CERN

2nd Workshop on Nb_3Sn Rutherford Characterization for Accelerator magnets

Critical Current Measurements of Nb_3Sn Rutherford Cables Under Transverse Compressive Stress

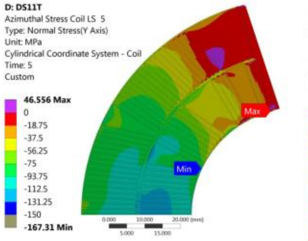
Gianluca De Marzi and Bernardo Bordini

Outline

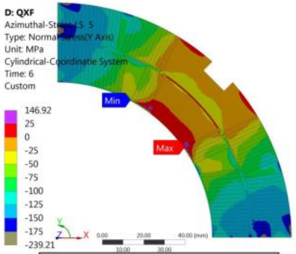
- Introduction: campaigns at CERN aimed at:
  - Studying the behavior of cables upon transverse loads
  - Defining their limits in terms of permanent degradation
- Sample holder for FRESCA test station
- Critical current measurements in FRESCA – Results
  - 18-strands PIT & RRP cables
  - In-field I_c measured up to P = 160 MPa, $\mu_0 H \approx 12$ T (T = 4.3 K)
  - Discussion of experimental results
- Conclusions

Introduction

- The HL-LHC will rely on a number of key innovative technologies, including cutting-edge 11-12 T superconducting magnets
- A key challenge for FCC is the development of high-field dipole magnets, capable of providing a 16 T field in a 50 mm aperture
- Large stresses on conductors due to high fields
  - Design limits for stress in the coils are ~150 MPa (DS11T, MQXF) and ~200 MPa (FCC)



DS11T powering 12.8 kA



MQXF powering 19.1 kA

C. Löffler CERN-THESIS-2017-078

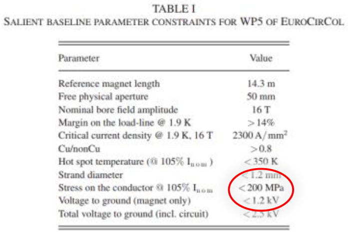
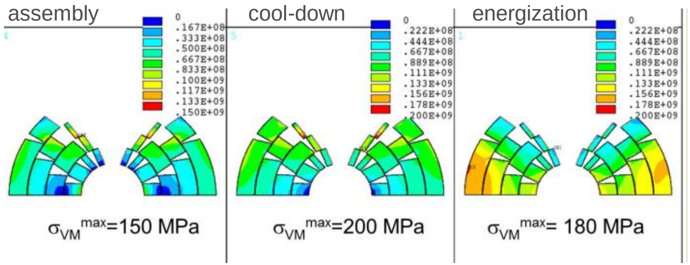


TABLE I
SALIENT BASELINE PARAMETER CONSTRAINTS FOR WP5 OF EUROCIRCOL

Parameter	Value
Reference magnet length	14.3 m
Free physical aperture	50 mm
Nominal bore field amplitude	16 T
Margin on the load-line @ 1.9 K	> 14%
Critical current density @ 1.9 K, 16 T	2300 A/mm^2
Cu/nonCu	> 0.8
Hot spot temperature (@ 105% I_{nom})	< 350 K
Strand diameter	< 1.2 mm
Stress on the conductor @ 105% I_{nom}	< 200 MPa
Voltage to ground (magnet only)	< 1.2 kV
Total voltage to ground (incl. circuit)	< 2.5 kV

D. Tommasini *et al.* 2017, IEEE TAS **27**, 4000405

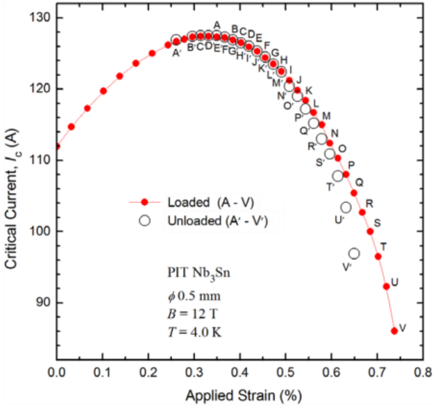


The INFN Cos-theta option for the 16 T FCC dipole

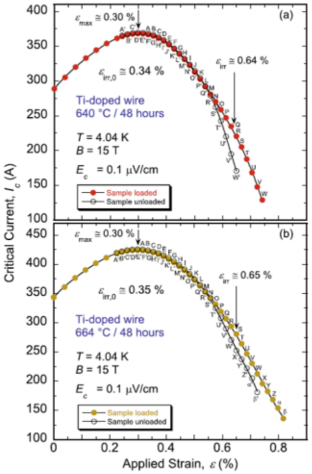
M. Sorbi *et al*. 2017, IEEE TAS **27**, 4001205

Introduction

- HL-LHC magnets will be the first high-field Nb_3Sn-based dipoles/quadrupoles ever operating in a particle accelerator
- Nb_3Sn is the *enabling technology* for these applications… but is also known for its strain sensitivity
- For the FCC magnets, which are assumed to be subjected to much higher stress conditions than those foreseen in HiLumi, it is thus essential to characterize the cables *vs. transverse load*, in conditions similar to those experienced in real coils.



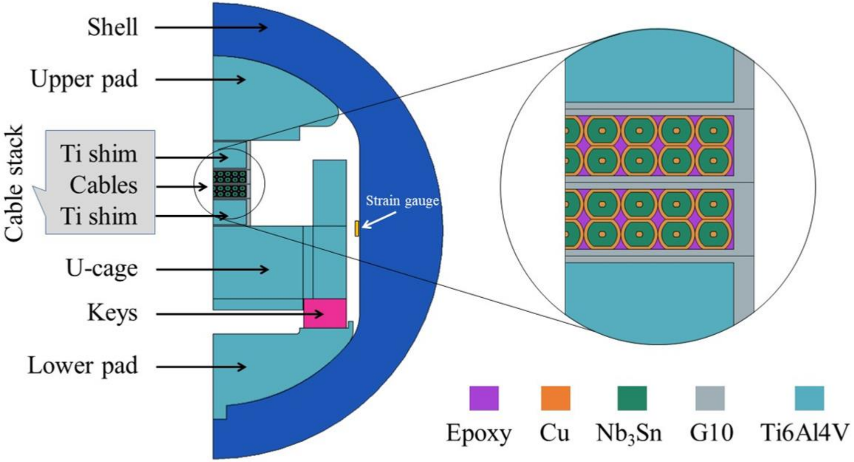
PIT wire



RRP Ti-doped wire

Cable I_c *vs.* Transversal Load

- CERN launched an experimental campaign to assess the in-field electrical properties of impregnated Rutherford cables
- Developed a sample holder for testing superconducting cables up to 200 MPa in FRESCA test station
  - Transverse load is provided by the *bladder and key* method to create interference fit at room temperature
  - Additional stress adds up at cryogenic temperatures, due to differential thermal contractions between Ti pads and Al shell



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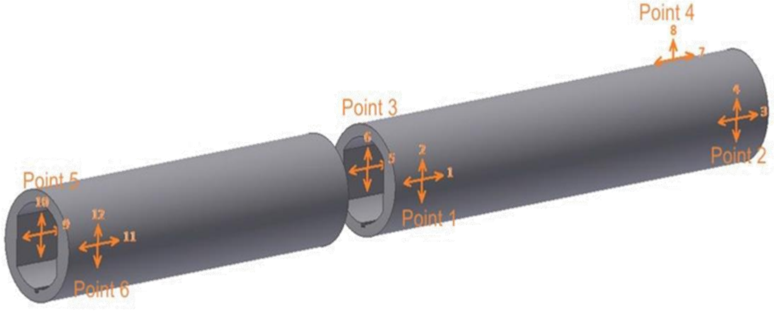
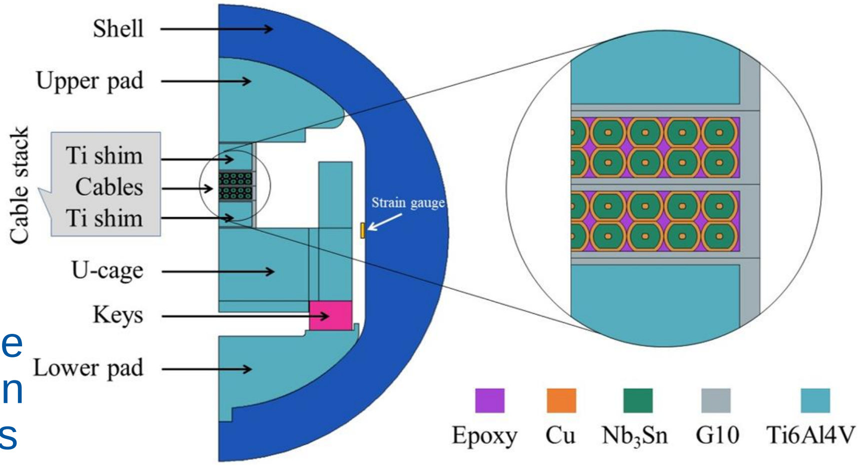
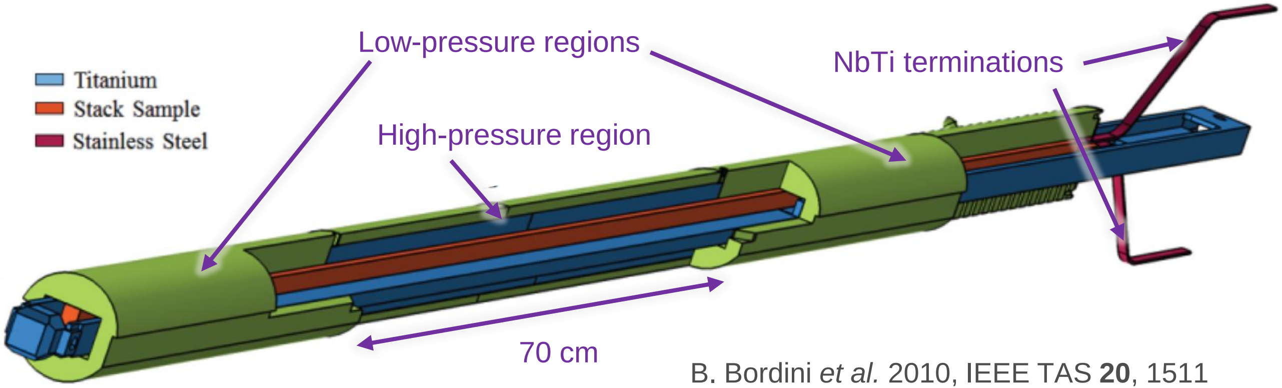




  - 12 strain gauges are installed in pair on the inner walls of the Al shell, measuring the strain along the azimuthal and longitudinal directions

CERN Cable Sample Holder



Max transverse force: **1750 kN**

Low-pressure regions

NbTi terminations

High-pressure region

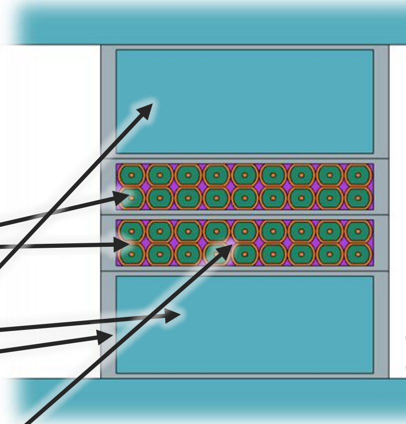
70 cm

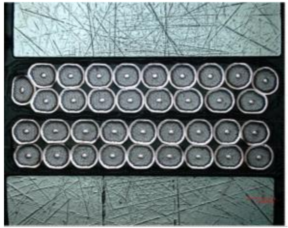
B. Bordini *et al.* 2010, IEEE TAS **20**, 1511

- High-pressure region extends over 700 mm field uniformity length
- Representative of the conductor behavior in accelerator magnets

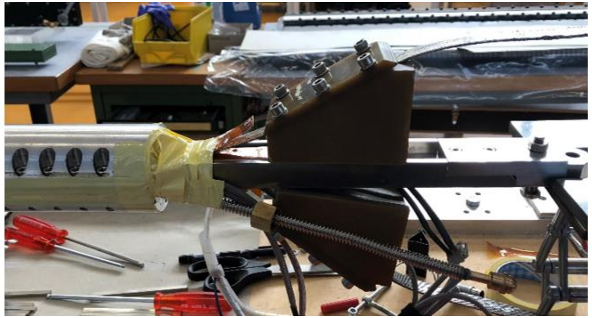
Samples

- Cables based on: 132/169 RRP® and 192 PIT
- Cable stacks (*samples*) are comprised of:
  - Two rectangular Rutherford cables based on eighteen Nb_3Sn strands (ϕ = 1 mm)
  - Two Ti6Al4V bars that *sandwich* the active cables
  - Fiberglass braid (RRP) or tape wrapping (PIT) separates the different stack's components
- Vacuum impregnation with CTD-101 epoxy
- Active cables spliced together at the bottom over a length of 15 cm, and on the top with NbTi cables



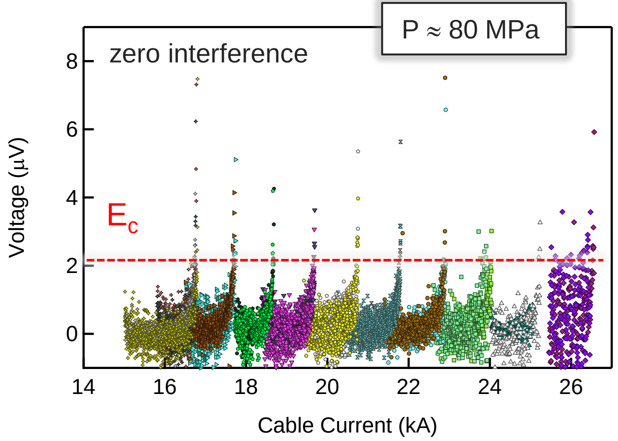


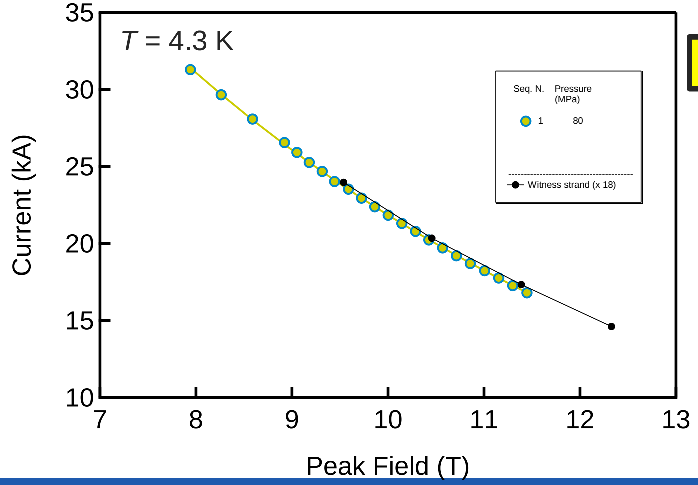
Courtesy of A. T. Pérez Fontenla and E. García-Tabarés Valdivieso



Tests on PIT Cable - Measurements 1/2

- I_c of cable defined at E_c = 3 μV/m
- First test done at *interf.* = 0 → ~ 80 MPa
  - In line with values expected from witness strand
  - I_c not significantly affected by transverse load



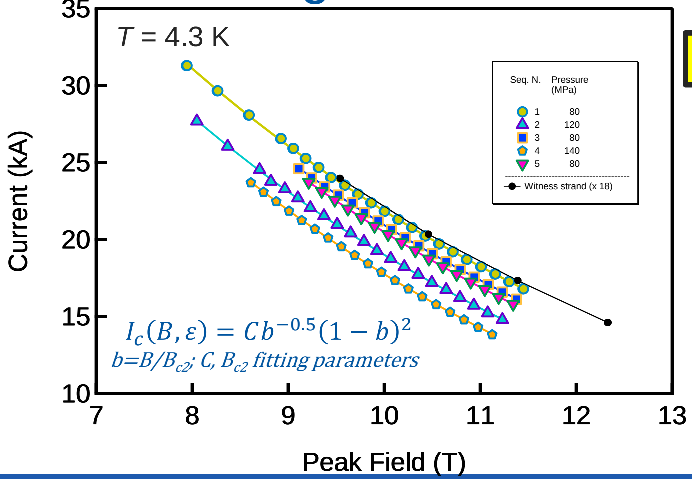


On-going campaign

- Then the sample is
  - Warmed up
  - Loaded at higher pressure
  - Cooled down
  - Measured again

Tests on PIT Cable - Measurements 1/2

- I_c measured at different transverse loads ranging from 80 to 140 MPa
- Each high-pressure test was followed by unloading, to check for irreversibility



On-going campaign

Courtesy of A. T. Pérez Fontenla
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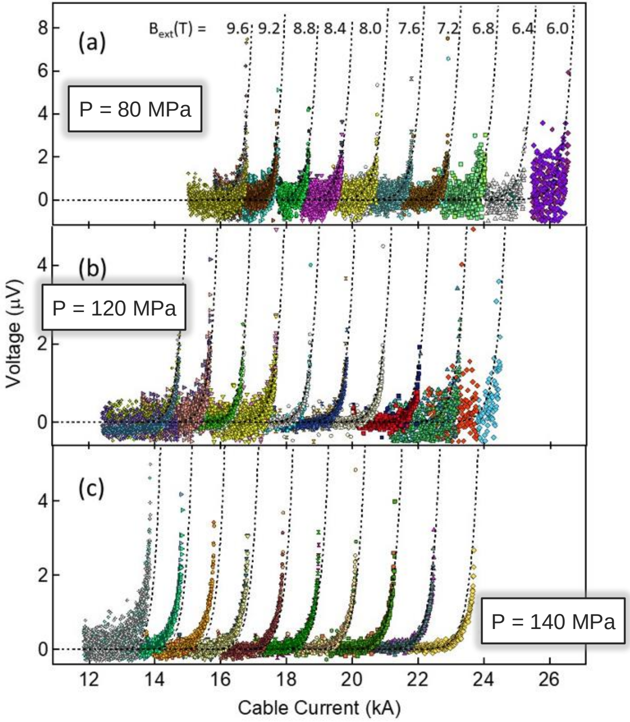
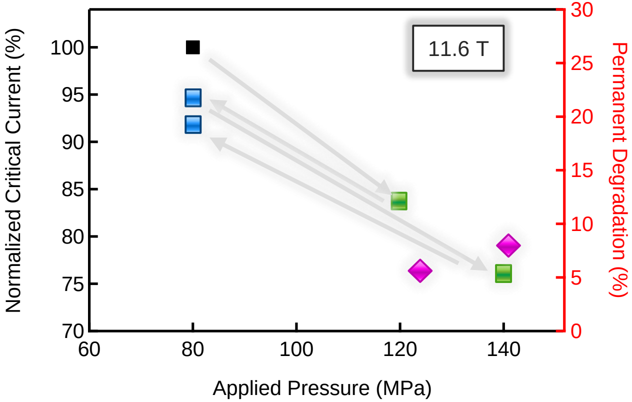
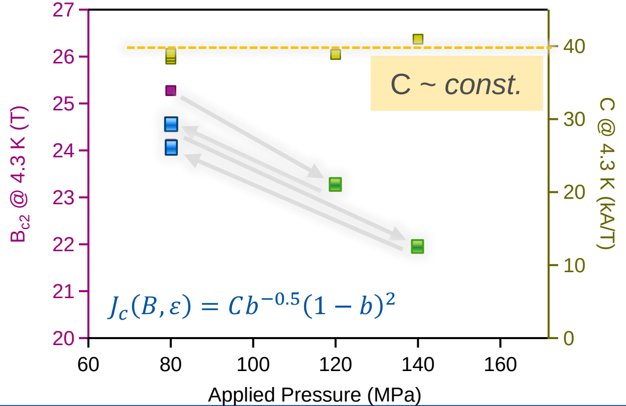
Micrographies *en cours*



Tests on PIT Cable – Results

- Observed a significant decrease of I_c at 120 MPa
  - At 11.6 T, the I_c is 84% of the low-pressure current
  - Due to the reduction of the B_{c2} through $s(\varepsilon)$
- Followed by strong recovery of I_c (~80 MPa)
  - At 11.6 T the I_c is 95% when compared to first measurement
  - Permanent degradation at 80 MPa is about 5%



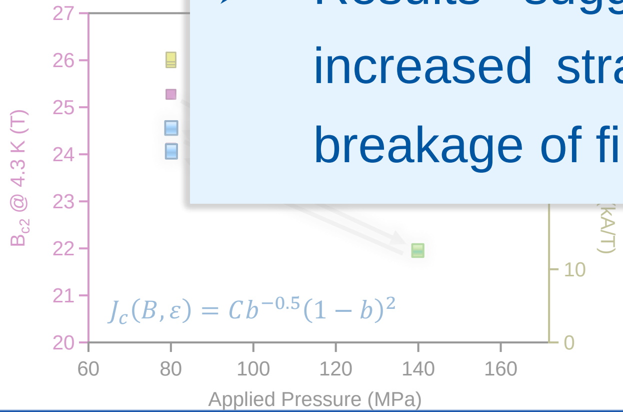


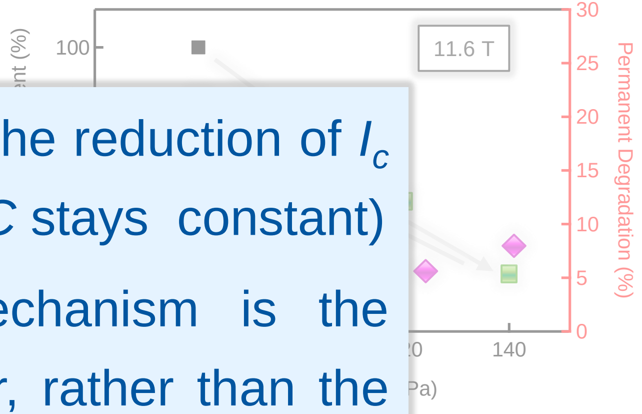
- Test at 140 MPa showed further decrease of I_c
  - I_c is 76% of the low-pressure current
- Next low-pressure test showed recovery again
  - I_c is 92% when compared to first measurement
  - Build-up of permanent degradation, up to about 8%

Tests on PIT Cable – Results

- Observed a significant decrease of I_c at 120 MPa
  - At 11.6 T the I_c is 84% of the low-pressure current
  - Due t
- Followe
  - At 11.
  - Perm

- Experimental findings: up to 140 MPa the reduction of I_c is completely due to the B_{c2} reduction (C stays constant)
- Results suggest that the **main** mechanism is the increased strain in the superconductor, rather than the breakage of filaments



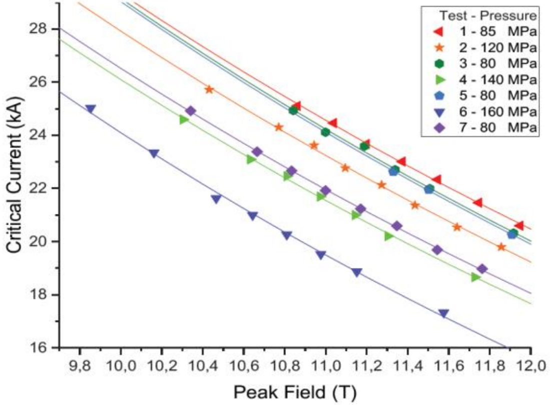


ease of I_c

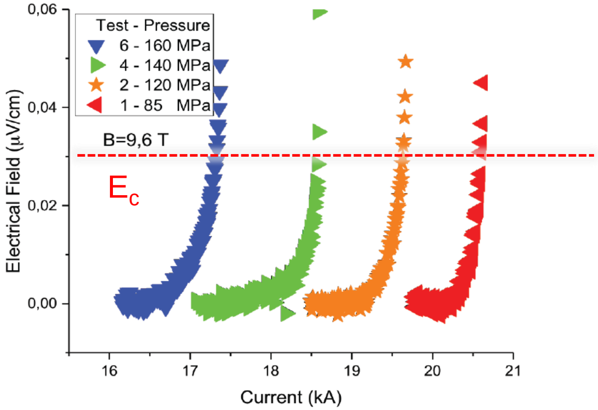
- Next low-pressure test showed recovery again
  - I_c is 92% when compared to first measurement
  - Raise of permanent degradation up to about 8%

Tests on RRP® Cable - Measurements

- Measured a 18-strand cable based on $\phi = 1$mm RRP wire, geometrically identical to the PIT cable



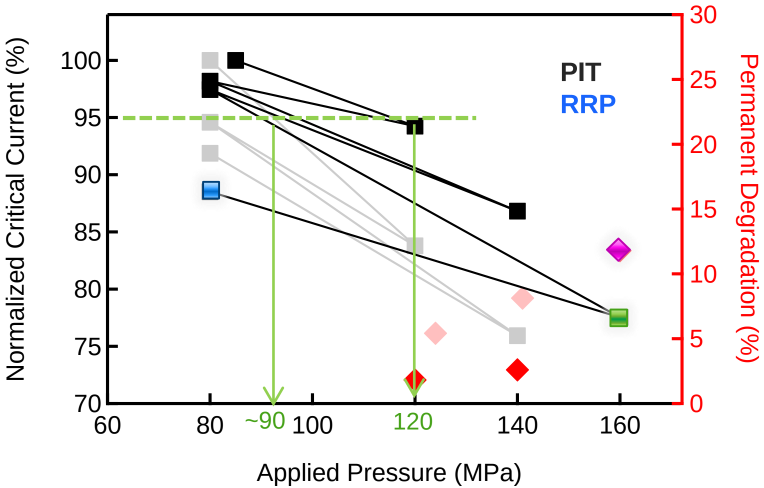
J.-E. Duvauchelle *et al.* 2018, IEEE TAS **28**, 4082305



- I_c measured at different transverse loads ranging from 80 to 160 MPa
- When compared to PIT, the RRP cable shows similar behavior

Tests on RRP® Cable - Results

- RRP® cable seems a bit less sensitive to transverse load
  - 5% reversible I_c reduction occurs at 120 MPa instead of 90 Mpa
  - Further decrease of I_c at 160 Mpa (77.6% of initial value)



- Test at highest pressure (160 MPa):
  - Significant reduction of *n*-index
  - Sharp rise of permanent degradation between 140 MPa and 160 MPa (> 10%; I_c retained: 88%)

Might be a sign of the presence of cracks

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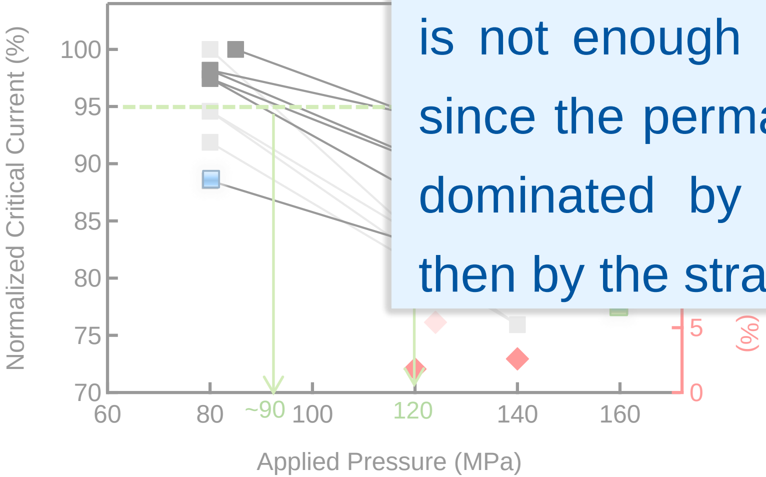


At 160 MPa, the mere reduction of $B_{c2}(\varepsilon)$ it is not enough to explain the I_c decrease, since the permanent degradation might be dominated by filaments breakage rather then by the strain state in Nb_3Sn

(160 MPa):

ndex

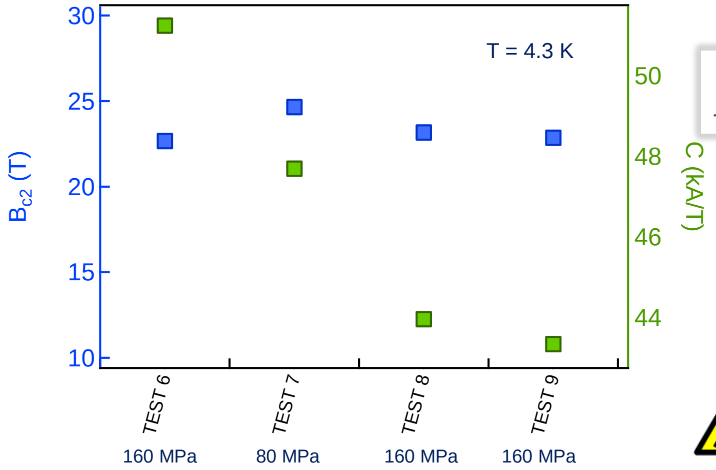
degradation between

10%; I_c retained: 88%)

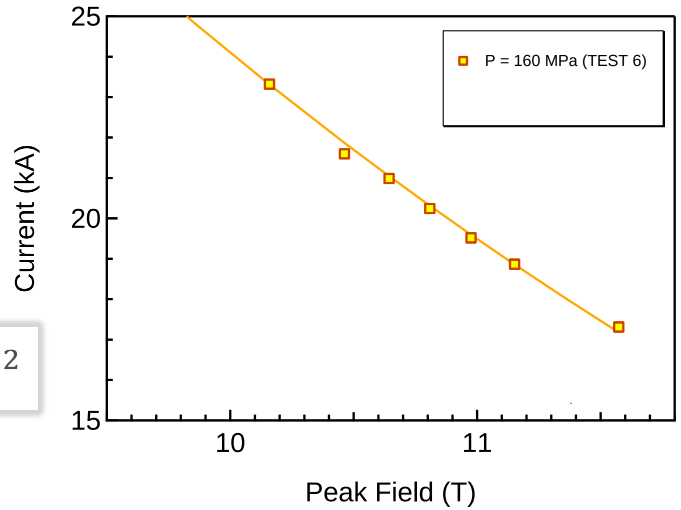
Might be a sign of the presence of cracks

Permanent Degradation – RRP® Cable

- Permanent degradation at highest pressure (~160 MPa)
  - Measured 2nd time at 160 MPa, after unload @ 80 MPa
  - Thermal cycle at 160 MPa (*i.e.* mechanical load ~80 MPa)



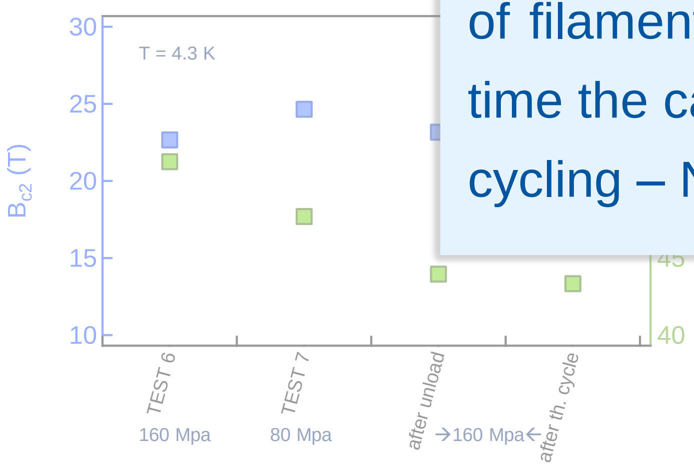
$$J_c(B,\varepsilon) = Cb^{-0.5}(1-b)^2$$

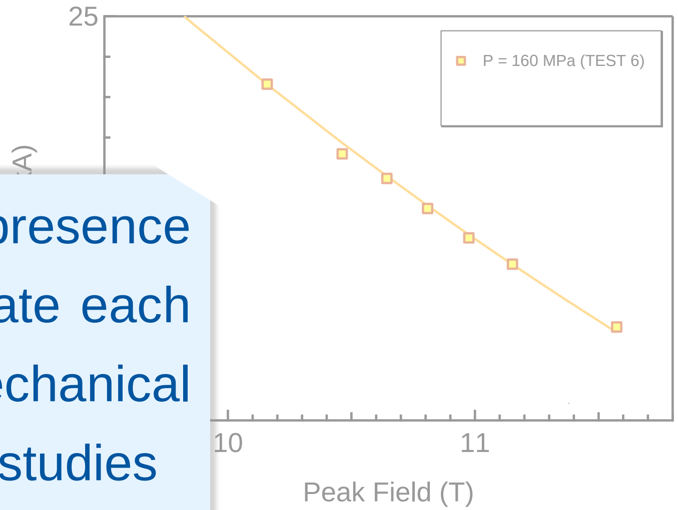


- B_{c2} does not change significantly (~23 T)
- On the contrary, *C* decreases with subsequent tests

Permanent Degradation – RRP® Cable

- Permanent degradation at highest pressure (~160 MPa)
  - Measured 2^{nd} time at 160 MPa, after unload @ 80 MPa
  - Additional thermal





Results are in favour of the presence of filament cracks that propagate each time the cable undergoes a mechanical cycling – Need metallographic studies

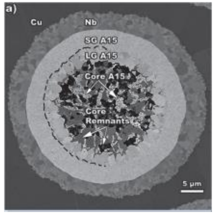
- B_{c2} does not change significantly (~22.9 T)
- On the contrary, *C* decreases with subsequent tests

RRP *vs.* PIT

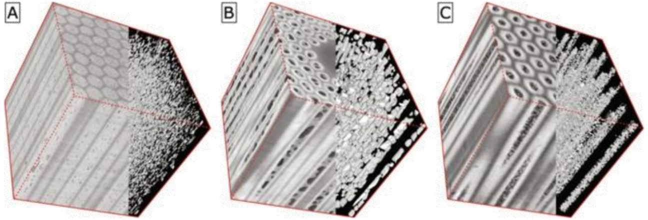
- The larger tolerance of RRP 132/169 to transverse load might be due to differences in grain morphology
- The A15 phase is supporting most of the mechanical load in the wire
- Two distinct A15 grain morphologies found in high-J_c conductors:
  - Large disconnected grains (> 1 μm) and small grains (<200 nm)
  - Correlation between void morphology and irreversibility

	RRP	PIT
SG (%vol)	58	30-40
LG (%vol)	4	18

C. Scheuerlein *et al.* 2015, IEE TAS **25**, 8400605
C. Tarantini *et al*. 2015, SuST **28**, 095001



FESEM-BSE image of a PIT wire
(C. Segal *et al.* 2016, SuST **29**, 085003)



Exemplary 3D assembled X-ray tomography images in a cube of Bronze (**A**) RRP (**B**) and PIT Nb_3Sn wires (**C**).

C. Barth *et al.* 2018, Sci. Rep. **8**, 6589

Summary thoughts

- Measurements of PIT and RRP cables under transverse loads, representative of cable behavior in real magnets/coils
- Tests showed that the *reduction* of I_c has double origin:
  - Strain state, with impact on $B_{c2}(\varepsilon)$ → *mainly reversible*
  - Filaments breakage → *irreversible* (build-up of cracks)
  - These two mechanisms can be present concurrently, with one dominating with respect to the other depending on the applied transverse load
- In both cables, the first mechanism is dominating up to 140 MPa
- RRP cable demonstrated less sensitivity to strain
  - However, 160 MPa can be high enough to trigger the formation of cracks

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