Finite Element Analysis of Transverse Compressive Loads on a Nb_3Sn Superconducting Wire Containing Voids

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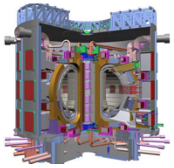
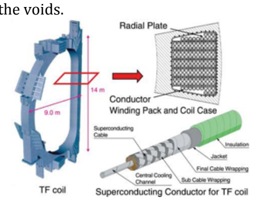
Abstract

High field superconductors play an important role in many large-scale physics experiments, particularly particle colliders and fusion devices such as the LHC and ITER. The two most common superconductors used are NbTi and Nb_3Sn. Nb_3Sn wires are favored because of their significantly higher J_c, allowing them to produce much higher magnetic fields. The main disadvantage is that the superconducting performance of Nb_3Sn is highly strain-sensitive and the material is very brittle.

The strain-sensitivity is strongly influenced by two factors: plasticity and cracked filaments. Cracks are induced by large stress concentrators due to the presence of voids, which form during the heat treatment phase of the wire fabrication, We will attempt to understand the correlation between Nb_3Sn's irreversible strain limit and the void-induced stress concentrations around the voids.



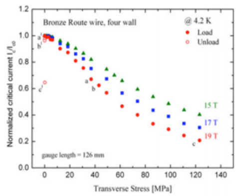


Methodology

We will develop accurate 2D and 3D finite element models containing detailed filaments and possible distributions of voids in a bronze-route Nb3Sn wire. We will apply a compressive transverse load for the various cases to simulate the stress response of a Nb_3Sn wire from the Lorentz force. Doing this will further improve our understanding of the effect voids have on the wire's mechanical properties, and thus, the connection between the shape & distribution of voids and performance degradation.

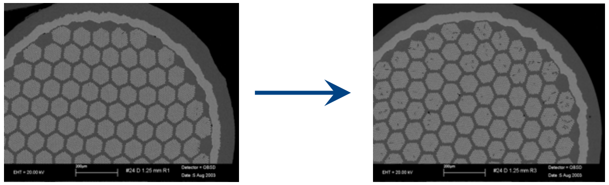
J_C vs Transverse Stress

Critical current density(J_c) is strongly influenced by the stress on the wire. The more stress on the wire, the less J_c, and thus the less maximum B-field. Additionally, J_c decreases more quickly with stress as the magnetic field is increased. The figure below shows that there is an irreversible limit of stress and exerting loads that result in stresses greater than this limit cause permanent degradation in the J_c.



Void Formation

Nb_3Sn strands in a bronze-route Nb_3Sn wire are formed during the heat treatment process. The CuSn matrix reacts with the Nb filaments producing brittle superconducting Nb_3Sn filaments. When the tin diffuses into the Nb filaments during this process, it leaves voids in its wake. These voids degrade the mechanical properties and are thought to be the primary cause of the cracking of filaments.

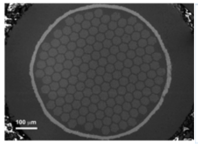


Bronze-route Nb_3Sn wire prior to and after heat treatment. These images were taken by X-ray tomography at the University of Geneva (UNIGE).

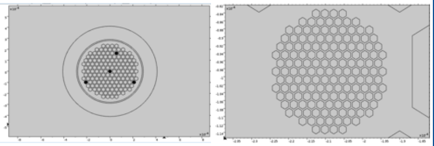
Building a Finite Element Model

2D Model

- The geometry was based on a cross-section of Bruker wire captured at UNIGE. Some bundles were replaced with filaments to be able to analyze the effect of voids.
- This was put in an epoxy casting and a load of 17 kN applied to the top, the bottom held fixed and the left and right kept free.
- Voids of different shapes were placed in varying distributions between filaments, to resemble the voids found in the tomography.
- The properties for the Epoxy, Copper, Tantalum, Bronze and Nb3Sn were based on Mitchell's paper[1] with the materials at 4K and remaining elastic.

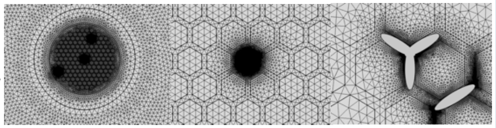


Bruker bronze-route wire.



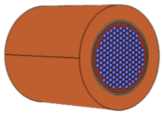
The geometry and scale of the wire compared to filaments.

Images of the mesh. The rightmost image shows mesh detail near voids.



3D Model

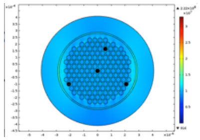
- This geometry consists of a simple wire model with bundles, extruded one millimeter.
- The Nb_3Sn wire was then cooled down from 923 K to 4 K
- The T-dependent material properties were based on Mitchell's data[1] and the stress strain relationships replaced by a Bilinear model.



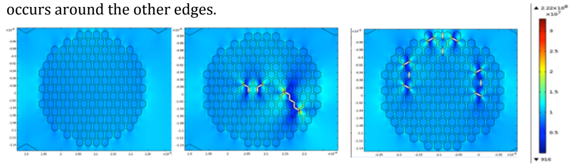
Results and Findings

	Bundle	In filaments	Between filaments
Mean Stress (MPa)	9.3	9.5	10.36

- Globally, the stress distribution in a wire with and without voids looks identical:



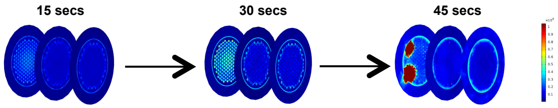
- Locally, voids cause perturbations in the stress distribution. Concentrations of high stress appear at the tips and interestingly, a significant decrease in stress occurs around the other edges.



- The stress induced is largely dependent the shape and orientation of the void:

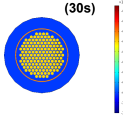
Void Type	Ellipse, 30/150	Ellipse, 90	Long Crack	Short Crack	Circular (A)	Circular (B)	Circular (C)
Peak Stress (MPa)	93.20/92.93	20.70	219.20	143.4	30.80	31.30	44.60
Min Stress (MPa)	0.1/0.17	1.69	0.02	0.019	1.69	0.58	1.90
Filament PS* (MPa)	61.50/65.52	17.60	154.60	114.08	20.10	16.10	35.90

3D Model



- The images shown above depict the von Mises stress as the wire cools from 923 K to 233 K. Three different slices are shown, at 0.96mm, 0.5mm and 0.08mm from the "front".
- The "back" is held fixed during the thermal loading process.
- An inverted mesh element occurs around 40s into the simulations.
- The thermal strain seen here is consistent with predicted values.

Thermal Strain (30s)



Future Work

- Inverted mesh issue needs to be corrected to look at the resulting pre-strain in the 3D model after full cool down from heat treatment temperatures
- Implementing 3D voids, based on UNIGE's statistical void data which we should receive in the fall
- Analyze the effect of voids on both axial and transverse stress in the wire, to correlate void types and distributions with the irreversible strain limit

References

[1] N. Mitchell, "Finite element simulations of elasto-plastic processes in Nb3Sn strands," Cryogenics, Volume 45, Issue 7, July 2005, Pages 501-515.
[2] C. Calzolaio, G. Mondonico, A. Ballarino, B. Bordini, L. Bottura, L. Oberli and C.Senatore,"Electro-mechanical properties of PIT Nb3Sn wires under transverse stress: experimental results and FEM analysis, Super cond. Sci. Tech., Feb. 2015