Characterization of irreversible degradation of Nb_3Sn Rutherford cables due to transversal compression stress at room temperature

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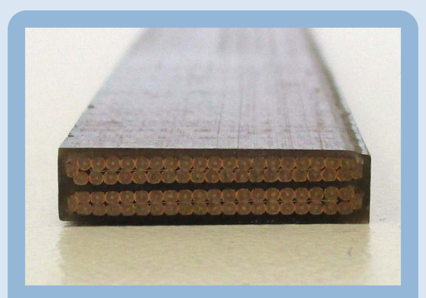
1) Introduction and objectives

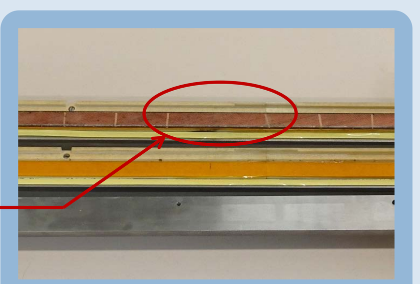
- In the frame of the **Future Circular Collider (FCC)** design study for a 100 TeV circular hadron collider, **16 T superconducting bending magnets** based on Nb_3Sn technology are being developed. In order to counteract the Lorentz force during operation, **pre-stress is applied on the superconductive coil during the magnet assembly at room temperature** [1]. The electrical properties of the **brittle** Nb_3Sn superconductor are **strain sensitive** and an excessive pre-stress leads to an **irreversible degradation of the superconductor**.
- The behaviour of Nb_3Sn, -strands and -cables **during stress at cryogenic temperature** have already been investigated, however the irreversible performance loss of recently developed superconducting cables have not been measured [2]-[5]. The knowledge of the described pre-stress was missing and the **limitation within the community was set to 150 MPa** [6].
- In order to **determine the level of acceptable pre-stress during the magnet assembly process,** reacted and impregnated Nb_3Sn cables were exposed to **compressive transversal stress up to 200 MPa at room temperature**. After each stress cycle the critical current of the cable specimens was characterized **at 4.2 K in the FRESCA test station**.

2) FRESCA-compatible specimen

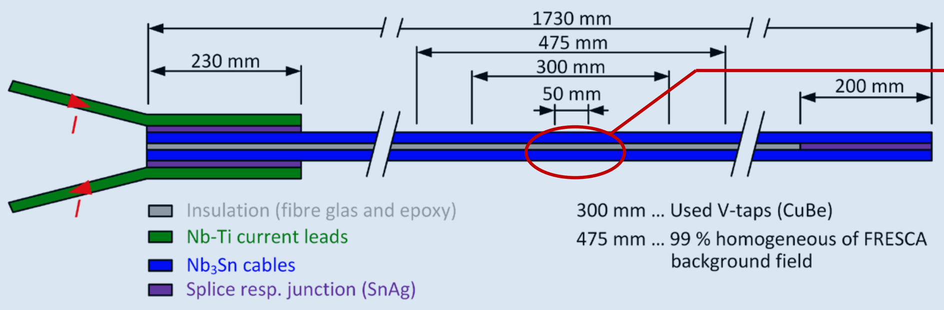
- Two insulated 1.73 m long Rutherford cables
- Cables are **impregnated and keystone-compensated** arranged to reach a planar surface for transversal stress application.
- **Top ends** connected to Nb-Ti current leads.
- **Bottom ends soldered** together, i.e. the current flows anti-parallel.
- **Area of pressing** was chosen in the centre of the specimen between the inner voltage-taps to ensure a homogenous field condition over the measured area.



Specimen cross section (15.6 x 3.8) mm²



Area of pressing 50 mm



Strand properties

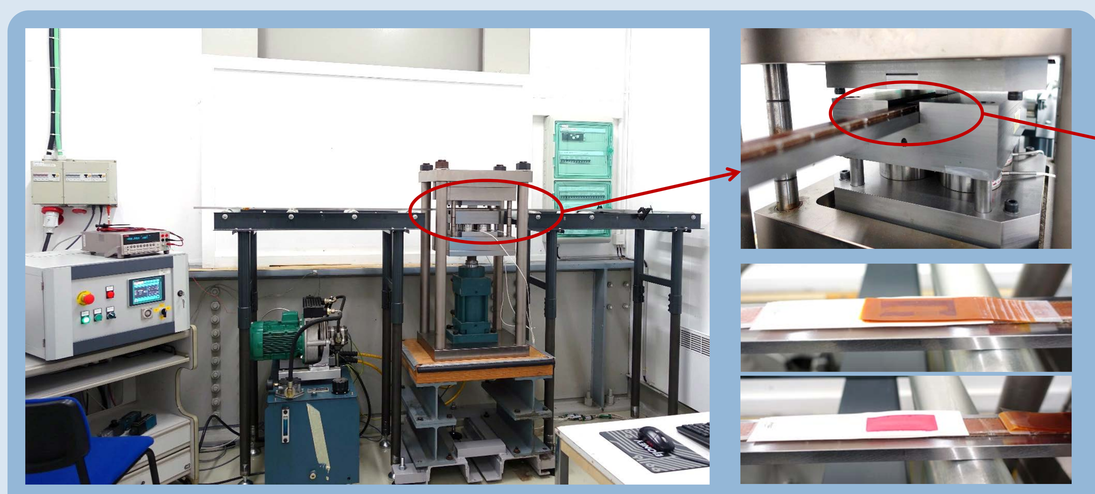
Type	RRP 144/169
Cu to Non-Cu volume ratio	1.08
Strand diameter	0.7 mm
Sub-element diameter	41 µm
Sub-element pitch length	14 mm
Virgin *RRR*	150
Virgin I_c(4.2 K,12 T)	438 A
Heat Treatment	48 h / 210 °C
	48 h / 400 °C
	50 h / 650 °C

Cable properties

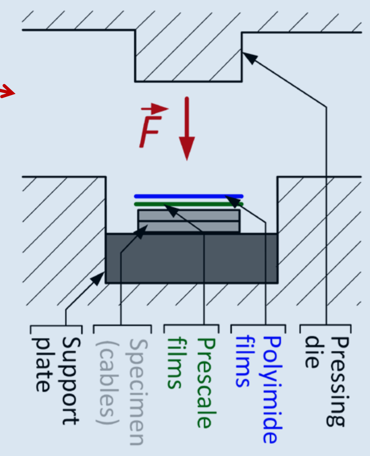
Cable ID	HT15OC0190
No. of strands	40
Transposition pitch	100 mm
Keystone angle	0.79°
Mid-thickness	1.25 mm
Width	14.7 mm
Insulation	S-2 glass braided
Core	316L
Packing factor	87.3%
Epoxy	CTD-101K

3) Application of transversal compressive stress

- Iterative compression **at room temperature before every I_c measurement.**
- Applying stress by using a hydraulic press and evaluation of force with **load cells** [7].
- Evaluation of **pressure distribution and optimization of the alignment** parameters by using FUJIFILM Prescale© [8].
- Self-written **image processing software** for evaluation of the Prescale films.
- Multilayer of Prescale films of different sensitivity was used to **cover a higher range.**

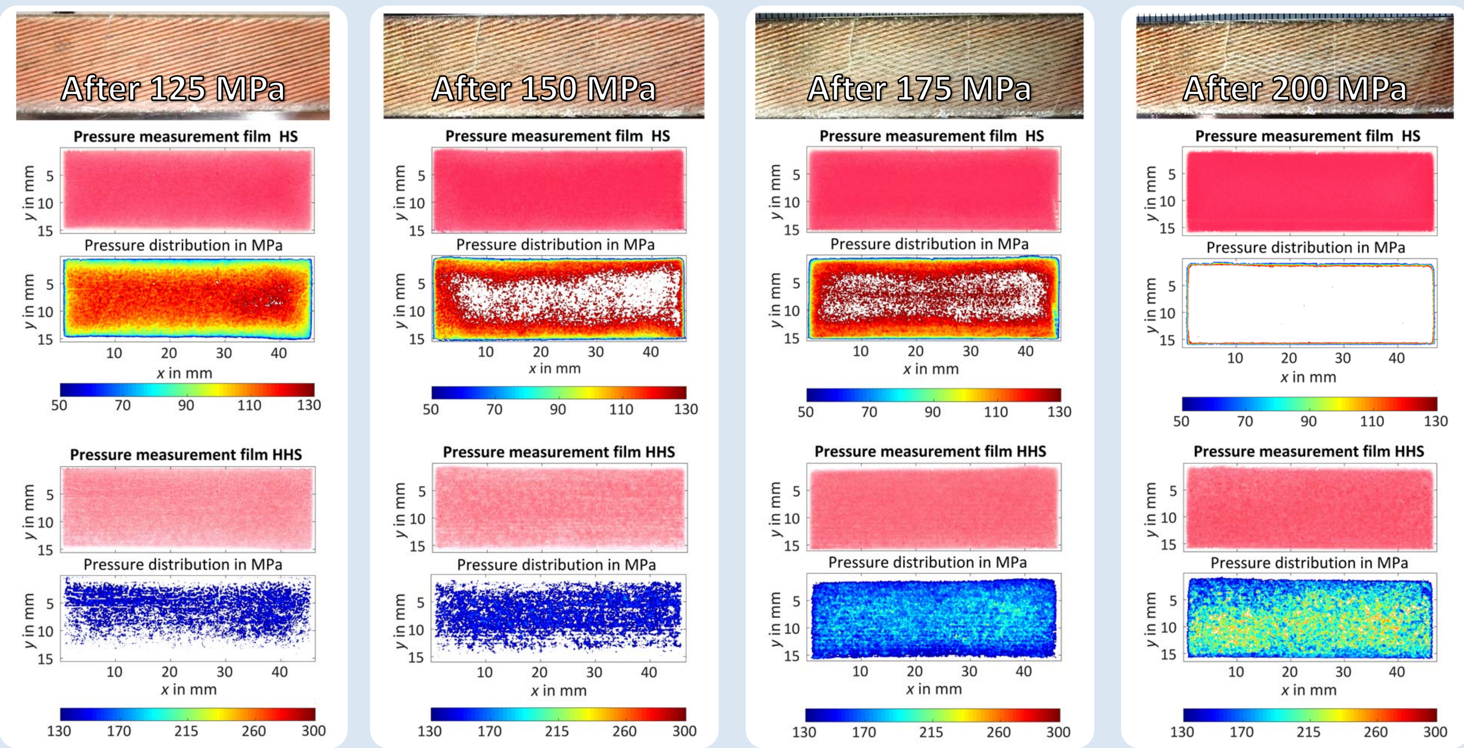


Hydraulic press for transversal stress



Stress application results

Nominal		$\sum_{i=1}^{4} F_{LoadCell,i}$	$\overline{\sigma}_{LoadCells}$
kN	MPa	kN	MPa
68.64	100	68.93	100.42
85.80	125	85.24	124.18
102.96	150	103.00	150.06
120.12	175	118.00	171.91
137.28	200	137.90	200.90



4) I_c measurement with FRESCA

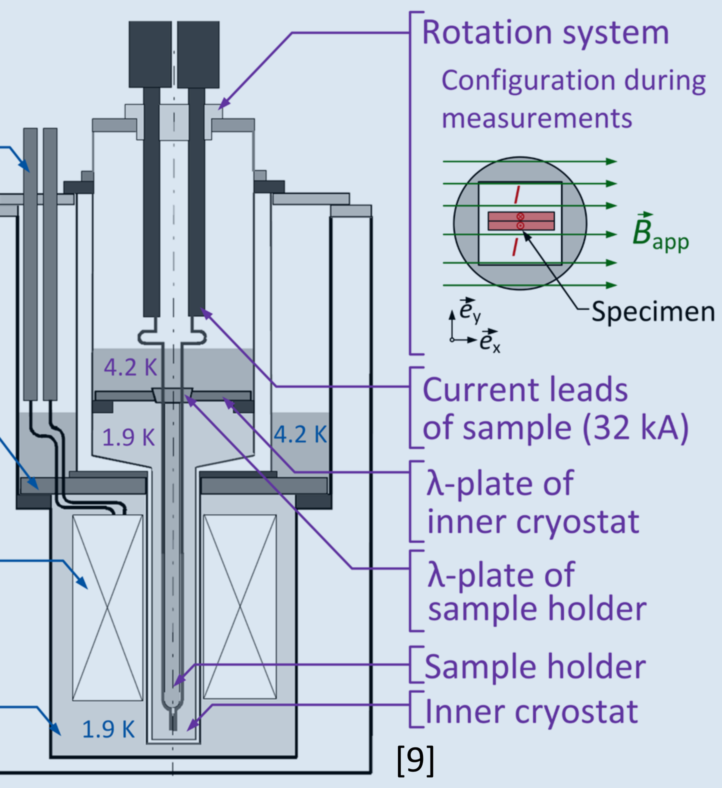
Subsequent to each stress application, the sample was transferred to the FRESCA test station for I_c measurement.

- FRESCA test station properties [9]
  - Operation current $I \leq 32$ kA (70 kA)
  - **Applied dipole field $B_{app} \leq 9.6$ T** with self-field **up to 12 T**
  - Homogeneity $B_{app}/\max(B_{app}) \geq 99$ % over a **length of 475 mm**
- **Measurement condition** of specimen
  - Applied field $\mathbf{B_{app} = 7 \ldots 9.6}$ **T**
  - Temperature $\mathbf{T = 4.2}$ **K**
  - $\mathbf{B_{app}}$ parallel to large surface of specimen and **perpendicular to the current**.
  - Both cables were measured and show the same degradation behaviour.

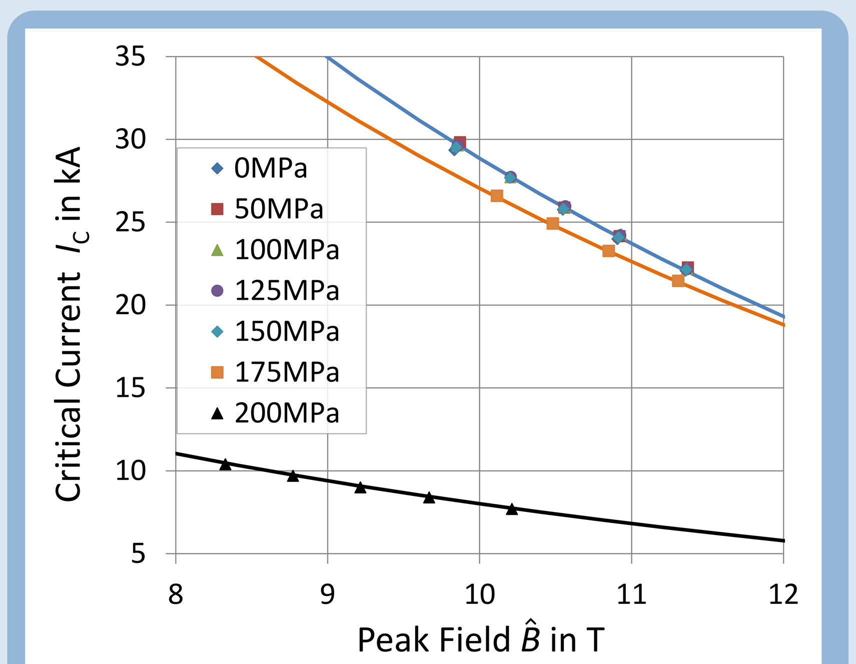
I_c measurement results at $\max(B_{app}) = 9.6$ T and $T = 4.2$ K

$\sigma_{nominal}$	I_c*	$I_c/I_{c,0MPa}$	n**
MPa	kA	1	1
0	22.1	1.00	60
50	22.2	1.00	60
100	22.2	1.00	60
125	22.2	1.00	60
150	22.2	1.00	60
175	21.45	0.97	60
200	7.9	0.36	<10

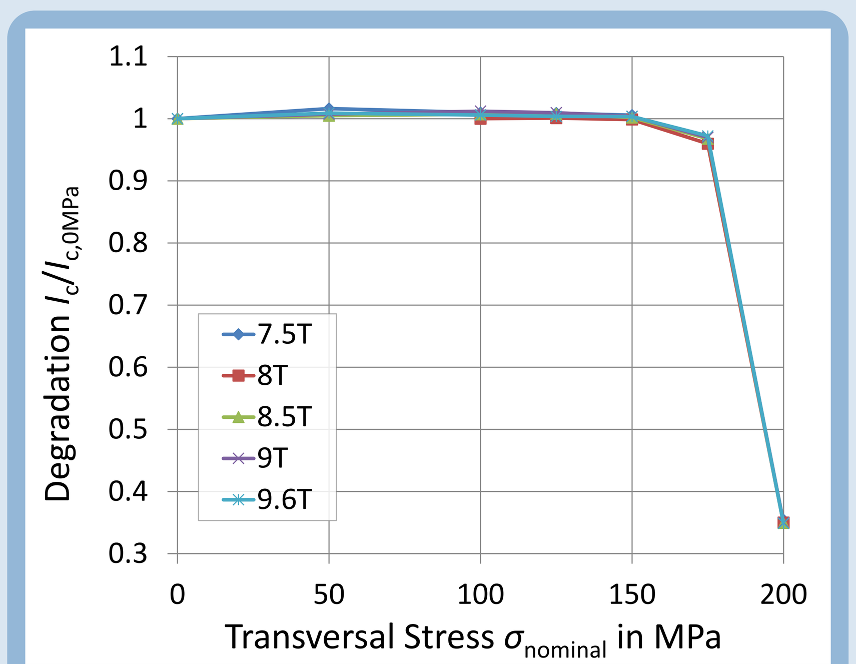
* $I_c := I(E = E_c := 3$ µV m$^{-1})$
** $E/E_c := (I/I_c)^n$, [10]



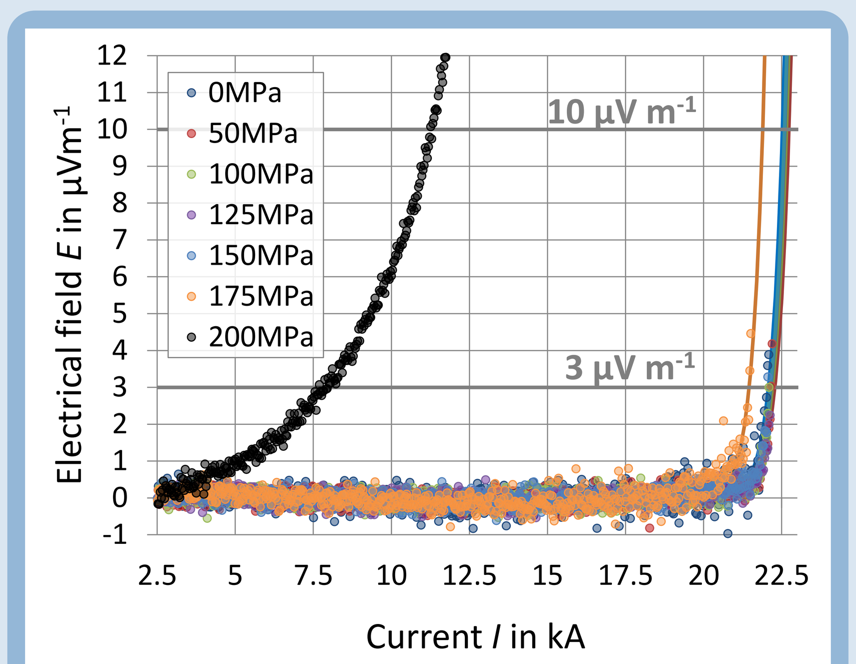
[9]



Results of I_c measurement at $T = 4.3$ K



Degradation of I_c at $T = 4.2$ K ($E_c = 3$ µV m^{-1})

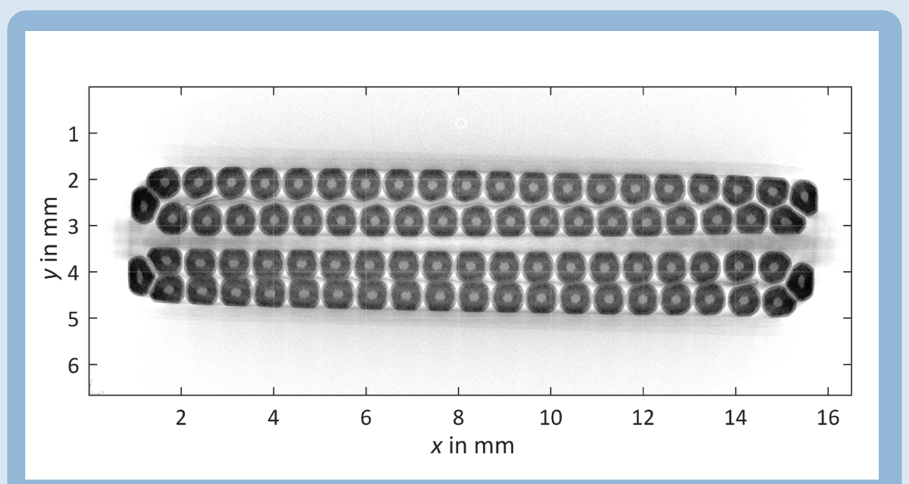


$E(I)$-comparison at $\max(B_{app}) = 9.6$ T

5) Post analysis

Investigation carried out after the measurement campaign

- **Visual inspection** of the pressing area shows on both sides several cracks of the epoxy resin matrix. An average **displacement in height of 0.02 mm** due to transversal stress was measured.
- **Non-destructive 3D X-ray tomography** by the Federal Institute for Materials Research and Testing (BAM) was carried out to identify damages caused by compressive stress.
  - **Plastic cable deformations caused by the applied stress are not revealed by the results. The spatial resolution is insufficient to visualise cracks** in the expected Nb_3Sn **filaments.**
  - **Deformations on the edges of the cables** and displacements of the core due to specimen manufacturing could be detected independent of the pressing. This leads to a degradation less than 5 % compared to the strand performance [11].



X-ray Tomography Snap Shot

6) Conclusion

In order to **determine the limits of pre-stress on the coil assembly for future high field accelerator magnets,** a **FRESCA-compatible Rutherford cable specimen was exposed to transversal compressive stress at room temperature** and subsequently the **critical current at 4.2 K was quantified** in several iterations up to 200 MPa.

A hydraulic press was used to perform transversal compressive stress and the **pressure distribution on the specimen was optimized.** The critical current was measured in the **FRESCA test station.**

The results show **a small I_c degradation after an applied stress of 175 MPa and the specimen was heavily damaged after the 200 MPa cycle. The critical current I_c and the resistive transition index n of the cable are reduced, which is caused by higher current sharing.** This measurement campaign also confirms that **the common pre-stress of 150 MPa does not cause any degradation** of the coil based on this study.

First visual inspection has shown **cracks and deformation on the surface of the epoxy resin.** Plastic deformation on the strand level and cracks in the impregnation layer or superconductive sub-elements could not be identified by the X-ray tomography.

7) Outlook

Additional to the non-destructive tomography a **microscopy** of the specimen is ongoing to understand the impact of transversal stress during room temperature on the superconductive Rutherford cable, especially the Nb_3Sn sub-elements of the strands.

Further campaigns with cables from the 11 T- and the MQXF- programme have been organised to confirm the observed results.

8) Acknowledgements

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