

Overview of EU efforts towards HTS accelerator magnets

Amalia Ballarino, CERN

CERN, CEA, INFN, KIT, PSI, SPIN, Un. of Geneva, Un. of Twente,
Un. of Southampton, Un. of Vienna

CCA2025

International Workshop on Coated Conductors for Applications

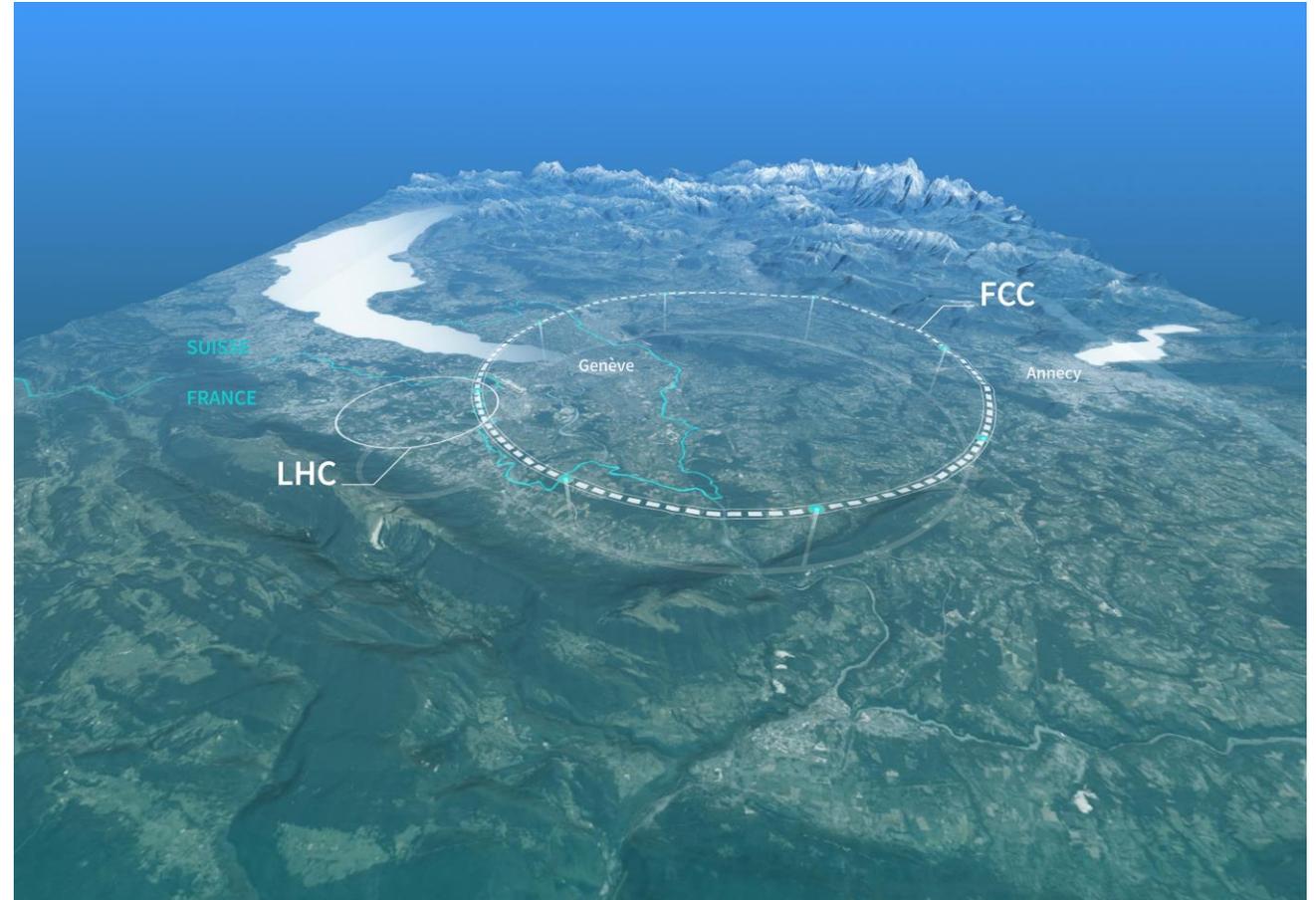
CERN | March 11-13, 2025

HTS in Future Accelerators

FCC hh baseline

FCC-hh parameters	CDR 2019	2024- Nb ₃ Sn	2024- HTS
Dipole field (T)	16.0	14.0	14-20
Temperature (K)	1.9	1.9	4.5-20
Tunnel length (km)	100	90.7	90.7
Arc length (km)	82.0	76.9	76.9
Arc filling factor (adim)	0.80	0.83	0.83
Energy c.o.m (TeV)	100	85	85-120
Non Cu jc 16 T 4.2 K	1500	1200	TBD
Loadline margin	86%	80%	TBD

E. Todesco, CERN



Maturity of technology (and cost) will drive the choice

HTS for Future Accelerators

Requirements and Challenges for high field magnets

- **High Field (14 T- 20 T)** - beyond the reach of Nb₃Sn
 - High forces
- **Field quality** in the different operating phase of the accelerator
 - Magnetization is a challenge (losses and field quality)
- **High current cables** (Rutherford cable is not an option for REBCO) - with **high Je** ($\geq \sim 600 \text{ A/mm}^2$ at the operational temperature and field)
 - Protection
 - The missing REBCO “accelerator quality” cable is today preventing progress on HTS magnets
- **Novel magnet concepts** (costheta vs other geometries)

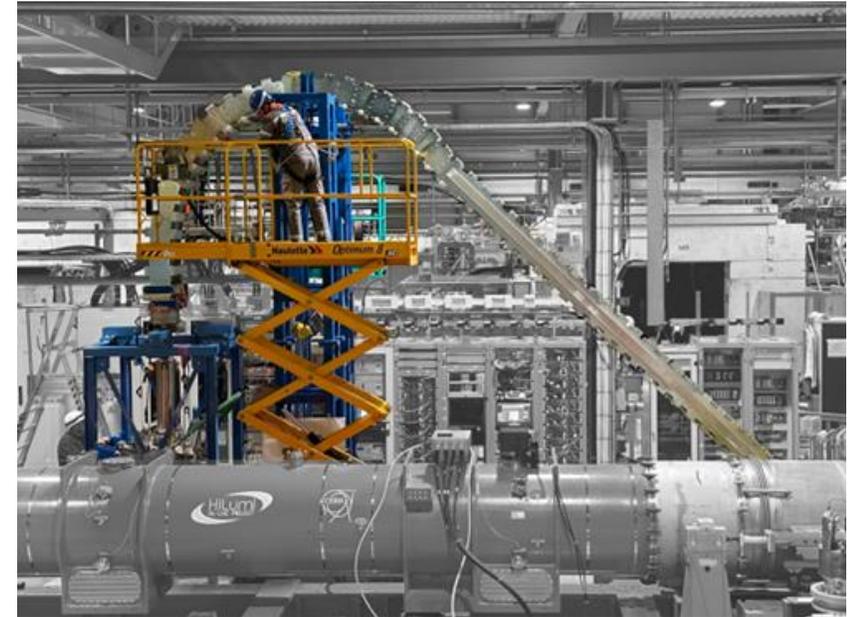
Sustainability and environmental impact

- Operation at **higher temperature** ($\sim 20 \text{ K}$ vs 1.9 K or 4.2 K for Nb-Ti and Nb₃Sn)
 - if affordable

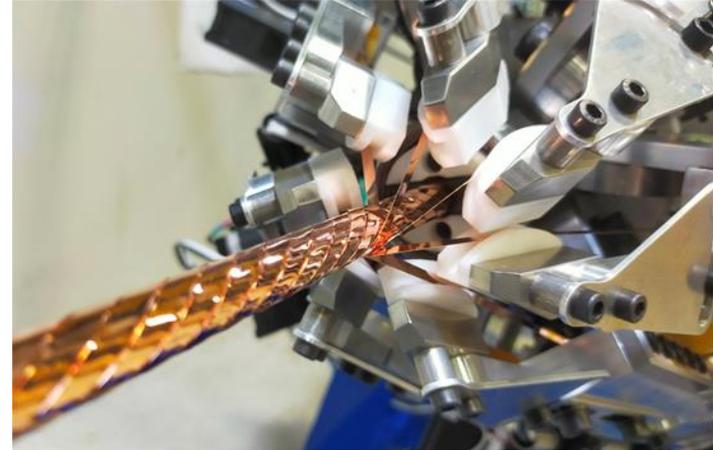
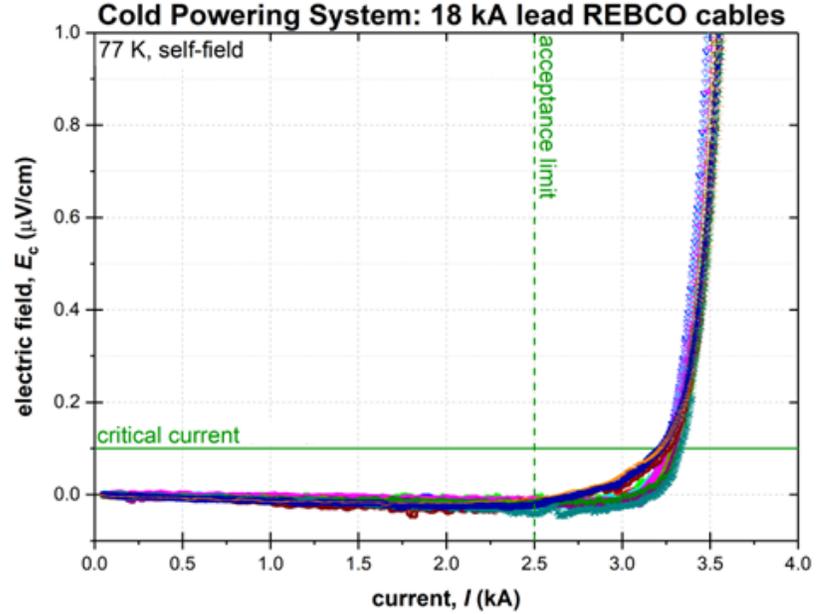
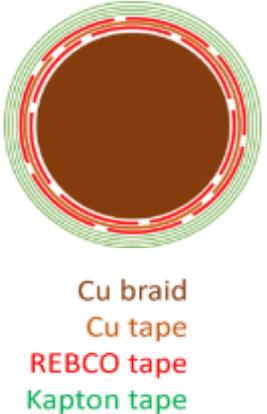
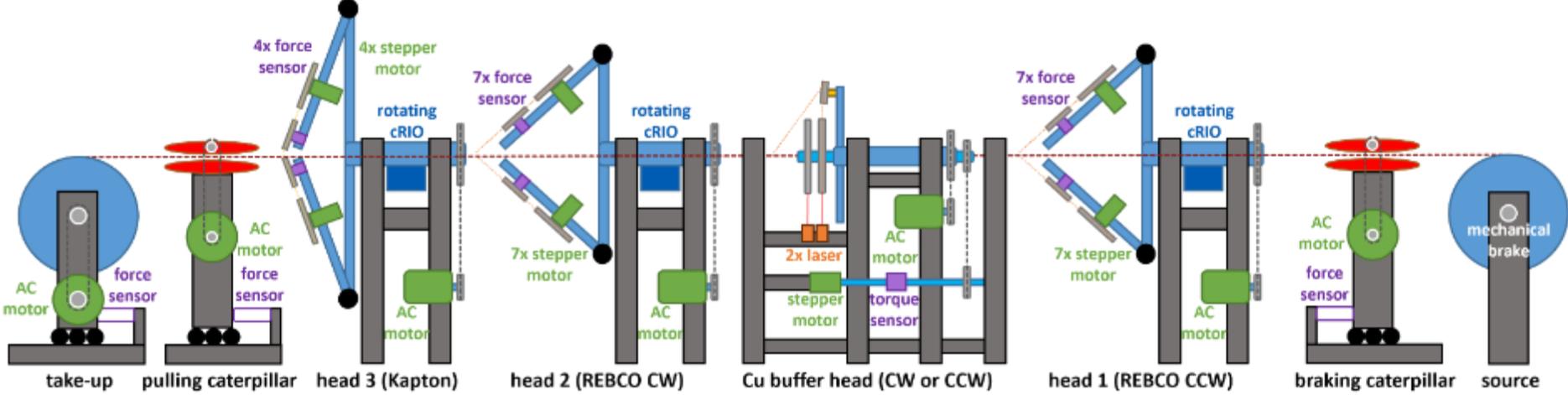
EU Effort is on REBCO

HTS in the Large Hadron Collider

- **LHC HTS Current Leads** (> 1000 units, altogether ~ 3 MA)
 - Stacks of **BSCCO 2223** tapes with **Ag/Au** matrix, soldered and coated. Operational in the LHC since its start in 2008
- **HL-LHC Superconducting Links** (~ 100 m long, up to 120 kA)
 - **MgB₂** (1500 km, up to ~ 20 K) and **REBCO** (from 20 K to ~ 60 K in helium gas) in the form of round cables. Development of cables and associated technology, e.g. high current (18 kA) REBCO electrical joints
 - First system successfully qualified in Q2 2024



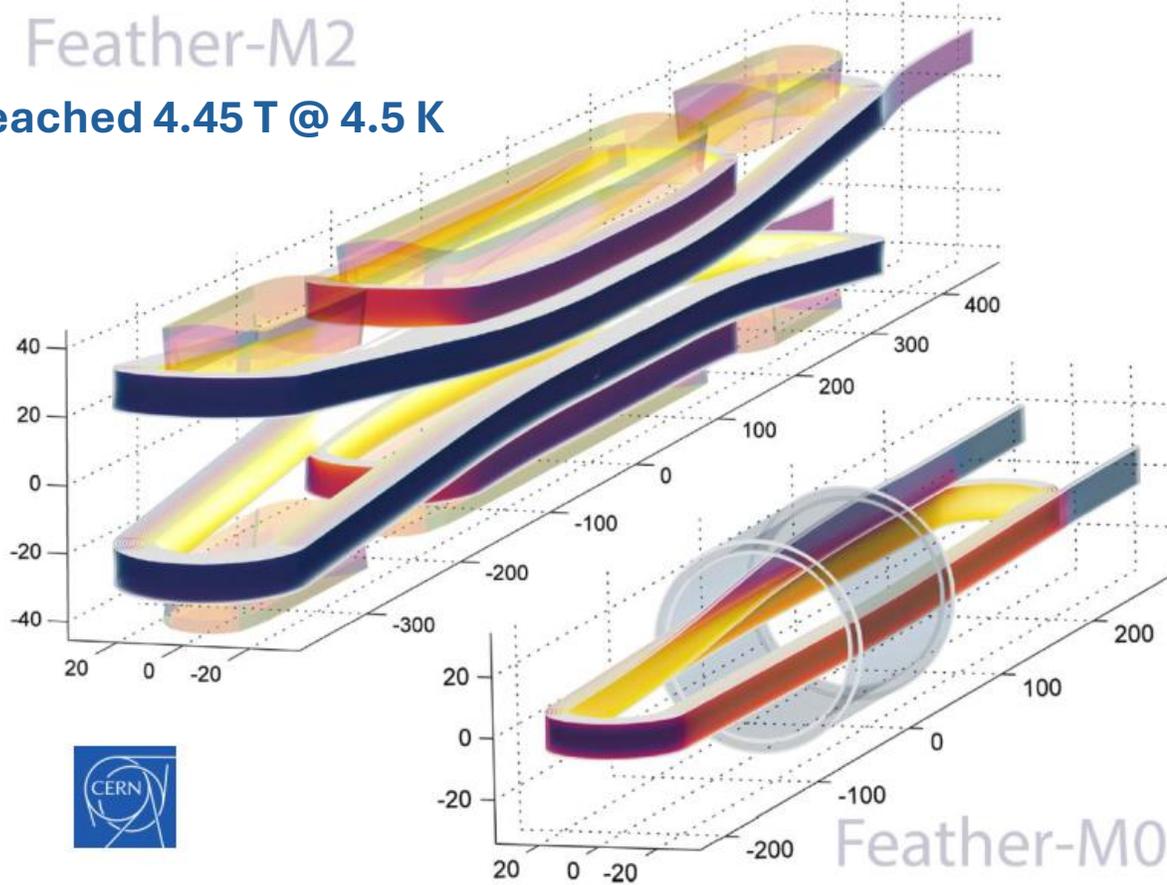
REBCO Round Cables and Cabling Machine at CERN



See presentation by Christian Barth

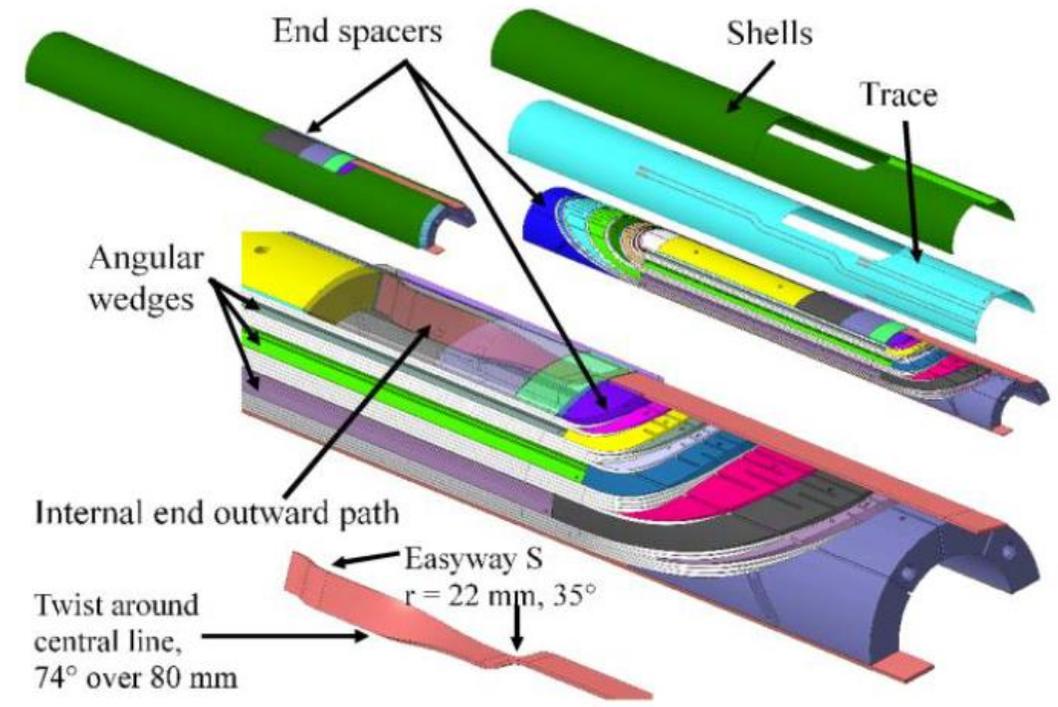
Past Developments – Eucard 2

Feather-M2
Reached 4.45 T @ 4.5 K



Feather-M0

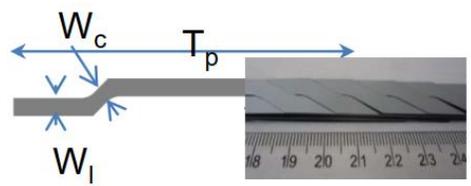
Cos- θ dipole Reached ~ 1.5 T @ 4.5 K



M. Durante et al, IEEE, DOI: 10.1109/TASC.2020.2978788

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



Roebel cables



W. Goldacker, A. Kario et al

HFM steering board

M. Lamont (chair)
P. Vedrine (co-chair)

High Field Magnet Programme

E. Todesco (Leader), B. Auchmann (Co-leader)

HFM collaboration board

C. Senatore (chair)
TBD (deputy)

Programme office

G. Riddone

RD1: Nb₃Sn conductor

1.1 Nb₃Sn wire and cable
T. Boutboul (CERN)

1.3 Internal oxidation wires
C. Senatore (UniGe)

1.15 Nb₃Sn development
M. Sugano (KEK)

1.18 Internal oxid. studies
A. Leineweber (BAF)

1.19 Nb₃Sn characterization
C. Senatore (UniGe)

RD1 line coordinators:
T. Boutboul (CERN)
C. Senatore (UniGe)

February 2025

RD2: HTS conductor+magnets

2.1 REBCO development
B. Holzapfel (KIT)

2.2 REBCO conductor
A. Ballarino (CERN)

2.5 Demonstrator DI coils
A. Baskys (CERN)

2.6 Solenoids and MuC
L. Bottura (CERN)

2.11 Demonstrator MI coil
T. Lecrevisse (CEA)

2.15 IBS development
A. Malagoli (CNR-SPIN)

2.16 HTS laboratory
C. Barth (CERN)

2.17 REBCO development
Y. Yang (SOTON)

2.18 HTS 10 T dipole
M. Statera (INFN)

2.19 REBCO racetrack
D. M. Araujo (PSI)

2.20 REBCO characteriz.
M. Eisterer (TUWien)

RD2 coord: A. Ballarino (CERN)

RD3: Nb₃Sn magnets

3.1 12 T cos θ CERN
A. Foussat (CERN)

3.2 12 T cos θ INFN
S. Farinon (INFN)

3.3 5-m-long block
J. Ferradas Troitino (CERN)

3.4 Technology development
A. Haziot (CERN)

3.5 14 T Block dipole BOND
J. C. Perez (CERN)

3.6, 3.12 Block dipole F2D2
E. Rochepault (CEA)

3.7 Common coil DAISY
F. Toral (CIEMAT)

3.11 14 T Cos θ
M. Sorbi (INFN)

3.14 CC stress managed
D. M. Araujo (PSI)

RD3 line coordinators:
F. Toral (CIEMAT)
A. Haziot, A. Foussat (CERN)

RD4: Integration, sustainability

4.3 Insulation and HV
R. Piccin (CERN)

4.5 Quench D+P
M. Wozniak (CERN)

4.6 Cryogenics, thermal
P. Borges de Sousa (CERN)

RD4 line coordinator:
P. Borges de Sousa (CERN)

6.1 Societal impact
E. Chesta (CERN)

RD5: Infrastructures

5.1 Test
F. Mangiarotti (CERN)

5.2 Conductors, cables
J. Fleiter (CERN)

5.4 Manufacturing
J. Axensalva (CERN)

5.5 MM, modelling
L. Fiscarelli (CERN)

5.7 CIEMAT lab
C. Martins (CIEMAT)

Collaboration WPs

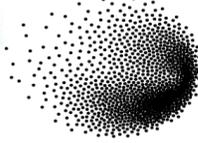
CERN WPs

Note: completed WPs
and WP2.9 not shown

HFM HTS – A European Effort

9 Contributors

Magnets



Superconductors



Measurement of Superconductors/Studies

UNIVERSITY OF TWENTE.



UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES



TECHNISCHE UNIVERSITÄT WIEN

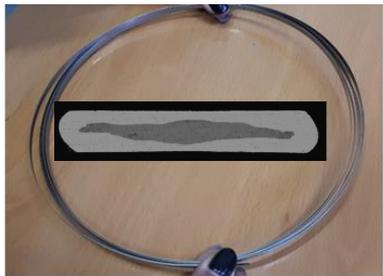
Topics on Accelerator Magnets Being Addressed

- **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 small coils
- **CERN**: Electrically Insulated Coils and REBCO cables (others than stacks)
- **INFN**: REBCO coils

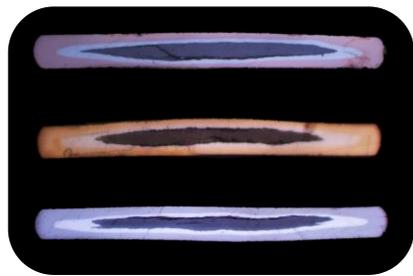
Being launched

Iron Based Superconductors - SPIN

- **SppC** (China): **IBS** baseline for **20 T**
- **IBS Laboratory at SPIN**, Genova, to investigate potentials of IBS for high field magnets (A. Malagoli et al)
 - **Ba122** ($B_{c2} \sim 70 \text{ T}$ @ 20 K , $T_c \sim 38 \text{ K}$)
 - **Goal**: multi-filamentary **Powder In Tube (PIT) Ba-122 round wire**
 - Investigation of wire layouts enabling **React & Wind** technology
 - **Target J_c** : 10^5 A/cm^2 @ 4.5 K and 16 T , 10^4 A/cm^2 @ 20 K and 10 T
 - **Powder developed** (focus of the first year of activity)
 - **First multi-filamentary wires produced**. Use of new sheets for higher densification and texturing



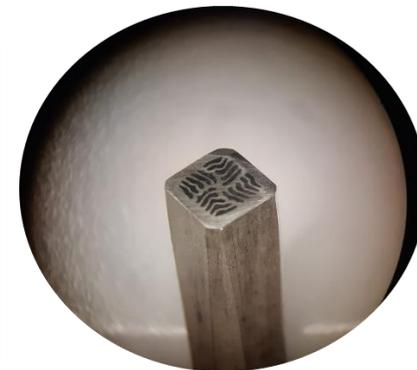
10 m mono-filamentary



500 μm

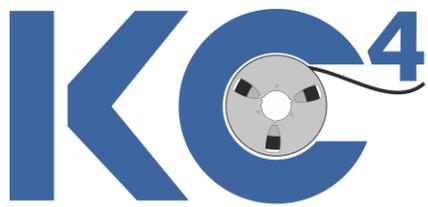


10 m multi-filamentary



Innovative multi-filamentary architecture





KIT-CERN Collaboration on CC

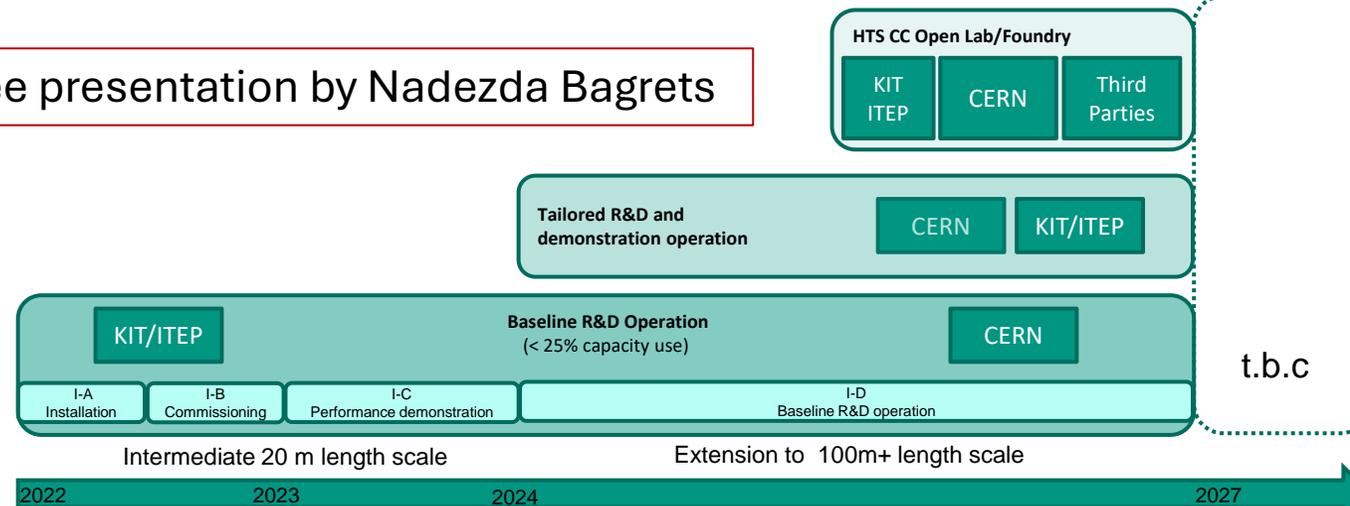
REBCO Tape - KIT

KIT-CERN Collaboration on Coated Conductors

- **Laboratory** bridging the gap between basic materials research and large-scale production in industry
- 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**

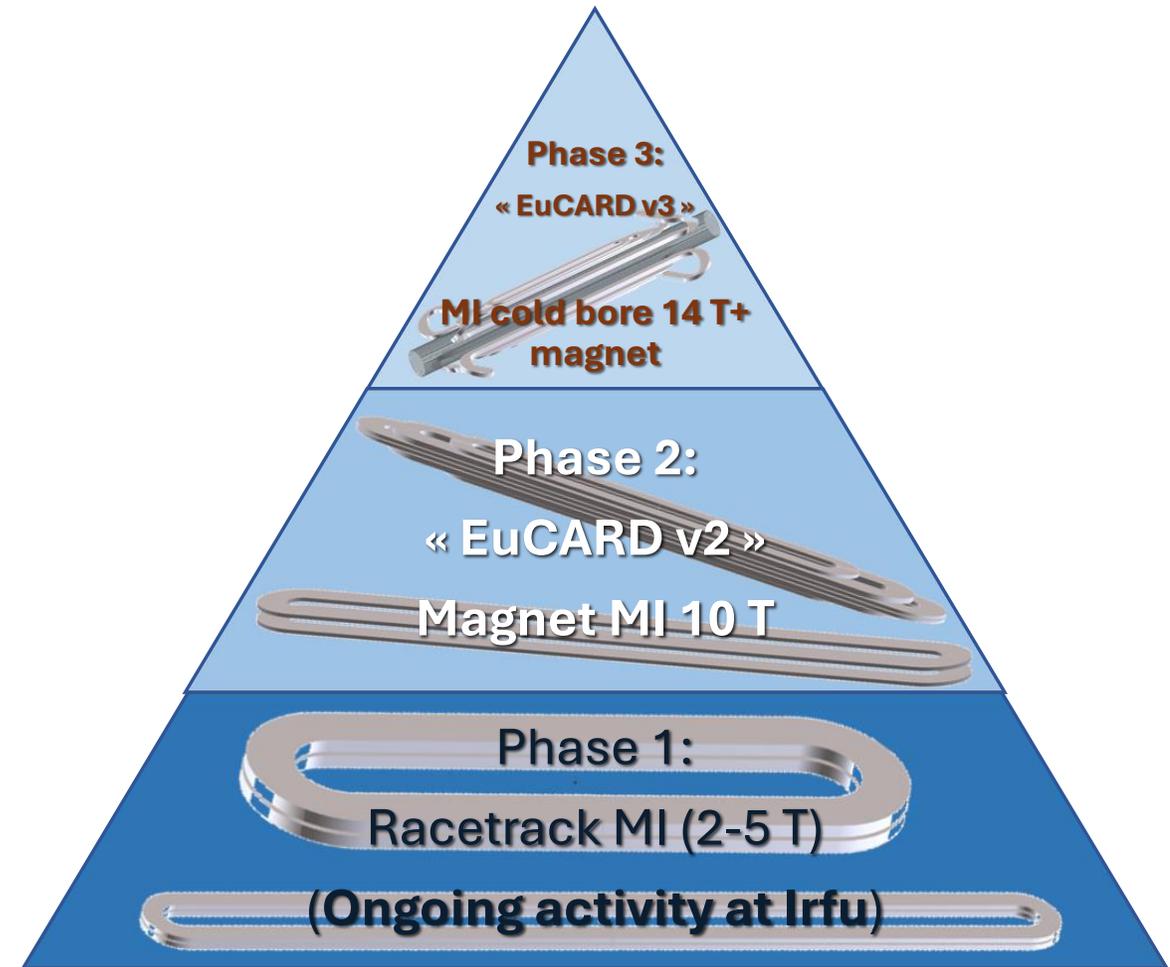


See presentation by Nadezda Bagrets



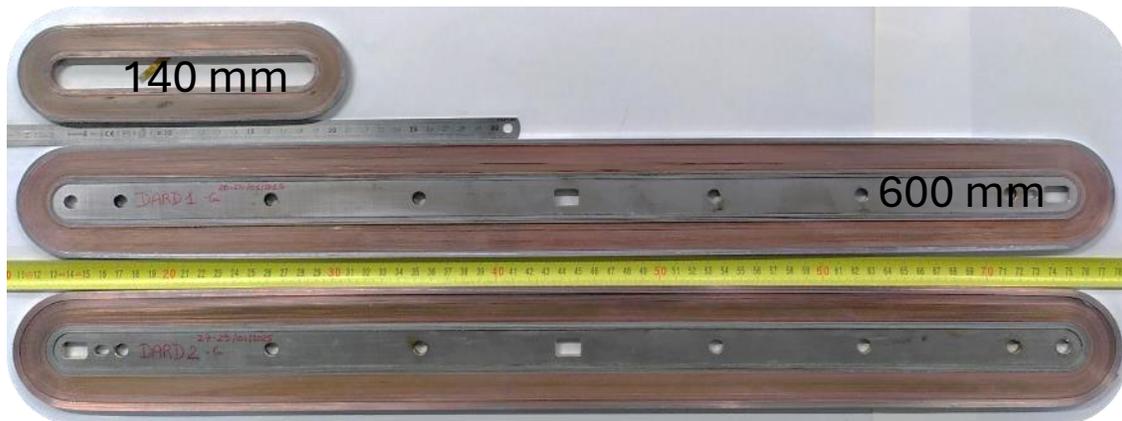
CEA – Development Strategy

- **Metal Insulation Technology** for accelerator dipoles initially validated on racetrack coils. **Metal insulation** to ease quench protection aspects
- Winding of **single REBCO tape, metal insulated**, in a **racetrack** configuration **on-going**. HTS REBCO tape, 4 mm width, procured by CERN. Goal (**Phase 1**): **2 T - 5 T @ 4.2 K in 2025**
- If R&D successful, **as from 2026** efforts will be on ~ **10 T metal insulated block-coil dipole (Phase 2)** with no aperture and no flared ends (~ 0.9 m length)
- Phase 2 to be followed by **14 T+ metal insulated block coil dipole (Phase 3)** with aperture and no flare ends (~ 0.9 m length)

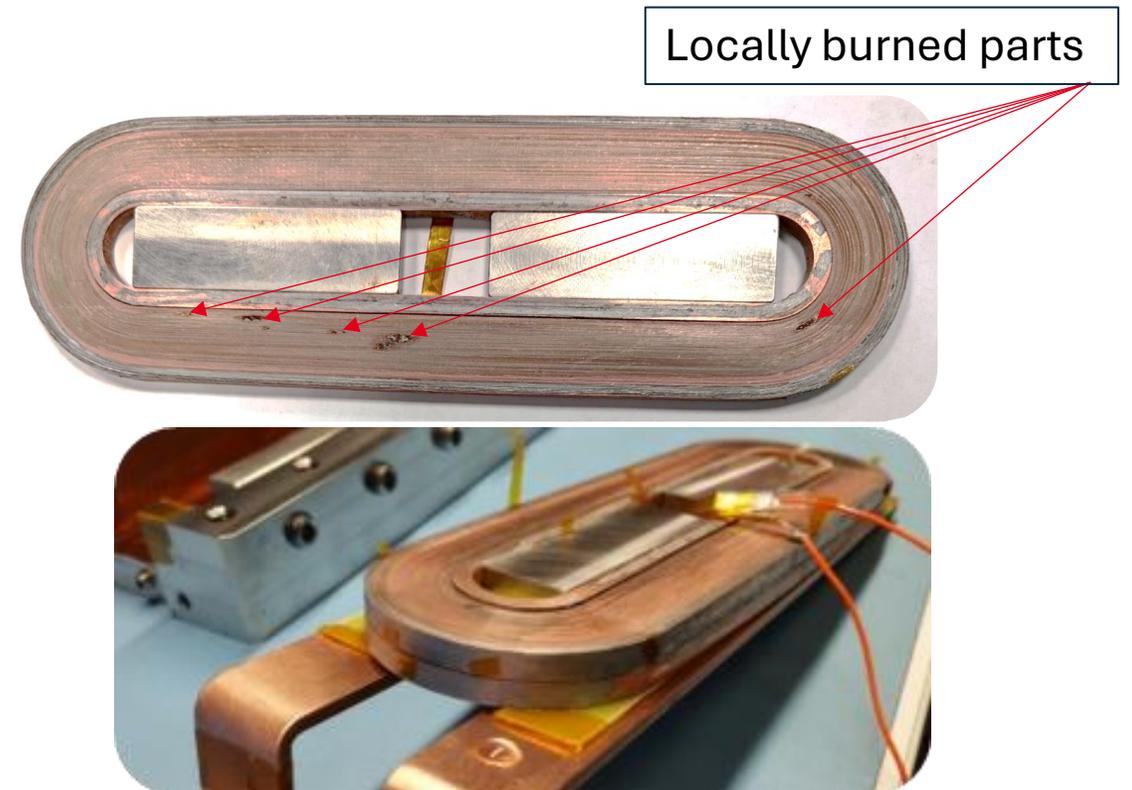


CEA – Recent Achievements

- **Phase 1:** Single and double racetracks wound with single SST tape (4 mm width). Racetrack **length:** 140 mm and 600 mm
- **Metal Insulation:** co-winding of REBCO tape with 30 μm thick Durnomag[®] tape
- **I_{op}** = 670 A @ 4.2 K ($\sim 1600 \text{ A/mm}^2$)
- **B_{center}** = 3.6 T, **B_{peak}** = 8.2 T @ 4.2 K

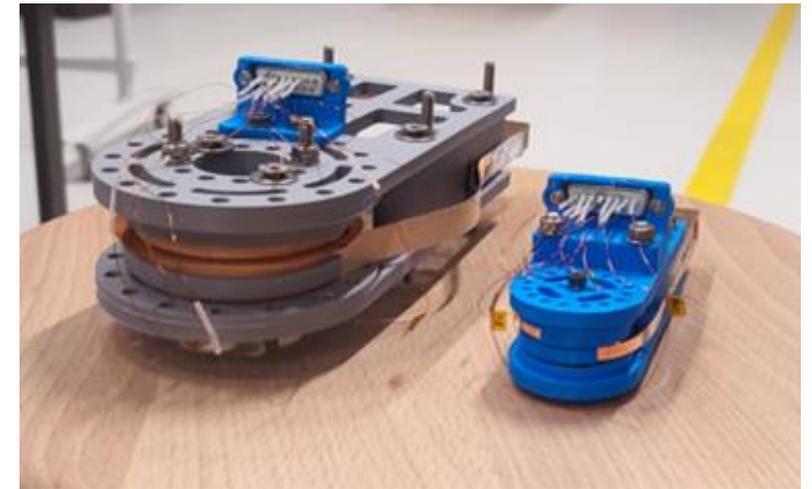
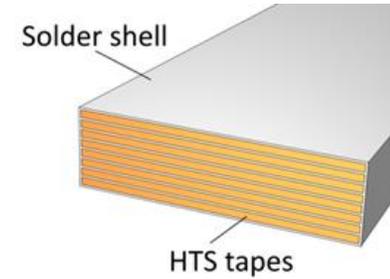


- Reached **2.7 T @ 4.2 K** (140 mm long double racetrack). 2 \times 55 m of tape
- Observed local degradation in the tape after 8 quenches (analysis on-going at CEA)



PSI/Chart

- **Electrically insulated stacks of soldered REBCO tape.** Soldering during winding to ease quench protection. Specific equipment designed and assembled
- **On-going:**
 - Modelling of AC losses
 - Development of **BabyHTS coils** used for AC loss model validation. Double **pancakes** with outer diameter of 30 mm, 40 mm and 70 mm. Measurement of AC losses at the University of Twente
 - Manufacturing of **racetracks (6-8 T on conductor)**
 - Study of **REBCO Block Coil dipole** - scaling with temperature (5 K – 30 K)

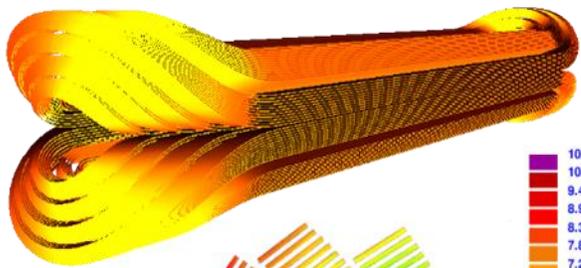


INFN

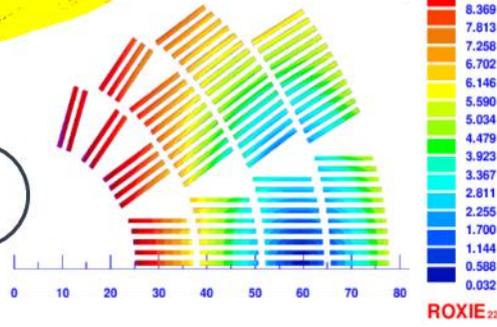
10 T dipole demonstrator (operated at 20 K) – 50 mm aperture

Conceptual studies

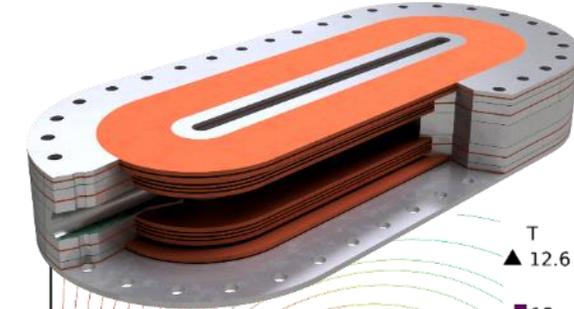
Common	B centre	Aperture diameter ¹	T _{op}	Straight section	Tape quality ²	Max. Unit Length	Target J _{Cu}
	10 T	50 mm	20 K	700 mm	FFJ 2021	200 m	800 A/mm ²



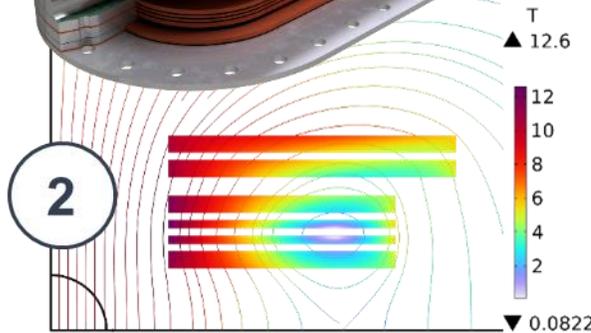
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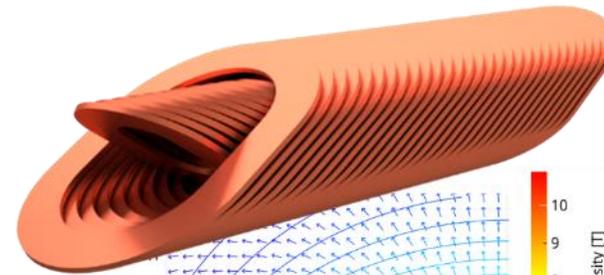
Cos-Theta



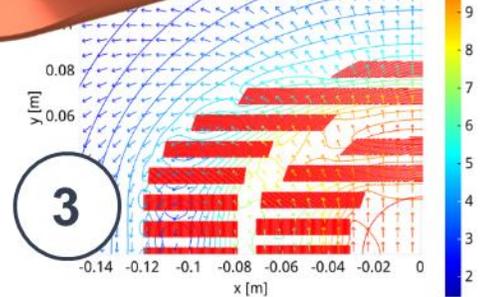
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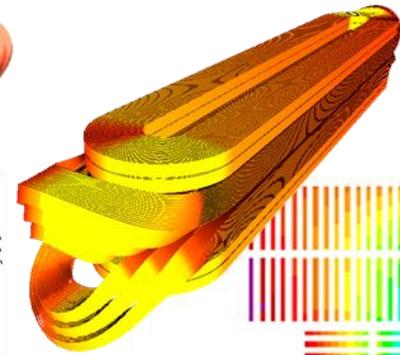
Racetrack



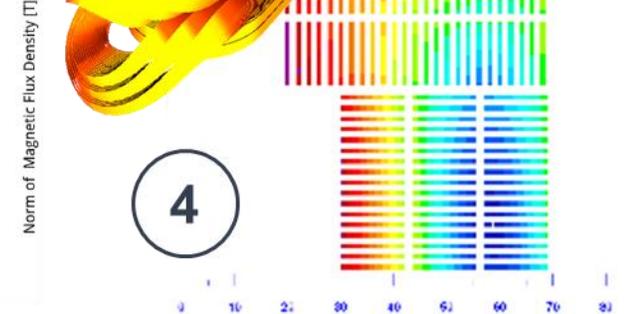
3



Pancake CCT



4



Hybrid

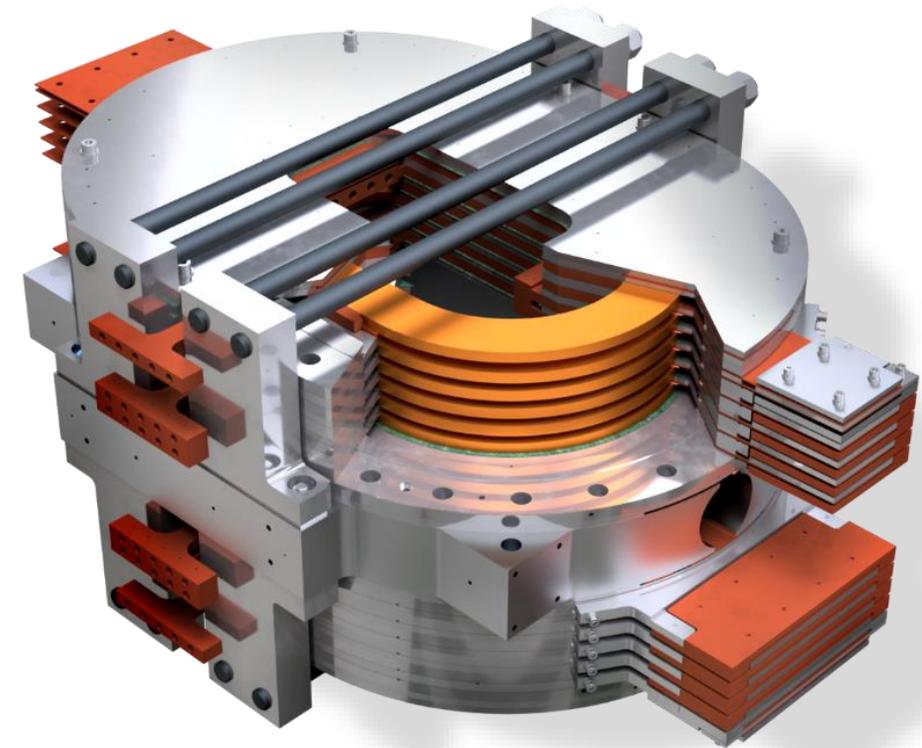
IRIS Energy Saving MAgnet (ESMA) open gap dipole test facility - Italy

- Test of operation with *cryogen-free technology*
- Test of *non-insulation technol.:* charge in 3 h (48 W)
- Flat racetracks, *12 mm REBCO tape, 15 km, FFJ*
- **Installed in INFN-Genoa SC lab at beginning 2026**

Design main choices:
INFN-LASA & Univ. Milan



Engineering design and
construction: **ASG, Genova**



Central field B0 (min. accept.)	tesla	10 (8)
Free aperture (coil gap)	mm	∅70 (100)
Good field region uniformity	N/A	±1.5%
Good field region	mm	H50xV30xL350
Operating temperature	K	20
Temperature margin at 10 T	K	> 10

CERN – REBCO Tape

- Procured ~ **33 km of REBCO tape** (2 mm, 4 mm and 12 mm width). **Four manufacturers:** SST, Furukawa, Faraday Factory, Fujikura. **Different widths** (2 mm, 4 mm and 12 mm), **different Cu thicknesses, w/wo coating** – good sampling of current industrial capabilities. Full delivery over a period of 7 months

- **Technical specification**

I_c (A/cm-width) \geq 800 A (4.2 K, 20 T)

$J_e \geq 1500$ A/mm² (4.2 K, 20 T)

I_c (A/cm-width) \geq 375 A (20 K, 20 T)

$J_e \geq 700$ A/mm² (20 K, 20 T)

Unit Length \geq 100 m (Target \geq 200 m)

RB \leq 20 mm (Target \leq 10 mm)

Rlayers \leq 100 n Ω ·cm²



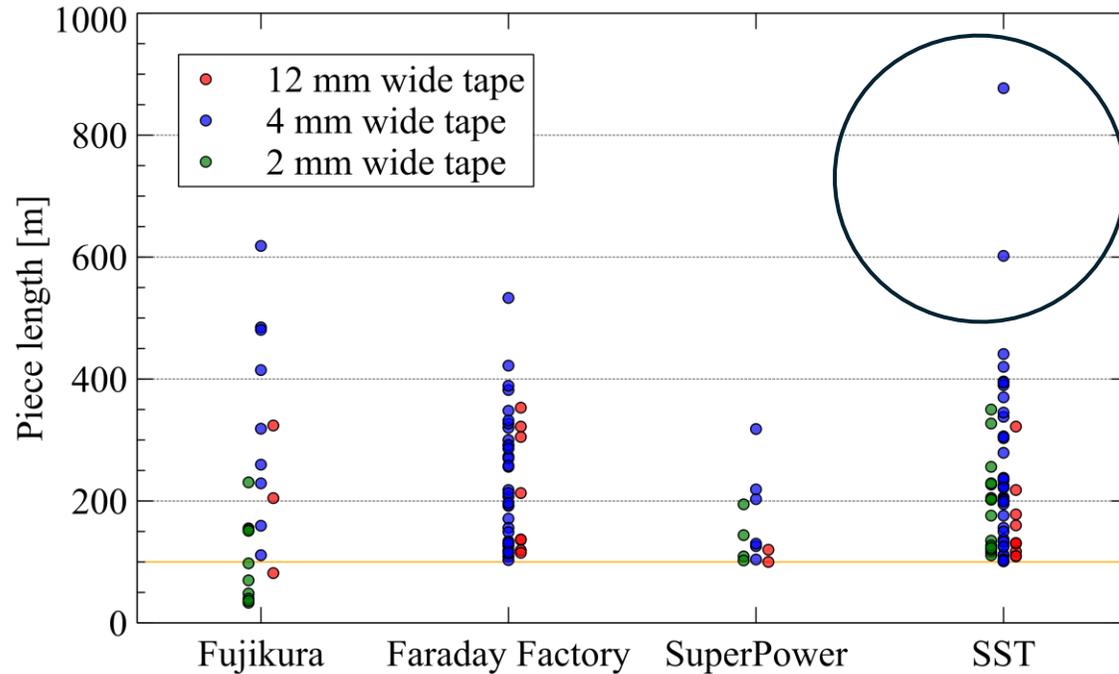
- **Cost (Euro/m) reduced by a factor of ~ 3** in the last couple of years



REBCO conductor procured from multiple suppliers

CERN – REBCO Tape

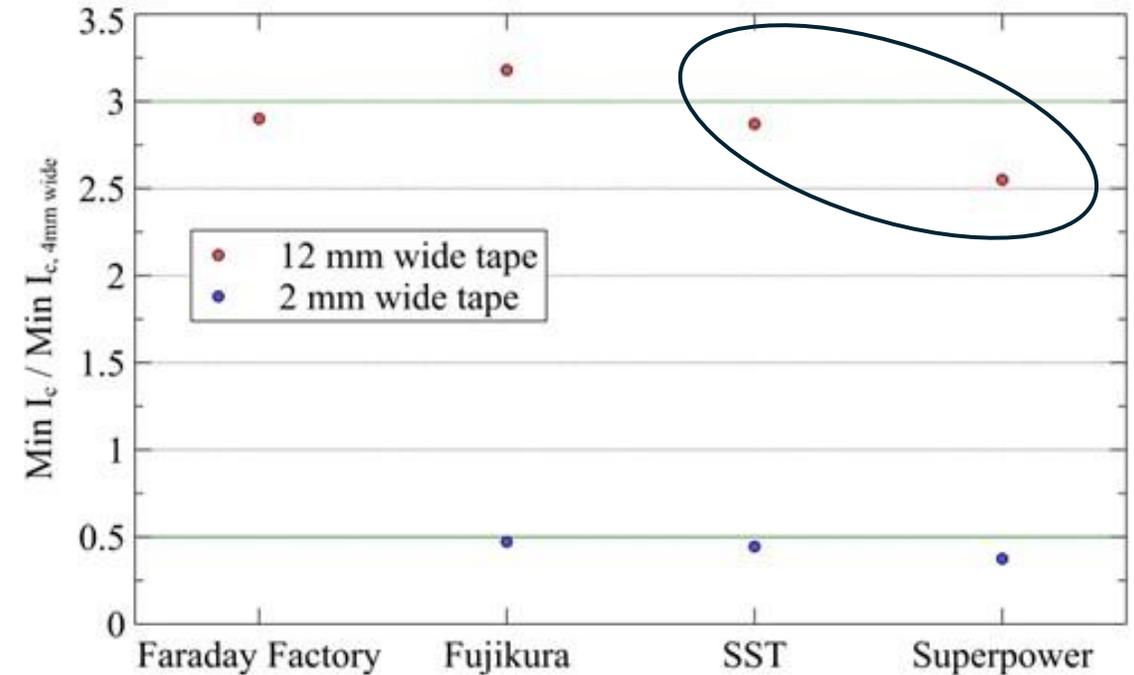
Piece lengths delivered for different tape widths



12 mm width: UL < 400 m

4 mm width: UL from 10 m up to ~ 850 m

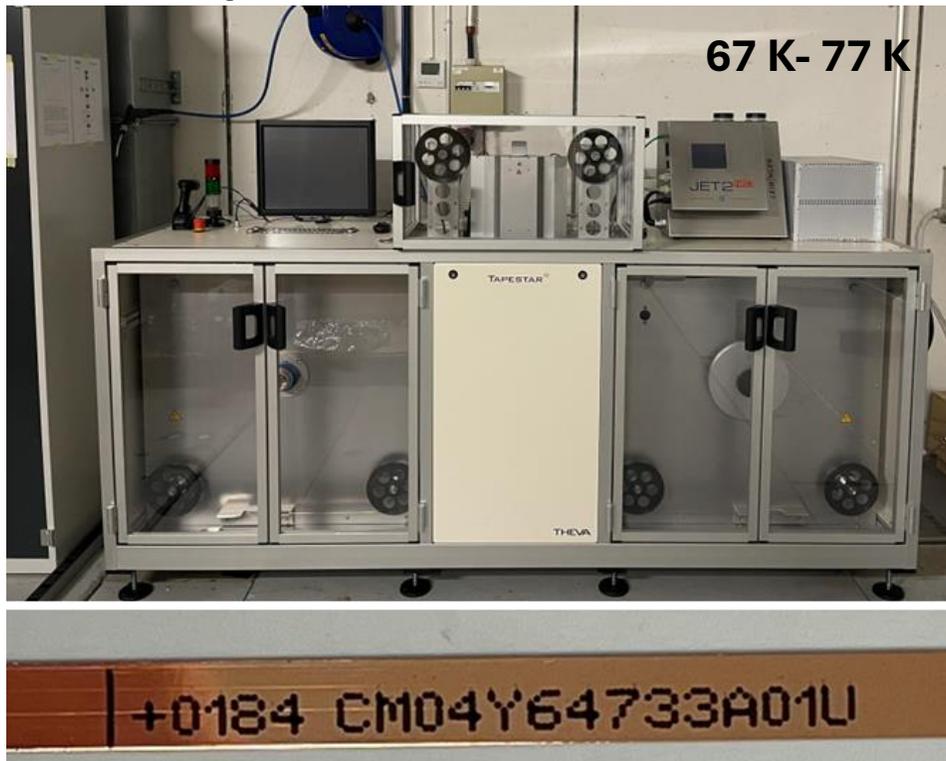
Scaling of I_c based on width



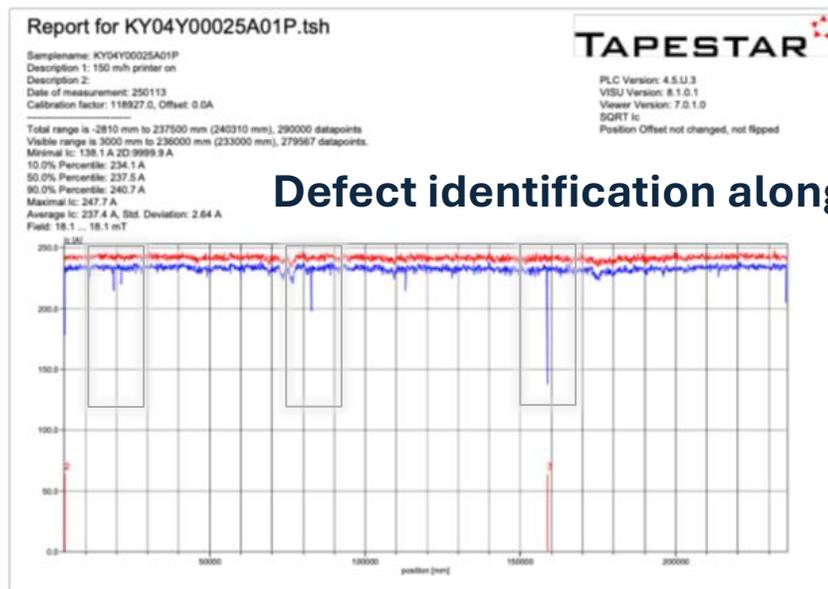
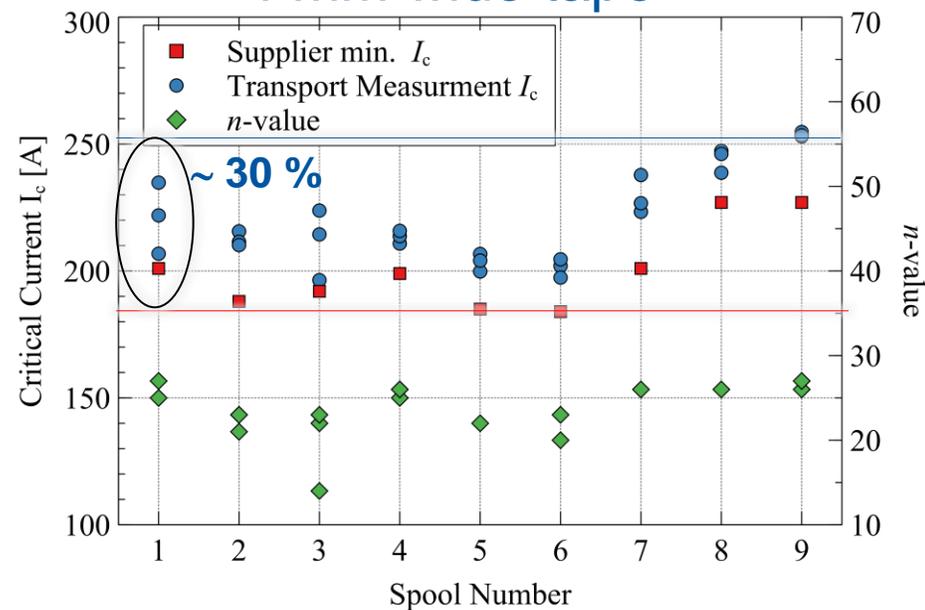
Deviation for 12 mm wide tape

CERN – REBCO Tape

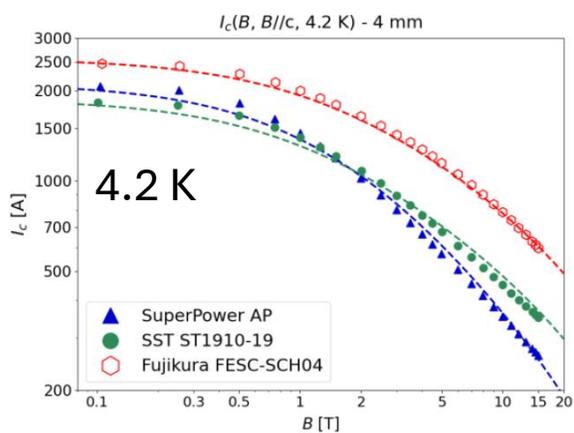
TAPESTAR™ operational at CERN since Q4 2024



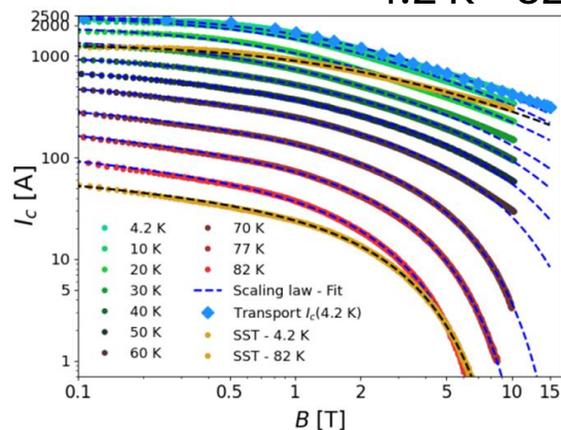
4 mm wide tape



Defect identification along tape length



4.2 K – 82 K



CERN – From Racetracks to Common Coil

Presently use of stack cable.

Program used also for validating different cable geometries

~ **0.6 T** at 4.2 K

~ **3 T** at 4.2 K

Coils available.

Components being manufactured

~ **9 T** at 4.2 K

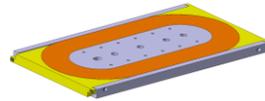
Design on-going

up to **15 T – 20 T** at 4.2 K

Qualification also at $T > 4.2$ K (10 K – 20 K)

Flat single
pancake coil

Flat double
pancake coil



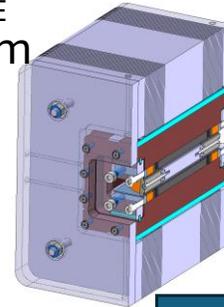
Flat double
pancake coils.
Grouped – 9 T

Flat double
pancake coils
Common coil – 5 T

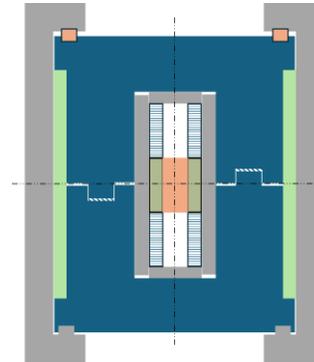
Flat double pancake coils.
Common coil (15 T – 20 T)



Φ_{BORE}
20 mm



Φ_{BORE}
50 mm



Cables with 4 mm wide and 12 mm wide tapes

12 mm wide tapes

Q2 2024

From Q3 2024

From Q3 2025

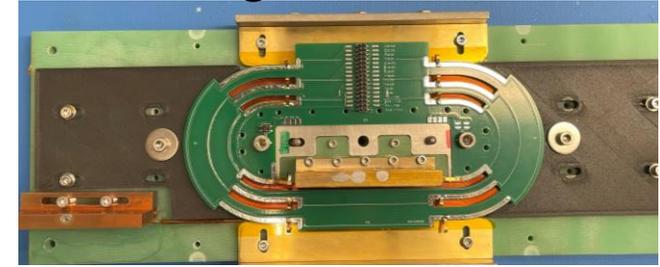
From Q1 2026

See presentation by Diego Perini

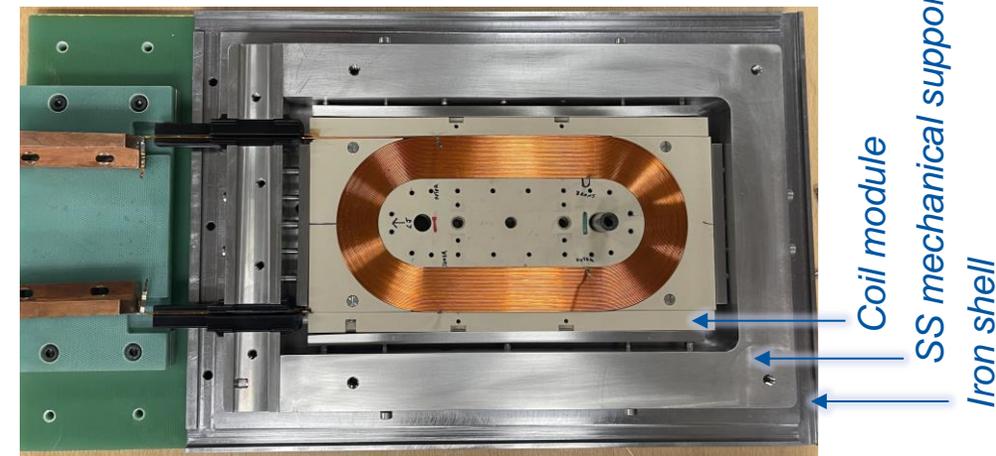
CERN Coils – Recent Achievements

- 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 design field: **2.7 T** in the central bore (**5.2 T** in the conductor)
- Working on **new concepts of REBCO flat transposed cables** for use in high field magnets

Single racetrack

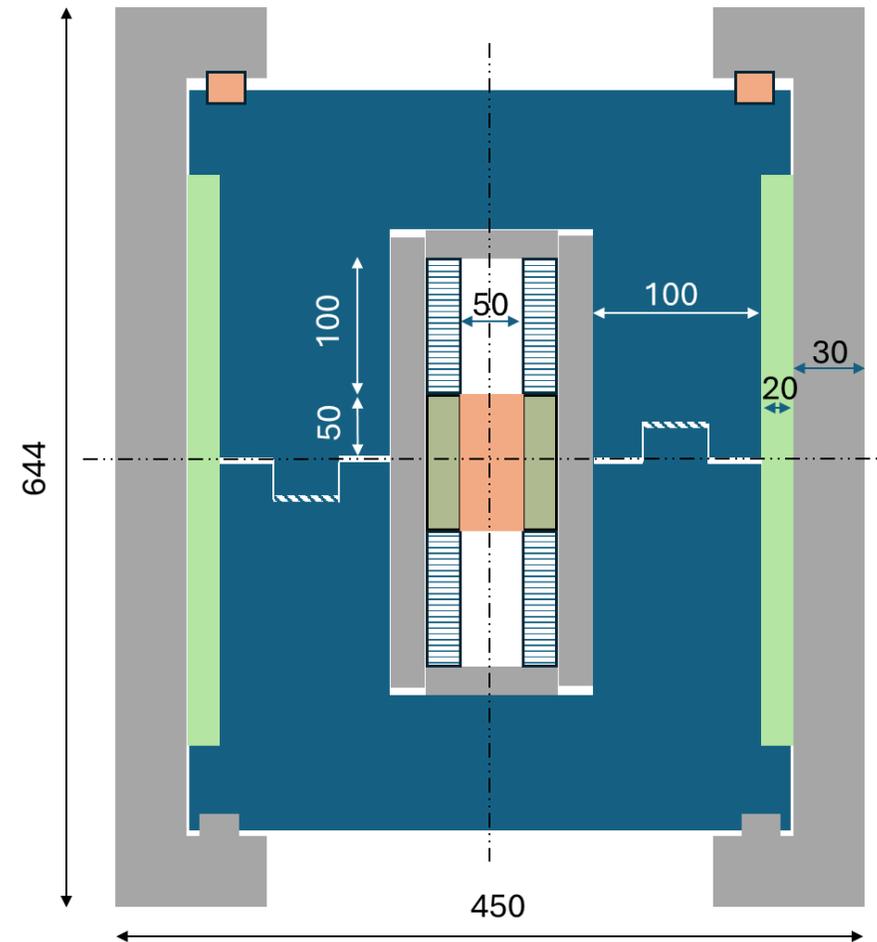


Double racetrack



CERN – Common Coil Dipole

- Development of double pancake made with stack cable made from **12 mm wide tape** started
- **Preliminary design of a 10 T, common coil double aperture, 50 mm aperture dipole** done. Final design by Q4 2025. Construction as from Q1 2026
- **Parametric studies of 15 T and 20 T configurations** (scaled from the 10 T design) in 2025



Preliminary mechanical design of
10 T Common Coil prototype

University of Southampton

AC losses in REBCO tapes and cables

Measurements and modelling of **new/special REBCO tapes** and **novel cable concepts**

- **Electromagnetic measurements at Southampton**

- Temperature range: 4K-85K
- AC fields up to 0.2T 2Hz-250Hz
- Sample length up to 100mm

- **Pulse field measurements at Southampton**

- Temperature range 4K-30K
- Single pulse 0.2T at dB/dt up to 20T/s
- Simultaneous electromagnetic and calorimetric
- Sample length up to 100mm (now) and 300mm (soon)

- **Modelling**

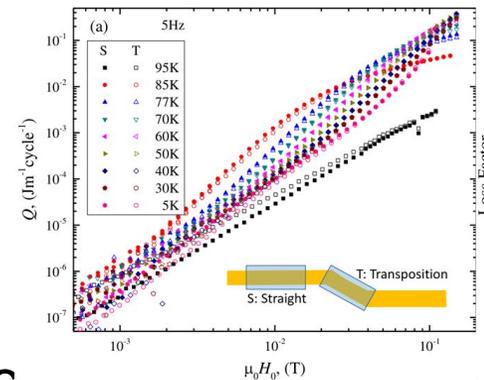
- Highly efficient custom codes for 3D effects of magnetisation and coupling
- Specifically tailored for assembled REBCO strands as thin strip
- Fast turnover for verifying new cable concepts

Small (insulated) REBCO pancakes and solenoids

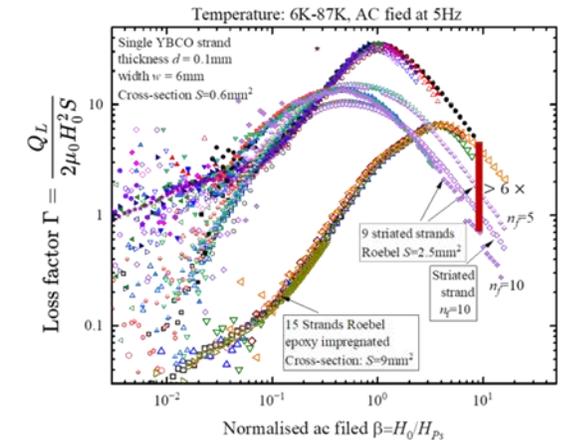
- Study of current distribution due to magnetisation effects
- Measurements of ac losses by integration methods
- As **5 T insert to extend transport $I_c(B)$ measurements of REBCO tapes to 20T**

AC losses of REBCO tapes at 4K-85K

Losses per unit length Q vs field H



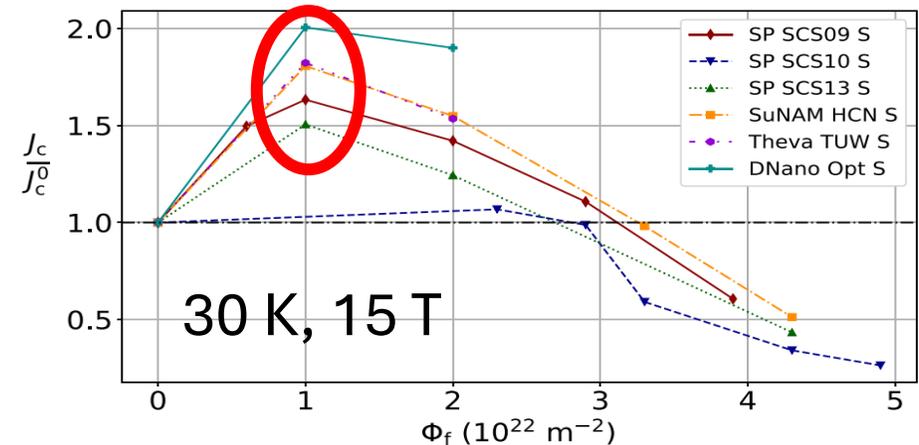
AC losses of Roebel cables standard and striated at 4K-85K



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?**

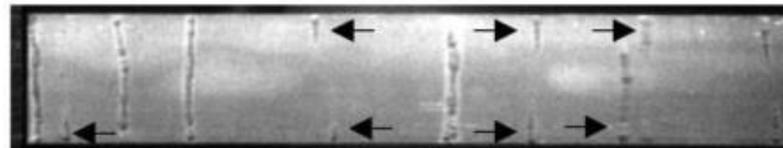
Increase by 50-100% due to irradiation



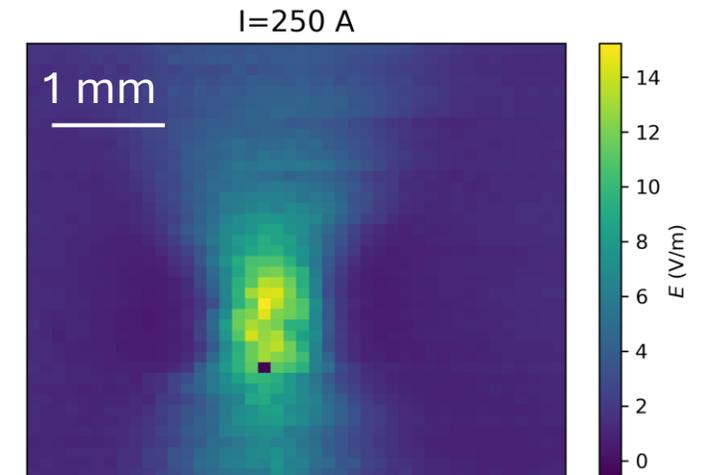
- **Better understanding of hot-spot formation at over-currents:**

- 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)



Local electric field around defect



HTS Magnets for Muon Colliders

Luca Bottura

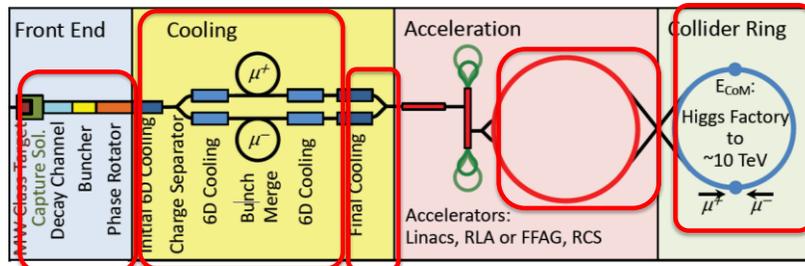
Complex	Magnet	Conductor	Aperture (mm)	Length (m)	Bore Field (T)/(T/m)	Stored energy (MJ)	Ramp-rate (T/s)	Heat load (W/m)	Radiation dose (MGy)	Temperature (K)	TRL range (-)
Target, decay and capture	Solenoid (HTS)	REBCO	1400	19	20	300	SS	2	80	20	5, 6
6D cooling	Solenoid (HTS)	REBCO	90...1500	0.08...0.5	2...14	100	SS			4.5...20	3, 4
Final cooling	Solenoid (HTS)	REBCO	50	0.5...1	> 40	10	SS			4.5	3, 4
Rapid cycling synchrotron	NC Dipole	Cu	30x100	5	± 1.8	0.05	500...4200	5		300	7, 8
	SC Dipole (HTS)	REBCO	30x100	1.5	10	10	SS	5		20	3, 4
Collider (3 TeV)	Dipole (NbTi)	Nb-Ti	160	4...6	5	5	SS	5	30	4.5	7, 8
	Dipole (Nb ₃ Sn)	Nb₃Sn	160	4...6	11	20	SS	5	30	4.5	6, 7
Collider (10 TeV)	Dipole (HTS)	REBCO	140	4...6	14	40	SS	5	30	20	3, 4
	IR Quadrupole (HTS)	REBCO	140	TBD	300	40	SS	5	30	4.5...20	3, 4

Target solenoids
Field: ~20T (15T) ... 2T
Bore: 1200 mm
Length: 18 m
Radiation heat: ≈ 4.1 kW
Radiation dose: 80 MGy

6D Cooling solenoids
Field: 4 T ... 19 T
Bore: 90 mm ... 600 mm
Length: 1 km (x 2)
Radiation heat: TBD
Radiation dose: TBD

Accelerator magnets
Field: ±1.8 T (NC), < 10 T (SC)
Rate: 400 Hz (NC), SS (SC)
Bore: 100 mm(H) x 30 mm(V)
Length: 3 m ... 5 m (x 1500)
Radiation heat: ≈ 3 W/m
Radiation dose: TBD

See presentation by Kathleen Amm



Final Cooling solenoids
Field: ≥30T (MAP), ≥40T (IMCC), ideally ≥50 T
Bore: 50 mm
Length: ≈ 500 mm (x 17)
Radiation heat: TBD
Radiation dose: TBD

Collider ring magnets
Field: 16 T peak (IR 20 T) – NOT a hard requirement! $\mathcal{L} \propto B_{dip}$
Bore: 150 mm
Length: 10 m ... 15 m (x 700)
Radiation heat load: ≈ 5 W/m
Radiation dose: ≈ 20...40 MGy

REBCO high field solenoids and dipole magnets: different objects, but many synergies

Conclusions

- In Europe work on **HTS high field accelerator magnets** is on **REBCO**
- **Focused R&D and innovation efforts** are required to establish the technology and fill the gap between HTS and LTS. On going activities address identified challenges via a coordinated effort
- Small **5 T -10 T REBCO coils** are the present focus - intermediate step toward higher fields and accelerator quality magnets
- A good contact with **REBCO tape manufacturers** is important for discussing findings, explaining needs and launching specific developments