Electromechanical characterization of Nb_3Sn conductors at University of Geneva

Description on current studies and past experience

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Outline

Carmine Senatore

Electromechanical studies – Effects of the transverse stress

H2020 EuroCirCol WP5 Task 5: Conductor studies

@ CERN : Bernardo BORDINI, Davide TOMMASINI

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Intrinsic mechanisms behind the irreversible degradation of the critical current

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Impact of the voids on the electromechanical properties of Nb_3Sn wires

Impact of Strand layout and mechanical props.

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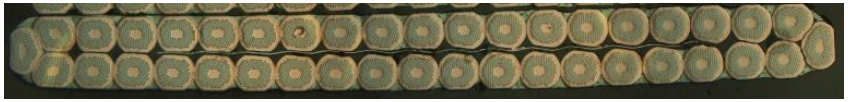
Impact of Strand layout and mechanical props.

Degradation upon transverse loads

New high-field Nb_3Sn magnets are being designed to operate at nominal conditions in a peak stress range of 150 - 200 MPa

Are the Nb_3Sn wires in the cable able to withstand such a high stress level? Which degradation is tolerable?



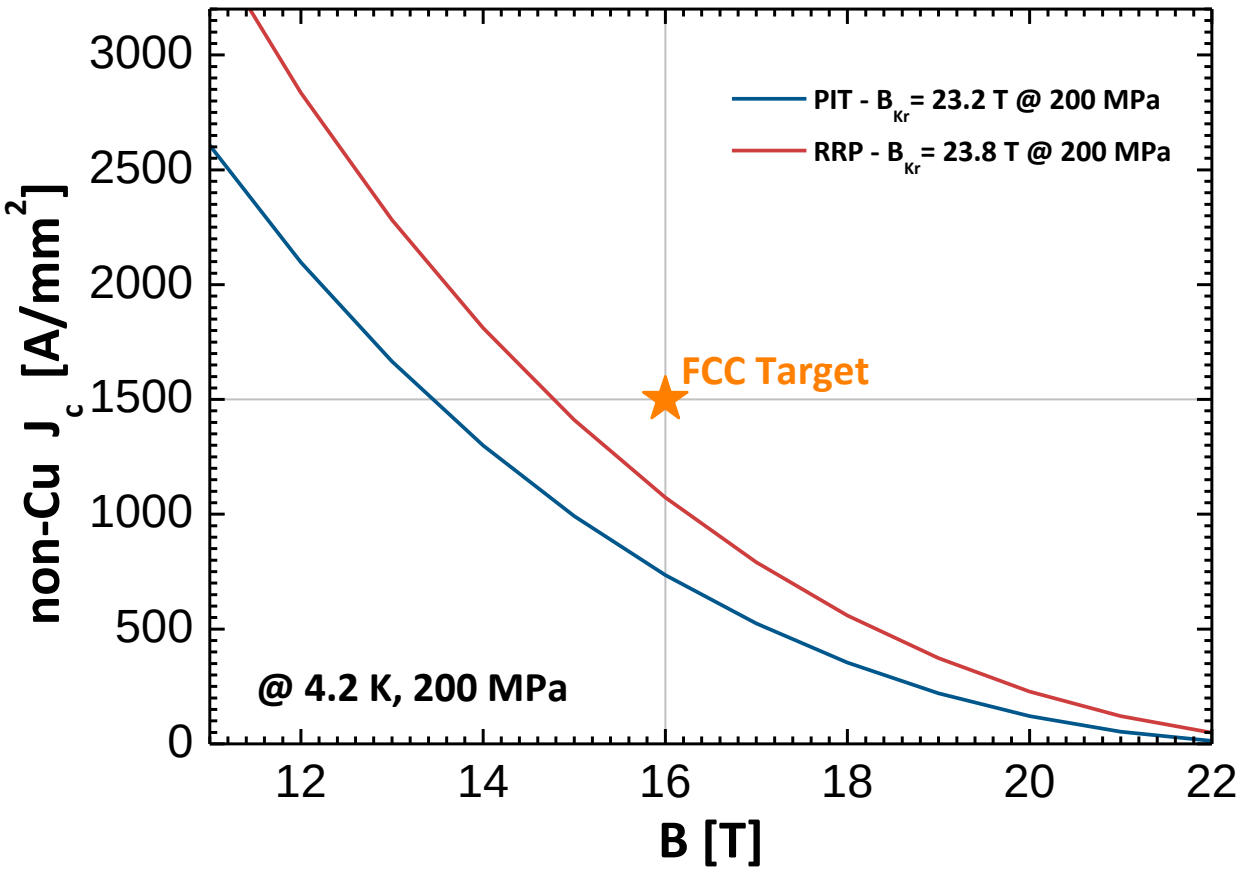
Nb_3Sn Rutherford cable for HL-LHC, 40 strands

- *Nb_3Sn wires are deformed during cabling*
- *Cables are braided with glass fiber*
- *The winding is impregnated with resin*

Is it possible to extrapolate the behaviour of the cable from a single wire experiment?

An FCC example:

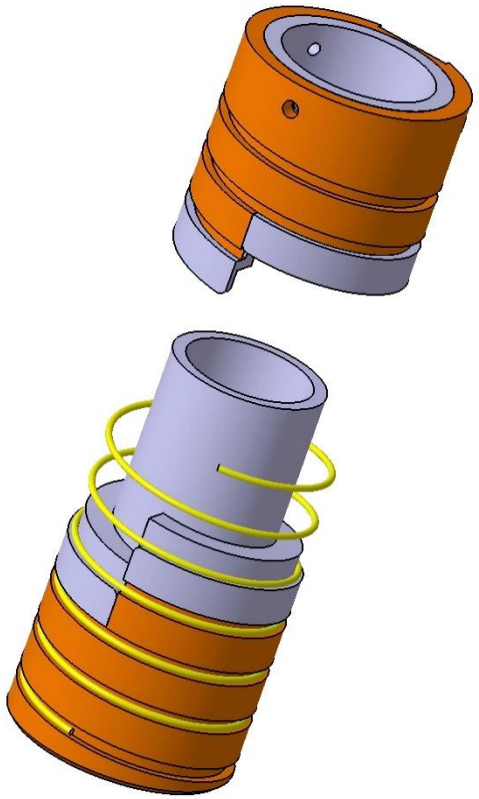
Performance target non-Cu J_c(4.2K,16 T) = 1500 A/mm² and 200 MPa



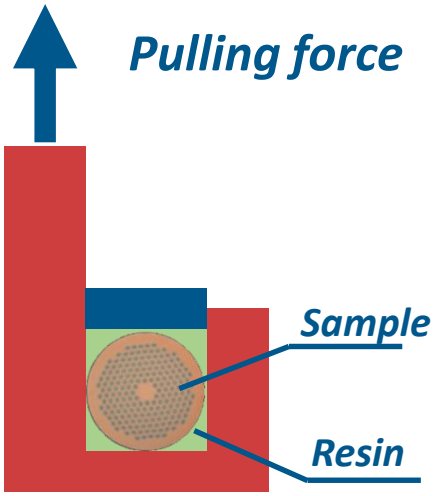
J. Parrell et al., AIP Conf. Proc. 711 (2004) 369

T. Boutboul et al., IEEE TASC 19 (2009) 2564

The WASP concept for I_c vs. transverse stress



4-WALL + impregnation

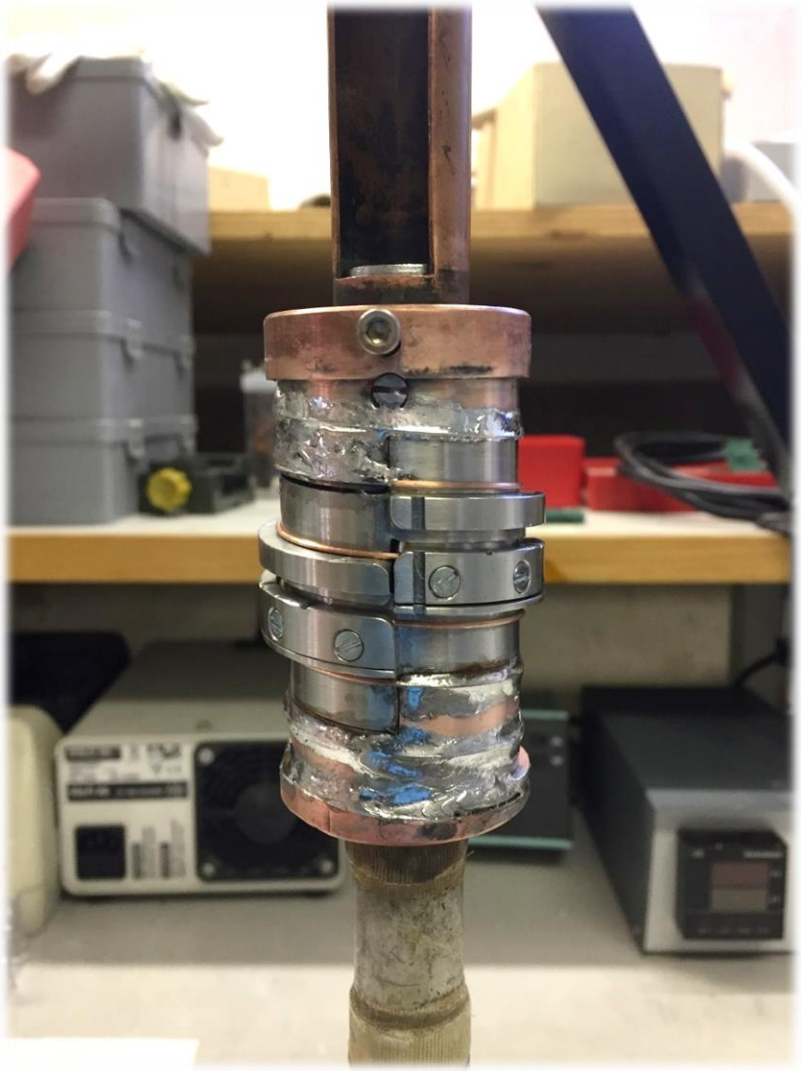


3 groove widths
- 1.30 mm
- 1.15 mm
- 1.00 mm

Groove / Gauge length — 126 mm

CERN-UNIGE collaboration agreement K1629/TE (2009-2012)

The WASP concept for I_c vs. transverse stress



How is the wire constrained?

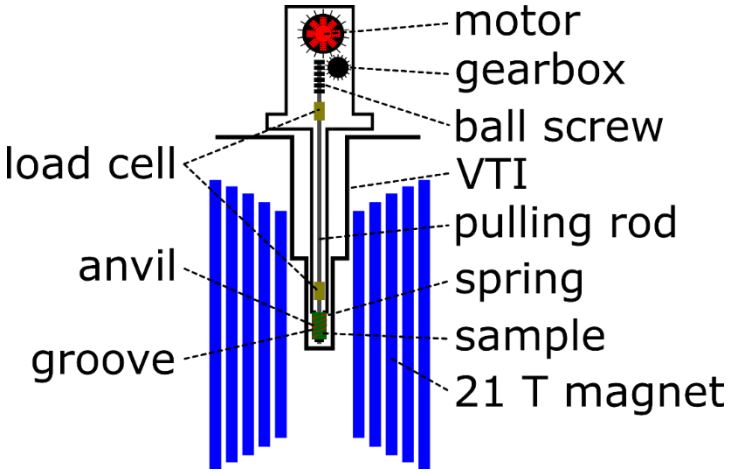
Strand soldered to the sample holder at both extremities.

Wire is free from the exit of the groove to the soldering points (1 turn respectively).

The anvil is always in contact with the top epoxy (2 mm height cavity).

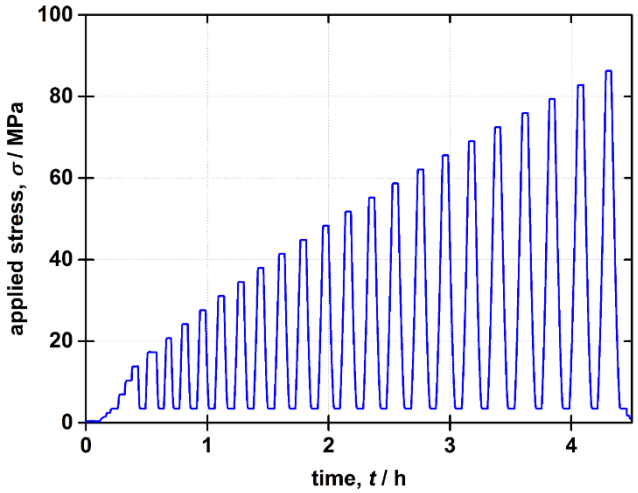
Voltage taps placed at the entrance / exit of the groove.

The WASP concept for I_c vs. transverse stress



How are the measurements performed?

2 load cells (1x @RT, 1x @4.2 K).
PID control loop, |Force deviation| < 20 N.
19 T (@4.2 K) measurements.
1 kA linear DC power supply.



Reference Ic measurements at 500 N.
Incr. force in 500N steps → Ic measurement.
Backstep to 500 N → Ic measurement.
If Ic,back < Ic,ref : Irreversibility reached.

The irreversible limit of the wire under transverse stress is influenced by several parameters

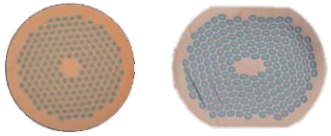
- *The type of impregnation (the elastic modulus of the resin)*
- *The redistribution of the applied stress on the wire*

Rolled wire to simulate the deformation during cabling

- *The type of wire*

PIT and RRP experimental campaigns

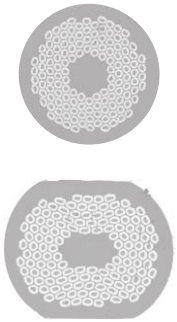
- ***The PIT experience***



PIT 192 1mm

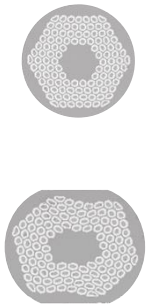
- *On-going RRP investigations*

"FCC"



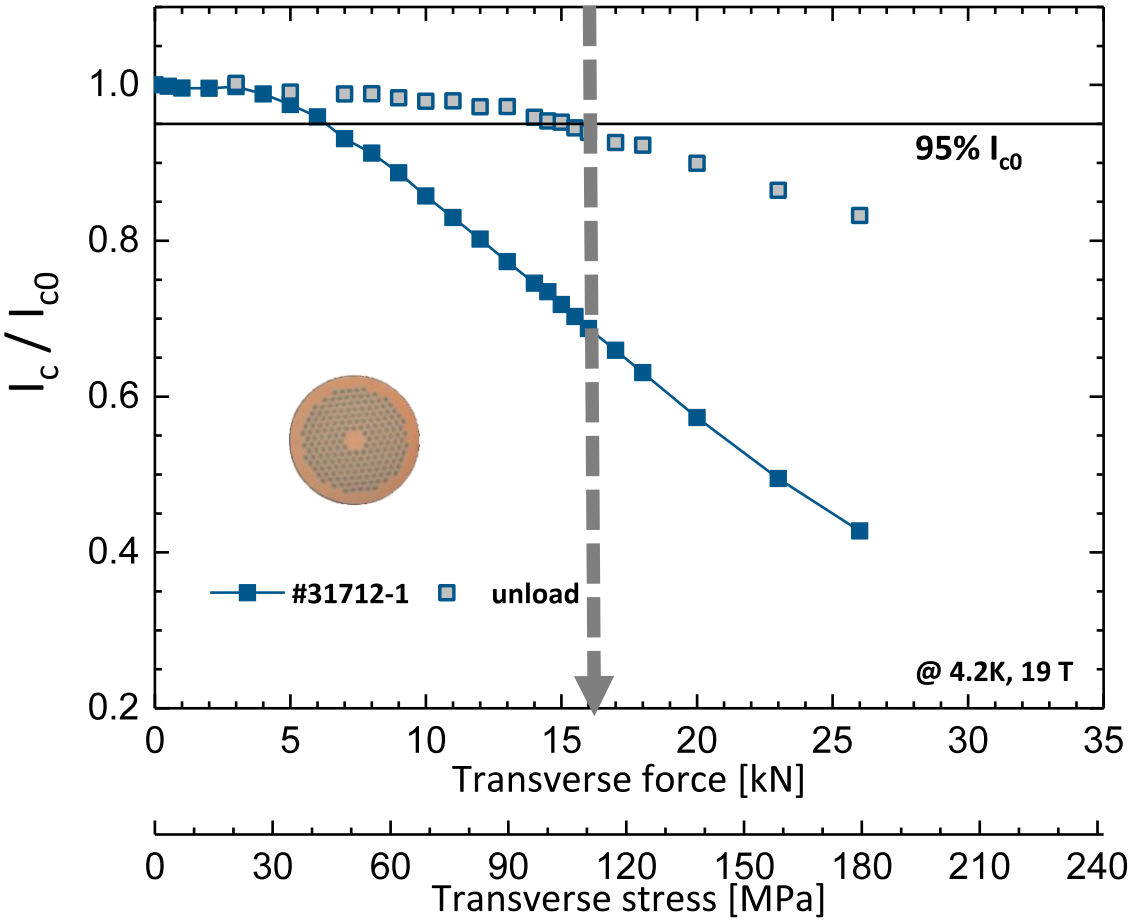
RRP 132/169 1mm

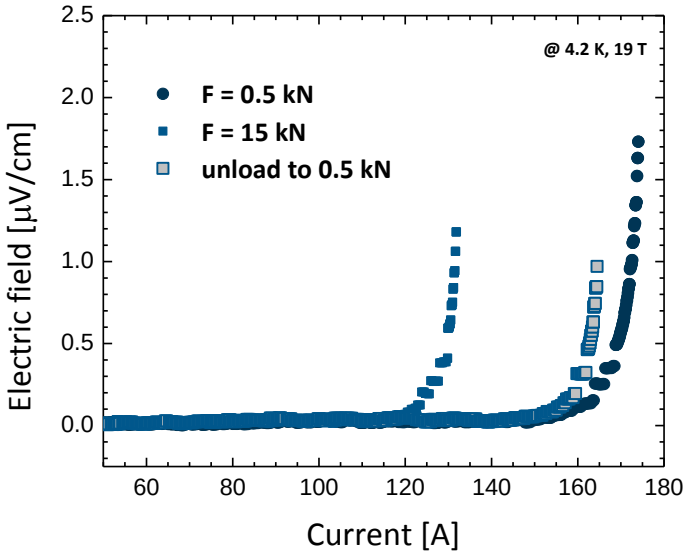
"HL-LHC"



RRP 108/127 0.85mm

I_c vs. transverse stress
PIT 192 + epoxy L





The irreversible limit is defined at the force level leading to a 95% recovery of the initial I_c after unload

Here

$$F_{irr} = 16\ kN$$

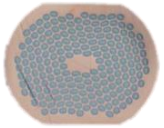
The corresponding irreversible stress limit is

$$\sigma_{irr} = 110\ MPa$$

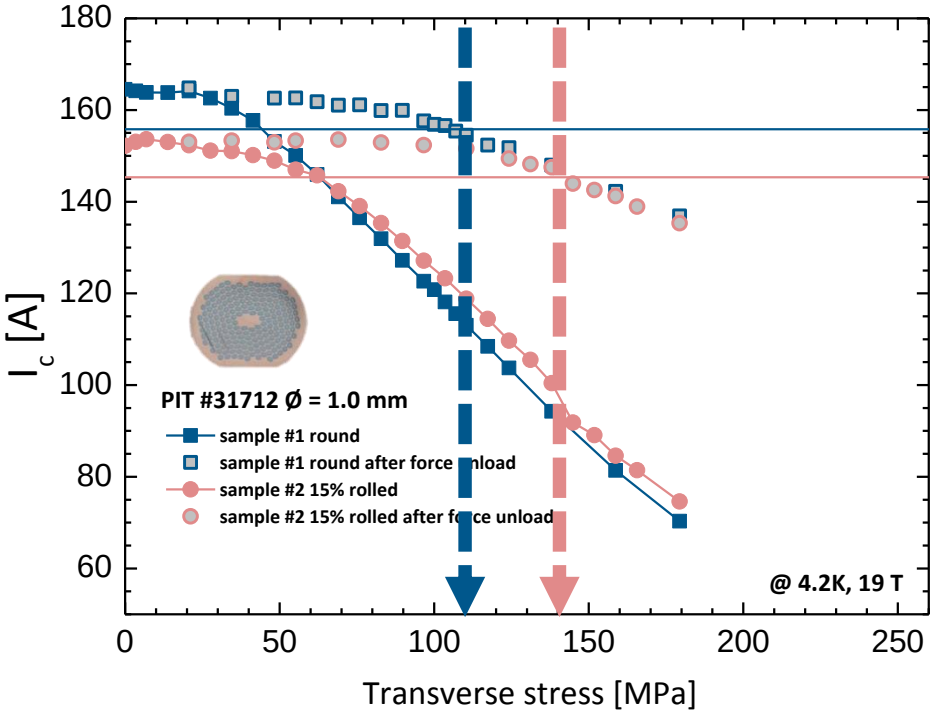
where

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

I_c vs. transverse stress on 15% rolled wires



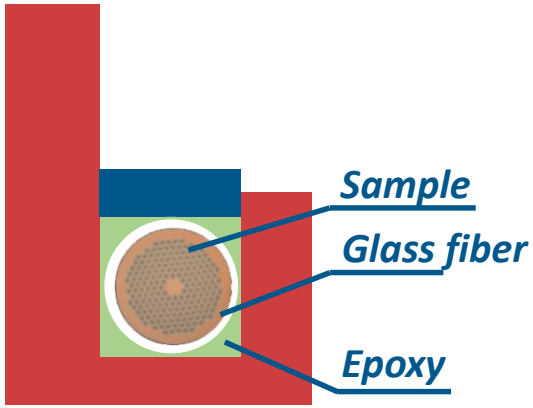
PIT 192 rolled

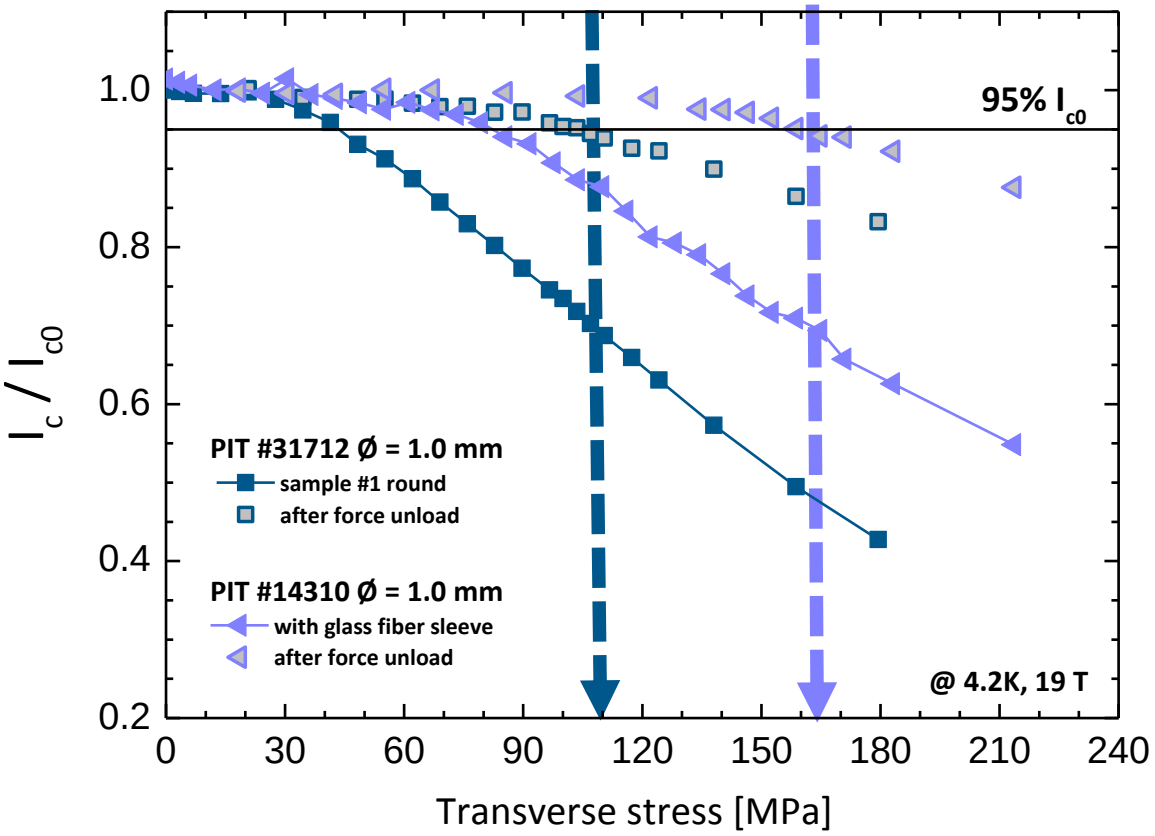


~7.5% I_c reduction by rolling
(Degradation due to rolling)

"Artificial" shift of σ_{irr} by ~ 40 MPa

I_c vs. transverse stress: wire in a glass fiber sleeve

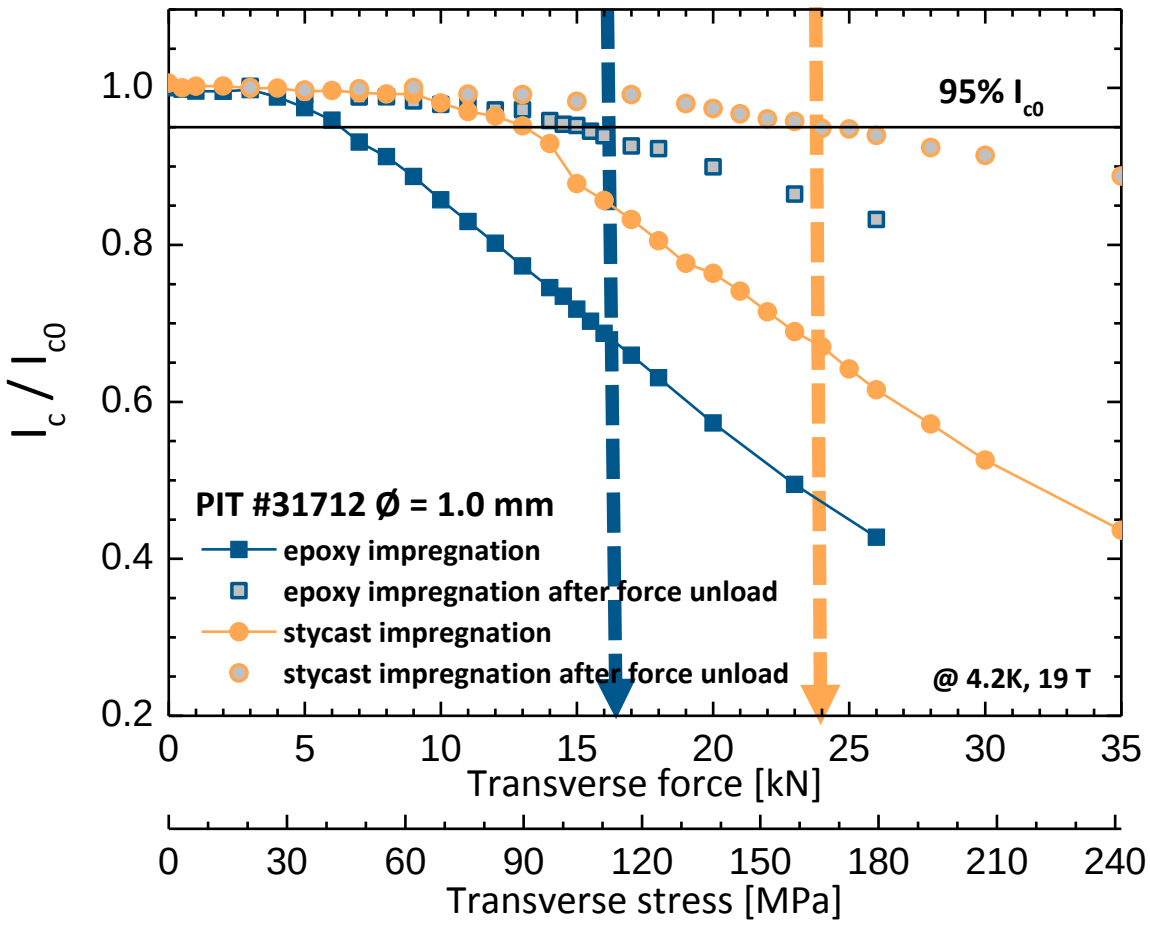




Shift of σ_{irr} by > 50 MPa

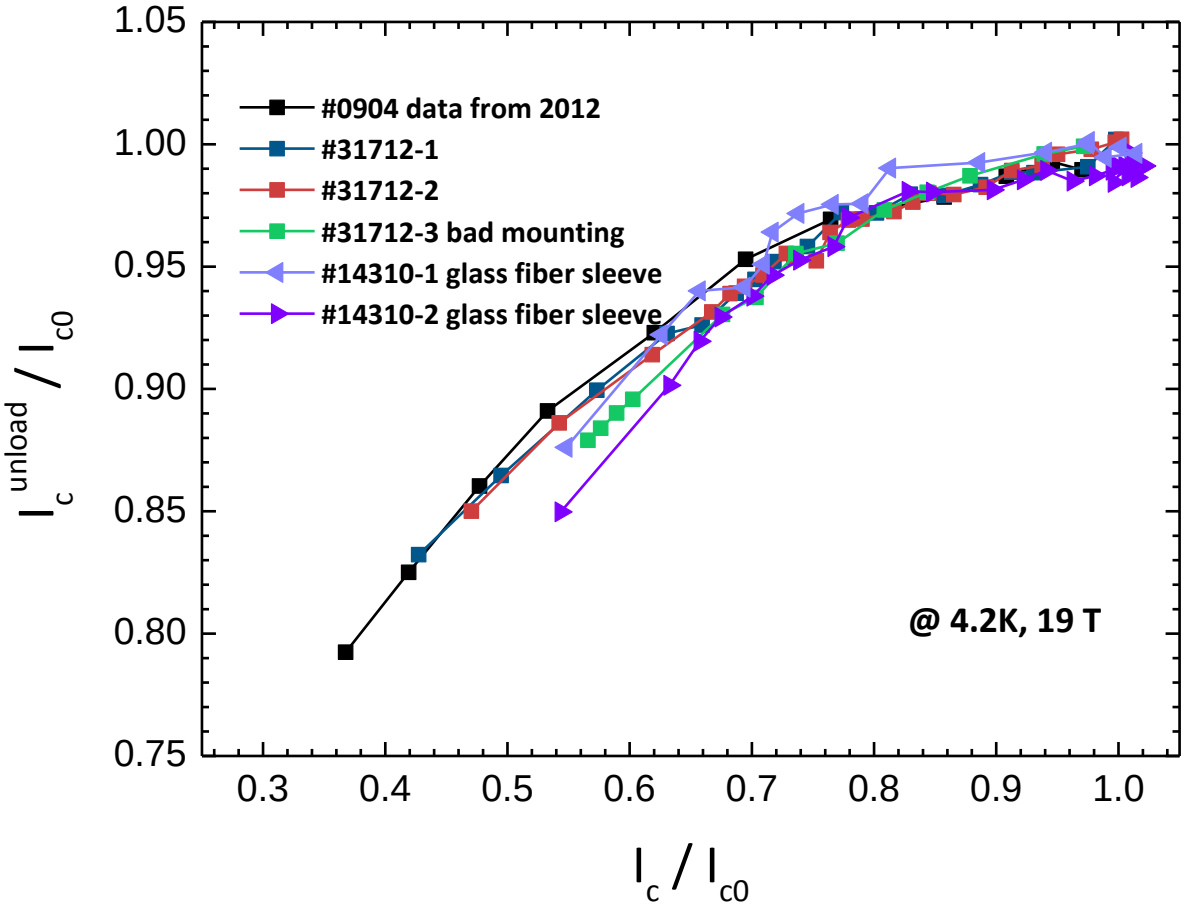
The wire with glass fiber sleeve was measured in a larger groove (1.30 mm vs 1.15 mm)

I_c vs. transverse stress: epoxy L vs. Stycast



The change of resin, from epoxy to Stycast, leads to an increase of σ_{irr} by > 50 MPa
The result is comparable to the value found with epoxy + glass fiber sleeve

PIT: I_c / I_{c0} vs. I_c^{unload} / I_{c0}



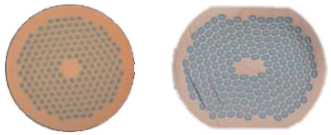
PIT 192 Round wires

X axis: I_c / I_{c0} Force
Y axis: I_c / I_{c0} Unloaded

Scaling behavior.
Local stress in the filaments.

PIT and RRP experimental campaigns

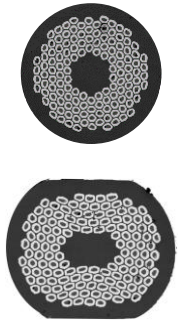
- *The PIT experience*



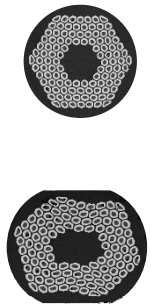
PIT 192 1mm

- ***On-going RRP investigations***

"FCC"



RRP 132/169 1mm

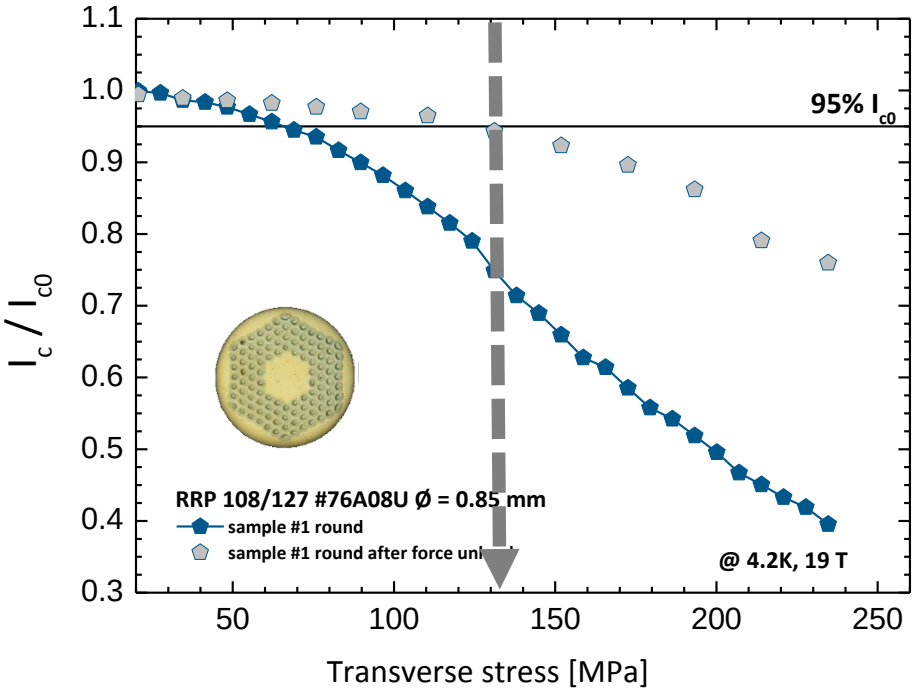


"HL-LHC"

RRP 108/127 0.85mm

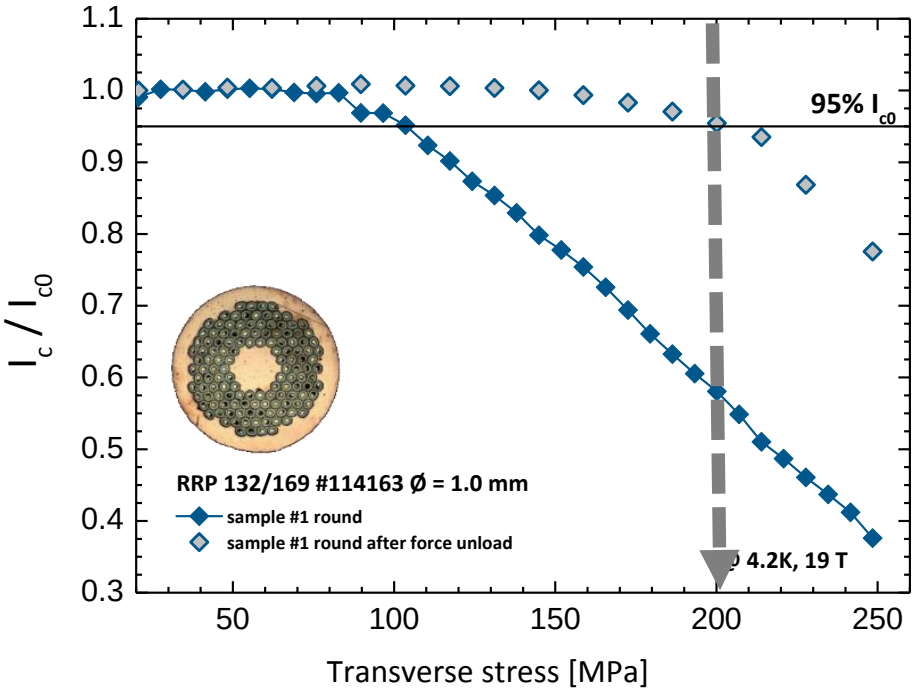
RRP: 132/169 vs. 108/127

Effect of the wire layout on the irreversible stress limit



RRP 108/127

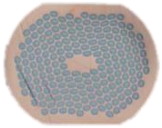
Irreversible stress limit at ~130 MPa



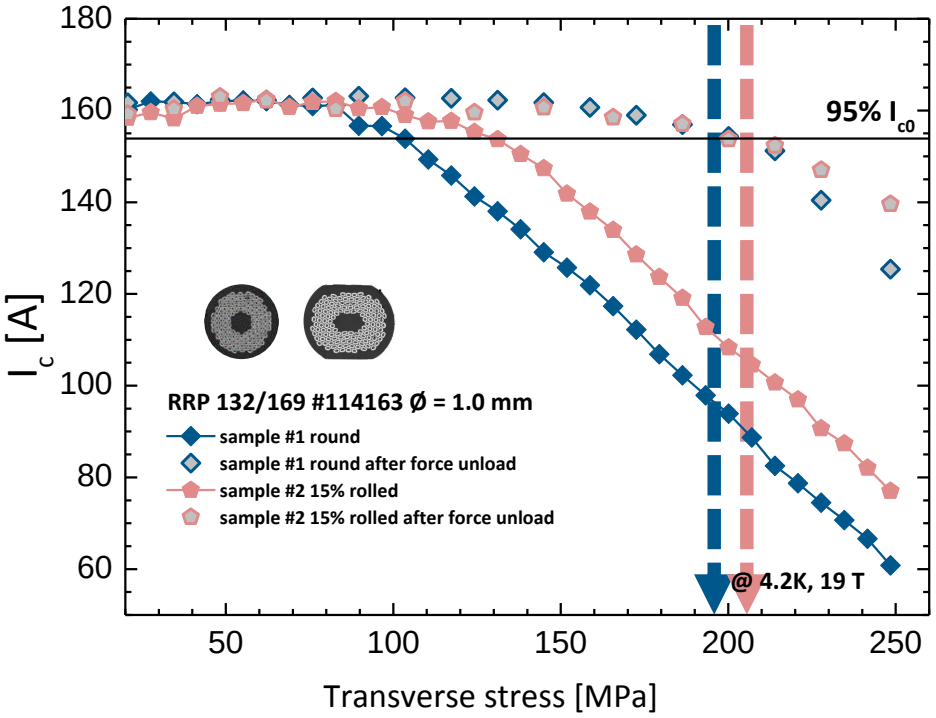
RRP 132/169

Irreversible stress limit ~200 MPa

I_c vs. transverse stress on 15% rolled wires



RRP 132/169

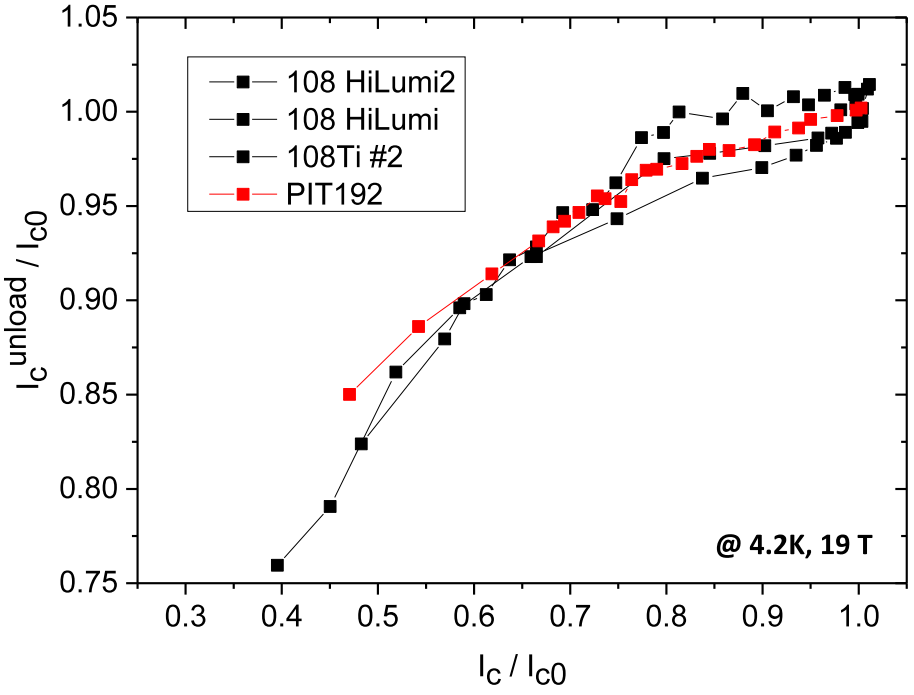


NO I_c reduction by rolling

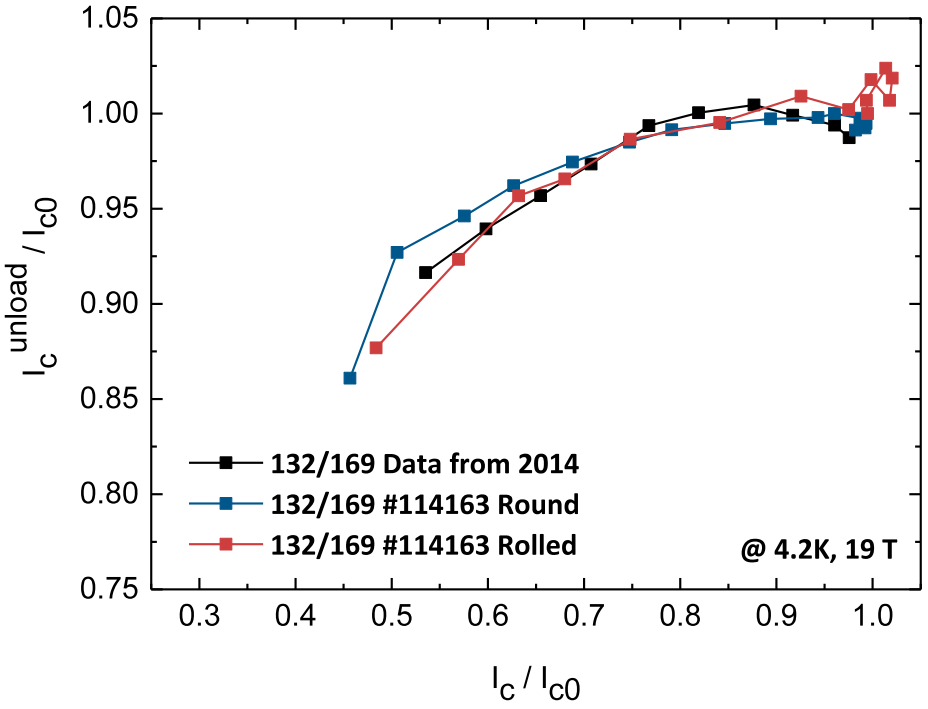
"Real" shift of σ_{irr} by ~ 15 MPa

Measurement on-going for the RRP 108/127 0.85mm strand

RRP: I_c / I_{c0} vs. I_c^{unload} / I_{c0}

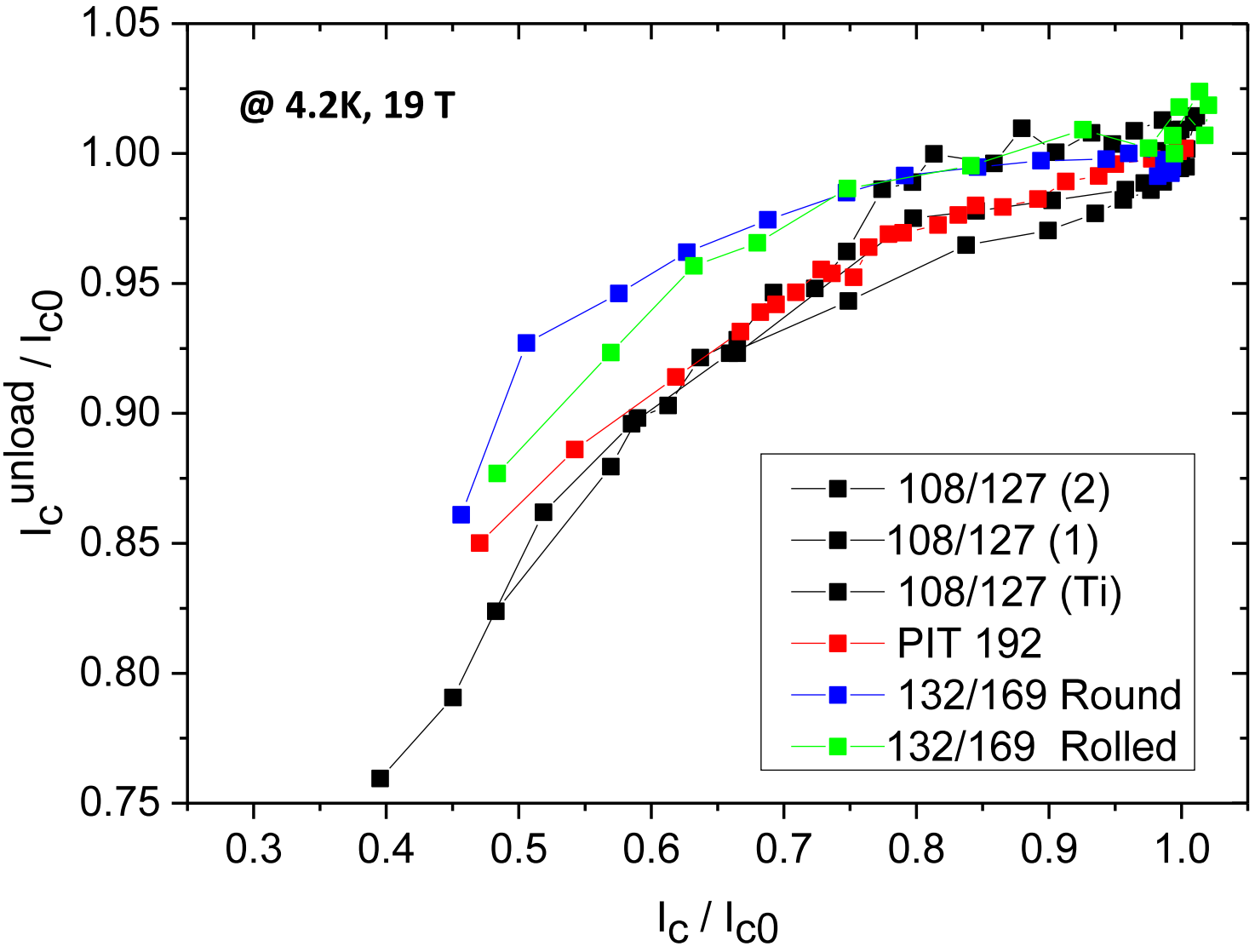


RRP 108/127 0.85mm



RRP 132/169 1mm

An Universal Nb_3Sn curve? Not yet…



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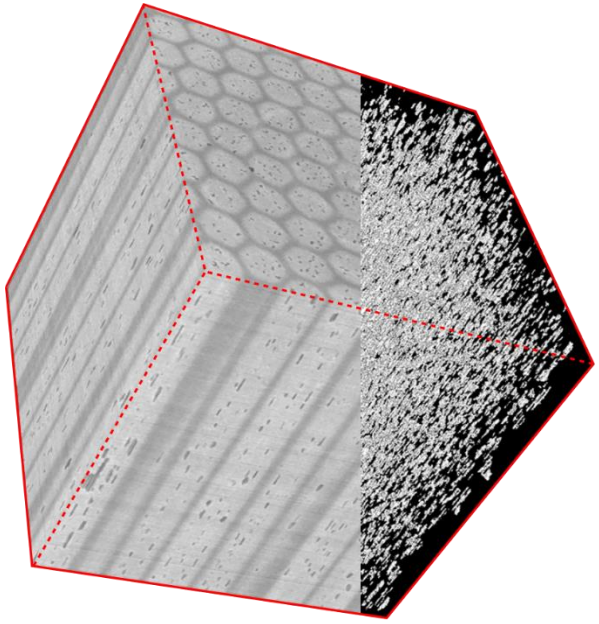
Impact of the voids on the electromechanical properties of Nb_3Sn wires.

Impact of strand layout and mechanical props.

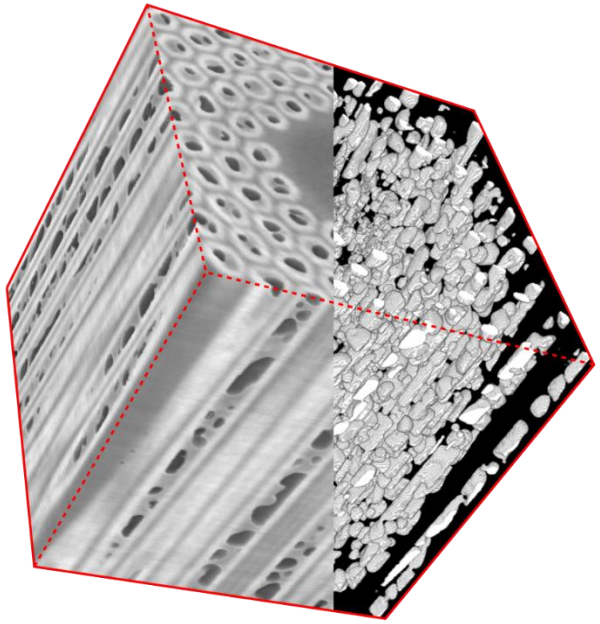
Voids in Nb_3Sn wires

XRD microtomography reconstruction



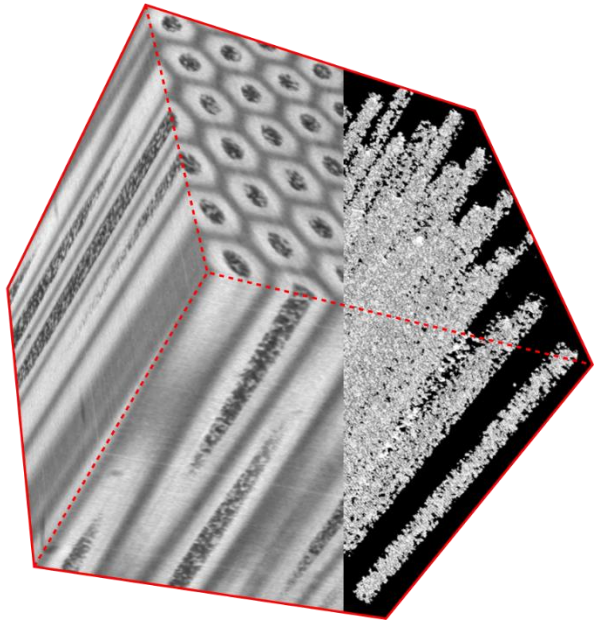
Bronze Route

121 x 121 filaments



RRP

132/169 subelements



PIT

192 filaments

Can we quantify the impact of voids on the electromechanical limits?

What has been done?

Changes in the voids correlate quantitatively with the changes in the electromechanical limits for a Bronze Route Wire

More details in SCIENTIFIC REPORTS

OPEN

Quantitative correlation between the void morphology of niobium-tin wires and their irreversible critical current degradation upon mechanical loading

C. Barth[1], B. Seeber[2], A. Rack[3], C. Calzolaio[1], Y. Zhai[4], D. Matera[1] & C. Senatore[1]

[1]Department of Quantum Matter Physics (DQMP), University of Geneva, Geneva, Switzerland. [2]Department of Applied Physics (GAP), University of Geneva, Geneva, Switzerland. [3]European Synchrotron Radiation Facility (ESRF), Grenoble, France. [4]Princeton Plasma Physics Laboratory (PPPL), Princeton University, Princeton, NJ, USA. Correspondence and requests for materials should be addressed to C.B. (email: christian.barth@unige.ch)

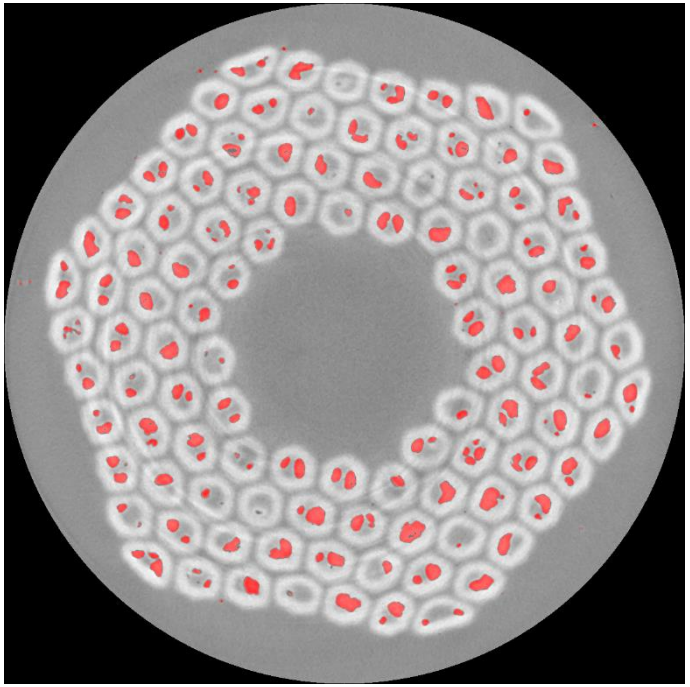
SCIENTIFIC REPORTS | (2018) 8:6589 | DOI:10.1038/s41598-018-24966-z

Case study on Bronze Route, what about RRP and PIT ?

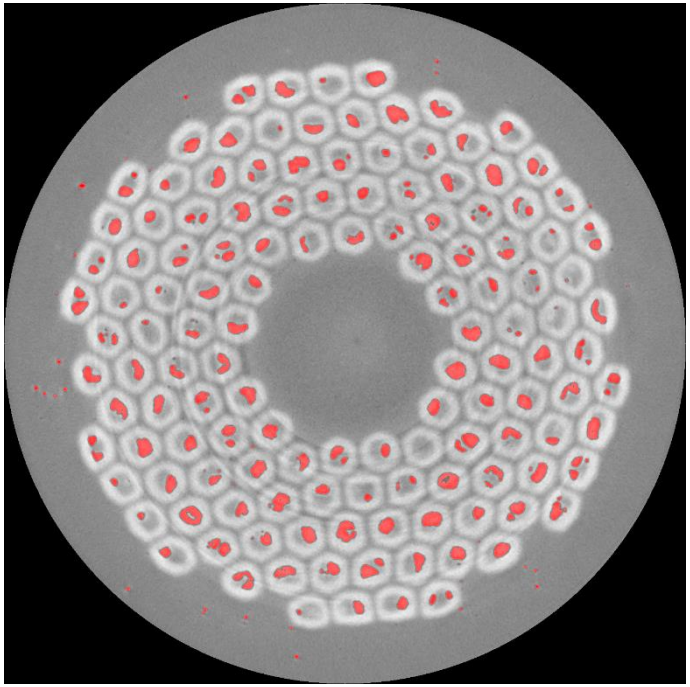
The same approach may lead to the prediction of how much ε_c can be increased by reducing the void fraction

Work on-going

The statistical analysis is being performed for the RRP wires: Size, quantity and location of voids.



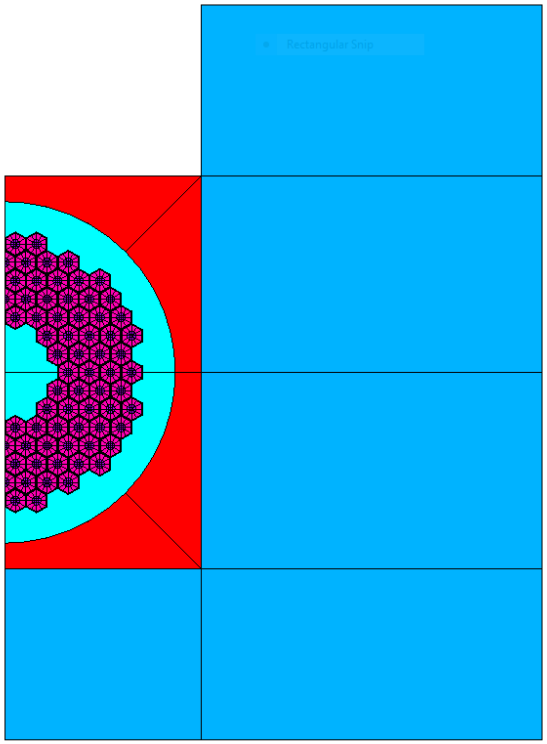
RRP 108/127 0.85mm



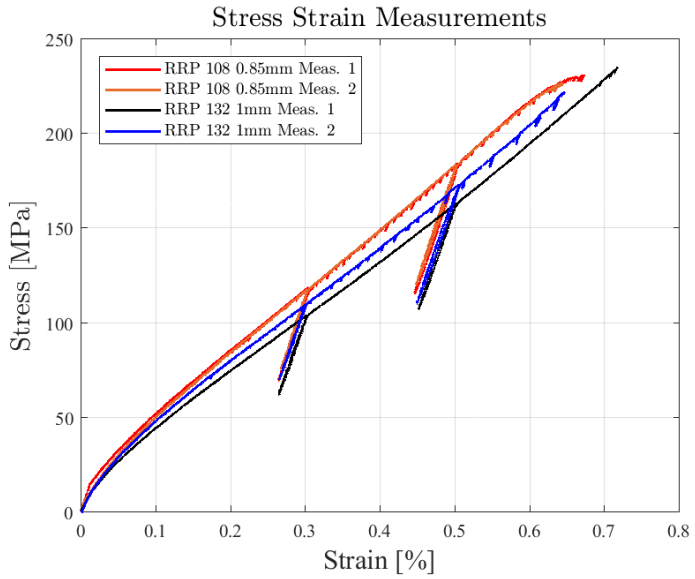
RRP 132/169 1mm

Results become inputs for FEM analysis!

Layout and mech. properties of Nb_3Sn strands



FE Model



Tensile measurements at cold

Can we explain the different behavior in terms of layout, voids and mechanical properties? Investigations on-going…

Summary

- *An extensive campaign for electro-mechanical characterization of Nb_3Sn strands is being completed.*
- *The reversible degradation and the irreversible limits for PIT and RRP strands under transversal loads are investigated.*
- *The non-negligible impact of voids needs to be considered.*
- *The study will be supported with detailed Finite Element simulations (Currently on-going).*

Thank you for the attention !

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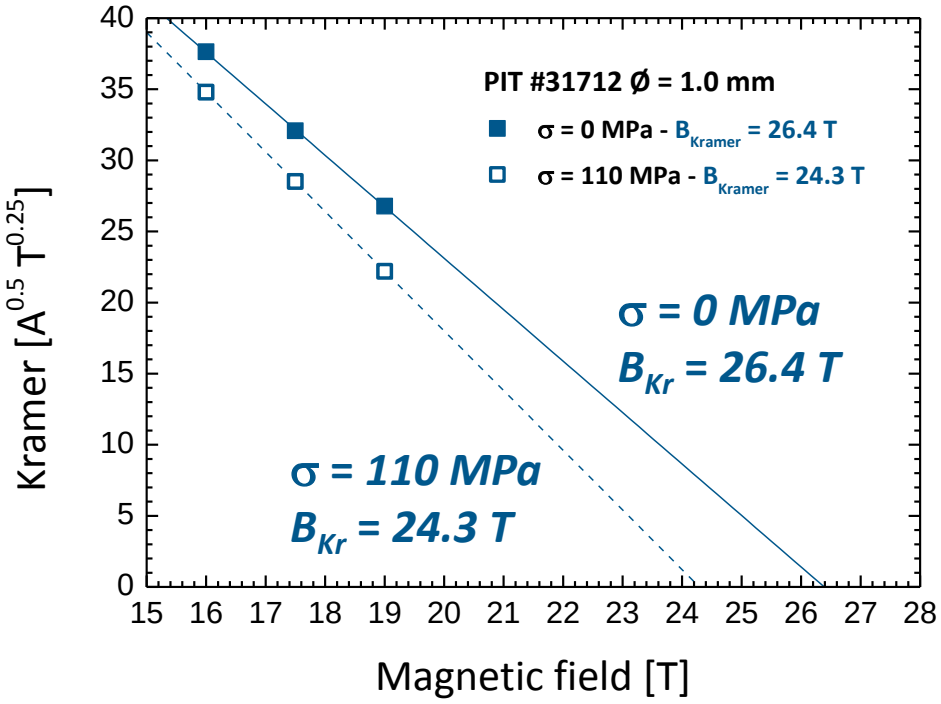
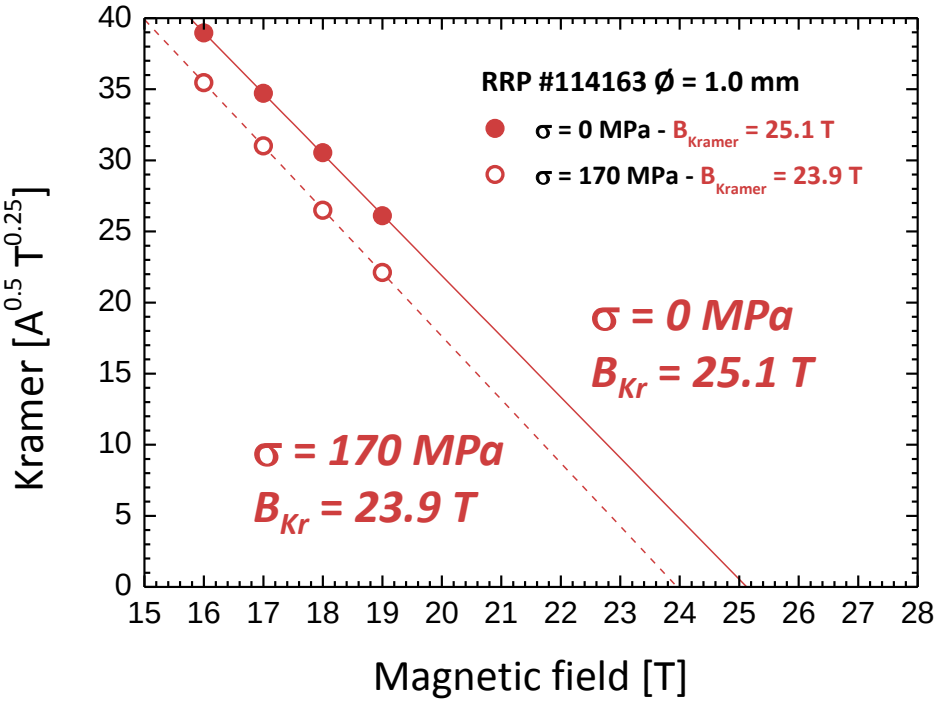
Kramer Plot : PIT 192 and RRP 132/169

Behind the reversible reduction of I_c





The RRP wire exhibits a slower decrease of B_{Kr} with stress