Superconductivity & Particle Accelerators conference 2024

Progress in technological solutions for EU-DEMO magnets advanced conductors

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On behalf of WPMAG team

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EUROfusion Consortium:
supports and funds fusion research activities to pave the way for fusion power reactors.
Consortium done by 31 European Research Units + 162 Affiliated Entities

Magnet System Work Package:
Design and develop technology for EU-DEMO Magnets

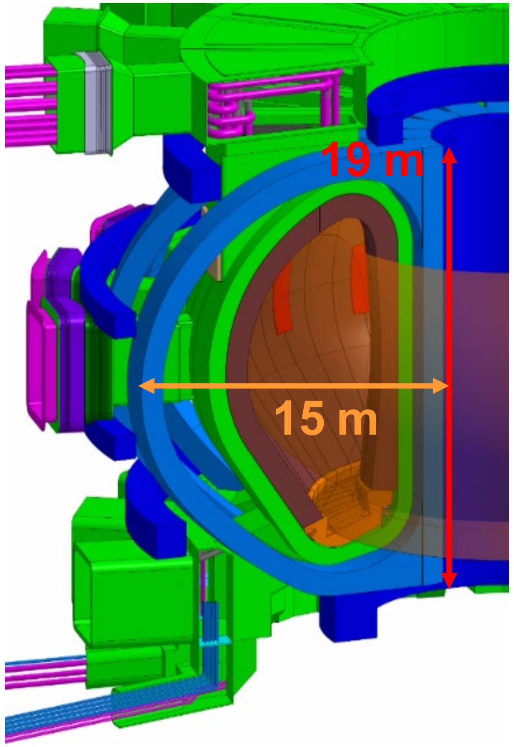
WPMAG members (~ 80 people):
CEA (France), CU (Slovakia), **ENEA (Italy),** EPFL (Switzerland), FOM-DIFFER (Netherlands), IAP (Romania), IPP.CR (Czech Republic), IPPLM (Poland), KIT (Germany), OEAW (Austria), VTT (Finland)

Outline

- Introduction on EU DEMO tokamak
- Quench Experiment on sub-scale HTS samples
- Design and R&D on Full-scale HTS conductors
- Conclusions

EU-DEMO tokamak

EU-DEMO reactor is designed for demonstrating net production of electricity and operation with a closed fuel cycle (TBR>1)



16 TF coils
(B_{peak}= 12T, E_{total} = 150GJ)

5 CS coils
(B_{peak}= 15.8 T, E_{total} = 15GJ)

6 PF coils
(B_{peak}= 8 T, E_{total} = 21GJ)

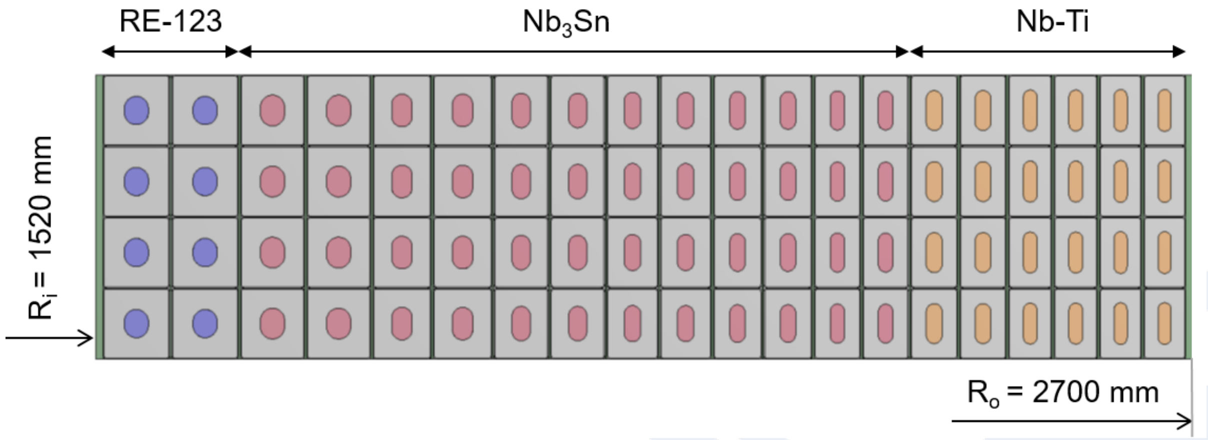
Parameters	Symbol	EU-DEMO
Major radius	R_0 (m)	**9**
Minor radius	a (m)	2.9
Aspect ratio	A	3.1
Plasma current	Ip (MA)	18
Safety factor	q	3.6
Plasma elongation	k_{95}	1.6
Triangularity	δ_{95}	0.33
Av. electron density	$\langle n_{e,vol} \rangle$ ($10^{20} m^{-3}$)	0.73
Eff. ionic charge	Z_{eff}	2.2
Confinement enhancement	H	1.1
Burn Time	t_{burn} (hrs)	**2**
Bootstrap fraction	f_{bs} (%)	37
Fusion Power	P_{fus} (MW)	2000
Net electric power	$P_{e,net}$ (MW)	**500**
Divertor configuration		Single null

DEMO CS WP: Hybrid variant

Design		Hybrid variant
Total current [MAt]		72.2
Cond current [kA]		46.3
R_i [mm]		1520
R_o [mm]		2700
Max B [T]		15.8
Mag flux [Wb]	Only CS	218.5
	CS+PF	239
σ_{hoop} [MPa]		295.4

5 modules CS (with a central double one)

- 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

Inlet Temperature = **4.5 K**

Peak field = **18 T**

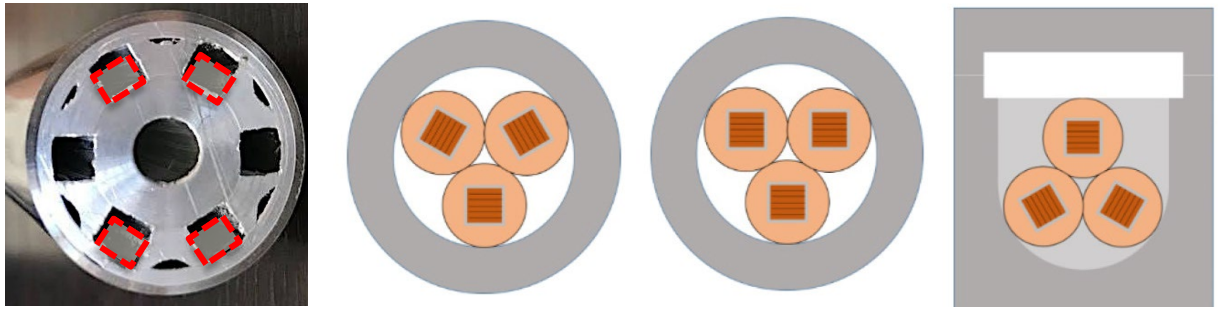
Operating current = **60 kA**

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.

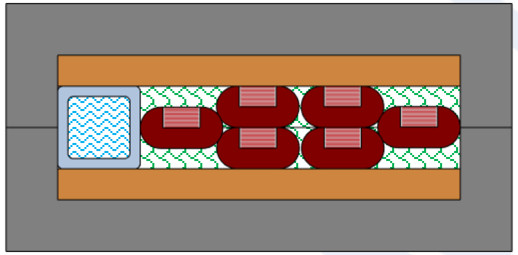


Conductors based on stacks of REBCO tapes

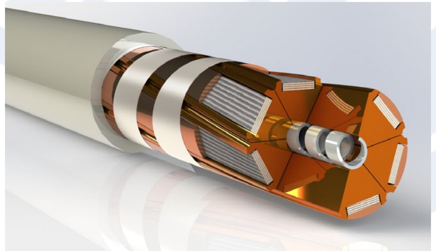
Assess the performance of full-scale HTS conductors with electromagnetic cycles

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

ASTRA



SECAS

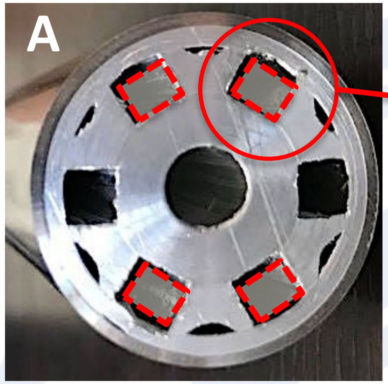


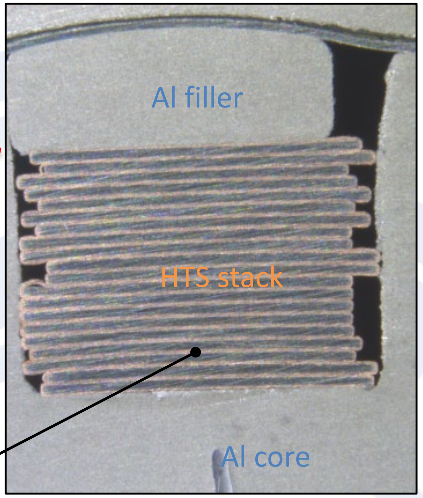
Quench Experiment

Quench test: Al slotted core sample

A: 4 stacks x 19 HTS tapes (76 SuperOx Tapes - No APC tapes)

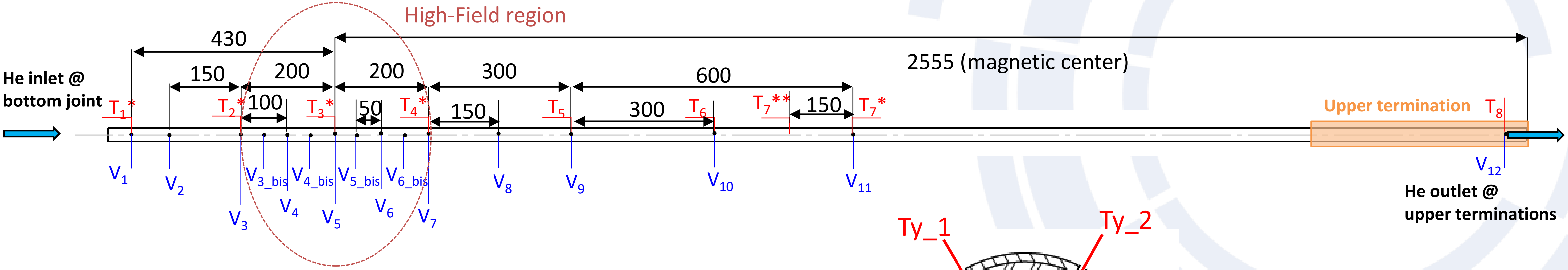
- 6-slot Al-core;
- Straight slots/straight stacks
- double jacket concept (inner Al and outer SS)





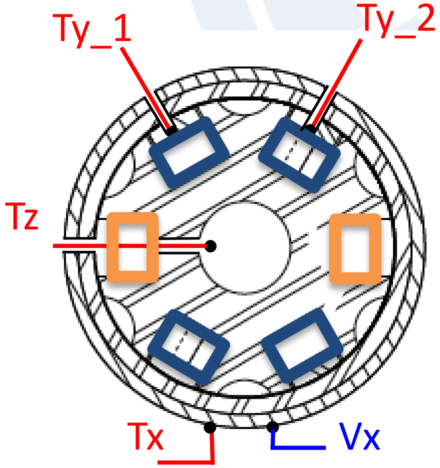
Stack is not soldered

SULTAN sample



Layout Sample A1: 21 *T* sensors

- **12 protruding** into the cable cross section (Ty, Tz) (implemented with technology developed by SPC);
- **7** on the steel jacket surface (T_x);
- **2** on the joint and upper termination;

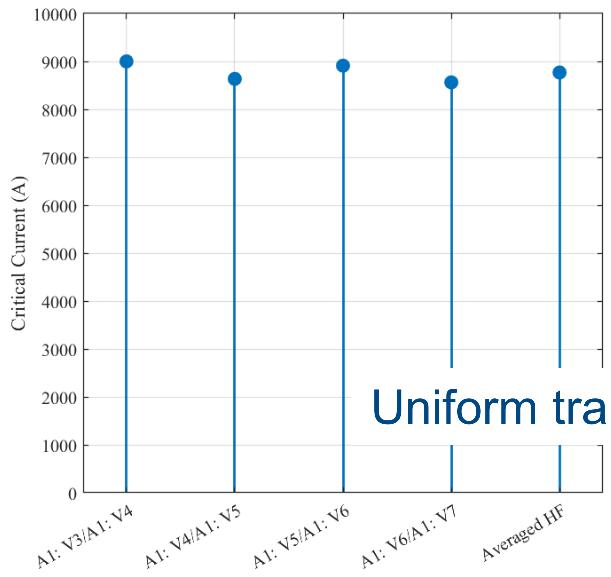


Layout of Sample A2:
- No Ty (HTS stack Temp)

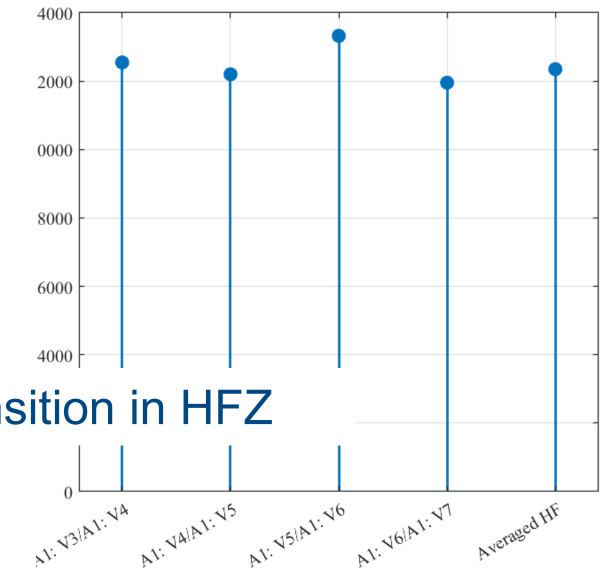
@ T_2*, T_3* and T_4*

Performance analysis of the conductor: I_c test

(Run 13)
20 K, 10.85 T → I_c = 8.7 kA



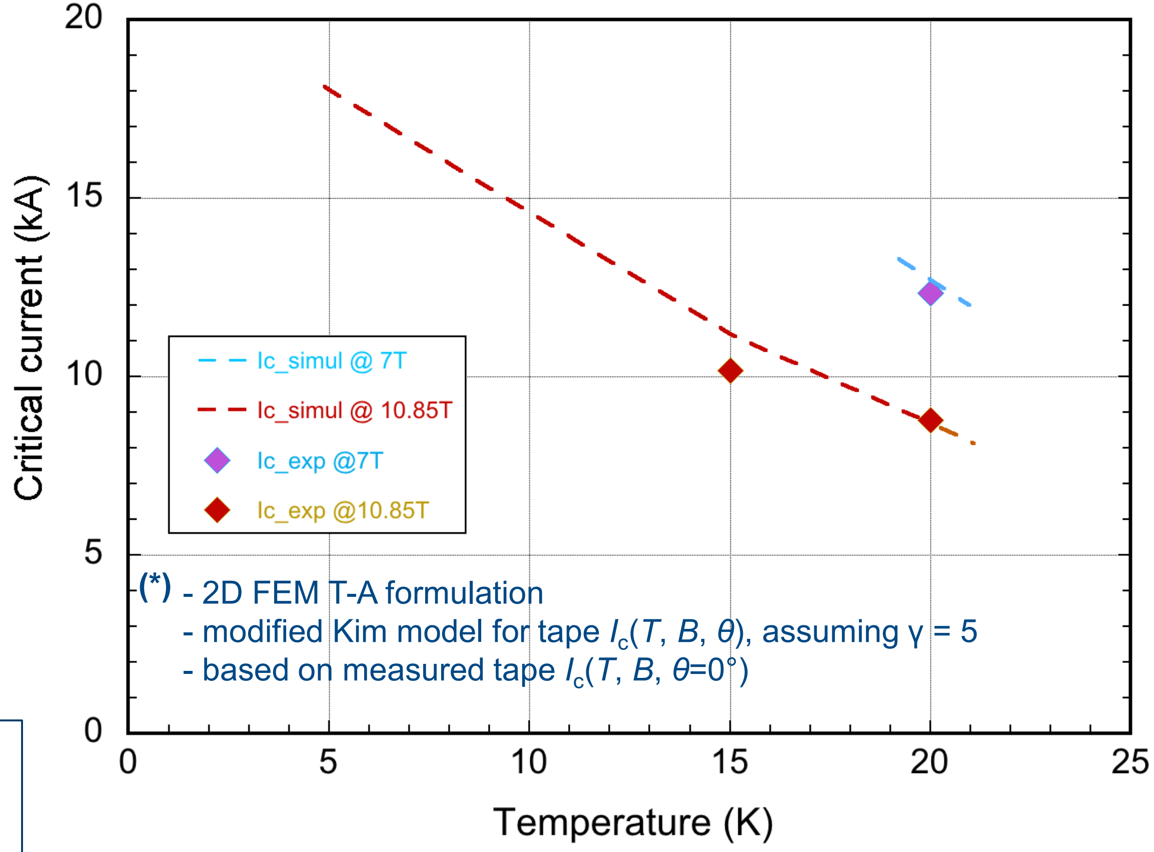
(Run 14)
20 K, 7 T → I_c = 12.3 kA



Uniform transition in HFZ

Comparison with simulation (*)

G. De Marzi *et al.*, SuST **34**, 035016 (2021)



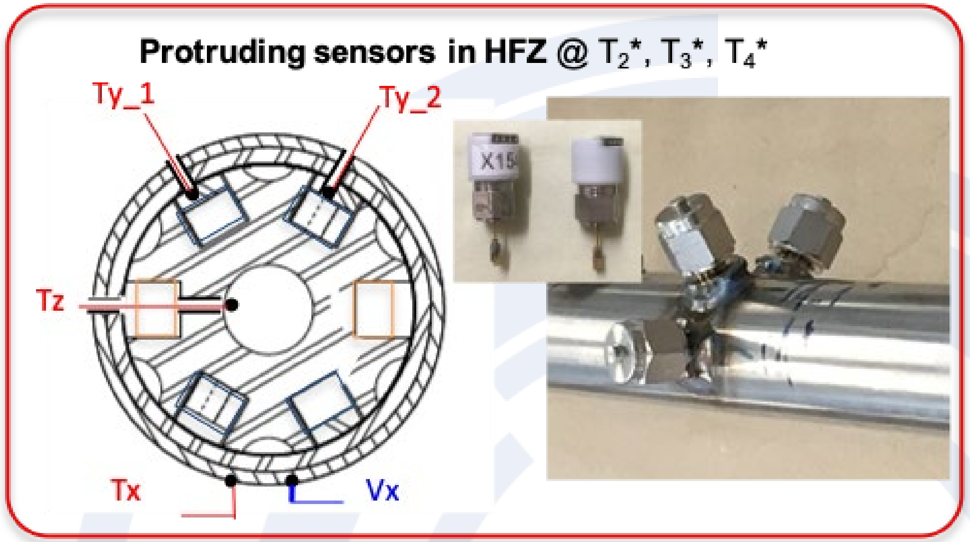
Good match between calculated and experimental I_c

Good SULTAN samples performance predictions

Quench tests @ 10.85 T, 15 kA

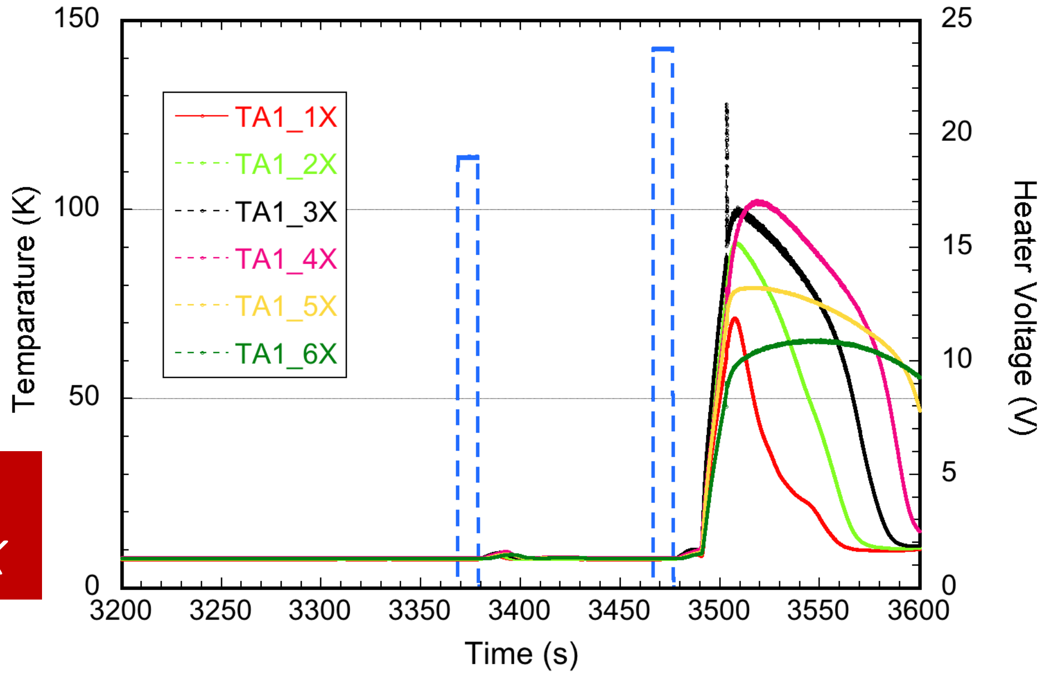
Quench tests:

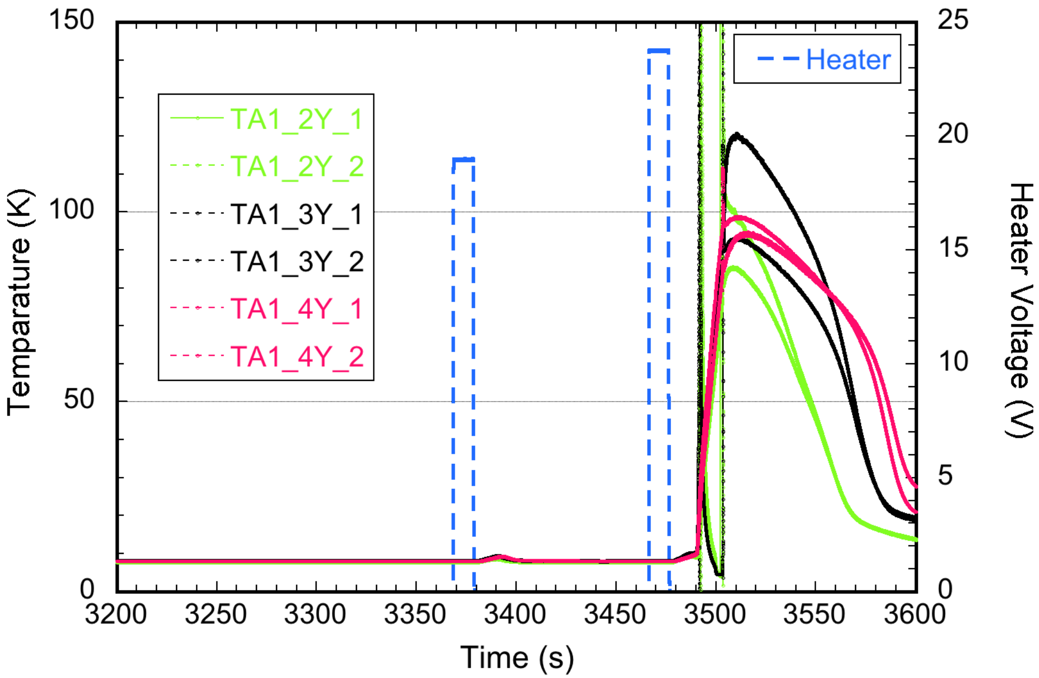
- direct power supply keeps the current constant
- quench is induced by heating the He at the inlet
- current is dumped when a T threshold is reached



Series of test → *T*_hot spot (reference *T*_3X)	
1st →	45 K
2nd →	72 K
3rd →	105 K
4th →	135 K
5th →	135 K
6th →	125 K
7th →	200 K

*T*_hot spot = 105 K (*T*_3X)

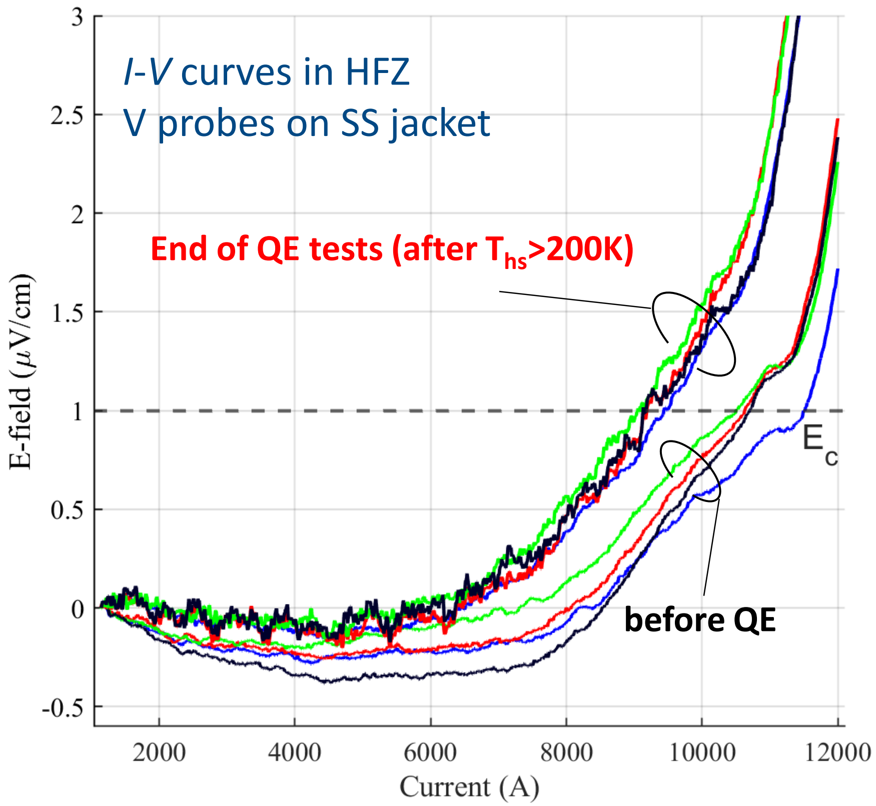




Degradation After T_{hs}>200K

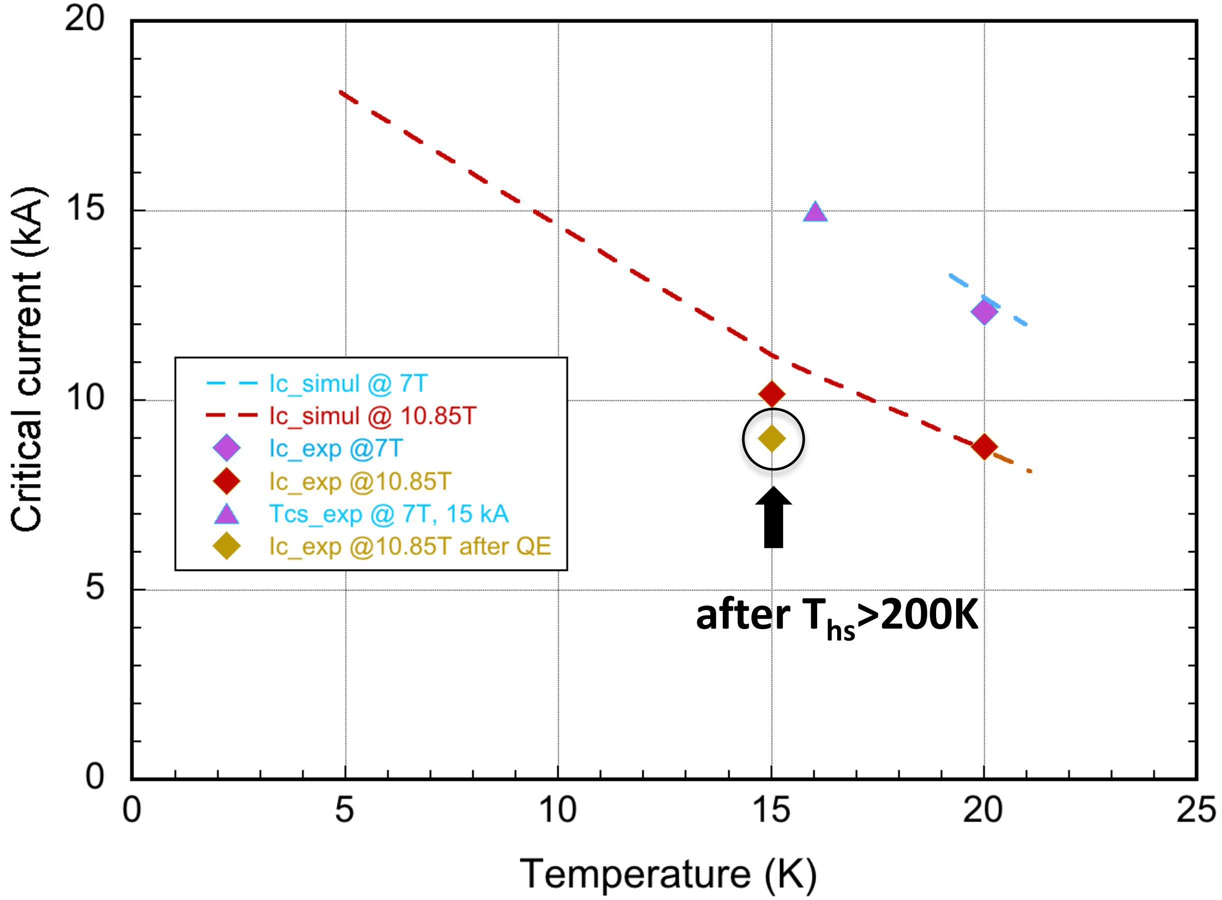
Quench tests – degradation after $T_{hot\ spot}$= 200 K

Final check with repetition of I_c @ 15 K, 10.85 T

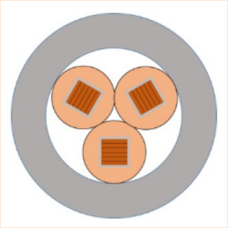
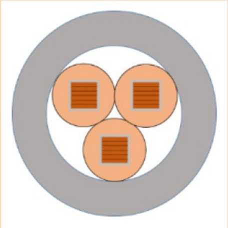
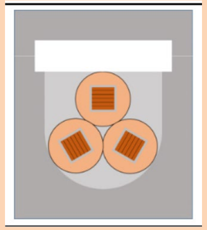
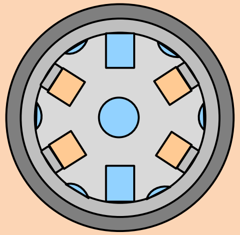


I_c = 8.9 kA → 10% reduction between test before and after QE tests

Appreciable degradation recognized by **10 % I_c** reduction (1.2 kA)



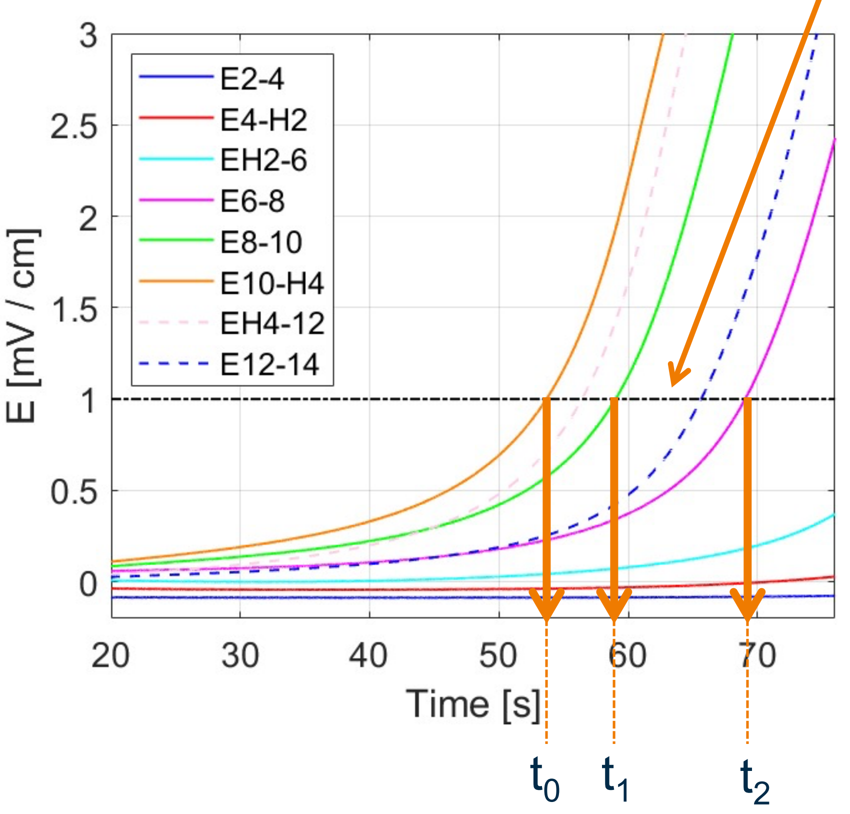
Quench Experiments: comparison with previously tested samples

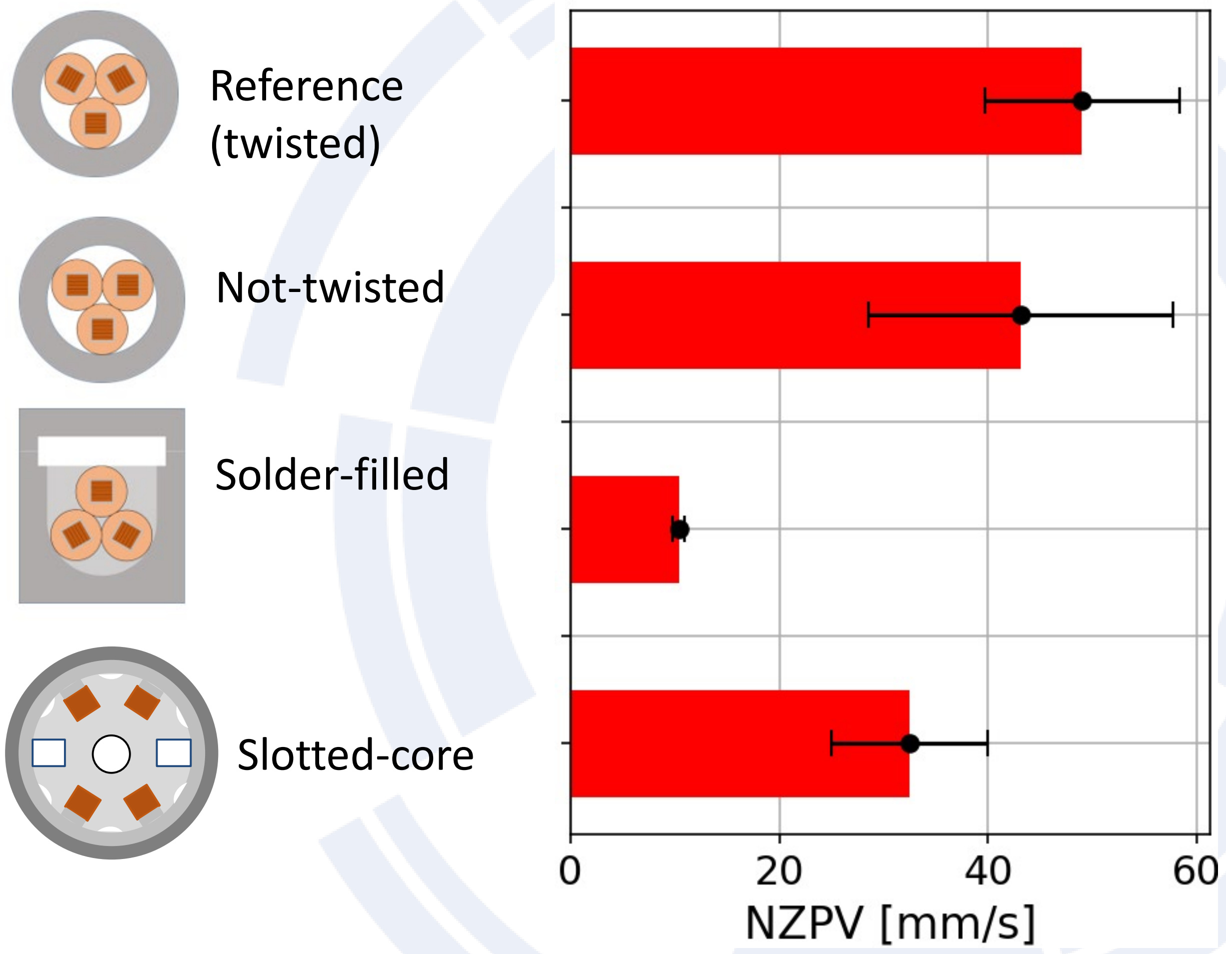
	Conductor	Stabilizer	Stabilizer cross section (mm^2)	$J_{stabilizer}$ (A/mm^2)	I_{op} (kA)	Steel cross section (mm^2)	Design and manufacture
	Reference (twisted)	Cu	**150**	100	15	**715**	SPC
	Non-twisted	Cu	**150**	100	15	**715**	SPC
	Solder-filled ($Bi_{57}Sn_{42}Ag_1$ solder)	Cu	**150**	100	15	**652**	SPC
	Aluminum Slotted Core	Al	**180 +12 (Cu in the tape)**	83	15	**81**	ENEA

- *N. Bykovskiy, SUST 36 (2023) 034002*
- *O. Dicuonzo 2022 PhD Thesis (http://infoscience.epfl.ch/record/293510)*

Quench Experiment: Normal Zone Propagation Velocity

Mark time at which $E > E_{threshold}$, knowing distance L between taps → **Normal Zone Propagation Velocity** (**NZPV**) = $L/(t_2 - t_1)$

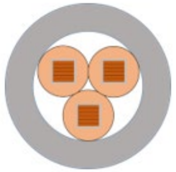




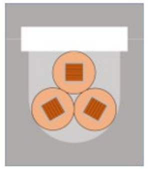
$E_{threshold}$ = 1 mV/cm: high enough to exclude sensors noise. At 1 mV/cm Ic~100 A (at about 70 K) -> all current is flowing in Cu

A. Zappatore, Cryogenics 132 (2023) 103695

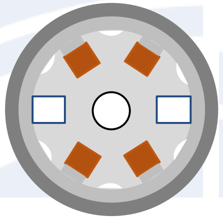
Temperature Evolution



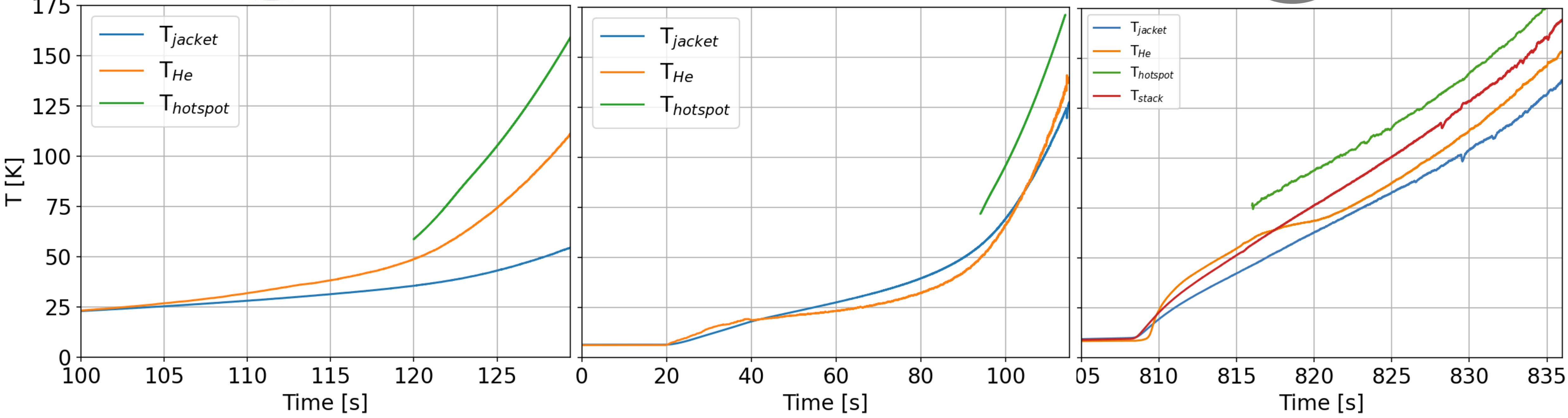
Reference (twisted)



Solder-filled



Al Slotted-core



- ❑ In reference conductor: largest temperature differences in the cross-section
- ❑ In solder-filled: smaller temperature differences, slowest temperature rise
- ❑ In Al slotted core: faster evolution, smaller temperature differences. Measured T_{stack} very close to $T_{hotspot}$ that is reconstructed from voltage:

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

Quench Experiments: comments

- In ENEA conductor the **sample degraded after T_{stack} =200 K** was reached, likely because of thermal gradients.

- **ENEA conductor and solder-filled conductor** guarantee a **better thermal contact** among their sub-elements → **ΔT_{max} ~ 35-40 K in the cross-section**;
  in reference and not-twisted conductors, point-contact between copper profile and jacket leads to ΔT_{max} >100 K in the cross-section.

- **NZPV** in range 10-50 mm/s, i.e., 1-2 orders of magnitude smaller than in LTS (ITER conductors)

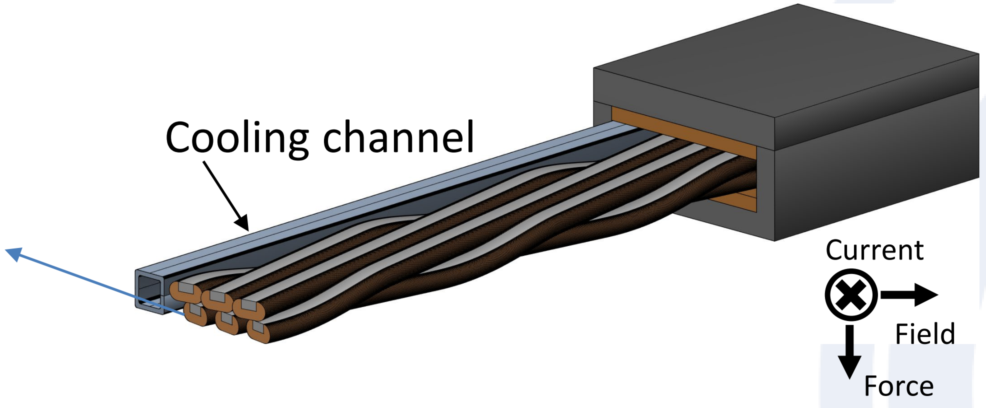
- Smaller NZPV in solder filled due to larger heat capacity wrt the other conductors.

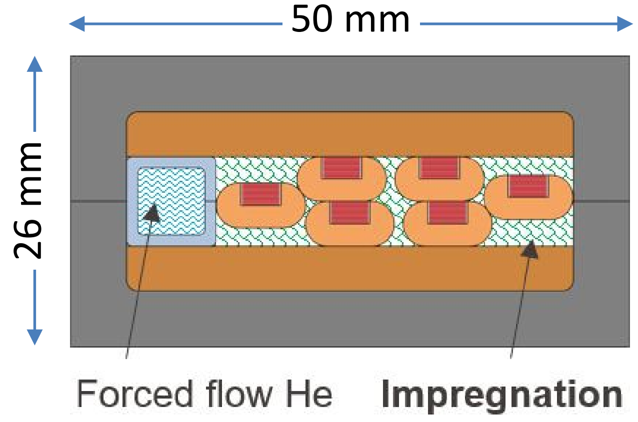
Full-scale HTS conductors

ASTRA conductor prototype layout

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | SWISS PLASMA CENTER

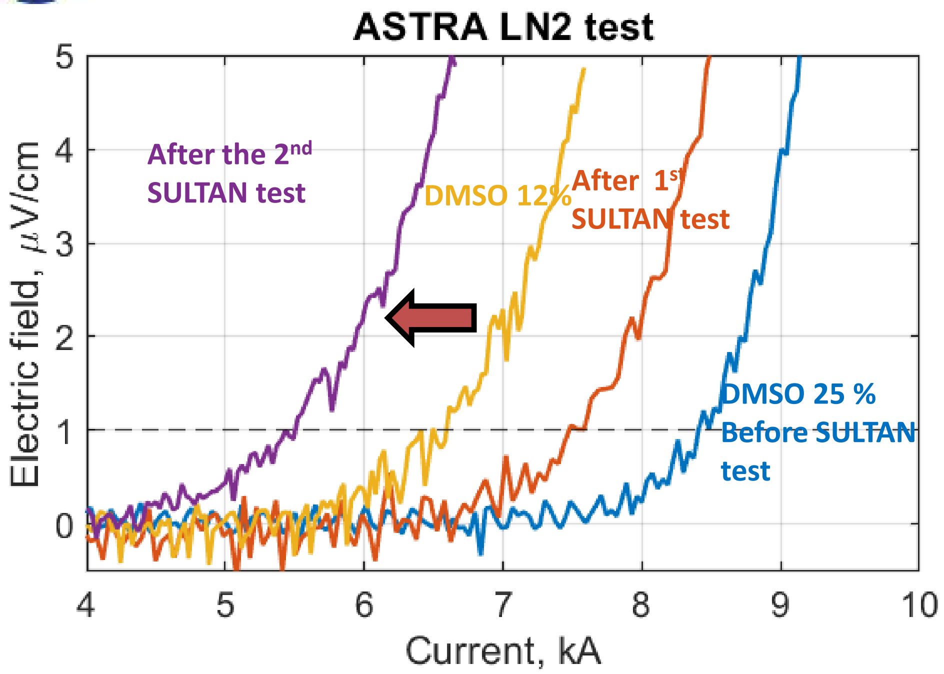
Aligned Stacks Transposed in Roebel Arrangement (ASTRA)

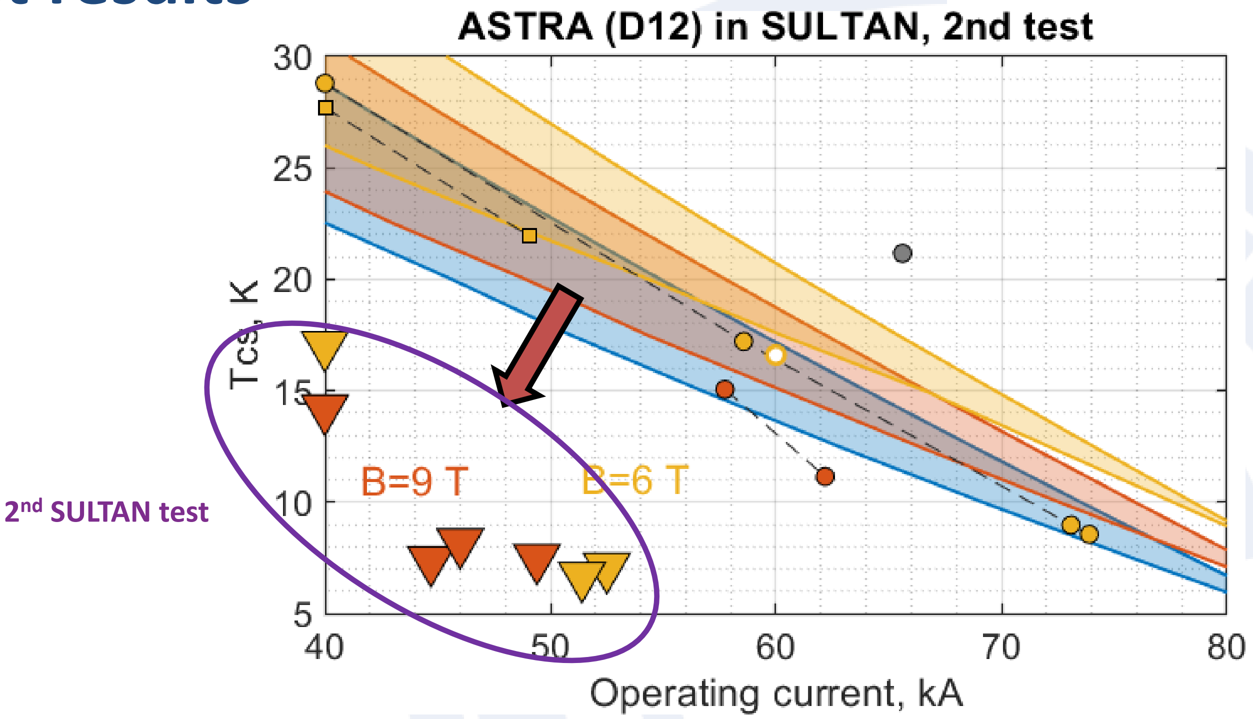


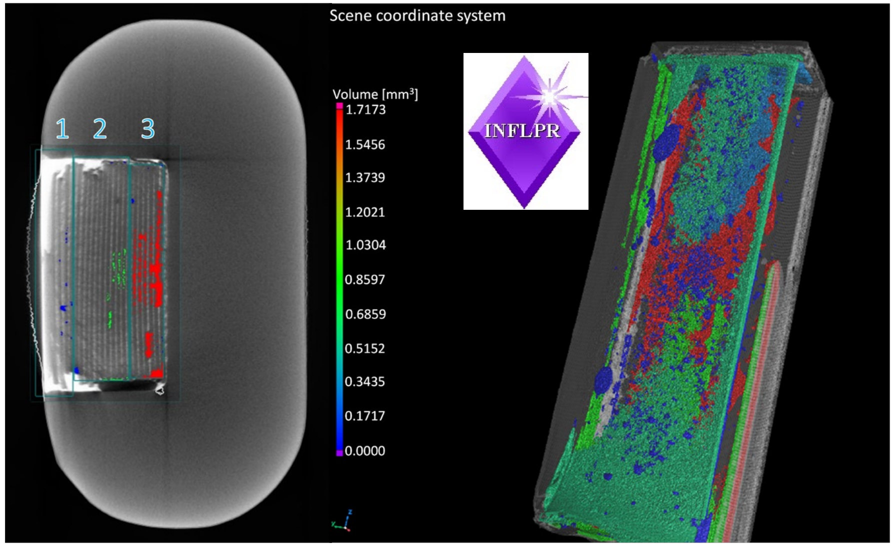


- 3.3 mm SST tapes, 21-tape **soldered stacks**
- 6 **transposed** strands (L~0.75 m) → reduce AC losses
- Aqueous DMSO (Dimethyl Sulfoxide) **impregnation** (for mechanical support)
- **Tight cooling channel** → conduction cooling
- Operation in **parallel background magnetic field** → reduce # tapes

ASTRA Conductor prototype: test results





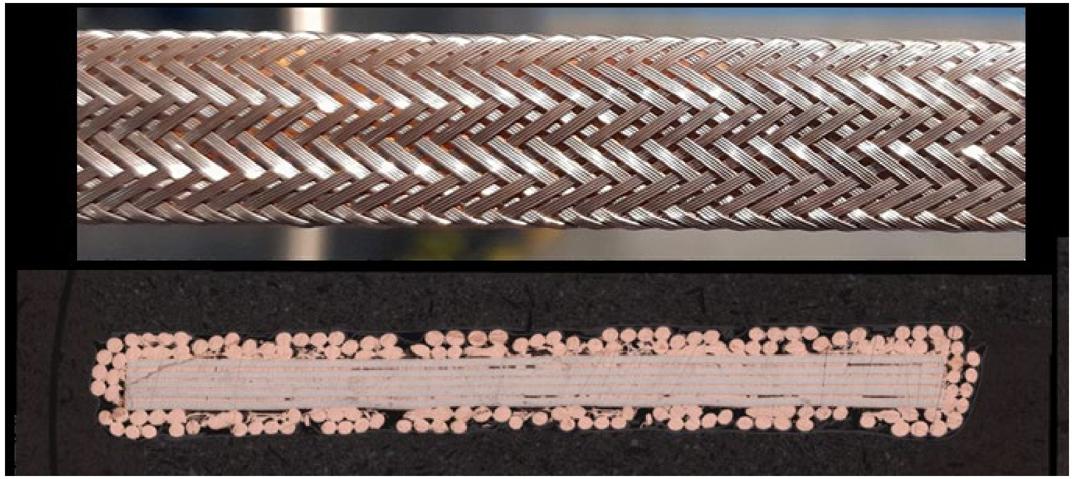


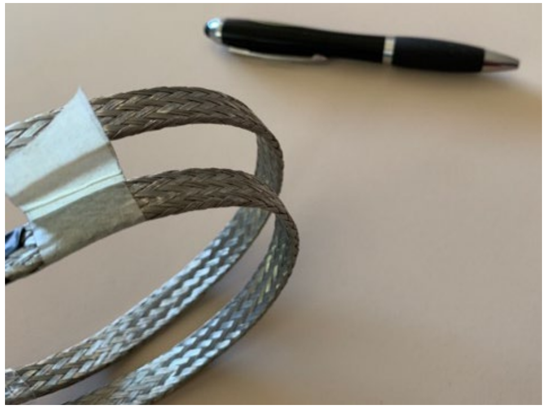
- Initial DC performance in-line with expectations both from LN2 bath and SULTAN testing.
- Strong performance reduction by EM load (at 9 T, 63 kA ~570 kN/m) and thermal stresses by frozen aqueous DMSO due to its thermal expansion
- Voids and pores in soldered stack might be the root cause, thus strand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

SECAS conductor development

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

High-current / high- field SECtor ASsembled ***(SECAS)*** CICC

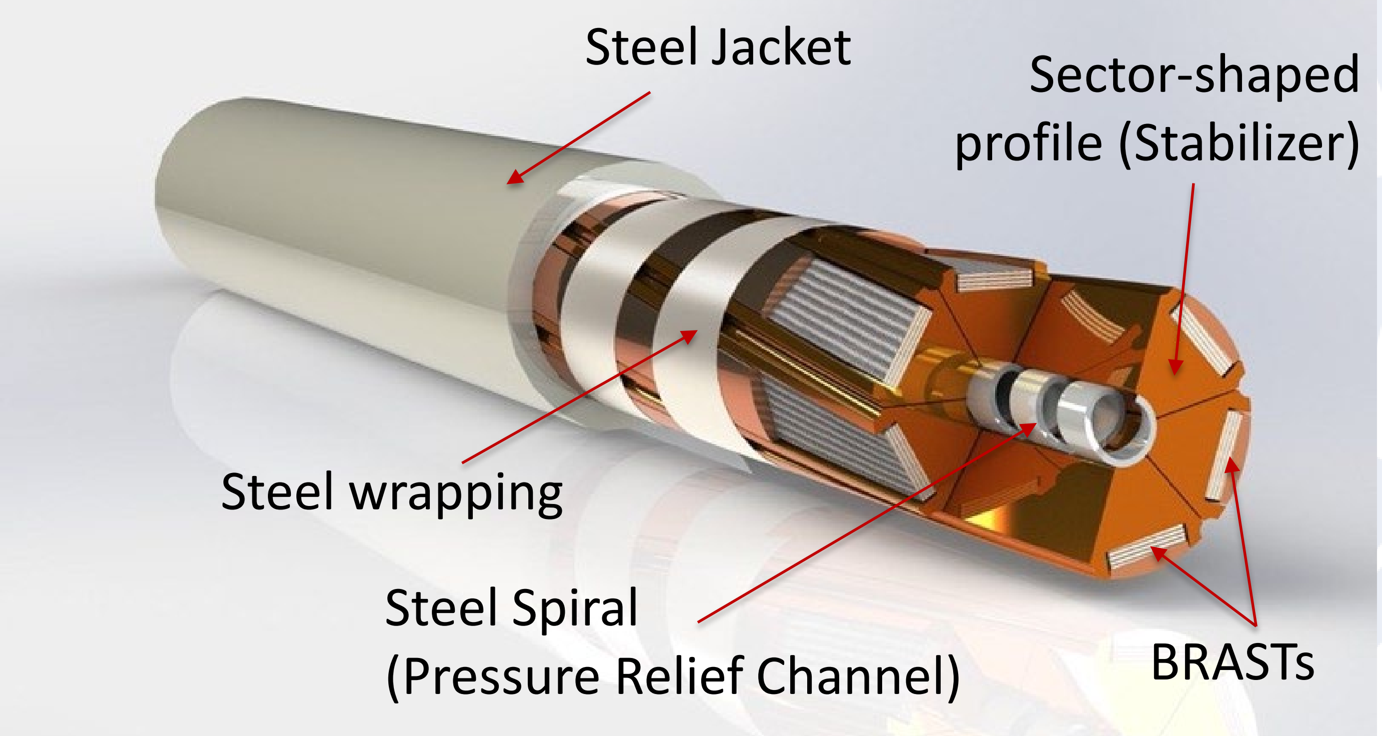




BRAST Features

Flexible
Compact
Easy to handle

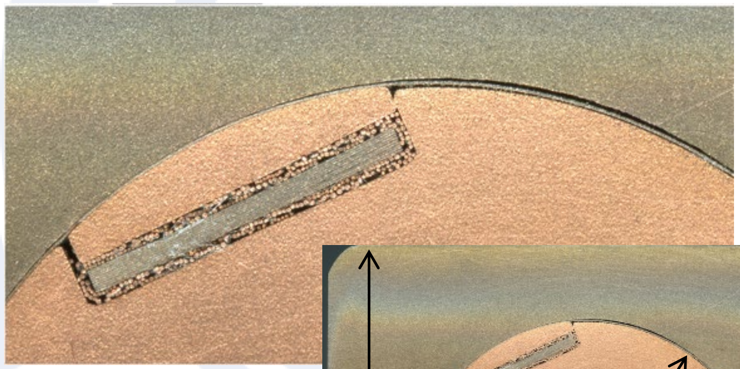
Multi-Stage Cable Processing



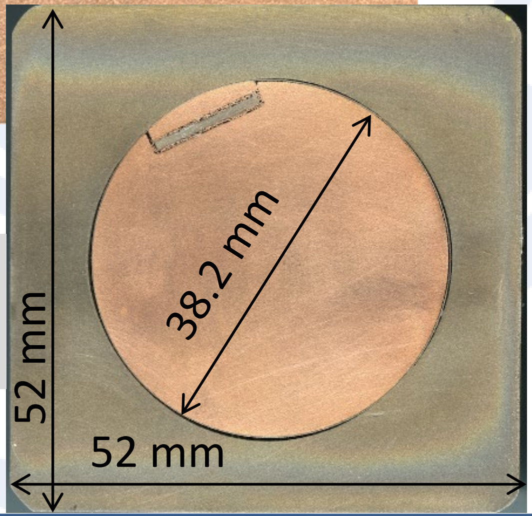
Non-monolithic structure of the stabilizer → limited AC losses?

BRAST mechanical assessment: twisting and compaction

Core: Cu tube, dia. 38 mm, with machined spiral slot (Twist Pitch 1.2 m)
HTS strand: **BRAST 10 tapes** (SuperOx Jp, 12 mm x 0.08 um), Braid: 144 Cu wires, dia. 0.15 mm
Jacket: Circle-in-square SS tube (PF ITER cable), 54 x 54 mm, compacted with a 4 rolls mill @CRIOTEC Impianti (Italy)



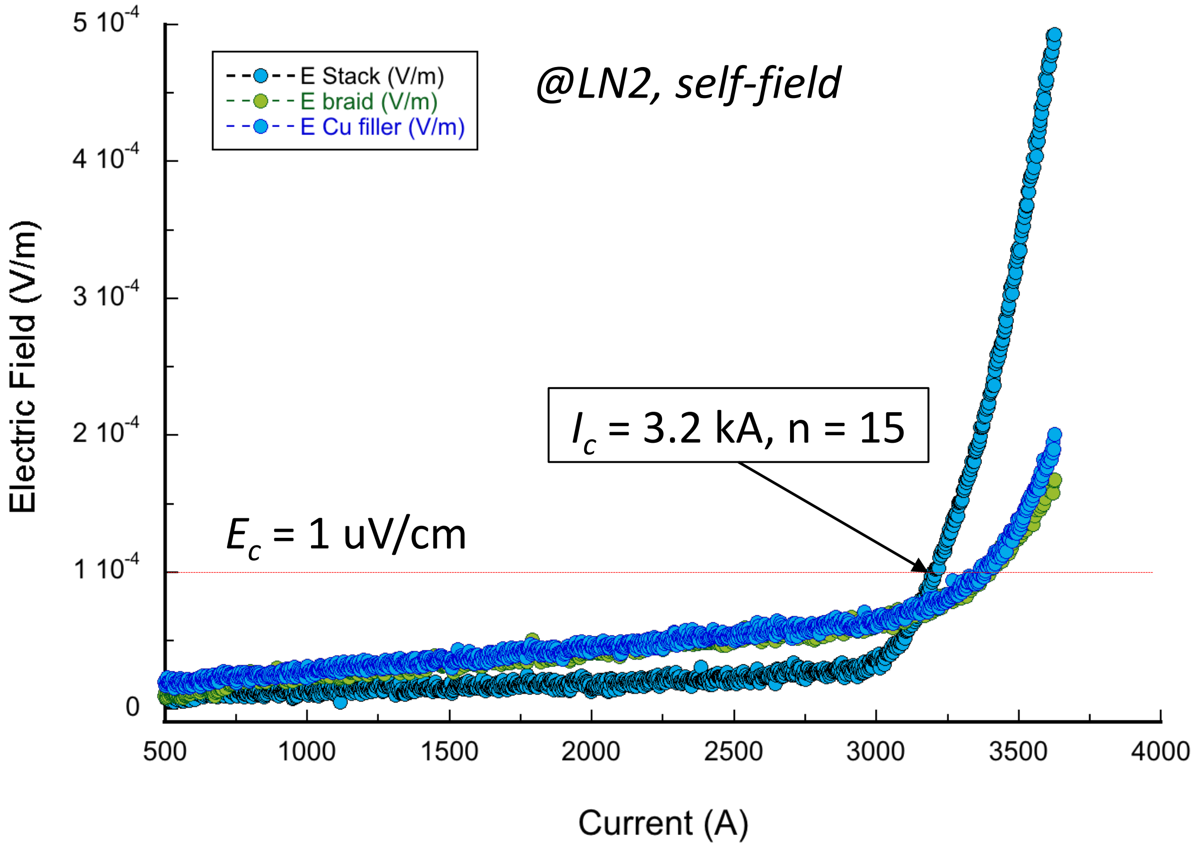
BRAST#3
Cross-section



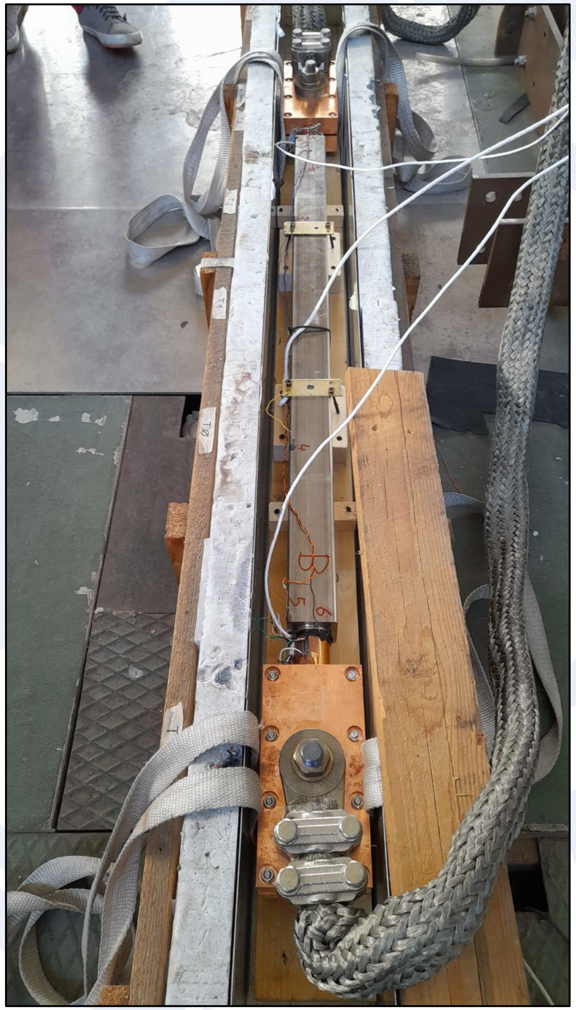
SECAS sub-cable: electric performances

In line with calculated cable critical current by FEM model

De Marzi, et al., SuST 34 (2021)



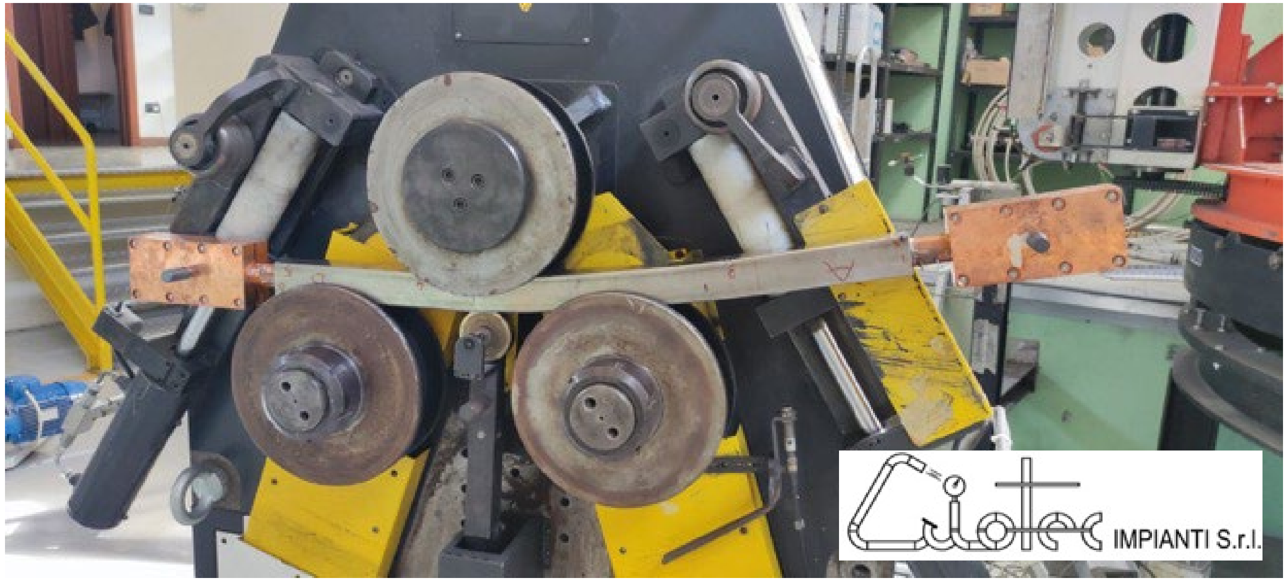
Sample TEST in LN2 @ the ENEA 20kA test facility



BRAST#3 Tests on BENT Conductor

BRAST#3 has been **BENT** to **R = 1.5 m** *(as required for the* ***EU-DEMO CS*** *coil winding)*

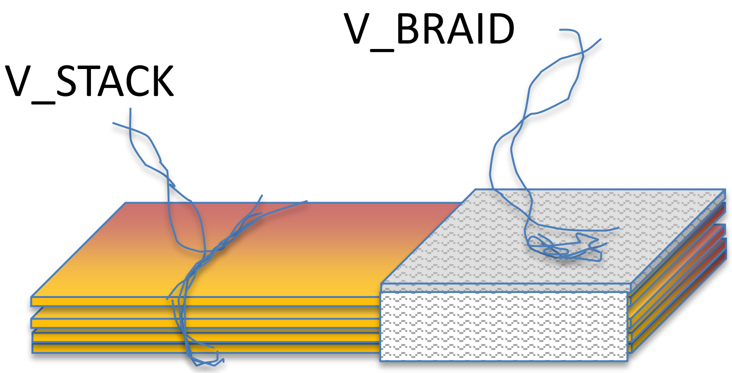
BRAST #3 bending to target R = 1.5 m

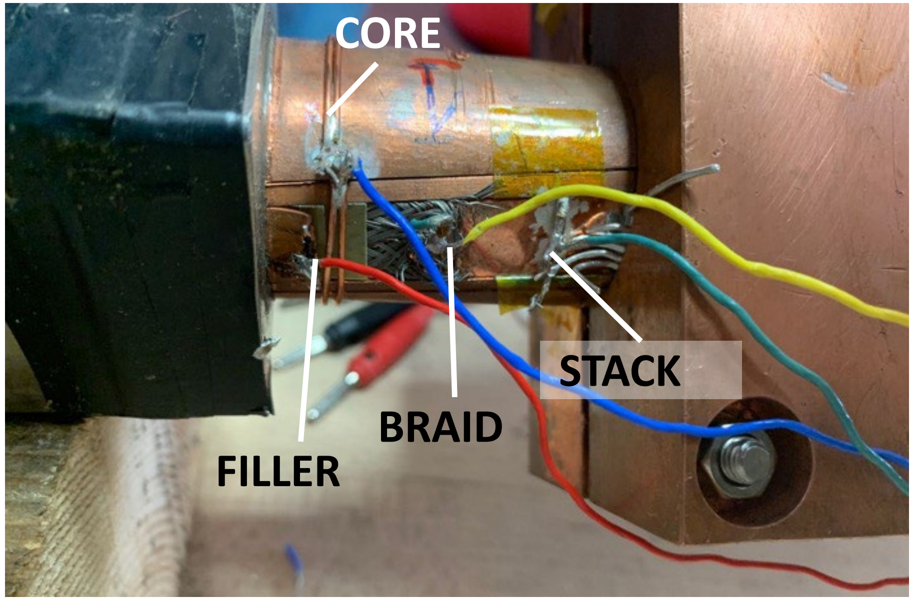


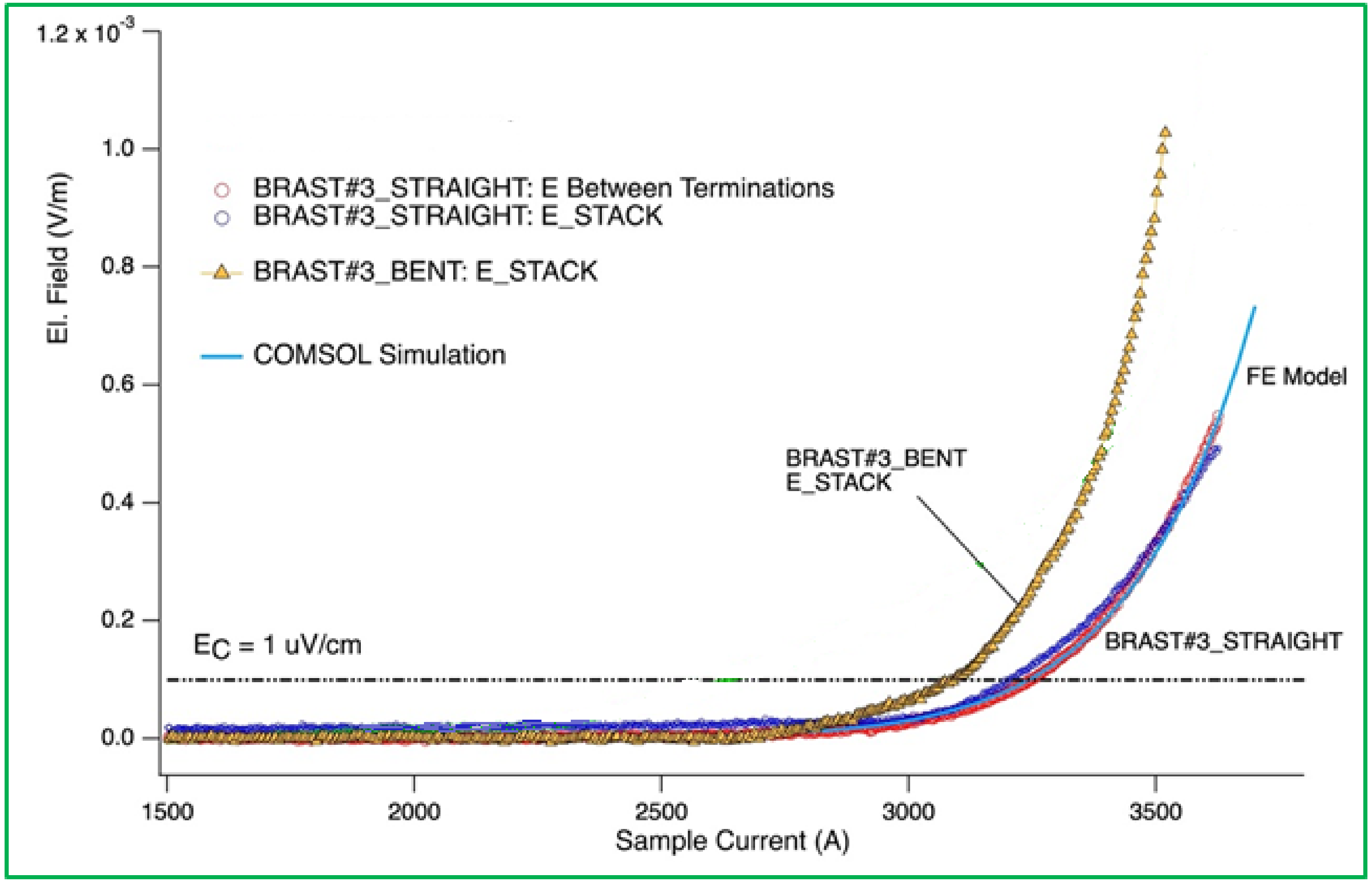
BRAST #3 in BENT configuration

BRAST#3: Test on BENT Conductor

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







Conclusions

Quench Experiment

1) The performance of ENEA Al-slotted core sample is in agreement with predictions and is stable.
   BUT I_c **degradation** by 10 % @ 10.85 T, 15 K occurred after the sample reached $\mathbf{T_{hot\ spot} > 200K}$
2) Despite the different configurations the **NZPV is in range 10-50 mm/s**, i.e., 1-2 orders of magnitude smaller than in LTS (ITER conductors)

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.

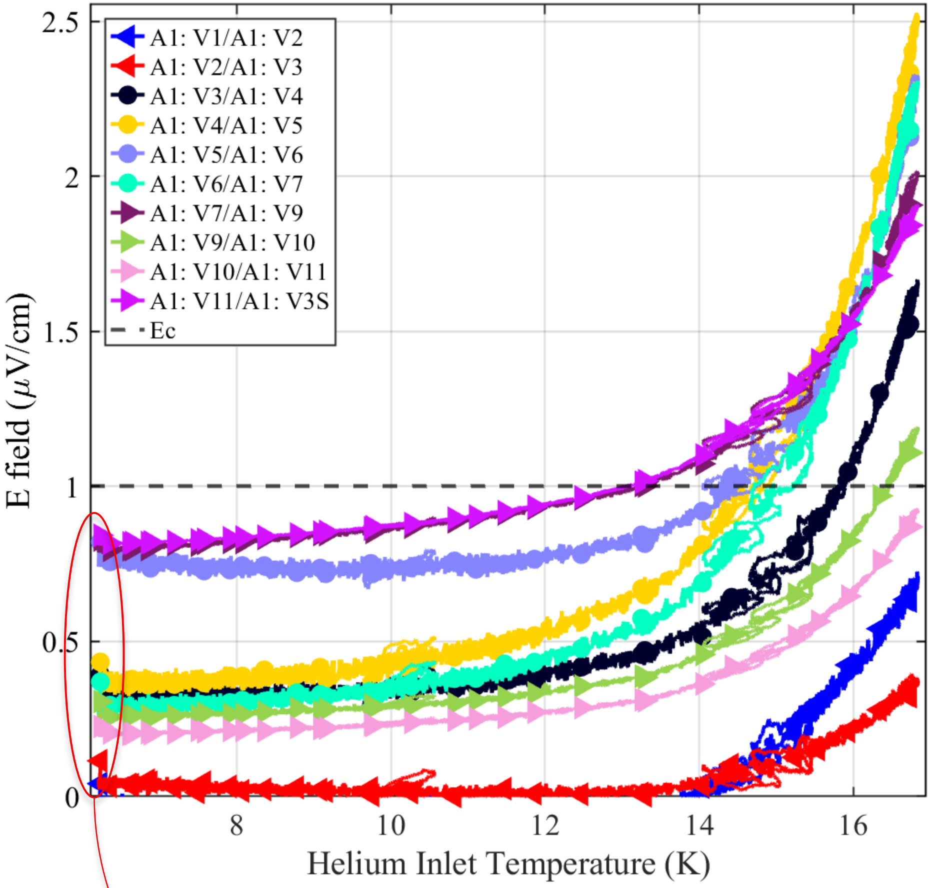
Thanks for your attention!

CNRS-Grenoble February 2024

A special thank to the WPMAG team members that worked on the topics shown in this presentation: H. Bajas, R. Bonifetto, P. Bruzzone, N. Bykovskiy, G. Celentano, G. De Marzi, A. Masi, L. Muzzi, M. Ortino, K. Sedlak, I. Tiseanu, D. Uglietti, A. Zappatore

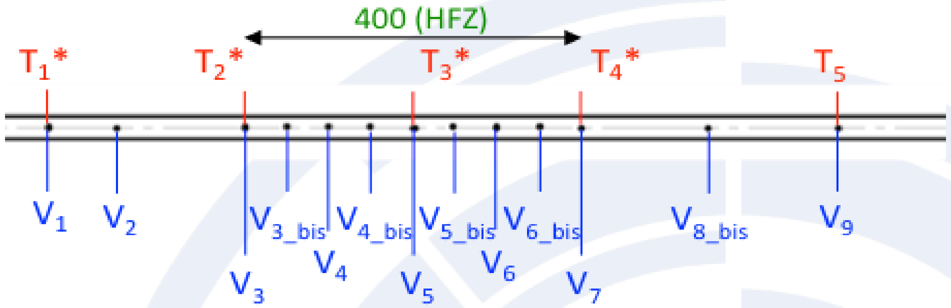
DC performance test: T_{cs} measurement

***T_{cs}* measurement @ 7 T, 15 KA**

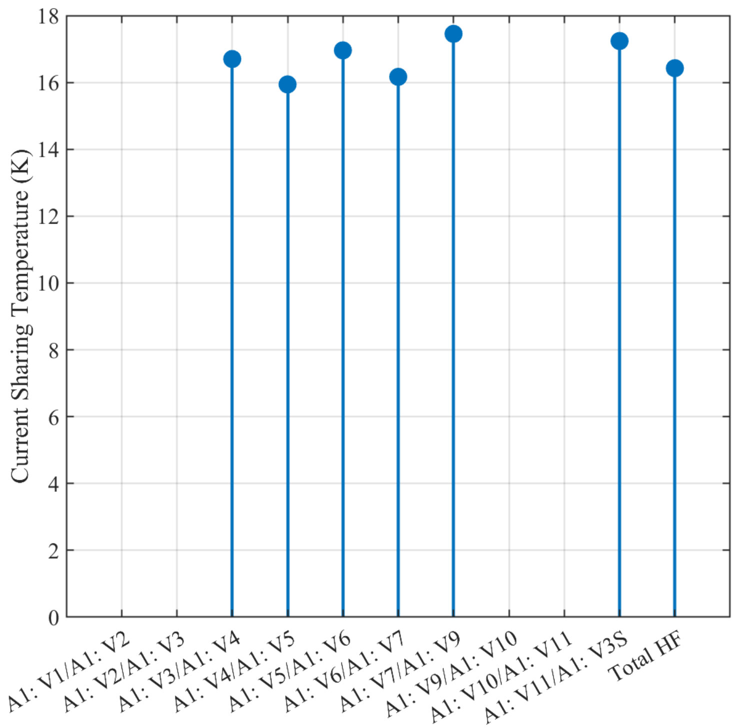


E_0 consistent with contribution from current fraction into the normal (Al/SS) component

He flow



T_{cs} estimate by fitting the curve with $E = E_0 + E_c(T/T_{cs})^m$

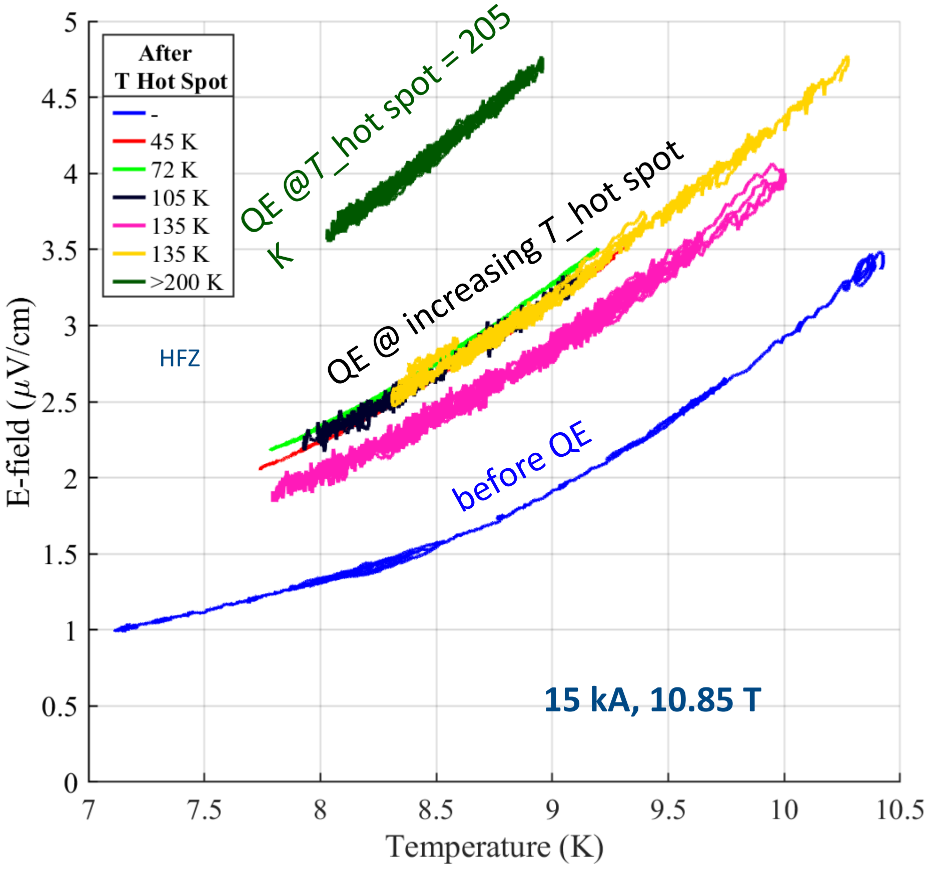


***Tcs* = 16.1 K (HFZ)**

16

Quench tests – degradation

Increasing hotspot temperatures → evolution of the *E*-*T* curves in HFZ

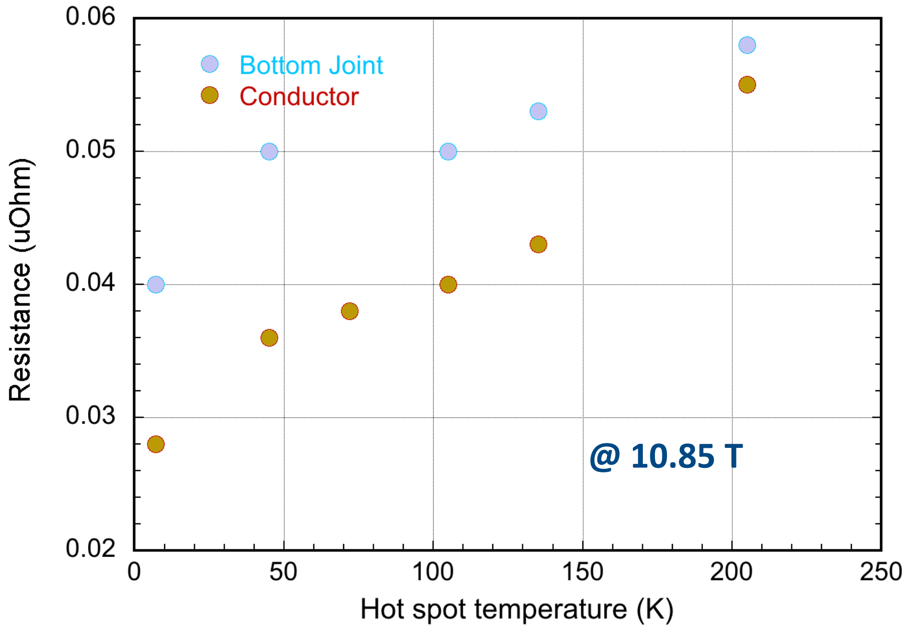


***E*-*T* curves shift** after first QE with $T_{hotspot}$ = 45 K
After QE @$T_{hotspot}$ = 205 K → larger shift

All curves have **same *T*-dependence (*)** appear **translated to larger *E*-field offset**

(*) Fit $E = E_0 + E_c(T/T_{cs})^m$ provide similar *T*cs, *m*-index

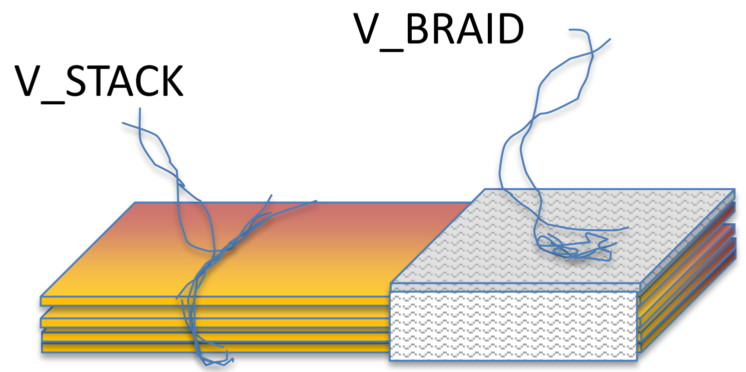
Increase in conductor and bottom joint resistances with QE (*T*_hot spot)

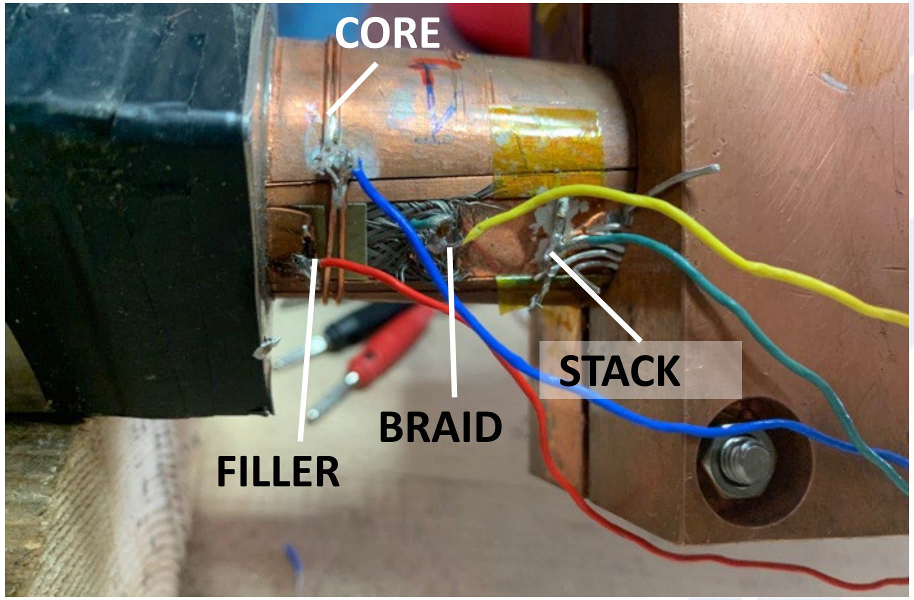


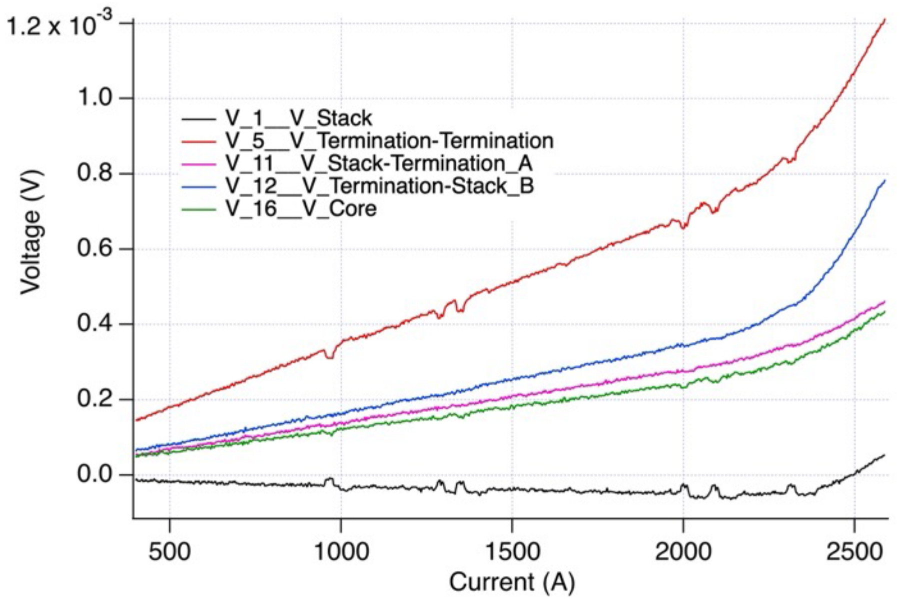
Increase in bottom joint R could determine a different fraction of current on Al/SS stabilizer → inducing larger *E*-field offset in *E*-*T* measurements

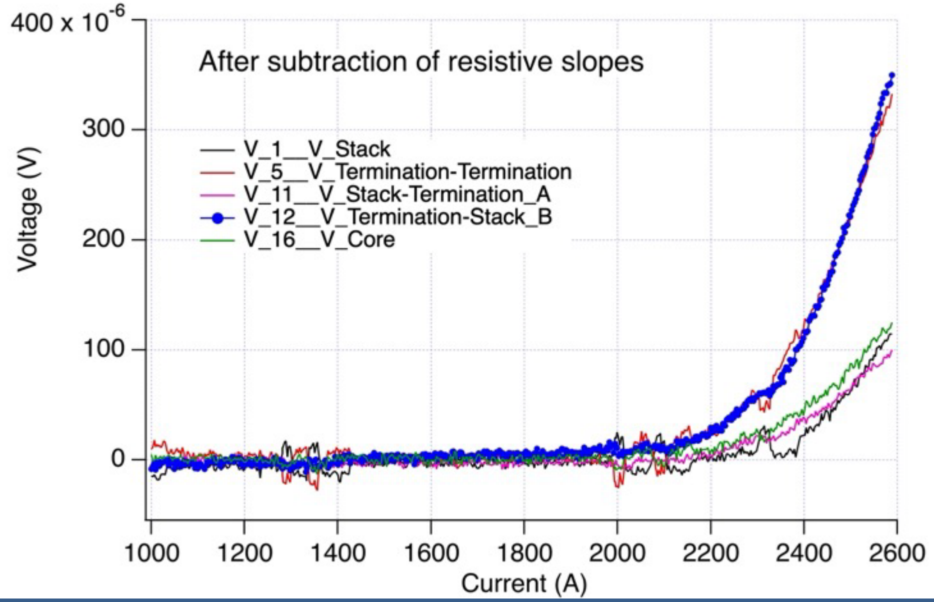
Effect on T_{cs} @ 15 kA, 10.85 T not detectable (possibly masked by this increase in E-field offset)

BRAST#3: First tests on BENT Conductor







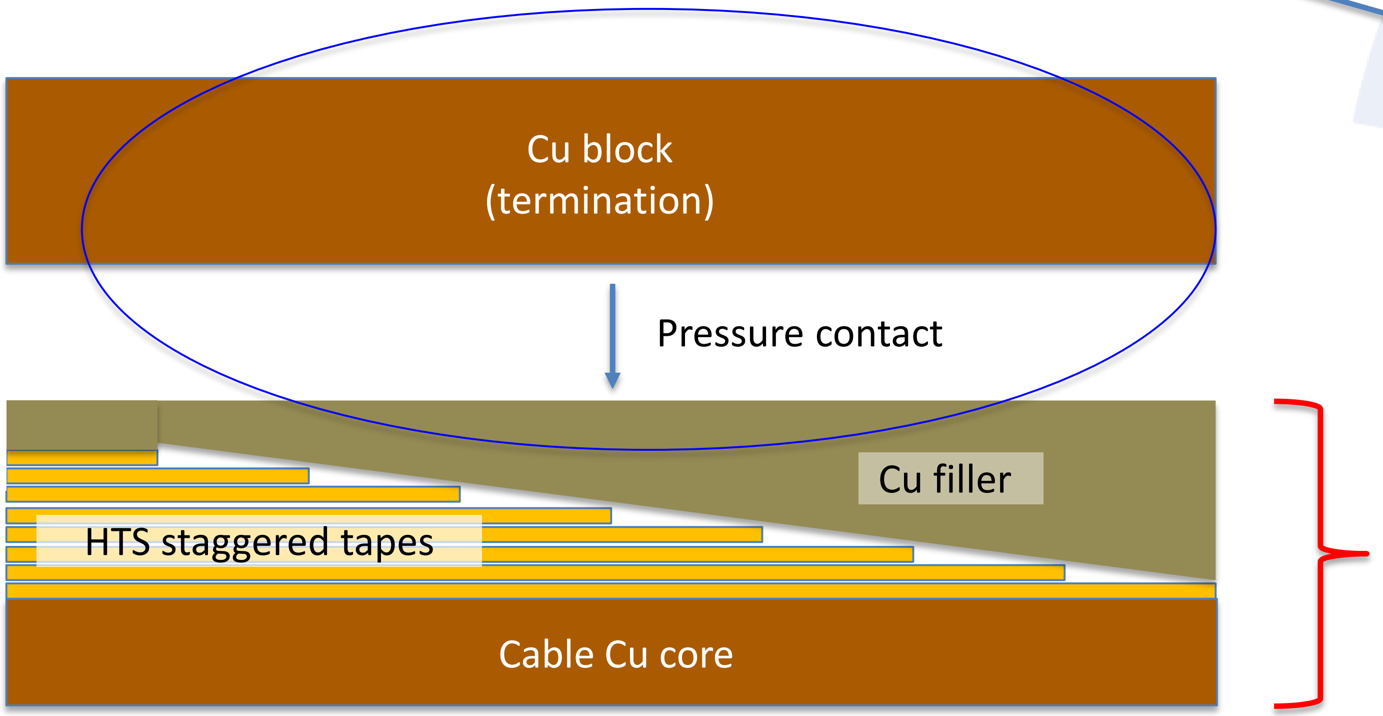


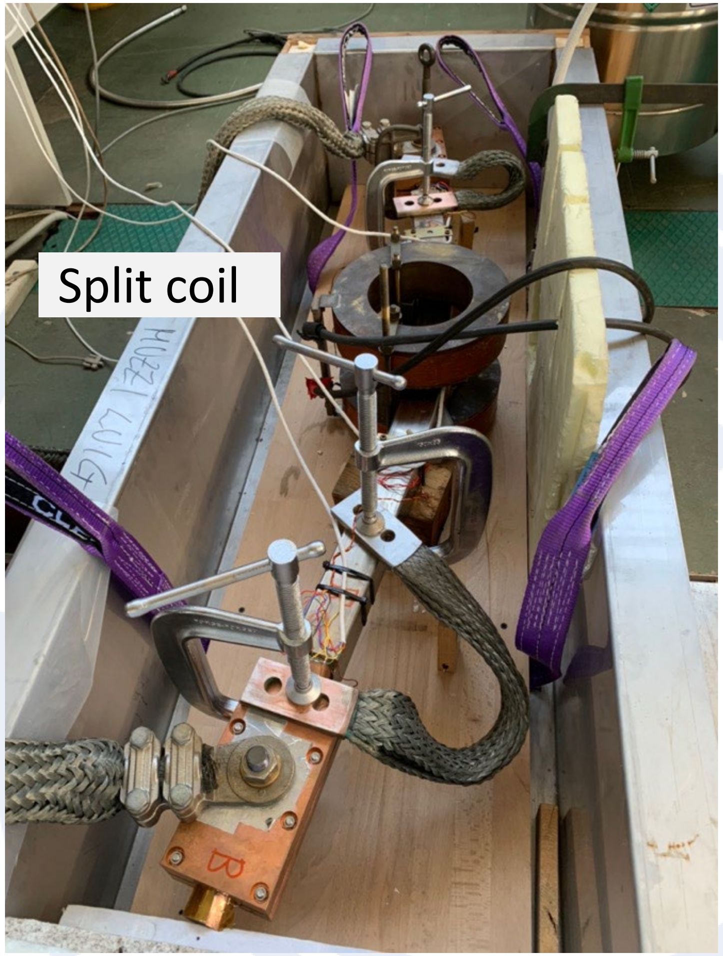
- ❑ Transition occurs at **20% lower** current than in Straight sample
- ❑ **BUT** transition occurs **at termination B**
- ❑ Evident **Current transfer phenomena** between tape stack and the other components in the cross-section.

Re-assembly of BRAST#3 termination

- Termination **(partially)** dismantled and re-assembled;

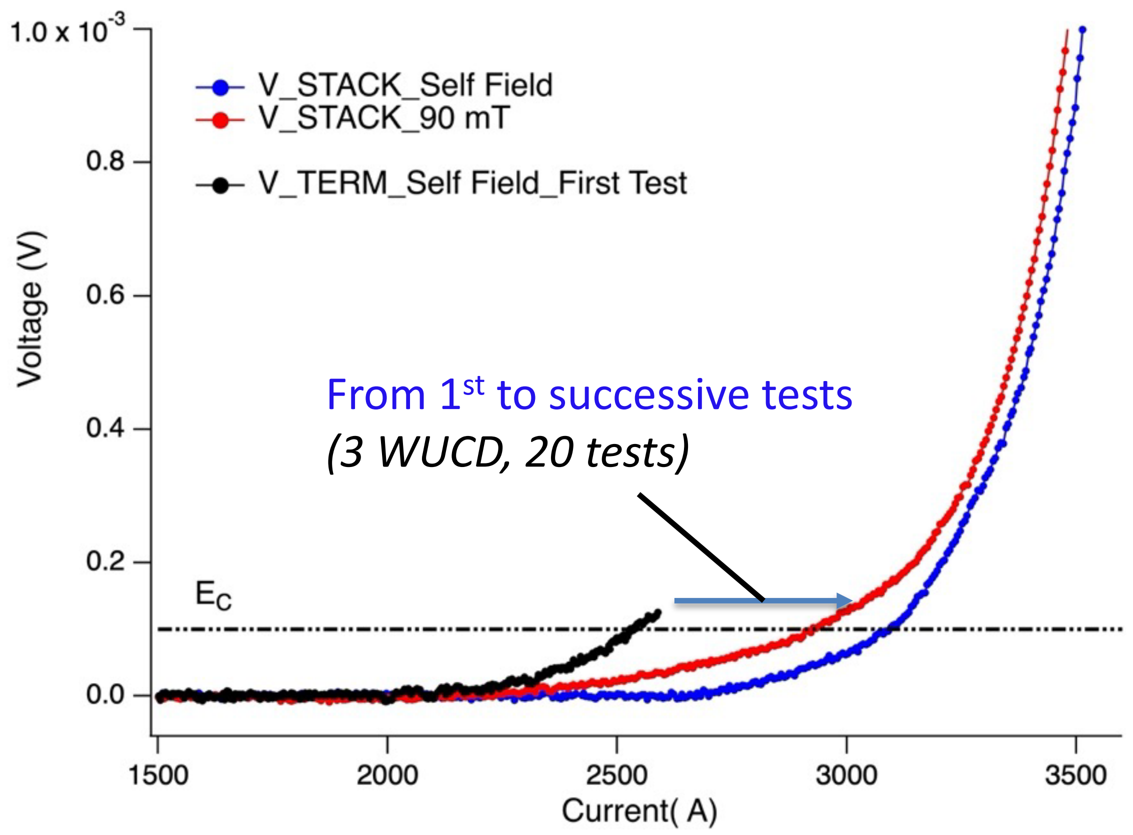
- A split coil **(B_{max} = 100 mT)** added, in the attempt to «force» the transition to occur at the center.



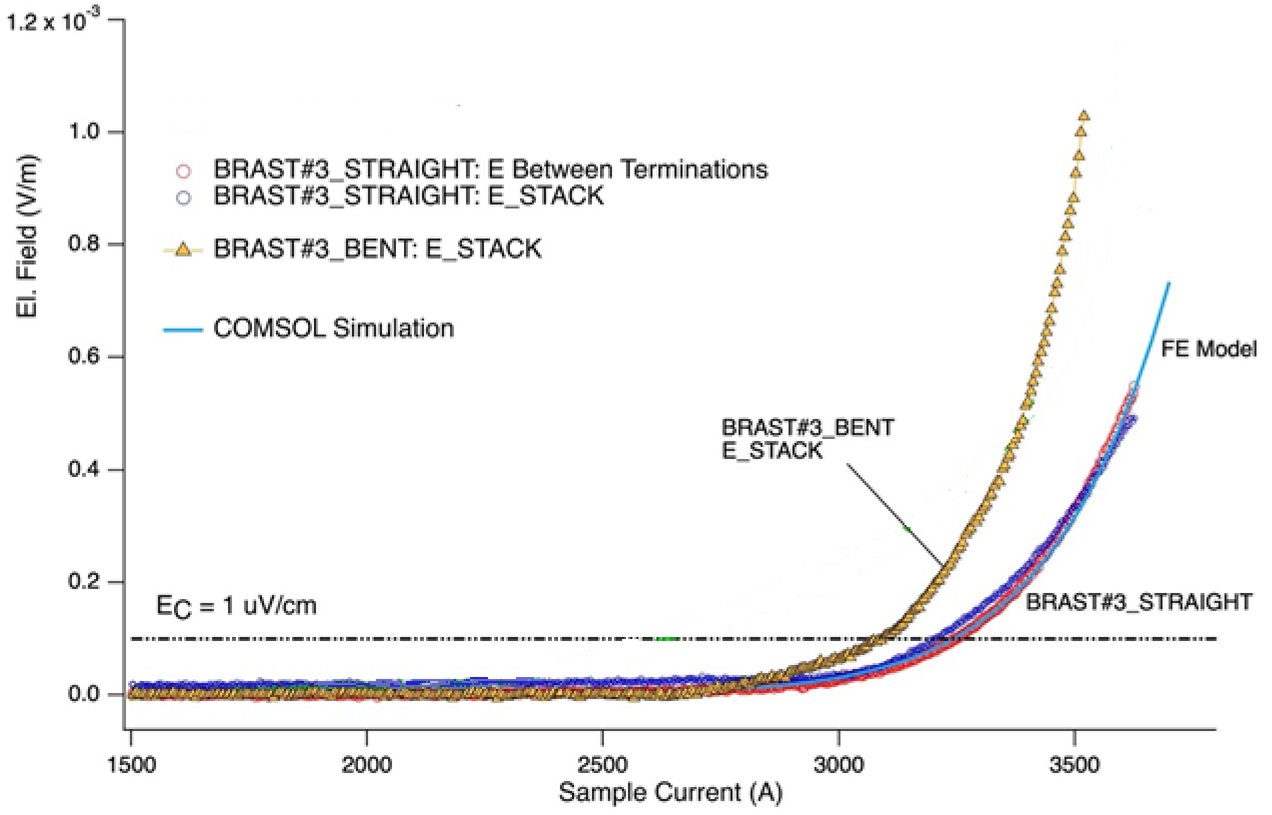


Pre-tinned and soldered

BRAST#3: Final tests on BENT Conductor



- Transition shifts to higher current values.
- Transition occurs most likely at the center.
- Transition measured over terminations is very similar to the one measured over the stack.



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