HFM

High Field Magnets Programme

TE-HFM Workshop

RD2: HTS Program

A. Ballarino

19/09/2024

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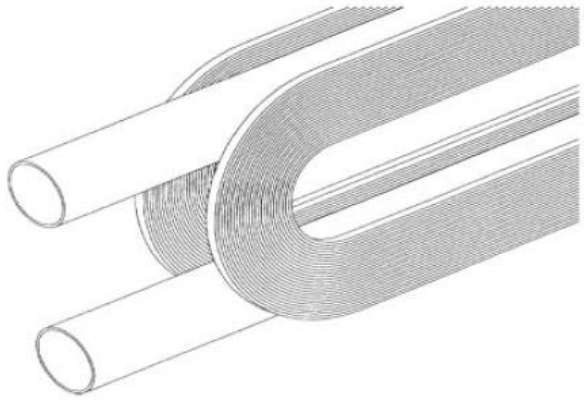
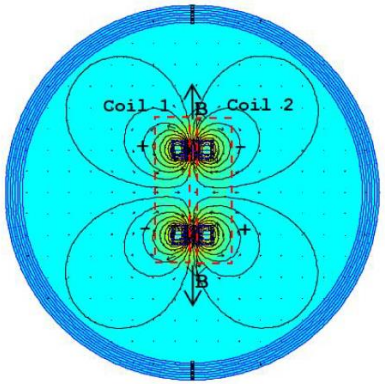
Strategy

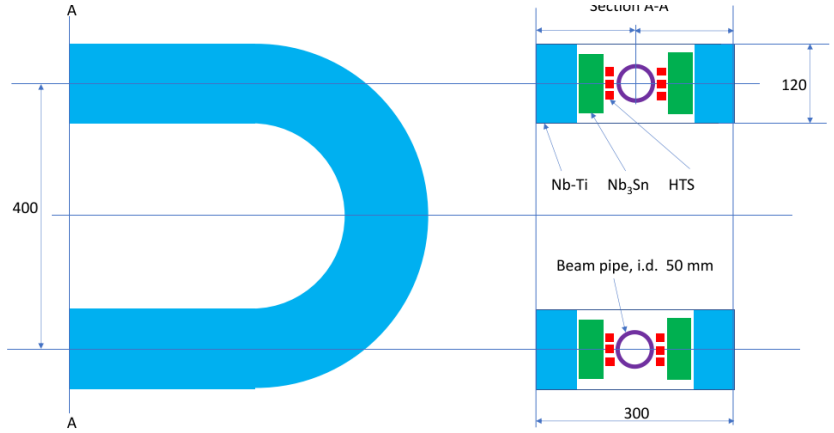
- **MSC HFM HTS Activities**, EDMS 2685835, Jan 2022
  - **REBCO Conductor, Iron Based Superconductors**
    - **REBCO Tape:** procurement, characterization, optimization via interface with tape manufacturers
    - **Iron Based Superconductors**: development of wire via R&D. Production at the collaborator(s)'s site(s)
  - **REBCO Coils**: Short Model Coil Program, from racetracks to Common Coil Dipole demonstrator



Common Coil (BNL)



Common Coil (EDMS 2685835)



Tests in SM-18 (EDMS 2685835)

Structure – RD2

Task	Deliverable	Description	Start date	End date
WP2-T1 Procurement REBCO conductor	Specification document		01.01.2023	30.09.2025
	EBCO Tape procurement - Phase 1 HFM FCC		30.09.2023	31.12.2025
	EBCO Tape procurement - Phase 2 HFM FCC		30.06.2025	31.12.2028
	EBCO Tape procurement - Solenoids		30.09.2023	31.12.2023
WP2-T2 Characterization	C Definition and implementation, including reproducibility and aling of performance		01.06.2023	31.12.2023
	ontinuous Critical Current Measurement set-up (liquid nitrogen, 5 K - 77 K): procurement/development, installation and mmissioning		01.10.2023	31.12.2024
	st station for higher temperatures (20 K- 50 K, 1 T to 2 T): rocurement, design and construction of components, stallation and commissioning	Important also for critical current scaling	01.01.2025	31.12.2026
	serts for split coils (10 T) and solenoid (20 T)	As from 2026		
	quid nitrogen test station for coils		01.01.2024	31.12.2025
	ualification of splices, cables and coils: inserts for easurements at 77 K and 4.2 K . Design, construction and mmissioning	Synergy with Nb_3Sn conductor WP1	01.10.2023	31.12.2028
	ooling and consumables (sample holders for various easurements at 77 K and 4.2 K, instrumentation, connectors, ooling for miscroscopic analysis, liquid nitrogen,...)		01.10.2023	31.12.2028
	easurement of REBCO in external high field laboratories	Grenoble/FSU	01.03.2024	31.12.2028
WP2-T3 Development of REBCO cables	ble concepts and cabling equipment (R&D)	Cabling/braiding machine	01.01.2024	31.12.2026
	ectrical insulation and impregnation techniques	Oven/Impregnation facility	01.01.2024	31.12.2028
	oating technologies	Tinning and coatings for cable properties	01.01.2024	31.12.2028
	inding tests and winding/cabling equipment (long units)	Winding machine(s)	01.10.2024	31.12.2025
WP2-T4 Development of small prototype coils	TS prototype coils. Concepts, modelling, assembly, test	Tests in buildings 288 (LN_2) and 163 (LHe). Background fields: 12.5 T and 15 T		
	easurement of REBCO solenoids in external high field boratories	Grenoble/FSU		
	TS Racetrack model coils. Concepts, modelling, assembly, test	Tests in buildings 288 and SM-18		
	ybrid model coils. Concepts, modelling, assembly, test	Tests in SM-18		
	Nb_3Sn Outserts for racetracks	Synergy with Nb_3Sn Magnet WP		
WP2-T5 Magnet demonstrator(s)	gh field demonstrator(s): Common Coil Design. Concepts, odelling, design, manufacturing, assembly	5 T @ 4.2 K and 10 K in background of 15 T		
	gh field demonstrator(s): Solenoids. Concepts, modelling, design, anufacturing, assembly. Budget includes specific winding uipment/machine	Up to 30 T		
WP2-T6 Other Superconductors and low-field applications	ther superconductors and low-field applications			
WP2-T7 Laboratory Infrastructure	pgrade of HTS laboratory			

REBCO Conductor

REBCO Coils

Other HTS

Laboratory

Implementation of strategy – Progress - Milestones

REBCO
Iron Based Superconductors

Demonstrator Coils and Milestones

Laboratory

Procurement of Tape

Procurement of tape based on Technical Specification (**synergy with HL-LHC WP6a).** IT-4924, 'Supply of REBCO Coated Conductor for the HFM Programme', was dispatched on 9th October 2023 to **six firms.** Tape started to be delivered in May 2024

Parameter	Minimum	Maximum	Target	Reference
Critical Current, I_c, per width (A/cm)				§ 3.3.1
at 4.2 K and 20 T	800	-	-	
at 20 K and 20 T	375	-	-	
Engineering Critical Current Density, J_e (A/mm^2)				§ 3.3.1
at 4.2 K and 20 T	-	-	≥ 1500	
at 20 K and 20 T	-	-	≥ 700	
Nominal substrate thickness (µm)	38	60	-	§§ 3.5 and 3.4.1
Nominal copper Stabiliser thickness, each face (µm)	5	-	20	§ 3.4.3
Minimum out-of-plane bend radius (mm)	-	20	≤ 10	§§ 3.3.3
Internal Resistance (nΩ cm^2)				§§ 3.3.2 and 9.1.2
for a test duration of 0 h	-	100	≤ 60 [1]	
for a test duration of 1 h	-	125	≤ 60 [1]	
Piece Length (m)	100	-	≥ 200 [2]	§ 3.3.5

New
(outcome of WP6 Activities)

200 ± 5 °C
≤ 50 °C/min

Orders placed and status of deliveries

Delivery delayed because of identified *NCs (HL-LHC WP6a Activity)

Identified *NC

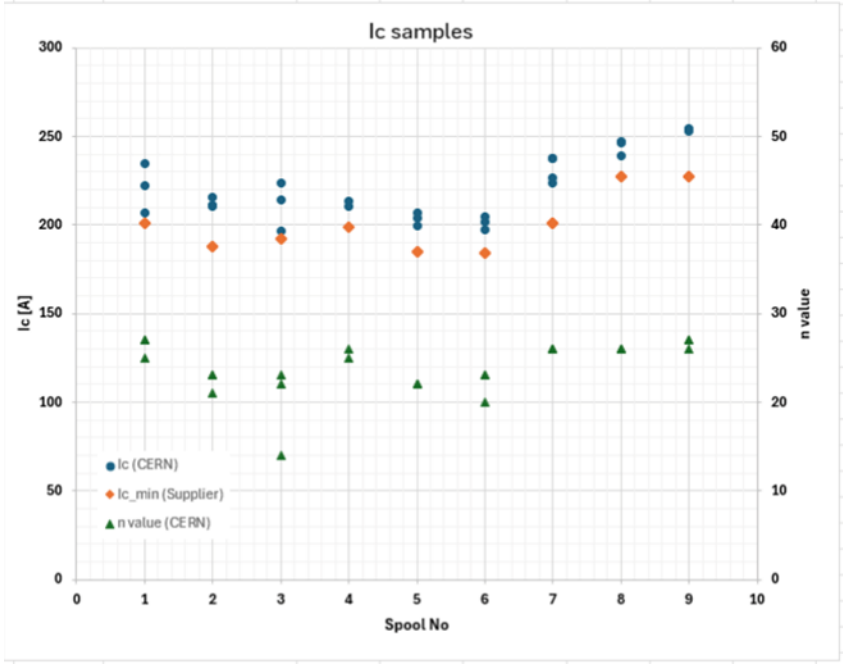
Supplier	Line Item	Lot	Leat time (mo)	Quantity (m)	Min. Piece length (m)	Width (mm)	Copper (mm), per side	Solder coating	Delivered length (m)	Delivered % of order	Order submitted	Receipt delay (days)
SST	1	1	4.5	1500	100	**2**	0.02	No	0	0.0%	03/04/2024	26
SST	2	1	4.5	1500	100	**2**	0.02	Pb37Sn63	0	0.0%	03/04/2024	26
SST	3	2	4.5	3500	100	**4**	0.02	Pb37Sn63	0	0.0%	03/04/2024	26
SST	4	2	4.5	3500	100	**4**	0.02	No	0	0.0%	03/04/2024	26
SST	5	2	4.5	1000	100	**4**	0	No	0	0.0%	03/04/2024	26
SST	6	2	2	2100	100	**4**	0.01	No	102	4.9%	03/04/2024	101
SST	7	3	4.5	800	100	**12**	0.02	Pb37Sn63	0	0.0%	03/04/2024	26
SST	8	3	4.5	800	100	**12**	0.02	No	0	0.0%	03/04/2024	26
Superpower	1	1	8	550	100	**2**	0.02	No	0	0.0%	03/04/2024	-79
Superpower	4	2	5	1100	100	**4**	0.02	No	0	0.0%	03/04/2024	11
Superpower	7	3	4	220	100	**12**	0.02	No	0	0.0%	03/04/2024	41
Faraday Factory	1	2	2	1000	100	**4**	0.02	No	0	0.0%	11/04/2024	93
Faraday Factory	2	2	6	7300	100	**4**	0.02	No	1344	18.4%	11/04/2024	-27
Faraday Factory	3	2	2	2000	100	**4**	0.02	Sn60Pb40	0	0.0%	11/04/2024	93
Faraday Factory	5	3	2	200	100	**12**	0.02	No	200	100.0%	11/04/2024	
Faraday Factory	6	3	2	1500	100	**12**	0.02	No	1500	100.0%	11/04/2024	
Fujikura	1	1	2	1000	30	**2**	0.02	No	1000	100.0%	03/04/2024	
Fujikura	2	2	1.25	1000	100	**4**	0.02	No	1000	100.0%	03/04/2024	
Fujikura	3	2	2	2000	100	**4**	0.02	No	2000	100.0%	03/04/2024	
Fujikura	4	3	1.25	200	100	**12**	0.02	No	200	100.0%	03/04/2024	
Fujikura	5	3	2	400	100	**12**	0.02	No	400	100.0%	03/04/2024	

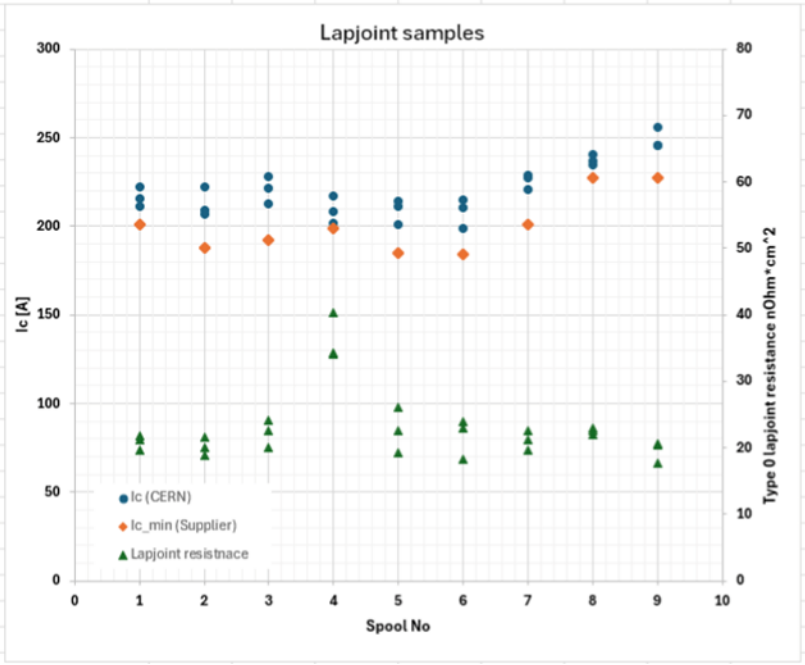
Deliveries started in Q2 2024

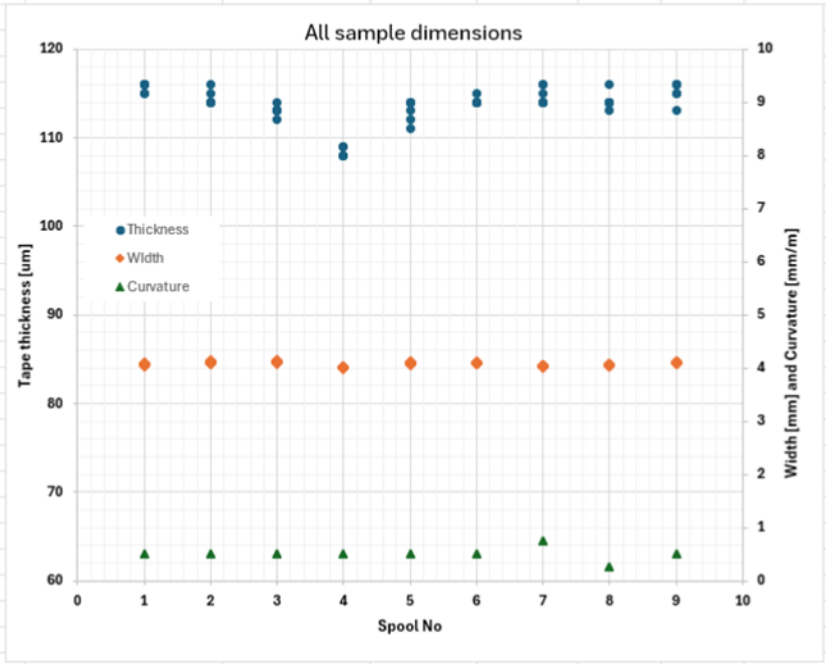
TOT ~ 32 km

*Identified Non-Conformities (NC) would have an impact on coils' performance. Iteration with manufacturers on-going

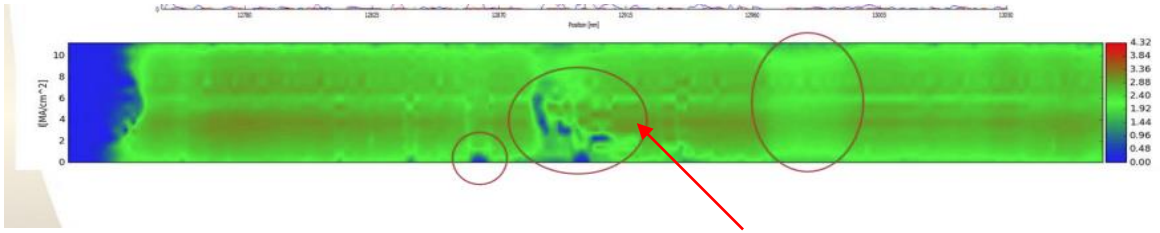
QA of delivered REBCO tape







New Equipment



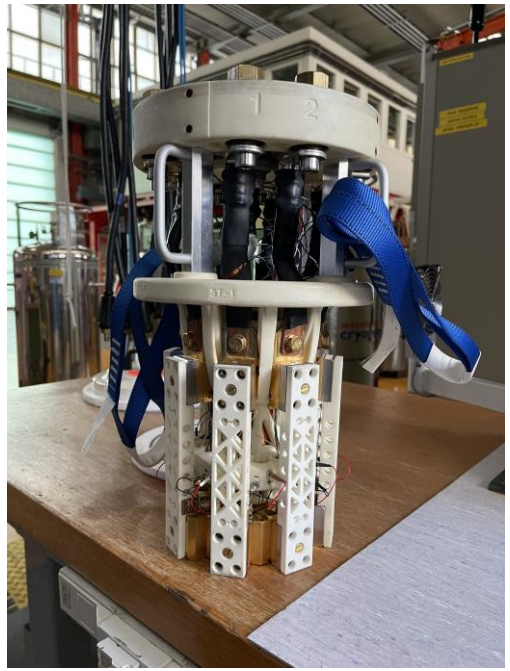
Procured: THEVA Tapestar™ XL-HF Reel-to-reel set-up for critical current

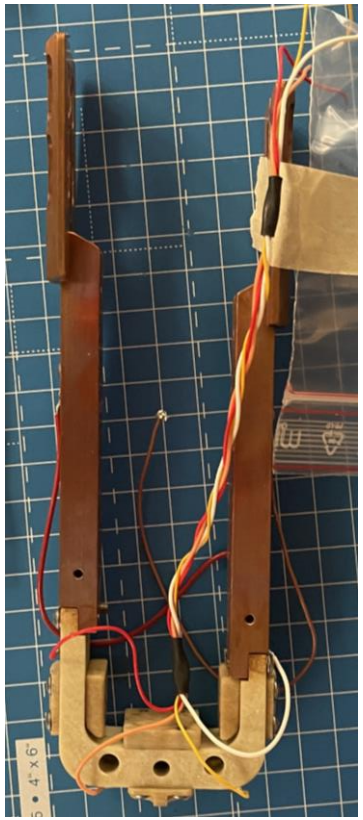
- Common throughout the industry
- High throughput (**200 m/h**)
- Can accommodate tape 2 - 12 mm wide
- Subcooling to **~67 K**
- Variable magnetic field to 1 T
- Tape marking (to mark length and defect positions)
- Yields information on **Ic along the tape length as well as information on defects**
- Accuracy **±3 %** (calibration required)
- Compact footprint (2.7 x 1 m)

Delivered in August 2024 (on schedule)

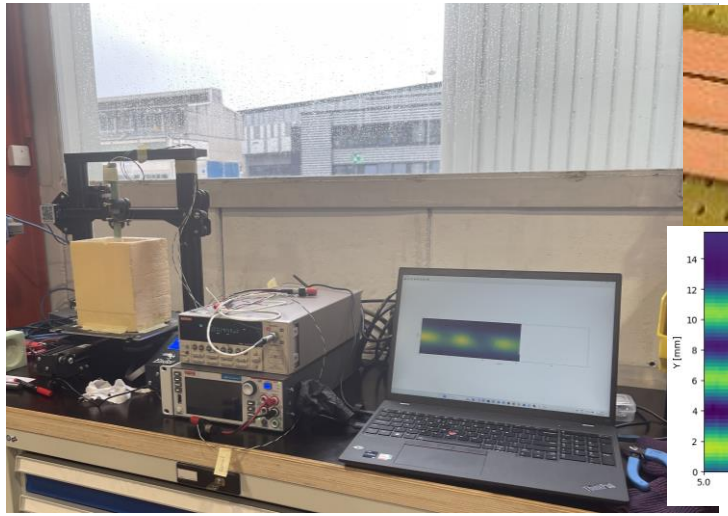
New set-ups

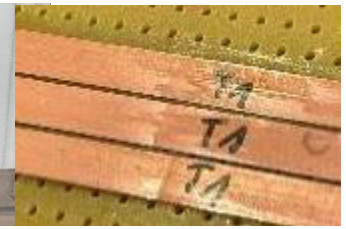
Critical current, magnetization and indirect measurements

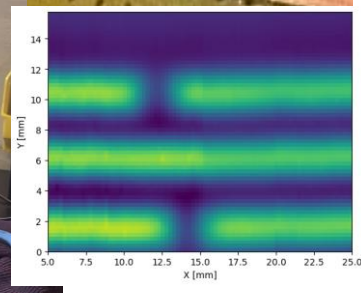


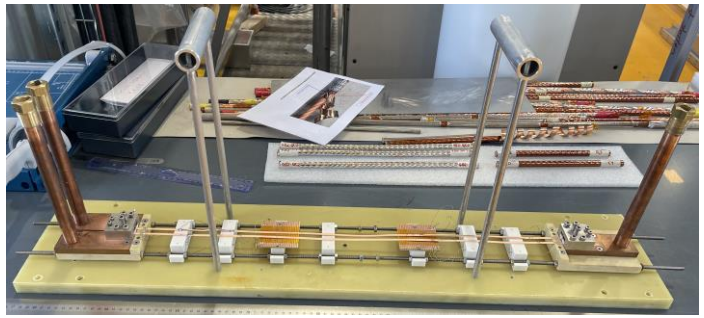


Hall-probe scanner









Acceptance tests
77 K at s.f.
I_c and lap-joint

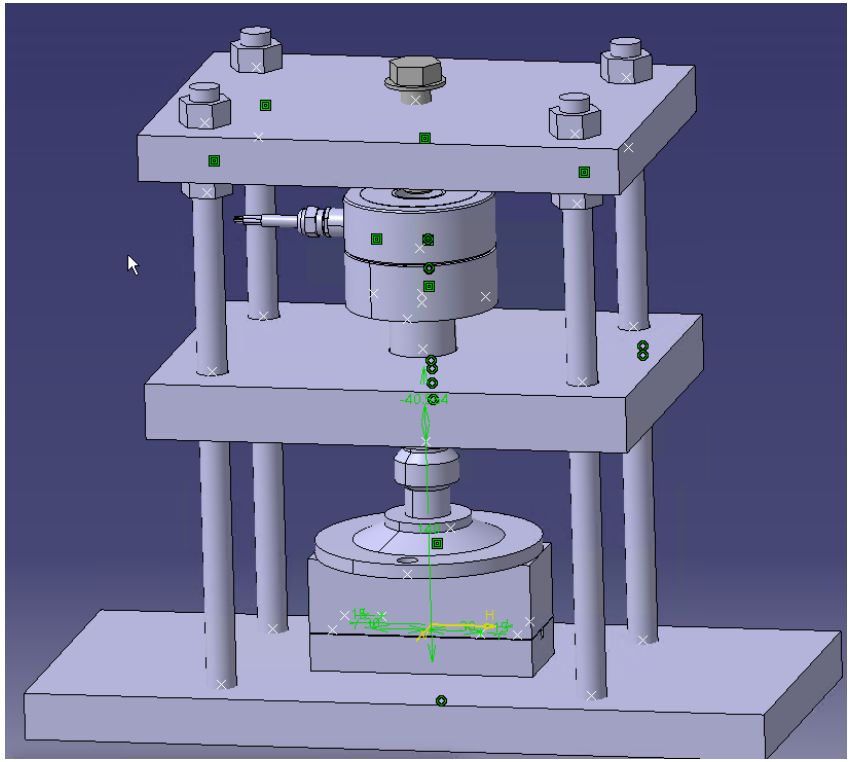
U-shape
0-15 T at 4.2 K

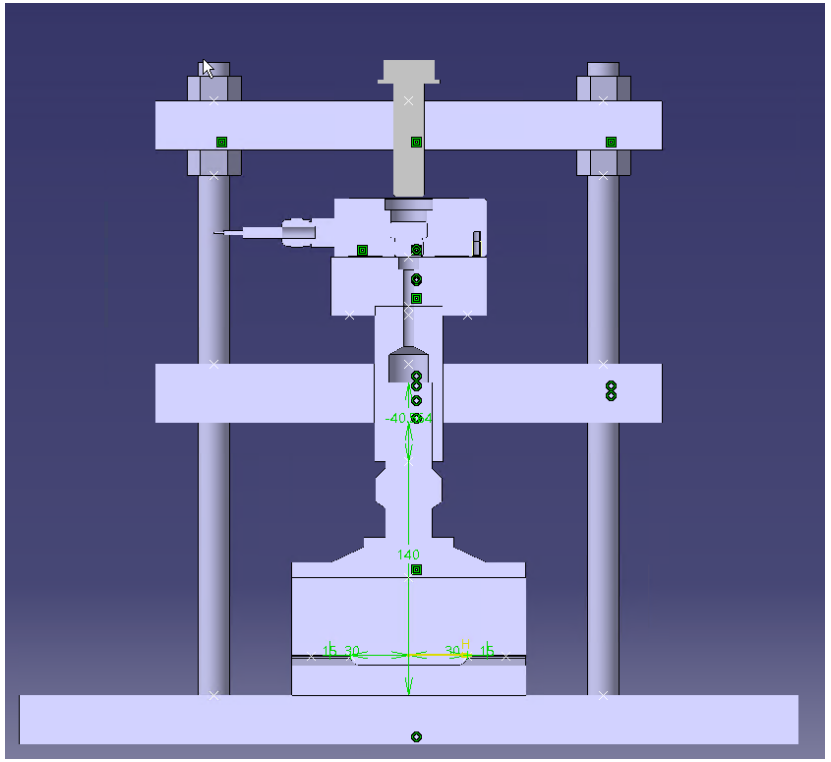
Vibrating sample magnetometer
0-10 T, 4.2–80 K

Extracted strand testing
77 K, s.f.

Contact resistance vs pressure

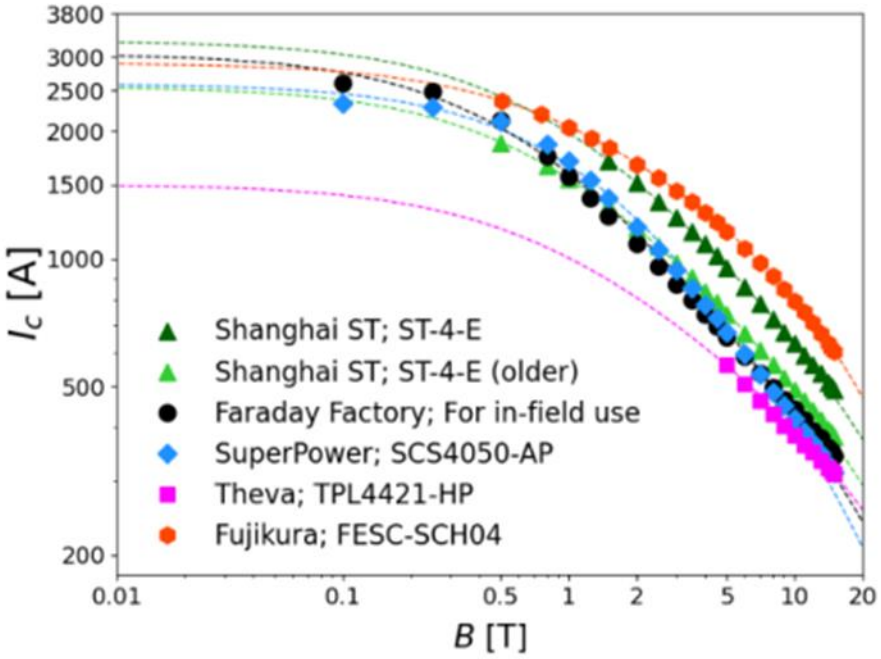
Current distribution in REBCO cables



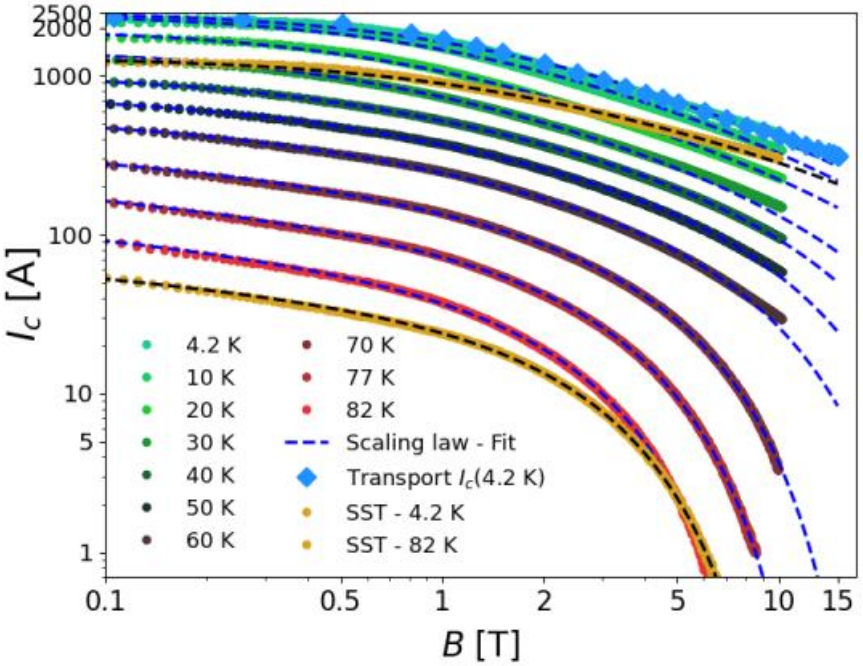


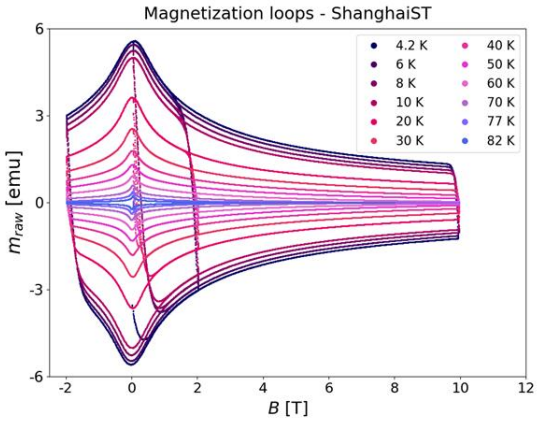
Measurements at CERN and Scaling Law

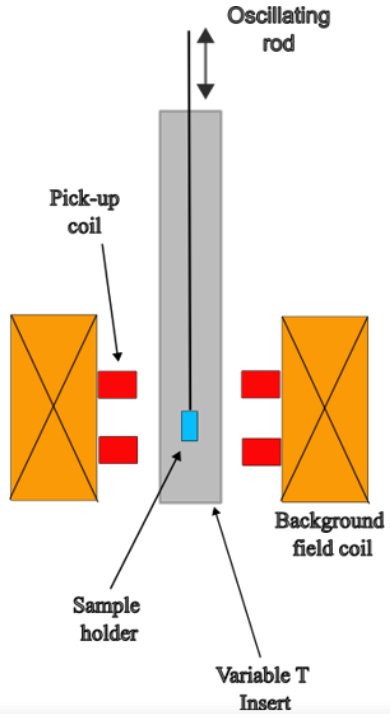
Ic @ 4.2 K, 4 mm width, B⊥



Ic vs T, 4 mm width, B⊥





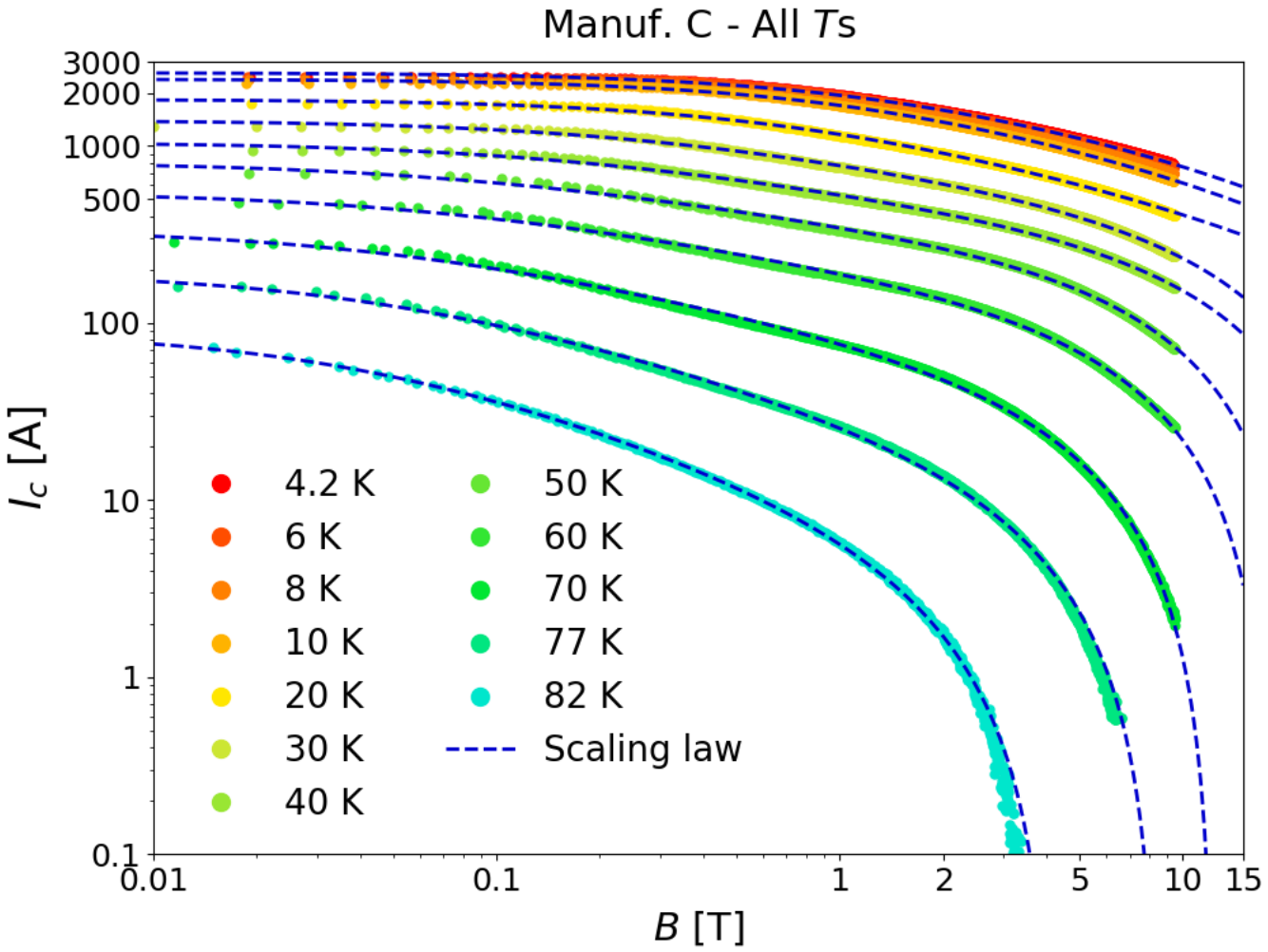


Direct measurements

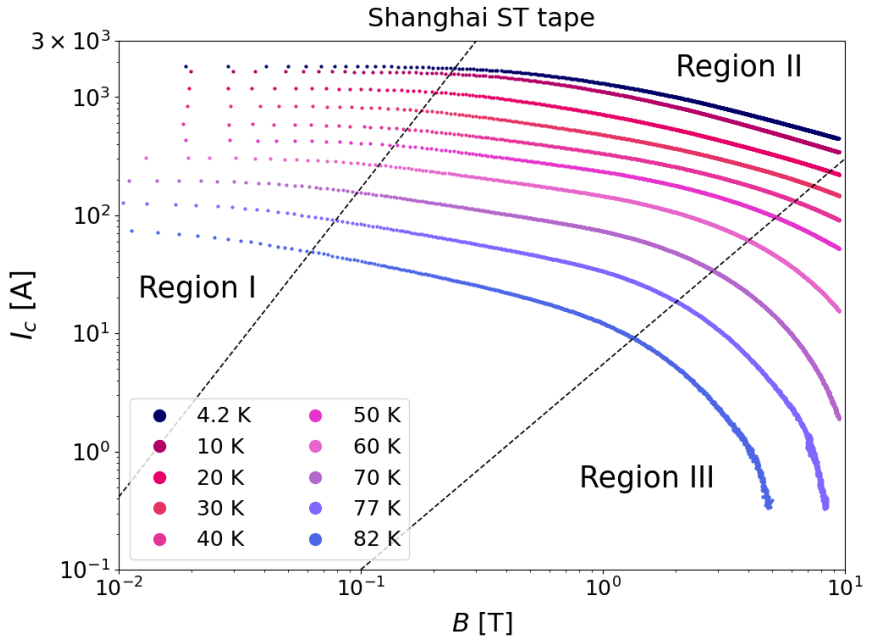
Magnetization measurements

Creation of a database on REBCO tape properties

Measurements at CERN and Scaling Law



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



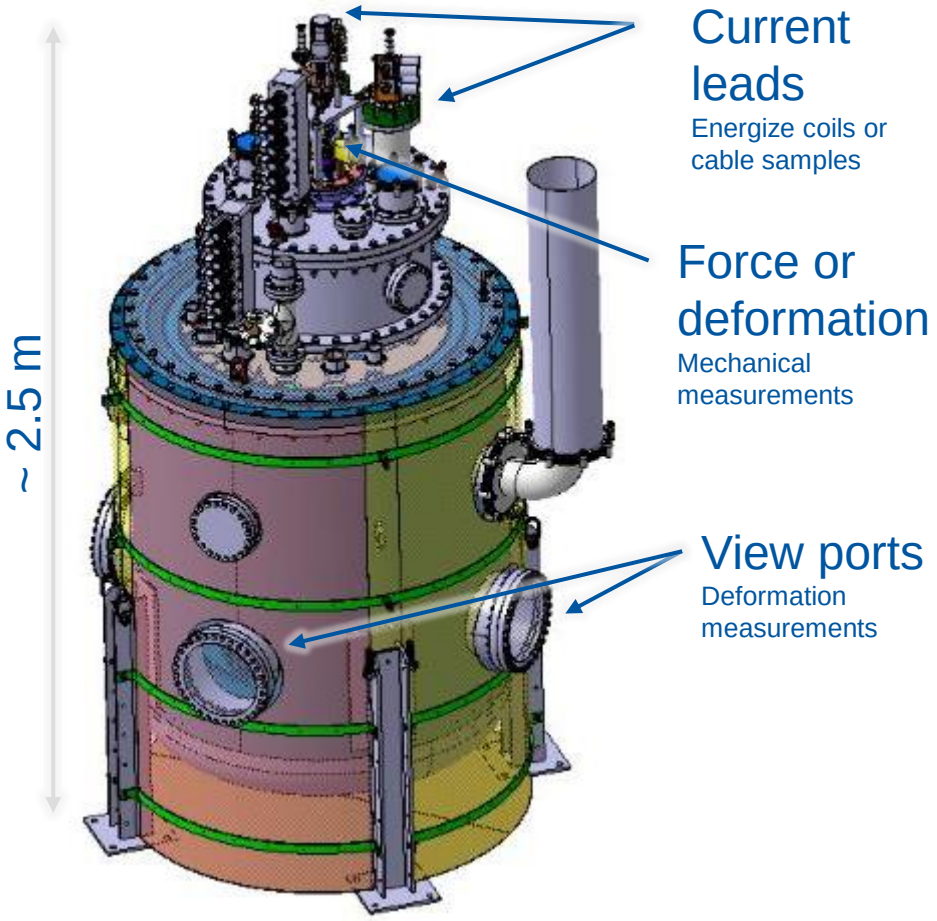
- Hundreds of measurements in the last few months
- Focus ALSO on Ic at low fields

G. Succi et al, proceedings of ASC 2024

Test Infrastructure

Design and manufacture of **multi-purpose cryostat** (operational in spring 2025). Highlights:

- Liquid helium or variable temperature He gas cooling
- Sample volume 0.6 x 0.6 x 0.6 m
- Four viewports for optical measurements
- Flexible feed-through for mechanical measurements
- 2 kA HTS current leads, with space for 2 more
- Mu-metal magnetic shielding
- Operation at 2.5 bar



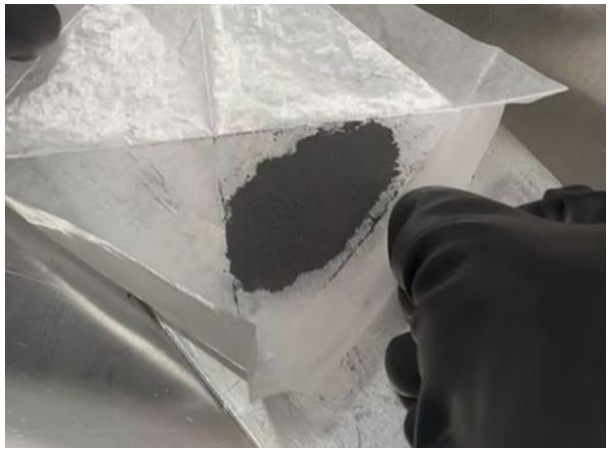
Synergies with Collaborators

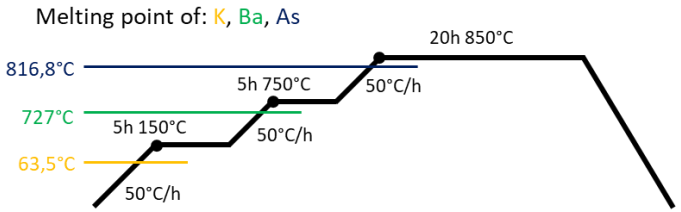
Iron Based Superconductors at SPIN, Genova.
Development of multi-filamentary iron based round wire. To date: production/synthesis of powder with the highest achievable purity. Production and characterization of mono-filamentary PIT Ba-122 wires. React&Wind.

Target Jc: 10^5 A/cm^2 @ 4.5 K and 16 T, 10^4 A/cm^2 @ 20 K, 10 T

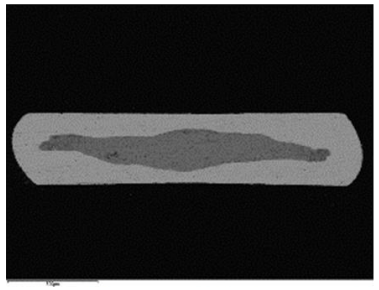
Industry has already declared interest in joining the effort.

REBCO tape at KIT, Karlsruhe: production of REBCO tapes (12 mm width). Study of specific aspects, e.g. origin of internal (in between layers) resistance in tapes





Ba-122 tape



Width~2 mm, Thickness~0.4 mm
Short samples (~ 2 m long)

Implementation of strategy – Progress - Milestones

REBCO
Iron Based Superconductors

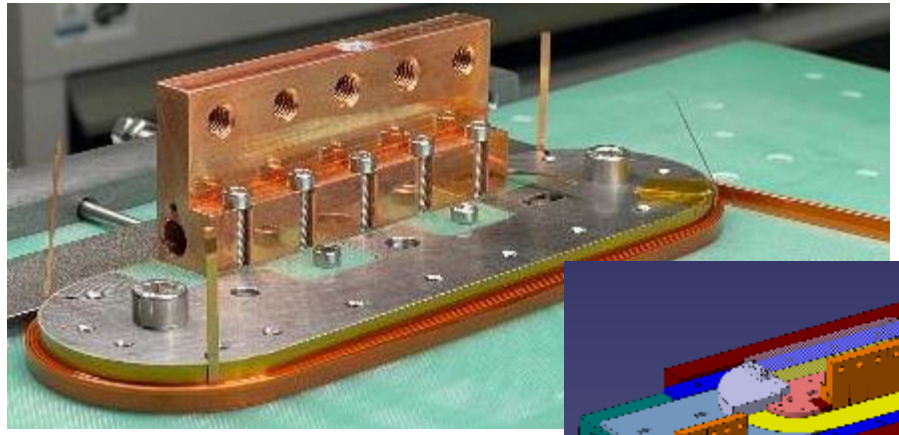
Demonstrator Coils and Milestones

Laboratory

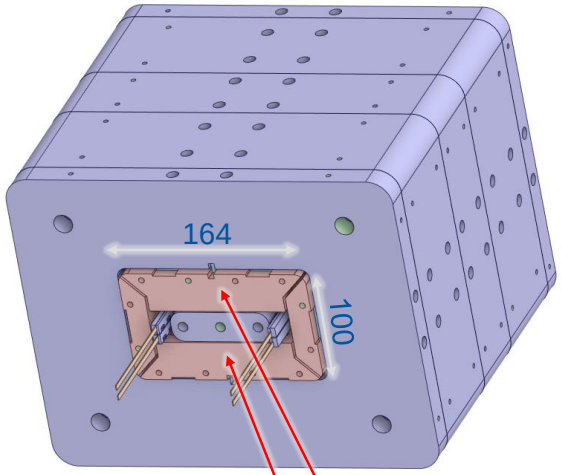
REBCO Cables and Coils

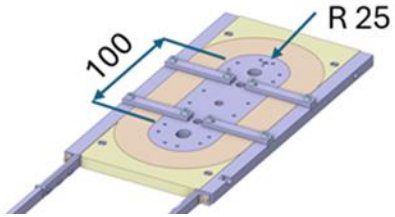
Modular approach, Intermediate milestones

- **Racetrack Model Program**
  - **Single Racetrack Demonstrators**. Fast throughput. Development of winding techniques, qualification of different REBCO cables (as from Q2 2024)
  - **Double Racetrack** Demonstrators (as from Q3 2024)
- **Mechanical structure for Common Coil Demonstrators (CCD):**
  - **Two Double Racetracks** (3 T at 4.5 K)
  - **Four Double Racetracks** (5 T at 4.5 K)
  - **Six Double Racetracks** (10 T at 4.5 K)



Straight section ~ 10 cm
L = 250 mm

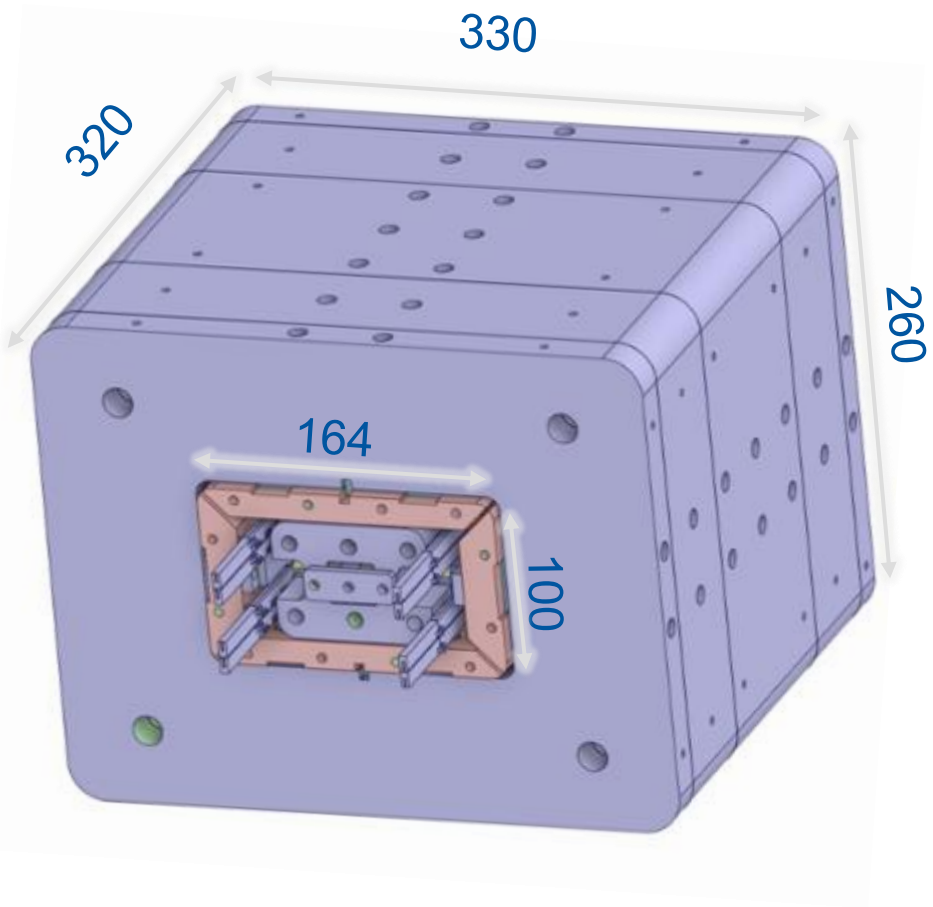


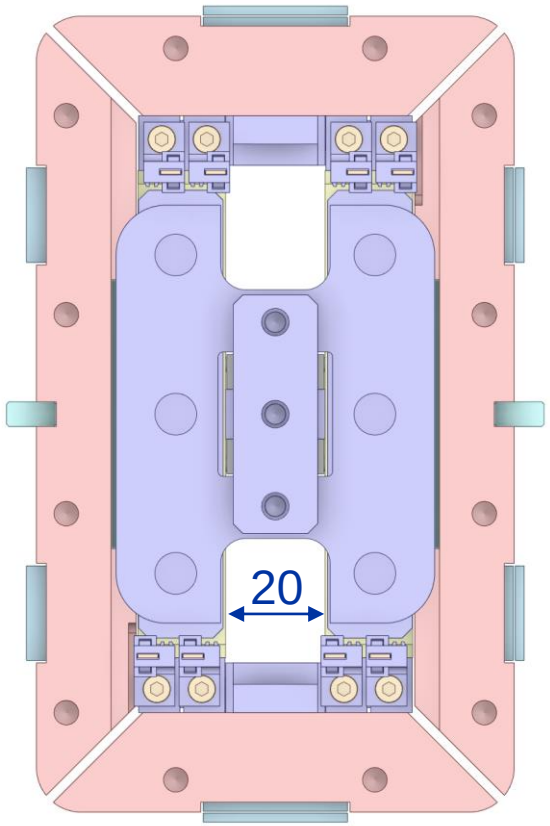


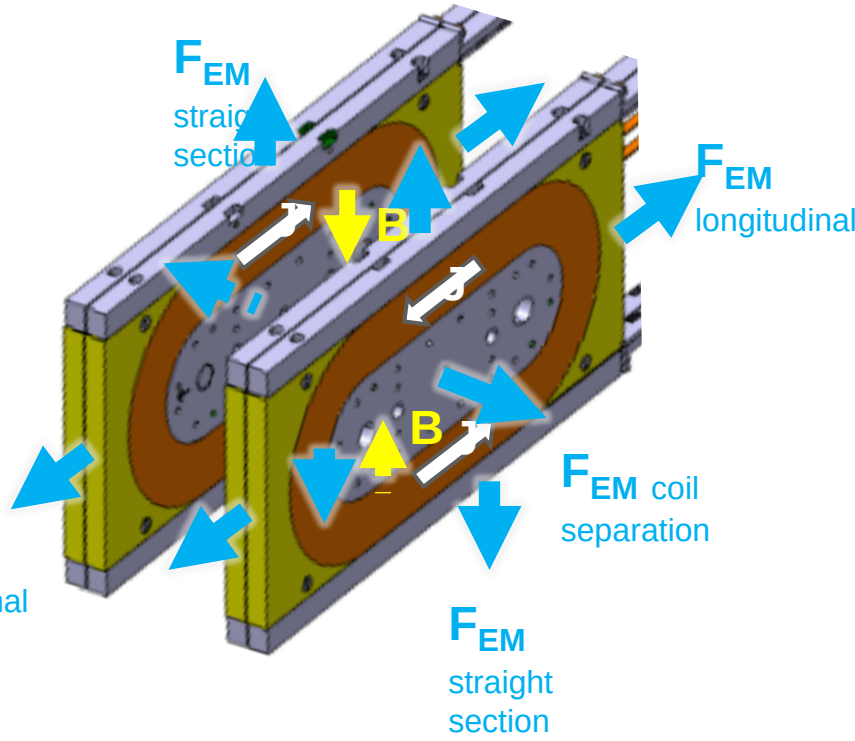
Optimized for number of racetracks

Development of electrically insulated REBCO cables

Common Coil Demonstrator







Weight ~ 300 kg

Moving toward higher temperatures

Coils will be measured also at higher temperatures

For there double racetracks: Bbore = 10 T @ 4.5 K, Bpeak = 12.7 T @ 4.5, ~ 7.7 T @ **20 K**)

Winding machine

Winding table from TE MSC MDT. Modification of the winding system with the addition of motors/brakes. System able to wind and keep in tension up to **7 tapes** in parallel

Parameter	Value
HTS tape	4 mm wide from SST
Required I_c @ 12.5 T	> 550 A
Number of HTS tapes	4
Additional copper	2 x 100 µm
Insulation thickness	100 - 150 µm Kapton

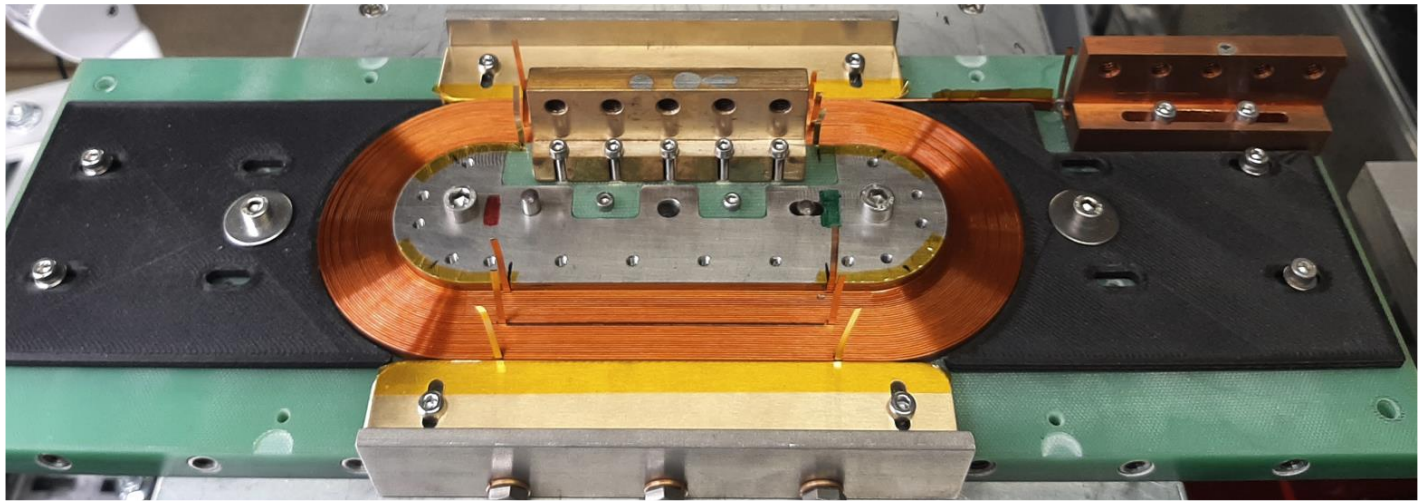
Up to 2 kA (Je = 625 A/mm^2)

Racetrack Coils

Produced in 2024:

- **Two** dummy **copper** racetracks
- **Three REBCO** single racetracks

  Characterized in liquid nitrogen
- **One REBCO** double racetrack

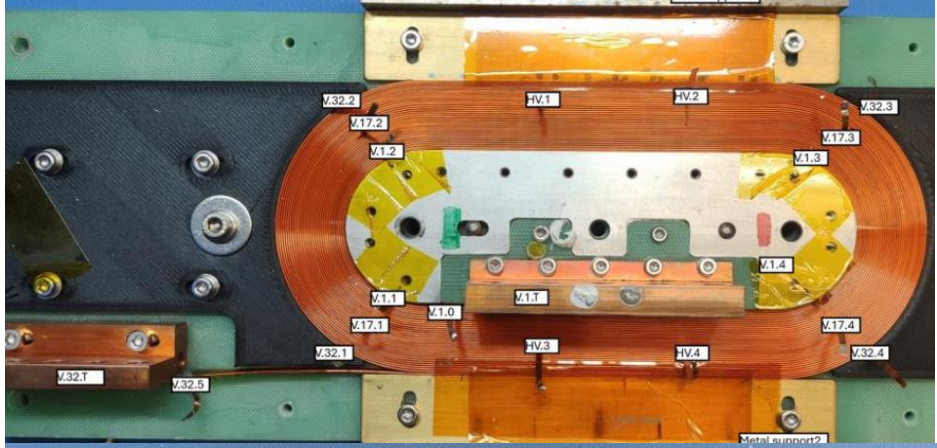


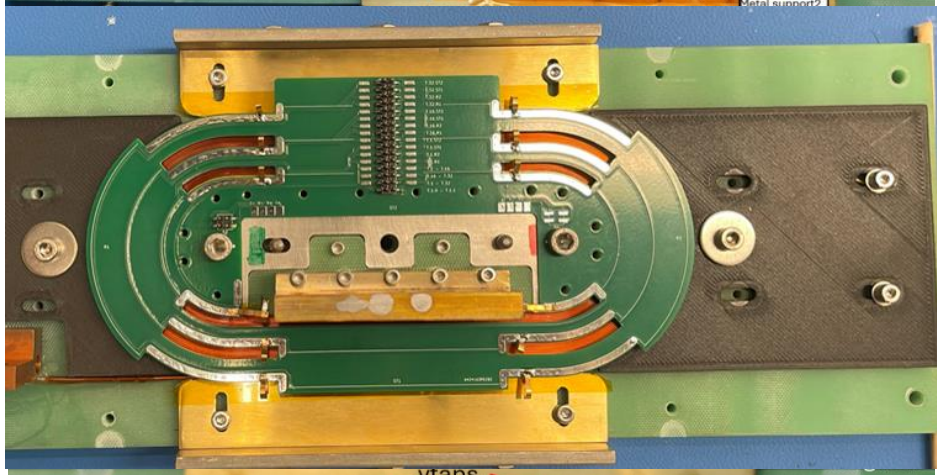
Development of test procedure for **localizing** and **analyzing defects** after measurement of the **coil**

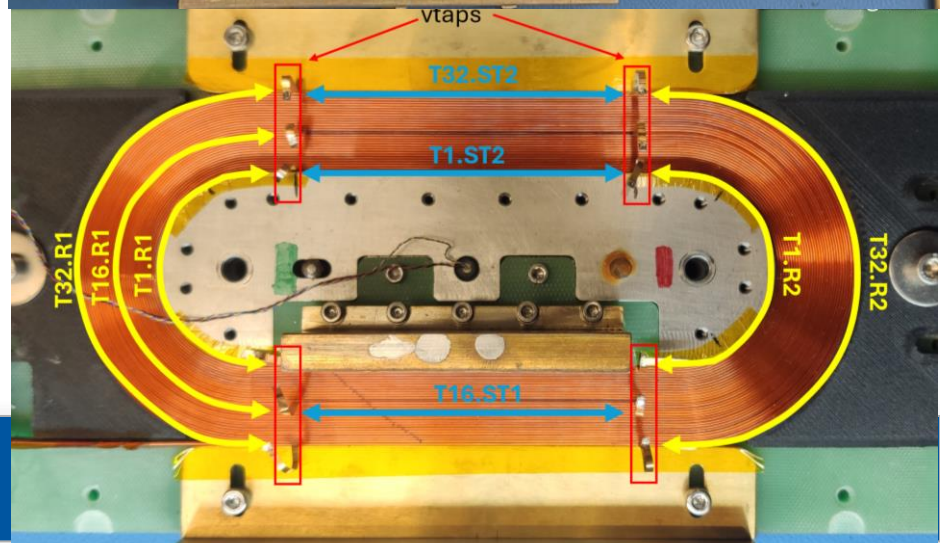
Racetrack coils

- **RC1:** Winding problem in the first layer (popping out of tape). New tooling and winding procedure implemented in RC2
  Tape manufacturer: SST
- **RC2:** Conductor locally damaged by V-tap. Developed new procedure for implementing V-taps in the coil. Implemented in RC3
  Tape manufacturer: SST
- **RC3:** Coil conform. After qualification, launched assembly of double pancake
  Tape manufacturer: Faraday Factory

For all coils, successful HV tests (**5 kV at RT**)



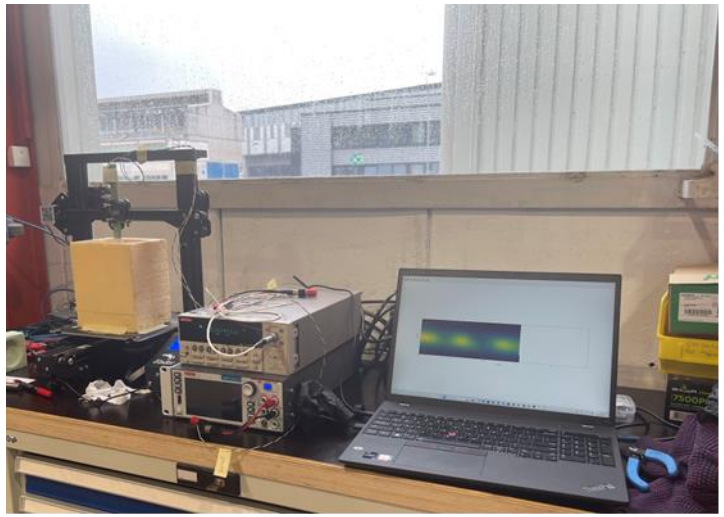


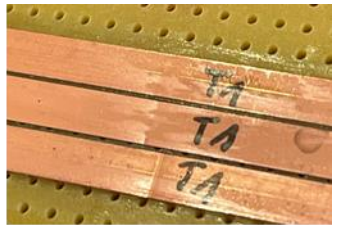


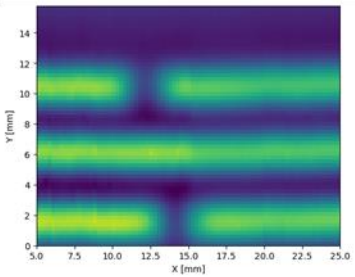
Racetrack coils – Measurements at 77 K

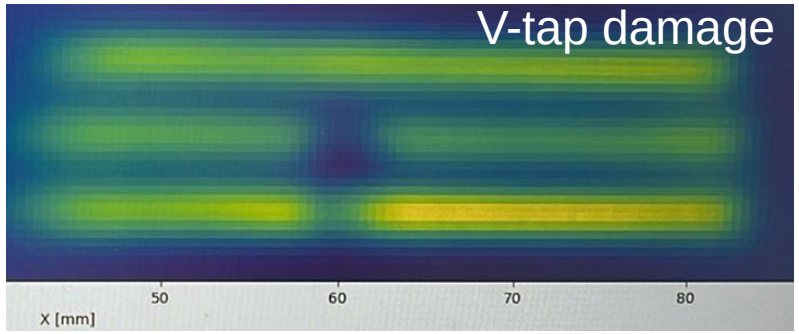
- RC1 and RC2 showed small reduction in Ic wrt calculated values. We decided to go through a post-test analysis. This enabled identification and localization of defects as well as development of a dedicated procedure
- Quench protection worked as expected (LN_2, lower current). Vth ~ 10 mV. No damage of the coils after quench

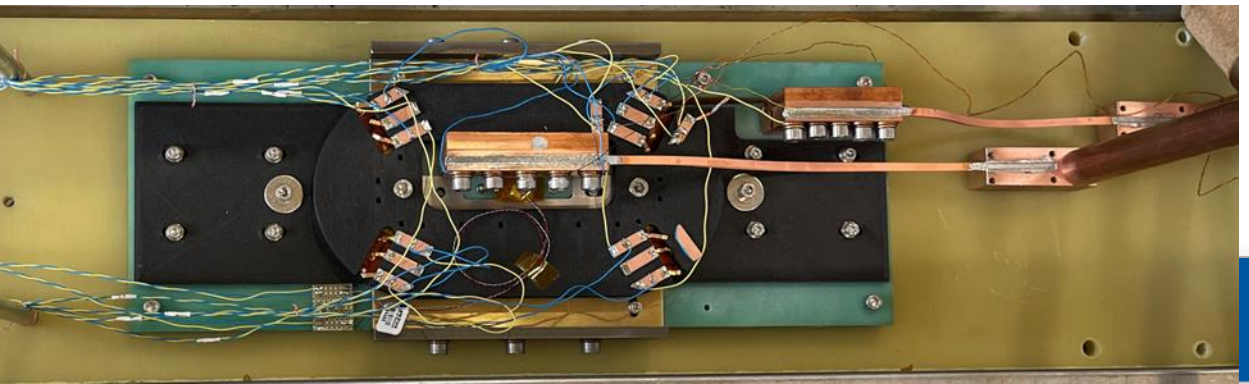
Hall Probe Scanner for identification of sub-mm size defects



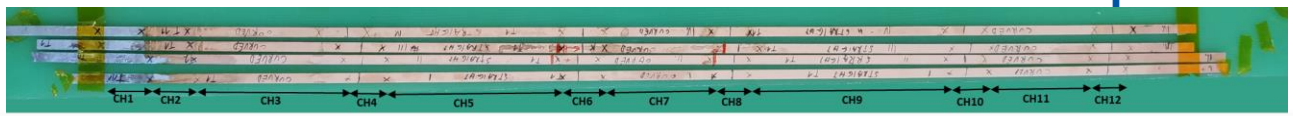




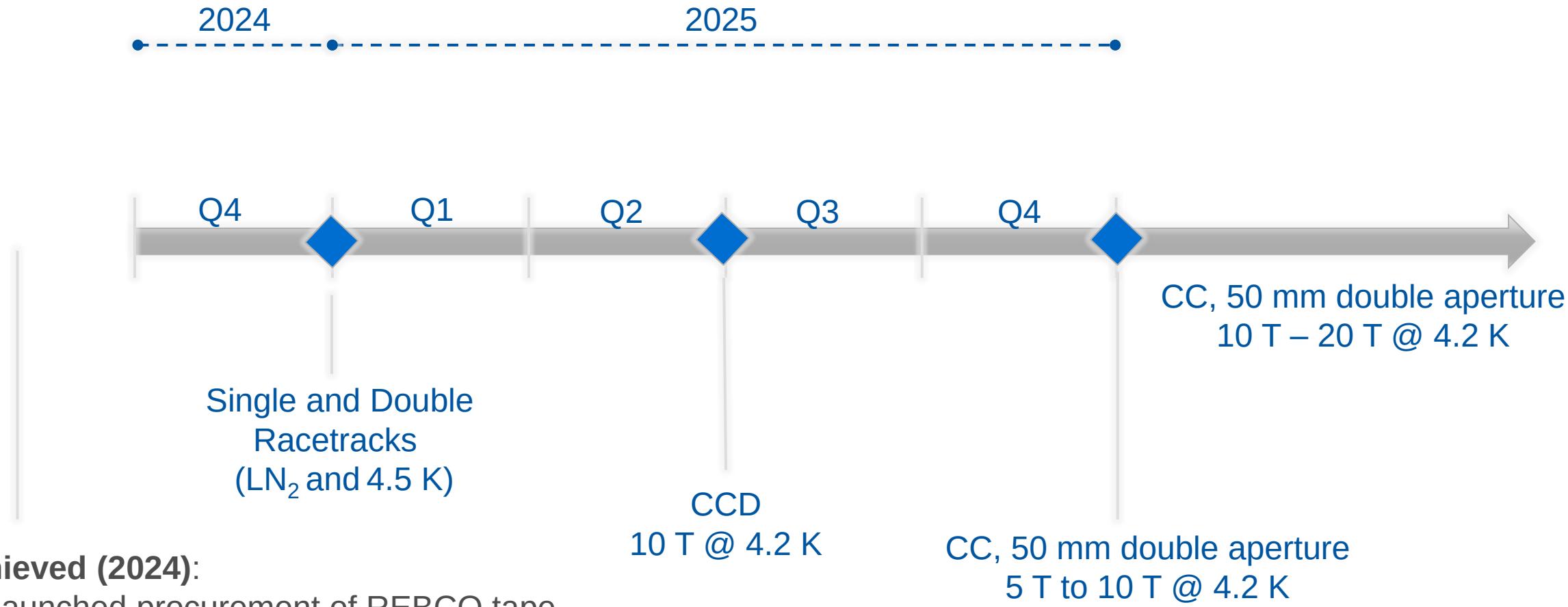




Direct current measurement of extracted tape



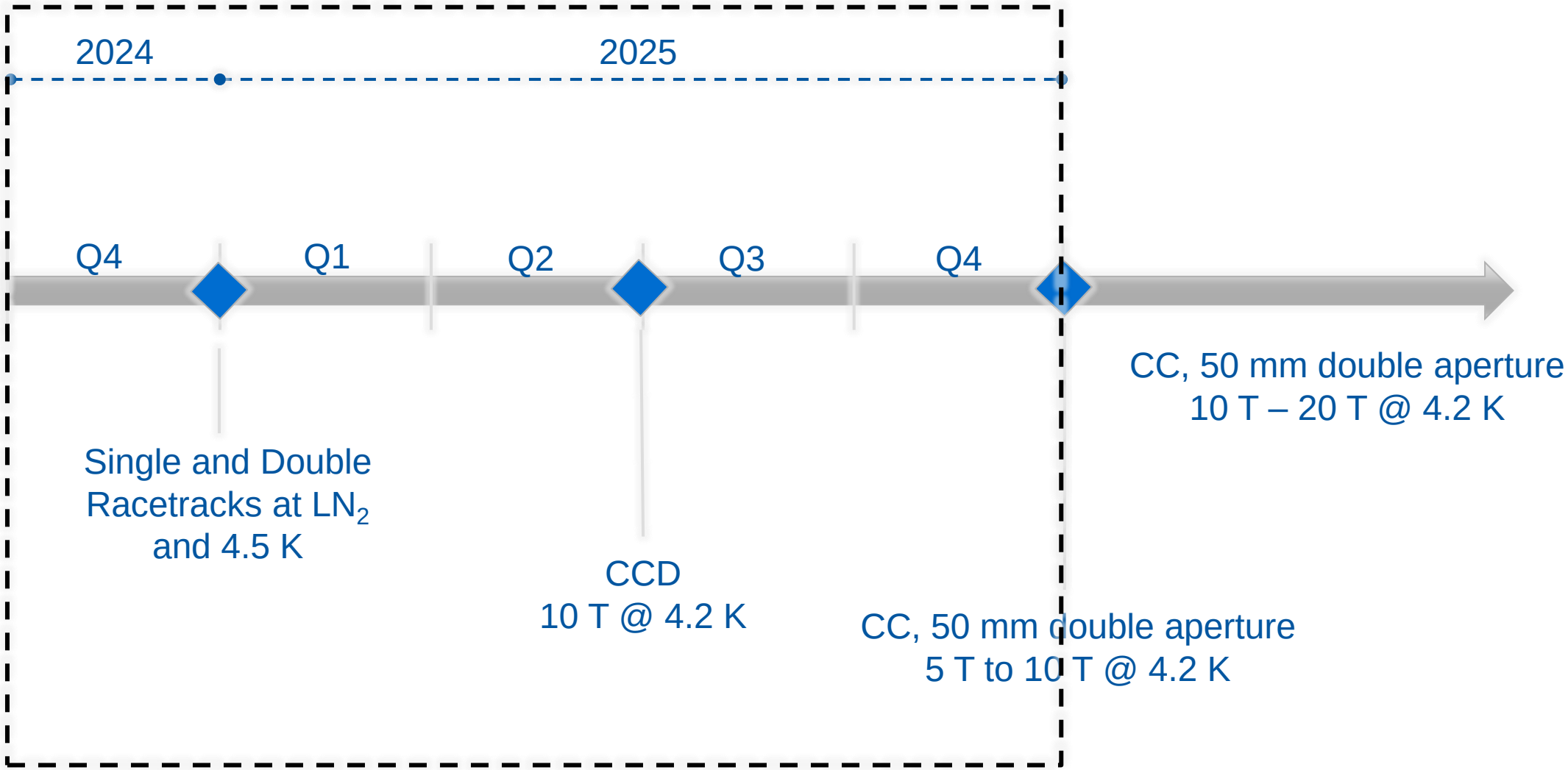
Upcoming Milestone



Achieved (2024):

- Launched procurement of REBCO tape
- Procured THEVA Tapestar™
- Launched Racetrack Model Coil Program (Single and Double racetracks)
- Developed REBCO Tape test equipment

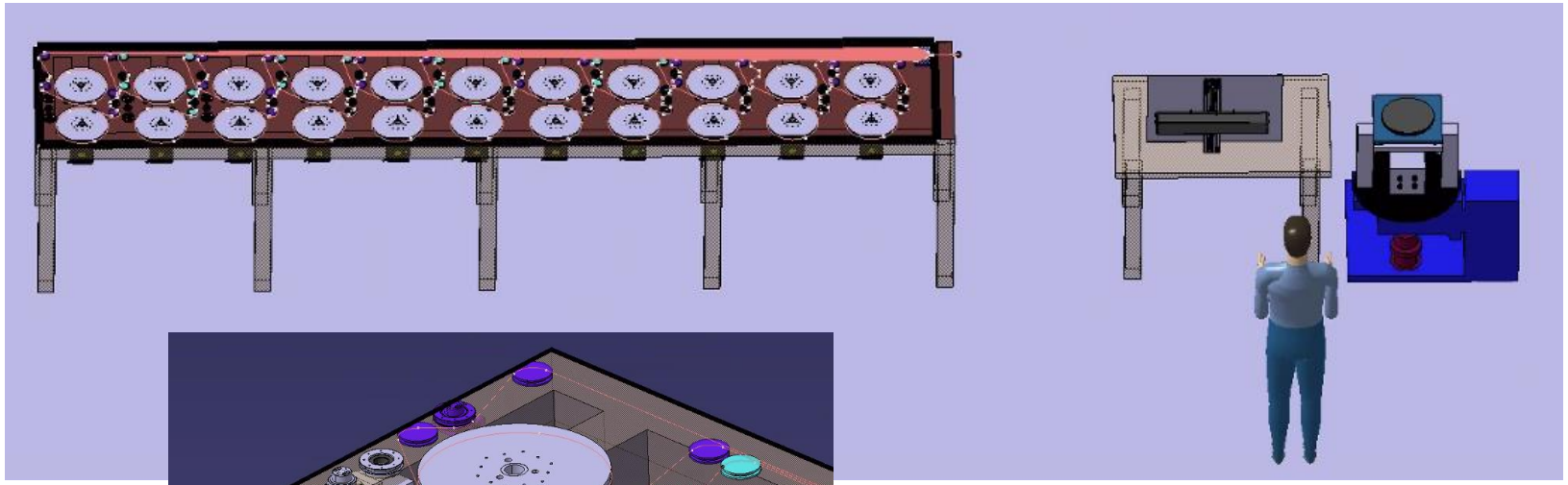
Upcoming Milestones

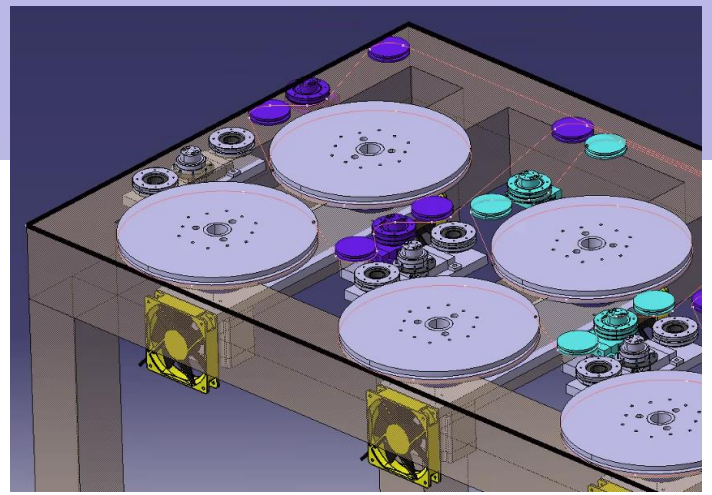


Development of cables, with different layouts, tested in a single racetrack configuration

New winding machine

Toward higher fields





- **On-going** development for **operation in 2025**
- Winding of up to **22** tapes
- Electronic control of tension of each tape

Upcoming milestones

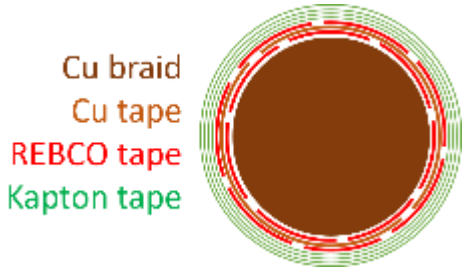
- Procurement of a laser cutting machine, to be used also for implementing striations in a tape
- On-going survey with tape manufacturers and laboratories to identify technical specification and potential suppliers

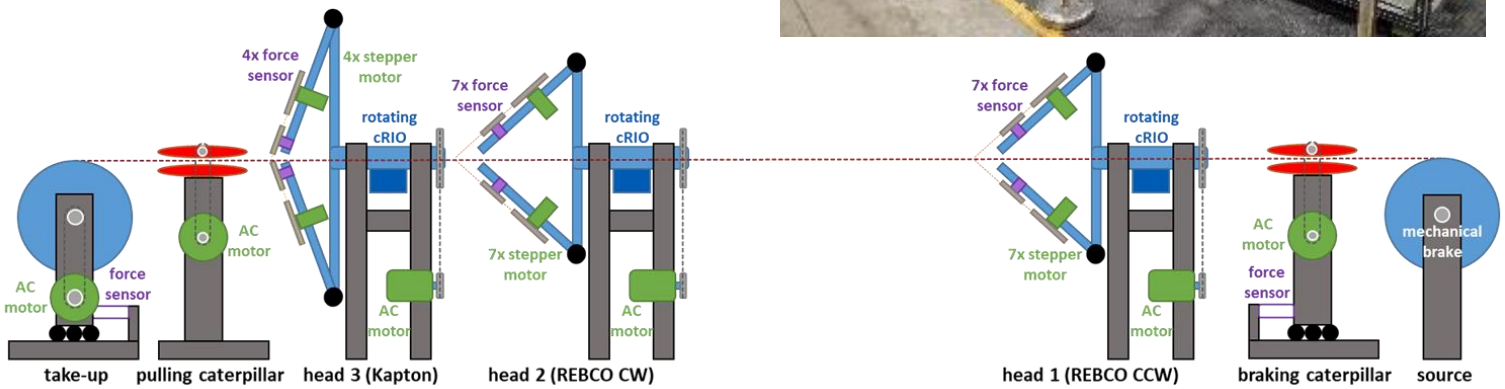
Other Cables and Magnet Geometries

Round REBCO Cables, HL-LHC WP6a

Cabling machine operated in building 927

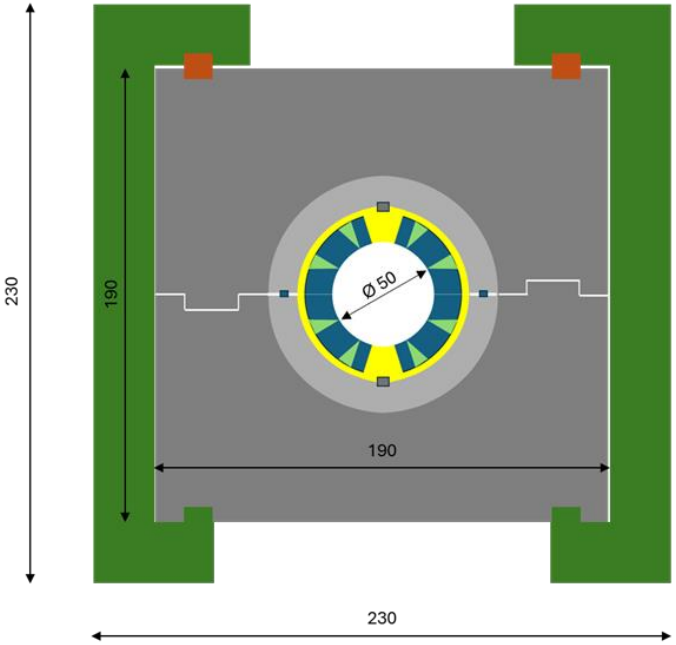
Up to 18 kA @ 25 K, s.f.





On-going study

Cos-theta geometry



Suitable for **CCT** coils – activities at LBNL

Implementation of strategy – Progress - Milestones

REBCO
Iron Based Superconductors

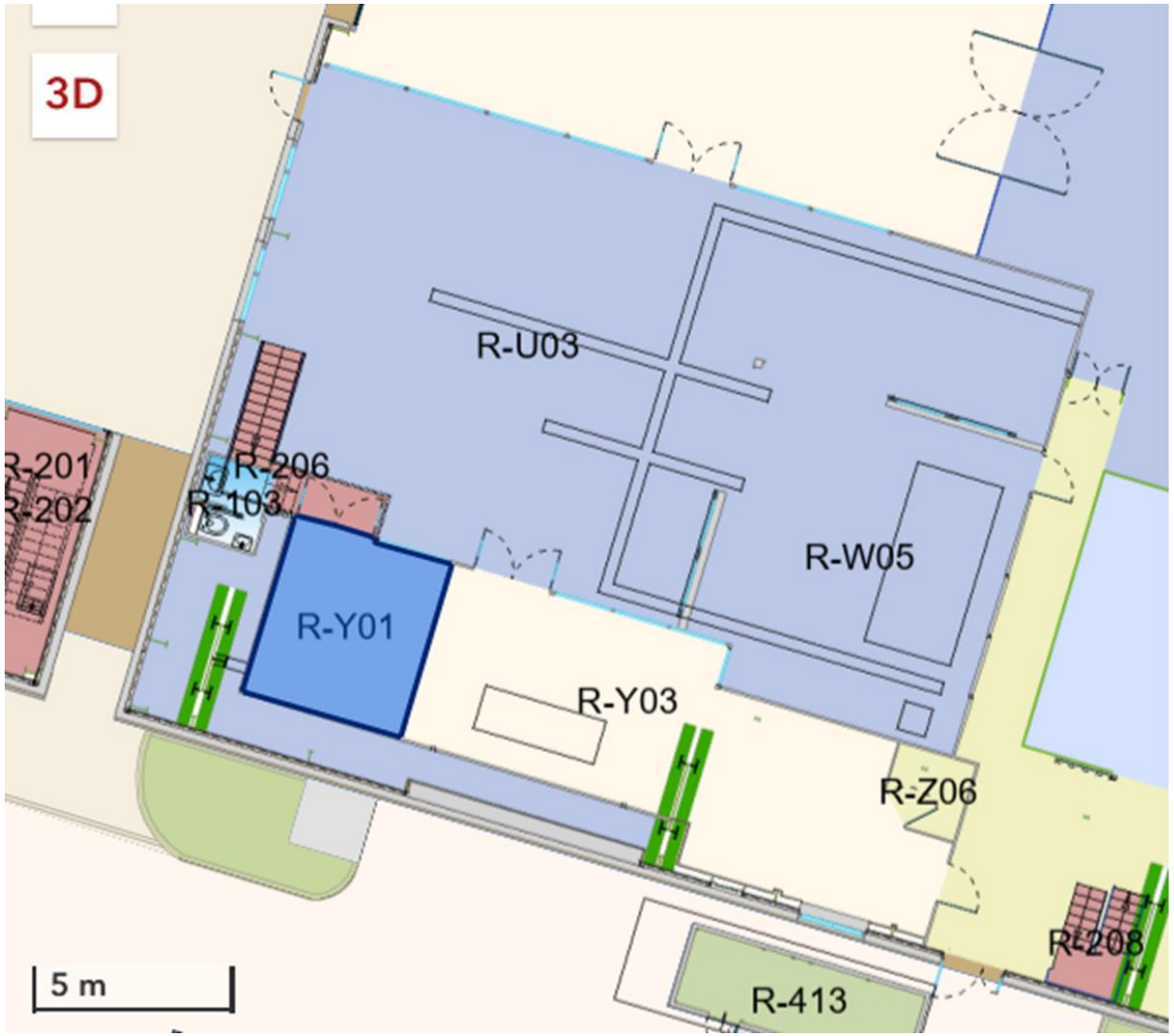
Demonstrator Coils and Milestones

Laboratory

Laboratory for HTS activities

- A dedicated laboratory for HTS activities
- It will be used for:
  - Conductor analysis and related equipment (optical image, SEM, reel-to-reel measurements at RT and in LN_2,…)
  - Cable short length development
  - Measurements in LN_2
  - Coil winding and assembly
- Tooling for CCD will be installed in the new laboratory

Laboratory for HTS activities



Building 180, Jura corner.
Ground floor

HFM

High Field Magnets Programme