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

HFM High Field Magnets

Recent activities on REBCO and IBS materials at ENEA

Andrea Augieri
(on behalf of the ENEA HTS group)

HFM annual meeting 2023 – October 31, 2023

Outline

Brief introduction on the ENEA Superconductivity Laboratory

Activities on REBCO

- Film nano-engineering (APC)
- Irradiation tests on REBCO
- HTS Cables

IBS Materials

- 11-coated conductors
- PIT wires

Conclusions and perspectives

ENEA Superconductivity Laboratory

The Superconductivity group

28 people

23 Researchers

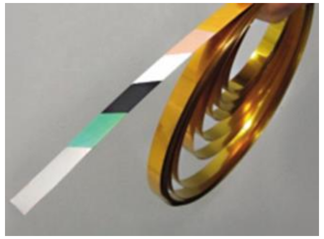
4 Technicians

1 Administrative

LTS group: 5 Engineers + 6 Physicists

Nb-alloys R&D;
LTS Cable design and manufacturing;
High field magnets design

Close collaboration on HTS cable activities

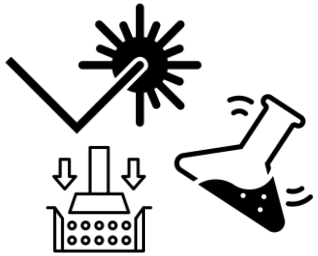


HTS group: 9 Physicists + 2 Chemists + 1 Engineer

Coated-Conductor R&D;
REBCO deposition and optimization;
HTS Cable design and manufacturing;
IBS materials R&D

ENEA Superconductivity Laboratory

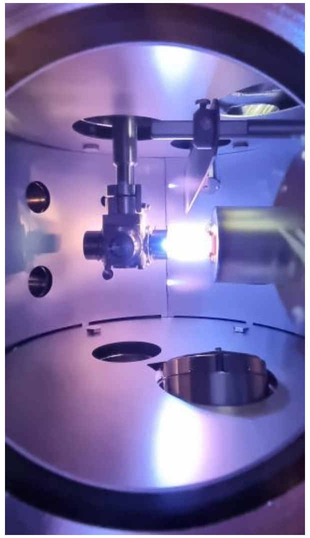
The Superconductivity laboratory equipment: material synthesis



PVD systems

3 PLD systems
operating with 2 Lasers
(KrF and Nd-YAG)

2 e-beam systems



CSD systems

Chemical lab for MOD
(furnaces, evaporator, spinner, …)

Material sintering systems

(Grinding, milling, glow boxes,
controlled ovens, …)

ENEA Superconductivity Laboratory

The Superconductivity laboratory equipment: characterizations

Structural-Morphological characterizations

Two **XRD**
SEM with **EBSD** and **EDX**
AFM

Electro-magnetic characterizations

VSM system (**12 T**)

3 A d.c. current system, (**12 T**)

18 T cryo-free system (**VSM**, **d.c. current 3 A**, χ_{ac})

14 T cryostat with 2 d.c. current probes

- **“walter spring”** for wires (**1000 A**)
- **d.c. current** for tapes up to **1500 A**

Laser writer

For sample patterning

High-current station for HTS cable characterization at LN2

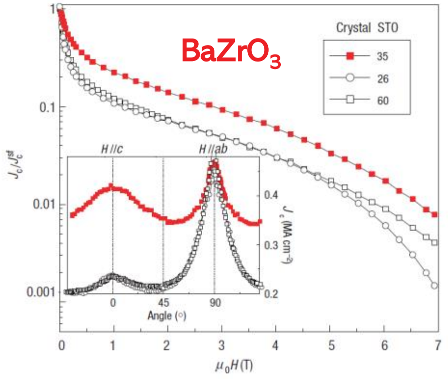
Self-Field *I*-*V* up to **20 kA**

Activities on REBCO

- Film nano-engineering (APC)
- Irradiation tests on REBCO
- HTS Cables

Film nano-engineering (APC)

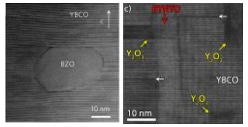
Controlled introduction of nano-metric Artificial Pinning Sites (APC)



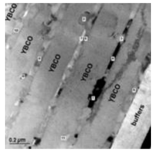
J. L. Macmanus-Driscoll *et al.*, *Nature Materials* **3** (2004)

Different Methods

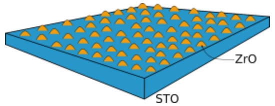
Second phases
(Y2O3, BaMO3, …)



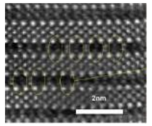
(quasi) Multi-layers



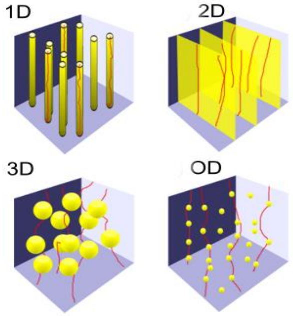
Surface decoration



Crystalline defects



Different shapes and densities



Made possible the use of CCs in High Field Magnets

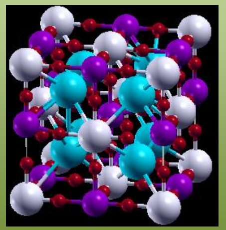
ENEA

Is active on the APC topic since the very beginning, using different methods and materials

Main activity:

PLD REBCO films with Double perovskite cubic - Fm3m

Ba_2YNbO_6



Ba_2YTaO_6

UNIVERSITY OF CAMBRIDGE

eurotapes EUROPEAN DEVELOPMENT OF SUPERCONDUCTING TAPES

EUROfusion

Task n.: AWP15-ENR-01-ENEA 08

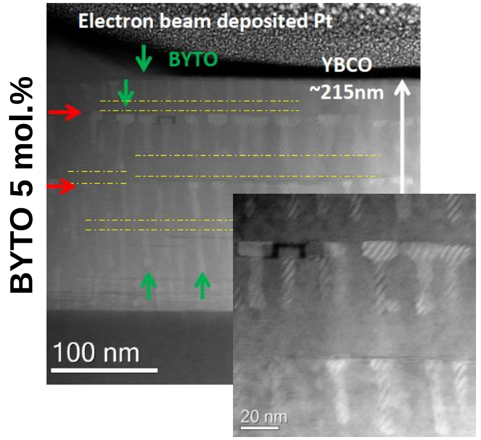
Task n.: AWP19-ENR-01-ENEA 04

Enabling Research Work Programme 2015-2017 and 2019-2020

Film nano-engineering (BYNTO)

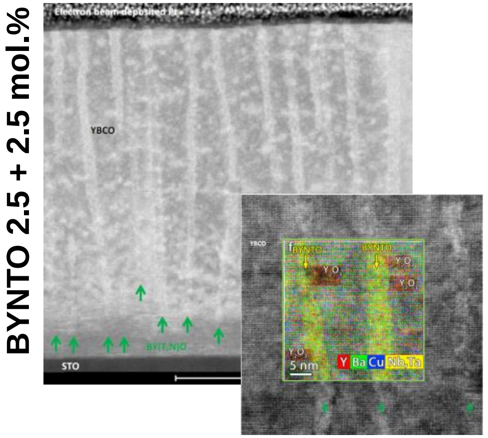
Composition

Ba_2YNbO_6 or **Ba_2YTaO_6**



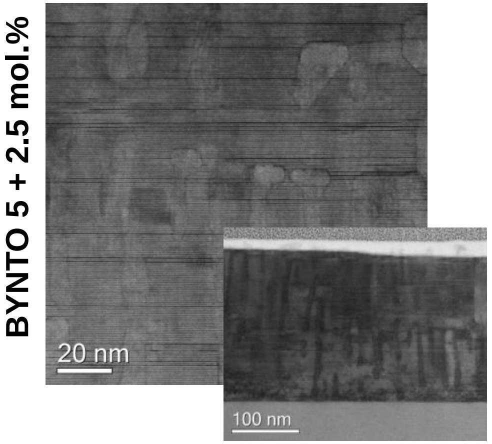
Ø = 5 nm B_ϕ = 5.2 T

Ba_2YNbO_6 + Ba_2YTaO_6



Ø = 5 nm B_ϕ = 5.2 T

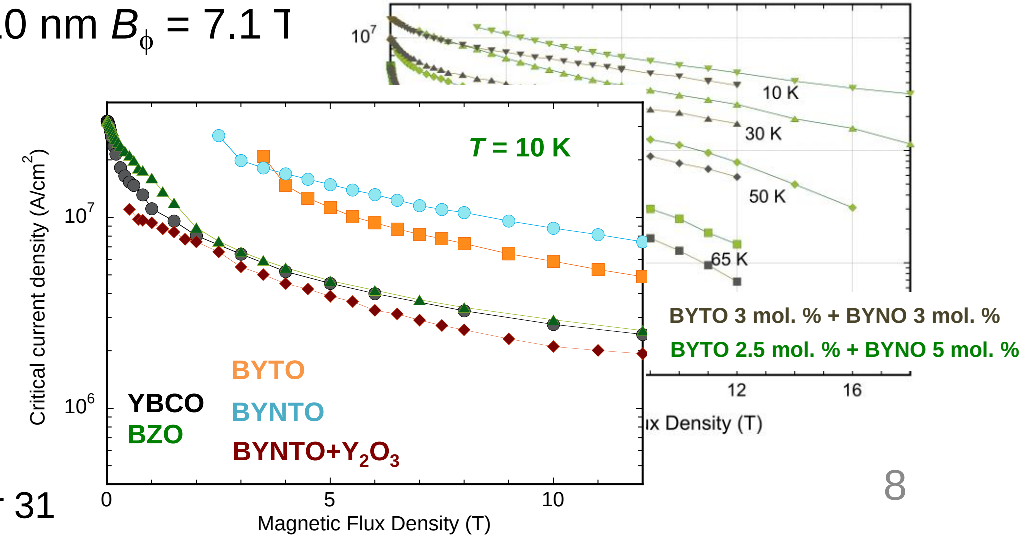
Ba_2YNbO_6 + Ba_2YTaO_6 unbalanced



Ø = 10 nm B_ϕ = 7.1 T

And others
- BYNTO+Y_2O_3
- total doping up to 15 mol.%
- different unbalance degree
- …

Playing with the second phase composition → Tuning of the film micro-structure → Change in the film performances



G. Celentano et al., Supercond. Sci. Technol. 33 (2020)

Film nano-engineering (APC)

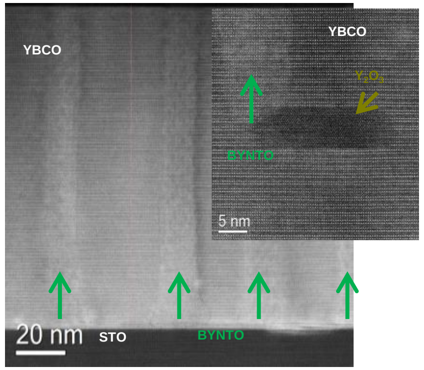
Deposition parameters

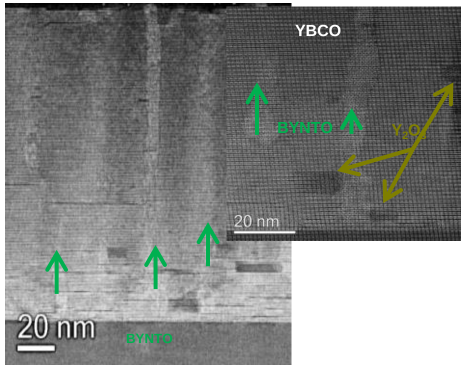
2.5 mol.% Ba_2YNbO_6 + 2.5 mol.% Ba_2YTaO_6

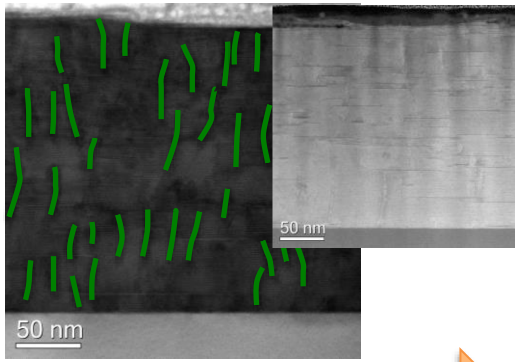
Laser wavelength (308 nm, 248 nm)

Laser rep. rate (1 Hz – 15 Hz)

Growth rate $\rho \approx 0.02 \div 1.8$ nm s^{-1}







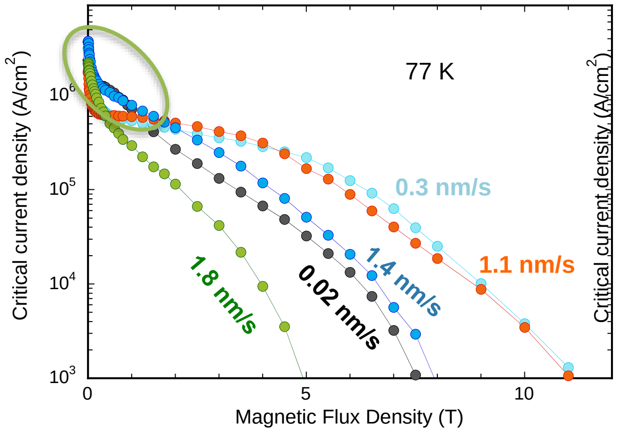
Increasing the growth rate

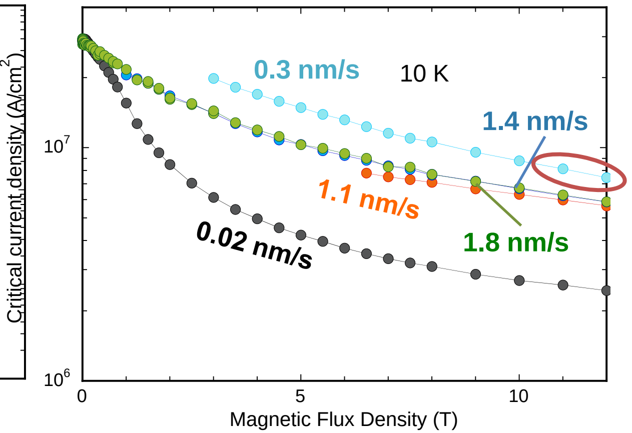
Reduced column
- diameter
- continuity
- straightness

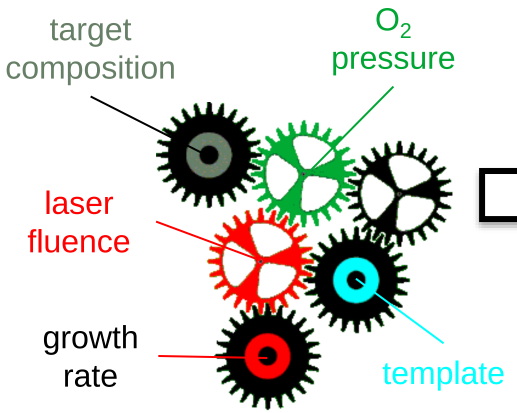
Increase density of Stacking faults

F. Rizzo et al., *Nanoscale* **10**, (2018)

ρ = 0.02 nm/s **ρ = 0.1 nm/s** **ρ = 1.8 nm/s**







Optimization for different applications

Activities on REBCO

- Film nano-engineering (APC)
- Irradiation tests on REBCO
- HTS Cables

14 MeV neutron irradiation test

ENEA-Frascati Neutron Generator

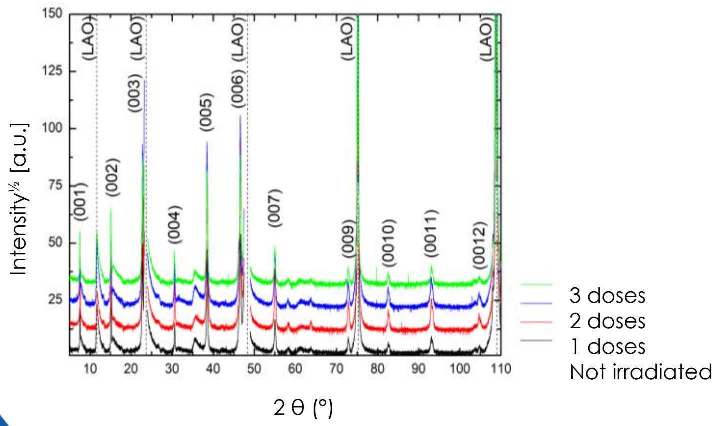
Irradiation of REBCO films with 14 MeV Neutrons

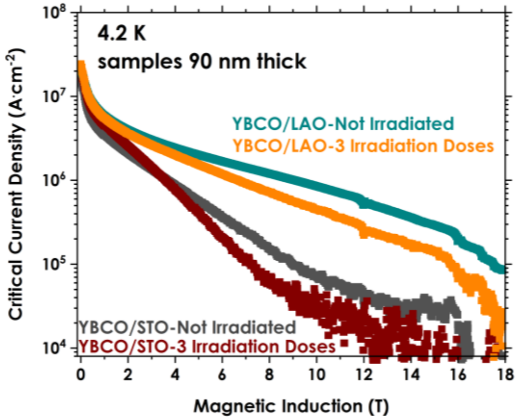
PLD YBCO films	MOD YBCO films (on STO and LAO)	Commercial CCs (SST and SO)
1 dose: $0.4 \cdot 10^{14}$ neutrons·cm^{-2}	2 doses: $0.8 \cdot 10^{14}$ neutrons·cm^{-2}	3 doses: $1.2 \cdot 10^{14}$ neutrons·cm^{-2}

72h of ITER plasma on TF

Preliminary results

No detectable difference on structural properties



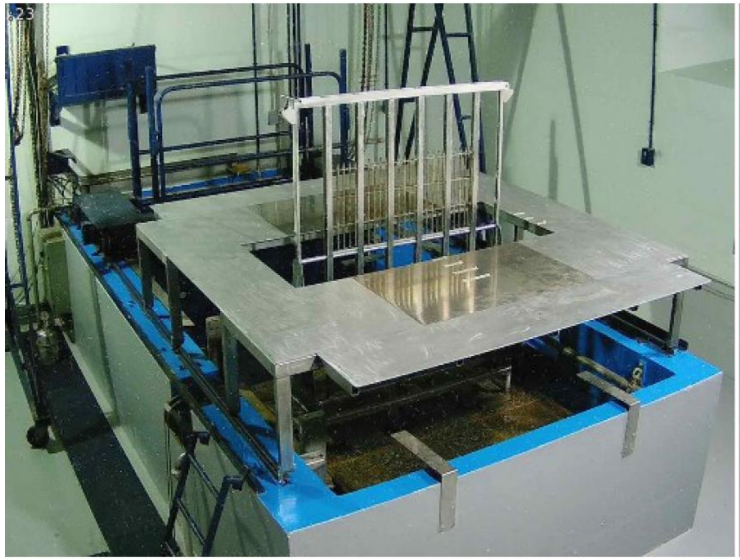


Slight decrease of the in-field properties

To do list

- ✓ Increase the neutrons dose
- ✓ Superconducting properties test during irradiation

γ-Irradiation test



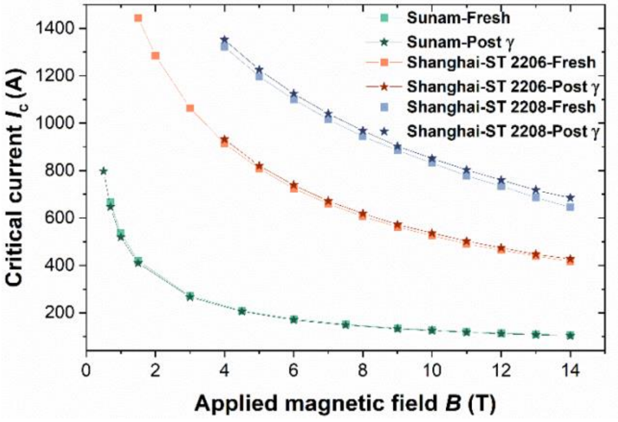
Calliope test facility at ENEA

Features	
Source	^{60}Co, stainless steel double encapsulated rod
Geometry	Plane rack
Emitted radiation	2 photons emitted in coincidence
Mean photon energy	1.25 MeV
Max licensed activity	$3.70 \cdot 10^{15}$ Bq (100 kCi)
Max dose rate (June 2023)	6.5 kGy/h

Commercial CCs
4 mm wide
with Ag and Cu layers

- **Sunam**
- **SST**
- **SuperOx**

Preliminary results on 1.016 kGy adsorbed dose (relevant for space applications)



No evident effect on the tapes in-field properties

To do list

✓ **Increase the γ-ray dose**

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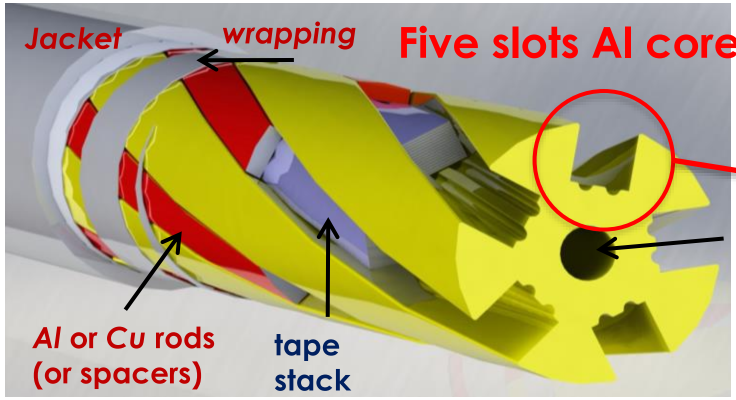
Activities on REBCO

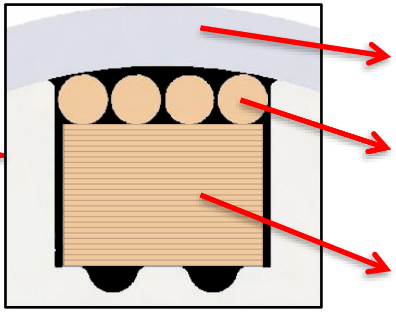
- Film nano-engineering (APC)
- Irradiation tests on REBCO
- HTS Cables

ENEA HTS Cable – historical overview



G. Celentano *et al.*, *IEEE Trans. Appl. Supercond.* **24** (2014)

5 slots 4.3x4.3 mm^2



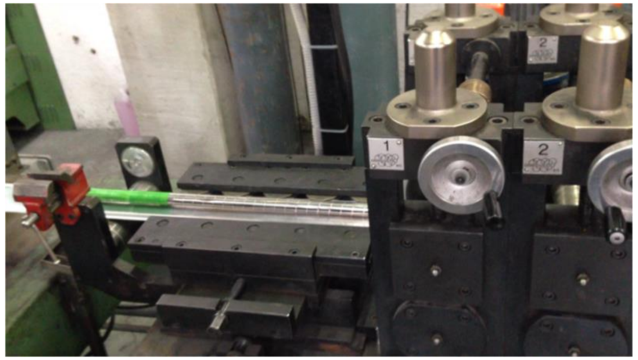
20 kA – class cable
for Fusion applications
(4.2 K - 12 T)

360 mm^2 cross section

Al core: Ø = 19 mm
Al or SS jacket: t = 1.2 mm

$J_e \approx$ **60 A/mm^2**

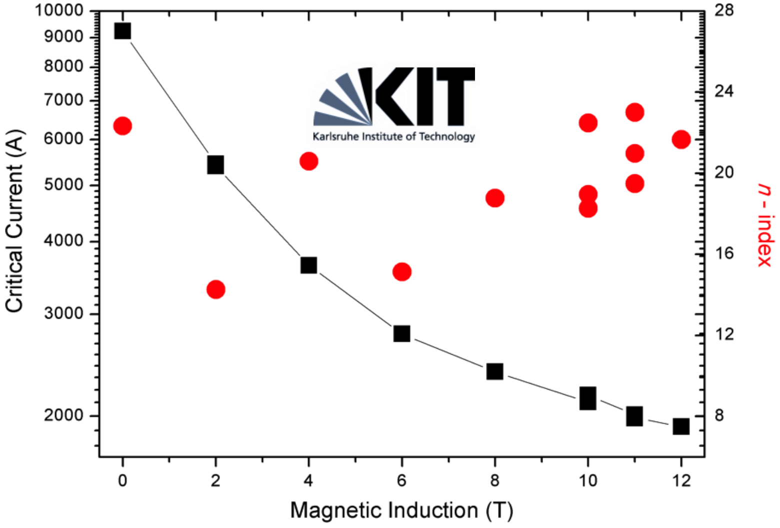
Cable design driven by industrial scalability



Operation ready cable

ENEA HTS Cable – historical overview

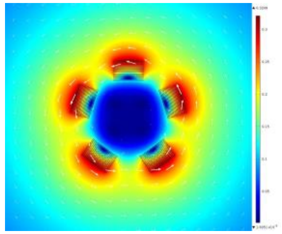
Test at LHe *B // c*-axis



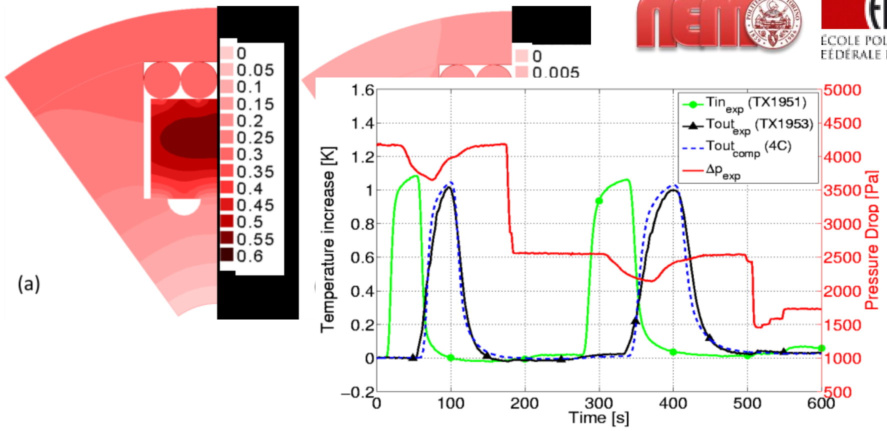
A. Augieri *et al.*, *IEEE Trans. Appl. Supercond.* **25** (2015)

Stack I_c = 1952 A 12 T
(using Sunam Tapes)

Predicted Cable I_c at
12 T **8970 A**
(**20 kA** using **SPI**)

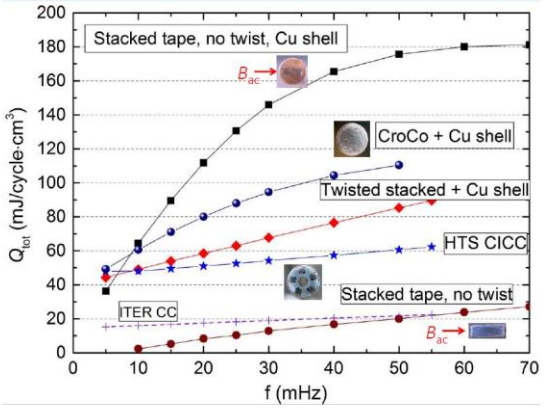


Thermal-hydraulic test

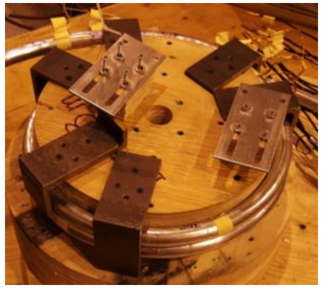


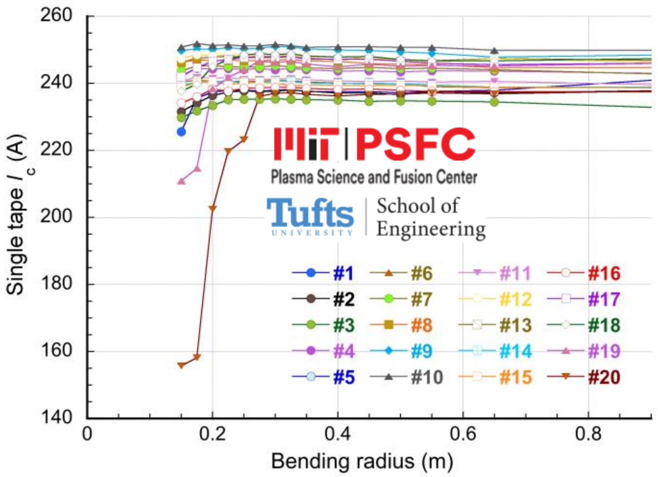
a.c. losses

UNIVERSITY OF TWENTE.



Bending test





Cable properties fully assessed

G. De Marzi *et al.*, *IEEE Trans. Appl. Supercond.* **26** (2016)
G. Celentano *et al.*, *IEEE Trans. Appl. Supercond.* **29** (2019)

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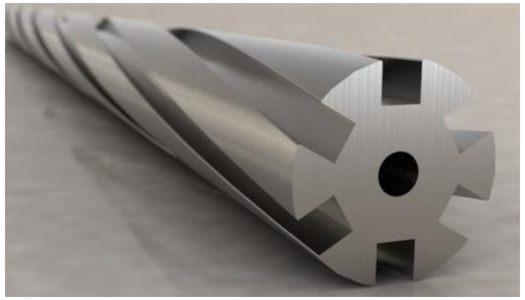
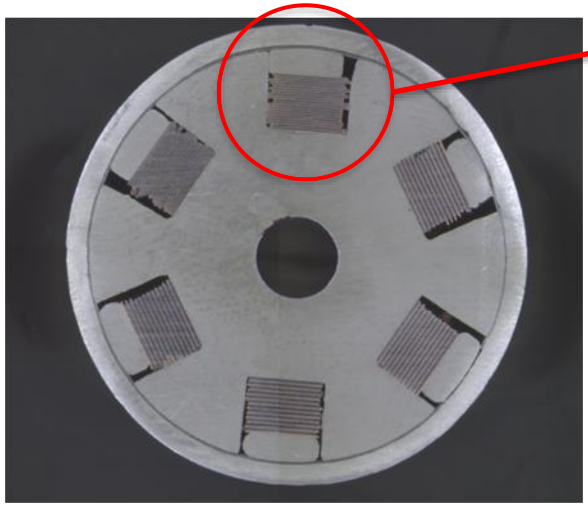
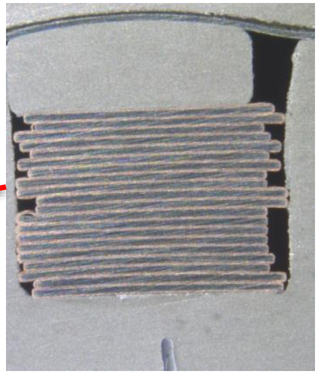
ENEA HTS Cable – historical overview



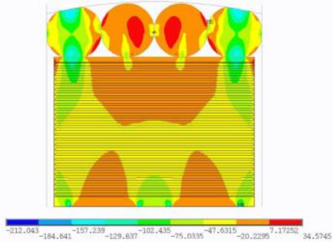
Twisted Al core

6 ducts 4.3x4.3 mm^2





Different duct profile:
no grooves
Different filler:
4x1.5 mm^2 **Al tapes**



Reduce mechanical stress on tapes

35 kA – class cable
(4.2 K - 18 T)

490 mm^2 cross section

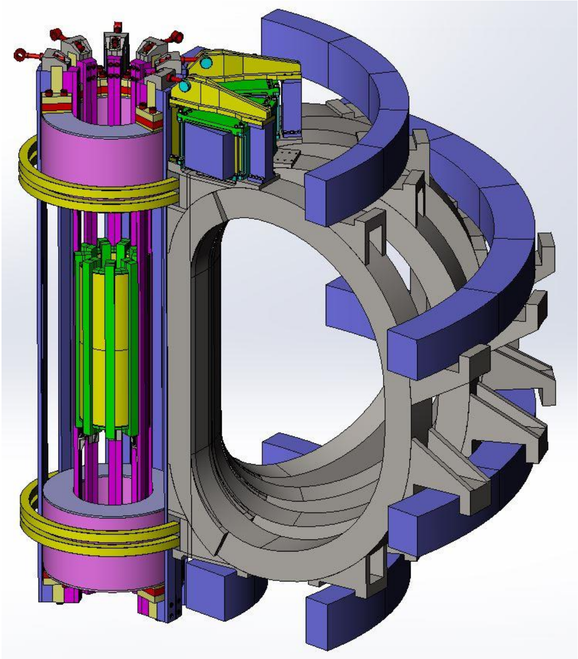
Al core: Ø = 22 mm
Al or SS jacket: t = 1.5 mm

$J_e \approx 70$ **A/mm^2**

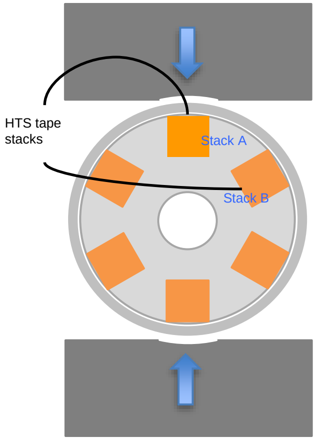
additional HTS insert
in DTT CS magnet

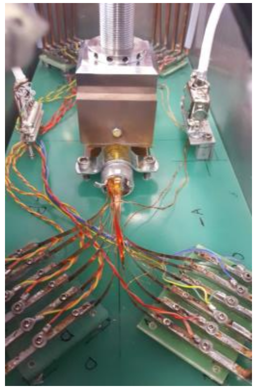
13.6 T current design (LTS)
18.7 T with HTS insert

DTT Divertor Tokamak Test



ENEA HTS Cable – historical overview





6-slots

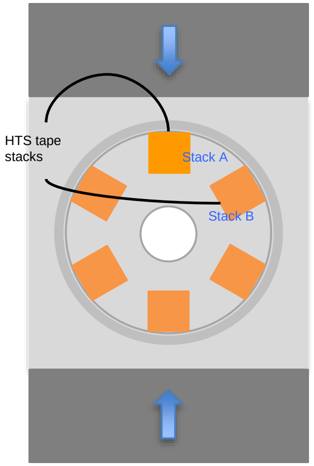
4 dummy slots
(12 SS tapes + 12 Cu tapes)

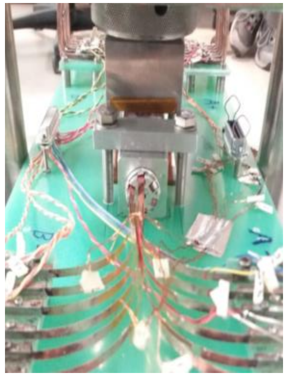
2 fully HTS slots
(20 SuNAM)

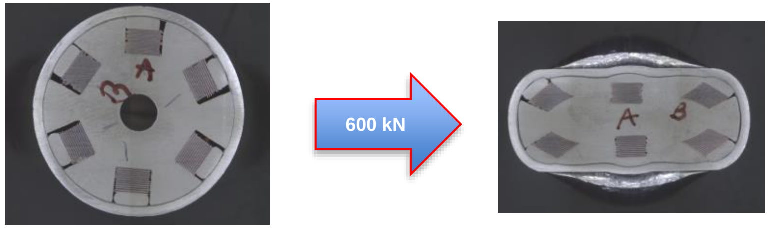
stack **A**: compres.
stack **B**: shear

6 tapes per slot
measured at **LN_2**

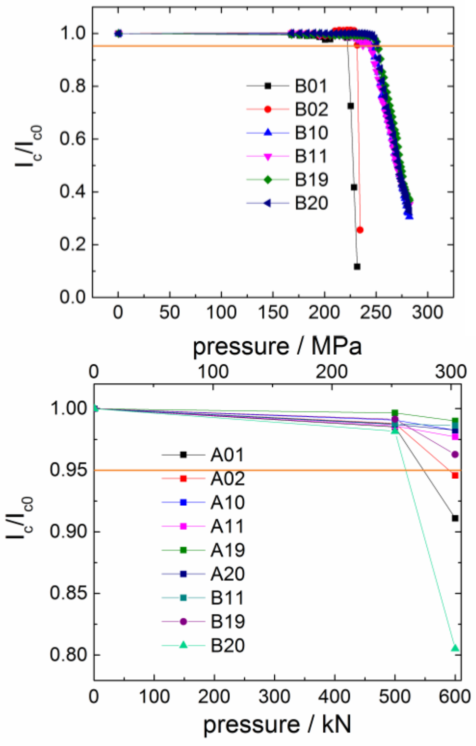
max available force **600 kN**







Karlsruhe Institute of Technology

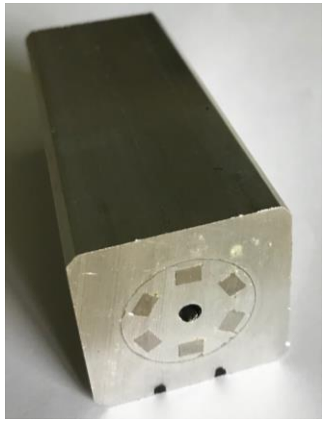


Round cable

degradation:
> 220 MPa

Square cable

degradation
@ 250 Mpa
< 3%

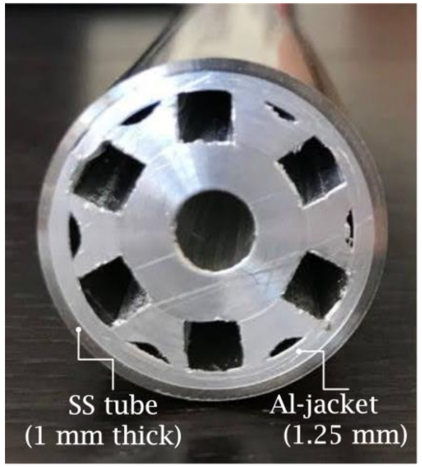


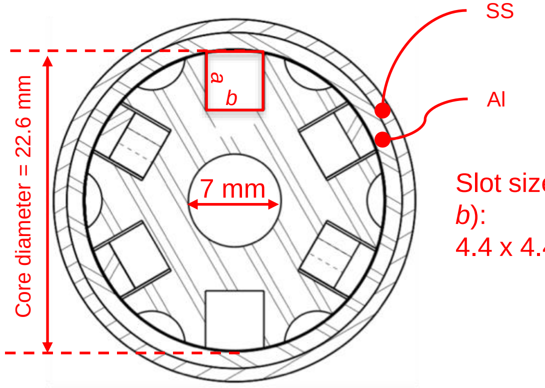
DTT compatible!

ENEA

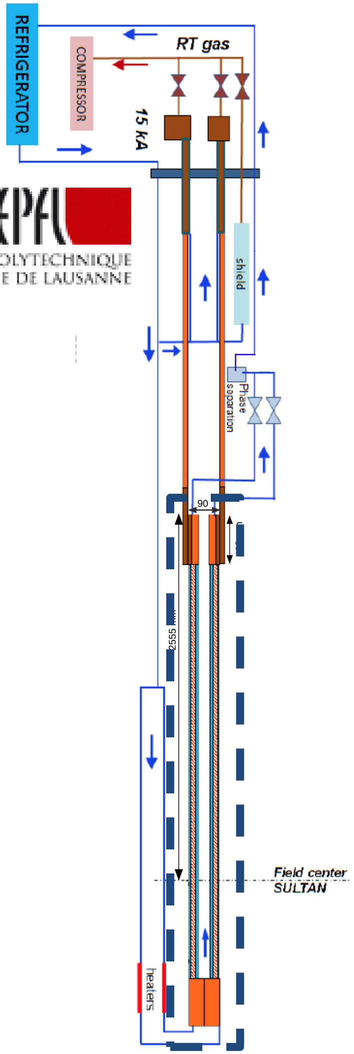
ENEA HTS Cable – historical overview

MAG EU-CN collaboration



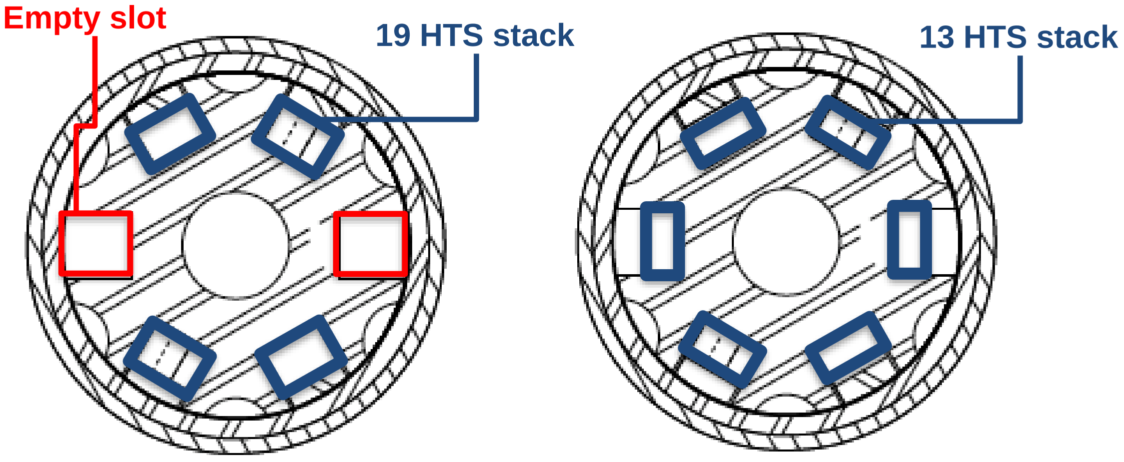


Slot size (a x b): 4.4 x 4.4 mm^2



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

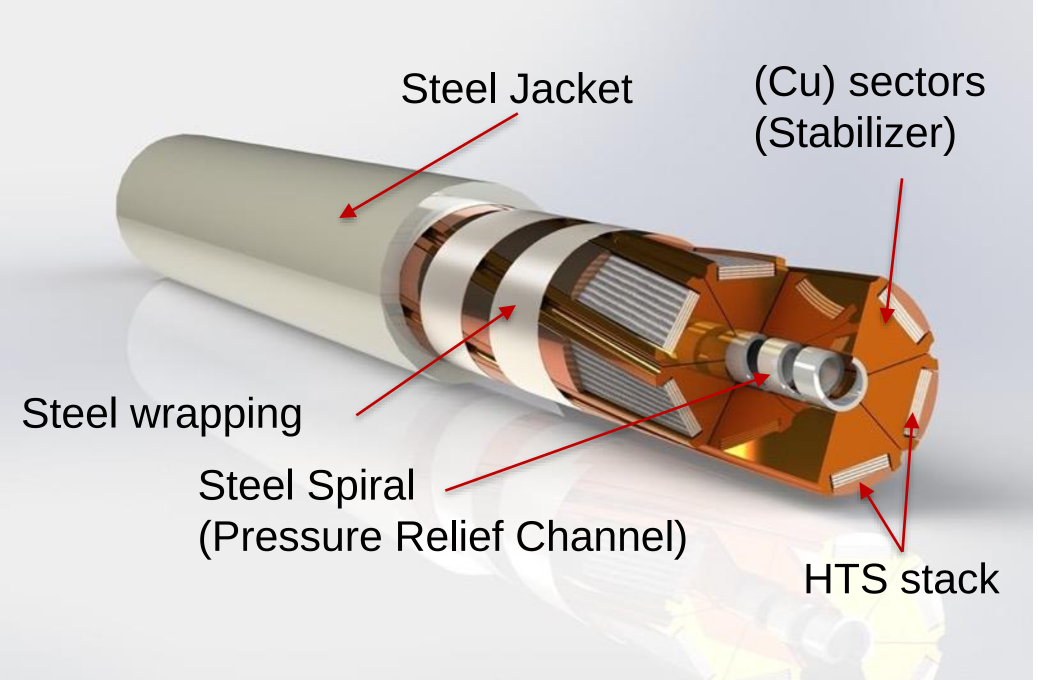
Sample for quench experiment consists of **two conductors** (*legs*) connected at the bottom through a **joint**
(Mechanical support structure designed to sustain e.m. loads**)**

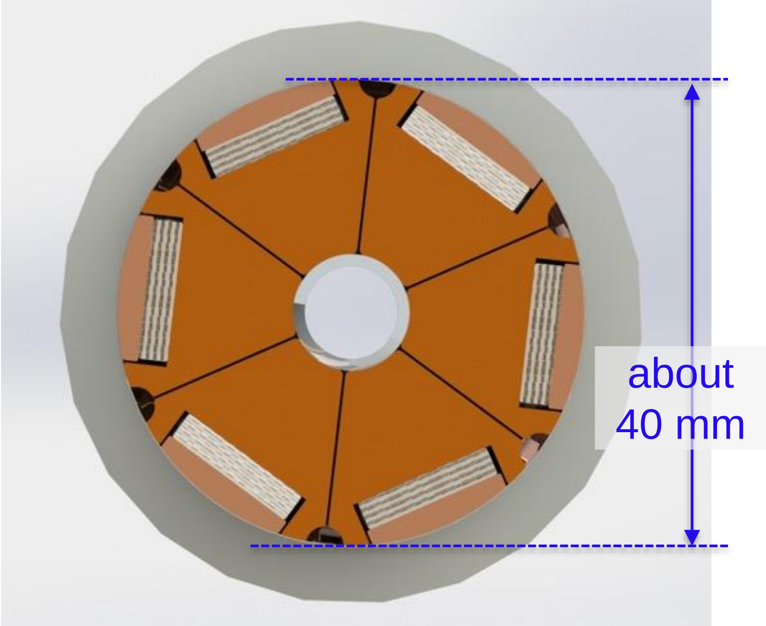


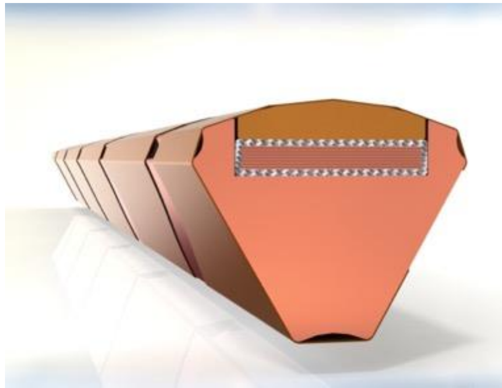
November 2023??

ENEA HTS Cable – historical overview

New cable concept: SECtor ASsembled ***(SECAS)*** CICC







Multi-Stage Cable Processing (easier manufacture)

Lower a.c. losses (non-monolithic structure)

60 kA – 18 T – 4.5 K – pulsed operation

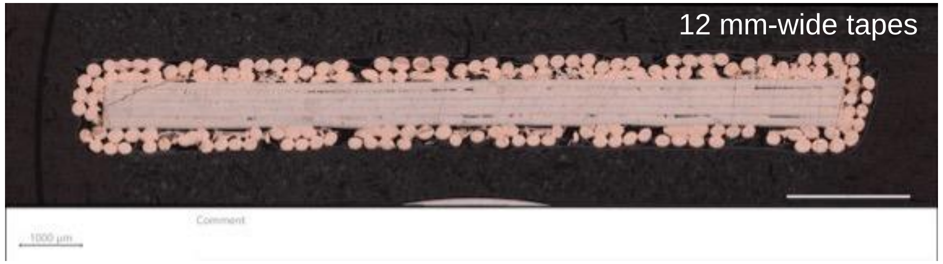
capable to sustain bending over 1.5 m radius

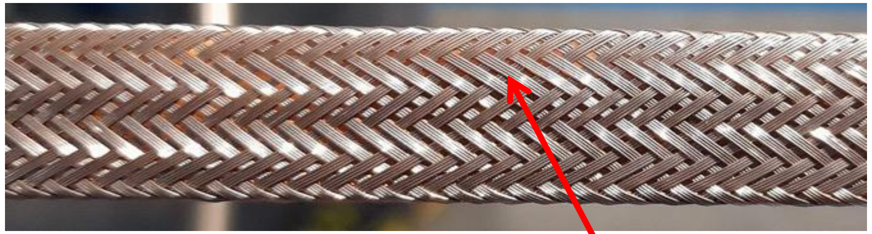
L. Muzzi *et al.*, *IEEE Trans. Appl. Supercond.* ***33*** (2023)

ENEA HTS Cable – historical overview

New stack concept: BRAided STack (***BRAST***)

Tape stack assembled into a **Cu wire braid**





Tin-coated Cu wires
(with diameter between 0.10 mm and 0.3 mm)

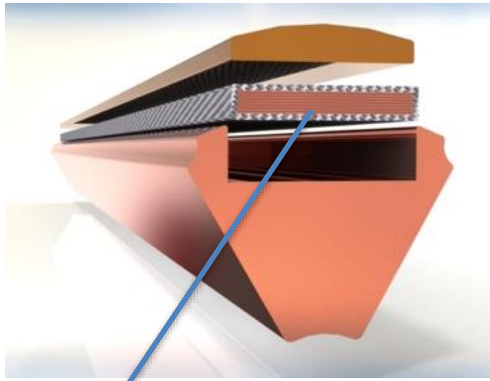
Main Features

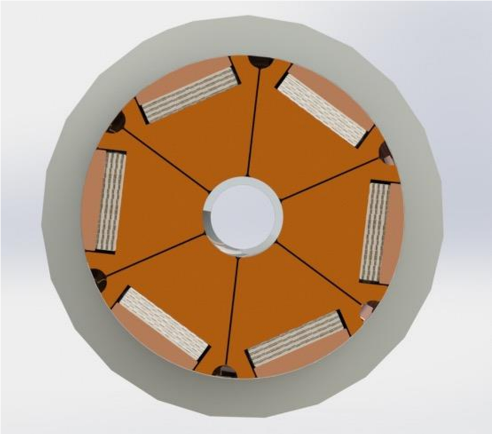
- extremely effective and easy processing step to build a (non-twisted) stack
- protection of the stack it during all successive handling steps
- flexible and easy-to-handle cable sub-unit

ENEA

ENEA HTS Cable – historical overview

SECAS + *BRAST*





3 options

#10 tapes - 12 mm wide

2 x #**5** tapes - 12 mm wide

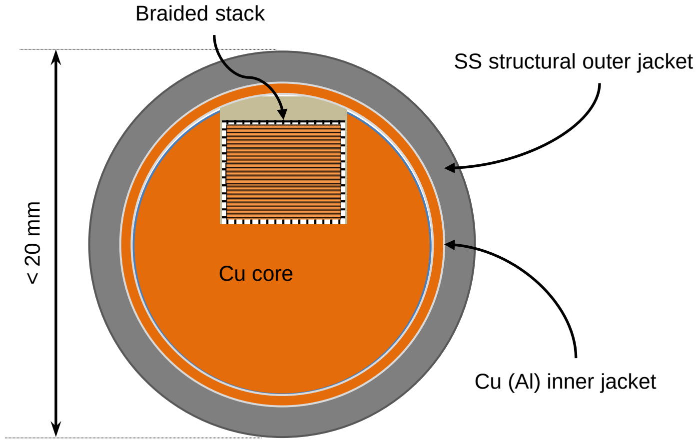
6 x **5** tapes - 4 mm wide

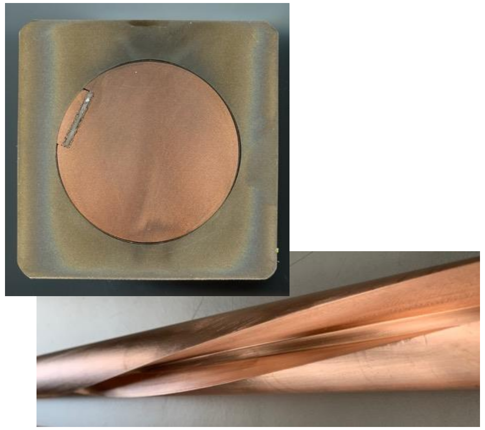
End of 2023

sub-size samples to be tested at **FBI facility (KIT)**
(Force 100 kN, current 10 kA, field 12 T, LHe)

2 Samples:
braided stack with 15 tapes
soldered stack with 15 tapes

Target **5/6 kA @ 4.2 K, 12 T**





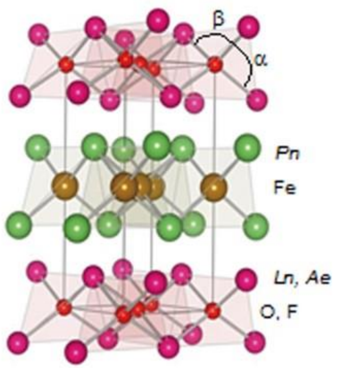
IBS Materials

- 11-coated conductors
- 1144 PIT wires

Iron Based Materials

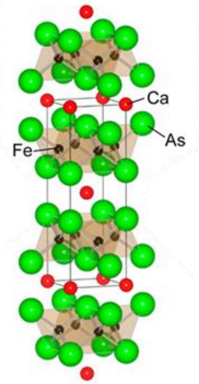
Pnictides

1111 IBS
(oxo-pnictides)



LaFeAsO
(*P4/nmm*)

122 IBS
(hole doping)

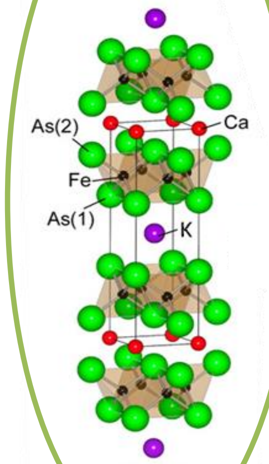


$CaFe_2As_2$
(*I4/mmm*)

Different ionic radius AE

substitution

1144 IBS
(stoichiometric)



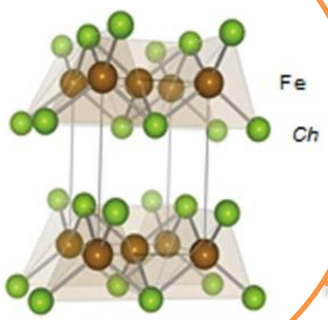
$CaKFe_4As_4$
(*P4/mmm*)

High pinning and H_{c2} values expected
Suitable for PIT wires manufacturing process

Chalcogenides

Ae: **Ca, Sr, Ba, K, …**
A: **Li, Na, K, Rb, …**
Pn: **As, P**
Ch: **Se, Te**
Ln: **La, Ce, …**

11 IBS



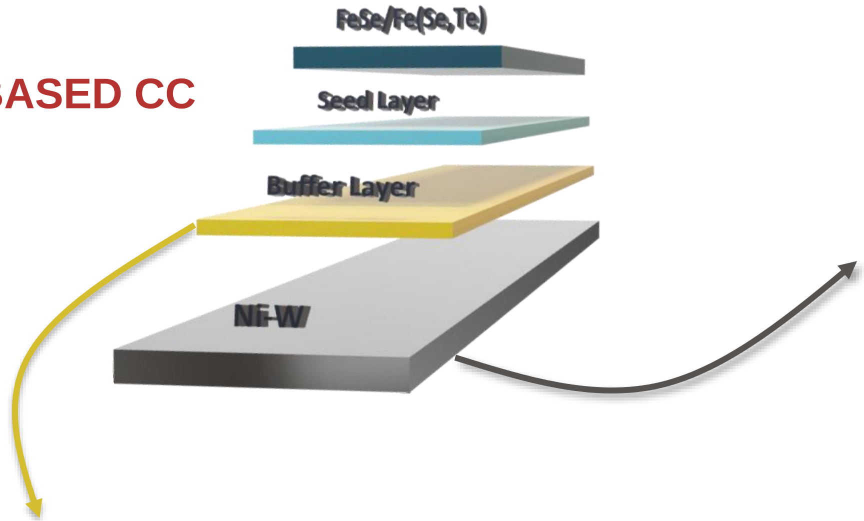
Simplified Coated-Conductor technology

Milder deposition conditions
Simpler buffer architectures
Lower sensitivity to bi-axial texture

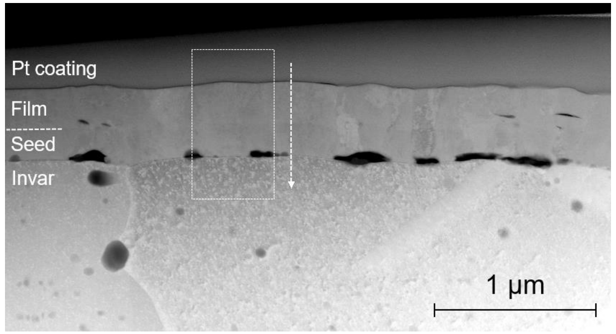
H. Hosono, *et al.*, *Sci. Technol. Adv. Mat.*, **16** (2015) DOI: 10.1088/1468-6996/16/3/033503
A. Iyo *et al.*, *J. Am. Chem. Soc.* **138** 3410–3415 (2016) DOI: 10.1021/jacs.5b12571
F.-C. Hsu *et al.*, *Proc. Natl Acad. Sci. USA* **105**,14262 (2008). DOI: 10.1073/pnas.0807325105
Q. Si, R. Yu, E. Abrahams, *Nat. Rev. Mater.* 1, 16017 (2016). DOI: 10.1038/natrevmats.2016.17

IBS-CCs: FeSe/Fe(Se,Te)

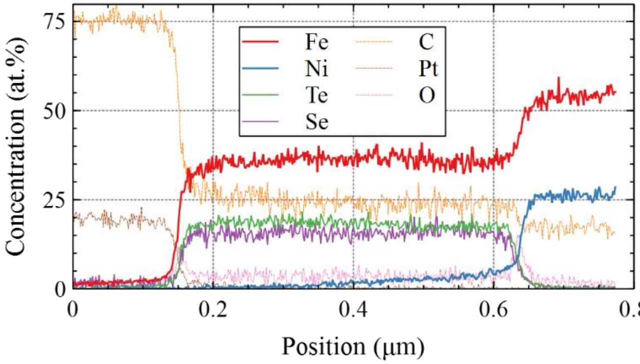
Fe-BASED CC



Fe(Se, Te) on INVAR with or w/o seed layer

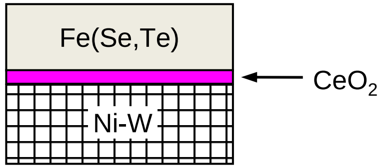


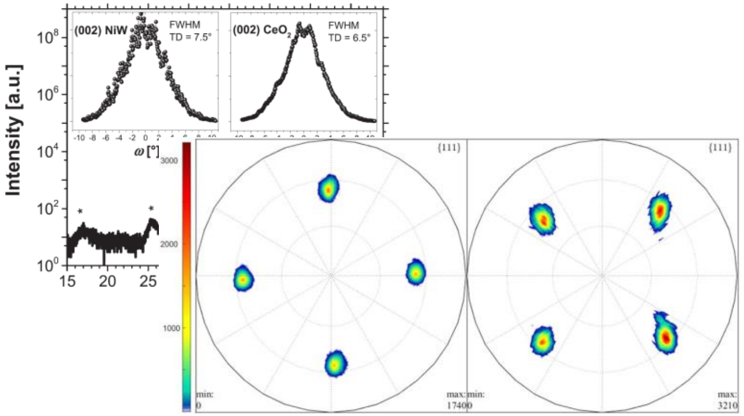
G. Sylva *et al., IEEE Trans. Appl. Supercond.* **29** (2019)

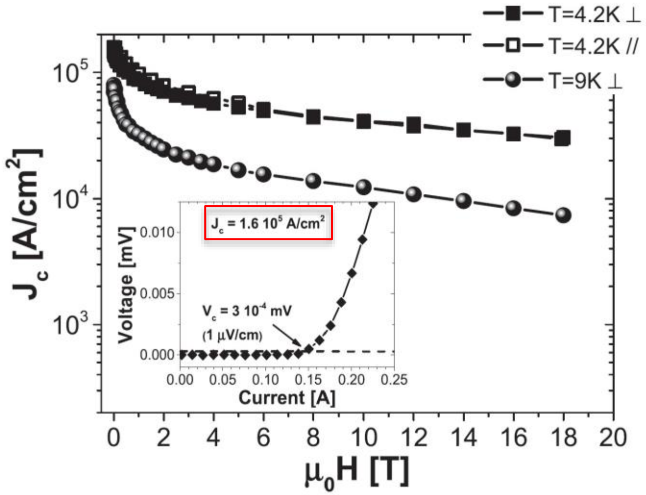


Buffer layer required!

PLD Fe(Se, Te) on PLD CeO_2(350 nm)/NiW







Promising Results

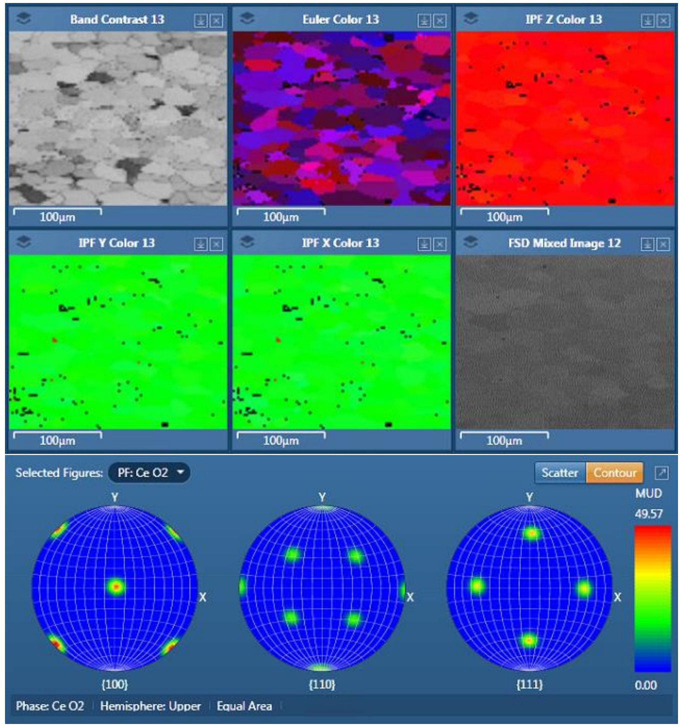
G. Sylva *et al., Supercon. Sci. Technol* **32** (2019)

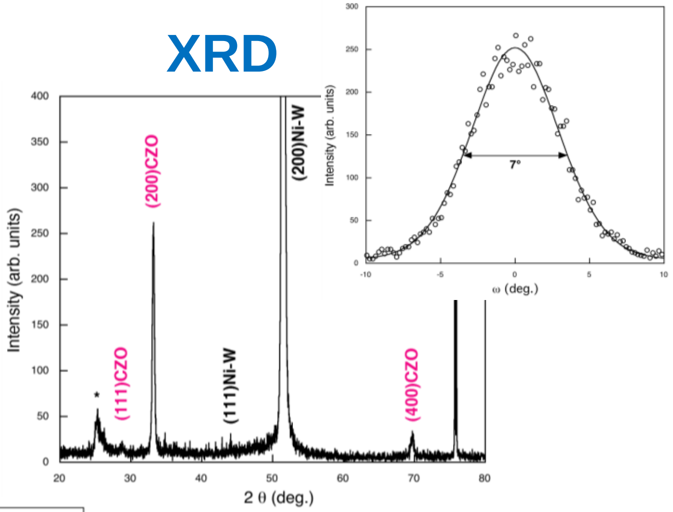
IBS-CCs: FeSe/Fe(Se,Te)

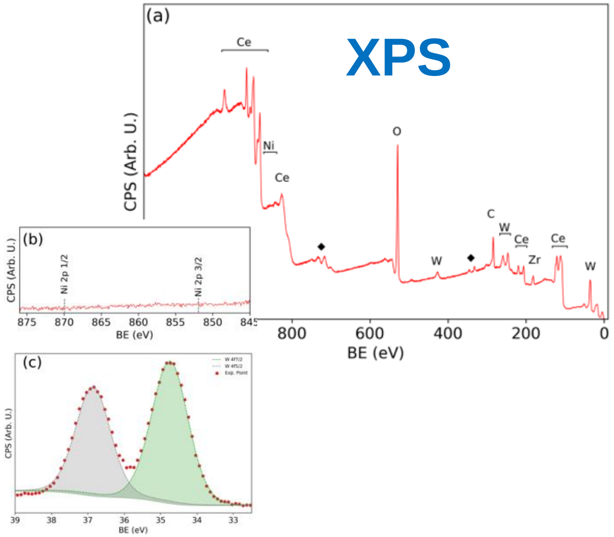
PRIN HIBiSCUS

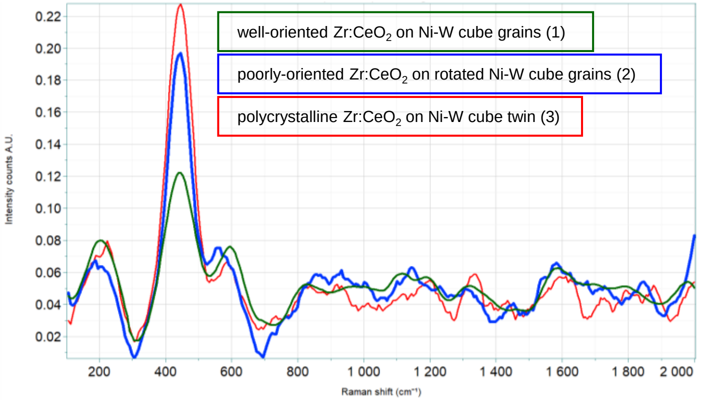
PLD Fe(Se,Te) on MOD Zr-CeO_2(30 nm)/NiW

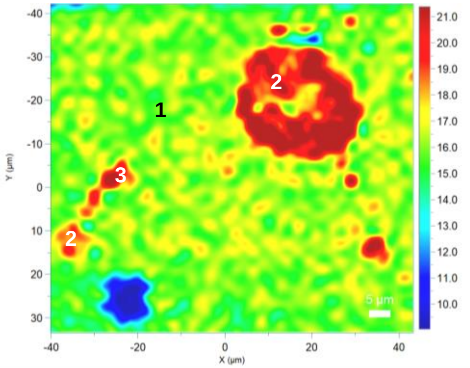
- Propionate precursor solution of Zr-doped (5%) CeO_2
- Deposition by spin coating on Ni-W (5%) by evico GmbH
- Thermal treatment for precursor solution conversion at 1100 °C for 15 min in flowing Ar-H_2









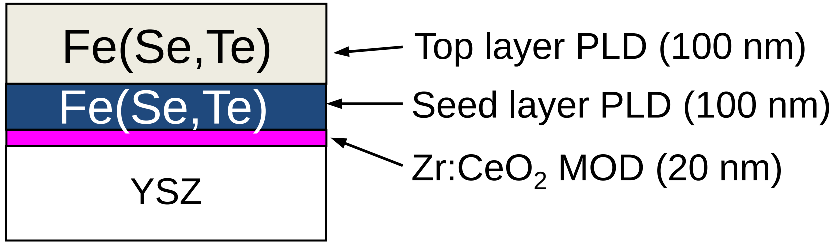


Perfectly suitable (only 30 nm)

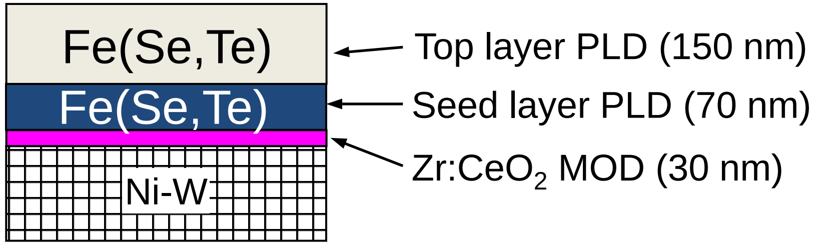
A. Vannozzi *et al.*, *under review* (2023)

IBS-CCs: FeSe/Fe(Se,Te)

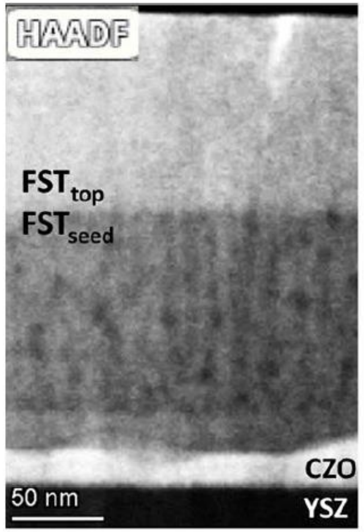
First test: single crystal

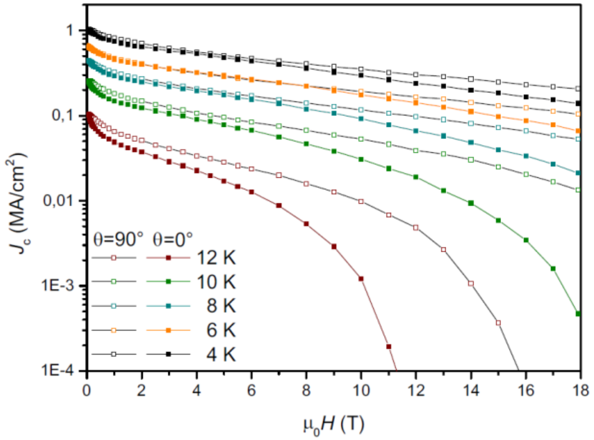


Final step: metallic substrate



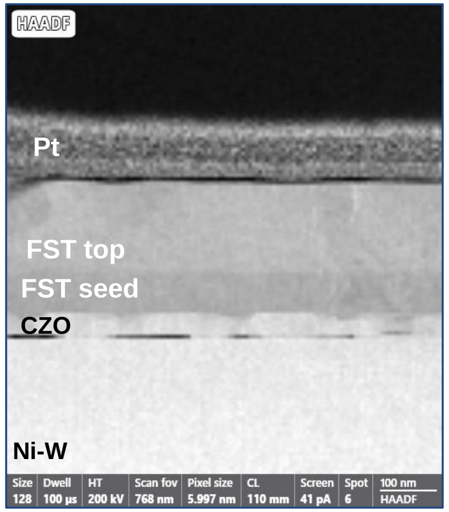
L. Piperno *et al.*, *Sci. Rep.* **13** (2023)

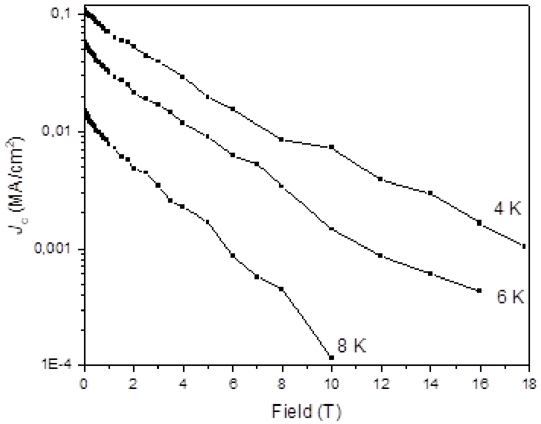




Very good results!

L. Piperno *et al.*, *in preparation*





Lower transport properties

Results in line with PLD-buffer

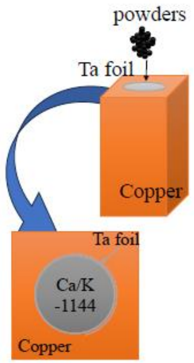
IBS Materials

- 11-coated conductors
- 1144 PIT wires

1144-IBS PIT wires

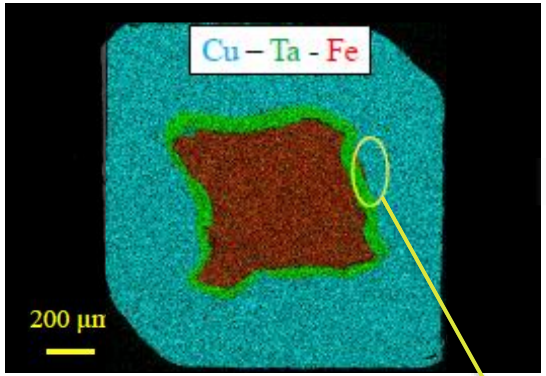
PIT process: powder insert + groove rolling + thermal treatment

A.Masi et al., Superconductivity 2 (2022) 100014

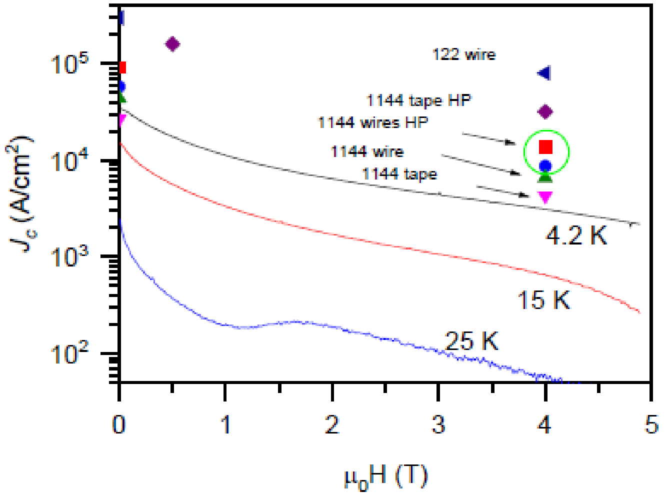


+

+



Some powder out of the barrier during insertion



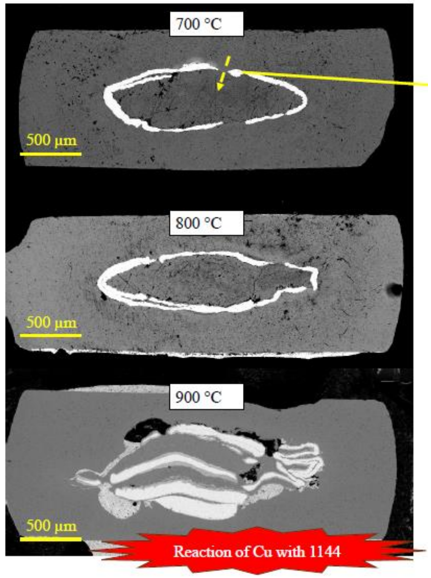
Promising results

Possible enhancements:

HiP process (densification)

Lamination (improves texturing)

A.Masi et al., Under review



Deformation issues on Ta sheet

Ongoing activity

FUNDED

EUROfusion

CfP-FSD-AWP24-ENR-04-ENEA-03

ENEA

Conclusions

The ENEA HTS group is mainly focused on Coated-Conductors in all its aspects, from material optimisation to applications.

The use of different deposition techniques allows us to study all the layers that make up a coated-conductor, while our combined expertise with the LTS group allows us to study the application of tapes in high field magnet cables

About IBS materials, our tape expertise was applied to the search for a simplified process for Fe(Se,Te) coated-conductors.

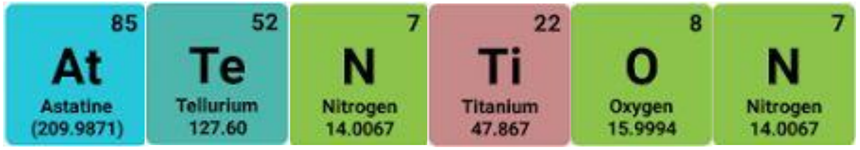
1144 material, with great potential in PIT wire applications, is also being studied showing very promising results

We are proudly the best in another wire manufacturing process

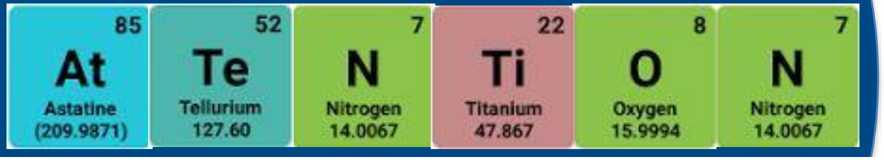
Fig. 1 - Left panel: Spaghetti wires (cold extruded) “alla amatriciana” (tomatoes, pig cheek lard, pecorino cheese, EV olive oil); Right panel: equipment used for the spaghetti wires manufacturing process

Open to collaborations on this topic

Thanks for your



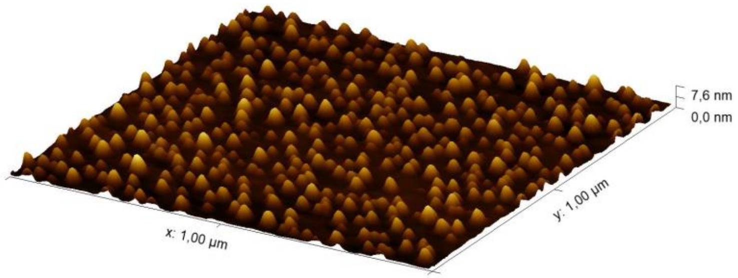
Thanks for your



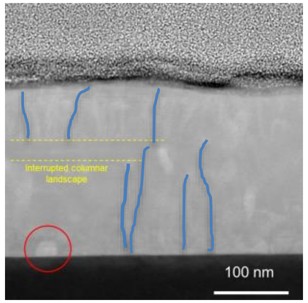
Film nano-engineering (APC) – additional slide

Modified template

MOD ZrO_2 nanoislands

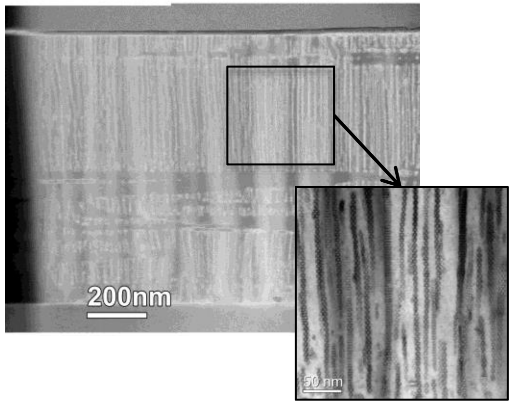


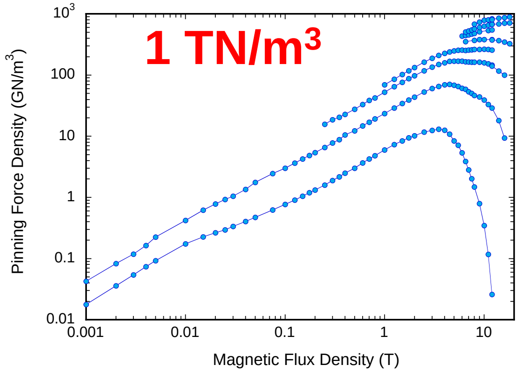
L. Piperno et *al.*, *Appl. Surf. Sci.* **484** (2019)



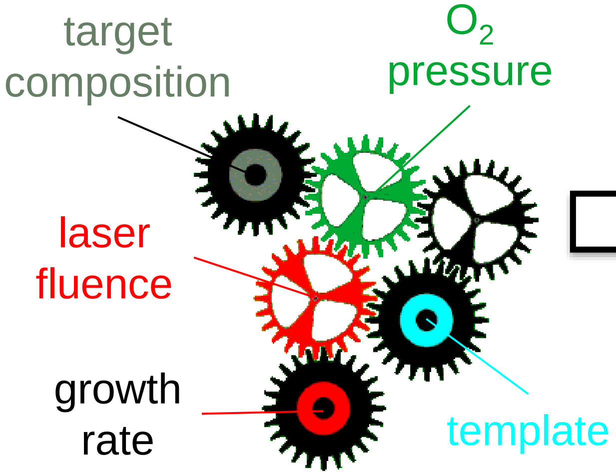
F. Rizzo, *in preparation*

Results replicated on Thick films (~ 1 µm)



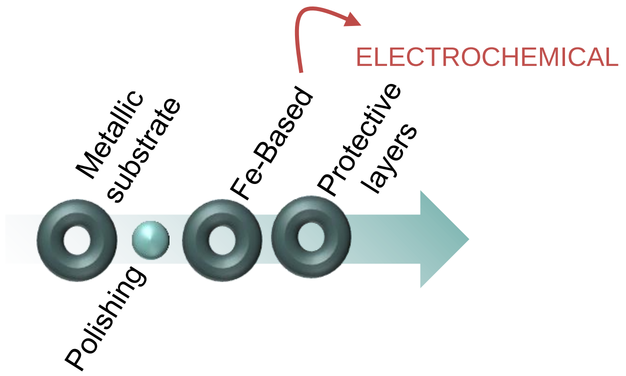


Deep knowledge on BYNTO/YBCO system

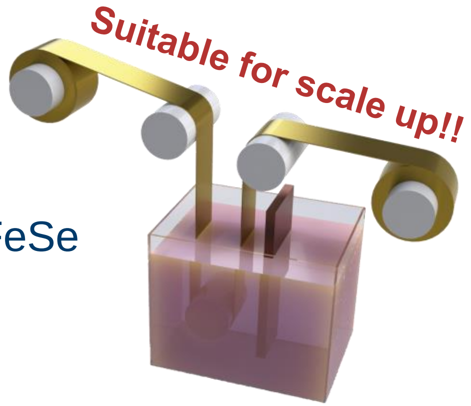


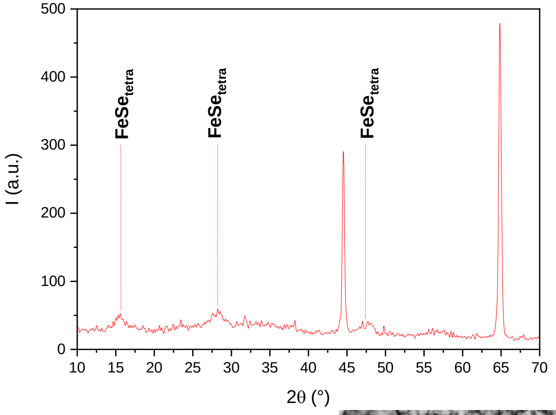
Optimization in specific operational regimes (*T*, *B*) for different applications

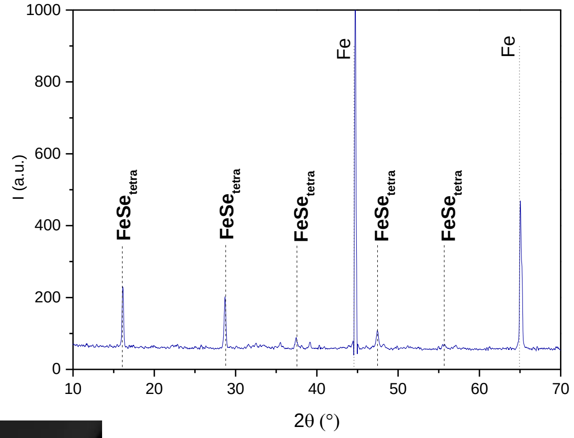
Process simplification for IBS-CCs additional slide

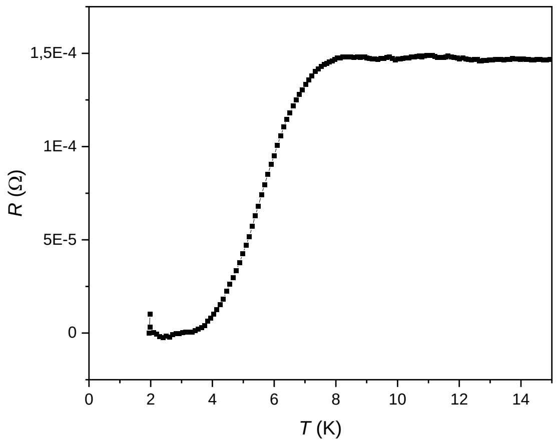


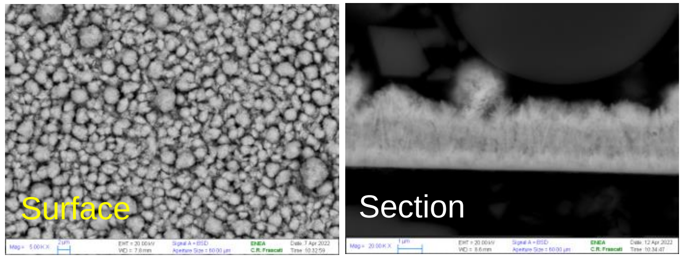
MATERIAL: FeSe
TECHNIQUE: Electrodeposition
RESULTS:
- Formation of $FeSe_{tetra}$
- Induced superconductivity in electrochemical FeSe









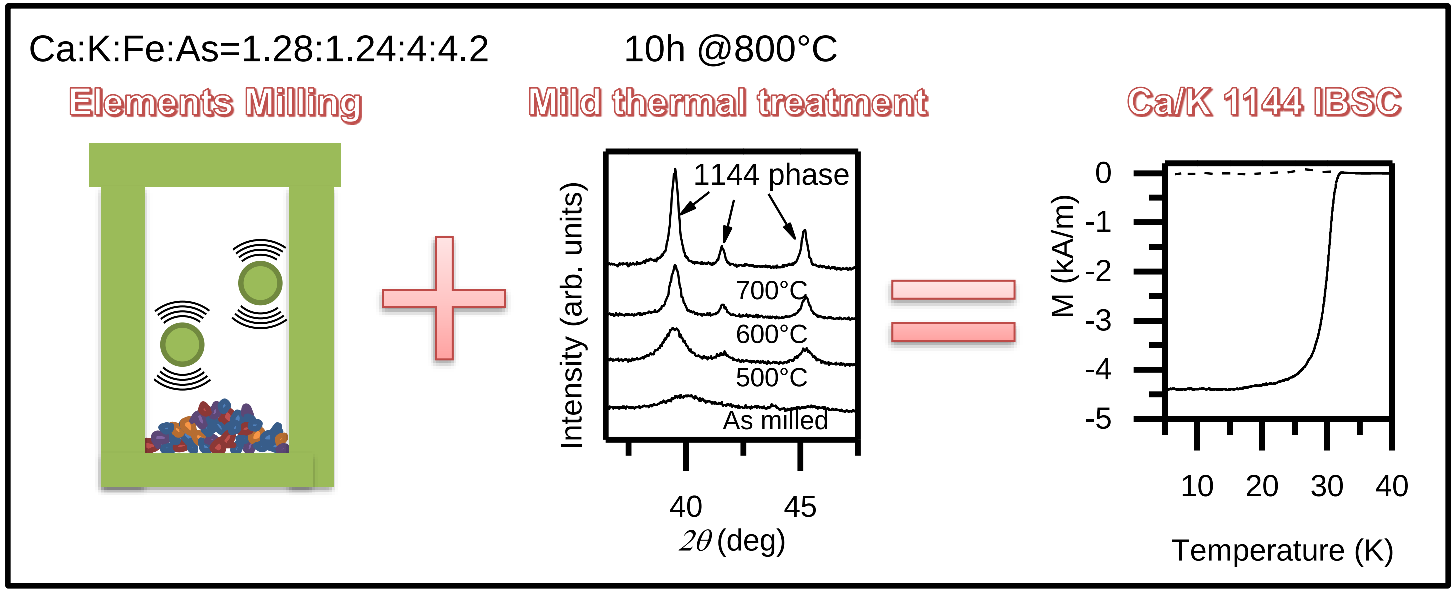


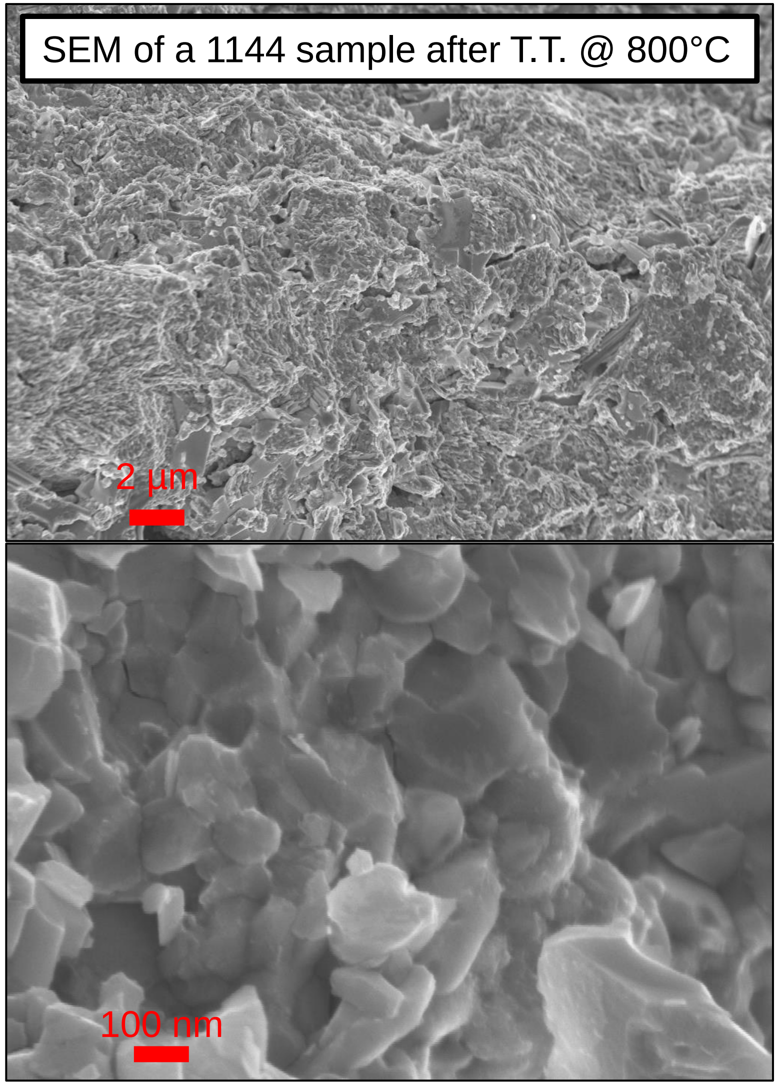
Activity still ongoing – challenging but promising

1144-IBS – additional slide

A.Masi et al., Supercond. Sci. Technol. 33 (2020)
A.Masi et al., J. Alloys Compd. 869 (2021)

Mechano-chemical synthesis of $CaKFe_4As_4$ (1144)





Polycrystalline Samples

Structure similar to 122 → PIT process

High potentiality in Wire Applications

S.Pyon et al, Appl. Phys. Express (2018)
Z.Cheng et al, Supercond. Sci. Technol. (2019)

ENEA

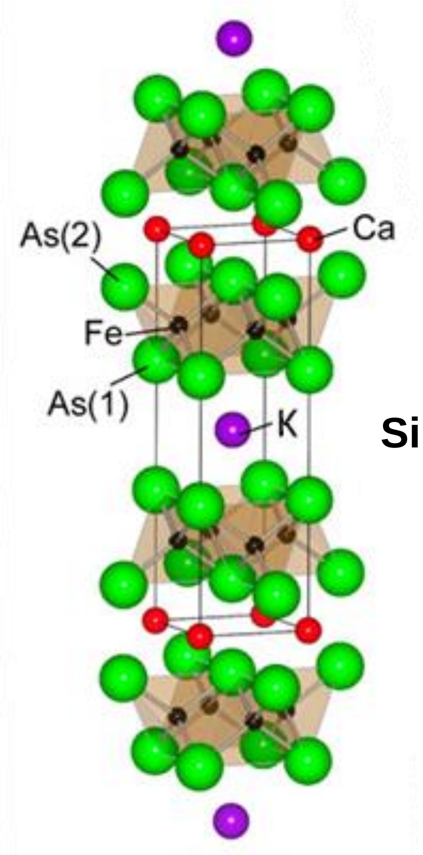
1144-IBS with aliovalent doping – additional slide

Aliovalent substitution:

different valence (alkaline <-> alkaline earth) – similar ionic radius

Increased entropy

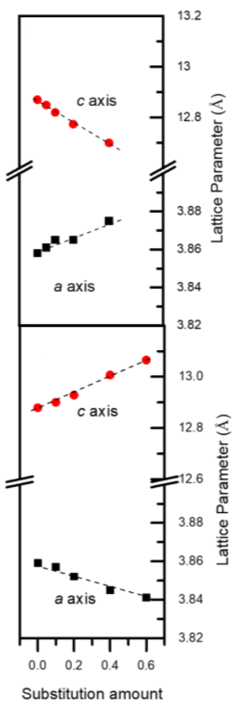
Influence on Pinning and/or GB

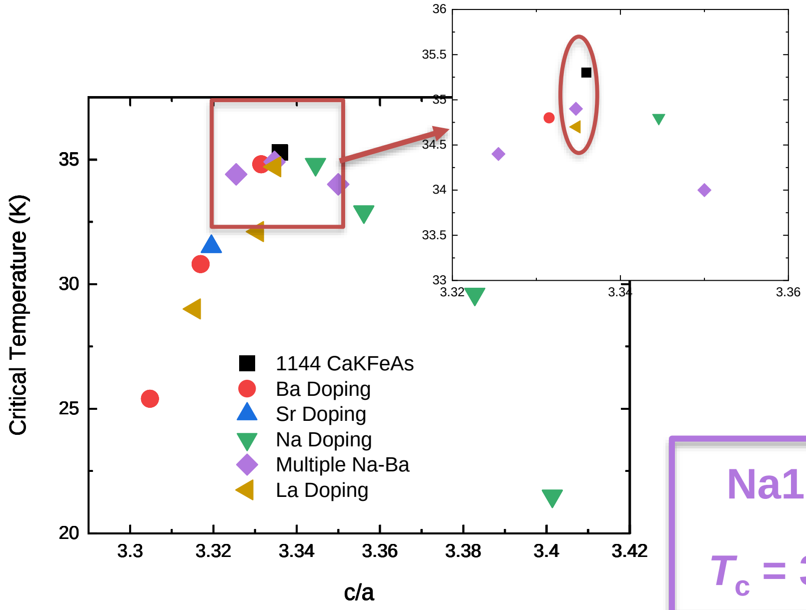


Ba
replacing K

Simultaneous doping

Na
replacing Ca





A. Masi *et al.*, *Supercond. Sci. Technol.* (2022)

A. Duchenko *et al.*, *under review* (2023)

1144

T_c **= 34.7 K**

Na1Ba05

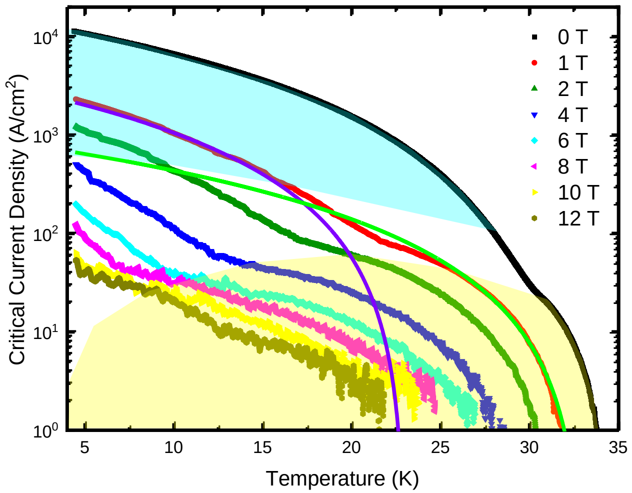
T_c **= 34.6 K**

La05

T_c **= 33.4 K**

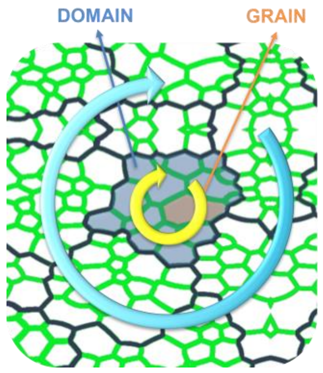
1144-IBS with aliovalent doping – additional slide

Detailed magnetic characterizations
(magnetization, magnetic relaxation, a.c. susceptibility)



Transport properties are still GB limited (10^7 A/cm^2 in s.c.)

Huge room for improvements

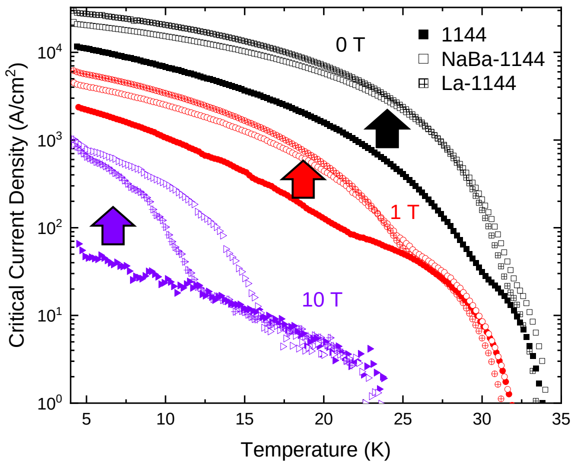


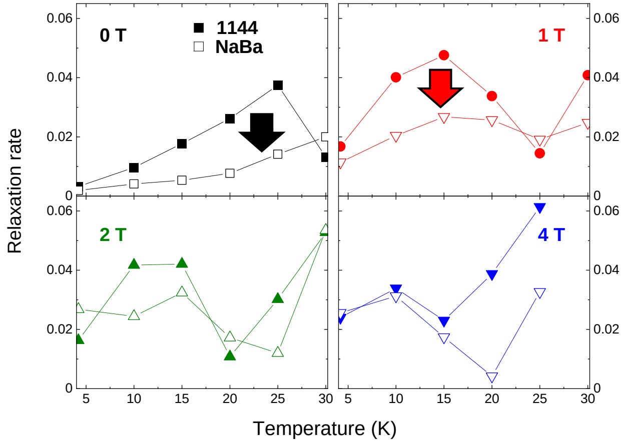
2 contributions:
- **Domain boundaries (active at LFT)**
- **Grain boundaries (active at HFT)**

A. Augieri *et al.*, *IEEE Trans. Appl. Supercond.* ***33*** (2023)

A. Augieri *et al.*, *Under Review*

Effect of aliovalent doping





s.f. J_c more than doubled
Magnetic properties improved in the LFT regime

Aliovalent doping influences the <u>Domain Boundaries</u> properties

Right path but further efforts required