WireChar Multiphysical characterization of advanced superconductors

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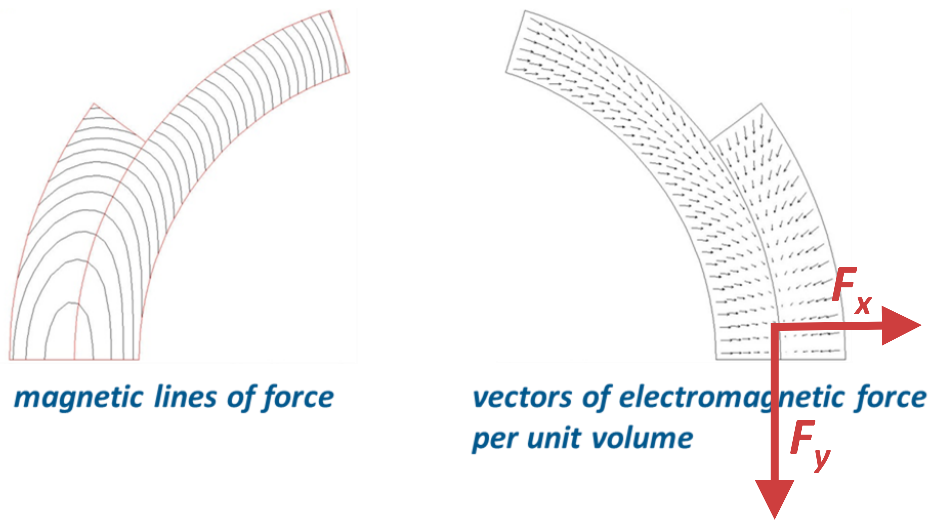
Outline

- Motivation of the work
  - Strain sensitivity and stress management in accelerator magnets based on Nb_3Sn
- Overview of the wire testing facilities at UNIGE
  - Focus on the properties relevant for magnet design
- Irreversible reduction of the critical current under mechanical loads
  - A combination of electromechanical tests, X-ray microtomography with deep learning and FE simulations to identify the dominant mechanism behind the degradation
- Summary and conclusions

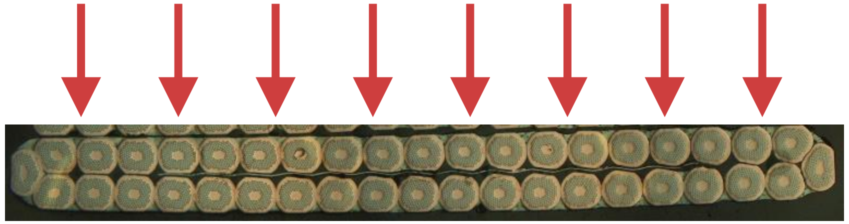
Stress management is key for Nb_3Sn-based accelerator magnets



The projects of the 11 T dipoles and the MQXF quadrupoles for the high luminosity upgrade of LHC provide very relevant experience on the use of Nb_3Sn conductors for accelerator magnets

All design options developed for the 16 T dipoles for a future 100 TeV collider share a peak stress in the range of 150-200 MPa at operation

The most severe electromagnetic loads are those acting in the transverse direction of the Nb_3Sn Rutherford cables

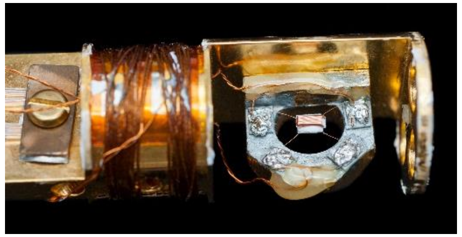


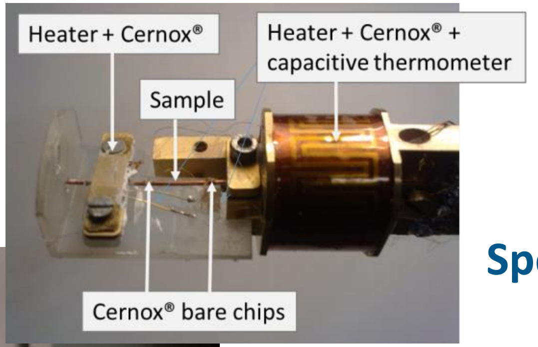
The brittleness of Nb_3Sn combined with huge electromagnetic forces, thermomechanical effects and tight tolerances and make easy to exceed the mechanical limits of the conductor and degrade the magnet performance

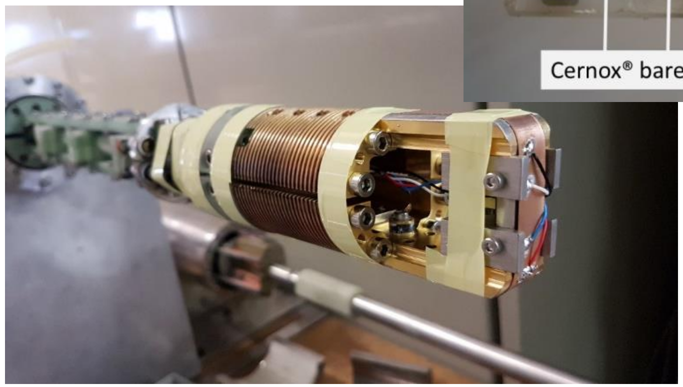
What is a safe maximum transverse stress limit to consider as magnet design criterion?

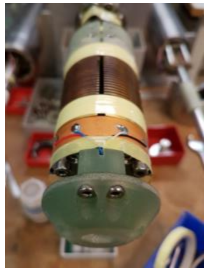
Overview of the wire testing facilities at UNIGE

High-Field Low-Temperature characterization of LTS and HTS for applications









The laboratory at UNIGE is equipped with a **19 T/ 21 T magnet** with a **50 mm** variable temperature insert

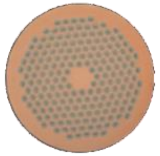
UNIGE has also developed **custom setups** for the measurement of **properties relevant for magnet design**:

- Critical current versus **longitudinal strain** (Walters spiral, aka WASP), up to 1 kA
- Critical current versus **transverse stress** (compressive WASP), up to 1 kA, 40 kN
- **Thermophysical properties** (heat capacity, thermal conductivity)

Specially developed for HTS characterization:

- Critical current versus magnetic field **up to 2 kA at 4.2 K, up to 1 kA in gas flow** (active stabilization of the temperature)
- Possibility to measure long samples at **various field orientations** (testing the anisotropy of HTS)

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
	RRP	132/169	1.2	~60 μm	1.0 mm	370 A	#15114 #114163	
				~50 μm	0.85 mm	245 A	#14393	

L. Gämperle, *et al.*, Phys. Rev. Research 2 (2020) 013211 DOI: 10.1103/PhysRevResearch.2.013211
J. Ferradas Troitino, *et al.*, Supercond. Sci. Technol., 34 (2021) 035008 DOI: 10.1088/1361-6668/abd388

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

- **Assessed the effect of the longitudinal strain state on the response to transverse stress**
  Investigated RRP wires under longitudinal and transverse loads

- **Investigated the impact of the wire deformation during cabling on the transverse stress tolerance**
  Performed measurements on PIT and RRP wires, round and 15%-rolled to simulate the effects of cabling

- **Assessed the basic mechanism behind the degradation of the critical current under transverse loads**

Tolerance to transverse stress of a single wire

Electromechanical tests on Nb_3Sn wires impregnated with epoxy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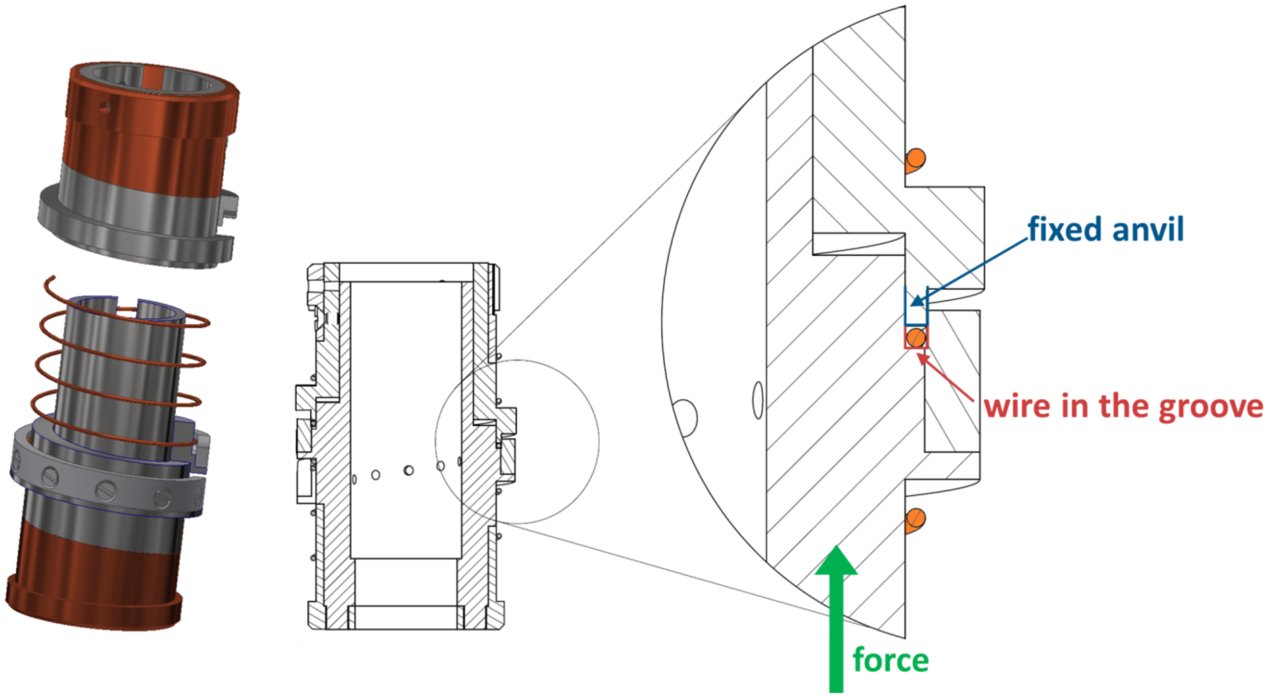
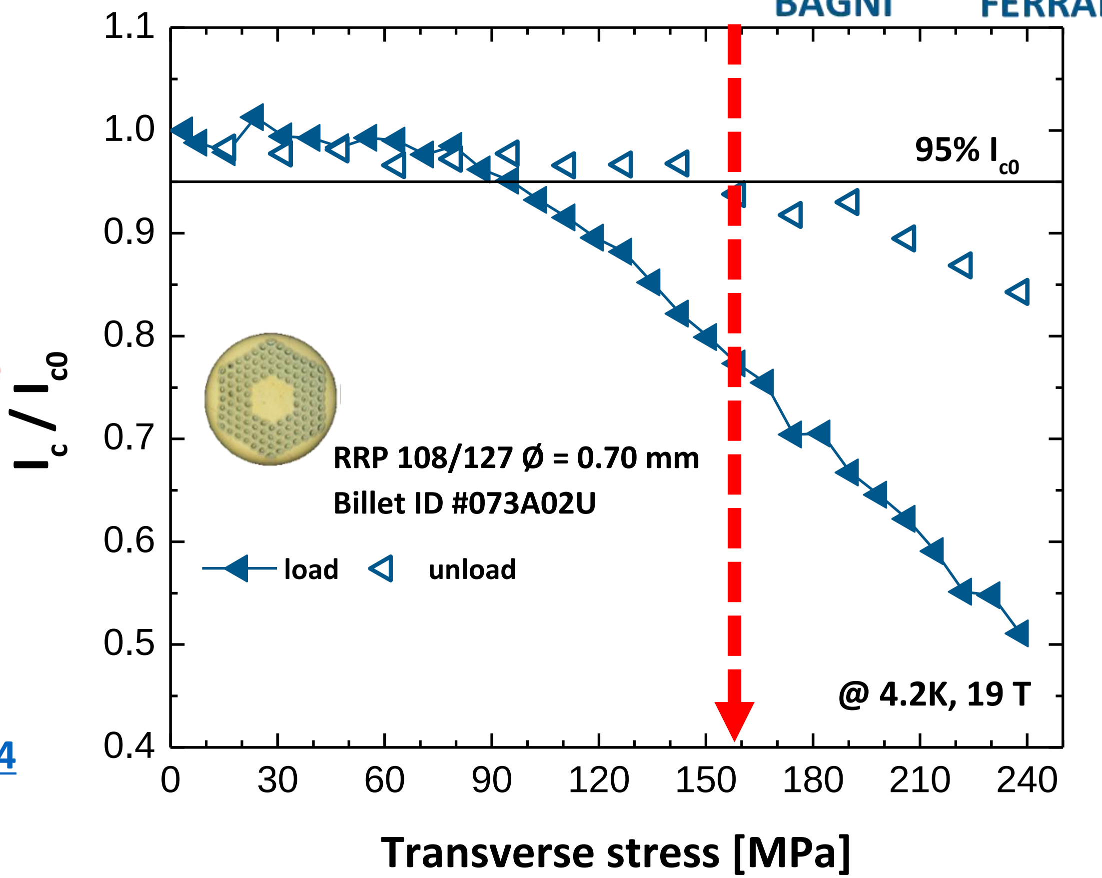


The WASP concept was adapted to transverse loads by
B. Seeber et al., IEEE TAS 17 (2007) 2643, DOI: 10.1109/TASC.2007.897934



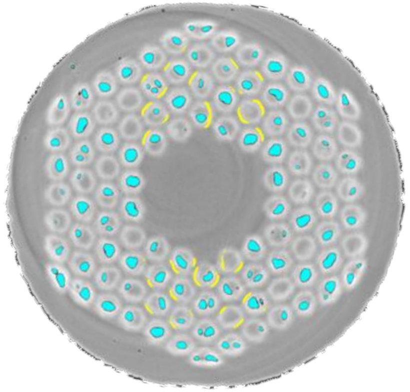
The irreversible limit is defined at the force level leading to a 95% recovery of the initial I_c after unload

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

Degradation mechanisms and irreversible reduction of I_c

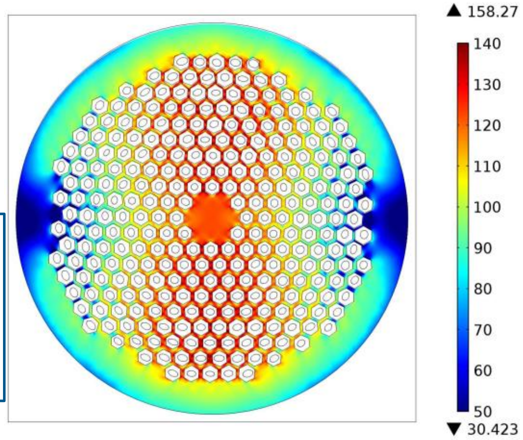
Two mechanisms govern the irreversible reduction of the critical current

- 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

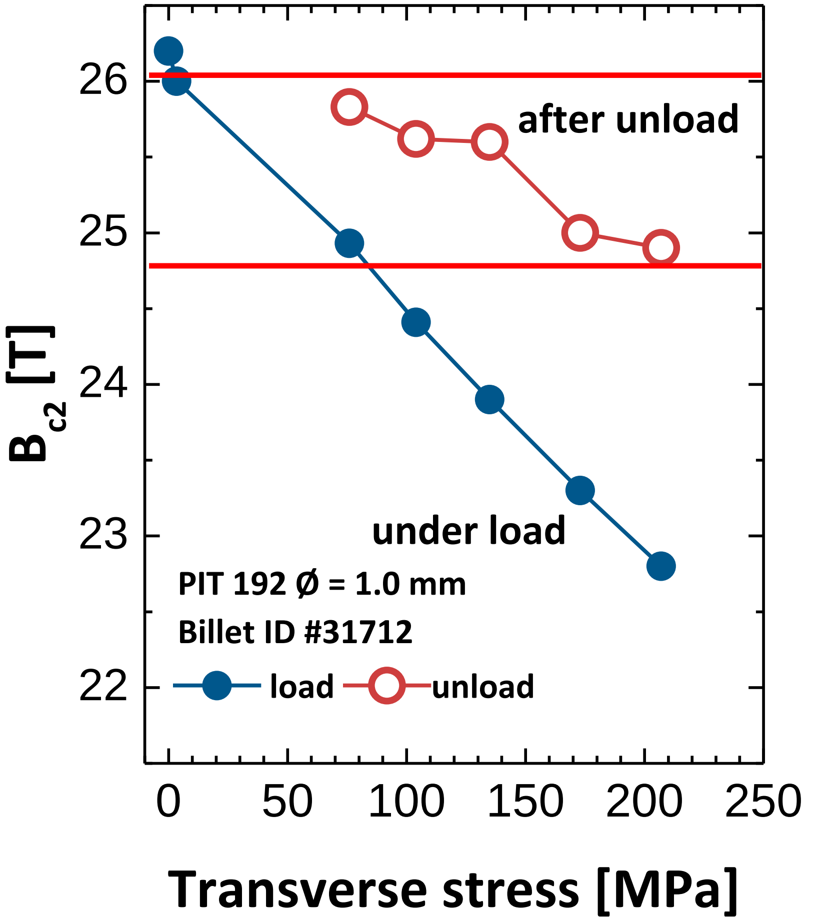
- Plastic deformation of the matrix and residual stress on the Nb_3Sn filaments



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

Comparison of B_{c2} under load and after unload

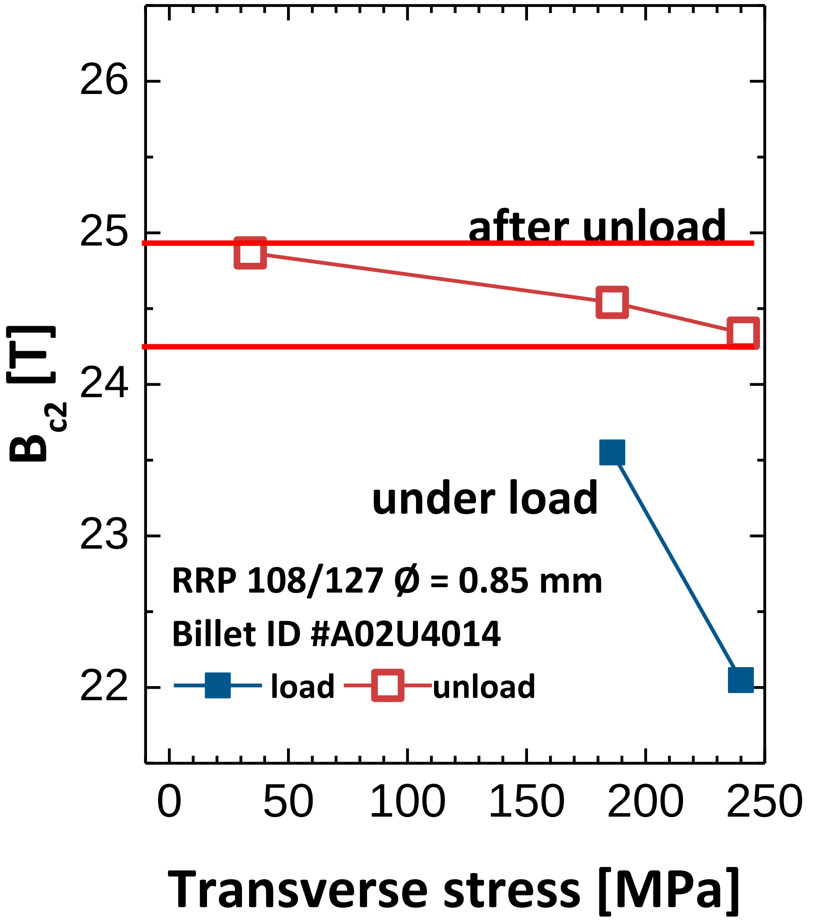
PIT, Ø = 1.0 mm



After unload from σ = 210 MPa

$\Delta B_{c2}^{unload} \approx 1$ T

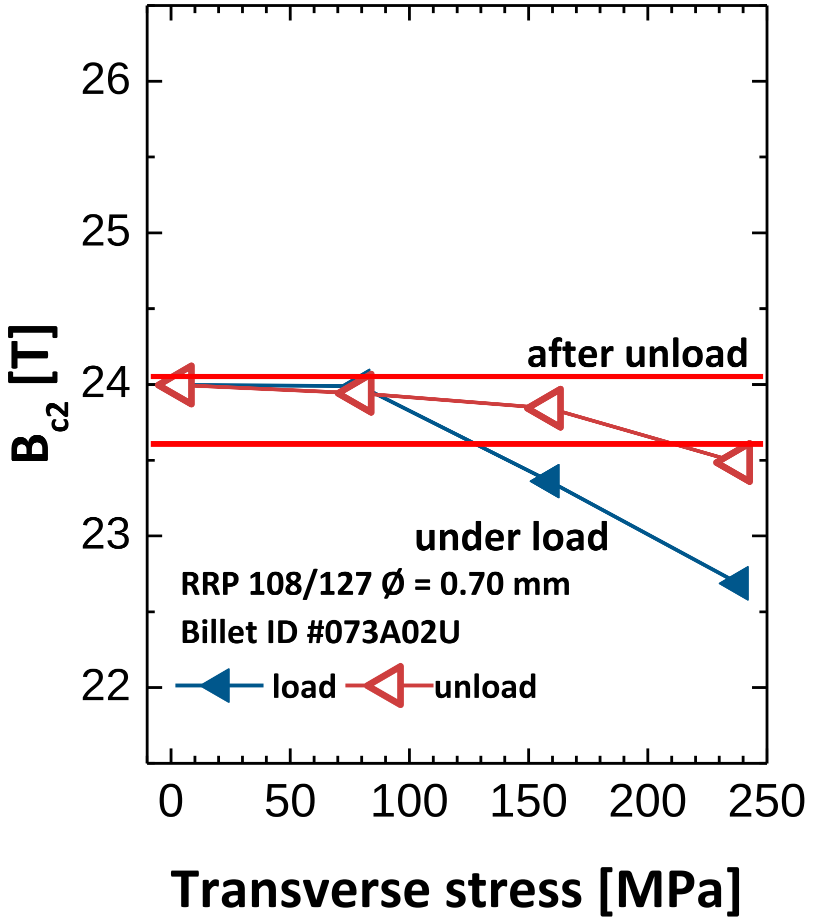
RRP, Ø = 0.85 mm



After unload from σ = 240 MPa

$\Delta B_{c2}^{unload} \approx 0.5$ T

RRP, Ø = 0.7 mm



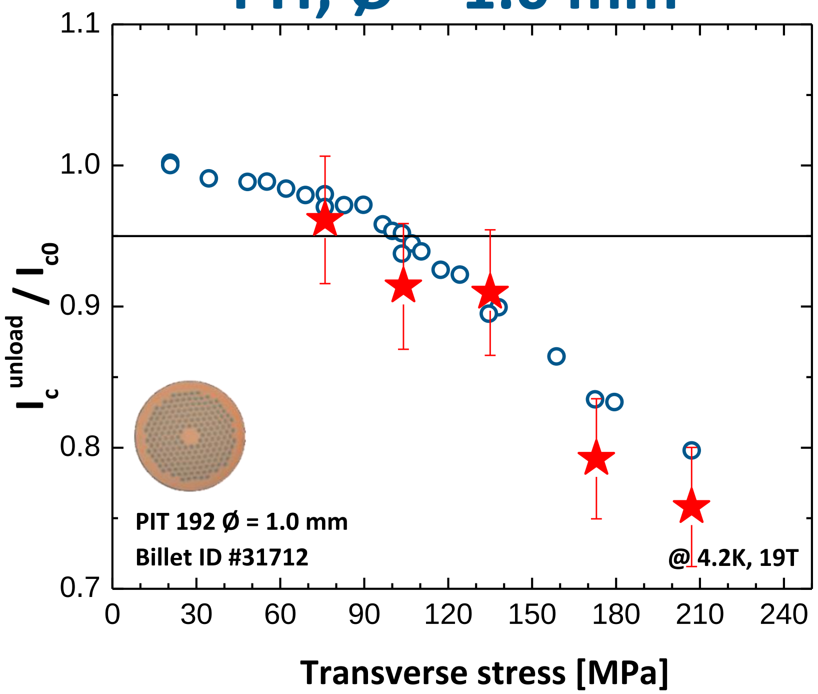
After unload from σ = 240 MPa

$\Delta B_{c2}^{unload} \approx 0.5$ T

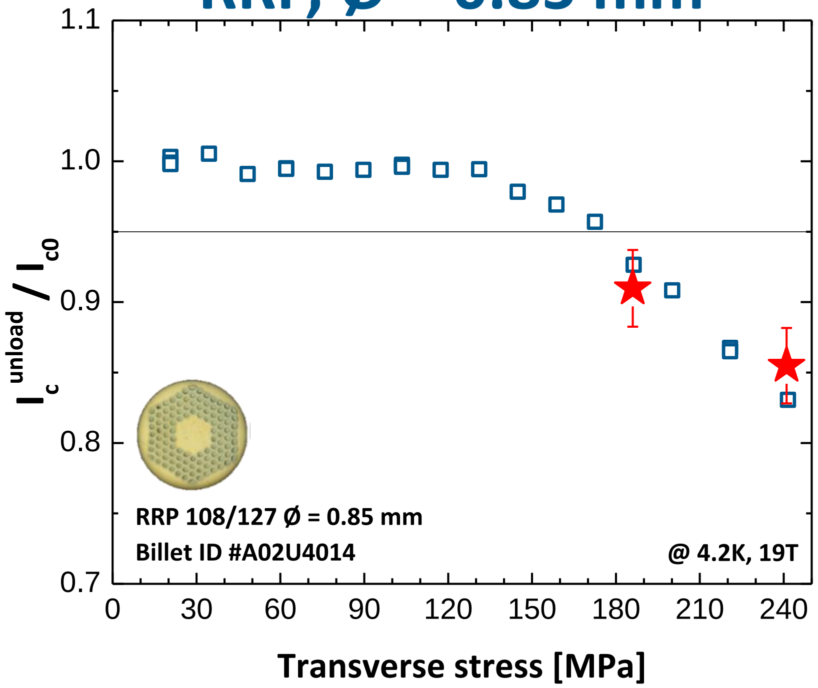
Measured I_c^{unload} vs expected degradation from residual stress

(open blue points) (solid red stars)

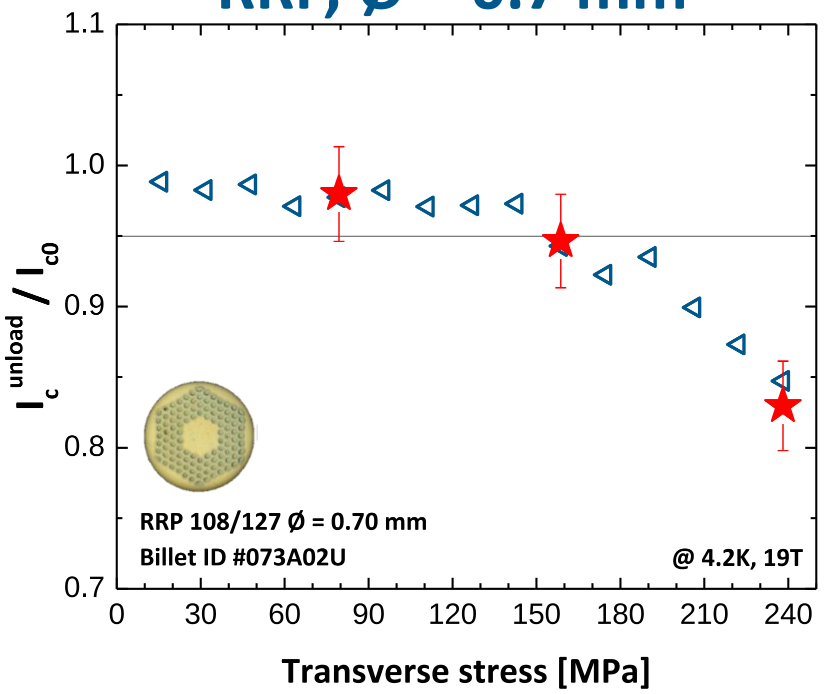
PIT, Ø = 1.0 mm



RRP, Ø = 0.85 mm



RRP, Ø = 0.7 mm



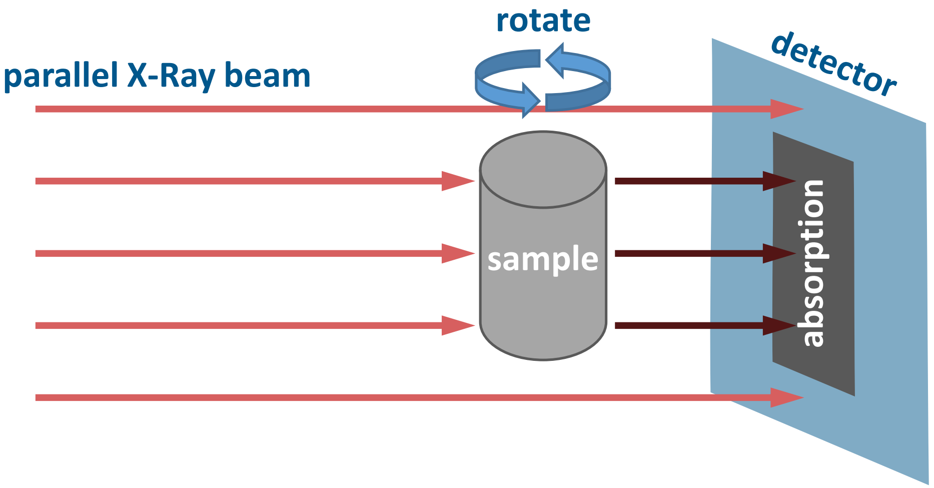
The observed permanent degradation of I_c after unload from σ up to 240 MPa originates mainly from the residual stress on Nb_3Sn due to the plastic deformation of Cu

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

X-ray tomography and Neural Networks for crack detection

An independent confirmation of the conclusions

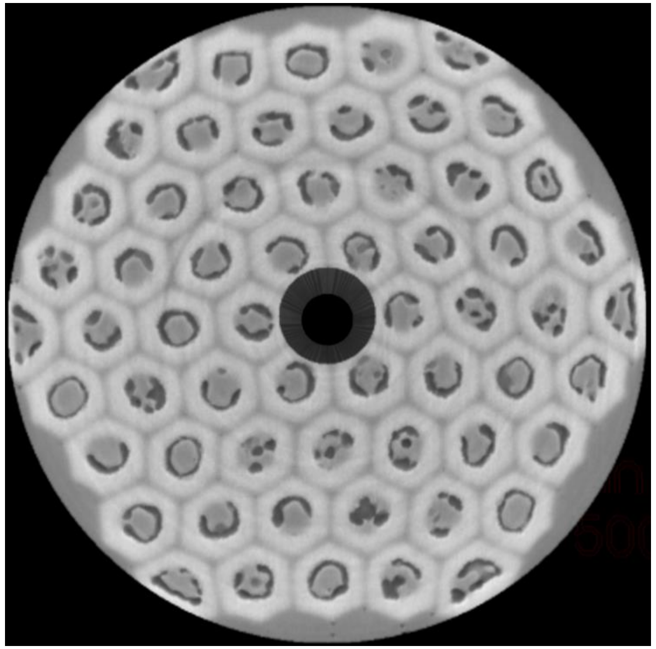

Tommaso BAGNI   Diego MAURO

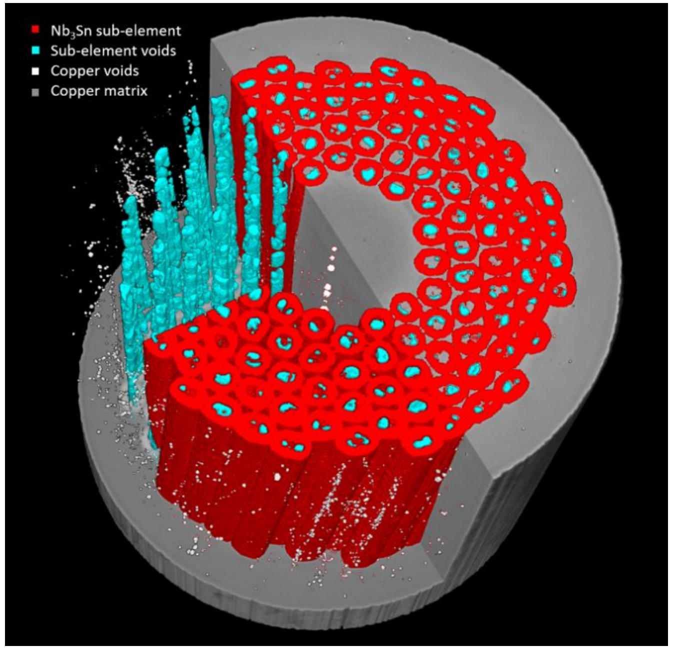


- X-ray photon energy = 80 keV
- 360° rotation of the sample
- 10’000 projections
- 2560 x 2160 pixels
- 0.57 μm/pixel resolution

ESRF The European Synchrotron

Marta MAJKUT
Alexander RACK





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

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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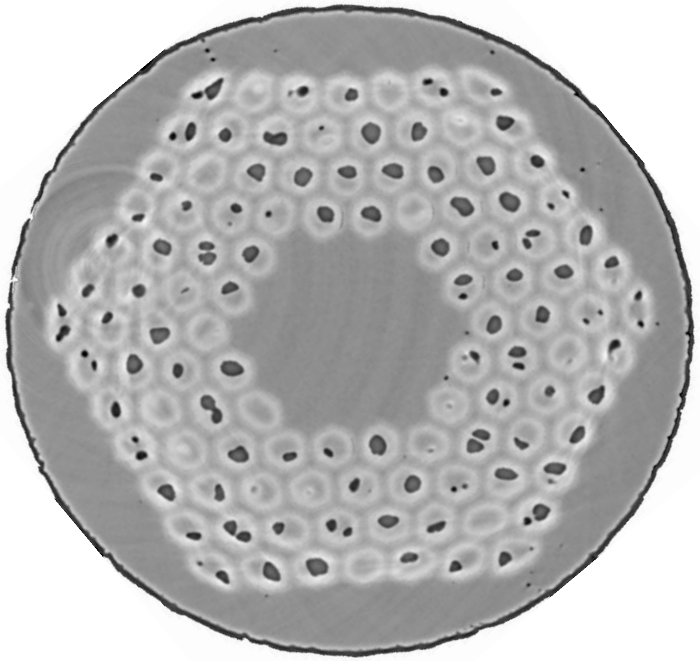
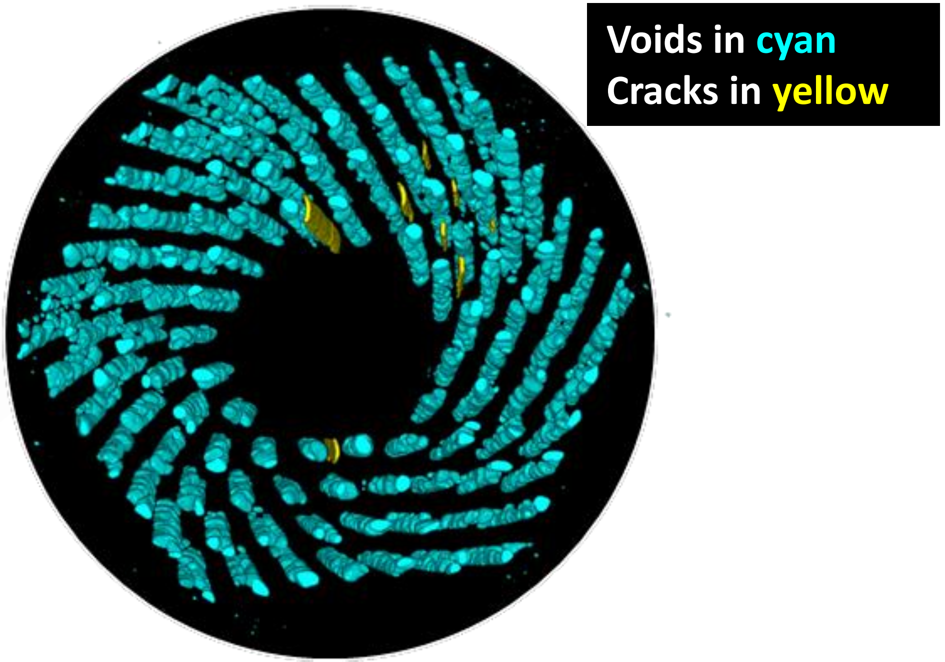
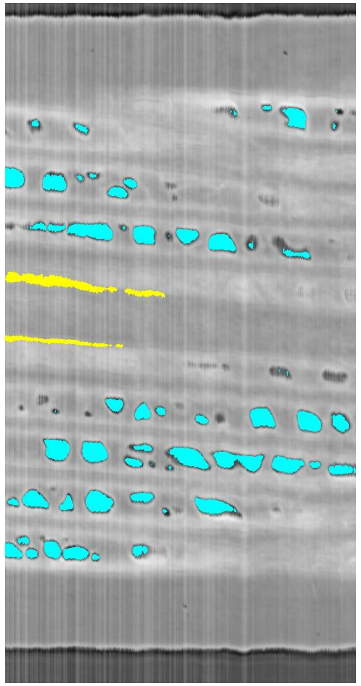






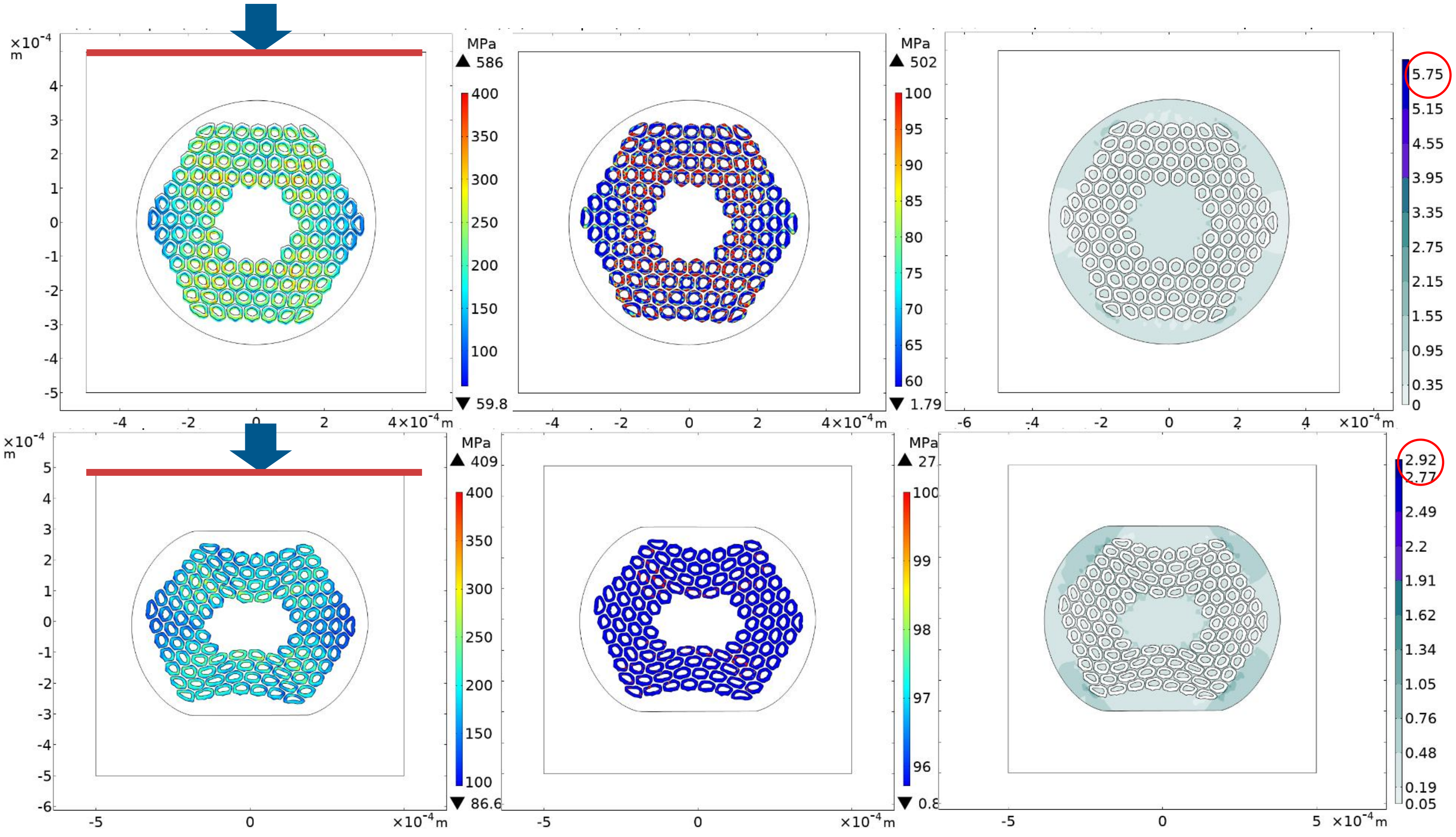
An analysis based on Convolutional Neural Networks was performed on the tomographic scan of the exact same sample used for the I_c vs σ test, after unload from 240 MPa

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

2D FE electromechanical models with PSI

I_c degradation from Cu plasticization and consequences of wire rolling

Ciro
CALZOLAIO



Von Mises stress in Nb_3Sn under a load of 30 kN

Von Mises stress in Nb_3Sn after unload from 30 kN

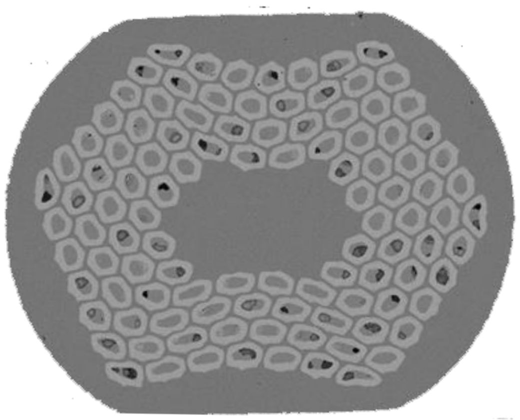
Plastic deformation of Copper after unload from 30 kN

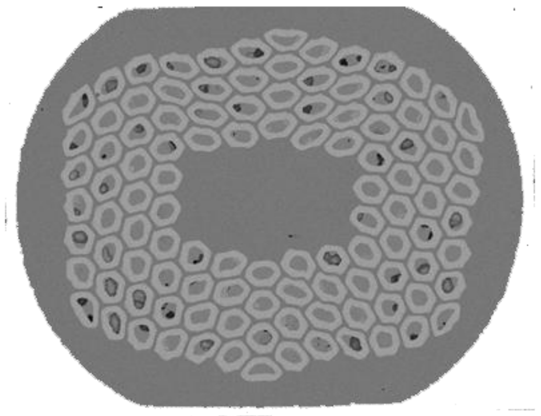
Simulations support the experimental evidence that 15% rolling is associated with a slight improvement of the tolerance to transverse stress

This is due to a better redistribution of the load

Summary and outlook

- Tolerance to stress is an issue as important as high critical current density for the conductors to be used in Nb_3Sn-based accelerator magnets
- Experiments show that up to 240 MPa the permanent degradation of I_c is dominated by the residual stress. Surprisingly, the effect of cracks seems negligible
- With the goal of providing new insights into the electromechanical modelling of the wires, a tool combining tomography and machine learning was developed to investigate the internal structure of the wires
- FE simulations represent a valuable tool for the development of tailored wire designs with improved stress tolerance
- There are many ideas to explore and a strong temptation to launch a WireNum project combining FE and machine learning
- Discussions are ongoing with CERN to start also the activities of WireChar on HTS in the frame of the HFR R&D





Thank you for the attention !

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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).

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