HFM

High Field Magnets

HTS REBCO tapes, cables and associated technologies at CERN

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CERN

Outline

- Overview of 2023-2027 CERN HFM program
  - Strategy and activities

- Activities at CERN in 2023

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Overview of CERN activities REBCO tape

- **Procurement and characterization of REBCO conductor** for:
  - CERN Program
  - HFM Collaborators
- **First procurement,** launched in October 2023,based on **target specification**. Exploration of performance of state-of-the-art REBCO conductor produced by manufacturers with different technologies
- **Second procurement** by mid 2025
- Extensive **measurement campaign** and definition and implementation of QC
- **Upgrade of infrastructure** for characterization

Overview of CERN activities
REBCO Cables

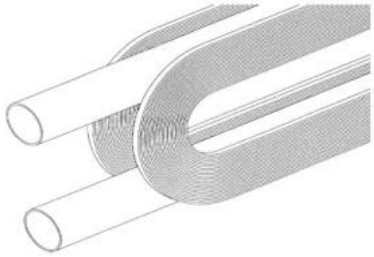
- **Development of REBCO cables**
  - Target: **10 kA @ 20 T** and up to ~ **10 K**
  - **Electrically insulated** cables
  - Novel cable **layouts** addressing **quench protection, field quality, mechanical robustness** and **windabilty** aspects
  - Having to move away from the Rutherford cable – and from multi-filamentary wire - is very challenging

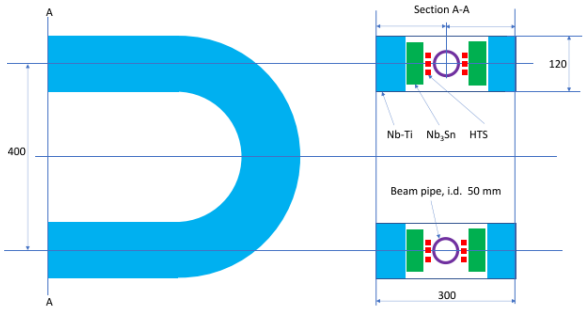
Overview of CERN activities REBCO Coils

- **Short Model Coil HTS Program** to test novel cables in a coil configuration: windibility, quench protection,
  - Target: **5 T - 8 T** at up to **10 K** in a **background field or 12 T-15 T**
- **Racetracks**
  - Full HTS
  - Hybrid (HTS in Nb_3Sn background field). Synergy with RD4 and with the extensive SMC Nb_3Sn program carried out at CERN
- Pancake **solenoids**

Overview of CERN activities Demonstrators

- **Dipole Common Coil**
  Racetrack coils measured in a Common Coil configuration. Advantages: **no out of plane bending** during the winding and **simple 2D end configuration** implementing large bending radii
  Target: **5 T** at up to **10 K** in a **background field of 15 T**





- **Solenoid** for use in our test stations (building 163) for the measurement of HTS conductor. **Target**: **> 20 T at 4.5 K**

Overview of CERN activities

- Close collaboration on **HTS conductor activities** at the collaborators' sites:
  - **REBCO Tape** development and production **at KIT**;
  - **Iron based PIT 122 round wire** development and production **at SPIN**

- Apply developed technology to **low-field HTS magnets** and **HTS sustainable technology** for future accelerators

Outline

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Procurement of REBCO Tape

- Launched in 2023 procurement of **28.5 km** of REBCO tape
- All orders will be placed before end 2023
- **Technical specification documents** incorporating QA requirements
  - HL-LHC and IFAST: project **required Jc** performance
  - HFM: **minimum Jc** performance

Project	Quantity	Width	Status
HL-LHC, Grade 1	11 km	4 mm	Tendering
HL-LHC, Grade 2	4 km	4 mm	Order placed
IFAST	2.5 km	4 mm	1 km delivered*
HFM CERN	11 km	2, 4 and 12 mm	Tendering

Series REBCO tape for HL-LHC Cold Powering

*Unit lengths of 113–378 m (mean 169 m)

Procurement of REBCO Tape

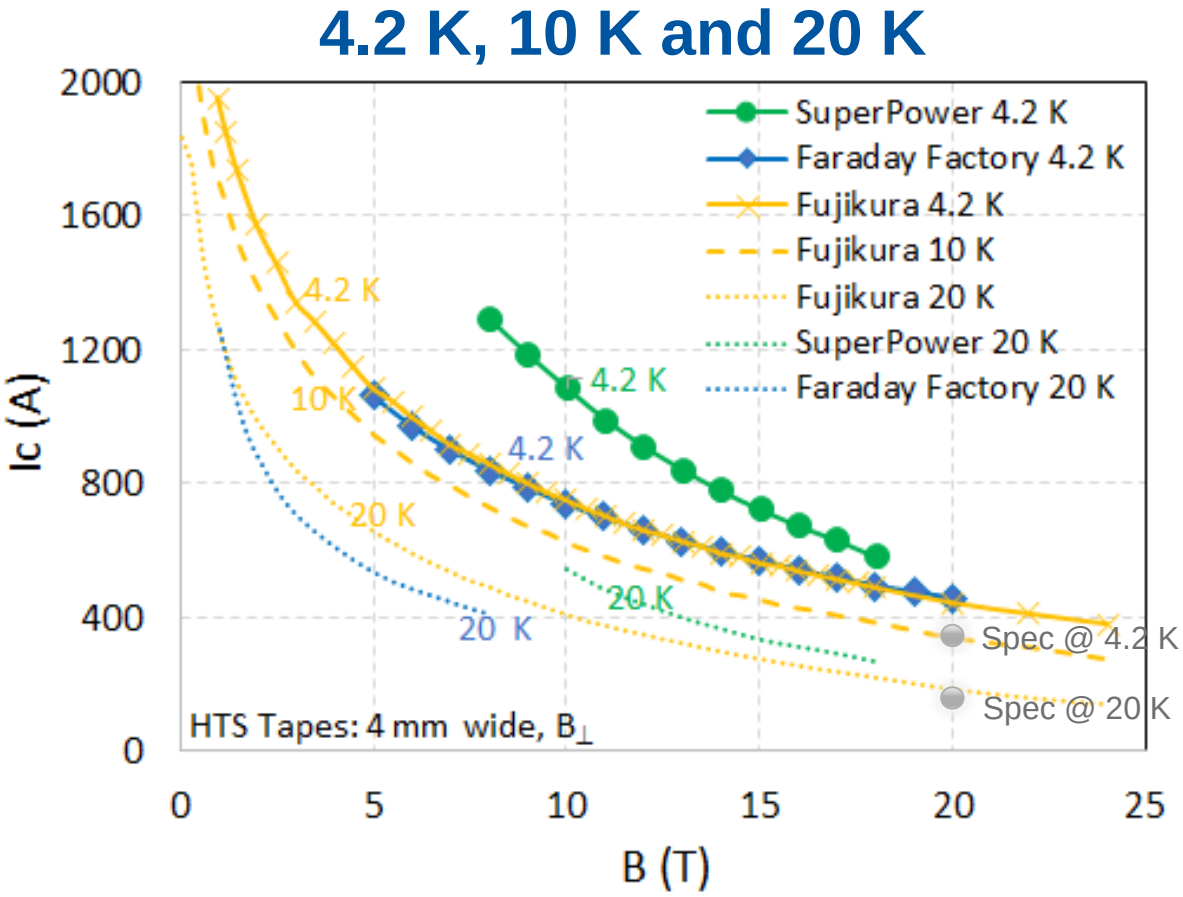
Specification – 4 mm wide tape

		T (K)	$B_\perp$ (T)	Ic (A)	UL (m)
High T, Low B	**HL-LHC Grade 1**	60	0.7	200	100
	HL-LHC Grade 2	60	0.7	200	100
Med T, Med B	**IFAST**	20 10	5 5	650 800	50 50
Low T, High B	**HFM CERN**	**4.2** **20**	**20** **20**	>320* >150**	100 100

* 800 A/cm

** 375 A/cm

Performance of REBCO Tape



Data presented by tape manufacturers at the HiTAT Workshop, CERN, March 2023

HFM Specification (4.2 K and 20 K)

REBCO Specification for HFM

Parameter	Minimum	Maximum	Target
Critical Current, I_c, per width (A/cm)			
at 4.2 K and 20 T	800	-	-
at 20 K and 20 T	375	-	-
Engineering Critical Current Density, J_e (A/mm^2)			
at 4.2 K and 20 T	-	-	≥ 1500
at 20 K and 20 T	-	-	≥ 700
Nominal substrate thickness (µm)	38	60	-
Nominal copper stabiliser thickness, each face (µm)	5	-	20
Minimum out-of-plane bend radius (mm)	-	20	≤ 10
Internal Resistance (nΩ cm^2)			
for a test duration of 0 h	-	100	≤ 60
for a test duration of 1 h	-	125	≤ 60
Piece Length (m)	100	-	≥ 200

Procurement of REBCO Tape

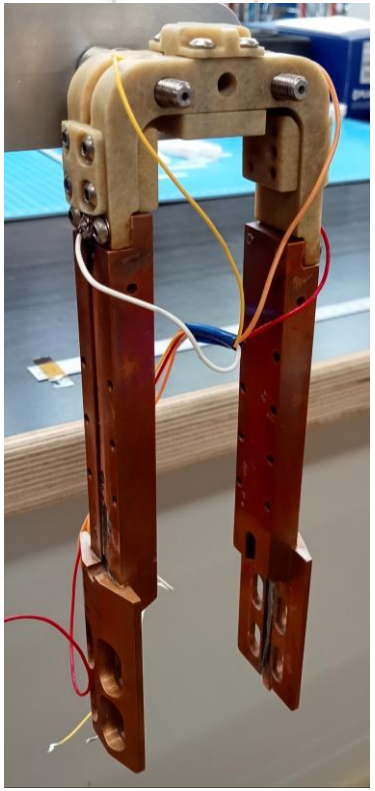
- Understand and quantify **performance of industrially available REBCO conductor.** Manufacturing process, tape layout, way of implementing artificial pinning change are specific to the manufacturer

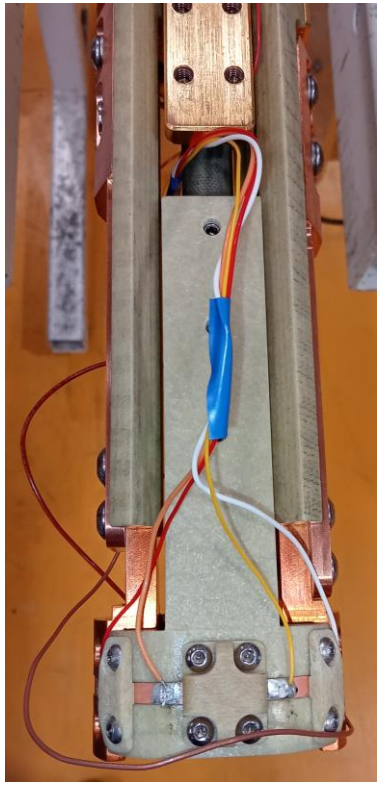
- Extensive **measurement campaign**. Data will be made available to the **community**. Synergy with activities at other laboratories

Procurement of REBCO Tape

- Discuss with **tape manufacturers problems** encountered and **specificity** of our requirements
  - Ex: identified, during R&D at CERN, **electrical resistance internal the tape** (EDMS N: 2366622) – either intrinsic to the tape and/or generated during temperature cycle (impregnation/splicing). Work then treated and confirmed at UNIGE. Now specific requirements implemented in technical specification document
- Discuss with **tape manufacturers pinning mechanism at different temperatures –** in the range 4.5 K to ~ 30 K (0 D pinning vs 1D and 3 D pinning, hybrid pinning). Possibly **optimize in-field performance** and **treat anisotropy**
  - Synergy with RD4 (operating temperature for FCC hh if GHe cooling and conductor temperature margin)
  - Synergy with activities at KIT

Measurements @ CERN





B⊥ U-Shape and **B*//*** sample holders
Up to ~ 2.6 kA, 15 T @ 4.2 K

Ic @ 77 K Self field

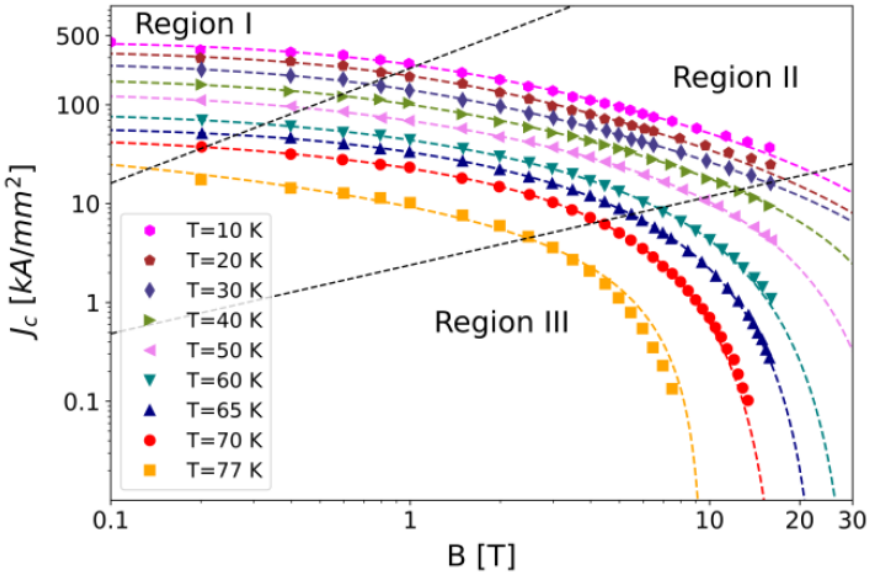
Scaling laws (1/2)

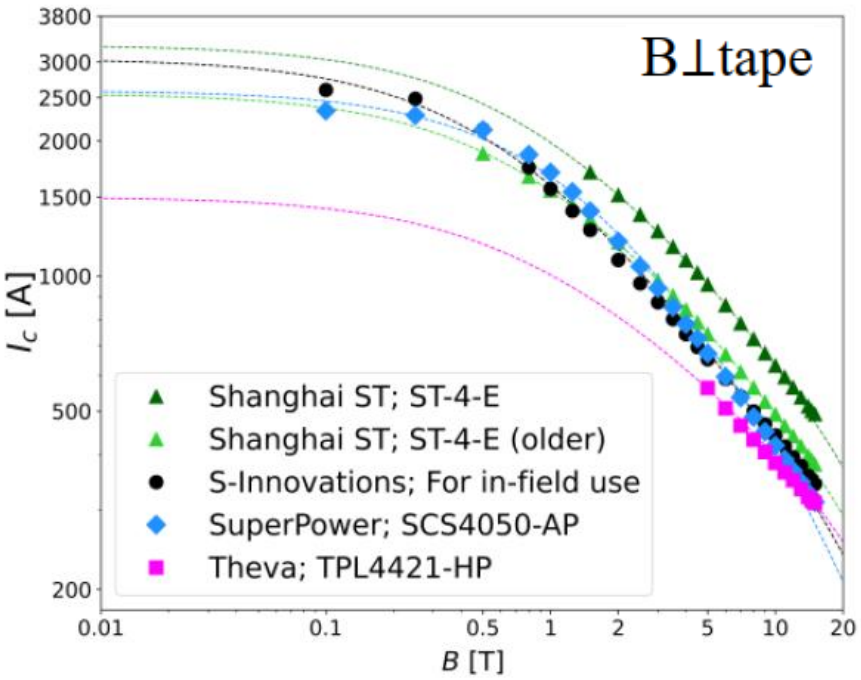
CERN and Univ. Southampton (PhD thesis)

- Scaling laws Ic(T,B,θ) in a wide range of B. Needed for modelling

$$I_c(B,T^*,\theta^*) = I^*_{c,0} \cdot \left(1+\frac{B}{B^*_0}\right)^{-\alpha^*} \cdot \left(1-\frac{B}{B^*_{irr}}\right)^{q^*}$$

Fitting parameters		$I_{c,0}$	α	B_0
Allowed ranges		≤3500 A	0.0 - 1.0	0.0 - 2.0 T
Manufacturer	**Tape type**			
Shanghai ST *	ST-4-E	3274 A	0.56	0.72 T
Shanghai ST	ST-4-E (older)	2553 A	0.56	0.72 T
S-Innovations	For in-field use	3052 A	0.63	0.57 T
SuperPower	SCS4050-AP	2593 A	0.84	1.5 T
Theva	TPL4421-HP	1500 A	0.44	0.71 T





G. Succi et al EUCAS23-3-MP-CC-03S

Magnetic Field and Temperature Scaling of the Critical Current of REBCO tapes

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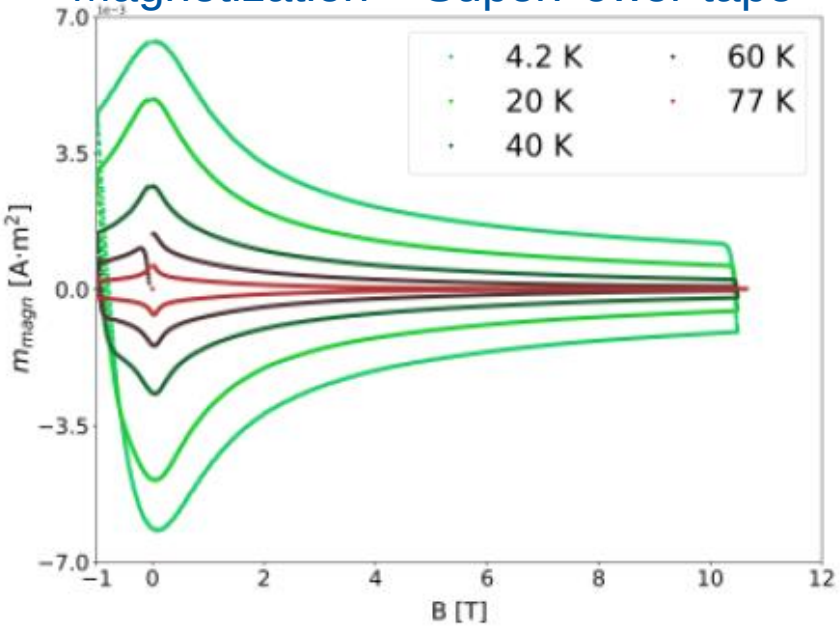
Scaling laws (2/2)

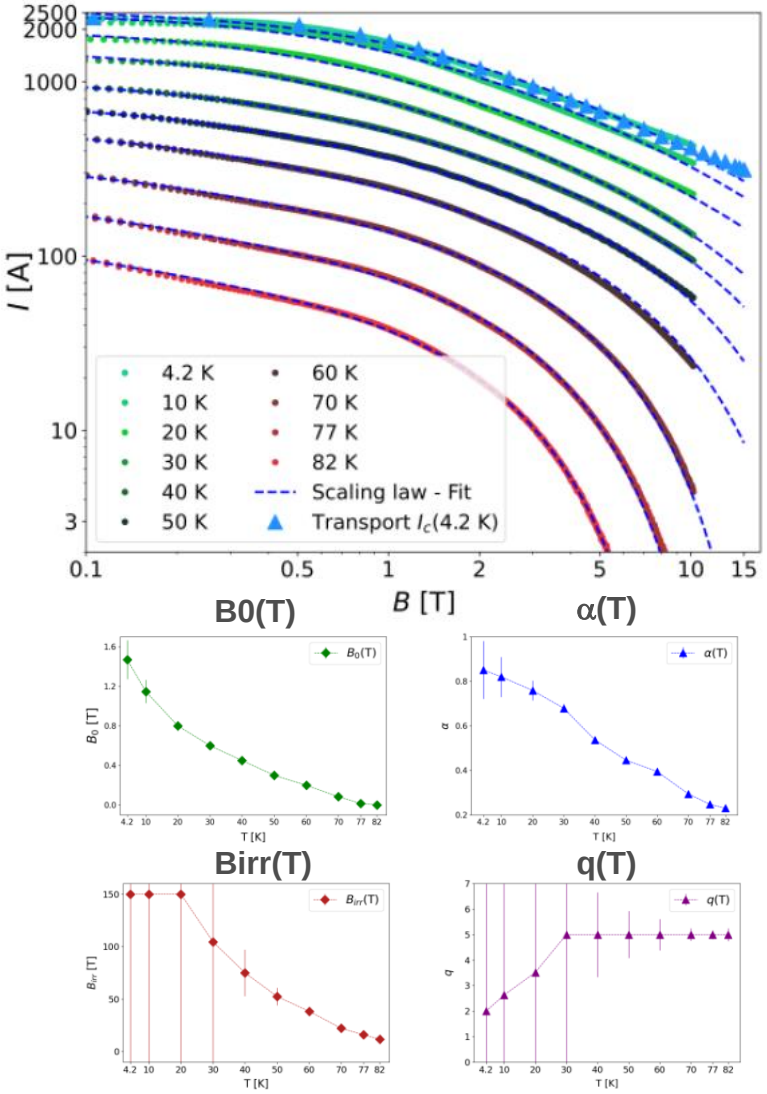
CERN and Univ. Southampton (PhD Thesis)

- Ic(B,T) dependence
- VSM Measurements @ CERN

Magnetization – SuperPower tape



Ic(T,B⊥) from magnetization



G. Succi et al EUCAS23-3-MP-CC-03S

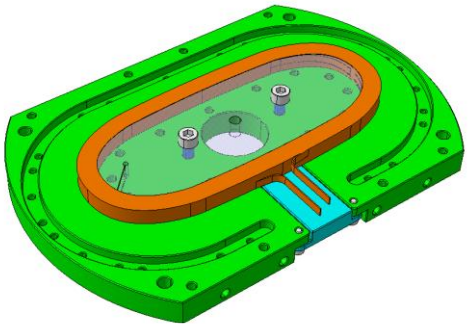
Magnetic Field and Temperature Scaling of the Critical Current of REBCO tapes

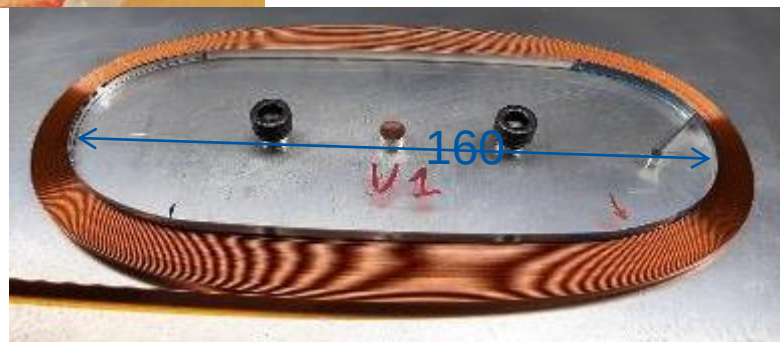
Superconducting cables

- Designed, built and operated - as from mid 2022 – a **cabling machine** for making round, flexible and insulated **REBCO cables** Work done in the framework of HL-LHC Cold Powering: **up to 18 kA @ 60 K** and 0.7 T. About 1 km needed, in ULs of 2-4 m. No degradation of conductor after cabling
- Studied **different cable layouts** (core, number of layers, Φ,…)
- Implementing a **reel-to-reel system** for cabling long unit lengths
- We will use of these cables in **coils**

Winding machine

- Designed and assembled at CERN a winding machine for the production of **solenoids** and **racetrack coils**. Implemeted **tension control** for each tape
- **Stacks of REBCO tapes.** Up to **15 tapes** per cable **+ insulation**
- Implemented **Polyimide insulation** in the reel-to-reel process (tested in air, 7 kV between layers and to ground)





Ø int 37 mm

New test stations (1/2)

REBCO TAPE, LONG LENGTHS

- Procurement of set-up for continuous measurement of **critical current along the tape length** - with millimeter resolution
- Goal: detect faults and non-uniformities
- Measurements in liquid helium in the range **65 K - 77 K**. External field ~ **1 T**
- Industrially available
- Installation and operation **at CERN in summer 2024**

REBCO COILS, HIGHER TEMPERATURE

- New test station for **measurement of coils in a variable temperature range** in helium gas cooling and in self-field
- Conceptual design relying on equipment developed for HL-LHC, i.e. **18 kA** REBCO HTS current leads used in Demo 1 and Demo 2 of HL-LHC Cold Powering
- Detailed design in Q1 2024, availability **by end 2024**

New test stations (2/2)

REBCO TAPE, SHORT SAMPLES

Being procured for installation and operation in building 163:

- **Solenoid 20** T @ 4.2 K
- Bore diameter 100 mm
- Field homogeneity better than 1% in a cylinder volume of 200 mm height and 85 mm diameter, centred around the magnetic centre of the solenoid
- Commissioning at CERN by **mid-2026**

Synergy with RD5 – See presentation on Infrastructure for superconductors (Th.Boutboul and D. Perini)

Conclusions

- Established the basis for starting next year development of novel REBCO cables and coils. The two technologies have to progress in parallel

- We are launching a challenging R&D. Synergies and support among HFM collaborating institutes will help in addressing challenges and defining the technological roadmap for future HTS accelerator magnets