

SuperEMFL and latest development at LNCMI: Towards 30 to 40 T high field all SC user magnets

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Coated conductors for Applications 2025
CERN, 10th -13th of March 2025

Super
EMFL

European Infradev Project
11 partners / Budget 2.9 M€ / 4 years
Started January 2021



The SuperEMFL-project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 951714.



High magnetic field facilities (Pulsed and DC)

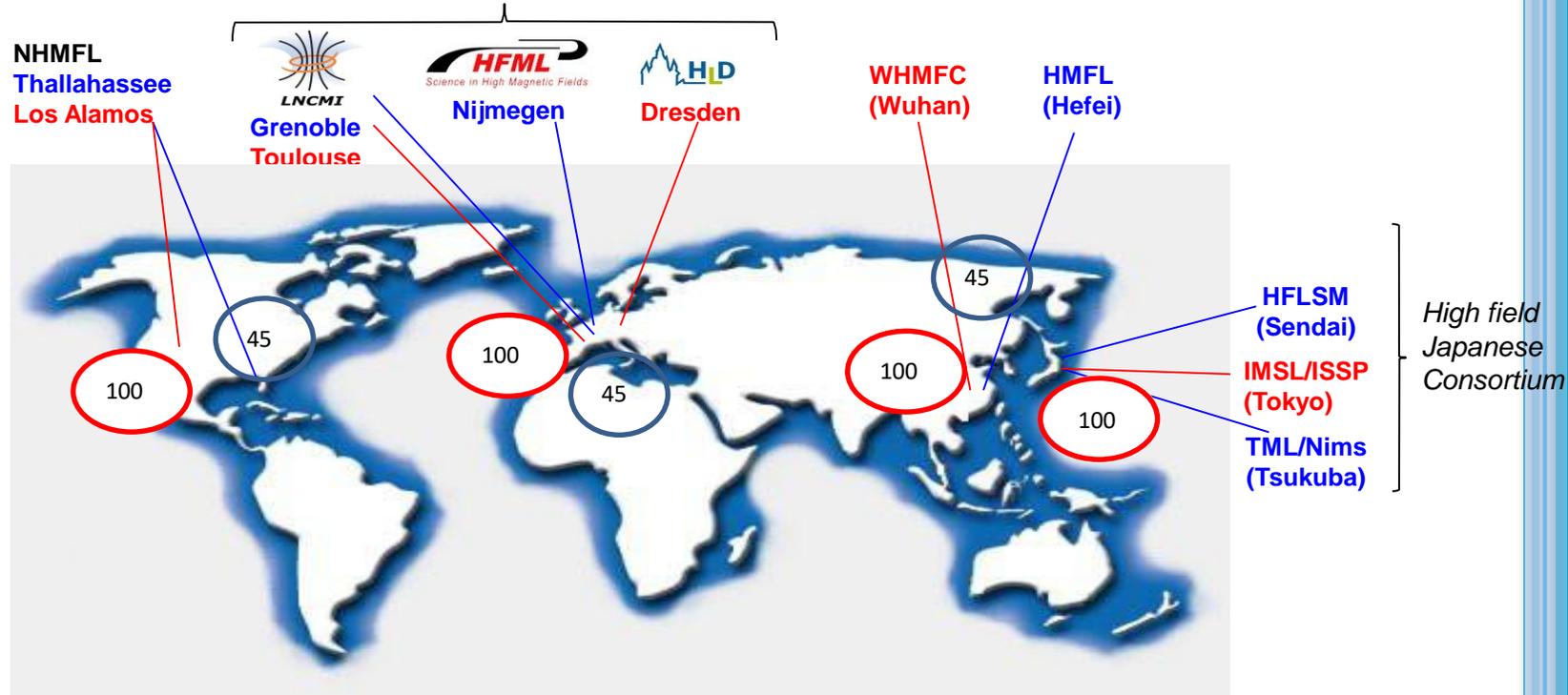


- 30 MW power supply
- 300 l/s water cooling

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 → 43 T in 2024



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



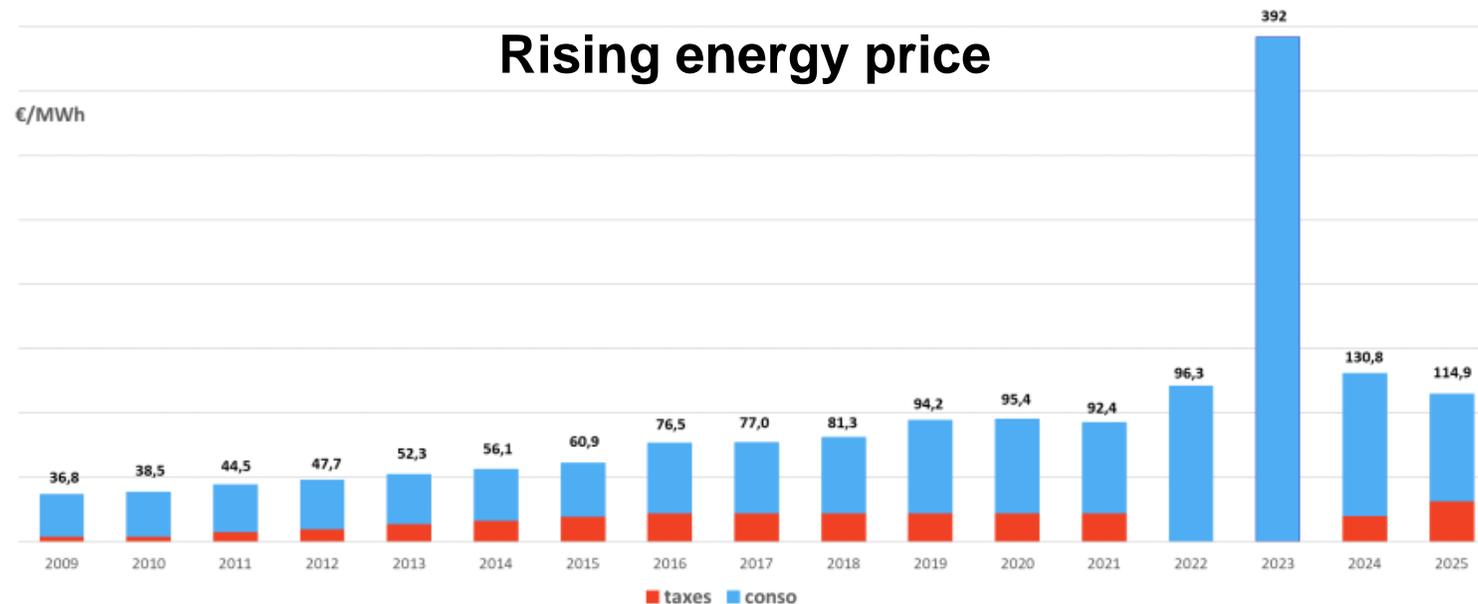
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HTS Superconductor for High Magnetic Field - A change of paradigm -

- A superconductor still passing large current above 20 T at 4.2 K
- Drastically reduced the energy / cost / carbon footprint* required to generate high magnetic field
- Allows long duration / low noise experiments

*Depends highly on the energy sources (renewable, nuclear, fossil fuel...)



Reference: 2024 LNCMI annual report

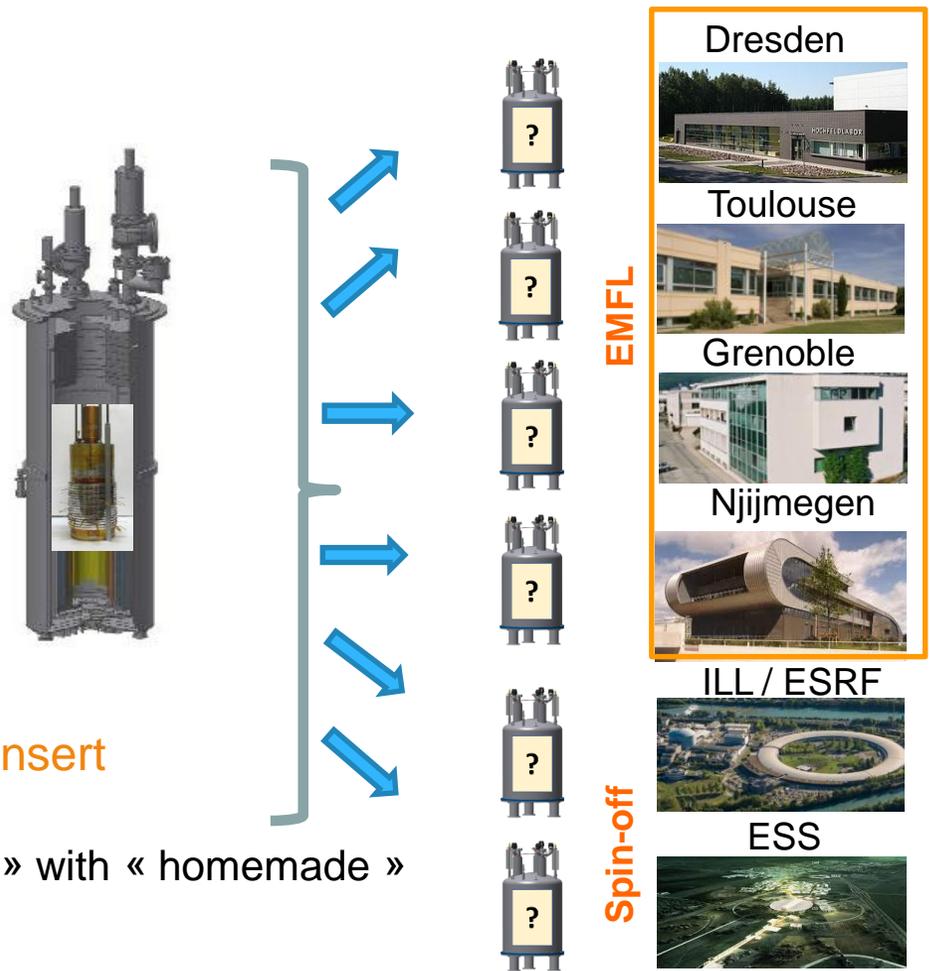


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SuperEMFL concept

A series of LTS + HTS superconducting magnets as new tools integrated within EMFL



LTS outsert + HTS insert

Combining « Commercial » with « homemade »

Max field
Bore size
Geometry
Homogeneity

Compatibility with local instruments

- DC 50 mm
- Pulse 25 mm
- Beam line

Opportunities with local equipment

- Helium recovery
- Helium liquefier

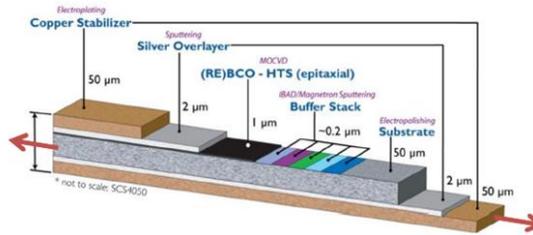


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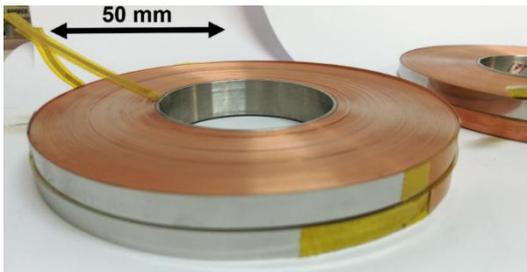
The 10 T Nougat HTS insert as starting point

- REBaCuO coated conductor



- ☺ High transport current under high magnetic field
- ☺ High mechanical strength due to Hastelloy

- Pancake coils



- ☺ Affordable for 100-200 m pieces
- Metal-as-insulation winding
- ☺ Best protection against quench
- Strained limited at 0.4 %



32.5 T
(18 T Ω + 14.5 T HTS)
in March 2019

Specifications

Parameters	Unit	Values
ID; OD	mm	50; 112
Height	mm	122.3
I_c DP coils @ 77 K	A	54.5 ~ 67.3
Number of DP		9
Turn per pancake		290
Total conductor length	km	~ 1.35
Stainless steel overband turns		44
OD after SUS overband	mm	119.0
Winding tension	MPa	92 ~100
Magnet inductance	H	0.825
Magnet constant	mT/A	44.5
Time constant (τ) at 4.2 K	s	23.06
Characteristics resistance (R_c)	m Ω	37
Contact surface resistance (R_{ct})	$\mu\Omega \cdot \text{cm}^2$	103

P. Fazilleau et al., Cryogenics **106** (2020) 103053
[doi: 10.1016/j.cryogenics.2020.103053](https://doi.org/10.1016/j.cryogenics.2020.103053)



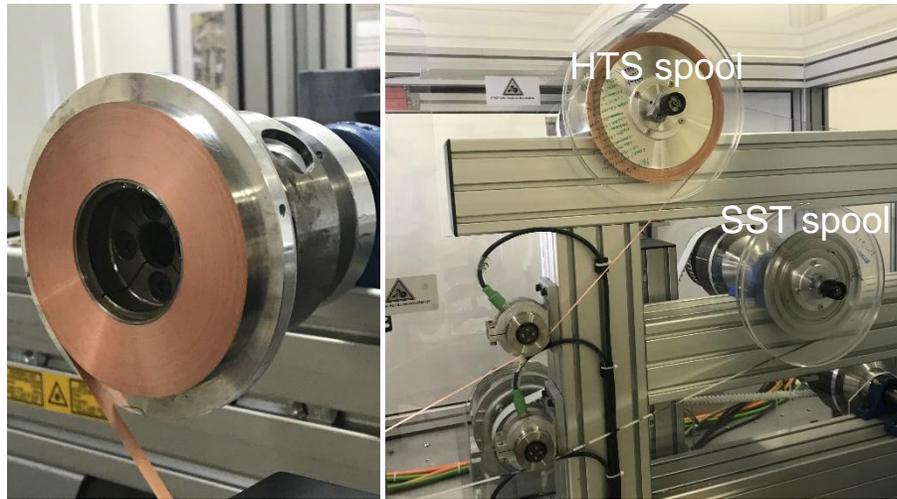
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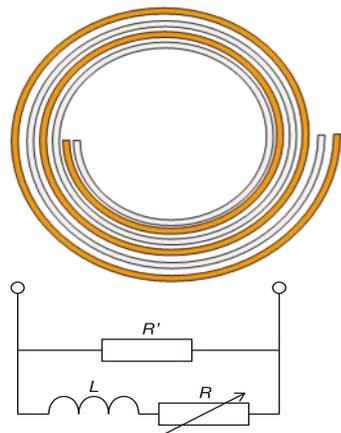
Metal-as-Insulation Technology

Bare HTS tape (75 μm) + SST Durnomag ribbon (30 μm)

T. L crevisse *et al.*, « Metal-as-insulation HTS coils », *Supercond. Sci. Technol.* **35** (2022) 074004
doi: 10.1088/1361-6668/ac49a5



- Local shunt of degraded part (similar to NI)
- Additional R_c (turn to turn R): lower time constant / protection
- Mechanical reinforcement
- Simple protection scheme : PS limited in voltage & return to zero

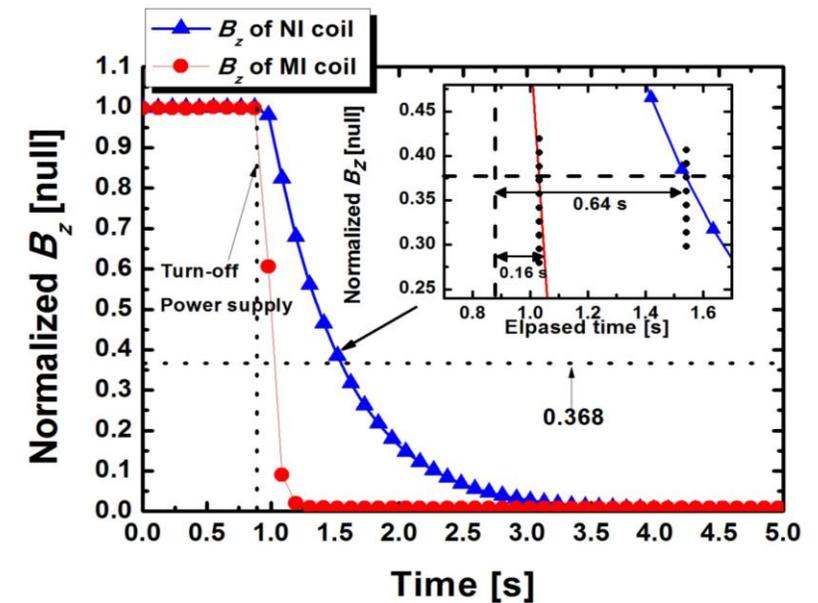


Non-Insulated coil
 $R' \sim 0$

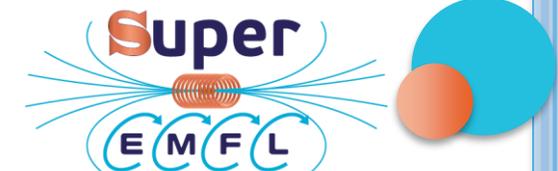
Metal-as-Insulation coil
 $R' \gg 0$

Insulated coil
 $R' \infty$

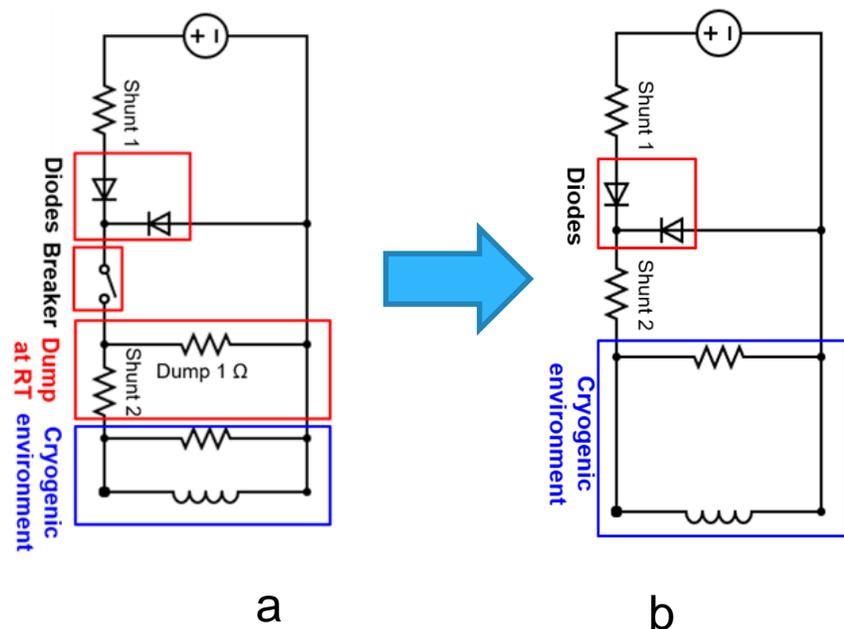
Sudden discharge test results of NI and MI REBCO coils



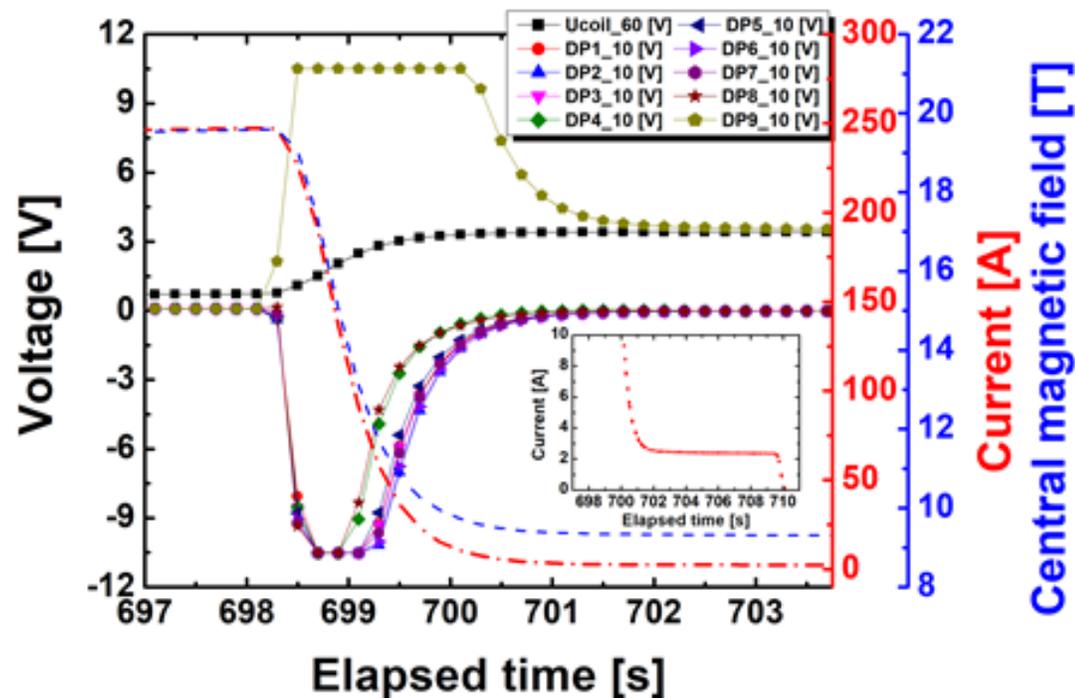
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Simplified quench protection scheme



Protection schemes of the HTS magnet:
 (a) detect and dump and (b) PS voltage limitation style



Quench behavior of the MI insert at $I_{op} = 247$ A at $B_{ext} = 9$ T at 4.2 K without switch and dump resistor. PS limitation set at 3.5 V.

J.-B. Song et al., "Metal-as-Insulation REBCO Insert: Simplified Protection Scheme and Investigation of Cooling Defect Under High-Field Operation", *IEEE TAS* **34** (2024) 4702405, doi: 10.1109/TASC.2024.3357474.



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HTS Roadmap

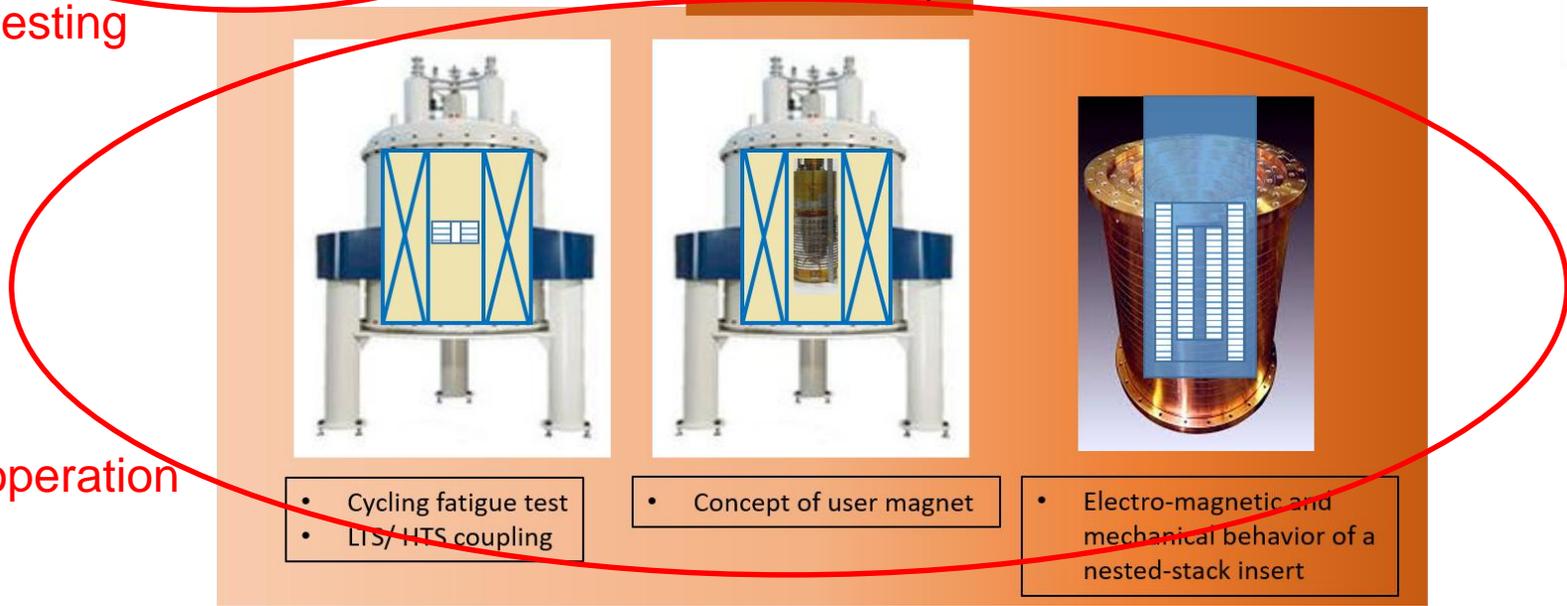
From tapes to a 40+ T all-superconducting magnet chart



Target : Conceptual design of a 40+ T all-SC user magnet

Byproducts : Dedicated intermediate field magnets of which a 32+ T all-SC user magnet

Materials testing



System operation

- LTS magnet 19T/150 mm + HTS insert 12-14 T
- LTS magnet 15T/250 mm + HTS nested-stack insert 20-25 T



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Performance evaluation of various REBCO tapes

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



THEVA

SST



SuperOx

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	[μm]	10 ± 2	10	10 ± 3	5
Substrate thickness	[μm]	50	45	37 ± 3	50
Total thickness	[μm]	63 - 89	75	No mark	75 - 76

Check

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

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



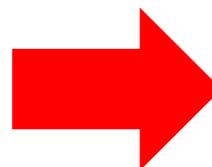
The SuperEMFL-project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 951714.



Delamination check

- Removing polyimide tape after attaching it to the REBCO tape.

Delaminated REBCO tapes after removing polyimide

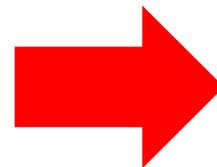
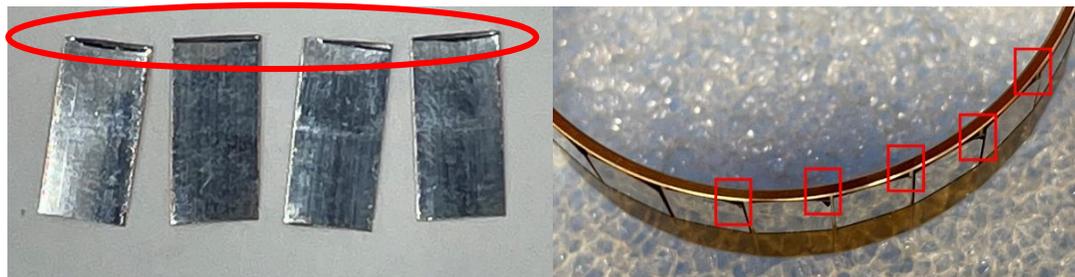


Issue !!

Start at edge of tape

- Cutting REBCO tapes after pre-tinning

Delaminated REBCO tapes after cutting REBCO tapes



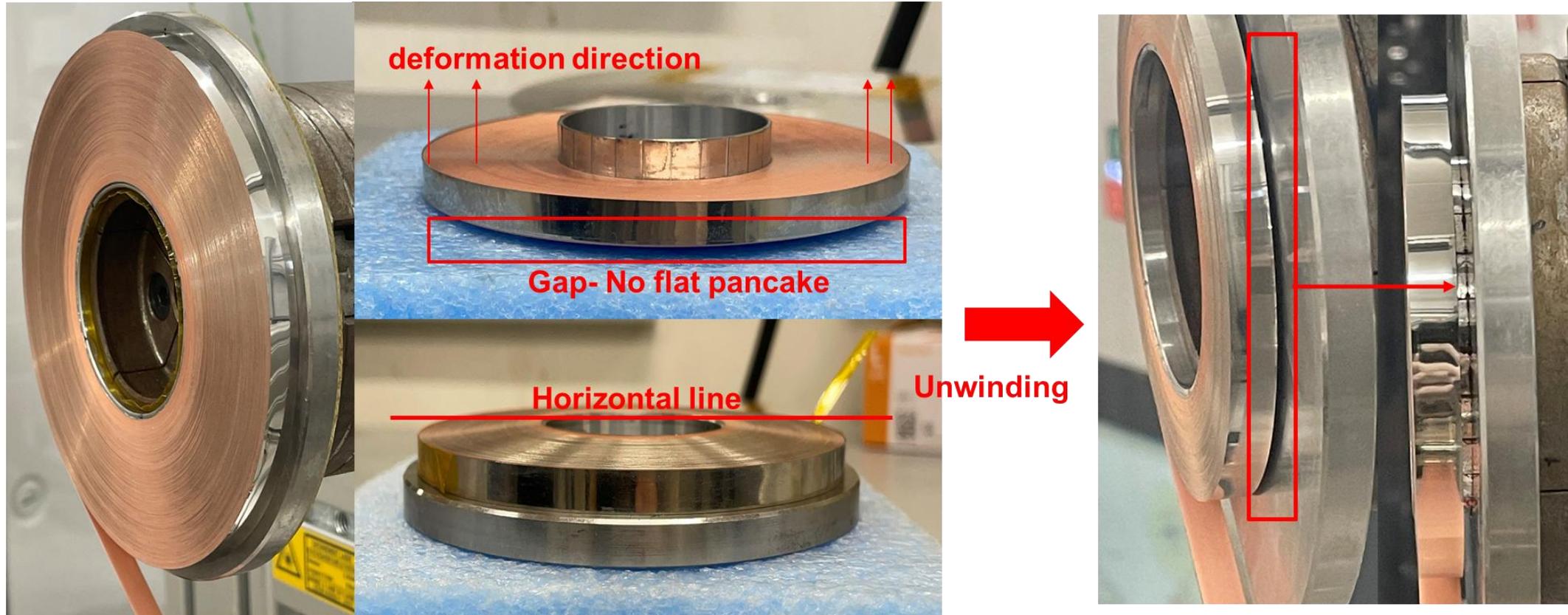
Three REBCO tapes: THEVA, Fujikura and FFJ

Two REBCO tapes: THEVA and FFJ

- Only SST tapes were not delaminated in both cases
- Delamination of THEVA and FFJ tape was improved

Uniformity and deformation of windings

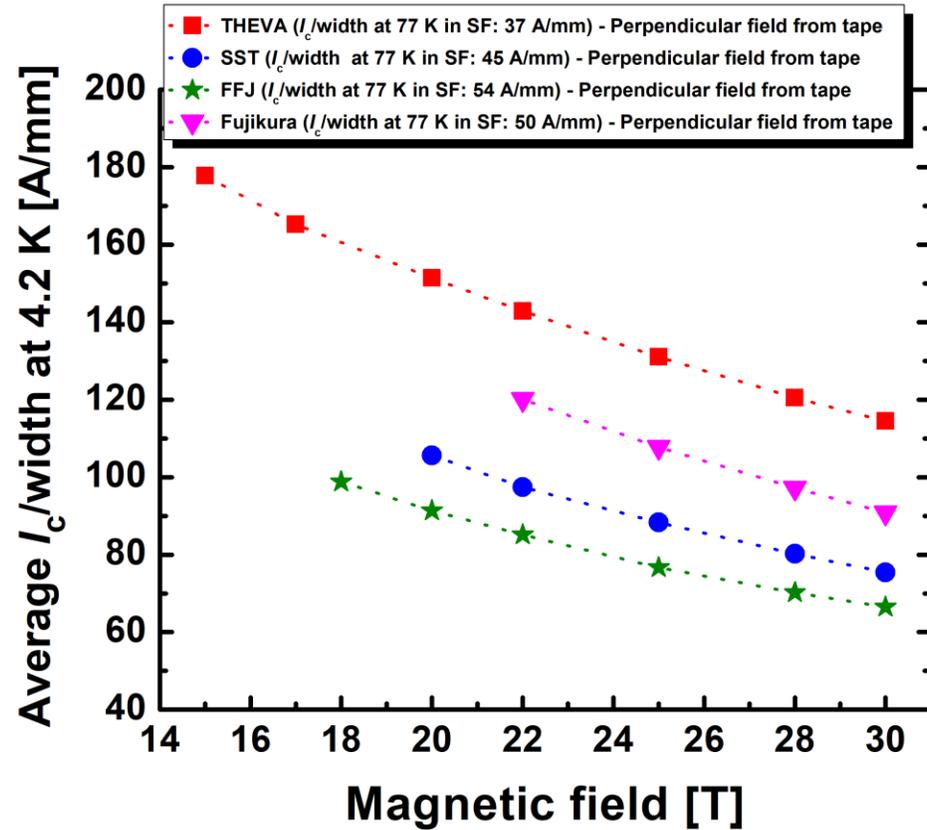
Example Fujikura DP winding



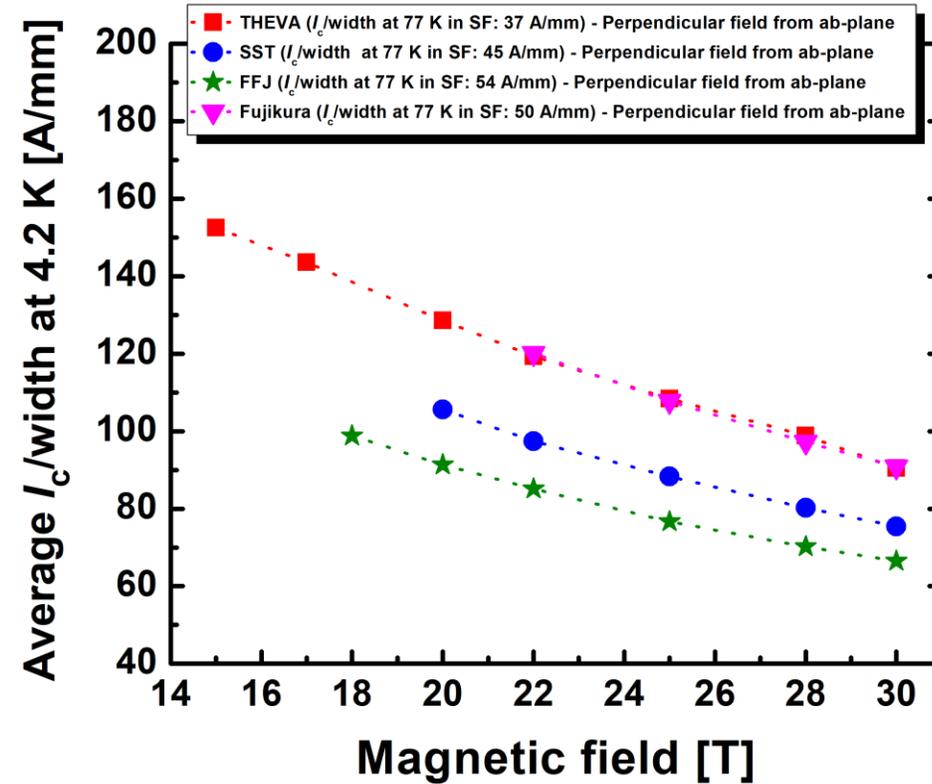
- Good winding uniformity
- Deformation of winding outer edge at tensions from 100 to 50 MPa

A tension of about 100 Mpa is required to keep turn to turn contact for MI protection

Current carrying capability per unit width



I_c /mm at 90 degree from tape



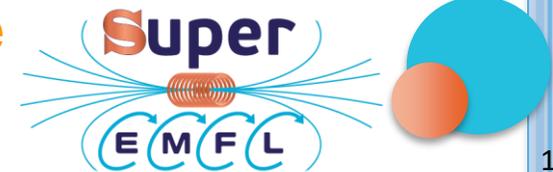
I_c /mm at 90 degree from ab-plane

All 50 μm substrate, except FFJ 38 μm

☞ all tapes show good performance ($J_c > 1000 \text{ A/mm}^2$) @ 4.2 K under a 30 T field perpendicular to ab-plane



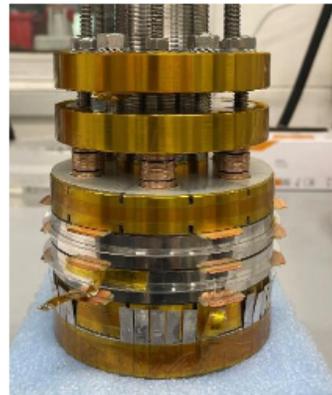
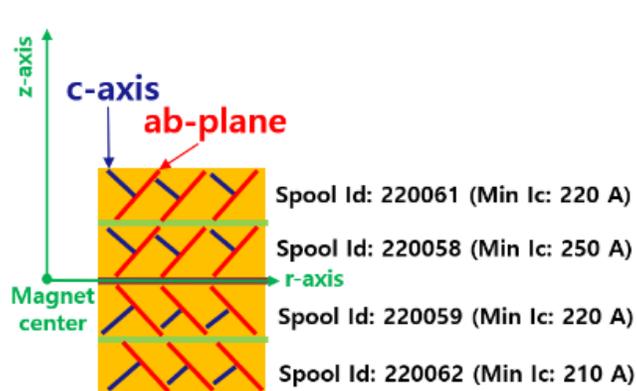
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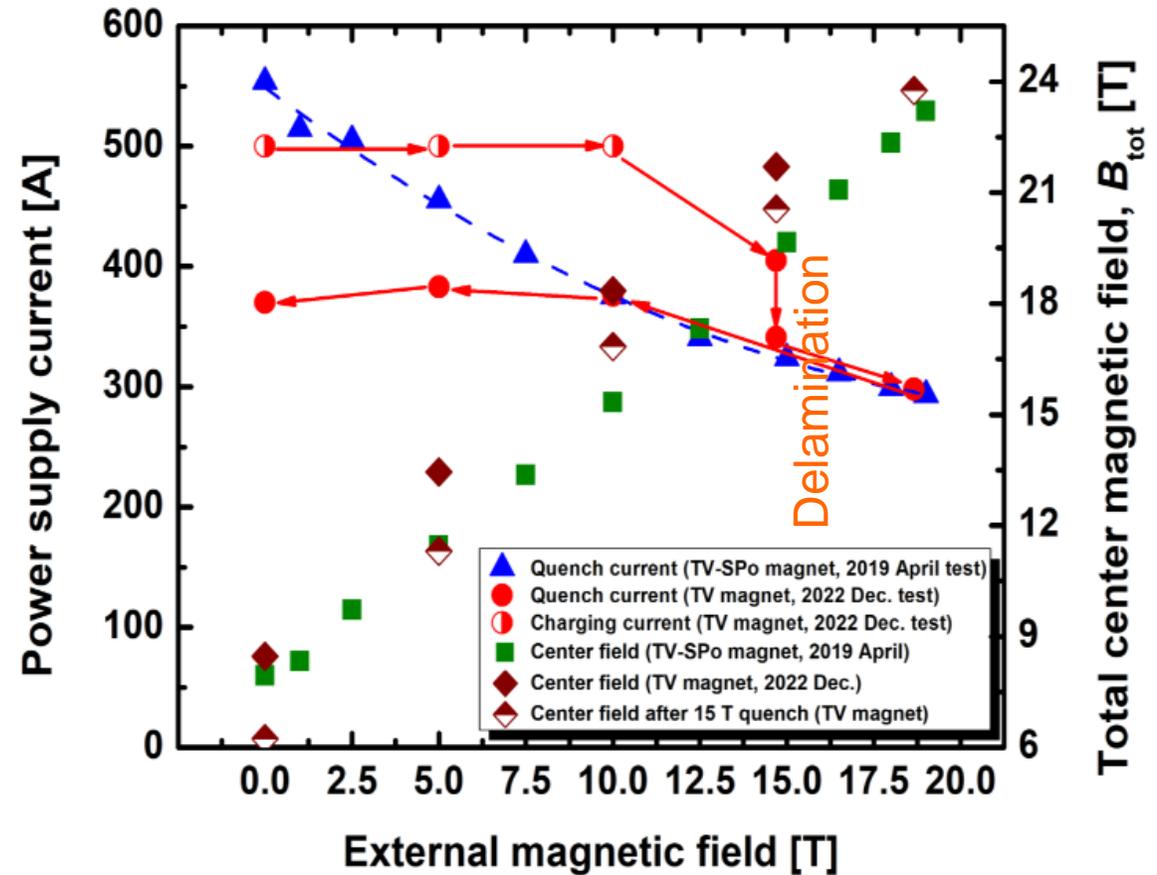
2DP prototypes with first batch from Theva

Specification of TV DP coils

Parameters	Bottom DP	Top DP
Minimum I_c (winding conductor) [A]	Top: 220, Bottom: 210	Top: 220, Bottom: 250
ID;OD; Height [mm]	50; 111.4; 12.8	
Number of turns	Top: 290, Bottom: 290,	
Conductor per pancake [m]	75	
Coil inductance [mH]	26.1	
Coil constant [mT/A]	9.4	
I_c of coil at 77 K [A]	64	70
Winding tension [MPa]	HTS:99, SS: 95	



C-axis arrangement of the magnet Stacked THEVA DP coils



Test results of THEVA-SuperPower and all THEVA test magnets under various B_{ext} at 4.2 K.



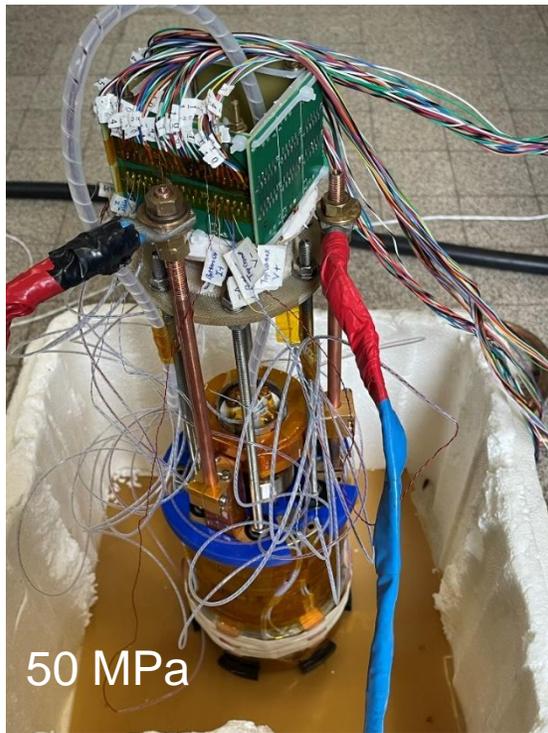
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Evaluation process : test of tapes in 2DP prototypes

Tests of 2 DP coils @ 4.2K @ 18-20 T

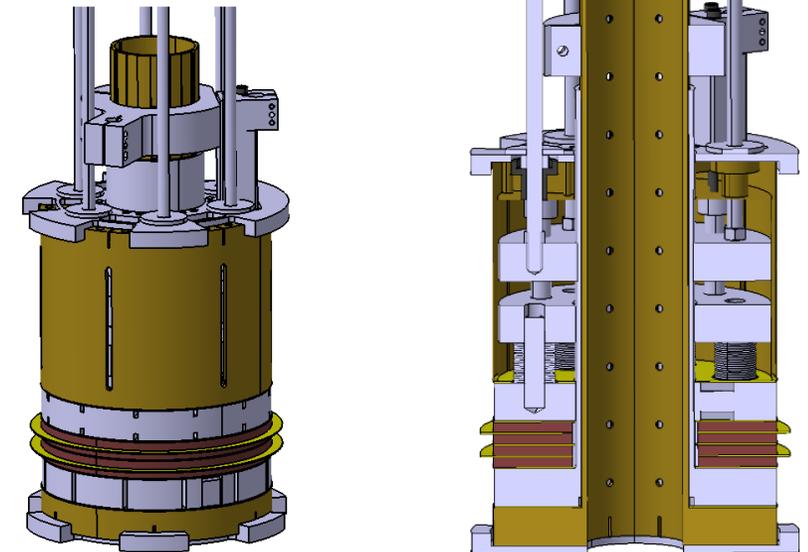
→ Evaluation of the coil I_c and of the mechanical limits



Fujikura 2DP in test at
HZDR Dresden



Two 2DP prototypes Theva &
SST ready for test at LNCMI

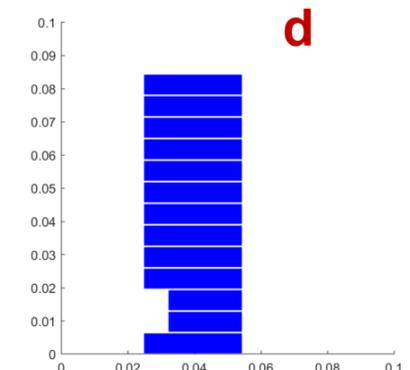
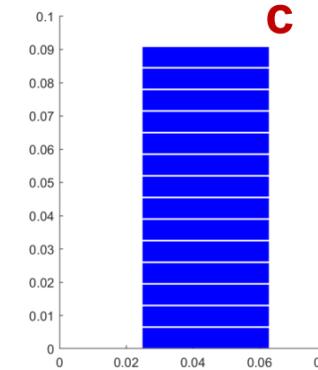
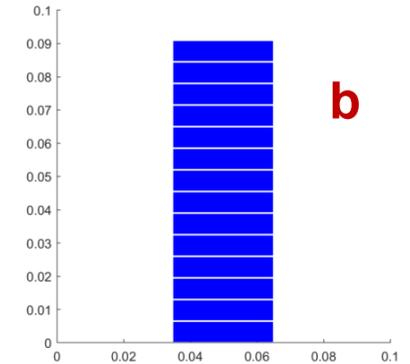
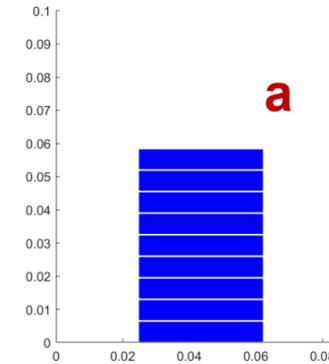


Schematic view of a 2DP coil

32 T+: Baseline designs

P. Fazilleau, CEA Saclay

	Basic Design (a)	High Volume (b)	High Field (c)	High Homogeneity (d)
<i>Design led by</i>	Volume	Mechanics	Mechanics	Volume
Geometry				
<i>Internal diameter (winding)</i>	50 mm	70 mm	50 mm	50 mm
<i>External diameter (winding+ob)</i>	106 mm	132.6 mm	128.6 mm	106 mm
<i>Number of DP</i>	8	14	14	13
<i>Turns per pancake</i>	250	284	360	250/187
<i>Total length</i>	957 m	2495 m	2771 m	1510 m
Electrics				
<i>SC Conductor</i>			THEVA APC	
<i>Nominal current</i>	333 A	271 A	287 A	326 A
<i>Critical current</i>	472 A	454 A	422 A	468 A
<i>Current margin on load line</i>	29 %	40 %	32 %	30 %
Magnetics				
<i>Magnetic field at center (HTS alone)</i>	13 T 32 T	13 T 32 T	18 T 37 T	13 T 32 T
<i>Homogeneity</i>	2071 ppm	784 ppm	666 ppm	39 ppm
<i>Inductance</i>	0.5 H	2.18 H	2.56 H	0.88 H
<i>Energy</i>	27.9 kJ	79.7 kJ	106 kJ	46 kJ
Mechanics				
<i>Winding tension</i>			100 MPa	
<i>Turns of over-bending</i>			50	
<i>Maximal hoop stress</i>	585 MPa	758 MPa	655 MPa	596 MPa



40 T+ design

- **Single solenoid** (of NOUGAT type) in a **19 T 150 mm LTS magnet** does not allow to reach **40 T with a 50 mm winding diameter** (34 mm for the users) with sufficient margin and safe strain.

40 T / 40 mm or 38 T / 50 mm possible

- A 40 T design with a large bore 50 mm requires nested coils in a large bore LTS magnet such as **15 T 250 mm**

M. Durochat *et al.*, "Design of All-Superconducting User Magnets Generating More Than 40 T for the SuperEMFL Project", IEEE Trans. Appl. Supercond. **34** (2024) 4904305
DOI 10.1109/TASC.2024.3368997



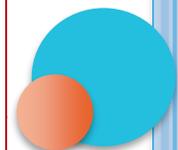
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Single solenoid

	Basic Design		High Field		High Volume
	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 %

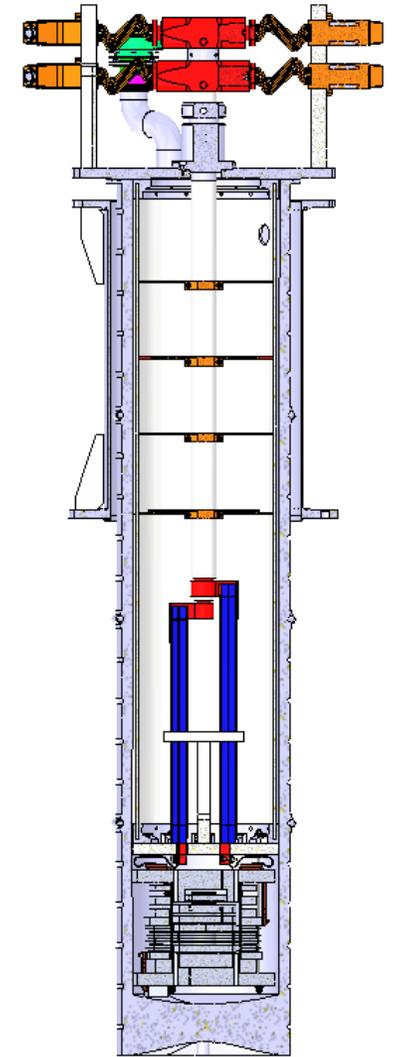
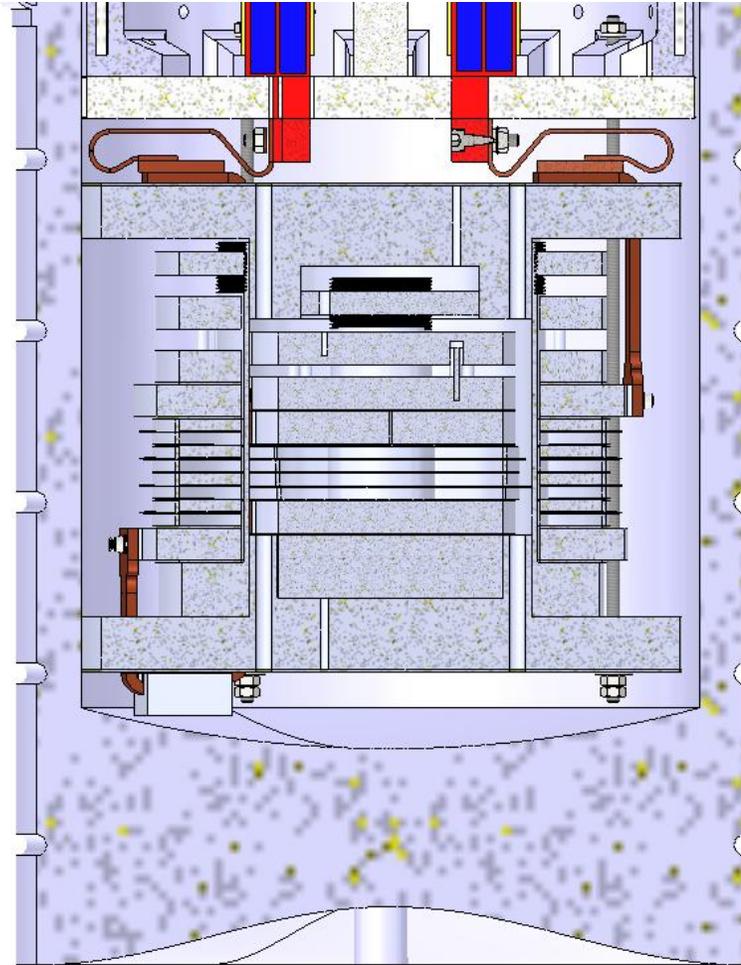
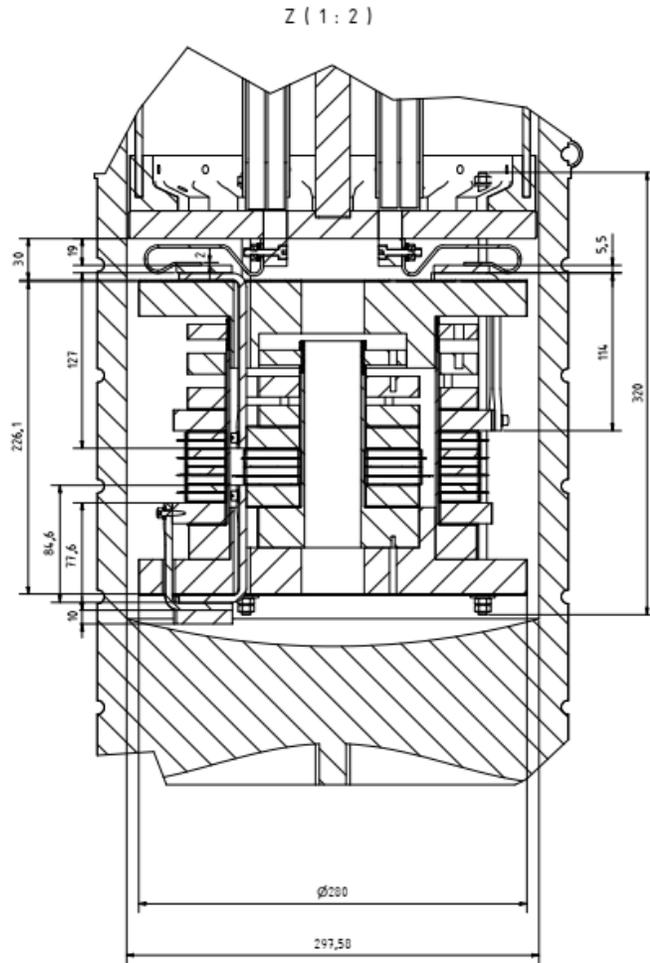
Nested coils

	Basic design		Low-stress design	High-Field Design	High-volume Design
	N1a	N1b	N2	N3	N4
Geometry					
Unit length	< 200 m	< 100 m	< 200 m	< 200 m	< 200 m
Internal diameter (winding)	50 mm	50 mm	50 mm	50 mm	70 mm
External diameter (windings+ob)	213.2 mm	167 mm	215.8 mm	215.8 m	214.8 mm
Gap between HTS1 and HTS2	15 mm	15 mm	10 mm	10 mm	10 mm
Number of double-pancakes HTS1	21	24	23	25	24
Turns per pancake HTS1	360	330	520	520	460
Number of double-pancakes HTS2	22	25	24	25	25
Turns per pancake HTS2	260	70	160	160	120
Maximal unit length	200 m	100 m	200 m	200 m	200 m
Total length	10 744 m	5934.8 m	12 051 m	13 470 m	11 961 m
Electrics					
SC conductor			THEVA APC		
Nominal current	231.2 A	339.7 A	208.8 A	238.3 A	239.1 A
Critical current	342.6 A	406.1 A	326.6 A	324.2 A	348.1 A
Current margin on load line	32.5 %	16.4 %	36.1 %	26.5 %	33.3 %
Magnetics					
Magnetic field at center (HTS alone)	25 T	25 T	25 T	29 T	25 T
Total magnetic field (HTS+LTS)	40 T	40 T	40 T	44 T	40 T
Mechanics					
Winding tension			100 MPa		
Turns of over-banding			50		
Maximal hoop stress HTS1	410.2 MPa	692.8 MPa	496.1 MPa	614.6 MPa	659.2 MPa
Non-thermal deformation (winding+field) HTS1	0.25 %	0.38 %	0.29 %	0.35 %	0.37 %
Maximal hoop stress HTS2	749.6 MPa	705.1 MPa	616.2 MPa	722.8 MPa	693.1 MPa
Non-thermal deformation (winding+field) HTS2	0.41 %	0.39 %	0.34 %	0.40 %	0.38 %



Nested coils proof-of-concept

(to be tested in 10T / 276 mm resistive configuration)



Not fabricated yet

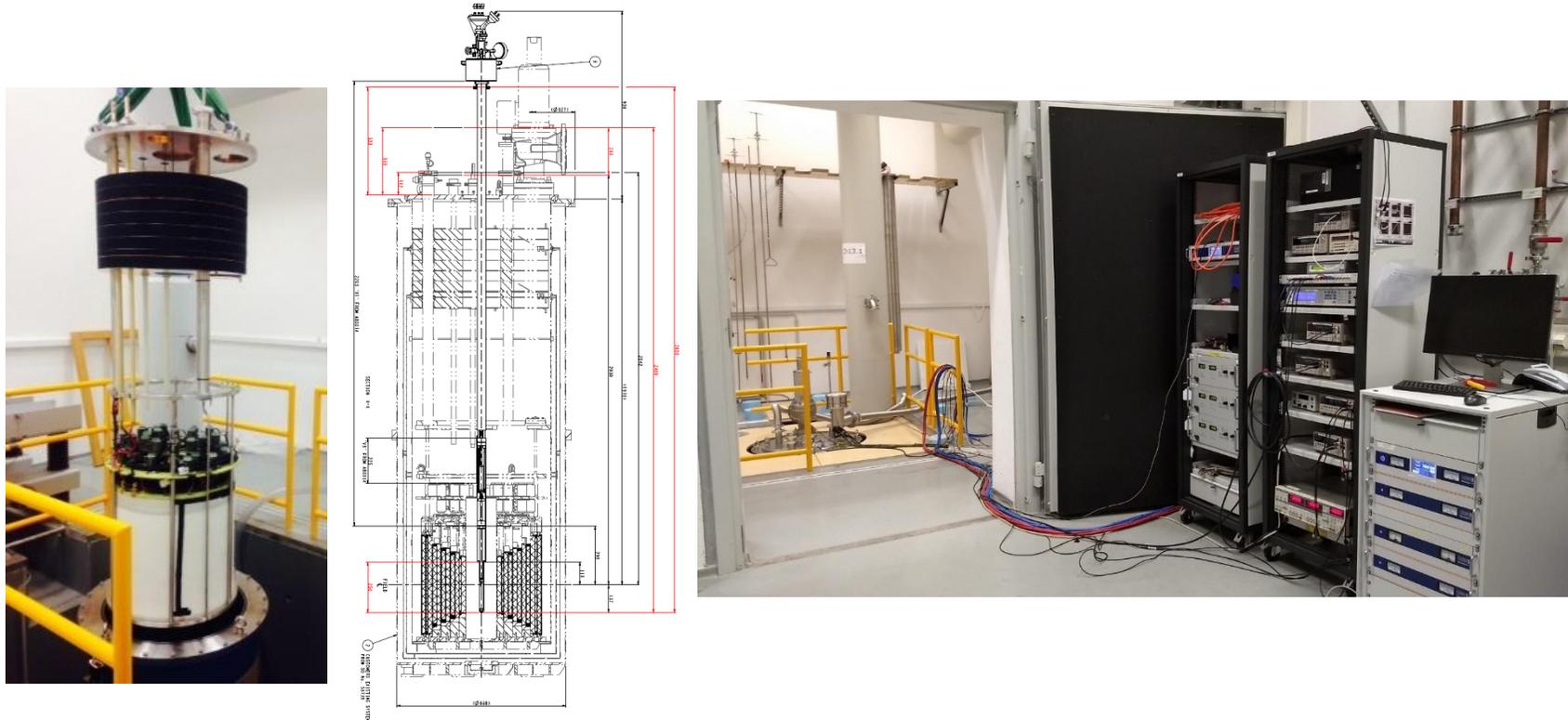


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Assessing the LTS/HTS combination

The 19 T / 150 mm LTS magnet at HZDR



Magnet designed and fabricated by Oxford Instruments

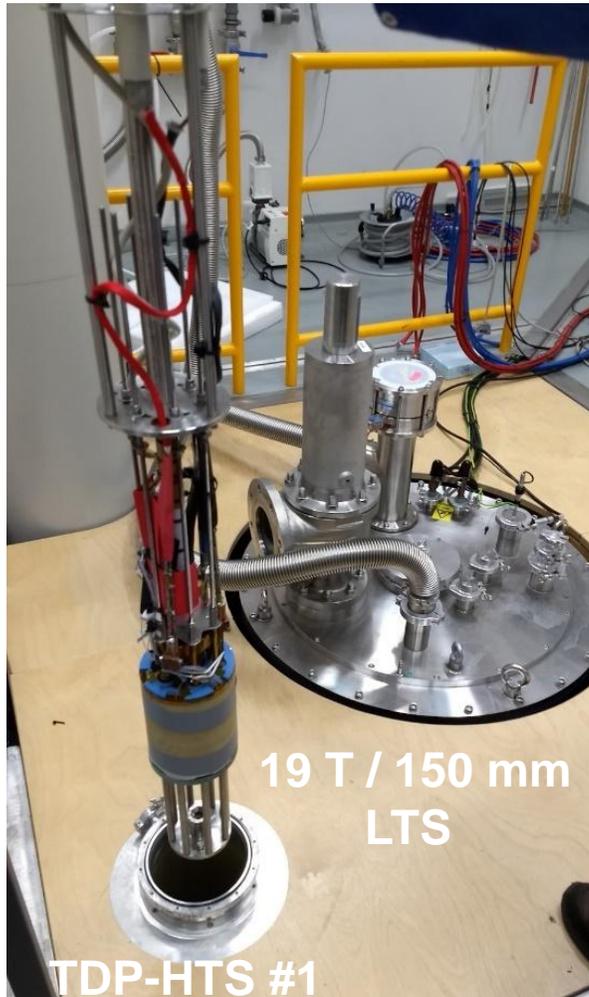


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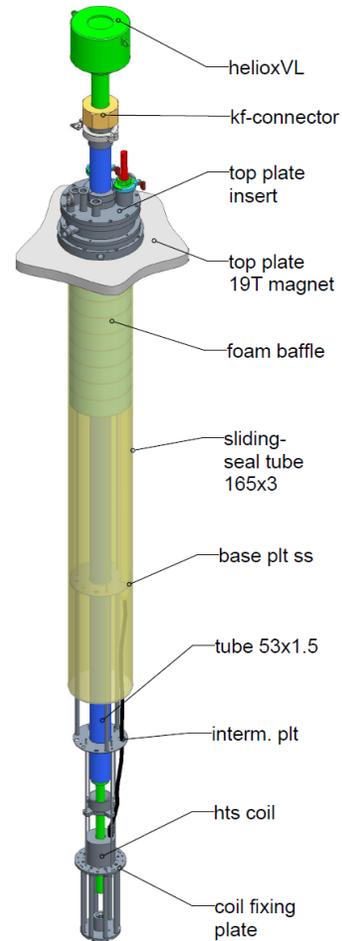
User magnet assessment

T. Herrmannsdoerfer

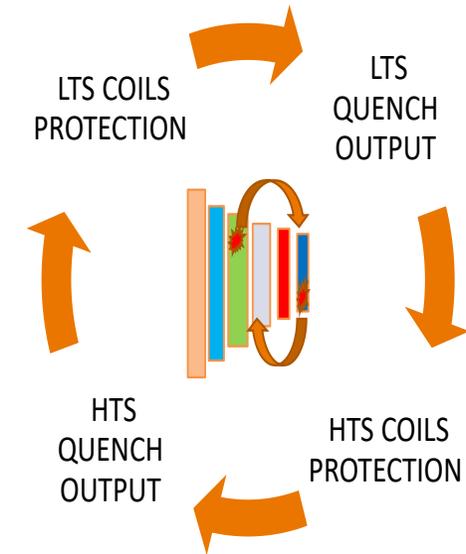
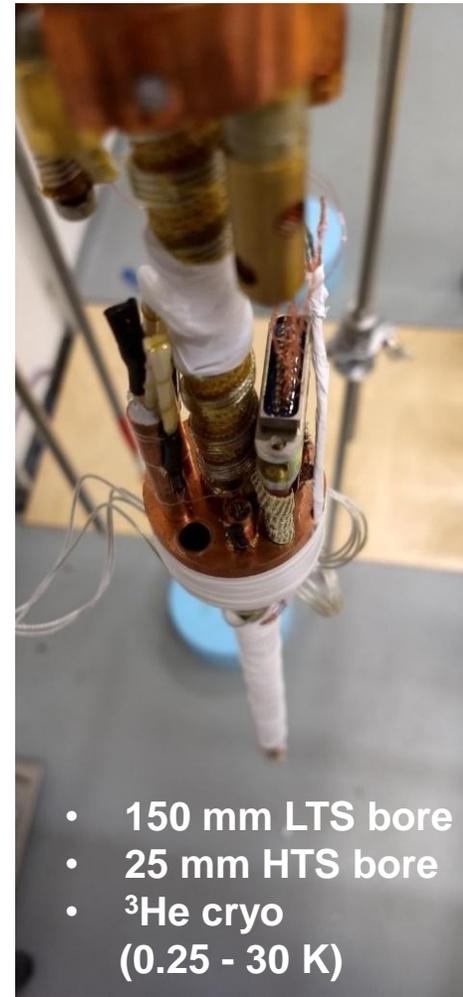


LTS-HTS interface build

Tested with low energy insert 22.3T
(17 T LTS + 5.3 T HTS)



25 mm VTI for LTS-HTS magnet



Iterative approach followed for
quench modelling and
protection of the
LTS/HTS hybrid

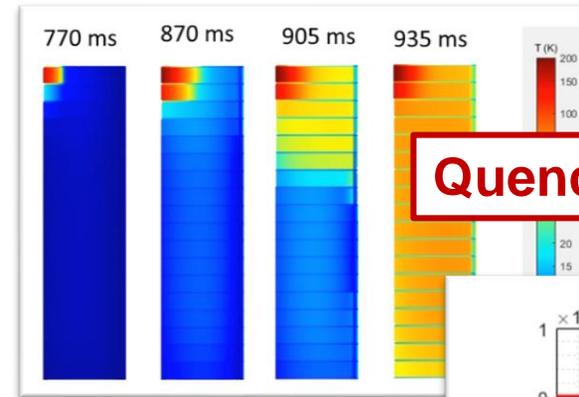
Mechanical reinforcement

CEA, OI, IEE, HZDR collaboration

P. Fazilleau, A. Varney, E. Pardo, T. Herrmannsdoerfer

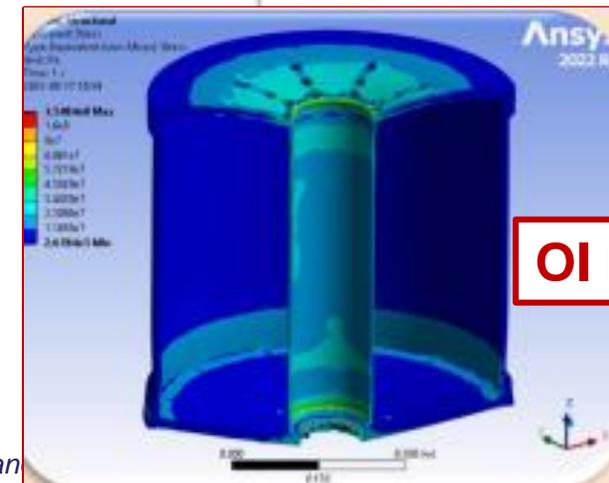
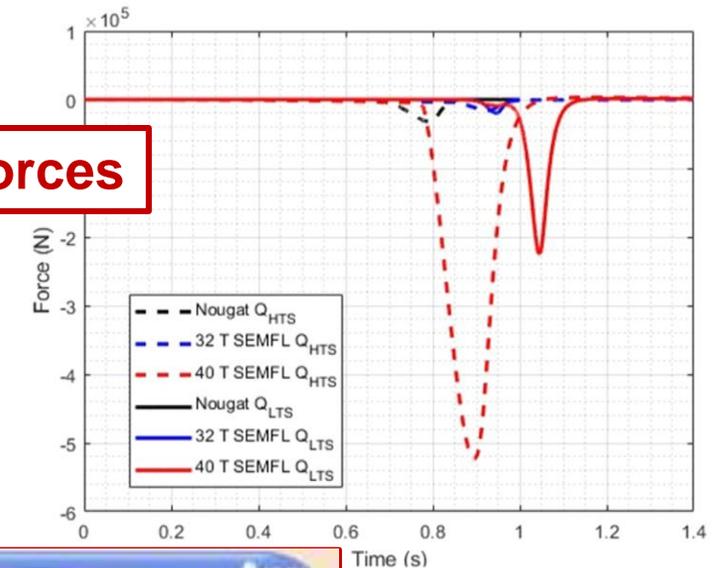
- Mechanical studies to estimate forces in case of quench of one or the two parts of the HTS/LTS magnet
- Worst scenario is a non symmetrical quench of the HTS yielding an axial force of several tons between the HTS and LTS part
- Reinforcement implemented by OI

P. Fazilleau *et al.*, "Behavior During Quenches of a 40 T Magnet Made of LTS and HTS Parts", *IEEE Trans. Appl. Supercond.* **34** 4704805
DOI 10.1109/TASC.2024.3370138



Quench of the HTS insert

Resulting axial forces

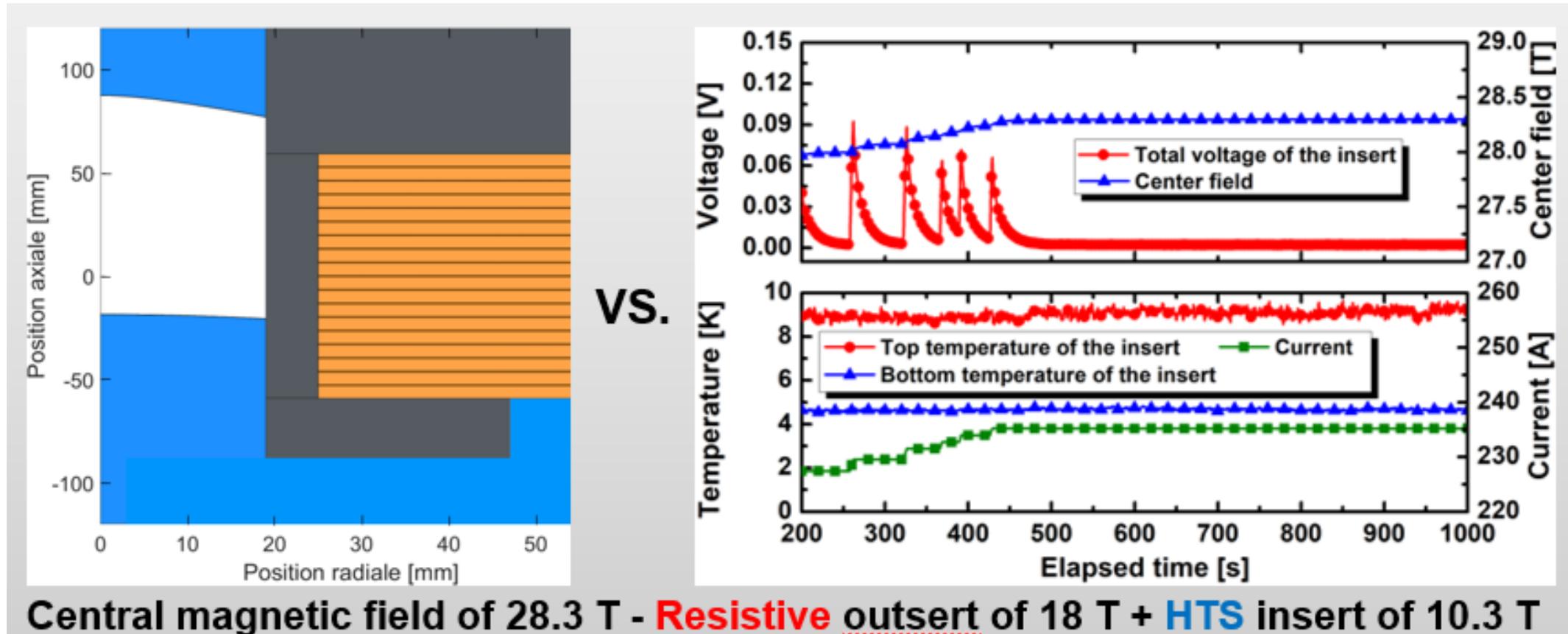


OI Reinforcement



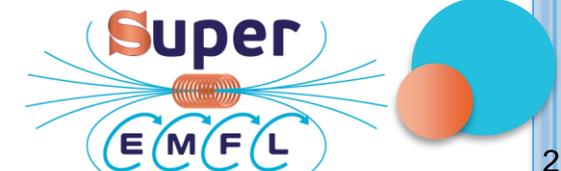
Trapped Helium bubble

Simulation using potential energy formulation vs experiment



J.-B. Song et al., "Metal-as-Insulation REBCO Insert: Simplified Protection Scheme and Investigation of Cooling Defect Under High-Field Operation", *IEEE TAS* **34** (2024) 4702405, doi: 10.1109/TASC.2024.3357474.

The SuperEMFL-project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 951714.



Conclusions

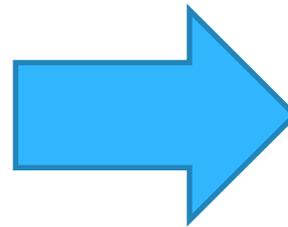
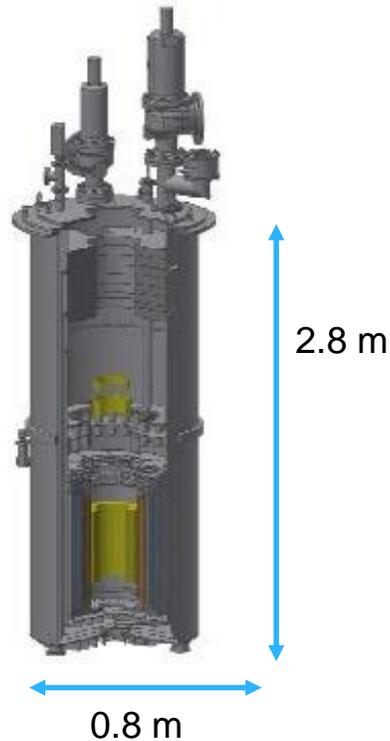
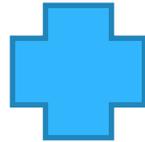
- **Based on the already demonstrated MI technology**
- **Modelling tools developed for simulations and optimizations**
- **Several designs proposed**
- **Evaluation of several HTS tapes**
- **Mechanics is the limit**
 - Deformation (geometry tolerances)
 - Calculation (multiphysics simulation)
 - Delamination (especially at soldered junctions)
 - Coupling forces in case of quench / Reinforcement of the LTS magnet
- **Next to come**
 - Tests of 2DP coils @4K, 20 T
 - Fabrication / Test of a nested coil as a proof of concept
 - A LTS/HTS magnet at LNCMI (FASUM project)



FASUM Forty Tesla All Superconducting User Magnet

(French research agency – Université Grenoble Alpes, CNRS, CEA – Started December 2021)

Fed by SuperEMFL



anr®
agence nationale
de la recherche

Custom HTS insert

« Commercial » LTS 19 T magnet

40 T class magnet for LNCMI users

Tapes received from THEVA

LTS magnet ordered at OI
Delivery 2026

Two inserts planned TBD: 32T and then 40T



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