CERN – 9th October 2017

Conductor Studies

B. Bordini, J.E. Duvauchelle – CERN
M. Dhallé, P. Gao – Uni. Twente
C. Senatore, L. Gamperle, C. Barth – UniGe

2nd Review of the EuroCirCol WP 5

Outline

- Introduction
  - EuroCirCol Baseline Conductor
  - Characteristics of the HL-LHC wires
- Main Conductor Study - Critical Current vs. Transversal Load
  - Introduction
  - The Exponential Strain Function:
    1. Characteristics, Potential
    2. Computing the effect of Reversible I_c degradation in Wires and Cables
  - Experimental Studies
    1. Plans and Goals
    2. Cable Measurements at CERN and at Twente University
    3. Wire measurements at the University of Geneva
- Conclusions

EuroCirCol Baseline Conductor

J_c (T, B) scaling

Scaling Law

$$J_c = \frac{C}{B}\cdot b^{0.5}(1-b)^2 \qquad b = \frac{B}{B_{c2}}$$

$$C = C_0\left[(B_{c2})(1-t^2)\right]^{\alpha}$$

$$t = \frac{T}{T_{c0}}$$

$$B_{c2} = B_{c20}\left[1-t^{1.52}\right]$$

Parameters

$$J_c(16\ \mathrm{T},\ 4.22\ \mathrm{K}) = 1.03\cdot 1500\ \mathrm{A/mm^2}$$

$$B_{c2}(4.22\ \mathrm{K}) = 25.5\ \mathrm{T}$$

$$T_{c0} = 16\ \mathrm{K}$$

$$\alpha = 0.96$$

- Assumed cable degradation 3 %
- Main parameters

J_c(16 T, 4.22 K) = **1545 A/mm²** B_{c2}(4.22 K) = **25.5 T**

Characteristics of the HL-LHC wires

Average values measured at CERN

	Layout	Sub-Element size	J_c (12 T), *RMS* [A/mm^2]	J_c (15 T), *RMS* [A/mm^2]	B_{c2}(4.3 K), *RMS* [T]	J_c (16 T), *RMS* [A/mm^2]	J_c (18 T), *RMS* [A/mm^2]	Degradation J_c (15% rolling) [%]	Minimum RRR (15% rolling) -
0.7 mm RRP	108/127	46 µm	**2676,** *68*	**1410,** *58*	**24.5,** *0.39*	**1098,** *55*	**610,** *47*	0	>100
0.85 mm RRP	108/127	55 µm	**2835,** *44*	**1601,** *33*	**25.9,** *0.19*	**1289,** *30*	**785,** *25*	0	>100
0.85 mm Bundle Barrier PIT	192	39 µm	**2323,** *83*	**1342,** *49*	**26.7,** *0.1*	**1093,** *40*	**688,** *26*	5.5 %	>150

- In the table the magnetic field is the background during I_c measurement; in terms of peak field the J_c is slightly higher
  - Peak field 16 T → J_c of the 3 wires is respectively 1134, 1339 and 1129 A/mm^2
- For the RRP conductor with a sub-element size of 55 µm not so far in J_c from what used to design FCC magnets and larger B_{c2} (→ better performance at larger fields)

J_c(16 T, 4.22 K) = **1339 A/mm^2** B_{c2}(4.22 K) = **25.9 T**

Main Conductor Study

Critical Current *vs.* Transversal Load - Introduction

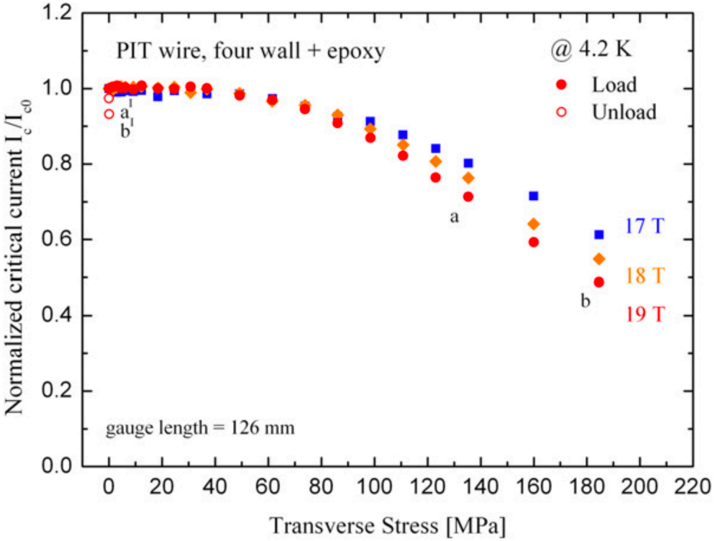
- In the development of a 16 T Nb_3Sn magnet one of the main issue is the large transversal stress applied on the conductor

- While a significant amount of experimental data exists about the performance of Nb_3Sn wires under axial strain, not much is available for the case of transversal load

- Around 2008 CERN started to develop a cable sample holder to measure samples in FRESCA test station under transversal load*

- In 2009 a collaboration was established between CERN and the University of Geneva to develop a set up for measuring wires under transversal load **

- In 2012 measurements of CERN cables under transversal pressure were performed at TWENTE University



Normalized I_c @ 4.2 K versus transversal load measured at UniGe in a 1.25 mm 288 PIT wire **

[*] B. Bordini, F. Regis, O. Crettiez, P. Fessia, M. Guinchard, J. C. Perez, and I. Sexton *IEEE Trans. Appl. Supercond.*, VOL. 20, NO. 3, JUNE 2010

[**] G Mondonico, B Seeber, A Ferreira, B Bordini, L Oberli, L Bottura, A Ballarino, R Flukiger and C Senatore SuST 25 (2012) 115002 (9pp)

Main Conductor Study

Strain (Reversible Region) & I_c Scaling

- The main parameter describing the strain dependence of the Nb_3Sn superconducting properties, it is the 'strain' function *s(ε)*

$$s(\varepsilon) = \frac{B_{c2}(0,\varepsilon)}{B_{c2}(0,0)}$$

$$T_c(\varepsilon) = T_c(0)s(\varepsilon)^{\frac{1}{w}}$$

$$B_{c2}(T,\varepsilon) = B_{c2}(0,0)s(\varepsilon)(1-t^{\upsilon})$$

$$F_p(T,\varepsilon) = J_c(T,\varepsilon) \times B = C\ g\big(s(\varepsilon)\big)h(t)b^p(1-b)^q$$

- The strain dependence of the superconducting properties (in the case of axial applied strain) can be written as a function of *s(ε)*

- Before the 'exponential' strain function (next slide), all the proposed functions were able (some better then others) to fit the experimental data (axial applied strain) but they did not have any extrapolation capabilities

The Exponential Strain Function*

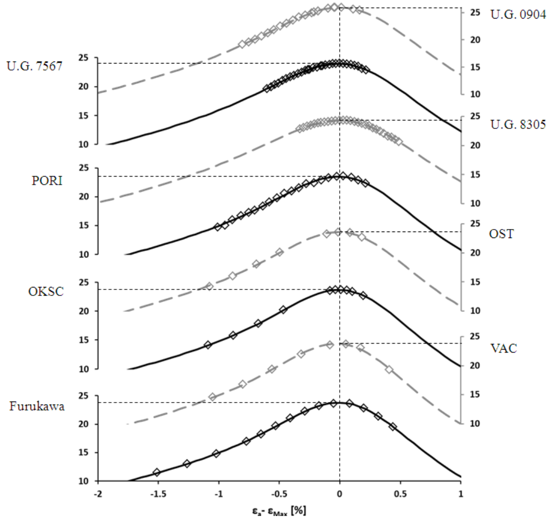
Characteristics

$$s(\varepsilon) = \frac{e^{-C_1\left(\frac{J_2+2}{J_2+1}\right)J_2} + e^{-C_1\left(\frac{I_1^2+2}{I_1^2+1}\right)\frac{I_1^2}{2}}}{2}$$

Where: I_1 is the first invariant of the strain tensor, J_2 second invariant of the deviator strain tensor

Strand	B_{c20} (T)	C_1	ε_{lo} %	ε_{Max} %	**RMS** (T)
Furukawa	28.67	0.901	-0.29	0.28	0.05
VAC	28.80	0.958	-0.30	0.29	0.14
OKSC	28.58	0.930	-0.08	0.08	0.03
OST	28.39	0.875	-0.10	0.09	0.12
PORI	28.24	0.869	-0.09	0.08	0.14
U.G. 8305	28.84	0.643	-0.28	0.28	0.05
U.G. 7567	28.62	0.752	-0.25	0.25	0.04
U.G. 0904	30.97	0.735	-0.18	0.18	0.06

- Only two fitting parameters:
  - ➢ C_1 that defines the sensitivity (curvature) of the material to the strain and
  - ➢ ε_{l0} the longitudinal pre-compression of the Nb_3Sn ($\varepsilon_{l0} \sim \varepsilon_{max}$ in I_c *vs.* Axial Strain measurements)



- More stable and has extrapolating capabilities
- Written such that it can be directly generalized to any 3-D load

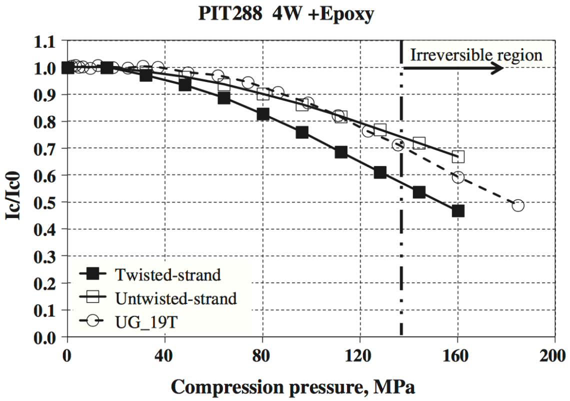
---

[*] Bordini B, Alknes P, Bottura L, Rossi L and Valentinis D 2013 SuST 26 075014

The Exponential Strain Function

Potential

- It has the potential to be a real 3-D strain function
- The exponential strain function was used to calculate the reversible degradation of a PIT wire under transversal pressure[*]
  - 2-D FE model[*] of a 1.25 mm 288 PIT wire measured under transversal pressure at UniGe[**]
  - The model is in good agreement with experimental data



- The exponential strain function was chosen as the most stable and extrapolative strain function in the recently released ESE scaling law [***]

---

[*] T Wang, L Chiesa, M Takayasu, B Bordini Cryogenics 63 (2014) 275–281

[**] G Mondonico, B Seeber, A Ferreira, B Bordini, L Oberli, L Bottura, A Ballarino, R Flükiger and C Senatore SuST, 25 (2012), p. 115002 [9pp]

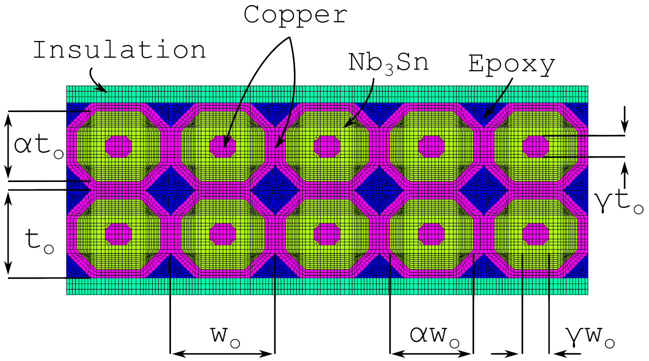
[***] Jack W Ekin, Najib Cheggour, Loren Goodrich and Jolene Splett SuST 30 (2017) 033005 (38pp)

The Exponential Strain Function

Computing I_c degradation of Rutherford cables under transverse load* - Mech. Model

- Developed a FEM mechanical model of the cable stack able to estimate the young modulus of the stack during loading (14 GPa) and unloading (37 GPa)
  - Good agreement with data measured on impregnated cable stacks;
  - The geometry of the cable is simplified, in particular the region where the sub-elements are embedded in a copper matrix is treated as a unique annulus of Nb_3Sn;
  - The simplified geometry respects the main parameters of the conductor (cable filling factor, Cu to non-copper ratio, height and width of the cable and of the stack etc..);
  - The material properties of the different components are taken from literature.

- The significant difference of the young modulus during loading and unloading is explained by the plastic deformation of the Cu (during loading)



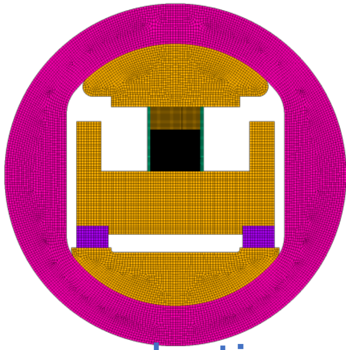
Courtesy of Giorgio Vallone

---

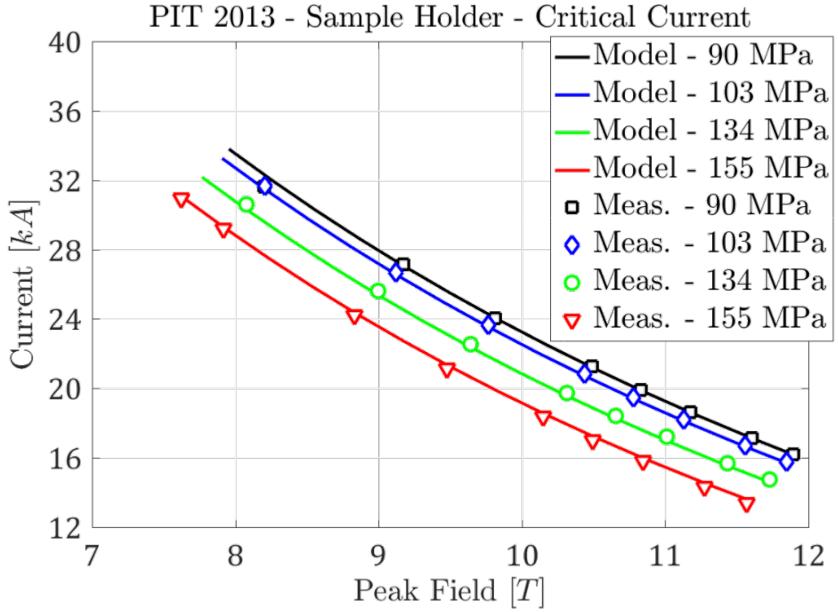
*G. Vallone, B. Bordini, P. Ferracin, presented at EUCAS 2017 and submitted for publication, *IEEE Trans. Appl. Supercond.*

The Exponential Strain Function

Computing I_c degradation of Rutherford cables under transverse load[*] - Results



- Calculated via a FEM model (2D and 3D) the strain in the cable stack during the test under transverse load in Fresca
- The computed 3D strain multiplied by a constant factor, which accounts for the concentration of the stresses in the superconducting sub-elements, is used to compute the strain function and the critical current



- The model is in good agreement with the experimental data measured[**] on PIT cable in FRESCA

Courtesy of Giorgio Vallone

---

[*] G. Vallone, B. Bordini, P. Ferracin, presented at EUCAS 2017 and submitted for publication, *IEEE Trans. Appl. Supercond.*

[**] B. Bordini, P. Alknes, A. Ballarino, L. Bottura, L. Oberli *IEEE Trans. Appl. Supercond.*, VOL. 24, NO. 3, JUNE 2014

Main Conductor Study

Experimental Studies – Plans and Goals

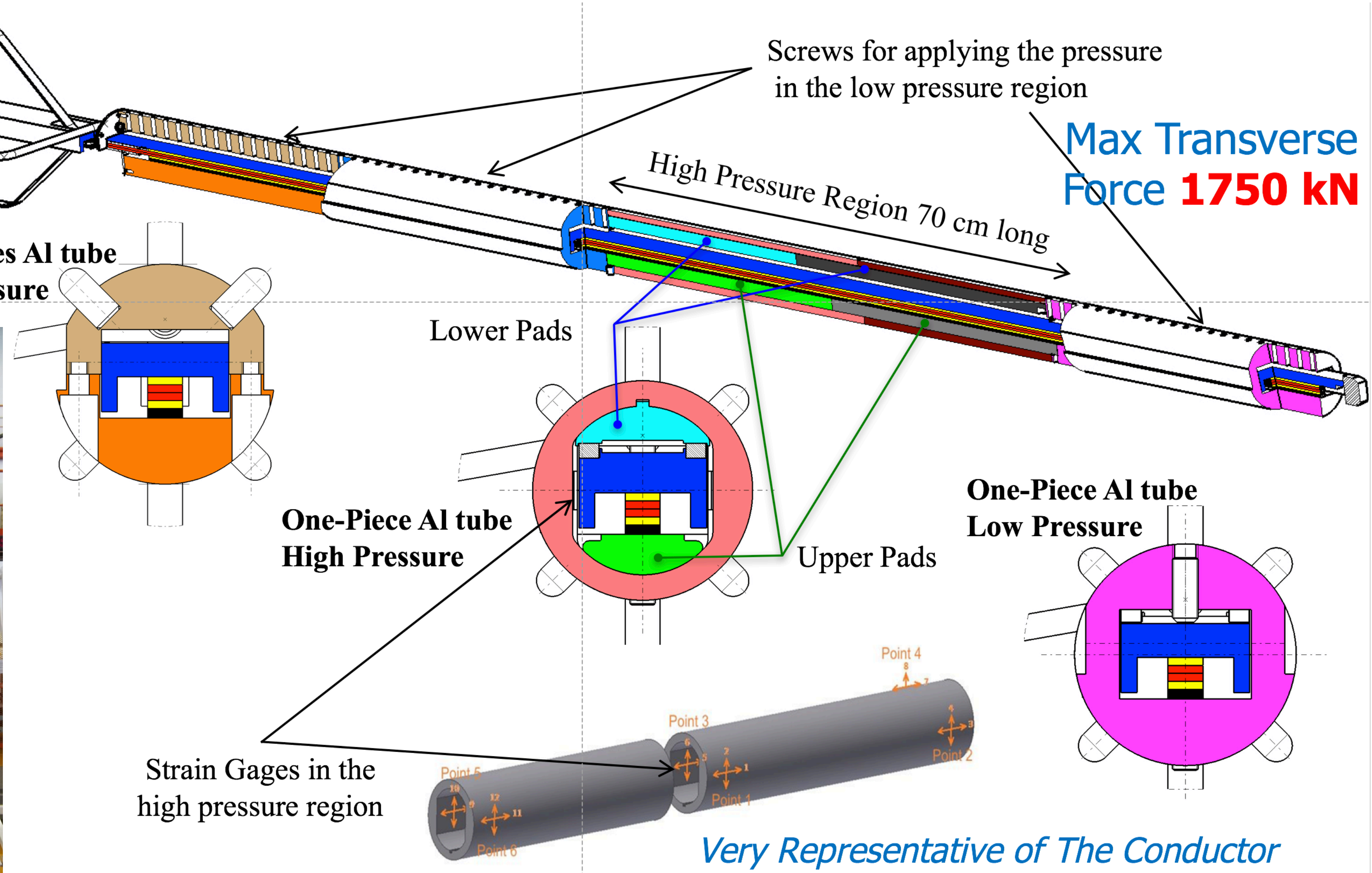
- Compare CERN and Twente set-ups for measuring cables under transversal pressure
  - CERN and Twente University both prepare and measure the same two cables, one based on the PIT wire and the other on the RRP
    1. 18 strands cables based on 1 mm strand
    2. The strands are FRESCA 2 wires: 132/169 RRP and 192 PIT

- Correlate the wire measurements under transversal pressure carried out at UniGe with cable measurements
  - UniGe measures the same wires used in the cable tests at CERN and Twente

- Verify the compatibility of high J_e with large transverse pressure on the conductor

Experimental Studies

CERN Cable Samples Holder



Screws for applying the pressure in the low pressure region

Max Transverse Force 1750 kN

High Pressure Region 70 cm long

Two-Pieces Al tube
Low Pressure

Lower Pads

One-Piece Al tube
High Pressure

Upper Pads

One-Piece Al tube
Low Pressure

Strain Gages in the high pressure region

Very Representative of The Conductor behavior in a magnet; Long Test campaigns

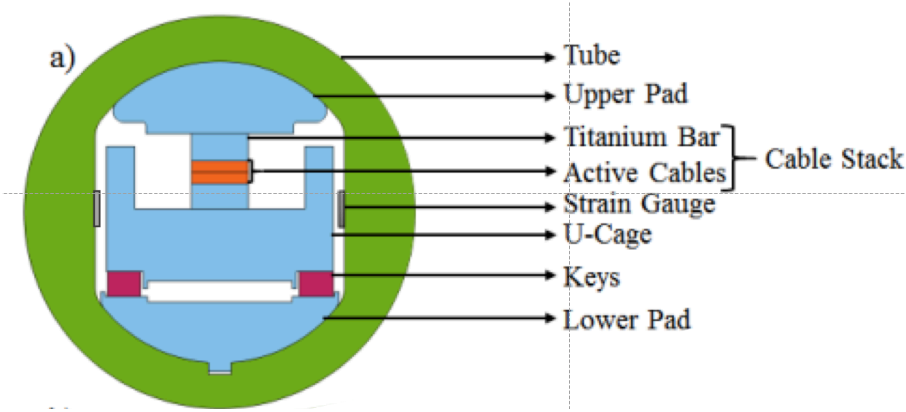
Experimental Studies

Test at CERN on a RRP cable* - Sample

- The cable sample tested was a rectangular 18 -strand Rutherford cable based on the 1 mm RRP 132/169

COPPER TO NON-COPPER (ADIM.)	1.22
TWIST PITCH (MM)	63
WIDTH (MM)	9.97
MID. THICKNESS (MM)	1.81
KEYSTONE ANGLE (°)	0
NUMBER OF WIRES	18

- The sample is constituted by:
  - Two 1.8 m long active cables that carry the current;
  - two Ti6Al4V bar, 3 and 4 mm thick, that sandwich the active cables;
- The different components of the sample stack are separated by fiberglass braid and the sample is vacuum impregnated with epoxy (CTD-101)
- The two active cables are spliced together in the bottom (along 15 cm) while on the top they are each spliced with a NbTi cable (along 20 cm)



---

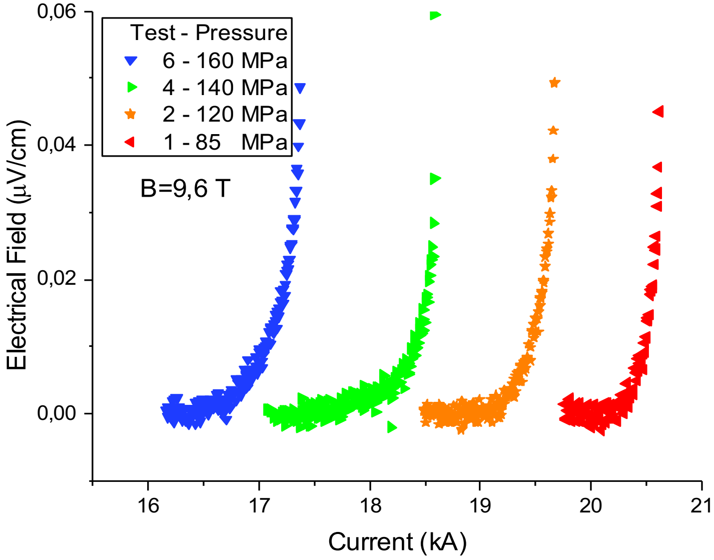
*J. E. Duvauchelle , B. Bordini, J. Fleiter, A. Ballarino presented at EUCAS 2017 and submitted for publication, *IEEE Trans. Appl. Supercond.*

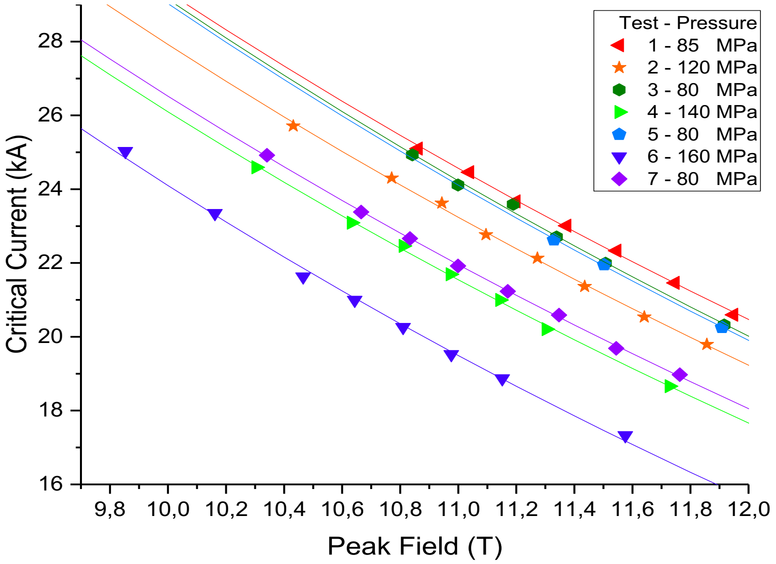
Experimental Studies

Test at CERN on a RRP cable* – Measurements

- The critical current of the cable was defined at an electric field equal to 0.03 μV/cm

- The first test was done at a relatively low transverse pressure (85 MPa)
  - at this pressure, as verified in the experiment, the I_c is not significantly affected by the transverse load





- The following tests consisted in measuring the I_c at higher and higher transverse loads;
  - in between these tests, I_c measurements at 80-85 MPa were carried out to verify whether or not the previous test produced a permanent degradation in the sample.

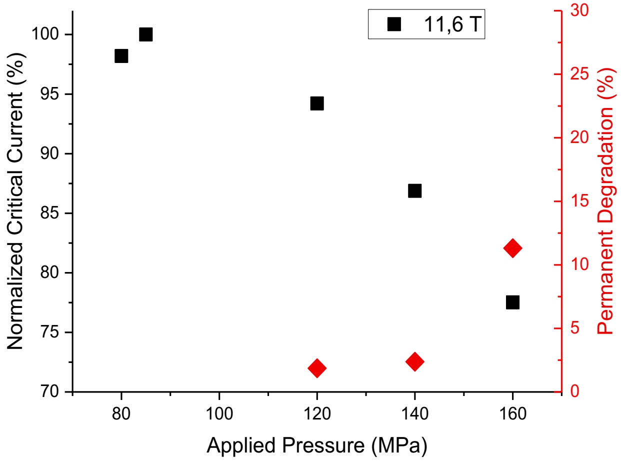
---

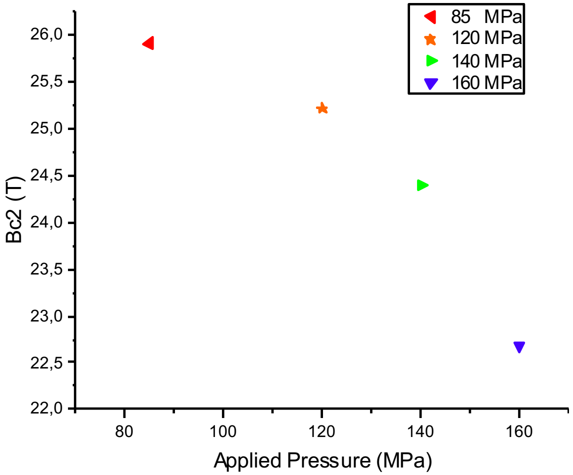
*J. E. Duvauchelle , B. Bordini, J. Fleiter, A. Ballarino presented at EUCAS 2017 and submitted for publication, *IEEE Trans. Appl. Supercond.*

Experimental Studies

Test at CERN on a RRP cable* – Results 1/2

- At 120 MPa observed a significant I_c decrease
  - at 11.6 T the I_c is 95.2% of the current at 85 MPa
  - associated with a reduction of the B_{c2}
- The following test (3) at 80 MPa showed a significant recovery of the critical current
  - permanent degradation only 1.8% at 11.6 T and part of it due to a small damage of the sample which occurred during the last part of the second test (120 MPa) when a couple of quenches were done inverting the current in the sample
- This behavior suggests that the degradation at 120 MPa is dominated by the reversible component and it is due to the strain on the superconductor that decrease the strain function





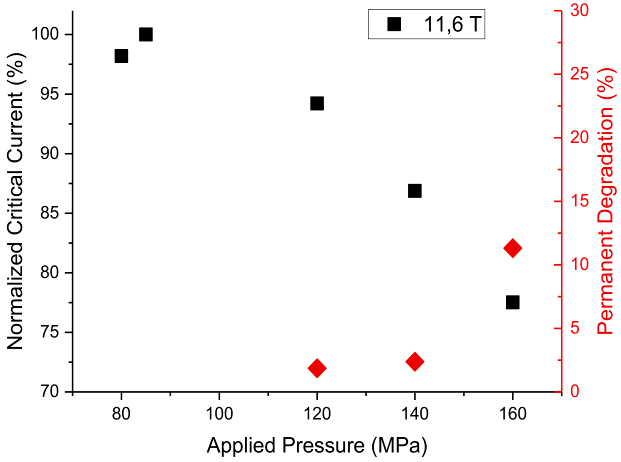
---

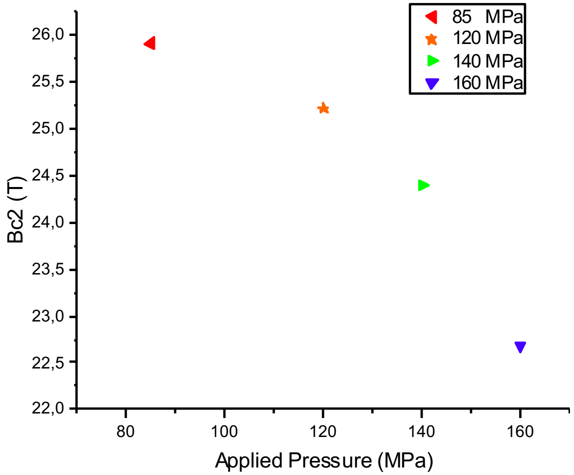
*J. E. Duvauchelle , B. Bordini, J. Fleiter, A. Ballarino presented at EUCAS 2017 and submitted for publication, *IEEE Trans. Appl. Supercond.*

Experimental Studies

Test at CERN on a RRP cable[*] – Results 2/2

- The test at 140 MPa (test 4) showed a further decrease of I_c and B_{c2}
- When retested (test 5) at 80 MPa, the permanent degradation was similar (2.4% at 11.6 T) to that one of the previous test at 80 MPa.
- At 160 MPa (Test 6) not only a further degradation of the B_{c2} (and I_c) but also a significant reduction of the n-value that suggested a relevant permanent degradation in the cable.
  - The last test at 80 MPa (test 7) confirmed this reduction of the n-value and showed a significant increase of the permanent degradation
- These results are consistent with what was found in a previous test on a similar cable based on the PIT conductor





---

[*] J. E. Duvauchelle , B. Bordini, J. Fleiter, A. Ballarino presented at EUCAS 2017 and submitted for publication, *IEEE Trans. Appl. Supercond.*

Experimental Studies

Tests at Twente – Plans and Goals

EuroCirCol WP5: $I_c(\sigma)$ and M(H) tests

✓Goals

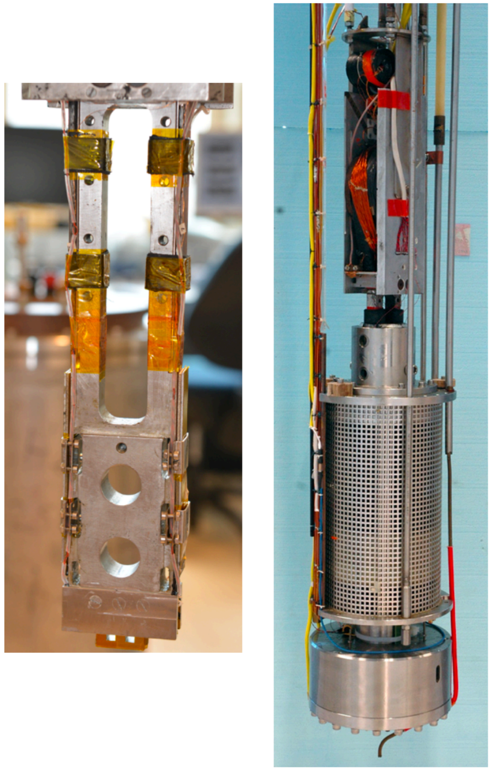
- To asses & qualify $I_c(\sigma)$ behavior of FCC-grade Nb_3Sn cables
- To verify expected M(H) & AC loss behavior

✓Experiments

- Short-sample ‘hairpin’ configuration / S.C. transformer / cryopress
- AC dipole with combined inductive /calorimetric loss set-up

✓Strategy

- $I_c(\sigma)$:
  - Phase 1: benchmark tests UT – CERN (FRESCA)
  - Phase 2: FCC-grade cabled structures
- M(H) : ad-hoc, as need arises



Experimental Studies

Test at Twente – Too Large Degradation

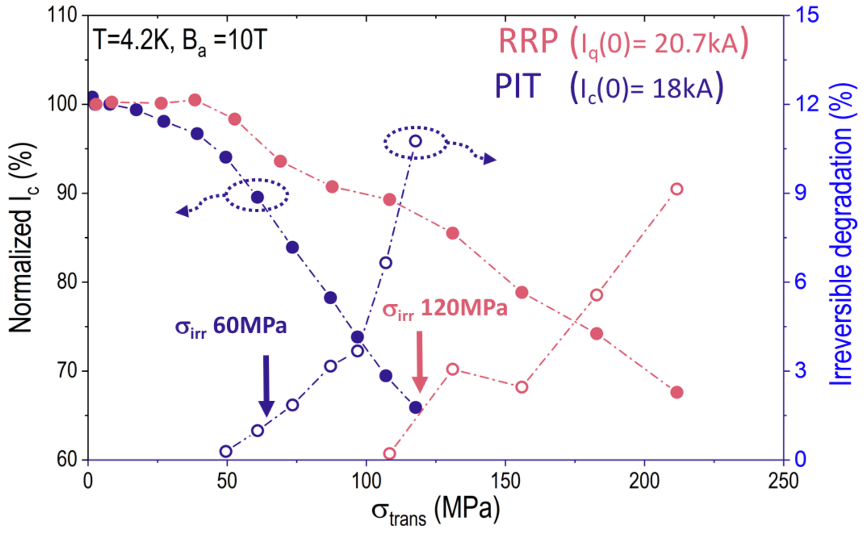
EuroCirCol WP5: $I_c(\sigma)$ and M(H) tests

$I_c(\sigma)$ benchmarking tests (ongoing)

Samples

- 18-strand Nb_3Sn cables ($w \times t$ = 10×1.81 mm^2, l_p = 63 mm)
- RRP (132/169, ϕ=1mm) ; PIT (192, ϕ=1mm)

1st results



σ_{irr} values @ UTwente significantly below FRESCA results

⇓

Diagnostics:

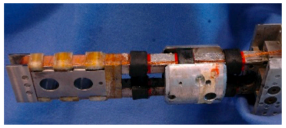
- ~~Cabling~~? (RRR, $I_c(0)$, FRESCA)
- ~~H.T.~~? (RRR, $I_c(0)$, FRESCA)
- Parallelism?

→ adapted impregnation under test

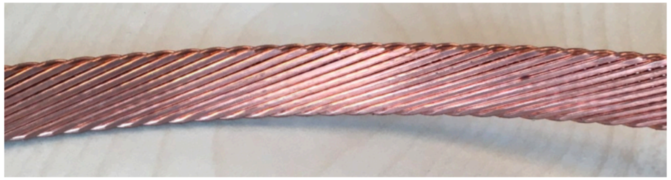
Experimental Studies

Test at Twente – Status

EuroCirCol WP5: $I_c(\sigma)$ and M(H) tests



- SAMPLES



'BENCHMARKING' WITH FRESCA

CABLE I : 18str., 63mm L_p, CTD101K, RRP, 2 SAMPLES;

CABLE II: 18str., 63mm L_p, CTD101K, PIT, 2 SAMPLES;

- PROGRESS

$I_c(\sigma)$ TESTED CONDITIONS: T = 4.2K, B_a = 10T

CABLE I-1st: $I_Q(\sigma_0) = 20.7$ kA, $\sigma_{\text{trans.-irr.}} \approx 110$ MPa

COMPARED WITH CERN'S RESULTS

- ○ WITNESS STRANDS: Identical I_c
  RRR(20K) ⟶ 124.6 ~ 138.4
- ○ EXTRACTED STRANDS: RRR(20K) ⟶ 146.7 ~ 148.4

CABLE I-2nd: Reacted, to be impregnated/ tested

- ○ WITNESS STRANDS: I_c ⟶ prepared, to be tested;
  RRR(20K) ⟶ 160.1 ~ 177.7
- ○ EXTRACTED STRANDS: RRR(20K) ⟶ 121.5 ~ 168.3

CABLE II-1st: $I_c(\sigma_0) = 18.0$ kA, $\sigma_{\text{trans.-irr.}} \approx 60$ MPa

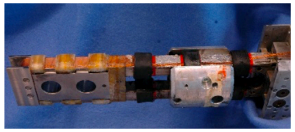
- ○ WITNESS STRANDS: I_c & RRR(20K) ⟶ prepared, to be tested;
- ○ EXTRACTED STRANDS: RRR(20K) ⟶ prepared, to be tested;

CABLE II-2nd: To be reacted.

Experimental Studies

Test at Twente – Plans

EuroCirCol WP5: $I_c(\sigma)$ and M(H) tests



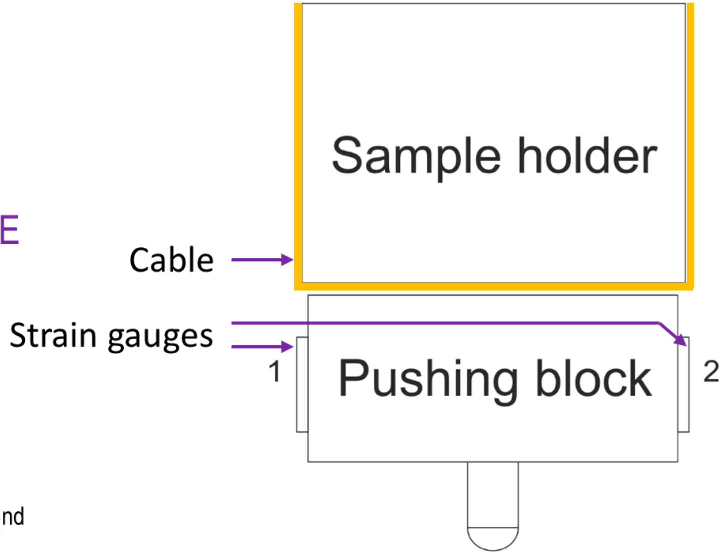
MAGNETIZATION:

- ○ CABLE PARAMETERS: "High-Lumni" LHC type
- ○ M-B LOOPS: Waiting for cables

POSSIBLE REASONS FOR LOWER TRANSVERSE PRESSURE TOLERANCE:

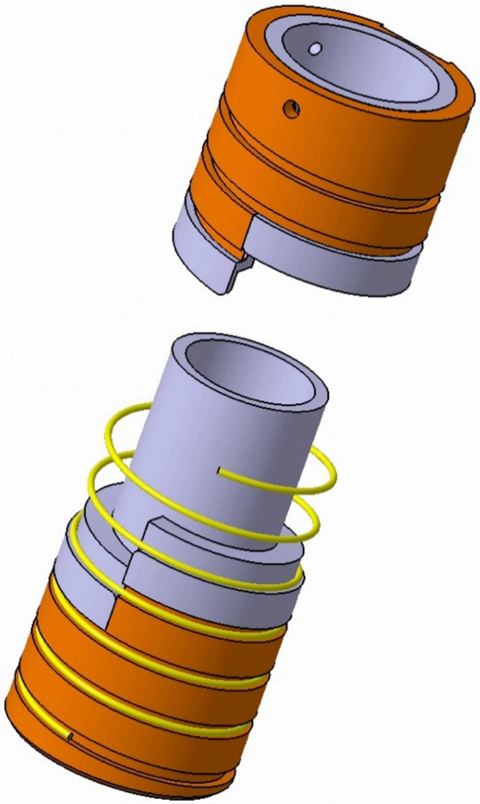
- ○ STRESS CONCENTRATION?
  Possible parallelism issue?
  SOLUTION: Modelling the angle(impregnated cable surface) effect on applied stress
  Adopting the 2nd impregnation for CABLE I-2nd & CABLE II-2nd

- ○ CABLING DEGRADATION?
  Probable damages on the edge?
  VALIDATION: Test I_c of extracted strands

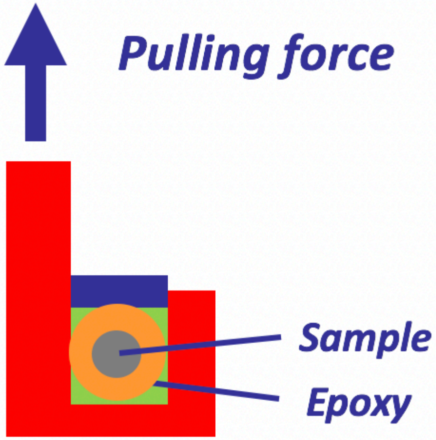


Experimental Studies

UniGe Wire Sample Holder for Transverse Load



4-WALL + impregnation



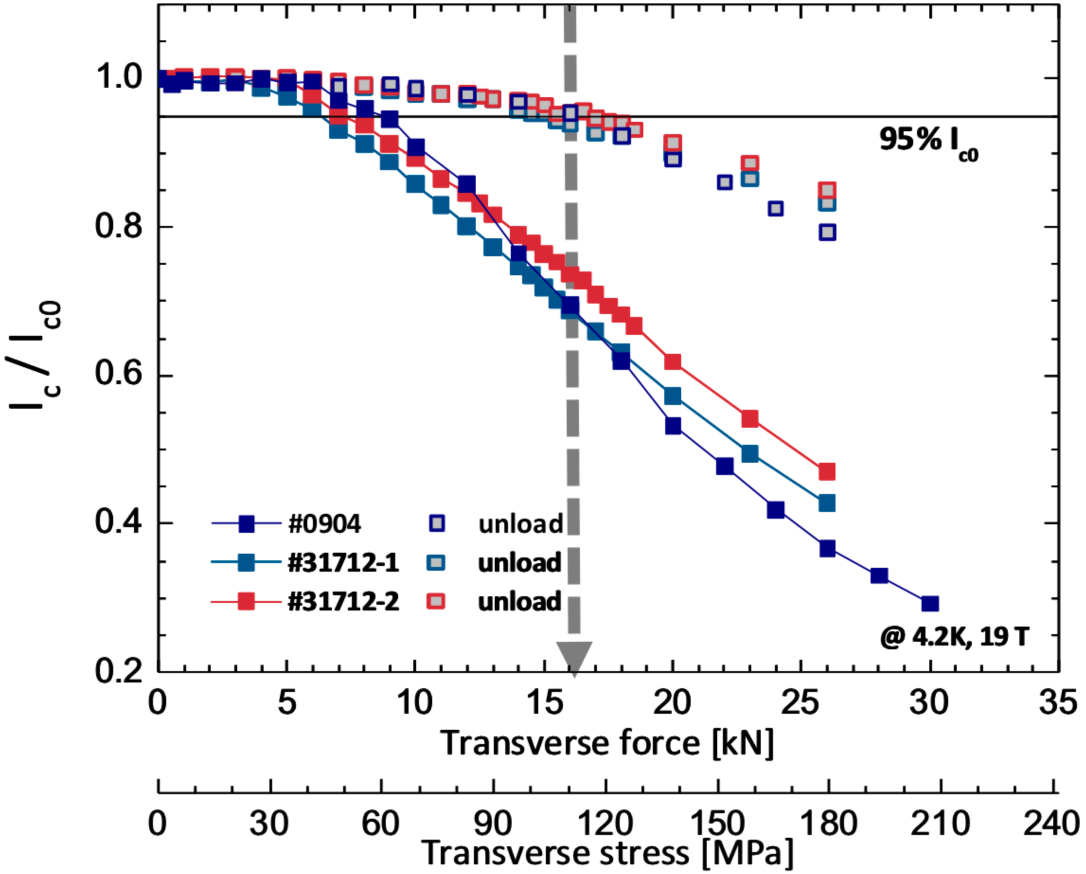
3 groove widths
- 1.30 mm
- 1.15 mm
- 1.00 mm

Wire impregnated
with epoxy
applied stress
uniformly distributed

Extremely Rapid and Versatile Test Set-Up for Superconducting Wires

Experimental Studies

1 mm round PIT wire @ UniGe – reproducibility



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

Here

$$F_{irr} = 16\ kN$$

The corresponding irreversible stress limit is

$$\sigma_{irr} = 110\ MPa$$

where

$$Stress = \frac{Force}{groove\ length \times groove\ width}$$

Results consistent with data taken in 2012 on wire #0904

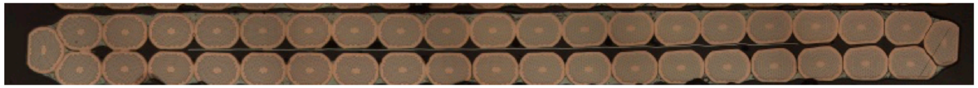
Experimental Studies

1 mm PIT wire @ UniGe – Rolling

Effects of wire rolling on the stress tolerance

Samples deformed at CERN and reacted at UNIGE

15% rolling to simulate the wire deformation during cabling

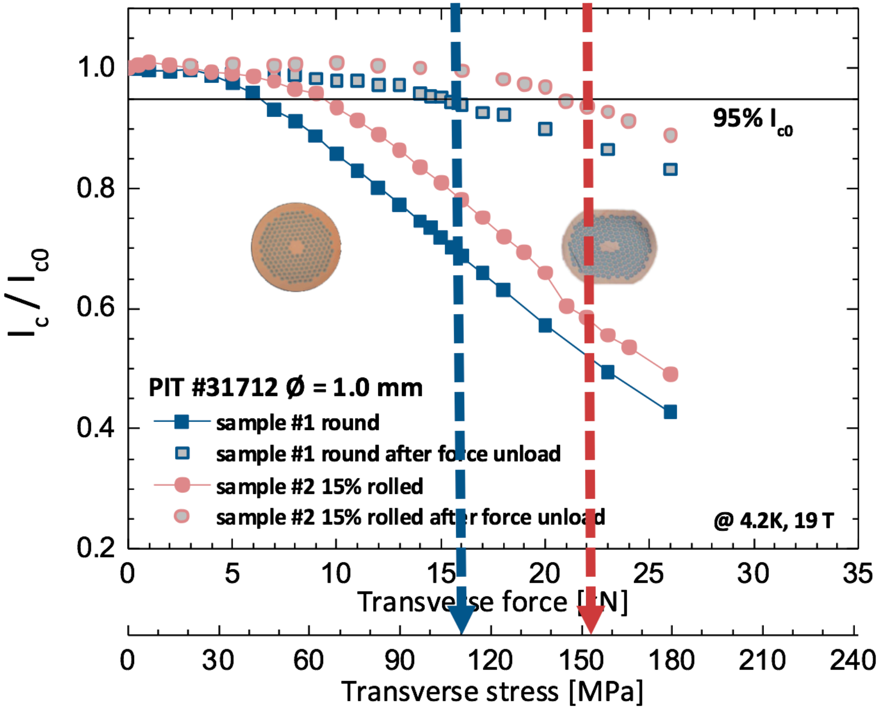


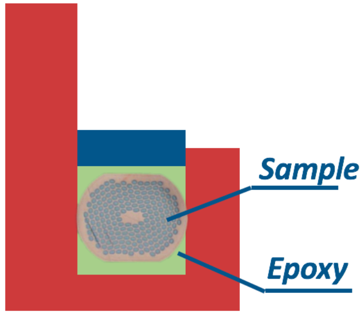
Better redistribution of the applied stress in the wire

Experimental Studies

1 mm PIT wire @ UniGe – Effect of Rolling 1/2

I_c vs. transverse stress on 15% rolled wires





F_{irr} = 22 kN

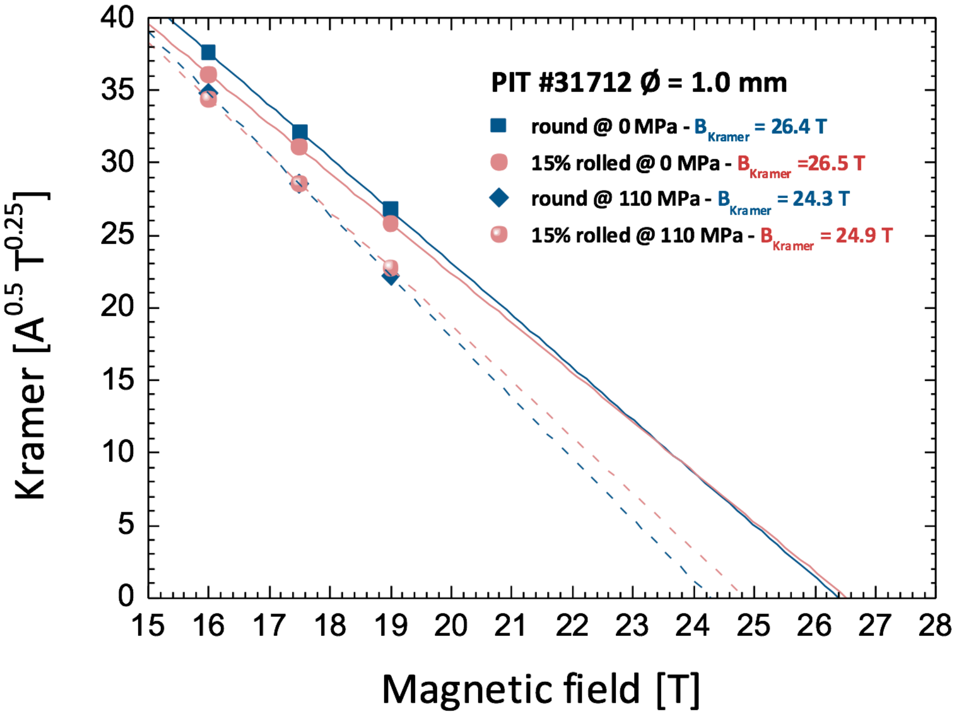
σ_{irr} = 150 MPa

Normalized I_c
Round vs. 15% rolled
Shift of σ_{irr} by ~ 40 MPa

Experimental Studies

1 mm PIT wire @ UniGe – Effect of Rolling 2/2

Kramer Plot : round vs. 15% rolled



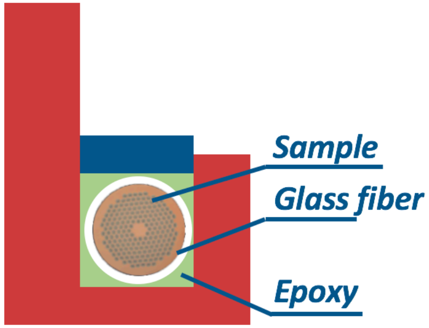
Without any applied load, the Kramer field is the same for the round and the rolled wire

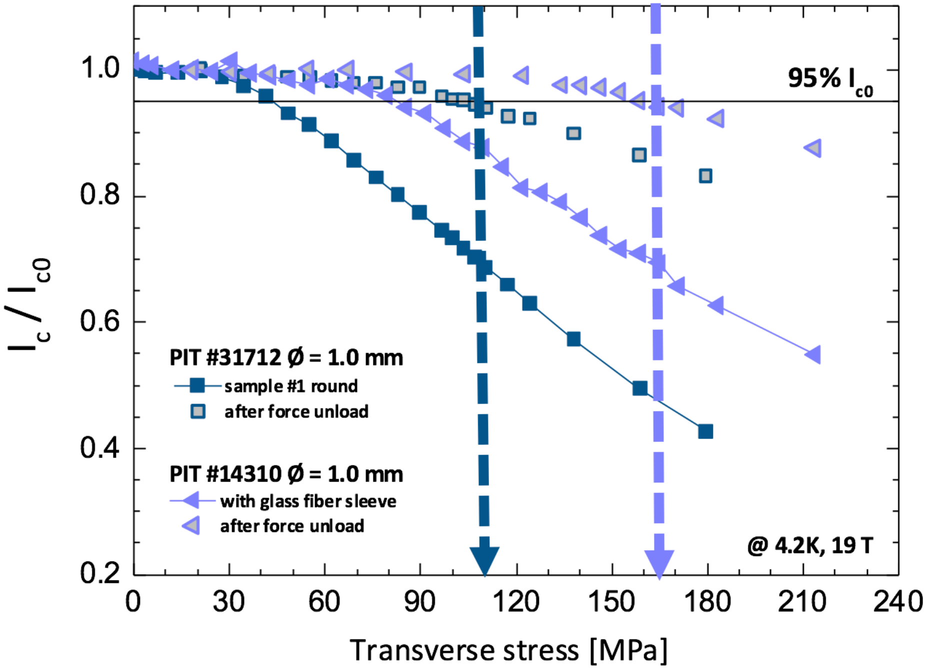
At σ = 110 MPa, the Kramer field decreases by about 2 T

Experimental Studies

1 mm PIT wire @ UniGe – Effect of Glass Fiber

I_c vs. transverse stress: wire in a glass fiber sleeve





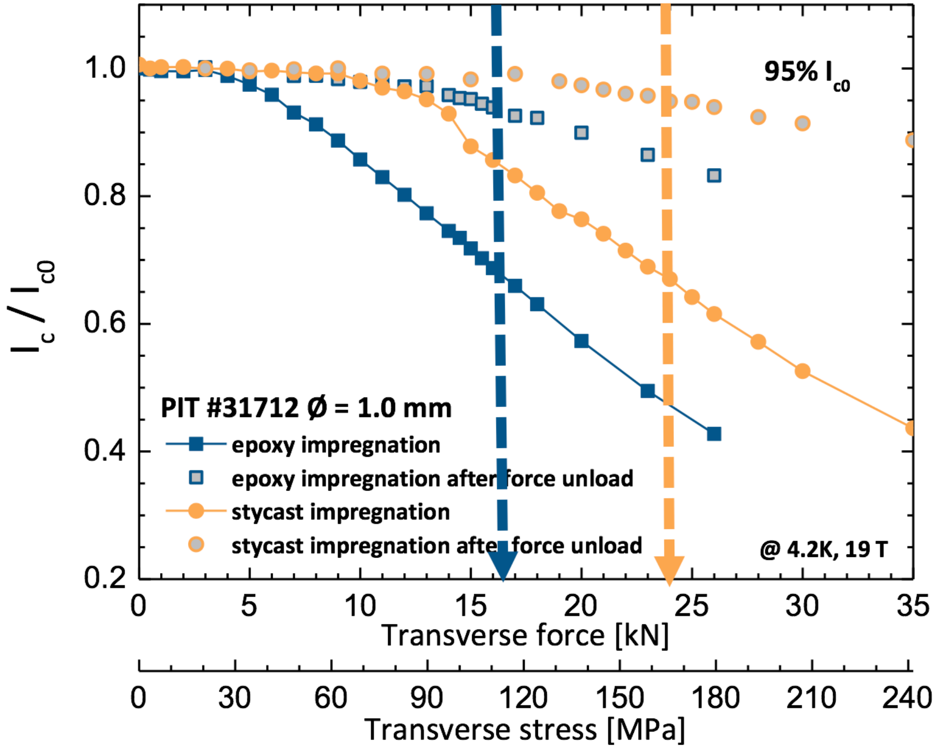
Shift of σ_{irr} by > 50 MPa

The wire with glass fiber sleeve was measured in a larger groove (1.30 mm vs 1.15 mm)

Experimental Studies

1 mm PIT wire @ UniGe – Epoxy vs. Stycast 1

I_c vs. transverse stress: epoxy vs. stycast



The change of resin, from epoxy to stycast, leads to an increase of σ_{irr} by > 50 MPa

The result is comparable to the value found with epoxy + glass fiber sleeve

Experimental Studies

1 mm RRP wire @ UniGe

- Heat Treatment on going
- First Results by the end of the year

Conclusions

- The average Critical Current of the HL-LHC RRP wire with a sub-element size of 55 μm is not so far from (14 %) the value used for the design of the FCC magnets; furthermore the B_{c2} is even slightly larger than what assumed

- Wire and Cable measurements under transverse load suggest that the effect of reversible degradation can not be neglected in the design of FCC magnets
  - The Exponential Strain Function associated to a FEM model can be a tool to assess the reversible degradation in cables and magnets
  - CERN and Twente will continue the benchmarking exercise to make sure of having reliable set ups that apply a uniform and controlled transverse pressure
  - Wire measurements are becoming more and more representative of the cable behavior – very powerful and versatile tool
  - We intend to investigate the effect of different wire/cable layouts and of different impregnation (materials)

Thank You For Your Attention !

- The average Critical Current of the HL-LHC RRP wire with a sub-element size of 55 μm is not so far from (14 %) the value used for the design of the FCC magnets; furthermore the B_{c2} is even slightly larger than what assumed

- Wire and Cable measurements under transverse load suggest that the effect of reversible degradation can not be neglected in the design of FCC magnets
  - The Exponential Strain Function associated to a FEM model can be a tool to assess the reversible degradation in cables and magnets
  - CERN and Twente will continue the benchmarking exercise to make sure of having reliable set ups that apply a uniform and controlled transverse pressure
  - Wire measurements are becoming more and more representative of the cable behavior – very powerful and versatile tool
  - We intend to investigate the effect of different wire/cable layouts and of different impregnation (materials)