WireChar Multiphysical characterization of Nb_3Sn wires and REBCO coated conductors

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Outline

- Transverse stress tolerance of Nb_3Sn : results of the measurement campaign on state-of-the-art and R&D wires
  - Irreversible reduction of I_c in PIT and RRP wires submitted to transverse loads, a method to identify the dominant mechanism behind the degradation
  - Effect of the wire rolling on the irreversible stress limit, FE simulations and experiments
  - First experiments on Distributed Tin (DT) Nb_3Sn wires
- A new experiment to test the delamination strength of REBCO coated conductors
- Summary and conclusions

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Stresses in Nb_3Sn-based accelerator magnets

There is a need for higher-field magnets in view of particle accelerators beyond LHC

The projects of the 11 T dipoles and the MQXF quadrupoles for HL-LHC provided very relevant experience on how critical is stress management for Nb_3Sn-based magnets

The combination of the electromagnetic forces with the pre-compression and the thermomechanical effects exposes the brittle and strain sensitive Nb_3Sn to the risk of degradation

Several works investigated Rutherford cables subjected to transverse pressure at room temperature and at low temperature

P. Ebermann *et al.,* Supercond. Sci. Technol., 31 (2018) 065009 DOI: 10.1088/1361-6668/aab5fa

K. Puthran *et al.,* IEEE TAS, 33 (2023) 8400406 DOI: 10.1109/TASC.2023.3241568

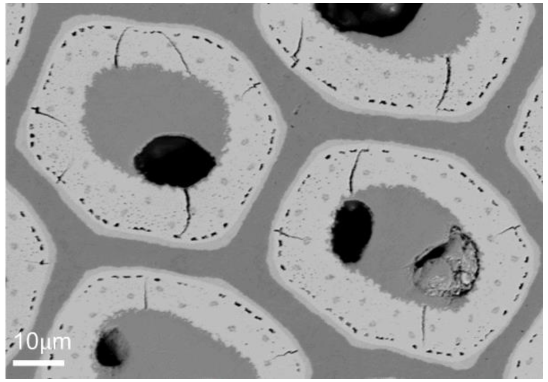
G. De Marzi *et al.,* Sci. Rep., 11 (2021) 7369 DOI: 10.1038/s41598-021-86563-x

Our experiments focused on the critical current degradation of state-of-the-art and R&D wires submitted to transverse pressure at 4.2 K

Degradation mechanisms and irreversible reduction of I_c

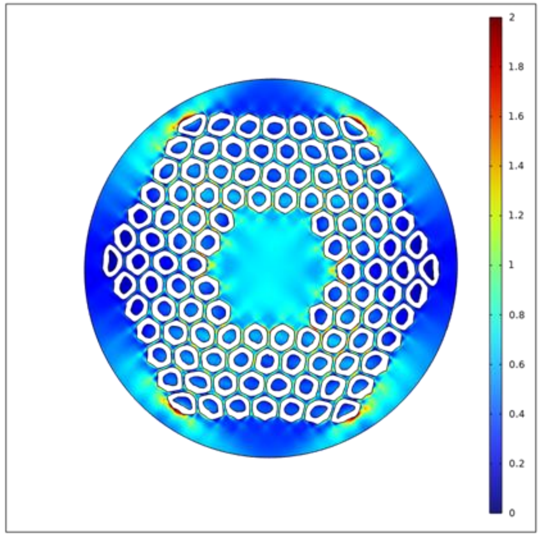
Two mechanisms govern the irreversible reduction of the critical current

- Formation of cracks in the Nb_3Sn filaments due, for instance, to the stress concentration at the voids



Cracks generate a reduction of the current carrying cross section ⇒ I_c^{unload}/I_{c0} is independent of the magnetic field

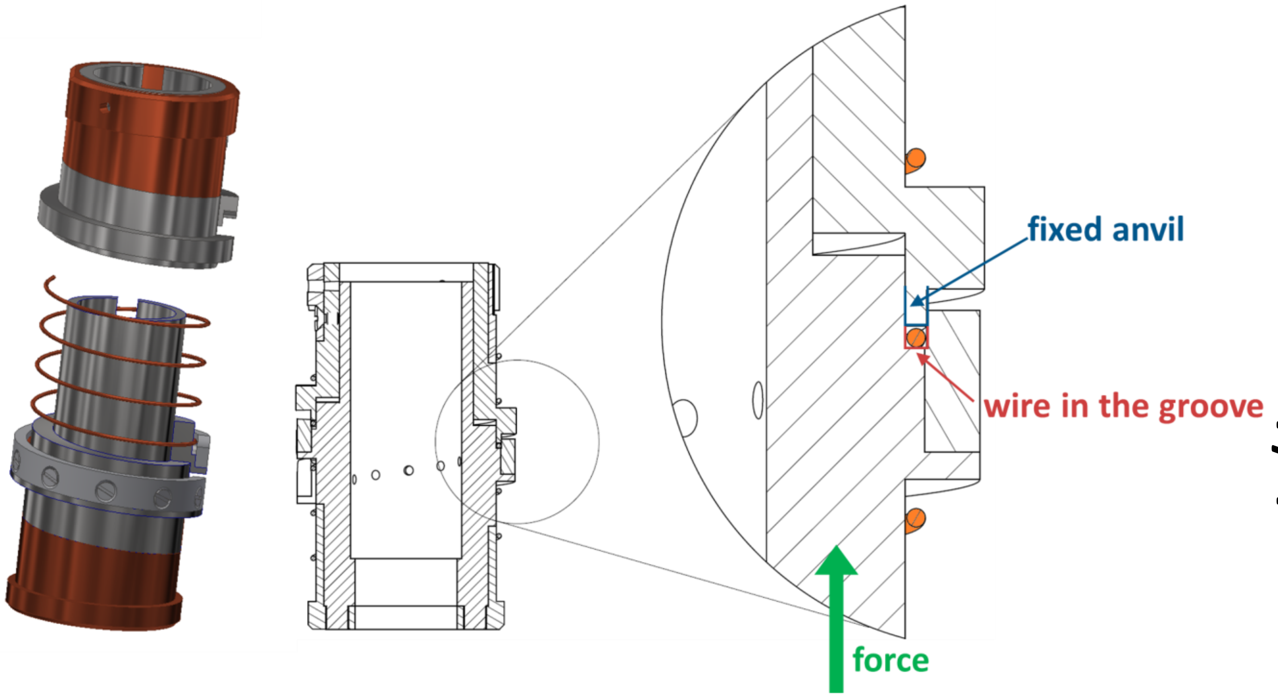
- Plastic deformation of the matrix and residual stress on the Nb_3Sn filaments

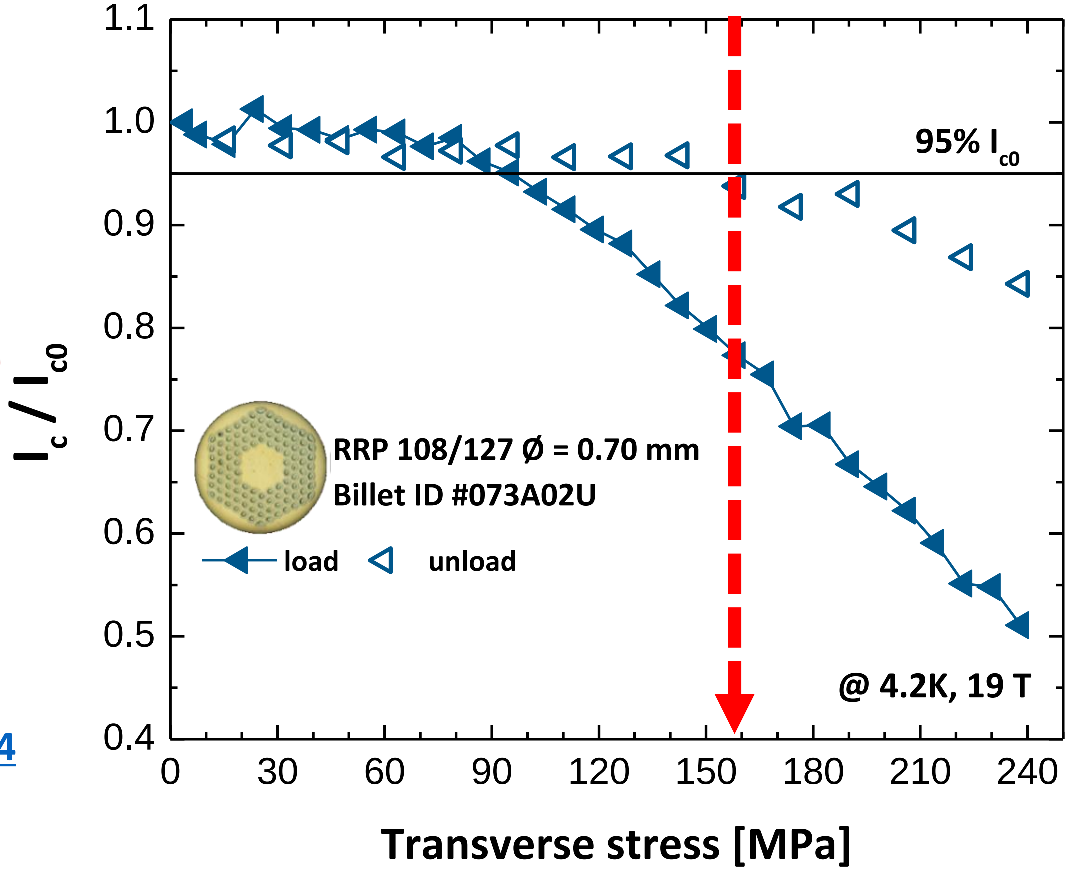


Residual stress induces a permanent reduction of B_{c2} after unload ⇒ I_c^{unload}/I_{c0} depends on of the magnetic field

Tolerance to transverse stress of a single wire

Electromechanical tests on Nb_3Sn wires impregnated with epoxy



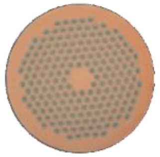
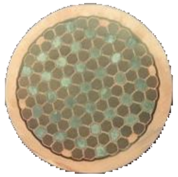


The WASP concept was adapted to transverse loads by
B. Seeber et al., IEEE TAS 17 (2007) 2643, DOI: 10.1109/TASC.2007.897934

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

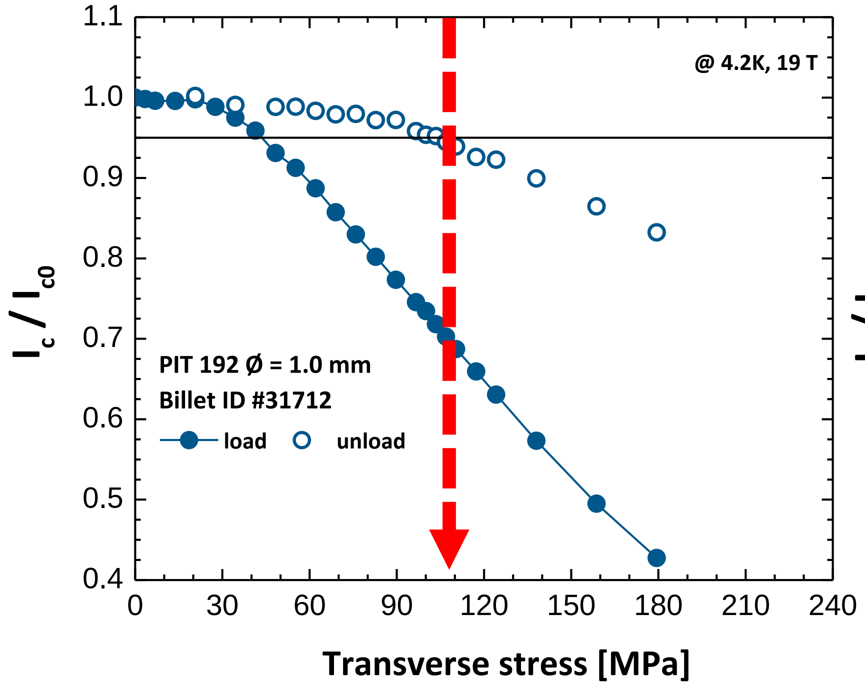
Here the irreversible stress limit is σ_{irr} (B=19T)= 155 MPa (force dived by groove area)

What has been tested – Catalogue of the Wires

	Technology	# of subelements	Cu/non-Cu	Subelement size/shape	Diameter	I_c(16 T)	Wire ID	
	PIT	192	1.22	50 μm round	1.0 mm	340 A	#0904 #31712 #14310	FRESCA-2
				43 μm round	0.85 mm	240 A	#29992	
	RRP	108/127	1.2	~55 μm	0.85 mm	280 A	#14753 #14516 (Ta) #76A08U #A02U4014 #271A05	MQXF
				~45 μm	0.7 mm	160 A	#073A02 #271A05	11 T
	DT		0.3		1.2 mm	680 A	R&D	

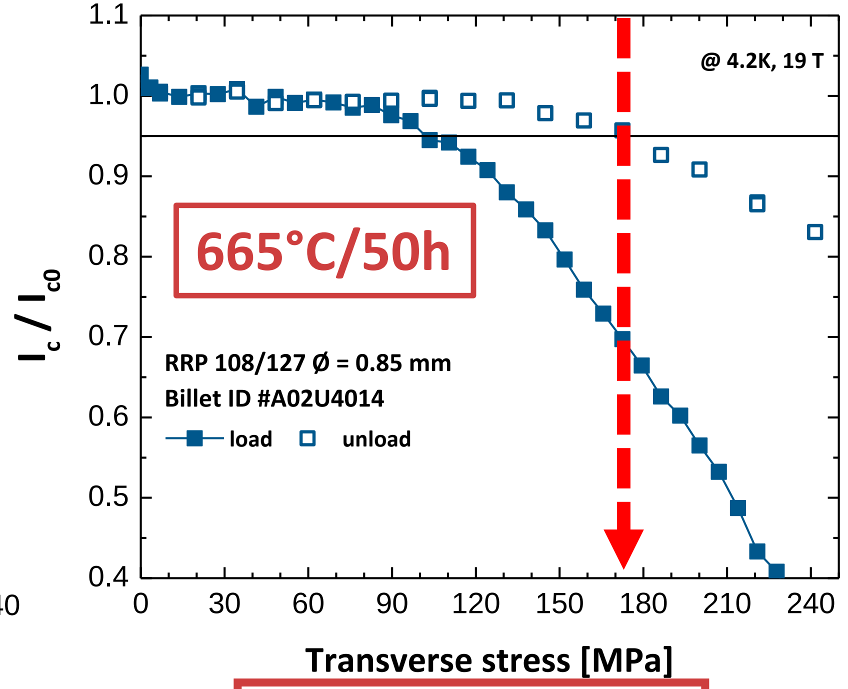
Irreversible stress limits at B = 19 T

PIT, Ø = 1.0 mm
Tested in a 1.15 mm groove



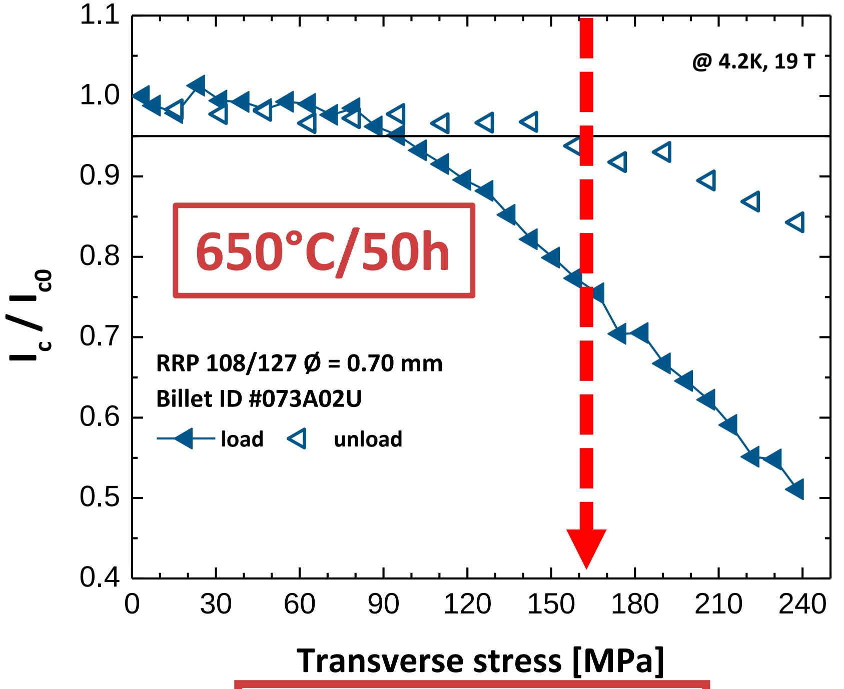
$\sigma_{irr} \approx$ **110 MPa**

RRP, Ø = 0.85 mm
Tested in a 1.15 mm groove



$\sigma_{irr} \approx$ **175 MPa**

RRP, Ø = 0.7 mm
Tested in a 1 mm groove

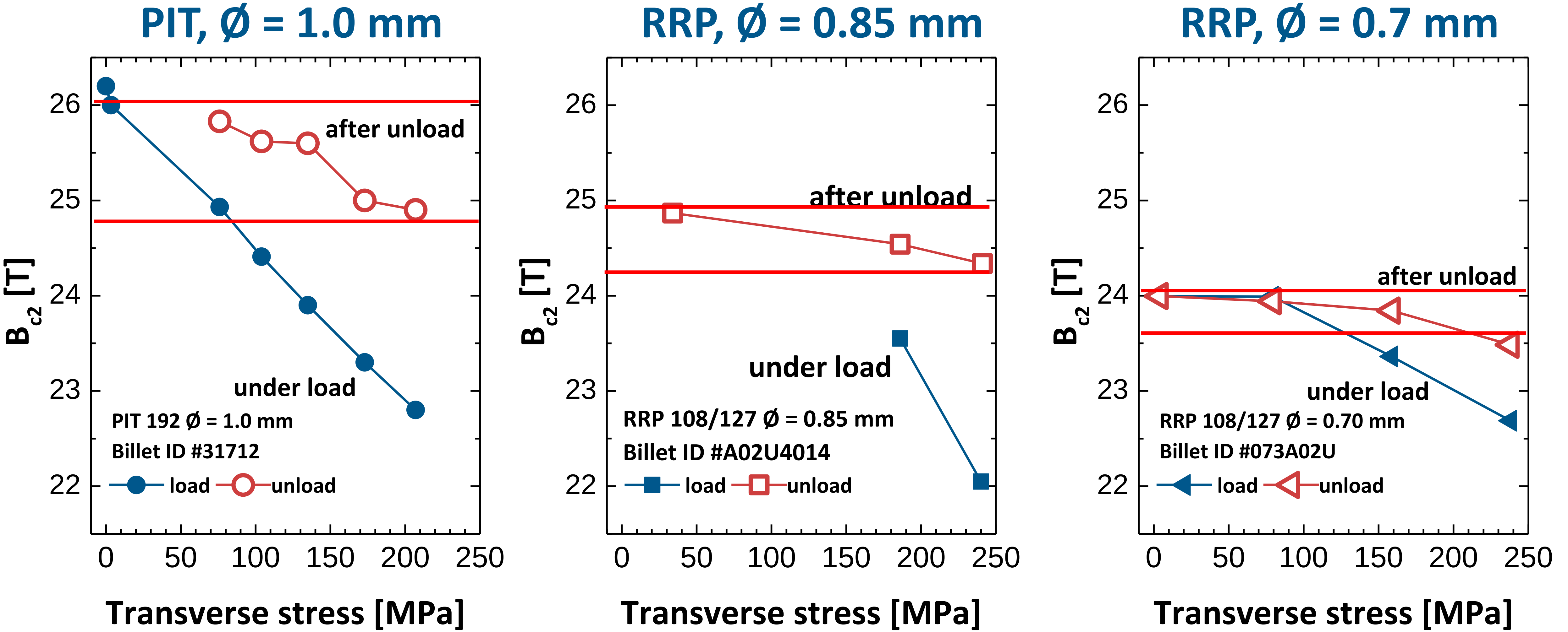


$\sigma_{irr} \approx$ **155 MPa**

- RRP wires are definitely more robust than PIT wires
- A reduction of σ_{irr} is measured for the RRP wire reacted at lower temperature (650°C)

CS *et al.*, Supercond. Sci. Technol., 36 (2023) 075001 DOI: 10.1088/1361-6668/acca50

Comparison of B_{c2} under load and after unload
(as determined from Kramer extrapolation)



After unload from σ = 210 MPa $\Delta B_{c2}^{unload} \approx 1$ T

After unload from σ = 240 MPa $\Delta B_{c2}^{unload} \approx 0.5$ T

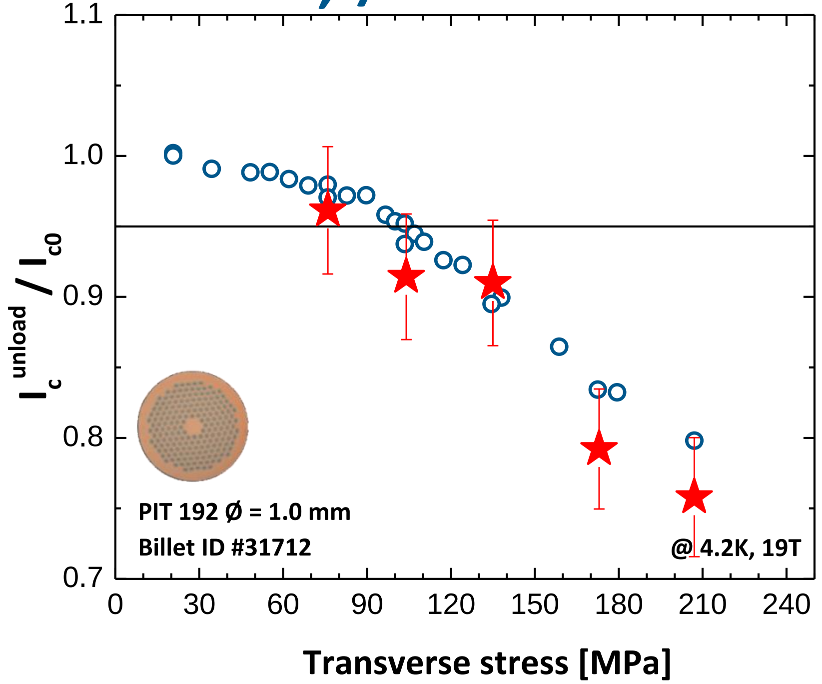
After unload from σ = 240 MPa $\Delta B_{c2}^{unload} \approx 0.5$ T

CS *et al.*, Supercond. Sci. Technol., 36 (2023) 075001 DOI: 10.1088/1361-6668/acca50

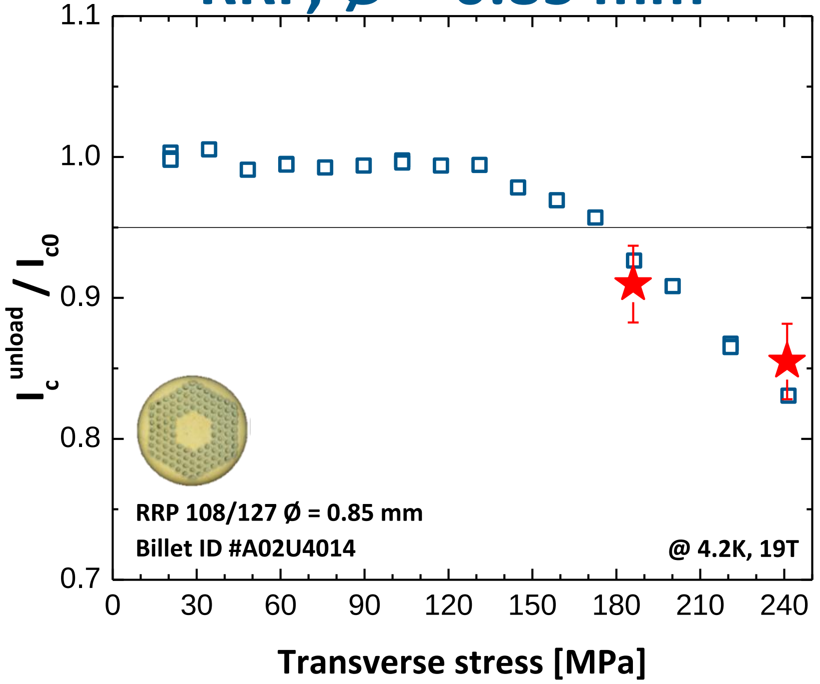
$$I_c^{unload}(B) = f\,C\left[\frac{B_{c2}^{unload}}{B}\right]^{0.5}\left[1-\frac{B}{B_{c2}^{unload}}\right]^2$$

Measured I_c^{unload} (open blue points) vs expected degradation from residual stress (solid red stars)

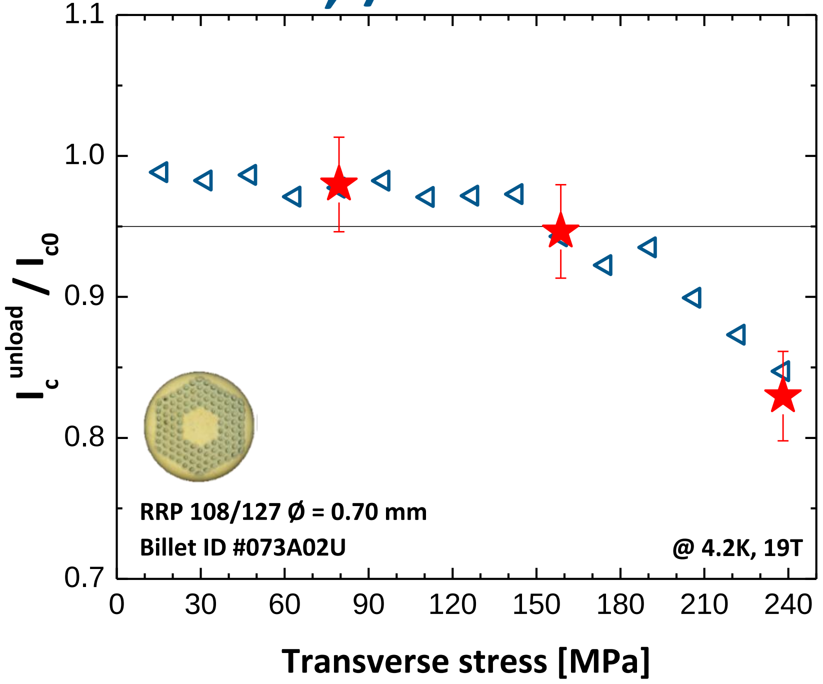
PIT, Ø = 1.0 mm



RRP, Ø = 0.85 mm



RRP, Ø = 0.7 mm



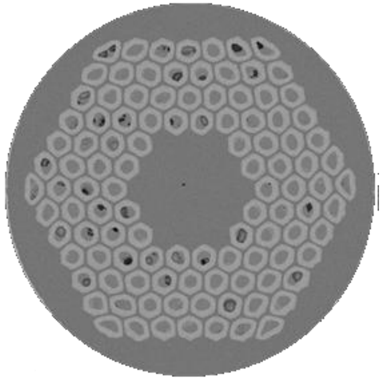
The observed permanent degradation of I_c after unload from σ up to 240 MPa originates mainly from the residual stress on Nb_3Sn due to the plastic deformation of Cu

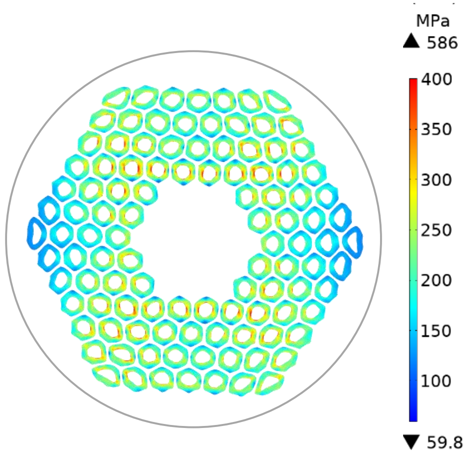
The effect of cracks seems negligible up to very high transverse stress values

CS *et al.*, Supercond. Sci. Technol., 36 (2023) 075001 DOI: 10.1088/1361-6668/acca50

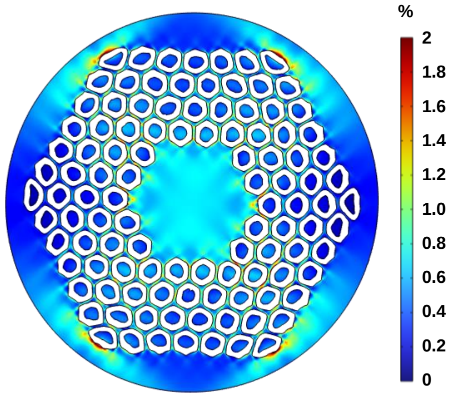
2D FE electromechanical models with PSI

An independent confirmation of the conclusions

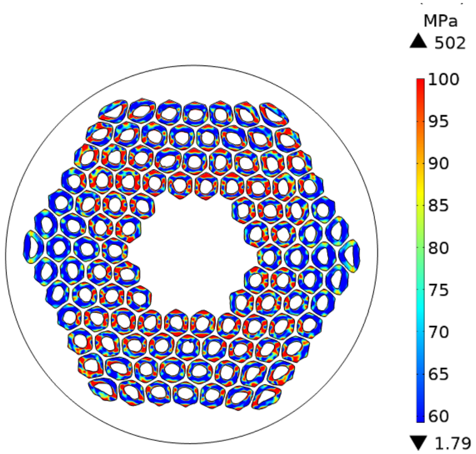




von Mises stress in Nb_3Sn under load at 30 kN



Plastic strain in Cu after unload from 30 kN



von Mises stress in Nb_3Sn after unload from 30 kN (residual stress)

2D plain strain model to visualize the stress and strain distributions in the wire reproducing the experimental conditions of an epoxy impregnated wire under transverse load

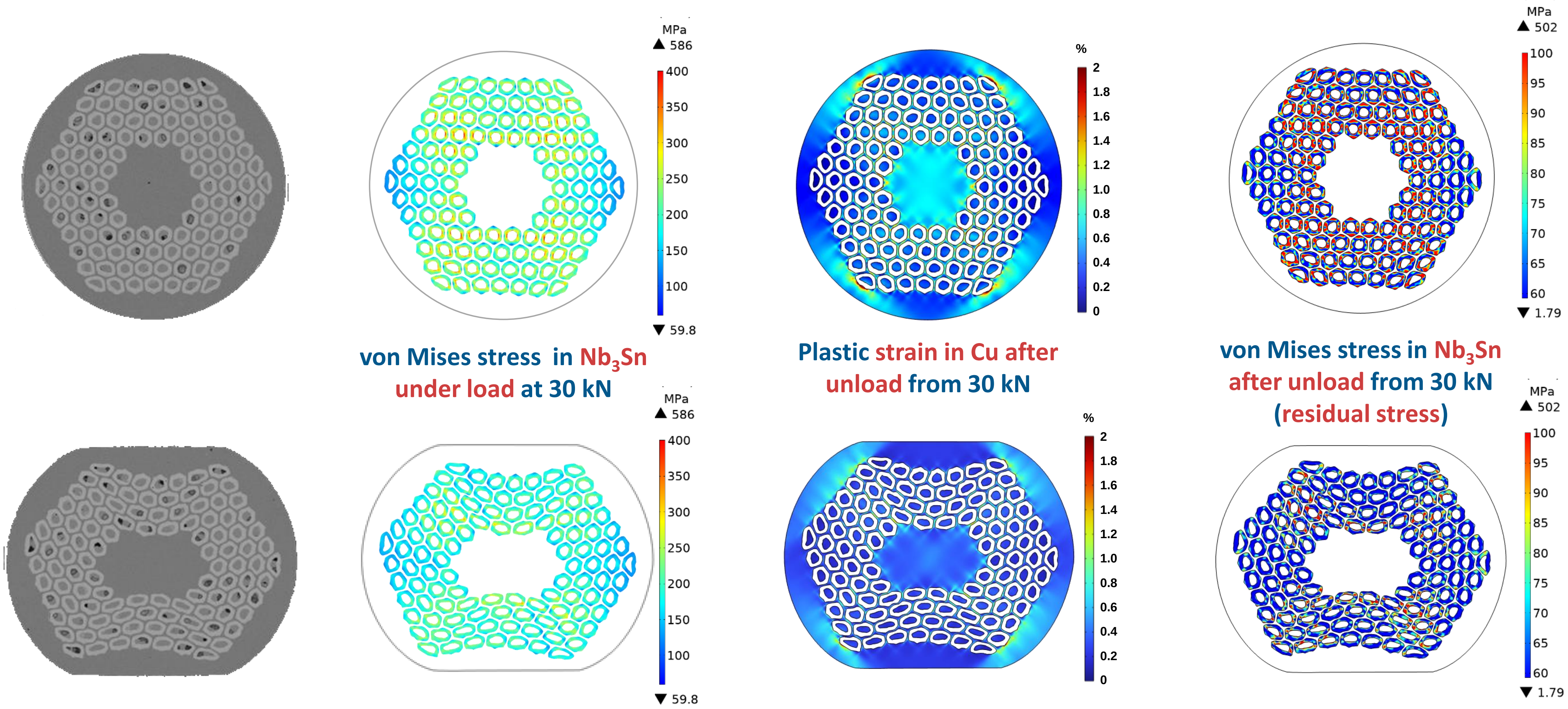
Three domains: Nb_3Sn, Cu and bronze – no voids

T. Bagni, C. Calzolaio *et al.*, in preparation

2D FE electromechanical models with

PAUL SCHERRER INSTITUT

Round vs 15%-rolled wire



von Mises stress in Nb_3Sn under load at 30 kN

Plastic strain in Cu after unload from 30 kN

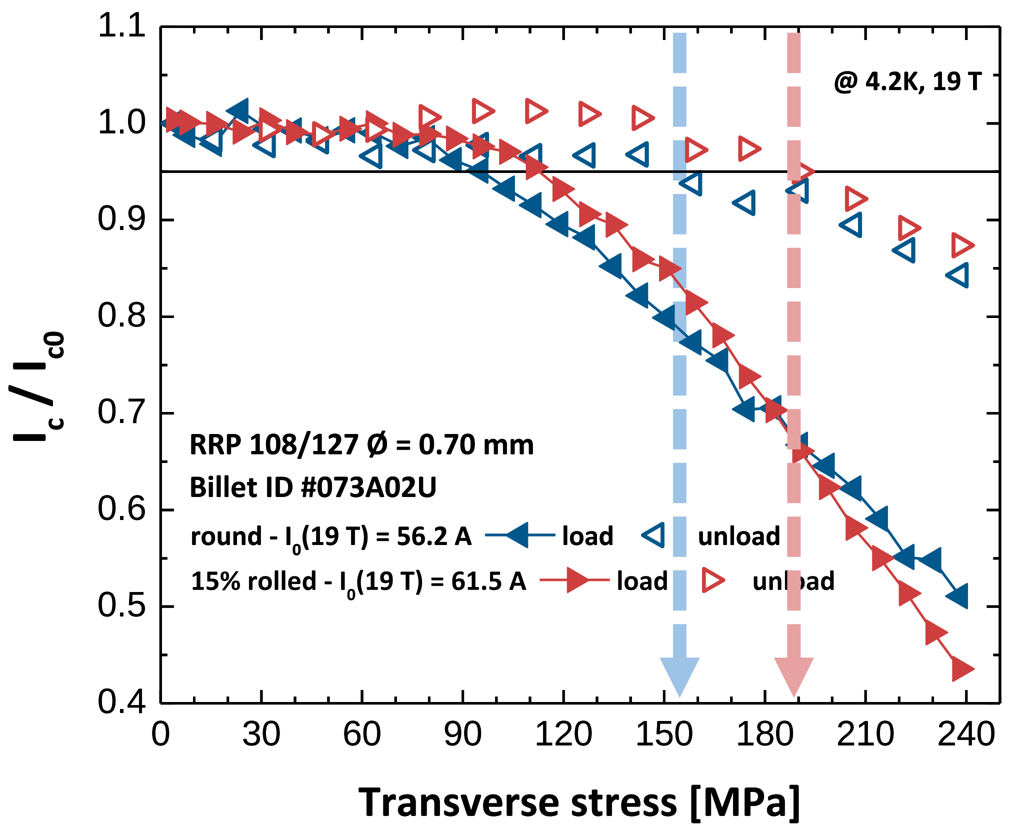
von Mises stress in Nb_3Sn after unload from 30 kN (residual stress)

According to the simulation, 15% rolling is associated with a reduction of the residual stresses

This is due to a better redistribution of the load between matrix and superconductor

Effects of wire rolling on the stress tolerance

Experimental verification of the outcome of the simulations



Round wire
I_{c0}(B=19T)= 56.2 A
$\sigma_{irr} \approx$ 155 MPa

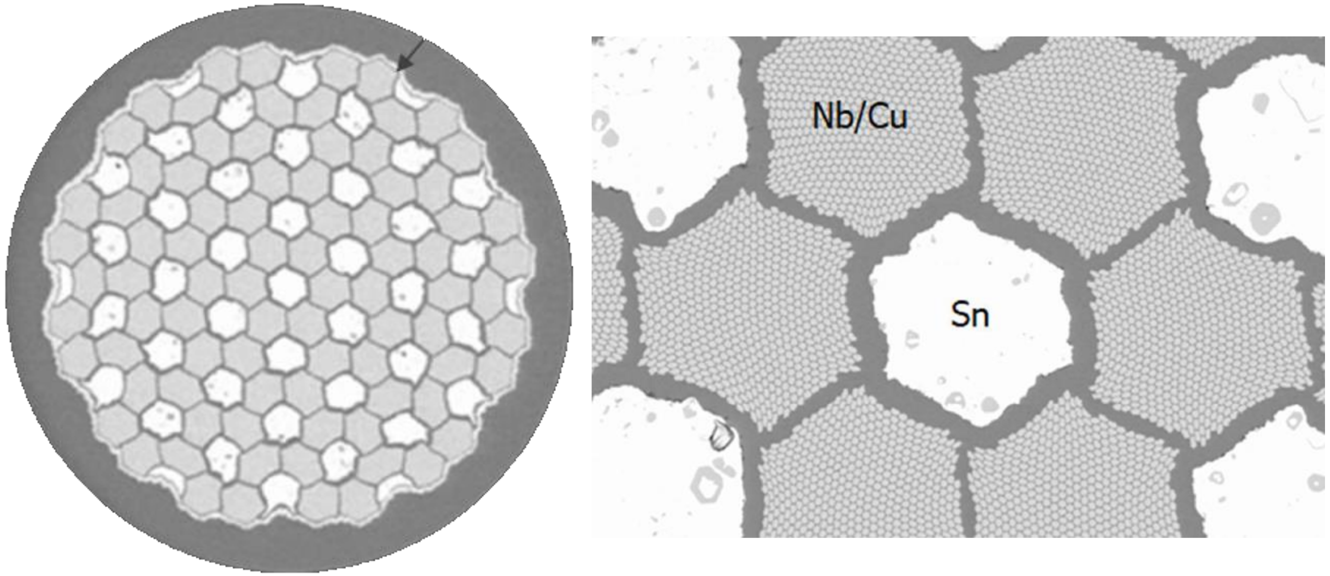
15%-rolled wire
I_{c0}(B=19T)= 61.5 A
$\sigma_{irr} \approx$ 185 MPa

A favorable stress redistribution in the 15%-rolled wire leads to an increased σ_{irr} by ~30 MPa

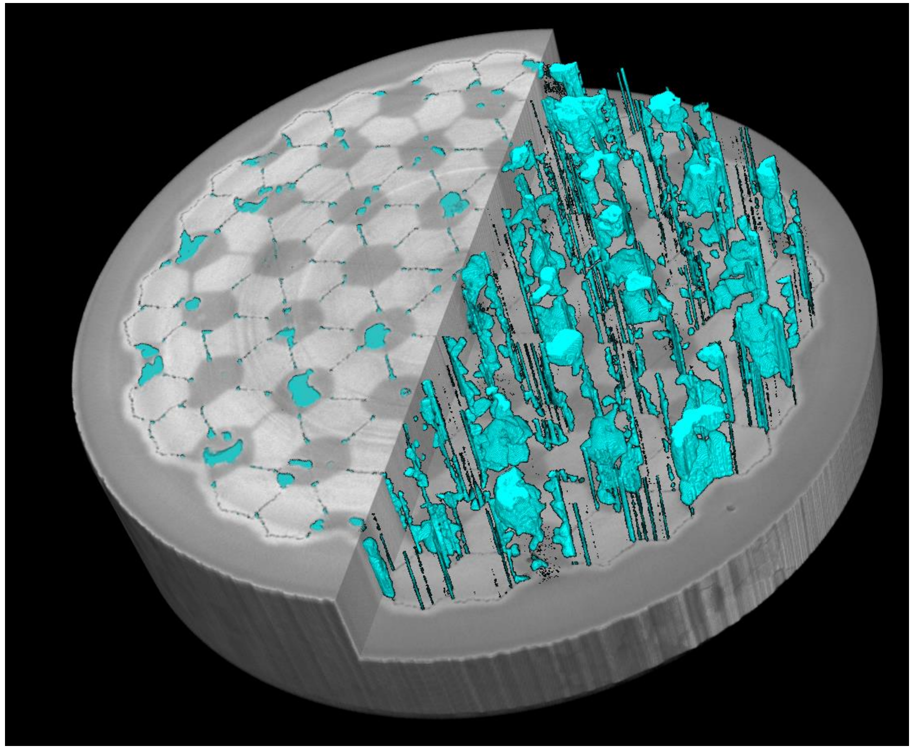
T. Bagni, C. Calzolaio *et al.*, in preparation

Is the degradation under transverse stress of Nb_3Sn wires always driven by residual stresses?

Distributed Tin (DT) wires from JASTEC SUPERCONDUCTOR

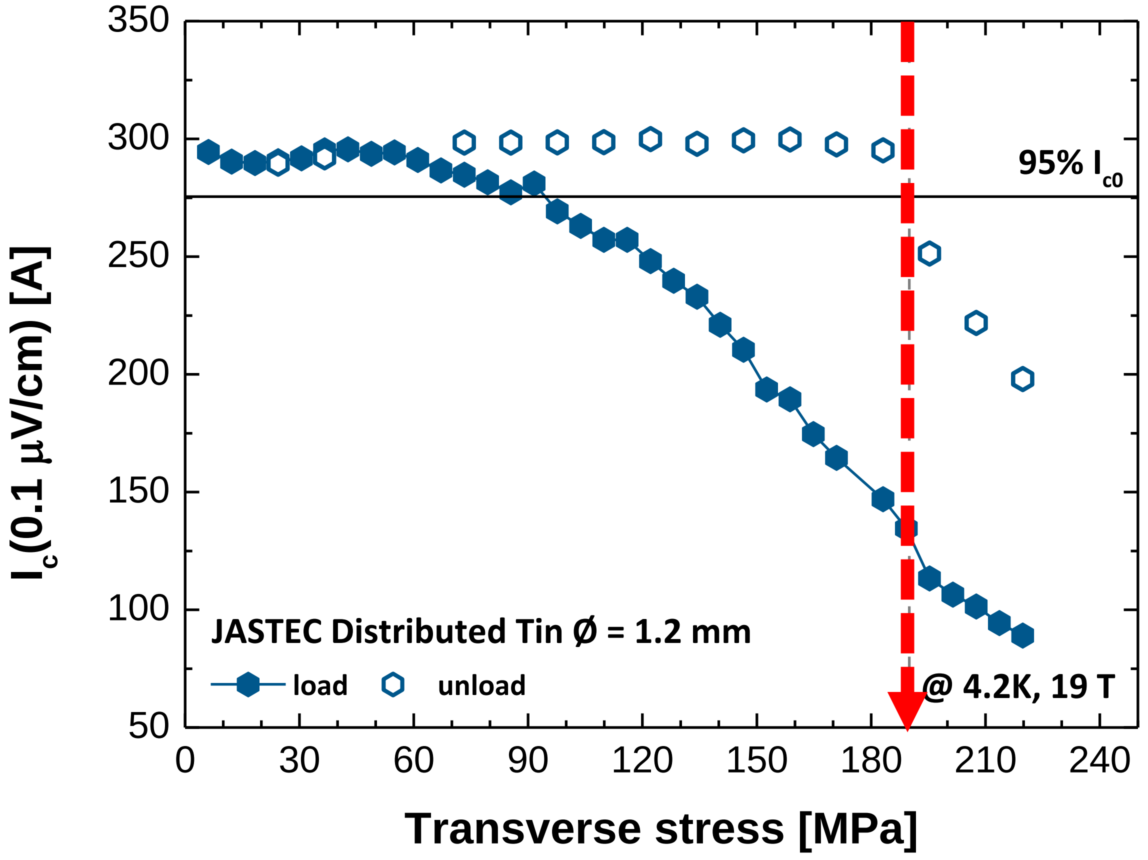


SEM picture courtesy of Dr. Yoshito Fukumoto from JASTEC



X-ray tomography reconstruction and void detection by machine learning, preliminary analysis

Irreversible degradation driven by cracks in DT wires



The abrupt decrease of I_c after unload at 190 MPa is a clear sign of degradation driven by the formation of cracks

The Cu/non Cu ratio is only 0.3
This can explain the marginal role of residual stresses

Similar conclusions reached in the paper of M. Nakamoto *et al.*, IEEE TAS, 33 (2023) 8400505
DOI: 10.1109/TASC.2023.3242919

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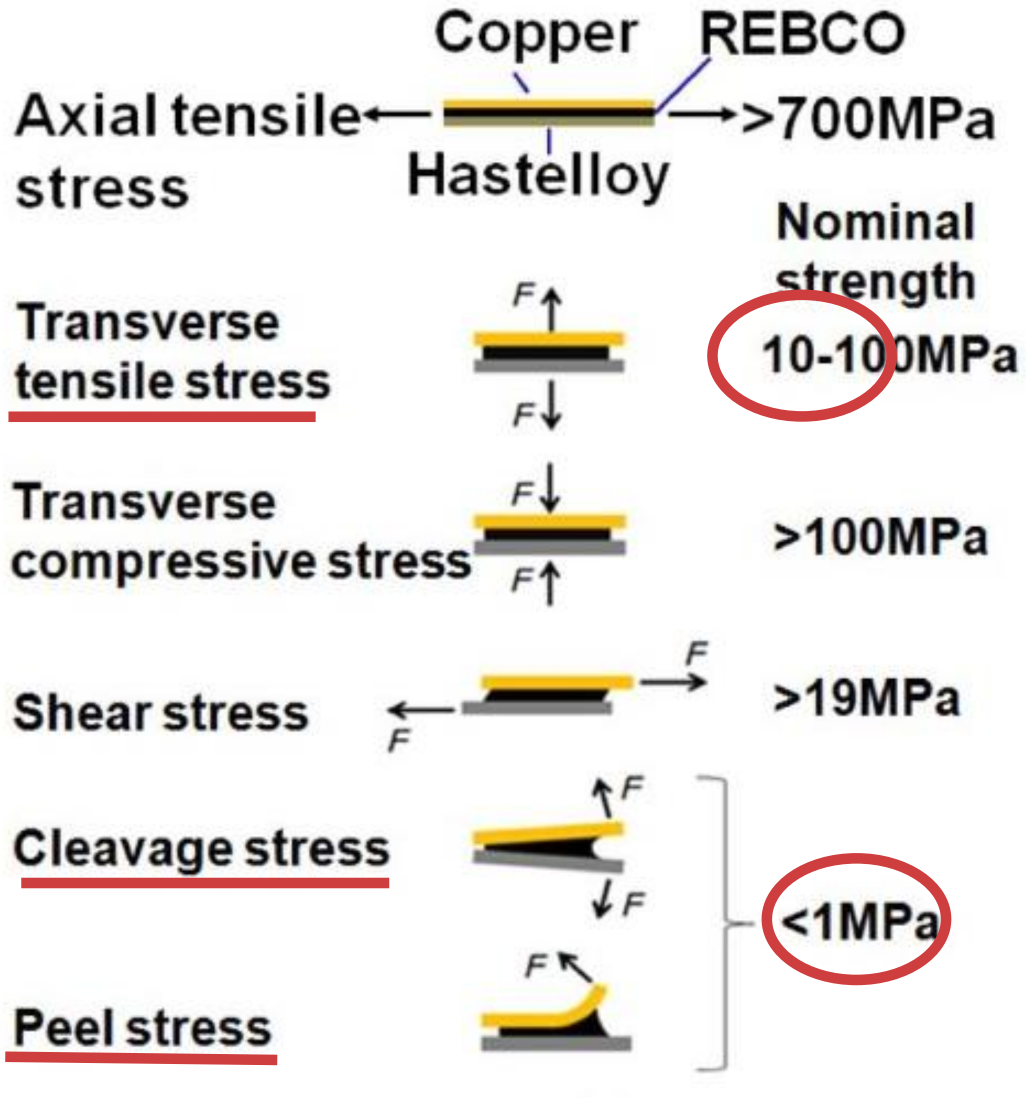
A short note on the mechanical properties of REBCO tapes

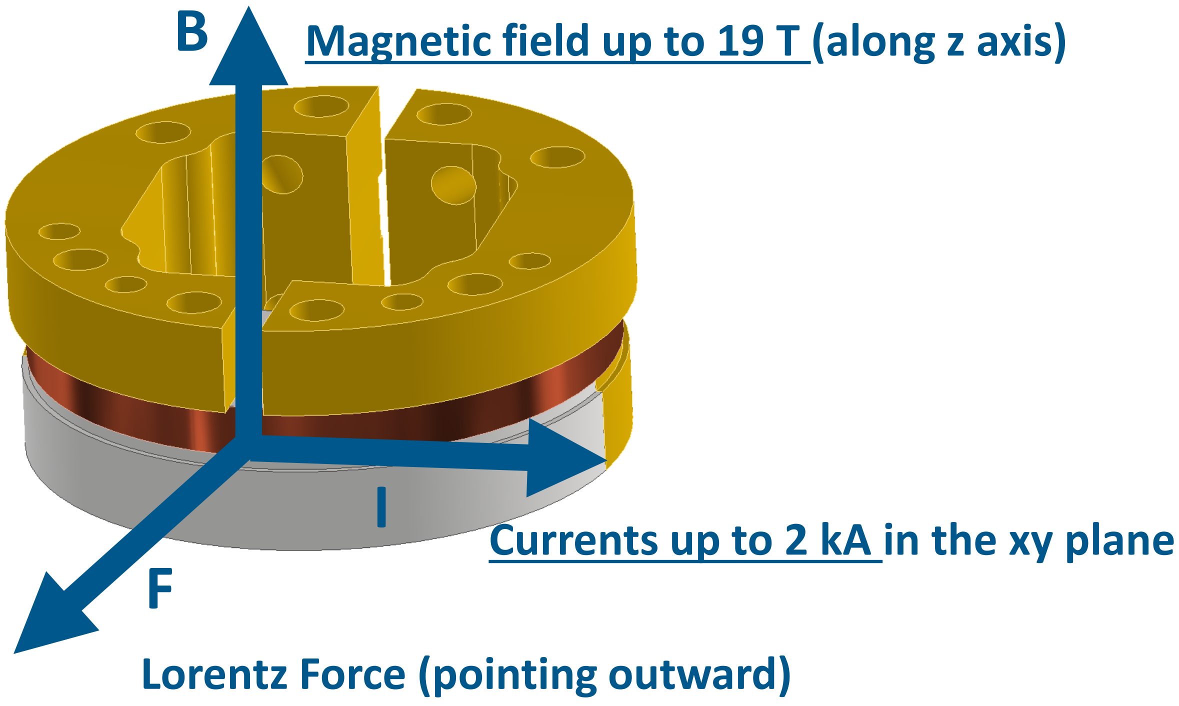


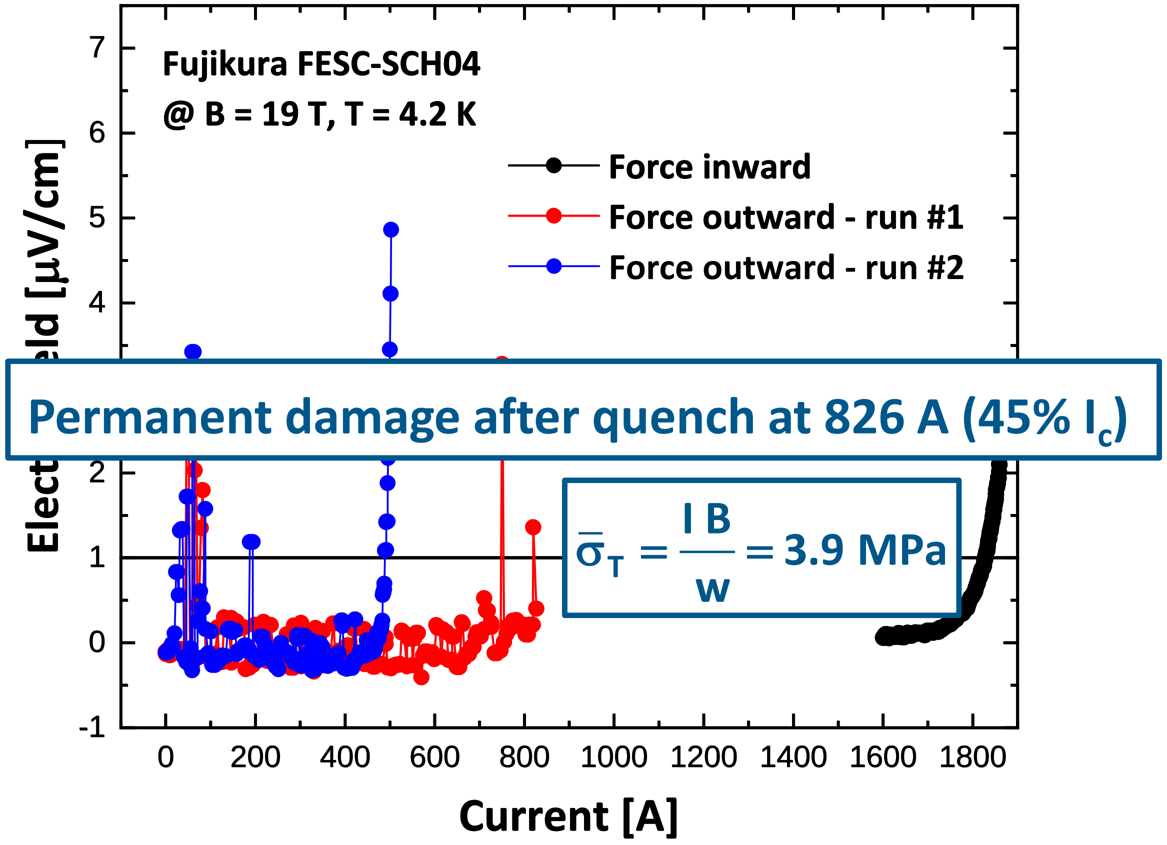
- REBCO tapes are inherently prone to delamination
- Adhesion between layers seems to be process dependent
- A standardized process to determine the properties of the tapes is missing

H. Maeda, and Y. Yanagisawa, IEEE Trans. Appl. Supercond., 24 (2014) 4602412
DOI: 10.1109/TASC.2013.2287707

Delamination strength measurements under I x B force

A novel experiment for a direct measurement of the conductor degradation





- The REBCO tape is mounted with the superconducting layer outward
- The Lorentz force is outward and tends to detach the REBCO layer from the substrate
- A transverse tensile stress in the range 1 – 10 MPa is generated

Conclusions

- Experiments show that the permanent degradation of I_c in PIT and RRP wires is dominated by residual stresses. The conclusion is supported by FE simulations

- The results obtained on a Distributed Tin wire suggest that degradation is driven by the formation of cracks. This particular wire has a very low Cu/non Cu ratio

- The study on rolled wires showed that FE simulations can become a valuable tool for the development of wire designs tailored to improve the stress tolerance

- The new experiment to measure the delamination strength of REBCO tapes aims to produce robust data with a reproducible process. The results may have many implications also on the manufacturing process

Thank you for the attention !

Carmine SENATORE

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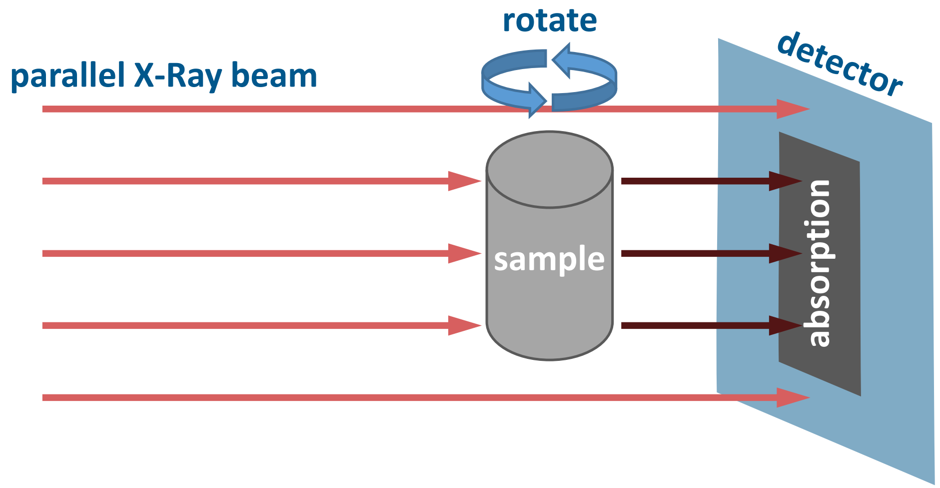
http://supra.unige.ch

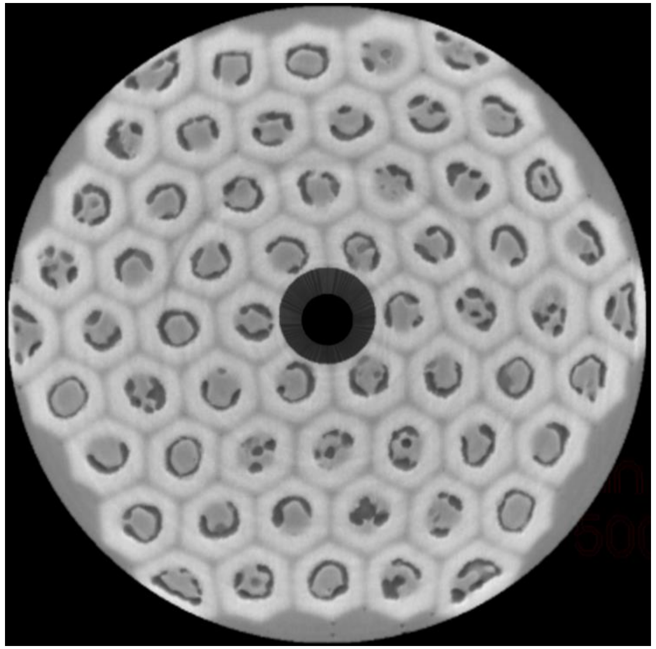
Acknowledgments: This work was done under the auspices of CHART (Swiss Accelerator Research and Technology Collaboration, https://chart.ch). Financial support was provided by the European Organization for Nuclear Research (CERN), Memorandum of Understanding for the FCC Study, Addendum FCC-GOV-CC-0176 (KE 4612/ATS).

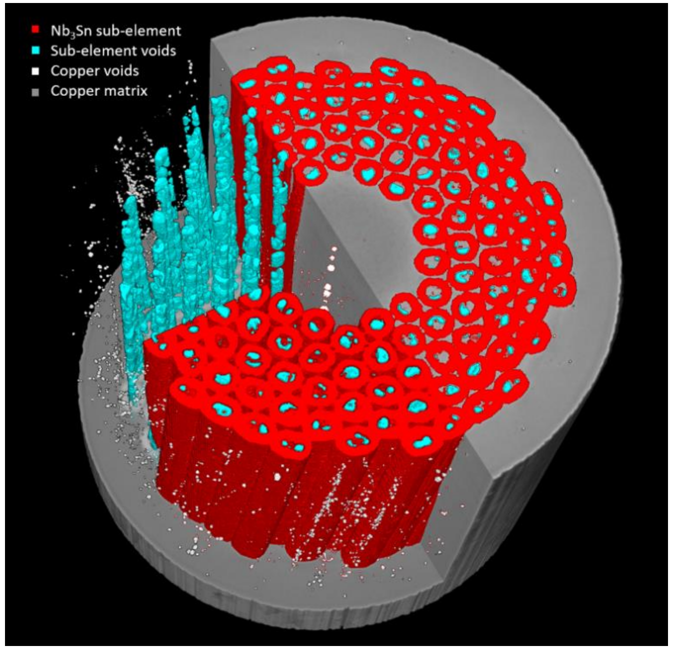
X-ray tomography and Machine Learning for crack detection

An independent confirmation of the conclusions



- X-ray photon energy = 80 keV
- 360° rotation of the sample
- 10’000 projections
- 2560 x 2160 pixels
- 0.57 μm/pixel resolution





A novel, non-destructive and non-invasive method to investigate the internal structure of high-performance Nb_3Sn wires combines X-ray microtomography with machine-learning algorithms

ESRF
The European Synchrotron

Marta MAJKUT
Alexander RACK

T. Bagni *et al.*, Sci. Reports 11 (2021) 7767 DOI: 10.1038/s41598-021-87475-6

X-ray tomography and Neural Networks for crack detection

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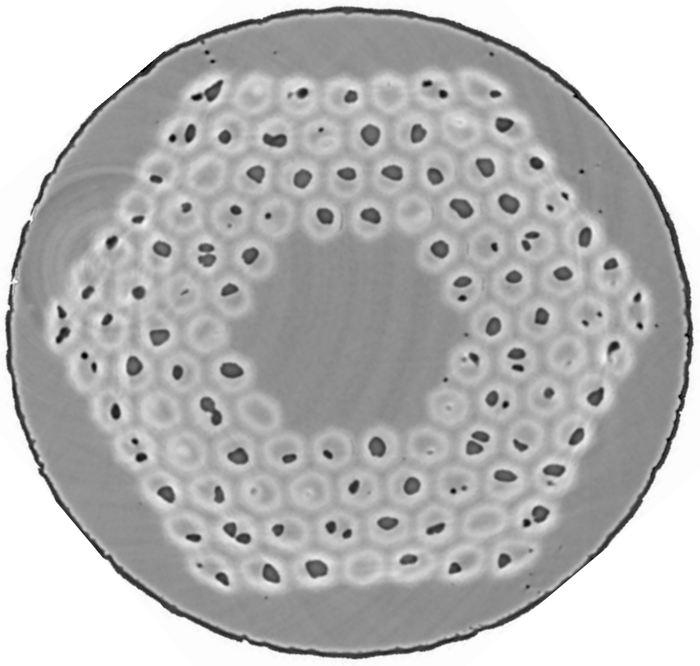
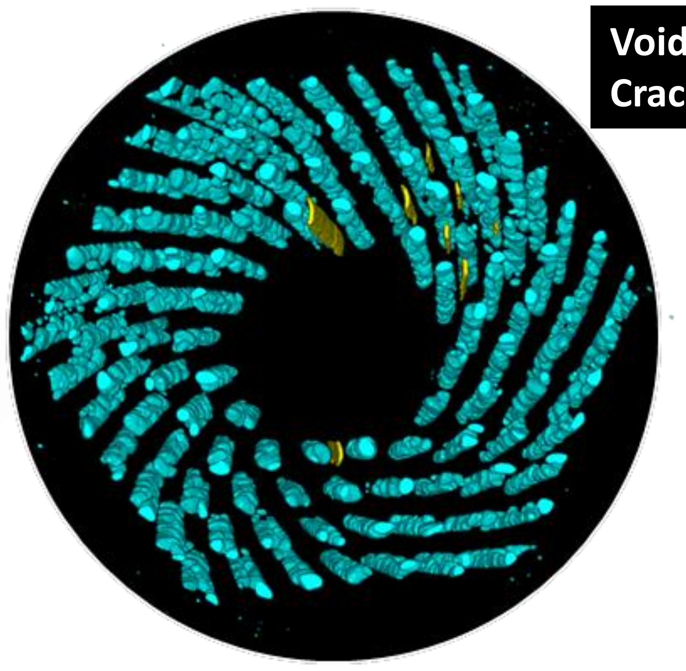
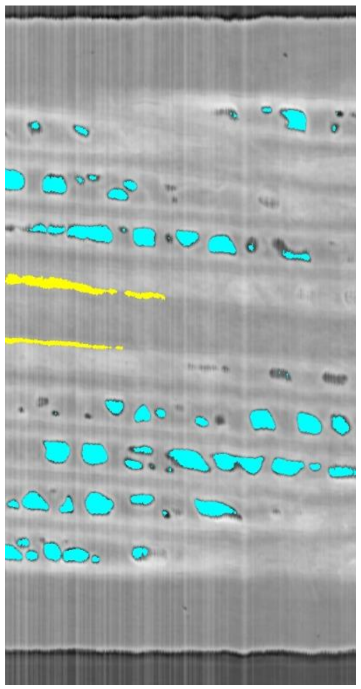






An analysis based on Convolutional Neural Networks was performed on the tomographic scan of the exact same sample used for the I_c vs σ test, after unload from 240 MPa

Very few cracks were detected, none of them interrupting the subelements and responsible for the measured degradation by 15% of I_c

T. Bagni *et al.*, Supercond. Sci. Technol., 35 (2022) 104003 DOI: 10.1088/1361-6668/ac86ac

What has been tested

A comprehensive campaign of electromechanical tests to gain knowledge on some very practical aspects

- **Probed the impact of the impregnation scheme on the transverse stress tolerance**

  Quantified the effect of the rigidity of the impregnation on the irreversible stress limit of PIT wires

  L. Gämperle, *et al.*, Phys. Rev. Research 2 (2020) 013211

  DOI: [10.1103/PhysRevResearch.2.013211](https://doi.org/10.1103/PhysRevResearch.2.013211)

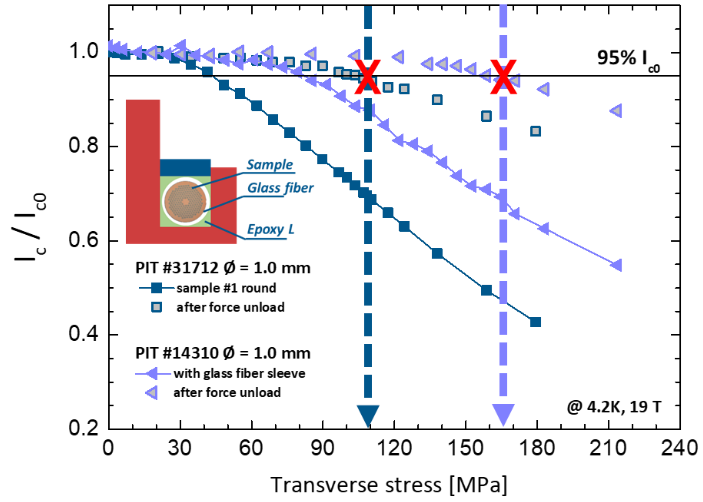
- **Assessed the effect of the longitudinal strain state on the response to transverse stress**

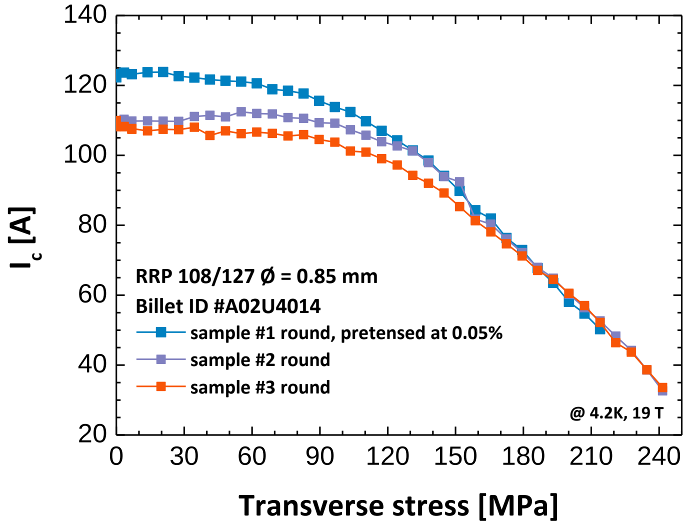
  Investigated RRP wires under longitudinal and transverse loads

  J. Ferradas Troitino, *et al.*, Supercond. Sci. Technol., 34 (2021) 035008

  DOI: [10.1088/1361-6668/abd388](https://doi.org/10.1088/1361-6668/abd388)

Wire in a glass fiber sleeve + Epoxy L





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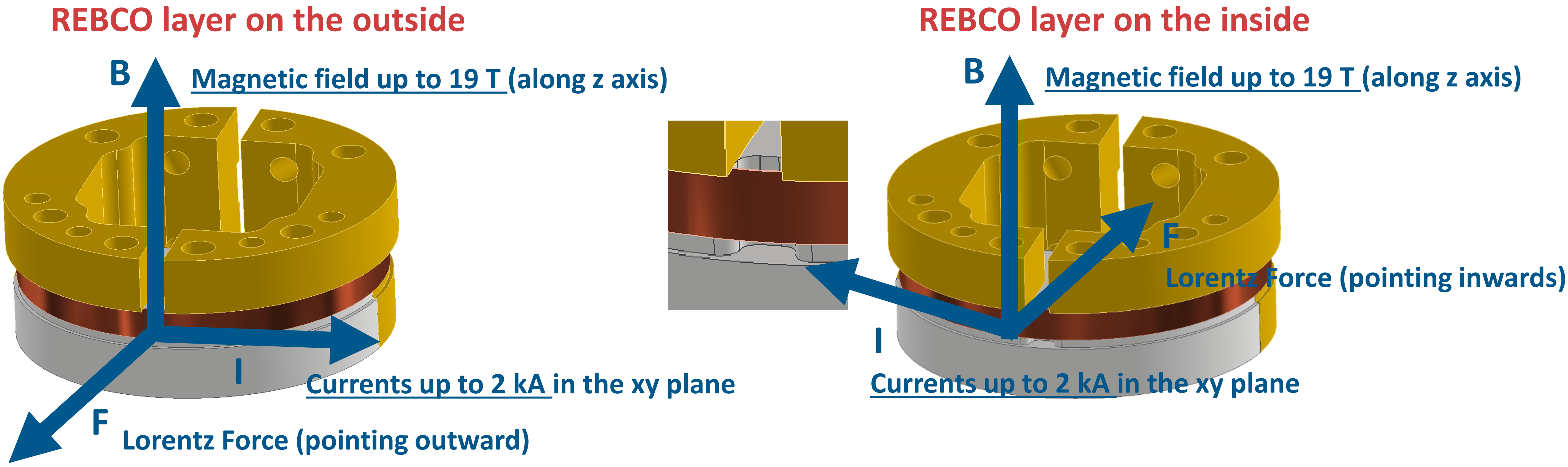
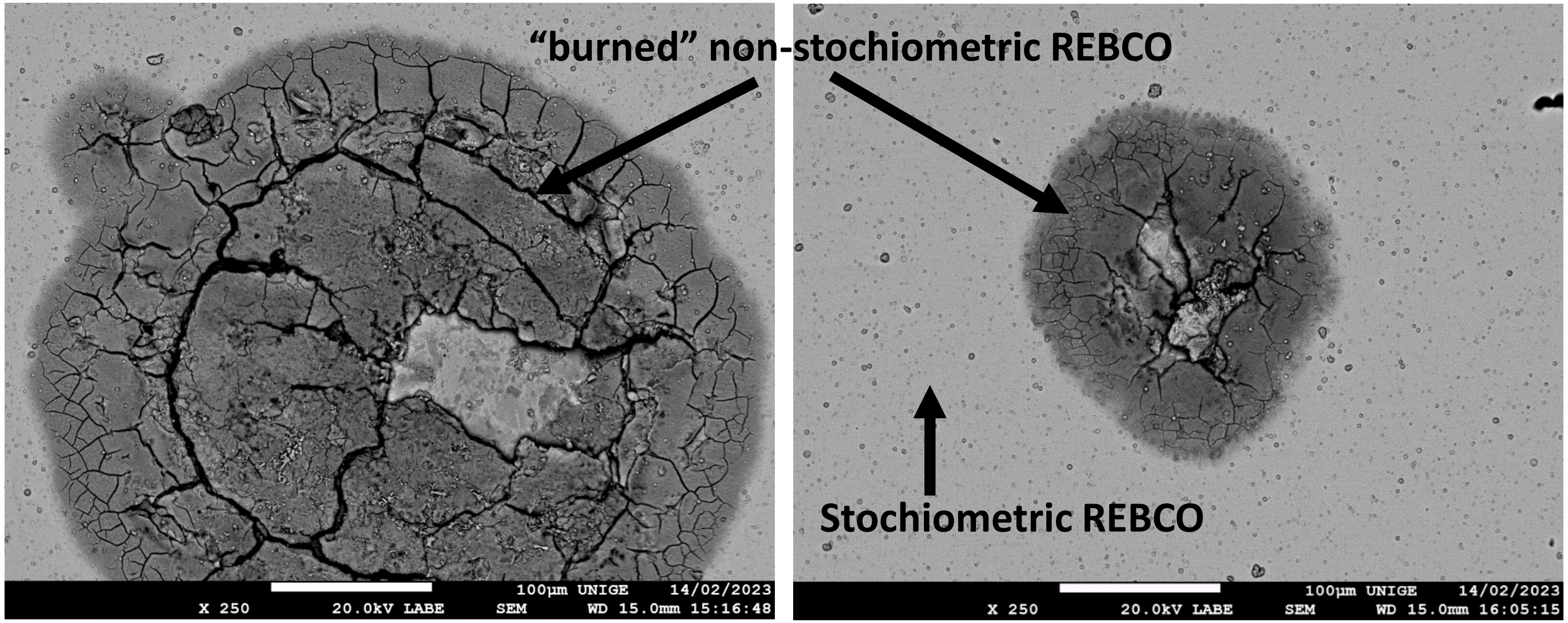


Delamination strength and forensic microscopy

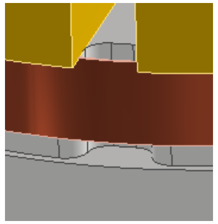
SEM-EDX and 3D Optical microscopy

Delamination → Quench → Local heating → Blistering

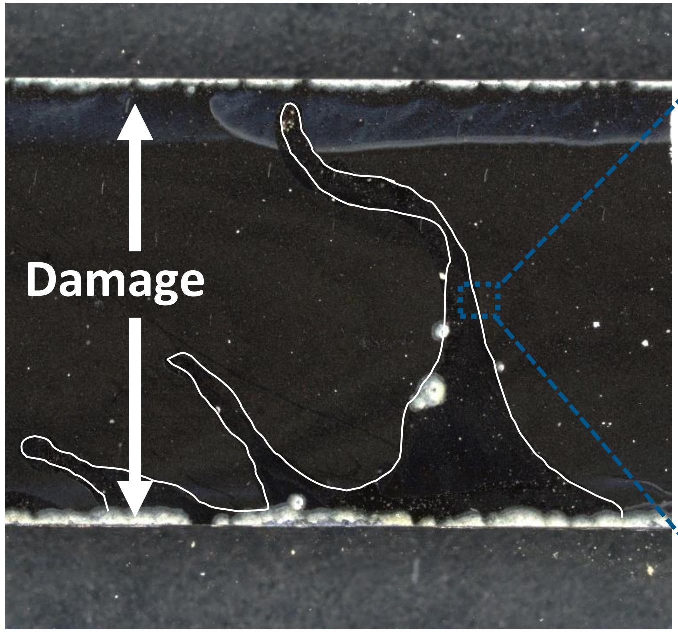


Delamination strength and forensic microscopy

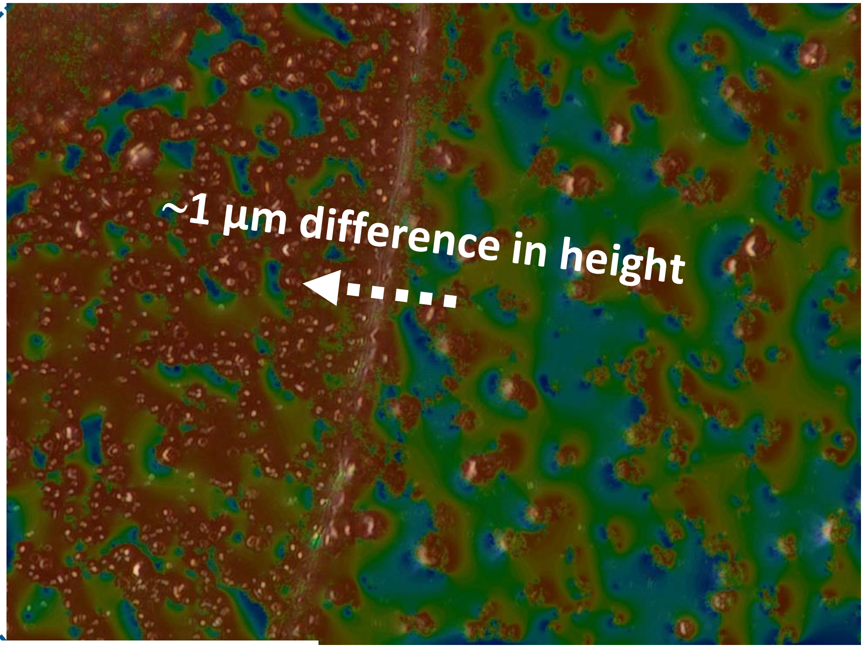
SEM-EDX and 3D Optical microscopy



Evidence of delaminated area where the tape was not supported



3D optical microscope analysis



z-axis color code

97% of I_c was lost after the delamination experiment

Summary

Fujikura

Type: FESC SCH04
Tape ID: 19-0008

Delamination strength ~ 4 MPa (45% I_c)

$\overline{\sigma}_T$ =3.9 MPa F$_L$ outward

$\overline{\sigma}_T$ =4.1 MPa F$_L$ inward

Longitudinal damage on both edges of the CC + Blisters

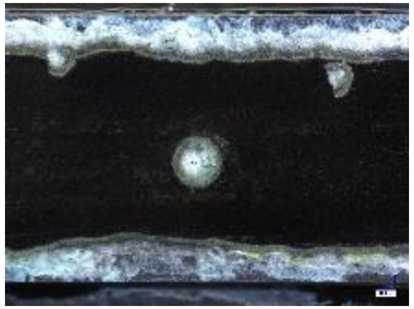
Fujikura

Type: FESC SCH02
Tape ID: 23-0010

Delamination strength ~ 4.3 MPa (39% I_c)

$\overline{\sigma}_T$ =4.3 MPa F$_L$ inward

Longitudinal damage on both edges of the CC + Blisters



SuperPower Inc.

Type: SCS4050-AP
Tape ID: M3-1464-7

Delamination strength ~ 5.5 MPa (82% I_c)

$\overline{\sigma}_T$ =5.5 MPa F$_L$ inward

Longitudinal damage on 1 edge of the CC + Blisters