Electro-mechanical Performance of Nb_3Sn Rutherford Cables

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Outline

- Introduction
  - ➢ Scaling Laws for state of the art Nb_3Sn wire in the case of applied axial strain
- Measurements of I_c vs. Transverse Load
  - ➢ Test at CERN and Twente University of a PIT Rutherford cable
    1. Can we use the scaling laws derived for applied axial strain to describe the results (in the reversible region)?
  - ➢ Test at Geneva University of the same PIT wire used in the measured cables
  - ➢ Test at CERN and Twente University of a RRP Rutherford cable
    1. Is the RRP less sensitive to transverse load?
- Modeling I_c vs. Transverse Load
- Conclusions

Introduction

Scaling Laws for state of the art (HL-LHC) Nb_3Sn wire 1/2

- Superconducting performance of Nb_3Sn are strongly dependent on the superconductor strain state
- In the case of applied axial strain:

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

Where $B_{c20} = B_{c2}(0,0)$, ε is the strain tensor, $t = \frac{T}{T_c(\varepsilon)}$

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

Where $T_{c0} = T_c(0)$

$$J_c(B,T,\varepsilon) = C_0\,\frac{B_{c20}}{B}\,(s(\varepsilon))^{\sigma}\,[(1 - t^{1.52})(1 - t^{2})]^{\alpha}\, b^{0.5}(1-b)^2$$

Where: $b = \frac{B}{B_{c2}(\varepsilon)}$; σ and α are parameters very close to 1 and; C_0 is a constant

Introduction

Scaling Laws for state of the art (HL-LHC) Nb_3Sn wire 2/2

$$J_c(B, T, \varepsilon)=C_0 \frac{B_{c20}}{B}(s(\varepsilon))^{\sigma}\,[(1-t^{1.52})(1-t^{2})]^{\alpha}\, b^{0.5}(1\text{-}b)^2$$

- Let's simplify by **assuming** that σ and α are equal to 1 and $s(\varepsilon)^{1/3}$ ~ constant; for a certain temperature we can write

$$J_c(B, \varepsilon)=C \frac{B_{c2}}{B}\, b^{0.5}(1\text{-}b)^2$$

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

Where C is a constant

- The dependence of the J_c on the strain is mainly due to the variation of the B_{c2}
  - At 1.9 K, assuming a B_{c2} equal to 28 T, a reduction of the B_{c2} by 10 % would produce a reduction of the J_c approximately equal to:

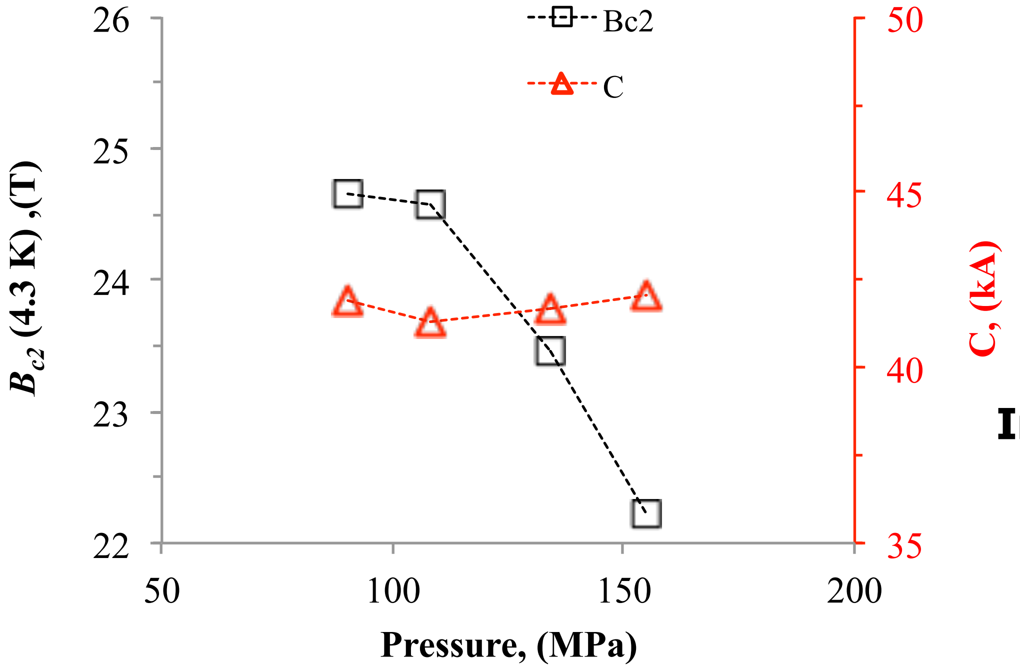
1. **20 %** at **12 T**
2. **31 %** at **16 T**
3. **44 %** at **19 T**

This scaling laws and results are well proved in the case of a wire pulled longitudinally; what about the case of a transverse load?

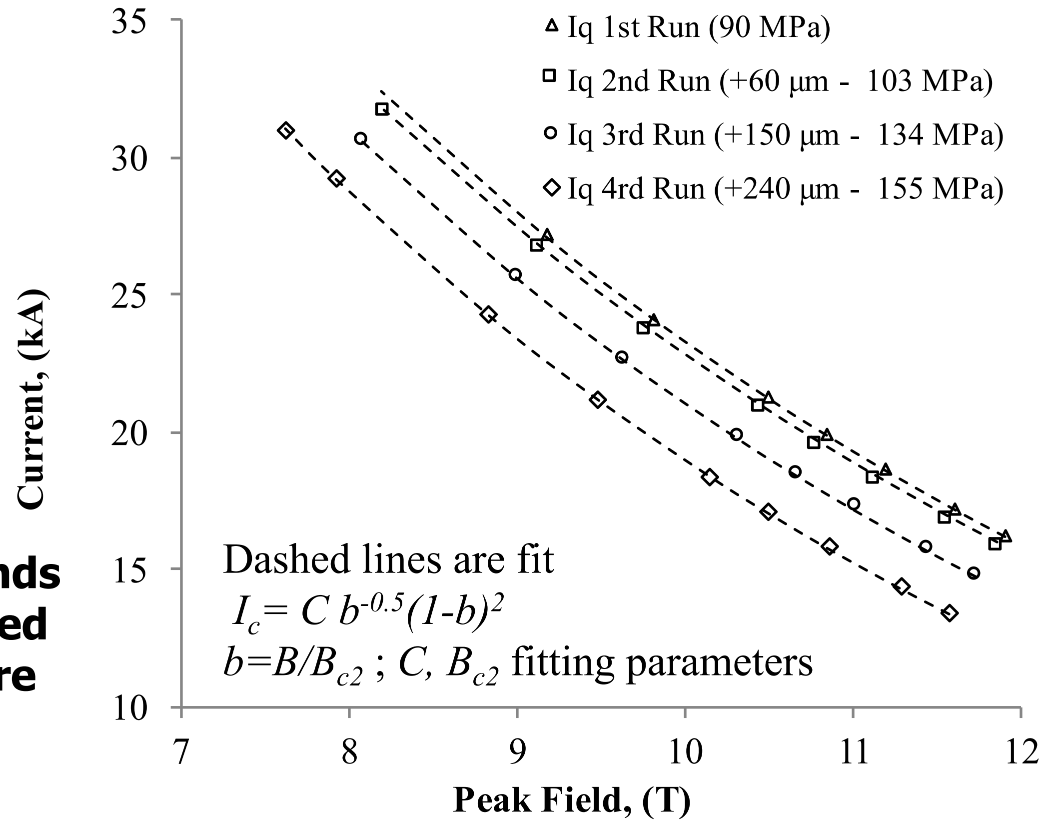
Cable I_c vs. Transverse Load

Test* at CERN on a PIT cable in 2013

What about the case of a transverse load?



Impregnated 18 strands Rutherford cable based on 1 mm 192 PIT wire



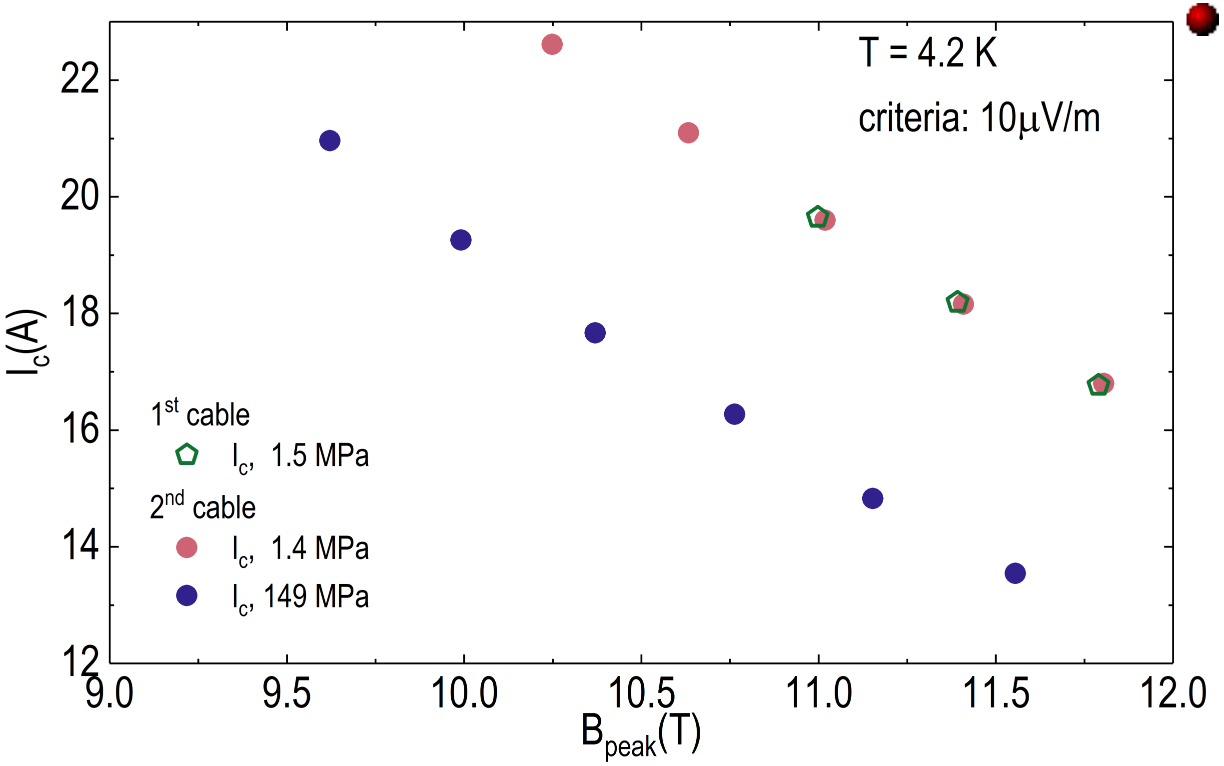
- The scaling law seems to work also in the case of transverse loads
- The variation of the B_{c2} is significant about 10% from 80 MPa and 155 MPa

* B. Bordini, P. Alknes, A. Ballarino, L. Bottura, L. Oberli *IEEE Trans. Appl. Supercond.*, VOL. 24, NO. 3, JUNE 2014

Cable I_c vs. Transverse Load

Test at Twente of a PIT cable in 2018 1/2

Are the results confirmed in a different set up?



- Twente University measured under transverse pressure the same PIT cable tested by CERN

Plot Courtesy of Marc Dhalle and Peng Gao

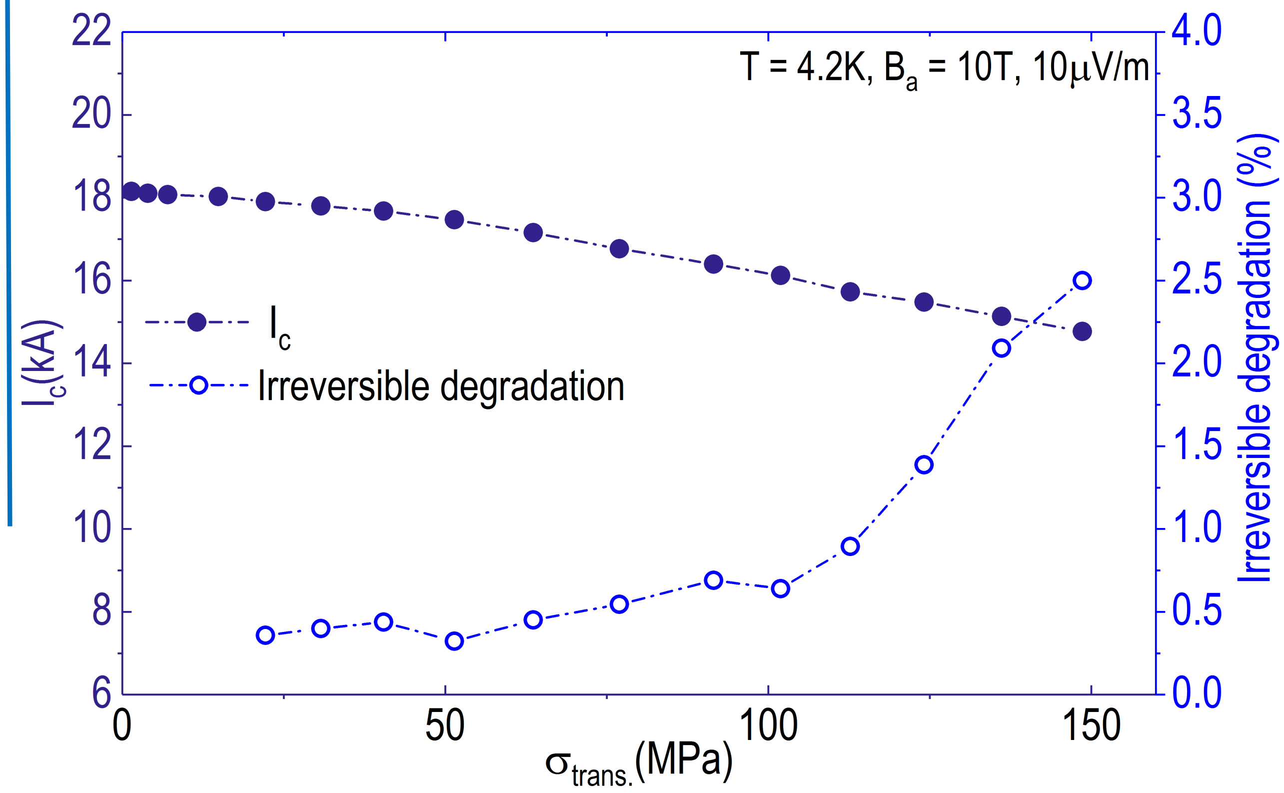
Data to be published at ASC 2018

At **150 MPa** the reduction of B_{c2} is larger than **10%** and at **11.6 T** the **critical current** is decreased by **24 %**, in line with what observed by CERN

- The measurement confirmed that up to 150 MPa, the reduction of the critical current is mainly reversible and it is dominated by the reduction of the upper critical field.

Cable I_c vs. Transverse Load

Test at Twente of a PIT cable in 2018 2/2



- Irreversible I_c degradation starts around 120 MPa however up to 150 MPa is still limited at 11.6 T peak field (10 T applied field)
- Cycling four times (at 4.2 K) the load between 150 MPa and 1.5 MPa did not further degrade irreversibly the critical current

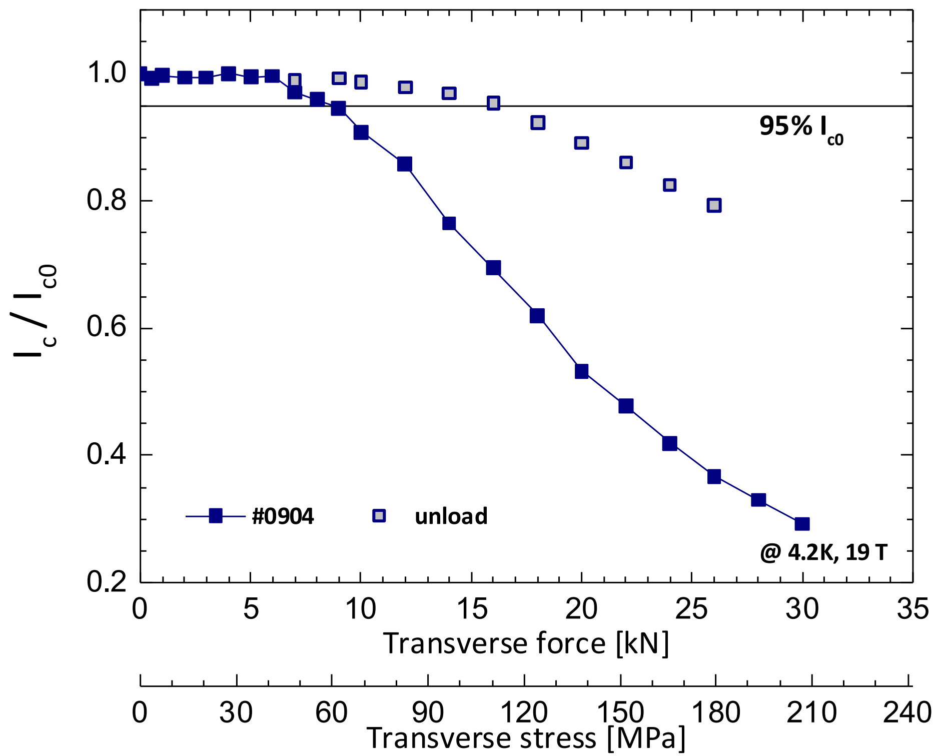
Plot Courtesy of Marc Dhalle and Peng Gao

Data to be published at ASC 2018

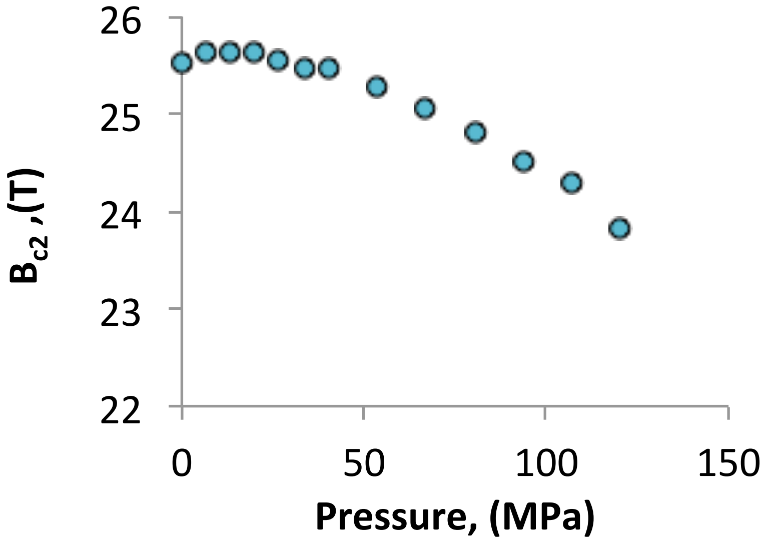
Wire I_c vs. Transversal Load

Test at UniGe on a PIT Wire (2012)

- Measurements on an impregnated 1 mm 192 PIT wire carried out at the University of Geneva showed a similar behavior*
  - reduction of the critical current in the reversible region mainly due to the reduction of the upper critical field



- Round wires degrades irreversibly significantly earlier than Rutherford cables



Data Courtesy of Carmine Senatore

*C Calzolaio et al 2015 Supercond. Sci. Technol. 28 055014

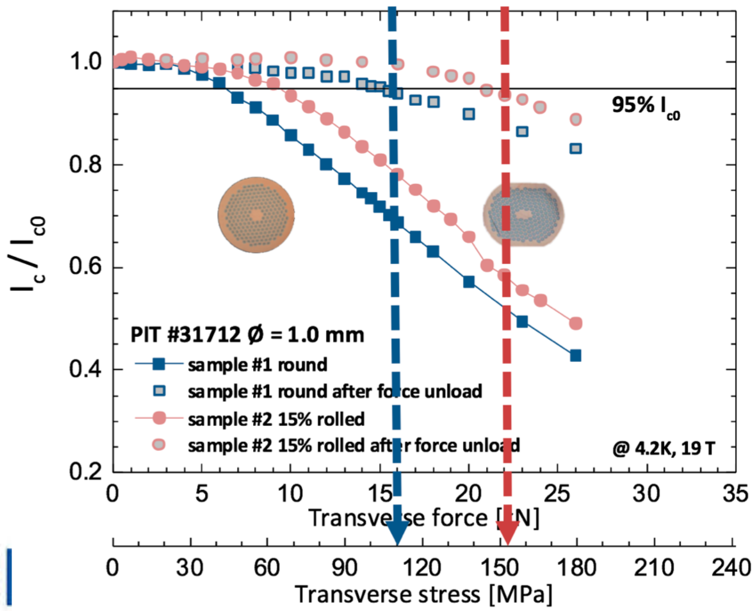
Wire I_c vs. Transversal Load

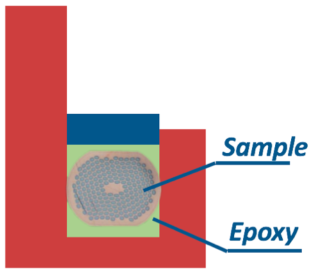
Test at UniGe on a PIT Wire Round vs Rolled (2017)

- The University of Geneva measured two adjacent pieces of 1 mm 192 PIT wire: one piece was kept round and the other was 15 % rolled (reduction of height)

- 15 % Rolled wires had an irreversible degradation at larger transverse loads
  - ➢ Onset around 110-120 MPa
  - ➢ 5 % permanent degradation (at 19 T) around 150 MPa
  - ➢ These values are similar to what observed in cable measurements at Twente

I_c vs. transverse stress on 15% rolled wires





F_{irr} = 22 kN

σ_{irr} = 150 MPa

Normalized I_c
Round vs. 15% rolled
Shift of σ_{irr} by ~ 40 MPa

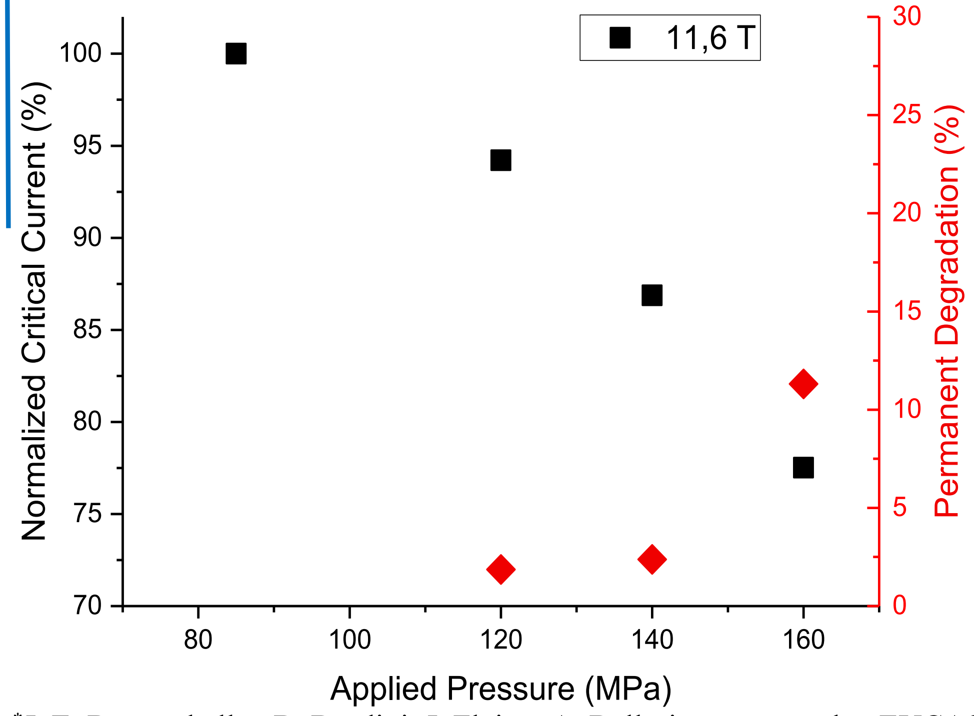
Data and Plot Courtesy of Carmine Senatore

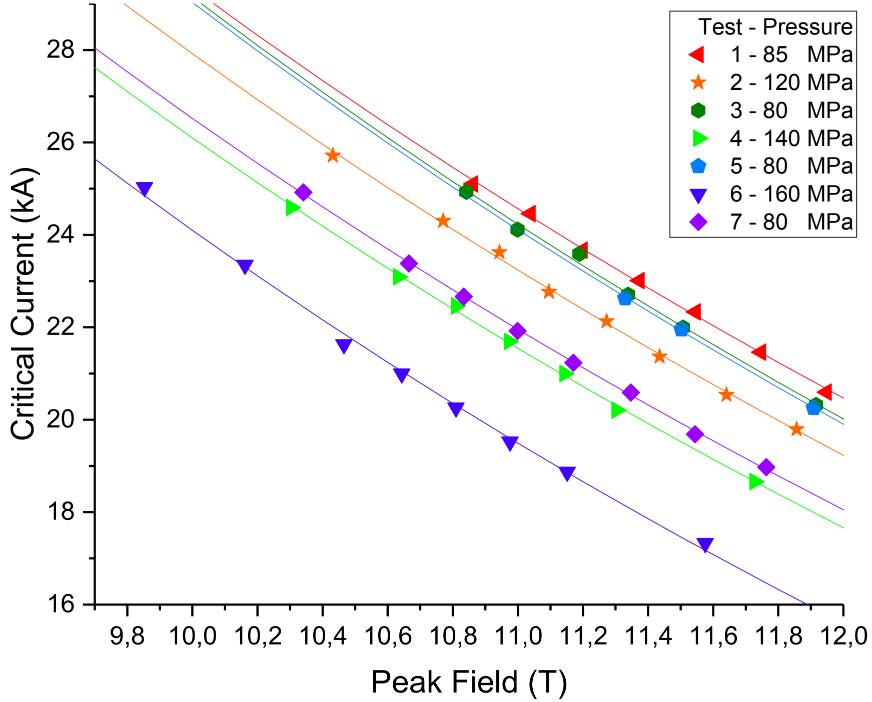
Cable I_c vs. Transversal Load

Test at CERN on a RRP cable (2017)

Is the RRP cable less sensitive in the reversible region?

- CERN measured* a 18 strands cable based on 1 mm 132/169 RRP – the cable was geometrically identical to the PIT cable presented in previous slides





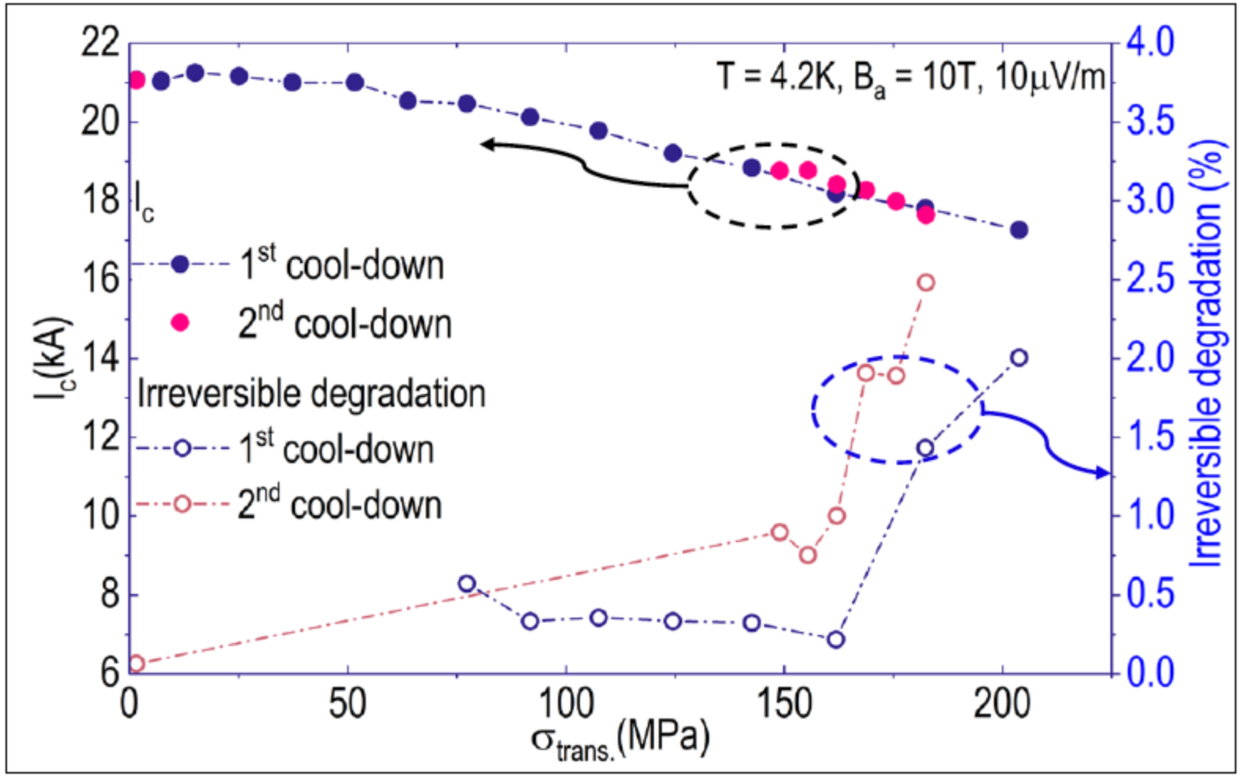
- The RRP cable shows* a behavior similar to the PIT cable however it seems a bit less sensitive to transverse load, at 11.6 T
  - ➢ 5% reversible I_c reduction occurs at 120 MPa instead of 100 MPa

*J. E. Duvauchelle , B. Bordini, J. Fleiter, A. Ballarino presented at EUCAS 2017 and accepted for publication, *IEEE Trans. Appl. Supercond.*

Cable I_c vs. Transversal Load

Test at Twente on a RRP cable (2017)

- The same RRP cable measured by Twente showed that
  - irreversible degradation occurs later than in PIT cable - onset at 170 MPa (instead of 120 MPa of the PIT)
  - At 11.6 T and 150 MPa the reversible I_c reduction is about 15 % (that is 6-7% lower than PIT)



Plot Courtesy of Marc Dhalle and Peng Gao

Data to be published at ASC 2018

- The larger irreversible degradation measured at CERN with 160 MPa might be due to the different load conditions
  - At Twente the load is applied at 4.2 K while at CERN, the cable experience a significant load already at room temperature

I_c vs. Transversal Load

RRP vs PIT

- The larger tolerance to transverse load of the 1 mm RRP 132/169 with respect to the 1 mm PIT 192 wire is most likely due to the larger amount of small Nb_3Sn grains in the strand cross section

  - The Nb_3Sn is the material that is supporting most of the mechanical load in the wire
  - The **PIT** filaments are constituted by only **30** to **40 %** (in volume) of Nb_3Sn **small grains** [1],[2] and by about 18% [1],[2],[3] of Nb_3Sn large disconnected[3] grains
    1. for a regular PIT, without the bundle barrier, to have a RRR equal to about 300 it is necessary to under-react→ small grains ~ 30%
  - In the **RRP** wire, the filaments are composed by about **58%**[1] of Nb_3Sn **small grains;** large grains are limited to only 4 % [1]

[1] C. Scheuerlein et al. , IEEE TAS, Vol. 25, NO. 3, June 2015

[2] C. Segal et al., Supercond. Sci. Technol., vol. 29, no. 8, p. 085003, 2016.

[3] C. Tarantini et al., Supercond. Sci. Technol., vol. 28, no. 9, p. 095001, Sep. 2015.

Modeling I_c vs. Transversal Load

Exponential strain function

$$J_c(B,T,\varepsilon)=C_0\,\frac{B_{c20}}{B}\,(s(\varepsilon))^{\sigma}\,[(1-t^{1.52})(1-t^{2})]^{\alpha}\,b^{0.5}(1-b)^{2}$$

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

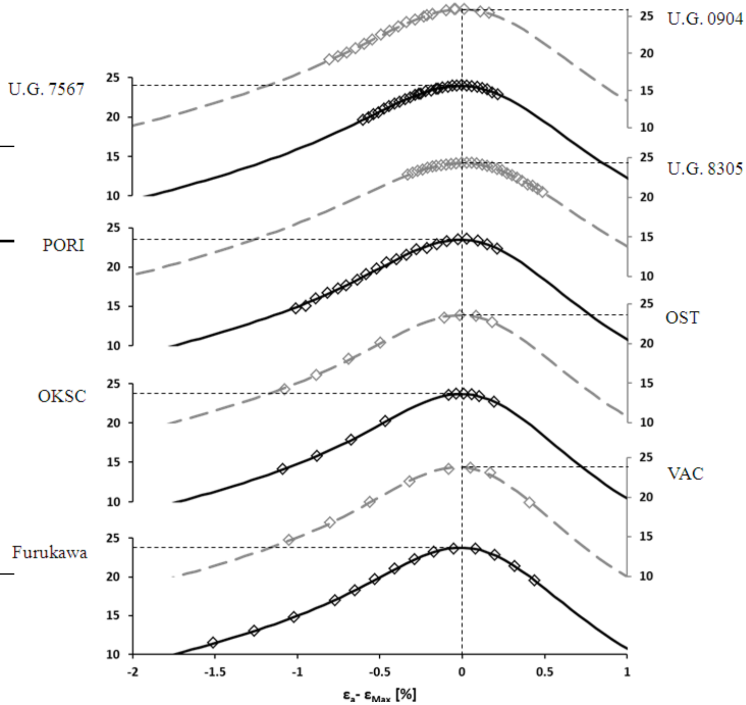
$$T_c(\varepsilon)=T_{c0}\,s(\varepsilon)^{\frac{1}{3}}$$

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

Where: I_1 is the first invariant of the strain tensor, J_2 second invariant of the deviator strain tensor

- Exponential strain function* two fitting parameters:
  - C_1 that defines the sensitivity (curvature) of the material to the strain a
  - ε_{l0} the longitudinal pre-compression of the Nb_3Sn ($\varepsilon_{l0} \sim \varepsilon_{max}$ *in* I_c *vs.* Axial Strain measurements)

Strand	B_{c20} (T)	C_1	ε_{lo} %	ε_{Max} %	RMS (T)
Furukawa	28.67	0.901	-0.29	0.28	0.05
VAC	28.80	0.958	-0.30	0.29	0.14
OKSC	28.58	0.930	-0.08	0.08	0.03
OST	28.39	0.875	-0.10	0.09	0.12
PORI	28.24	0.869	-0.09	0.08	0.14
U.G. 8305	28.84	0.643	-0.28	0.28	0.05
U.G. 7567	28.62	0.752	-0.25	0.25	0.04
U.G. 0904	30.97	0.735	-0.18	0.18	0.06



- The exponential strain function was developed to estimate the I_c *vs.* Axial Strain measurements

- **Can we use it for the I_c *vs.* transverse load ?**

* Bordini B, Alknes P, Bottura L, Rossi L and Valentinis D 2013 SuST 26 075014

Modeling I_c vs. Transversal Load

2D FEM of a wire + Exponential strain function

- The exponential strain function was used to calculate* the reversible I_c reduction experienced by a 1.25 mm PIT wire under transverse pressure in the UniGe set-up
  - The strain state was calculated via a 2D FEM mechanical model (plane strain)
  - The strain invariants were plugged in the exponential strain function
  - All the parameters in the exponential strain function were derived by I_c vs axial strain measurements performed at UniGe

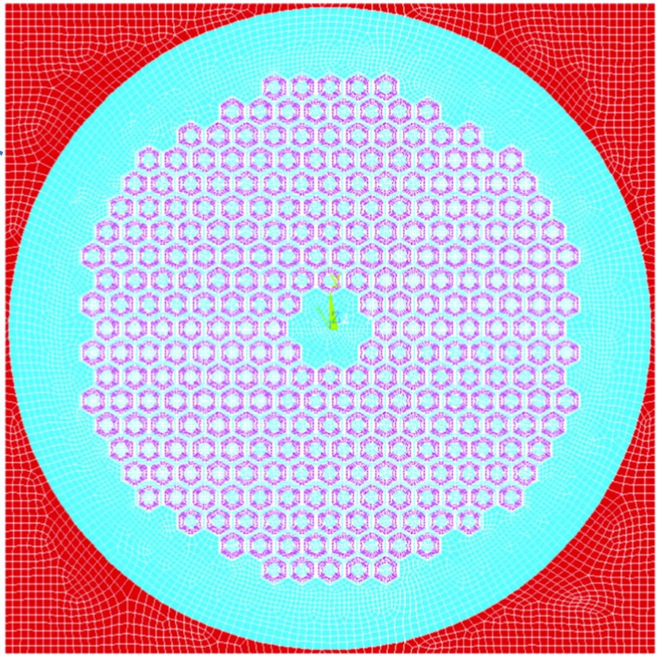
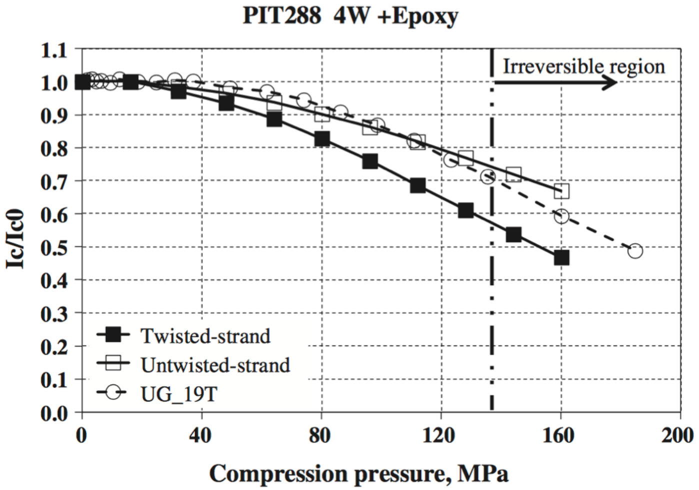


Fig. 1. FE model of the PIT288 strand with epoxy (4 W + epoxy). Note that no sliding, separation is modeled between strand and epoxy.

- The model* is in good agreement with the experimental data**



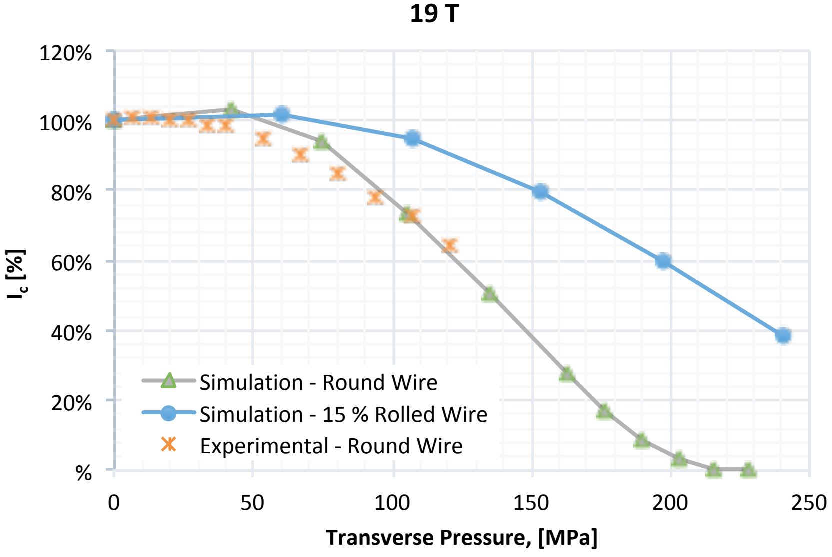
*T Wang, L Chiesa, M Takayasu, B Bordini Cryogenics 63 (2014) 275–281

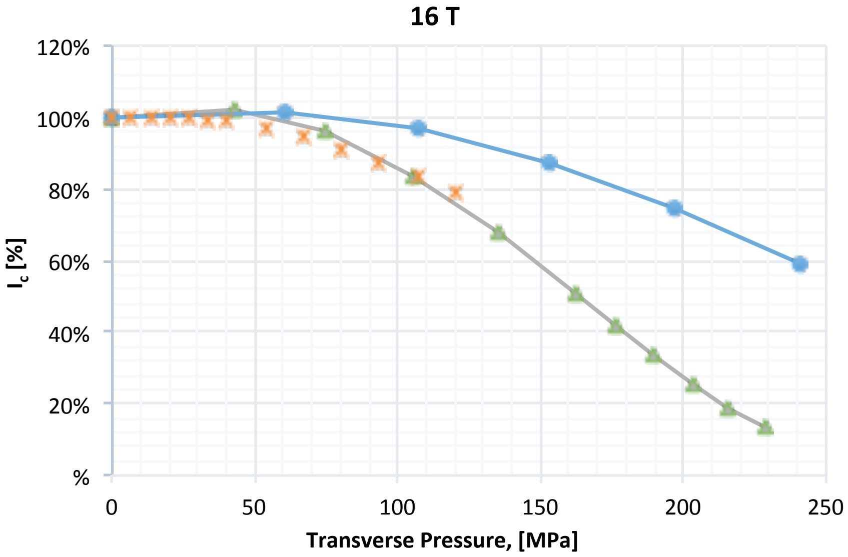
** G Mondonico, B Seeber, A Ferreira, B Bordini, L Oberli, L Bottura, A Ballarino, R Flükiger and C Senatore SuST, 25 (2012), p. 115002 [9pp]

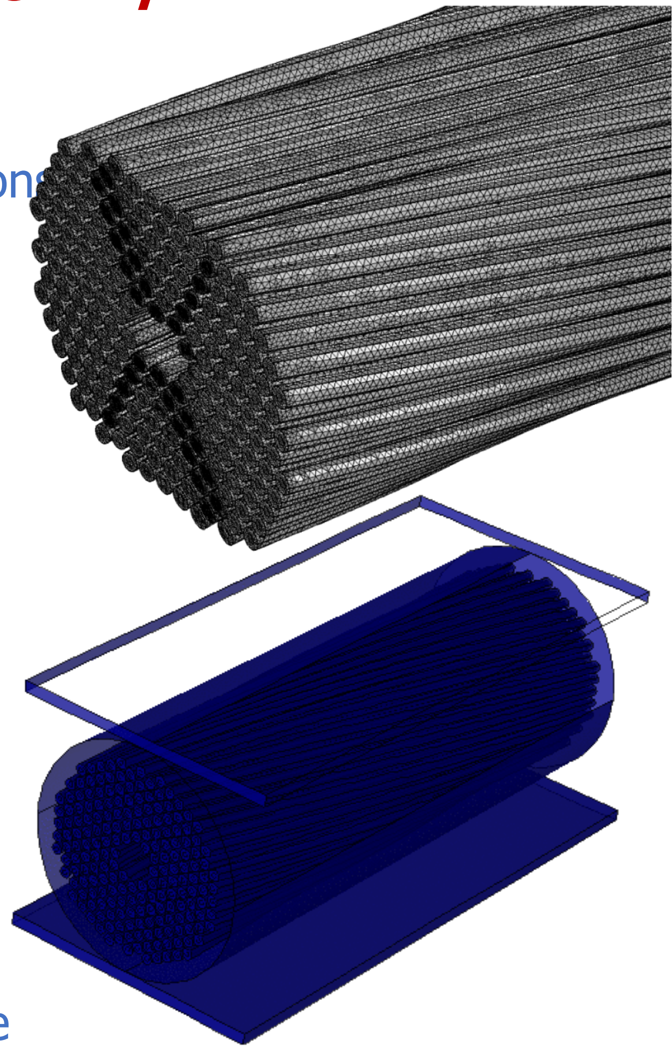
Modeling I_c vs. Transversal Load

3D FEM of a wire + Exponential strain function 1/2

- A 3D FEM model was developed* to investigate the role of
  - Twisted filaments; Rolling the wire; Different Boundary conditions and Impregnation







- A very good agreement was found in the case of no longitudinal elongation of the wire (plain strain in a 2D model) – 1 mm 192 Round PIT
  - The model also shows that rolled wires are more tolerant to transverse pressure

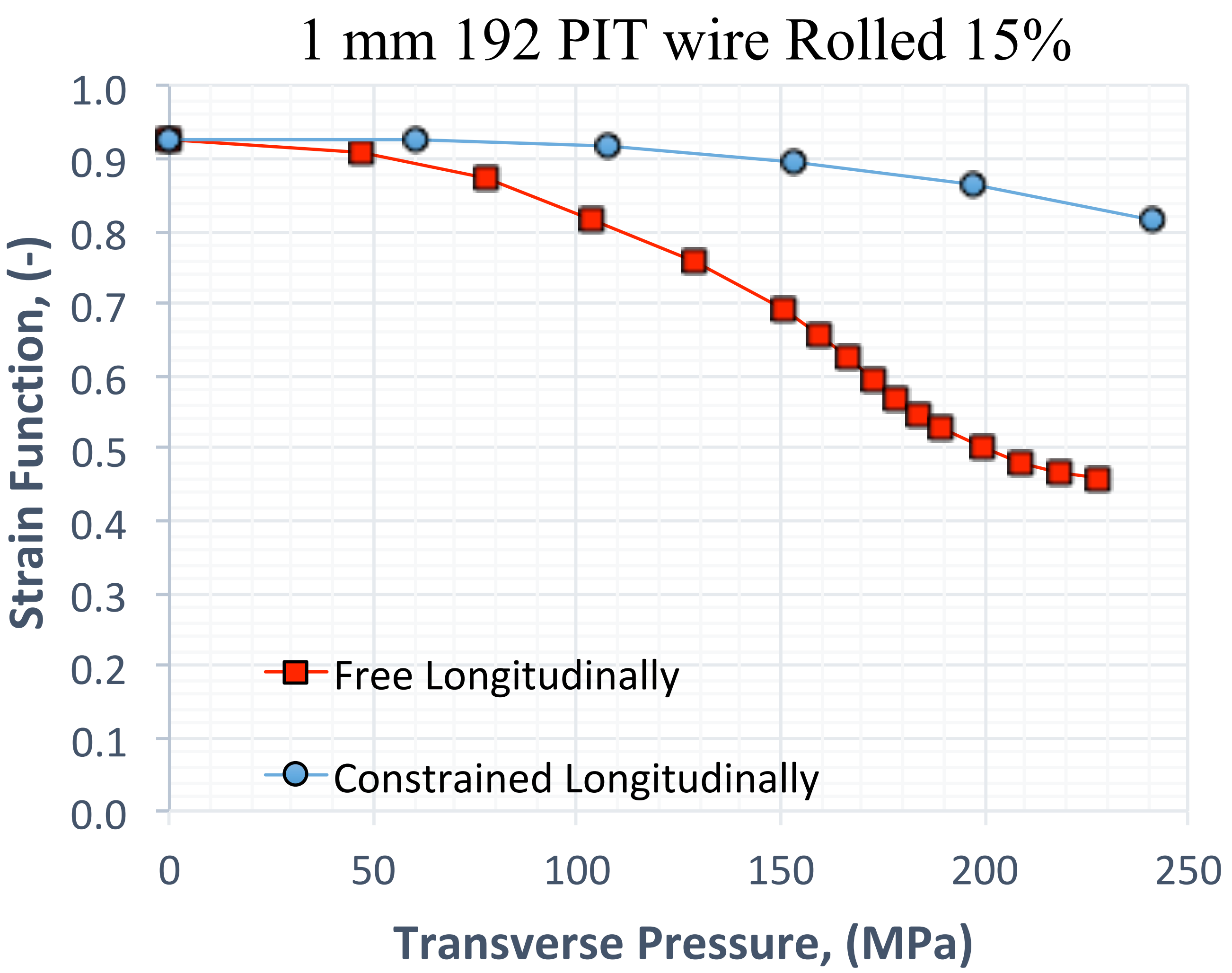
* A. Cattabiani, B. Bordini to be presented at the ASC 2018 conference

Courtesy of A. Cattabiani

Modeling I_c vs. Transversal Load

3D FEM of a wire + Exponential strain function 2/2

- In the case the wire is free to move longitudinally (plain stress in a 2D model),
  - the model* predicts a much larger reduction of the strain function (and hence of the critical current)



Courtesy of A. Cattabiani

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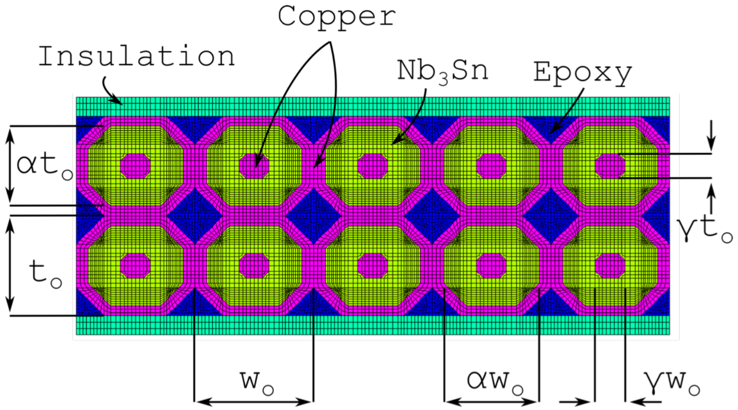
Modeling I_c vs. Transversal Load

2D FEM of a cable

- Developed a FEM mechanical model* of the cable stack able to estimate the young modulus of the stack during loading (14 GPa) and unloading (37 GPa)
  - Good agreement with data measured on impregnated cable stacks;
  - The **geometry** of the cable is **simplified**, in particular the region where the sub-elements are embedded in a copper matrix is treated as a **unique annulus** of Nb_3Sn;
  - The simplified geometry respects the main parameters of the conductor (cable filling factor, Cu to non-copper ratio, height and width of the cable and of the stack etc..);
  - The material properties of the different components are taken from literature.

- The significant difference of the young modulus during loading and unloading is explained by the plastic deformation of the Cu (during loading)

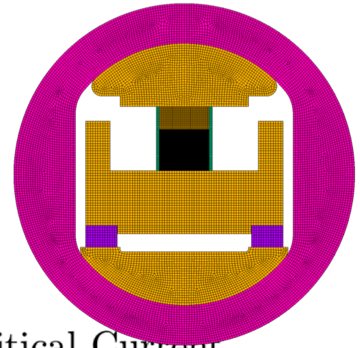


Courtesy of Giorgio Vallone

*G. Vallone, B. Bordini, P. Ferracin, presented at EUCAS 2017 and accepted for publication, *IEEE Trans. Appl. Supercond.*

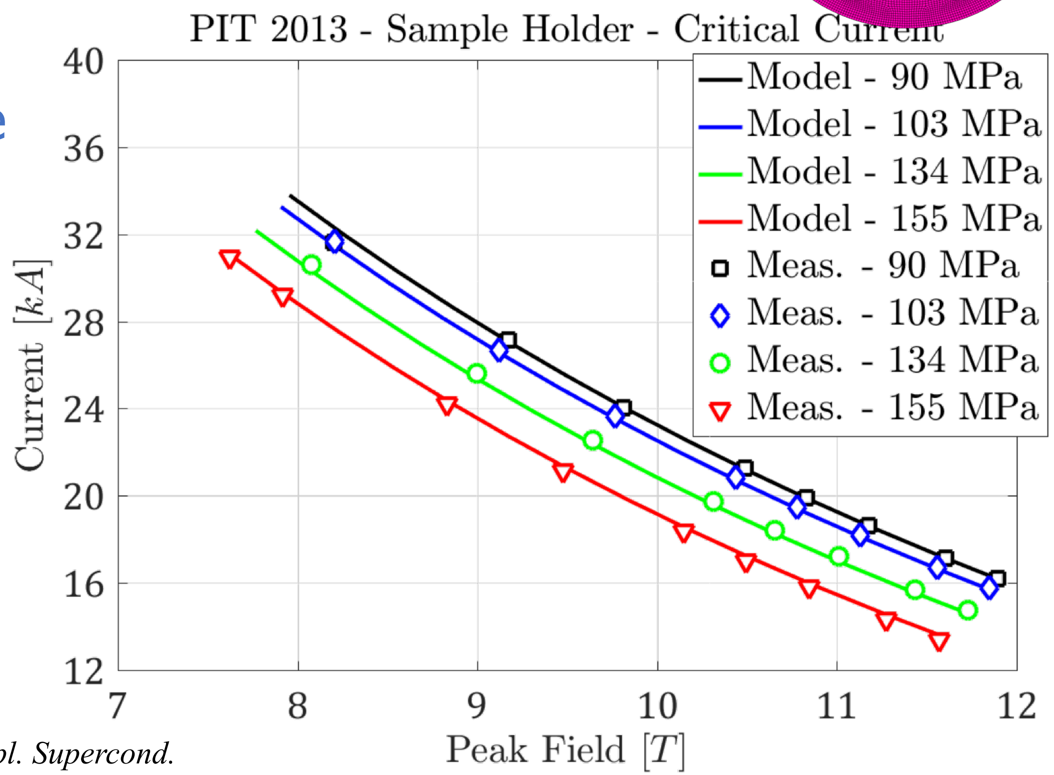
Modeling I_c vs. Transversal Load

2D FEM of a cable + Exponential strain function



- Calculated via a FEM mechanical model* (2D, plain stress) the strain in the cable stack during the test under transverse load in Fresca
- The computed 3D strain multiplied by a constant factor, which accounts for the concentration of the stresses in the superconducting sub-elements, is then used to compute the strain function and the critical current

The model* is in good agreement with the experimental data measured** on PIT cable in FRESCA



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** B. Bordini, P. Alknes, A. Ballarino, L. Bottura, L. Oberli *IEEE Trans. Appl. Supercond.*, VOL. 24, NO. 3, JUNE 2014

Conclusions

- Measurements of cables and wires under transverse load at CERN, Twente and Geneva Universities showed that the **reversible reduction** of the critical current is mainly due to a **decrease** of the $\boldsymbol{B_{c2}}$
  - At 1.9 K, assuming a B_{c2} equal to 28 T, a reduction of the B_{c2} by 10 % would produce a reduction of the J_c approximately equal to: 20 % at 12 T, 31 % at 16 T , 44 % at 19 T
- The **RRP cable** was **less sensitive** to transverse loads than the PIT cable (same cable geometry)
  - At 150 MPa and 11.6 T peak field the reversible reduction of the critical current was around 15% in the RRP cable and about 6-7% larger in the PIT cable
  - More important is the difference in terms of **irreversible degradation**: when applying all the load at 4.2 K, the onset of the irreversibility is around 120 MPa for the PIT cable and at 170 MPa for the RRP cable
- The reversible reduction of the critical current due to transverse load can be estimated via mechanical **FEM** models in conjunction with the **exponential strain function**
  - In the case the conductor is free to move longitudinally the model predicts a significantly larger reduction
  - This approach should be used to estimate the margin of the FCC Nb_3Sn magnets

Thanks For Your Attention !

Conclusions

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