Effect of strand diameter, magnetic field and injection length on the current entrance length of internal tin Nb₃Sn strand

C. Zhou, C. Reurslaag, R. Lubkemann and A. Nijhuis

University of Twente, Faculty of Science & Technology, The Netherlands
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Motivation

- Knowledge of the current entrance effect of Nb₃Sn strands provides insight on current distribution inside and among strands in cables, essential for CICC performance and stability.
- Periodic strain patterns cause current redistribution between filaments/strands, the current.
- Larger strand diameter aims for higher strand/CICC stiffness (EU DEMO), but how does it affect current redistribution and transport performance?

Current entrance, transfer length

Current redistribution among filaments/strands

EU DEMO CICC, ENEA, 81.7 kA, 13 T, 7 K

ITER TF CICC
Strand characteristics

Nb$_3$Sn internal tin, WST, CN

Same strand layout/geometry, in scale with the strand diameter

Diameter of filaments: ~ 6, 8 and 12 μm

Matrix: bronze; diffusion barrier, Ta
Experimental setup 1:
• Copper potential tips (diameter of 50 µm) on sample by spot-welding to monitor potential distribution along sample length.
• Focus on region close to current joint; CTL Model validation

Experimental setup 2:
• Standard ITER barrel for $I_c$ test
• For strands with strong entrance effects
• Voltage taps between turns

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Results: current transfer length (setup 1)

- Experimental results for Nb$_3$Sn bronze wire with thousands of filaments and high resistive matrix in filamentary zone
- Note that “classical” current transfer model predicts current in matrix to decay exponentially with distance to current lead.
- Instead, a distinct upward curvature is noticeable.
Results: current transfer length (setup 1)

- Dependences of magnetic field and transport current vs. distance away from current joint
- Layer by layer penetration
- Magneto-resistivity
Results: current transfer length (setup 2)

- Entrance effect observed even in strand region 45 mm away from joint
- Entrance effect is more present in thicker strands
- Current has to travel further in thicker strand to reach the center
A three-layer analytical model is proposed.

A saturated filamentary ring with increasing thickness along with injected current is introduced.

Effective current transfer length scale $\lambda_{\text{eff}}$ adds influence of high resistive matrix layer into 1D ‘classical’ model.

$$I_{sc}(x) = I_{in} \left(1 - \exp\left(-\frac{x}{\lambda}\right)\right)$$

$$\lambda_{\text{eff}} = \sqrt{\frac{R_{\text{eff}} \cdot h_{ms}}{\rho_{ms}}} = \sqrt{\frac{(R_\Box + \rho_{tf} h_{tf}) \cdot h_{ms}}{\rho_{ms}}} = \sqrt{\lambda_0^2 + \frac{\rho_{tf} h_{tf} h_{ms}}{\rho_{ms}}}$$

$$\lambda_0 = \sqrt{\frac{R_\Box \cdot h_{ms}}{\rho_{ms}}}$$

$$R_{\text{eff}} = R_\Box + \rho_{tf} h_{tf}$$

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Twente 3D Strand Model

- Strand modelled by 3D resistive network of matrix elements and filaments.
- Filament-to-matrix contact resistance $R_{fm}$ Nb$_3$Sn: $1 \times 10^{-15} \sim 10^{-14}$ (Ωm$^2$)
- Transverse coupling resistance between matrix elements (RRR, EDX)
- Filament resistance is given by power law with $I_c$ and $n$-value

- Input resistive parameters are measured intra-strand resistances
- Superconducting filament parameters: $I_c$ and $n$-value
- Boundary condition: injected current is distributed to matrix (Cu) in outer ring.


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A good agreement between strand model prediction and experimental data validates the measured and extracted intra-strand resistance from direct measurements.

Deviations in analytical model predictions: increasing with distance, high-likely caused by difference for wire shape (a multi-layered block vs circle).
Strand Model to JackPot (cable)

Twente-ITER strain scaling law (PACMAN)

3D strand model

function: \( Ic(B, T, \varepsilon, \text{crack}) \)

\( N(B, T, \varepsilon, \text{crack}) \)

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Modeling results

**UT strand model**

Total filament number: 55, 6 cracks

**JackPot**

**MQE test simulation**

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Summary

• Current entrance and current transfer length (CTL) of prototype DEMO superconducting Nb$_3$Sn internal-tin strands have been investigated in terms of strand diameter, magnetic field and current injection joint length.

• Good matches between experiments and models.

• Transfer length is longer for lower magnetic fields due to higher absolute currents and for samples with shorter current injection length.

• Entrance effect is stronger in strands with a larger diameter due to their higher transverse resistance.

• Further investigation on influence of CTL on current redistribution among strands in CICC, thus on the CICC performance and stability.
Thank you for your attention!