Enhanced superconducting wires for fusion applications

1. Project idea

Understanding irreversible performance degradation of superconducting wires under transverse mechanical loading is a critical issue for the design of large-scale fusion magnets such as those being developed for International Thermonuclear Experimental Reactor (ITER), currently under construction in southern France with the goal being to prove the viability of fusion as an energy source. Recent tests indicate that most ITER cable-in-conduit conductors made of Nb_3Sn wires processed by various fabrication techniques show similar irreversible degradation under cyclic mechanical loading. The irreversible degradation is due to filament fracture and strain accumulation of the superconducting wire and it cannot be described by the existing strand scaling law.

Tomographic imaging experiment combined with fracture mechanics modelling of filament micro-crack formation inside the Nb_3Sn wires under increase mechanical loading will significantly improve our understanding to the degradation mechanisms. Important questions such as how initial voids degrade the microstructural homogeneity of wire filament and cause sufficient local stress concentration that leads to filament crack propagation will be answered.

We propose a three year Geneva/Princeton partnership research collaboration to understand influence of filament micro-structure and initial void distribution on the irreversible degradation of Nb_3Sn wires under mechanical loads. Study at University of Geneva will focus on X-ray tomography for three-dimensional visualization of voids in the filament structure of Nb_3Sn wires processed by the Bronze Route, Internal Sn diffusion and Powder-in-tube techniques. Study at Princeton Plasma Physics Laboratory will focus on numerical modelling of Nb_3Sn wires using fundamental fracture mechanics to understand micro-crack propagation due to initial voids inside the superconducting wires.

Mechanical loads have a paramount importance in the design of a superconducting device. When a superconducting magnet is energized, the magnetic Lorentz forces generate significant stresses on the conductors in the winding. The so-called magnetic hoop stress, acting along the axis of the conductor, increases in proportion to the radius of the winding. In large magnets, such as the magnets for plasma confinement in the thermonuclear fusion reactors, the conductors have to carry several tens of kiloamps in high magnetic fields. In order to achieve the required current specifications, superconducting wires are arranged in cable in conduit conductors (CICC) in the coil design for ITER. In these arrangements the superconductor experiences transverse stresses in addition to the hoop stress, as the Lorentz force determines wire-to-wire contacts and presses the wires against the containment structure [1].

A key area of interest in this field is the improvement of the mechanical properties and in particular the enhancement of the irreversible degradation limit under stress for the high performance multifilamentary Nb_3Sn wires intended for use in the ITER magnets as well as in the next generation of accelerator magnets, for the upgrade of the Large Hadron Collider (LHC) at CERN. Nb_3Sn is an intermetallic superconductor used to generate magnetic fields up to 23.5 Tesla. In practical conductors hundreds of Nb_3Sn filaments are embedded in a copper matrix. The critical current I_c of the Nb_3Sn wires under high mechanical loads undergoes a permanent degradation as a result of cracks within the superconducting filaments. A stochastic process is at the base of this phenomenon, related to the distribution of inhomogeneities and voids in the microstructure of the wire. Voids formation occurs during the wire deformation process and the reaction heat treatment [2] and is in turn determined by multiple parameters, as the wire fabrication technology and the reaction heat treatment conditions (temperature, duration, pressure). The total void volume is ~5% of the total wire volume, the single void cross-section ranging between $\leq 1\ \mu m^2$ and $10\ \mu m^2$. Therefore, voids degrade the microstructural homogeneity of the filaments and cause localized stress concentrations which act as nucleation points for crack formation. This results in an irreversible degradation of the critical current beyond a certain value of the applied stress.

The research proposed here aims to understand the mechanism behind the performance degradation of superconducting wires submitted to mechanical loads and, in particular, to establish a correlation between size distribution of the voids within the Nb_3Sn filaments and the stress value corresponding to the occurrence of the irreversible degradation of I_c. Our approach combines the quantitative description of the voids obtained from synchrotron tomography, an extensive characterization of the superconducting properties under mechanical loads and numerical modelling of the micro-crack fracture mechanics.

2. Role and contributions by the two partners

2.1 University of Geneva (UNIGE)

The project will be carried out at the Department of Condensed Matter Physics and at the Department of Applied Physics of the University of Geneva. The group of Applied Superconductivity led by Prof. Carmine Senatore is active in the development and characterization of superconducting materials for applications, offering world-wide unique facilities for the study of the material properties at low temperature/high magnetic field.
Our contributions to this project can be divided into two categories:

- Voids morphometry by XRD nanotomography;
- Electromechanical properties of superconducting wires.

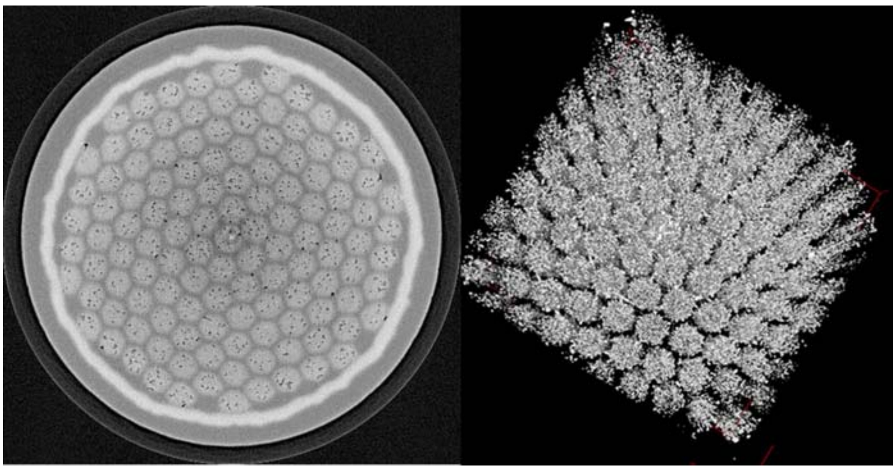

Figure 1 Nb_3Sn wire cross section acquired by synchrotron tomography (left) and 3D view of the voids inside the superconducting filaments (right)

2.1.1 Voids morphometry by XRD nanotomography

Fig. 1 shows the transverse cross section of a Nb_3Sn wire and a 3D view of selected voids inside the wire, as obtained from synchrotron microtomography in a previous experiment conducted at the European Synchrotron Radiation Facility (ESRF). In order to investigate the influence of void size and distribution on the irreversible degradation of the critical current of Nb_3Sn wires we will have access to the facilities of the beamline X02DA at the Paul Scherrer Institute (PSI) to perform tomographic microscopy experiments. We intend to probe the different aspects influencing the formation of voids in the Nb_3Sn filaments:

- *Fabrication technology*: samples processed by the three main industrial routes, Bronze Route, Internal Sn diffusion and Powder-In-Tube technique, will be examined to determine the differences in the void morphology;
- *Wire design, filament size and configuration*: Nb_3Sn is formed in the wire during the reaction heat treatment by the diffusion of Sn into Nb. The dimension of the filaments in a wire may vary largely depending on its target application and this has an influence on the reaction paths and thus on the mechanism behind the void formation. This aspect will be examined on selected samples;
- *Heat treatment parameters and reaction kinetics*: heat treatment temperature and temperature ramp rate determine the reaction process. In particular, initially identical non-reacted Nb_3Sn wire samples undergoing different heat treatment schedules will be prepared at UNIGE to investigate the differences in the void volume and distribution.

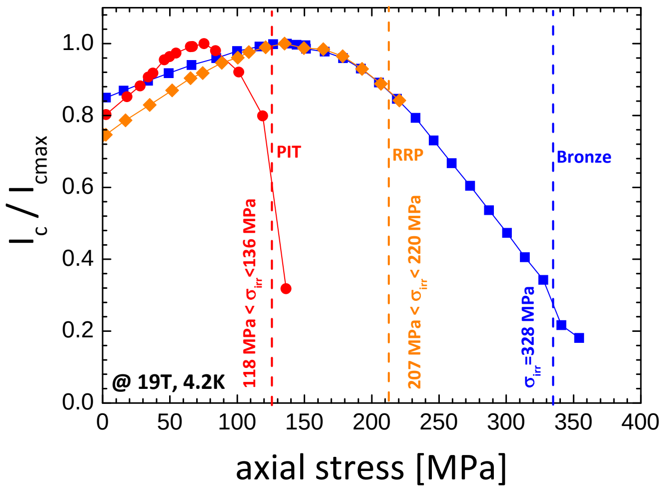

Figure 2 Critical current versus stress for three Nb_3Sn wires fabricated by different methods: the irreversible stress limit, indicated by a dashed line, is strongly influenced by the wire fabrication technology.

2.1.2 Electromechanical properties of superconducting wires

The critical current I_c of the wires examined by XRD tomography will be measured as a function of the axial stress in order to determine the onset of the irreversible degradation of I_c. An innovative setup for this experiment is already implemented at UNIGE and allows the detection of the irreversible stress limit with high accuracy [3,4]. As shown in Fig. 2 the degradation of the electrical transport properties under stress strongly depends on the wire fabrication technology. Measurements of the critical current I_c as a function of the applied stress σ will be performed using the concept of the Walters spring: the superconducting wire is soldered on a helical spring and stress is applied by rotating one end of the spring. In comparison to other probes, an important advantage of this setup is the possibility to measure over long length of the conductor, typically over 50 cm. This allows the application of very low voltage criteria for the I_c measurements and thus the detection of the onset of the I_c degradation with high accuracy. $I_c(\sigma)$ curves will be measured at currents up to 1000 A and fields up to 21 T, with temperatures ranging between 4.2 K and T_c.

2.2 Princeton Plasma Physics Laboratory (PPPL)

Research at Princeton will focus on modelling of imperfect Nb_3Sn wires using fundamental fracture mechanics to understand micro-crack propagation due to initial defects inside the superconducting filaments or the copper matrix of the Nb_3Sn wires. Fig. 3 shows the micro-cracks of different orders observed in the polished longitudinal cross-section of the ITER OST strand after applying periodic peak bending strain [5]. We will apply first principle fracture mechanics combined with novel technique for predicting stress concentrations in composite wires to study influence of void size and distribution to crack propagation, and the correlation between initial defects and the fatigue crack growth threshold stress limit. Fig. 4 presents the three different regimes of stable fatigue crack propagation. Region C on the right of Fig. 4 is fast fracture as a result of the high local stress intensity and low material fracture toughness, region B is the linear region where crack growth follows the Paris law, and region A is the crack growth threshold limit region, where the local stress intensity around initial voids inside the wires under mechanical loading is sufficiently low such that no crack will propagate.

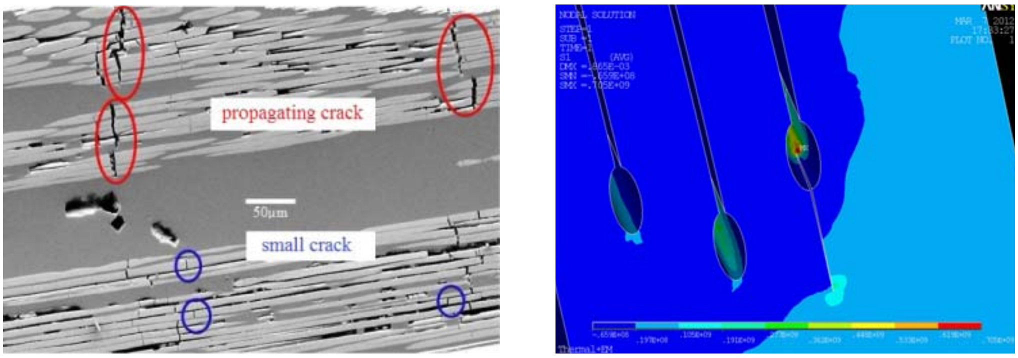

Figure 3 Micro-cracks observed in the polished longitudinal cross-section of the OST strand after periodic peak bending (left) and modelling of defects with initial crack propagation due to local stress concentration (right).

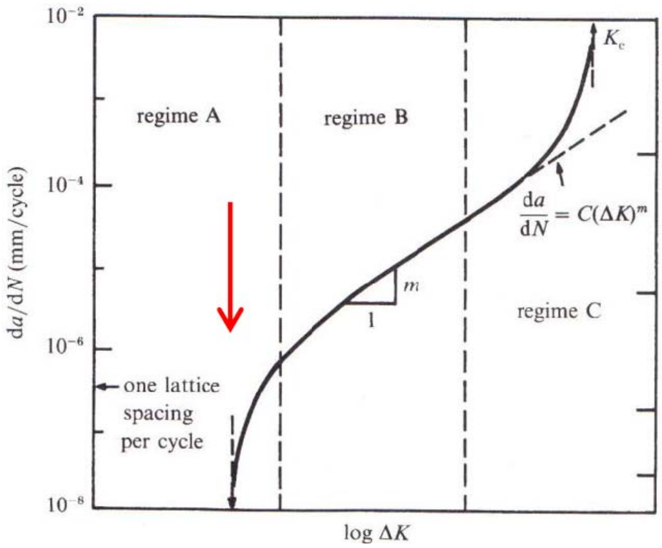

Figure 4 Schematic illustration of the different regimes of stable fatigue crack propagation. Highlighted in regime A is the crack threshold limit below which crack will not propagate.

We will first develop two- and three-dimensional finite element fracture mechanics models of composite wires with initial defect distributions based on X-ray tomography study done by Prof. Carmine Senatore's Group at University of Geneva, then perform parametric studies to understand what local stress condition will promote initial crack propagation and what filament-matrix composite geometry condition will either prevent crack growth or deflect a propagating crack at the filament-matrix interface boundary. Both stress intensity and local energy release rate are important parameters for crack growth criteria. The result of this study will guide the design optimization of enhanced superconducting wires for fusion applications. Fig. 5 shows the local stress concentration and crack propagation for two- and three-dimensional crack propagation analysis using the finite element method, where initial defects are modelled as elliptic holes and the color contours represent the first principal stress distribution around defects for mode I crack.

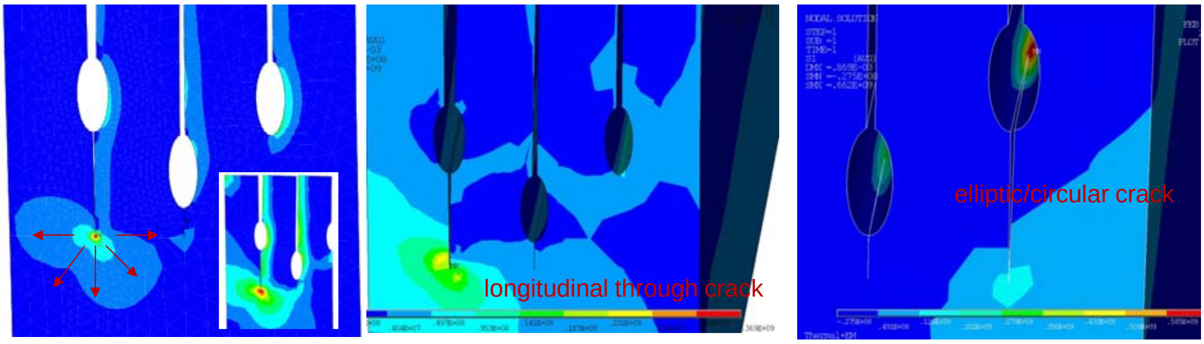

Figure 5 Local stress concentration and crack propagation for two- and three-dimensional crack propagation analysis using the finite element method. Initial voids are modelled as elliptic holes and the color contours represent the first principal stress for mode I crack.

Summer internship student will have the opportunity to 1) learn fracture mechanics modelling of multiscale composite wires under Dr. Zhai's guidance 2) use the most advanced multiphysics simulation tool at the plasma physics laboratory for hands-on parametric design study of enhanced superconducting wires.

References

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