Mechanical characterisation of Nb₃Sn cable insulation systems at ambient temperature used for HL-LHC accelerator magnets.

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ABSTRACT

The insulation system is a key component of Nb₃Sn superconducting accelerator magnets under construction for the LHC High Luminosity upgrade (HL-LHC). It needs to ensure the magnet operation at 1.9 K and to guarantee the functionality during the complete service life of the magnet in the accelerator under high mechanical stress and irradiation dose up to 35 MGy. A first set of experimental tests have been performed at room temperature to confirm the stress-strain behaviour, the mechanical strength and the failure mechanisms of the cable insulation system used for the HL-LHC Nb₃Sn accelerator magnets. CERN is performing non-standardised combined compressive shear test, which are considered to be representative for magnet conditions during assembly. The tested samples consist of the same raw insulation material and follow similar specific manufacturing procedures as the ones of the 11T Nb₃Sn dipole and the MQXF Nb₃Sn quadrupole magnets. In order to represent the different design criteria of these magnets, the sensitivity to the mechanical behaviour of the CTD-101K resin impregnated samples to a varying S2-glass yarn density, sizing and fibre volume fraction is investigated with different types of samples as well as the effect of mica used in the insulation system.

THE HL-LHC CABLE INSULATION SYSTEM

Impregnation system

CTD-101K, a Diglycidyl Ether of Bisphenol-A (DGEBA) with anhydride curing agent

11T cable insulation system MQXF cable insulation system

42 µm S2 glass and 80 µm mica on a glass fibre grid

145 µm S2 glass yarn

Load on the cable insulation system in the magnet 11T dipole magnet (5.5m):

- Manufacturing: Radial shear (red) and transversal compressive stress during pole insertion and magnet pre-loading
- Operation: Axial induced shear stress (green) due to thermal contraction difference between conductor and insulation system

MQXF quadrupole magnet (7.5m):

- Manufacturing: Transversal and radial compressive axial during Moulding loading
- Operation: Axial induced shear stress (green) due to thermal contraction difference between conductor and insulation system

Theoretical thickness

- 11T: 8.5 mm
- MQXF: 9.7 mm

Material characterization

- Electrical Insulation for High Energy Accelerator Research (HEAR)
- Organisme européen pour la recherche nucléaire (CERN)
- HEAL (Staphan)
- CEA-ITU (Felix Wolf)
- Jean-Pierre Fouquet (STFC RAL)
- Wolf Foussat (STFC RAL)
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- Remy Gauthier (STFC RAL)
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- Steve Robertson (STFC RAL)

The samples

- Glass fibre sheath extracted from cables used for 11 T and MQXF magnet production was used as ply material
- The glass fibre stacks have been heat treated for 50h at 650°C under argon atmosphere
- Vacuum impregnated with CTD-101K
- Pre-cutting of the composite material
- Cylindrical disk surface treatment, sand blasting and acetone cleaning
- Gluing of composite (Araldit 2015) in special alignment fixture
- Grinding of composite to final dimension of the disk

Shear compression test

- Test enables the determination of the mechanical strength under shear compressive load of a material
- Ratio between shear and compressive stress is set by the fixture angle τ = cot θ - σ
- Shear stress and compressive stress are equal at the fixture angle of 45°
- Stress at failure is determined by the maximum load, recorded with a load cell
- The test station enables tests at ambient temperature and at 77 K
- No lateral forces are applied on the test machine due to the multi part test tooling
- The alignment between sample and sample holder is done by stainless steel shims (0.01 mm
- The test requires just a very small quantity of material compared to standardized mechanical tests

Test results

- Bonding failure of an insulation system without mica
- All single sleeve samples (11TSC) failed with a bonding failure
- All double sleeve sample (11TDC) failed with a bonding failure
- The inter laminar failure is expected to be higher than the bonding strength

THE SAMPLES

Manufacturing procedure:

- Glass fibre sheath extracted from cables used for 11 T and MQXF magnet production was used as ply material
- The glass fibre stacks have been heat treated for 50h at 650°C under argon atmosphere
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Sample parameters

- 11T TDC airport
- 11T M DC airport
- 11 T M SC airport
- 11 T DC airport
- 11 T M DC airport
- 11 T M SC airport

CONCLUSIONS

Outlook:

- Improvement of the bonding between steel disc and composite by surface treatment and glue variation
- Manufacturing of samples with impregnated steel pads
- Continuation of the test campaign with MQXF ply material
- Study the effect of temperature (77 K) and irradiation dose up to 35 MGy
- Comparison to short beam bending test results with samples manufactured from the same material with a similar volume fraction
- Determination of the fibre volume fraction by microscopy and density method

Investigation of the effect of a varying fibre volume fraction on the shear compressive strength

*single sleeve provides two layers of glass fibre, **double sleeve provides four layers of glass fibre

Schematic of sample and test fixture.

(a) Cross section of an 11T (a), MQXF (b) magnet and shear stress definition in a sector of a cross section of a coil segment (c), courtesy CERN.

(b) MQXF sheath (red) and MQXF coil (green) with shear load (yellow) applied.

Test matrix with tested path in green.

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Shear-compressive test results of the tested samples in a 45° test fixture at room temperature. The error bar indicates the standard deviation of the test results.