Effect of transverse compressive stress on Nb_3Sn Rutherford cables for accelerator magnets

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The accelerator magnets for the High Luminosity upgrade of the Large Hadron Collider (HL-LHC) use Nb_3Sn conductor to achieve in-field performance exceeding Nb-Ti based technologies. To sustain Lorentz forces during operation, a pre-compression is applied to the conductor during the fabrication of the magnet. This can lead to an irreversible degradation due to the mechanical sensitivity of the Nb_3Sn material.

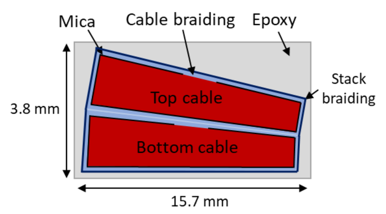
The impact of the pre-compression is investigated using a reacted double-stack of Rutherford cables.

The stack is submitted to **transverse stress at RT**. The **critical current** is then measured in **liquid helium** and in a **background field** of up to 9.6 T in the FRESCA test station at CERN. The pressure applied at room temperature on a reduce portion covers the range from 130 MPa to 190 MPa with a 10 MPa step increase.

On smaller specimens, **monotonic** and **cumulated pressures** were employed to analyse the impact of the **cyclic loading**. **Microscopic analysis** of cross-sections were performed following procedures specifically developed to minimize surface damage during samples' preparation. These observations were used to **correlate** the **irreversible effect of the transverse pressure** to the A15 damage.

Architecture of the 11T cable specimen

- Latest strand and cable configuration for the 11T magnet
  - RRP 108 / 127 strand
  - "small mica gap" (gap: 0.9 mm)
- Double stack configuration
- Not inverted
  - ⇨Evaluation of the impact of inhomogeneous resin distribution
  - ↳Impregnation layer around the stack not uniform ➔ can represent impregnation inhomogeneities
  - ⇨Top and bottom surfaces are flat ➔homogeneous distribution of pressure on the surfaces of the specimen



Strand Parameters

Architecture	RRP 108/127
Manufacturer	OST
Diameter	0.7 mm
Sub-element size	50 µm
Cu / non Cu	1.19
Ic (4.3 K, 12 T)	470 A
RRR	280

Cable Parameters

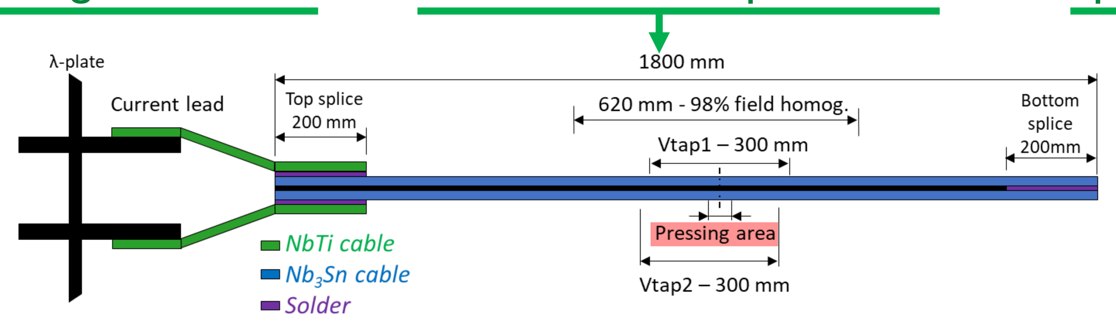
ID	H15OC0220B
Number of strands	40
Transposition pitch	100 mm
Keystone	0.808 °
Mid-thickness	1.25 mm
Width	14.7 mm
Insulation	S-2 glass C-shaped MICA
Core material & dim.	316L (24.3 µm x 12 mm)
Impregnation	CTD-101K

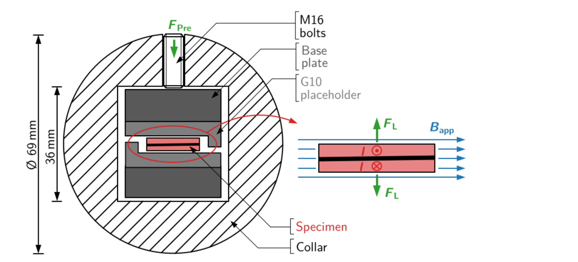
FRESCA test

Damage investigation

I_c measurement under magnetic field of a double-stack specimen after application of pressure at RT.

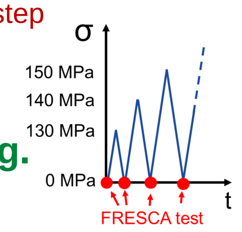
- FRESCA test station [1]
  - Test at a temperature of 4.3 K and 1.9 K up to a current of 32 kA in an external applied field up to 9.6 T.
  - Sample holder and field direction



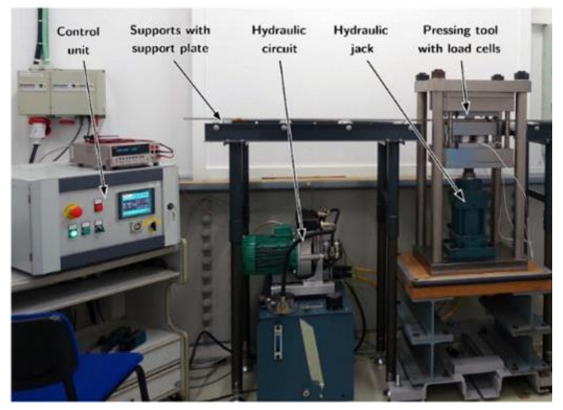


Schematic cross-section of the FRESCA sample holder and field direction on the sample [2]

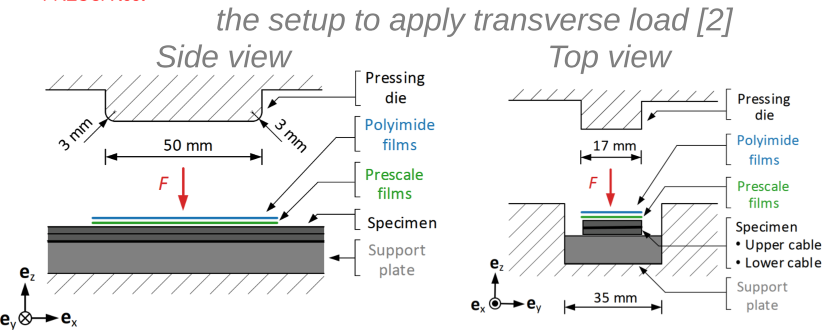
- Test Procedure
  1. Measurement at virgin state ➔ baseline,
  2. Warming up and application of pressure @ RT,
  3. Cool down and measurement in FRESCA,
     ⇨**The sample is submitted to a cumulated loading.**
  4. After the 190 MPa step, specimen loaded to 20 cycles at 190 MPa and measured in FRESCA,
  5. Then, 6 thermal cycles were performed.



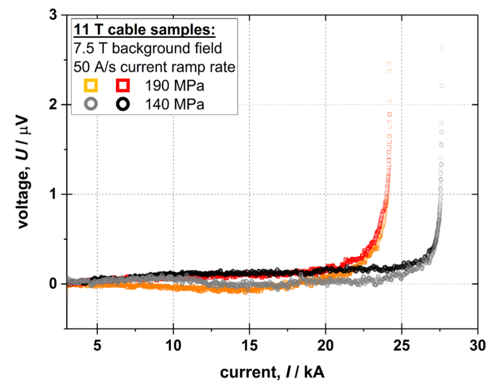
- Hydraulic press [2] [3]



Hydraulic press and schematic view of the setup to apply transverse load [2]

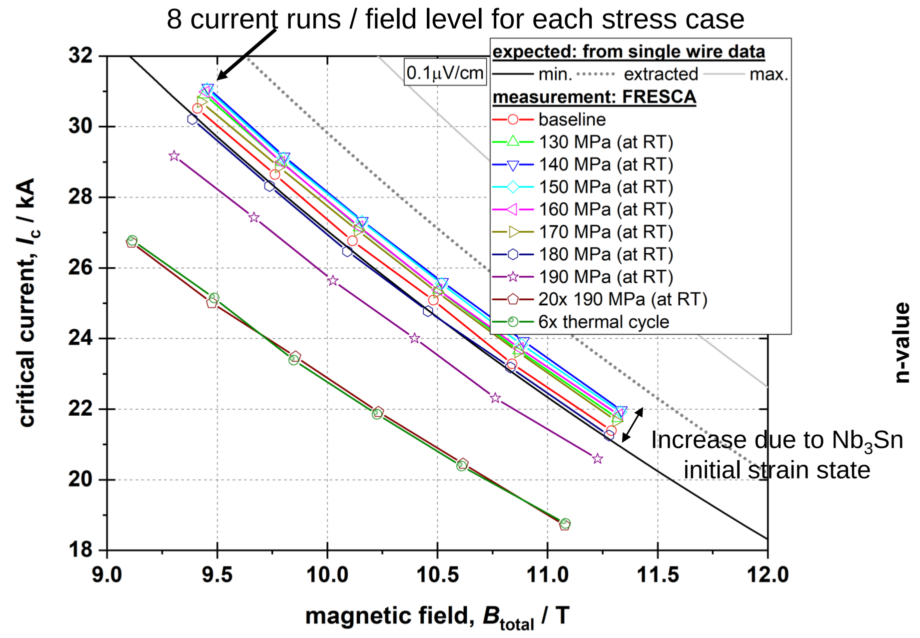


- Measurements
  - Vtaps in the high field region.
  - I_c as average of the two cables behavior.
  - Non-linear fit performed on $E = E_0 + m * I + E_c \left(\frac{I}{I_c}\right)^n$ (Offset, Resistive slope, Power law) with $E_c = 0.1\ \mu V/cm$.

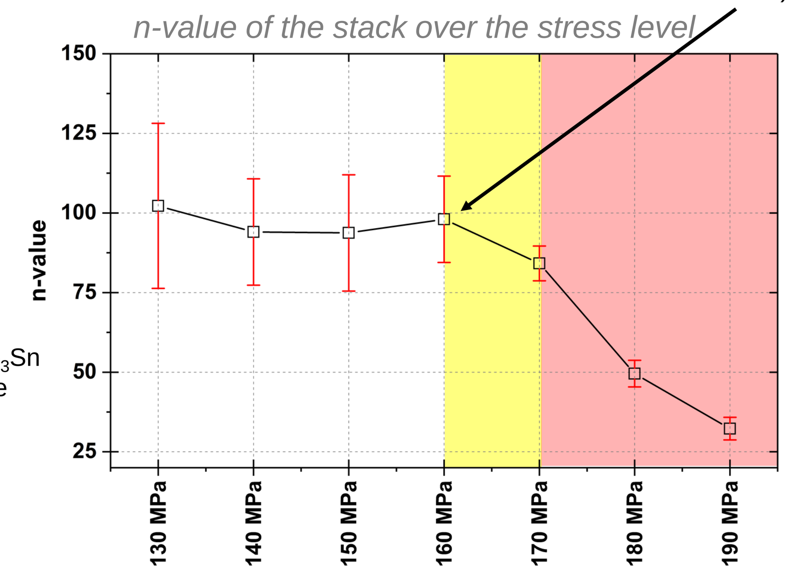


U-I curves of two stress cases measured on each cable

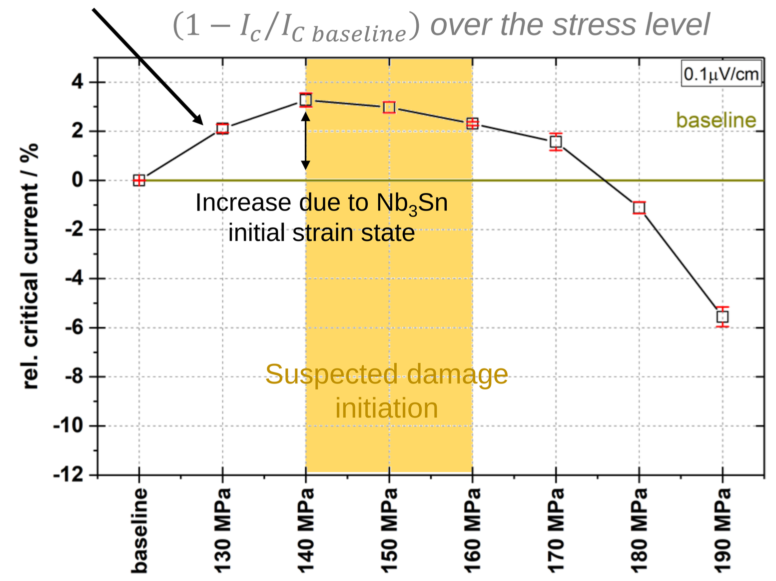
➔Results



From I_c-B_{total} results and expected single wire data
- ↳ Baseline: Ic just within expected range,
- ↳ ≤170 MPa: within expectations,
- ↳ ≥180 MPa: below expectations,
- ↳ Mechanical cycles - 20x190 Mpa ~16.5 % < baseline,
- ↳ Thermal cycles: 5x 77 K & 1x 4.2 K: no effect BUT performed after severe degradation.



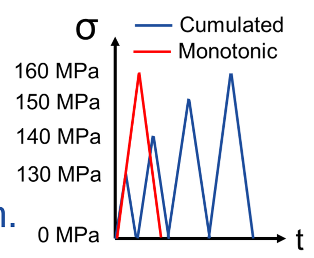
From n-value results:
- ↳ 160 MPa-170 MPa: reduction ⇨ degradation,
- ↳ From 170 MPa: cable irreversibly damaged.



From I_c degradation & damage analysis:
- ↳ Degradation appears before 160 Mpa FOR A NON-INVERTED CONFIGURATION.
- ➔ Impact of damage initiated in early stress level not visible on electrical measurements.

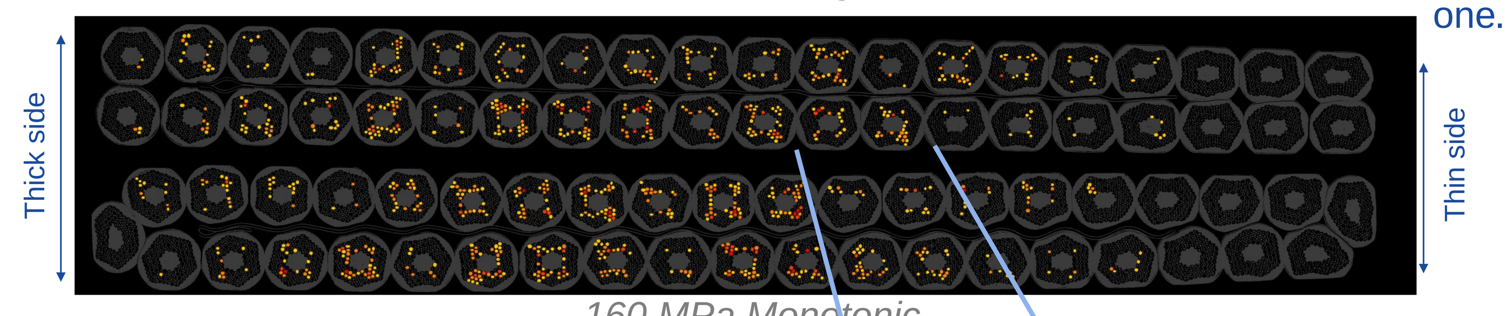
➔Reproduce stress cases of FRESCA test on separate samples to perform destructive metallographic observations.
➔Evaluate the impact of the cumulated loading on the damage state by comparison with samples loaded monotonically.

- Specimens ➔ 60 mm lengths w/o Vtaps:
  160 MPa Monotonic, 160 MPa Cumulated,
  170 MPa Monotonic, 170 MPa Cumulated,
  180 MPa Monotonic, 180 MPa Cumulated,
  190 MPa Cycled area cut from FRESCA specimen.

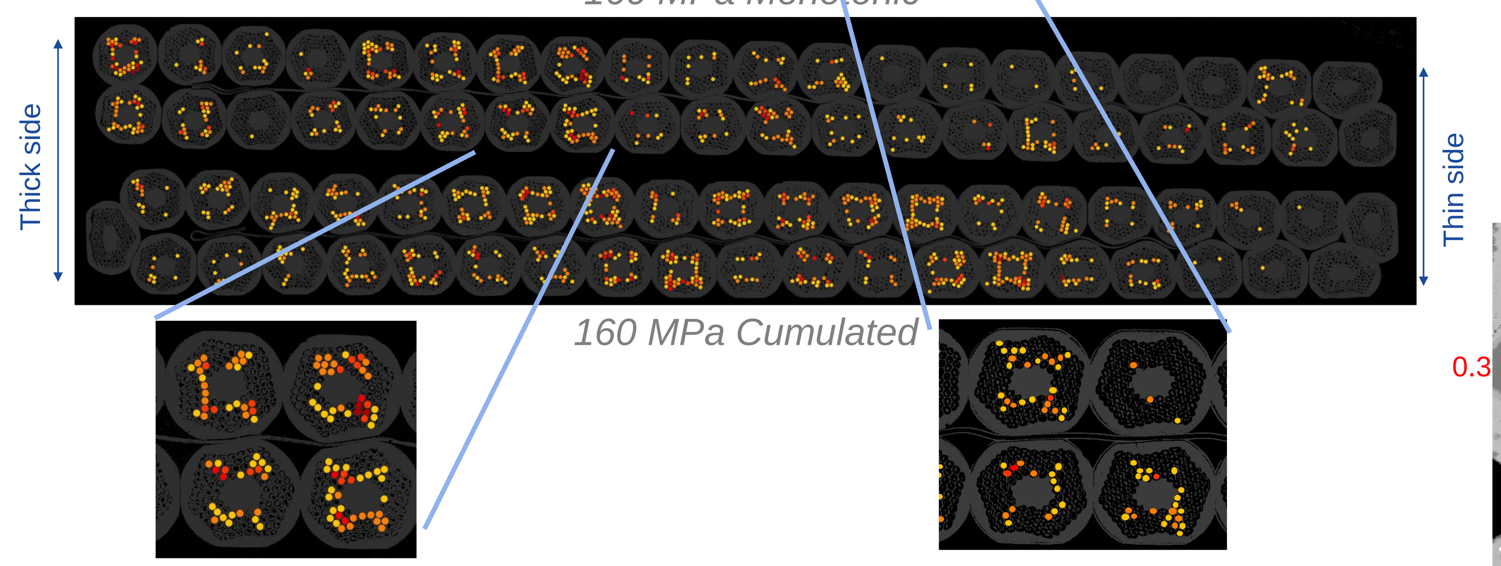


Comparison of the crack distribution of the 160 MPa monotonic and cumulated samples.
- *↳ Crack density is more important in the cumulated sample.*
- *↳ Center of stack is mainly damaged.*
- *↳ Thin side is less damaged than thick side.*

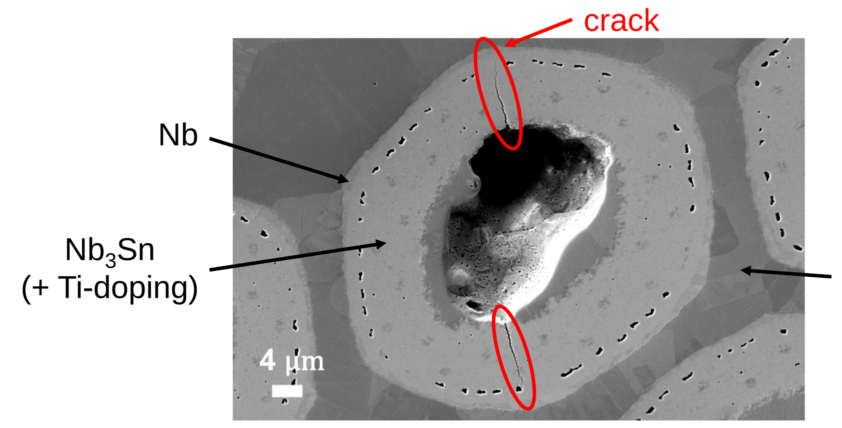
- Preparation
  - Reference sample (not cracked) prepared together with the analyzed samples to guarantee the preparation procedure didn't induce damage,
  - Grinding and polishing with decreasing particle size (SiC papers and water-based diamond pastes) - Vibro-polishing final step.
- Analysis procedure
  - Optical microscope for global analysis and small cracks under SEM.
  - Quantification of cracks by B&W stack pictures with color scheme assigned to cracked filaments:
    - yellow-1crack, orange-2, red-3 and dark red-4 & more.
    - **Doesn't represent the size of the crack!**
    One yellow coded sub-element may have a 3 µm long crack or a 10 µm long one.



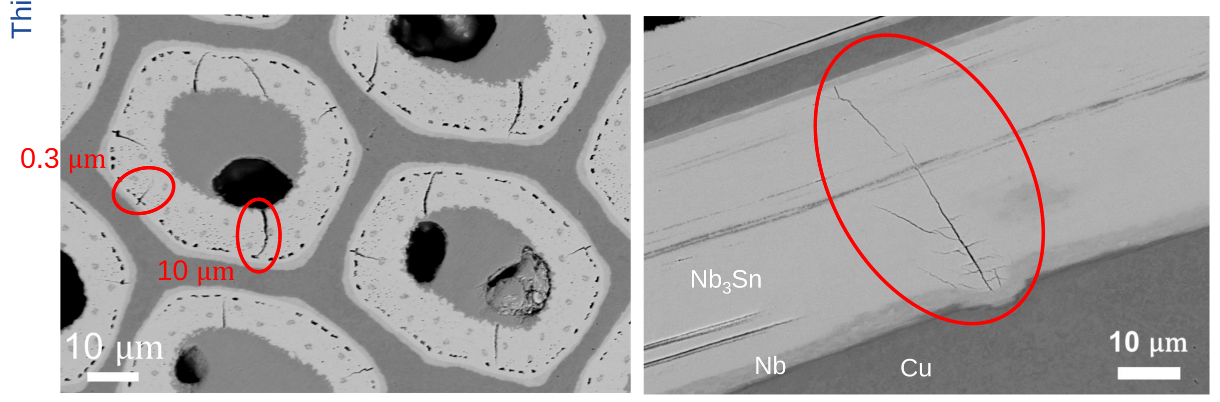
160 MPa Monotonic



160 MPa Cumulated



Example of cracks in a sub-element of the 160 monotonic sample



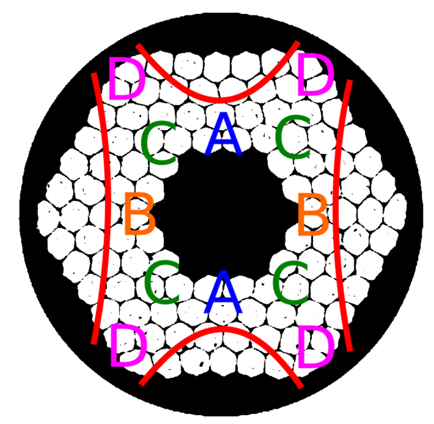
Longitudinal cracks in sub-elements in a transverse cross-section

Transverse cracks in a sub-element in a longitudinal cross-section

SEM observations of the 190 Cycled.

➔ Results & conclusions

- **All samples show cracks, even the lowest one: 160 MPa Monotonic.**
- Density of cracks more important in **cumulated loaded samples** than **monotonic one.**
- Damage in cables localized mainly in center, thin side less damaged than thick side.
  - ↳ non-inverted configuration (can be confirmed by comparison with inverted configuration analysis).
- Pattern of cracks in sub-element:
  - Cracks are localized in the 45° planes from loading direction.
  - Damage sub-elements orientation does not vary wrt. the rotation of the hexagon structure.
  - Majority of the cracks oriented // to loading direction (vertical).
    ↳ Horizontal cracks appear in severely damage sub-elements localized in zone C.
  - In strands with less damage (1 to 10 sub-elements affected) cracks localized in A,B & C.
    As cracks density ↗, localized in C.
    Heavily damage strands, zone D is reached and multiple cracks



Schematic map of the damage area in a strand

Conclusions

- Metallographic analysis clearly shows **difference** in damage occurring in **monotonic** and **cumulated / cyclic loadings.**
- **Electrical test underestimates** the damage phenomenon and doesn't allow to evaluate the initiation of damage.
  ⇨ Investigation to evaluate if cracks can appear at low pressure without macroscopic impact and could lead to degradation with a cyclic loading.

Questions

- Effect of cyclic loadings (mech. & thermal) at lower pressure?
- At which pressure / stress level the first cracks appear?
- Physical phenomena and damage process involved?

Perspectives & On-going work

- 11T sample
  - Metallography
    - **Lower stress cases,**
    - Longitudinal cross-section,
    - Statistics (crack density, size, pattern).
  - **Inverted double-stack configuration**
- **Analysis of MQXF stack cable**
- Numerical twin using the CoCaSCOPE approach [4]

Acknowledgement: Thanks to O. Kalougine for the preparation of the sample and G. Peiro to operate during test.

Ref.: [1] A. P. Verweij et al., IEEE Trans. Appl. Supercond., 1999, doi: 10.1109/77.783259. [3] F. Wolf et al., IEEE Trans. Appl. Supercond., 2018, 10.1109/TASC.2017.2780850.
[2] P. Ebermann et al., Supercond. Sci. Technol., 2018, 10.1088/1361-6668/aab5fa. [4] F. Nunio et al., IEEE Trans. Appl. Supercond., 2019, doi: 10.1109/TASC.2019.2903981.

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