EPFL

R&D on React&Wind Nb3Sn Superconductors for Fusion Magnets

Kamil Sedlak

EPFL – Swiss Plasma Center

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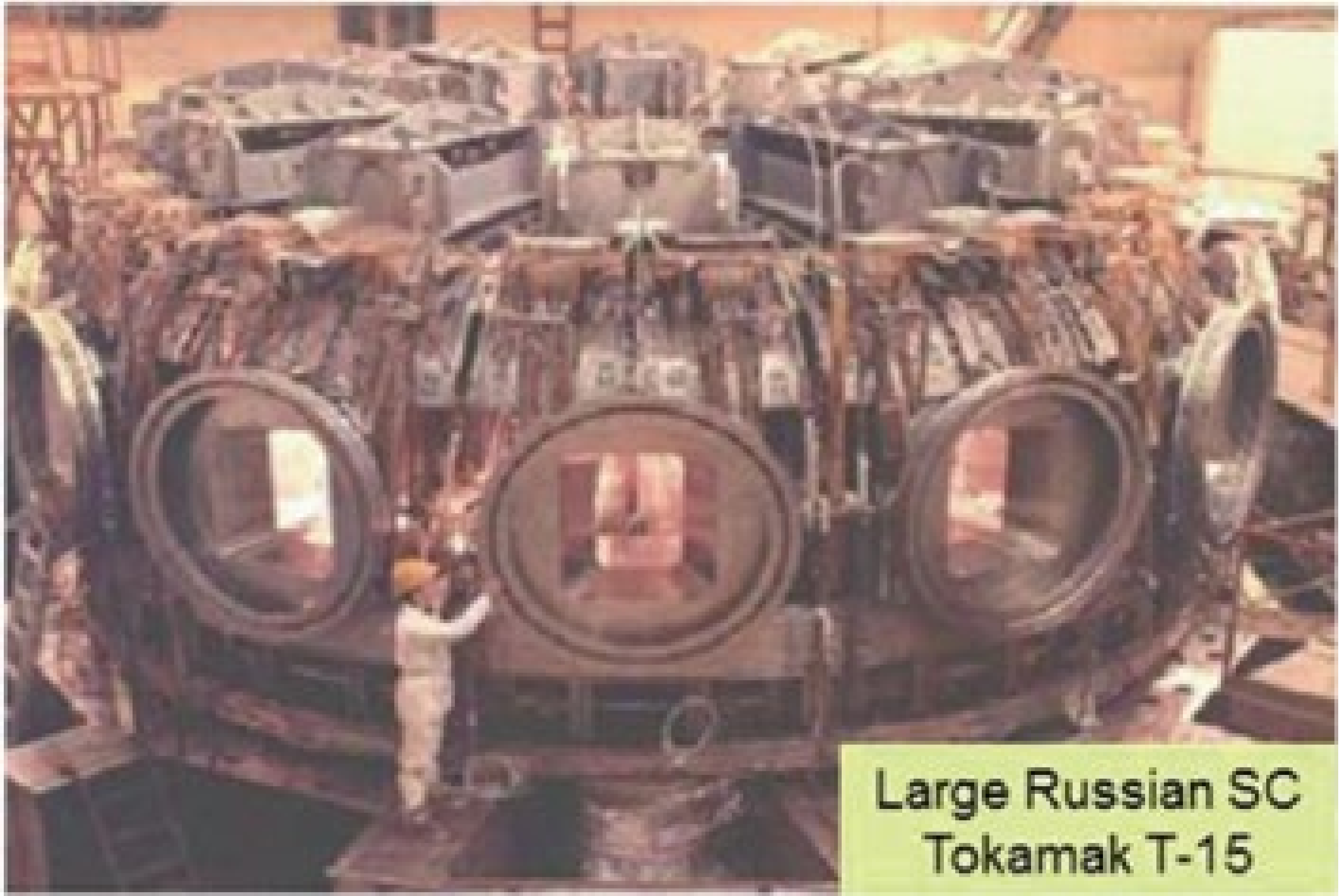
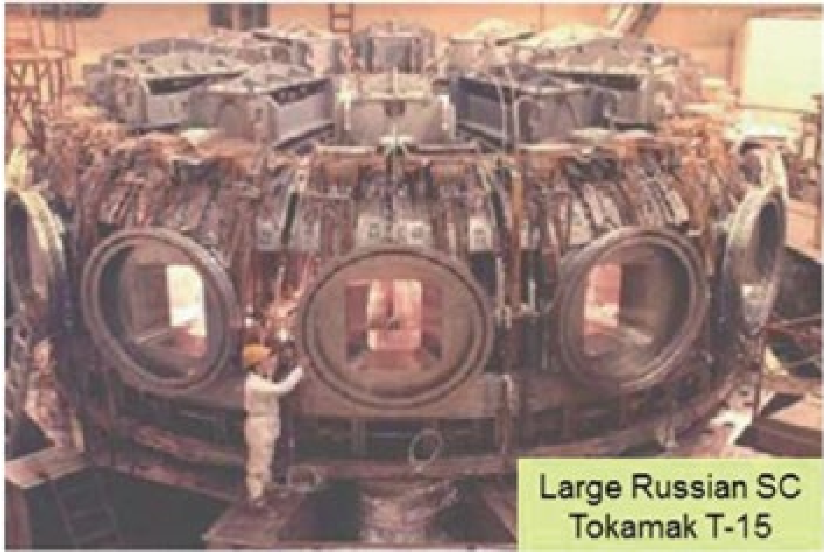
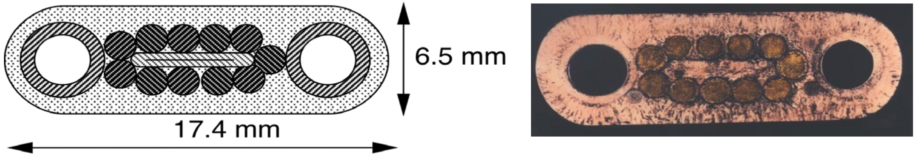
Kurchatov Institute, Soviet Union, 1988, Tokamak T-15



Kurchatov Institute, Soviet Union, 1988, Tokamak T-15



RW Nb3Sn conductor of T15 TF coil

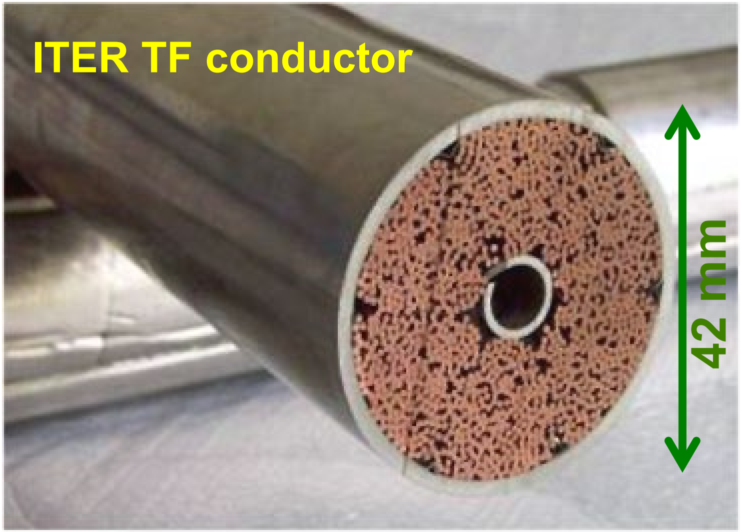


- The first industrial tokamak using superconducting coils for plasma confinement.
- R = 2.4 m,   r = 0.7 m
- TF coils made of Nb_3Sn superconductor using the so-called react&wind (RW) technology.
- Due to its brittleness, Nb_3Sn filaments were broken during the coil winding ➔ irreversible damage, the coils did not work (kW range of ohmic heating ➔ coil could operate for just a few seconds after charging with the electric current).
- **Lesson learned by many tokamak designers – never ever use RW technology for a tokamak again!**
- ITER takamak – based on wind&react (WR)

Villigen, Switzerland, 2024, SULTAN Test Facility

- SULTAN test facility:
  - B_{Max} = 10.8 T
  - T_{op} = 4.5 – 60 K
  - I_{max} = 100 kA
  - Sample cross-section: 142x92 mm^2
- ➔ Unique test facility for testing superconductors for fusion magnets.
- At SPC, we are not afraid of RW conductors. In fact, we like them, we make R&D on them.
- **Why?**
- Testing of any sample brings us money and fame?
- Do we like to see samples failing? (“Schadenfreude”)?
- **No! We like RW because SULTAN main coils are made by RW technology and they have been working reliably for more than 40 years, with hundreds of cycling loads!**

Why React & Wind?



ITER TF Coils:

- Nb_3Sn, Wind & React CICC.
- Conductors functional and tested.
- Developed manufacturing know-how.
- No serious troubles during manufacturing reported.

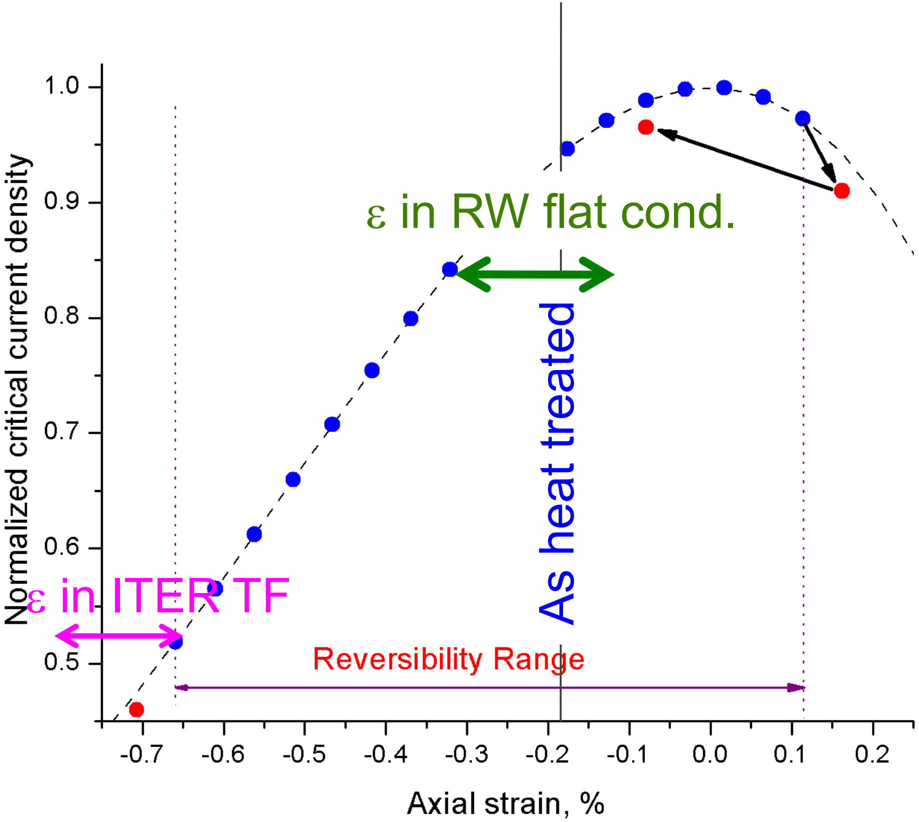
So why (for EU DEMO) to bother with React&Wind, which is:

- Delicate – risk of Nb_3Sn filament breaking during coil winding.
- Not tested in an ITER-size machine.

?

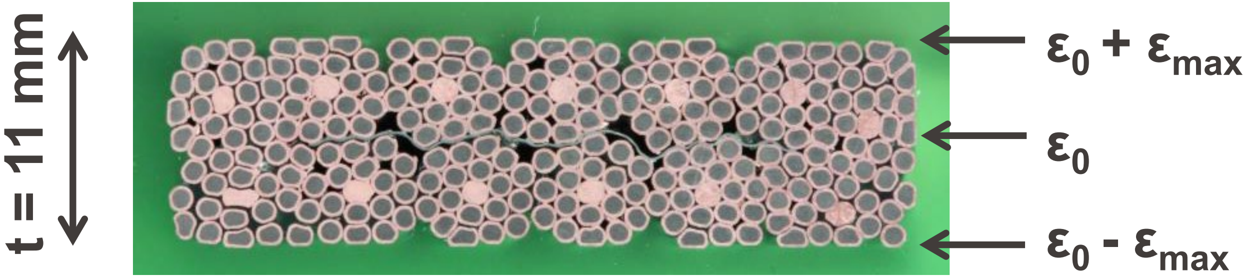
Why React & Wind?

- Our primary motivation was saving on the amount of Nb_3Sn. How?
- I_C of Nb_3Sn depends on strain, ε.
- Due to different thermal expansion coefficient of steel jacket and superconducting cable (Nb_3Sn, Cu), a thermal strain is built up on Nb_3Sn during magnet cool down to cryogenic temperatures:
  - WR: Cool down from 650ºC to 4.5K leads to ε = -0.7 to -0.8%
  - RW: Cool down from 20ºC to 4.5K leads to ε = -0.27%



Maximum bending of the RW Conductor in the Operation

- Bending of React & Wind conductor is not problematic, if the bending strain is “small”. This is the case in huge DEMO TF coils, with the bending radius R_{coil} of ~3 meters.



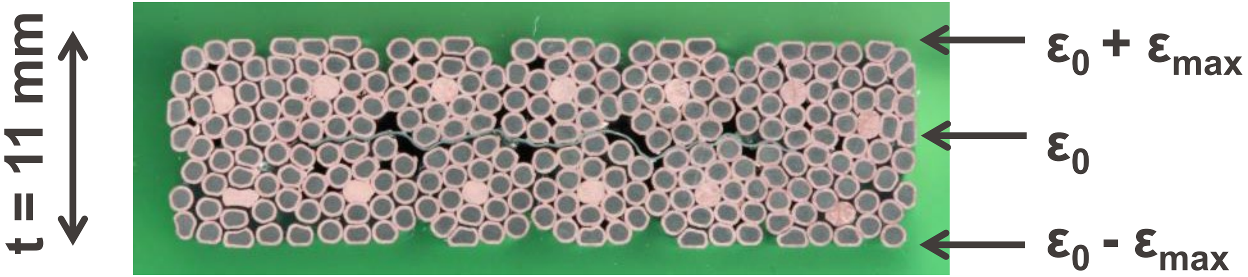
- Ideally, the heat treatment radius, R_{ht}, should be the same as R in the winding. However, this is not always possible, e.g. in a TF coil with the “D” shape.
- For a RW cable of thickness t, the maximum bending strain, $\varepsilon_{\max}$, is:

$$\varepsilon_{\max} = \pm \frac{t}{2}\left(\frac{1}{R_{\mathrm{ht}}} - \frac{1}{R_{\mathrm{coil}}}\right)$$

- For a good coil performance, $\varepsilon_{\max}$ should not exceed **~0.1%.**

Maximum bending of the RW Conductor during Manufacture

- Bending of React & Wind conductor is not problematic, if the bending strain is “small”. This is the case in huge DEMO TF coils, with the bending radius R_{coil} of ~3 meters.



- The heat-treated cable must be straightened for jacketing after heat treatment.
- The bending strain during “handling” from heat treatment to final winding must be controlled to avoid exceeding the *threshold for irreversibility:*

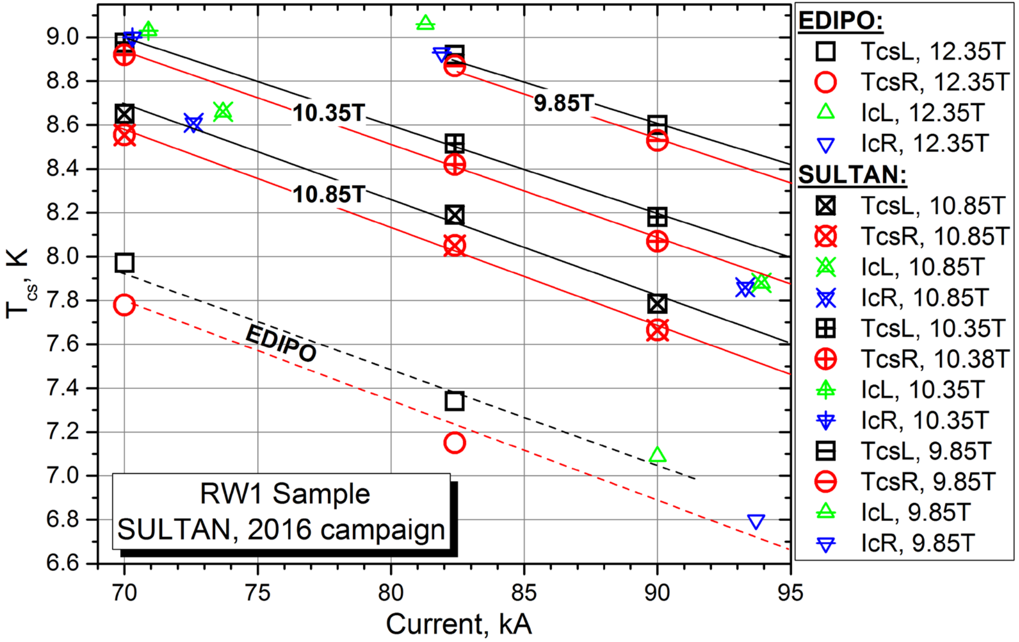
$$\varepsilon_{\text{max}}^{\text{handling}} = \pm\frac{t}{2}\left(\frac{1}{R_{\text{ht}}} - \frac{1}{R_{\text{jacketing}}}\right) = \pm\frac{t}{2R_{\text{ht}}}$$

- For a good coil performance, $\varepsilon_{\text{max}}^{\text{handling}}$ should not exceed **~0.3%.**

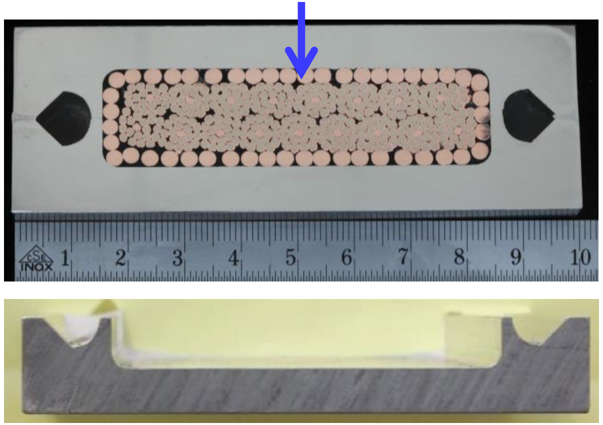
RW 1 (RW Prototype #1)

RW 1 prototype (2015-2016):

- T_{CS} almost as expected, ε_{eff} = -0.28% / -0.35% (theoretically estimated from the thermal contraction: ε_{eff} = -0.27%)



Segregated Cu-wires



However:

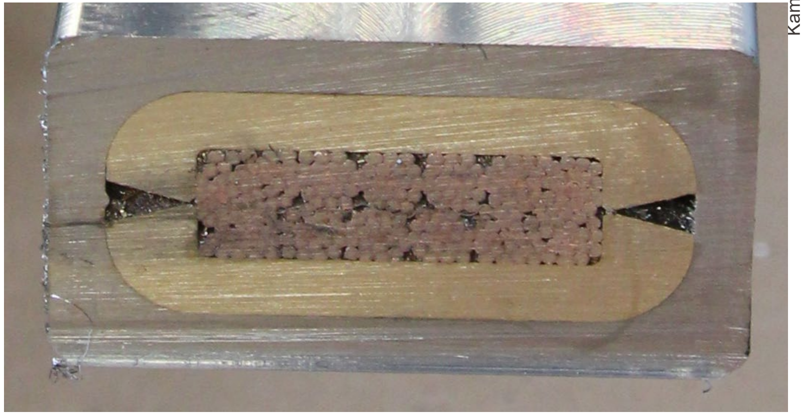
- Voltage spikes during current ramps, presumably due to the gaps in the Cu wires surrounding the cable.
- Sudden quenches originating from a low-field region near the bottom sample termination.
- Conductor too wide.

RW 2

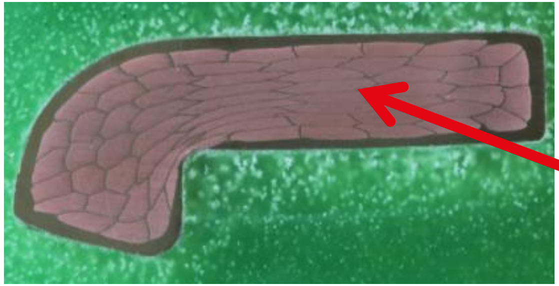
RW 2 prototype (2017-2019):

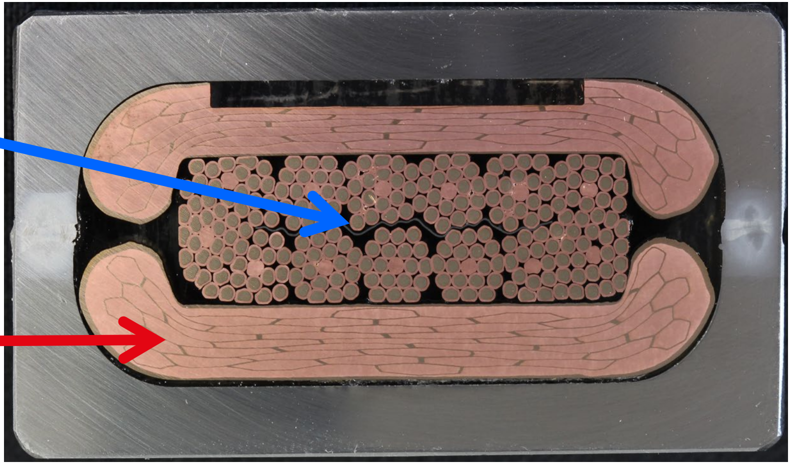
- Various stabilizers tried in order to support the cable and to reduce the AC losses: Brass, and Mixed-Matrix (copper cells segregated by CuNi boundaries)
- Importance of transverse preload discovered.
- Final sample worked very well.

Brass stabilizer
“loose” cable in the conduit

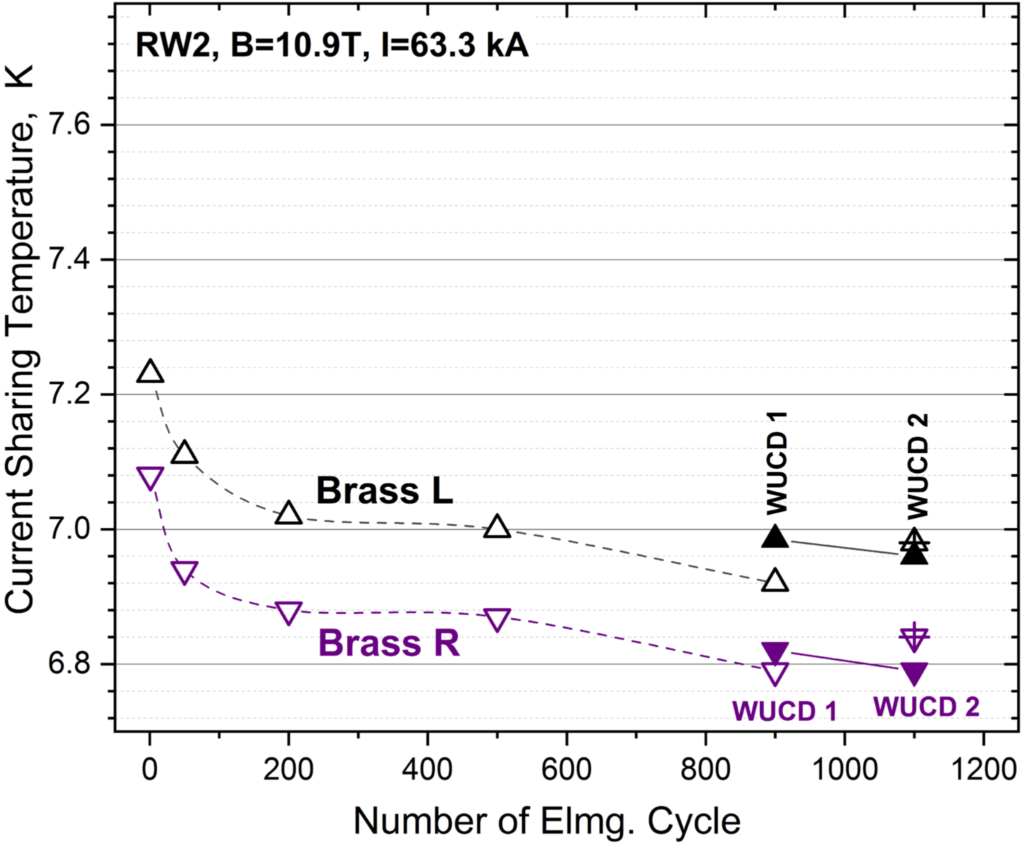


Half-size mixed matrix
ENEA, Tratos; “tight fit”



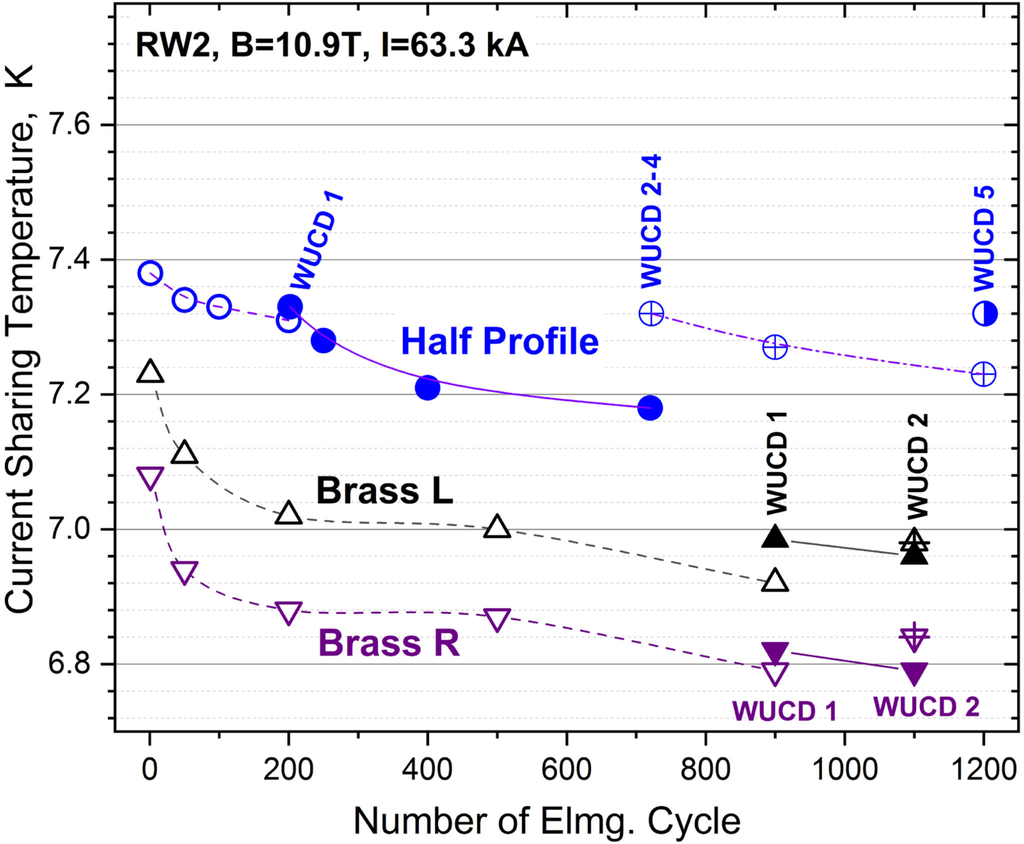


RW 2 – DC Performance



- Samples with brass stabilizer = “loose” cable inside of the jacket → lowest performance + degradation

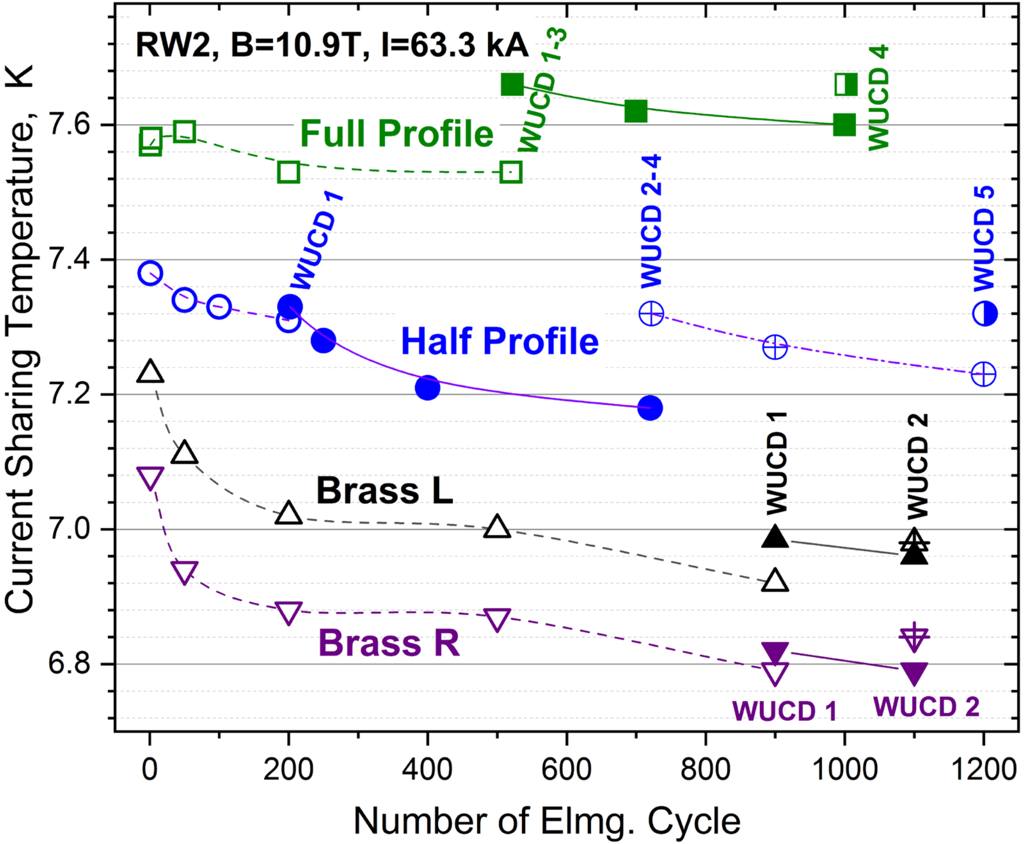
RW 2 – DC Performance



- Sample with half-size mixed matrix = cable tightly fitted in jacket → medium performance

- Samples with brass stabilizer = “loose” cable inside of the jacket → lowest performance + degradation

RW 2 – DC Performance

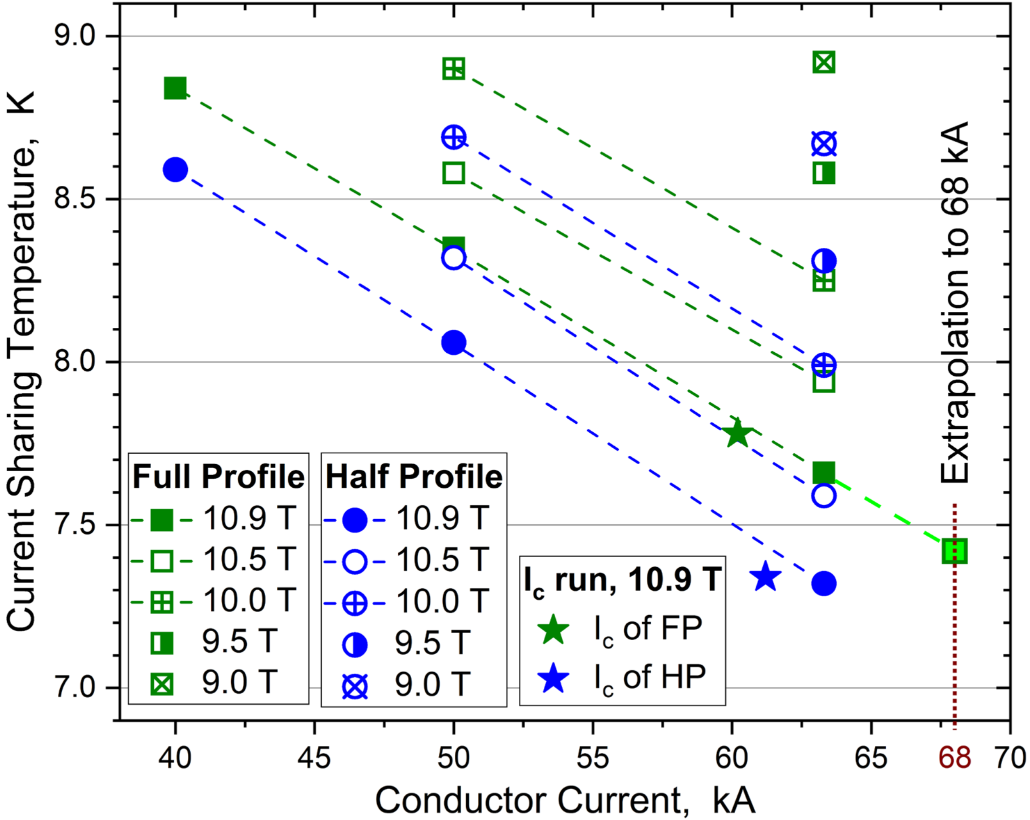


- Sample with full-size mixed matrix (preloaded cable):
  - Even higher Tcs .
  - Almost no degradation along cyclic loading.

- Sample with half-size mixed matrix = cable tightly fitted in jacket → medium performance

- Samples with brass stabilizer = “loose” cable inside of the jacket → lowest performance + degradation

Comparison of RW 2 with ITER TF Conductor



Extrapolation to ITER TF operating conditions, 68 kA, B_{SULTAN}=10.9T:

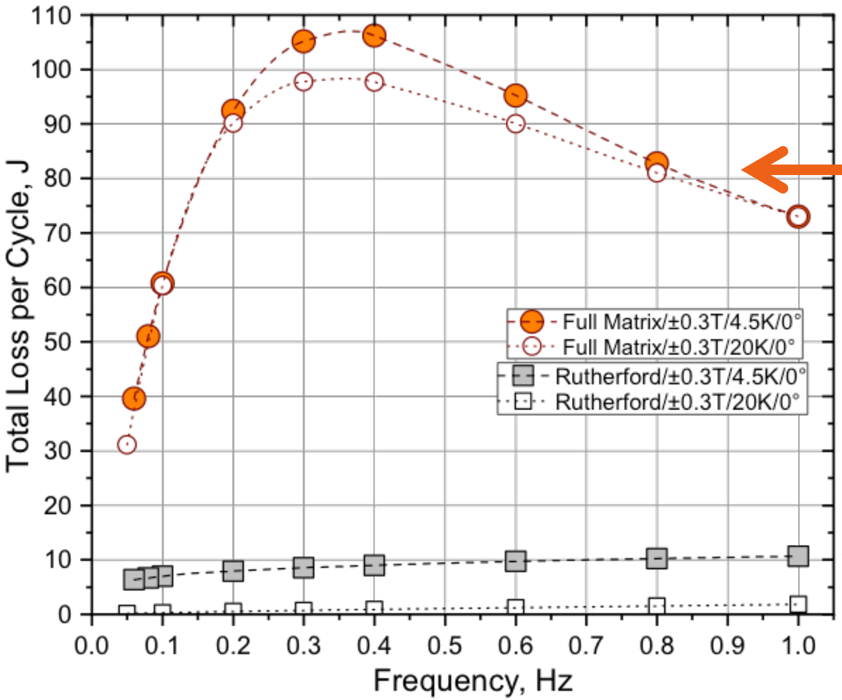
- $\mathbf{T_{cs}^{RW2} = 7.4\ K}$

Typical $T_{cs}^{ITER\ TF}$ = 5.9-6.5 K after cyclic loading.

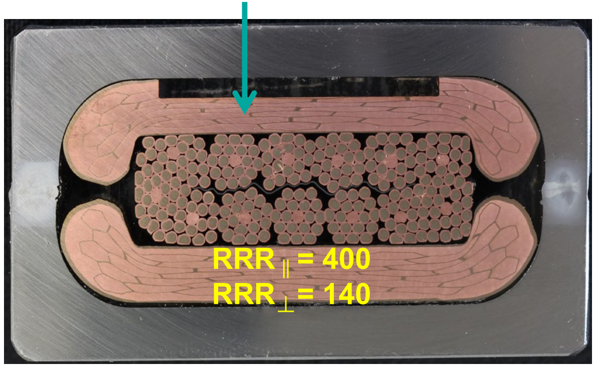
A_{SC}(RW2) = 132 mm²

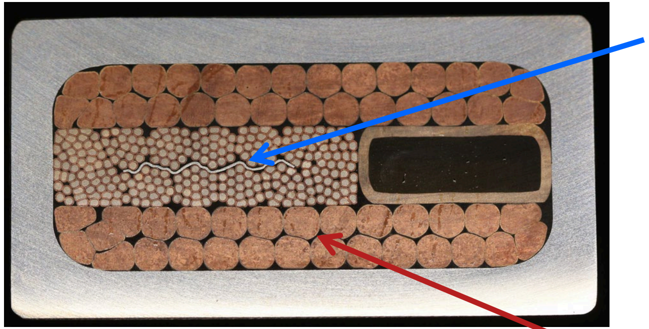
A_{SC}(ITER TF) = 235 mm²

RW 2 – AC Performance



Cu/CuNi mixed matrix





Steel strip

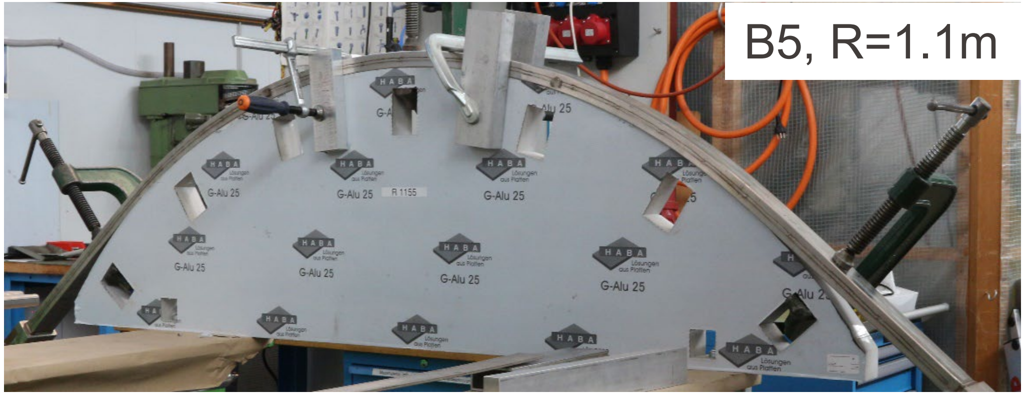
Cu Rutherford cable with CuNi cladding

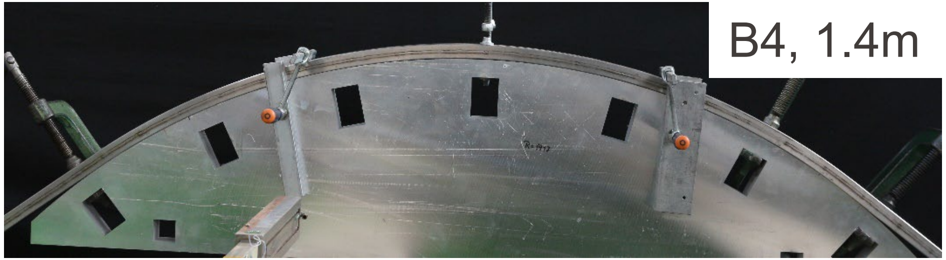
- RW 2 conductor with the mixed matrix stabilizer has one order of magnitude larger AC losses compared to RW 2 with cabled stabilizer
- RW2 with the cabled stabilizer and central strip seems to be a good candidate even for the Central Solenoid (pulsed coil operation).

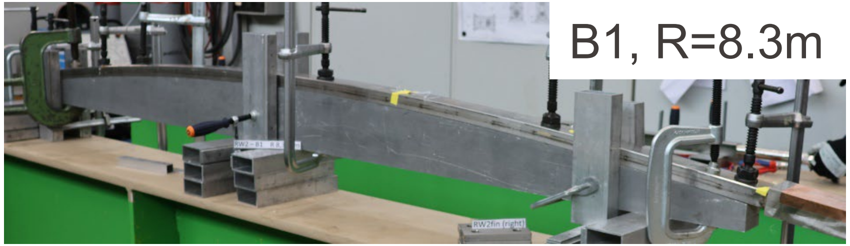
Testing of the Bending Limit

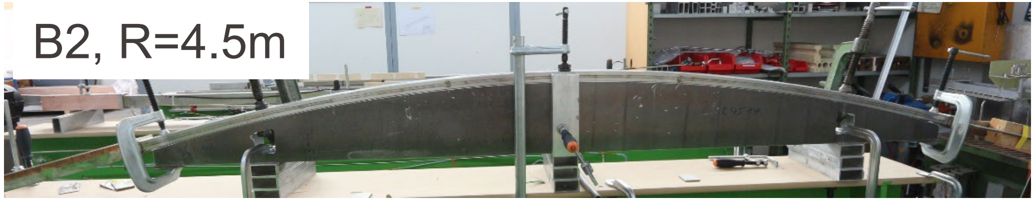
- SULTAN campaigns in 2023:

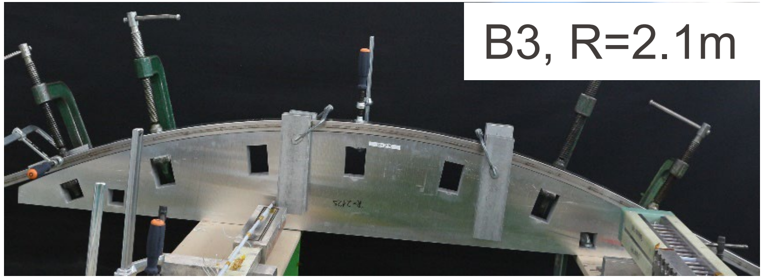
- B0 – to benchmark 2018
- B1 – after bending to ε = **± 0.065 %**
- B2 – after bending to ε = **± 0.12 %**
- B3 – after bending to ε = **± 0.25 %**
- B4 – after bending to ε = **± 0.38 %**
- B5 – after bending to ε = **± 0.46 %**


B5, R=1.1m


B4, 1.4m

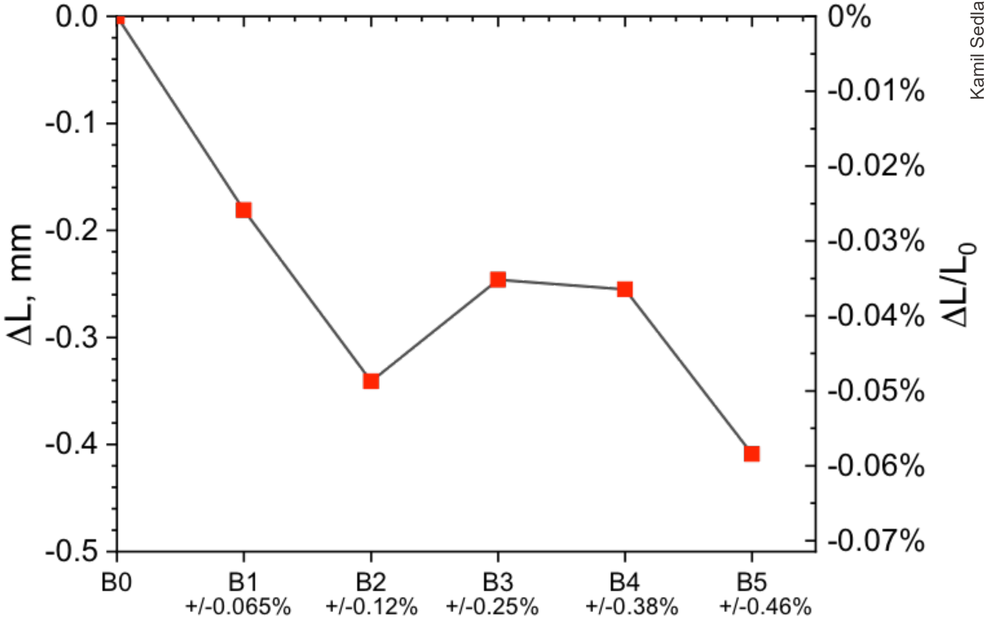

B1, R=8.3m


B2, R=4.5m


B3, R=2.1m

RW 2 – Bending

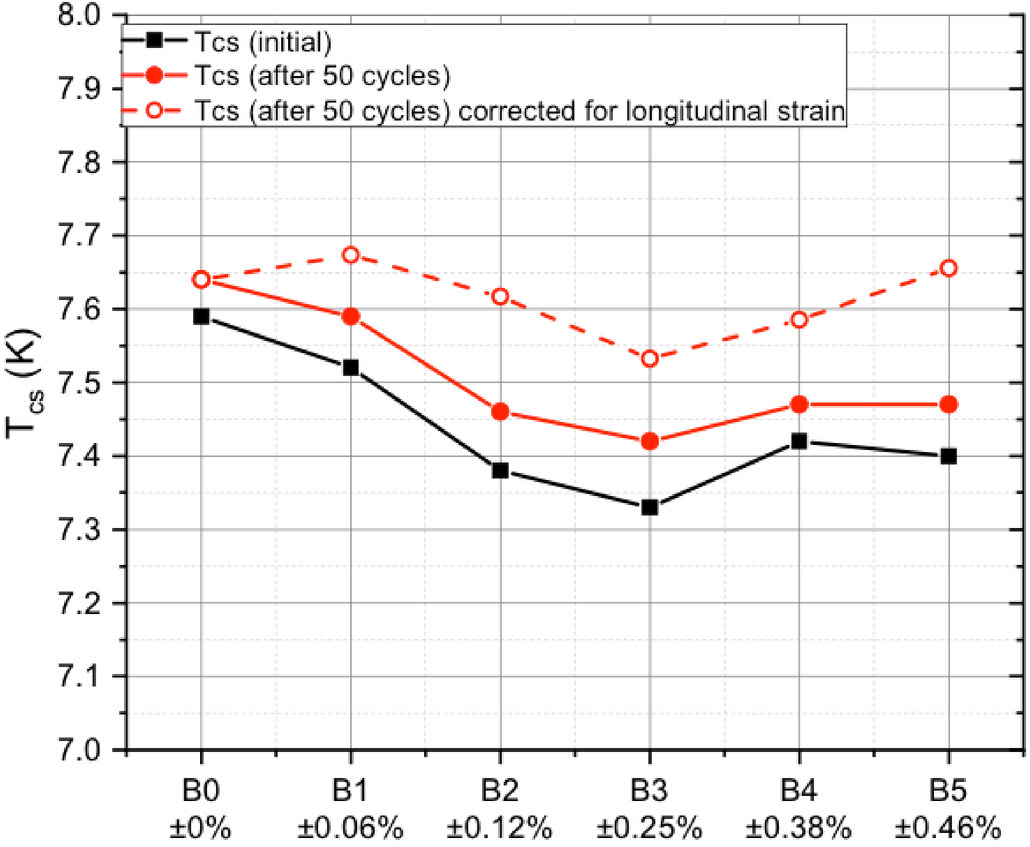
- During the SULTAN test campaign with bent RW2 conductors in 2023, we observed that the jacketed conductor shrank upon bending and straightening.
- The shrinkage is a concern because an additional compressive axial strain on the cable reduces the current sharing temperature: according to the scaling law, 0.01% change in strain leads to 50 mK change in T_{CS}.



Test campaign	Former radius	Bending strain	Length before bending	Length after bending	Long. Strain wrt B0
B0	-	-	699.714 mm	699.714 mm	-
B1	8300 mm	±0.065%	699.714 mm	699.533 mm	-0.026%
B2	4514 mm	±0.12%	699.552 mm	699.373 mm	-0.049%
B3	2125 mm	±0.25%	699.39 mm	699.468 mm	-0.035%
B4	1417 mm	±0.38%	699.449 mm	699.459 mm	-0.036%
B5	1155 mm	±0.46%	699.431 mm	699.305 mm	-0.058%
B6	1000 mm	±0.53%	699.269 mm	699.542 mm	-0.025%

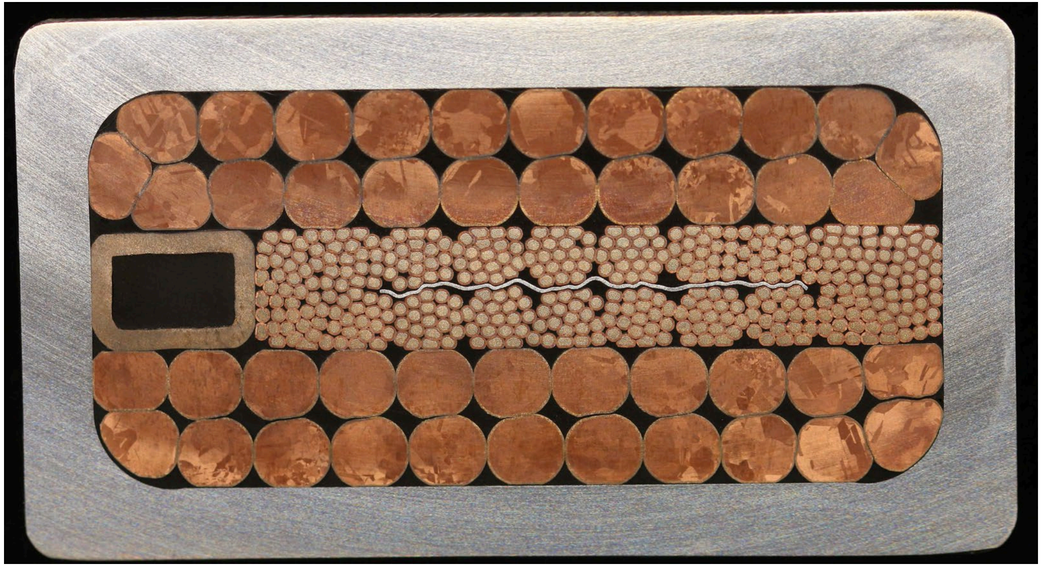
T_{CS} Results after Bending

- T_{CS} changes, however not due to the degradation, but due to the change in the length of the conductor after bending (axial strain).
- A correction on T_{CS} has been applied based on the 2/3 of the longitudinal strain measured on the jacket.
- The change of the steel jacket length will be further studied.



RW 3 and RW 4

- After RW 2, we intended to continue with:
  - RW 3: very similar for RW 2, motivation: systematic bending studies
  - RW 4: 105 kA current (compared to 60-70 kA in previous RW prototypes)
- However, due to problematic Nb_3Sn strand, RW3 and RW4 did not work as expected.

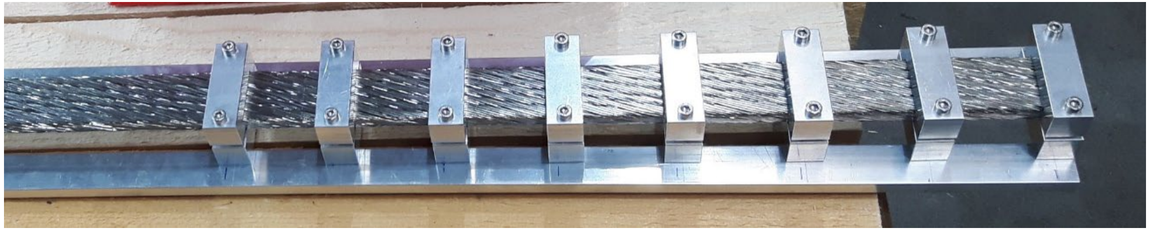


RW 4 conductor designed to very high current, which shall reduce the high voltage induced during coil safety discharge.

Future Plan: RW5 – like RW4 but using a new Nb_3Sn strand.

RW Conductor Joint

- Two overlap-joint samples made of RW2 were assembled and tested.

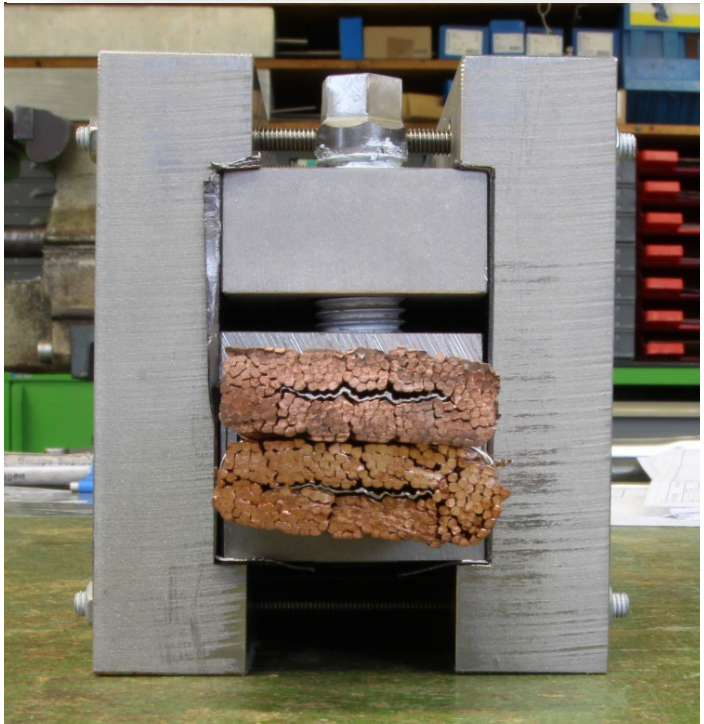


- The cable ends of two reacted flat cable sections are Cu sprayed over 400 mm.

- The surface is then milled flat to obtain a good contact surface.

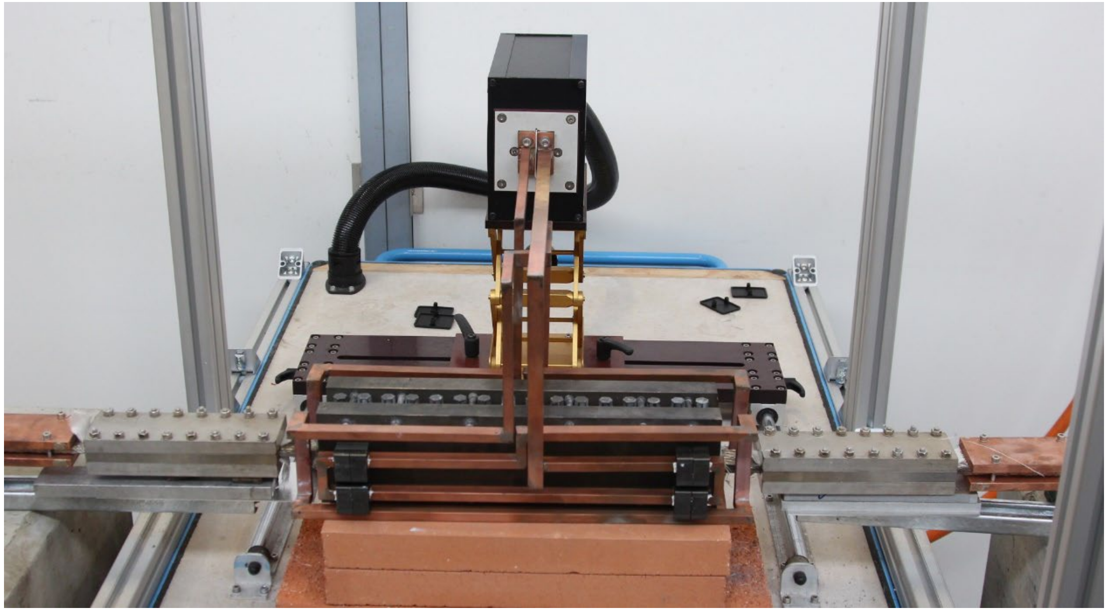
RW Joint Manufacture – Diffusion Bonding

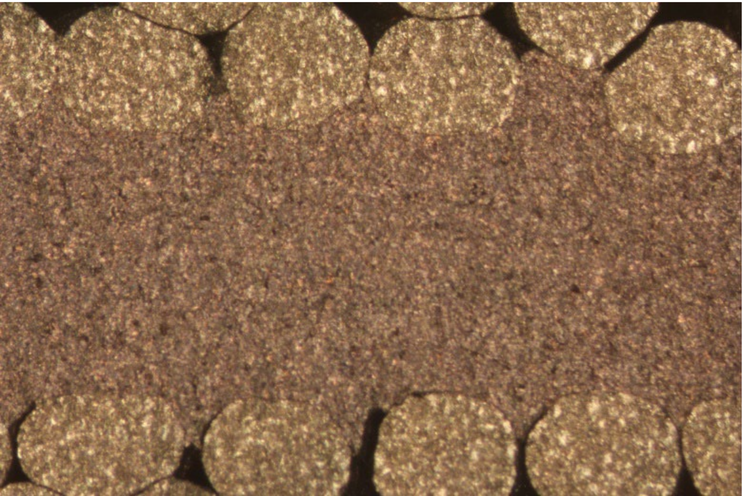
- The overlap of two cables is pressed into an Inconel clamp to provide a pressure of ~30MPa once heated to 650ºC.



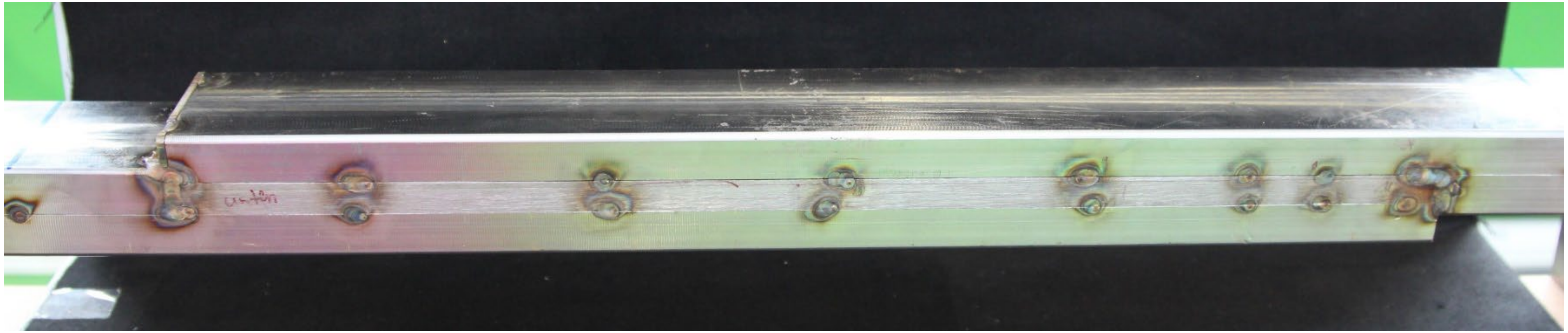
RW Joint Manufacture – Diffusion Bonding

- The assembly is heated by induction to 650ºC for two hours in inert gas to obtain a wide diffusion bonded joint.





RW2 Joint – Assembly and Test

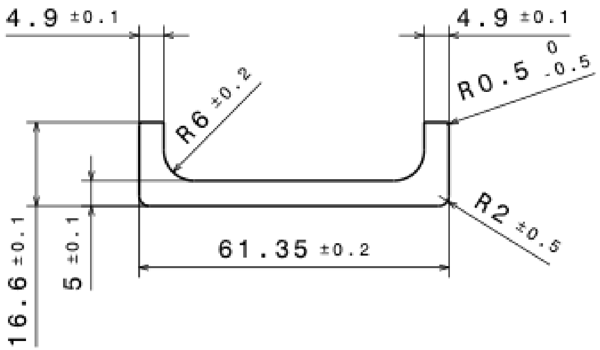


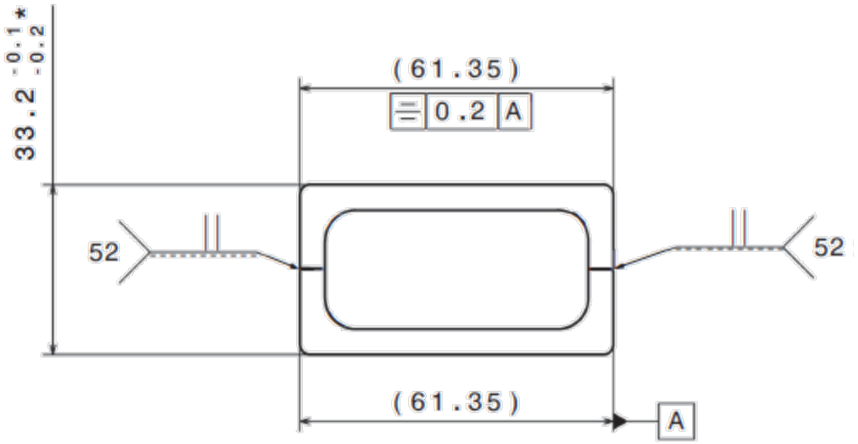
- The stabilizer and the steel jacket was reconstructed around the joint.
- A SULTAN sample was built such that the overlap joint was exposed to the high field in SULTAN.
- The test was carried out at 8 T (expected field at the joint location) and 66 kA. **The measured resistance R(8T, 66kA) = 0.6 nΩ.**
- The joint assembly procedure is fully “portable” and can be implemented during the coil winding.

Longitudinal Laser Welding

- In 2022, we launched an industrial task aiming at developing a **laser-welding assembly line for the production and inspection of R&W conductors** for DEMO.

- The contract was staged in **two phases** :
    1. Manufacture of a **1-km-long, empty tubular steel demonstrator**, including assembly, laser welding and relevant QA.
    2. Manufacture of a **100-m-long full LTS conductor prototype**





Longitudinal Laser Welding of 1000 m Empty Jacket

BENDING MACHINE

LASER WELDER

AIR TREATMENT UNIT

ASPIRATION UNIT

SPOOLING SYSTEM

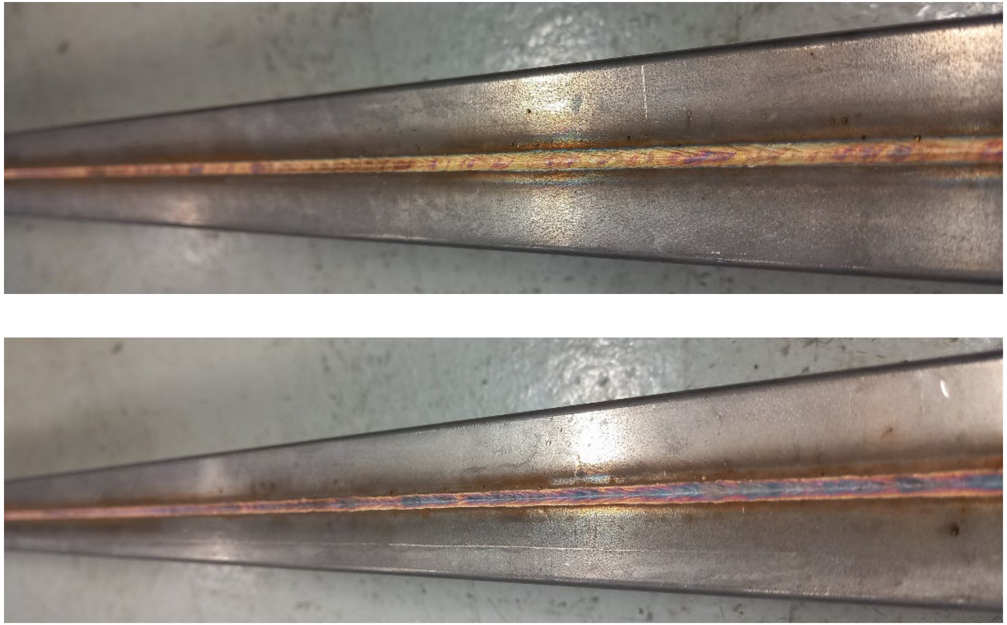
LASER CHILLERS

POWER SUPPLY

HYDRAULIC SYSTEM

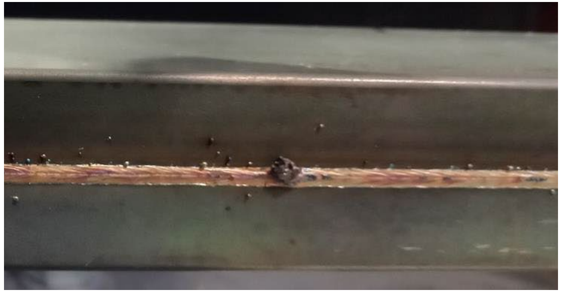
LASER HEADS CHILLER

Most of the Time the Welding Went Fine ...



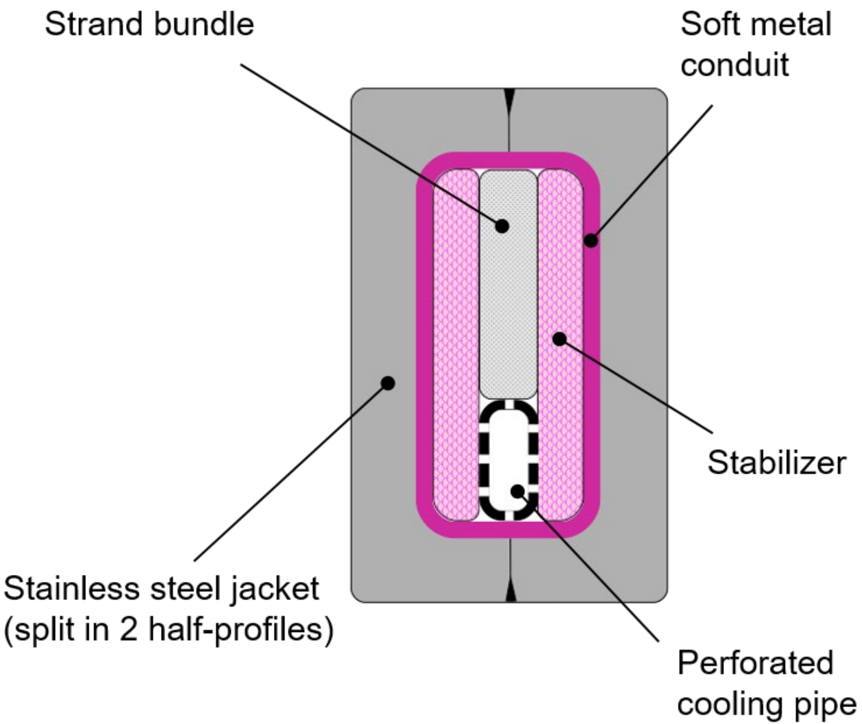
... but Occasionally There Were Defects

- **Passing holes** were the most concerning (often resulting in secondary defects)
- **Spatter** deposition complicated the UT inspection
  (i.e., false positives):
  - Internal spattering
  - External spattering



➔ **Improvement are needed before we can demonstrate an industrial production of a 100 m long RW conductor.**

Double Jacket RW Conductor for the CS Coil



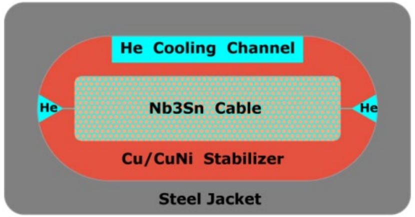
- One critical aspect of the tokamak CS coil is the **fatigue crack growth** in the conductor jacket, which might end up in a leak of Helium into the coil volume.
- Therefore, we are investigating an option of a fatigue-tolerant conductor based on a **double-jacket design.**
- The production of an industrial prototype is planned for 2025.

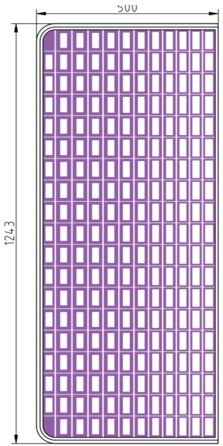
Other Advantages of React & Wind Technology

- The benefits of RW technology are best exploited when combined with coil layer winding (unlike ITER pancake-winding). Each layer can be graded independently in Nb_3Sn, helium, copper and steel:
  - Additional significant saving of Nb_3Sn. (Total saving of 73% of Nb_3Sn compared to WR, pancake-wound DEMO.)
  - Different jacket thickness in every layer → smaller radial build of the coil.
- An important advantage of the RW technology is the simplicity of the coil winding:
  - done in a continuous process, in which joints are made at the winding table before bending the conductor.
  - Electrical insulation is easily applicable just after jacketing.
  - Tooling is simplified and risks reduced – the coil manufacture resembles that of NbTi.
- Contrary to WR, the jacket and welds are not exposed to heat treatment, which avoids material embrittlement and simplifies quality assurance.
- Practically unlimited conductor manufacturing length (unlike in WR).

TF coil options of EU DEMO

WP#1

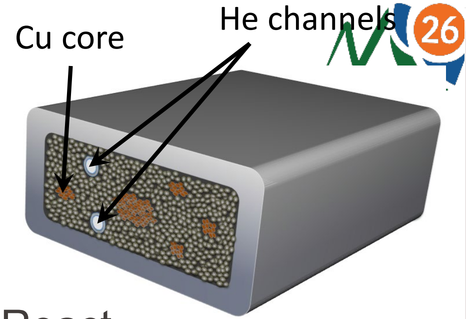


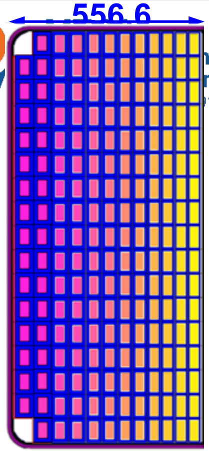


- React & Wind (low strain)
- Layer winding (grading)
- No radial plates

WP#2

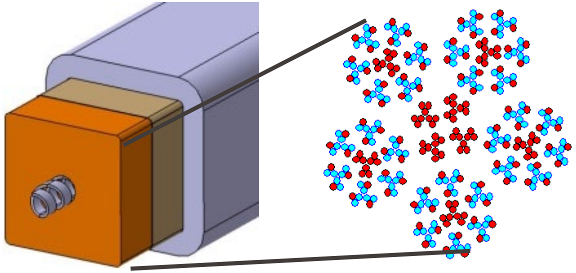
ENEA

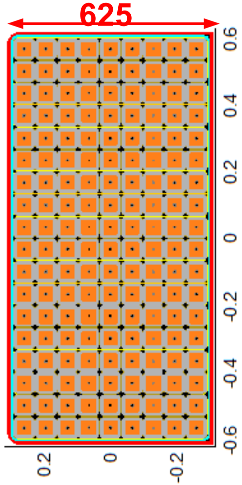




- Wind & React
- Double-Layer winding (grading)
- No radial plates

WP#3





cea

- Wind & React
- Pancake winding
- No radial plates

WP#4

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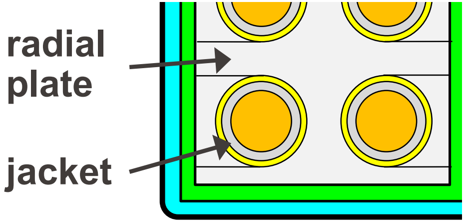

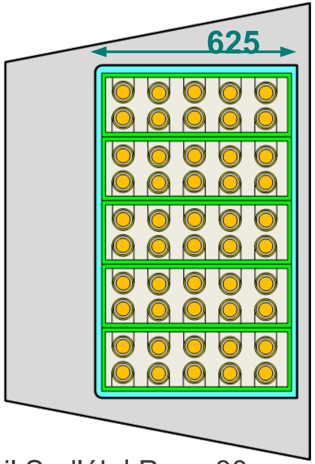

- Wind & React
- Pancake winding
- Radial plates

Conclusions

- React & Wind Nb_3Sn technology has a great potential, even though some R&D is still necessary to get it mature for an industrial-scale production.
- RW coils can be more compact than their WR counterparts and reach somewhat higher magnetic fields.
- AC losses can be low → RW conductors can be used not only in TF, but also in CS and PF tokamak coils.
- As the coil is wound after heat-treatment, they can be naturally combined with the layer-wound HTS conductors in a hybrid coil arrangement (much easier compared to WR).