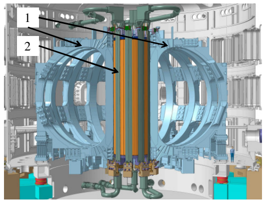
# Fracture Statistics of Individual $Nb_3Sn$ Filaments

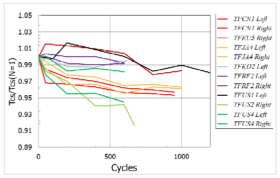
Sam Schultz, Maxwell Dylla, Nicholas Sullivan, and Dr. Matthew Jewell ⚡ Materials Science Program ⚡ University of Wisconsin-Eau Claire

## Introduction

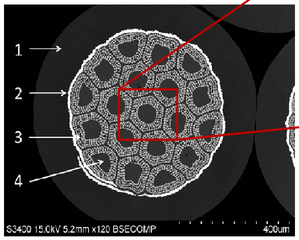
Superconductors are a class of material that when cooled to low temperatures, conduct electricity with zero resistance. The main use of superconductors is in large magnet systems for particle accelerators and the ITER experimental fusion reactor being built in France. $Nb_3Sn$, processed into composite, multifilamentary wires, is one of the main superconducting materials used in these magnet systems. Due to Lorentz forces induced during magnet operation, the brittle $Nb_3SN$ filaments in these wires crack, causing a degradation of the performance of the magnets. Previous experiments probing the fracture mechanics of $Nb_3Sn$ filaments have utilized whole wires in their tests. This work extracts the tiny $Nb_3Sn$ filaments from their component wires for testing and is therefore able to probe the intrinsic properties of $Nb_3Sn$.



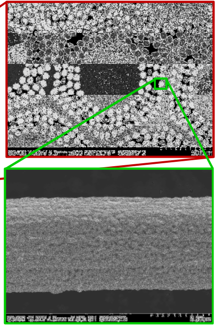
ITER Tokamak design. Both the Toroidal Field magnets and the Central Solenoid are $Nb_3Sn$ magnets.
1. Toroidal Field magnets
2. Central Solenoid



The performance of $Nb_3Sn$ wires can degrade during magnet operation. The degradation is due to $Nb_3Sn$ filaments cracking in the wires.



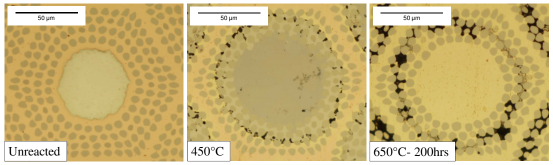
A composite $Nb_3Sn$ wire used in our research.
1. Stabilizing Cu
2. Nb diffusion barrier
3. $Nb_3Sn$ filaments
4. Interfilamentary Cu



A single $Nb_3Sn$ filament. Nodular surface shows individual $Nb_3Sn$ grains.

## Heat Treatment

ITER style, Internal Sn processed $Nb_3Sn$ wires were vacuum sealed in quartz tubes and heat-treated in a furnace to react the Nb filaments with the Sn cores, making $Nb_3Sn$. Wires are reacted after processing because $Nb_3Sn$ is a brittle material and would fracture under the stresses during processing.

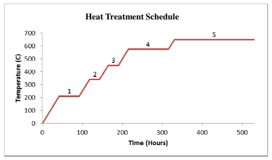


Unreacted

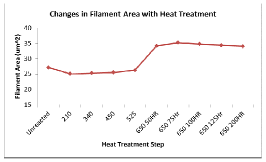
450°C

650°C- 200hrs

During heat treatment Sn cores gradually react with the Nb filaments, forming $Nb_3Sn$.



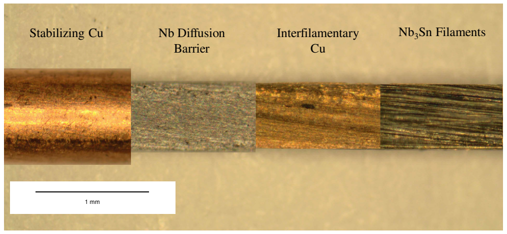
Heat treatment schedule
210°C- 50 hours
340°C- 25 hours
450°C- 25 hours
575°C- 100 hours
650°C- 200 hours



Filaments swell in size as they react to form $Nb_3Sn$.

## Filament Extraction

After heat treatment, 2 cm long sections of wire were cut from the 650°C- 200 hour samples and etched with the following acids to expose the $Nb_3Sn$ filaments.
- 50% $HNO_3$ acid wash to remove stabilizing Cu
- 50% HF acid wash to remove Nb diffusion barrier
- 50% $HNO_3$ acid wash to remove interfilamentary Cu

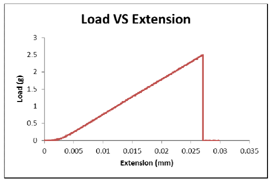


Composite image showing the stages of filament extraction.

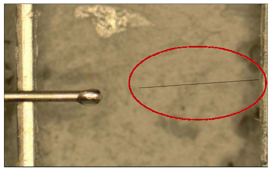
## Filament Tensile Testing

$Nb_3Sn$ filaments were transferred to notecards attached to steel plates in our tensile tester. Then using superglue, filaments were fixed to the notecards, using alignment indicators on the notecards as guides. The glue was left to dry for one hour before beginning the test.

Our tensile tester. Test set-up highlighted.

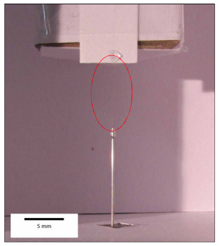


Typical Load-Extension curve generated during a tensile test with a 5 N load cell.

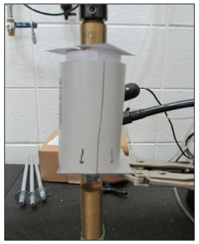


Tensile testing set-up. Superglue fixes filaments to stainless steel tubing.

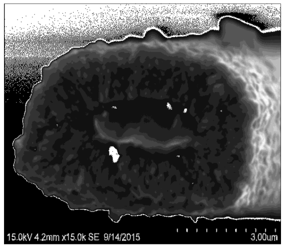
## Positioning Development and Unreacted Cores



An incased testing method was developed to catch filament fragments from tests. The filament itself is fitting into a small diameter steel tube (highlighted) and is hung from the top grip to ensure maximum vertical alignment. Superglue is then applied to hold in place.



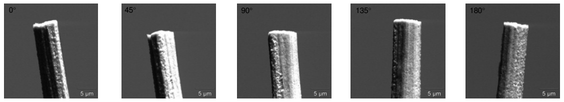
The entire setup is then encased to ensure filament capture once fracture occurs. Any fragments of the filament will then be used for SEM analysis. The case also ensures no air currents touch or disturb the filament setup before testing begins.



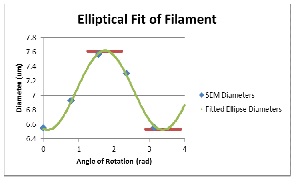
This is an image of a tested filament who's core has been purposefully unreacted. These cores are thought to weaken the filaments to mechanical fracturing. This image was taken at 15,000 times magnification to show the filament head at the point of fracture.

## Filament Area Calculations

After tensile testing, individual broken filament ends were removed from their fixtures and mounted in a SEM. Five images were taken as the filaments were rotated around their longitudinal axis. The perceived diameters at these five orientations were used to calculate the area of each filament by fitting an elliptical model to the data through a sin function.

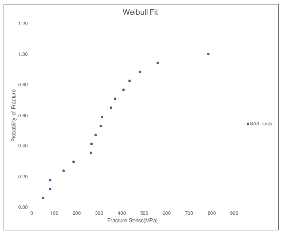


Five images taken at 45° increments of rotation around the longitudinal axis



Plot showing the close sin function fit to the filaments perceived diameter. This sin function is used to find the length of the major and minor axis (highlighted with red) of a conscribed ellipse whose area can be calculated.

## Fracture Stress Distribution



Plot showing the accumulated distribution of tests that have been performed and their respective fracture stress values calculated from tensile data and cross sectional area results.

As can be seen in the data plot, there are a wide range of values the filaments fracture at, with one group of points clustered around 150 and 300MPa. The presence of a Nb core reduces, on average, the fracture strength of a filament by **38%** and the strain to failure by **29%**. Future statistics of the filaments will help to build fracture prediction models and give design guidance for future development and manufacturing of these superconducting alloys.

## Acknowledgements

Blugold Fellowship Program and the ITER Organization for project funding
UWEC Material Science & Engineering Center for facilities use and support
Dr. Brian Mahoney (UWEC Geology) for use of the HF digestion lab

This research has been submitted for publication: M.T. Dylla, S.E. Schultz, and M.C. Jewell, "Fracture Strength Distribution of Individual Nb3Sn filaments," submitted for publication to IEEE Transactions on Applied Superconductivity, 22 January 2016.

April 27,28 2016 Celebration of Excellence in Research and Creative Activity