Effect of transverse pressure on Nb$_3$Sn wires

An electromechanical study

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Motivation

High field dipoles based on high $J_c$ Nb$_3$Sn Rutherford cables require coil pre-stresses larger than 100 MPa, with peak stress of $\sim$200 MPa at operation.

Are the Nb$_3$Sn wires in the cable able to withstand such a high stress level? Which degradation is tolerable?

- Nb$_3$Sn wires are deformed during cabling
- Cables are braided with glass fiber
- The winding is impregnated with resin

Is it possible to extrapolate the behaviour of the cable from a single wire experiment?
Outline

The WASP concept for $I_c$ vs transverse force measurements

How it works

Results on impregnated PIT Nb$_3$Sn wires
  - Effects of wire rolling
  - Effects of glass fiber insulation

Preliminary tests on RRP Nb$_3$Sn wires

Conclusions & Outlook
The WASP concept for $I_c$ vs. transverse stress

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

4-WALL + impregnation

Pulling force

Sample
Epoxy

Wire impregnated with epoxy applied stress uniformly distributed

CERN-UNIGE collaboration agreements KE1629/TE and KE2196/TE
How the measurement works

![Graph showing the measurement process](image)

- **Wire ID**: #31712
- **Diameter [mm]**: 1.0
- **# of filaments**: 192
- **Filament size/shape**: ~50 µm round
- **Cu/nonCu**: 1.22
- **Non-Cu $J_c(12T, 4.2K)$ [A/mm²]**: 2450

@ 4.2K, 19 T

**Legend**:
- #31712-2
- unload

**Transverse force [kN]**

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<th>Transverse force [kN]</th>
<th>Current [A]</th>
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**Electric field [μV/cm]**

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$I_c$ vs. transverse stress: Reproducibility

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

Here

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

The corresponding irreversible stress limit is

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

where

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

Results consistent with data taken in 2012 on wire #0904
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
$I_c$ vs. transverse stress on 15% rolled wires

**Graph:**
- PIT #31712 Ø = 1.0 mm
- @ 4.2K, 19 T

**Axes:**
- Transverse force [kN]
- Transverse stress [MPa]

**Data Points:**
- Sample #1 round
- Sample #1 round after force unload
- Sample #2 15% rolled
- Sample #2 15% rolled after force unload

**Normalized $I_c$:**
- Round vs. 15% rolled
- Shift of $\sigma_{irr}$ by ~ 40 MPa

**Summary:**
- $F_{irr} = 22$ kN
- $\sigma_{irr} = 150$ MPa
$I_c$ vs. transverse stress: round vs. 15% rolled

The curve for the rolled wire starts from lower $I_c$ but above 10 kN merges with the curve for the round wire.

Same behavior for the unload points.

Above 20 kN the points overlap.

$I_c$ degradation in PIT wires upon rolling is currently observed.

RRP wires exhibits no or negligible degradation upon rolling.

Critical current

Round vs. 15% rolled
Without any applied load, the Kramer field is the same for the round and the rolled wire.

At $\sigma = 110$ MPa, the Kramer field decreases by about 2 T.
\( I_c \) vs. transverse stress: wire in a glass fiber sleeve

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

**Shift of \( \sigma_{irr} \) by > 50 MPa**
$\frac{I_c}{I_{c0}}$ vs. $\frac{I_{c \text{ unload}}}{I_{c0}}$

@ 4.2K, 19 T

Green curve – bad mounting
... about the mechanisms behind the irreversible degradation ...
**FEM: stress redistribution in the wire**

Irreversible degradation is determined by filament cracks and residual strain on $\text{Nb}_3\text{Sn}$ imposed by plastically deformed Cu.

FEM suggests that smaller filaments and higher Cu/nonCu ratio lead to higher stress tolerance.

*C. Calzolaio, CS et al., SuST 28 (2015) 055014*
... some tests on RRP
RRP: 132/169 vs. 108/127

**RRP 132/169**

*Irreversible stress limit* > 200 MPa

**RRP 108/127**

*Irreversible stress limit at* ~130 MPa
XRD Microtomography
Void morphology in RRP wires

Experiments performed at the European Synchrotron Radiation Facility
from Sep 30 to Oct 02 2015
Conclusions
Conclusions and outlook

Consolidating a tool for testing the electromechanical properties of SC wires at conditions "close to" the operation in a Rutherford cable

Tested PIT wires after rolling and with glass fiber insulation

Observed a scaling of $I_c$ after unload vs. $I_c$ upon loading

Preliminary investigations on RRP wires already performed

Include in the FE model the distribution of voids in the superconducting subelements, as obtained from synchrotron microtomography

Perform a systematic investigation on the type of impregnation
Thank You!

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$I_c/I_{c0}$ vs. transverse stress: field dependence

**PIT #29992**

600C/100h + 625C/200h

Data from 2013

$PIT \#29992 \ \varnothing = 0.85 \ \text{mm}$

was measured in the 1.15 mm groove

$\sigma_{irr} \approx 130 \ \text{MPa}$ and

$\text{Stress} = \frac{\text{Force}}{\text{groove length} \times \text{groove width}}$
$I_c$ vs. transverse stress: glass fiber sleeve – test #1

PIT #31712
620C/100h + 640C/90h

PIT #14310
620C/120h + 650C/90h

PIT #14310 with glass fiber sleeve was measured in a larger groove (1.30 mm vs 1.15 mm)

$\sigma_{irr} \approx 150$ MPa !! We need a systematic study of the resins
$I_c / I_{c0}$ vs. $I_c^{unload} / I_{c0}$

- #0904 data from 2012
- #31712-1
- #31712-2
- #31712-3 bad mounting
- #14310 glass fiber sleeve
- #31712 rolled #1
- #31712 rolled #2

Green curve – bad mounting
**Bi2212 wires: transversal stress sensitivity**

[Graph showing transversal stress sensitivity for Bi2212 wires with various conditions.]

**Irreversible stress limit at ~ 75 MPa**

**No substantial improvement with OP or extra Mg**

**Results consistent with old tests on Rutherford cables**

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*Graph showing stress vs. current ratio for different samples.*

- Bi2212 OP@100 bar
- Bi2212 with extra AgMg OP@10 bar
- RRP Nb<sub>3</sub>Sn, 0.85 mm

 force

Sample

Epoxy

Wire impregnated with epoxy applied stress uniformly distributed