This work has been carried out within the framework of the EUROfusion Consortium, partially funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). The Swiss contribution to this work has been funded in part by the Swiss State Secretariat for Education, Research and Innovation (SERI). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, the European Commission or SERI. Neither the European Union nor the European Commission nor SERI can be held responsible for them.

34th SOFT 2026

34th SYMPOSIUM ON FUSION TECHNOLOGY

HTS model coils for quench protection of large-scale magnets

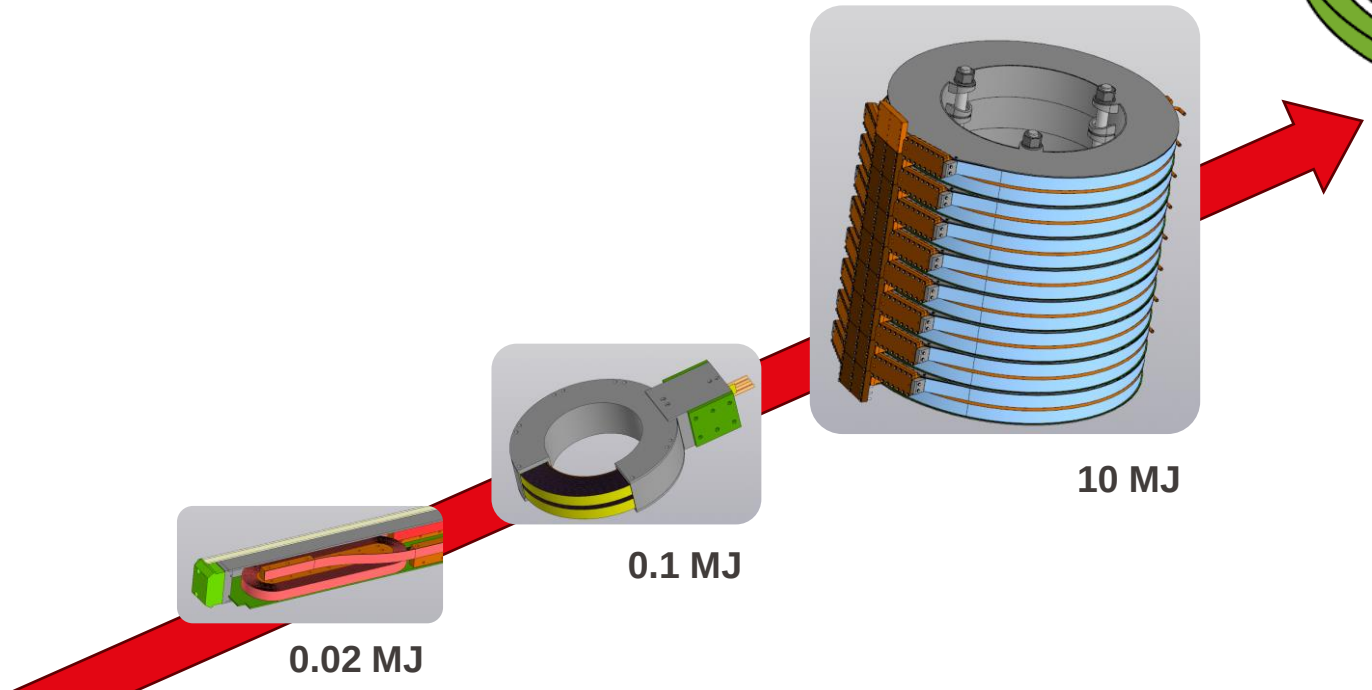
N. Bykovskiy
J. Talwar
D. Uglietti
L. Giannini
C. Luongo
A. Portone
V. Corato

SWISS PLASMA CENTER

21/09/2026

Outline

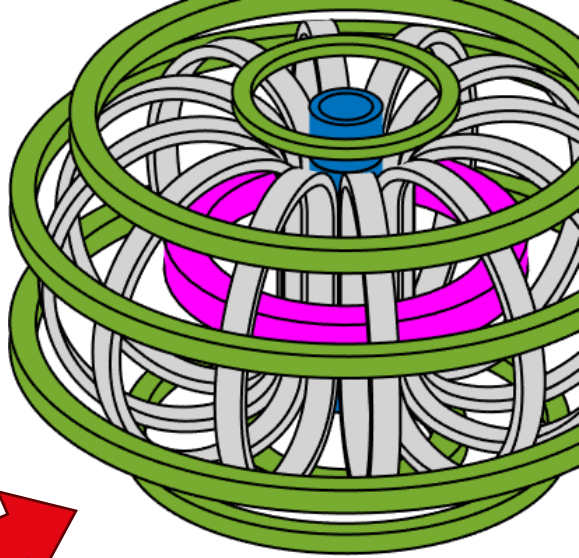
Motivation:
demonstrate maturity of insulated HTS coils for fusion



0.02 MJ

0.1 MJ

10 MJ

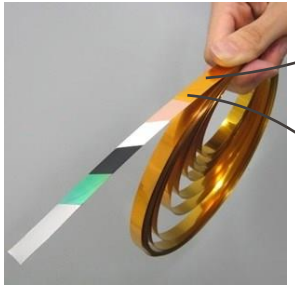


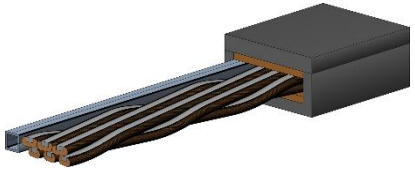
VNS magnets:
TF 4400 MJ
PF 990 MJ
CS 190 MJ

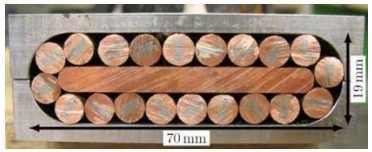
HTS fusion conductors: CICC vs 'dry'?

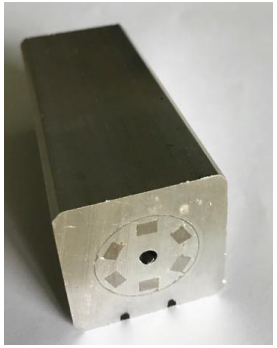
Cable-in-conduit conductors (cooling flow along transport current)

ReBCO tape

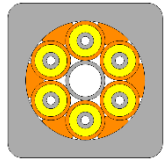




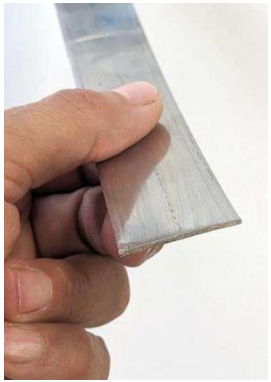










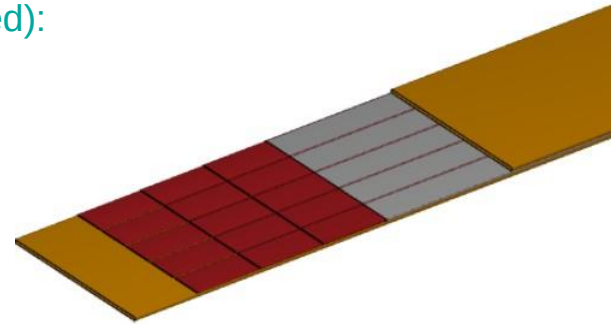


'Dry' conductors (cooling channels routed independently)

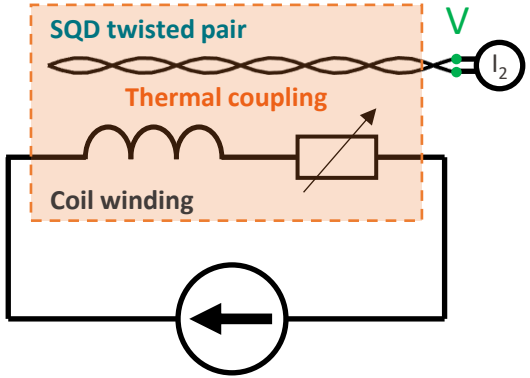
→ LASSO (laminated stacked-tape soldered):

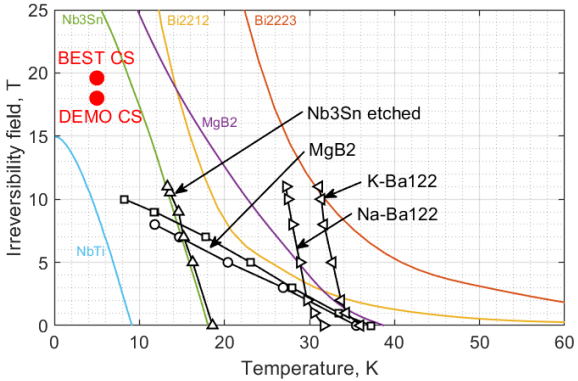
Potential advantages:

- Simplified and cheaper manufacturing
- Straightforward splicing and grading
- Industrial availability



T-based quench detection: SQD





→ measuring resistance of insulated thermally-coupled SC wire:

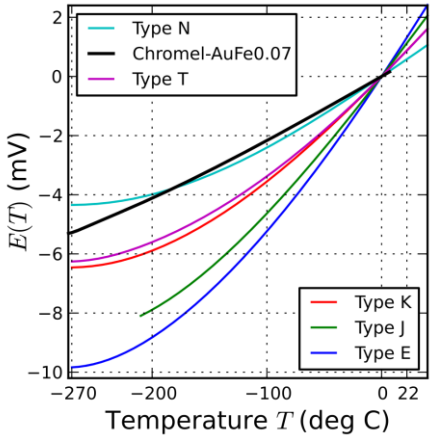
- Distributed spatial sensing
- Sensitivity controlled by I_2 and wire off-state resistance
- Twisted-pair SQD allows eliminating inductive noise and necessity of electrical contact with the main winding (no HV penetration!).
- SQD practically immune to mechanical strain
- $T_c(B_{max})$ of SQD wire > conductor Tq
  Tq of LTS conductors ~ Tc (i.e. ~10 K)
  Tq of HTS conductors? It depends… (10 to 40 K)
- Hot-spot cannot be localized

T-based quench detection: TCC

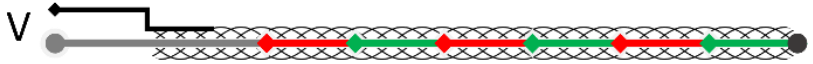
Conventional thermocouple:
response on ΔT **only at the ends**



$$V = \int_{T_{\text{ref}}}^{T_{\text{sense}}} (S_+(T) - S_-(T))\, dT = E(T_{\text{sense}}) - E(T_{\text{ref}})$$

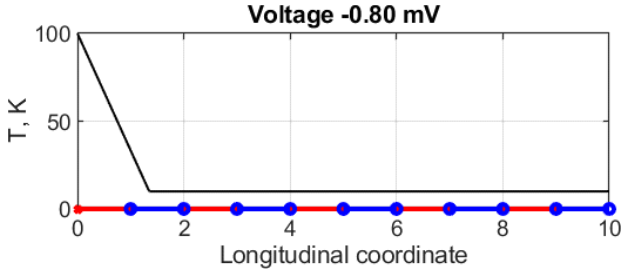


Array of thermocouple wires connected in series:
response on ΔT **along the length**

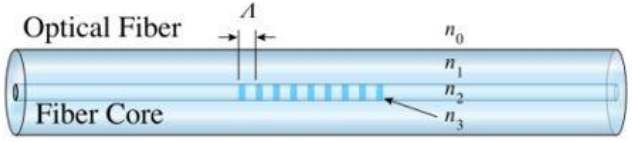


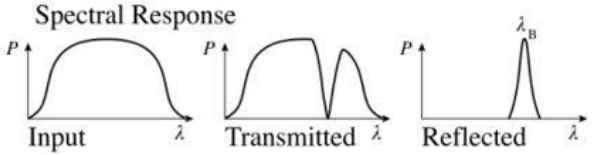
→ measuring voltage over series connected thermocouple wires ('thermocouple chain' TCC):

- Continuous response on T gradient among joints
- Immune to EM noise by using shielding sleeve
- Varying sensitivity due to discrete sensing
- Hot-spot cannot be localized



T-based quench detection: optical fibers





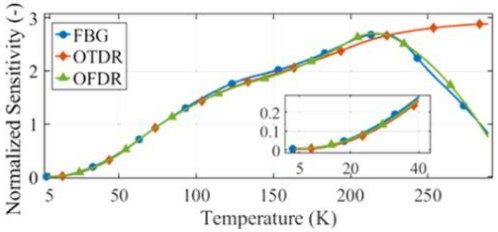
→ measuring spectral shift of light reflected by each FBG:

- Continuous temperature monitoring at each FBG location
- Impact of mechanical strain should be eliminated or distinguished
- Brittle; high spatial resolution over long length is cumbersome

Alternatively, distributed fiber-optic sensing (DFOS)…

1. Rayleigh OFDR by ENEA:

Spatial resolution ~5 mm, Rate ~100 Hz, Range ~0.1 km

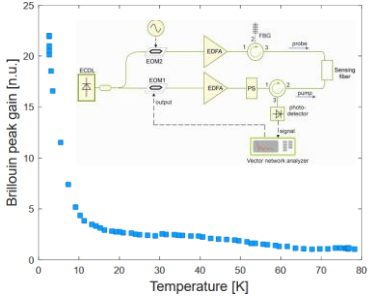


Sensitivity decreasing at low temperature

https://doi.org/10.1109/TASC.2025.3532931

2. Brillouin OFDA by University of Campania:

Spatial resolution ~10 mm, Rate ~10 Hz, Range ~0.3 km

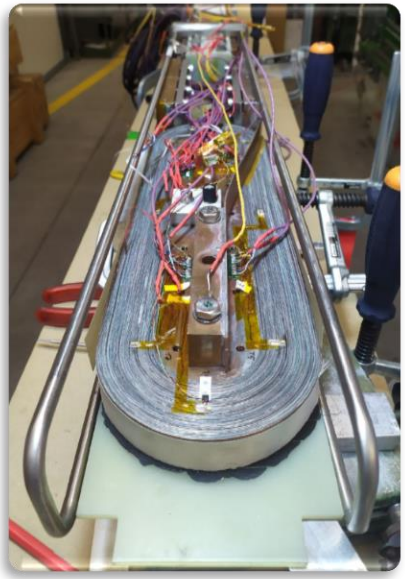


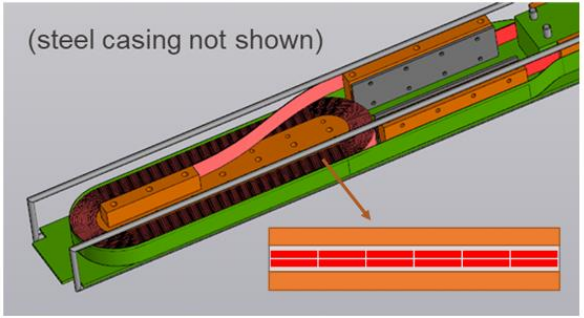
Closed-loop sensing

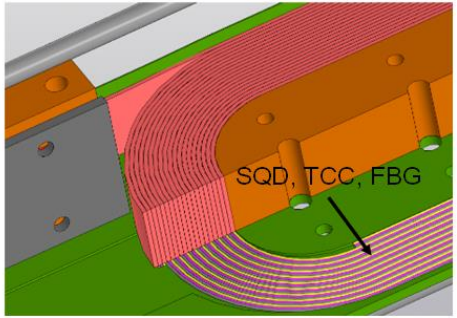
Sensitivity increasing at low temperature (!)

https://doi.org/10.1109/SAS60918.2024.10636574

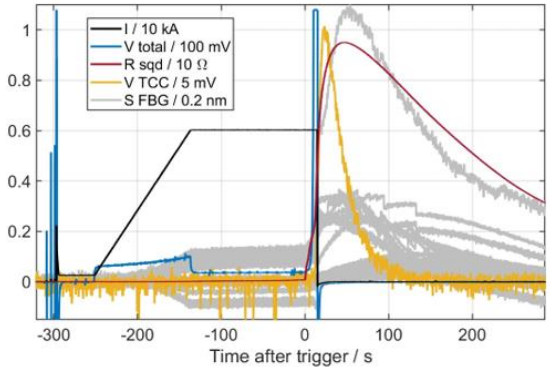
Sample 1: flat racetrack coil tested in SULTAN (2024)

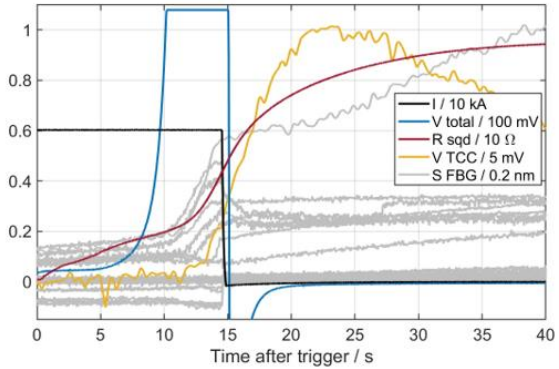




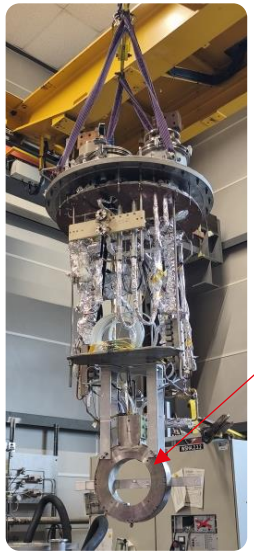


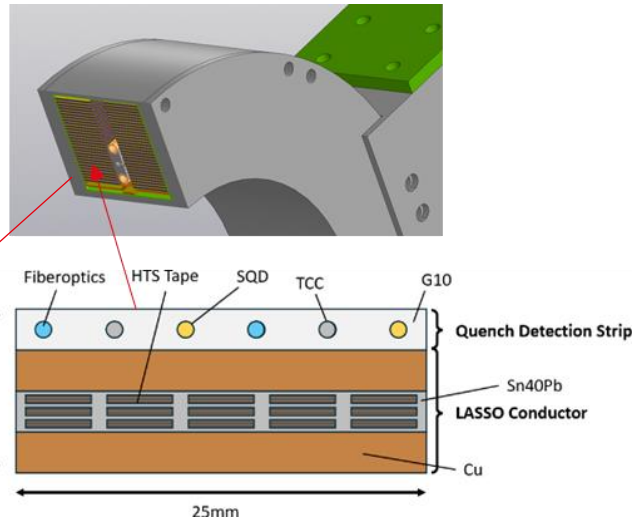
- ~20 m long 12-tape LASSO
- Impregnated by 13% DMSO
- Nb_3Sn SQD wires
- TCC copper shielded



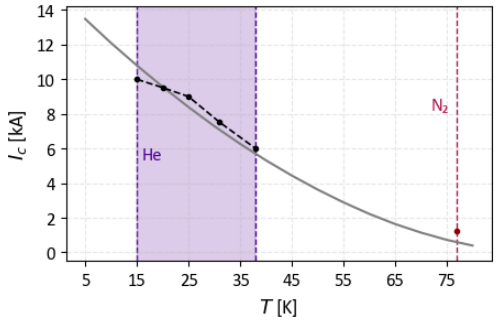


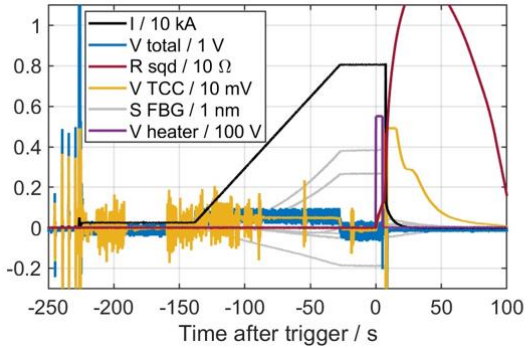
Sample 2: double pancake coil tested in JORDI (2025)

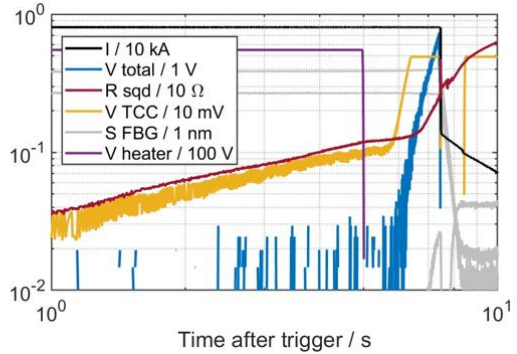




- ~50 m long 15-tape LASSO
- ID 200 mm, L ~1 mH
- Cooling pipe placed between the pancakes
- Impregnated by 13% DMSO
- Nb_3Sn SQD 0.2 mm wires
- DFOS placed between turns, FBG between pancakes





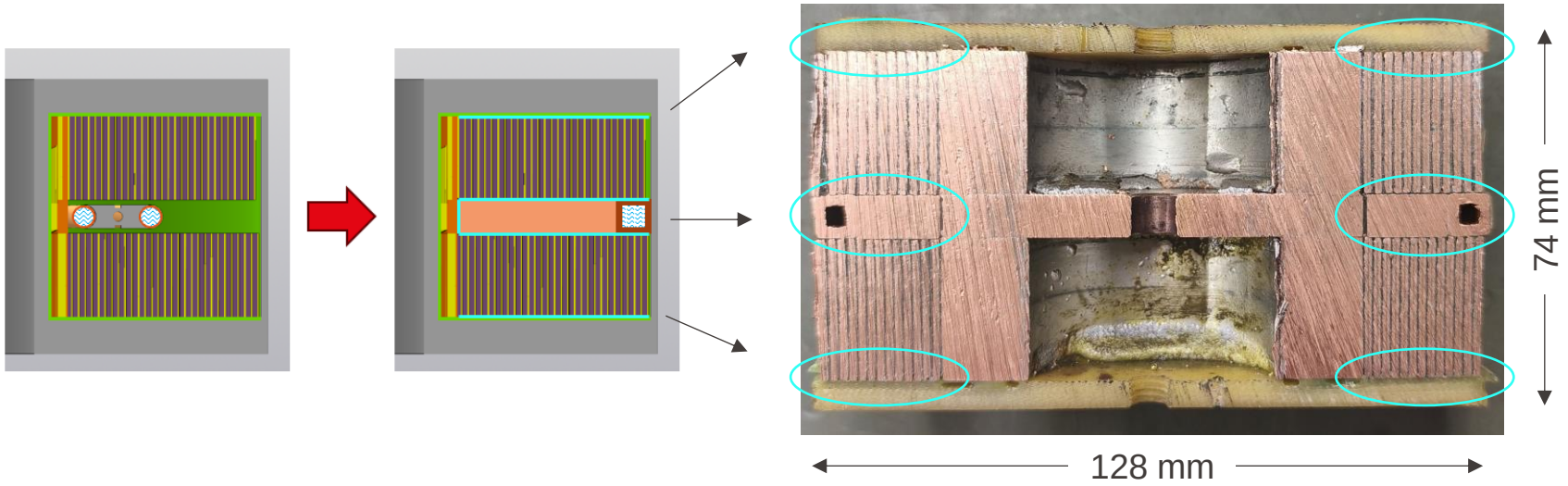


Sample 3: double pancake coil in SULTAN (2026)

Aiming to validate mechanical support structure for coil operation up to ~18 T / 10 kA

Main modifications:

1) aqueous DMSO → pre-preg edge impregnation

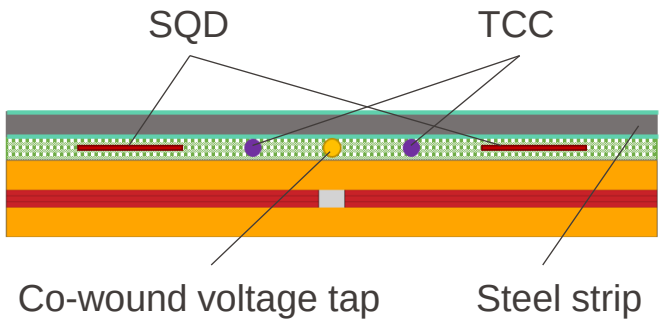


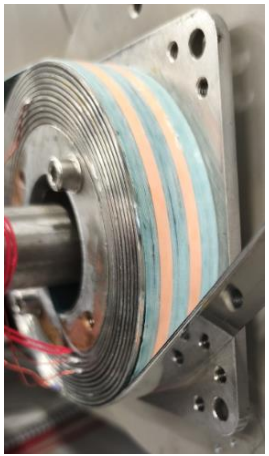
Sample 3: double pancake coil in SULTAN (2026)

Aiming to validate mechanical support structure for coil operation up to ~18 T / 10 kA

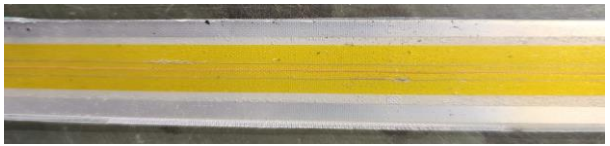
Main modifications:

1) aqueous DMSO → pre-preg edge impregnation
2) Nb_3Sn → ReBCO SQD





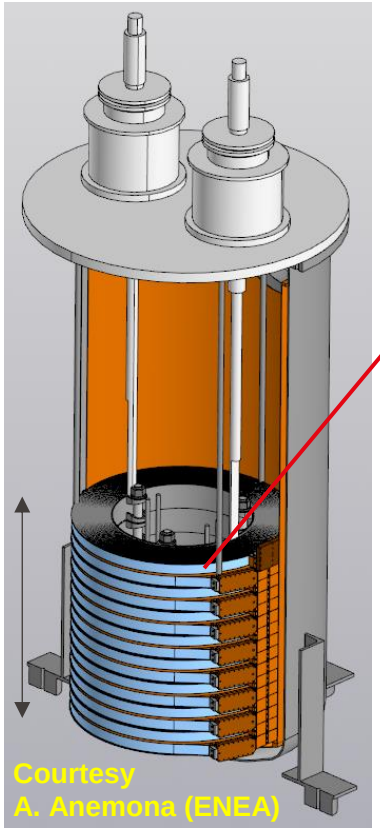




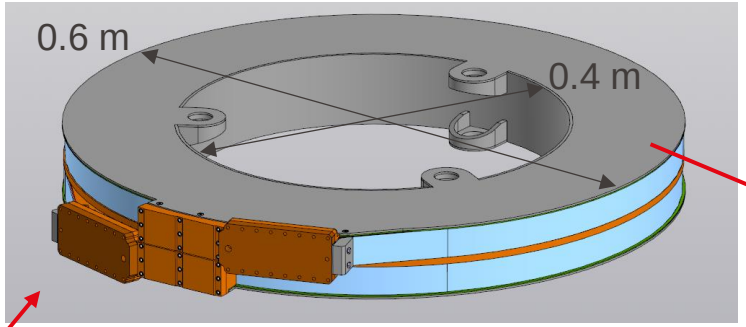
- Heat treatment of SQD ReBCO tapes for improved QD performance by decreasing Tc and Ic
- Various integration layouts being studied…

10 MJ sample for testing in JORDI (2027-2028)

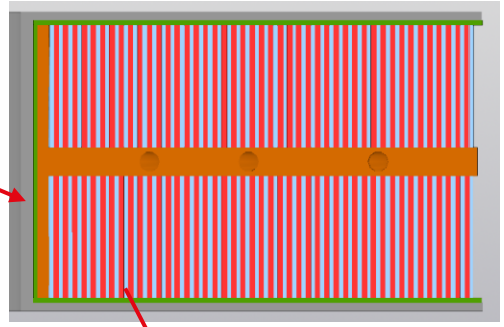
JORDI test stand

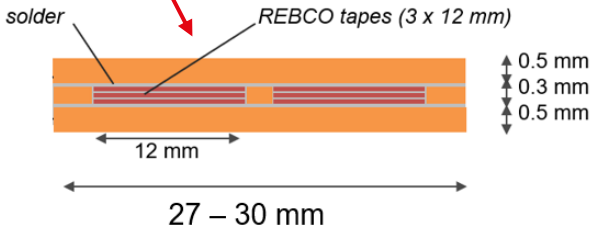


Double-pancake module



Winding pack of the module

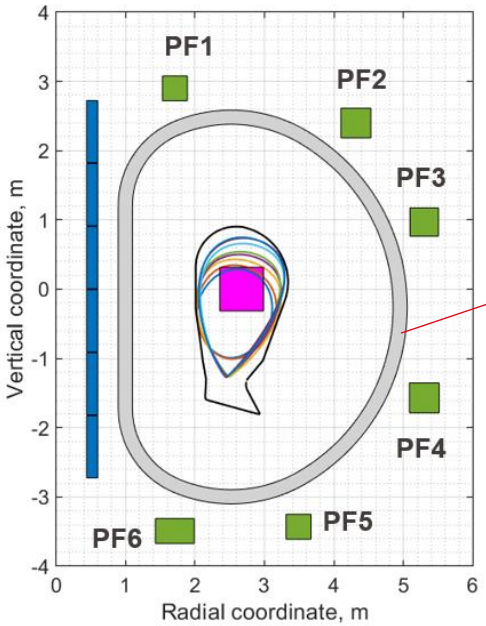


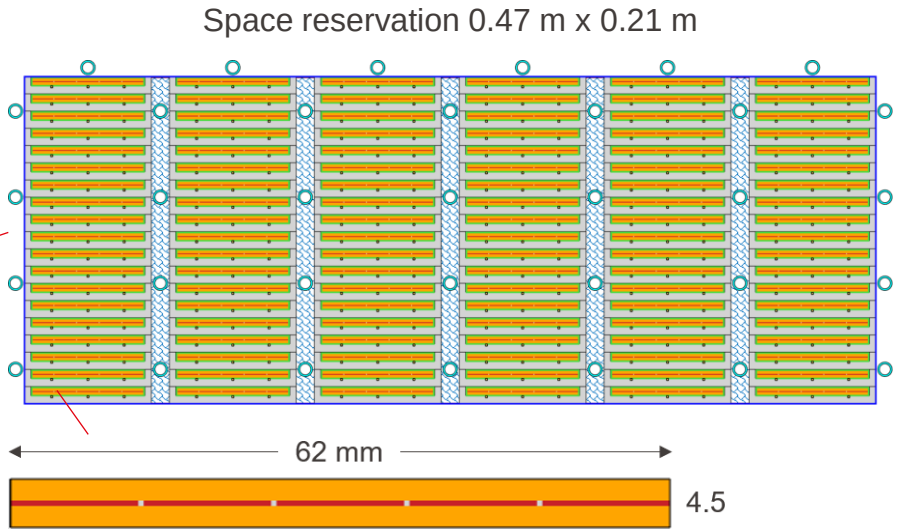


→ Scaling up the coil design to 10 MJ
by stacking double-pancakes modules

- Coil operation at 10 kA: central field ~15 T, peak field ~18 T
- LASSO conductor: 1.3 km total length, ~150 m per double-pancake

VNS magnet system (Proposal for a Pilot Plant)





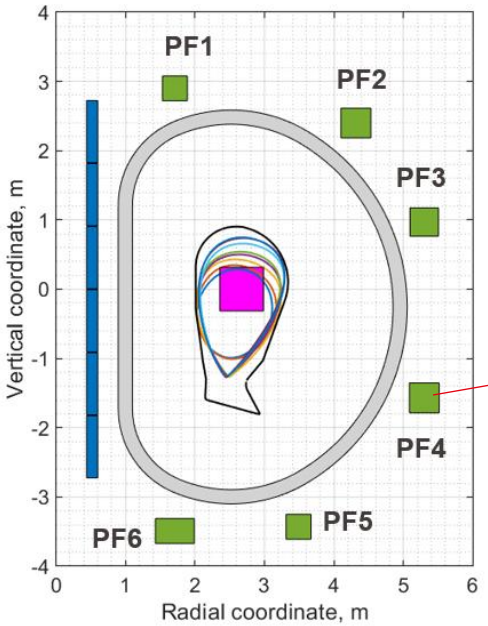
TF coils: stationary operation at 6.2 MA.t per coil

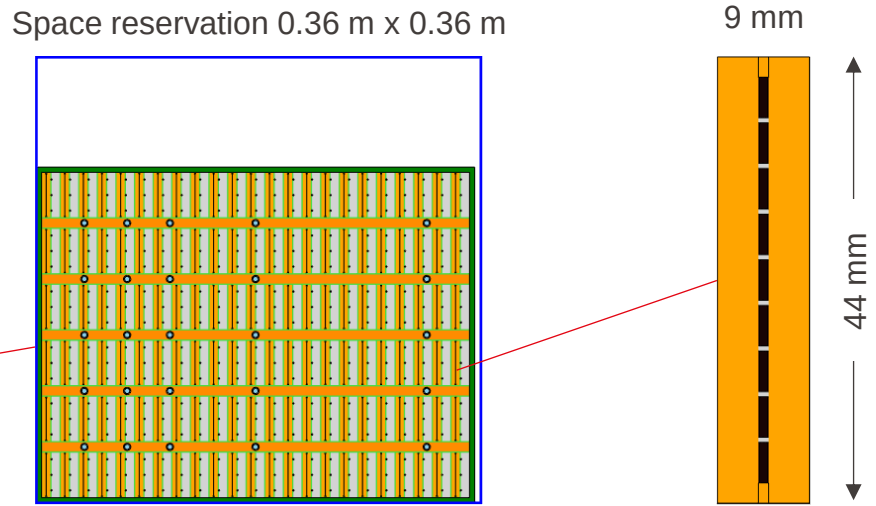
13.8 T peak field, 4400 MJ stored energy (366 MJ per coil)

LASSO conductor for TF operation at 50 kA:

- 12 mm wide tapes in 5 x 6 stack (30 tapes)
- T_{cs} min 10 K (at 9.5 T, 46 deg)
- Tape length ~60 km, cost ~3 M$ (per 1 TF coil)
- Conductor length ~2 km, cabling cost ~1 M$ (?)

VNS magnet system (Proposal for a Pilot Plant)





PF4 coil (most demanding):
pulsed operation up to 8 MA.t
8.0 T peak field
600 MJ stored energy

LASSO conductor for PF4 operation at 60 kA:

- 4 mm wide tapes in 9 x 10 stack (90 tapes)
- T_{cs} min 10 K (at 8.0 T, 0 deg)
- Tape length ~410 km, cost ~7 M$
- Conductor length ~4.6 km, cabling cost ~2-3 M$ (?)

Conclusion

Insulated coil windings made of LASSO cables and embedded temperature-based quench detection methods are being scaled up to demonstrate maturity of the concept at sufficiently large scale for fusion magnets.

Industry involvement is crucial to mature the concept:

- ✓ LASSO cables can already be procured by SST and FFJ (in 25 mm width)
- ➢ Call for tender for the 10 MJ insulated LASSO coil should soon be released

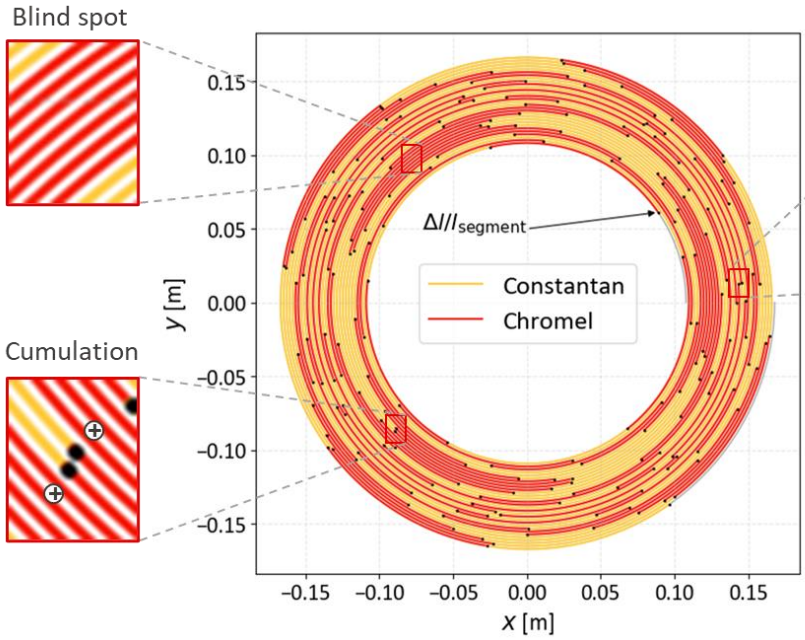
Compared to conventional CICC-based fusion magnets, this concept can offer simplified and cheaper manufacturing as well as reduced risk of high-voltage failures.

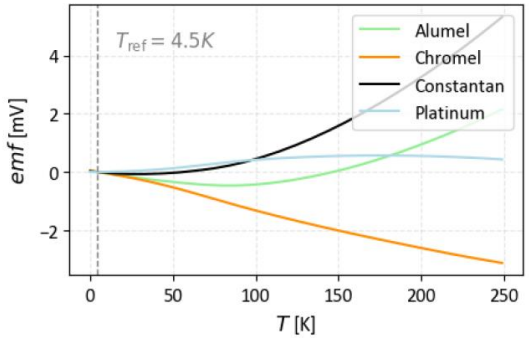
THANK YOU FOR YOUR ATTENTION!

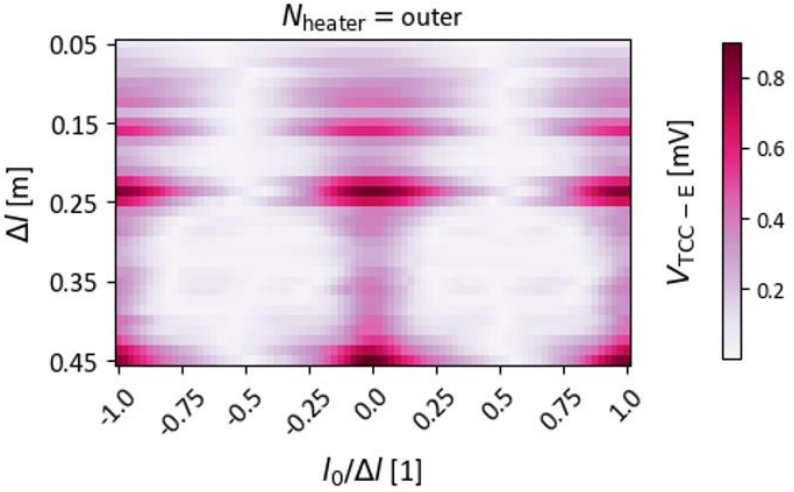
Nikolay Bykovskiy

TCC response (1)

$$V_{TCC} = \sum_i \Delta V_i$$

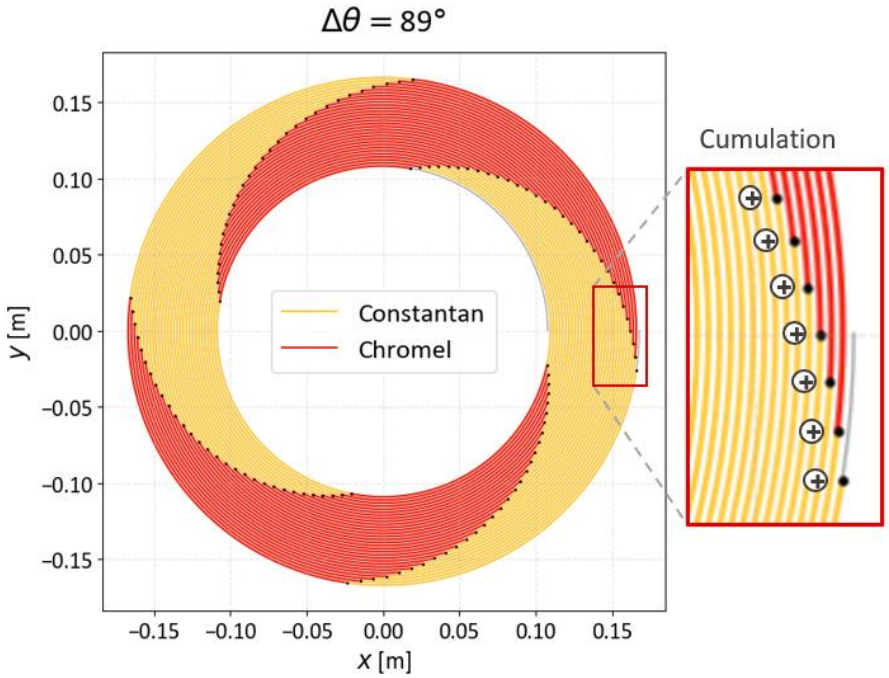


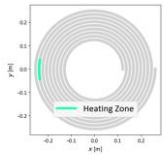


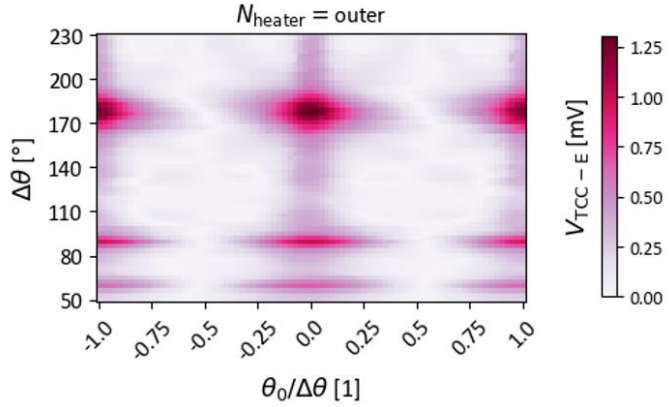


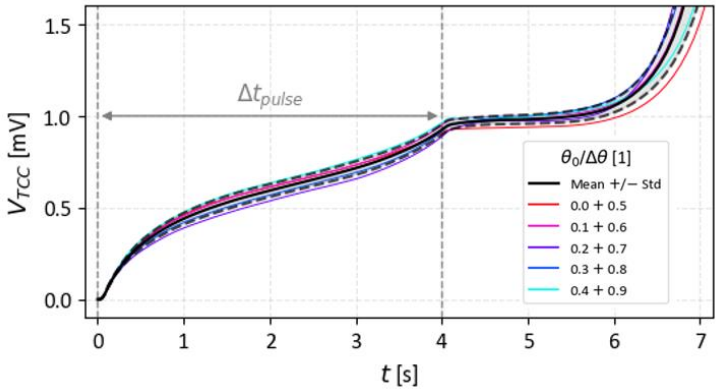
Constant-length segments → response strongly dependent on the temperature distribution

TCC response (2)









Constant-arc segments → response nearly independent by combining two TCCs shifted by half an arc