Electro-mechanical properties of Nb$_3$Sn conductors for application to high-field magnets

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Introduction

Critical Current Measurements of Cables under Transverse Load

Computational Modeling

Conclusions
Introduction

Strain dependence of Nb$_3$Sn

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

- In the case of applied axial strain, with a good approximation we can write

  \[ B_{c2}(T, \varepsilon) = B_{c2}(T, 0) s(\varepsilon) \]
  \[ J_c(B, T, \varepsilon) = C(T) b^{-0.5} (1-b)^2 \]

  Where \( s(\varepsilon) \) is the strain function that ranges between 0 and 1, and

  \[ b = \frac{B}{B_{c2}(T, \varepsilon)} \]

- Before cracking the filaments, the same equation proved to be valid also in the case of transverse loads.
Critical Current vs Transverse Load

CERN cable sample holder

- **Pro**: very representative of the conductor behavior in a magnet

- **Contra**: long test campaigns, only narrow cables (~10 mm) can reach up to 250 MPa

Max transverse force: 1750 kN

Low-pressure regions

High-pressure region

NbTi terminations

70 cm

Electro-mechanical properties of Nb$_3$Sn conductors for application to high-field magnets - B. Bordini
PIT cable based on 1-mm wires

Voltage-Current Measurements

Typical results for a PIT Cable measured at CERN at 4.3 K (full test sequence in next slide)

- Significant Reversible Reduction of the critical current
New measurements at CERN and Twente confirmed and consolidated the results observed in 2013; furthermore they allowed extending our understanding.

PIT cables with identical geometry measured @ CERN; Cable #2 & #3 adjacent samples

11.6 T, 4.3 K

Onset permeant reduction \( \sim 130 \text{ MPa} \), up to \( \sim 180 \text{ MPa} \) most likely due to plasticization of copper afterwards, to cracks in the filaments.
 scaling the $I_c$ Reduction

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

$b = \frac{B}{B_{c2}(T, \varepsilon)}$

- $I_c$ reduction mainly due to the decrease of the upper critical field $B_{c2} \rightarrow$ larger $I_c$ reduction at larger fields: at

150 MPa and 1.9 K $\sim 20\%$ at 12 T and $\sim 45\%$ at 19 T
**Critical Current Reduction**

- The **RRP** cable has still the same behavior of the **PIT** cable but it is **less sensitive** to transverse load.

- **Onset** *permanent* $I_c$ reduction
  1. **PIT**: $\sim 130$ MPa
  2. **RRP**: $\sim 170$ MPa

- **Total** $I_c$ reduction at 11.6 T and **150 MPa**
  1. **PIT**: $\sim 20\%$
  2. **RRP**: $\sim 15\%$

*Courtesy of M. Dhalle*
Computational Modeling

Introduction – Previous Studies

Wang – wire, UniGe

Vallone – cable, FRESCA


General Idea

2D mechanical FEM $\rightarrow$ strain field $\varepsilon$ $\rightarrow$ scaling law $J_c(s(\varepsilon))$

$s(\varepsilon) = s(I_1, J_2)$ [5] where $I_1$ is the first invariant of the strain tensor and $J_2$ is the second invariant of the deviatoric strain tensor

Both models were quite successful in reproducing the experimental results however, they rely on some assumptions that deserve to be further investigated.

How?

A 3D FEM model with no geometrical and material assumptions and no hypothesis on the longitudinal strain Add, in the future, an electric 3D model to simulate the possible current redistribution

1. longitudinal strains/stresses (plane strain [6] and the plane stress [7])
2. the necessary strain amplification factor when the wire layout is simplified and the material properties are homogenized [7]
3. no current redistribution

Aim

Study these assumptions to enhance the understanding of the physical phenomena involved. Most relevant assumptions:

High computational costs: smallest representative segment = 2.5 mm long

No homogenizations: All the 192 filaments are modeled

The strand is twisted (15 mm)
Groove and anvil are treated as rigid bodies: modeled as boundary constraints

- Lateral and bottom faces are free to slide on their respective planes
- Progressive, compressive displacement on the top face
Two possible set of boundary conditions on the strand ends to study the extreme cases:

**Clamped** and symmetric by translation: continuity $u_1 = u_2$

**Free to elongate** and symmetric by translation: $u_1 - u_2 = [q \ 0 \ 0]'$ with $q$ such that forces and couples are null:

$F_1 = F_2 = M_1 = M_2 = 0$
**Results:** $I_c$ reduction in round PIT wires

- **Hypothesis:** no current redistribution
  - $I_c$ dictated by the most strained filament
- **Good agreement with experimental data** [4]

**Equation:**
\[
\text{Load} = \frac{1}{A} \int_A \sigma_{zz} dA
\]
\[
A = 1.15 \text{ mm} \times 2.5 \text{mm}
\]

**Graph:**
- $I_c_{\text{min}} / I_c^0$ vs. Load [MPa]
- Red line: round - free
- Blue line: round - clamped
- Delta symbol: experimental data

**Data:**
- 19 T, 4.2 K

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

In order to study this case, the deformed configuration is required.

An additional simulation of rolling is performed: the strand is deformed plastically between 2 rigid plates.
Computational Modeling

Results $I_c$ reduction PIT wires: Round vs 15% Rolled

- The model reproduces the lower sensitivity of 15% rolled samples with respect to round wire samples
  - The same performance reduction is obtained at 40 MPa larger loads
  - The model is in good agreement with the experimental data from the University of Geneva

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Free ends

19 T, 4.2 K

Clamped ends

0.00 50.00 100.00 150.00 200.00 Load [MPa]

0.2 0.4 0.6 0.8 1.0 $I_c$ min / $I_c0$

0.00 50.00 100.00 150.00 200.00 Load [MPa]

round - free

rolled - free

round - clamped

rolled - clamped

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PIT #31712 $\varnothing = 1.0$ mm

sample #1 round
	sample #1 round after force unload
	sample #2 15% rolled
	sample #2 15% rolled after force unload

@ 4.2K, 19 T

Transverse force [kN]

0 5 10 15 20 25 30 35

Transverse stress [MPa]

0 30 60 90 120 150 180 210 240

$I_c / I_c0$

0.2 0.4 0.6 0.8 1.0

Courtesy of C. Senatore
Conclusions

- The **effect** of the **transverse load** on the **superconducting performance** of Nb$_3$Sn cables is **relevant** already at **150 MPa** and has to be taken into account in the **design** of high field accelerator **magnets**

- **Before cracking** the filaments (at least up to 180 MPa), the **critical current reduction**:
  
  ➢ is mainly due to a **decrease** of the **upper critical field** and can be **described** with the well established **scaling laws** developed for the case of applied axial strain
  $$I_c(B, T, \varepsilon) = I_c(B, T, s(\varepsilon))$$ - where $s$ is the **strain-function**

  ➢ can be **estimated** with mechanical Finite Element Method models coupled with the **exponential strain-function** developed at CERN
THANK YOU FOR THE ATTENTION