Italian National Agency for New Technologies, Energy and Sustainable Economic Development

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Designing and Manufacturing of REBCO-based Al-slotted core Cable-In–Conduit Conductors for quench experiments

On-line oral presentation, November 19th 2021

Acknowledgment: WPMAG International Collaboration EU-CN 2019-2020

EUROfusion

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The TEAM: people involved & main roles

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Role: Experiment conceptualization, Sample Designing & Manufacturing

Italian National Agency for New Technologies, Energy and Sustainable Economic Development

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Role: Sample Designing

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Role: Sample Manufacturing

Outline

- **Motivation**

  → quench investigation on high current HTS conductors suitable for large magnets
  → fusion suitable REBCO Al-slotted slotted core conductor

- **Quench experiment REBCO Al-slotted core sample**
  - Quench experiment conditions at SULTAN facility;
  - Conductor layout;
  - Sample performance predictions;
  - Cooling scheme & Diagnostic layout;
  - Sample manufacturing key features;

- **Conclusions and perspectives**

Motivation: lack of knowledge on HTS cables quench properties

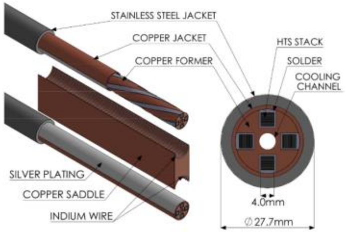
Quench is a well-known phenomenon **potentially destructive** for large coils

M.Wilson, Superconducting Magnets, Oxford (1983)
Y. Iwasa, Case Studies in Superconducting Magnets, Springer 2009

Deeply **studied for LTS magnets** → mature **detection** and **protection** technologies

Quench on (more recently developed) high current **HTS REBCO fusion cables** is still much **less studied**

Z. Hartwing,et al., Supercond. Sci. Technol. 33 (2020) 11LT01 (8pp)



Different architecture/composition and material properties between **LTS wires and HTS tapes** → different thermal and electric properties → different quench behaviour

For HTS there is a **need** for dedicated **experimental activity** and implementation of **new quench-related models / simulations**

Motivation: Al-slotted core cable for REBCO tapes

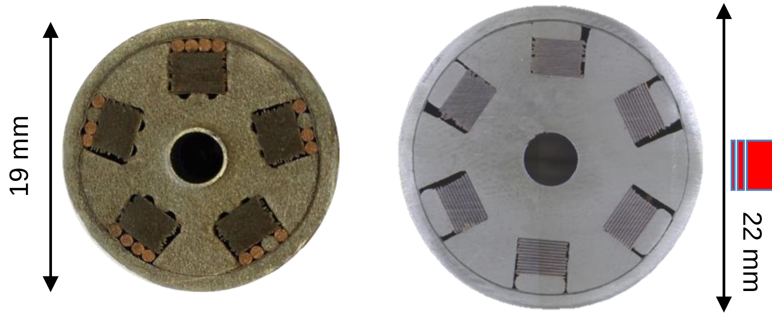
Cable key features → Aluminum slotted-core + HTS tape stack

G. Celentano, et al., IEEE TAS 24, 2014
A. Augieri, et al., IEEE TAS 25, 2015
G. De Marzi., et al, IEEE TAS 26, 2016

Mostly developed in two versions:

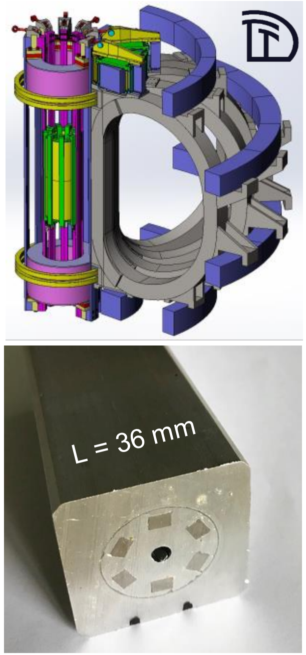
5 HTS stacks | **6 HTS stacks**

(20/30 tapes per stack)



20 kA @ 4.2 K, 12 T | **30 kA @ 4.2 K, 18 – 20 T**

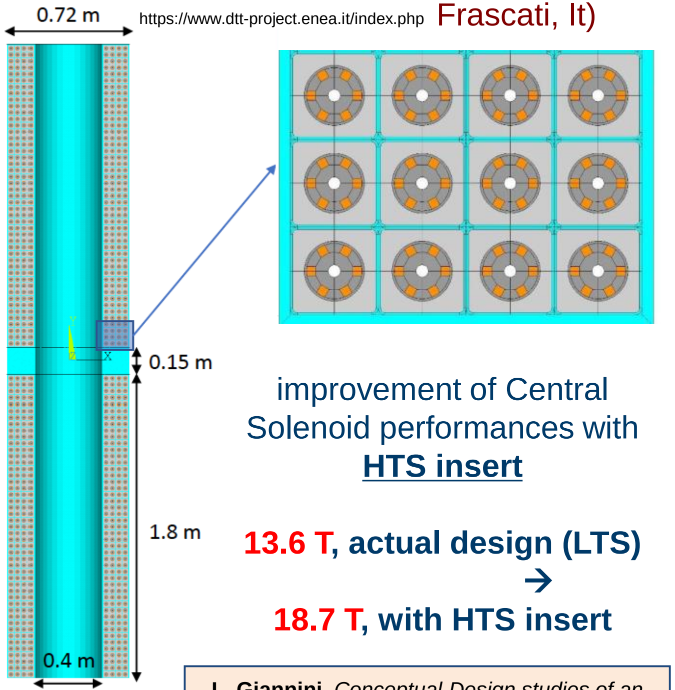
Concept early demonstration → **DTT CS insert coil**



Structural jacket: High – strength Al-alloy (circle-in-square)

DTT Divertor Tokamak Test facility (ENEA Frascati, It)

https://www.dtt-project.enea.it/index.php



improvement of Central Solenoid performances with **HTS insert**

13.6 T, actual design (LTS)
→
18.7 T, with HTS insert

L. Giannini, *Conceptual Design studies of an HTS insert for the DTT Central Solenoid* - presented at EUCAS 2021

Quench test @ SULTAN

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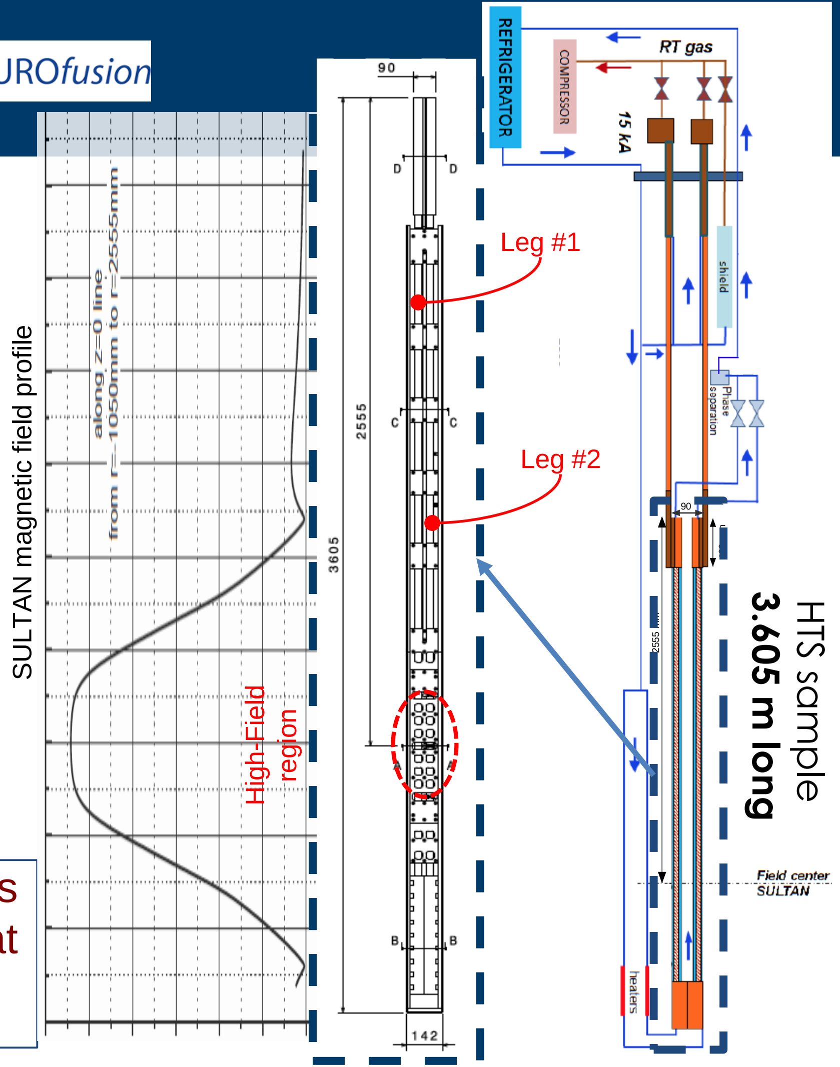
Test at SULTAN facility: **15 kA D.C.** current source**;**
forced flow SHe cooling; Max field **11 T**

Quench test experimental specifications

- max $B_{background}$ = **10.9 T**;
- max I_{op} = **15 kA**;
- Cooling by **forced flow SHe** with T_{op} range **5 - 20 K** and mass flow rate **d*m*/d*t* < 10 g/s**

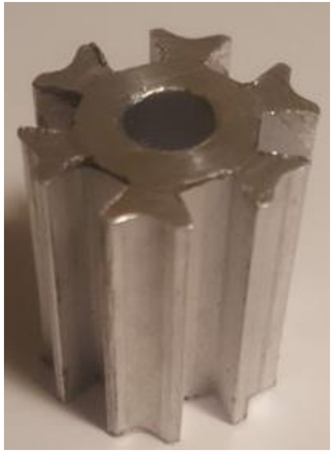
Quench triggered by increasing
→ coolant temperature up to T_{cs}
→ the operating current up to I_c.

Sample for quench experiment consists of **two conductors** (*legs*) connected at the bottom through a **joint**
(Mechanical support structure designed to sustain e.m. loads)



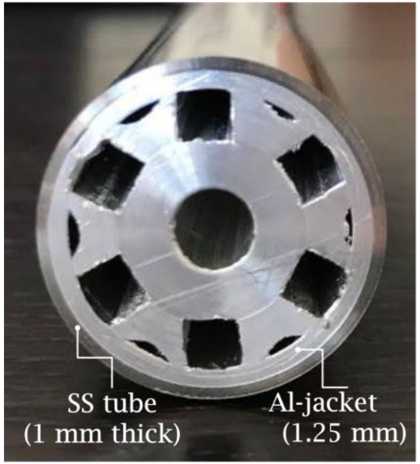
ENEA

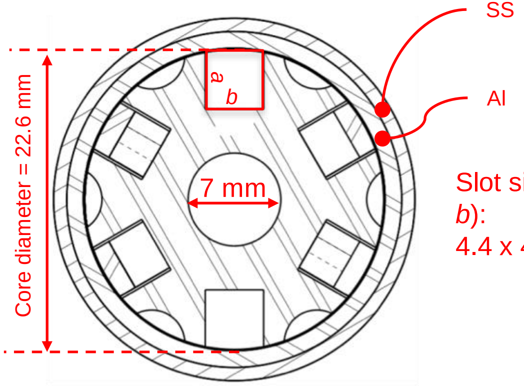
Quench test @ SULTAN: HTS sample



- new release of the Al-core with 6-slots for advanced cooling performances with pressure relief channels;

- double jacket concept (inner Al and external SS tubes) to sustain the electro-magnetic loads and guarantee a proper He tightness;

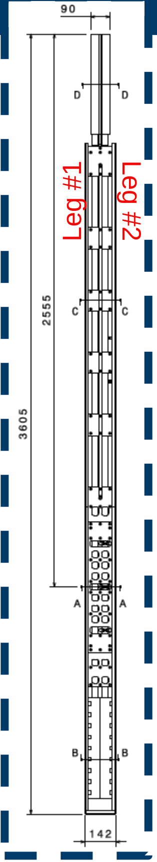




Slot size (a x b):
4.4 x 4.4 mm^2

Jackets are compacted by drawing

Quench test @ SULTAN: HTS sample #1



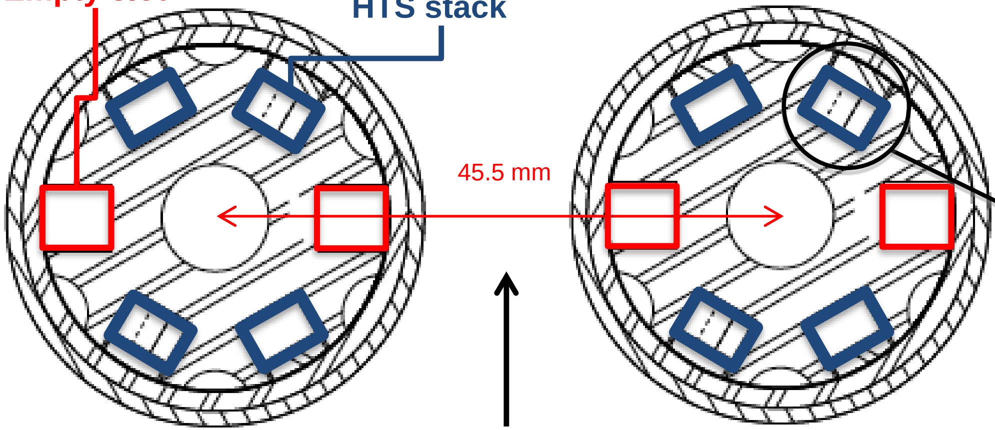
The HTS conductor (i.e. the number of tapes) is designed to achieve the target performances: $I_c \approx$ 15 kA @ 5 K, 11 T

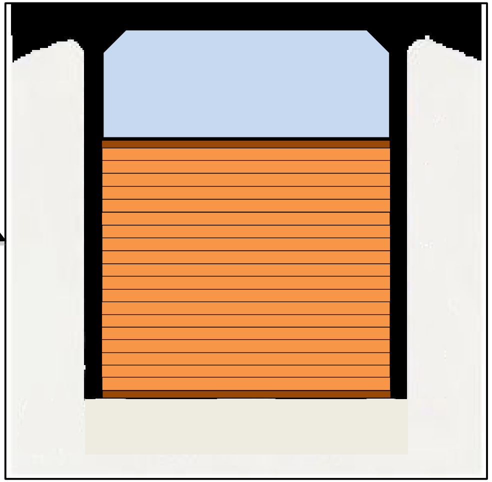
SULTAN SAMPLE #1 (2 x layout A)

Straight slots *(untwisted HTS stacks)*
Not soldered-stack

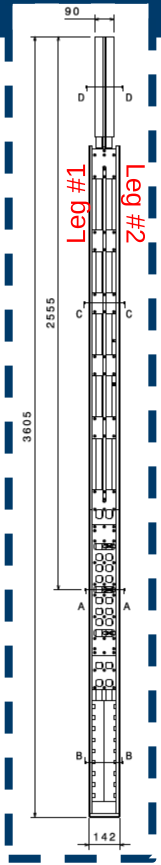
Layout A

4 HTS stacks (76 tapes) + **2 empty slots**
HTS stack = **19 tapes** (0.15 x 4 mm)
Stack size (nominal) = 2.85 x 4 mm





Quench test @ SULTAN: HTS sample #2



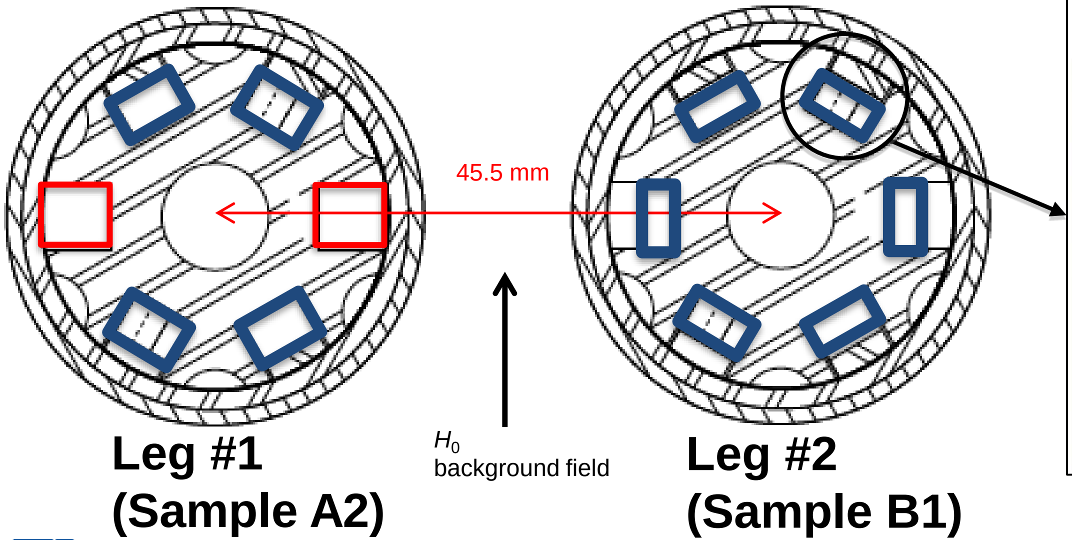
The HTS conductor (i.e. the number of tapes) is designed to achieve the target performances: $I_c \approx$ 15 kA @ 5 K, 11 T

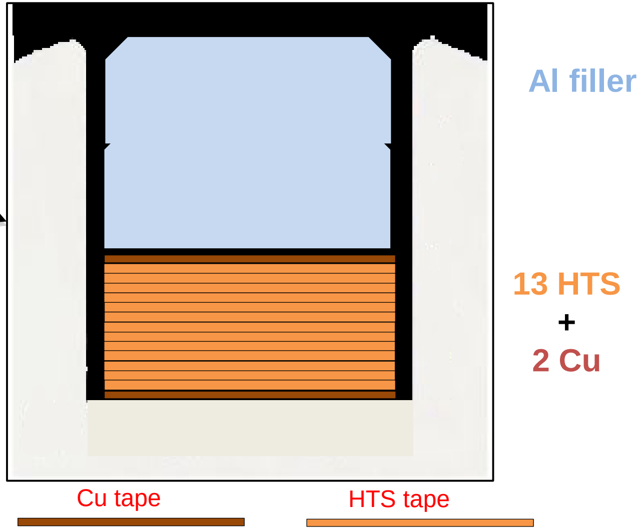
SULTAN SAMPLE #2
(1 layout A + 1 layout B)

Straight slots (untwisted HTS stacks)
Not soldered-stack

Layout B

6 HTS stacks (78 tapes)
HTS stack = **13 tapes** (0.1 x 4 mm)
Stack size (nominal) = 1.59 x 4 mm



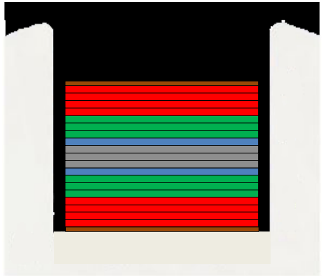


SULTAN Sample: e.m. performances

Sample A1 & A2: 4 HTS stacks nominally equivalent

Tapes sorted by I_c @ 77 K

- ≃ 210 A;
- ≃ 185 A;
- ≃ 167 A;
- ≃ 157 A;



I_c @ 4.2 K, 11T (from exp. Lift factor)

- ≃ 280 A;
- ≃ 250 A;
- ≃ 225 A;
- ≃ 210 A;

Uniform performances of HTS stacks by controlling tape I_c distribution

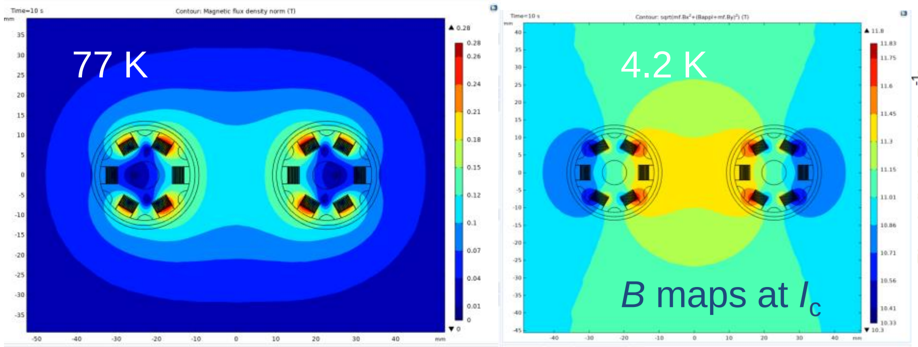
Predicted sample performances

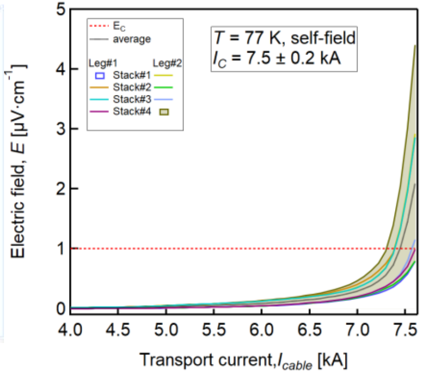
77 K, s.-f. → I_c ≈ 7 kA for both samples # 1&2
4.2 K, 11 T → I_c ≳ 15 kA (for sample #1**)**

Conductor and SULTAN samples performance predictions by **2D finite-element model, based on the *T-A* formulation** G. De Marzi *et al.*, SuST **34**, 035016 (2021)

Sample #1

N.B. Assuming a typical I_c angular dependence with $\gamma = 5$





Self-field + tape I_c anisotropy → **all stacks behave differently**

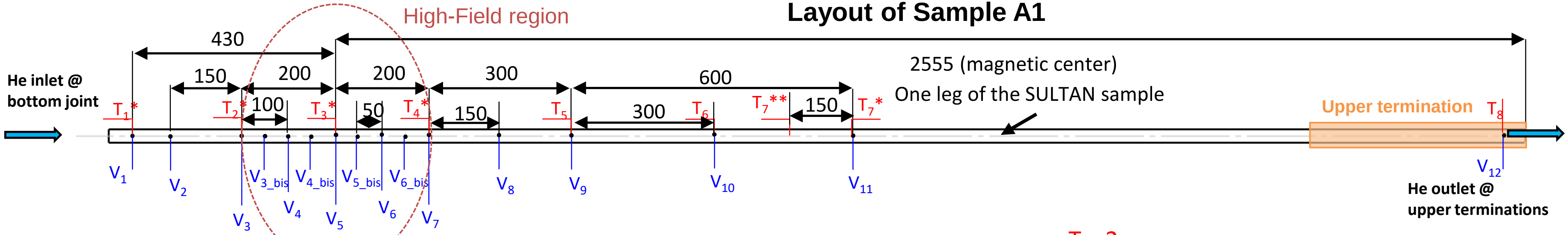
On Sample #2 work in progress

Sample cooling scheme and diagnostic layout

- **Quench monitored by voltage taps and thermal sensors** distributed along the cable length;
- Thermal sensors are envisaged for: *i*) He temperatures (at central channel), *ii*) for HTS stacks, *iii*) and the jacket temperature (mostly in the High-Field region);
- Quench behaviour will be analysed by a properly implemented numerical model (*);

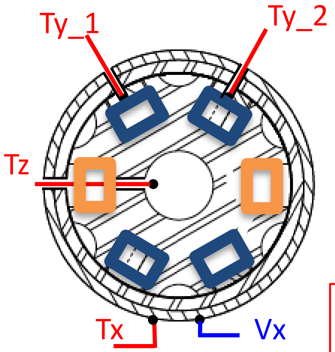
(*) **A. Zappatore** et al., IEEE TAS 30 (8) 4603307 (2020) , **A. Zappatore** et al., IEEE TAS 31 (5) 4800805 (2021)

Layout of Sample A1



- **21 *T* sensors**
- <u>12 protruding</u> into the cable cross section (Ty, Tz) (to be implemented with technology developed by SPC. Work in progress);
- **7** on the steel jacket surface (T_x);
- **2** on the joint and upper termination;

- **15 V taps** spot welded on the steel jacket (+ 2 on the joint and upper termination);



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

Sample B1:
- No Tz (He Temp)

@ T_2*, T_3* and T_4*

SULTAN sample: high current termination concept

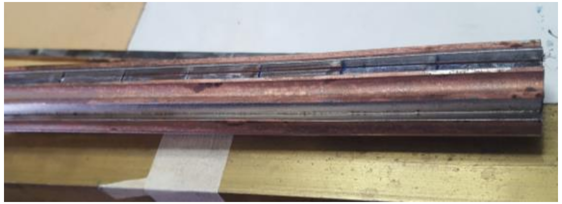
Key features for low resistance current terminations

- electrodeposited Cu coating of Al core extremities;
- staggered HTS stack ends;

SULTAN sample: high current termination concept

Key features for low resistance current terminations
- electrodeposited Cu coating of Al core extremities;
- staggered HTS stack ends;

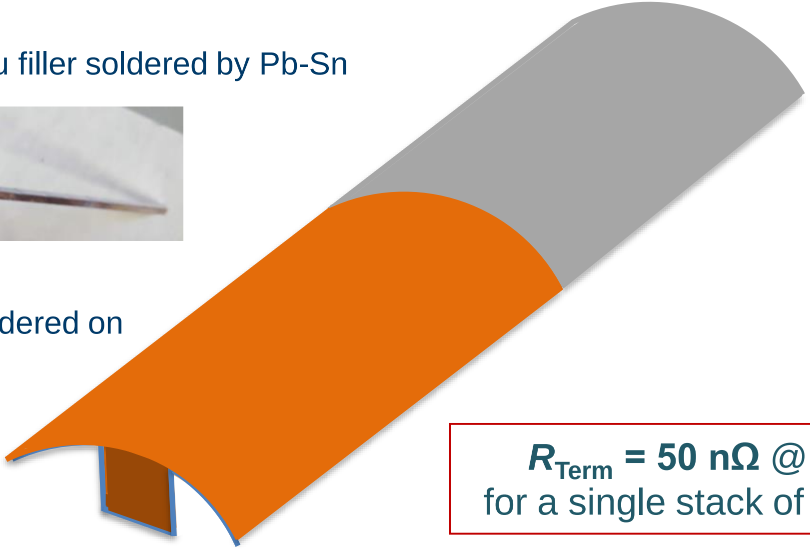
1 - electrodeposited Cu coating of slots;



2 - staggered stack end inserted into the slot;

3 - Triangle-shaped-stepped Cu filler soldered by Pb-Sn

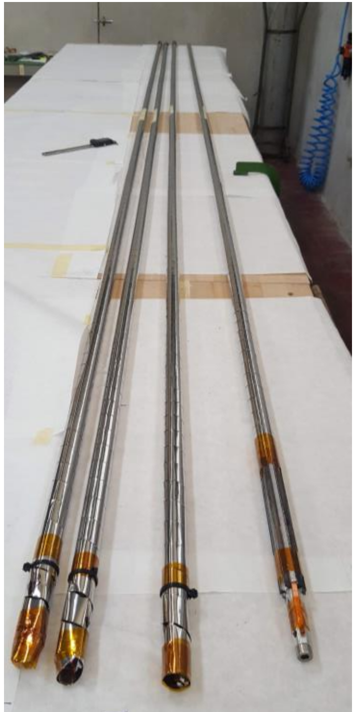
4 - Cu-SS composite block soldered on with In-Sn solder (m.p. 118°C)



$\boldsymbol{R_{Term}}$ **= 50 nΩ** @ 77 K
for a single stack of 19 tape

SULTAN sample manufacturing and test schedule

HTS tape stacking and insertion into the slots



4 HTS conductor samples before jacketing (3 SULTAN legs + 1 spare)

Conductors and Terminations manufacturing stage

Jacket removal at the conductor extremity and staggered stack preparing

Time schedule for quench experiment

- Conductors → done
- Terminations → on going
- Support structure manufacturing → on going
- Shipment to SULTAN by end of 2021/beginning of 2022
- Diagnostic (thermal/voltage sensors) arrangement @ SULTAN → t.b.d.

Conclusions and perspectives

Quench experiment at SULTAN facility is foreseen for REBCO-based Aluminum-slotted-core conductors suitable for fusion applications.

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- REBCO-based Aluminum-slotted-core conductor design and manufacturing stages are close to the end (hopefully by the end of 2021!).
- **Technical challenges** were identified and addressed. **Scientific background knowledge and analysis tools** (either quench or e.m. simulation codes) were developed;
- Quench test will be planned in SULTAN facility **in the next months**.

Most of the outputs of the quench experiment will drive the future development of HTS fusion conductors

Next activity:

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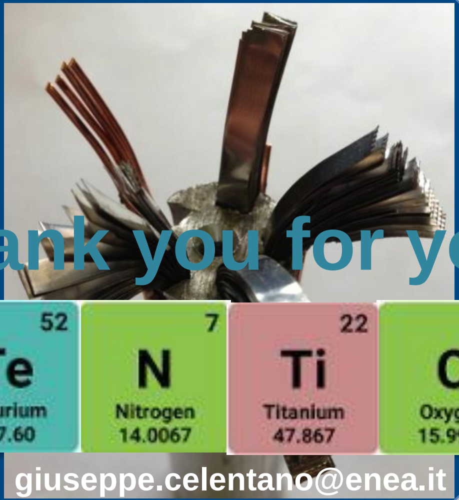
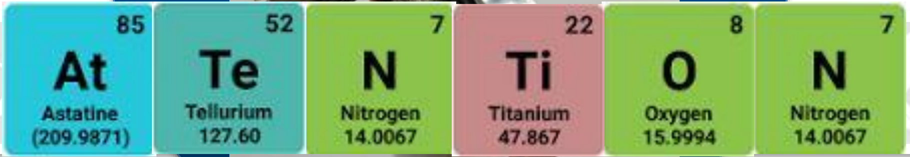
- Design and development of **HTS conductor for DEMO** hybrid LTS/HTS CS system. Reference operating conditions at 4.5 K, 18 T, 60 kA and 1.5 m bending radius (DEMO hybrid LTS/HTS CS system relevant conditions);
- Design an **HTS insert for the DTT Central Solenoid**, and model coil manufacture and test;

Thank you for your





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