Effect of transverse compressive stress on Nb₃Sn Rutherford cables for accelerator magnets

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27th International Conference on Magnet Technology (MT27)
Fukushima, Japan / 2021

WED-PO2-604-03

The accelerator magnets for the High Luminosity upgrade of the Large Hadron Collider (HL-LHC) use Nb₃Sn conductor to achieve in-field performance exceeding Nb-Ti based technologies. To sustain Lorentz forces during operation, a pre-compression is applied to the conductor during the fabrication of the magnet. This can lead to an irreversible degradation due to the mechanical sensitivity of the Nb₃Sn material.

The impact of the pre-compression is investigated using a reacted double stack of Rutherford cables.

The stack is submitted to transverse stress at RT. The critical current is then measured in liquid helium and in a background field of 9 T in the FRESCA test station at CERN. The pressure applied at room temperature on a reduced portion covers the range from 130 to 150 MPa with a 10 MPa step increase.

On smaller specimens, monotonic and cumulated pressures were applied to analyse the impact of the cyclic loading. Microscopic analysis of cross-sections were performed following procedures specifically developed to minimize surface damage during sample preparation. These observations were used to correlate the irreversible effect of the transverse pressure to the A15 damage.

From I, degradation & damage analysis:
- Degradation appears before 160 MPa for a NON INVERTED CONFIGURATION.
- Impact of damage initiated in early stress level not visible on electrical measurements.

From n value results:
- 160 MPa-170 MPa: reduction ≥ degradation.
- From 170 MPa, cable irreversibly damaged.

Microscopic analysis clearly shows difference in damage occurring in monotonic and cumulated / cyclic loadings.

Electrochemical test underestimates the damage phenomenon and doesn’t allow to evaluate the initiation of damage.

Investigation to evaluate if cracks can appear at low pressure without microscopic impact and could lead to degradation with a cyclic loading.

Questions:
- Effect of cyclic loadings (mech. & thermal) at lower pressure?
- At which pressure / stress level the first cracks appear?
- Physical phenomena and damage process involved?
- Analysis of MQXF stack cable
- Micrography using the CoCaSCOPE approach
- Inverted double-stack configuration
- Microscopic analysis
- Longitudinal cross-section
- Statistics (cyclic load size, pattern)

Perspectives & On-going work:
- Analysis of MQXF stack cable
- Numerical twin using the CoCaSCOPE approach
- Inverted double-stack configuration

Conclusions:
- Reproduce stress cases of FRESCA test on separate samples to perform destructive metallographic observations.
- Evaluate the impact of the cumulative loading on the damage state by comparison with samples loaded monotonically.

FRESCA test [1]
- Test at a temperature of 4 K and 1.9 K up to a current of 32 kA on an external applied field up to 9.6 T.
- Sample holder and field direction

I₀ measurement under magnetic field of a double-stack specimen after application of pressure at RT.

FRESCA test station [1]
- Measurements:
  - V taps in the high field region.
  - I₀, as a function of the two cables behavior.
  - Non-linear fit performed on $I = I₀ + a \cdot x + b \cdot y$ with $x = Eₘ \pi r²$.
- Test Procedure:
  - Measurement at virgin state: baseline.
  - Warming up and application of pressure @ RT.
  - Cool down and measurement in FRESCA.
  - The sample is submitted to a cumulative loading.
  - After the 190 MPa step, specimen loaded to 20 cycles at 190 MPa and measured in FRESCA.
- Then, 6 thermal cycles were performed.

Hydraulic press [2] [3]
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Results & conclusions:
- All samples show cracks, even the lowest one: 160 MPa Monotonic.
- Density of cracks more important in cumulated loaded sample than monotonic one.
- Damage in cables localized mainly in center, thin side less damaged than thick side.
- non-inverted configuration (can be confirmed with inverted configuration analysis).
- Pattern of cracks in sub-element:
  - Cracks are localized in the 45° planes from loading direction.
  - Damage sub-elements orientation does not vary, the rotation of the hexagon structure.
  - Majority of the cracks oriented to loading direction (vertical).
  - Horizontal cracks appear in severely damaged sub-elements localized in zone C.
  - In strands with less damage (1 to 10 sub-elements affected) cracks localized in A,B & C.
- As cracks density increases, located in C.
  - Heavy damage strands, zone D is reached and multiple cracks.

Hydraulic press and schematic view of the setup to apply transverse load

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Comparison of the crack distribution of the 160 MPa monotonic and cumulated samples.

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