

# A 3D Finite Element Model of the Reversible Critical Current Reduction due to transverse load in Nb<sub>3</sub>Sn wires

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# Outline

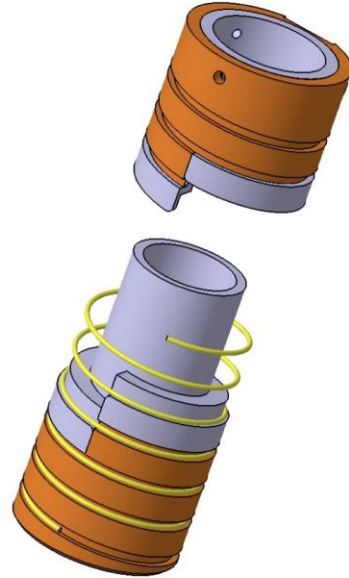
- Introduction
- Reference experiment and previous 2D studies
- Description of the first set of simulations:  
3D model of a **round** strand PIT 192, 1mm
- Results of the **round** strand simulations
- Description of the second set of simulations:  
3D model of a **rolled** strand PIT 192, 1mm
- Results of the **rolled** strand simulations
- Conclusions & Perspectives

# Introduction

- The next generation of high-field accelerator magnets (High-Luminosity-LHC, Future Circular Collider projects) employs Nb<sub>3</sub>Sn Rutherford cables
- High-field magnets experience large mechanical loads: up to 200 MPa of stresses for the FCC 16 T dipoles. This implies high strains in the superconducting strands
- Nb<sub>3</sub>Sn superconducting properties are sensitive to strains
- Our aim is to create a 3D mechanical model capable of simulating, through a scaling law, the reversible I<sub>c</sub> reduction of a strand subject to transverse loads

# Modelling of The Experiment conducted at UniGe

PIT 192, 1 mm  $\varnothing$ ,  
15 mm twist pitch

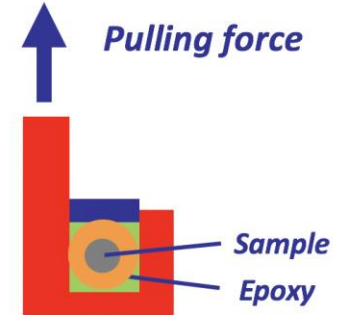


3 groove widths  $\left\{ \begin{array}{l} 1.30 \text{ mm} \\ 1.15 \text{ mm} \\ 1.00 \text{ mm} \end{array} \right.$



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DE GENÈVE

4-WALL + impregnation



Wire impregnated  
with epoxy  
applied stress  
uniformly distributed

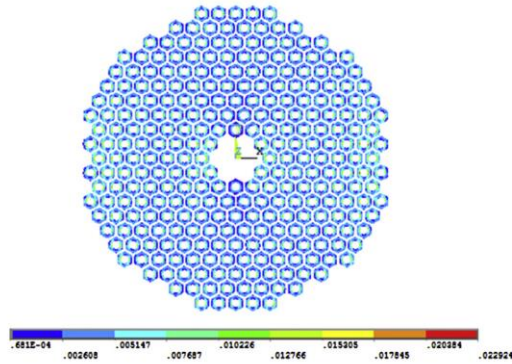
Courtesy of C. Senatore  
(UniGe)

C. Calzolaio *et al.*, "Electro-mechanical properties of PIT Nb<sub>3</sub>Sn wires under transverse stress: experimental results and FEM analysis," *Supercond. Sci. Technol.*, vol. 28, no. 5, pp. 1–11, 2015.

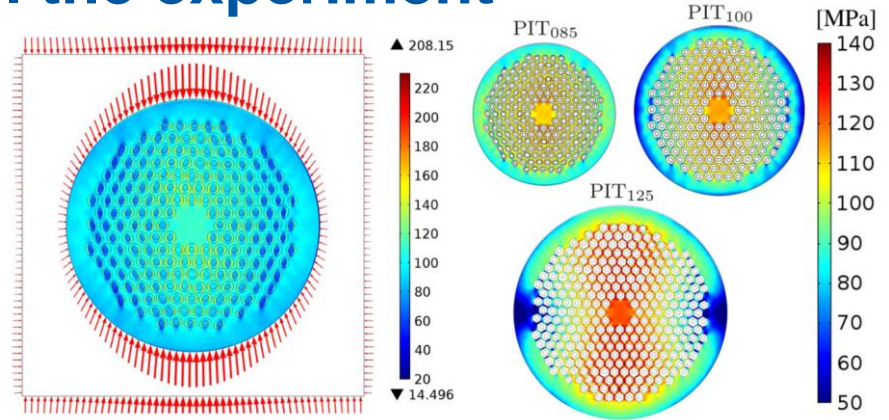


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# Other 2D studies that model the experiment



T. Wang, L. Chiesa, M. Takayasu, and B. Bordini, "A novel modeling to predict the critical current behavior of Nb<sub>3</sub>Sn PIT strand under transverse load based on a scaling law and Finite Element Analysis," *Cryogenics (Guildf.)*, vol. 63, pp. 275–281, 2014.

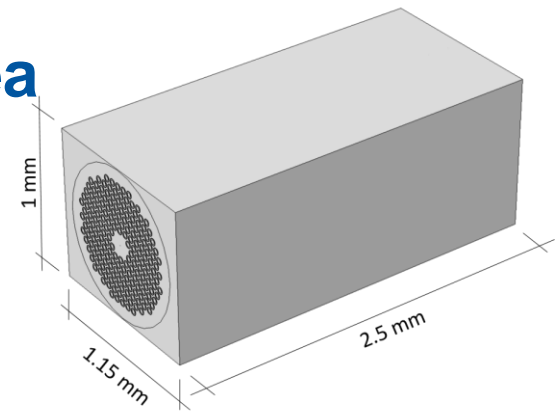


C. Calzolaio *et al.*, "Electro-mechanical properties of PIT Nb<sub>3</sub>Sn wires under transverse stress: experimental results and FEM analysis," *Supercond. Sci. Technol.*, vol. 28, no. 5, pp. 1–11, 2015.

- The experiment has already been studied employing 2D mechanical simulations
- Our aim is to run a 3D simulation campaign to investigate in more detail the experiment

# 3D Simulation Campaign: General Idea

- Mechanical model of a PIT 192, 1 mm, subject to up to ~ 200 MPa of transverse load
- Strain tensor is extracted and linked to  $I_c$  using an exponential scaling law\*



$$s(\boldsymbol{\varepsilon}) = \frac{1}{2} \left( e^{-c_1 \frac{I_1^2+3}{I_1^2+1} I_1^2} + e^{-c_1 \frac{J_2+3}{J_2+1} J_2} \right)$$

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

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

\*B. Bordini, P. Alknes, L. Bottura, L. Rossi, and D. Valentini, "An exponential scaling law for the strain dependence of the Nb3Sn critical current density," *Supercond. Sci. Technol.*, vol. 26, no. 7, p. 075014, 2013.

$$B_{c2}(\boldsymbol{\varepsilon}, t) = s(\boldsymbol{\varepsilon}) B_{c20} (1 - t^{1.52})$$

$$t = T / T_{c0}(\boldsymbol{\varepsilon})$$

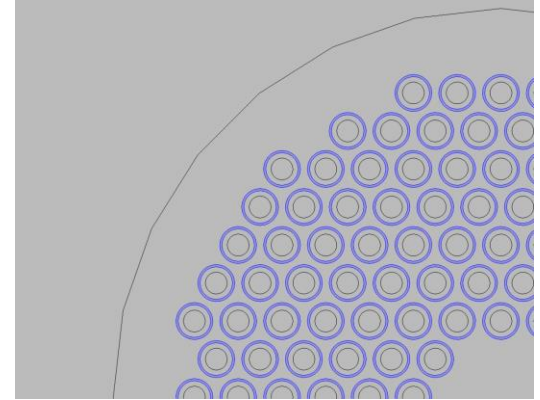
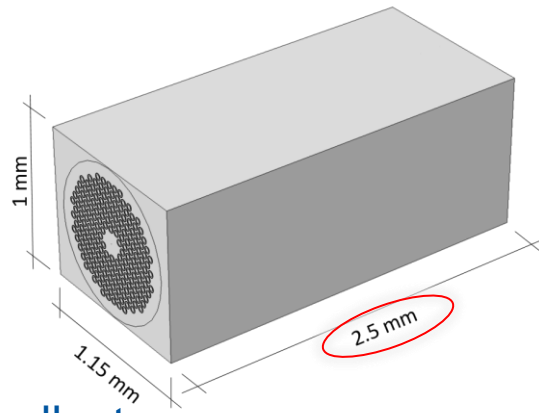
$$T_{c0}(\boldsymbol{\varepsilon}) = T_{c0} s(\boldsymbol{\varepsilon})^{\frac{1}{3}}$$

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

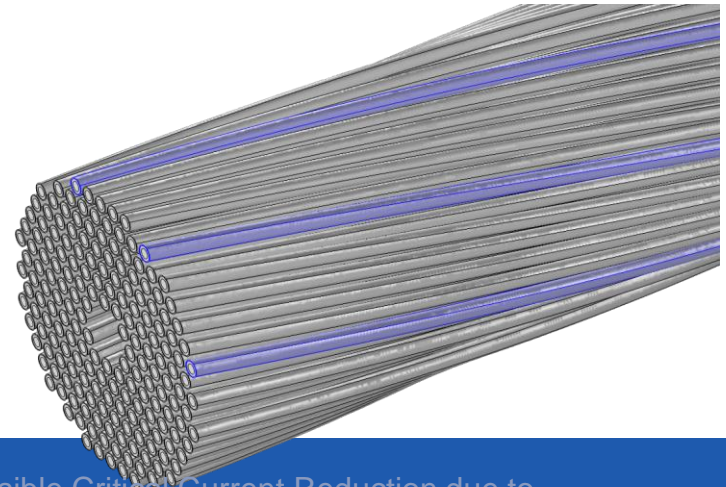
$$h(t) = (1 - t^2)(1 - t^{1.52})$$

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

# Model Geometry

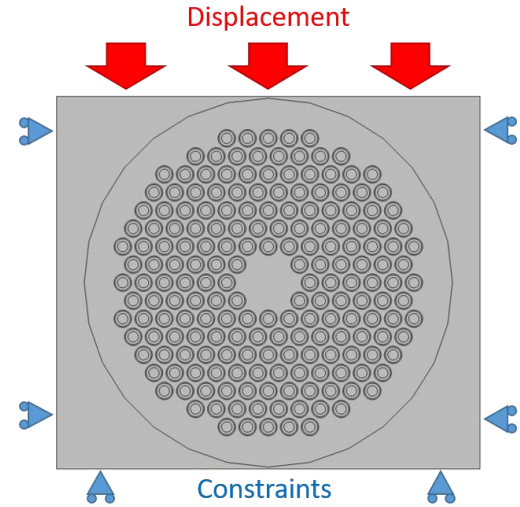


- High computational costs: smallest representative segment = **2.5 mm** long
- **No homogenizations**: All the 192 filaments are modeled. Additionally,  $\text{Nb}_3\text{Sn}$  filaments are encased in unreacted Nb jackets (~23% of filament area)
- The strand is **twisted** (15 mm)



# 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

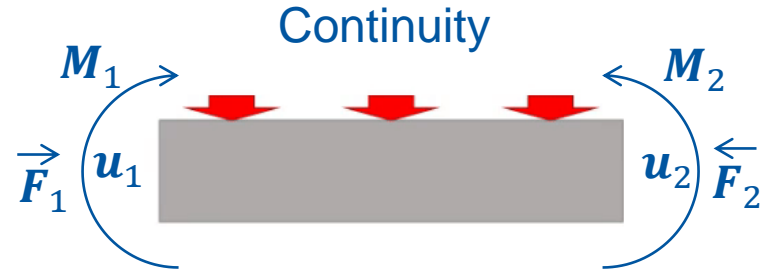




# Boundary conditions: strand ends

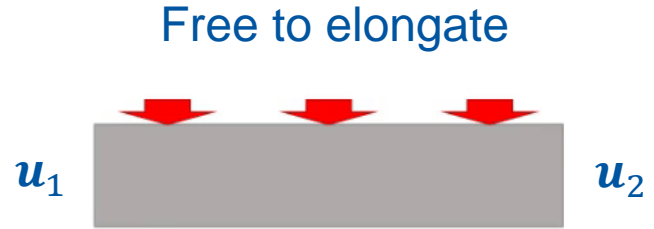
Two possible set of boundary conditions on the strand ends to study the extreme cases:

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



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

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

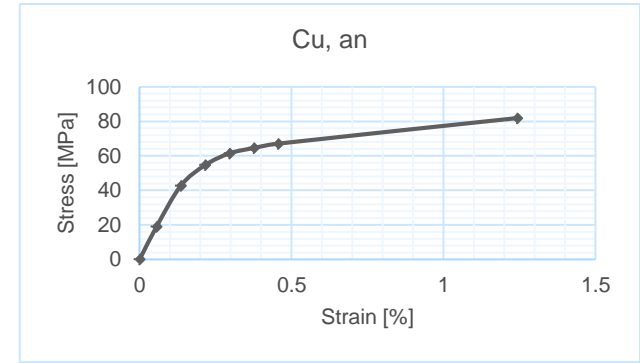


# Boundary conditions: free to elongate longitudinally

- $\mathbf{u}_1 - \mathbf{u}_2 = [q \ 0 \ 0]'$  is, so far, extremely slow to converge
- However, the solution differs from the free-ends result (where we impose only  $\mathbf{F}_1 = \mathbf{F}_2 = \mathbf{M}_1 = \mathbf{M}_2 = 0$  on the strand ends) only near the ends. If we are not interested in the solution near the boundaries, the free-ends simulation is sufficient
- We will demonstrate, using the exact boundary condition at, that the free-ends simulation is sufficient

# Material Properties

- Filament cores are negligible
- ~23% of unreacted Nb. Still cold-worked and orthotropic. In this load range it is elastic
- All data are at 4.22 K



	Description	E [GPa]	$\nu$	$E_y$ [MPa]
Cu, an	Isotropic, plastic	118.8	0.343	46.2
Nb <sub>3</sub> Sn	Orthotropic, elastic	[106, 116, 116]'	0.38	-
Nb	Orthotropic, elastic	[103, 113, 113]'	0.38	-
Epoxy L	Isotropic, elastic	5.5	0.35	-

# Residual strains

Heat treatment produces **residual strains** between the copper matrix and the filaments. It is modelled in post-processing as additional strain components in the Nb<sub>3</sub>Sn filaments\*

$$\begin{cases} \epsilon_{cl} = -0.0018 \\ \epsilon_{ct} = -\nu\epsilon_{cl} \end{cases}$$

\*B. Bordini, P. Alknes, L. Bottura, L. Rossi, and D. Valentini, "An exponential scaling law for the strain dependence of the Nb<sub>3</sub>Sn critical current density," *Supercond. Sci. Technol.*, vol. 26, no. 7, p. 075014, 2013.

# Computational costs

## Windows Comsol cluster at CERN

	Current	Precedent set ups
N of Nodes	~3.6 Millions	~9 Millions
Sockets	8	16 (half of the cluster)
Time	~8-10 hours	4-5 days

# Results: $I_c$ reduction

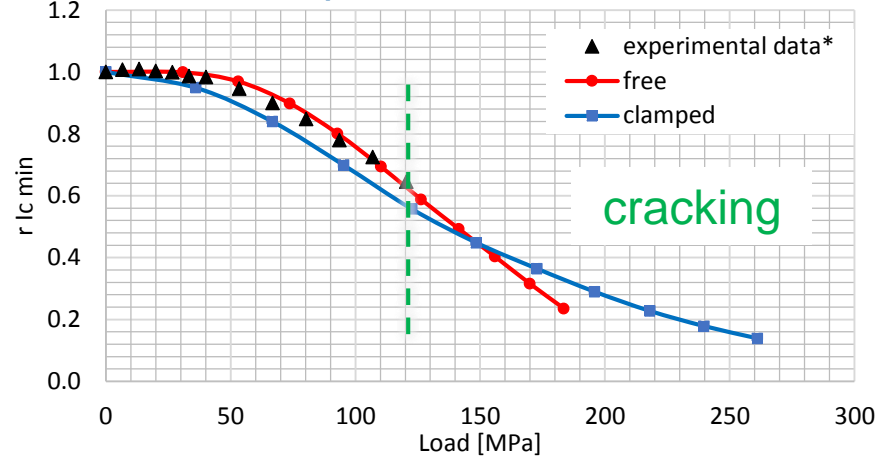
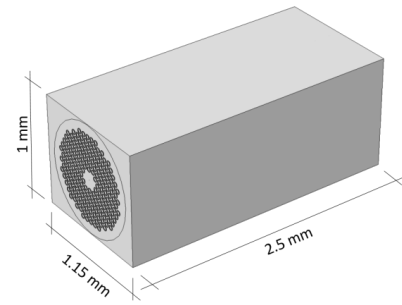
- Conservative hypothesis: no redistribution of the current.  $I_c$  is dictated by the most strained filament
- Boundary conditions** are crucial
- Above  $\sim 120$ MPa, cracks appear in the Nb<sub>3</sub>Sn phase: simulations are no more representative
- $I_c$  reduction is very sensitive to **initial strains**. Further studies are foreseen

$$r_{I_{c_{min}}} = \frac{I_{c_{min}}(\epsilon)}{I_{c_0}} = \min_{f_i} \left( \int_{A_{f_i}} J_c(\epsilon) dA_{f_i} \right)$$

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

$$A = 1.15 * 2.5 = 2.875 \text{ mm}^2$$

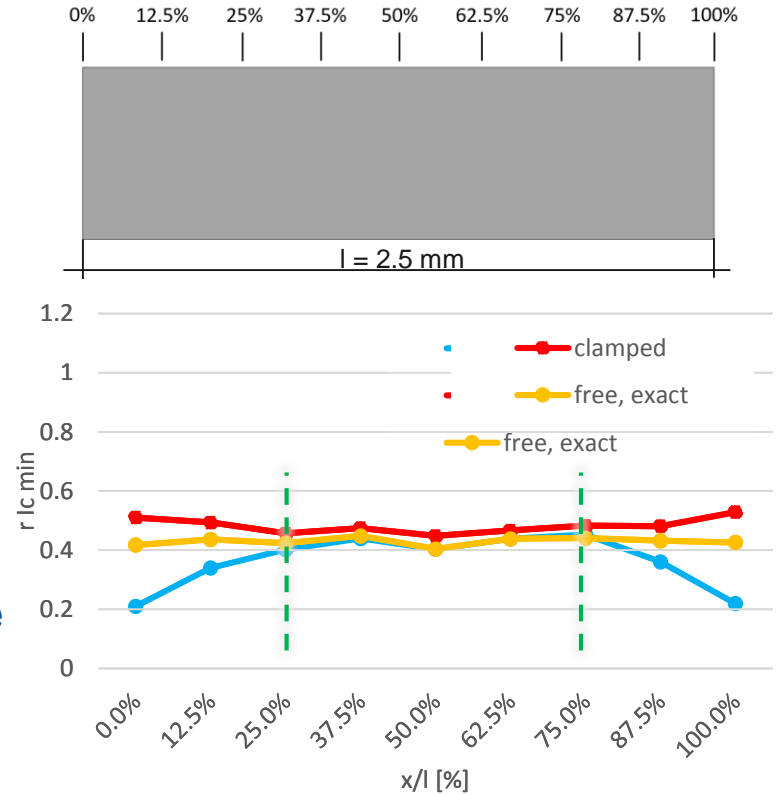
$$B_{c20} = 30.97 \text{ T}, T_{c0} = 17 \text{ K}, B_p = 19 \text{ T}, T = 4.22 \text{ K}$$



\*C. Calzolaio *et al.*, "Electro-mechanical properties of PIT Nb<sub>3</sub>Sn wires under transverse stress: experimental results and FEM analysis," *Supercond. Sci. Technol.*, vol. 28, no. 5, pp. 1–11, 2015.

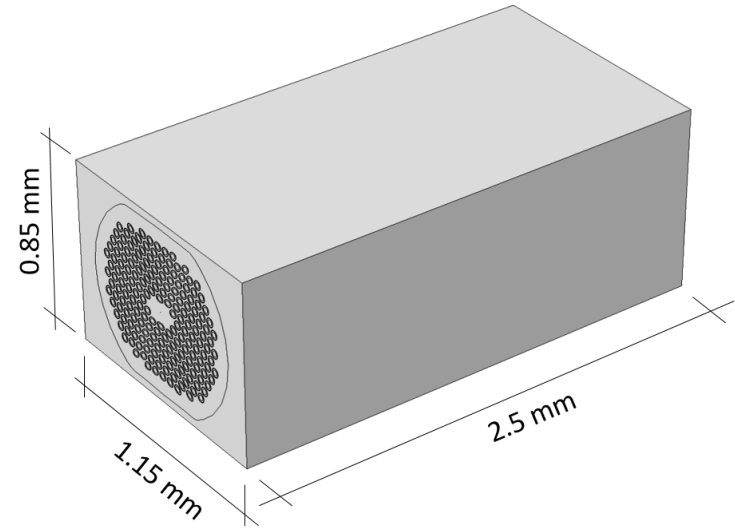
# Results: reduction Along the Strand at ~150 MPa

- $I_c$  reduction is **constant along the strand**: the particular pair section layout, load direction does not significantly change results
- However, **free ends  $\neq$  plane stress**. Stresses between Cu and  $Nb_3Sn$  are relevant along the whole strand
- Approximated and exact solutions differ only near strand ends ( $\sim 25\% x/l$ ). This, in conjunction with the fact that  $I_c$  reductions are constant along the strand, demonstrates that the study of the free-ends case is, indeed, sufficient



# 3D mechanical model to study the $I_c$ reduction of a **rolled** PIT 192, 1mm subject to transverse load

- Rolled strands are more representatives of the conditions in a Rutherford cable
- During cabling, the strand is flattened before the heat treatment. The deformed geometry can distribute loads differently modifying  $I_c$
- Real experiments are ongoing at the University of Geneva

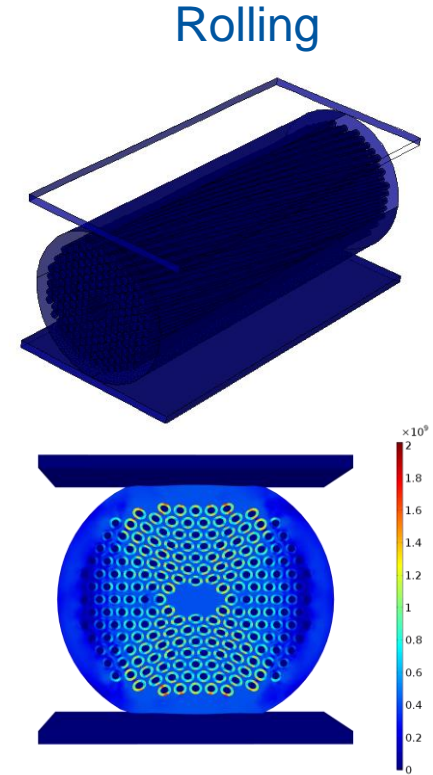




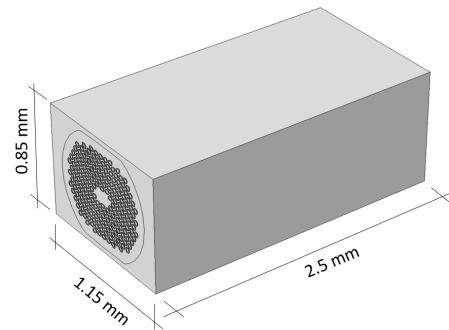
# Rolled strand: deformed configuration

- 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
- Everything is isotropic, plastic and at room temperature

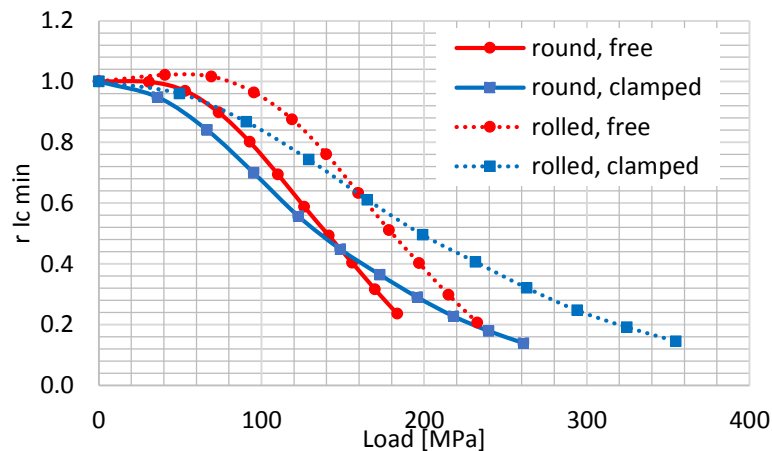
	<b>E [GPa]</b>	<b><math>\nu</math></b>	<b><math>E_y</math> [MPa]</b>
Cu	126.5	0.343	397
Nb	125.7	0.38	910.2



# Results: $I_c$ reduction in a rolled strand



- $I_c$  reduction in rolled strand is mitigated compared to round ones
- In order to present similar  $I_c$  reduction levels, rolled strands undergo  $\sim 40$ MPa of additional stress (confirmed by ongoing UniGe experiments)



# Conclusions

- We developed a **mechanical 3D model** that, coupled with a scaling law, satisfactorily simulates the behavior of a superconducting strand subject to transverse loads
- Reversible  $I_c$  reductions can be fully explained with just the strain function  $s(\epsilon)$
- **Rolling** mitigates the  $I_c$  reduction related to transverse loads thanks to stress redistribution

# Conclusions

- $I_c$  reduction is constant along the strand. The particular pair section layout/load direction does not significantly modify the  $I_c$  reduction due to transverse loads
- 3D Free ends simulations  $\neq$  2D plane stress approximation: stresses along the strand are relevant due to Cu-filaments interactions
- Boundary conditions and initial strains due to heat treatment are crucial

# Perspectives

- Detailed study of **initial strains** generated by the heat treatment
- Introduction and coupling of the **electric model** to simulate the current flow
- Modelling the case of applied **longitudinal strain**
- Study the effect of **stiffer impregnations**
- Analyze the **bundle barrier PIT and RRP strands**
- Investigate **alternative strand layouts** that mitigate transverse load effects

Thank you for your attention,  
questions?



# Results: reduction Along the Strand at ~150Mpa

- In both cases (free and continuity) reduced reduction for the rolled examples
- $r_{I_{c_{avg}}} - r_{I_{c_{min}}}$ : indirect measure of load concentration (average over the strand length)
  - Rolled simulations present smaller differences supporting our hypothesis

$r_{I_{c_{avg}}} - r_{I_{c_{min}}}$			
Round		Rolled	
Free	Continuity	Free	Continuity
25.5%	17.8%	10.3%	8.9%

