STATUS OF THE WOUND CONDUCTOR TASK

CERN (TE-MSC, EN-MME, TE-CRG)

FCC Week, Amsterdam, 9th of April, 2018
CHARACTERIZATION OF Nb₃Sn WOUND CONDUCTOR

Irreversible degradation

- Quantify irreversible degradation of the conductor during the magnet assembly at RT
- Develop knowledge about stress distribution on Rutherford cable stack under the transversal load

Windability

- Development of winding test setup to define a “windability factor” allowing comparison between different Rutherford cables
- Development of adequate scanning method to quantify strand displacements during the winding process

Material characterization

- Improving knowledge of magnet material parameters for refinement of analytical design study and FE modelling
- Impact of thermal expansion on coil stiffness
- Thermal expansion of Rutherford cables during the reaction heat treatment

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The dominating load case in accelerator magnets is transverse compressive.

Coils are loaded during the assembly, cooling, powering, quenching & thermal cycles.

Experimental results about the room temperature (RT) stress limits of Nb₃Sn wires, cables and coils at which irreversible conductor degradation occurs are lacking.

The ongoing experiment aims to determine the critical RT transverse compressive stress limits of cured, reacted and impregnated Nb₃Sn coil components.

The degradation is quantified in terms of critical current and n-value.

This work is carried out within an ongoing FCC-PhD. Collaboration with MSC-SCD, and profound academic supervision from the ATI (TU WIEN) as well as the work carried out from EN-MME and the USTEM (TU WIEN).
The critical current of a reacted and impregnated two stack cable sample is measured in applied field in a high test current facility (FRESCA).

Sample is taken out from FRESCA and compressed in a controlled manner at ambient temperature.

The sample is re-measured in FRESCA to check if, and by how much the compression has modified the $I_c$.

The test setup has been optimized in order ensure a known pressure distribution during the load step.

FRESCA sample, RRP – Nb$_3$Sn 11T cable stack

Cable compression on hydraulic press

Improved knowledge on stress-distribution
\( E_c = 3 \mu \text{V m}^{-1} \), \( \frac{dl}{dt} = 100 \text{ A s}^{-1} \), \( d=300 \text{ mm} \), \( B_{\text{self}} \approx 80 \text{ mT(kA)}^{-1} I \)

- Correction of inductive offset and resistive part
- Degradation of less than 4 % after 175 MPa

\textit{P. Ebermann et al., „Irreversible degradation of Nb}_3\text{Sn Rutherford cables due to transverse compressive stress at room temperature“, SuST, accepted for publication}
- Metallographic preparation and **SEM** observation
  - Longitudinal
  - Transversal
  - Entire etching with HNO$_3$

- Performed with
  - TU-WIEN (USTEM)
  - CERN (EN-MME)

- Ongoing work for analysis of
  - Cracks
  - Crack shape and surface
  - Crack density with digital image processing
  - Development of analytical and numerical model to predict imposed stress peaks leading to the observed crack patterns.
- Measure and model the geometrical evolution of cables during winding.
- Identification of the parameters dominating this process to possibly provide feedback for cabling & winding.
- Set-up a standard to quantify a “windability factor” or similar.

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- **CERN-LMF, 11T dipole winding machine**
- **CERN-LMF, 11T dipole pole end**

**Courtesy of D. Pulikowski**

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Typical findings during the winding of Nb$_3$Sn coils

- Protrusion from the mandrel surface
- Strand pop-out

- Quantify geometrical displacements due to observed instabilities
- Proposal and definition of a “windability factor” allowing to compare results of different cable geometries
- Allows to wind specimens with the Rutherford type cables in 1 DOF
- Provides repeatable conditions;
- Allows to adjust several winding parameters:
  - Winding tension, Bending radius, Pretorsion, Cable guide position and angle & winding direction.

Sample holder for winding tests
1 DOF WINDING SCANNER

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The average winding performance of three specimens wound with various winding mass and different winding direction.

- With increased winding tension the envelope deformation is becoming smaller. No significant difference between various winding direction.
- Strand pop-out shows less dependence on the winding parameters, the deformation improvement is not as clear as for the envelope deformation. Small difference between the winding directions.
- The protrusion shows the largest dependence on the winding direction, exhibiting in average smaller values for the unfavourable direction.
- Depending on the deformation type, one can find different winding tension and direction providing the smallest values. Therefore the pre-torsion study was launched, aiming to investigate the improvement by introducing new parameter to the winding study.
Pre-torsion – maintaining the cable twist throughout the winding with use of the angular guide. Investigating the clockwise twist, i.e. tightening of the cable.

Investigating the winding process improvement due to the additional DOF

- Adjusting the cable torsion with the angular guide: 0°, 22.5°, 45°;
- The adjustment of the torsion angle improves the winding quality and performance.


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Determining the position of the cable center in the longitudinal axis after winding with use of image analysis.

Improved QC allows observing the relative turn deviation between consecutive production steps.
Additional work on mechanical properties:

- Magnet coil constituents
  - Static tensile and compression tests
  - Dynamic E-modulus and shear modulus tests
  - Thermal expansion measurements
  - Friction measurements
- Coil block stiffness
Precise Young’s moduli can be derived from static stress-strain measurements of materials that exhibit pronounced linear elastic behaviour (e.g. Ti6Al4V).

The temperature dependence of the Young’s modulus can be determined by dynamic resonance tests.

Temperature dependent expansion of Nb$_3$Sn coil and magnet constituents:

Relative length change of DISCUP C30/3, Ti6Al4V, 316LN and Nb3Sn RRP type wire during (a) first heating and (b) cool down from 650 °C. The thermal expansions of Cu, Nb and Nb$_3$Sn bulk are shown for comparison.

• At RT in air at a pressure of 100 MPa Ti6Al4V shows smooth and stable sliding against 316LN with a friction coefficient of ~0.4.

• At 4.2 K@100 MPa a strong stick-slip effect is observed, which could be one potential origin of magnet quenches.

• Application of the solid lubricant MoS$_2$ lowers the 4.2 K friction coefficient to about 0.08.

• In liquid He at 100 MPa Polyimide shows smooth and stable sliding against steel 316 LN with a friction coefficient of ~0.2.

- Uncertainties caused by the compliance of the test set-ups avoided by using extensometers (direct strain measurements).
- All samples are made from \( \text{Nb}_3\text{Sn} \) 11 T dipole Rutherford cable, with Mica and S2 glass insulation (cube, 15 mm).
- Ten-stack samples reacted in a dedicated mould, three different levels of compaction.
- 11 T dipole coil block sample machined from coil after cold test
- Impregnation (CTD-101K)
- Non-impregnated 11 T dipole ten-stack sample has been tested for comparison.

- Ten stack
- Coil segment
- Non-imprg. ten stack

Effect of transverse stress applied during reaction heat treatment on the stiffness of Nb₃Sn Rutherford cable stacks

- Stiffness comparison with respect to the compaction level (during RHT) due to clearance variation.
- Stiffness comparison for different load directions.

Transverse compressive stress-strain curve of the ten-stack sample reacted with the lowest compaction.

Stiffness comparison of different compaction levels due to clearance variation in the RHT mould. Non-impregnated stack reacted with lowest compaction.

Stiffness in different sample directions, medium compaction during RHT

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F. Wolf: Effect of transverse stress applied during reaction heat treatment on the stiffness of Nb₃Sn Rutherford cable stacks

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Compressive stress strain measurement of a coil segment, reloaded sample

- The transverse stiffness of the ten-stack samples with the medium compression during RHT matches well the 11 T dipole coil block stiffness.
- A strong creep behaviour is observed when the transversal load exceeds about 125 MPa.

Stiffness comparison of impregnated and non impregnated cable stacks and a 11T coil conductor block.

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CONCLUSIONS

- The results coming from the characterization of the irreversible cable degradation at RT, though very preliminary seem encouraging and support the choices performed within the EuroCirCol study and are of use within the HL-LHC coil fabrication.

- The winding setup may allow to define a windability factor useful for future cable development and winding process (robust and repeatable quality, production time).

- The effects of load direction, pre-compression during heat treatment and load history on the stiffness of Nb3Sn Rutherford cable blocks have been determined.

- A number of studies are under way to refine thermomechanical properties of magnet coil constituents as input parameters and meshes for FE analysis, and to predict the internal stress distribution in Nb3Sn coils under different assembly and operating conditions.
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