

2025 Coated Conductor for Applications Workshop

The technological development of HTS conductors for fusion in the EU-DEMO programme

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On behalf of WPMAG team



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Outline

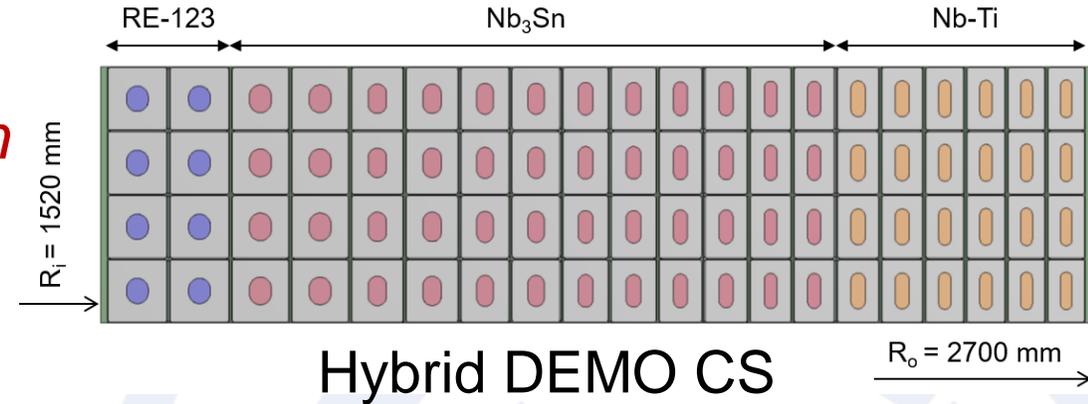
- ❑ **Strategic interest of HTS for fusion**
- ❑ **Quench Experiment on sub-scale HTS samples**
- ❑ **Design and R&D on Full-scale HTS conductors**
- ❑ **Conclusions and Perspectives**



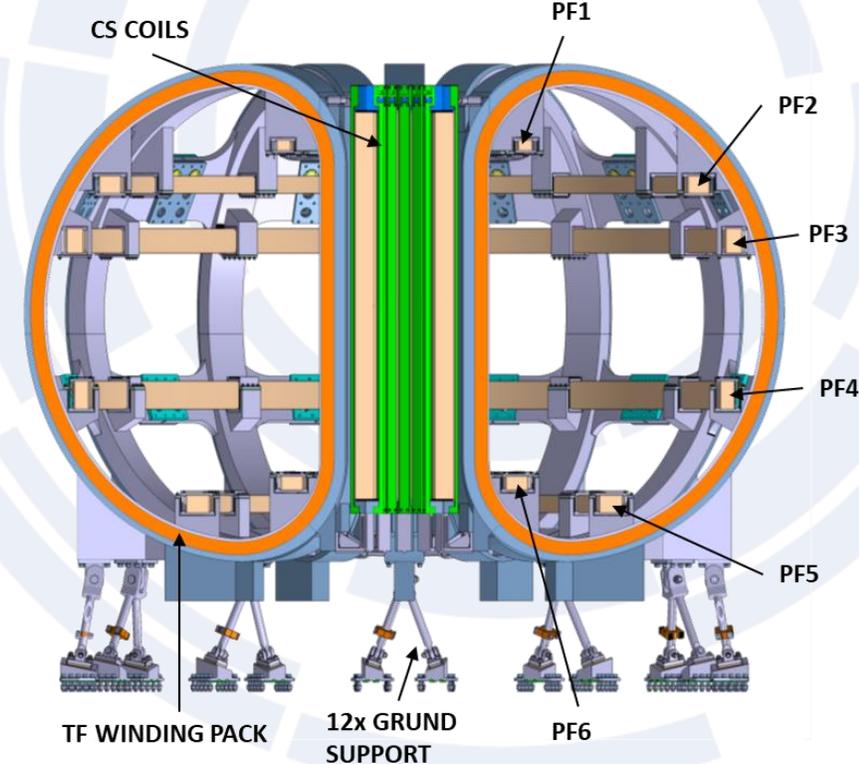
Strategic interest of HTS for fusion

HTS: a smart way to add flexibility to the design

- High Magnetic field
- High Temperature margin
- Innovative solutions for winding (in-situ winding)
- Design simplification decoupling thermal and mechanical/transport functions (indirect cooling)

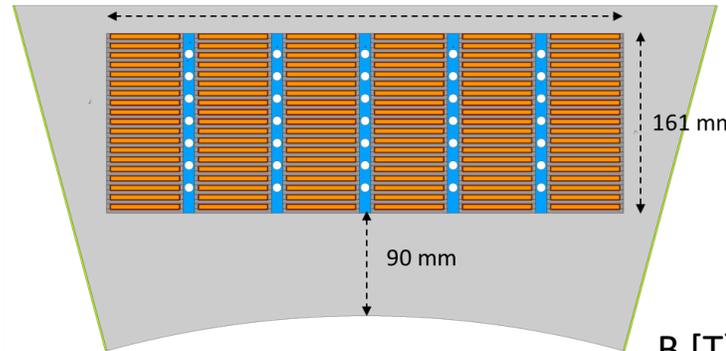


L. Giannini et al., FED 205 (2024) 114530

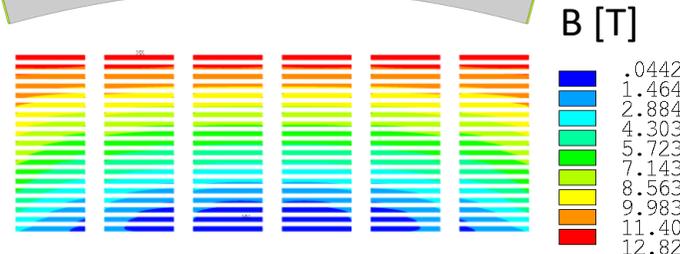


Volumetric Neutron Source

TF coil	PF-in-TF
Number of coils	12
Total current [MA]	5.7
Self-inductance [mH]	300
Stored Energy [MJ]	366
Nominal peak field [T]	12.8
Centering force [MN]	142
Vertical Force [MN]	64



HTS





Strategic interest of HTS for fusion

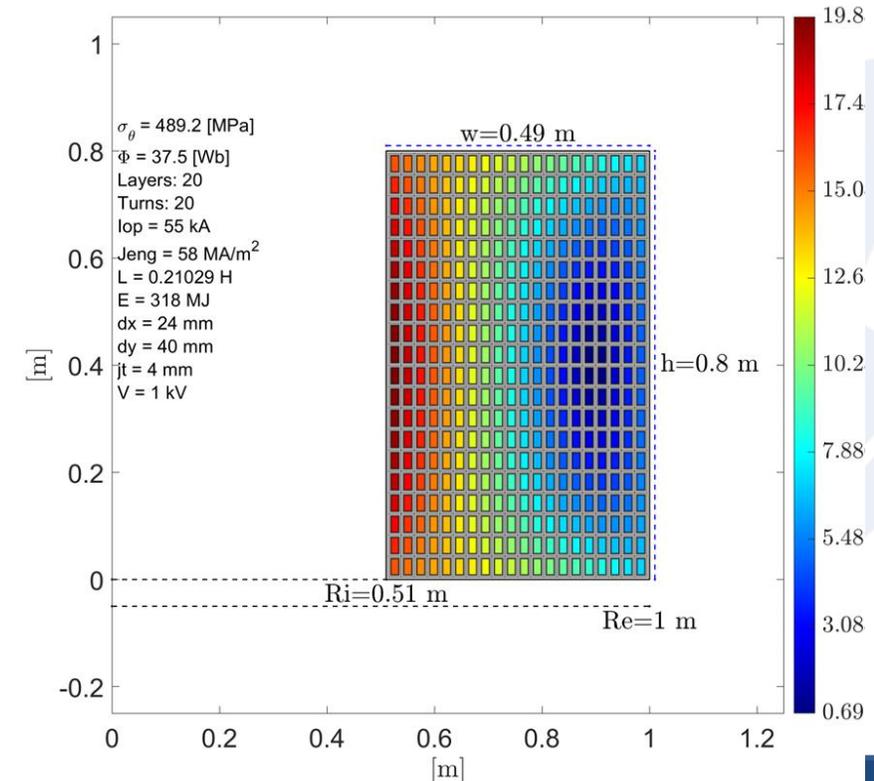
Goal: closing the gaps for a reliable use of HTS magnets

2021-2024 activities

- Study on the Quench propagation
- Assessment of the performance of full-scale HTS conductors with electromagnetic cycles
- Irradiation of HTS tapes

2025-2029 activities

- ❖ Demonstration of HTS conductor manufacturing on long lengths
- ❖ EUROfusion, in collaboration with CERN, F4E and other European partners is planning a large investment for **validating the quench detection and protection schemes** on a 300 MJ HTS model coil



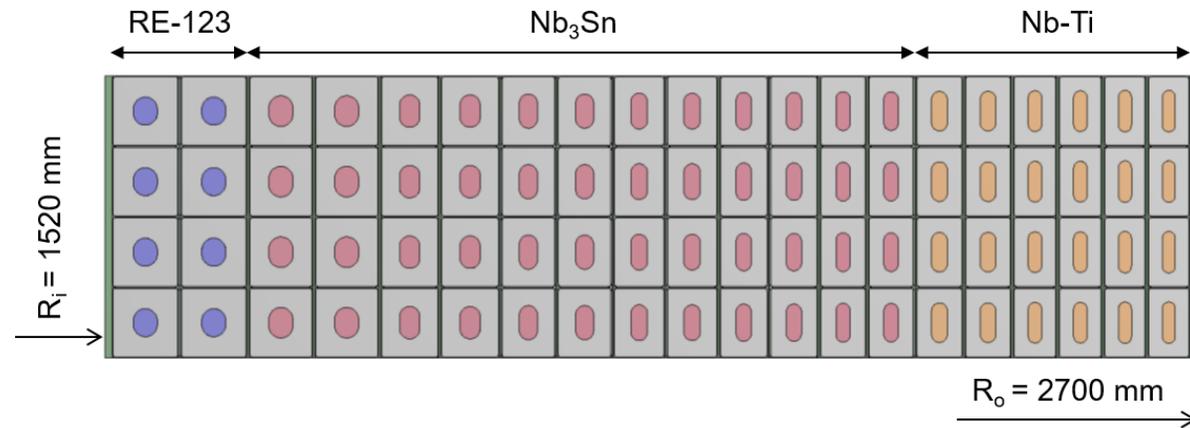


DEMO CS WP: Hybrid variant

5 modules CS (with a central double one)

Design		Hybrid variant
Total current [MA]		72.2
Cond current [kA]		46.3
Max B [T]		15.8
Mag flux [Wb]	Only CS	218.5
	CS+PF	239
σ_{hoop} [MPa]		295.4

- The hybrid variant allows the **Increase of the magnetic flux** wrt the ITER-like design of 13%.
- **Layer winding with grading on superconductor and stainless-steel**



Need to study HTS conductors suitable for the EU-DEMO central solenoid



Experimental activity on HTS conductors

Partially done under the European-Chinese Collaboration

Inlet Temperature = 4.5 K

Peak field = 18 T

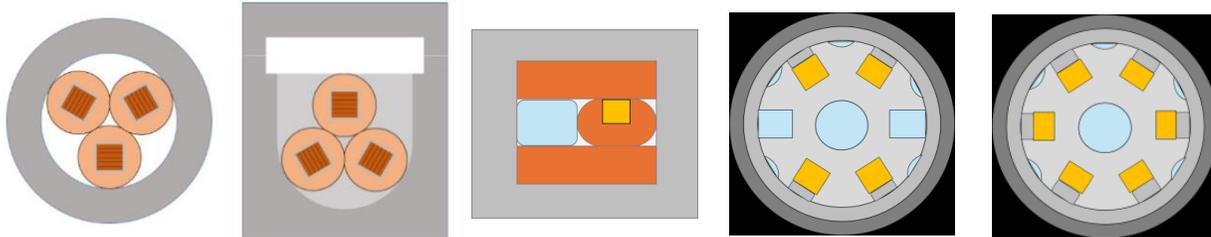
Operating current = 60 kA

Minimum bending radius = 1.5 m

DEMO
CS target

Experiment to study the quench propagation on sub-scale (15 kA) HTS conductors.

Motivation: quantify the slow propagation velocity of the hot spot after a quench (compared to LTS conductors), which may require a change in the quench detection approach.

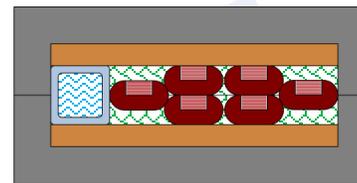


Conductors based on stacks of REBCO tapes

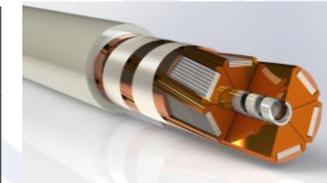
Assess the performance of full-scale HTS conductors with electromagnetic cycles

Motivation: Trying to reduce the degradation of the performances with cyclic electromagnetic loads in full-scale HTS conductors.

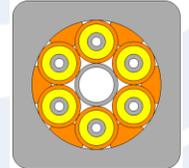
ASTRA



SECAS



HFRC

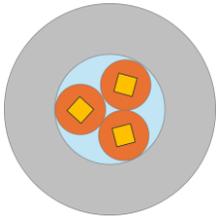
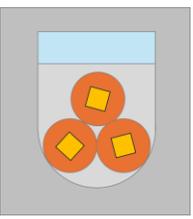
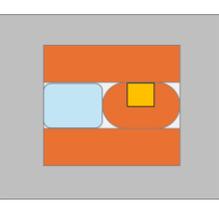
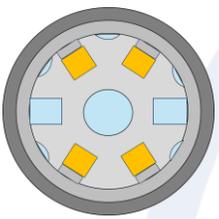
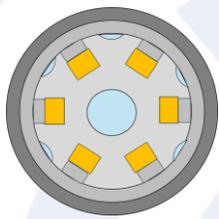




Quench Experiment



Quench Experiment: 15 kA REBCO SULTAN samples

Conductor	Reference / Non-twisted	Solder-filled ($\text{Bi}_{57}\text{Sn}_{42}\text{Ag}_1$)	ASTRA	ENEA A1	ENEA B1
					
Stabilizer material	Copper			Aluminum	
$A_{\text{stabilizer}}$ [mm ²]	150	150	144	255	292
A_{jacket} [mm ²]	715	652	360	94+82 (SS)	94+82 (SS)
Stack of tapes	Soldered	Soldered	Soldered	Not soldered	Not soldered
Twisting	T/NT	T	NT	NT	NT
#tapes x #stack	3.0 mm width × 25 × 3		3.3mm x 21 x1	4mm x19x4	4mm x13 x 6
Cooling	direct	indirect	indirect	direct	direct

- N. Bykovskiy, *SUST* 36 (2023) 034002
- O. Dicuonzo 2022 PhD Thesis (<http://infoscience.epfl.ch/record/293510>)
- A. Zappatore, *Cryogenics* 132 (2023) 103695
- A. Zappatore et al., submitted to *Cryogenics*



Quench tests @ 10.85 T, 15 kA

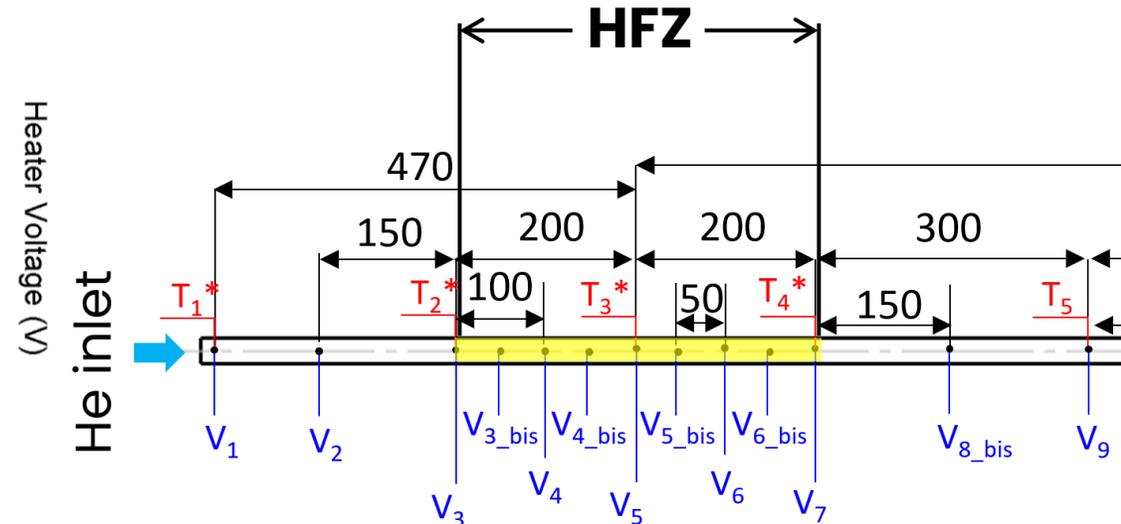
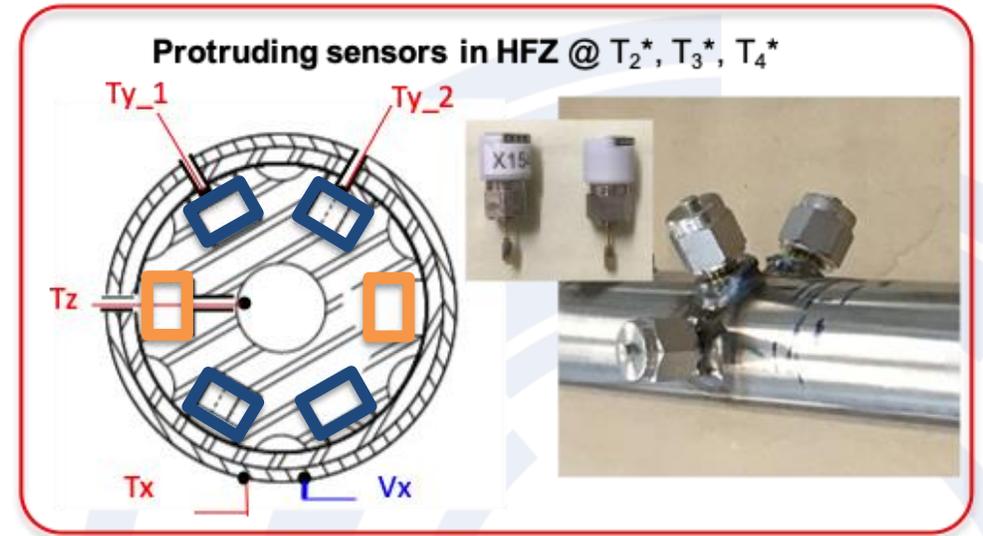
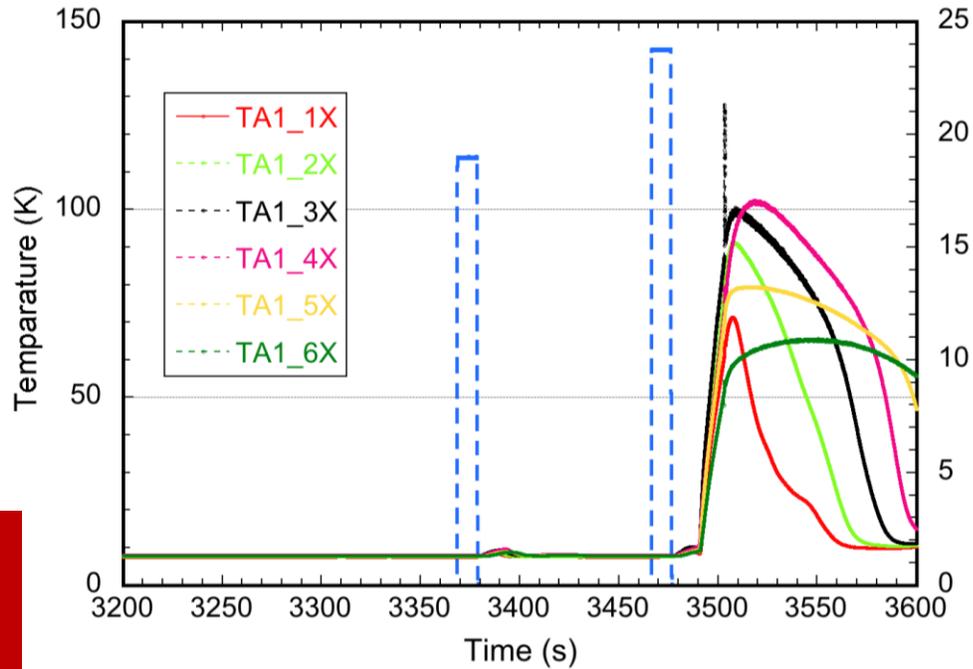
Quench tests:

- direct power supply keeps the current constant
- quench is induced by heating the He at the inlet (for ASTRA, also localized heaters were used)
- current is dumped when a T threshold is reached

Series of test →
 $T_{hot\ spot}$
 (reference T_{3X})

- 1st → 45 K
- 2nd → 72 K
- 3rd → 100 K
- 4th → 135 K
- 5th → 135 K
- 6th → 200 K

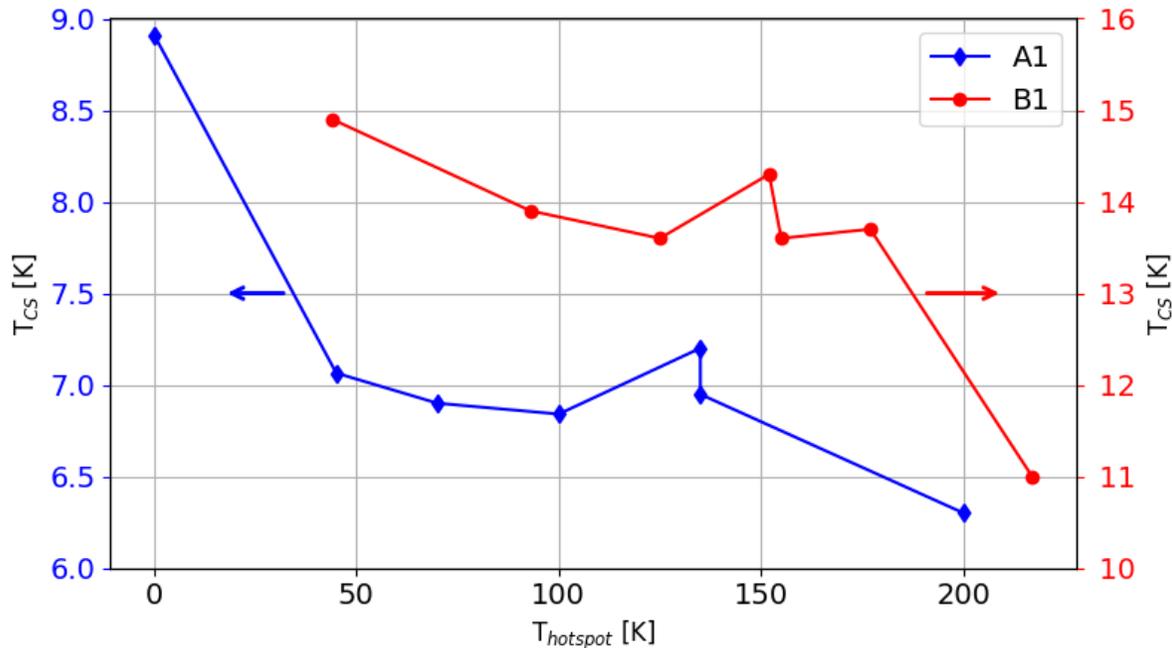
*Degradation
 after the last
 quench*





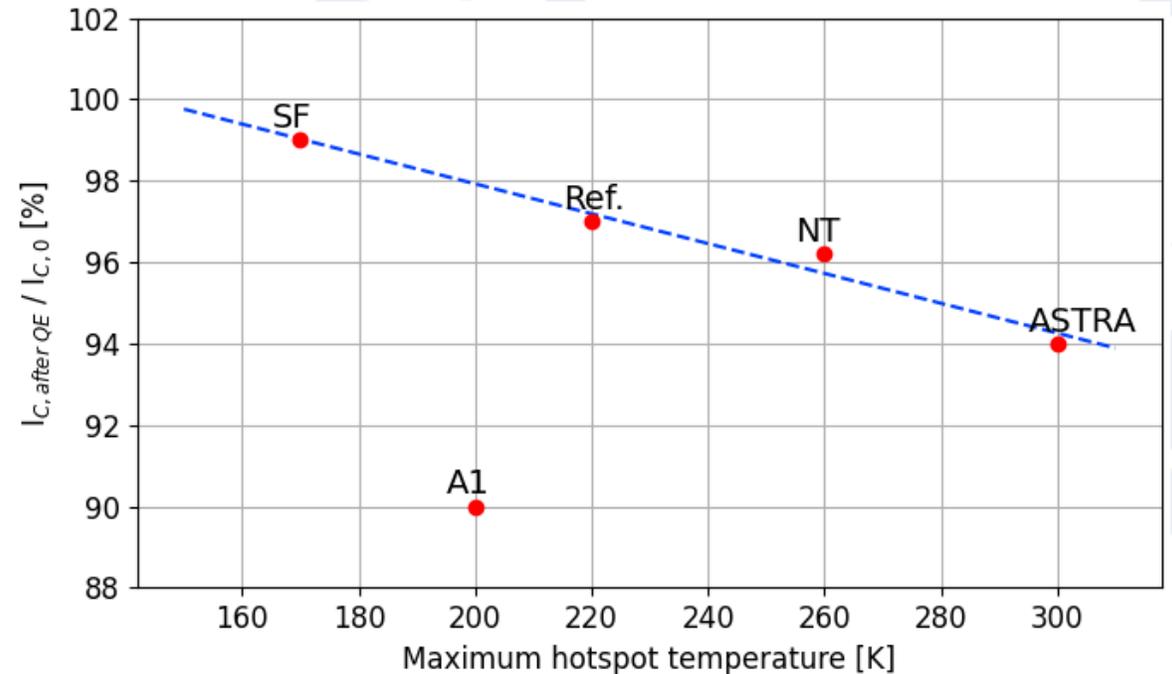
Quench test: DC Performance

ENEA A1 and B1 underwent T_{CS} test before each quench test → clear reduction beyond 130-170 K, respectively → **150 K** may be a first reference threshold for the maximum hotspot in stacked HTS conductors.



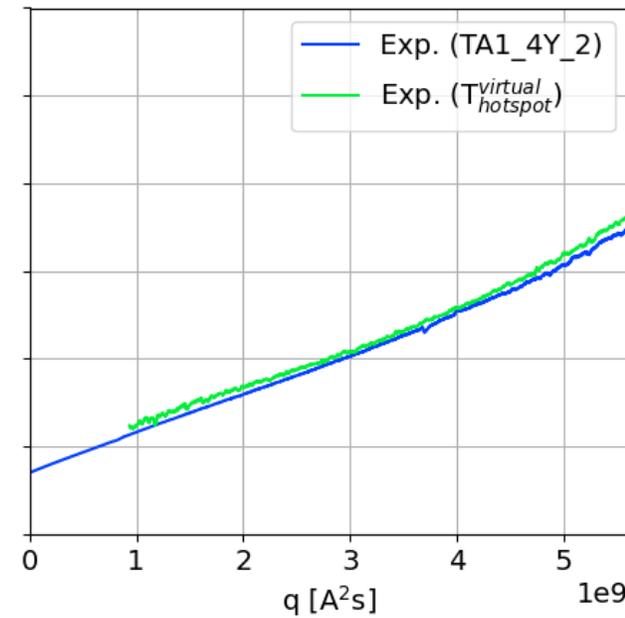
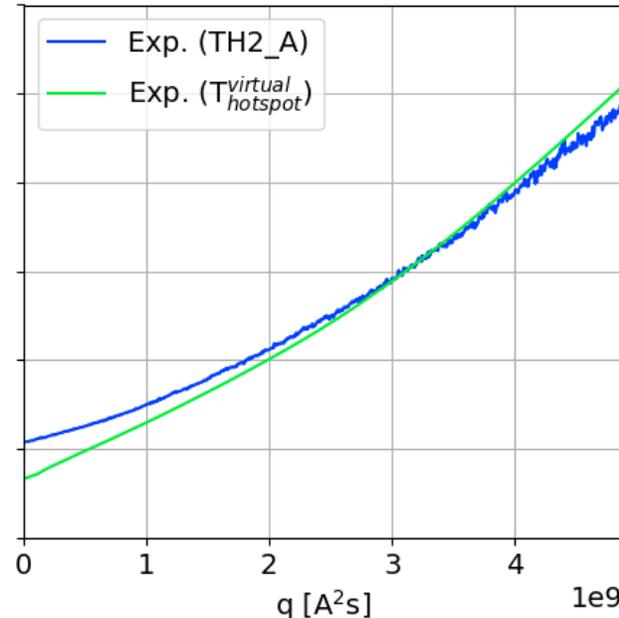
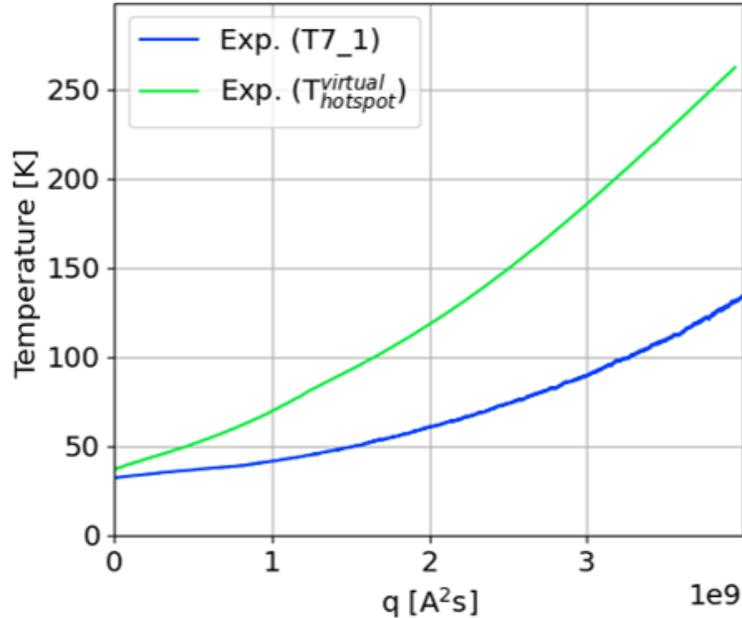
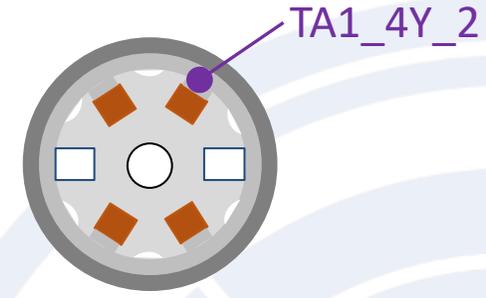
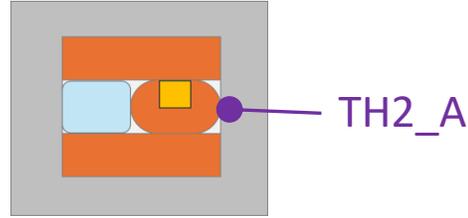
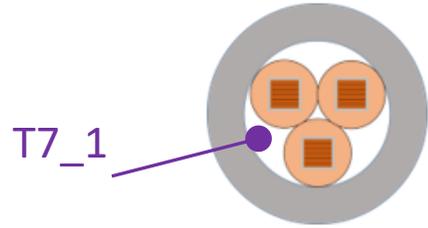
I_C reduction conductors after QE tests:

- Impact of **EM cycles**? Maybe yes
- Also, the **quench** seems to have an effect (the larger the hotspot, the larger the reduction), probably **due to temperature gradients**





Hot spot Temperature in quench experiment



$q = \int_0^t I(t)^2 dt$
proportional to the energy deposited during the quench propagation

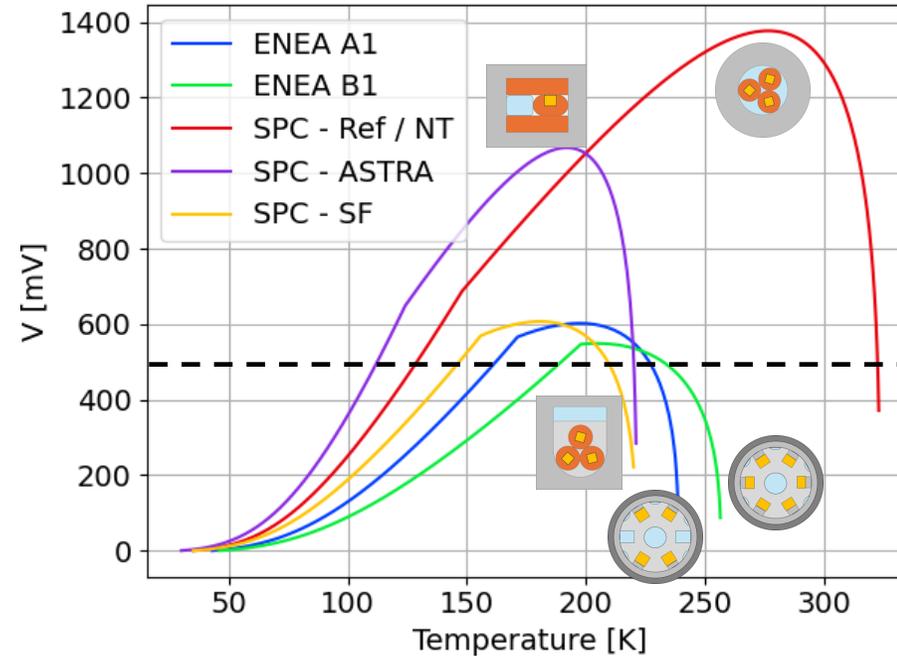
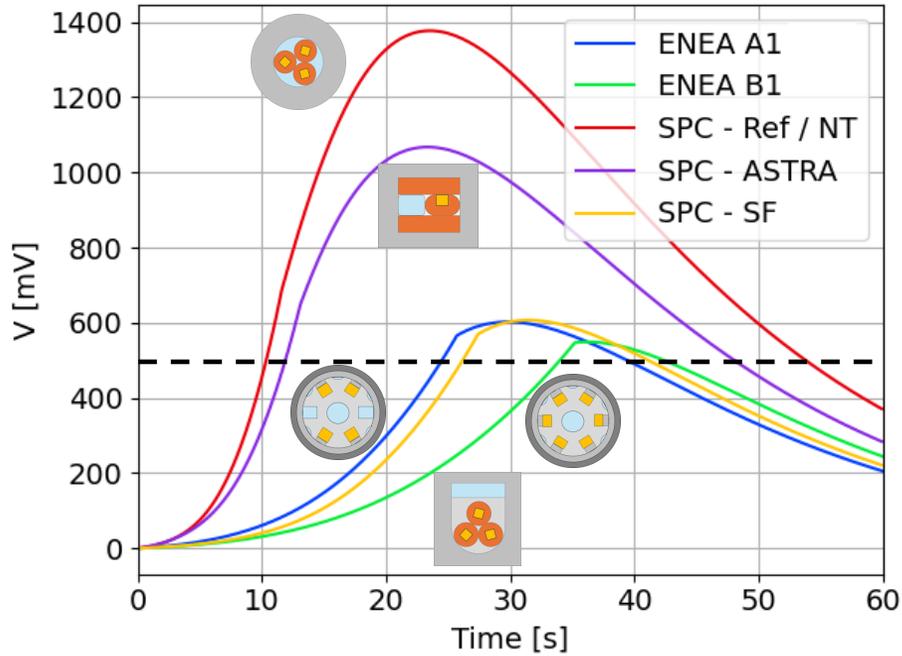
T_{hotspot} (virtual) is reconstructed from voltage:

$$\Delta V_q = L \frac{\rho_{e,\text{stabilizer}}(T_{\text{hotspot}})}{A_{\text{stabilizer}}} \cdot I_{\text{tot}}$$

When temperature is measured sufficiently close to the hotspot, virtual temperature matches very well → use this temperature as hotspot temperature for the analysis



Projection to magnet (CS) operation



Parameter	Value
B [T]	18
I [kA]	60
τ [s]	15
t_{delay} [s]	1.1
$V_{\text{threshold}}$ [mV]	500
T_0 [K]	5

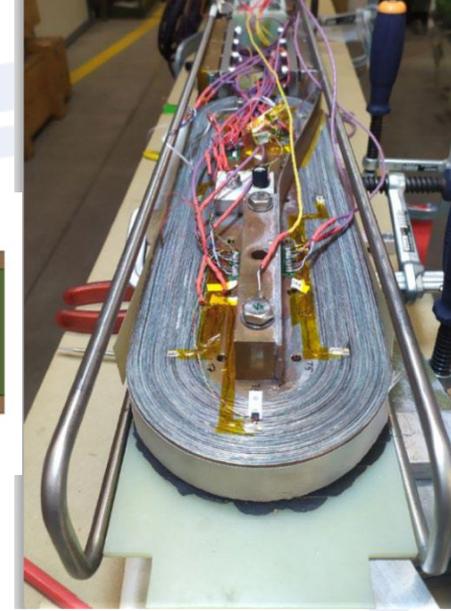
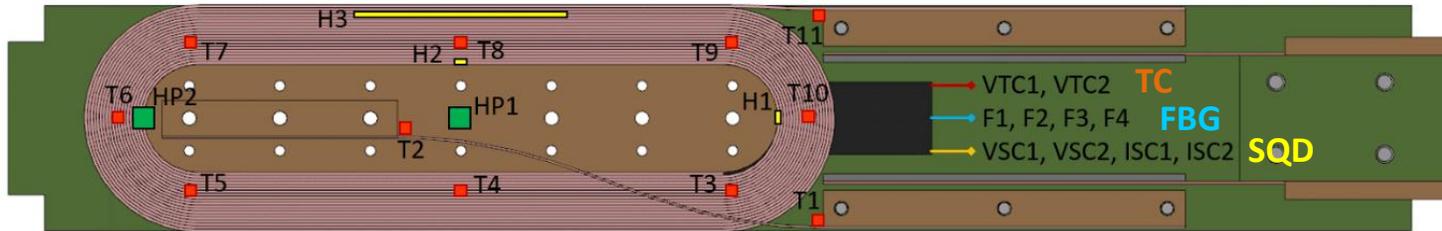
- Quench in [Reference / Non-twisted](#) is detected before than the others, but low effective thermal capacity leads to large temperature increase
- Conductors with a **good thermal coupling between jacket and stabilizer** end up with **smaller hotspot temperature**
- ASTRA is a trade-off between Reference and Solder-filled wrt Quench Propagation Velocity and effective thermal capacity
- **All conductors overcome the 150 K threshold** → work to be done on
 - ❖ detection (quench is detected when conductors are already at >100 K)
 - ❖ conductor design, improving thermal contact among stabilizer and jacket



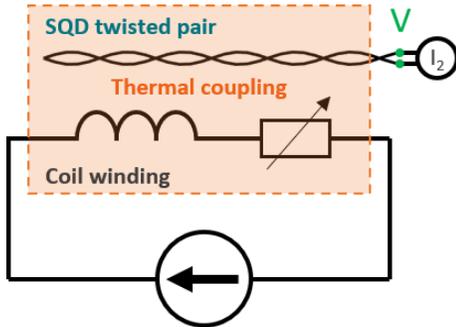
Alternative quench detection methods

Alternative QD methods relying on Temperature-based response are under study:

Laminated stacked-tape soldered conductor (LASSO)



SQUID twisted-pair

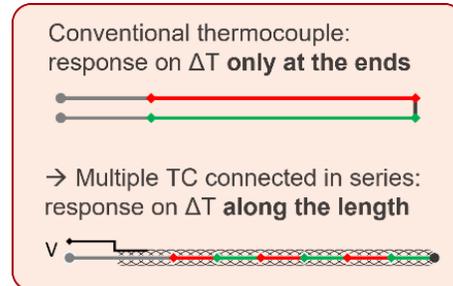


→ measuring resistance of SC quench detection (SQUID) wire

Pros: distributed spatial sensing, sensitivity controlled by I_2

Cons: limited choice for $T_c(B)$ threshold; hot spot is not localized

Thermocouple chain

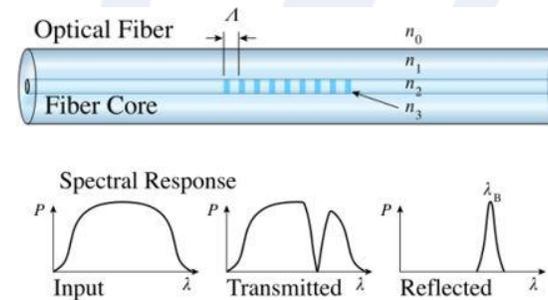


→ measuring voltage over series connected thermocouple wires

Pros: continuous response on temperature gradient among joints

Cons: discrete sensing

Fiber Optic Sensing (FOS)



FBG optical fibers

→ measuring spectral shift of light reflected by each FBG

Pros: continuous temperature monitoring at each Fiber Bragg Grating location

Cons: brittle, high resolution over long length is difficult

Distributed Fiber Optic Sensing

→ measuring spectral shift of light diffracted by each fiber

Pros: continuous temperature monitoring along the fiber; suitable for long lengths

Cons: brittle, expensive post processing for interrogators



Full-scale HTS conductors

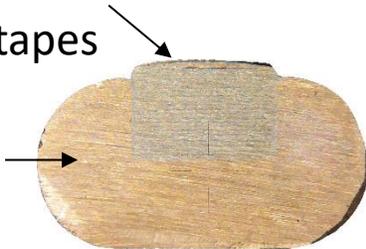


ASTRA conductor prototype layout

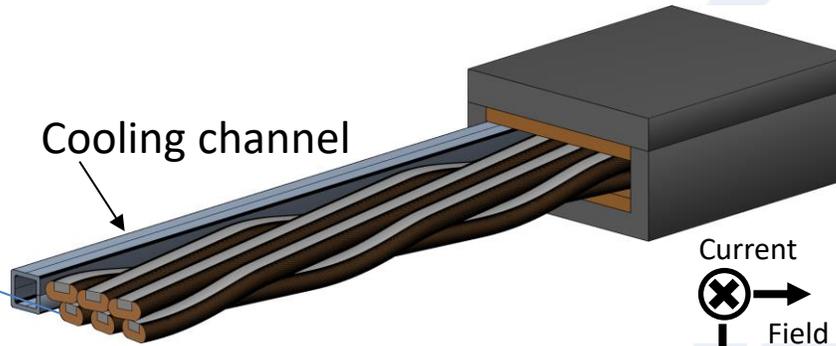
Aligned Stacks Transposed in Roebel Arrangement (ASTRA)

Stack of REBCO Non-twisted soldered tapes

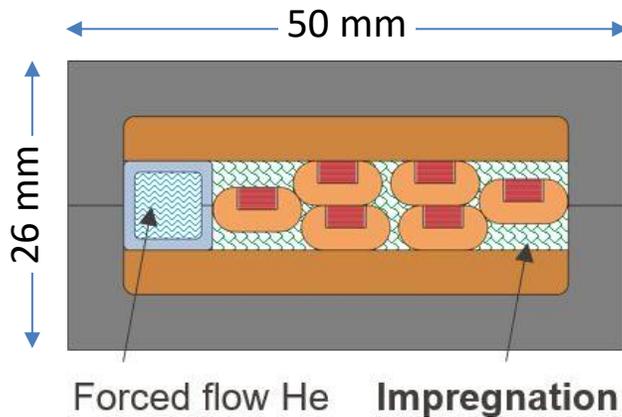
Cu profile



Cooling channel



Current
Field
Force

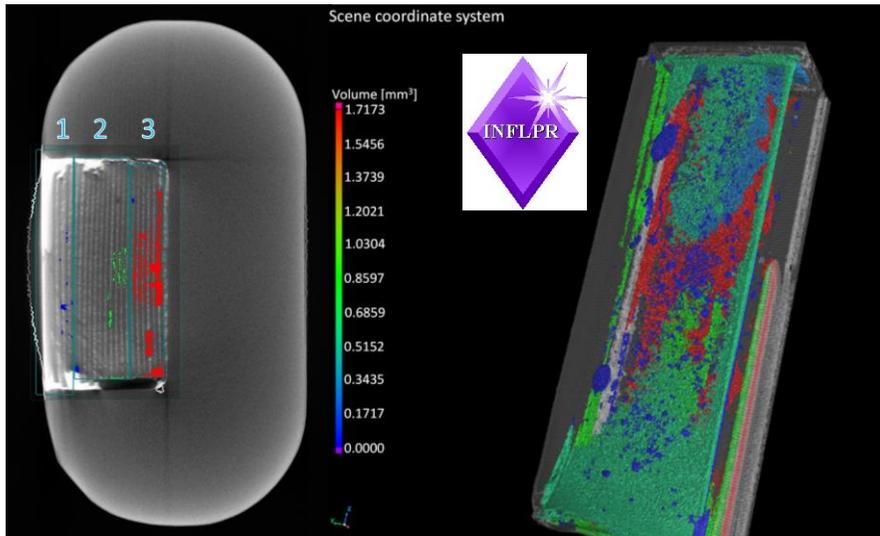
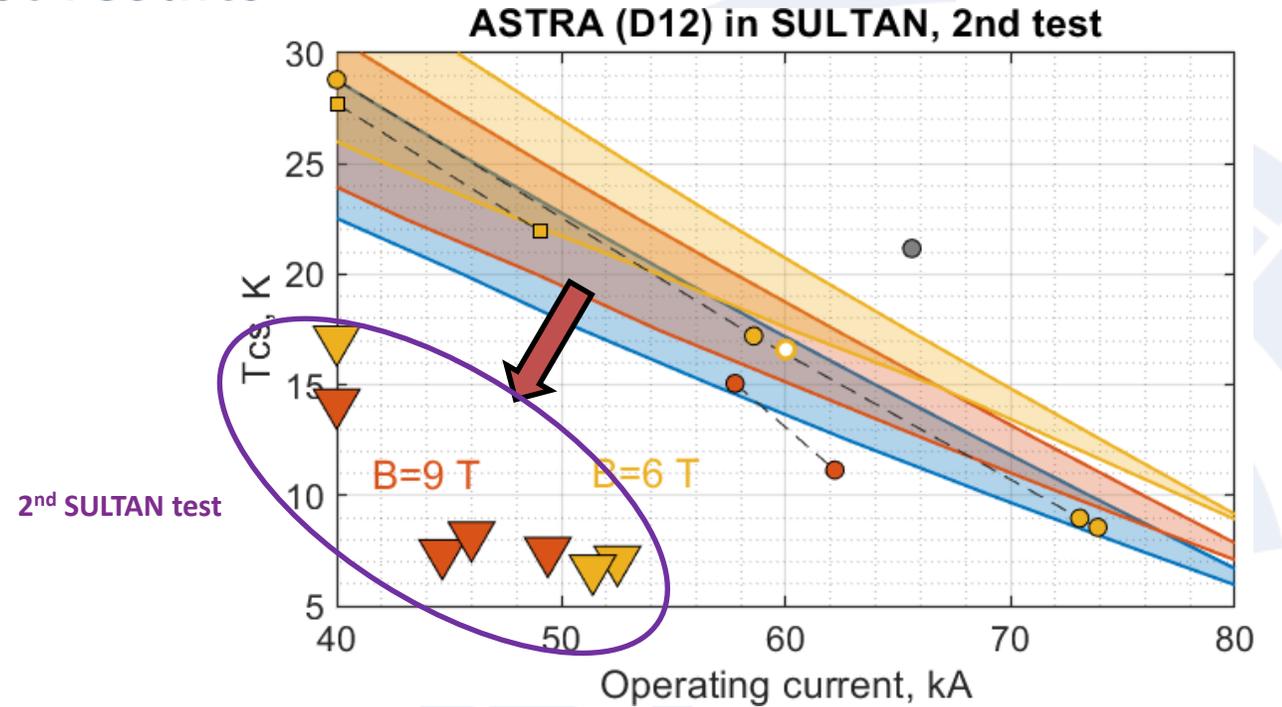
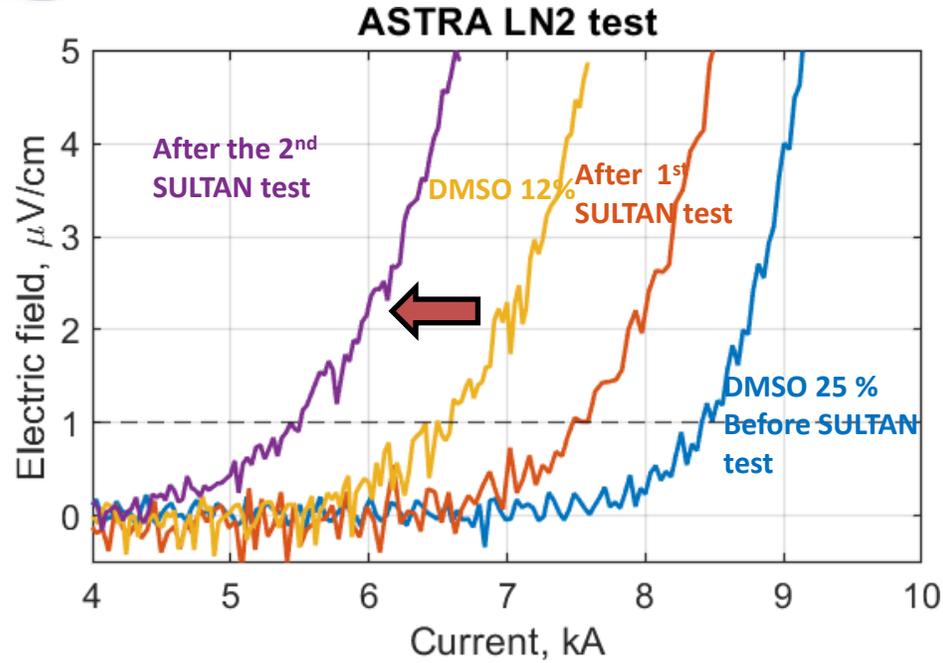


- 3.3 mm SST tapes, 21-tape **soldered stacks**
- 6 **transposed** strands ($L \sim 0.75$ m) \rightarrow reduce AC losses
- Aqueous DMSO (Dimethyl Sulfoxide) **impregnation** (for mechanical support)
- **Tight cooling channel** \rightarrow conduction cooling
- Operation in **parallel background magnetic field** \rightarrow reduce # tapes





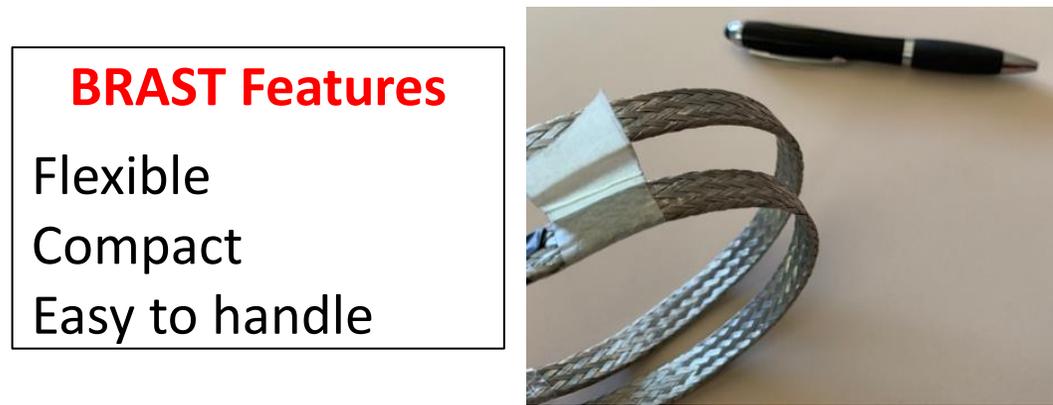
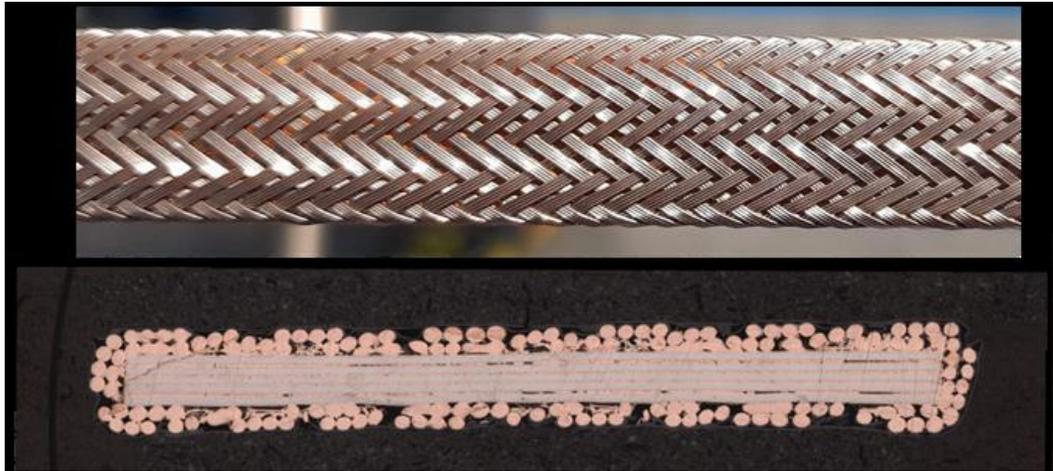
ASTRA Conductor prototype: test results



- Initial DC performance in-line with expectations both from LN2 bath and SULTAN testing.
- Strong performance reduction by EM load (at 9 T, 63 kA ~ 570 kN/m) and thermal stresses by frozen aqueous DMSO due to its thermal expansion
- Voids and pores in soldered stack might be the root cause, thus strand manufacturing is being revised trying either to improve soldering or avoid using it (using BRAST strands).



BRAided STACKs (**BRAST**) of REBCO tapes

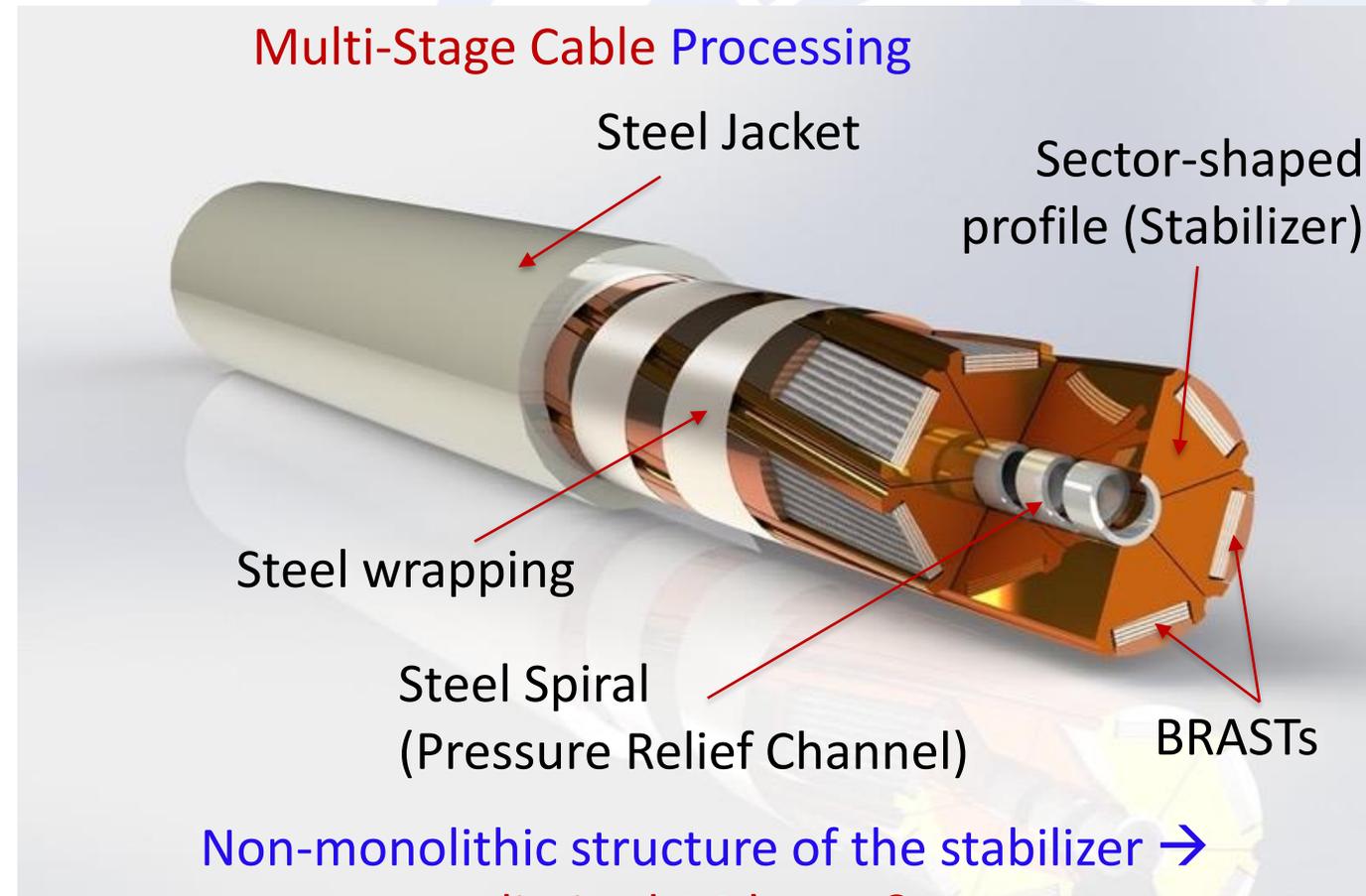


BRAST Features

- Flexible
- Compact
- Easy to handle

L. Muzzi et al. 2023, IEEE TAS 33 (5) 1-6

High-current / high- field **SECTOR ASSEMBLED (SECAS) CICC**



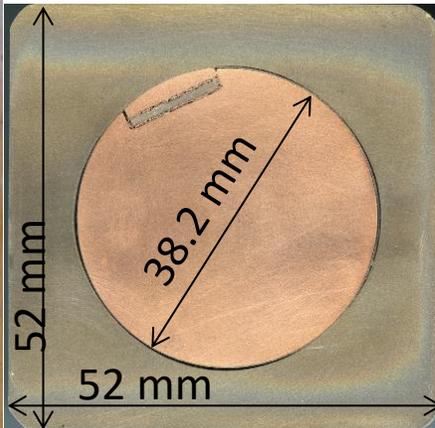
Non-monolithic structure of the stabilizer → limited AC losses?



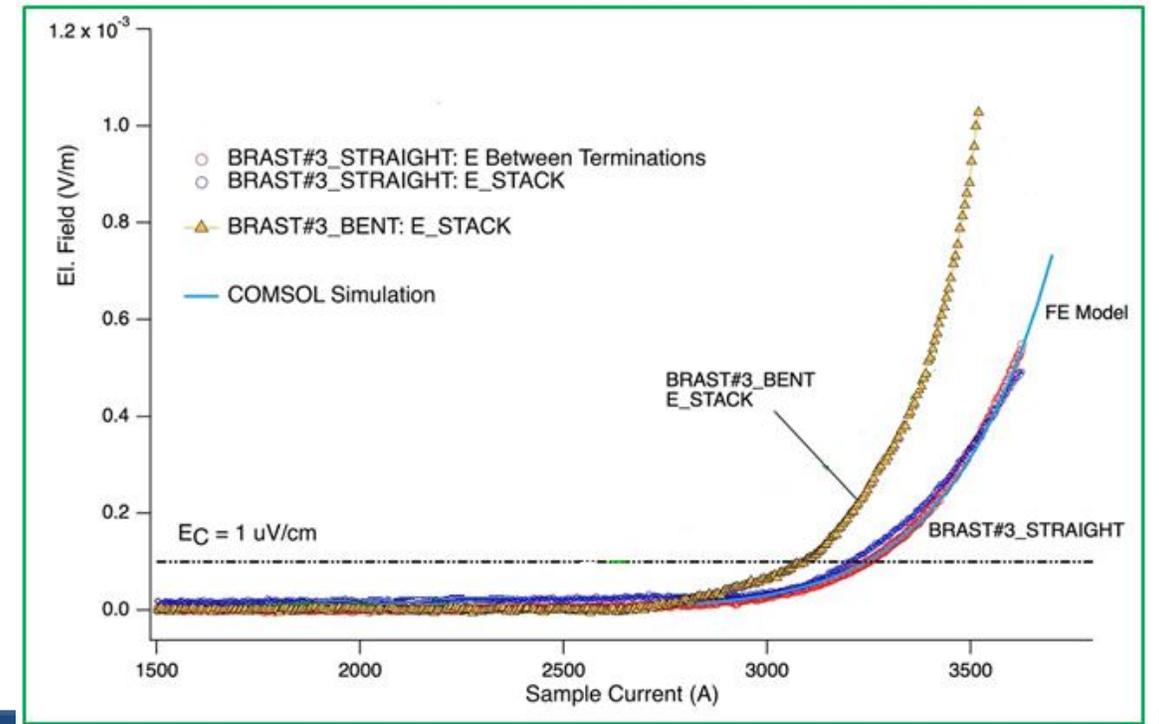
BRAST mechanical assessment: twisting, compaction and bending



BRAST #3 bent to $R = 1.5 \text{ m}$
(as required for **EU-DEMO CS**)



A limited (5%) reduction in I_c is observed on the bent sample compared to the straight one.





Conclusions

Quench experiment

- ❑ **Thermal gradients** in HTS conductors may induce a degradation in the transport performances. Our experiments suggest to **limit the T_{hotspt} on the stack of tapes to 150 K** in the design phase.
- ❑ Conductors with a **good thermal coupling** between jacket and stabilizer end up with smaller temperature difference in the cross section and a **smaller hot spot temperature**.
- ❑ The Quench Propagation Velocity **QPV** ranges from ~ 10 mm/s to 300 mm/s at 15 kA operation, which can be explained by difference in joule heating density and cooling conditions.
- ❑ The projection to magnet operation suggests that the **voltage detection** may be unsuitable. Alternative QD methods are under study.

Full-scale conductor characterization

- ❑ All HTS conductor prototypes have initial performances in line with expectations
- ❑ **ASTRA conductor:** degradation of the performances due to voids and pores in soldered stacks
- ❑ **SECAS conductor:** full-size design is complete, the manufacture is in progress. SULTAN test in 2025. The subsize sample performances are as expected. Under bending, a limited (5%) reduction in I_c is observed.



- ❑ HTS full-scale conductors manufactured and tested in SULTAN with the integration of optical fibers: ASTRA and NTNT (not-twisted not-transposed) conductor with improved soldering, SECAS conductor, CORC-like conductors.
- ❑ Demonstration of HTS conductor **manufacturing on long lengths**
- ❑ Validating the quench detection and protection schemes on a **300 MJ HTS model coil**
- ❑ Design of the **Volumetric Neutron Source** (TF and PF coils in HTS):
 - Exploring the benefits of indirect cooling and high temperature margins
 - Decoupling thermal and mechanical/transport functions
 - Exploring the possibility of in-situ winding



Thanks for your attention!

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ENEA - Frascati
February 2025*



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