Post-Mortem Mechanical Investigation of ITER TF Conductor Samples After Heat Treatment and SULTAN Testing

china eu india japan korea russia usa

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Introduction

- **What issues are we addressing?**

❖ The ITER TF conductor can show performance degradation after electro-magnetic and thermal cycling.

❖ In this study we perform a post-mortem investigation of as-heat-treated and SULTAN-tested TF conductors to understand the basis for degradation in the cable cross-section.

- **What approach are we taking?**

❖ We use direct mechanical deconstruction and digital image analysis techniques to understand the mechanical impact of electromagnetic cycles on ITER TF superconducting cable-in-conduit conductors.

❖ We wish to identify a set of ideal operating conditions that will minimize the mechanical and electrical degradation of the superconductor.

❖ In this poster, we compare a **TF Insert (TFI) SULTAN tested** conductor with an **untested, heat treated** TF conductor.

Acknowledgements

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Procedure

1. Wire Analysis in Transverse Cross-Section

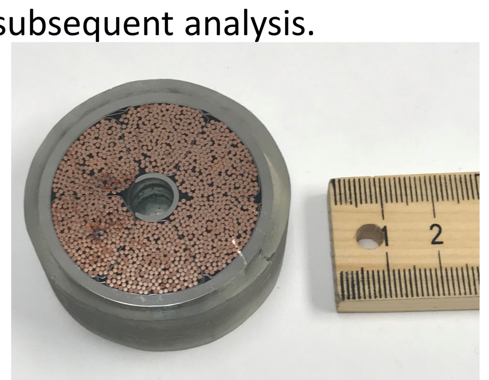
❖ To obtain a transverse cross-sectional image, the cable is filled with a conductive epoxy and mechanically cut into slices ("cookies") for preparation.

❖ Next, the cookie is polished until there the surface is free of scratches.

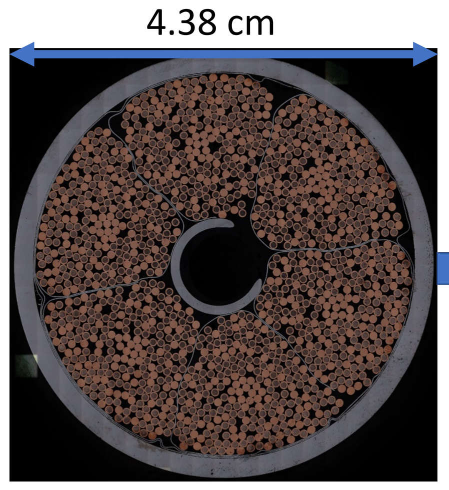
❖ Once polished, the sample is imaged using the a **scanning confocal laser microscope** to produce 400 individual images which are subsequently stitched using **FIJI** software.

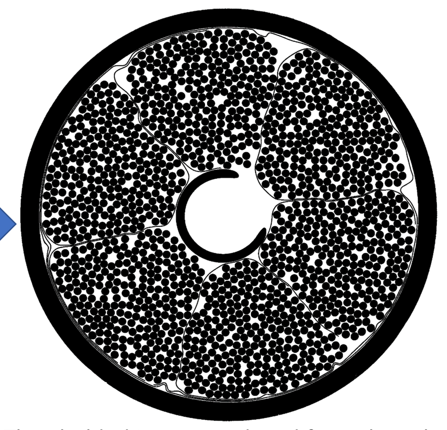
❖ From the stitched image we use FIJI to make a clear image threshold for subsequent analysis.

Cut length of a sample that has been filled with epoxy



"Cookie" that has been polished to a 0.05 micron finish





Thresholded image produced from the color image using FIJI

2. Dent Deformation

❖ To characterize the plastic deformation in the wires, we first disassembled a baseline conductor sample (10 cm) using **electrical discharging machining (EDM)** to section the conductor.

❖ We proceeded to separate individual wires based off the level of damage and region-based damage presented on the wire.

❖ We use **Laser Scanning Confocal Microscopy (LSCM)** to measure the cross-section and height of the dents.

3. Filament Cracking in Wires

❖ Filament crack analysis occurs through the same disassembly process, but with 3 cm sections of conductor instead of 10 cm.

❖ After the disassembly of the shorter conductor into individual wires, specific wires with deformation are chosen to be mounted, polished and imaged.

❖ A series of polishing steps are performed down to 0.05 colloidal silica in a vibratory polisher.

❖ Once polished, imaging was conducted using the LSCM.

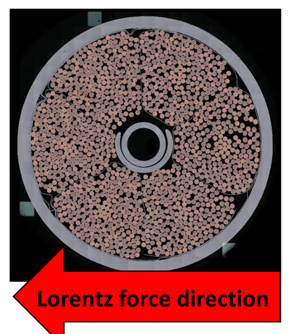
Evidence of Wire Movement and Damage from Cross-Sectional Images and Dent Analysis

Types of Degradation

❖ In this project, we look at several parameters to compare an **untested, heat treated sample** and a **fully tested sample (called TFI SULTAN)** for evidence of degradation as a result of the Lorentz force.

❖ In ITER TF conductors, the degradation behavior tends to stabilize with repeated electromagnetic (EM) cycling or thermal warm-up, cool-down (WUCD) cycling. However the behavior is less well understood when the EM and WUCD cycles are intermixed.

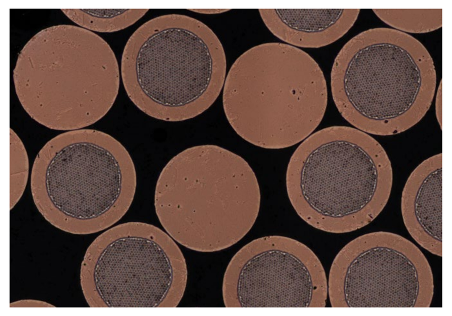
❖ By quantifying the various macroscopic and microscopic defects that occur during SULTAN testing, we hope to better understand the interplay of the EM and WUCD effects, and how each of these processes can lead to conductor performance degradation.



Visual Evidence of Damage

❖ Polishing the epoxy-impregnated conductor allows us to look for evidence of debris in the cable. Images comparing sections of the **heat treated** and **TFI SULTAN** samples are given below:

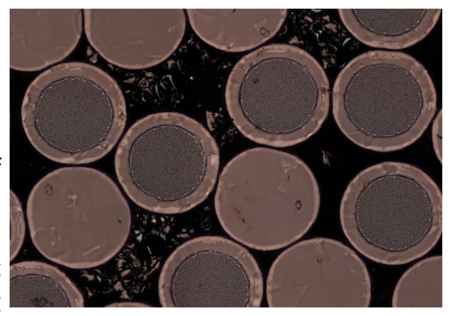
Heat Treated



The area between the wires of the heat treated sample is clear and free of debris.

In the TFI SULTAN sample, many smaller particles of copper and chromium can be seen between the wires. These likely exist as a result of the wires scraping against each other as they moved around during testing.

TFI SULTAN



Dent Deformation

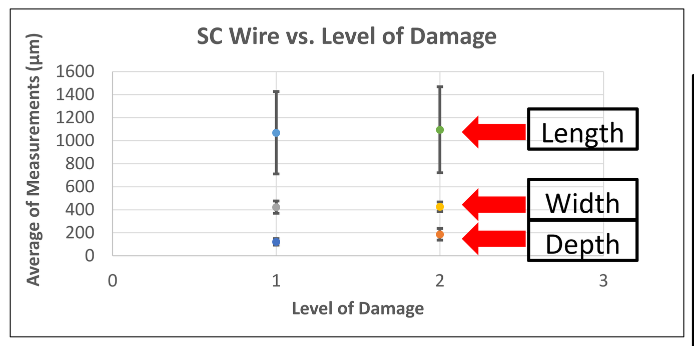
❖ Dents form in the wires during cabling and due to Lorentz forces. Here we attempt to identify the amount of visible damage that is due to testing.

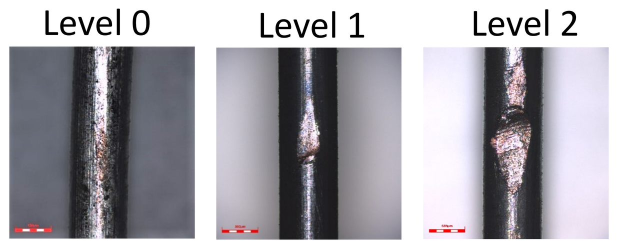
❖ The level of damage is determined through a 0 - 2 scale with 0 indicating no damage and 2 indicating extensive damage.

❖ Level 0 – No copper visible (Cr intact) with allowed possible chromium scratches

❖ Level 1 – Damage has penetrated the Cr in at least one location with visible copper

❖ Level 2 – Damage covers a wide length with a variety of dents or long copper scratches



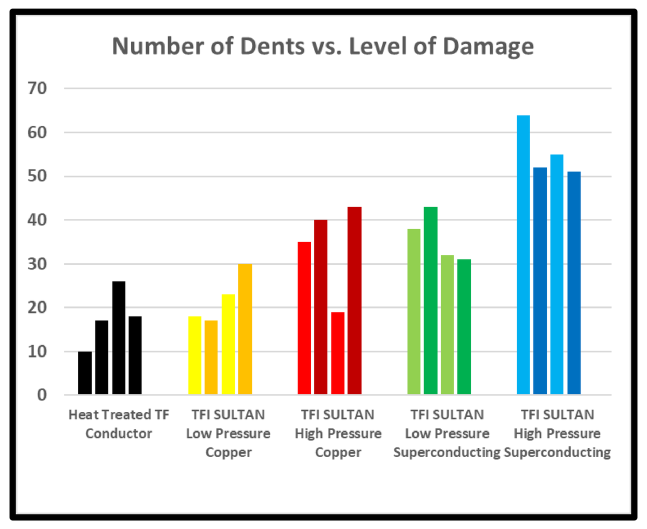


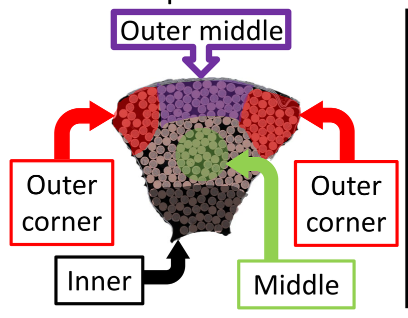
Key Result: The similarity in measurements suggest to only focus on level 2 wires for further analysis of cracked Nb_3Sn filaments.

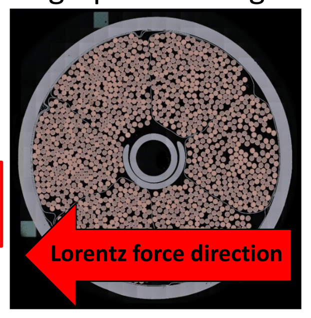
Dent Deformation Numerical Results

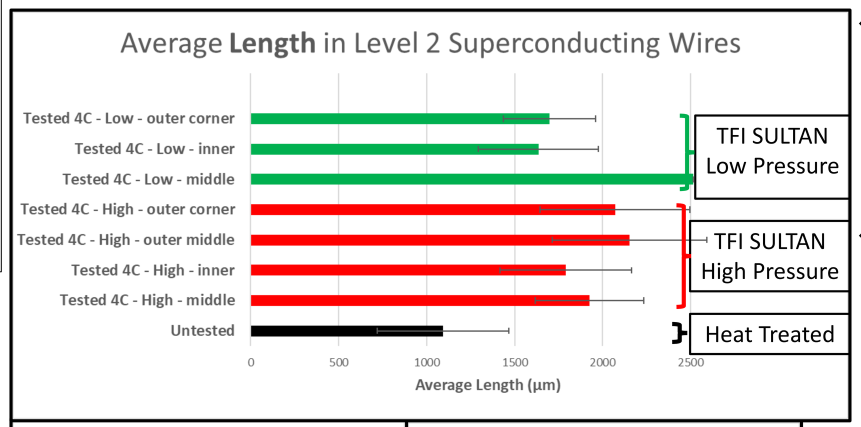
❖ The TFI SULTAN samples consistently show more wires exhibiting deformation compared to heat treated samples.

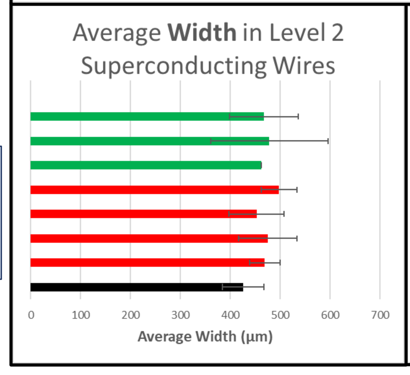
❖ For both Cu and SC wires, we found there to be greater than twice the amount of dents compared to the heat treated sample as shown in the graph to the right.

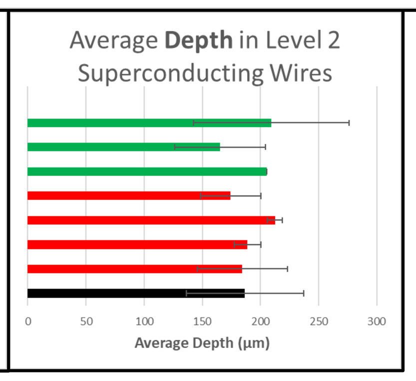












❖ The image above left shows the regions where wires were selected from the disassembled cable to observe deformation levels within the petal.

❖ To the left are measurements made regarding level 2 wires that show surface defects get longer (but not wider or deeper) after SULTAN testing.

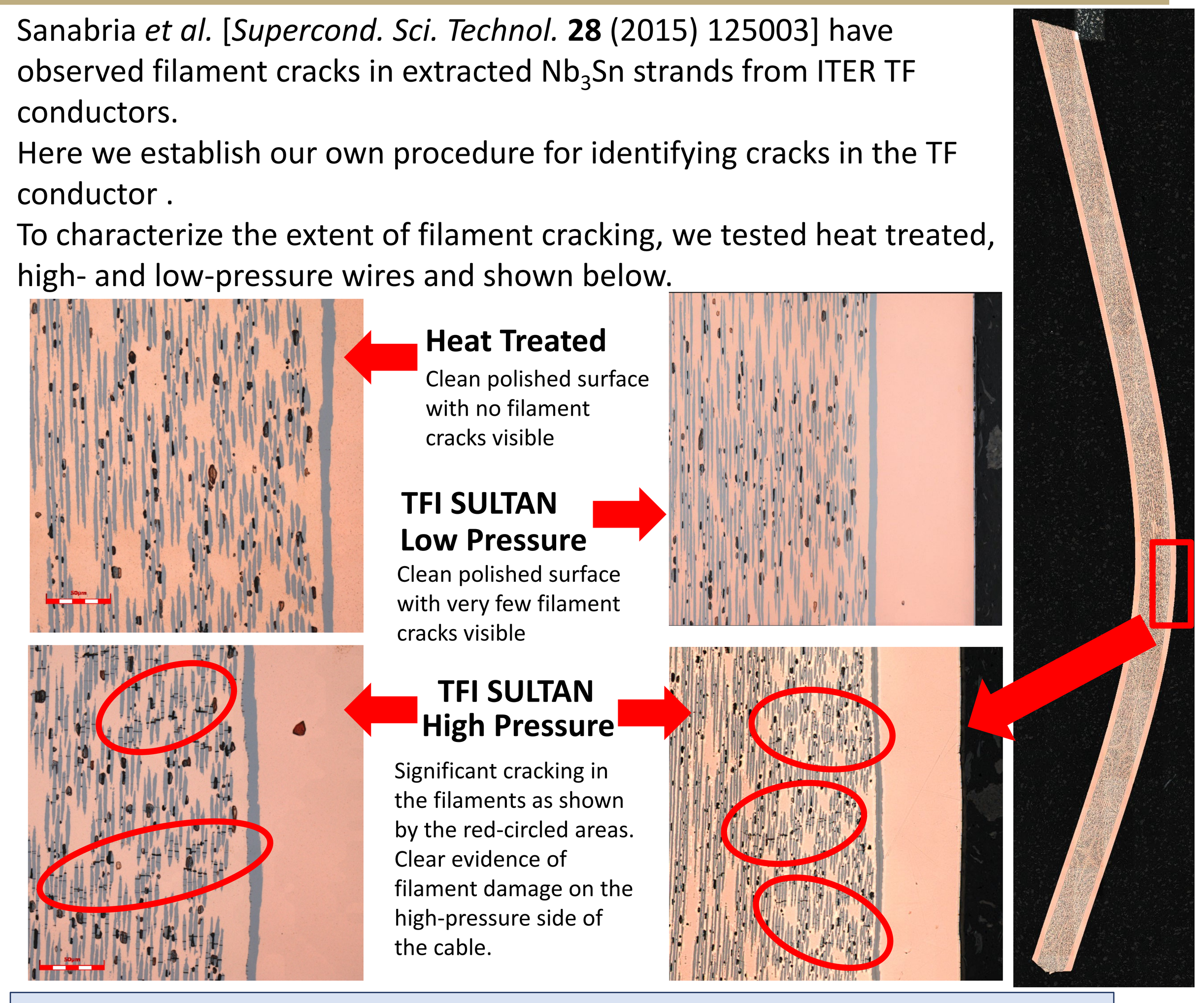
Key Result: The mechanical Lorentz force causes the surface defects to elongate but not deepen, suggesting that the primary motion during testing is wire rubbing rather than wires pressing against each other.

Filament Cracking

❖ Sanabria *et al.* [*Supercond. Sci. Technol.* **28** (2015) 125003] have observed filament cracks in extracted Nb_3Sn strands from ITER TF conductors.

❖ Here we establish our own procedure for identifying cracks in the TF conductor .

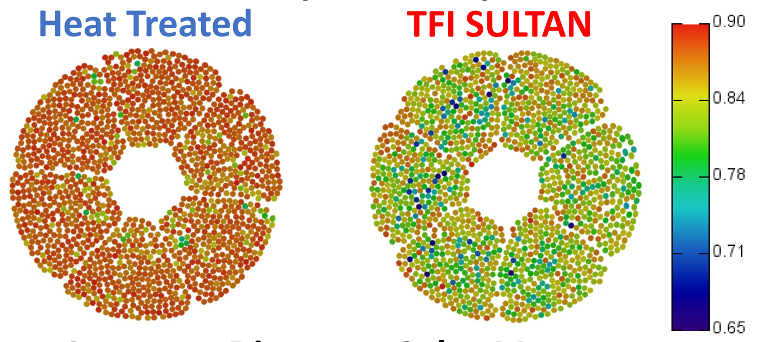
❖ To characterize the extent of filament cracking, we tested heat treated, high- and low-pressure wires and shown below.

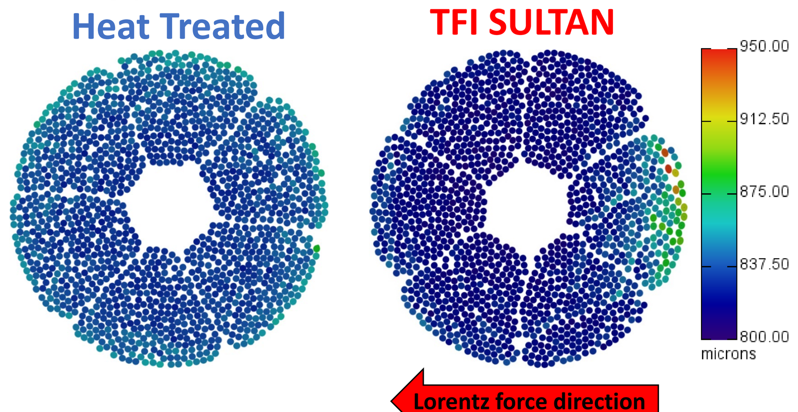


Key Result: Filament cracking occurs predominately in the bent regions of wires on the high-pressure side of the TF cable. Little to no filament cracking is found in the heat treated and low pressure wires.

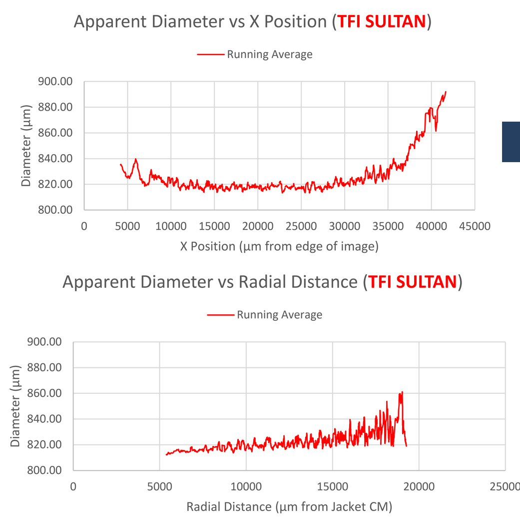
Wire Movement and Shape

❖ Our digital image analysis can detect changes in the wire cross-sections before and after SULTAN testing. For example, the tested conductors have lower wire circularity (possibly a result of the debris observed above), and the low-pressure side of the tested conductor shows greater strand bending (measured here by apparent diameter).





❖ The graphs below show a comparison of the apparent diameters of the wires as a function of the X position and Radial Position.



Key Result: 1. The circularity of the wires degrades after extensive testing.
2. Wires shift during testing causing wires on the low pressure side to tilt/bend, which is shown as a change in their apparent diameter.

Conclusions and next steps

Conclusions

- Our destructive examination and image analysis techniques provide clear differentiation between the heat-treated and TFI SULTAN conductors for ITER.
- Filament cracking is localized on the high pressure side of the cable, but there is significant strand bending on the low pressure side.
- Visible debris is generated during testing and is measured by the circularity of the wire surfaces.

Next Steps

- This work will be continued with additional SULTAN samples that have undergone various testing envelopes, to understand the role of EM and WUCD cycling in degrading the cable performance.
- We will also extend the digital image analysis techniques to study Nb_3Sn strand movement during the warming/cooling process, using tomographic images of the TF CICC.

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