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Review of Scientific Results Obtained During Production of ITER TF and PF Conductors in Russia

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Outlines

- Introduction
- Rotation and untwisting
- Stability at SULTAN test and micrography
- RRR statistical study
- Hydraulic study
- More studies
- Final remarks
- References

Introduction: What ITER is for us

- **ITER was not only production** and delivery of high-tech superconductors
- It was the **great scientific and technological challenge** in development of tricky technologies in many aspects and directions
- It was **great management school** to cooperate in international society- sometimes in wavy and stormy conditions
- It also permitted us **to get many interesting scientific results**

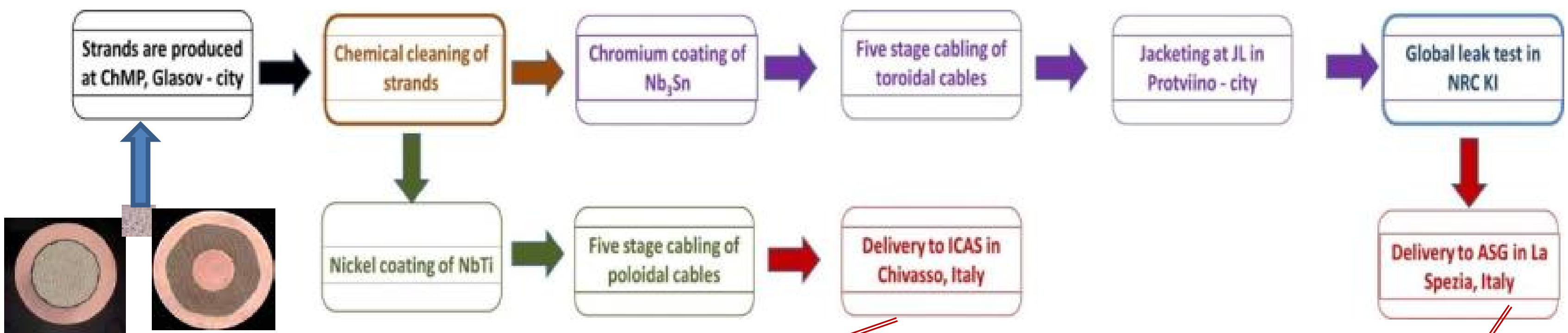
Science in ITER

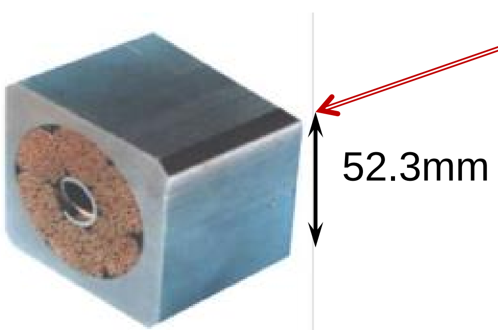
- Besides technology and production developments, a lot of R&D scientific studies have been performed during ITER works.
- Most of them were **to improve technologies or to understand and to describe some phenomena** observed during production processes.
- In this review we are presenting just some of them.

Introduction: What ITER superconductors are for RF

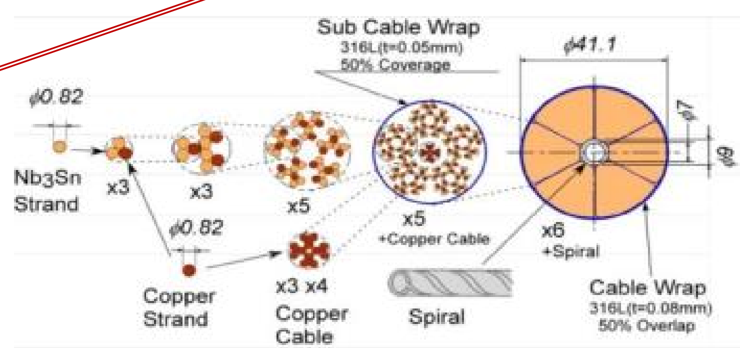
The high-tech technological complex to produce PF cables for both the Russian Federation and European parts and TF conductors for RF part have been built and fully certified for PF cables and TF conductors production

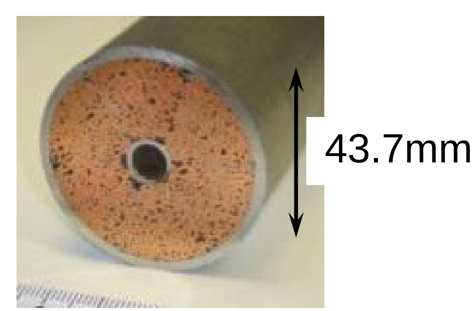
General technology route of TF conductors and PF cables in RF





PF conductor





TF conductor

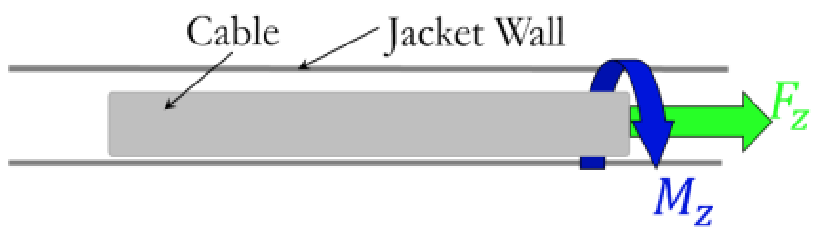
Introduction: What could happen with superconductor during manufacturing

- Wires production – characterization and verifications of $J_c(B,T)$
- Electro-chemical cleaning surface of NbTi and Nb_3Sn strands – *change of RRR;*
- NbTi –Ni coating, Nb_3Sn – Cr coating – *change of RRR, properties of surface*
- Cabling – *mechanical stresses; change of RRR;*
- Jacketing – *rotation and untwisting; mechanical stresses; AC loss could change*
- Global leak test – *hydraulic behavior*
- Heat treatment for TF conductors – *reduction of RRR – change of stability;*
- Cycling test at high field at SULTAN Facility – *change of T_{cs}; change of RRR, AC losses*

Science in ITER

Rotation and untwisting

- Cable rotation during insertion could led to untwisting of a cable head with possible increase of AC losses
- The model has been developed to describe rotation and untwisting



$$\theta(A) = \left(\frac{2A}{\frac{1}{A}\cdot\sqrt{r_0^2 + r_{sp}^2\cdot(A^2-1)} + r_{sp}} \sqrt{\frac{L_0^2}{h_0^2 A^4} - \frac{1}{4\pi^2}} + \frac{1}{h_0} \right) 2\pi$$

$$h(A,\theta(A)) = \frac{A^2 \cdot 2\pi z}{2\pi z - \theta(A) h_0}$$

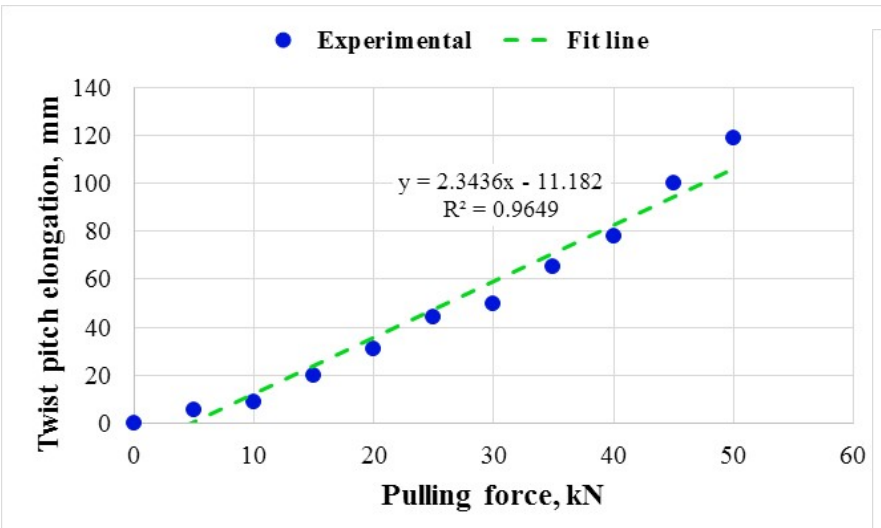
– is rotation number of cable head, r_0 and r_{sp} are initial ble radius and spiral radius correspondingly, L_0 – subcable ıgth, h_0 – initial twist pitch, z – cable length

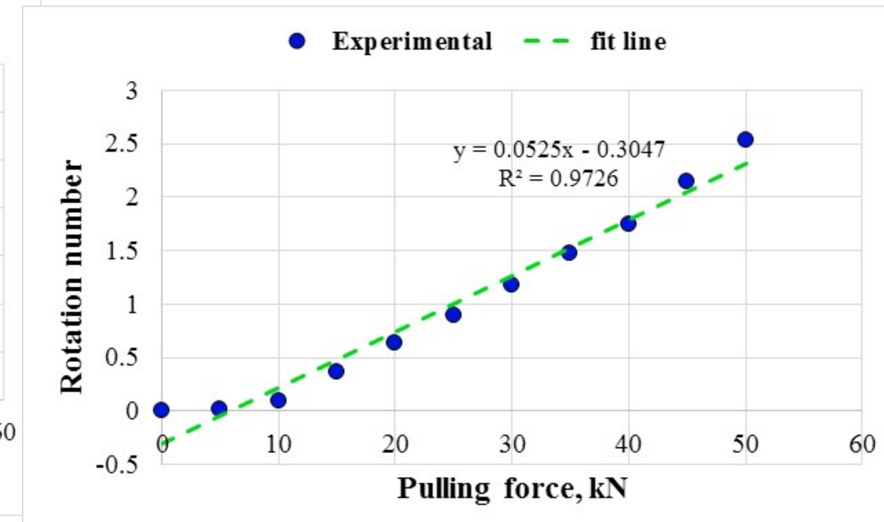
some experiments were performed in Hitachi cable (samples from five to ten meters – **thanks to IO ITER, JP DA (Takahashi-san) and Hitachi cable**) and in VNIIKP, particularly after removing jacket from the cable with the rope broken during insertion

Science in ITER

Rotation and untwisting

Adjusting parameter *A* has been determined from experiments by fitting experimental curves



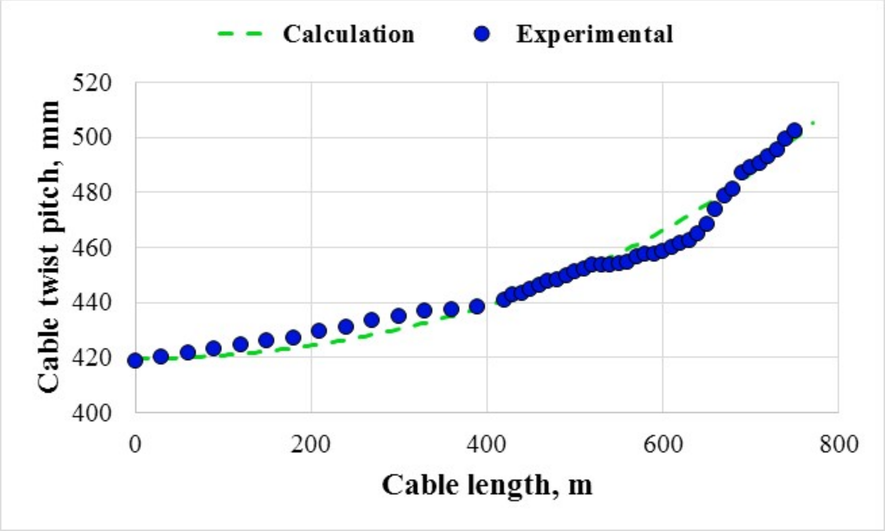


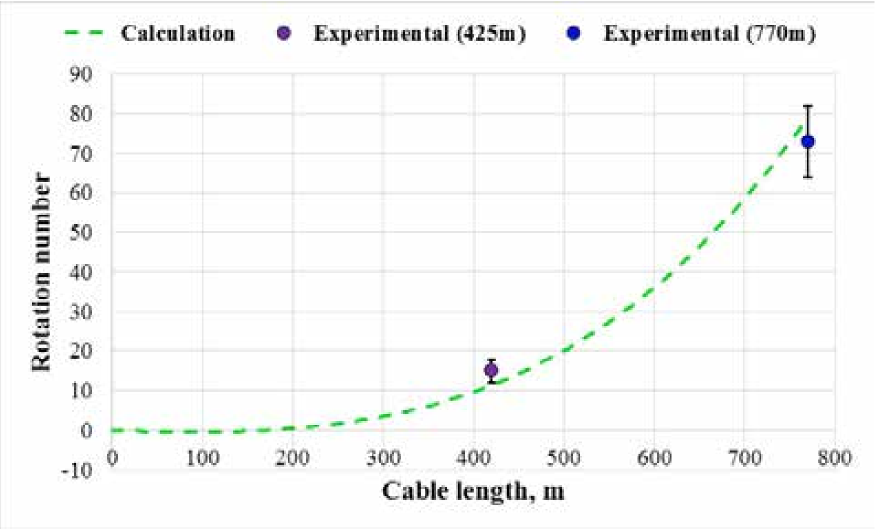
$$A(F,z) = (1.565 \cdot 10^{-5} \cdot F - 1.451 \cdot 10^{-4}) \cdot z + 0{,}999$$

Science in ITER

Rotation and untwisting

Comparison of experiments and calculations by the model – demonstrated good coincidence





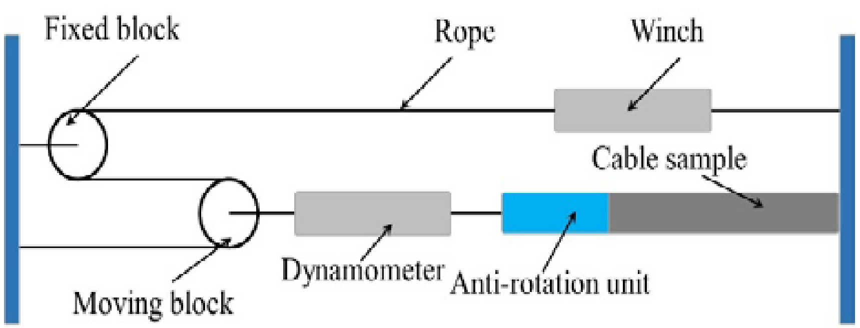
How to avoid untwisting and AC loss increase?

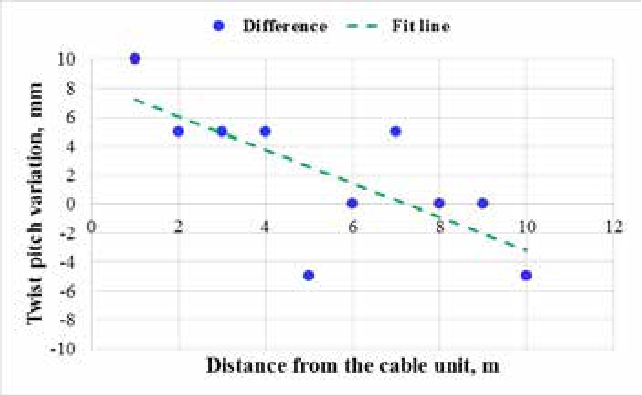
Science in ITER

Rotation and untwisting

How to avoid untwisting and AC loss increase?
Two ideas:

- Programmable variable twist calculated in accordance with model : at the head of a cable more short twist, then more long
- Untwisting device: same cable with opposite twist: it does work – we tested this





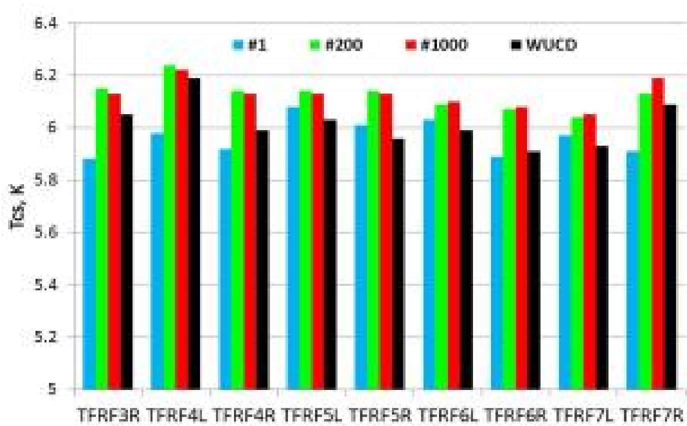
The **technology can be improved** on the base of study to avoid a cable untwisting during insertion

Science in ITER

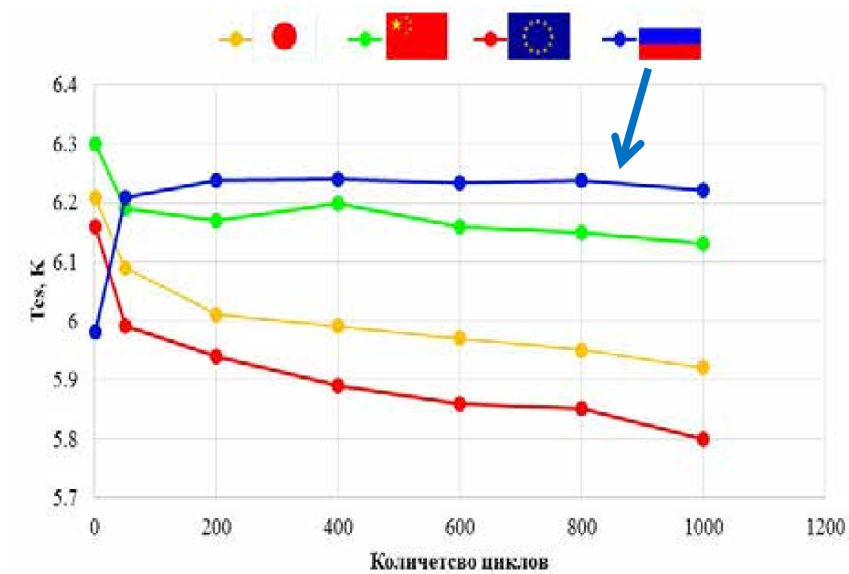
Stability at SULTAN test and micrography

This is still a mystery!
(A.Devred – at the conductor meeting in ITER, Sept. 2015)

Russian TF conductors at SULTAN cycling tests demonstrated rise and good stability of T_{cs} (before WUCD)



The plot provides the results obtained on RF TF conductors, heat treated in accordance with ITER cycle B (final plateau of 650 C for 100 h).
TFRF3 sample corresponds to 100m Qualification UL.
TFRF4L is a preproduction stage UL.
The rest of the samples is coming from production ULs.
Very good reproducibility of results is observed as well as specific unusual behavior as Tcs increases between 1st and 50th cycle.



We made a look inside strands after they were tested at SULTAN

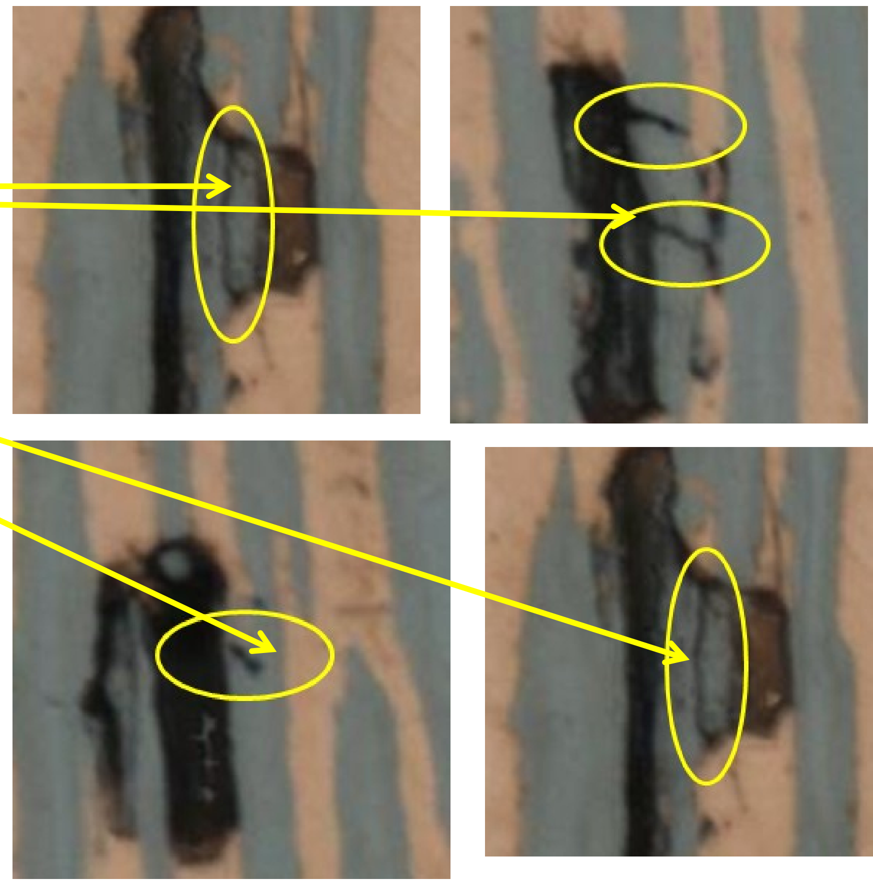
Science in ITER

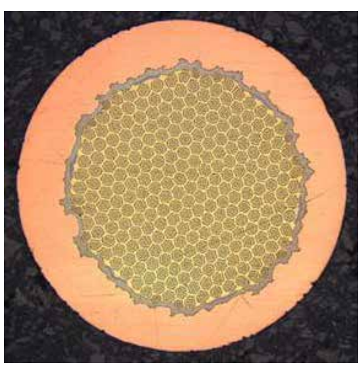
Micro-graphical study of Russian Nb3Sn strands

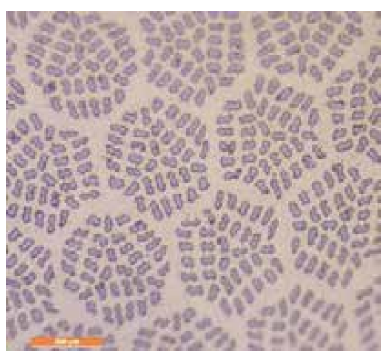
Filament cracks analysis

Types of crack were studied.

Besides usual cracks at the angle between 90° and 45° to filament axis which are typical for all Nb_3Sn strands, the other two types of cracks (semi-cracks and longitudinal cracks) can be attributed to a “fillet” shape of filaments formed by stacking of pair Nb rods



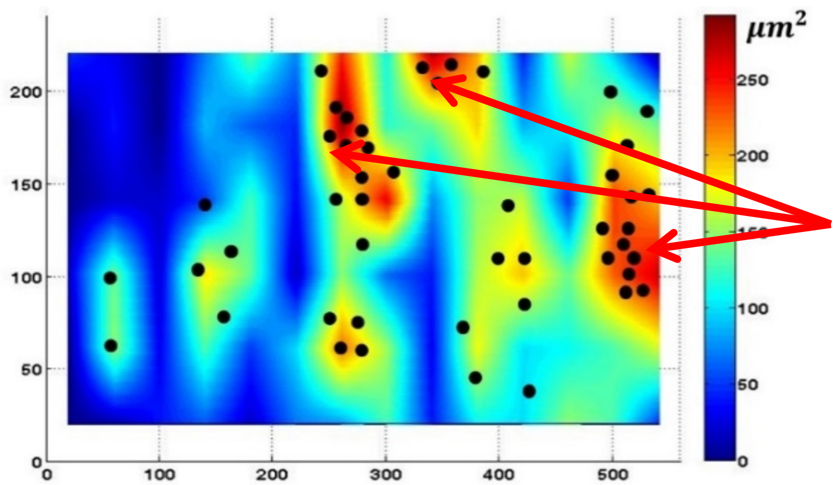




Science in ITER

Micro-graphical study of Russian Nb_3Sn strands

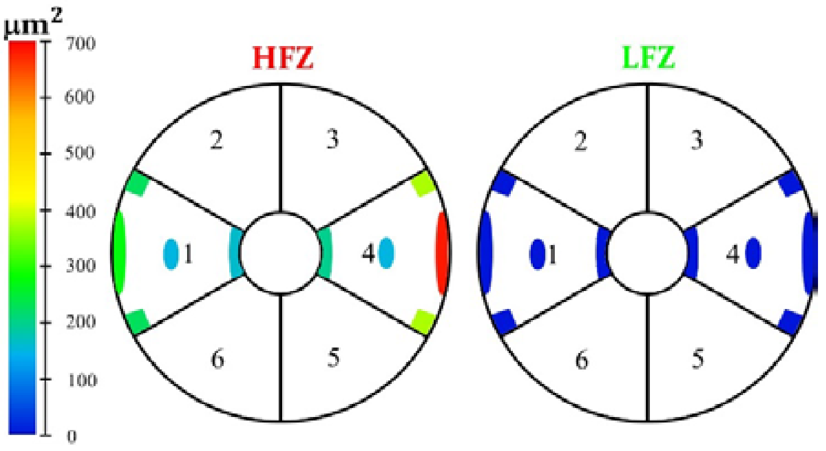
Number of crack in different positions counted



Cracks increase near voids inside a strand bronze.
Voids in bronze appear due difference in diffusion rates of Sn and Cu.

Almost no cracks in Low Field Zone – thermo-cycling does not lead to cracks?

In High Field Zone more cracks in outer parts of petals

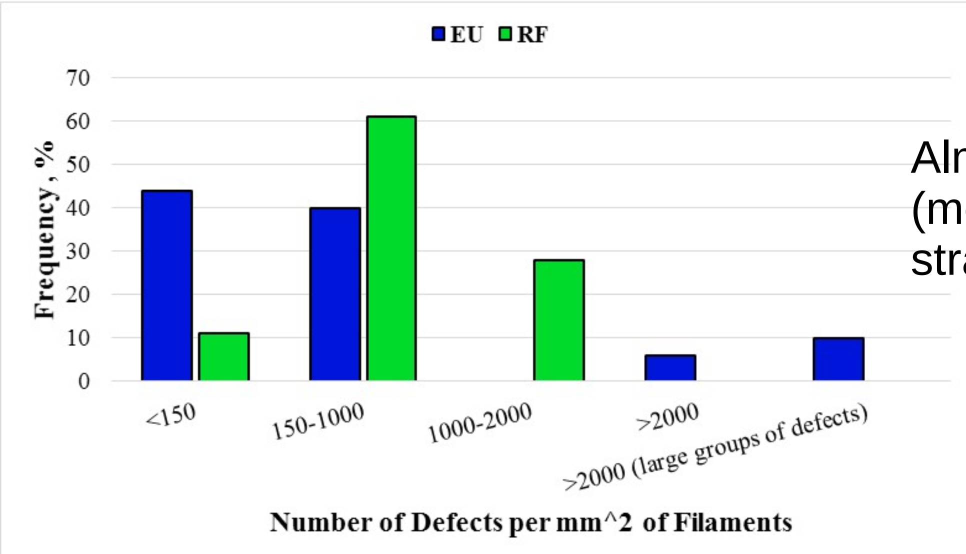


Science in ITER

Micro-graphical study of Russian Nb_3Sn strands

Number of cracks is less in Russian strands

5-level scale (cracks/mm^2 of filament area) suggested by C. Sanabria:
Supercond. Sci. Technol., vol. 25, p. 075007, 2012



Almost no cracks in 4th and 5th levels (more than 2000 per mm^2) in Russian strands

So, why are Russian strands less broken, and TF conductor is more stable?

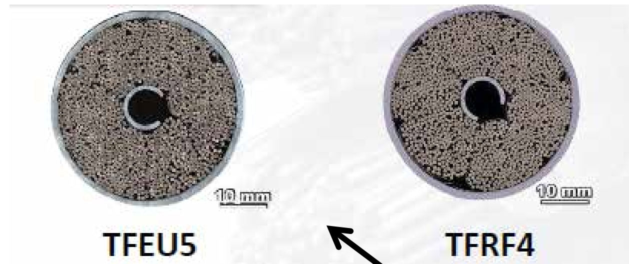
C.Sanabria – 2012, P-L. Bruzzone ate FEC – 2014: A possible reason is the frictional property of the Cr plating of the Russian vendor, which may promote the sliding at the strand crossovers and mitigate the local strand bending.

Science in ITER

Micro-graphical study of Russian Nb_3Sn strands

Our three suggestions are:

- very dense cable due to use of special roller compactors;



RF conductor looks more dense than EU one.

From ASC-2014 - Student Paper Competition - SCLS6 – Metallography of ITER Conductors - Sanabria

- rough Cr coated surface: we agree with this

- good strand layout of RF TF strand providing high mechanical properties

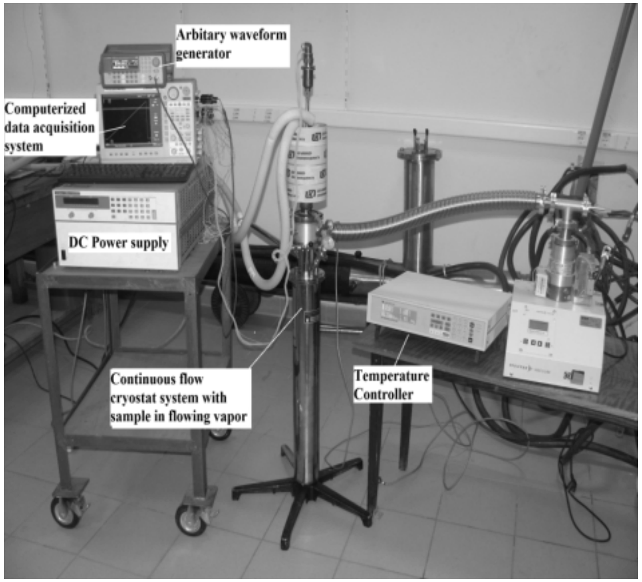
working altogether that lead to high stability of RF TF conductors.

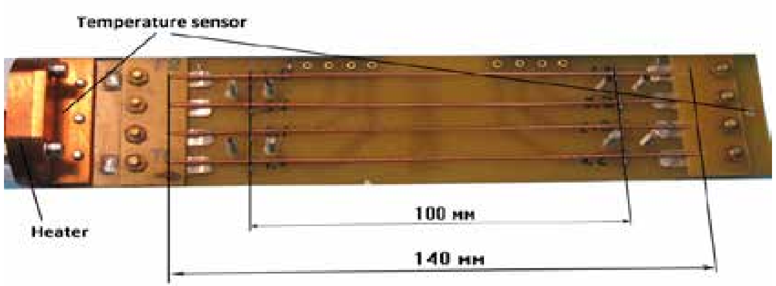
The study helps to **understand behavior of TF conductor**

Science in ITER

Residual Resistance Ratio Statistics

- RRR is important to provide stability of superconductor and protection during quench possible.
- Strict requirements to keep average RRR > 100 for both NbTi and Nb_3Sn strands.
- **Statistical studies** of Residual Resistance Ratio (RRR) of Nb_3Sn and NbTi strands permitted **to track the RRR change during manufacturing processes** and Sultan tests.
- Test facility for mass measurements was developed.
- More than 800 samples of both types were measured for statistical credibility.





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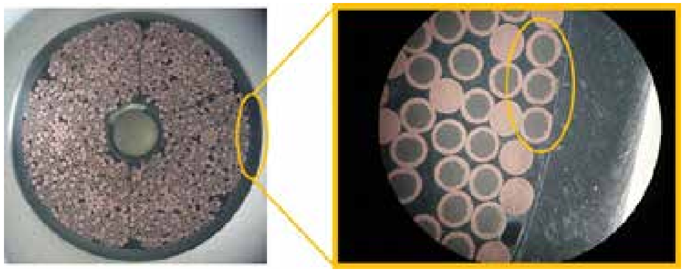
Science in ITER

Residual Resistance Ratio Statistics

- Both types of strands demonstrated reduction of RRR during manufacturing process and tests
- The RRR reduction is mostly associated with the bending due to deformation on the guide rollers of the electrochemical plating facilities and strands deformation in cables during twisting and compaction of conductors

TABLE I.
RRR OF NBTI STRANDS

Stage	Average RRR
Bare strand as-received	139
Ni-plated strand	130
Strand from compacted PF conductor	116
Strand from LFZ at SULTAN	116
Strand from HFZ at SULTAN	117



PF conductor based on NbTi strands seems insensitive to electromagnetic cycling, and its average RRR remains at the level of compacted conductor.

The impacts of strand position during testing at the SULTAN (low-field zone or high-field zone) on RRR degradation have not been revealed statistically even in the areas most exposed by mechanical stresses.

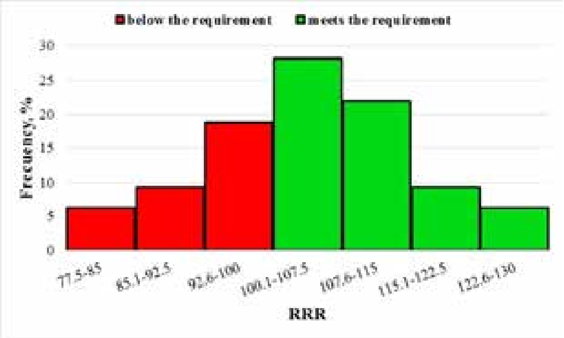
Science in ITER

Residual Resistance Ratio Statistics

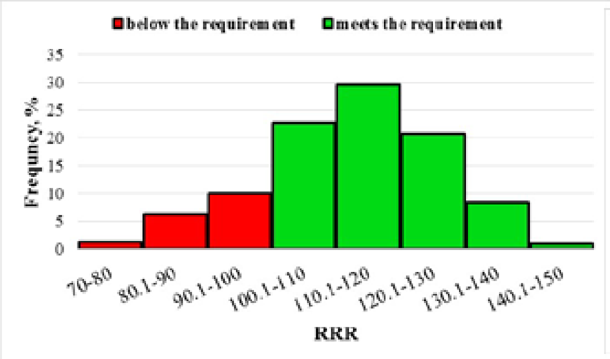
- The average RRR of TF conductor decreases, especially in **Nb_3Sn** strands located near spiral and jacket in the length corresponding to HFZ. There is about 34% of strands having the RRR values less than 100 after SULTAN test.

TABLE I.
RRR OF NB_3SN STRANDS

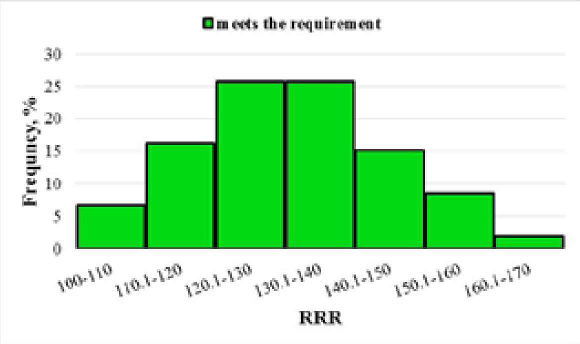
Stage	Average RRR
Bare strand as-received	208
Cr-plated strand	169
Strand from compacted TF conductor	145
Cr-plated strand heat treated by Cycle A	110
Cr-plated strand heat treated by Cycle B	138
Strand from LFZ at SULTAN	120
Strand from HFZ at SULTAN (near spiral and jacket)	106



RRR distribution for the strands taken from HFZ of TFRF3 conductor sample. 34% are less than 100, anyway, average is more than 100.



Cycle A (650 ^{0}C – 200 hours) , 18% of strands are less than 100



Cycle B (650 ^{0}C – 100 hours) , all strands are above 100

Heat treatment influence:

- After cycle A – 18% of strands have RRR<100

- After cycle B 100% strands have RRR >100

Science in ITER

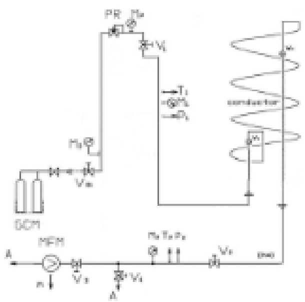
Residual Resistance Ratio Statistics

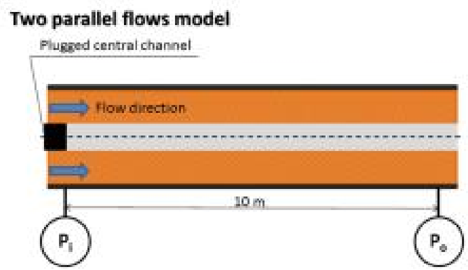
- The statistical study of RRR of NbTi and Nb_3Sn strands demonstrated:
  - For both strands, reduction of RRR has been observed during manufacture and testing
  - The NbTi RRR practically no change during tests, all changes are during manufacture
  - The Nb_3Sn RRR strongly depends on heat treatment, and changes after SULTAN tests in high field zone

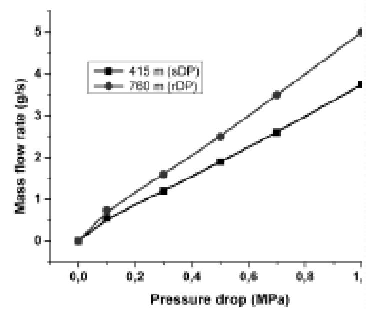
The statistical study of RRR **permits to set demands** on initial level of RRR on strands on delivery

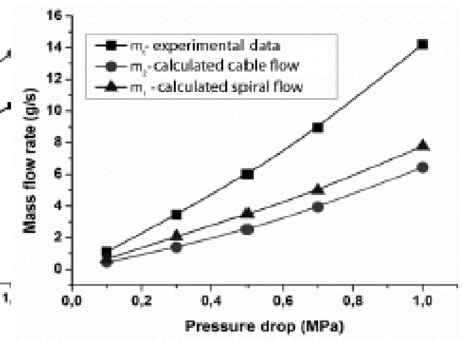
RF - Science in ITER

Hydraulic performance









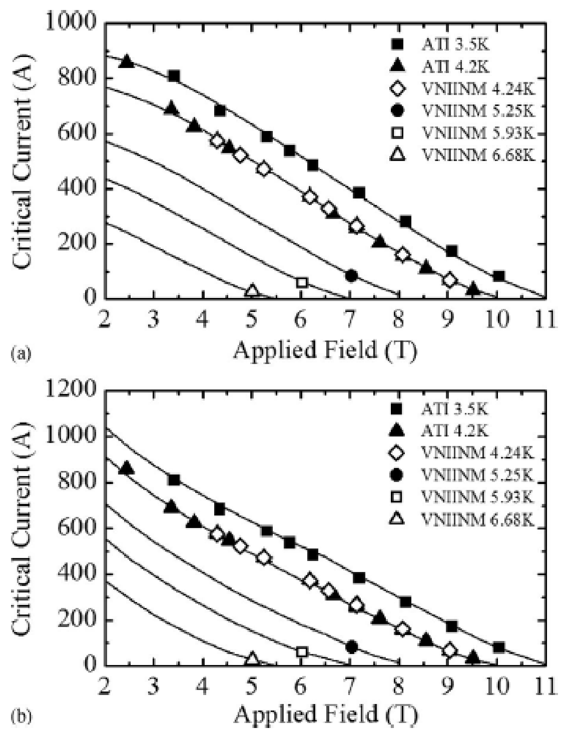
- The hydraulic performance has been measured in the short samples of TF conductor 10 m and 100 m). Two parallel flows model has been developed.
- The short sample of conductor with the smooth tube instead of central spiral was manufactured and tested. The main results of the tests are the following:
  - The cable equivalent hydraulic diameter and formula of the friction factor were determined;
  - Hydraulic performances of the central spiral were determined;
  - With parameters obtained it is possible to predict hydraulic performances of conductor for helium flow at any temperature

Hydraulic study permits to **predict behavior of superconductor** in operational conditions

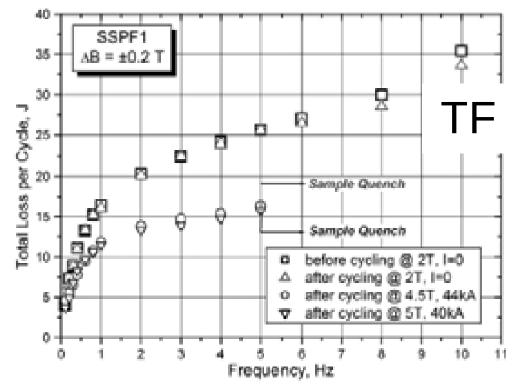
Science in ITER

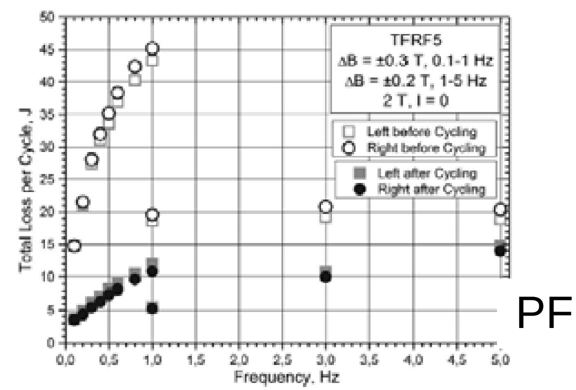
More studies were done

For example:



Strands characterization – comparison single (top) and two – component (bottom) models [23,24]





Change of AC losses after cycling tests at SULTAN [25]

And more, and more…

Final remarks

- ITER production and delivery was the great job to do, and we really did it with our best knowledge and enthusiasm.
- ITER inspired us for many scientific studies that provided a lot of results to improve technology or to understand what happens with superconductors during manufacturing
- We hope that this review and the references attached will be useful for future projects, especially if CICC technology will be used.
- ***Very important thing was that we learned how to work, to cooperate, collaborate, and to do science inside the great, devoted, creative International Team; to do the newest and most complicated machine in the world.***
  - **We would like to thank all ITER folks for their great collaboration!**

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THANK YOU FOR YOUR ATTENTION!