

The background of the slide is an aerial photograph of a valley. In the distance, there are blue mountains under a clear sky. A river flows through the center of the valley, surrounded by green hills and forests. In the foreground, there are green fields and a road. A red banner is overlaid on the right side of the image, containing the main title. A yellow arrow points from the red banner to a building in the aerial view.

An overview of HTS high-current conductors tested in SULTAN

N. Bykovskiy

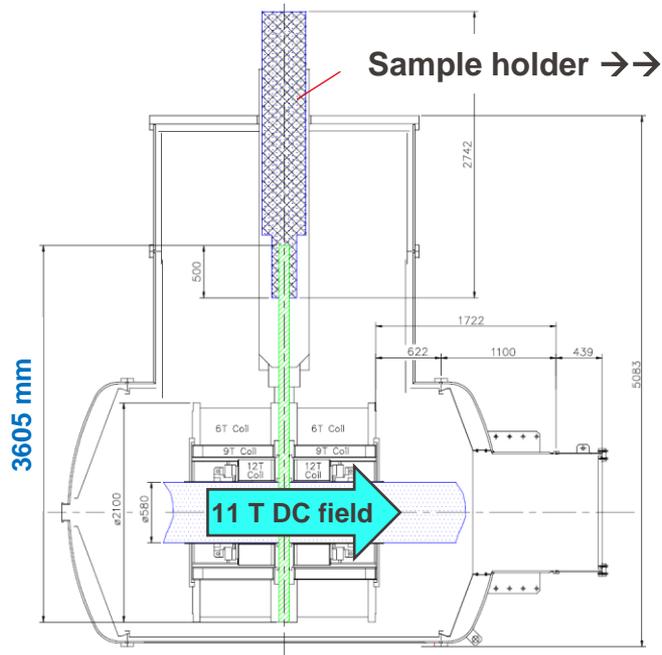
D. Uglietti

K. Sedlak

**CCA
workshop**

12 / 03 / 2025

SULTAN test facility



- ❖ **Sample volume:** 142 mm x 92 mm x 3605 mm (~400 mm HFZ)
- ❖ Supercritical helium flow cooling (10 bar, 4.5 K, 10 g/s)
- ❖ Possible testing: I_c , T_{CS} , AC loss, EM cycling, WUCD, quench, hydraulics
- ❖ Various sample holders, depending on **the main test objective:**

1: SC transformer

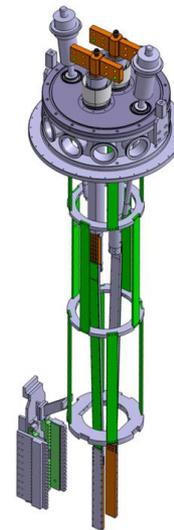


EM loading

~100 kA
<1 V
4 – 20 K

2: Direct drive operation

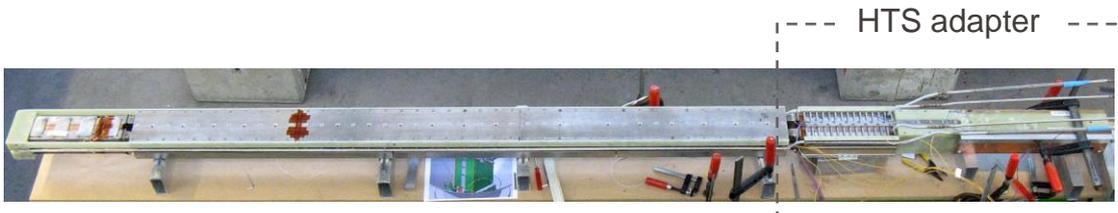
'Quench Experiment' (QE)



Quench

15 kA
10 V
4 – 300 K

HTS SULTAN samples

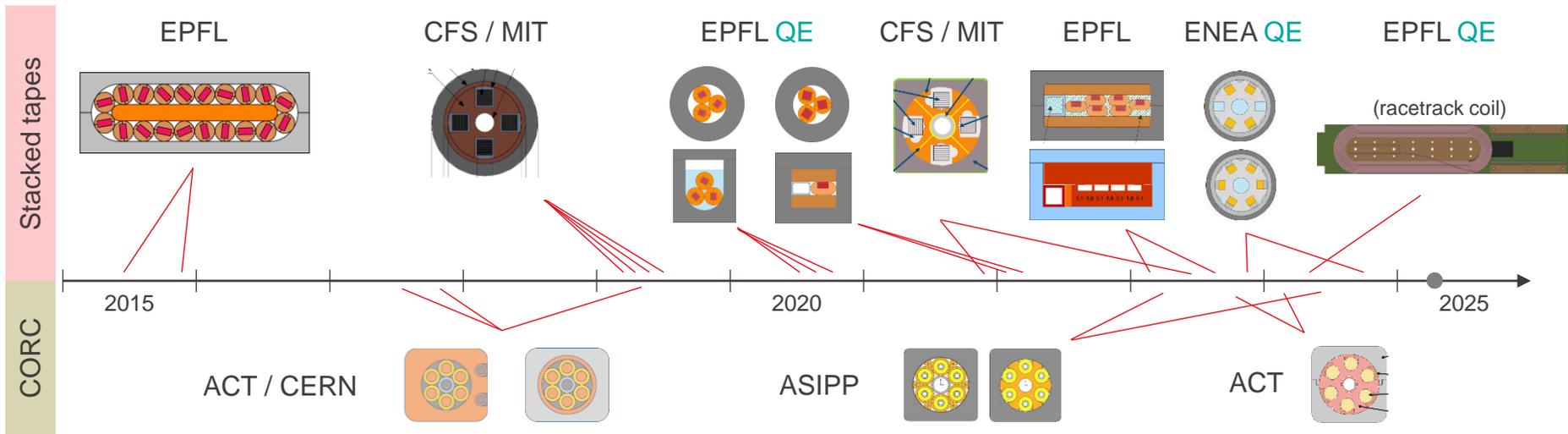


HTS adapter

A pair of ~3.6 m long conductors with joints at the top and the bottom

Samples for SC trafo can be equipped with 'HTS adapter' to reach Top ~50 K (optional, but always used so far)

An overview of HTS high-current conductors tested in SULTAN



Broad variation in the cable-in-conduit conductor (CICC) design... Is there a systematic view?

Comparison metrics (focus on tapes)

Mechanical coupling

Loose (flexible)  Rigid (resilient to EM loads)

Electrical coupling

Insulated (low AC losses)  Soldered (local current sharing)

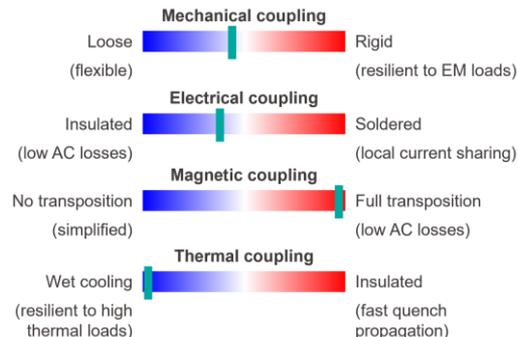
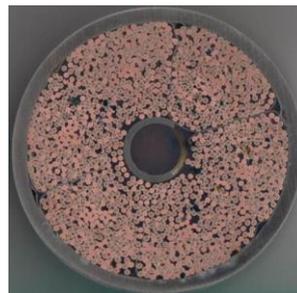
Magnetic coupling

No transposition (simplified)  Full transposition (low AC losses)

Thermal coupling

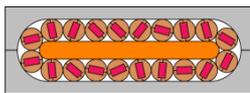
Wet cooling (resilient to high thermal loads)  Insulated (fast quench propagation)

LTS CICC as a reference:

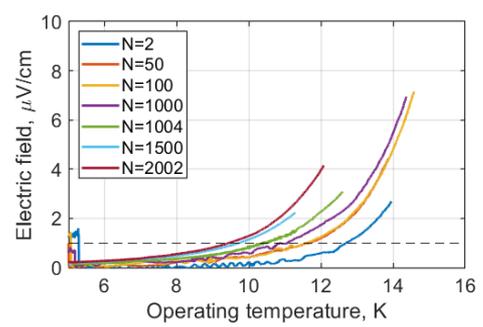
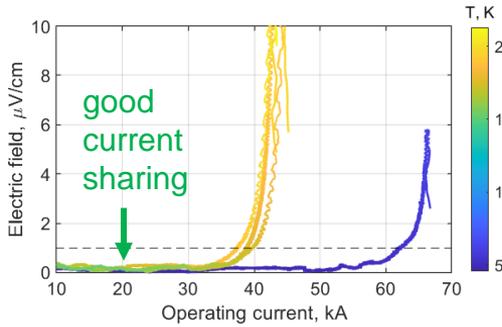
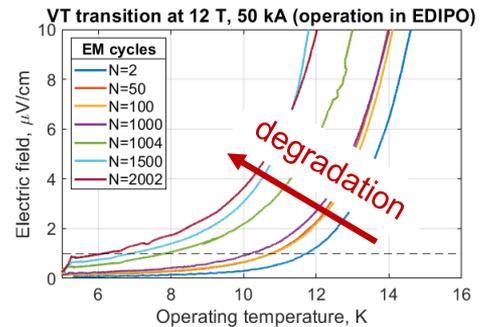
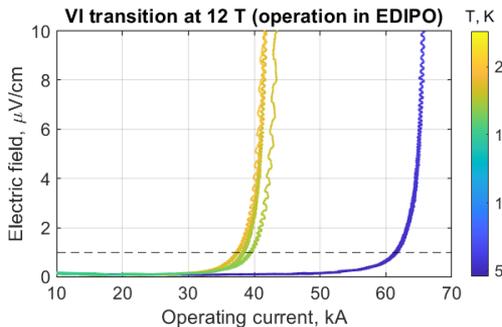
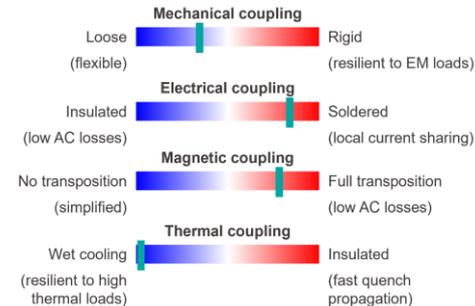


CICC is the baseline choice for LTS fusion magnets. While complex, it offers superior cooling and minimizes the mechanical impact of neighboring turns, essentially allowing model coil programs to be skipped. But is CICC also a 'must-have' in case of HTS fusion conductors?

<https://infoscience.epfl.ch/record/231964>



<https://doi.org/10.1088/0953-2048/28/12/124005>

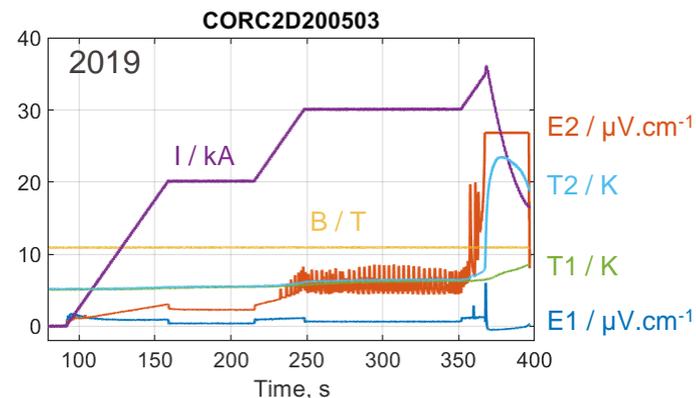
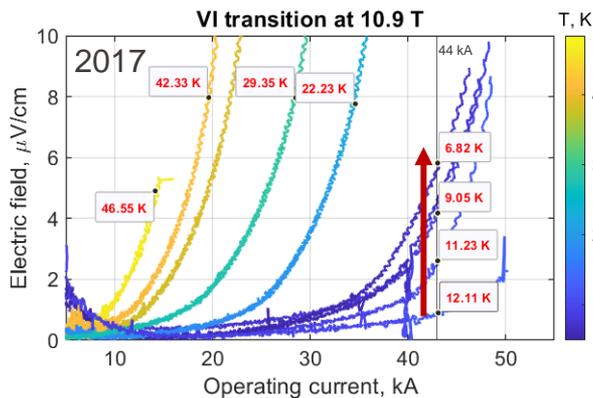
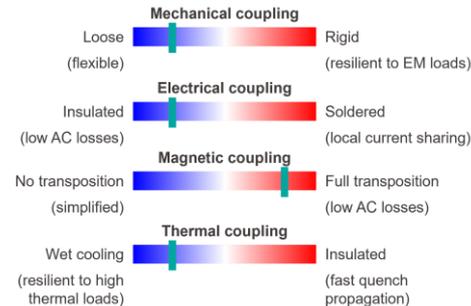
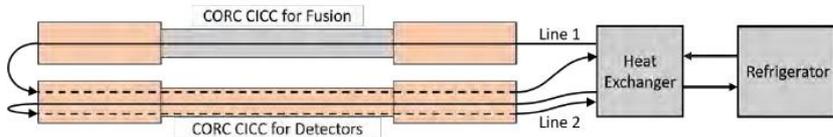


- Rutherford cable layout
- 320 tapes of 4 mm width
- Cable Lorentz force ~ 740 kN/m
- Tape transverse pressure ~ 20 MPa

EM loading strongly decreased DC performance of the two conductors



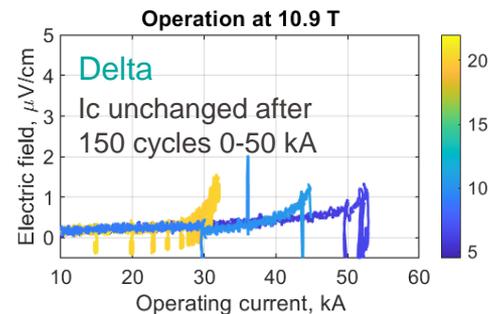
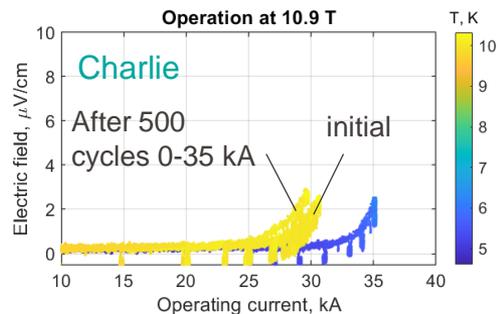
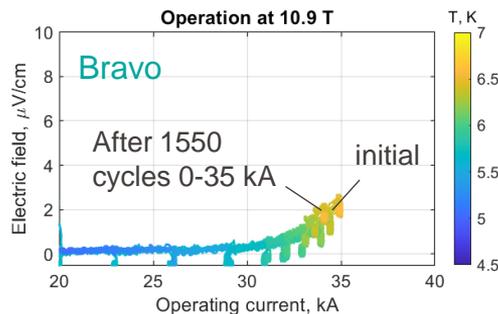
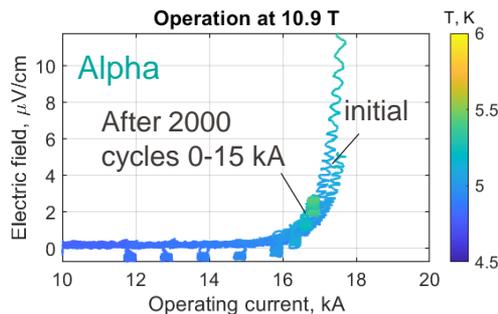
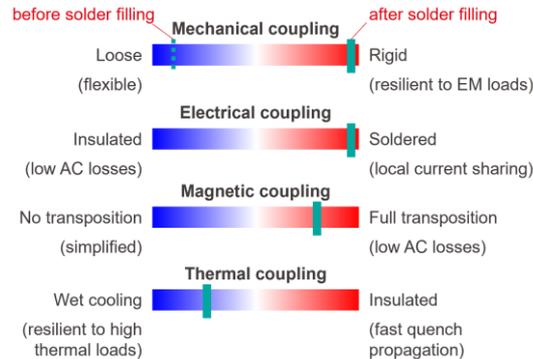
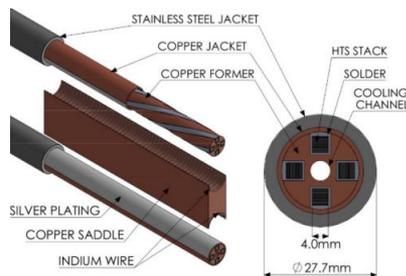
<https://doi.org/10.3990/1.9789036546164>



- 6-around-1 layout, 252 tapes of 4 mm width
- Cable Lorentz force up to ~550 kN/m in 2017
- Testing 2017 and 2019 limited by poor performance of the 'CICC for detectors' leg

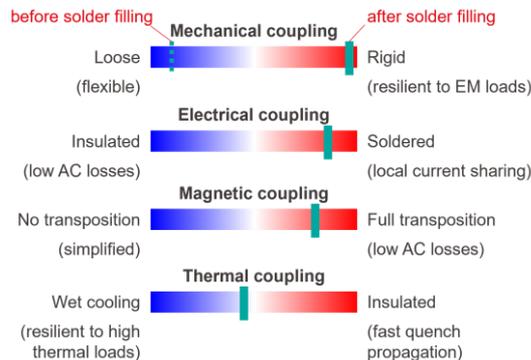
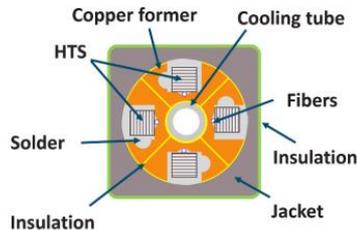
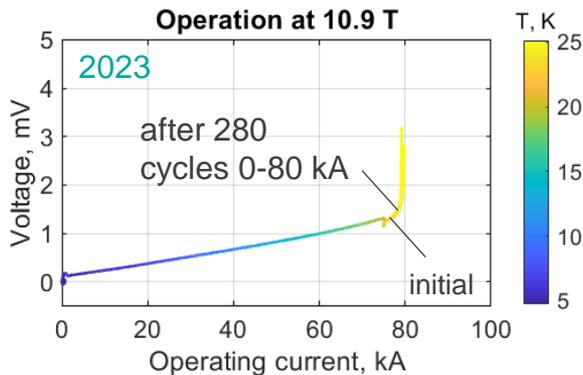
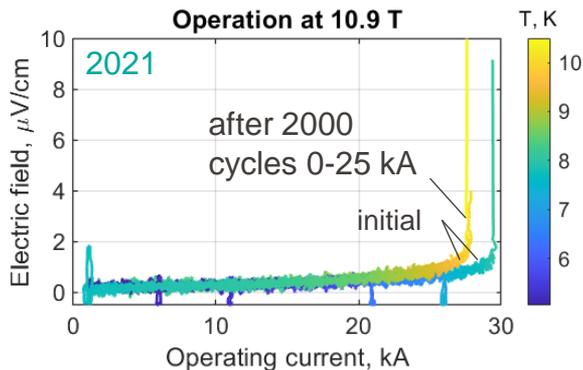
VIPER: vacuum pressure impregnated, insulated, partially transposed, extruded, and roll-formed

<https://doi.org/10.1088/1361-6668/abb8c0>



- Alpha, Bravo, Charlie:
96 tapes of 4 mm width in 1 of 4 channels
Cable Lorentz force ~ 180 kN/m (Alpha) and ~ 380 kN/m (Bravo, Charlie)
 - Delta:
200 tapes of 4 mm width in 4 channels
Cable Lorentz force ~ 570 kN/m
- Stable DC performance after EM cycling (within few percent)

<https://doi.org/10.1088/1361-6668/ad7efc>

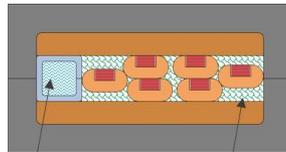
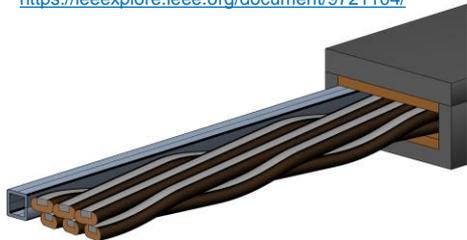


- PIT VIPER (2021):
~50 tapes of 4 mm width in one slot
Cable Lorentz force ~300 kN/m
- Test of lap joint in HFZ (2023):
Resistance ~15 n Ω at ~20 K
Cable Lorentz force ~900 kN/m

Stable DC performance after EM cycling (within few percent)

Note: pulsed-coil conductors require low T-excursion during transients \rightarrow trade-off between AC losses and heat removal

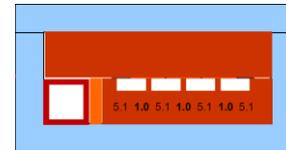
<https://ieeexplore.ieee.org/document/9721104/>



Aligned stacks
transposed in Roebel
arrangement (ASTRA)

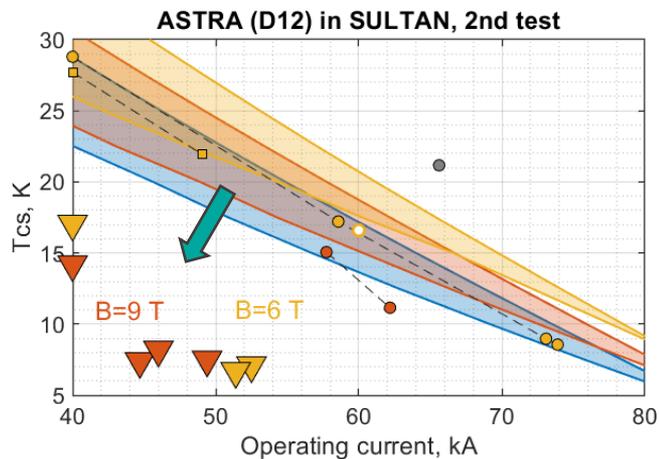
Forced flow He Impregnation

- 126 tapes of 3.3 mm width
- Aqueous DMSO impregnation

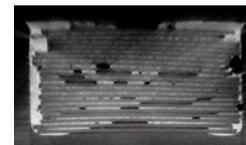
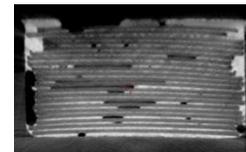


Non-twisted
non-transposed
(NTNT)

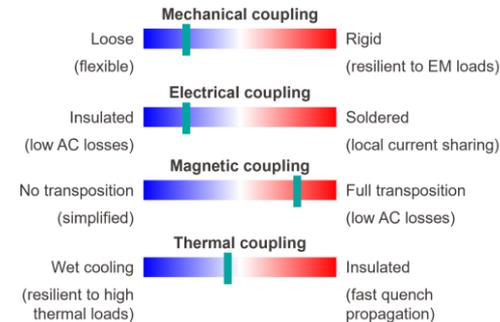
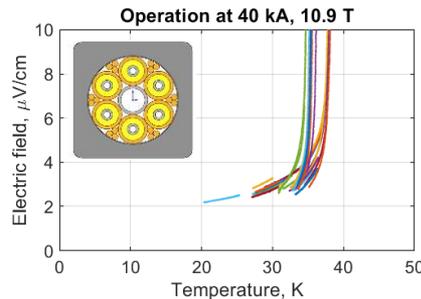
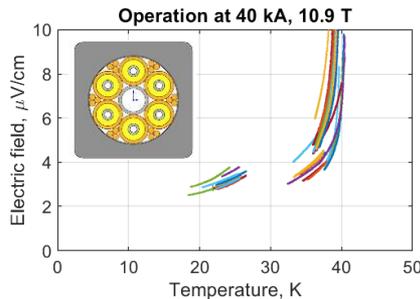
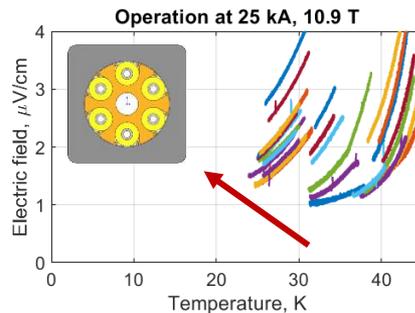
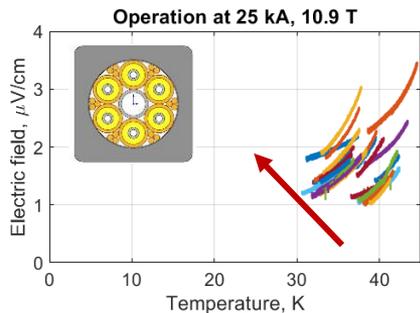
- 92 tapes of 4.8 mm width



- Initial DC performance in-line with expectations both from LN2 bath and SULTAN testing
- SULTAN testing stopped prematurely due to increasing sample terminal resistance (up to ~ 100 n Ω at 10.9 T)
- T_{cs} reduction observed after reaching EM load ~ 570 kN/m (operation at 9 T, 63 kA)
- ASTRA further degraded by stresses due to expansion of aqueous impregnation upon freezing (caused by voids present in the soldered stacks)



CORC 6-around-1 layout



2023:

- 210 and 212 tapes of 4 mm width
- Cable Lorentz force up to ~600 kN/m for EM cycling 0-55 kA at 10.9 T
- Strong I_c degradation

2024:

- 240 and 288 tapes of 4 mm width
- Cable Lorentz force up to ~920 kN/m for EM cycling 0-85 kA at 10.9 T
- DC performance substantially improved

Current sharing is a common issue leading to resistive voltage offset (data analysis is vague)

ACT (2023, 2024)

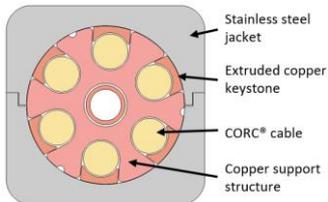
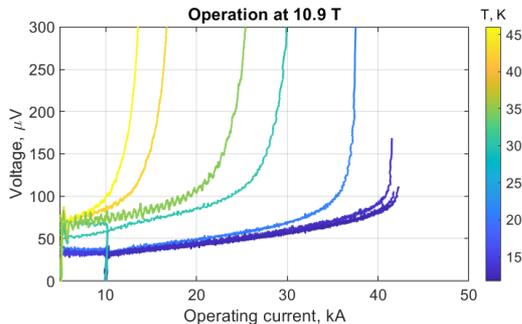
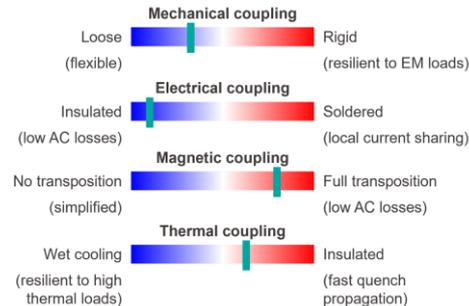
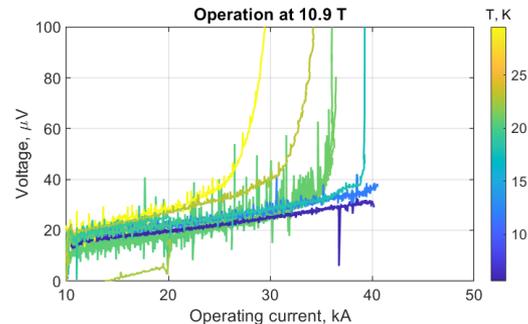


illustration of the mechanical support by copper structure (actual details may differ)



2023: $I_{\text{max}} = 43 \text{ kA}$ at 10.9 T (470 kN/m)



2024: $I_{\text{max}} = 41 \text{ kA}$ at 10.9 T (450 kN/m)

Insulated strands, thus only end-to-end voltage measurements.

Current limitation is due to thermal instability at the connection with the HTS adapter, though its standalone operation was validated at higher I_{op} (up to 60 kA @35 K, 10.9 T)



<http://infoscience.epfl.ch/record/293510>

<https://doi.org/10.1088/1361-6668/acb17b>

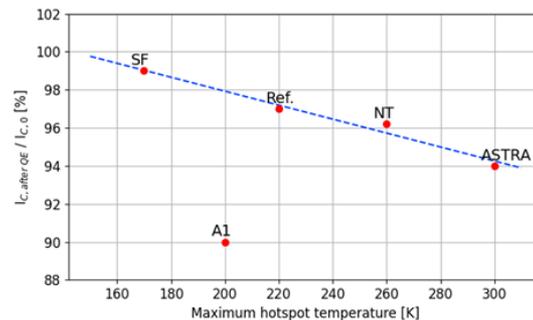
Conductor	I , kA	QPV, mm s ⁻¹	T_t , K
ASTRA ($f = 0.60$)	9	6–21	~35
	12	27–41	~30
	15	200–300 ^a	~10
BISCCO ($f = 0.25$)	12	30–100	~25
	15	40–90	~25
Ref ($f = 0.25$)	12	13–20 ^b	~40
	15	54–66	~30
No-twist ($f = 0.25$)	15	46–61	~30
Filled ($f = 0.50$)	15	11–20 ^b	~35

^a Obtained on ASTRA1 (n -value ~ 40) and ASTRA2 overcurrent.
^b Upstream quench propagation.

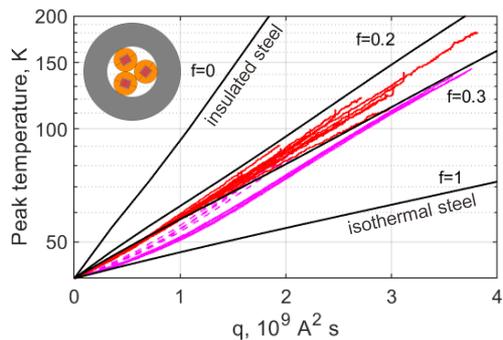
$$\int_{T_0}^{T_q} (I^2 R_1(I, T) - q_{HeP}) \cdot k \cdot dT = 0$$

$$QPV = I \left(\frac{R_1 \cdot kS}{CS \int_{T_0}^{T_t} CS dT} \right)^{\frac{1}{2}}$$

Quench temperature (T_q) and quench propagation velocity (QPV) depend strongly on cooling conditions

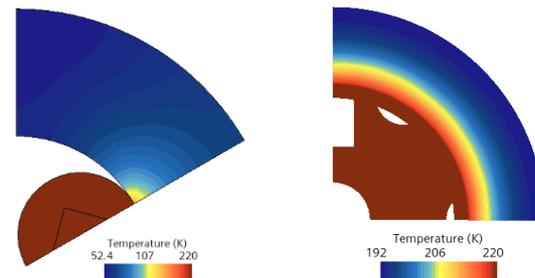


Temperature gradients lead to I_c degradation...
 Need for distributed heating during fast discharge?



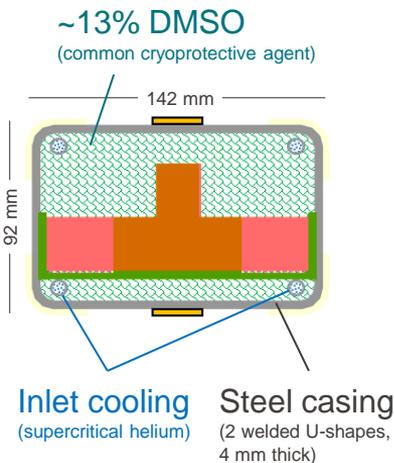
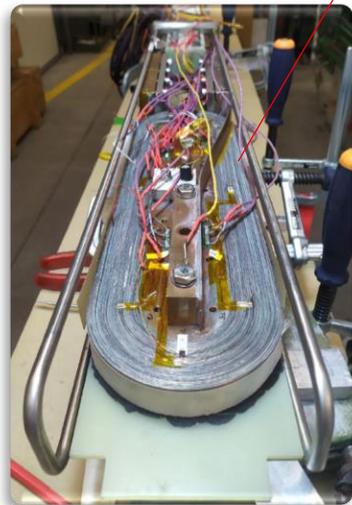
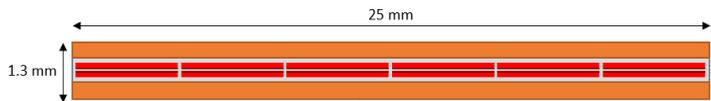
$$\int_{T_q}^{T_{max}} CS/R_1 dT = \int_0^t I^2 dt = q$$

T_{max} rises adiabatically, thus strong thermal coupling among the conductor components reduces T_{max} substantially

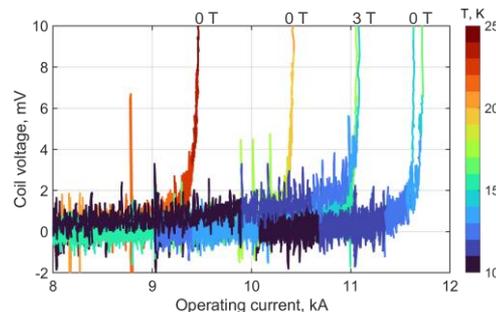
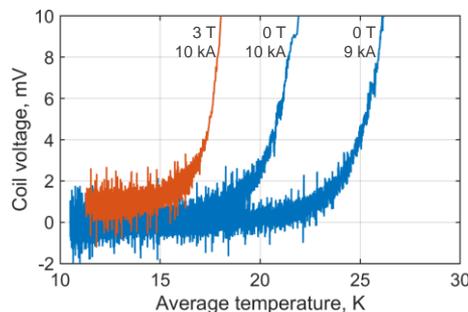
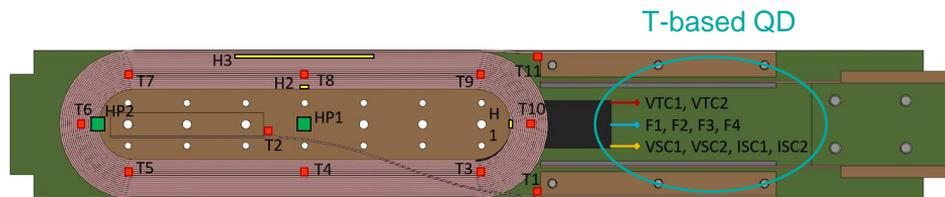


Courtesy A. Zappatore

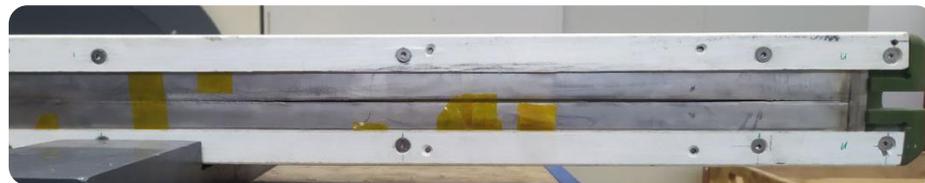
Laminated stacked-tape soldered conductor (LASSO)



- 20-turn flat racetrack
- Fiberglass turn insulation
- Impregnated and indirectly cooled



Steel casing cracked at ~1200 kN/m EM load (8.3 kA, 7.2 T)

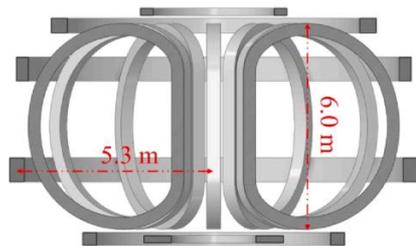


LASSO is not CICC, is it relevant to fusion magnets?

Example: 'in-situ' TF coil winding for VNS tokamak

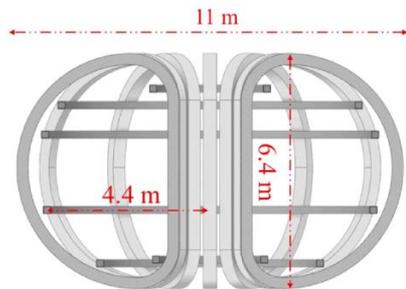
An innovative coil fabrication and assembly process for the VNS tokamak based on in-situ winding

Lorenzo Giannini ^a, Cesar Luongo ^a, Janos Balazs Bajari ^a, Christian Bachmann ^a,
Francesco Maviglia ^a, Mattia Siccino ^b, Gianfranco Federici ^c



a)

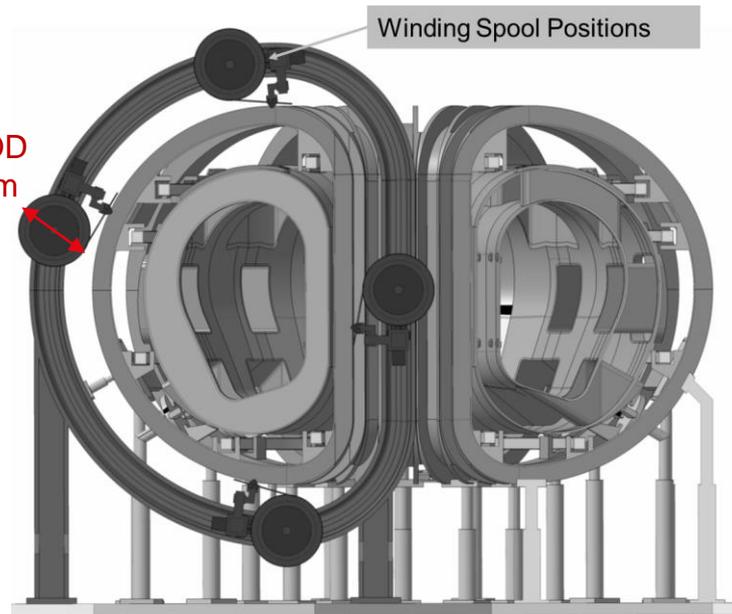
PF outside TF
(conventional for SC tokamaks)



b)

PF inside TF
(used in copper TF systems of TCV, STX, D-IIID tokamaks)

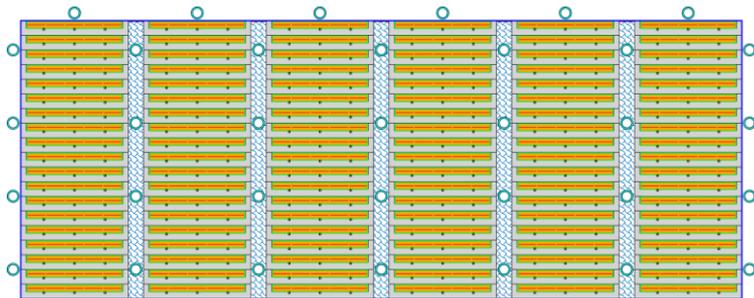
max OD
~1.2 m



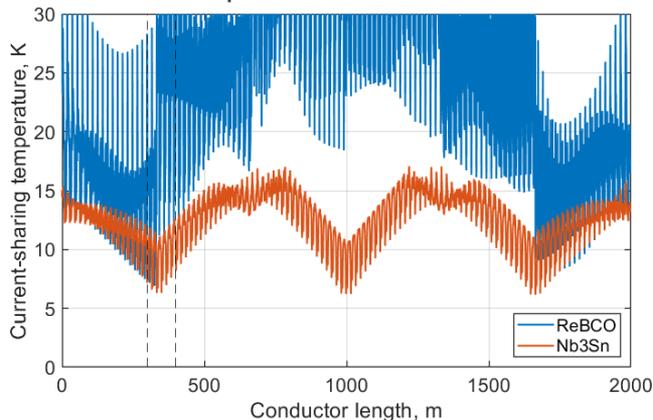
'In-situ' TF coil winding is similar to demountable TF coils in terms of advantages over conventional SC tokamak design:

- Improved plasma control (original motivation)
- Improved mechanics: bucked TF coils, not wedged
- Higher CS magnetic flux, less demanding PF system
- Simplified construction of plasma vacuum vessel

TF winding pack layout



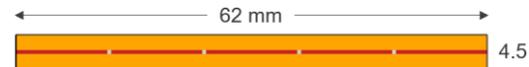
operation at 50 kA



Operating current ~50 kA at 12 T peak field

Stored on a winding spool of OD ~1.2 m

→ CICC not applicable anymore. Instead, need for thin and wide conductor cooled indirectly, i.e. excellent fit for LASSO cables.



ReBCO LASSO:

- 12 mm wide tapes, 5 x 5 stack
- T_{CS} min 6.9 K at 8.6 T, 46 deg
- Tape length ~50 km (~500 kg), cost ~3 M\$ (per coil)

Nb₃Sn React & Wind cables:

- 0.7 mm high-jc wires, 24 x (6+1) layout
- T_{CS} min 6.2 K at 12.5 T (77 deg)
- Wire mass ~1000 kg (~350 km), cost ~2 M\$ (per coil)



SULATAN 12 T conductor

ReBCO is price-competitive with Nb₃Sn even at a 13 T peak field and low T_{CS} , and it becomes a cheaper option if higher T_{CS} is necessary!

- A variety of HTS CICC conductors have been tested in SULTAN over the past decade. So far, a monolithic structure is the most effective way to prevent Ic degradation. However, it is not just about 'using soldering'; rather, the entire manufacturing process ensuring that tapes are immobilized and voids are eliminated.
- Quench characteristics are also crucial. Thermal, electrical, and magnetic aspects of the conductor design determine the quench temperature, propagation velocity, and hot-spot temperature. Consequently, they define the actual requirements for quench detection and protection systems.
- The unique characteristics of ReBCO tapes (high T_c , large aspect ratio, strong anisotropy in mechanical and electrical properties) should be seen as design features rather than flaws. For example, a conductor layout consisting of parallel indirectly cooled ReBCO tapes can be a suitable choice for certain fusion magnet applications!

Many thanks to the entire SULTAN team, as well as
Andrea Zappatore (PoliTo), Tim Mulder (CERN), Danko van der Laan (ACT),
Jinggang Qin (ASIPP), Charlie Sanabria (CFS) and Zach Hartwig (MIT)!