Influence of design parameters on the electromechanical properties of high performance Nb_3Sn wires under mechanical loads

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Outline

- *Superconductivity for HEP applications at UNIGE*
- *Electromechanical properties of SC wires under transverse loads*
- *Experimental results and Finite Element analysis on high performance Nb_3Sn wires*
- *Failure mechanism: applied stress versus local stress on Nb_3Sn*
- *Conclusions and perspectives*

Superconductors for HEP magnets

Activities @ UNIGE

http://supra.unige.ch

Superconducting wires in view of accelerator magnets above 10 T

12 T-quadrupoles and 11 T-dipoles for HL-LHC

Collaboration agreement CERN UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES

Towards 20 T HTS-based dipoles

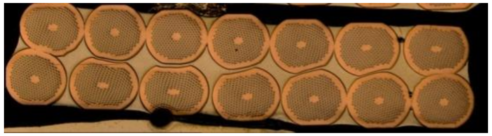
EuCARD² *funded by* 7 CAPACITIES *coordinated by* CERN

Towards 16 T Nb_3Sn-based dipoles

EuroCirCol *funded by* HORIZON 2020 *coordinated by* CERN

Motivation

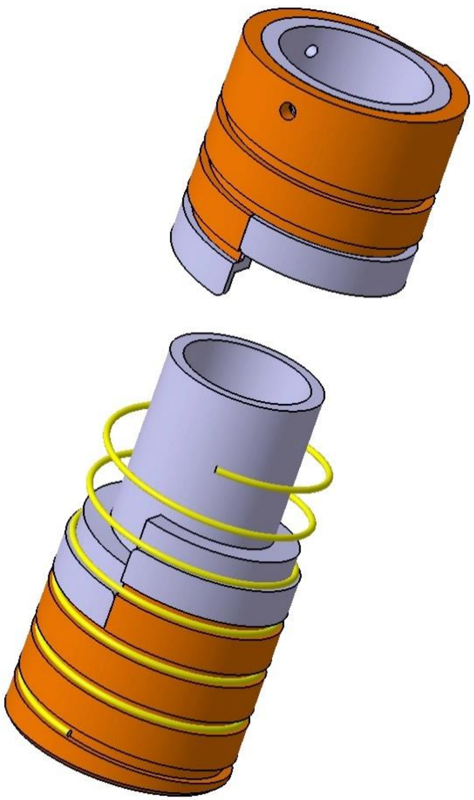
- *Next generation accelerator magnets based on high J_c Nb_3Sn Rutherford cables*
- *Wires in cables exposed to large axial and transverse loads, it will require coil pre-stresses larger than 100 MPa*
- *Electromechanical tests on full size cables are complex and expensive*



Short Model Coil dipole cable
14 wires (Ø 1.25 mm)

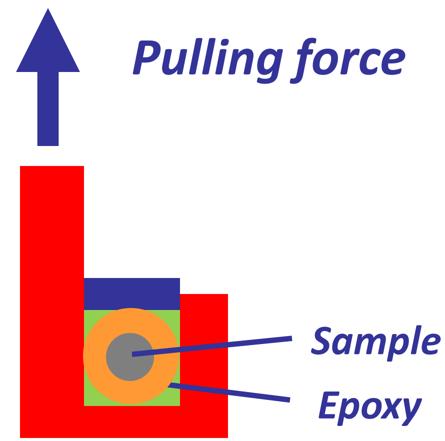
Fresca2 dipole cable
40 wires (Ø 1.0 mm)

The WASP concept : I_c vs. transverse stress



2 groove widths: 1.30 mm / 1.15 mm

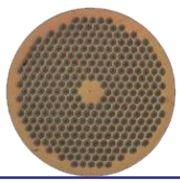
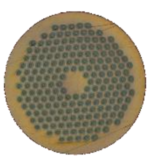
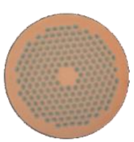
4-WALL + impregnation



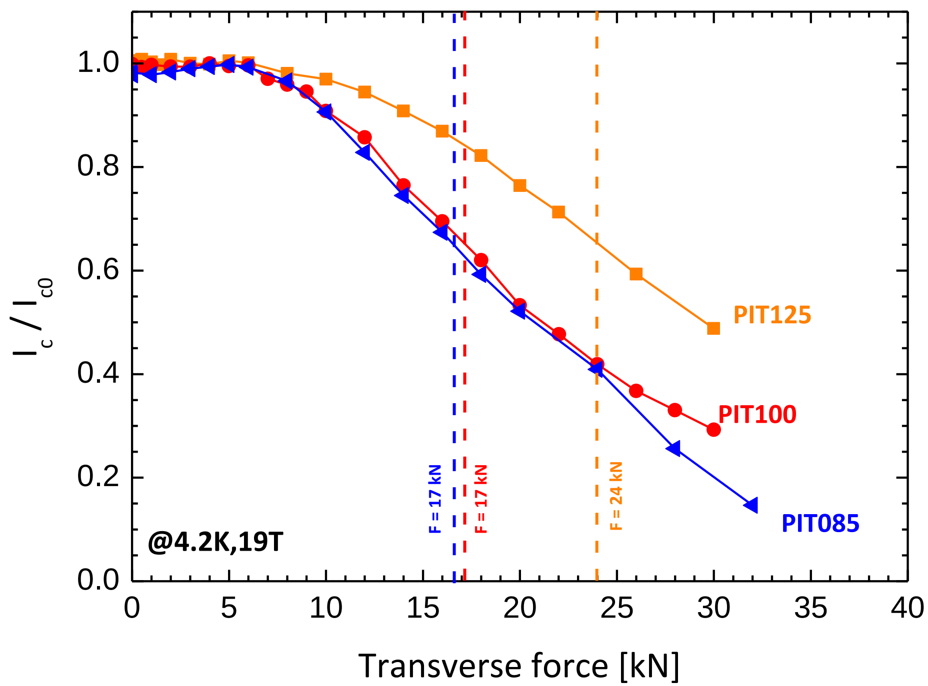
Wire impregnated
with epoxy
applied stress
uniformly distributed

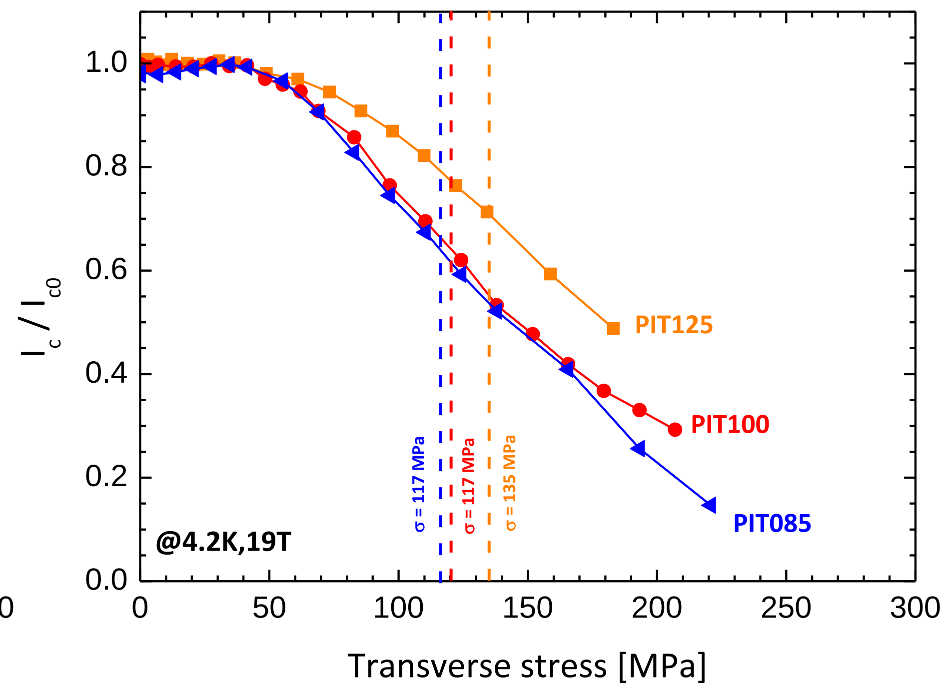
PIT Nb_3Sn wires from BRUKER

Bruker EST

	Wire ID	Diameter [mm]	# of filaments	Filament size/shape	Cu/nonCu	Non-Cu J_c(12T,4.2K) [A/mm²]
	#10401 short model coil	1.25	288	~50 µm hexagonal	1.22	2700
	#0904 Fresca2	1.0	192	~50 µm round	1.22	2450
	#29992 high-lumi quads	0.85	192	~40 µm round	1.22	2450

I_c vs. transverse force and vs. transverse stress

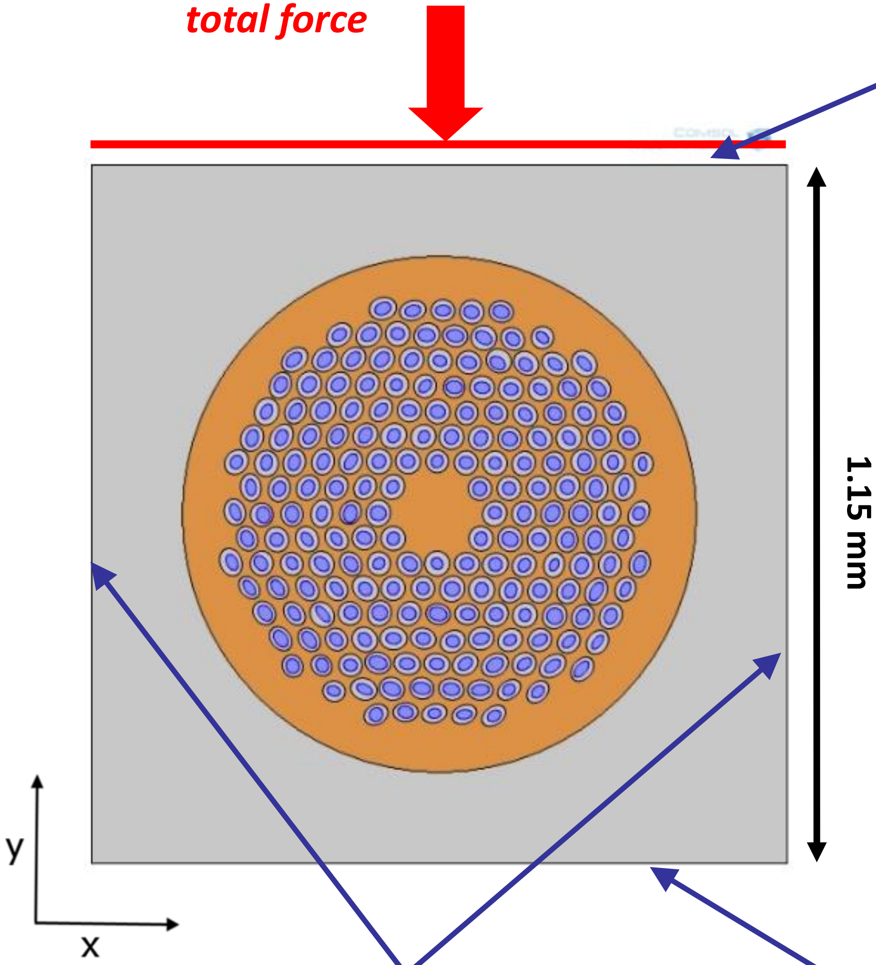




	F_{irr}	σ_{irr}
PIT125	24 kN	135 MPa
PIT100	17 kN	117 MPa
PIT085	17 kN	117 MPa

$$Stress = \frac{Force}{groove\ length \times groove\ width}$$

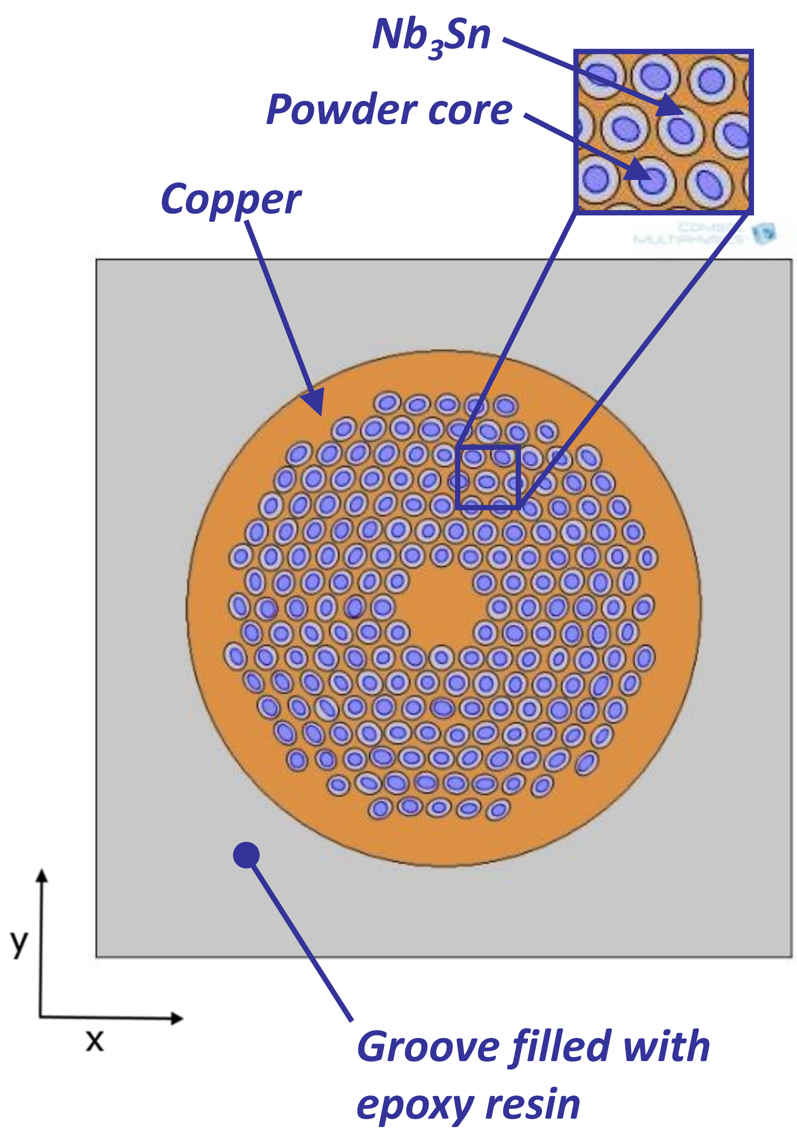
Finite Element Modeling



The response to stress of each wire has been modeled via FEM analysis in a 2D approximation (plane strain)

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{pmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & 0.5-\nu \end{pmatrix} \begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix}$$

Finite Element Modeling : Materials



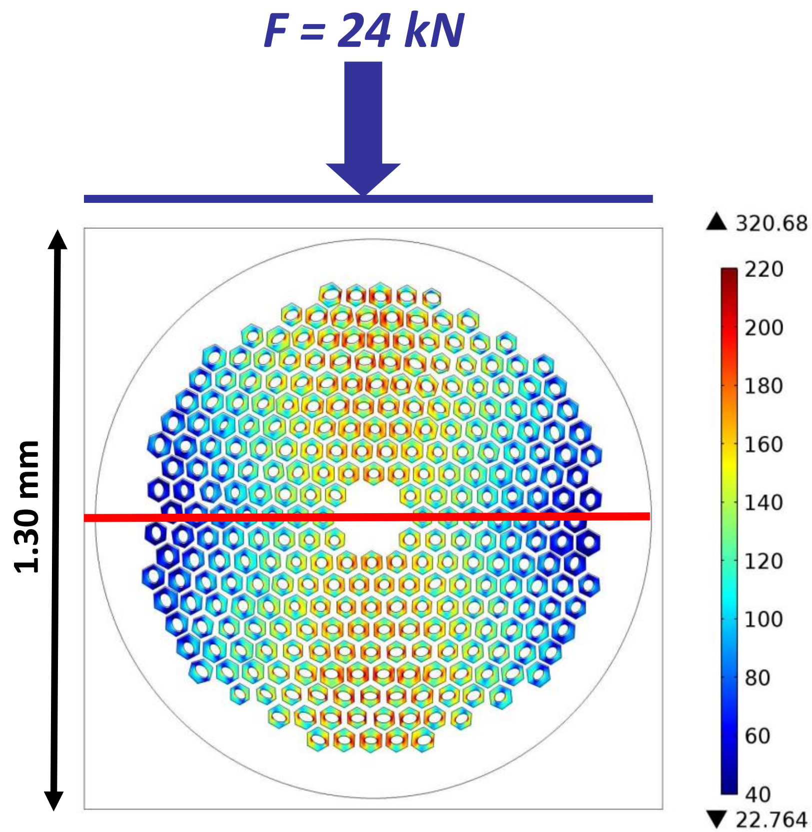
Material	E [GPa]	ν
Nb_3Sn	80	0.36
Powder core	40	0.3
Epoxy	8	0.3

Compression !!

The Young modulus of copper has been considered as a function dependent on strain, on the basis of the experimental $\sigma(\varepsilon)$

$$\left(\frac{d\sigma}{d\varepsilon}\right)_{wire} = V_{Nb_3Sn} E_{Nb_3Sn} + V_{Cu}\left(\frac{d\sigma}{d\varepsilon}\right)_{Cu}$$

von Mises stress in Nb_3Sn at the irreversibility



PIT125

Force on the equatorial plane of the wire

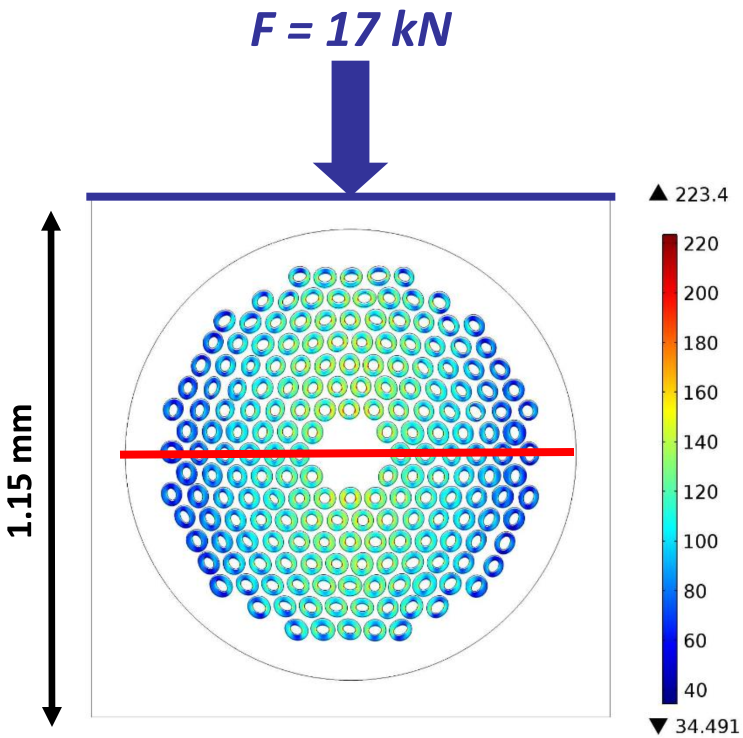
$$\int_{l} \sigma_{Mises} dx = 101700 \text{ N/m}$$

(98% of F)

Average von Mises stress in Nb_3Sn

$$\frac{1}{S_{Nb_3Sn}} \iint_{S_{Nb_3Sn}} \sigma_{Mises} dS = 118 \text{ MPa}$$

von Mises stress in Nb_3Sn at the irreversibility

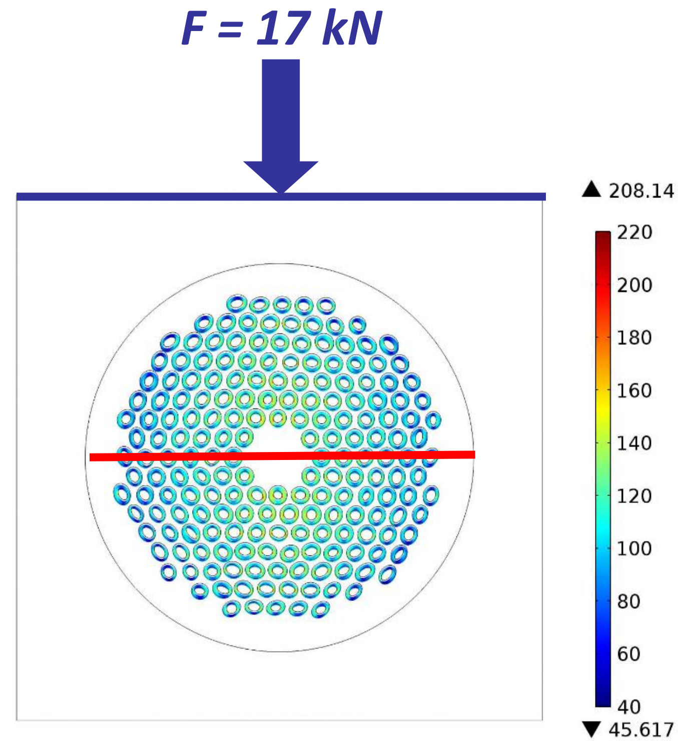


PIT100

$$\int_l \sigma_{Mises} dx = 82820\, N/m$$

(97.1% of F)

$$\frac{1}{S_{Nb_3Sn}} \iint_{S_{Nb_3Sn}} \sigma_{Mises} dS = 102\, MPa$$



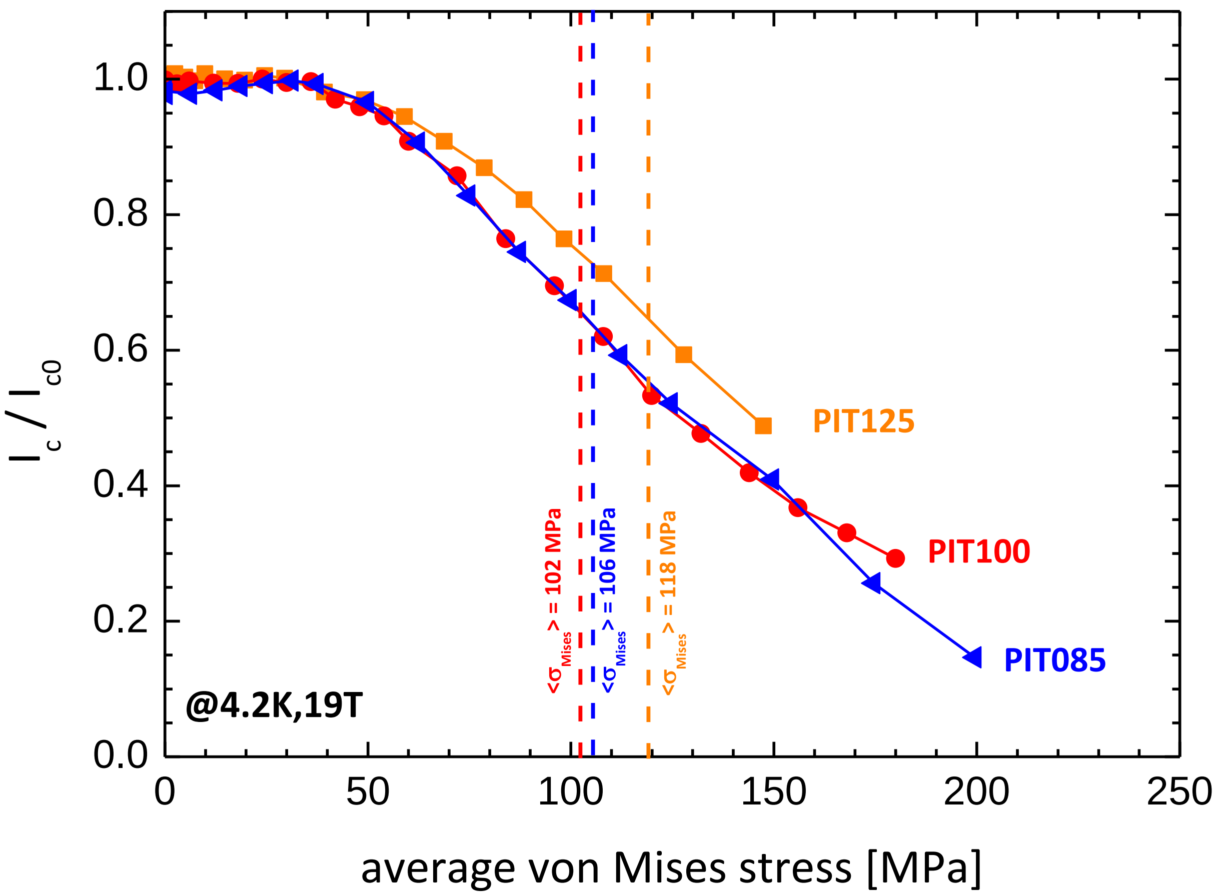
PIT085

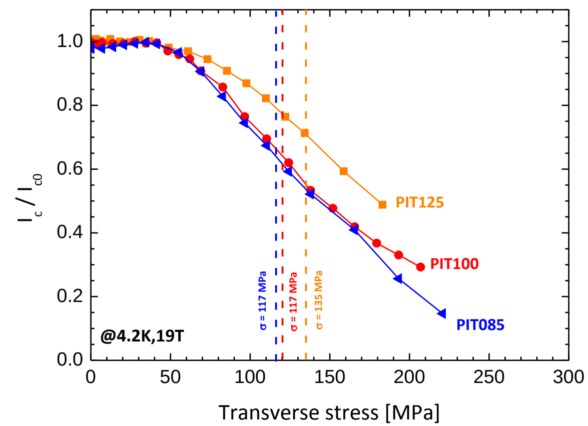
$$\int_l \sigma_{Mises} dx = 76790\, N/m$$

(93.1% of F)

$$\frac{1}{S_{Nb_3Sn}} \iint_{S_{Nb_3Sn}} \sigma_{Mises} dS = 105\, MPa$$

I_c vs. stress : stress values corrected according to the FEM analysis



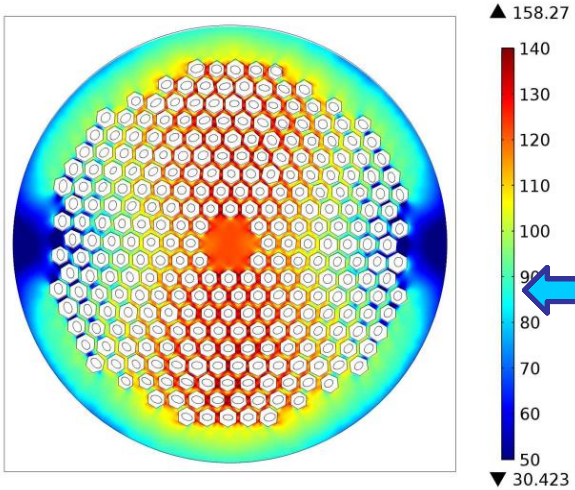


Normalized I_c vs. the average von Mises in the Nb_3Sn filaments

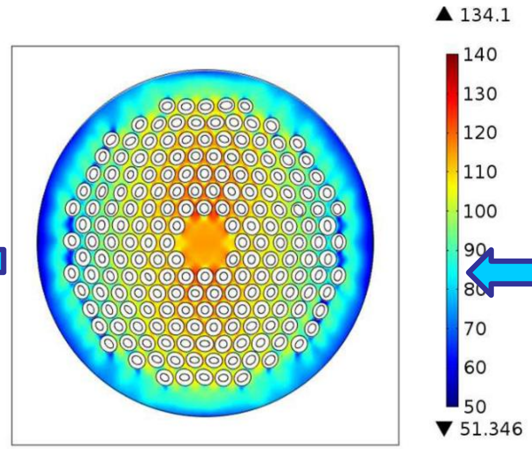
Irreversible degradation phenomena

Two irreversible phenomena play together

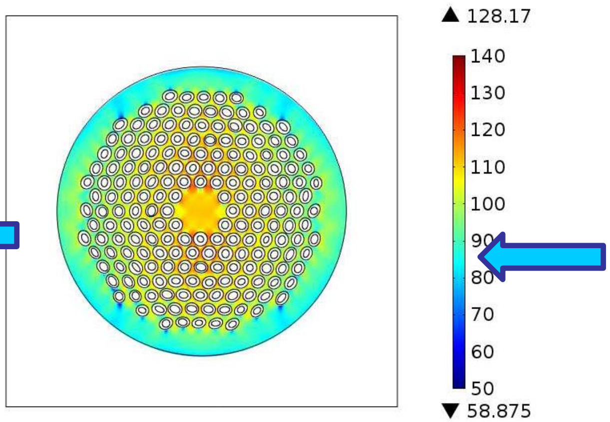
- ***Crack formation in Nb_3Sn***
- ***Plastic deformation of the Cu matrix***



PIT125 @ 24 kN



PIT100 @ 17 kN



PIT085 @ 17 kN

Yield strength of Cu $\sigma_y = 86$ MPa

What is the residual stress on Cu after unload ?

$$\sigma_{res}^{Cu} = \max(\sigma_{Mises}^{Cu} - \sigma_y , 0)$$

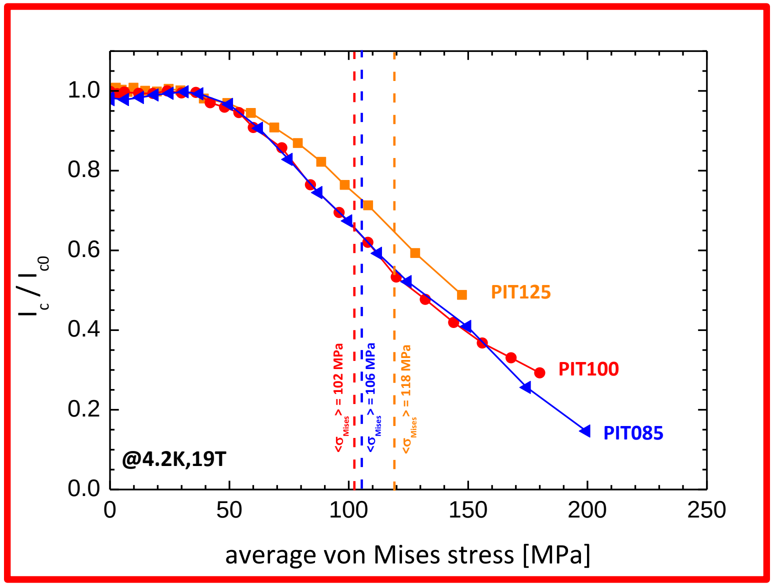
Irreversible degradation phenomena (2)

What is the residual stress on Cu after unload ?

$$\sigma_{res}^{Cu} = max(\sigma_{Mises}^{Cu} - \sigma_y , 0)$$

Plastic deformation of Cu leaves Nb_3Sn under stress after force unload

Using σ_{res}^{Cu} as an input, the code determines the residual stress on Nb_3Sn σ_{res}^{Nb3Sn}

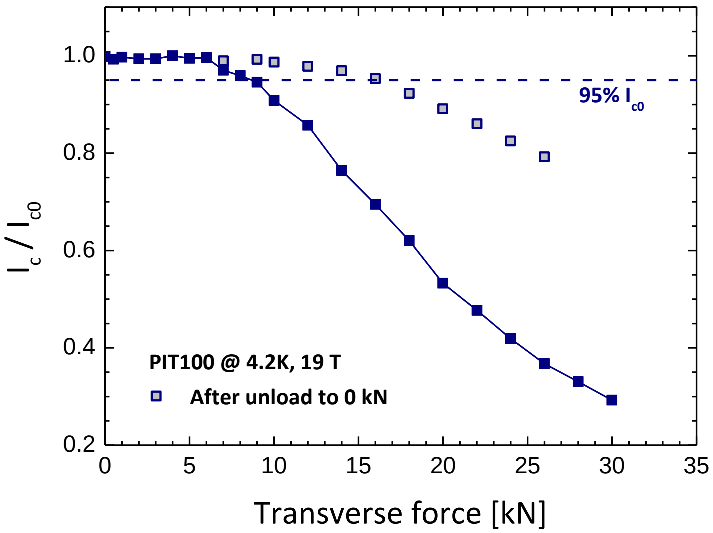


Then the irreversible degradation of I_c is easily determined

$$\Rightarrow \quad \frac{\Delta I_{c-plastic}^{irr}}{I_{c0}}$$

Irreversible degradation phenomena (3)

How to estimate the role of cracks ?



1. $\dfrac{\Delta I^{irr}_{c-total}}{I_{c0}}$ is directly measured for a given force

2. $\dfrac{\Delta I^{irr}_{c-plastic}}{I_{c0}}$ is calculated using FEM

3. $\dfrac{\Delta I^{irr}_{c-crack}}{I_{c0}} = \dfrac{\Delta I^{irr}_{c-total}}{I_{c0}} - \dfrac{\Delta I^{irr}_{c-plastic}}{I_{c0}}$

Assumption: $\dfrac{\Delta I^{irr}_{c-crack}}{I_{c0}}$ represents also the percentage reduction of Nb_3Sn area due to cracks

FEM allows us to estimate the uniaxial compressive strength of Nb_3Sn filaments

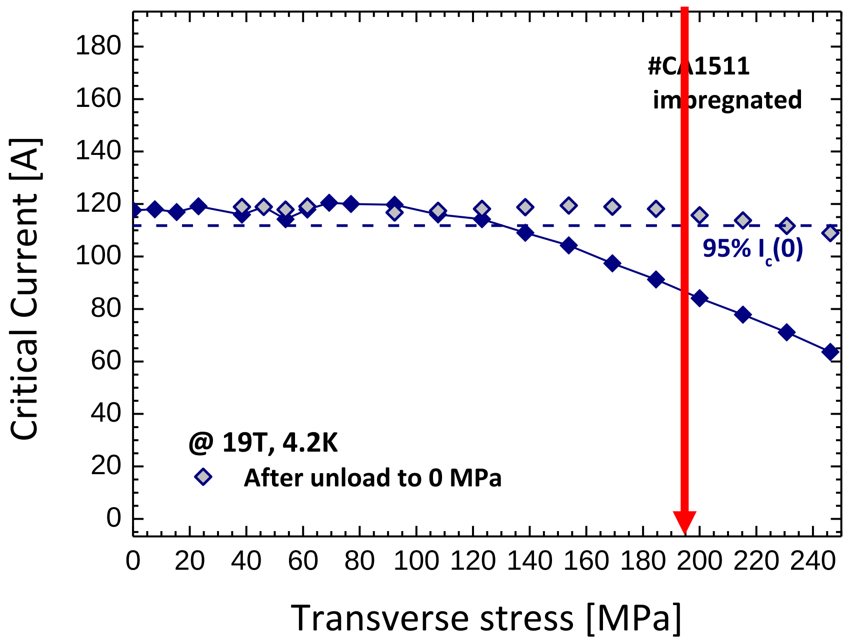
	PIT125	PIT100	PIT085
σ_c [MPa]	$275 \pm 5\%$	$265 \pm 5\%$	$278 \pm 5\%$

RRP Nb_3Sn wires from OXFORD INSTRUMENTS

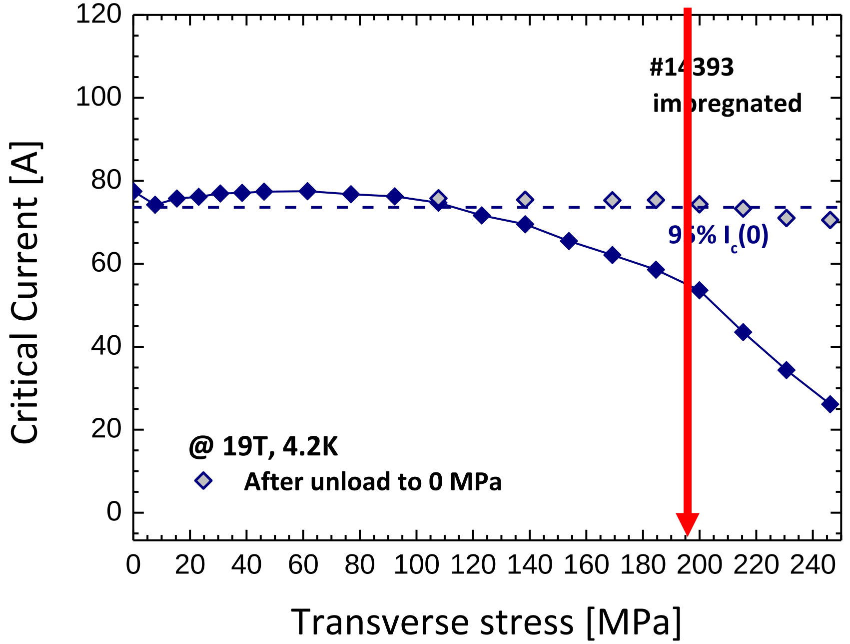
	Wire ID	Diameter [mm]	# of subelements	Subelement size	Cu/nonCu	Non-Cu J_c(12T,4.2K) [A/mm^2]
	#CA1511 Fresca2	1.0	132/169	~60 µm	1.28	~2800
	#14393 high-lumi quads	0.85	132/169	~50 µm	1.28	n/a

$$Stress = \frac{Force}{groove\ length \times groove\ width}$$

RRP : I_c vs. transverse stress



RRP100



RRP085

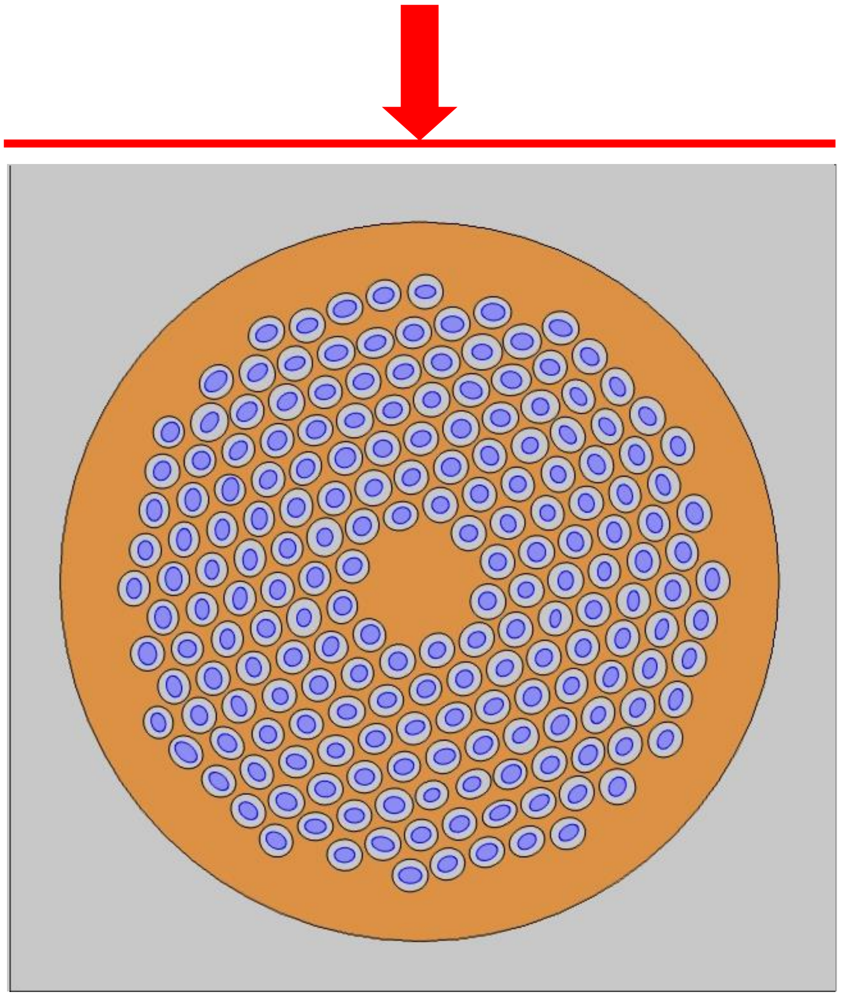
Irreversible stress limit above 180 MPa !!

Conclusions

Conclusions & future activities

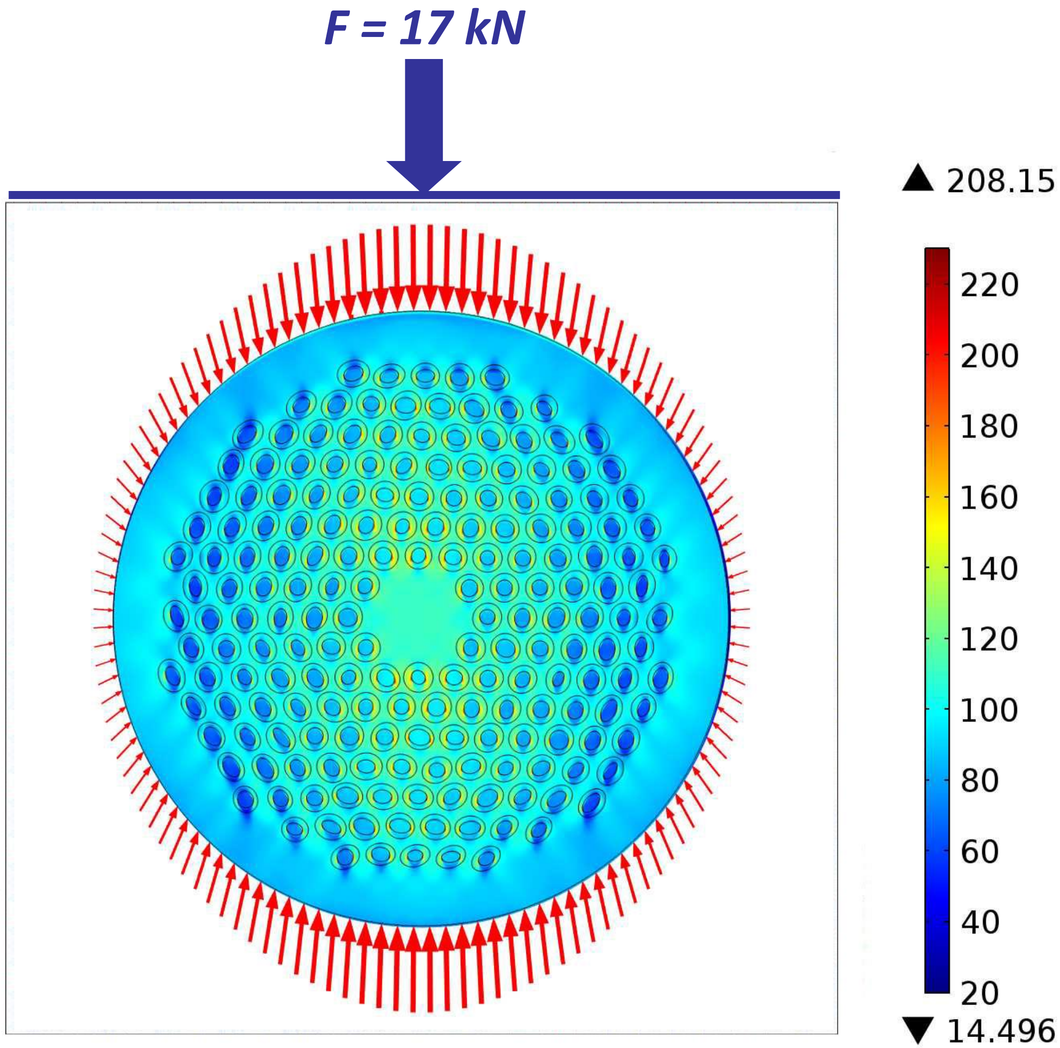
- Developed a setup for testing the electromechanical properties of SC wires at conditions "close to" the operation in a Rutherford cable
- Consolidated a FE model for the analysis of the results
- New experiments on RRP wires: effects of the subelement number (108/127 vs. 132/169) and of the alloying element (Ti vs. Ta)
- Is the FE model predictive ? Study of PIT wires with different layout, analysis of the experiments on RRP wires
- Try to include in the FE model the microstructure of the superconducting filaments / subelements (as obtained from synchrotron microtomography)
- New experiments on Bi2212 wires (ongoing collaboration with FSU)

Finite Element Modeling : Twist pitch effect



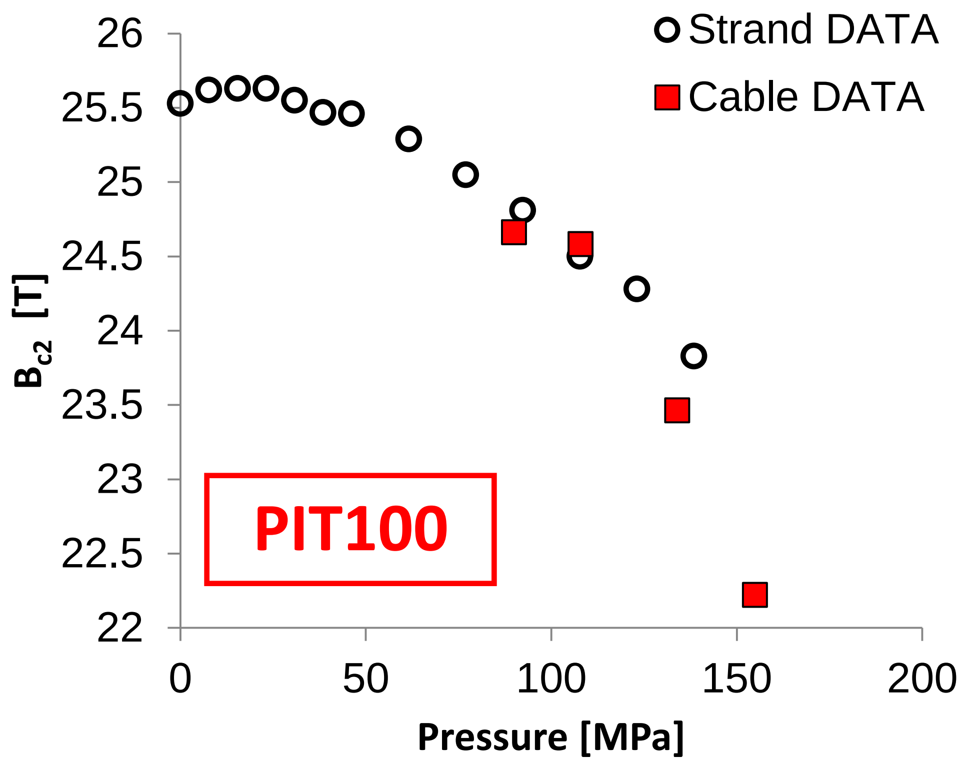
The effect of the twist pitch has been simulated changing the wire angular position in the groove

Force distribution around the wire



PIT085

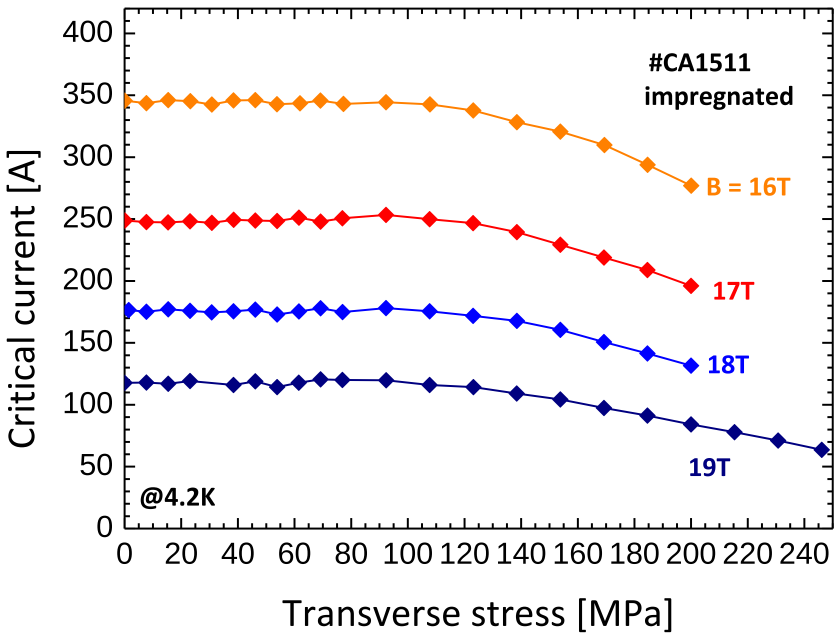
Wire vs. cable

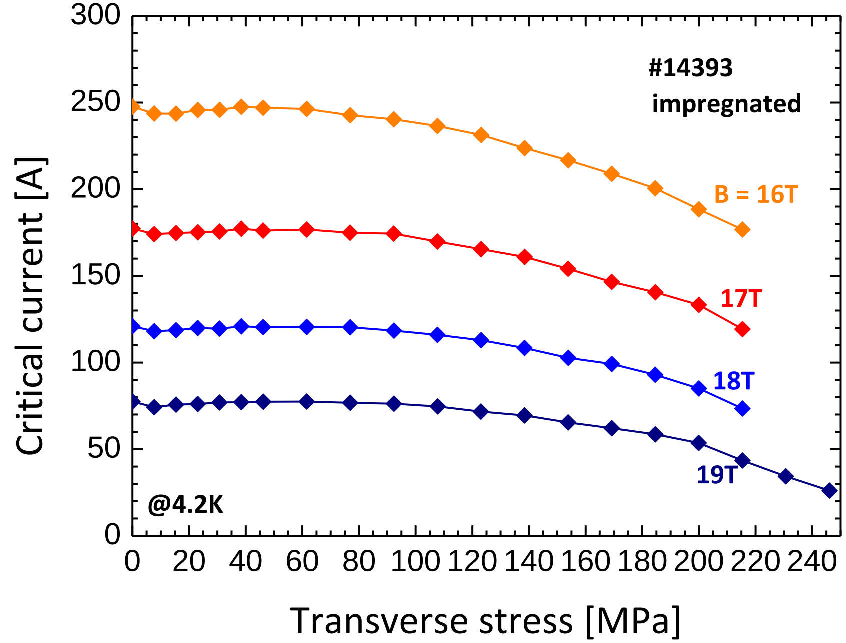


Upper critical field at 4.2 K estimated from the critical current measurements under transverse stress, performed on the wire @ UNIGE and on the cable @ CERN

Bordini et al., TAS 24 (2014) 9501005

I_c vs. transverse stress : field dependence





RRP100

RRP085