Workshop on ultra high field solenoids 2025, Nov 25 – 26 2025, CERN

Advances in UHF solenoids for the EMFL:

SuperEMFL and FASUM projects
for towards 30 to 40 T high field all SC user magnets

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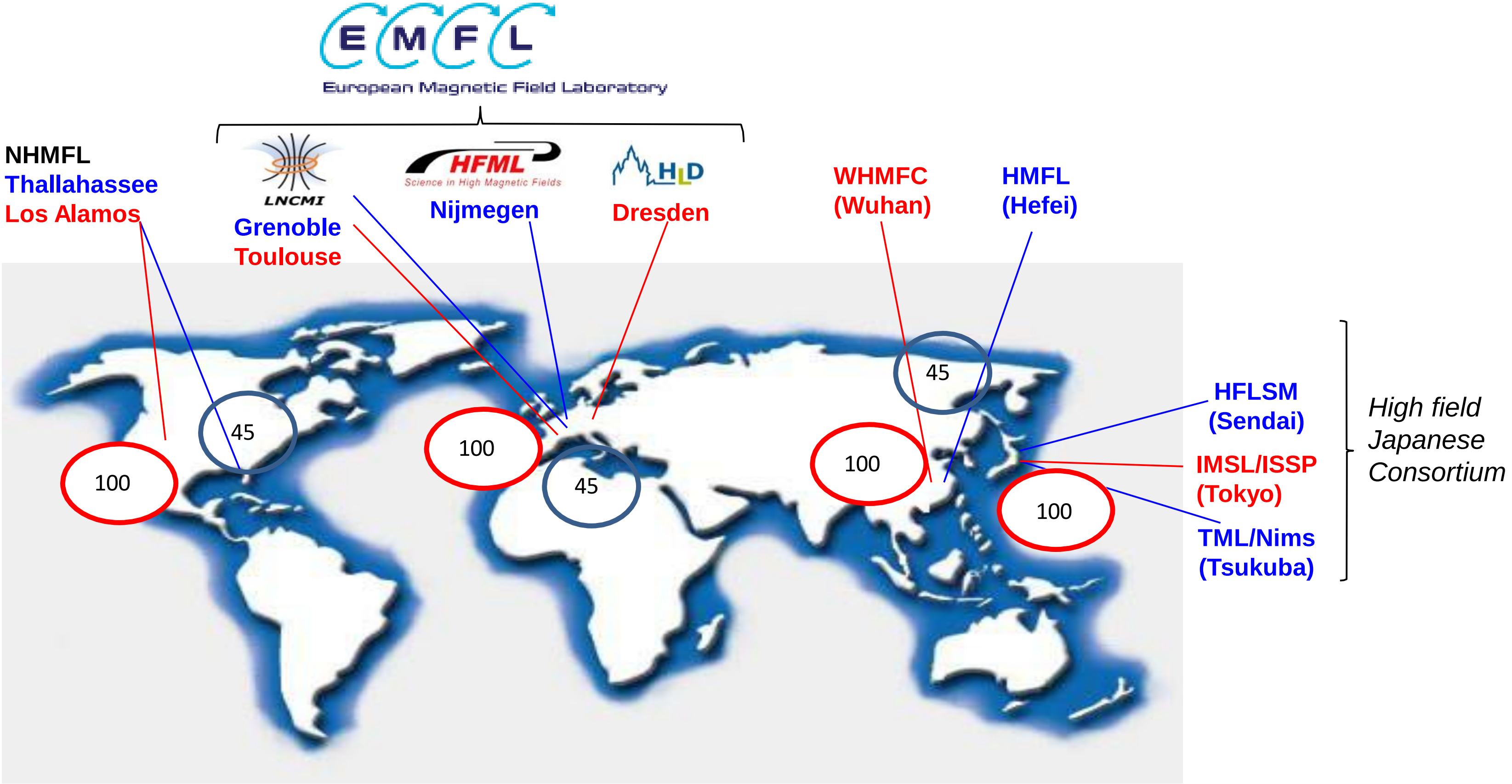
High magnetic field facilities (Pulsed and DC)

- 30 MW power supply
- 300 l/s water cooling

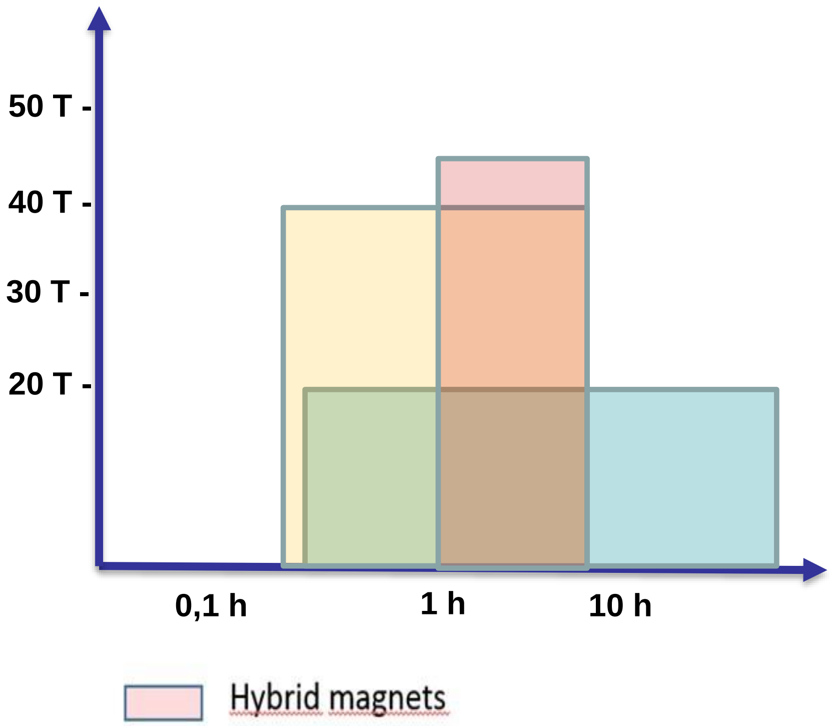
Resistive magnets	Hybride
10 T in 376 mm bore ➔	17 T
20 T in 170 mm bore ➔	27 T
31 T in 50 mm bore ➔	38 T
37 T in 34 mm bore ➔	42 T in 2025



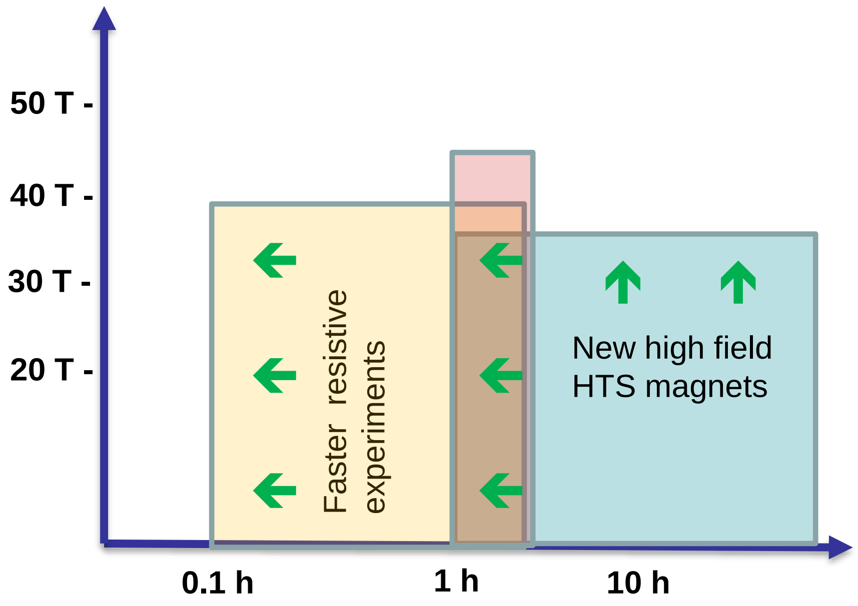
EMFL is gathering the European High Magnetic Field facilities producing pulsed fields up to 100 T and DC fields up to 45 T.

Maximum magnetic field and experiment duration

« Today »



In the future : including HTS magnet



Combined use of resitive and HTS magnets permit to :

- Reduce the duration of resistive experiments (30 MW)
- Long duration experiments for « new » sciences

HTS project for UHF magnet in LNCMI

A recently completed UHF project (2025): SuperEMFL supported by EU Horizon 2020

Design stage (phase1) for development of very high field all superconducting magnet (11 partners)

Ongoing UHF HTS project – FASUM supported by ANR

Construction and installation of all superconducting user magnet

(1) 40 T/25 mm all superconducting magnet or (2) 32 T/38 mm all superconducting magnet for end-users

Design 40 T magnet for FASUM/SuperEMFL

[1] M. Durochat *et al.*, "Design of All-Superconducting User Magnets Generating More Than 40 T for the SuperEMFL Project “, *IEEE* TAS **34** (2024) 4904305 doi: 0.1109/TASC.2024.3368997

Simple insert (of the NOUGAT type) with a 19 T LTS magnet in a 150 mm bore do not allow reaching 40 T with a winding diameter of 50 mm (34 mm user bore) while maintaining sufficient margins and manageable stresses; the feasible options are 40 T/40 mm or 38 T/50 mm.

Simple Solenoid

Name	***Basic Design***		***High Field***		***High Volume***
Ref.	***S1***	***S2a***	***S2b***	***S2c***	***S3***
Design led by	Mechanics	Mechanics	Mechanics	Mechanics	Mechanics
Geometry					
Internal diameter (winding)	**40 mm**	**30 mm**	**40 mm**	**50 mm**	**42 mm**
External diameter (winding+ob)	122.8 mm	121.2 mm	122.8 mm	125.4 mm	124.8 mm
Number of double-pancakes	25	25	25	25	25
Turns per pancake	380	420	380	360	380
Total length	4769.3 m	4888.6 m	4769.3 m	4959 m	4769.3 m
Electrics					
SC conductor			THEVA APC		
Nominal current	293 A	303.9 A	308.9 A	283.3 A	295.4 A
Critical current	388.1 A	373.1 A	389.1 A	398.1 A	389.2 A
Current margin on load line	**24.5 %**	**18.5 %**	**20.6 %**	**28.8 %**	**24.1 %**
Magnetics					
Magnetic field at center (HTS alone)	**21 T**	**24 T**	**22 T**	**19 T**	**21 T**
Total Magnetic field at center	**40 T**	**43 T**	**41 T**	**38 T**	**40 T**
Mechanics					
Winding tension			100 MPa		
Turns of over-banding			50		
Maximal hoop stress	**655.8 MPa**	**677.9 MPa**	**707.3 MPa**	**667.2 MPa**	**678.6 MPa**
Non-thermal deformation (winding+field)	0.37 %	0.38 %	0.39 %	0.37 %	0.38 %

Thermal and mechanical analysis during quench event

[1] P. Fazilleau *et al*., "Behavior During Quenches of a 40 T Magnet Made of LTS and HTS Parts ", *IEEE* TAS **34** (2024) 4704805 doi: 10.1109/TASC.2024.3370138

Thermal Analysis Results:

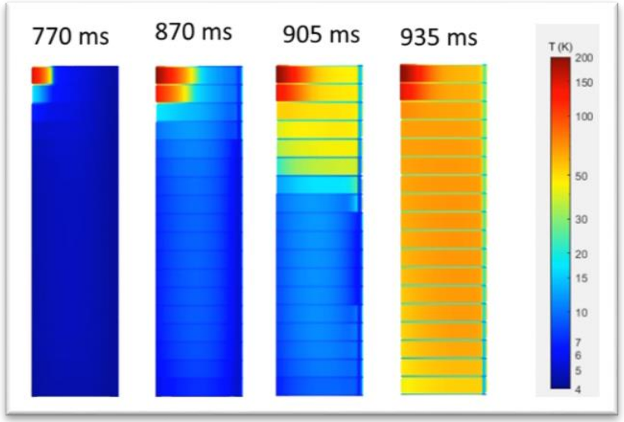
- The thermal analysis confirmed that the proposed magnet designs operate safely during quench events.

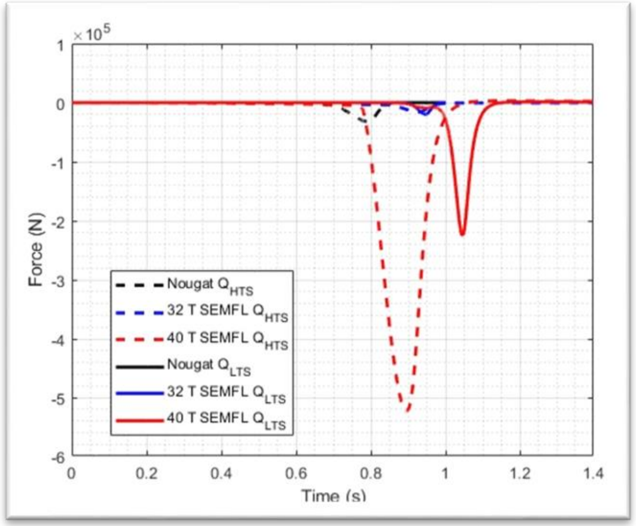
Mechanical Analysis Summary:

- Evaluated decentering forces between HTS and LTS magnets, including quench-induced forces.
- Worst case: HTS quench generates large asymmetric forces (tens of tons) on LTS magnet.
- Mechanical reinforcement is required, reducing HTS bore from 150 mm → 140 mm.

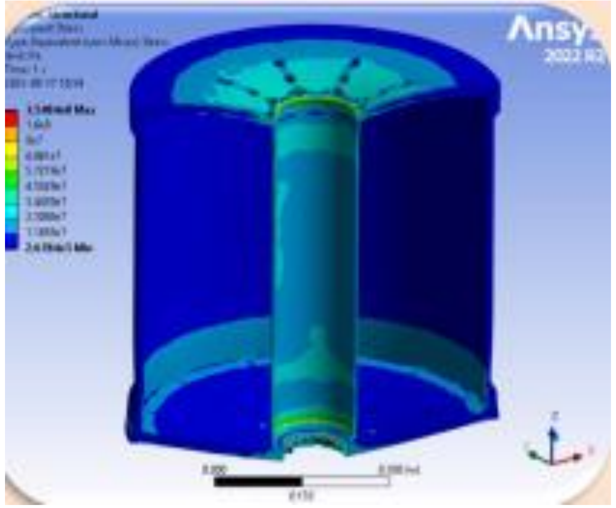
A detailed overview of the mechanical analysis of the FASUM magnet will be presented by Thibault de Chabannes La Palice on the 26th at 09:30.

Temperature evolution in the HTS insert during quench





Resulting axial forces



Renforcement of OI magnet

The LTS outsert

- Designed and fabricated by Oxford Instruments (OI)

Specifications

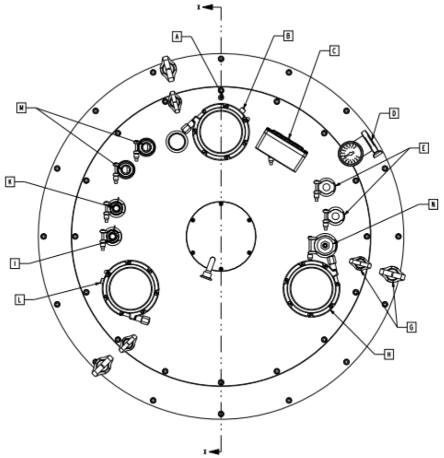
Magnet

Central field only	19 T @ 4.2 K
Homogeneity:	≤ 0.05% (500 ppm) over a 1 cm DSV
Magnet bore diameter	150 mm
Usable cold bore space	140 mm
Operating current	≤ 240 A at 19 T
Inductance	267 H
Stored energy	5.6 MJ
Ramp time to 19 T	2 hours
Magnet weight	850 kg

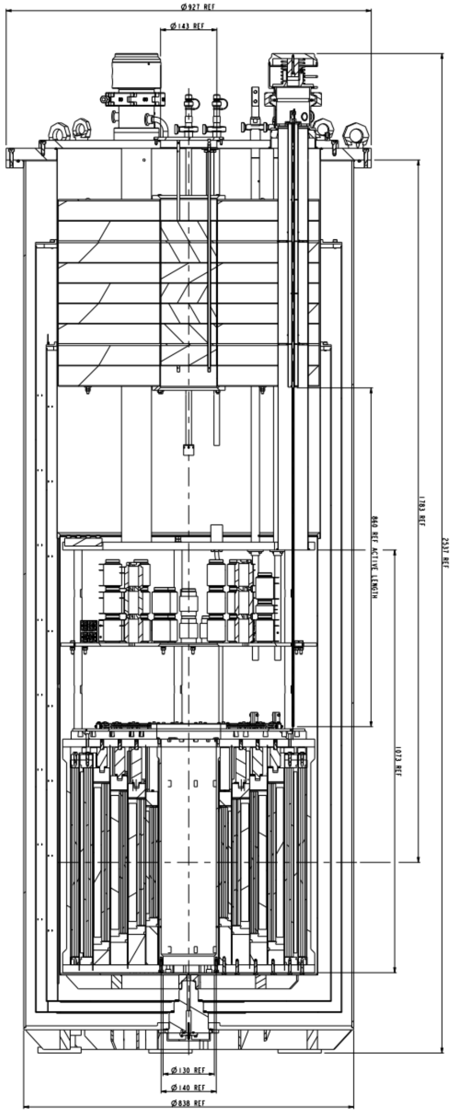
- **1400 L of He for cooldown**
- **Capacity: 280 L He (310), 150 L usable**
- **Static consumption: < 2 L/h**
- **With current: < 3.5 L/h**

Cryostat

Upper and lower flange diameter	838 mm
Total height	2537 mm
Central access diameter to the magnet	142 mm (compatible with insert rod and Oxford VTI)
Distance from upper flange to maximum field line	1833 mm
Weight of cryostat and magnet support	1510 kg (without cryogens)
Minimum ceiling height required	**4.6 m plus clearance for hoist and slings**



	DESCRIPTION	
A	EARTHING POINT	M6
B	He LEVEL PROBE	FISCHER
C	25 WAY MAGNET DIAGNOSTICS	-
D	OVC VACUUM PORT	NW40
E	CUSTOMER HTS CURRENT LEADS	NW25
F	CUSTOMER WIRING	NW40
G	LIFTING EYE BOLTS	-
H	RELIEF VALVES - 3 OFF	NW80
I	SYPHON ENTRY PORT - COOLDOWN	12.7
K	SYPHON ENTRY PORT - REFILL	12.7
L	ERDU ELECTRICAL PORT (MAGNET HEATER)	-
M	SYSTEM CURRENT LEADS	NW25
N	He EXHAUST	NW40
P	MAGNET SENSOR	FISCHER

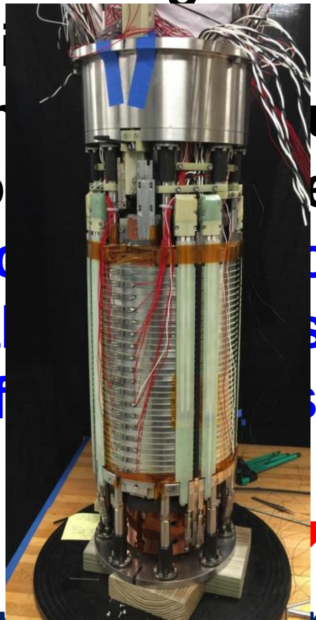


Conductor requirements for HTS magnet applications

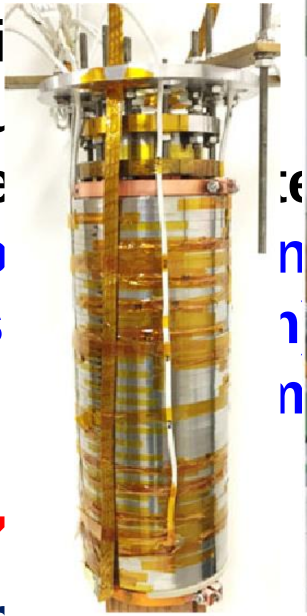
Very-high field magnets

- Compact size
- Small winding bore

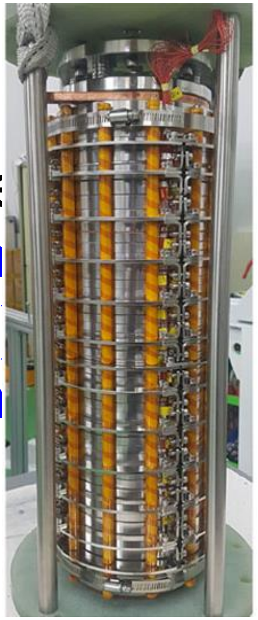
LNCMI



NHMFL



MIT



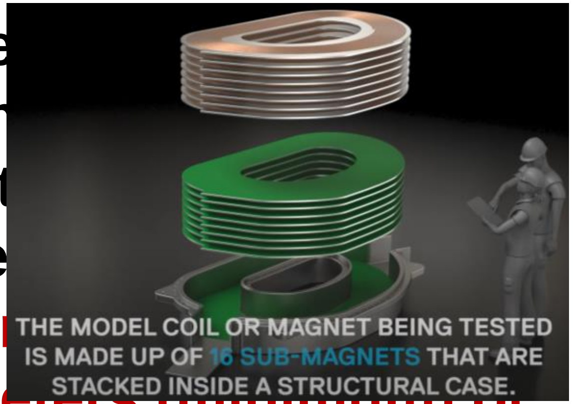
SUNAM

Key requirements:

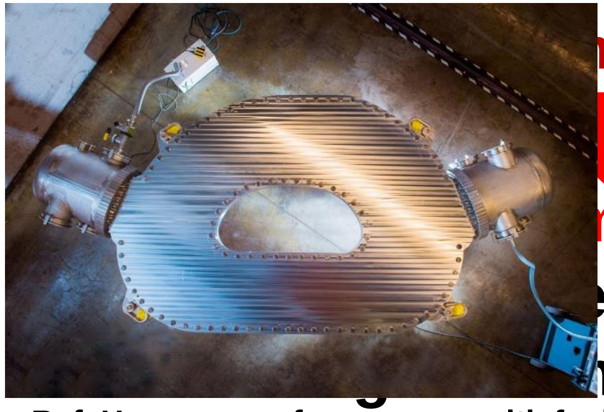
- High current density
- High mechanical strength
- Highest physical qualities

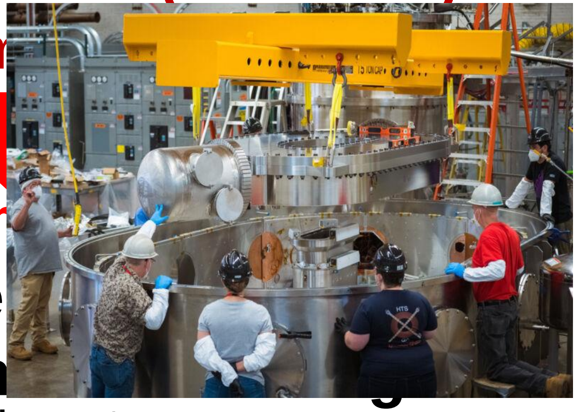
Fusion or accelerator magnets

- Huge size



Hundreds of kilometers (minimum) of





Ref. Homepage of commonwealth fusion system

- Long piece length
- Lowest price

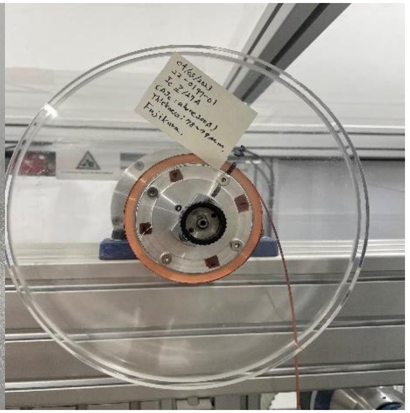
Performance evaluation of various REBCO tapes

Selected 4 providers: THEVA, SST, FFJ, and Fujikura

TV
(THEVA)

SST
(Shanghai Superconducting Tech.)

FFJ
(Faraday Factory Japan)



FJK
(Fujikura)

Physical description of REBCO tapes provided by suppliers

	Unit	THEVA	SST	FFJ	Fujikura
Width	[mm]	6 ± 0.1	6 ± 0.1	6 ± 0.1	6 + 0.2
Stabilizer thickness per side	[um]	10 ± 2	10	10 ± 3	5
Substrate thickness	[um]	50	45	37 ± 3	50
Total thickness	[um]	63 - 89	75	No mark	75 - 76
Production date of old tape		Sep. 2022	Sep. 2022	Oct. 2022	Dec. 2022
Production date of new tape		Jan. 2024	Nov.2023 Feb. 2024	May. 2024	-

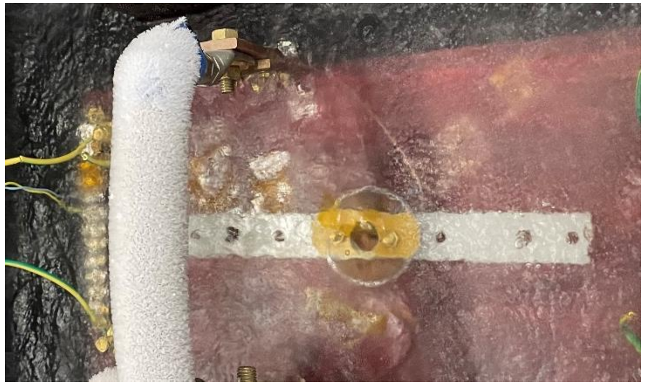
Check

1. Resistance and I_c values of joining samples in 77 K
2. Delamination
3. Uniformity and deformation of windings
4. Characterization results of REBCO tapes

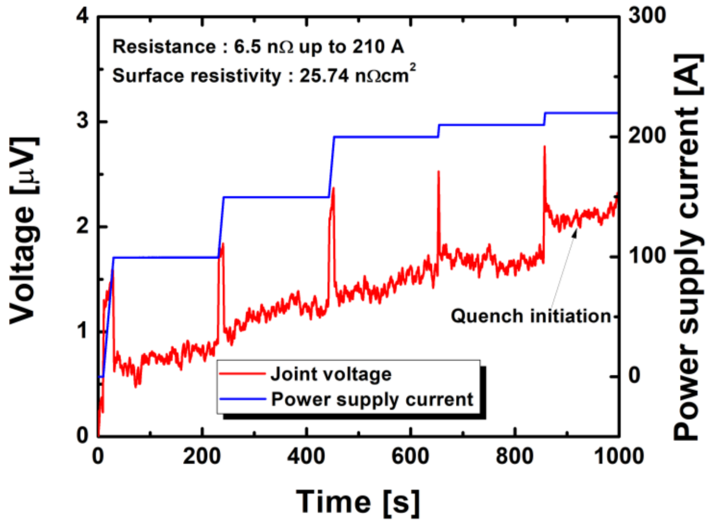
[1] J. B. Song *et al.*, "Estimation of Physical and Electrical Properties of Various REBCO Tapes for Construction of Very-High-Field REBCO Magnet", *IEEE* TAS **34** (2024) 6600205 doi: 10.1109/TASC.2023.3340134

[2] J. B. Song *et al.*, "Evaluation of the physical qualities and electrical performances of HTS mock-up magnets wound with various REBCO tapes under external fields at 4.2 K ", Accepted in *IEEE* TAS (2025 November).

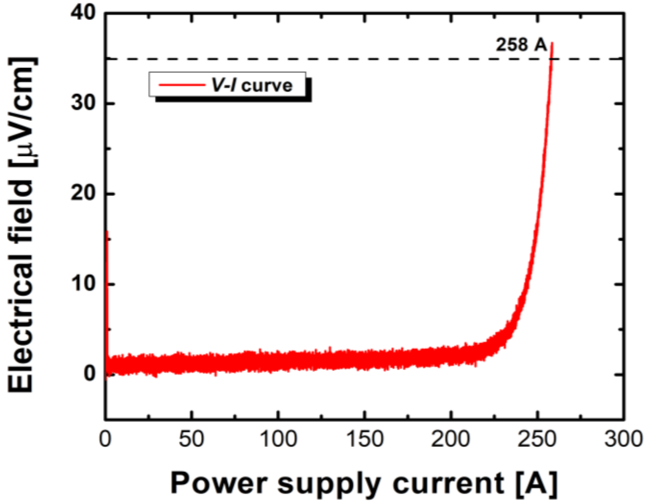
Joint estimation of REBCO tapes at 77 K



Tests of a joining sample in bath of LN2 at 77 K



Estimation joint resistance



I_c Estimation of joining sample

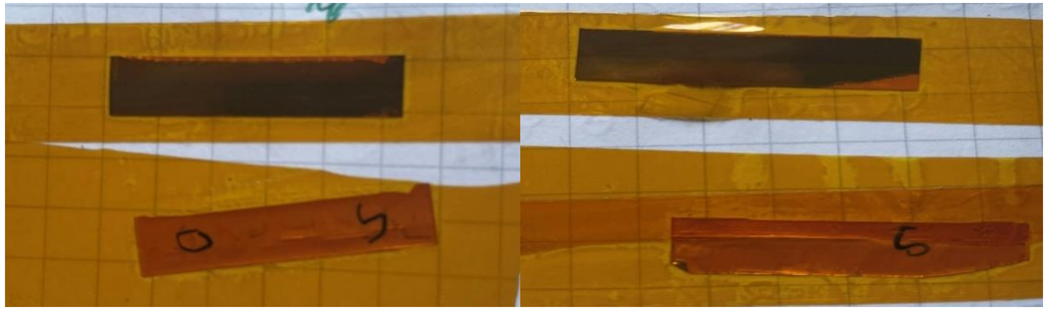
	Unit	THEVA	SST	FFJ	Fujikura
Minimum (Aver.) I_c value of HTS joint pieces at 77 K	[A]	130 (180)	224 (267)	272 (330)	200 (250)
Minimum I_c (Aver.) value of conductor at 77 K	[A]	220 (260)	224 (267)	179 (249)	200 (250)
Average joint resistance of joining samples at 77 K	[nΩ]	6.1	16.8	6.5	11.3
Average surface resistivity of the samples at 77 K	[nΩ·cm^2]	24.2	60.6	25.7	44.75
Average I_c value of the joining samples at 77 K	[A]	218	263	258	274

Delamination check

Old REBCO tapes manufactured in 2022

1. Removing polyimide tape

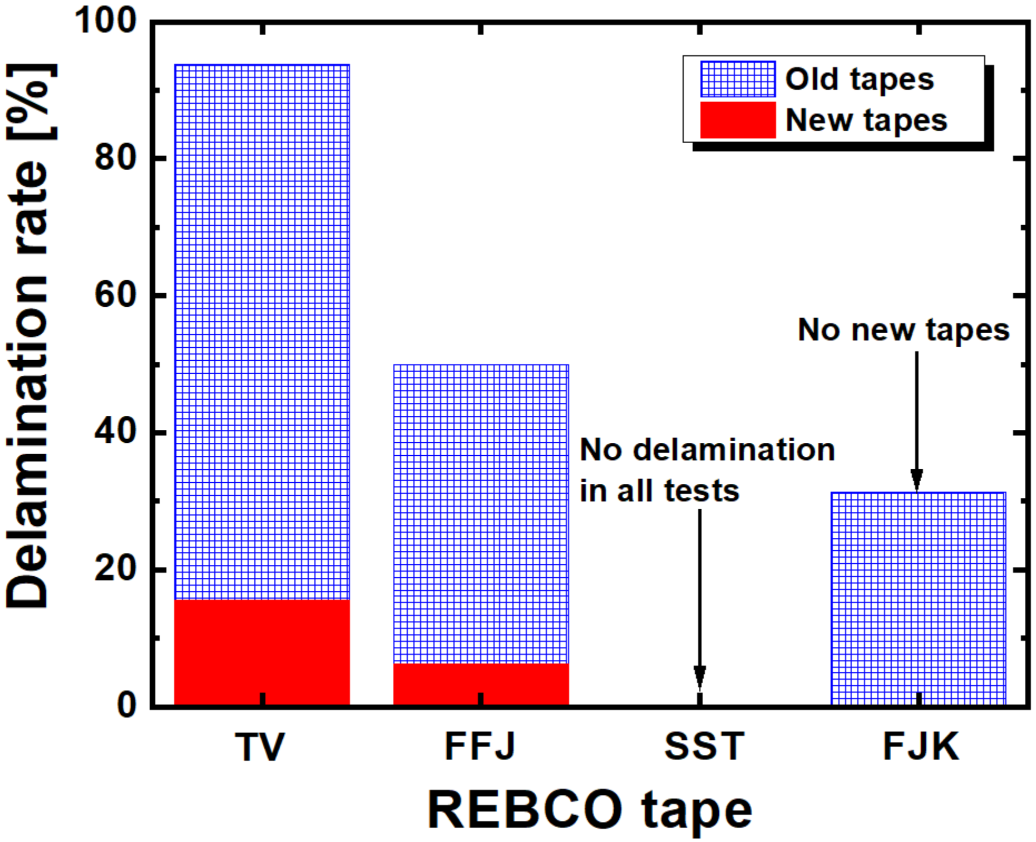
Three REBCO tapes: THEVA, Fujikura and FFJ



2. Cutting REBCO tapes after pre-tinning

Two REBCO tapes: THEVA and FFJ

New REBCO tapes manufactured in 2023-24

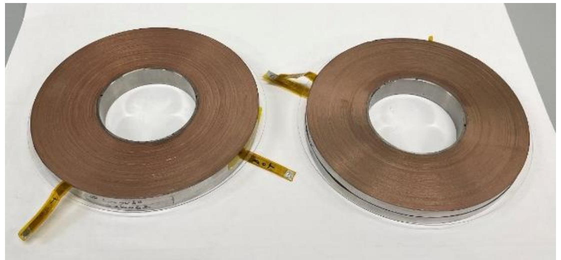


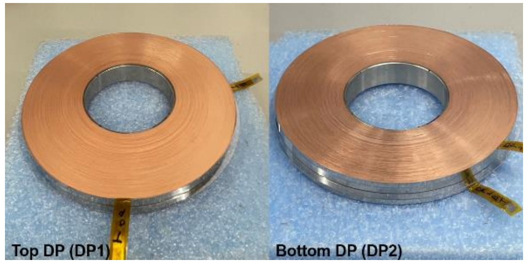
Old tapes vs. New tapes

Windability of old and new REBCO tapes

Old THEVA

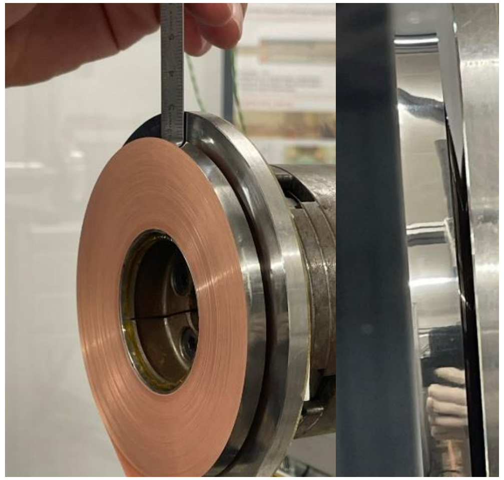
New THEVA





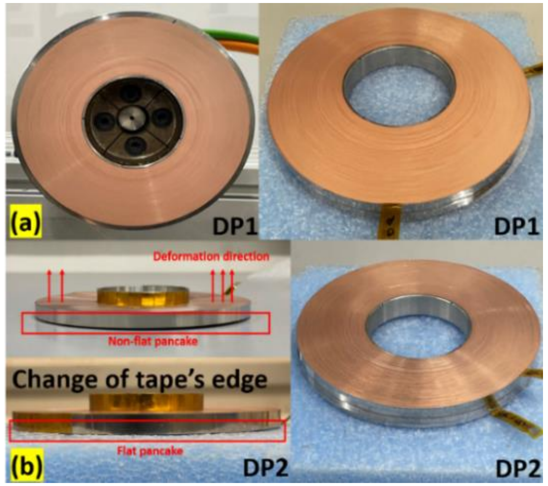
Perfect winding at WT of 100 MPa WO deformation

Old SST



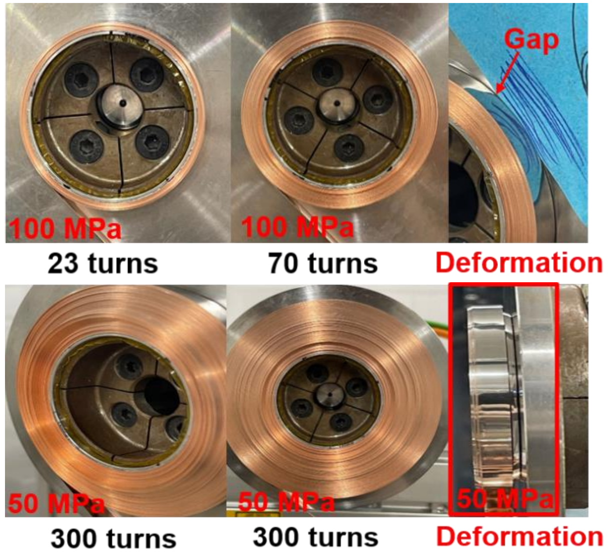
Conical shape deformation
Starting from 60 MPa

New SST



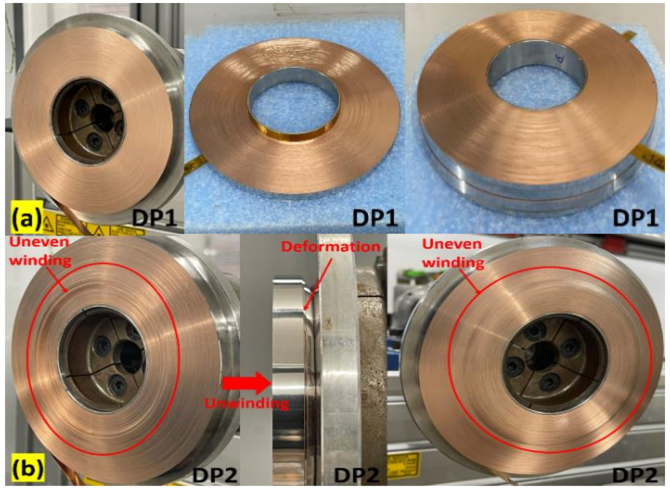
Enhanced winding capability, with partial deformation dependent on the spool

Old FFJ



Uneven and deformed winding

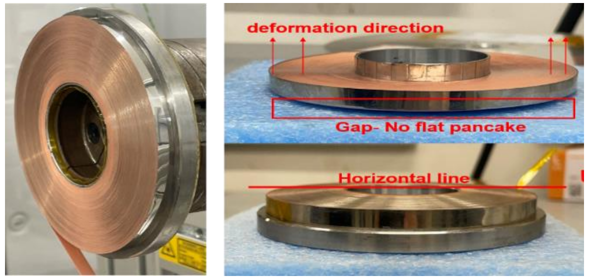
New FFJ



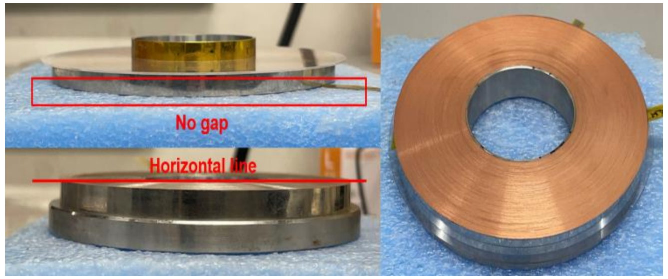
DP1: Success,
DP2: Uneven and deformation

Old FJK → Old FJK

Changed edge direction

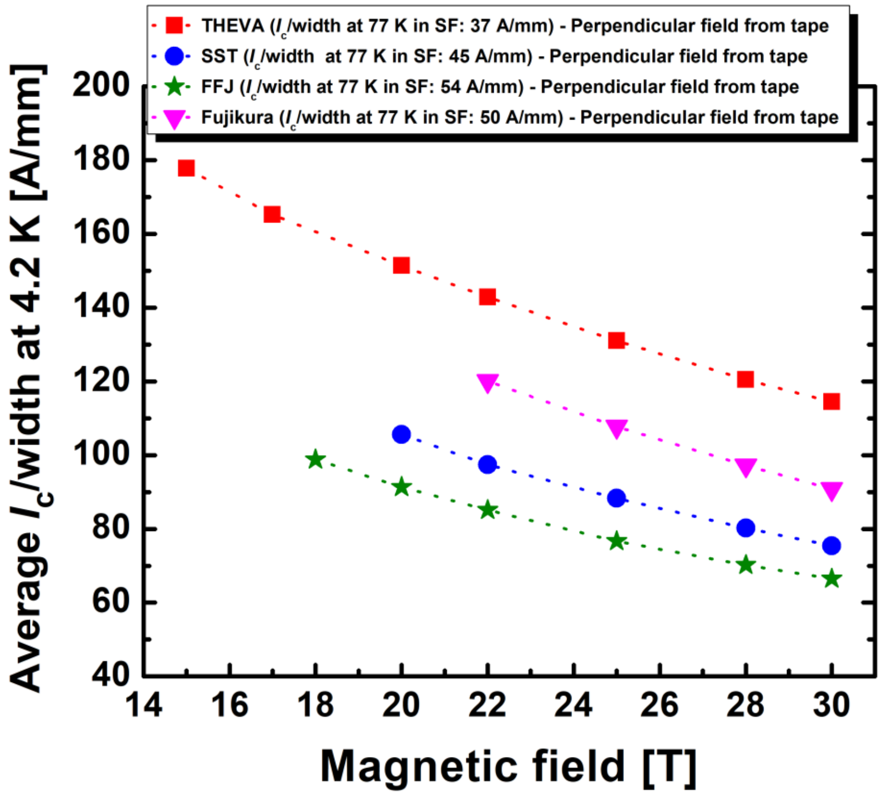


Suddenly deformation

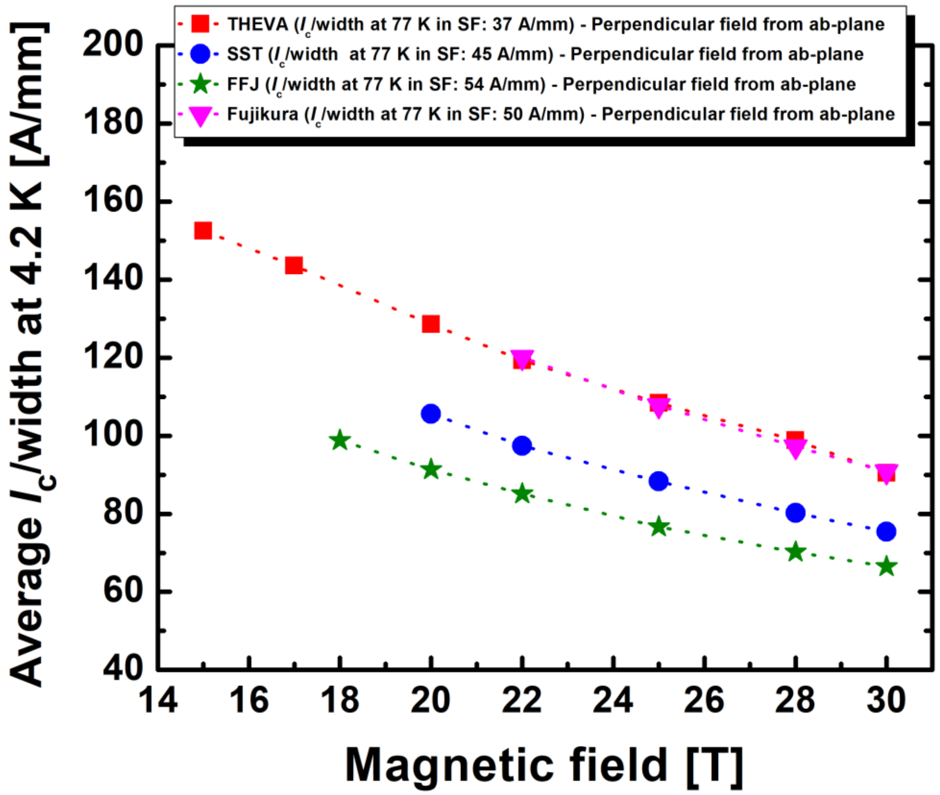


Moderated deformation

Current carrying capability per unit width



I_c/mm at 90 degree from tape



I_c/mm at 90 degree from ab-plane

All 50 µm substrate, except FFJ 38 µm

All tapes show good performance (J_c >1000 A/mm^2)
@ 4.2 K under a 30 T field perpendicular to ab-plane

Summary

Old tapes (2022) vs. New tapes (2023-2024)

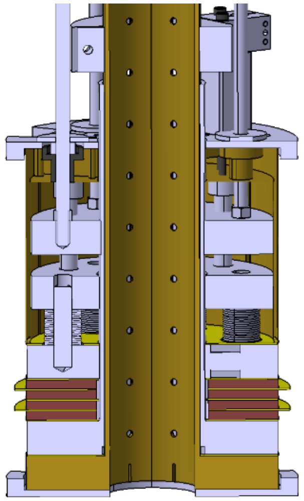
	THEVA	SST	FFJ	Fujikura
Delamination strength	☹ ➡ ☺	☺ ☺	☹ ➡ ☺	😐
Joint resistance	☺ ☺	☺ ☺	☺ ☺	☺ ☺
Winding uniformity	☺ ☺	☺ ☺	☹ ➡ 😐	☺ ☺
Winding deformation	☺ ☺	😐 ➡ ☺	☹ ➡ 😐	😐
Thickness accuracy	☺ ☺	☹ ➡ ☺	☺	😐

☺ ☺ : Perfect, ☺ : Usable (Check), 😐 : Limited (Check) , ☹ : Not usable

Note: There is no estimation for the new version of FJK tape in this summary.

- In terms of electrical property, all tapes show good performance (J_c >1000 A/mm^2) under perpendicular field of 30 T from ab-plane at 4.2 K.
- The new REBCO tapes manufactured in 2023-24 exhibit enhanced physical properties, yet further improvements in thickness uniformity and winding stability are required.

The construction of three mock-up magnets
- TV (new), SST (new) and FJK (old)

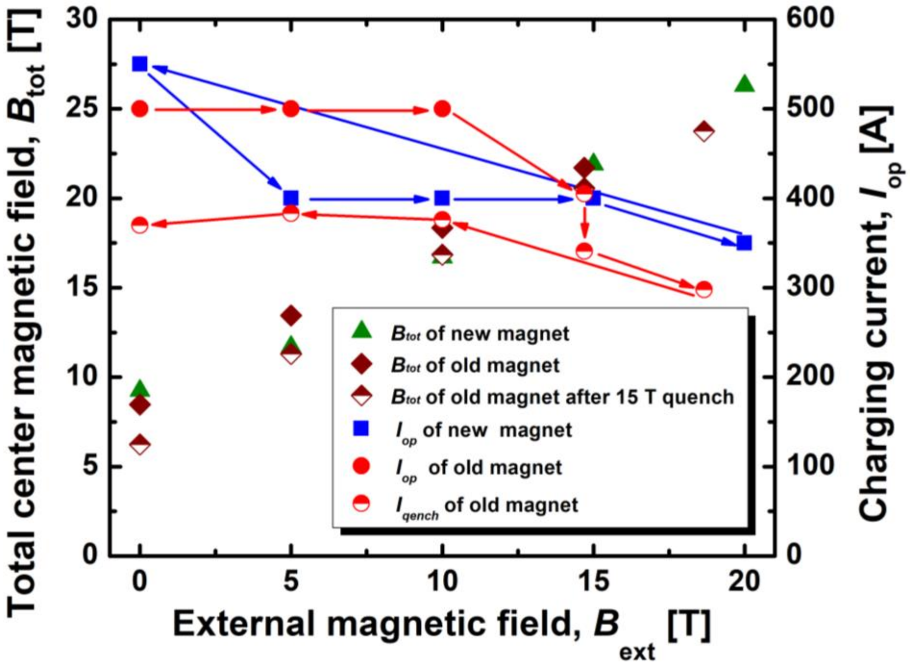


A schematic drawing and a picture of constructed three mock-up magnets.

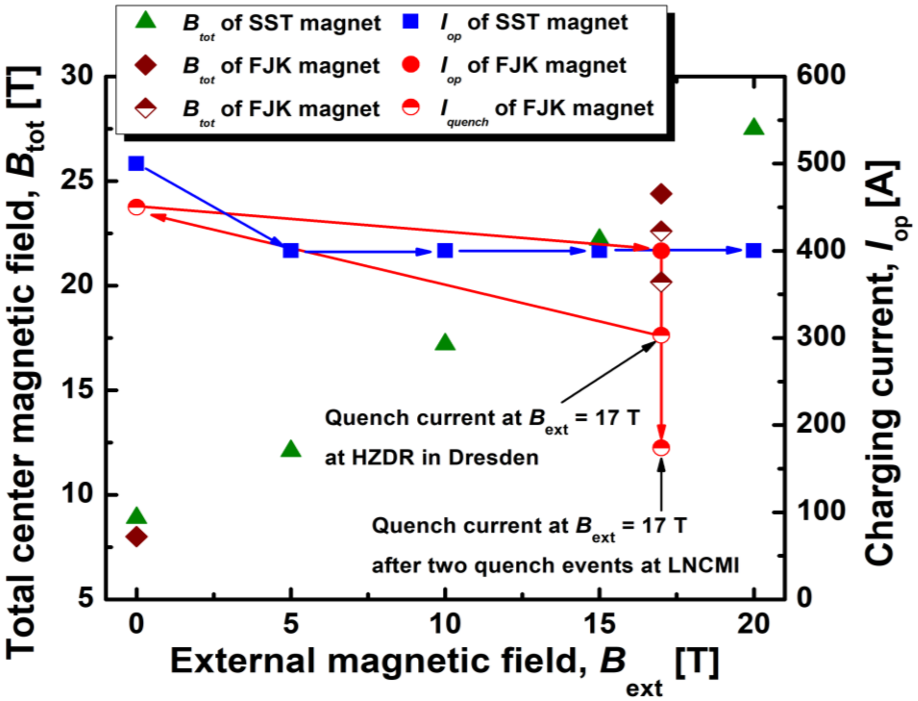
Specifications of three mock-up magnets

Parameters		TV	SST	FJK
Number of DP		2	2	2
Average ID; OD	[mm]	50; 111.5	50; 111.4	50; 113.8
Number of turns per SP		281	295	304
Winding tension	[MPa]	100	100	50
Overbanding turns		48	48	48
Overbanding tension	[MPa]	100	100	100
Coil constant	[mT/A]	17.2	18.2	18.5
Magnet inductance	[mH]	83	91.6	98.5
Quench initiation current @ 77 K in SF	[A]	48	47	52

Charging tests of the magnets



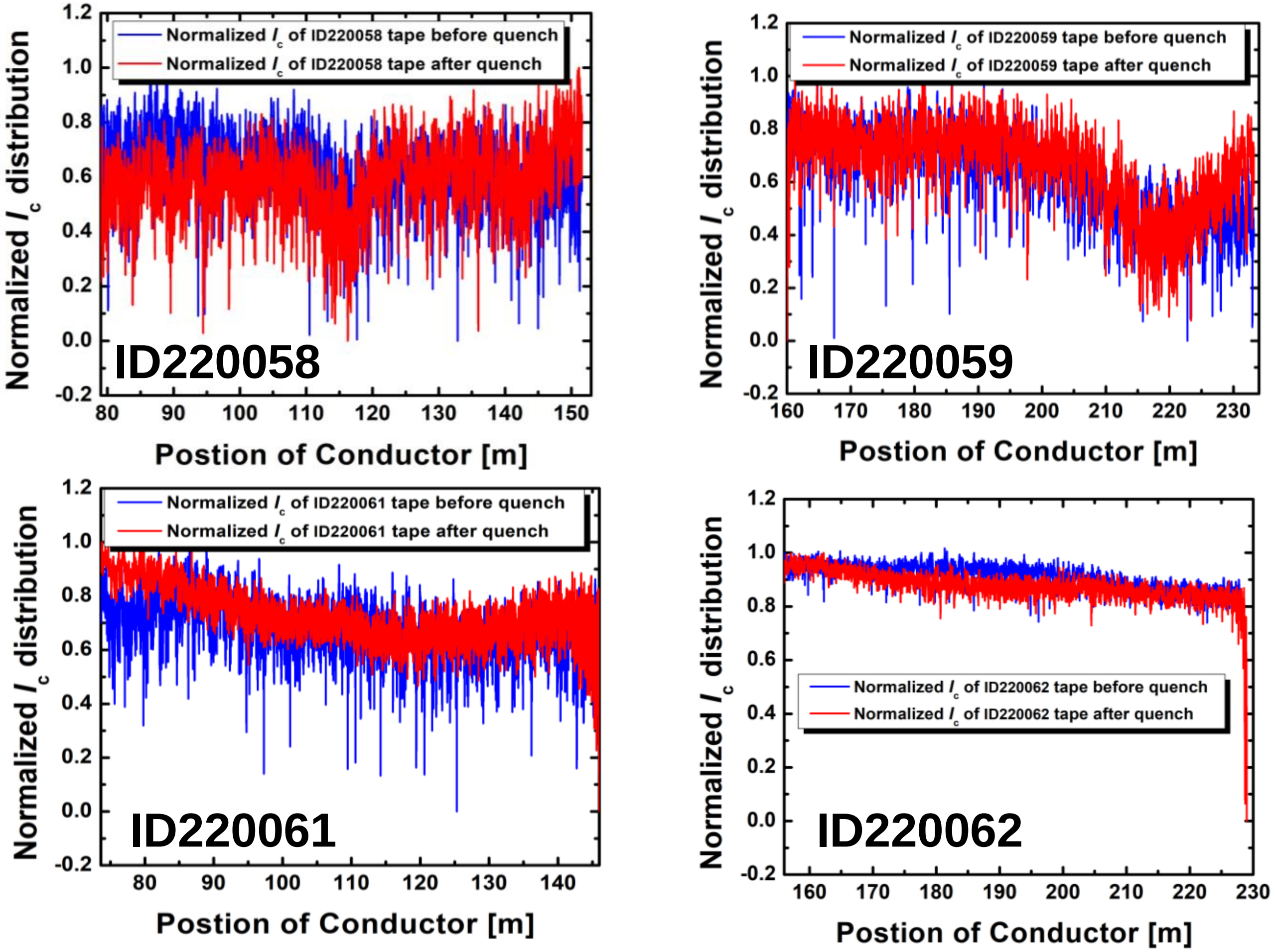
I_{op}/I_{quench} and B_{tot} of old and new TV magnets under various B_{ext} at 4.2 K



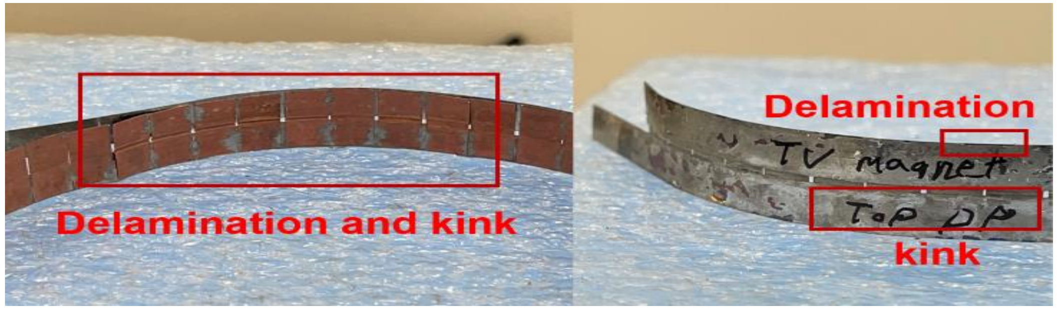
I_{op}/I_{quench} and B_{tot} of SST and FJK magnets under various B_{ext} at 4.2 K.

- At B_{ext}= 20 T, B_{ext} of the new TV and SST magnets were 26.3 T and 27.5 T, respectively.
- The old TV and FJK magnets were degraded by unexpected quench event during charging.
- The weak delamination strength of tape is a critical issue not only for magnet fabrication but also for high field operation/protection of the magnet.

I_c distribution of old TV tapes before and after quench



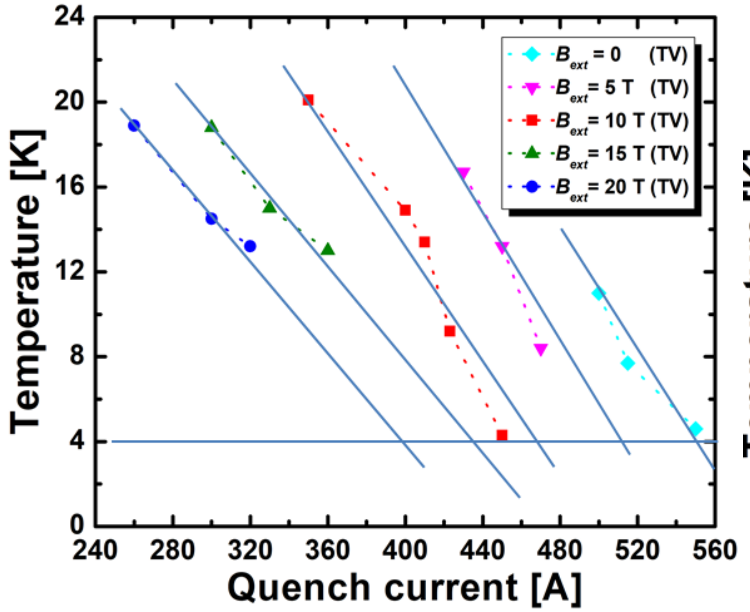
I_c distribution along the conductor length of each SP coil before winding and after quench tests



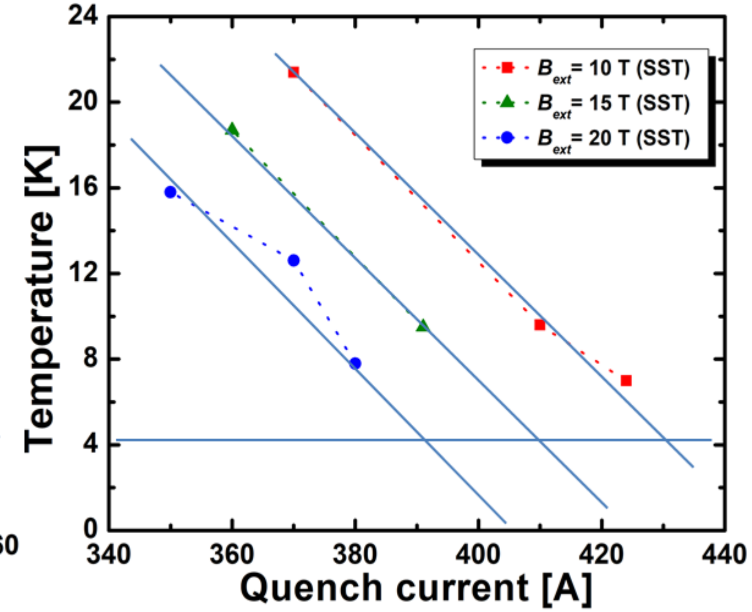
Photographs of the internal electrical junction between SP after quench events.

- Electrical junctions were delaminated
- Windings were not damaged
- Due to the weak delamination strength of the tape, it is easy to damage the junctions during high magnetic field charging and quenching of the magnet

Quench tests of the magnets

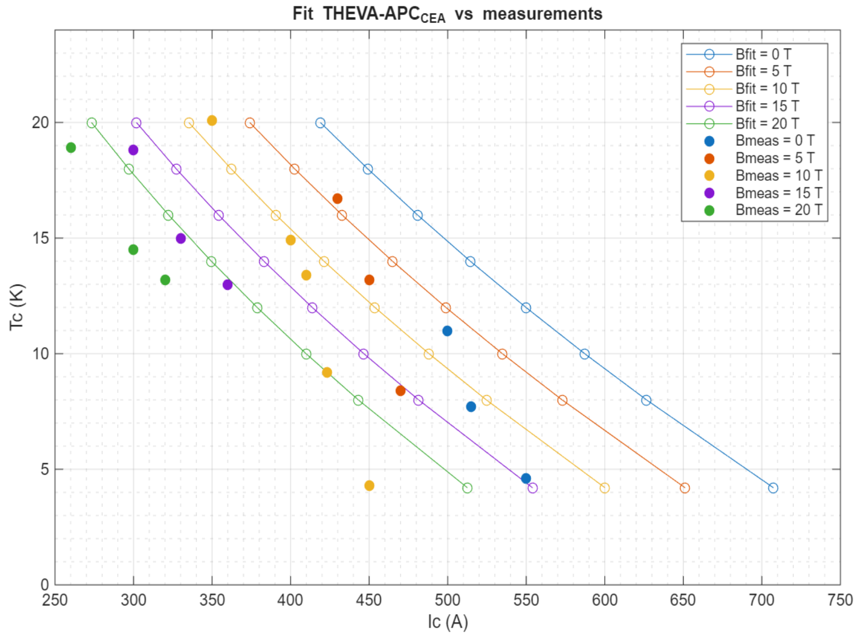


(a) TV



(b) SST

Quench currents of new TV (a) and SST (b) magnets



Calculated I_c and measured quench currents of TV magnet

Calculated I_c values of TV and SST tapes at 4.2 K

External field		Critical current	
		TV	SST
0	[A]	718	593
10 T	[A]	608	568
20 T	[A]	511	529

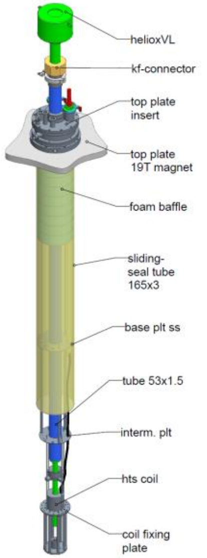
Experimental quench current < calculated I_c
Local degradation of the winding (joints, winding, etc.)

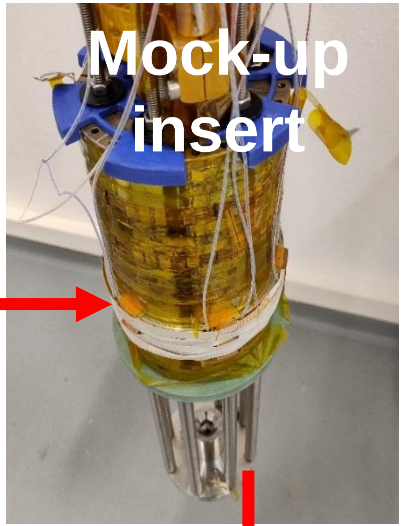
Note that I_c calculation performed by Philippe Fazilleau is based on the paper below.
- V Zermeño et al., *Supercond. Sci. Technol.* vol. 28, no. 8, p. 085004, June 2015.

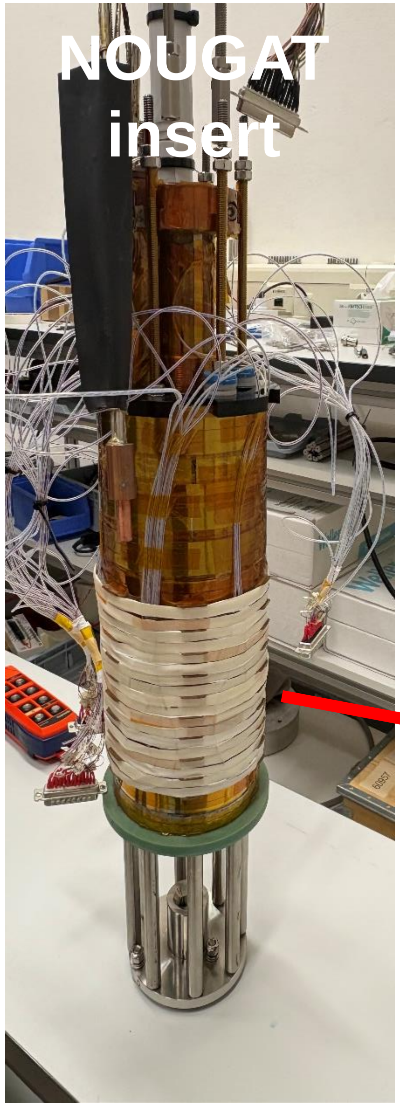
Resistive-HTS vs. LTS-HTS Hybrid Magnets

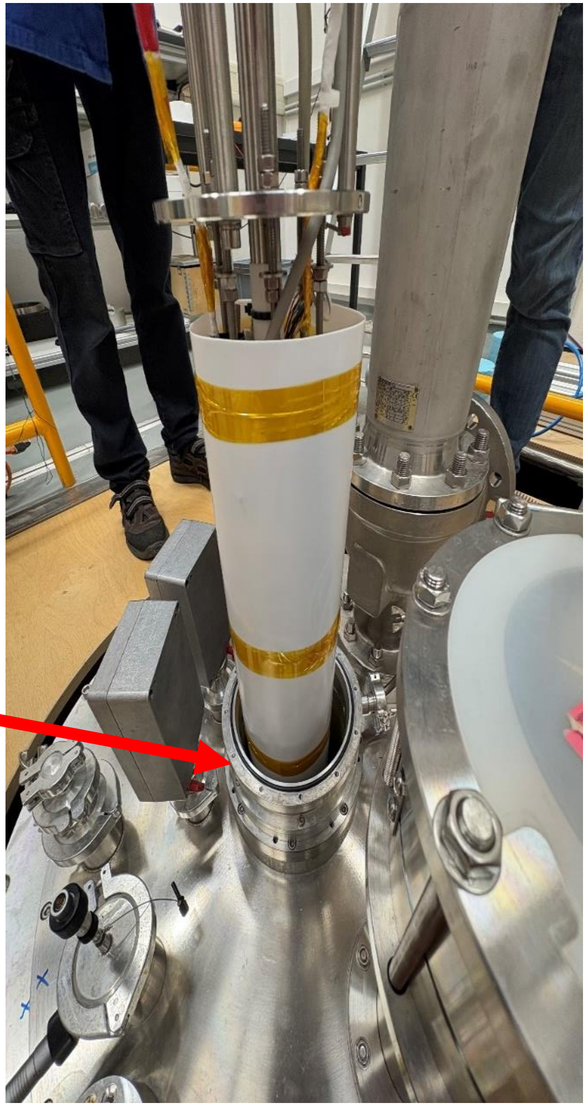
Category	Resistive + HTS	LTS + HTS
Inductance	Low	Very high
Response during HTS quench	Induced voltage and current, but energy small	Large dΦ/dt → large induced current/voltage
Arcing risk	Higher (fast transients)	Lower
Outsert damage risk	Voltage surges/arcing	Quench propagation + energy dump
HTS-quench impact	Voltage surges dominate	Large inductive energy discharge
Protection focus	Voltage-based	Energy-based
Quench propagation risk	None	Possible
Protection design difficulty	Lower	Higher
Test facility	LNCMI	HZDR

Tests of LTS outsert/HTS insert hybrid magnet in HZDR



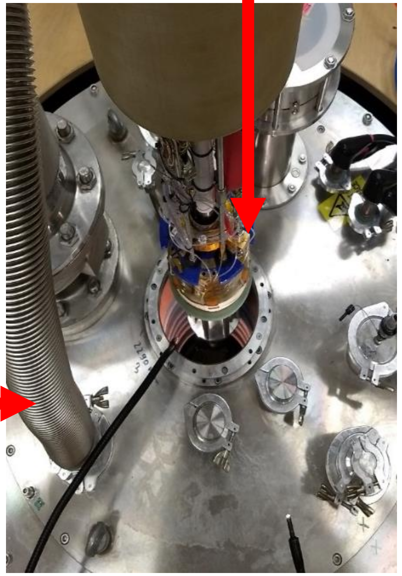






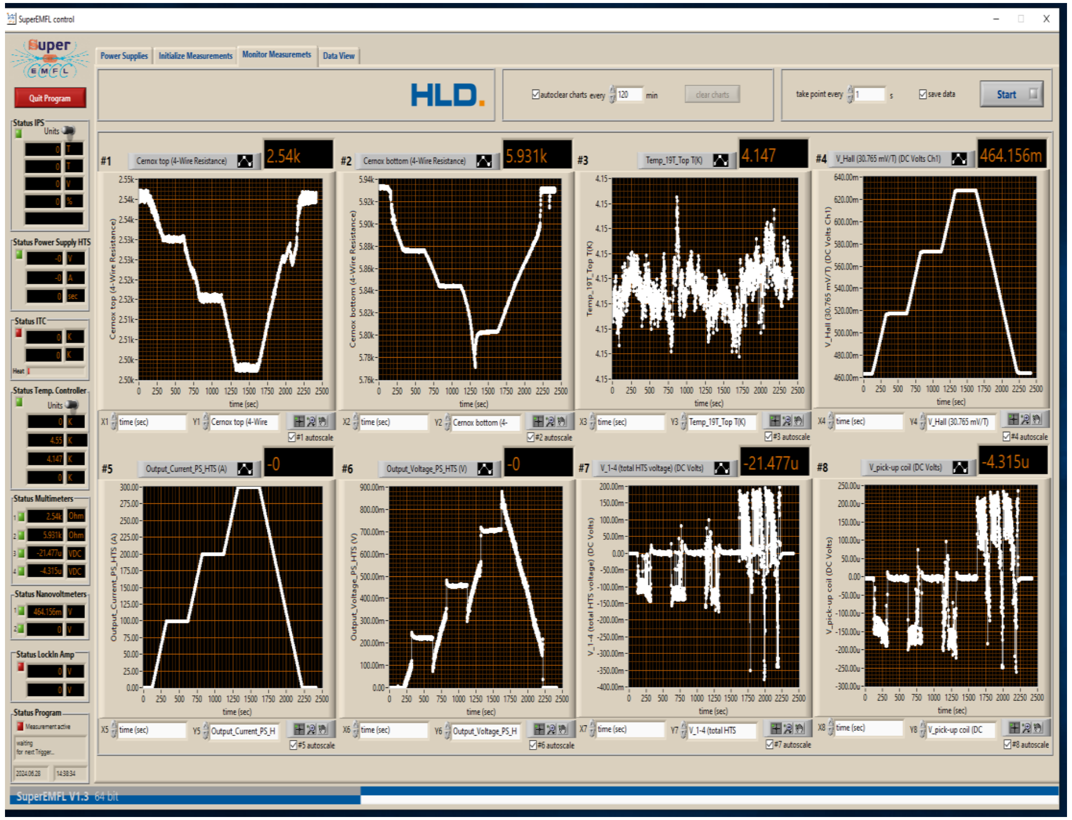
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Note: The LTS magnet at HZDR was designed and fabricated by OI.



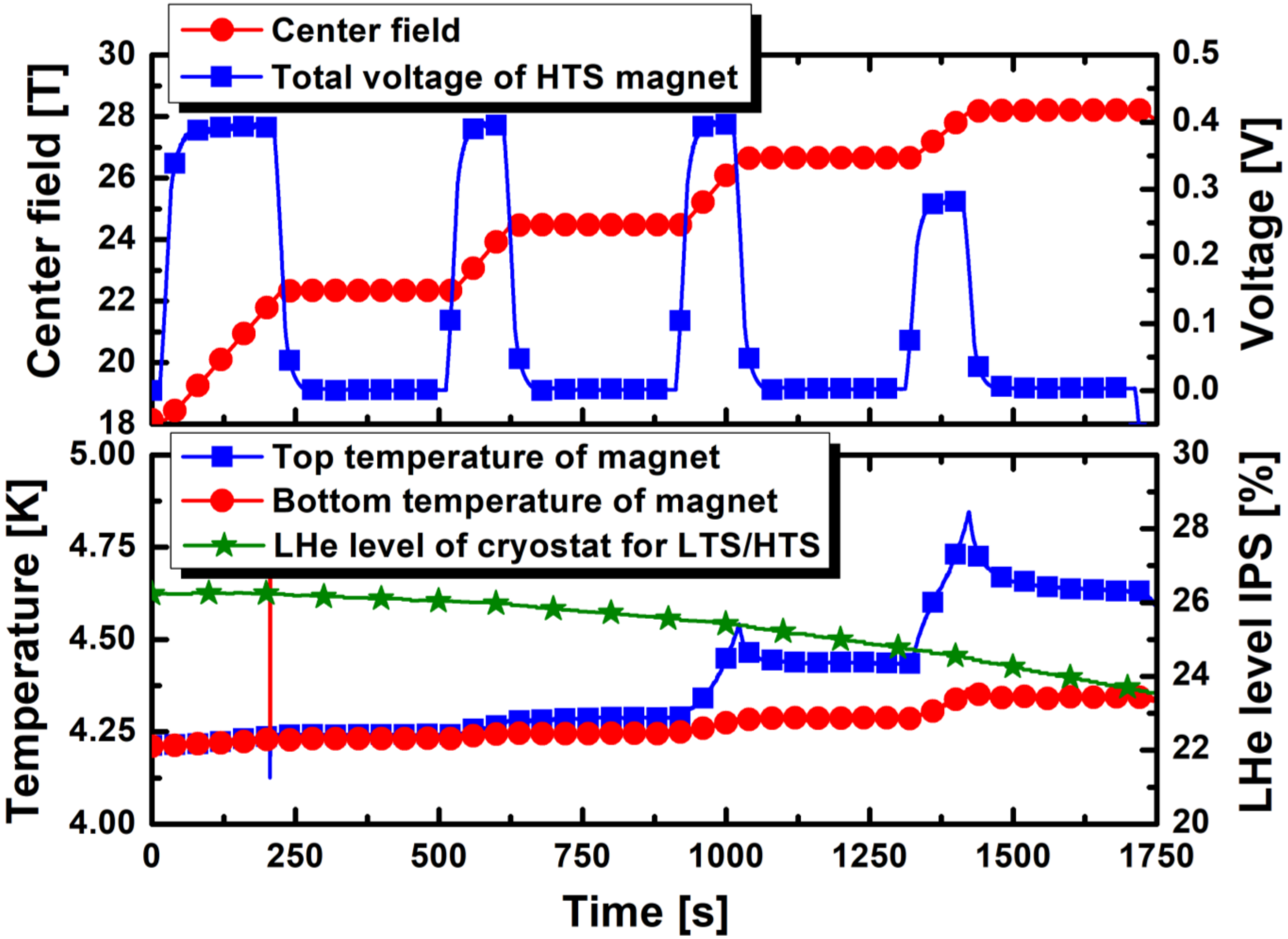
Tests of LTS outsert/HTS mock-up insert in HZDR

Note : Mock-up magnet wound with Fujikura REBCO tape



Quench of HTS mock-up insert and LTS outsert 22.6T
(17 T LTS + 5.6 T HTS mock-up insert)

Test of LTS outsert/NOUGAT insert hybrid magnet in HZDR



Voltage, center field, temperatures of HTS insert under 18 T of LTS outsert at 4.2 K

- Total magnetic field reached 28.2 T (HTS: 10.2 T under LTS: 18 T)
- Above 24 T, Joule heating observed at the top area of the HTS insert; temperature 4.6 K at 28.2 T
- LHe level (IPS) decreased from 26.2% to 23.6% (Δ 2.6%) over ~29 minutes, from HTS charging start to discharge at 28.2 T.
- Test stop due to no voltage signal from joint 6 between DP6 and DP7

Conclusion

- All REBCO tapes exhibited a critical current density exceeding 1000 A/mm² under a 30 T field perpendicular to the ab-plane at 4.2 K, demonstrating their suitability for very-high-field magnet applications within current mechanical limits.

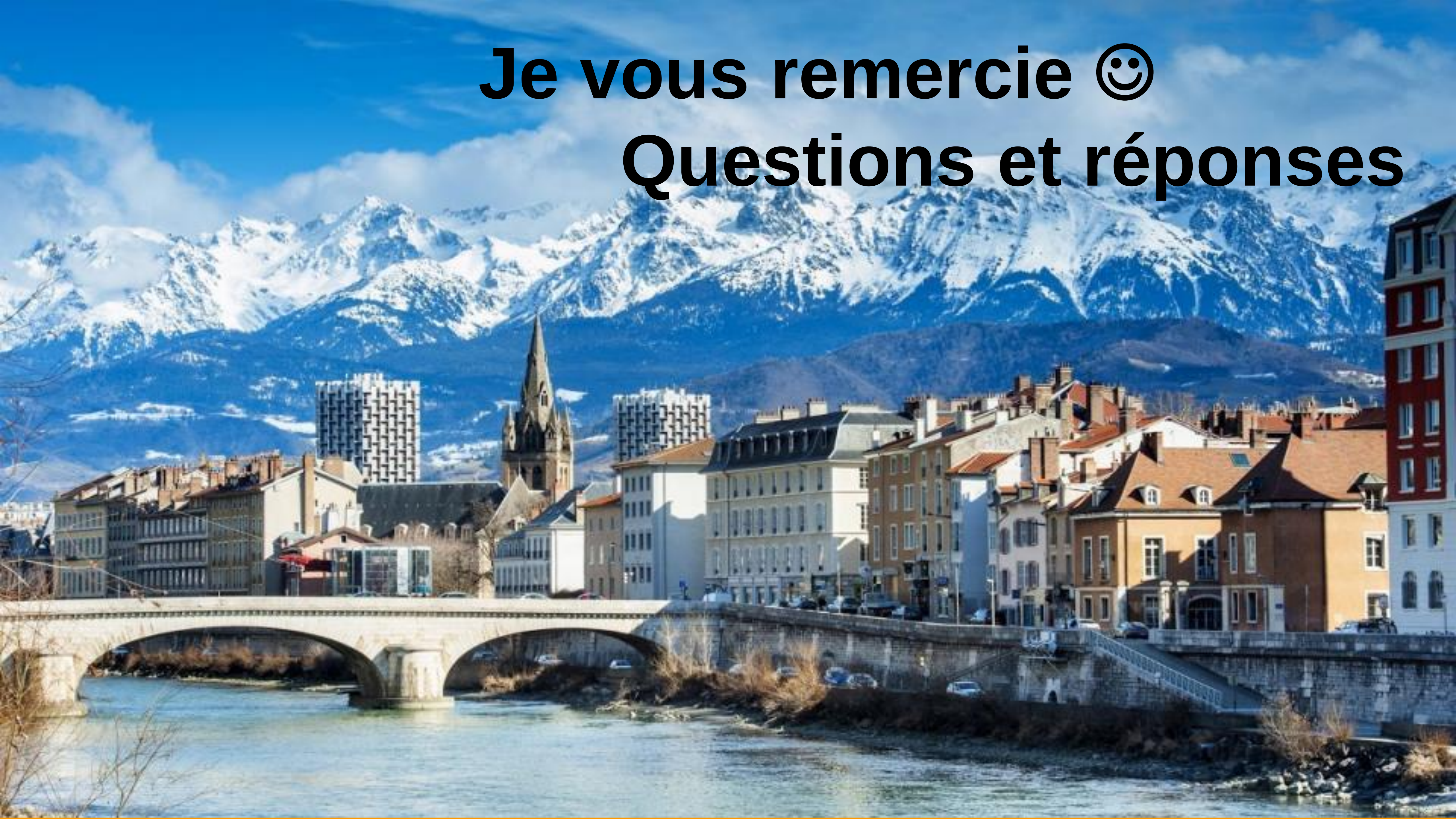
- Although improved tapes addressing delamination strength and thickness uniformity were produced in 2024, these advancements are still not fully sufficient. In particular, noticeable variations in windability remain depending on the quality of each tape spool.

- The LTS outsert (19 T / 150 mm), designed and fabricated by OI, is scheduled for installation at LNCMI in March 2027.

- For the HTS insert, THEVA tape was selected for its excellent electrical properties and superior windability.

- The design study for the HTS insert is ongoing, and final optimization will proceed once the Scientific Council confirms the specifications of the combined LTS/HTS magnet.

- To support design optimization, the NOUGAT HTS insert will undergo experiments in the HZDR LTS magnet in early December, including high-field tests and quench behavior if possible. Afterwards, LNCMI will fabricate and evaluate mock-up magnets (2-DP and 9-DP inserts) using the THEVA tapes delivered as the final conductors for the FASUM HTS insert within the LTS outsert.


Je vous remercie ☺
Questions et réponses