



Progress towards HTS HFM Magnet and Conductor Strategy

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CEA: T. Leconte

PSI: B. Auchmann

KIT: B. Holzapfel, N. Bagrets

SPIN: A. Malagoli

INFN: L. Rossi, M. Statera

Univ. of Southampton: Y. Yang

Univ. of Vienna: M. Eisterer

Univ. of Twente: A. Nijhuis, Hans van Oort

HTS HFM Strategy

- ❑ **LDG Roadmap:** “demonstrate the suitability of High-temperature superconductor (HTS) for **accelerator magnet** applications, providing a proof-of-principle of HTS magnet technology beyond the range of Nb_3Sn , with a **target in excess of 20 T**”

- ❑ **HTS Conductor**
 - ❑ Iron Based Superconductor (Ba-122)
 - ❑ REBCO

- ❑ **HTS Magnets**
 - ❑ REBCO Coils

Work on Bi-2212 is in the USA

Iron Based Superconductors – Why ?

SppC in China: IBS Ba-122 baseline
for **20 T – 24 T magnets** (125 – 150 TeV)
– with Nb₃Sn + REBCO as option

Better than Nb₃Sn

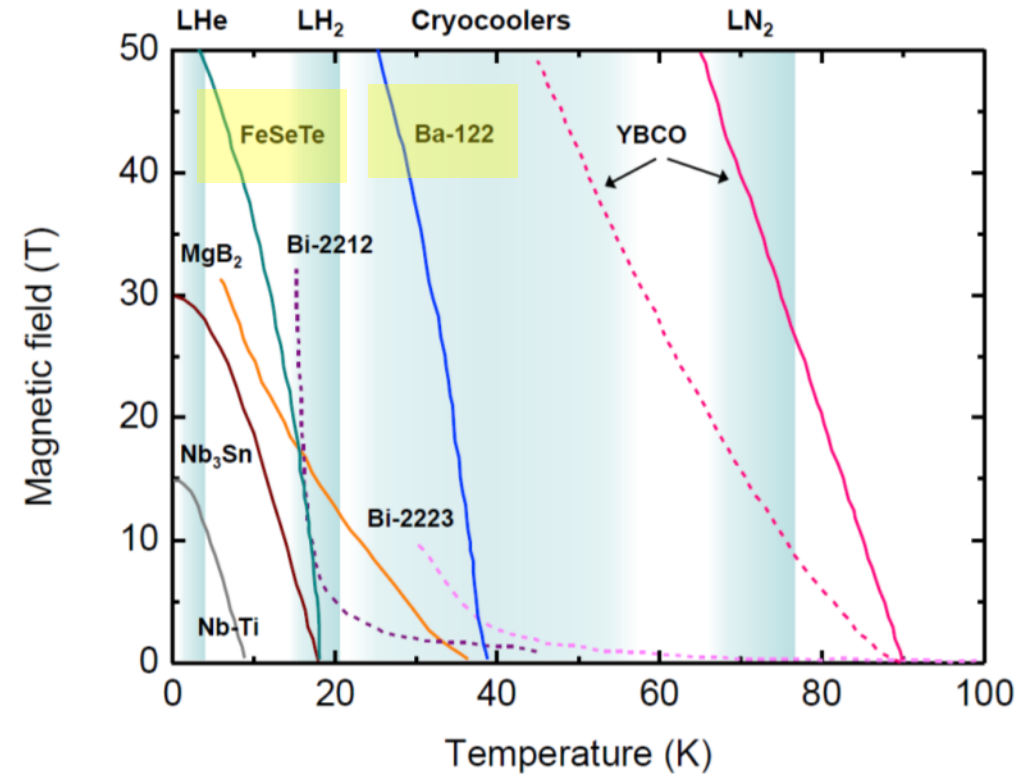
Bc2 ~70 T @ 20 K
Tc ~ 38 K

Better than HTS - REBCO

Low Anisotropy
Improved grain connectivity

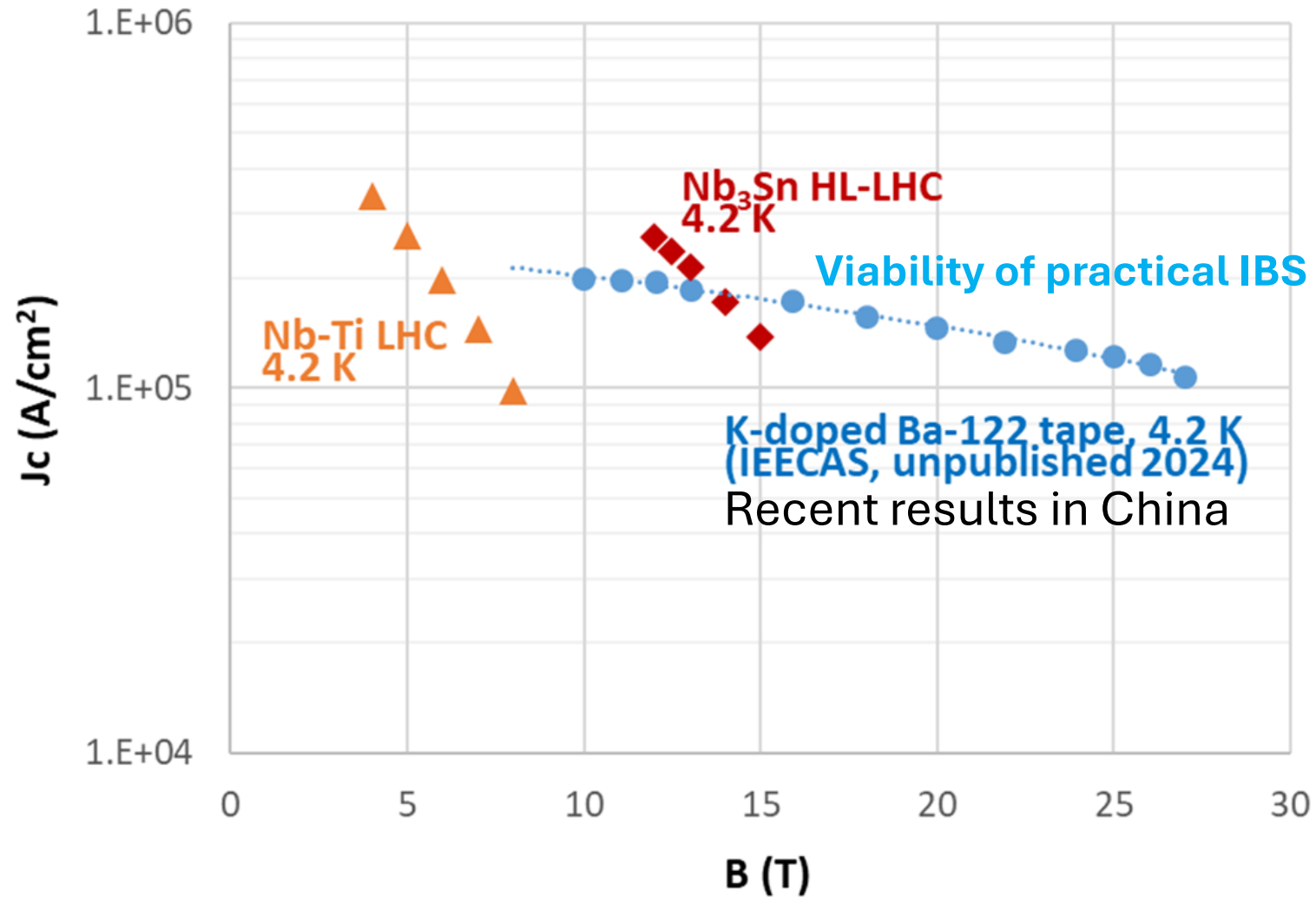
Powder In Tube (PIT) technology for
tapes and wires (used for Nb₃Sn,
MgB₂, BSCCO 2212 and BSCCO 2223)

Potentially low cost

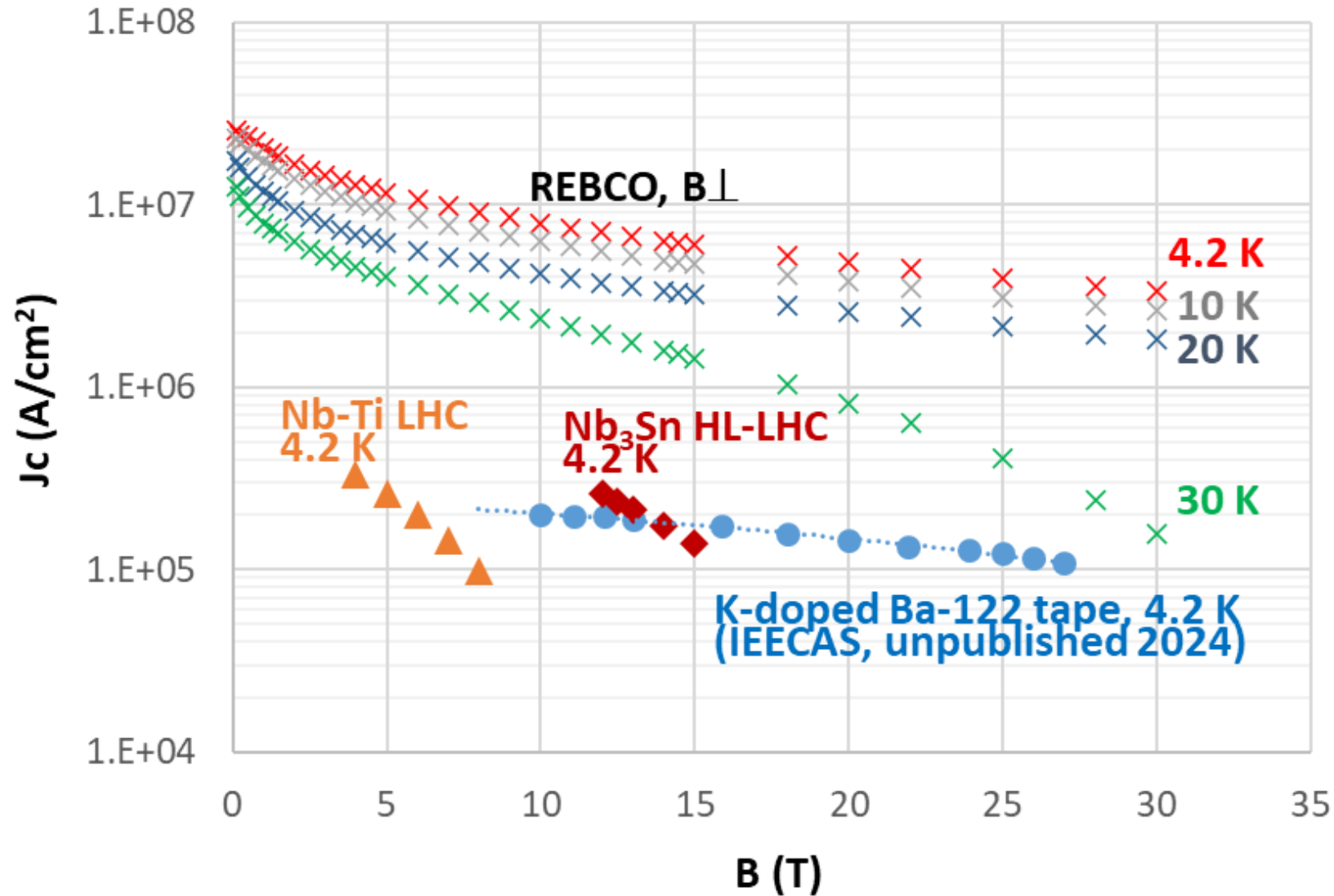


- A Gurevich, *Ann. Rev. Cond. Matt. Phys* 5 (2014) 35
- C Yao and Y Ma, *iScience* 24 (2021) 102541

Ba-122 Iron Based Superconductor



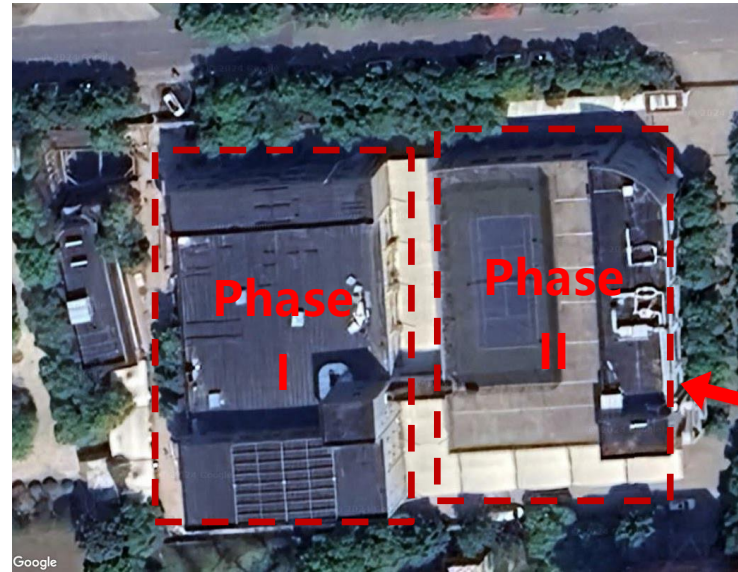
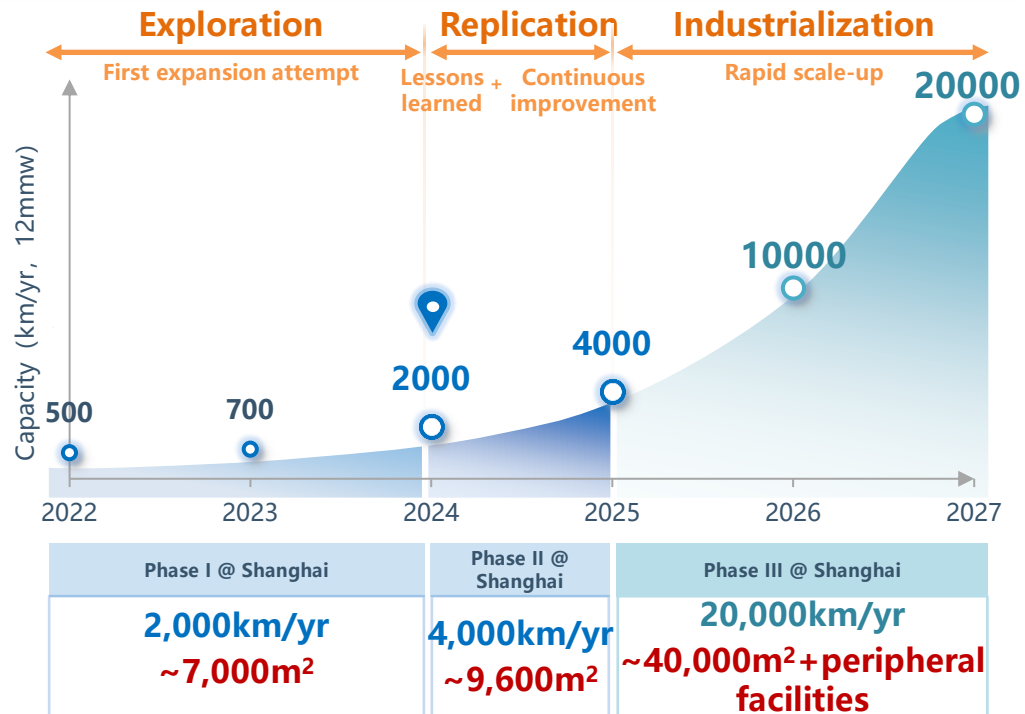
REBCO – Why ?



REBCO Performance refers to conductor recently procured by CERN in unit lengths > 200 m
Cost (E/m) reduced by a factor ~ 3 in the last two years

SST - Shanghai Superconductor Technology

2022 Q1: completion of fundraising
 2022 Q2: expansion project initiated
 2023 Q3: moving to new site
 2024 Q1: Output at 1200 km/yr (12mmw)
 2024 Q2: Capacity at 2000 km/yr (12mm-w), Phase I project complete.
 2024 H2: Output at 2000 km/yr (12mmw), Phase II in renovation, and Phase III siting finalized.



Staff
280+

REBCO Production plan



Year	Production (GAm)	Production (km @ 12 mm)	Production (km @ 4 mm)
2024	0.7	1,400	4,200
2025	0.7	1,400	4,200
2026	0.7	1,400	4,200
2027	0.95	1,900	5,700
2028	1.2	2,400	7,200
2029	1.45	2,900	8,700
2030	1.7	3,400	10,200

Much more aggressive growth scenarios are possible, depending on market situation

Transition from small-scale to large-scale production

- **Small-scale production**

- Low throughput and low yield
- Low material usage efficiency
- Lack of in-line monitoring and control
- Longer machine downtime for maintenance and repair
- High production cost

Transition



- **Large-scale production**

- High throughput and high yield
- Higher material usage efficiency
- Improved operation stability with in-line monitoring, closed-loop control
- Reduced machine downtime (planned and unplanned)
- Reduced production cost



Next generation MOCVD system under design

HTS Tape Manufacturers

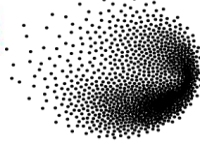
Several manufacturers worldwide:

Shanghai Superconductors (SST), Faraday Factory,
SuperPower/Furukawa, THEVA, Sumitomo Electric, SuNAM, HTSI, ...

HFM HTS – A European Effort

9 Contributors

Magnets



Superconductors



Measurement of Superconductors/Studies

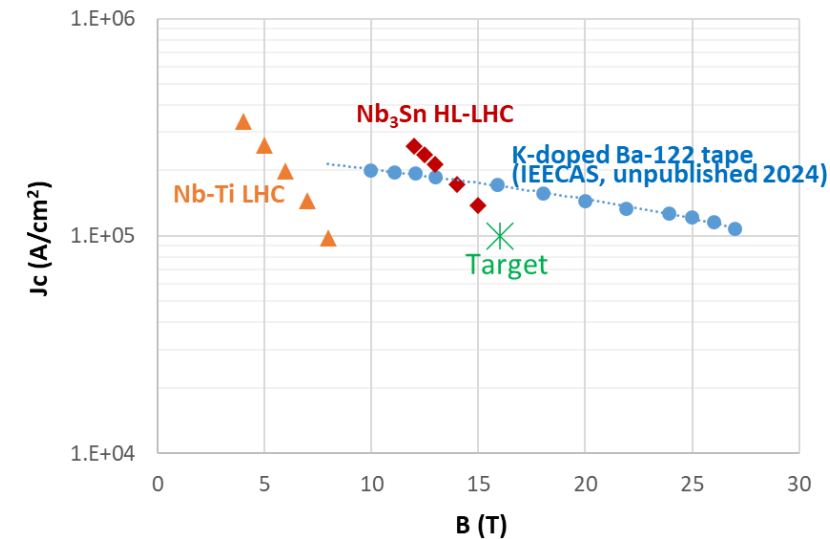


Topics on Accelerator Magnets Being Addressed

- **SPIN**: a laboratory on iron-based superconductors
- **KIT**: a laboratory on REBCO tape
- **TU Wien**: pinning (irradiation) and quench protection studies
- **University of Southampton**: AC losses and small coils (solenoid)
- **University of Twente**: BSCCO 2212 cable qualification (and AC losses)
- **CEA**: Metal Insulated Coils
- **PSI/Chart**: Modelling of AC losses and electrically insulated coils
- **CERN**: Electrically Insulated Coils and REBCO cables (other than stacks)
- **INFN**: REBCO coils

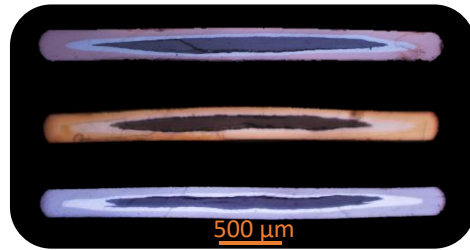
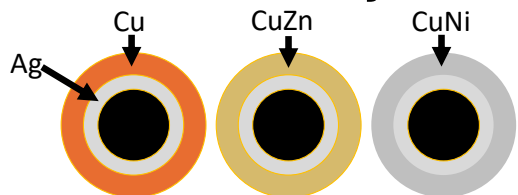
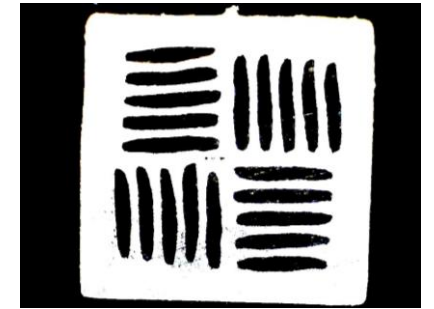
Iron Based Superconductors – SPIN (1/3)

- **IBS Laboratory at SPIN**, Genova, to investigate potentials of IBS for high field magnets (A. Malagoli et al)
- **Ba-122**
 - Multi-filamentary **Powder In Tube (PIT) Ba-122 round wire**
 - Investigation of wire layouts enabling **React & Wind** technology
 - **Target J_c : 10^5 A/cm² @ 4.5 K and 16 T, 10^4 A/cm² @ 20 K and 10 T**
 - Development of **powder**, development of optimized **wire layouts and composition**, production and qualification of multi-filamentary **tape and wire** (with unit lengths ≥ 100 m)
 - **Challenge:** J_c across grain boundaries (inter-grain connectivity)

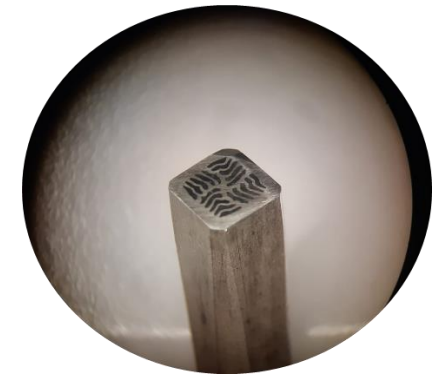


Iron Based Superconductors – SPIN (2/3)

- **Powder developed** (see poster of E. Bellingeri “Impact of powder granulometry”, today). Required both quality and quantity (today ~ 50 g/week). **K doping (K-Ba 122)** and study of effect of excess of K doping on grain size
- First multi-filamentary tapes and wires produced. Study of different **sheath architectures**, with Ag and Nb identified as good options as chemical barriers
- Working on **multi-filamentary** wire **architecture** on-going. New architectures being studied for better grain alignment and reduction of grain boundary misorientation - to improve intergrain connectivity

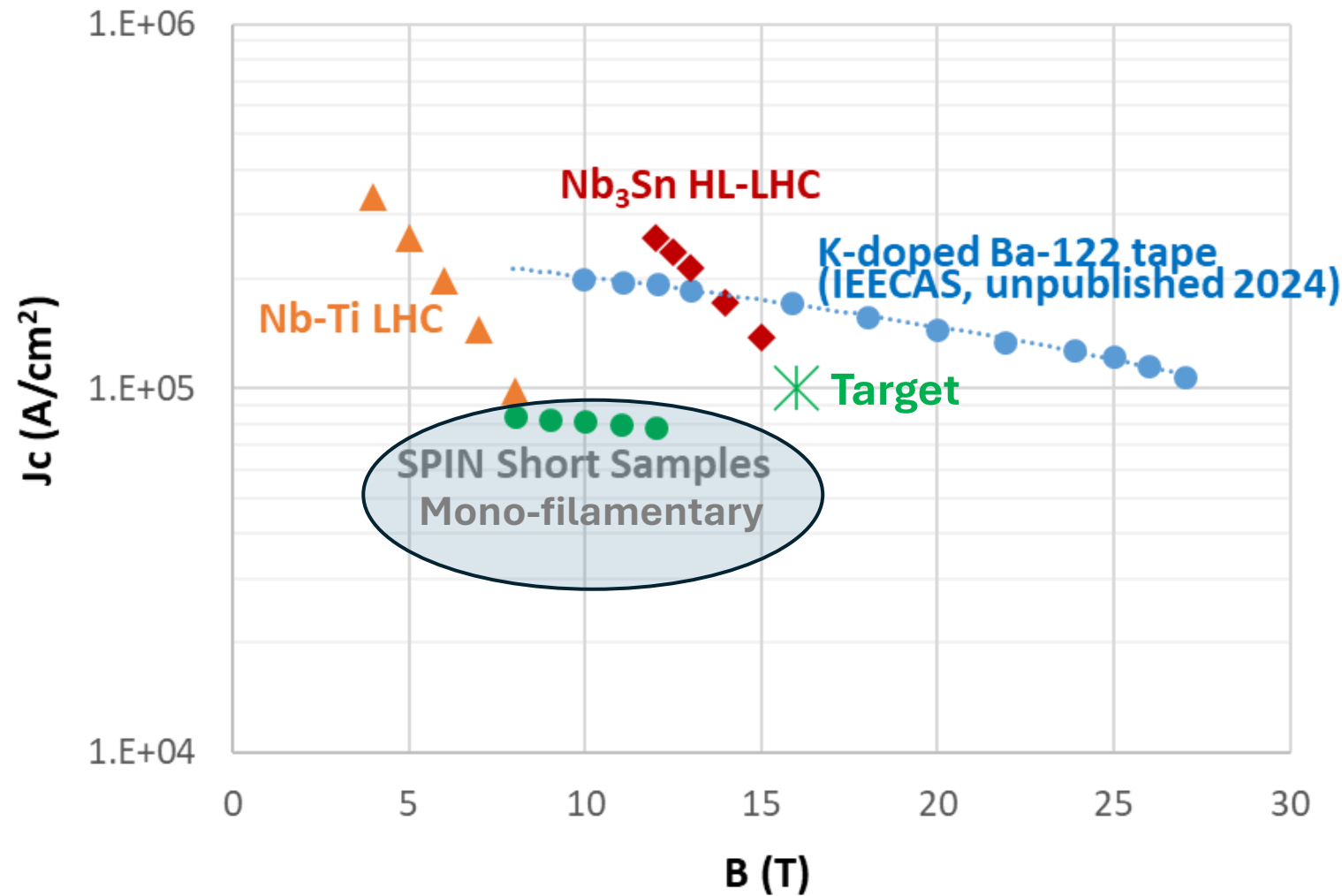


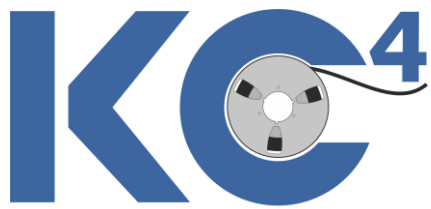
10 m multi-filamentary



Innovative multi-filamentary architecture

Ba-122 multi-filamentary wire/tape at SPIN (3/3)



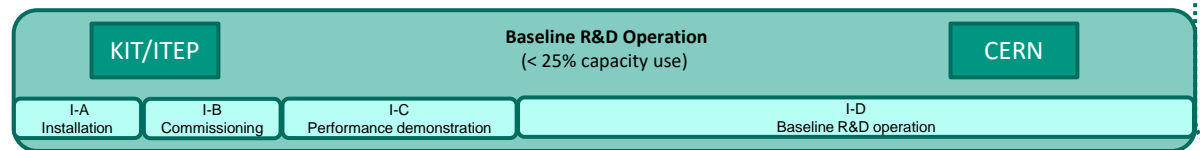
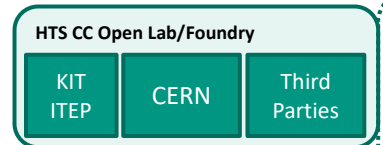
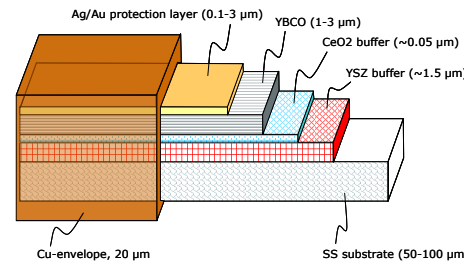


KIT-CERN Collaboration on CC

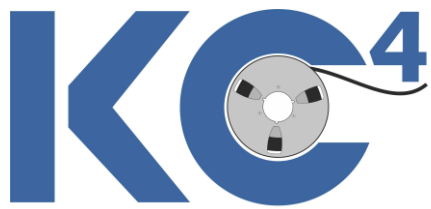
REBCO Tape – KIT (1/2)

KIT-CERN Collaboration on Coated Conductors

- **Laboratory** bridging the gap between basic materials research and large-scale production in industry (B. Holzapfel, N. Bagrets, et al)
- Transfer to KIT of BRUKER HTS R&D-line. **Operational at KIT since March 2024**
- **IBAD/PLD CC**. IBAD MgO tapes procured. At KC⁴: PLD buffer and REBCO deposition, Ag coating, O₂ loading, Cu plating
- **Tailored developments**. Present focus:
 - Understanding and improving **internal resistance** in between layers of a tape;
 - Implementing **REBCO on both sides of the tapes**;
 - Implementing **filamentization in REBCO layer**



t.b.c

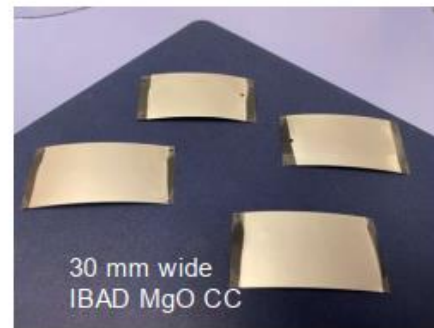
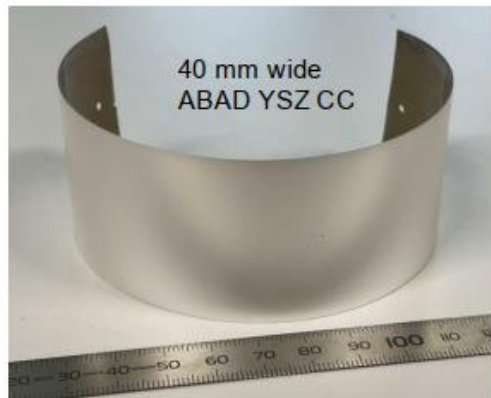
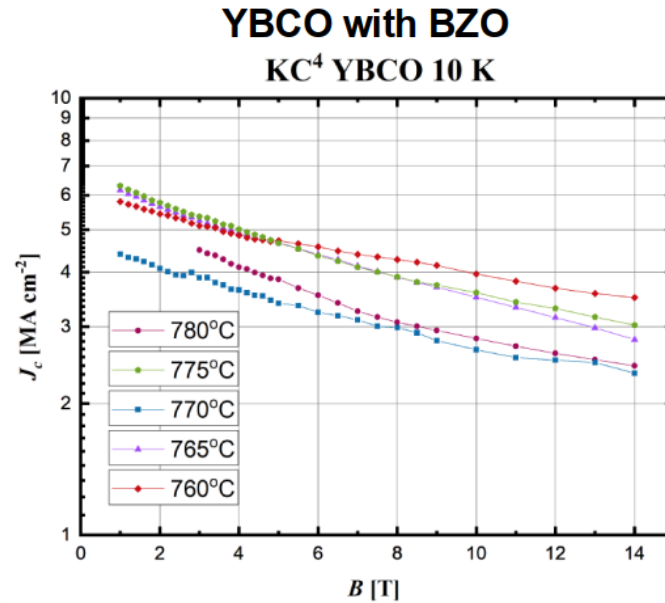


KIT-CERN Collaboration on CC

REBCO Tape – KIT (2/2)

KIT-CERN Collaboration on Coated Conductors

More than 50 m of tape delivered to CERN for qualification

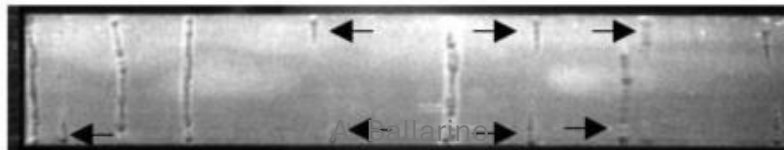


Wide (30 mm - 40 mm) tape development. Activity for HIGHEST-I.FAST (High-Gradient RF Applications, S. Calatroni)

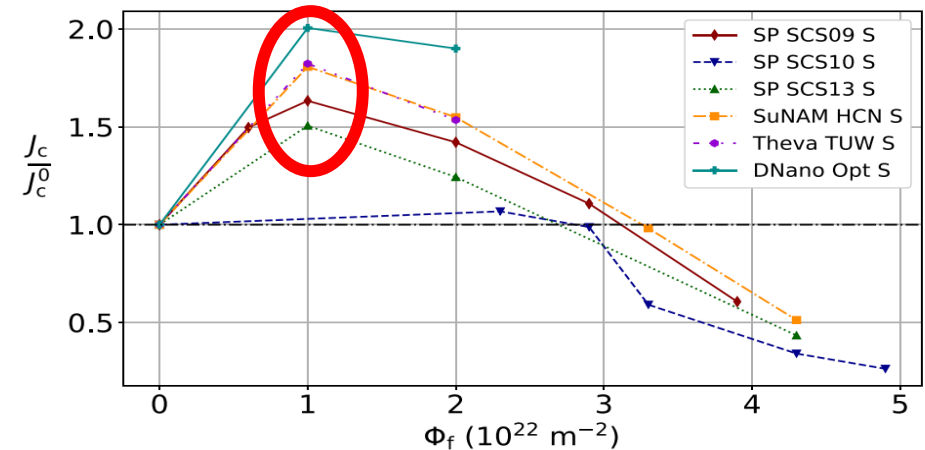
TU Wien – Pinning and hot-spot formation

- Change of **critical current between 4.2 K and 30 K**: balance between cooling costs and conductor performance.
- Full angle dependence: $I_c(\mathbf{B}, T, \theta)$.
- Benchmarking with **fast neutron irradiation** experiments. I_c **not optimized in state-of-the-art conductors?**
- **Better understanding of hot-spot formation at over-currents:**
 - Local measurement of electric field
 - Local measurement of current density
 - Local dissipation
- Spatial resolution: 100 μm

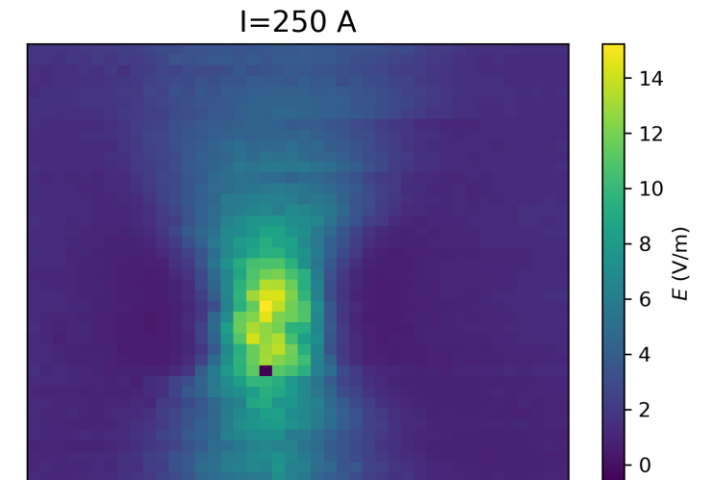
Bubble formation in liquid nitrogen
(Previous work at Grenoble)



Increase by 50-100% due to irradiation



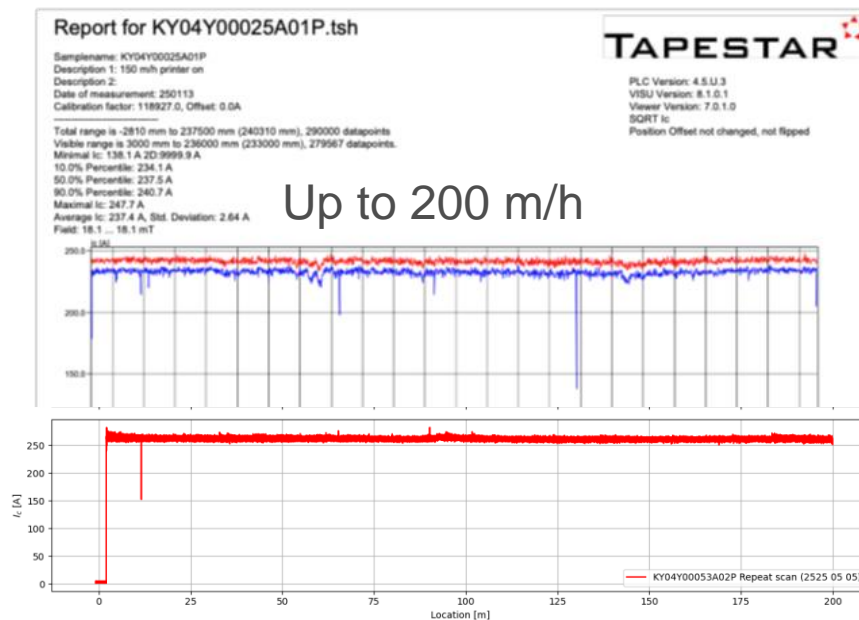
Local electric field around defect



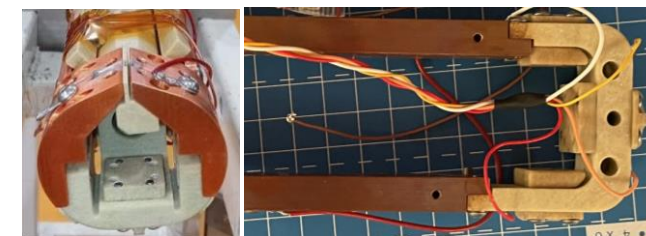
REBCO Tape – CERN (1/2)

- Procured **33 km** of tape from different manufacturers (2, 4 and 12 mm width)
- Unit lengths of **up to 850 m** (for a 4 mm wide tape)
- Defining and performing **QC measurements**

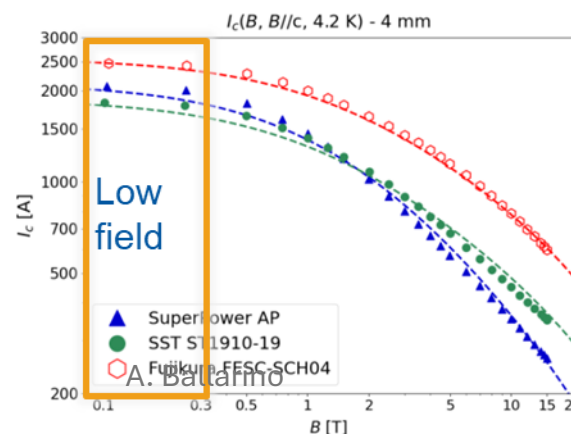
TAPESTAR™ (reel-to-reel critical current measurement)



Laser cut bridge on REBCO at KIT



Holders for in-field (\parallel and \perp) I_c measurements



Transport (I_c)

VSM

Tape marking and width/thickness measurement

REBCO Tape – CERN (2/2)

Scaling law – covering also the low field region

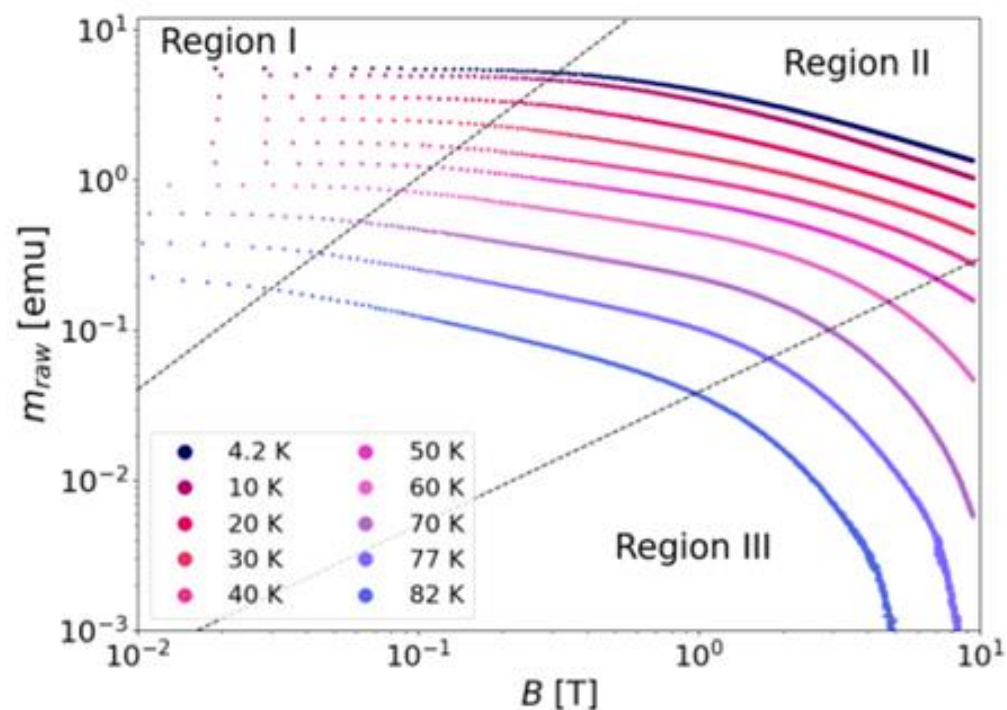
G. Succi, PhD thesis, SOTON and CERN

$$I_c(B, T^*, \theta^*) = I_{c,0} \cdot \left(1 + \frac{B}{B_0^*}\right)^{-\alpha^*} \cdot \left(1 - \frac{B}{B_{irr}^*}\right)^{q^*}$$

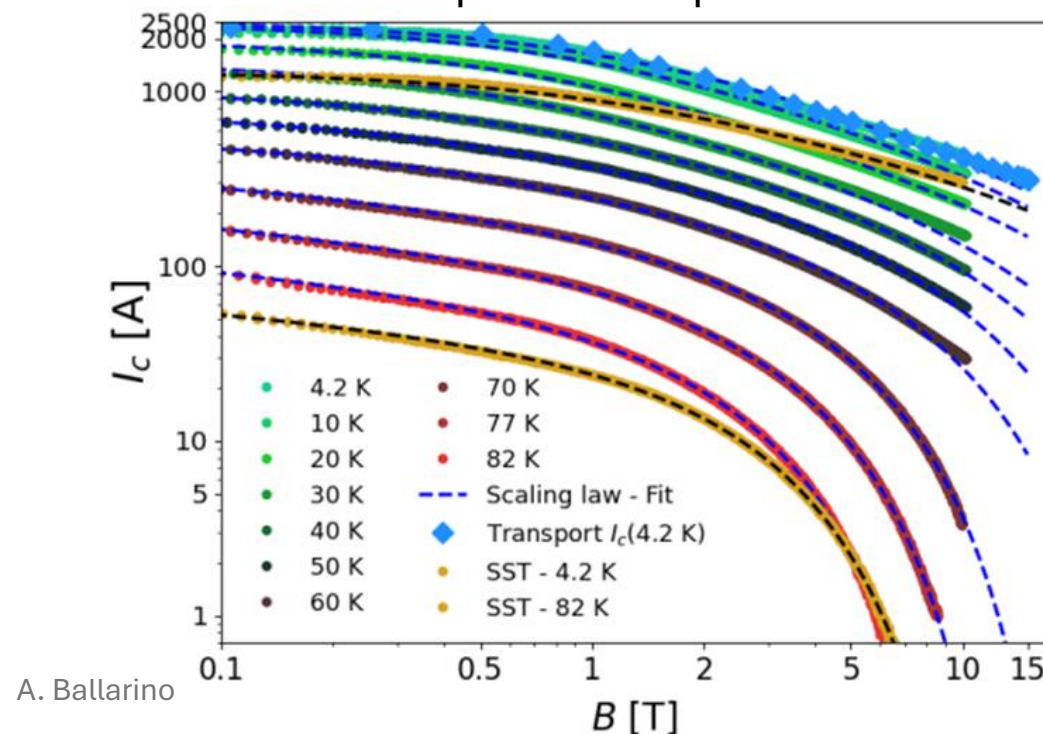
Manufacturer	SP	SST	Fujikura	FFJ
Route	IBAD+MOCVD	IBAD+PLD	IBAD+PLD	IBAD+PLD
SC layer	(Y,Gd)BCO	GdBCO	EuBCO	YBCO
Pinning	BZO nanorods	No APC	BHO nanorods	Y ₂ O ₃ nanop.

Manufacturer	$I_{c,0}$ [A]	α	B_0 [T]
Shanghai ST	1878	0.52	1.06
SuperPower	2120	0.78	1.42
Fujikura	2565	0.50	1.39
Faraday FJ	3920	0.67	0.84

Pinning in REBCO



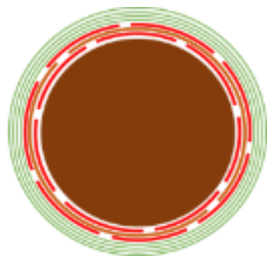
Temperature dependence



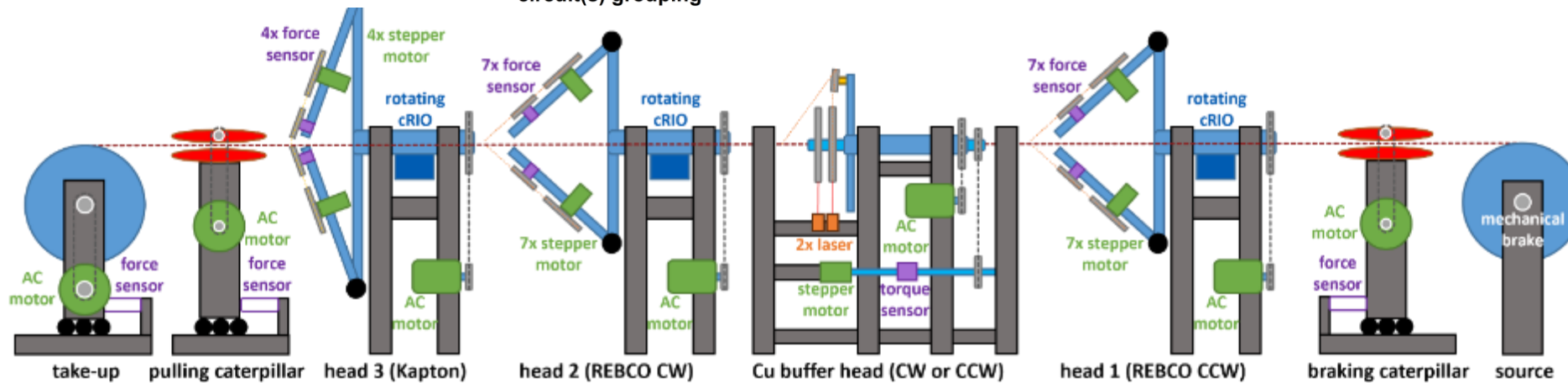
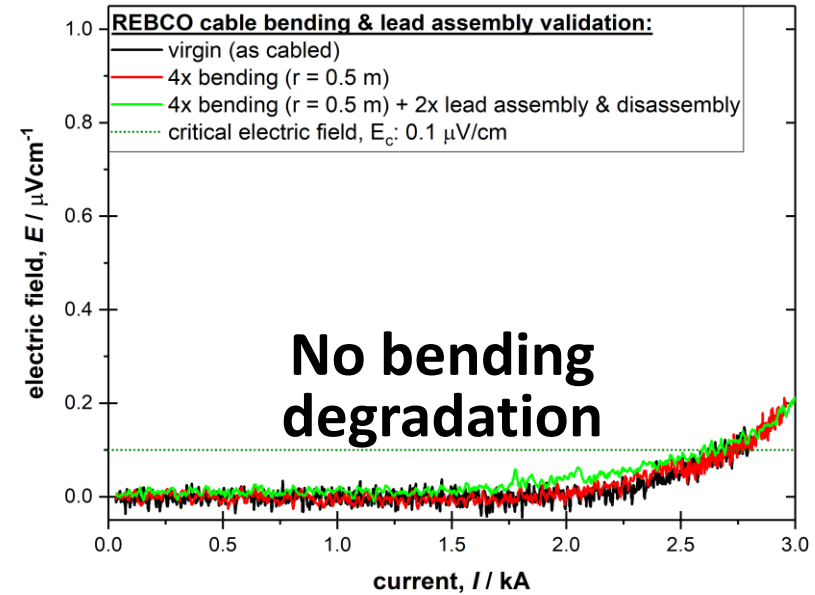
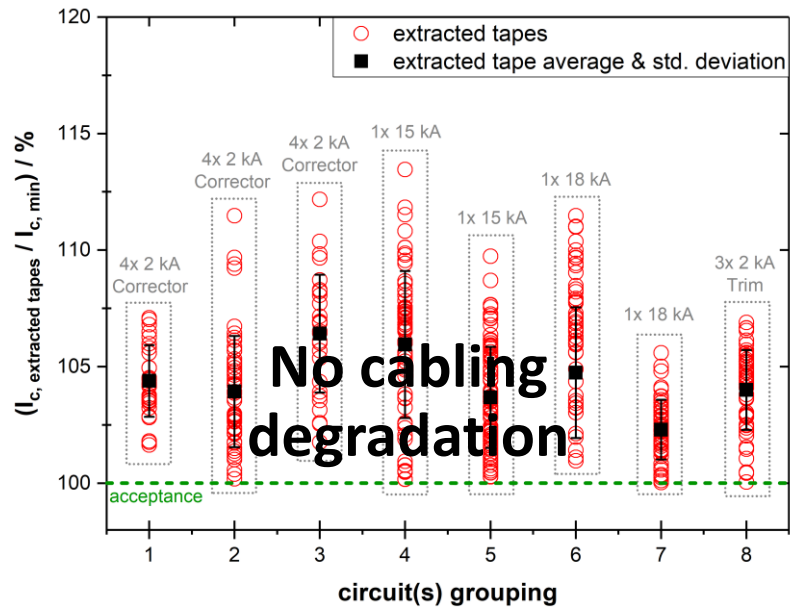
A. Ballarino

REBCO Cables – CERN

REBCO in HL-LHC



Cu braid
Cu tape
REBCO tape
Kapton tape



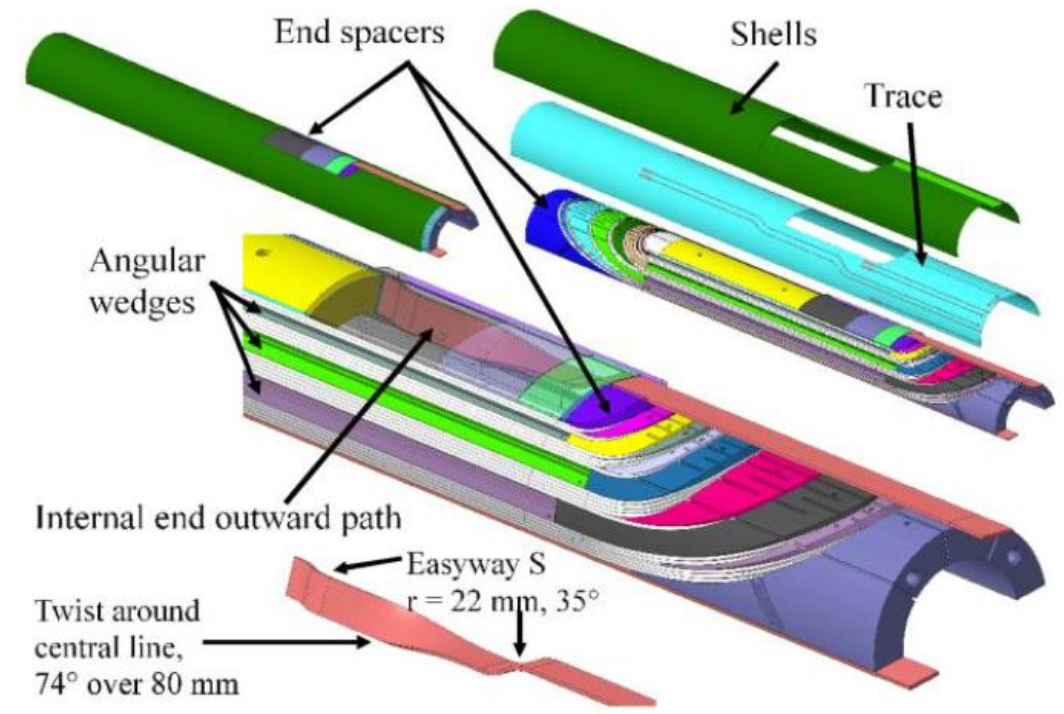
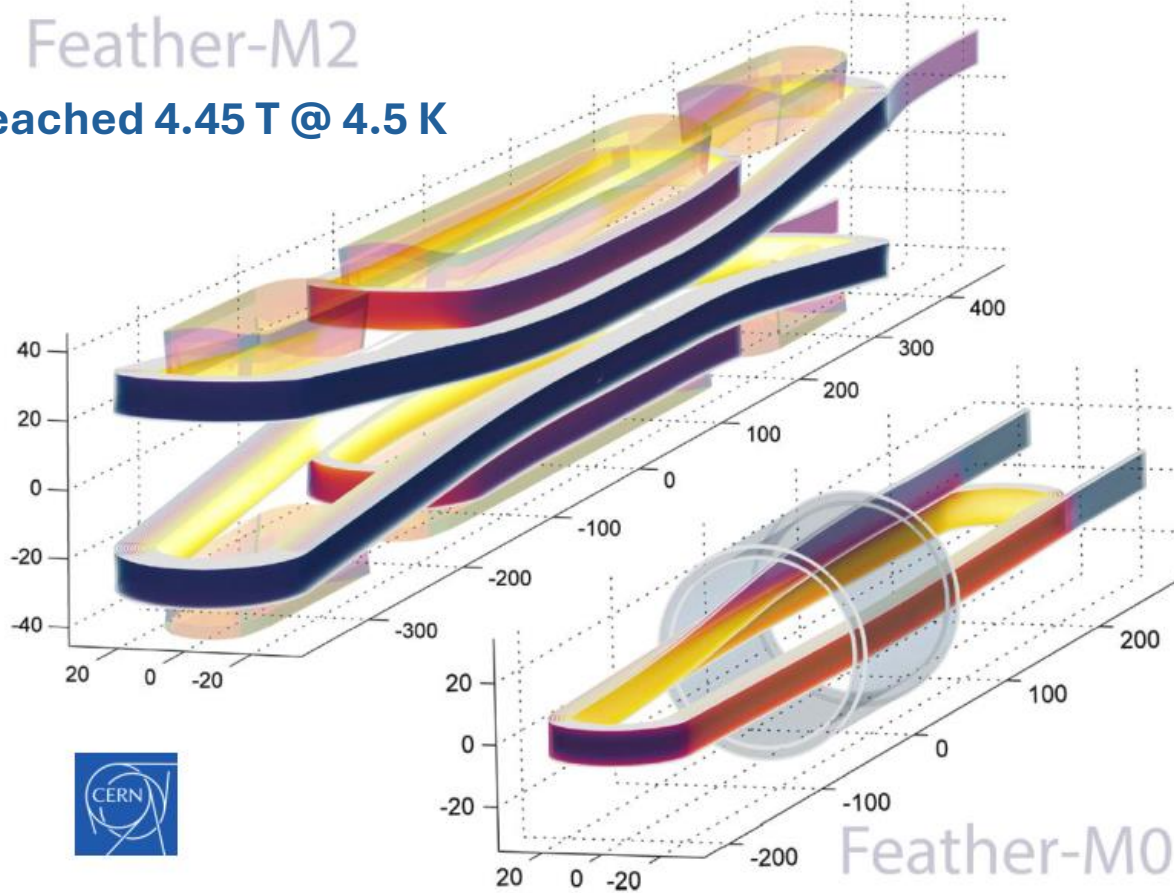
CERN Cabling Machine

Working on novel concepts of transposed cables

Past Developments – Eucard 2

Feather-M2

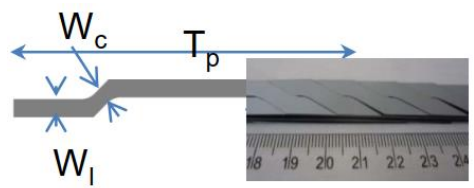
Reached 4.45 T @ 4.5 K



Target: 5 T dipole field in a 40 mm bore
Background field: 13 T (Fresca 2)

G. A. Kirby, J. van Nugteren et al, CERN-ACC-2015-0024

A. Ballarino



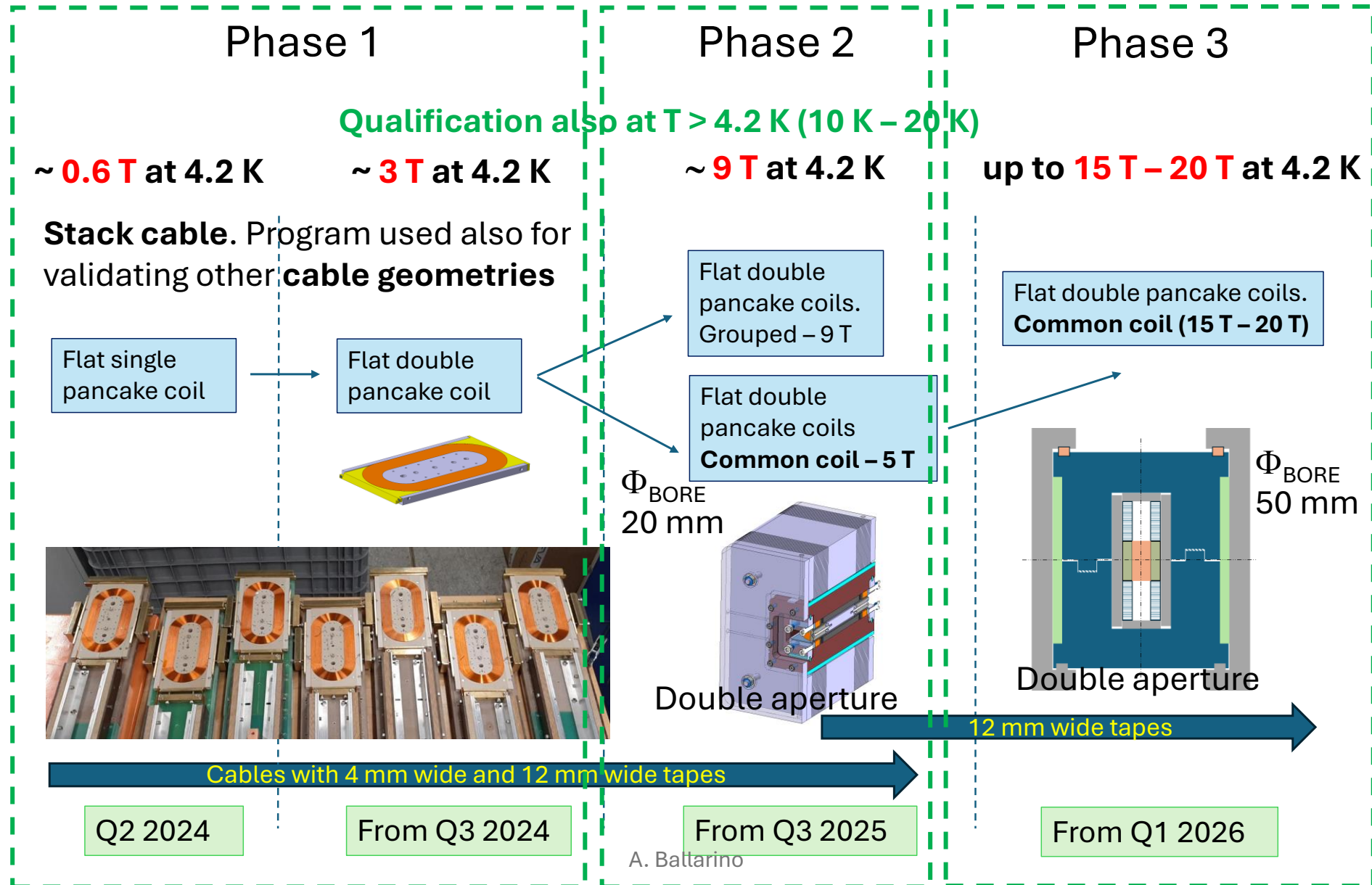
Roebel cables



W. Goldacker, A. Kario et al

CERN – From Racetracks to Common Coil

Single-layer and double-layer racetracks - Multi-racetrack and Common Coil - Common Coil

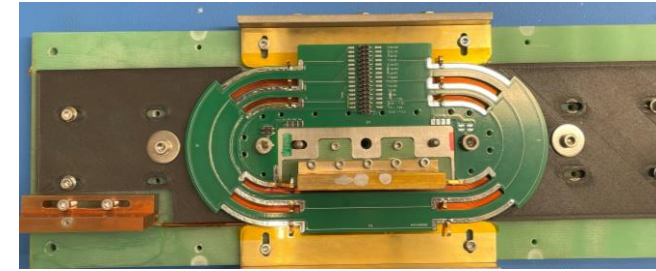


CERN Coils – Recent Achievements

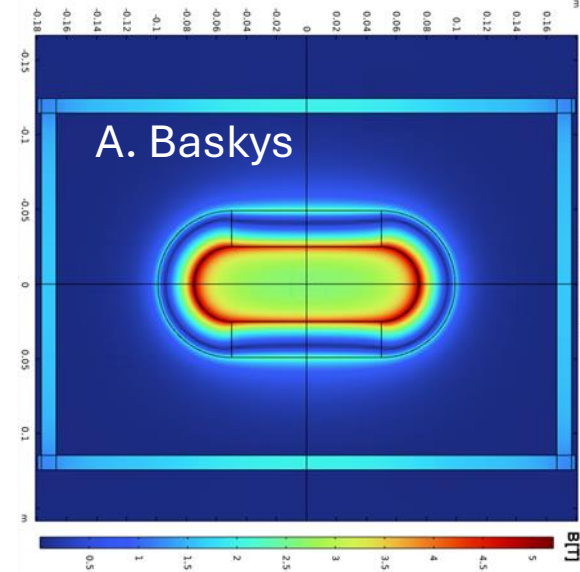
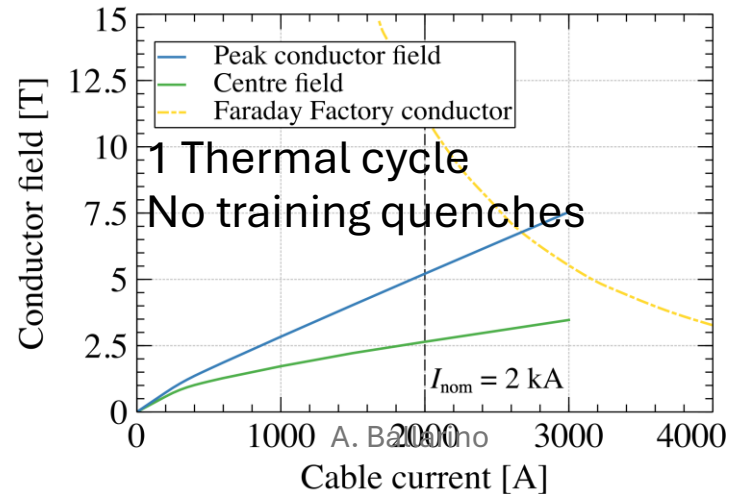
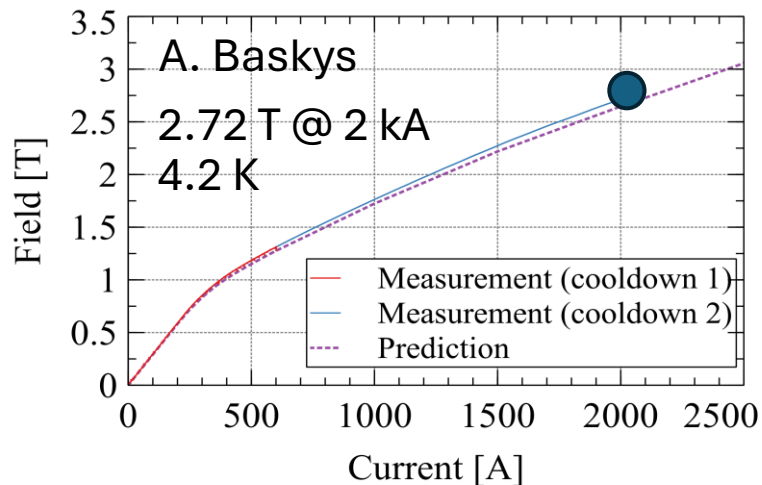
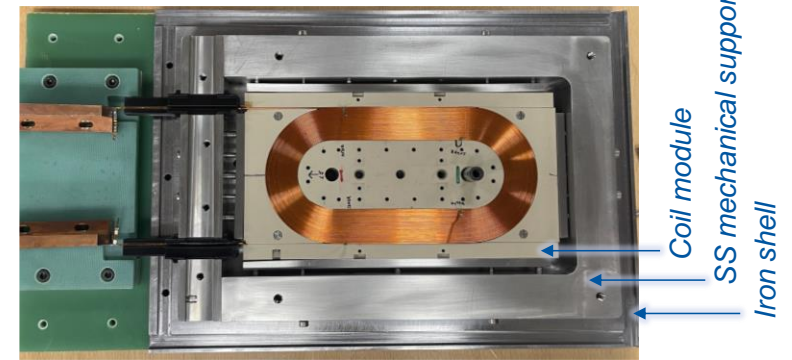
Phase 1

- Produced **several single-layer** and **double-layer racetracks** and **qualified them in liquid nitrogen** and one in **liquid helium**. In-house made winding machine
- The cable is a stack of tapes electrically insulated**: 4 REBCO tapes, 2 copper tapes, Kapton[®] electrical insulation
- Measured double racetrack at 4.2 K**. Reached the design field: **2.72 T in the central hole (5.2 T peak field in the conductor)**

Single racetrack



Double racetrack

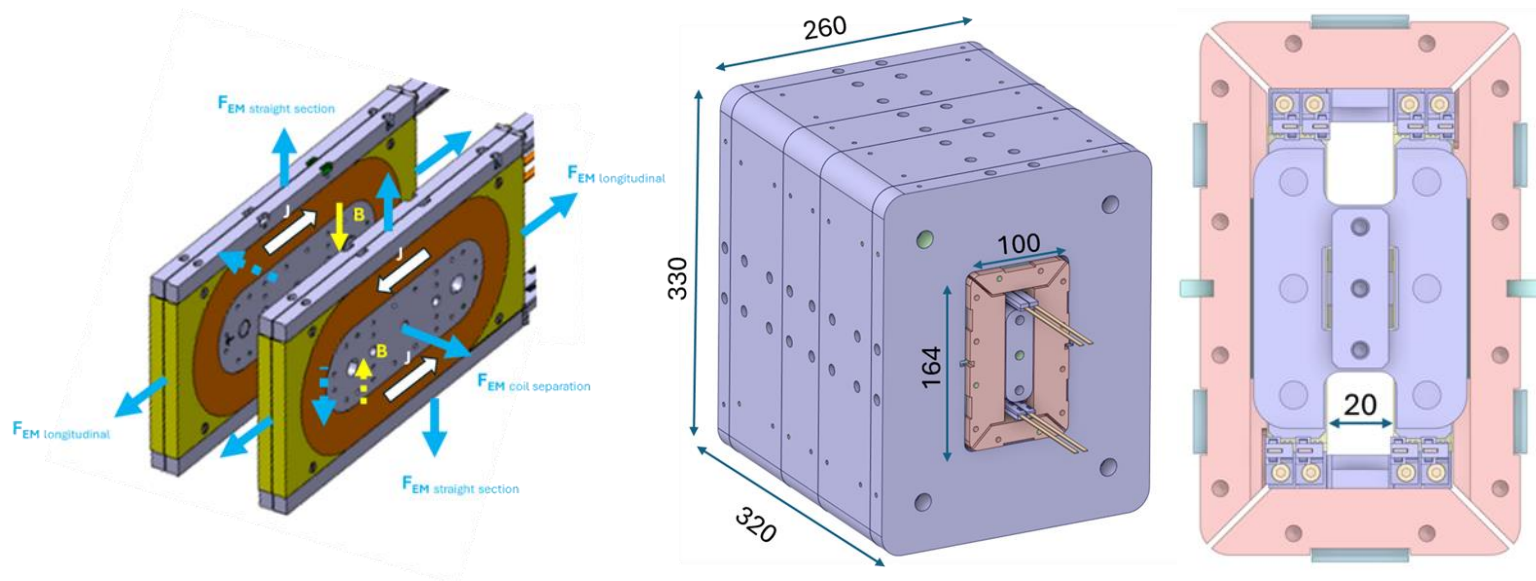
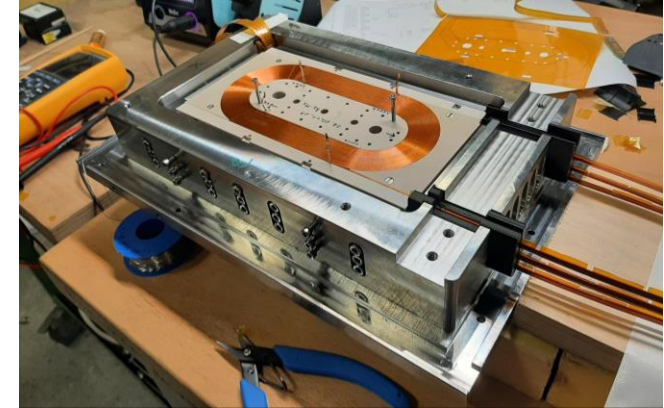


CERN Coils – Recent Achievements

Phase 2

- Assembled **three double racetracks** in a mechanical structure. Design field: **5.4 T** at **4.2 K** in the central hole (**8.8 T** peak field in the conductor). Measured in **liquid nitrogen: 1.12 T** in the central hole. Measurements in liquid helium in the following weeks
- Common coil dipole, **20 mm bore**, by end 2025

Three double racetracks



2+2 Double racetracks

4 mm wide tape

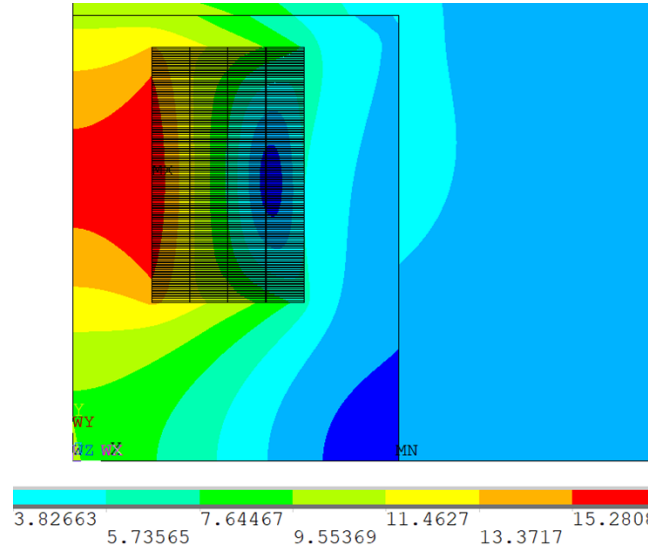
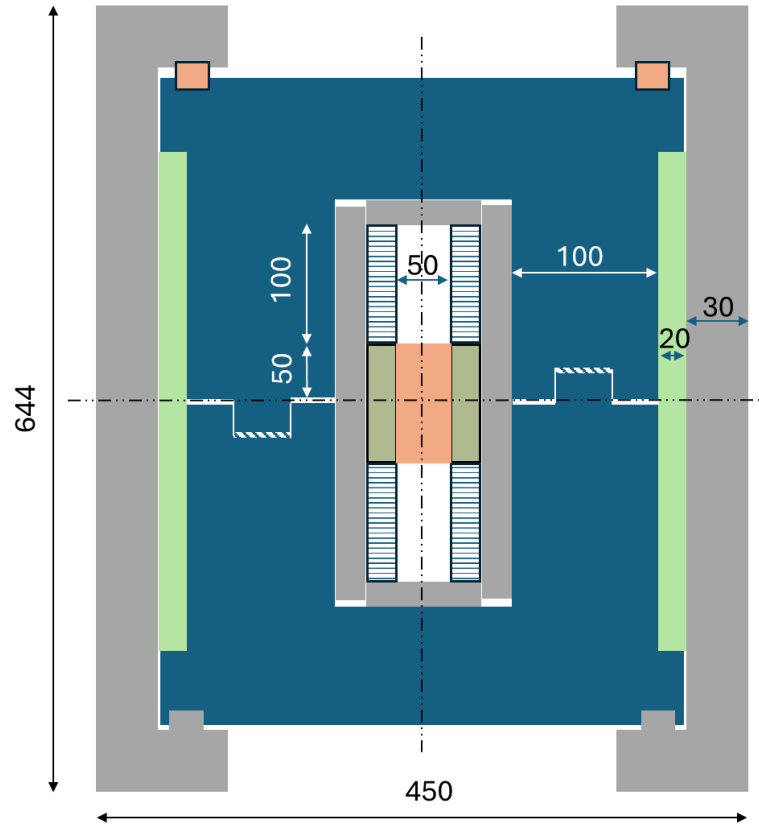
~ 5 T @ 4.2 K in the center of each bore ($\Phi = 20$ mm)

~ 9 T @ 4.2 K in the central hole if **six double racetracks** in series

5.4 T in the center and up 9 T on the conductor (without bore and with bore with 50 mm diameter)

CERN – Larger aperture, higher fields

Phase 3



14 T – 50 mm bore



	Field in the bore [T]	Field in the center [T]	Tape in the magnet [m]	Average σ_x [N/mm ²]	Average σ_y [N/mm ²]
4-mm tape					
PL - 20 mm bore	5		600	19	19.5
PL - 6 coils piled		9	750	16	
12-mm tape					
7 T – 30 mm bore	7		680	25	4
14 T – 50 mm bore	14		3320	116	8

D. Perini

2+2 Double racetracks
12 mm wide tape
~ 14 T @ 4.2 K in the center of each bore ($\Phi = 50$ mm)

Magnet assembly line under commissioning

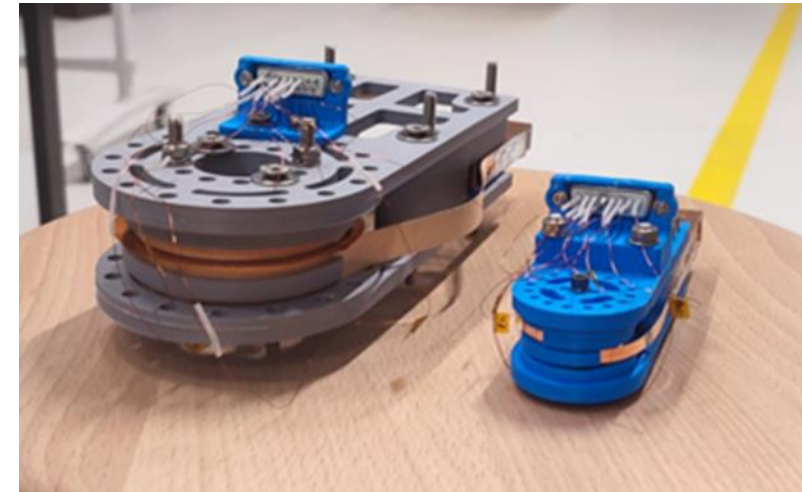
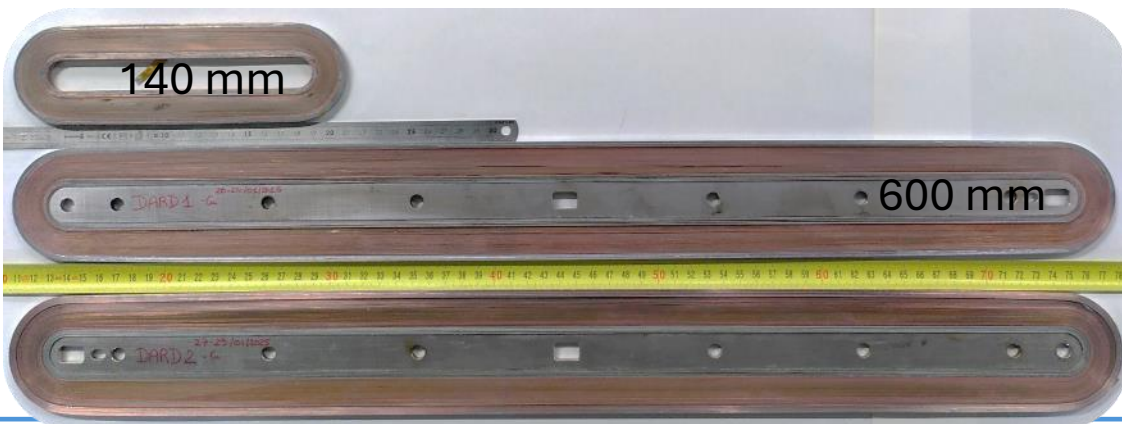
14 T in the center (bore with 50 mm diameter)

CEA

HFM HTS Activities

PSI

- Single and double racetracks wound with **single REBCO tape** (4 mm width). Tape procured by CERN. Racetrack **length**: 140 mm and 600 mm
- **Metal Insulation to ease protection**: co-winding of REBCO tape with 30 μm thick Durnomag[®] tape
- $I_{op} = 670 \text{ A @ } 4.2 \text{ K}$ ($\sim 1600 \text{ A/mm}^2$)
- $B_{center} = 3.6 \text{ T}$, $B_{peak} = 8.2 \text{ T @ } 4.2 \text{ K}$ in February 2025. New record (see next presentation of E. Rochepault)
- Modelling (with LittleBeast) and measurement (at University of Twente) of **AC losses** of REBCO coils
- **Electrically insulated stacks of two soldered REBCO tape**. Soldering during winding to ease quench protection
- Study of **REBCO Block Coil dipole** - scaling with temperature (5 K – 30 K)



See this afternoon presentations by E. Rochepault (**CEA**), B. Auchmann (**PSI**), A. Pampaloni (**INFN**)

Conclusions

- In Europe work on **HTS high field accelerator magnets** is on **REBCO**. There is **development of IBS Ba-122 wire** and interesting results have already been achieved
- **REBCO is an enabling material** ($B > \sim 15$ T and/or $T > \sim 5$ K). However, **focused R&D and innovation efforts** are required to establish the technology and **fill the gap between HTS and LTS**. Accelerator technology has specific and challenging requirements that ask for dedicated R&D
- Ongoing activities address identified challenges via a **coordinated effort** between laboratories and academia
- Small **5 T -10 T REBCO coils** are the present focus. This is a required intermediate step toward higher fields and accelerator quality magnets