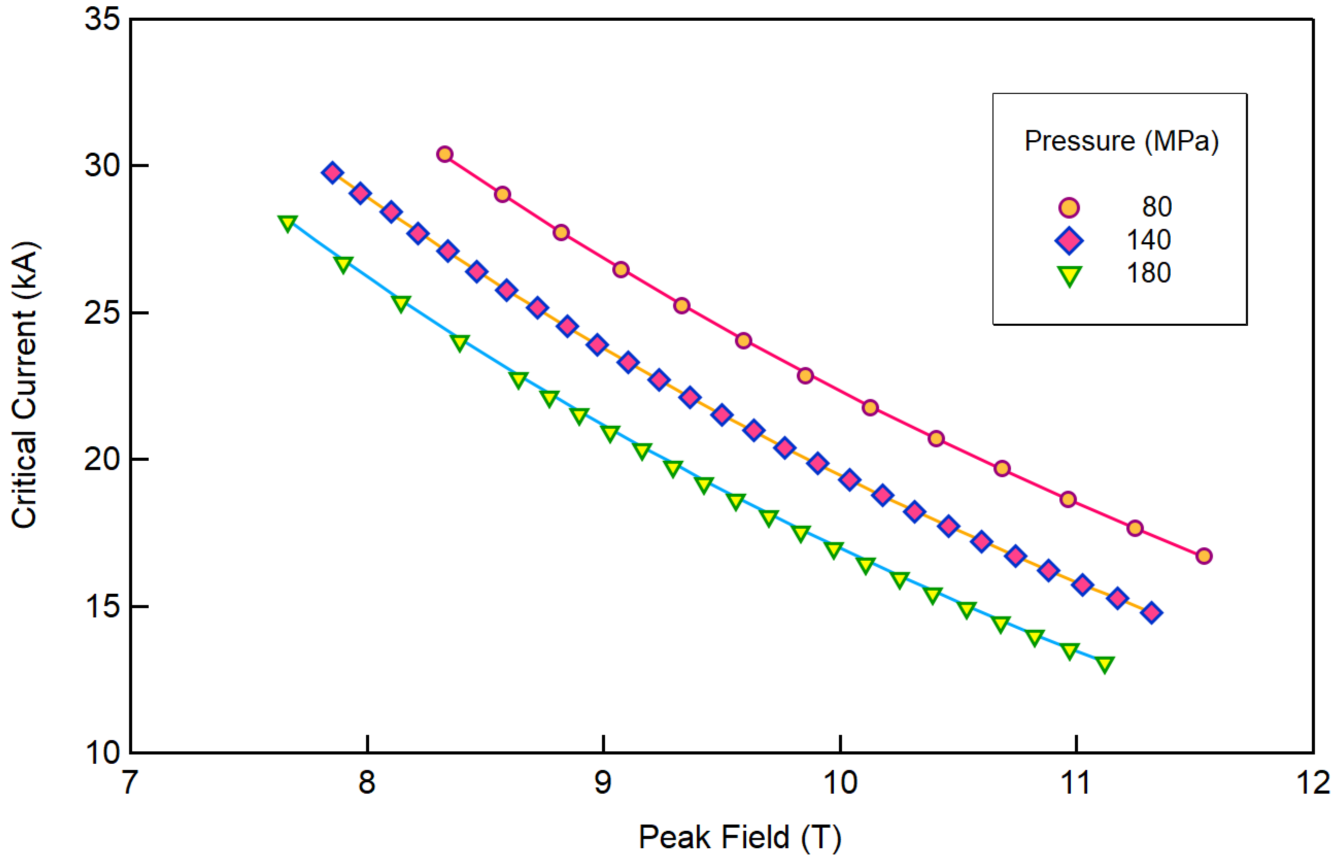


- Pro: very representative of the conductor behavior in a magnet
- Contra: long test campaigns, only narrow cables (~10 mm) can reach up to 250 MPa

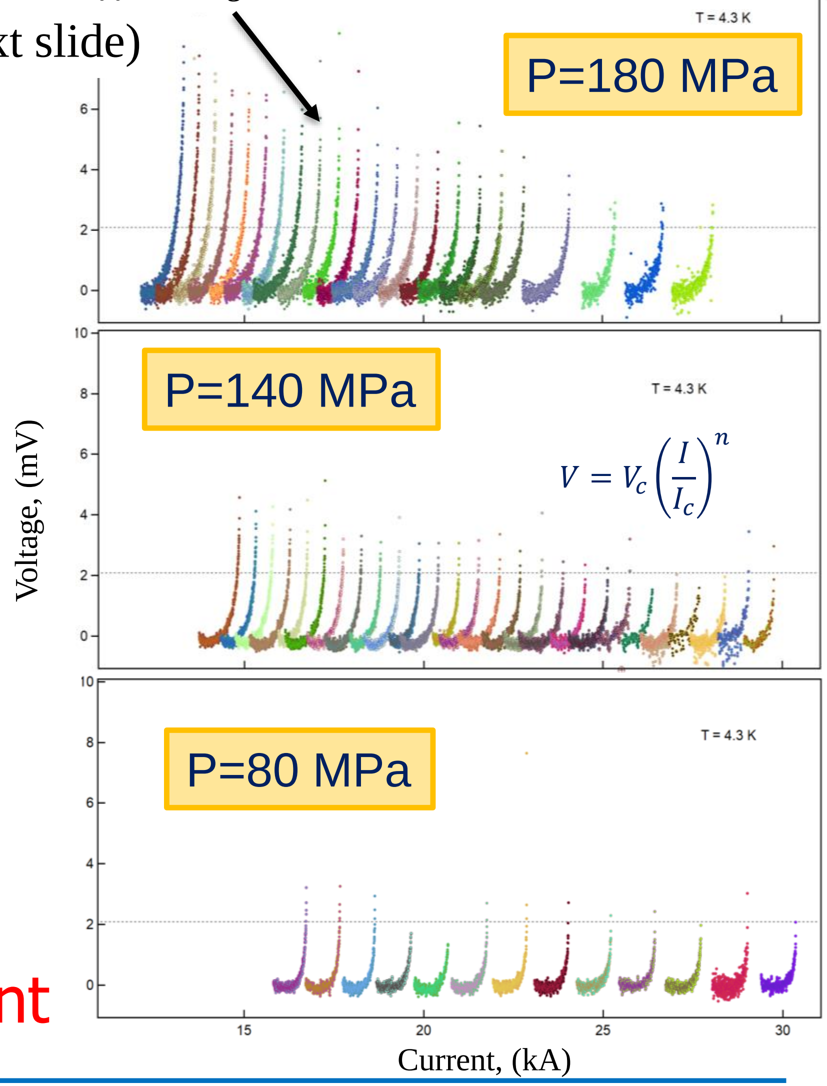
PIT cable based on 1-mm wires

Voltage-Current Measurements

Typical results for a PIT Cable measured at CERN at 4.3 K (full test sequence in next slide)



Different Curves at different applied magnetic fields

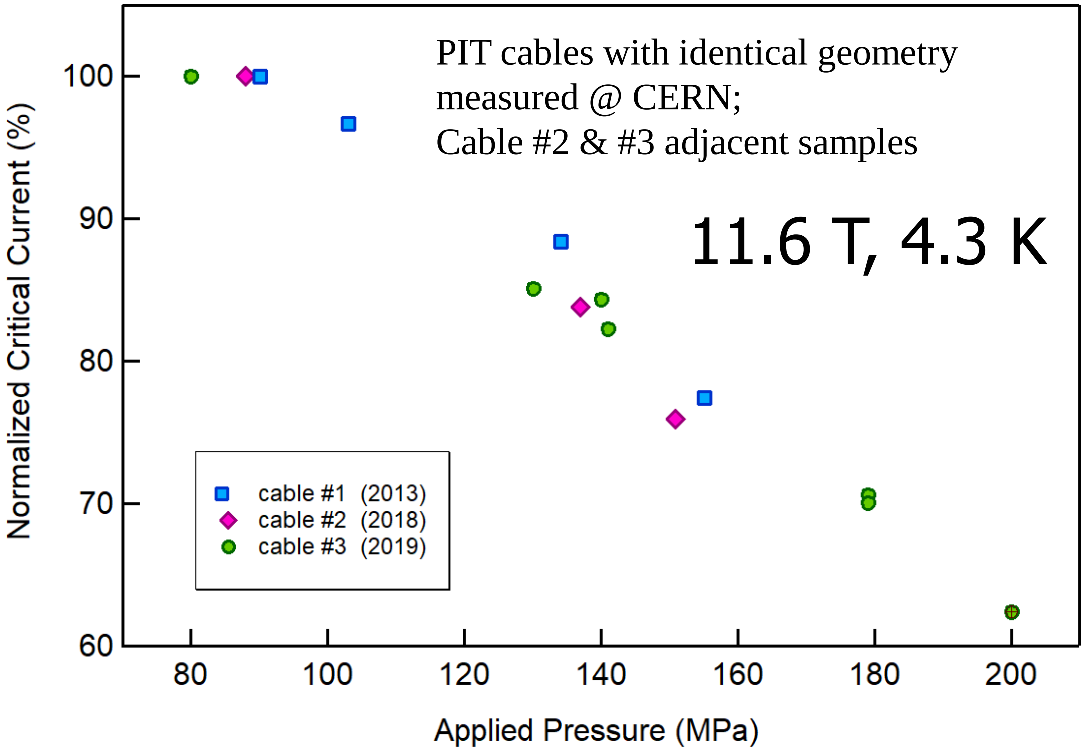


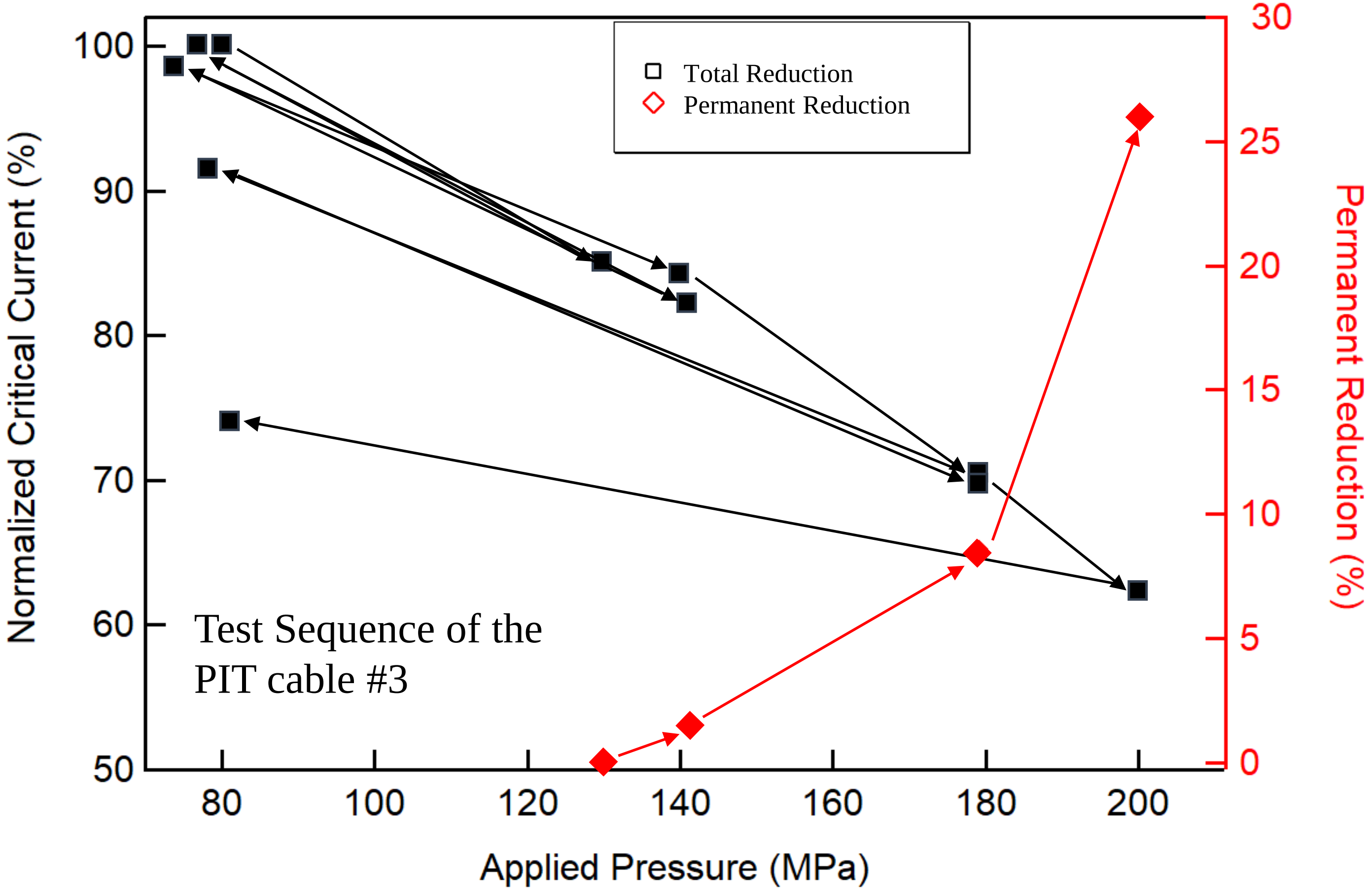
- **Significant Reversible Reduction** of the critical current

PIT cable based on 1-mm wires

Measurement Reproducibility & Permanent Reduction

New measurements at CERN and Twente **confirmed** and **consolidated** the results observed in 2013; furthermore they allowed **extending** our **understanding**

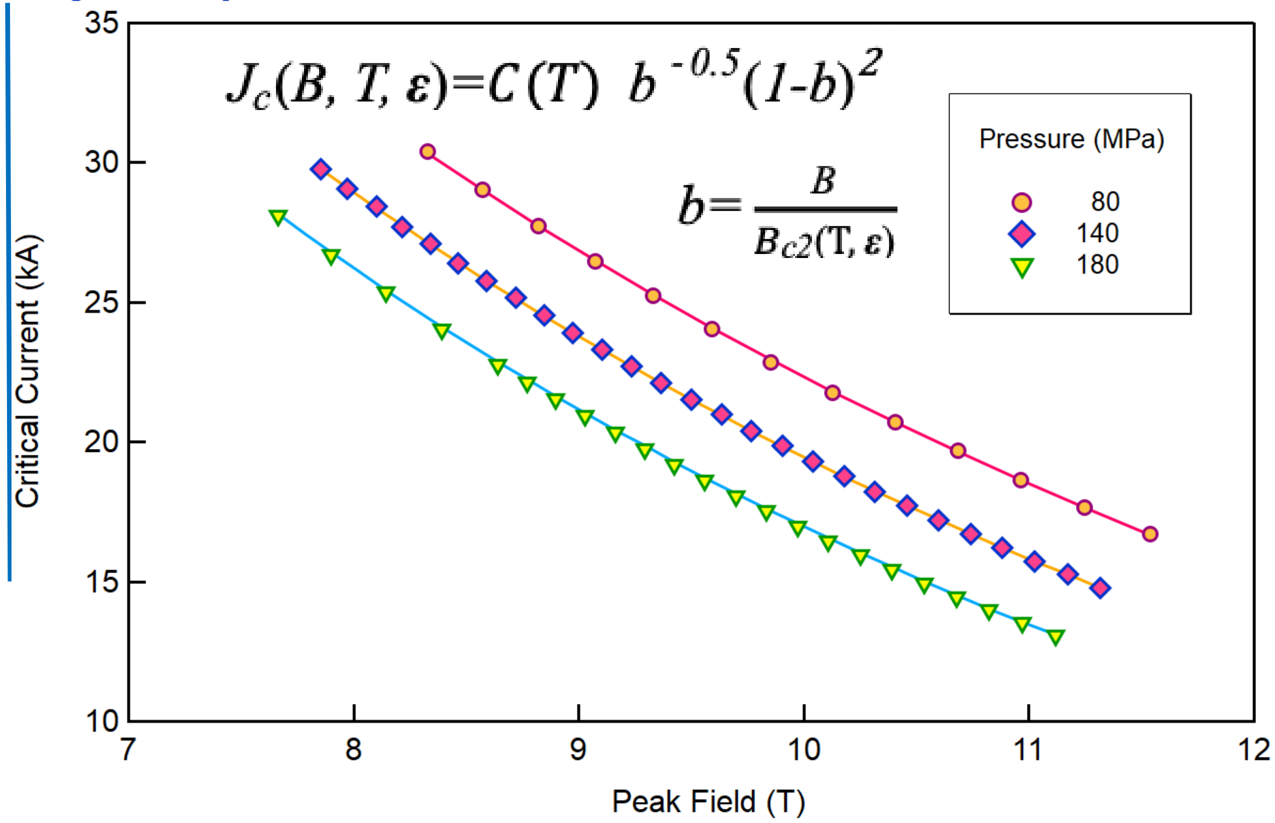


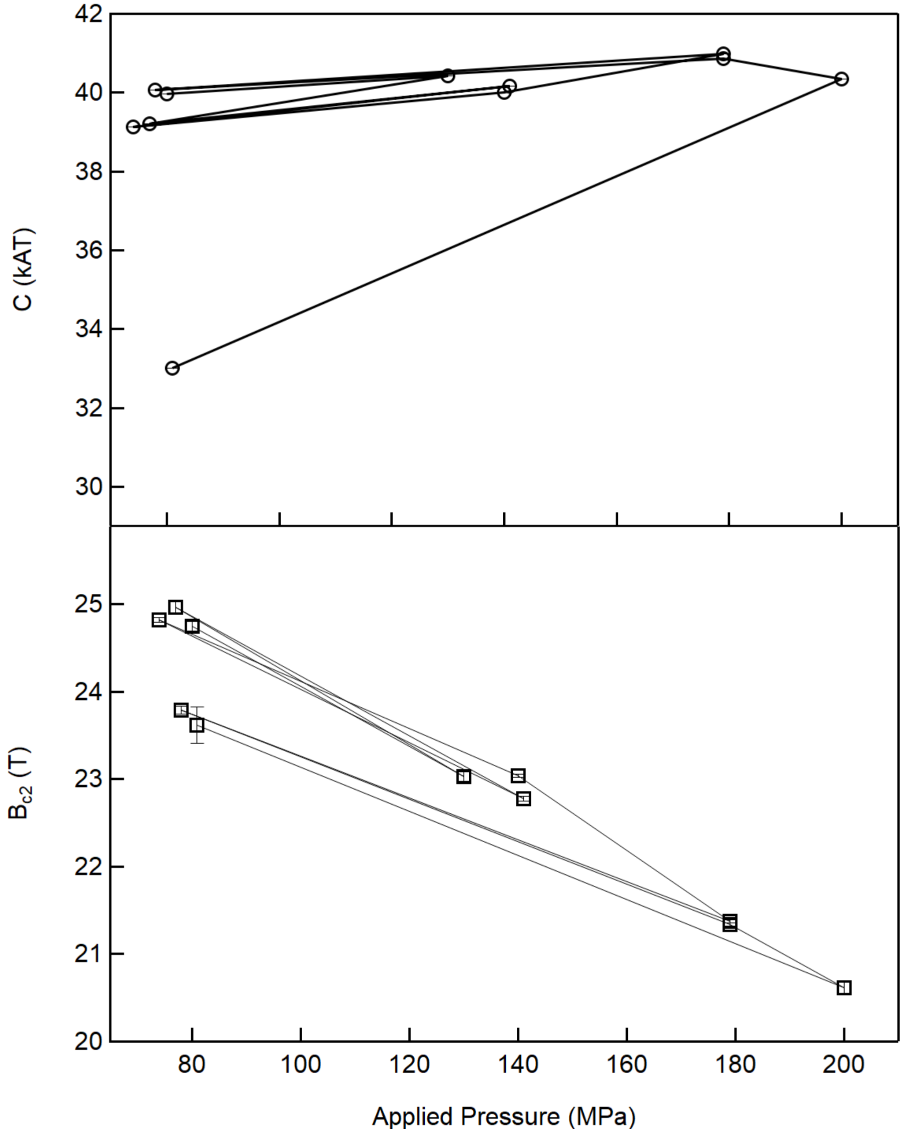


Onset permeant reduction **~130 MPa**, up to ~ 180 MPa most likely due to plasticization of copper afterwards, to cracks in the filaments

PIT Cable based on 1-mm wires

Scaling the I_c Reduction

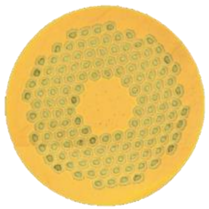




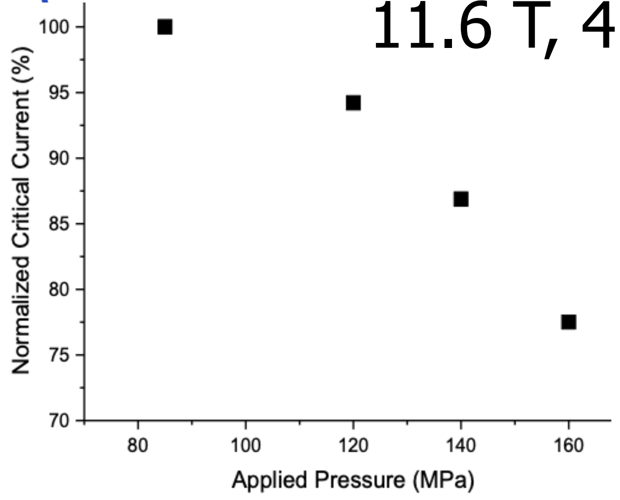
- I_c reduction mainly due to the decrease of the upper critical field B_{c2} → larger I_c reduction at larger fields: at **150 MPa and 1.9 K** ~ 20% at 12 T and ~ 45% at 19 T

RRP Cable based on 1-mm wires

Critical Current Reduction

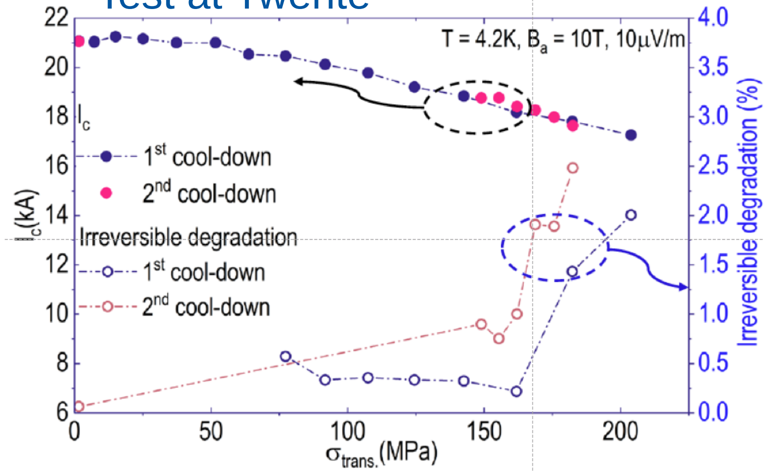


Test at CERN



11.6 T, 4.3 K

Test at Twente*



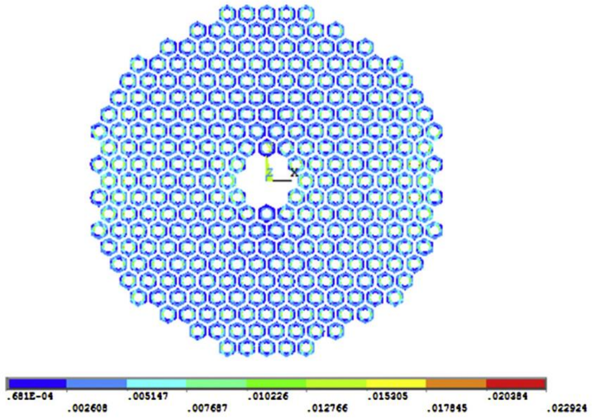
*Courtesy of M. Dhalle

- The **RRP** cable has still the same behavior of the PIT cable but it is **less sensitive** to transverse load

- Onset **permanent** I_c reduction
  1. **PIT**: **~130 MPa**
  2. **RRP**: **~170 MPa**
- **Total** I_c reduction at 11.6 T and **150 MPa**
  1. **PIT**: **~ 20 %**
  2. **RRP**: **~ 15 %**

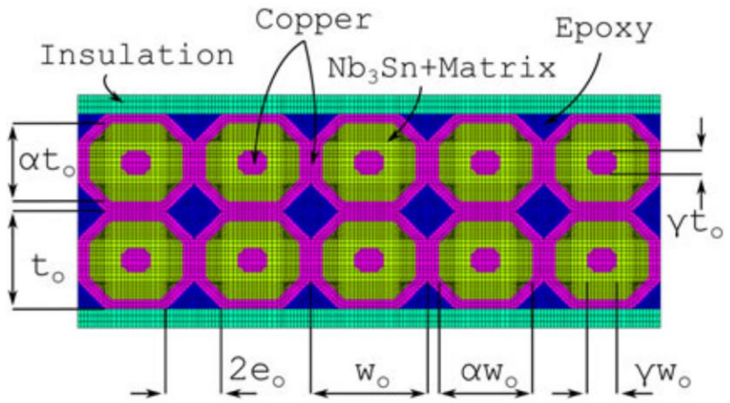
Introduction – Previous Studies

Wang – wire, UniGe



T. Wang, L. Chiesa, M. Takayasu, and B. Bordini, *Cryogenics (Guildf).*, vol. 63, pp. 275–281, 2014.

Vallone – cable, FRESCA



G. Vallone, B. Bordini, and P. Ferracin, *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, 2018.

General Idea

- 2D mechanical FEM → strain field $\boldsymbol{\varepsilon}$ → scaling law $J_c(s(\boldsymbol{\varepsilon}))$
- $s(\boldsymbol{\varepsilon}) = s(I_1, J_2)$ [5] where I_1 is the first invariant of the strain tensor and J_2 is the second invariant of the deviatoric strain tensor

[5] B. Bordini, P. Alknes, L. Bottura, L. Rossi, and D. Valentinis," *Supercond. Sci. Technol.*, vol. 26, no. 7, p. 075014, 2013.

Computational Modeling

Introduction – Aims of this work

Both models were quite successful in reproducing the experimental results however, they rely on some assumptions that deserve to be further investigated

Aim

Study these assumptions to enhance the understanding of the physical phenomena involved. Most relevant assumptions:

1) longitudinal strains/stresses (plane strain [6] and the plane stress [7])
2) the necessary strain amplification factor when the wire layout is simplified and the material properties are homogenized [7]
3) no current redistribution

How?

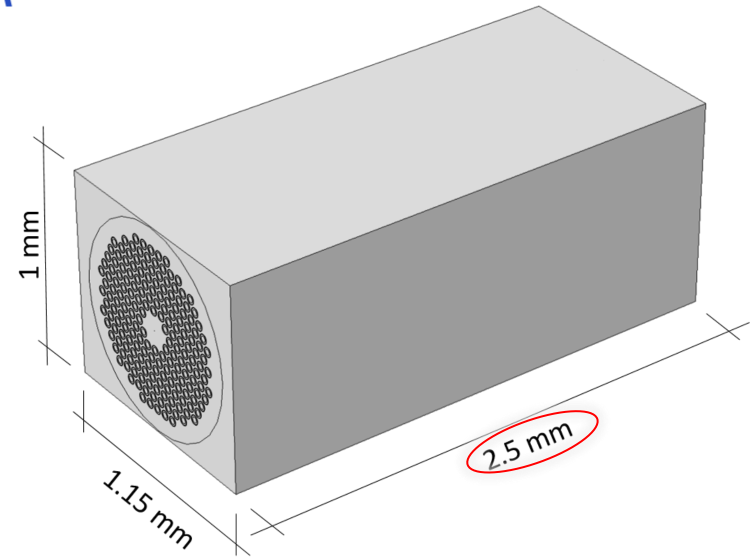
A 3D FEM model with no geometrical and material assumptions and no hypothesis on the longitudinal strain

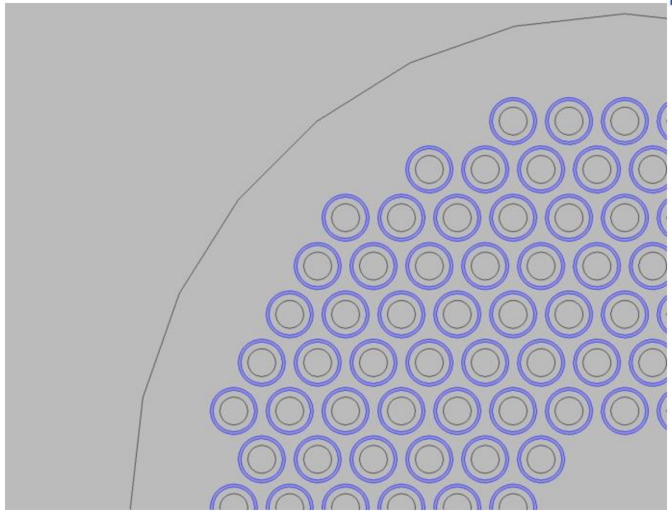
Add, in the future, an electric 3D model to simulate the possible current redistribution

[6] T. Wang, L. Chiesa, M. Takayasu, and B. Bordini, "Cryogenics (Guildf)., vol. 63, pp. 275–281, 2014.
[7] G. Vallone, B. Bordini, and P. Ferracin, IEEE Trans. Appl. Supercond., vol. 28, no. 4, 2018.

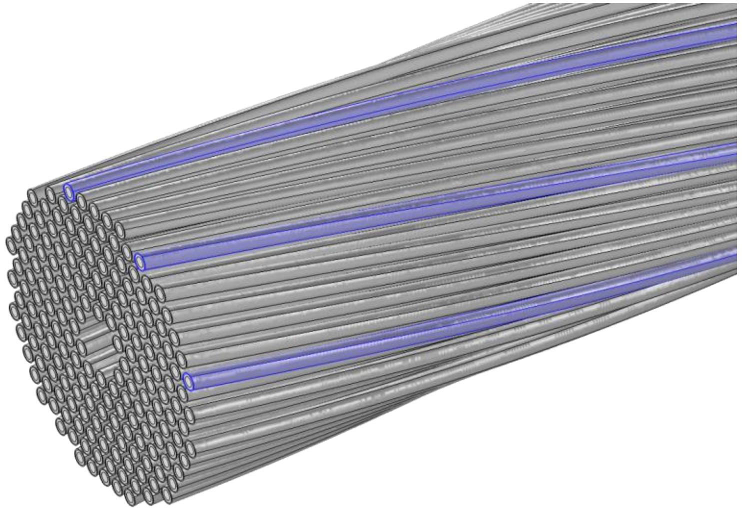
Computational Modeling

Model Geometry





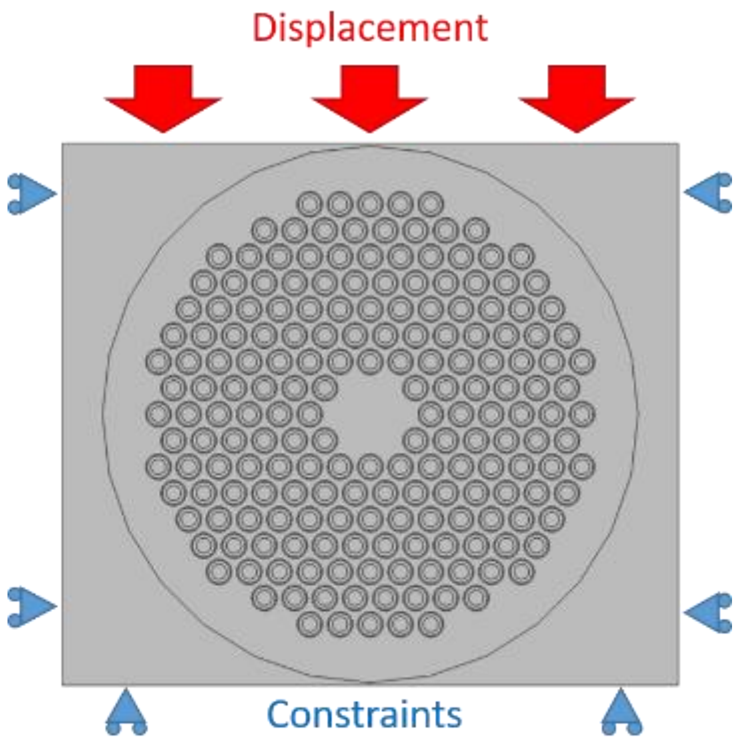
- High computational costs: smallest representative segment = 2.5 mm long
- No homogenizations: All the 192 filaments are modeled
- The strand is twisted (15 mm)



Computational Modeling

Boundary conditions: along the strand

- Groove and anvil are treated as rigid bodies: modeled as boundary constraints
  - Lateral and bottom faces are free to slide on their respective planes
  - Progressive, compressive displacement on the top face

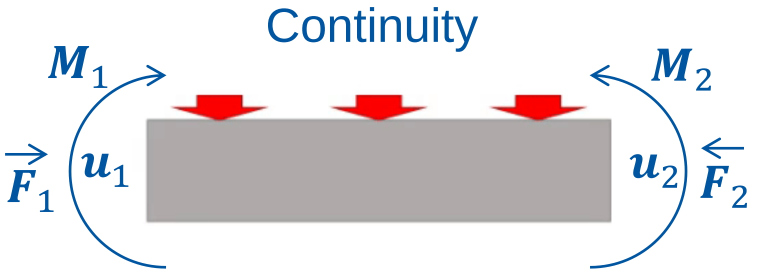


Computational Modeling

Boundary conditions: strand ends

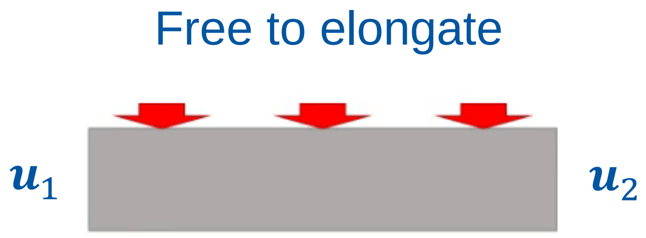
Two possible set of boundary conditions on the strand ends to study the extreme cases:

Clamped and symmetric by translation: continuity $\boldsymbol{u}_1 = \boldsymbol{u}_2$



Free to elongate and symmetric by translation: $\boldsymbol{u}_1 - \boldsymbol{u}_2 = [q \quad 0 \quad 0]'$ with q such that forces and couples are null:

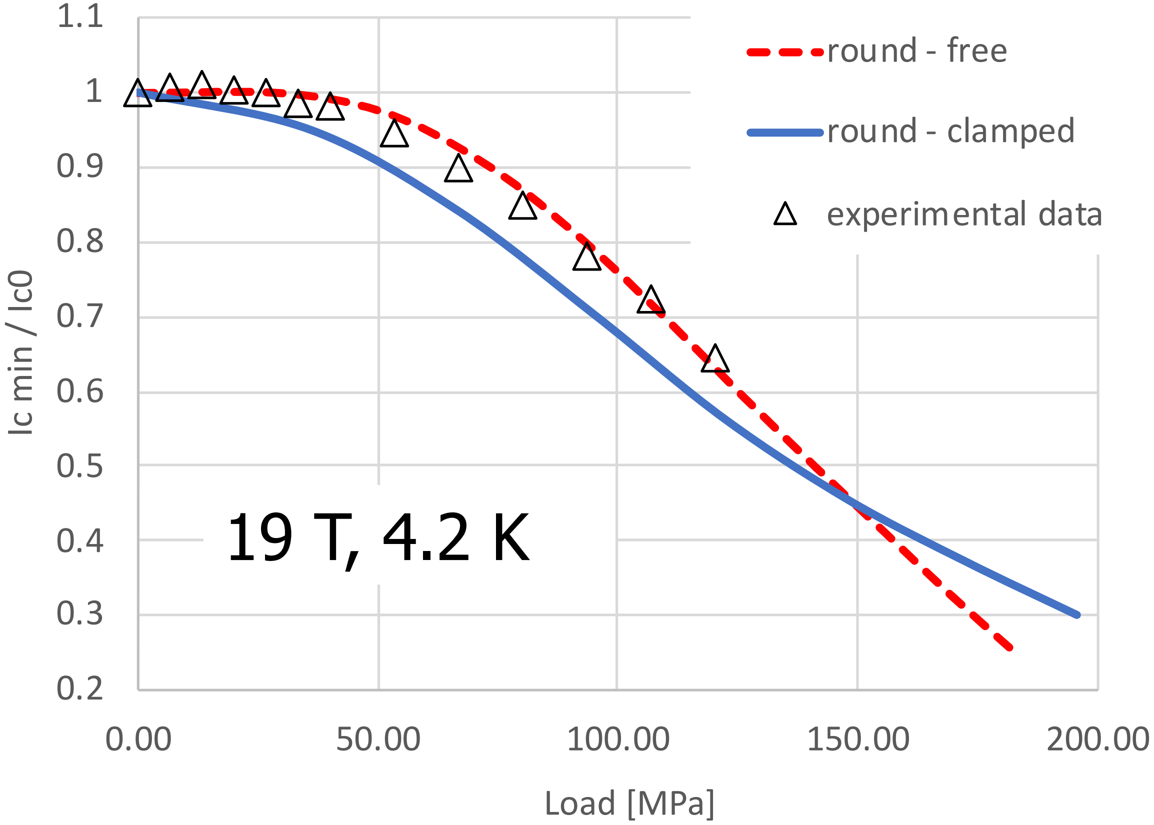
$$\boldsymbol{F}_1 = \boldsymbol{F}_2 = \boldsymbol{M}_1 = \boldsymbol{M}_2 = 0$$

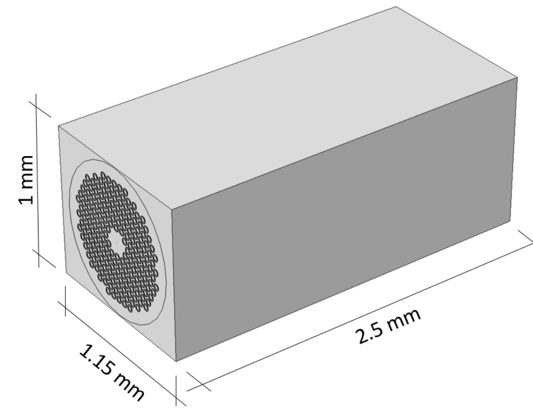


Computational Modeling

Results: I_c reduction in round PIT wires

- Hypothesis: no current redistribution
  - I_c dictated by the most strained filament
- Good agreement with experimental data [4]





$$\text{Load} = \frac{1}{A}\int_A \sigma_{zz} dA$$

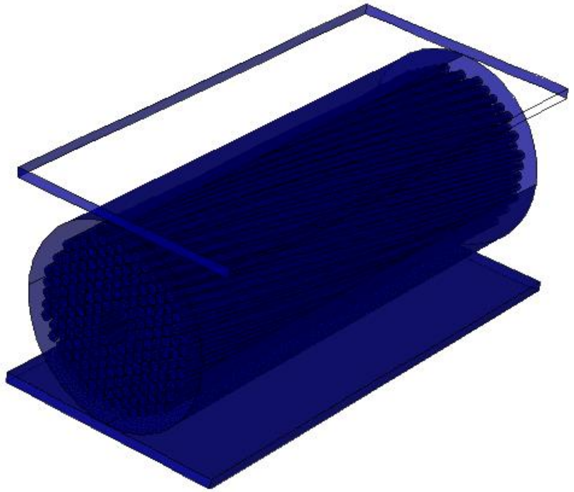
$$A = 1.15\, mm * 2.5 mm$$

[4] C. Calzolaio *et al.*, *Supercond. Sci. Technol.*, vol. 28, no. 5, pp. 1–11, 2015.

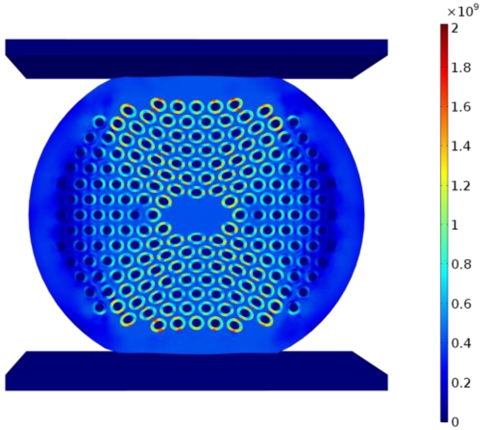
Computational Modeling

Rolled strand: deformed configuration

- Rolled strand (15% def.) are more representative of the geometry of the strand in a Rutherford cable
- In order to study this case, the deformed configuration is required
- An additional simulation of rolling is performed: the strand is deformed plastically between 2 rigid plates

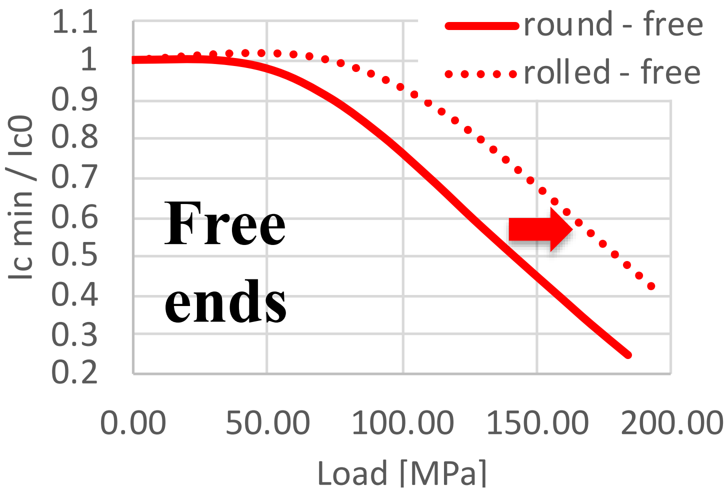


Rolling

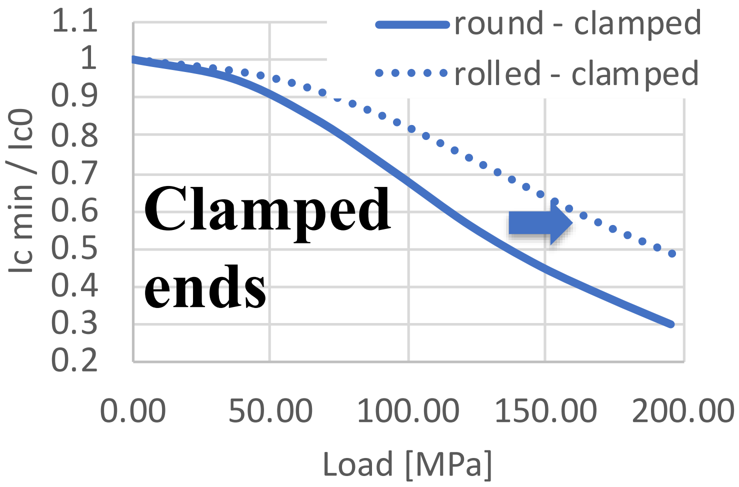


Computational Modeling

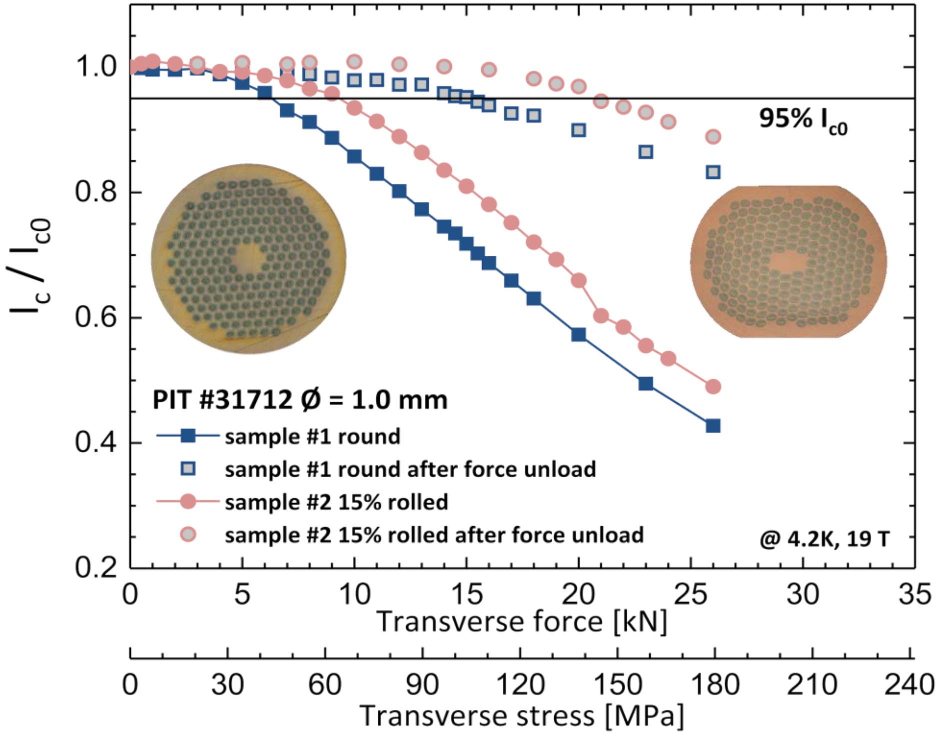
Results I_c reduction PIT wires: Round vs 15% Rolled



19 T, 4.2 K



- The model reproduces the lower sensitivity of 15% rolled samples with respect to round wire samples
  - The same performance reduction is obtained at **40 MPa larger** loads
  - The model is in good agreement with the experimental data from the University of Geneva



Courtesy of C. Senatore

Conclusions

- The **effect** of the **transverse load** on the **superconducting performance** of Nb_3Sn cables is **relevant** already at **150 MPa** and has to be taken into account in the **design** of high field accelerator **magnets**

- **Before cracking** the filaments (at least up to 180 MPa), the **critical current reduction**:
  - is mainly due to a **decrease** of the **upper critical field** and can be **described** with the well established **scaling laws** developed for the case of applied axial strain $I_c(B,T,\varepsilon) = I_c\big(B,T,s(\varepsilon)\big)$ - where *s* is the *strain-function*
  - can be **estimated** with mechanical Finite Element Method models coupled with the ***exponential* strain-function** developed at CERN

THANK YOU FOR THE ATTENTION

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