Electro-Mechanical Performance of $\text{Nb}_3\text{Sn}$ Rutherford Cables

B. Bordini

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Outline

- **Introduction**
  - Scaling Laws for state of the art $\text{Nb}_3\text{Sn}$ wire in the case of applied axial strain

- **Measurements of $I_c$ vs. Transverse Load**
  - Test at CERN and Twente University of a PIT Rutherford cable
    1. Can we use the scaling laws derived for applied axial strain to describe the results?
  - Test at Geneva University of the same PIT wire used in the measured cables
  - Test at CERN and Twente University of a RRP Rutherford cable
    1. Is the RRP less sensitive to transverse load?
  - Test at Geneva University of the same RRP wire used in the measured cables

- **Modeling $I_c$ vs. Transverse Load**

- **Conclusions**
Superconducting performance of Nb$_3$Sn are strongly dependent on the superconductor strain state.

In the case of applied axial strain:

$$B_{c2}(T, \varepsilon) = B_{c20} s(\varepsilon) \left(1 - t^{1.52}\right)$$

Where $B_{c20} = B_{c2}(0,0)$, $\varepsilon$ is the strain tensor, $t = \frac{T}{T_c(\varepsilon)}$

$$T_c(\varepsilon) = T_{c0} s(\varepsilon)^{\frac{1}{3}}$$

Where $T_{c0} = T_c(0)$

$$J_c(B, T, \varepsilon) = C_0 \frac{B_{c20}}{B} (s(\varepsilon))^{\sigma} \left[(1 - t^{1.52})(1 - t^2)\right]^\alpha b^{0.5} (1-b)^2$$

Where: $b = \frac{B}{B_{c2(\varepsilon)}}$; $\sigma$ and $\alpha$ are parameters very close to 1 and; $C_0$ is a constant.
Introduction
Scaling Laws for state of the art (HL-LHC) Nb$_3$Sn wire 2/2

\[ J_c(B, T, \varepsilon) = C_0 \frac{B_{c20}}{B} (s(\varepsilon))^{\sigma} [(1 - t^{1.52})(1 - t^2)]^{\alpha} b^{0.5}(1-b)^2 \]

Let’s simplify by assuming that $\sigma$ and $\alpha$ are equal to 1 and $s(\varepsilon)^{1/3} \sim$ constant; for a certain temperature we can write

\[ J_c(B, \varepsilon) = C \frac{B_{c2}}{B} b^{0.5}(1-b)^2 \]

\[ J_c(B, \varepsilon) = C b^{-0.5}(1-b)^2 \]

Where C is a constant

The dependence of the $J_c$ on the strain is mainly due to the variation of the $B_{c2}$

- At 1.9 K, assuming a $B_{c2}$ equal to 28 T, a reduction of the $B_{c2}$ by 10 % would produce a reduction of the $J_c$ approximately equal to:
  1. 20 % at 12 T
  2. 31 % at 16 T
  3. 44 % at 19 T

These scaling laws and results are well proved in the case of a wire pulled longitudinally; what about the case of a transverse load?

Are these scaling laws still valid?
Cable $I_C$ vs. Transverse Load

Test* at CERN on a PIT cable in 2013

What about the case of a transverse load?

The scaling law seems to work also in the case of transverse loads

The variation of the $B_{c2}$ is significant about 10% from 80 MPa and 155 MPa


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Dashed lines are fit

$I_c = C b^{-0.5} (1-b)^2$

$b = B/B_{c2}$; $C, B_{c2}$ fitting parameters
Cable $I_c$ vs. Transverse Load
Test at CERN on a PIT cable in 2018 - 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

![Diagram](image-url)

$T = 4.3$ K

On-going campaign

$I_c(B, \varepsilon) = C\varepsilon^{-0.5}(1 - \varepsilon)^2$

$b = B/B_{c2}$; $C, B_{c2}$ fitting parameters

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

Micrographies en cours

Courtesy of Gianluca De Marzi

Electro-mechanical Performance of Nb$_3$Sn Rutherford Cables - B. Bordini

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Cable $I_c$ vs. Transverse Load
Test* at CERN on a PIT cable in 2018

- 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%

$C_{const}$

$B_{c2} (T) = C ~ const$

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

Permanent Degradation (%)

Normalized Critical Current (%)

Applied Pressure (MPa)

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%

Credit: Gianluca De Marzi
Cable $I_c$ vs. Transverse Load

Test at Twente of a PIT cable in 2018 1/2

Are the results confirmed in a different set up?

Twente University measured under transverse pressure the same PIT cable tested by CERN

Plot Courtesy of Marc Dhalle and Peng Gao

Data to be published at ASC 2018

At **150 MPa** the reduction of $B_{c2}$ is larger than **10%** and at **11.6 T** the **critical current** is decreased by **24 %**, in line with what observed by CERN

The measurement confirmed that up to **150 MPa**, the reduction of the critical current is mainly reversible and it is dominated by the reduction of the upper critical field.
Cable $I_c$ vs. Transverse Load

Test at Twente of a PIT cable in 2018 2/2

- Irreversible $I_c$ degradation starts around 120 MPa however up to 150 MPa is still limited at 11.6 T peak field (10 T applied field)

- Cycling four times (at 4.2 K) the load between 150 MPa and 1.5 MPa did not further degrade irreversibly the critical current

Plot Courtesy of Marc Dhalle and Peng Gao

Data to be published at ASC 2018

Electro-mechanical Performance of Nb$_3$Sn Rutherford Cables - B. Bordini
Measurements on an impregnated 1 mm 192 PIT wire carried out at the University of Geneva showed a similar behavior:

- reduction of the critical current in the reversible region mainly due to the reduction of the upper critical field

Round wires degrades irreversibly significantly earlier than Rutherford cables

Data Courtesy of Carmine Senatore

* C Calzolaio et al 2015 Supercond. Sci. Technol. 28 055014
The University of Geneva measured two adjacent pieces of 1 mm 192 PIT wire: one piece was kept round and the other was 15% rolled (reduction of height).

15% Rolled wires had an irreversible degradation at larger transverse loads:

- Onset around 110-120 MPa
- 5% permanent degradation (at 19 T) around 150 MPa – shift of about 40 MPa
- These values are similar to what observed in cable measurements at Twente

Data and Plot Courtesy of Carmine Senatore
Wire $I_c$ vs. Transversal Load

Test at UniGe on a PIT Wire wire in a glass fiber sleeve (2017/2018)

Data and Plot Courtesy of Carmine Senatore

**Shift of $\sigma_{irr}$ by > 50 MPa**
Wire $I_c$ vs. Transversal Load
Test at UniGe on a PIT Wire: epoxy L vs. Stycast (2017/2018)

The change of resin, from epoxy to Stycast, leads to an increase of $\sigma_{irr}$ by 50 MPa
The result is comparable to the value found with epoxy + glass fiber sleeve

Data and Plot Courtesy of Carmine Senatore
Is the RRP cable less sensitive in the reversible region?

- CERN measured* a 18 strands cable based on 1 mm 132/169 RRP – the cable was geometrically identical to the PIT cable presented in previous slides

- The RRP cable shows* a behavior similar to the PIT cable however it seems a bit less sensitive to transverse load, at 11.6 T

  ➢ 5% reversible $I_c$ reduction occurs at 120 MPa instead of 100 MPa

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- 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)

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

\[
J_c(B, \epsilon) = C b^{-0.5} (1 - b)^2
\]
The same RRP cable measured by Twente showed that:

- Irreversible degradation occurs later than in PIT cable - onset at 170 MPa (instead of 120 MPa of the PIT)
- At 11.6 T and 150 MPa the reversible $I_c$ reduction is about 15% (that is 6-7% lower than PIT)

Plot Courtesy of Marc Dhalle and Peng Gao

Data to be published at ASC 2018

The larger irreversible degradation measured at CERN with 160 MPa might be due to the different load conditions:

- At Twente the load is applied at 4.2 K while at CERN, the cable experience a significant load already at room temperature
Wire $I_C$ vs. Transversal Load
Test at UniGe on a RRP Wire (2017/2018)

Irreversible stress limit $\sim 200$ MPa

Data and Plot Courtesy of Carmine Senatore

Shift of $\sigma_{irr}$ by $\sim 15$ MPa
The larger tolerance to transverse load of the 1 mm RRP 132/169 with respect to the 1 mm PIT 192 wire is most likely due to the larger amount of small Nb₃Sn grains in the strand cross section.

- The Nb₃Sn is the material that is supporting most of the mechanical load in the wire (the Nb of the sub-element diffusion barrier also carries a not negligible load).

- The PIT filaments are constituted by only 30 to 40 % (in volume) of Nb₃Sn small grains [1],[2] and by about 18% [1],[2],[3] of Nb₃Sn large disconnected[3] grains.

  1. for a regular PIT, without the bundle barrier, to have a RRR equal to about 300 it is necessary to under-react\(\rightarrow\) small grains \(\sim\) 30%.

- In the RRP wire, the filaments are composed by about 58%[1] of Nb₃Sn small grains; large grains are limited to only 4 % [1].

Modeling $I_C$ vs. Transversal Load

Exponential strain function

$$J_c(B, T, \varepsilon) = C_0 \frac{B_{c20}}{B} (s(\varepsilon)) \sigma \left[ (1 - t^{1.52})(1 - t^2) \right]^a b^{0.5} (1-b)^2$$

$$B_{c2}(T, \varepsilon) = B_{c20} s(\varepsilon) \left( 1 - t^{1.52} \right)$$

$$T_c(\varepsilon) = T_{c0} s(\varepsilon)^{\frac{1}{3}}$$

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

*Exponential strain function* two fitting parameters:

- $C_1$ that defines the sensitivity (curvature) of the material to the strain $\varepsilon$
- $\varepsilon_{l0}$ the longitudinal pre-compression of the Nb$_3$Sn ($\varepsilon_{l0} \sim \varepsilon_{\text{max}}$ in $I_C$ vs. Axial Strain measurements)

The exponential strain function was developed to estimate the $I_C$ vs. Axial Strain measurements

Can we use it for the $I_C$ vs. transverse load?

<table>
<thead>
<tr>
<th>Strand</th>
<th>$B_{c20}$ (T)</th>
<th>$C_1$</th>
<th>$\varepsilon_{l0}$</th>
<th>$\varepsilon_{\text{Max}}$</th>
<th>RMS (T)</th>
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<tbody>
<tr>
<td>Furukawa</td>
<td>28.67</td>
<td>0.901</td>
<td>-0.29</td>
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<td>VAC</td>
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<td>OKSC</td>
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<td>OST</td>
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<td>PORI</td>
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<td>0.735</td>
<td>-0.18</td>
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<td>0.06</td>
</tr>
</tbody>
</table>

* Bordini B, Alknes P, Bottura L, Rossi L and Valentinis D 2013 SuST 26 075014
Modeling $I_c$ vs. Transversal Load

2D FEM of a wire + Exponential strain function

- The exponential strain function was used to calculate* the reversible $I_c$ reduction experienced by a 1.25 mm PIT wire under transverse pressure in the UniGe set-up
  - The strain state was calculated via a 2D FEM mechanical model (plane strain)
  - The strain invariants were plugged in the exponential strain function
  - All the parameters in the exponential strain function were derived by $I_c$ vs axial strain measurements performed at UniGe

- The model* is in good agreement with the experimental data**

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* T Wang, L Chiesa, M Takayasu, B Bordini Cryogenics 63 (2014) 275–281
Modeling $\mathcal{I}_C$ vs. Transversal Load

3D FEM of a wire + Exponential strain function* 1/3

- A 3D FEM model was developed* to investigate the role of
  - Twisted filaments; Rolling the wire; Different Boundary conditions and Impregnations

![Graph showing experimental data for cracking]

$$B_p = 19 \, T, T = 4.22 \, K$$

$$r_{\mathcal{I}_{C_{\text{min}}}} = \frac{\mathcal{I}_{C_{\text{min}}} (\varepsilon)}{\mathcal{I}_C (0)} = \min_{f_i} \left( \int_{A_{f_i}} \mathcal{I}_C (\varepsilon) \, dA_{f_i} \right)$$

$$P = \frac{1}{A} \int_A \sigma_{zz} \, dA$$

$A = 1.15 \, mm \times 2.5 \, mm$

- A very good agreement was found – 1 mm 192 Round PIT

* A. Cattabiani, B. Bordini to be presented at the ASC 2018 conference

Courtesy of A. Cattabiani
Rolled strand (15% def.) are more representative of the geometry of the strand in a Rutherford cable.

To study the response of a rolled wire, the deformed wire geometry is required.

Carried out a simulation of the rolling process: the strand is deformed plastically between 2 rigid plates.

Everything is isotropic, plastic and at room temperature.

 Courtesy of A. Cattabiani

*A. Cattabiani, B. Bordini to be presented at the ASC 2018 conference*
Modeling $I_c$ vs. Transversal Load

3D FEM of a wire + Exponential strain function* 3/3

- $I_c$ reduction in rolled strand is mitigated compared to round ones
- In order to present similar $I_c$ reduction levels, rolled strands undergo $\sim 40$MPa of additional stress
  - Results in line with UniGe experiments

Courtesy of A. Cattabiani

* A. Cattabiani, B. Bordini to be presented at the ASC 2018 conference

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Electro-mechanical Performance of Nb$_3$Sn Rutherford Cables - B. Bordini
 Modeling $I_c$ vs. Transversal Load

2D FEM of a cable

- 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$_3$Sn;

- 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)

Modeling $I_c$ vs. Transversal Load

2D FEM of a cable + Exponential strain function

- Calculated via a FEM mechanical model* (2D, plain stress) 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 then 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.

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Conclusions

- Measurements of cables and wires under transverse load at CERN, Twente and Geneva Universities showed that the **reversible reduction** of the critical current is mainly due to a **decrease** of the $B_{c2}$
  - At 1.9 K, assuming a $B_{c2}$ equal to 28 T, a reduction of the $B_{c2}$ by 10% would produce a reduction of the $J_c$ approximately equal to: 20% at 12 T, 31% at 16 T, 44% at 19 T

- The **RRP cable** was **less sensitive** to transverse loads than the **PIT cable** (same cable geometry)
  - At 150 MPa and 11.6 T peak field the reversible reduction of the critical current was around 15% in the RRP cable and about 6-7% larger in the PIT cable
  - More important is the difference in terms of **irreversible degradation**: when applying all the load at 4.2 K, the onset of the irreversibility is around 120 MPa for the PIT cable and at 170 MPa for the RRP cable

- The **reversible reduction** of the critical current due to transverse load can be estimated via mechanical **FEM** models in conjunction with the **exponential strain function**
  - This approach should be used to estimate the margin of the FCC Nb$_3$Sn magnets
Thanks For Your Attention!
Conclusions

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