EUROfusion

Update on the Conceptual Design of the EU DEMO Magnet System

Kamil Sedlák on behalf of the **DEMO WPMAG Group**

EPFL
SWISS PLASMA CENTER

MT 26
International Conference on Magnet Technology
Vancouver, Canada | 2019

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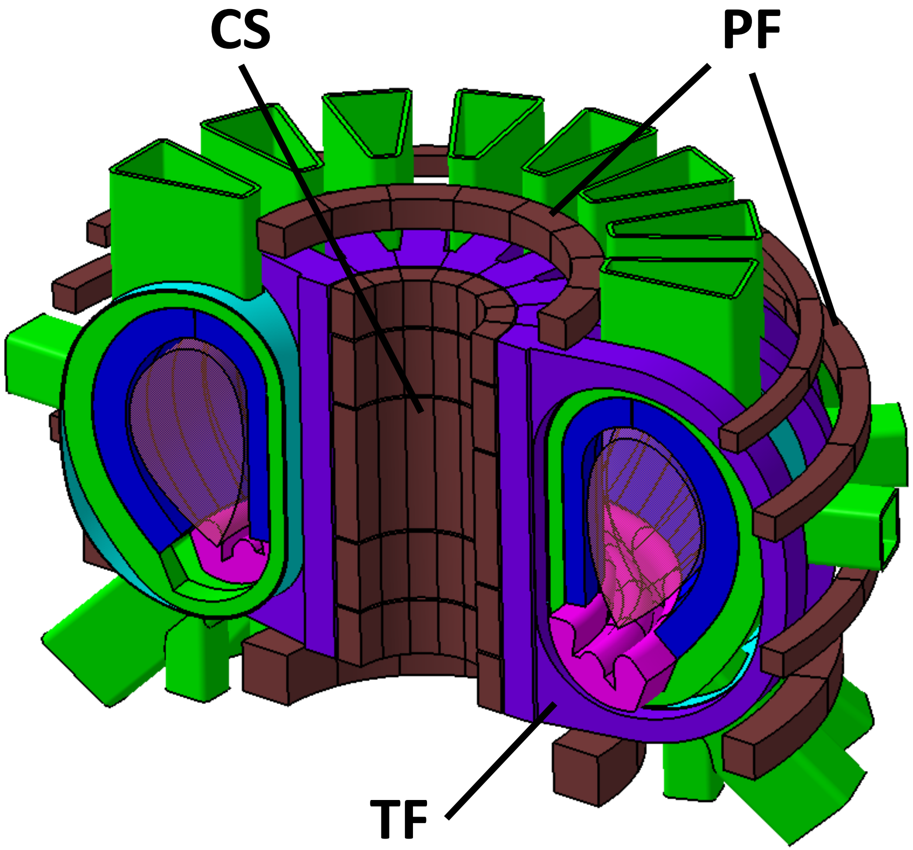
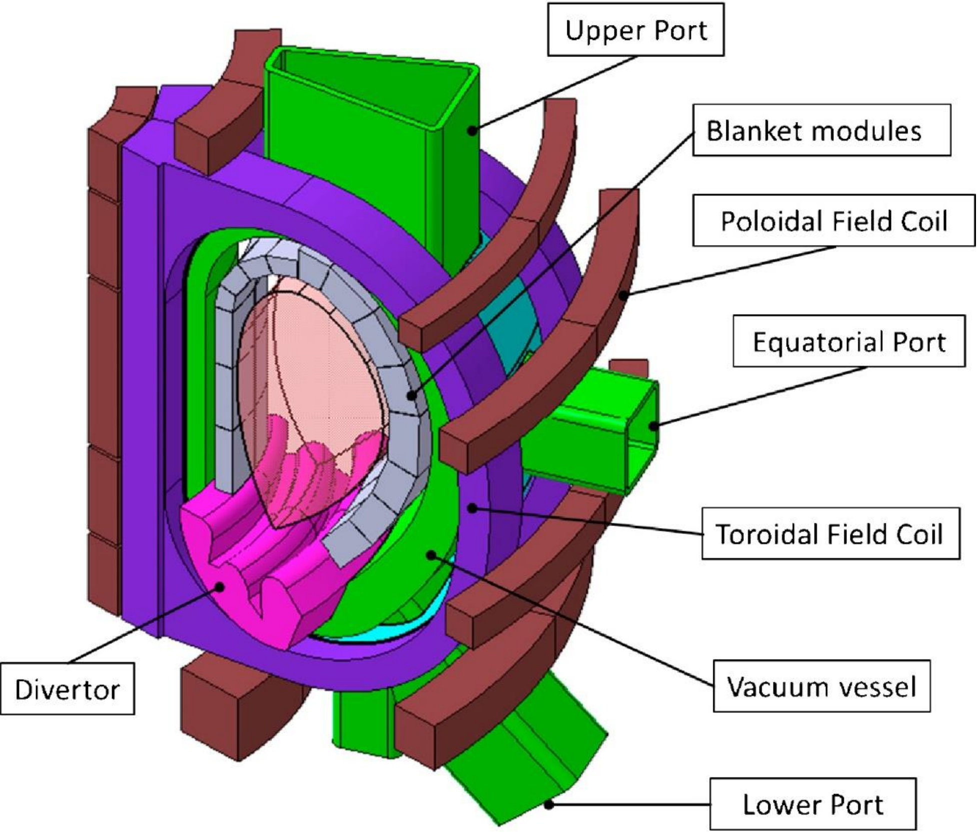
Outline

- EUROfusion DEMO
- TF coils
- CS coils
- HTS conductors development
- HTS quench experiment
- Conclusions



European DEMO



- Demonstration of net production of electricity and operation with a closed fuel cycle (TBR>1).
- **500 MW net electric power**, supplied to the grid.
- The intermediate step between ITER and a commercial fusion power plant.
- The DEMO design approach relies on a progressive flow of validation input from ITER prior the DEMO construction (2040).

DEMO and ITER Schedule

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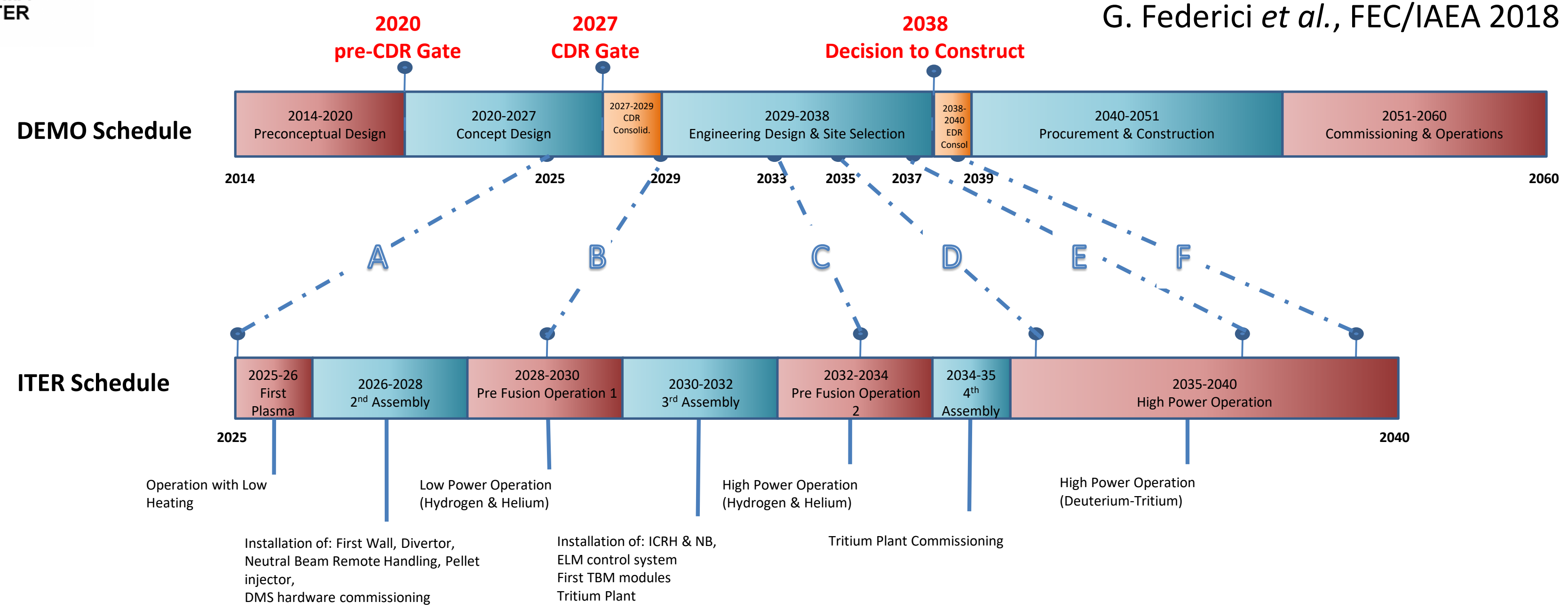
G. Federici *et al.*, FEC/IAEA 2018



A

Validated Assembly, Integrated Design, Testing & Commissioning, SC magnets, VV fabrication validation

B

Integrated diagnostics validation, ECRH performance, Disruption characterisation, Divertor remote maintenance validation

C

H-mode transition threshold, Validation of ELM control & disruption mitigation, NB & ICRH performance, Diagnostics validation, Validation of TBM fabrication

D

Burn scenarios, Bootstrap fraction, Full plasma control incl. He and impurities , First wall heat loads,, Exhaust at high power Tritium plant validation, H&CD and fuelling validation

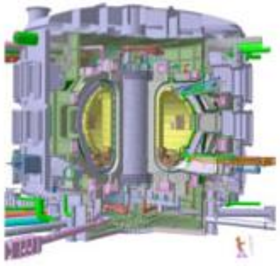
E

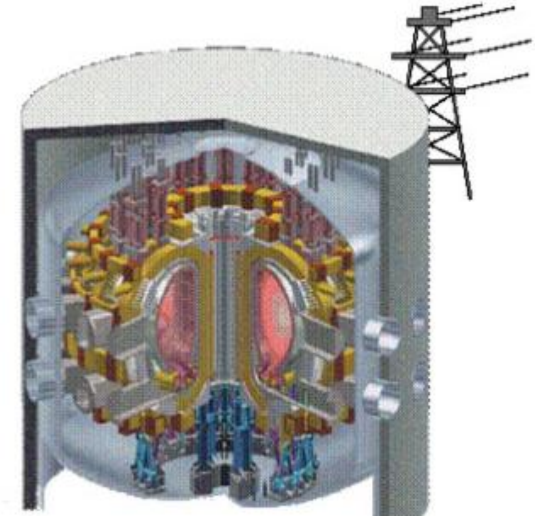
TBM Validation, Operational scenario refinement, Q=10 (short pulse)

F

Long pulse) burning plasma

DEMO Size Challenge

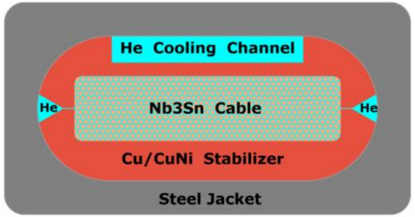


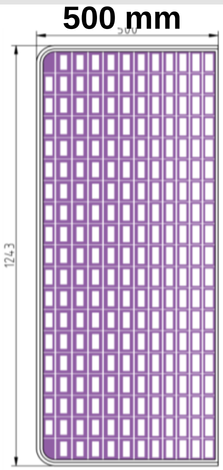


ITER		DEMO 2018
6.2	Major radius R_0 (m)	9.0
2.0	Minor radius a (m)	2.9
5.3	Magnetic field at plasma B_T,(T)	5.9
400	P_{fus} (MW)	2000
-	$P_{e,net}$ (MW)	500

TF Coils - Overview

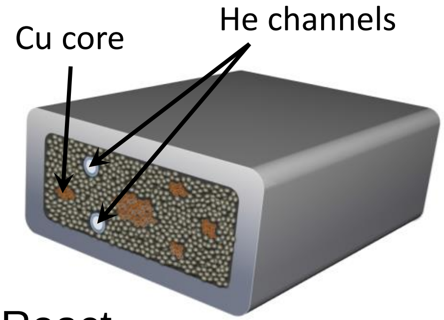
WP#1

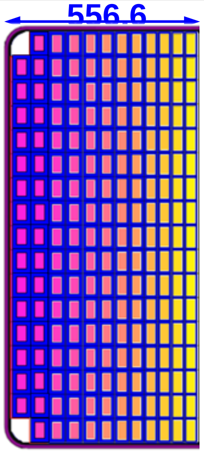




- React & Wind (low strain)
- Layer winding (grading)
- No radial plates

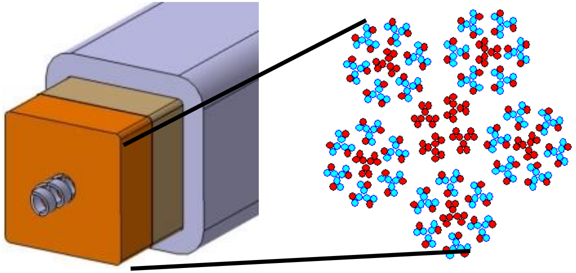
WP#2

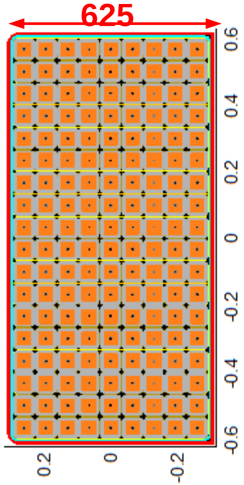




- Wind & React
- Double-Layer winding (grading)
- No radial plates

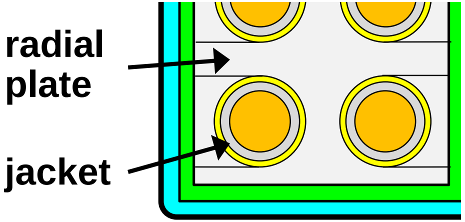
WP#3

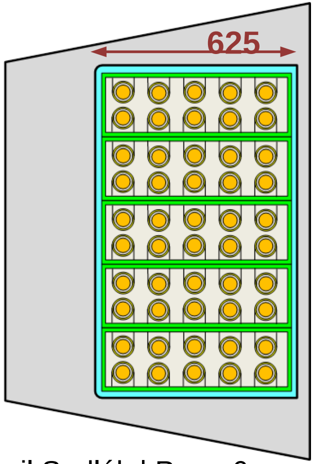




- Wind & React
- Pancake winding
- No radial plates

WP#4

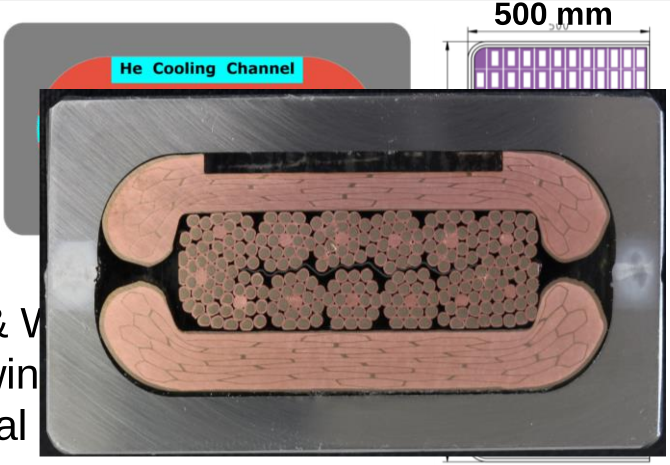




- Wind & React
- Pancake winding
- Radial plates

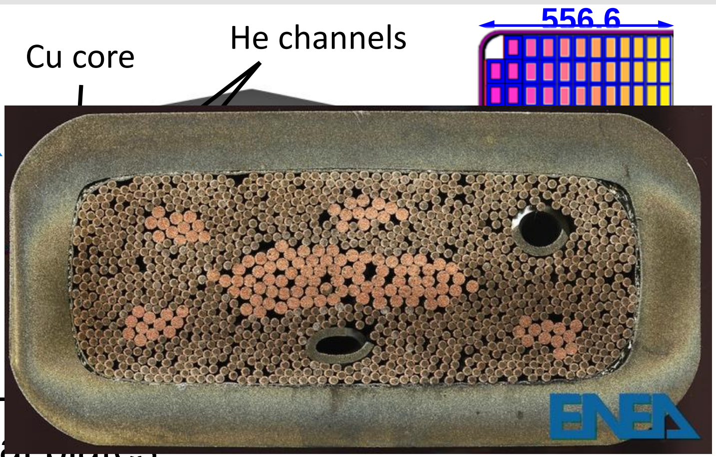
TF Coils – Prototype Testing

WP#1



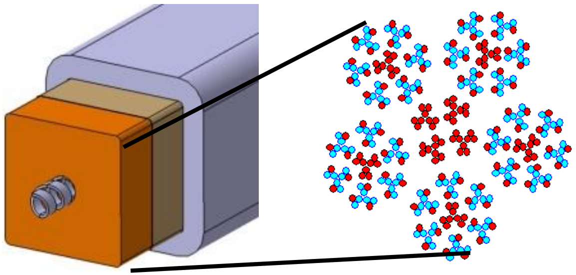
- React & W
- Layer win
- No radial

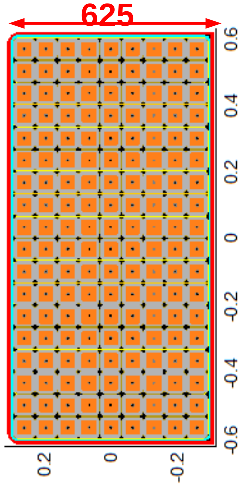
WP#2



- Wind &
- Double-
- No radial plates

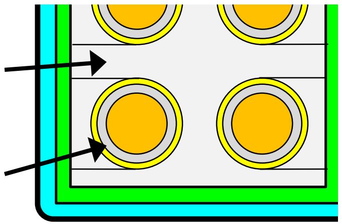
WP#3

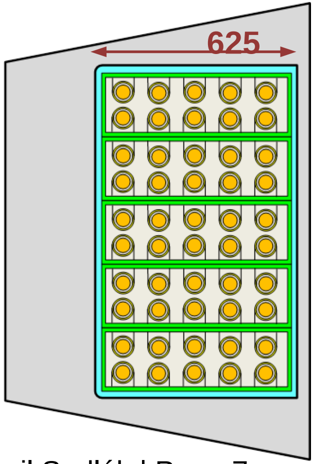




- Wind & React
- Pancake winding
- No radial plates

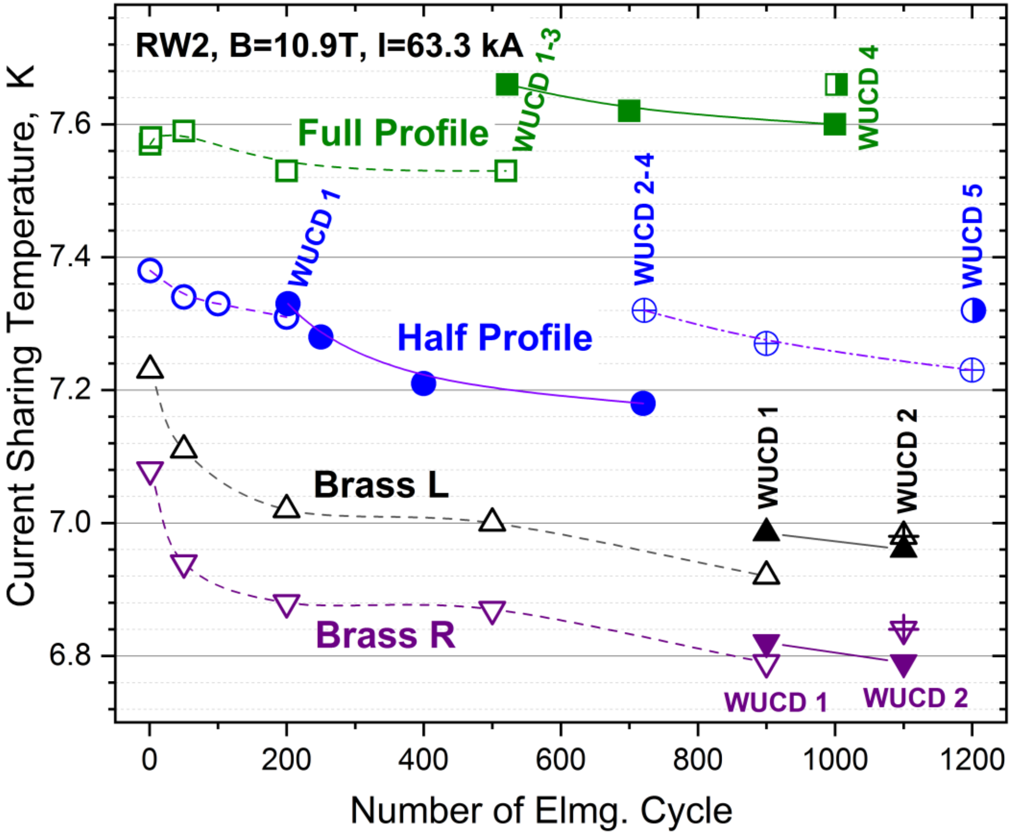
WP#4

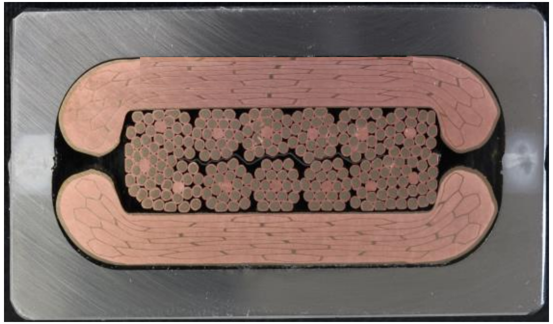




- Wind & React
- Pancake winding
- Radial plates

WP#1 – Cyclic Loading Performance





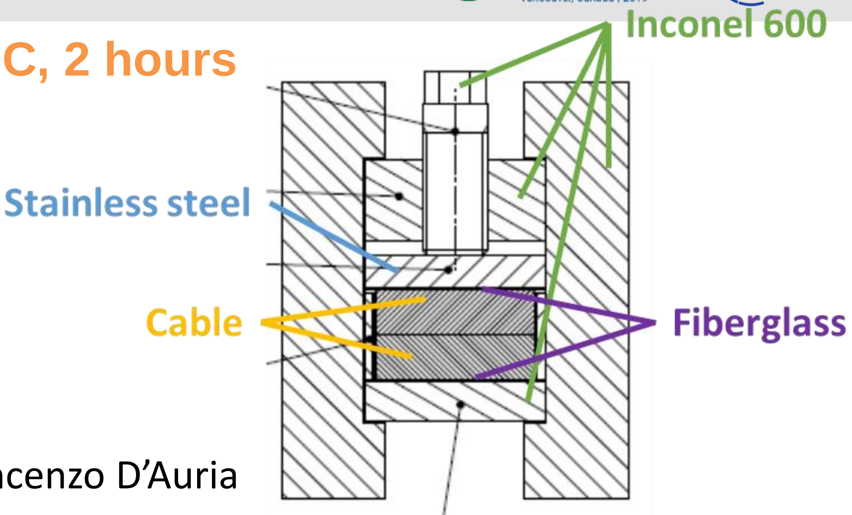
- Effective strain of the "Full Profile" sample ε_{eff} = -0.27%
- T_{cs} (63kA/12.2T) = 7.16K
- Transverse preload very beneficial for improving T_{cs}, and preventing cyclic degradation.

WP#1 – Joint Development for R&W cable

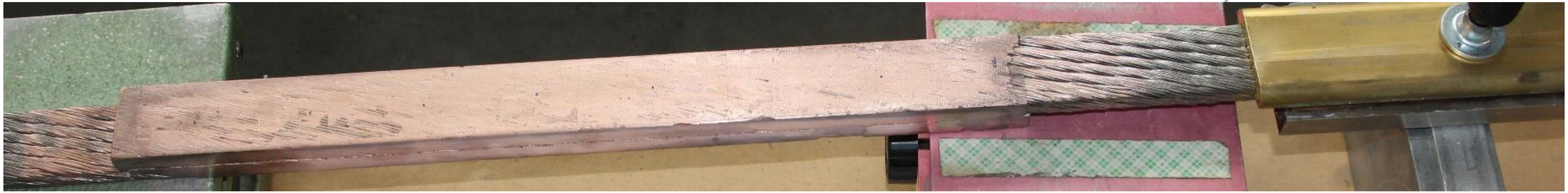
30 MPa, 650C, 2 hours

Preliminary Results:

- The first diffusion-bonded joint of R&W prototype cables successfully tested.
- $R_{Initial}$ at 10.9T and 63.3 kA = 0.7 nΩ
- R_{final} at 10.9T and 63.3 kA = 1.0 nΩ



Vincenzo D'Auria

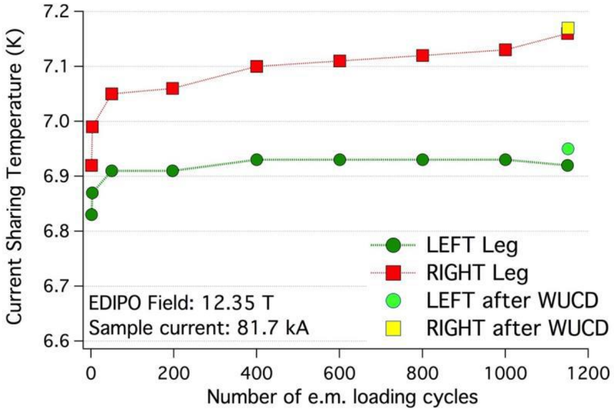


Inductive heating → transportable and compact system

WP#2 (ENEA)

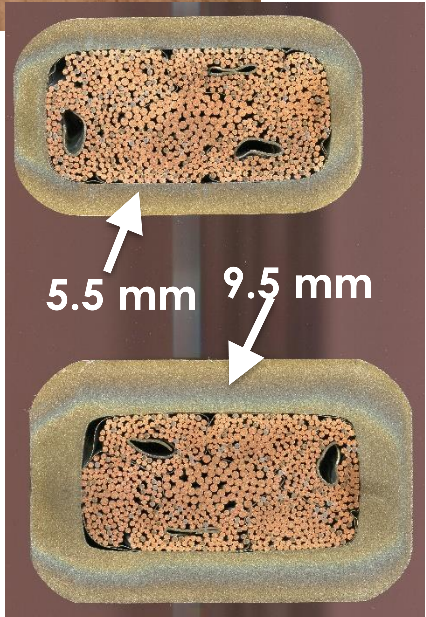
2015-2016

The first prototype successfully tested in 2016 in SULTAN. Very good DC performance (ε=-0.5%).



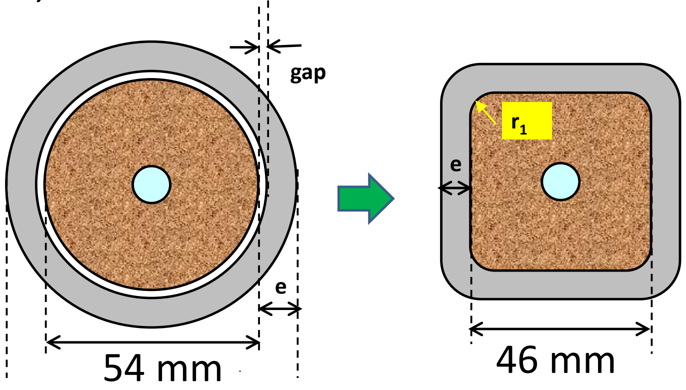
2019

- Various aspect ratios explored.
- Round-to-rectangular compaction with a thick jacket OK.
- Thin spiral (0.5mm/1mm) still to be optimized.
- **Joint sample** between two conductors of different layers being prepared for SULTAN tests.



WP#3 (CEA):

The first prototype in preparation, conductor to be manufactured by ASIPP, China in 2019.



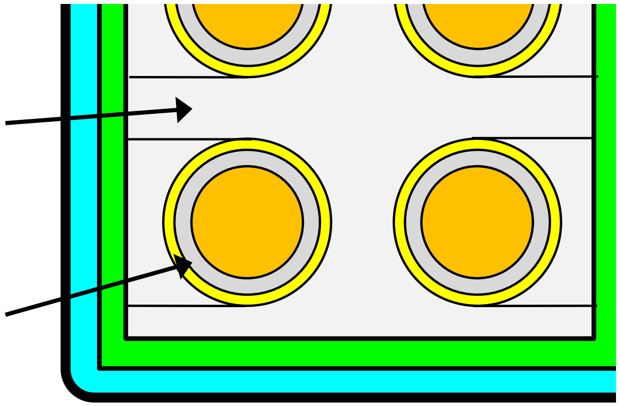
Jacket thickness	2 mm
Void fraction	32.5 %
r_2	5 mm
Gap	1 mm
Spiral ext. diam.	12 mm

WP#4 (CEA):

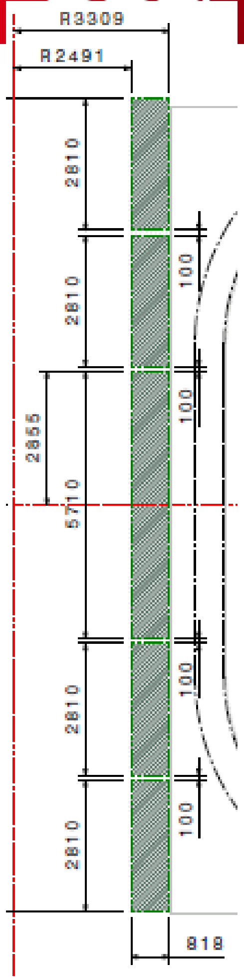
- ITER-like design with radial plates
- design work in progress
- the technology is known from ITER (no special R&D needed at this moment)

radial plate

jacket



CS Coil Option 1 – ITER-like CS

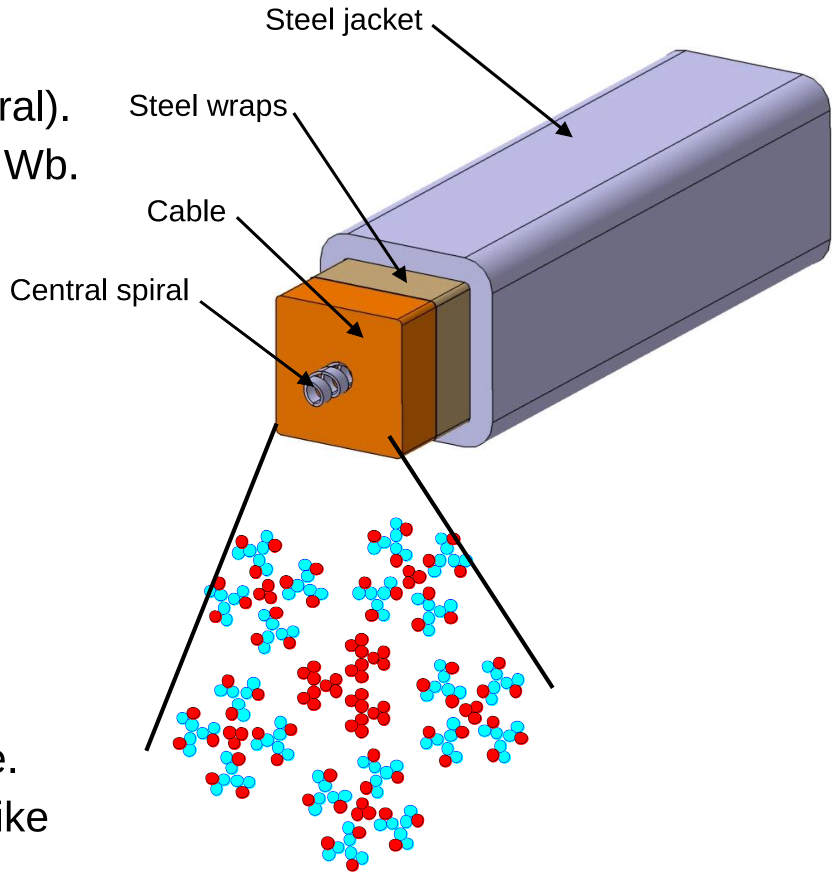


DEMO CS Coil:

- Consists of 5 modules (double central).
- 2018 design: Requested flux = 250 Wb.

Nb_3Sn Conductor main features

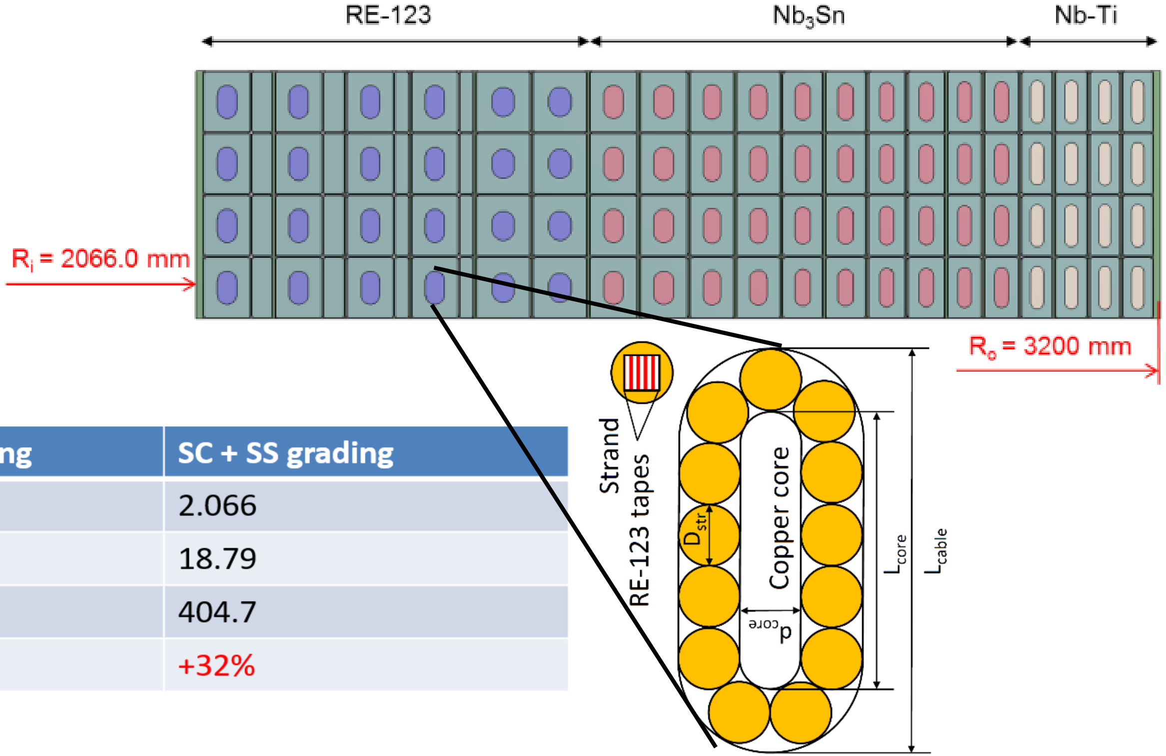
- Design very close to ITER CS.
- Cable-in-conduit concept.
- 5 stages cable (+ subwrapping).
- Strands full transposition.
- Central spiral in the cable.
- Double pancake winding.
- Wind & React manufacturing route.
- Square-in-square conductor (unlike round-in-square in ITER).



CS Coil Option 2 – The Hybrid-Coil

- Layer wound, allows grading: HTS, Nb3Sn and NbTi layers
- HTS allows to reach higher magnetic fields ➔ Smaller coil for a required magnetic flux.

Design on DEMO Reference 2015



Parameter	UCD CS1	SC grading	SC + SS grading
Inner radius [m]	1.892	1.9257	2.066
Peak field [T]	18.28	18.86	18.79
Flux (only CS) [Vs]	358.5	366.8	404.7
Gain in flux [%]	+16.8%	+19.5%	+32%

CS Coils – Fatigue Analysis

- In order to ensure fatigue lifetime (20,000 plasma cycles) using SS316LN jackets with an initial defect size of 2 mm^2 (surface) or 5 mm^2 (embedded), the **hoop stress** has to be limited to **290-300 MPa.**
- Given the space allocated for the CS coil in the DEMO baseline 2018 and the required magnetic flux (Ψ = 250 Wb), it looks not possible to satisfy the fatigue lifetime (20,000 plasma cycles + Safety factors) with a conventional steel.
- **Other strategies being investigated:**
  - buckling of the CS coil by the TF coils
  - Zylon-epoxy composite for a cylindrical support structure
  - Double-wall conduit: a soft-steel inner wall (He confinement), a hard-steel outer wall (mechanical stiffness)

HTS Conductor Development

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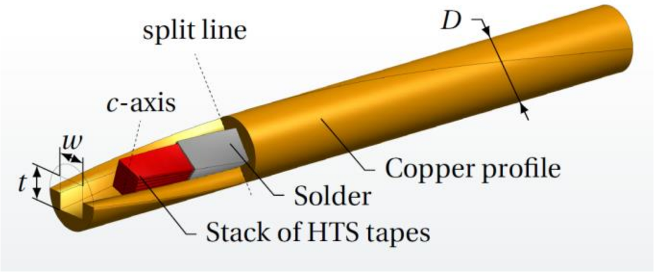
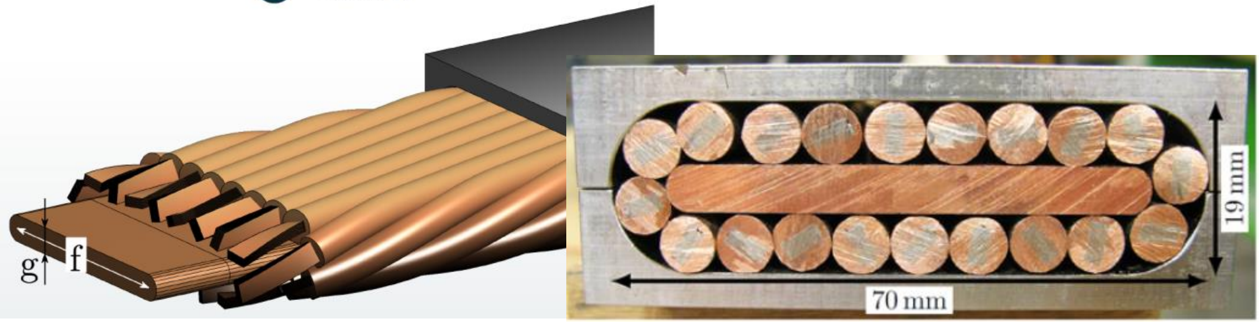
1 Strand:

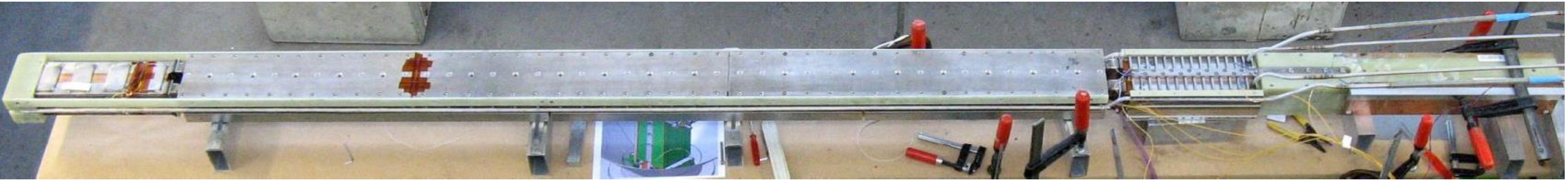


2 Cable:



2015-2016, N. Bykovsky: 60 kA/12 T full size HTS fusion cable measured in EDIPO.

- 10-20% degradation of T_{cs} after 2000 electromagnetic cycles (SuperPower and SuperOx).
- Problem tracked down to the local damages in the strands, especially at the conductor edge.
- Since 2017 – R&D of the problem, preparation for the second HTS prototype.



HTS Development 2019

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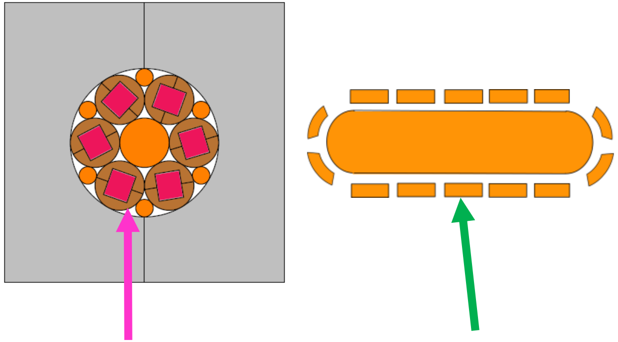
Twisted stack of coated conductors



Strands in Cu shells, circular cable

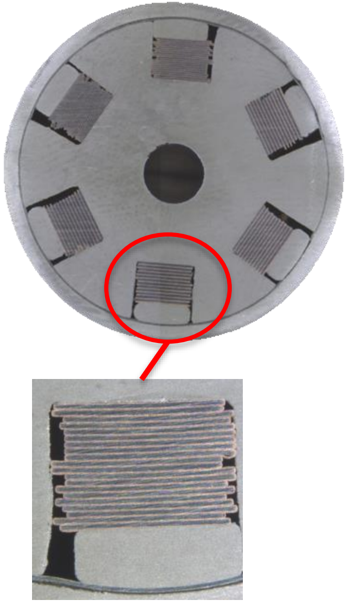
Strands in a solder around oval Cu core.

- Strand manufacture has started
- **Goal: to test the sample in SULTAN in 2020.**

ENEA

Twisted 6 slot Al-core

(t.p. = 500 mm)



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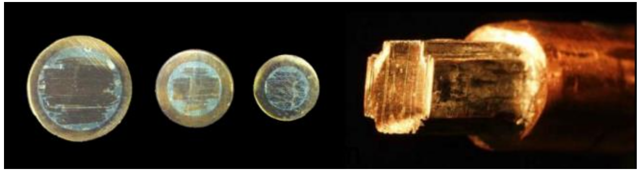

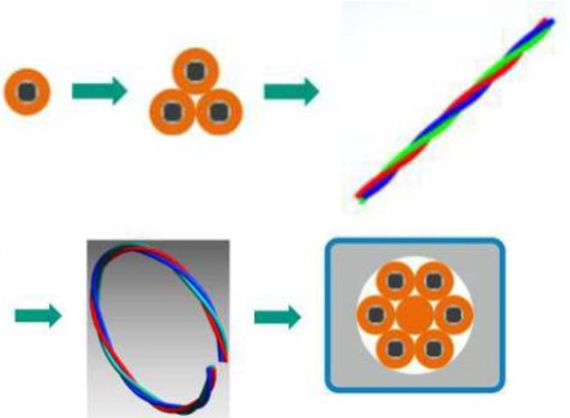

HTS CroCo: presently testing the straight triplets

HTS Quench Experiment 2020

HTS quench experiments to be done in 2020, in the scope of EU DEMO – China CFETR collaboration:

- Test facility: modified SULTAN (SPC, EPFL, Switzerland), B = 11 T.
- 100 kA supercond. transformer ➔ 15 kA power supply
- **Goal: to study the quench propagation and hot spot temperature.**

The differences to a quench in a tape/strand:

- The effect of (forced flow) Helium on the quench propagation.
- The effects related to current re-distribution within the HTS tapes, and between HTS tapes and segregated copper.
- The heat transfer in “transverse” direction (from HTS and segregated copper to the steel jacket).

HTS Quench Experiment 2020

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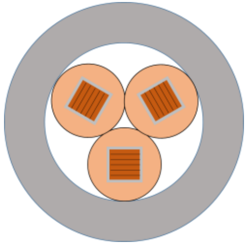

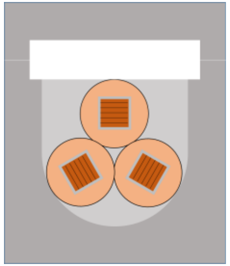

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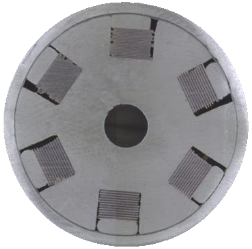

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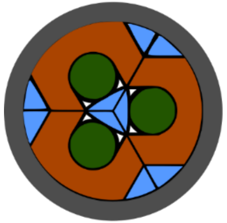


Conclusions

- Pre-conceptual design phase will finish up with a Gate Review in 2020.
- Conceptual design phase: 2020-2027.
  - Further R&D (many short samples, joints, 100-m long LTS sample, 50-m long HTS sample, insulation mock-up tests, two insert coils).
  - Down-selection of TF, CS and PF coil design options to two – a main one and a back-up solution (2024).
  - Design of a model coil.
- Construction of EU-DEMO expected between 2040-2050, operation after 2050.
- DEMO magnet design benefits from the ITER experience, but also tries to push the technology further and benefit from the technological progress of the past 20 years.
  - TF coil: React&wind technology; longitudinal welding; avoiding radial plates.
  - CS coil: High temperature superconductors in the hybrid coil.

Thanks for your attention!

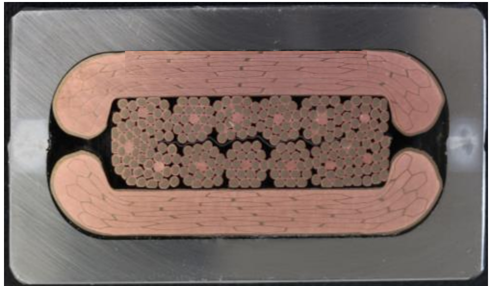
WP#1 – Performance of Prototype 2

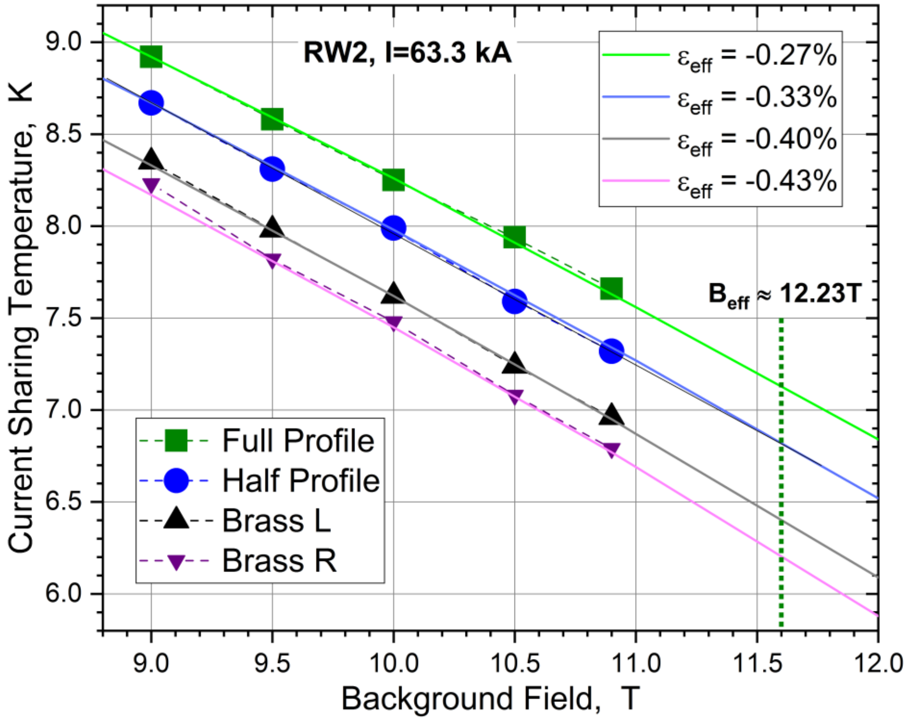
SULTAN test facility – extrapolation of T_{cs} to DEMO operating conditions.

SULTAN background field limited to 10.9 T
➔ extrapolation to B_{eff}=12.23 T.

The four samples differ in how tightly the cable is fixed in the jacket – the best performance has the pre-loaded (Full Profile) sample, with T_{cs} at 12.23 T of 7.16K (requested T_{cs} = 6.7 K).

Effective strain in the FP sample ε_{eff} = -0.27%





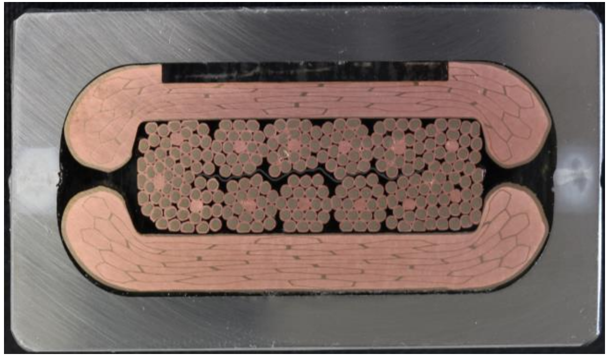
WP#1 – Performance of Prototype 2

DC test results in SULTAN very satisfactory.

AC loss of the conductor dominated by the eddy current loss in the copper matrix stabilizer. The AC loss of the cable alone (excluding the stabilizer) very small ($n\tau$ = 50 ± 10 ms) ➔ sufficiently low even for the CS coil.

Ideas for further improvements:

- Cooling channel has to be redesigned in order to allow transverse preload of the cable
- Copper matrix will be replaced by a highly compacted Rutherford cable made of copper wires coated with nickel (to reduce eddy currents).



Further Development

- **PF Coils**
  - Two design options investigated in parallel, one close to ITER, the second one trying to simplify the conductor manufacture (no separate cooling channel, jacketing with longitudinally welded half-profiles).
- **HTS conductors**
  - TF winding pack made of HTS.
  - Measurement of heat-transfer coefficients in HTS conductor geometries.
- **Cryo-Distribution Optimization**
  - The whole cryogenic cooling circuit, including the conductors, is modelled.
  - Trying to optimize the inlet temperature and helium coolant pressure drop over the (TF) winding pack in order to minimize the required refrigeration power.

Further Development

- **Irradiation studies on the superconducting materials.**
- **Studies on TF electric circuit topology; investigation of fault conditions:**
  - Nominal design of coil protected by circuit breakers and external dump resistors.
  - Alternative design with extremely long discharge time constant (linear discharge of TF coils of 200 s instead of 35 s) with current discharge driven by the power supply.
- **Mechanical, Thermal-Hydraulic, Electromagnetic analyses.**
- **Modeling of AC loss.**