Effect of transverse pressure on Nb_3Sn wires

An electromechanical study

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Motivation

High field dipoles based on high J_c Nb_3Sn Rutherford cables require coil pre-stresses larger than 100 MPa, with peak stress of ~200 MPa at operation

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?

Outline

The WASP concept for I_c vs transverse force measurements

How it works

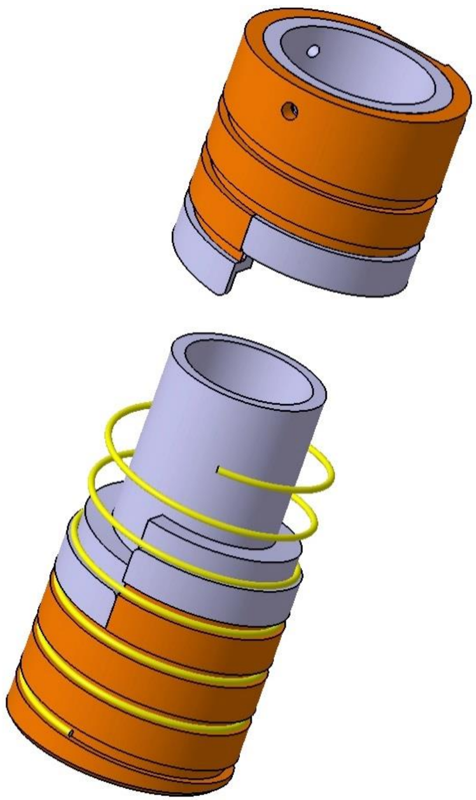
Results on impregnated PIT Nb_3Sn wires

- *Effects of wire rolling*
- *Effects of glass fiber insulation*

Preliminary tests on RRP Nb_3Sn wires

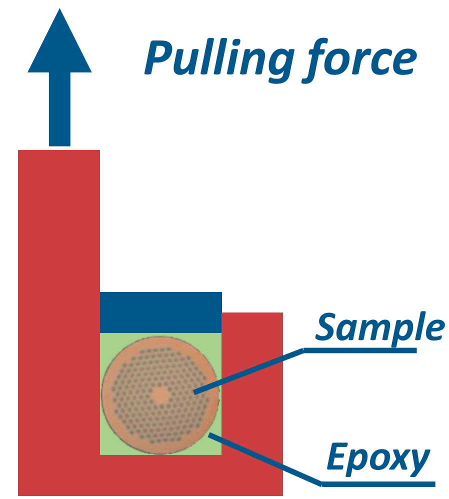
Conclusions & Outlook

The WASP concept for I_c vs. transverse stress



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

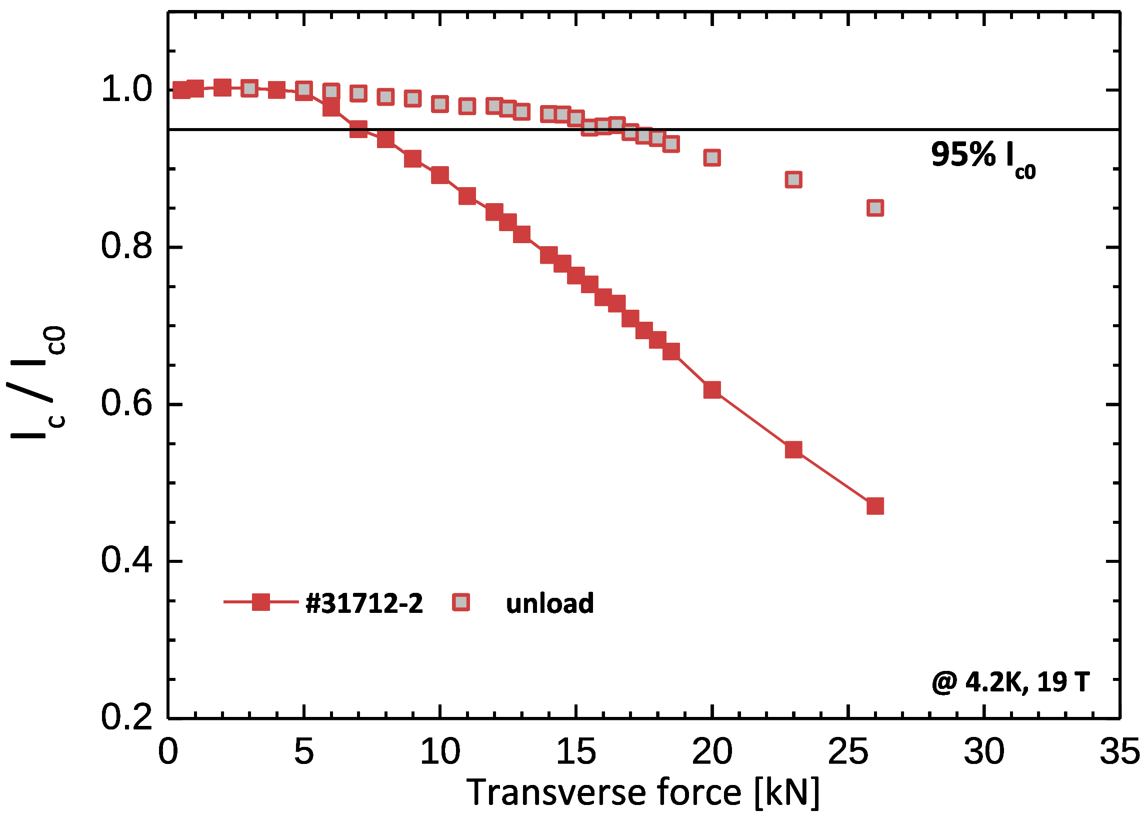
4-WALL + impregnation

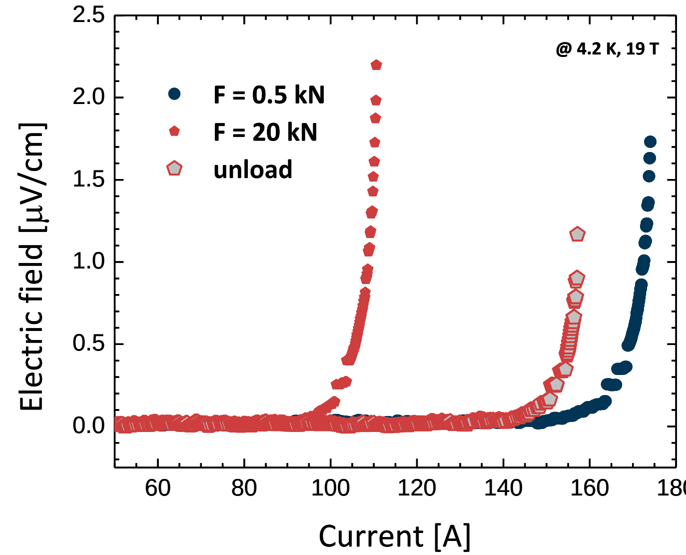


Wire impregnated with epoxy applied stress uniformly distributed

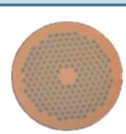
CERN-UNIGE collaboration agreements KE1629/TE and KE2196/TE

How the measurement works

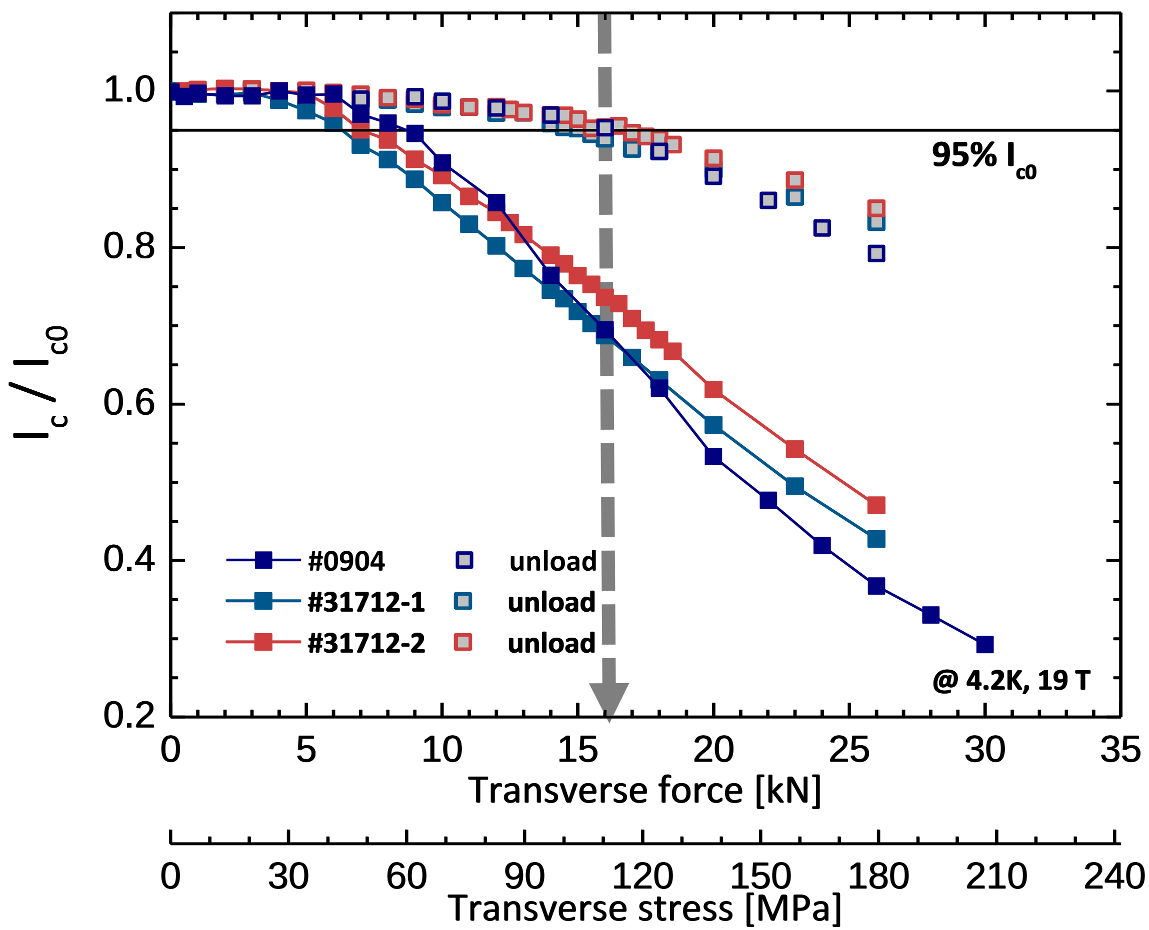




Bruker EST

	Wire ID	Diameter [mm]	# of filaments	Filament size/shape	Cu/nonCu	Non-Cu J_c(12T,4.2K) [A/mm²]
	#31712 #14310 Fresca2	1.0	192	~50 µm round	1.22	2450

I_c vs. transverse stress: Reproducibility



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

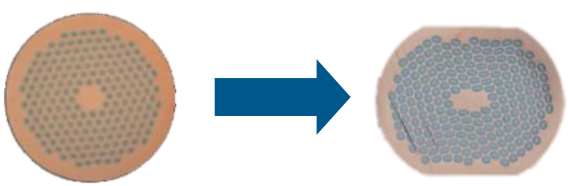
$$\sigma_{irr} = 110\ MPa$$

where

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

Results consistent with data taken in 2012 on wire #0904

Effects of wire rolling on the stress tolerance

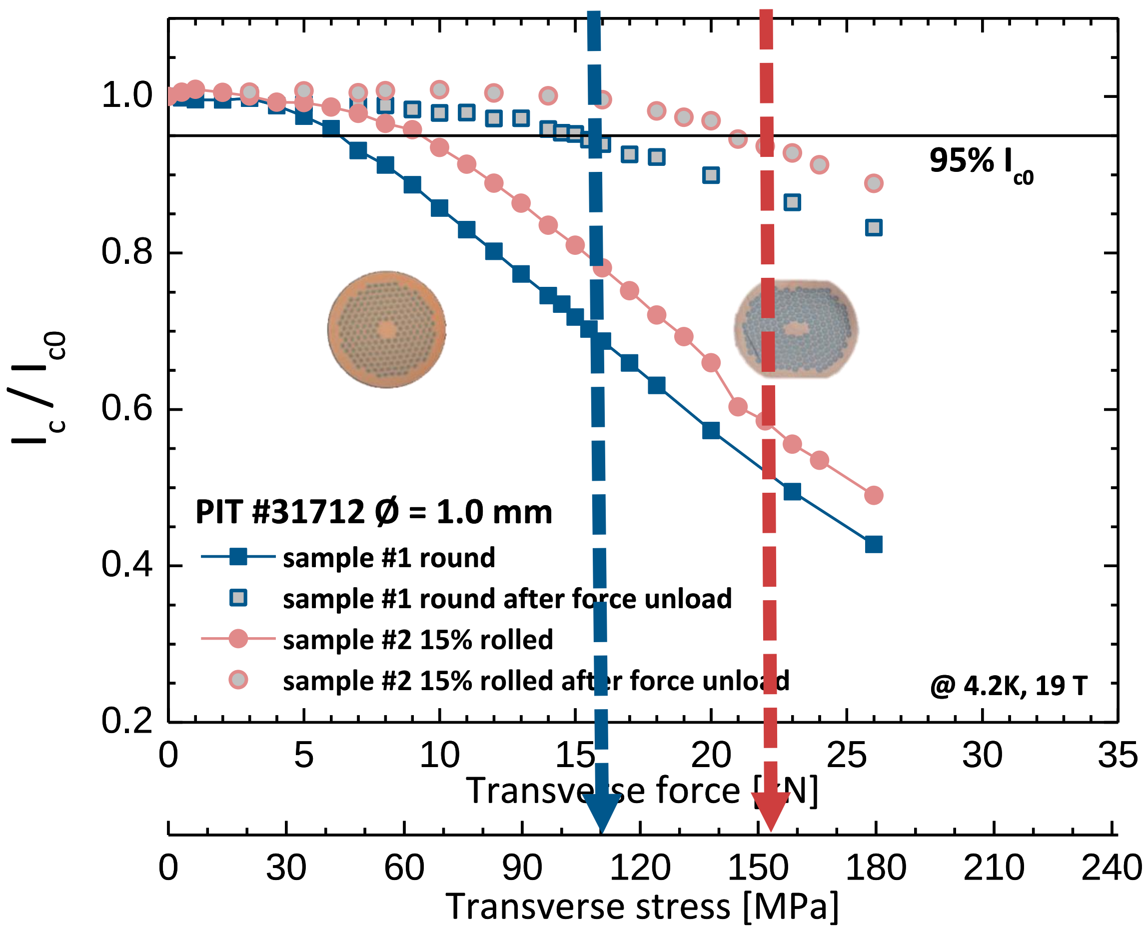


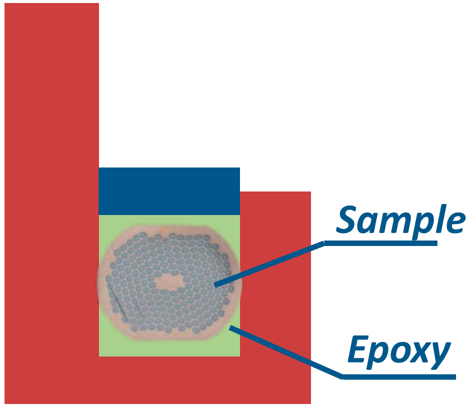
Samples deformed at CERN and reacted at UNIGE

15% rolling to simulate the wire deformation during cabling

Better redistribution of the applied stress in the wire

I_c vs. transverse stress on 15% rolled wires





F_{irr} = 22 kN

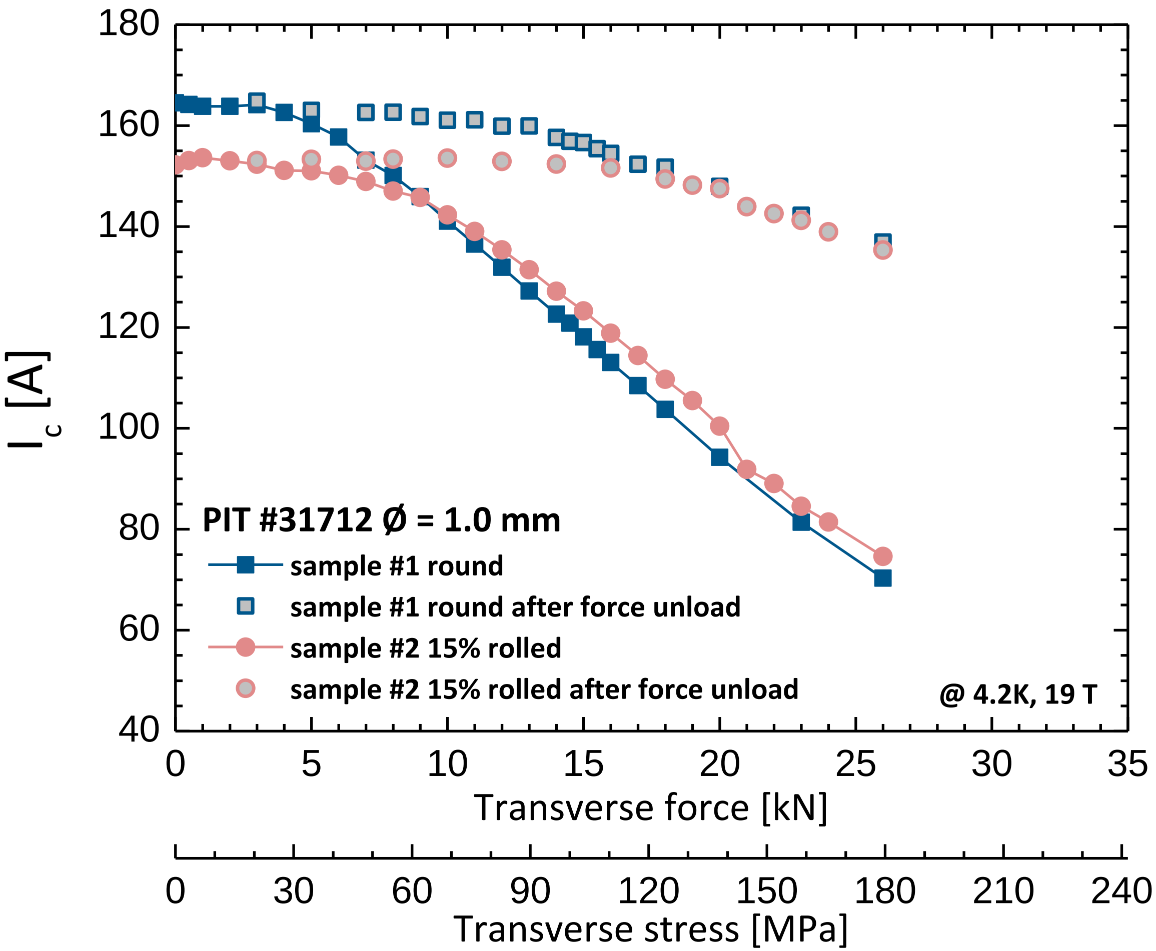
σ_{irr} = 150 MPa

Normalized I_c

Round vs. 15% rolled

Shift of σ_{irr} by ~ 40 MPa

I_c vs. transverse stress: round vs. 15% rolled (2)



Critical current

Round vs. 15% rolled

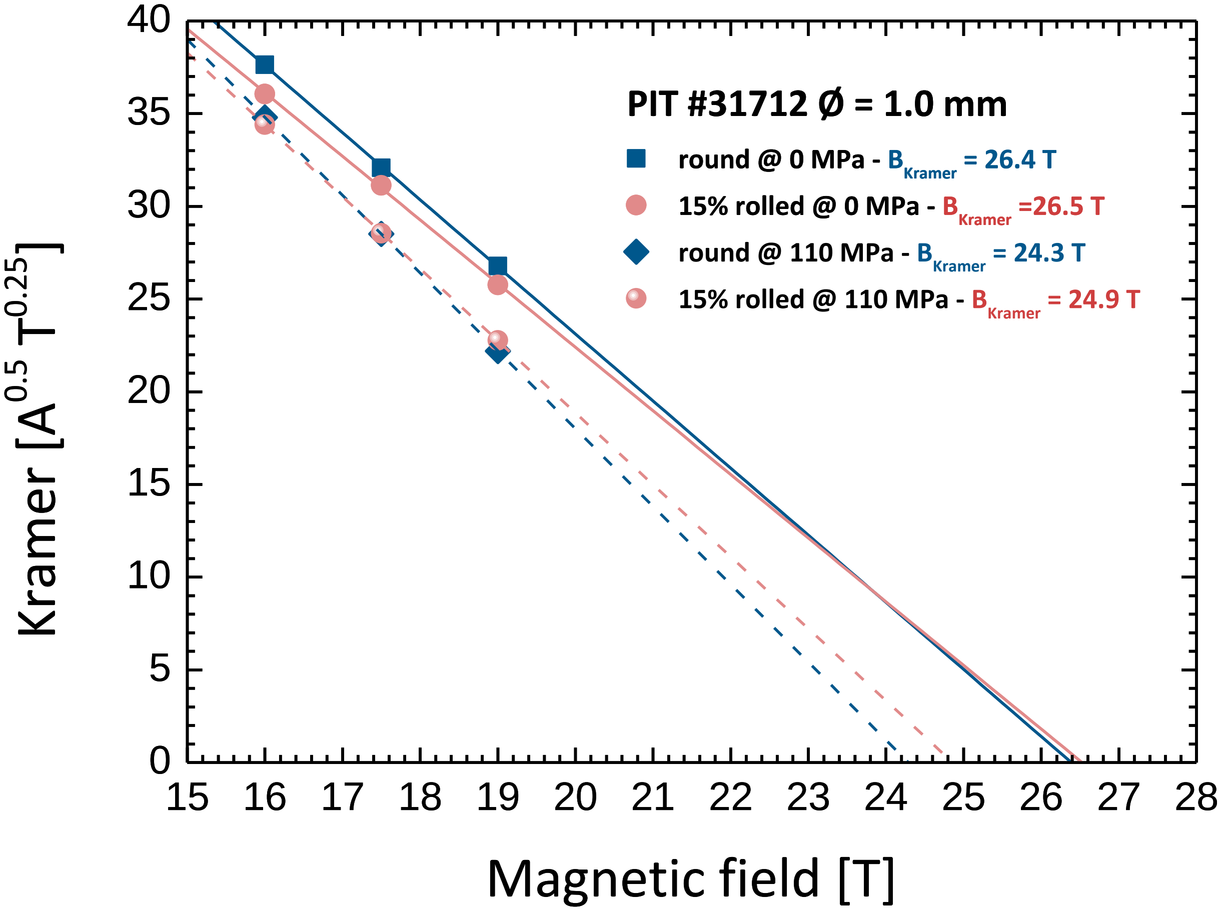
The curve for the rolled wire starts from lower I_c but above 10 kN merges with the curve for the round wire

Same behavior for the unload points
Above 20 kN the points overlap

I_c degradation in PIT wires upon rolling is currently observed

RRP wires exhibits no or negligible degradation upon rolling

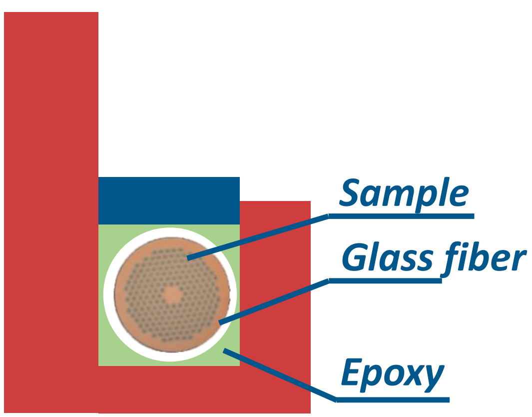
Kramer Plot : round vs. 15% rolled

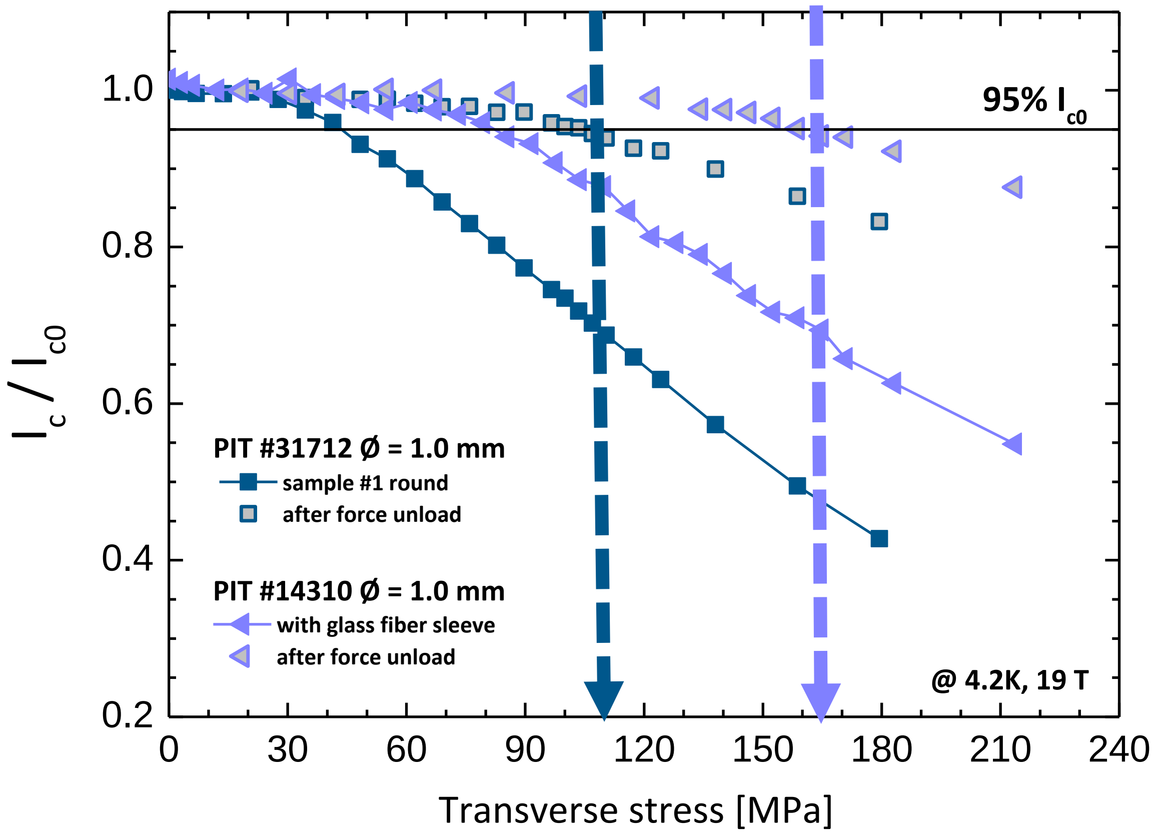


Without any applied load, the Kramer field is the same for the round and the rolled wire

At σ = 110 MPa, the Kramer field decreases by about 2 T

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

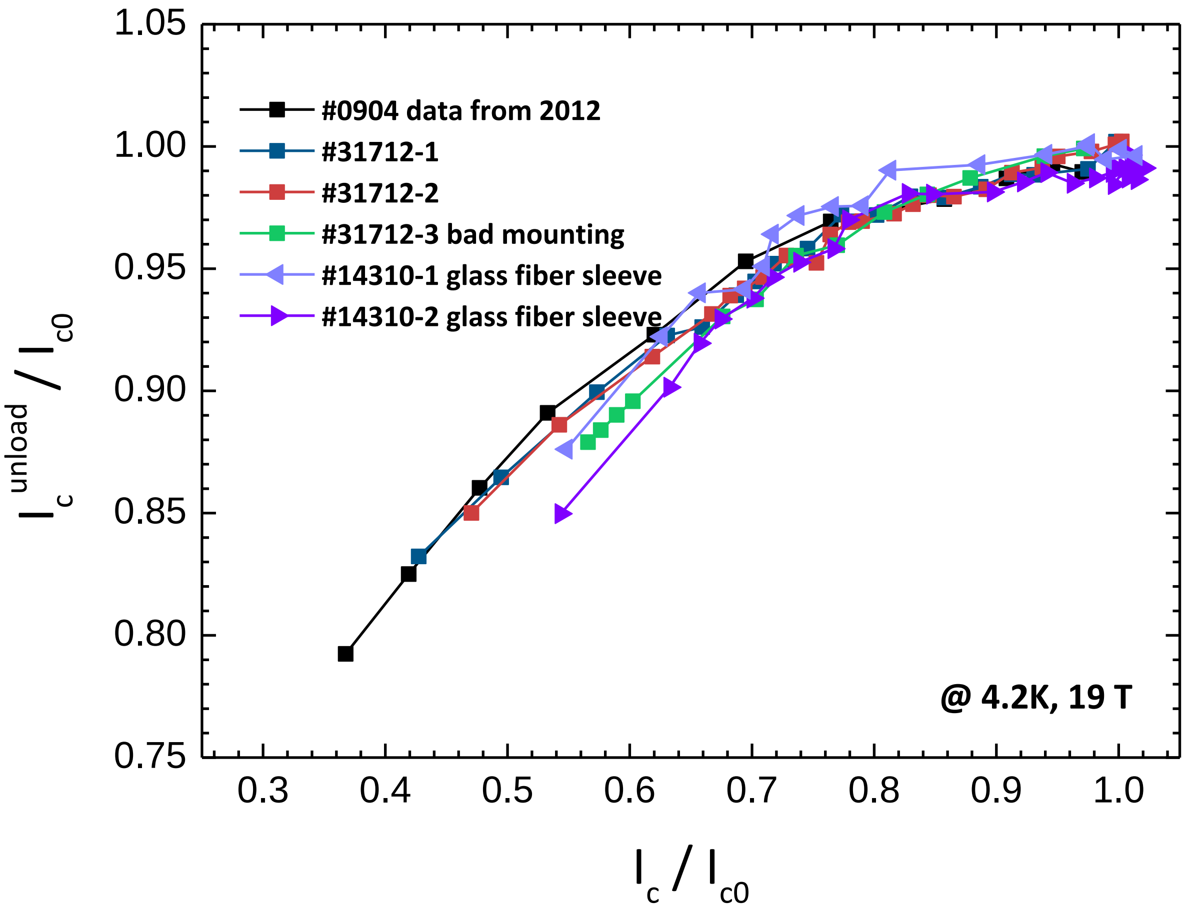


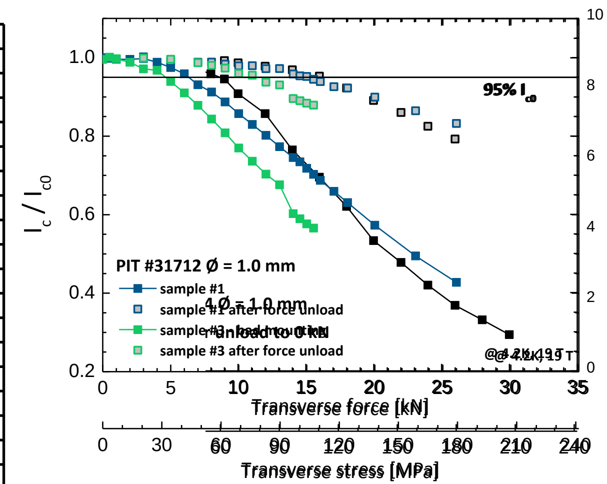


Shift of σ_{irr} by > 50 MPa

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

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

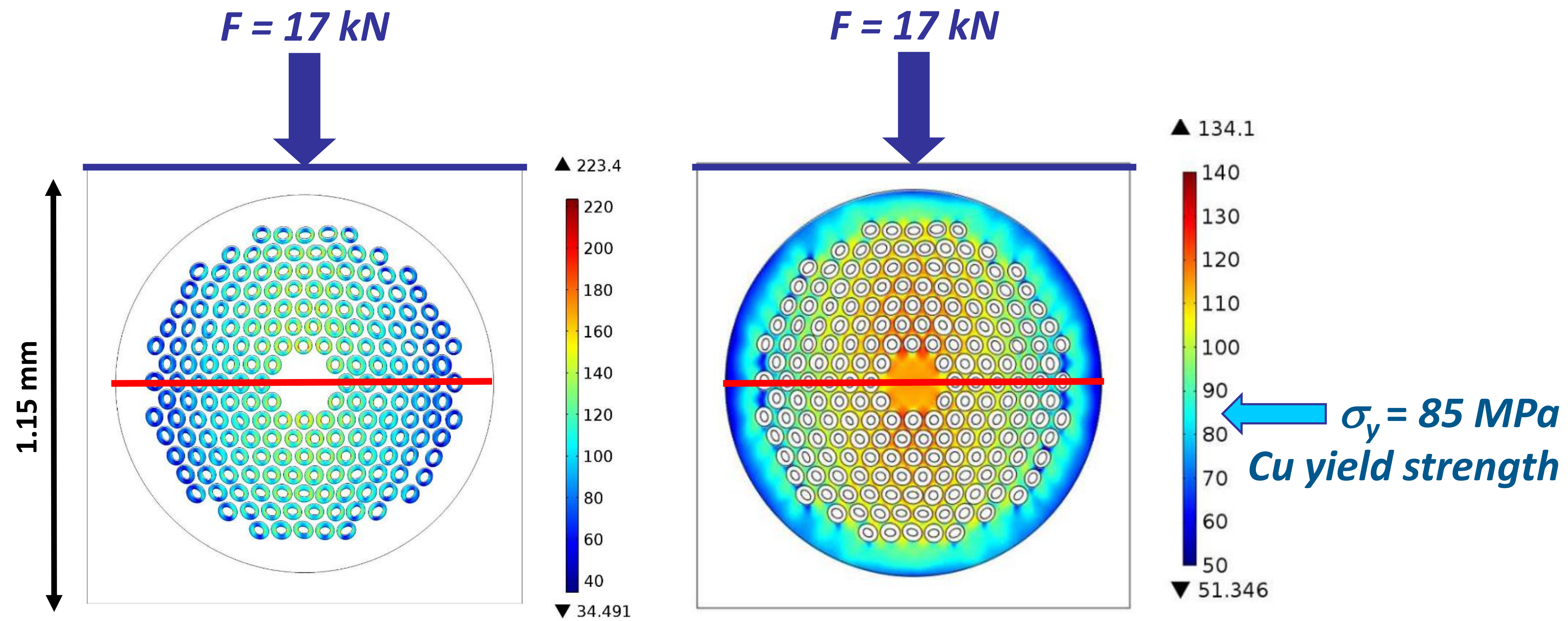




Green curve – bad mounting

… about the mechanisms behind the irreversible degradation …

FEM: stress redistribution in the wire



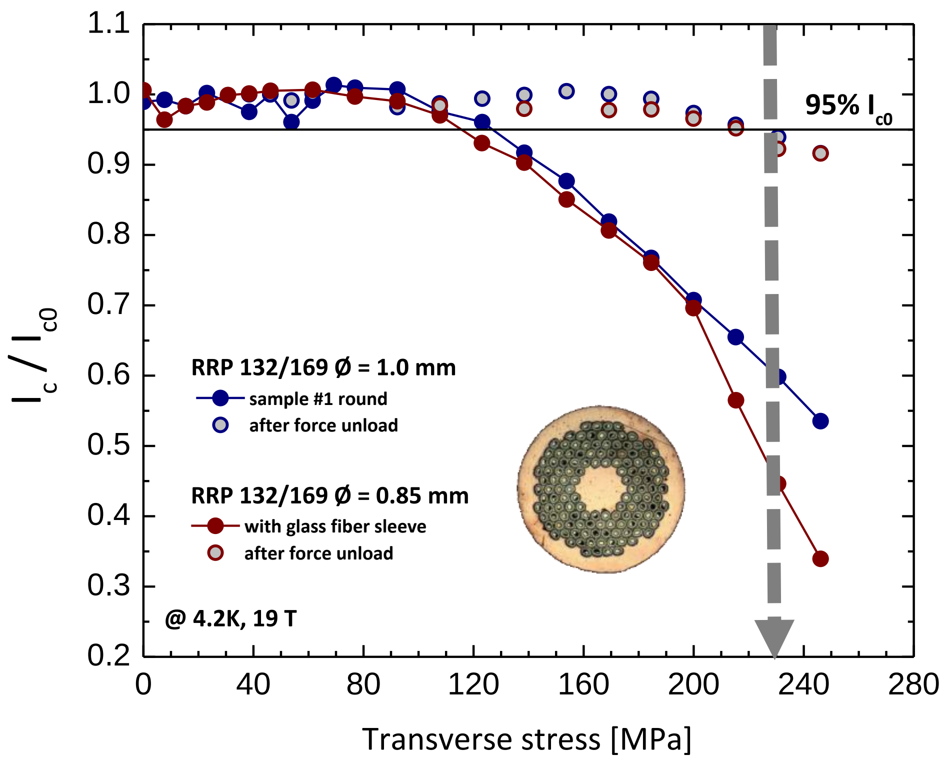
Irreversible degradation is determined by filament cracks and residual strain on Nb_3Sn imposed by plastically deformed Cu

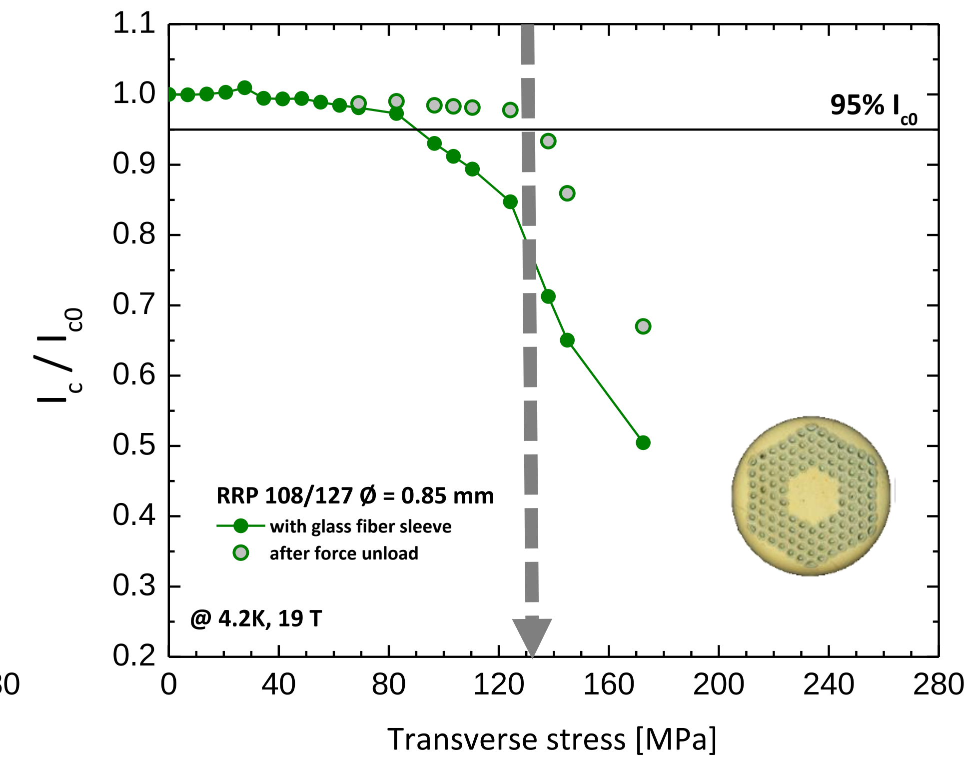
FEM suggests that smaller filaments and higher Cu/nonCu ratio lead to higher stress tolerance

C. Calzolaio, CS et al., SuST 28 (2015) 055014

… some tests on RRP

RRP: 132/169 vs. 108/127





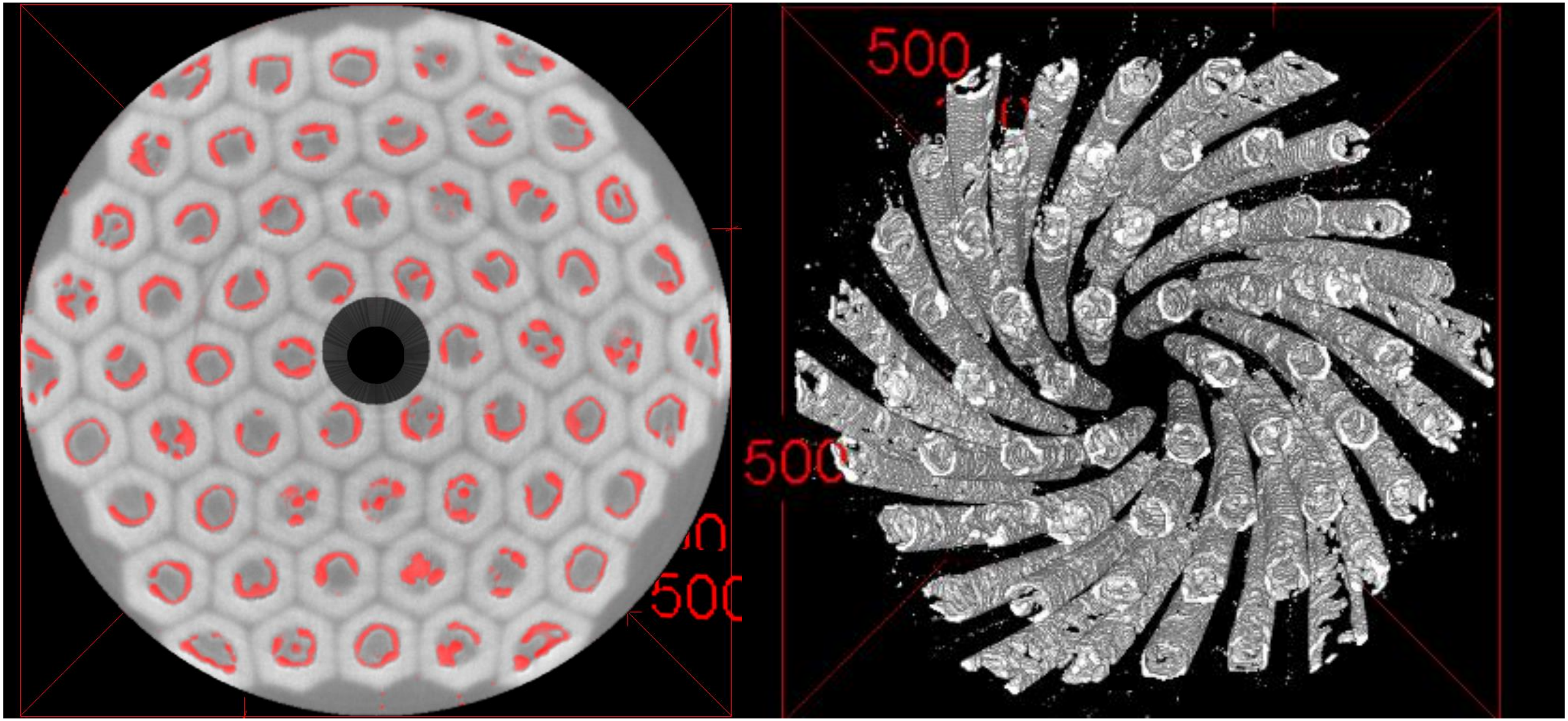
RRP 132/169

Irreversible stress limit > 200 MPa

RRP 108/127

Irreversible stress limit at ~130 MPa

XRD Microtomography
Void morphology in RRP wires



Experiments performed at the European Synchrotron Radiation Facility from Sep 30 to Oct 02 2015

Conclusions

Conclusions and outlook

Consolidating a tool for testing the electromechanical properties of SC wires at conditions "close to" the operation in a Rutherford cable

Tested PIT wires after rolling and with glass fiber insulation

Observed a scaling of I_c after unload vs. I_c upon loading

Preliminary investigations on RRP wires already performed

Include in the FE model the distribution of voids in the superconducting subelements, as obtained from synchrotron microtomography

Perform a systematic investigation on the type of impregnation

Thank You !

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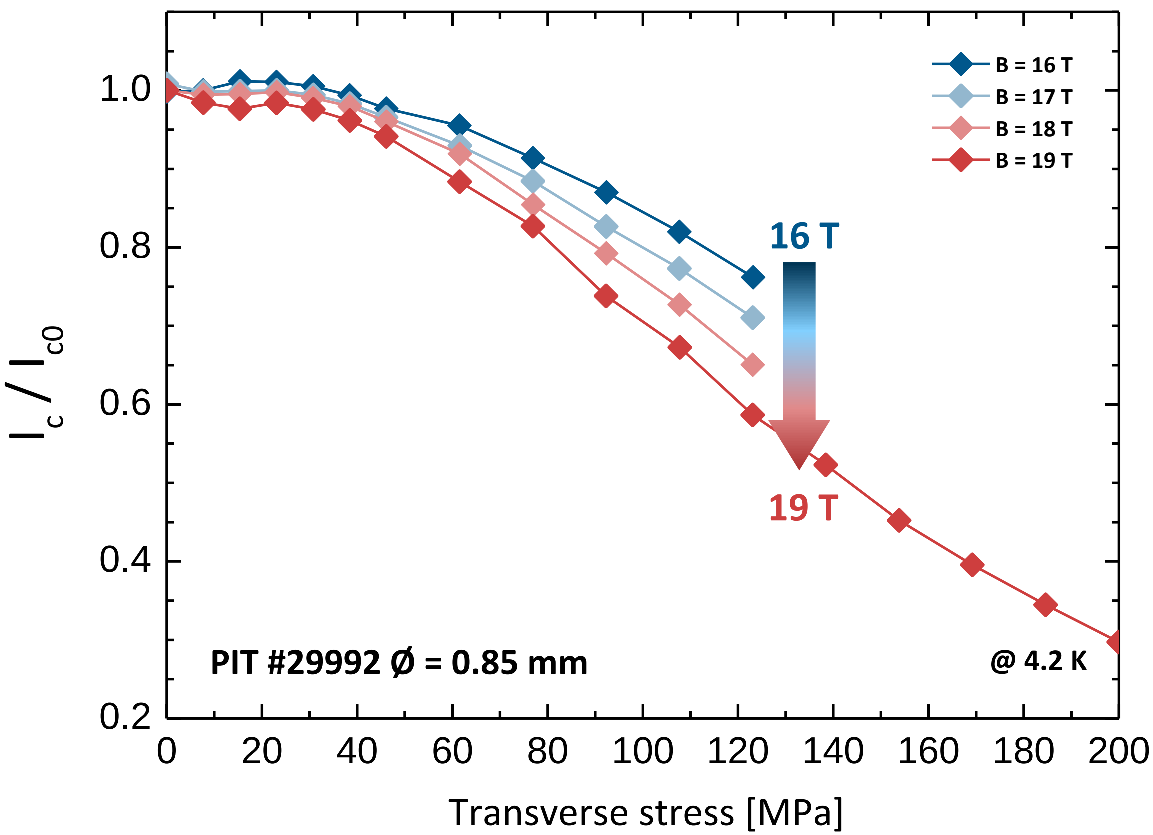
I_c / I_{c0} vs. transverse stress: field dependence



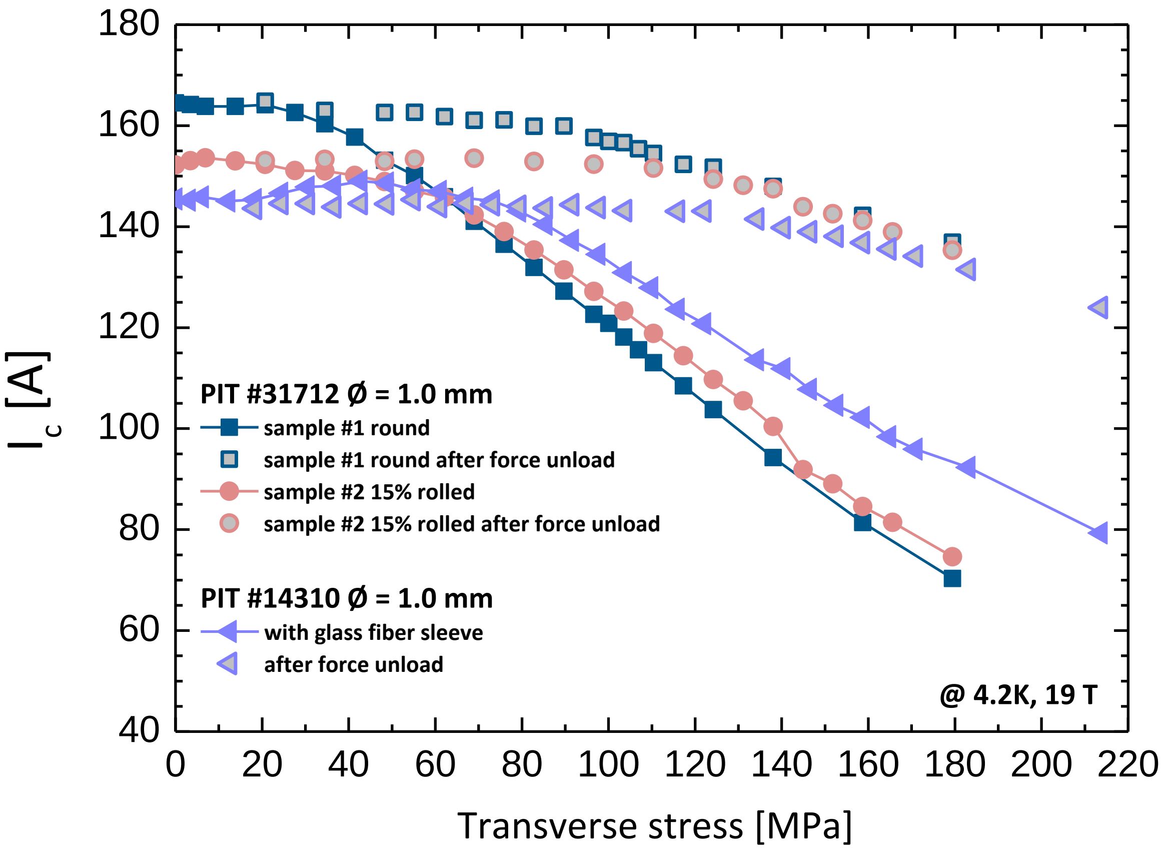
PIT #29992
600C/100h + 625C/200h

Data from 2013

PIT #29992 (Ø= 0.85 mm) was measured in the 1.15 mm groove

$$\sigma_{irr} \approx 130 \text{ MPa and Stress} = \frac{Force}{groove\ length \times groove\ width}$$

I_c vs. transverse stress: glass fiber sleeve – test #1



PIT #31712
620C/100h + 640C/90h

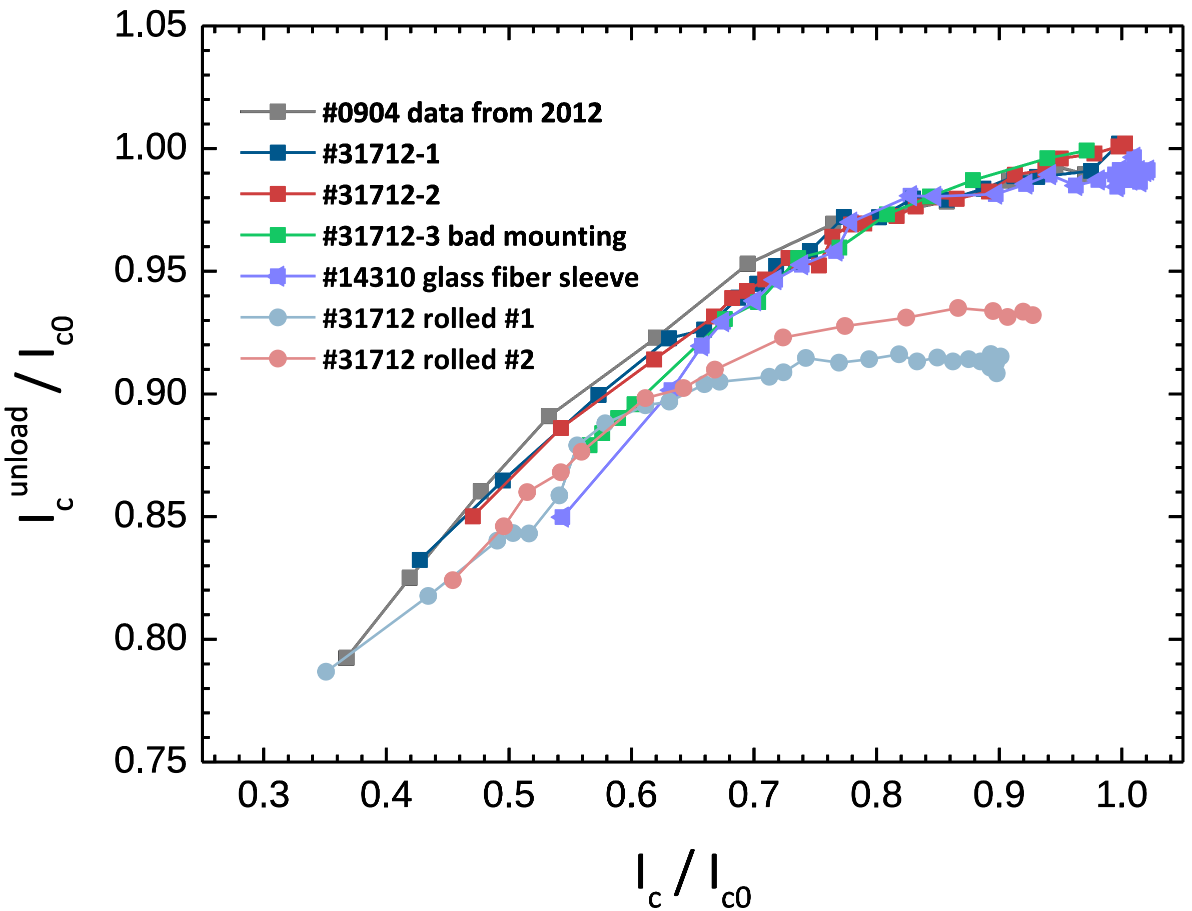
PIT #14310
620C/120h + 650C/90h

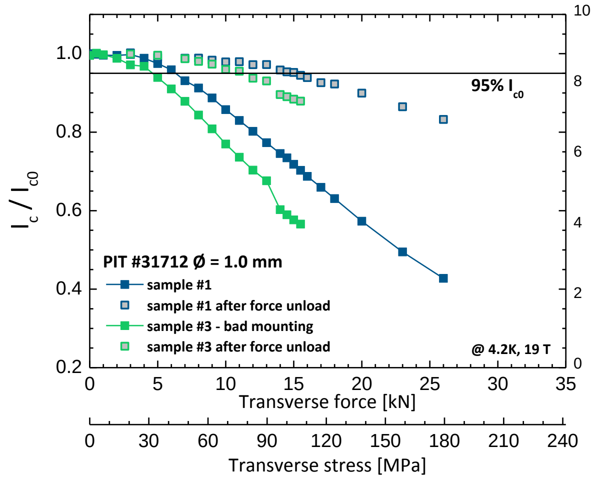
PIT #14310 with glass fiber sleeve was measured in a larger groove (1.30 mm vs 1.15 mm)

$\sigma_{irr} \approx$ 150 MPa !! We need a systematic study of the resins

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

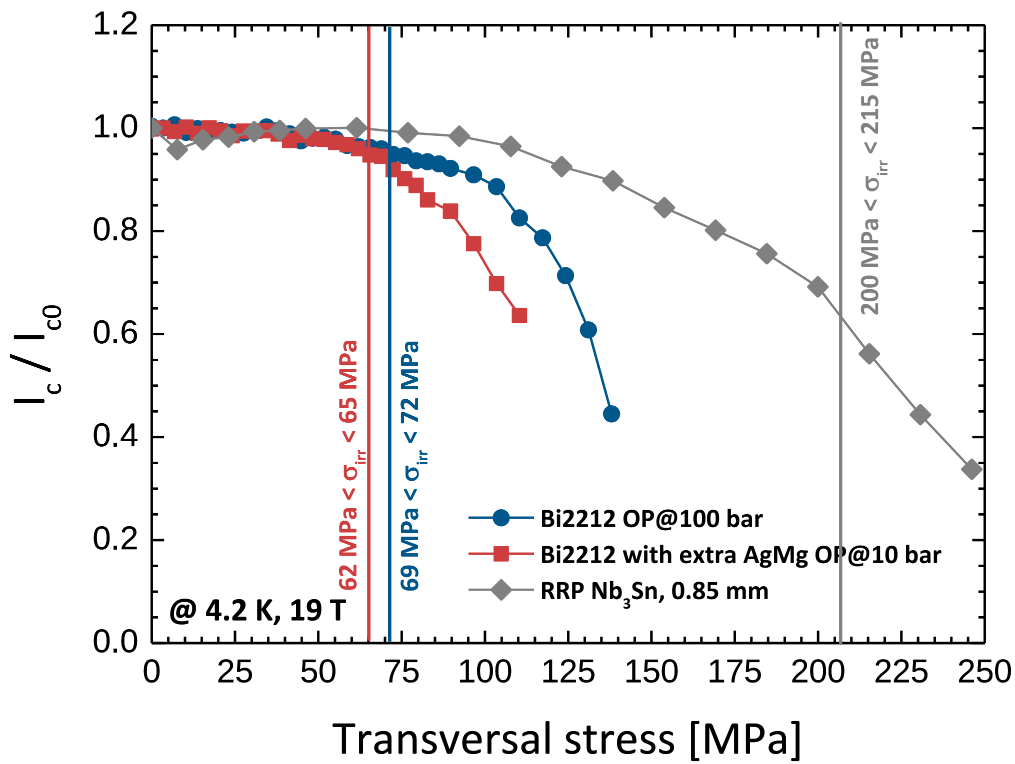
I_c / I_{c0} vs. I_c^{unload} / I_{c0}

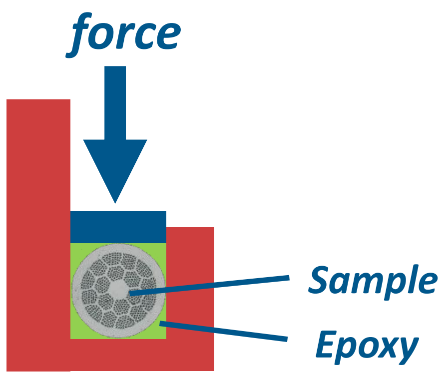




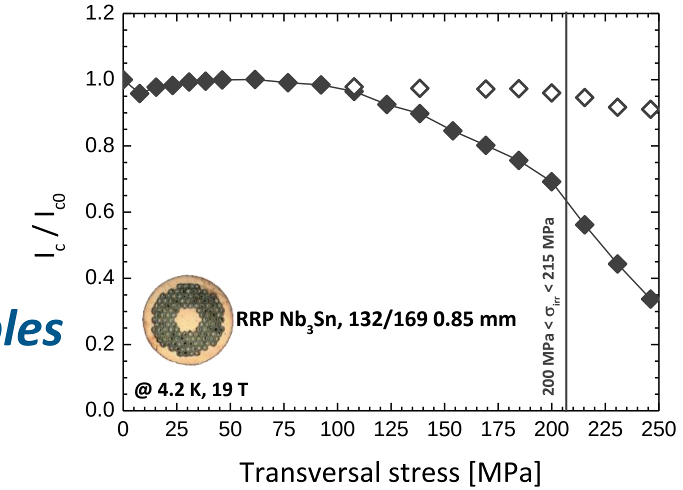
Green curve – bad mounting

Bi2212 wires: transversal stress sensitivity





Wire impregnated with epoxy applied stress uniformly distributed



Irreversible stress limit at ~ 75 MPa

No substantial improvement with OP or extra Mg

Results consistent with old tests on Rutherford cables

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