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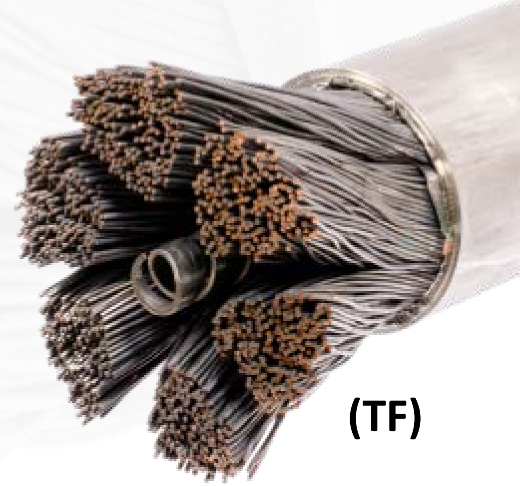
To Slip or Not to Slip!

The Importance of Strand Surface Roughness in Long Twist Pitch Conductors

(CS)



(TF)

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[1] Applied Superconductivity Center, NHMFL, Florida State University, Tallahassee, FL 32310, USA

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Special thanks to **Nicolai Martovetsky** (US-ITER), **Matthew Jewell** (ITER, now at UW Eau-Claire) and **Ian Pong** (ITER, now at BNL) for fruitful discussions.
The CICCs were provided by courtesy of **Pierluigi Bruzzone** (Plasma Physics Research Center) with agreement from the Japan Atomic Energy Agency (**JAEA**), ***ITER Russia*** and **US-ITER**. *The views and opinions expressed here do not necessarily reflect those of the **ITER organization***. This work was supported by the ITER Organization under purchase order ITER/CT/11/4300000511, US –ITER under contract 6400011187, the **US Department of Energy** Office of Fusion Energy Sciences under award DE-FG02-06ER54881 and the **State of Florida**.

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Outline

- **Introduction:**
  - Cable-in-Conduit Conductors (CICC)
  - SULTAN test results

    Russian federation conductors are the only Long Twist Pitch (LTP) conductors with a T_{cs} increase
- **Strain state in a CICC.**
  - Dominant stresses **before** Lorentz loading
  - Possible **strain rearrangements** when Lorentz force is cycled
- **SULTAN samples deconstructed**
  - Transverse movement, strain changes and T_{cs} changes.
- **The difference of the Russian strand.**
- **A hypothesis… To slip or not to slip…**

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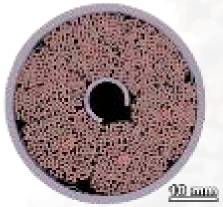
Introduction – The Cable-in-conduit Conductors

Toroidal Field (TF)

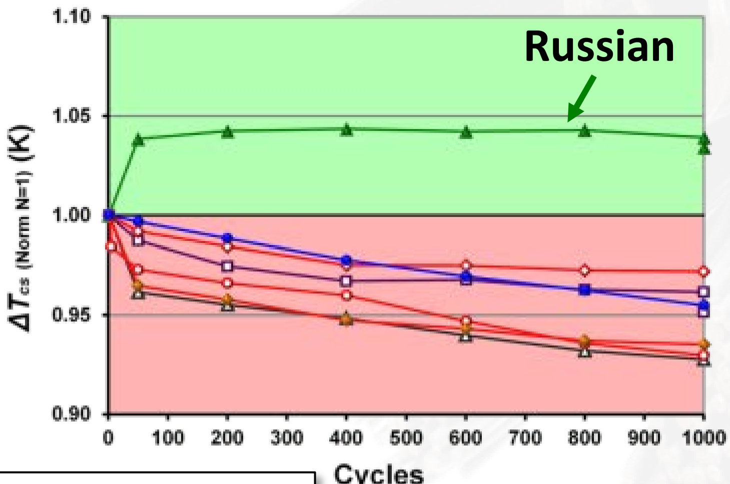


~900 Nb_3Sn strands

(1000 cycles)

Long twist pitch

Starting at 45 mm



Courtesy of A. Devred

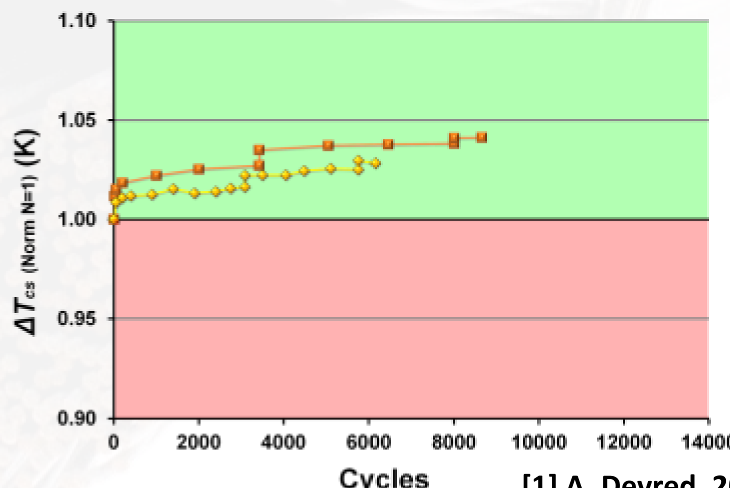
Central Solenoid (CS)

~500 Nb_3Sn strands

(60,000 cycles)

Short twist pitch

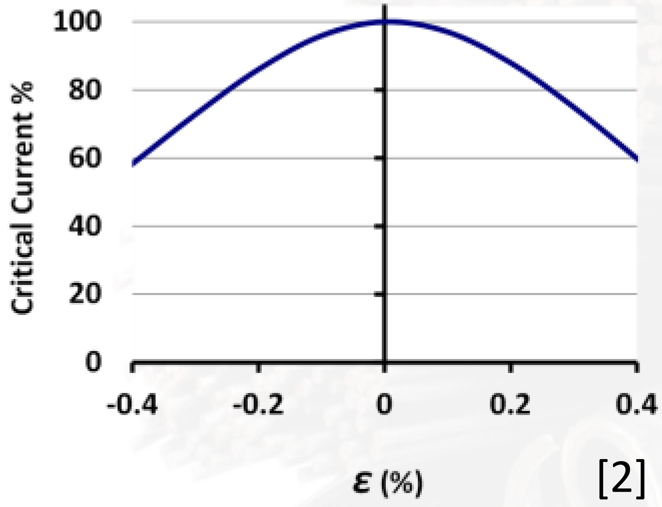
Starting at 22 mm

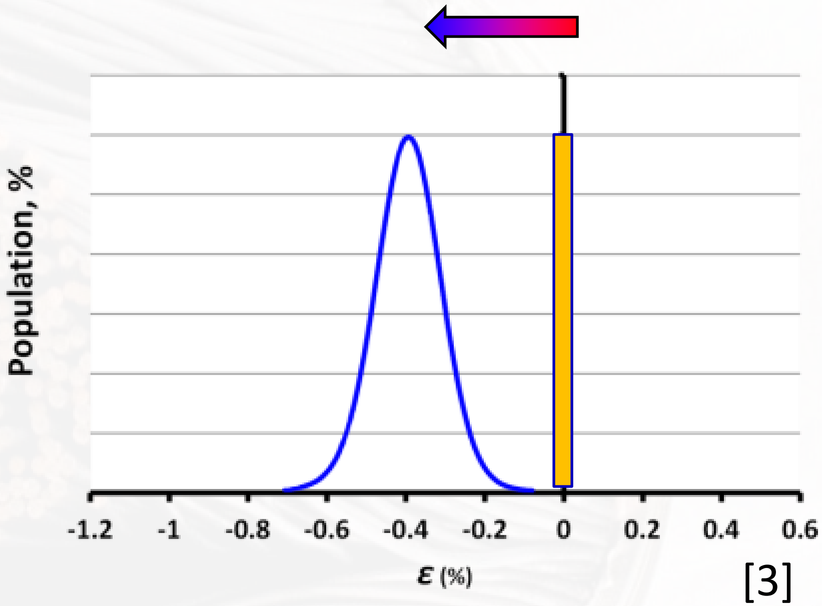


[1] A. Devred, 2014

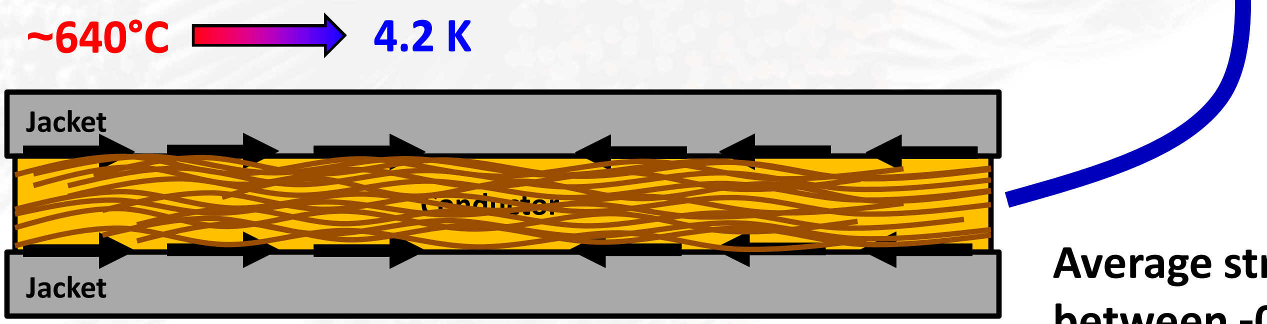
Strain state in an ITER CICC before Lorentz Force Loading

Nb_3Sn is very strain dependent





Compression from the jacket is dominant



Average strain state: between -0.4% to -0.6% [3,4,5]

[2] Godeke, **2009** [3] Calzolaio **2014** [4] N. Mitchell, **2007,** [5] Bajas, **2010.**

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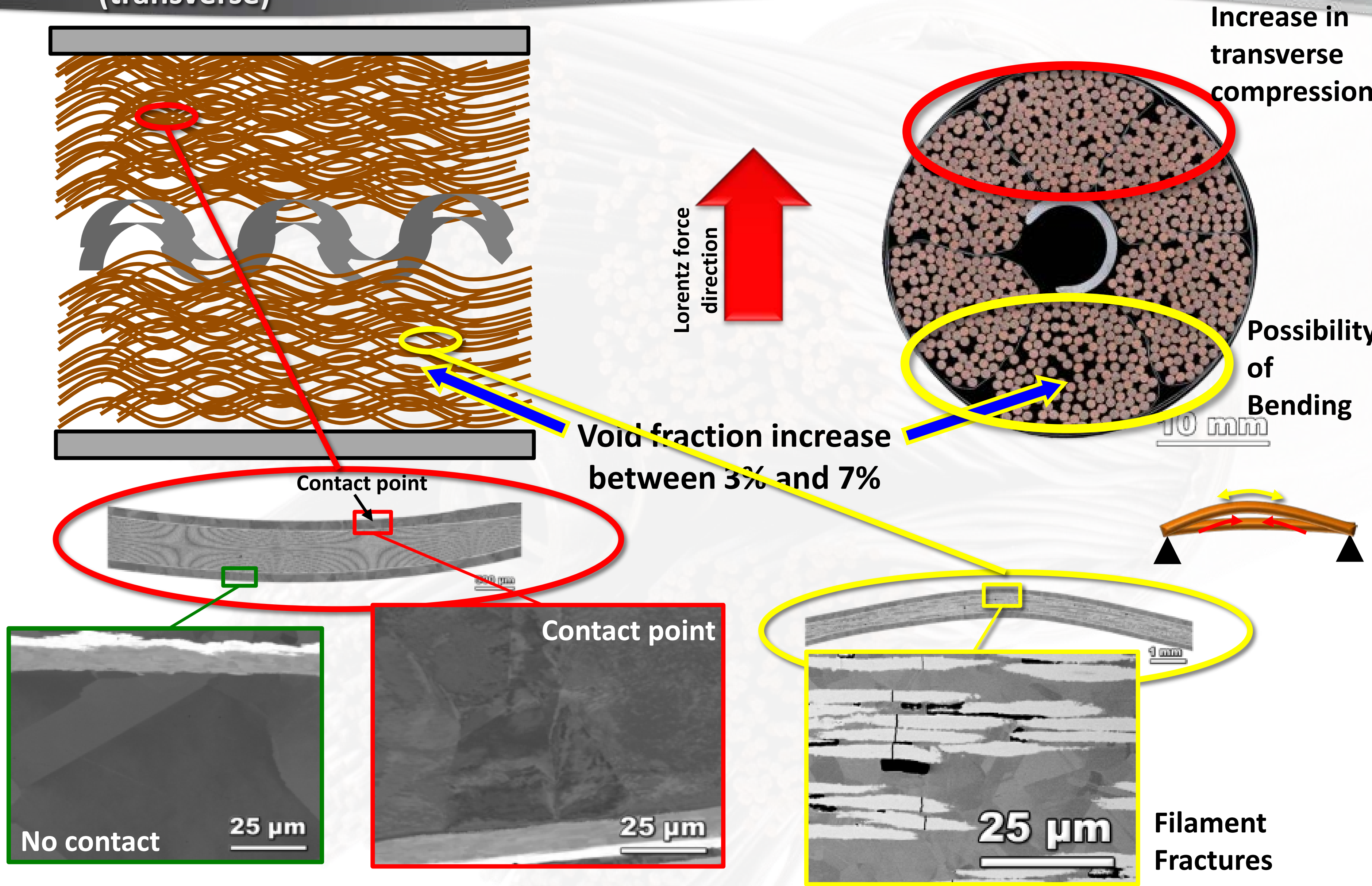
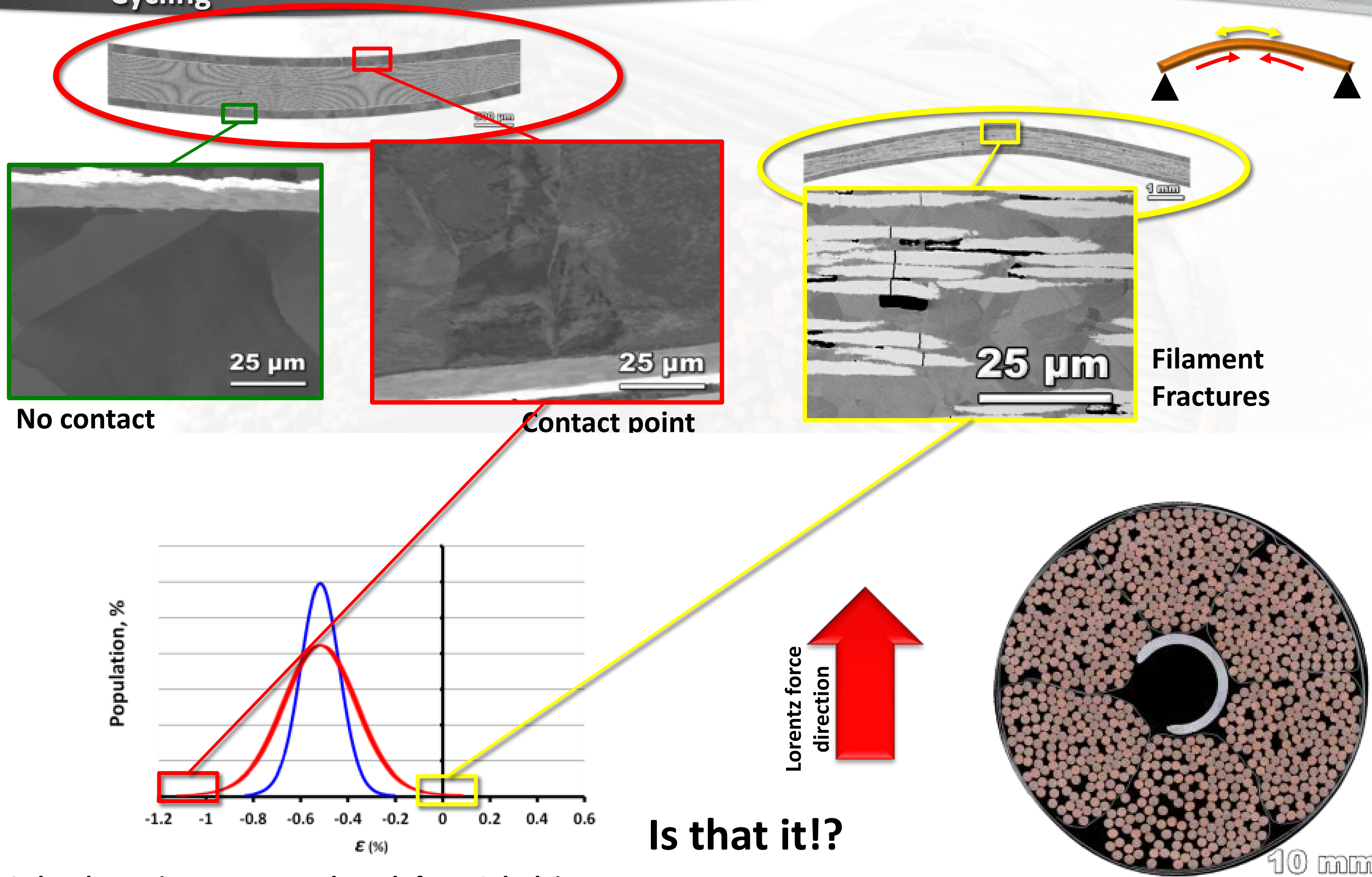
Possible Strain re-Arrangements in a CICC After Electromagnetic Cycling (transverse)



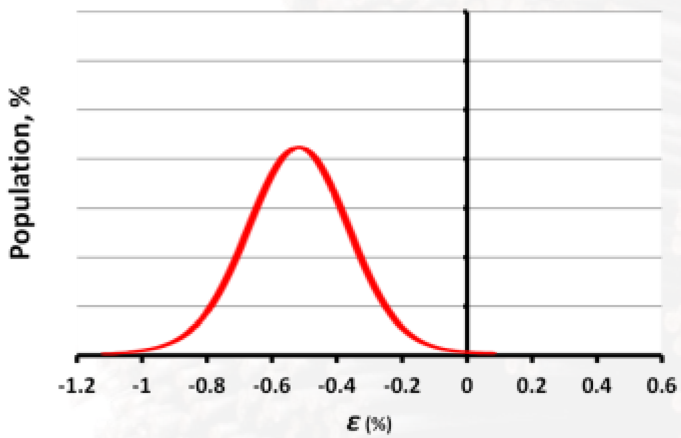
Possible Transverse Strain re-Arrangements in a CICC After Electromagnetic Cycling



Is that it!?

Only schematic, not an actual result from Calzolaio

Possible Longitudinal Strain re-Arrangements in a CICC After Electromagnetic Cycling

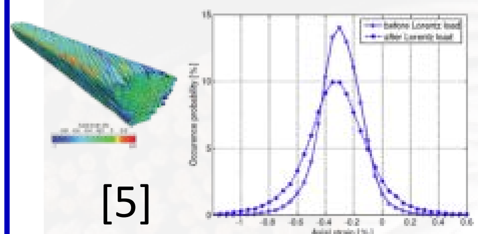


Only schematic, not an actual result from Calzolaio

- Friction controlled longitudinal movement may be an artifact of the SULTAN testing [6].

- The impact of this overall shift on T_{cs} should be larger than the broadening of the tails obtained by transverse movement.

Problems with longitudinal movement



[5]

Extremely difficult to model

Transverse cross sections can't provide this information

[6] A. Devred, **2012.** [5] Bajas, **2010.**

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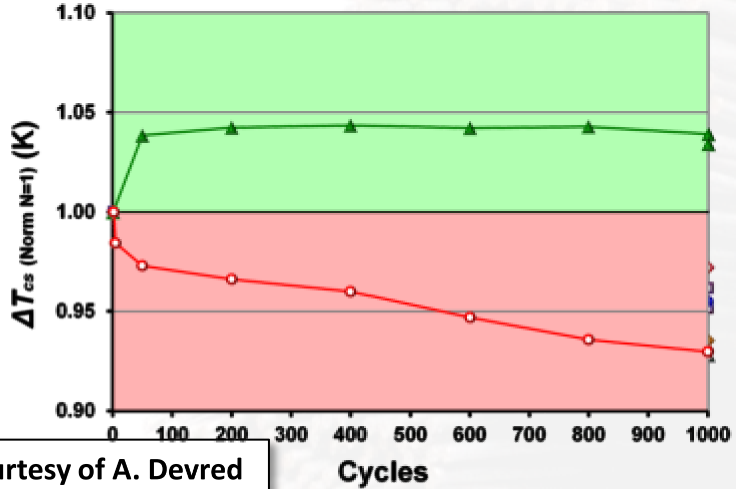
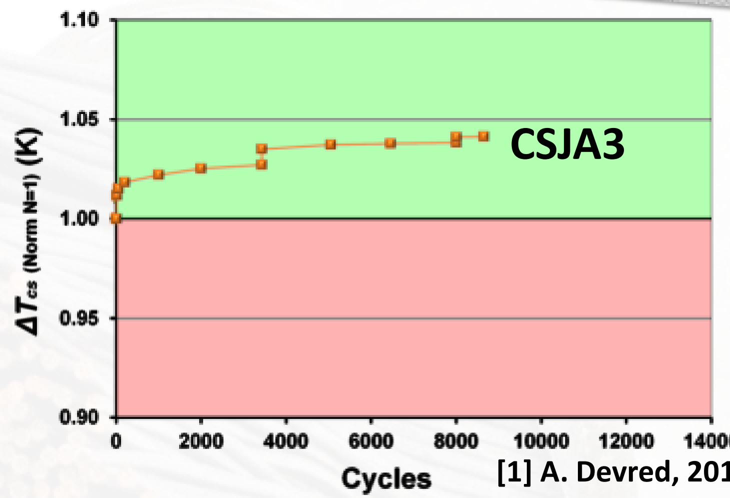
Samples Studied



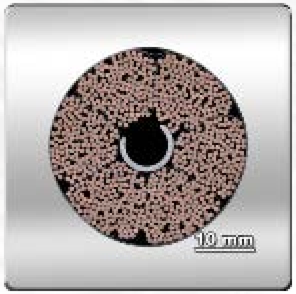
Courtesy of A. Devred



[1] A. Devred, 2014

TFEU5

TFRF4



CSJA3

TF Long twist pitch

CS Short twist pitch

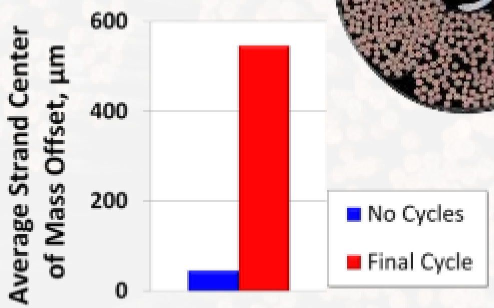
Parameters to Look After

1) Change in T_{cs}?

Increase?

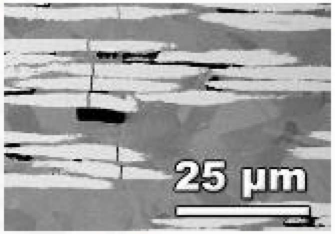
Decrease?

2) Transverse Movement?

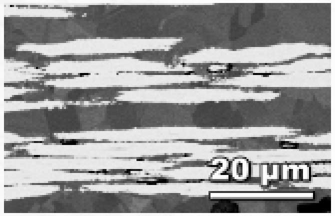


3) Cracks in outliers?

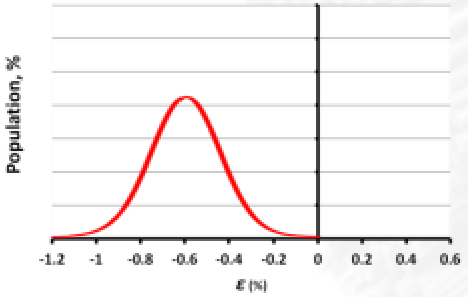
Yes?



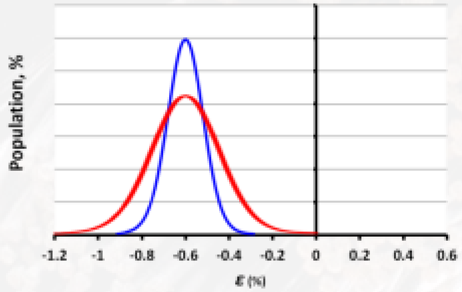
No?



4) Shifting of the ε Distribution?



5) Broadening of the ε Distribution?



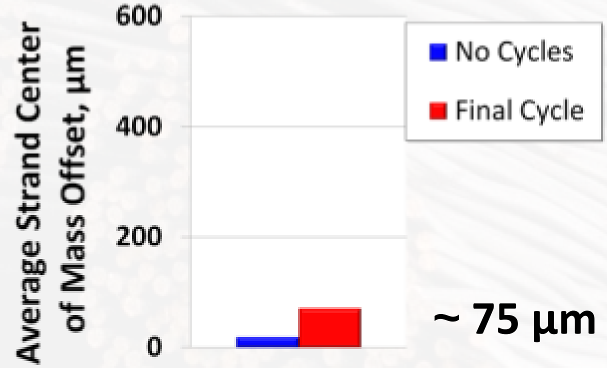
CS Short Twist Pitch Conductor experiences only longitudinal effects

CSJA3

Short Twist Pitch

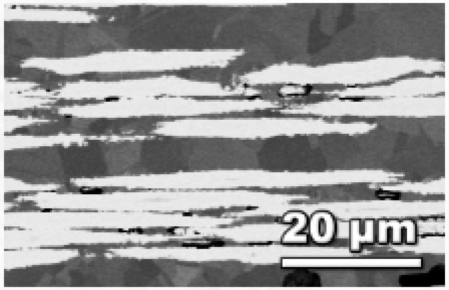
T_{cs} Increase

Very Low Transverse Movement



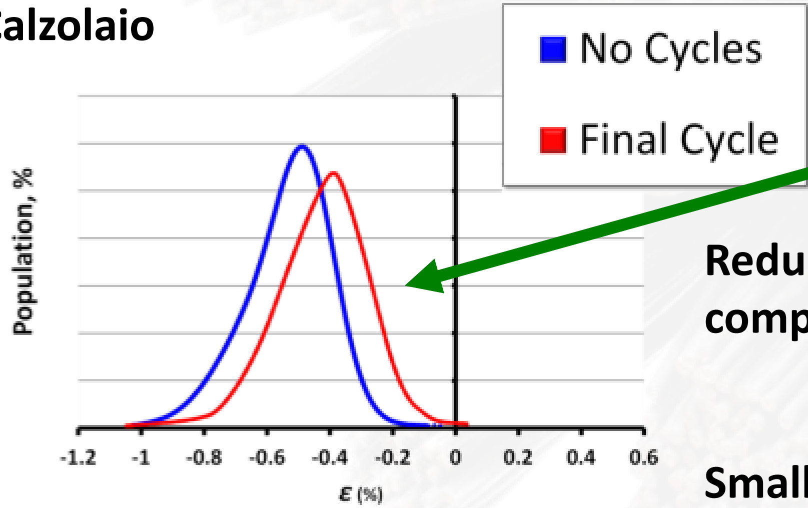
~ 75 µm

No Cracks



Sanabria

Calzolaio



Reduced compression

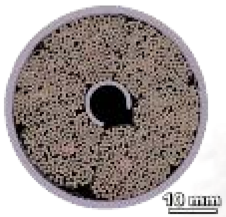
Small broadening

[3] Calzolaio **2014** (for CSJA5 with identical configuration)

- Jacket slippage?
- Given the tight entanglement of this sample I propose YES!

Russian Conductor experiences transverse effects and beneficial longitudinal effects

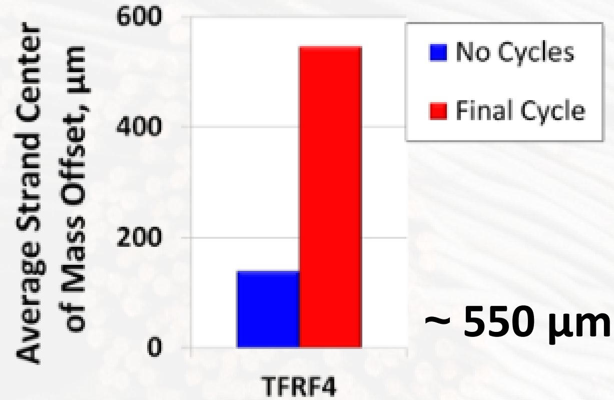
TFRF4



Long Twist Pitch

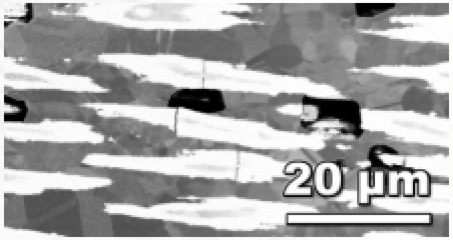
T_{cs} Increase

High Transverse Movement



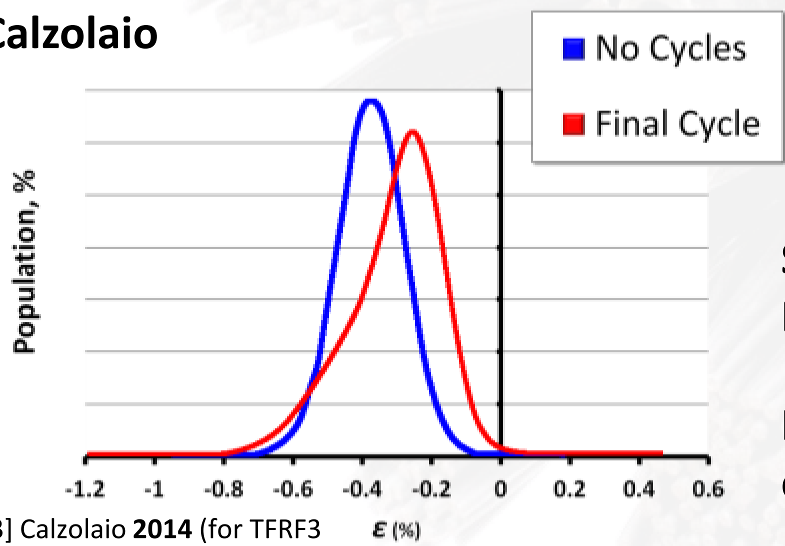
~ 550 µm

Cracks



Sanabria

Calzolaio



[3] Calzolaio **2014** (for TFRF3 with identical configuration)

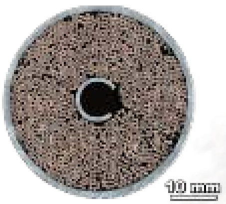
Significant Broadening

Reduced compression

- **Beneficial jacket slippage**
- **Detrimental transverse movement due to lack of entanglement (LTP)**

Other LTP Conductors experience transverse effects and detrimental longitudinal effects

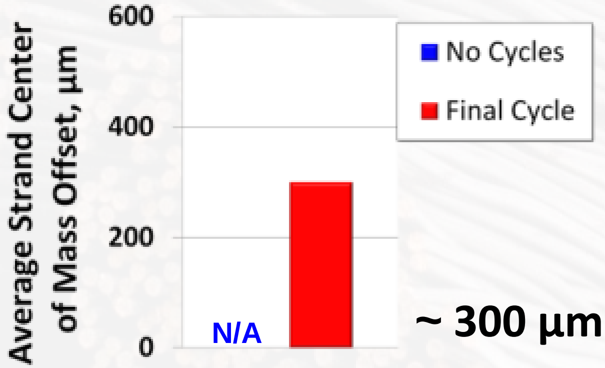
TFEU5



Long Twist Pitch

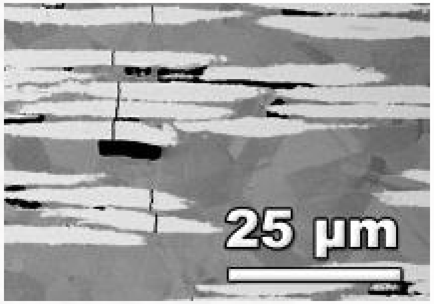
T_{cs} Decrease

Moderate Transverse Movement



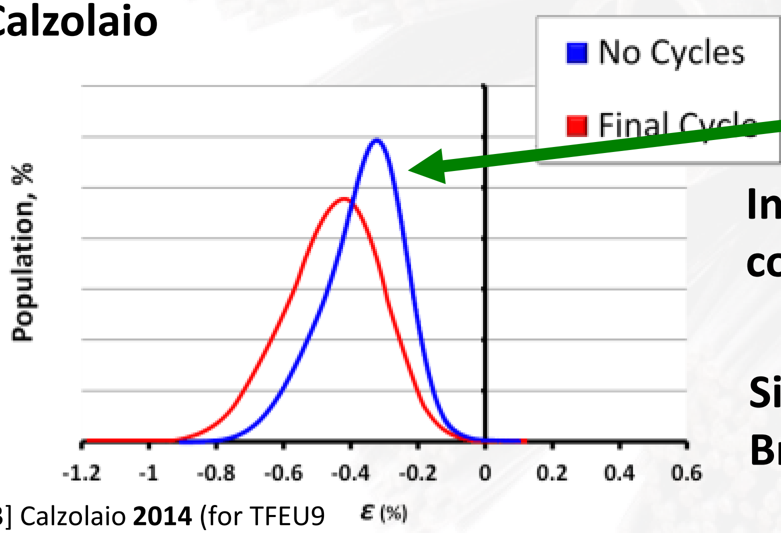
~ 300 µm

Cracks



Sanabria

Calzolaio



Increased compression

Significant Broadening

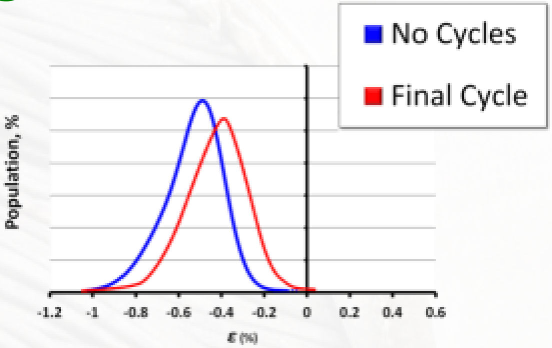
[3] Calzolaio **2014** (for TFEU9 with identical configuration)

- **Detrimental longitudinal movement?**
- **Detrimental transverse movement due to lack of entanglement (LTP)**

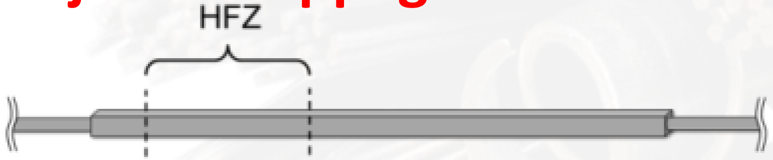
The Million Dollar Question

The STP sample hinted us that jacket slippage is beneficial.

Behaves like a single unit therefore a compression decrease should come from the jacket

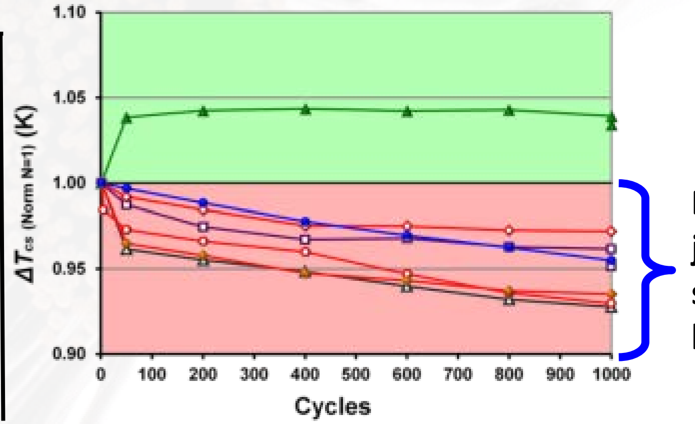


But jacket slippage is known to happen in LTP conductors as well.



[6] Nabara, **2012**. [7] Hemmi, **2013**. [8] March, **2013**.

There was less residual strain in the jacket of the High Field Zone than the Low Field Zone [6,7,8].



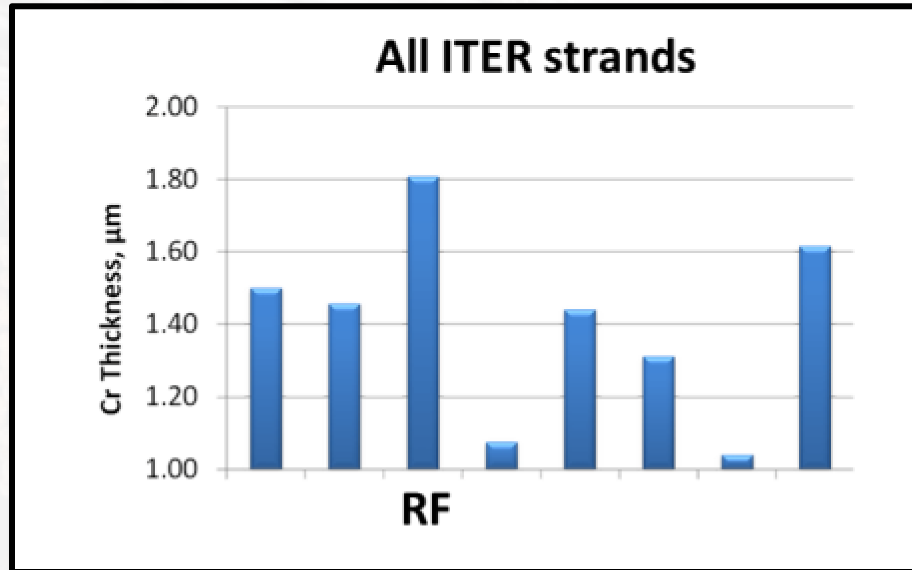
Evidence of jacket slippage has been found

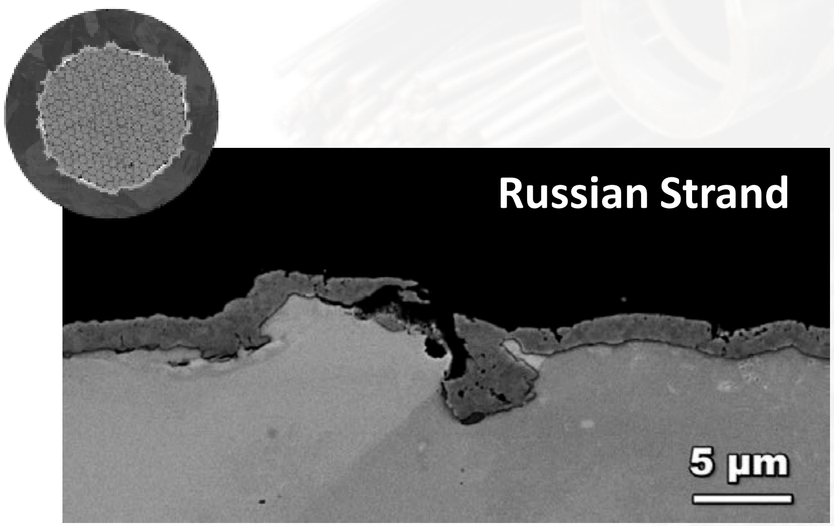
What is counteracting the effects of jacket slippage in LTP conductors?!

Could it be happening within the strands?

The Russian strand has a much rougher surface than any other ITER strand

- **An unusual chromium coat was observed**





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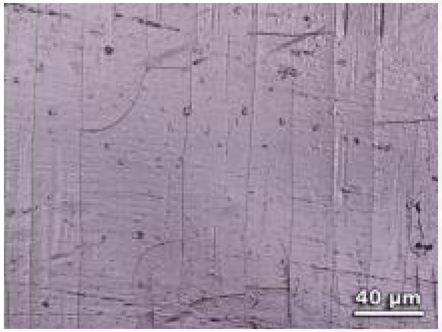
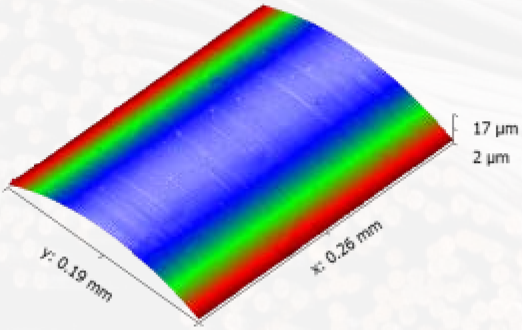
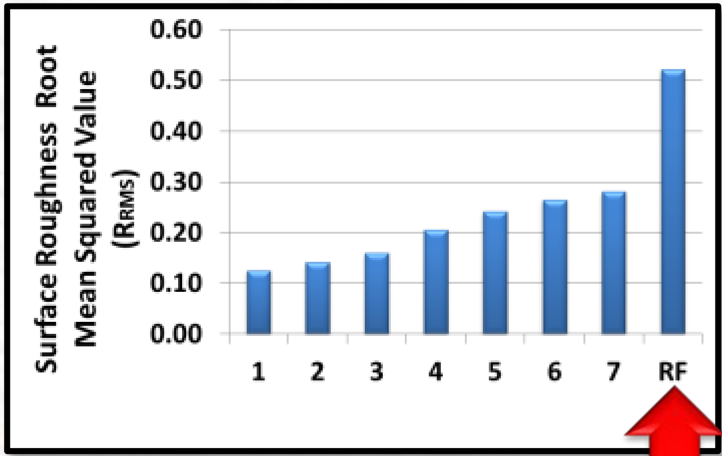
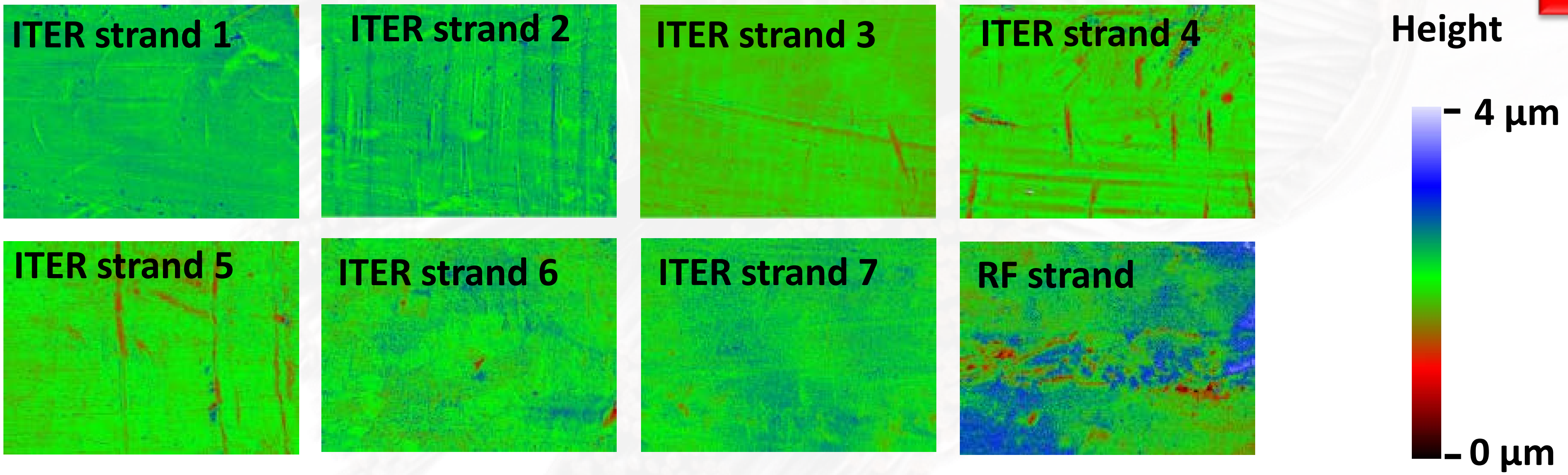
The Russian strand has a much rougher surface than any other ITER strand

- **Using an open source software [9] a surface roughness parameter [10] was obtained.**





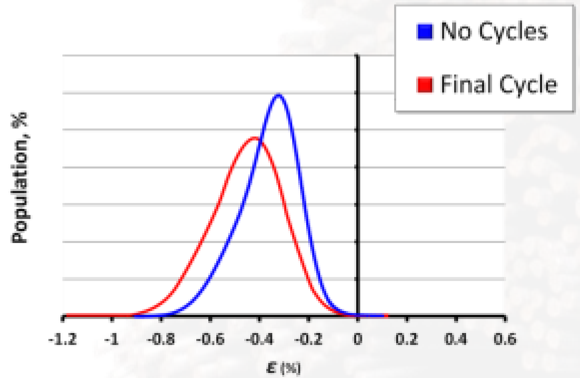




[9] http://sourceforge.net/projects/gwyddion/?source=dlp
[10] D. Whitehouse, **2002**.

Strand 5 = CSJA3
Strand 7 = TFEU5

Slip & Lock Hypothesis

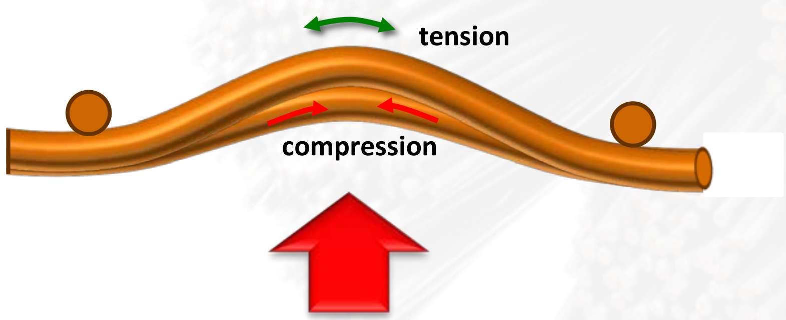


- **The surface roughness differences suggest a possible mechanism that originates at the contact points.**

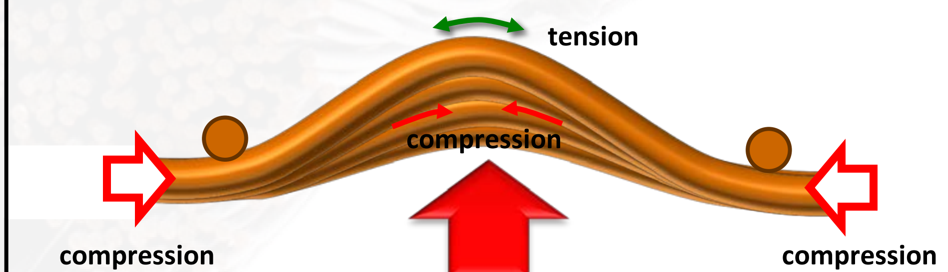
- **Consider a single strand with two contact (pivot) points**

Slip & Lock mechanism enabled by a low surface roughness

If there is NO inter-strand slip



If there is inter-strand slip



Conclusion

Facts:

- Transverse movement is not the main degradation mechanism.
- Jacket slippage (*i.e.* compression relief) is beneficial.
- There is a secondary mechanism which degrades LTP conductors.
- The RF strand has a significantly higher Cr surface roughness.

Hypotheses:

- A slip & lock mechanism seems to be responsible for the degradation of LTP conductors.
- This deleterious mechanism could be prevented by increasing the surface roughness of the strands.

References and Acknowledgments

References

1. A. **Devred**, *Supercond. Sci. Technol.*, vol. 27, no. 4, p. 044001, Apr. **2014**.
2. A. **Godeke**, et. al., IEEE Transactions on Applied Superconductivity, vol. 19, no. 3, pp. 2610–2614, Jun. **2009**.
3. C. **Calzolaio** and P. Bruzzone, *IEEE Transactions on Applied Superconductivity*, vol. 24, no. 3, pp. 1–4, Jun. **2014**.
4. N. **Mitchell,** *Supercond. Sci. Technol.*, vol. 20, no. 1, p. 25, Jan. **2007**.
5. H**. Bajas**, et. al., *IEEE Transactions on Applied Superconductivity*, vol. 20, no. 3, pp. 1467–1470, **2010**.
6. Y. **Nabara**, et. al., I*EEE Transactions on Applied Superconductivity*, vol. 22, no. 3, pp. 4804804–4804804, Jun. **2012**.
7. T. **Hemmi**, et. al., *Superconductor Science and Technology*, vol. 26, no. 8, p. 084002, Aug. **2013**.
8. S. A. **March**, et.al., *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, pp. 4200204–4200204, **2013**.
9. http://sourceforge.net/projects/gwyddion/?source=dlp
10. D. **Whitehouse**, "*Surfaces and Their Measurement*", D. Whitehouse, Ed. Oxford: Kogan Page Science, **2002**.

Acknowledgments

- Special thanks to **Nicolai Martovetsky** (US-ITER), **Matthew Jewell** (ITER, now at UW Eau-Claire) and **Ian Pong** (ITER, now at BNL) for fruitful discussions.
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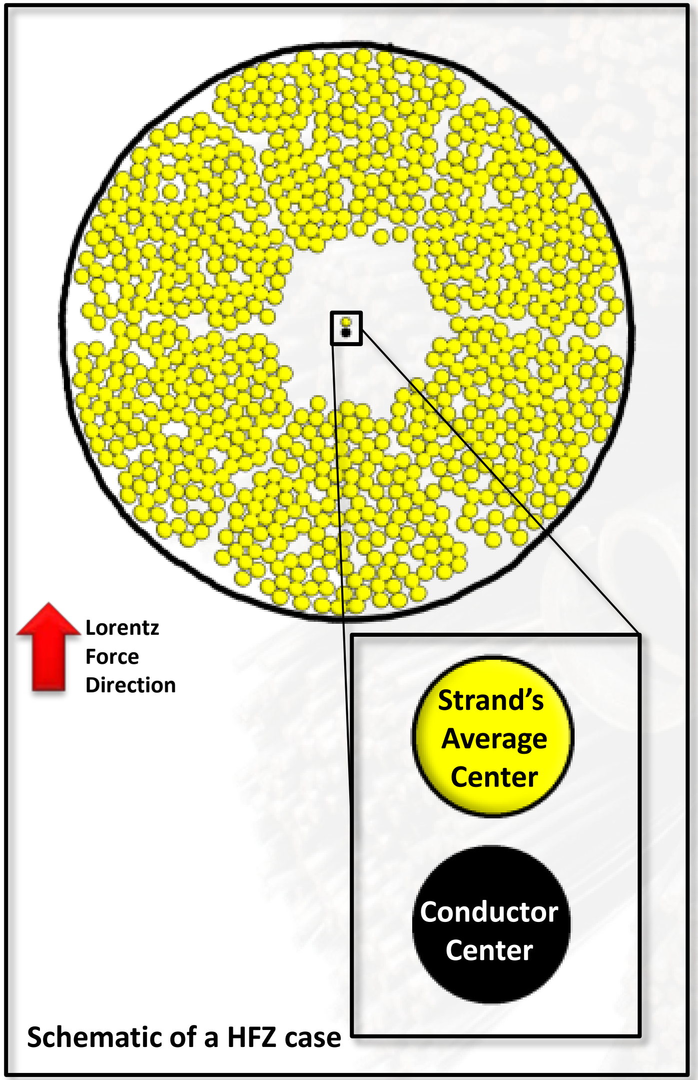
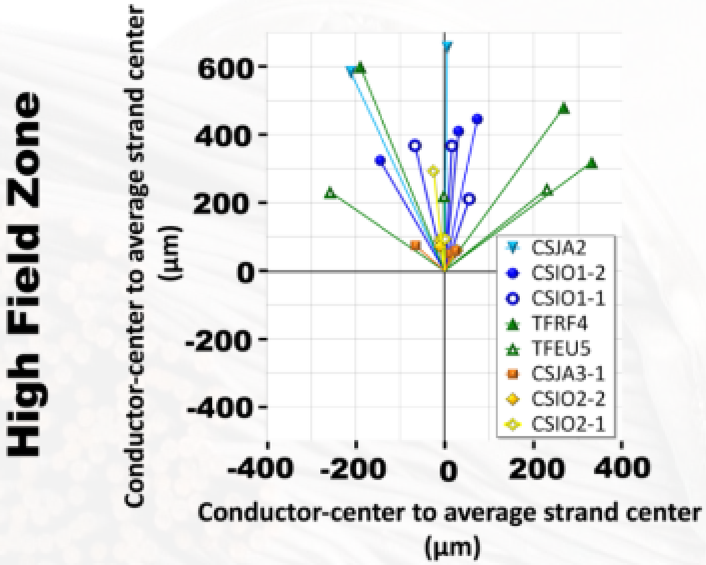
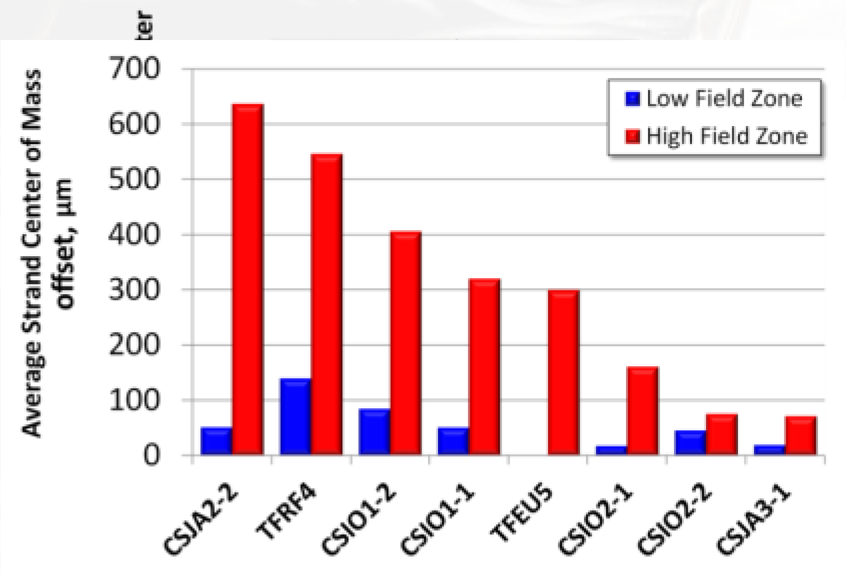
Appendix

Center of mass movement of several conductors

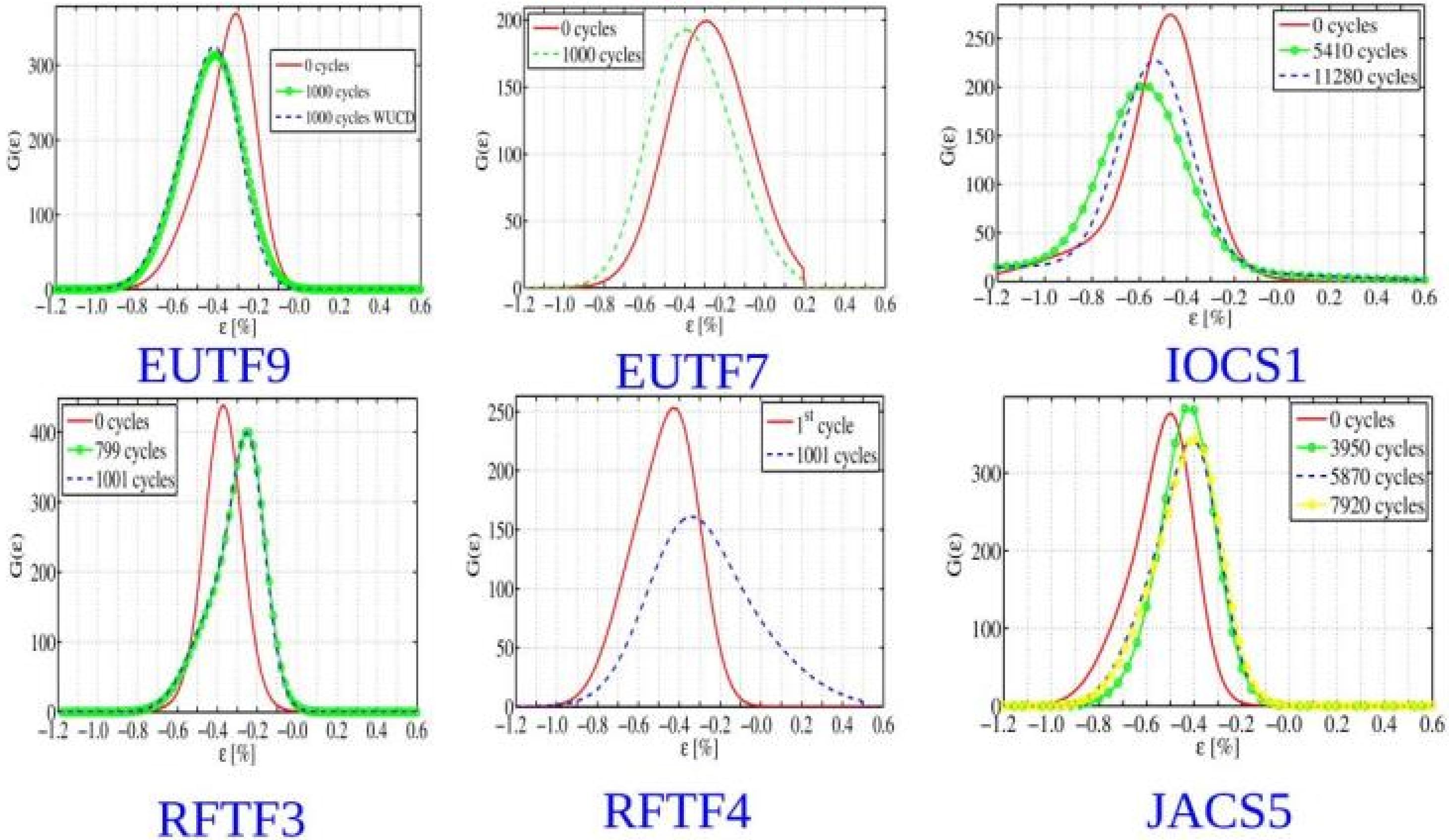






Calzolaio's Results presented at MT-23

ε distributions inferred from the magnetic measurements



CRPP

Ciro Calzolaio, MT23, Boston- MA, July 18th 2013

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Jacket strain measurements

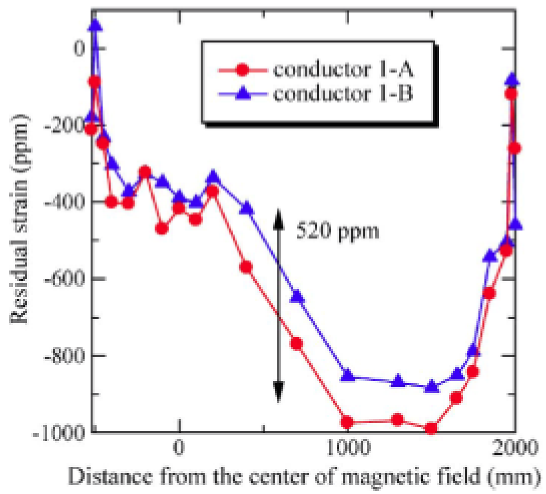


Fig. 7. Longitudinal residual strain distribution of sample 1 after the test.

[6] Nabara, **2012**.

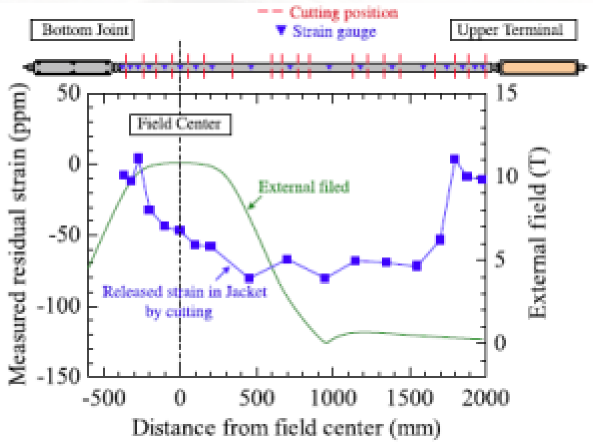


Figure 9. Residual strain on the jacket after cutting of the CSJA01 L at RT and the background field distribution of the SULTAN facility.

[7] Hemmi, **2013.**

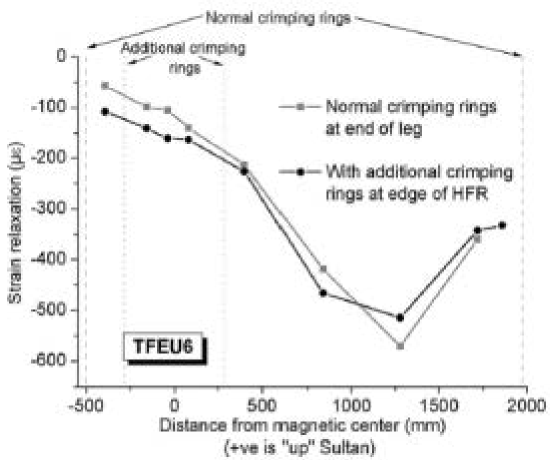


Fig. 6. Jacket strain relaxation of the two TFEU6 legs after test in SULTAN, cutting by spark erosion, and removal of the cable bundle. Presented strain is the average of four gauges at each location.

[8] March, **2013**.

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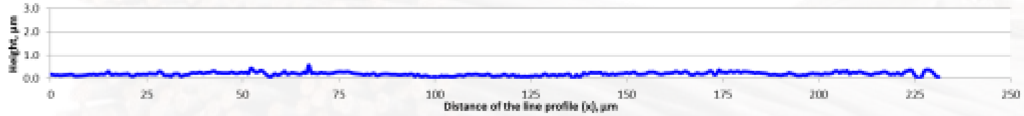
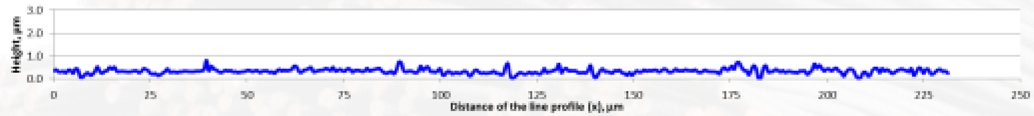
Two-dimensional profiles of strand surfaces

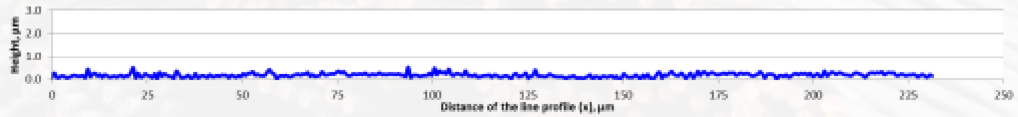
ITER strand 1



ITER strand 2

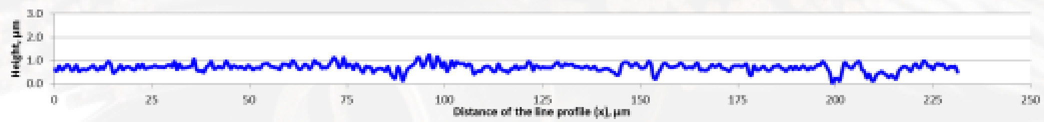


ITER strand 3

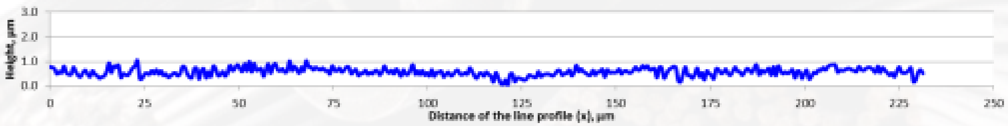


ITER strand 4

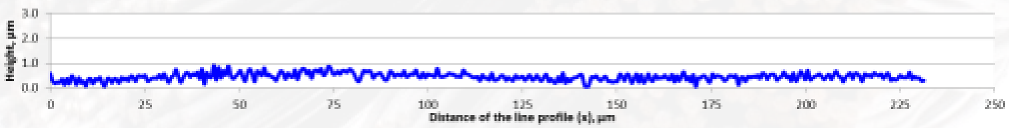
ITER strand 5



ITER strand 6



ITER strand 7



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