CHART Scientific Report (Final Report for Phase 2)

Multiphysical Properties of Advanced Superconductors (WireChar)

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1. Introduction / Original goals of this project

Future particle colliders in search of new physics at the energy frontier require the development of accelerator magnets capable of producing fields well beyond those attained in the Large Hadron Collider (LHC). As the next generation of high-field accelerator magnets is planned to be based on Nb_3Sn, it is crucial to establish the mechanical limits at which this brittle and strain-sensitive superconductor can operate safely. Accelerator magnet coils are wound using insulated Rutherford cables composed of many single Nb_3Sn wires transposed together. The mechanical design of the magnets aims to avoid deformation or movement of the wires in the cables during powering, which may lead to premature quenches. This is achieved by applying a mechanical pre-compression to the superconducting coils during magnet assembly. The pre-stress applied at room temperature increases further during the cool-down to cryogenic temperatures, reaching its maximum at the coil mid-planes when the magnet is powered, in the transverse direction of the Rutherford cables.

In the design of next-generation accelerator magnets, peak stresses in the coils ranging from 150 to 200 MPa, which are close to the currently understood limits of Nb_3Sn wires, must be considered. Therefore, it becomes essential to precisely establish the mechanical limits to be adopted in the magnet assembly, cooling, and operation phases.

Within this context, UNIGE and CERN signed a research agreement under the auspices of CHART-2, with the goal of assessing the electromechanical limits of state-of-the-art and R&D Nb_3Sn wires, with a special focus on wires extracted from production billets used at CERN for the development of magnets.

2. Realisation

At the University of Geneva, we developed a dedicated experiment to extract quantitative information about the degradation of Rutherford cables under transverse stress from electromechanical tests on single wires. We perform critical current, I_c, measurements on single Nb_3Sn wires subjected to transverse compressive loads at 4.2 K in magnetic fields up to 19 T. The wires are resin-impregnated to replicate the working conditions in the Rutherford cables of accelerator magnets. During the experiment, samples undergo load/unload cycles at low temperatures with increasing transverse stress values, allowing us to determine the reversible and irreversible components of the measured reduction in I_c.

In addition to the electromechanical tests, we developed a novel non-destructive and non-invasive method to investigate the internal structure of Nb_3Sn wires and perform forensic analyses to understand the microscopic mechanisms behind the observed degradation of I_c. Our method combines high-resolution X-ray tomography images, taken at the High Energy Scattering beamline of the European Synchrotron Radiation Facility (ESRF), with deep learning networks. By implementing deep learning Convolutional Neural Networks, our tool can not only reconstruct the porosity in the superconducting filament structure but also identify cracks formed after exposure to transverse stress.

The experimental results were corroborated by a mechanical Finite Element Model (FEM) designed to analyze the stress distribution within the Nb_3Sn wire composite under transverse load. The model was based on wire geometries extracted from scanning electron microscope (SEM) images processed with a machine-learning-based algorithm.

3. Results / Conclusions / Deliverables

We investigated the stress dependence and the permanent reduction of critical current, I_c, under transverse compressive loads up to 240 MPa in accelerator-grade Nb_3Sn wires produced by different routes. The examined wires are multifilamentary composites produced either by metallurgy or powder-metallurgy methods. These wires differ in the architecture and configuration of the filaments, including the presence or absence of diffusion barriers separating the Nb and Sn precursors from the Cu matrix. The electro-mechanical response of these wires to transverse stress is determined by a combination of factors, which are intrinsic and extrinsic to the wires. They include the wire production route, the deformation of the wire section due to Rutherford cabling, and the stiffness of the resin system used for impregnation.

In general, two phenomena play together to determine the permanent reduction of the performance of a wire submitted to mechanical loads: cracks and plastic deformations. First, Nb_3Sn is a brittle intermetallic compound characterized by a strong propensity to fracture. The formation of filament breakages at sufficiently high pressures leads to the reduction of the current-carrying section of the wire. Second, the superconducting filaments of a Nb_3Sn wire are embedded in a soft Cu matrix which is prone to plastic deformation. Plastic deformation of the stabilizing matrix due to an external load leaves the Nb_3Sn under residual stress after unloading, resulting in a permanent distortion of its crystal structure. This, in turn, reduces the upper critical field after unload, B_{c2}, compared to the value measured on the virgin wire. By following the evolution of B_{c2} after unloading, we were able to experimentally identify which of the two is the dominant degradation mechanisms under transverse compression.

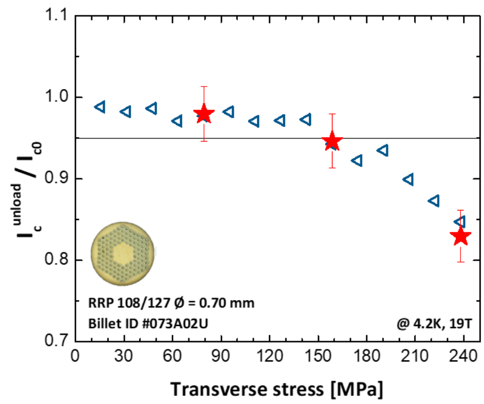

Figure 1 Evolution of the normalized critical current after unload as a function of the applied transverse stress for a RRP® wire. The solid stars represent the expected values predicted considering residual stress as the only mechanism of degradation.

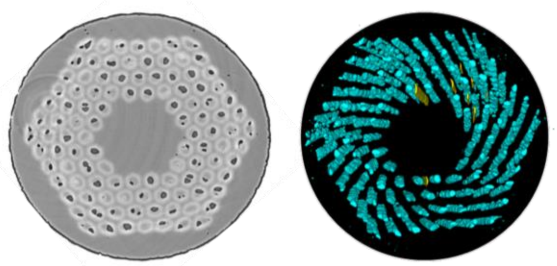

Figure 2 X-ray tomography cross section of a RRP® wire tested at the ESRF facility after Ic measurement under transverse load up to 240 MPa (left). 3D porosity reconstruction and crack detection performed by means of Convolutional Neural Networks (right): very few cracks were detected, none of them interrupting the Nb_3Sn filaments.

The analyses focused primarily on wires developed for the High Luminosity upgrade of the LHC, used in the MQXF and 11 T dipole magnet programs. These wires were produced by two distinct methods: the Powder-In-Tube (PIT) technique and the Rod-Restack Process (RRP®). The experiments revealed significant differences in tolerance to transverse stress between the two types of wires. Notably, the RRP® wires demonstrated superior tolerance, with an irreversible stress limit, σ_{irr}, defined conventionally as the stress level leading to a permanent 5% reduction of I_c at 19 T, ranging from 155 to 175 MPa. In contrast, the PIT wires showed an irreversible stress limit of only 110 MPa. These specific tests were performed using a relatively soft wire impregnation. However, the use of a resin with a higher elastic modulus or the addition of glass-fiber reinforcement can increase σ_{irr} by up to 50 MPa, as observed in other experiments we conducted. Despite the significant difference in σ_{irr} between the two types of wire, the permanent reduction of I_c measured after unloading from up to 240 MPa can be fully explained by the reduction of B_{c2} due to residual stresses from the plastic deformation of the Cu matrix (Figure 1). Surprisingly, crack formation appears to play a negligible role in the degradation of I_c of PIT and RRP® wires within the explored stress range. Independent confirmations of this conclusion came from a study combining X-ray tomography and deep learning networks, as well as from Finite Element (FE) mechanical simulations. Specifically, tomography images taken on the exact same samples tested for the I_c vs transverse stress dependence were analyzed by means of a convolutional neural network, to identify and segment cracks inside the wire volume. Interestingly, only a few cracks were detected in these samples exposed to very high stresses and none of these cracks was creating interruptions to the flow of the current in the Nb_3Sn cross section (Figure 2). Further evidence of the dominant role of residual stresses emerged from the Finite Element (FE) analysis. We conducted simulations to analyse the stress distribution within the cross-section of an impregnated wire, replicating the conditions of our transverse compression experiment both during loading and after unloading. The simulations compared the response of round wires with that of rolled wires, the latter intended to replicate the deformation caused by Rutherford cabling. Our analysis indicated that the transverse load applied to the flat surface of a rolled wire induces less plastic strain in the Cu matrix for a given external force (Figure 3). Consequently, this results in lower residual stress values in Nb_3Sn after unloading, suggesting an expected increase in σ_{irr} for rolled wires. This hypothesis was experimentally confirmed on a RRP® wire, where the σ_{irr} in the rolled variant was approximately 30 MPa higher than that of the round wire.

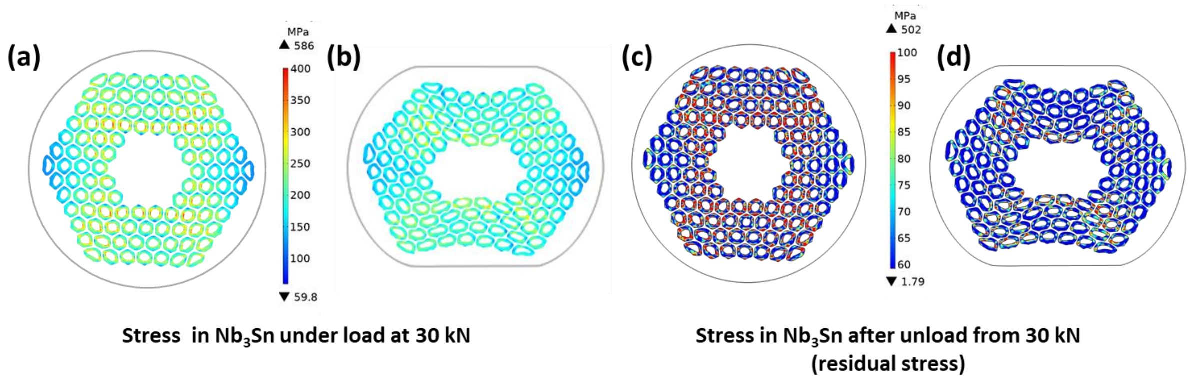

Figure 3 FEM simulations of the stress distribution in Nb_3Sn when a transverse force of 30 kN is applied (a) to a RRP® round wire and (b) to the same wire with rolling deformation. FEM simulations of the residual Von Mises stress in Nb_3Sn after unload from 30 kN for (c) the round wire and for (d) the rolled wire.

In conclusion, our experiments provided valuable insights into the mechanical limits of accelerator-grade Nb_3Sn wires relevant for magnet design, derived from single wire tests. We have assessed the mechanism of degradation of the wire performance under transverse compression, highlighting the dominant role of residual stresses, while acknowledging the potential variability in stress tolerance among wires produced with different technologies. Additionally, our project has been marked by innovation, particularly in the development of advanced tools for the analysis of tomography images using deep learning techniques, whose applications extend potentially beyond the scope of this activity. Furthermore, the Finite Element model employed in our analysis opens avenues for testing new wire designs and guiding the development of methods to enhance their mechanical limits. Overall, these findings contribute to a deeper understanding of the behaviour of Nb_3Sn wires, which is crucial for advancements in superconducting magnet technology.

4. Publications and Outreach

Peer reviewed paper in scientific journals

- L. Gämperle, J. Ferradas, C. Barth, B. Bordini, D. Tommasini, C. Senatore, "Determination of the electromechanical limits of high-performance Nb_3Sn Rutherford cables under transverse stress from a single-wire experiment," Phys. Rev. Research., vol. 2, 013211, 2020, DOI: 10.1103/PhysRevResearch.2.013211
- J. Ferradas Troitino, T. Bagni, C. Barth, B. Bordini, P. Ferracin, L. Gamperle, D. Tommasini, D. Zurmuehle, C. Senatore, "Effects of the initial axial strain state on the response to transverse stress of high-performance RRP Nb_3Sn wires," Supercond. Sci. Technol., vol. 34, 035008, 2021, DOI: 10.1088/1361-6668/abd388
- T. Bagni, G. Bovone, A. Rack, D. Mauro, C. Barth, D. Matera, F. Buta, C. Senatore, "Voids in RRP Nb_3Sn wire and their implications on electro-mechanical and electrothermal stability: an X-ray tomography analysis," Sci. Reports, vol. 11, 7767, 2021, DOI: 10.1038/s41598-021-87475-6
- T. Bagni, D. Mauro, M. Majkut, A. Rack, C. Senatore, "Formation and propagation of cracks in RRP Nb_3Sn wires studied by deep learning applied to x-ray tomography," Supercond. Sci. Technol., vol. 35, 104003, 2022, DOI: 10.1088/1361-6668/ac86ac
- T. Bagni, H. Haldi, D. Mauro, C. Senatore, "Tomography analysis tool: an application for image analysis based on unsupervised machine learning," IOPSciNotes, vol. 3, 015201, 2022, DOI: 10.1088/2633-1357/ac54bf
- C. Senatore, T. Bagni, J. Ferradas Troitino, B. Bordini, A. Ballarino, "Degradation of I_c due to residual stress in high-performance Nb3Sn wires submitted to compressive transverse force," Supercond. Sci. Technol., vol. 36, 075001, 2023, DOI: 10.1088/1361-6668/acca50
- T. Bagni, C. Calzolaio, G. Bovone, J. Ferradas-Troitino, C. Barth, A. Ballarino, C. Senatore, "Investigating the effect of rolling deformation on the electro-mechanical limits of Nb_3Sn wires produced by RRP and PIT technologies," accepted for publication in Supercond. Sci. Technol., 2024

Presentations at international conferences and workshops

- *Effects of the initial axial strain state on the response to transverse stress of high-performance RRP Nb_3Sn wires,* Presenting author: Jose FERRADAS TROITINO, contributed oral at ASC2020, the Applied Superconductivity Conference, virtual event, October 24 – November 7, 2020;
- *X-ray tomography analysis of voids' distribution and morphology in high-performance RRP Nb_3Sn wires for the next generation accelerator magnets,* Presenting author: Tommaso BAGNI, contributed oral at ASC2020, the Applied Superconductivity Conference, virtual event, October 24 – November 7, 2020;
- *Deep learning applied to X-ray tomography as a new tool to analyze the formation and propagation of cracks in RRP Nb_3Sn wires*, Presenting author: Tommaso BAGNI, contributed oral at EUCAS 2021, the 15th European Conference on Applied Superconductivity, virtual event, September 5 – 9, 2021;
- *Degradation of I_c after mechanical unload in high performance Nb_3Sn wires: the role of filament breakages and residual stress*, Presenting author: Carmine SENATORE, contributed oral at EUCAS 2021, the 15th European Conference on Applied Superconductivity, virtual event, September 5 – 9, 2021;

- *Recent developments of Nb_3Sn wires for application*, Presenting author: Carmine SENATORE, invited oral at ISS2021, the 34th International Symposium on Superconductivity, virtual event, November 30 – December 2, 2021;
- *Frontiers of Nb_3Sn conductor technology for applications in high field accelerator magnets,* Presenting author: Carmine SENATORE, invited oral at IEEE CSC Italy Chapter Workshop, Rome, Italy, June 13, 2022;
- *Degradation of I_c in high-performance Nb_3Sn wires: a study combining electromechanical investigations and machine learning applied to X-Ray tomography,* Presenting author: Carmine SENATORE, contributed oral at ASC2022, the Applied Superconductivity Conference, Honolulu, USA, October 23 – 28, 2022;
- *Investigating the impact of transverse compressive stress on Nb_3Sn wires for high-field accelerator magnets,* Presenting author: Carmine SENATORE, contributed oral at MT28, the 28th International Conference on Magnet Technology, Aix-en-Provence, France, September 10 – 15, 2023;
- *Stress Tolerance and Degradation Mechanisms of Accelerator-Grade Nb_3Sn Wires under Transverse Compression,* Presenting author: Carmine SENATORE, invited oral at MEM24, the 11th International Workshop on Mechanical and Electromagnetic Properties of Composite Superconductors, Spokane, USA, June 10 – 14, 2024;
- *Advancing Superconductor Technology for High Field Applications: Current State and Emerging Trends,* Presenting author: Carmine SENATORE, plenary oral at ICEC 29 – ICMC 2024, 29th International Cryogenic Engineering Conference and International Cryogenic Material Conference 2024, Geneva, Switzerland, July 22 – 26, 2024.

This final report is only a very brief summary of all activities. More detailed scientific reports are published at https://chart.ch/reports/