Introduction

Nb₃Sn and Strain

➢ One of the major challenge for a 16 T Nb₃Sn accelerator magnet is the conductor behavior under large transverse load: $P \propto B \Rightarrow P \ (16 \text{ T}) \approx 150-200 \text{ MPa}$

16 T FCC cos-theta main dipole

➢ The Nb₃Sn is a brittle material and its superconducting performance are strongly dependent on the superconductor strain state

➢ While the behavior of the conductor under axial strain is well established, not much data were available for the transverse load case

Max $\sigma_{VM}$

181 MPa
Introduction

Studies Preceding the EuroCirCol Conductor Program

- One Rutherford cable based on PIT wires and a few PIT wires were previously measured under transverse load respectively by CERN and the University of Geneva.

- The results showed: 1) a significant reduction of the critical current and of the Upper critical field $B_{c2}$ already at 150 MPa.

- The limited data available, the complexity of the experiments and the fact that only PIT technology was tested, did not allow drawing general conclusions also because other studies indicated that up to a transverse load of 200 MPa, the effect on the superconducting performance was limited in Nb$_3$Sn Rutherford cables.
Introduction

Aim of the Study & Outstanding Questions

- If confirmed, CERN and UniGe conductor measurements would have had a significant impact on the design of Nb₃Sn accelerator magnets.

- In the framework of WP5, CERN coordinated a campaign of measurements in collaboration with the Universities of Geneva and Twente to try answering the following questions:
  - Are CERN cable’s measurements reproducible? Are the results reproducible in a different set-up?
  - Can we extend these results to the Restacked Rod Process (RRP) Nb₃Sn superconductor?
  - At which pressure permanent $I_c$ reduction occurs in cable test?
  - Why wire measurements show a larger sensitivity to transverse load than cable measurements?
Measurement Campaign
Critical Current vs Transverse load

- The point of reference was the 10 mm wide Rutherford cable based on 1 mm Nb$_3$Sn wires – that is the same cable geometry previously measured by CERN

- CERN and Twente University measured each:
  - Two cable samples based on the 192 PIT wires
  - Two cable samples based on the 132/169 RRP wires

- The University of Geneva measured at least two of the following wire samples
  - Round 192 PIT
  - 15% - rolled 192 PIT
  - Round 132/169 RRP
  - 15% - rolled 132/169 RRP

15% Rolling used to simulate the wire deformation during cabling
**Measurement Set-Ups**

### UniGe wire sample holder
- **Pro:** Large transverse loads, rapid and economic test campaigns
- **Contra:** Single wire measurement

*Courtesy of Carmine Senatore UNIVERISTÉ DE GENÈVE*

### TWENTE cable sample holder
- **Pro:** Large transverse loads and rapid test campaigns
- **Contra:** Short samples (45 mm), large magnetic fields gradients

*Courtesy of Marc Dhalle UNIVERSITY OF TWENTE.*

### CERN cable sample holder
- **Pro:** Very representative of the conductor behaviour in a magnet
- **Contra:** Long test campaigns, only narrow cables (~10 mm) can reach up to 250 MPa

*Courtesy of Marc Dhalle*
Main Results on Cable tests

$I_c$ Reduction Under Transverse Load

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

- **Significant Reversible Reduction** of the critical current $I_c$
- $I_c$ reduction mainly due to the decrease of the upper critical field $B_{c2}$
  - larger $I_c$ reduction at larger fields:
    - at 150 MPa and 1.9 K ~ 20% at 12T and ~ 45% at 19T

![Graph showing critical current vs. peak field with different pressures](image)

**Table:**

<table>
<thead>
<tr>
<th>Pressure (MPa)</th>
<th>Voltage (mV)</th>
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<tbody>
<tr>
<td>80</td>
<td></td>
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<tr>
<td>140</td>
<td></td>
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<tr>
<td>180</td>
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Different Curves at different applied magnetic fields

**Courtesy of G. De Marzi**
Main Results on Cable tests
Reproducibility at CERN

The new measurements confirmed and consolidated the results observed in 2013; furthermore they allowed extending our understanding.

Onset permeant reduction $\sim 130$ MPa, up to $\sim 180$ MPa most likely due to plasticization of copper afterwards, to cracks in the filaments.
Main Results on Cable tests

Same Results in Twente’s set Up? What about the RRP conductor? What is irreversible limit?

- Measurements carried out at Twente, confirmed the results found by CERN

- 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**: $\sim 15\%$

![Test of a **PIT** cable at Twente](image)

![Test of a **RRP** cable at Twente](image)

Courtesy of M. Dhalle
Main Results on Strand tests

Why wire measurements show a larger sensitivity to transverse load than cable measurements?

- **15%-rolled** wire samples are less sensitive than round wire samples
  - The same performance reduction is obtained at 40 MPa larger loads
- It was proved that the stress concentration in round wires is at the origin of the difference
  - \( I_c \): Measurement of rolled wires under transverse load are significantly more representative of the cable behavior

![Graph showing the sensitivity of wire measurements to transverse load compared to cable measurements.](image)

Courtesy of C. Senatore
Impact of the Study

- The conductor study proved that the **reversible reduction** of the critical current due transverse load must be taken **into account** in the **design** of high field Nb$_3$Sn magnets.

- The study **sensitized the magnet international community** and there now several efforts to account for the transverse load in the design of the magnets.

![Graph showing the estimate of the current margin in the mid-plane of a 11 T Nb$_3$Sn cos-theta dipole magnet](image-url)
Conclusion

- The **EuroCirCol Conductor program**, coordinated by CERN in collaboration with the Universities of Geneva and Twente, **successfully answered the outstanding questions** set at the beginning of the study.

- The **effect of the transverse load on the superconducting performance** of Nb$_3$Sn cables and wires was **understood and quantified**.
  - This effect is **relevant at high fields** and has to be taken into account for the design of High Field Nb$_3$Sn magnets.

- There now **several efforts** in different magnet groups **to account for the transverse load** in the **design of High Field Nb$_3$Sn magnets**.
Thank you for your attention