A 3D Finite Element Model of the Reversible Critical Current Reduction due to transverse load in Nb_3Sn 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_3Sn Rutherford cables

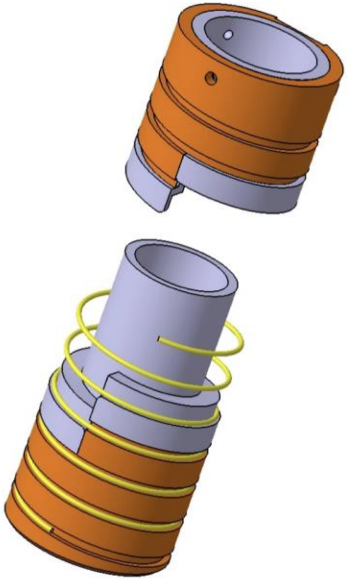
- High-field magnets experience large mechanical loads: up to 200 MPa of stresses for the FCC 16 T dipoles. This implies high strains in the superconducting strands

- Nb_3Sn superconducting properties are sensitive to strains

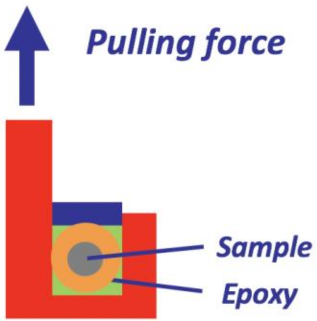
- Our aim is to create a 3D mechanical model capable of simulating, through a scaling law, the reversible I_c reduction of a strand subject to transverse loads

Modelling of The Experiment conducted at UniGe

PIT 192, 1 mm Ø,
15 mm twist pitch



4-WALL + impregnation



3 groove widths
- 1.30 mm
- 1.15 mm
- 1.00 mm

Wire impregnated with epoxy applied stress uniformly distributed

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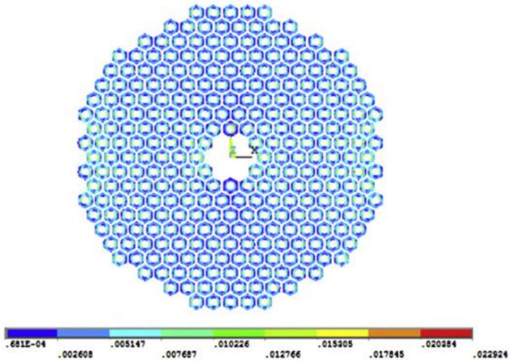
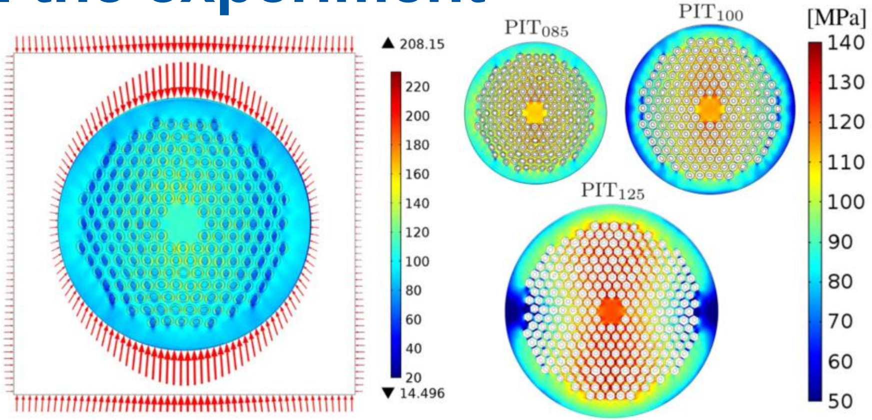
Courtesy of C. Senatore (UniGe)

C. Calzolaio *et al.*, "Electro-mechanical properties of PIT Nb3Sn wires under transverse stress: experimental results and FEM analysis," *Supercond. Sci. Technol.*, vol. 28, no. 5, pp. 1–11, 2015.

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 Nb3Sn PIT strand under transverse load based on a scaling law and Finite Element Analysis,” *Cryogenics (Guildf).*, vol. 63, pp. 275–281, 2014.



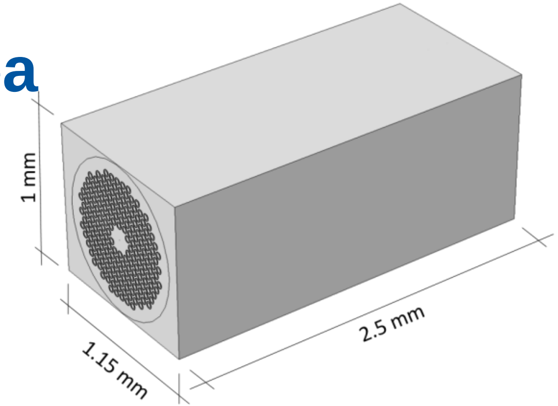
C. Calzolaio *et al.*, “Electro-mechanical properties of PIT Nb3Sn wires under transverse stress: experimental results and FEM analysis,” *Supercond. Sci. Technol.*, vol. 28, no. 5, pp. 1–11, 2015.

- 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*



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

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

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

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

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

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

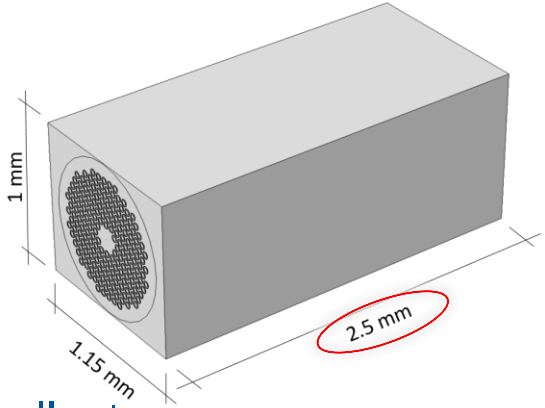
$$J_c = C_0 s(\boldsymbol{\varepsilon}) h(t) b^{0.5} (1-b)^2 B_p^{-1}$$

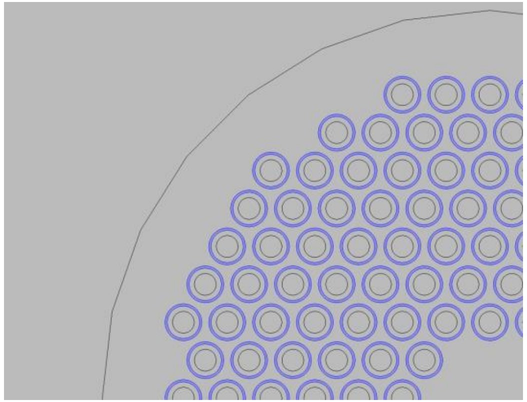
$$h(t) = (1 - t^2)(1 - t^{1.52})$$

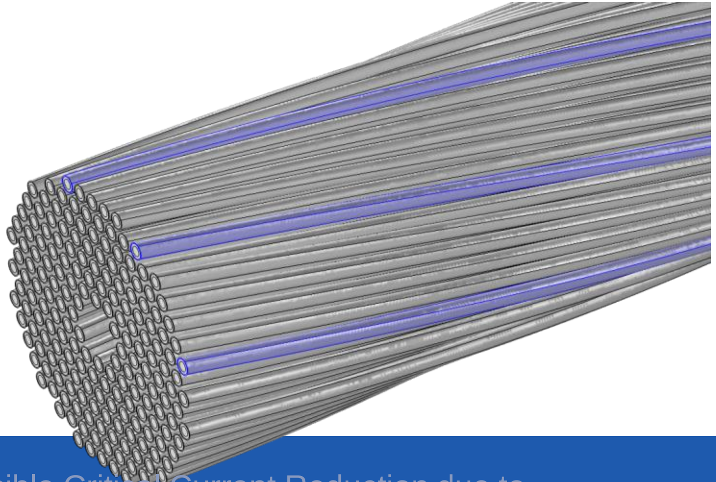
$$b = {B_p}/{B_{c2}(\boldsymbol{\varepsilon}, t)}$$

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

Model Geometry



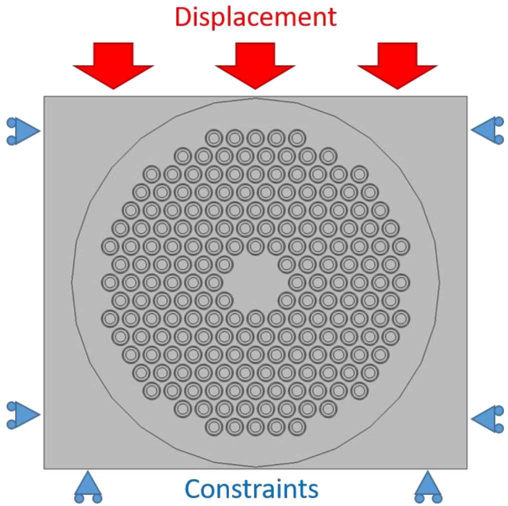




- High computational costs: smallest representative segment = 2.5 mm long
- No homogenizations: All the 192 filaments are modeled. Additionally, Nb_3Sn filaments are encased in unreacted Nb jackets (~23% of filament area)
- The strand is twisted (15 mm)

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 $\boldsymbol{u}_1 = \boldsymbol{u}_2$

Continuity

- 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:

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

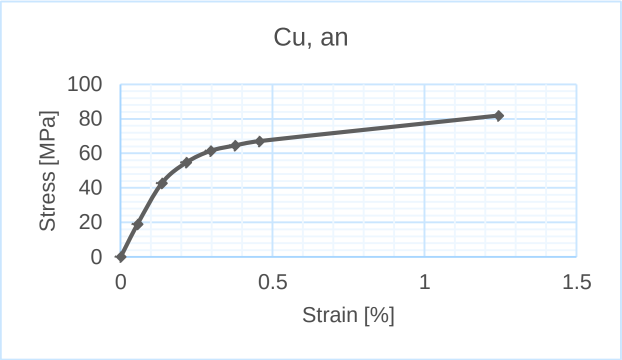
Free to elongate

Boundary conditions: free to elongate longitudinally

- $\boldsymbol{u}_1 - \boldsymbol{u}_2 = [q \quad 0 \quad 0]'$ is, so far, extremely slow to converge
- However, the solution differs from the free-ends result (where we impose only $\boldsymbol{F}_1 = \boldsymbol{F}_2 = \boldsymbol{M}_1 = \boldsymbol{M}_2 = 0$ 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]	v	E_y [MPa]
Cu, an	Isotropic, plastic	118.8	0.343	46.2
Nb_3Sn	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_3Sn filaments*

$$\begin{cases} \epsilon_{c\,l} = -0.0018 \\ \epsilon_{c\,t} = -\upsilon\epsilon_{c\,l} \end{cases}$$

*B. Bordini, P. Alknes, L. Bottura, L. Rossi, and D. Valentinis, “An exponential scaling law for the strain dependence of the Nb3Sn 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

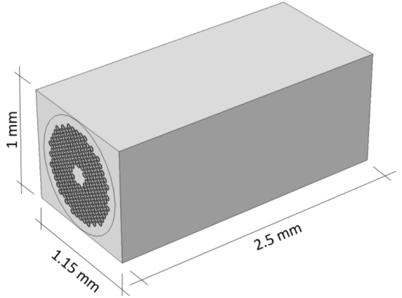
- Conservative hypothesis: no redistribution of the current. I_c is dictated by the most strained filament
- Boundary conditions are crucial
- Above ~120MPa, cracks appear in the Nb3Sn phase: simulations are no more representative
- I_c reduction is very sensitive to initial strains. Further studies are foreseen

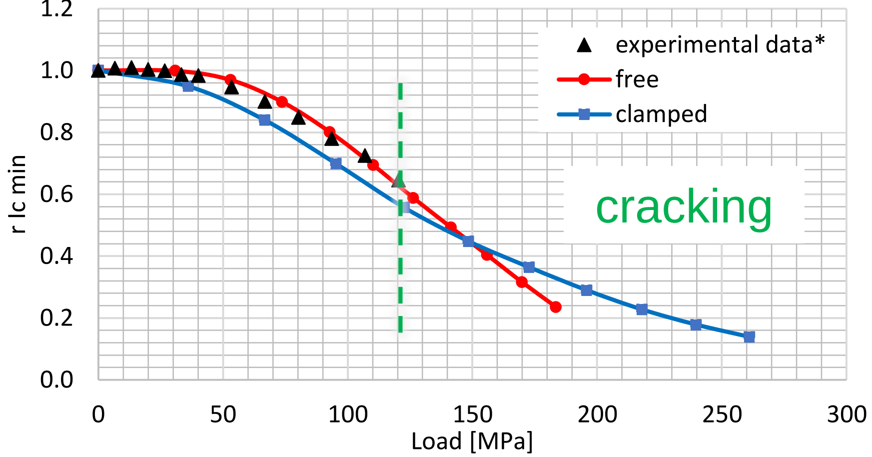
$$r_{I_{c_{min}}} = \frac{I_{c_{min}}(\boldsymbol{\varepsilon})}{I_{c_0}} = \min_{f_i}\left(\int_{A_{f_i}} J_c(\boldsymbol{\varepsilon})\, dA_{f_i}\right)$$

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

$$A = 1.15 * 2.5 = 2.875\ mm^2$$

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





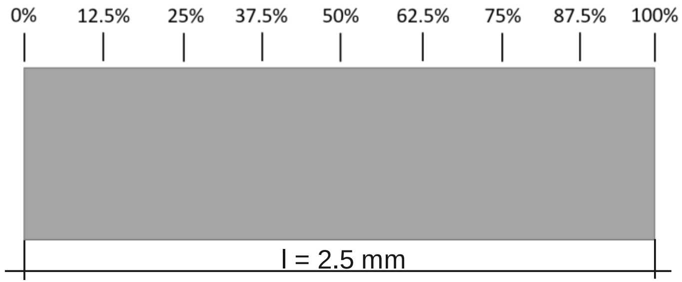
*C. Calzolaio *et al.*, "Electro-mechanical properties of PIT Nb3Sn wires under transverse stress: experimental results and FEM analysis," *Supercond. Sci. Technol.*, vol. 28, no. 5, pp. 1–11, 2015.

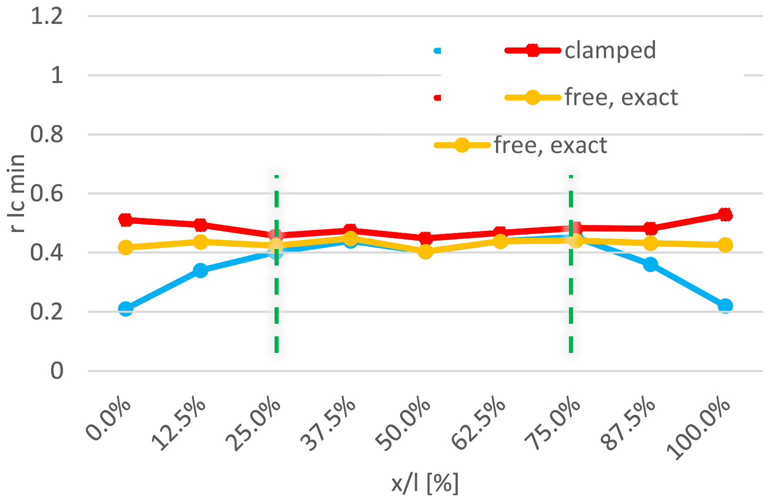
Results: reduction Along the Strand at ~150 MPa

- I_c reduction is constant along the strand: the particular pair section layout, load direction does not significantly change results

- However, free ends ≠ plane stress. Stresses between Cu and Nb_3Sn are relevant along the whole strand

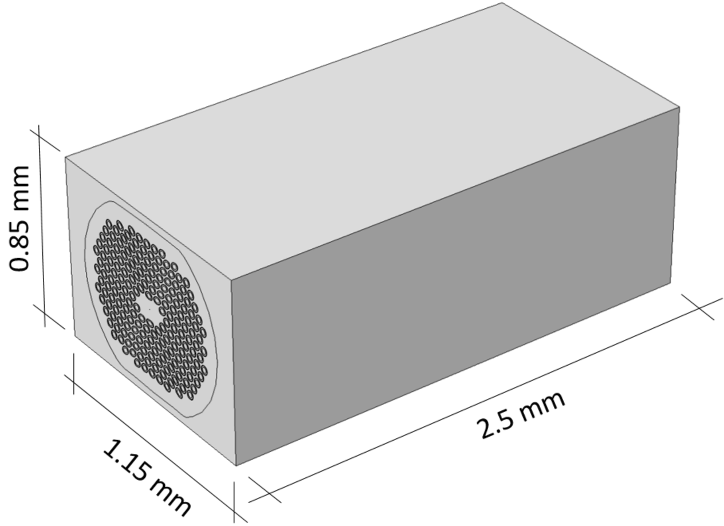
- Approximated and exact solutions differ only near strand ends (~25% x/l). This, in conjunction with the fact that I_c reductions are constant along the strand, demonstrates that the study of the free-ends case is, indeed, sufficient





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

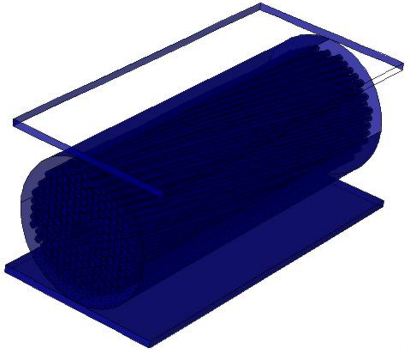


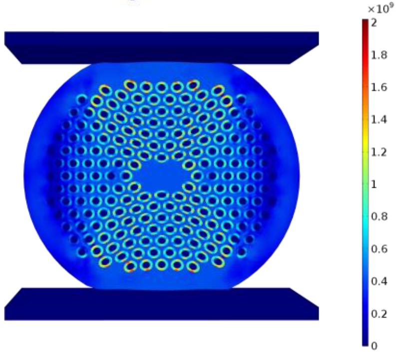
Rolled strand: deformed configuration

- 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

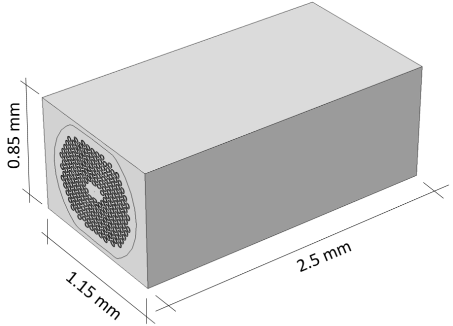
	E [GPa]	v	E_y [MPa]
Cu	126.5	0.343	397
Nb	125.7	0.38	910.2

Rolling

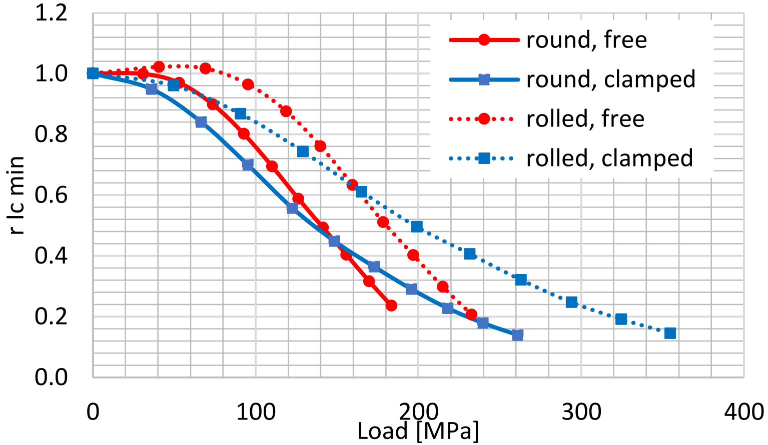




Results: I_c reduction in a rolled strand



- I_c reduction in rolled strand is mitigated compared to round ones
- In order to present similar I_c reduction levels, rolled strands undergo ~40MPa 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 $s(\boldsymbol{\varepsilon})$
- 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%