September 1 - 6, 2024, Salt Lake City, Utah

Development of a ReBCO non/metal-insulated 40 T solenoid for the Muon Collider

Funded by the European Union

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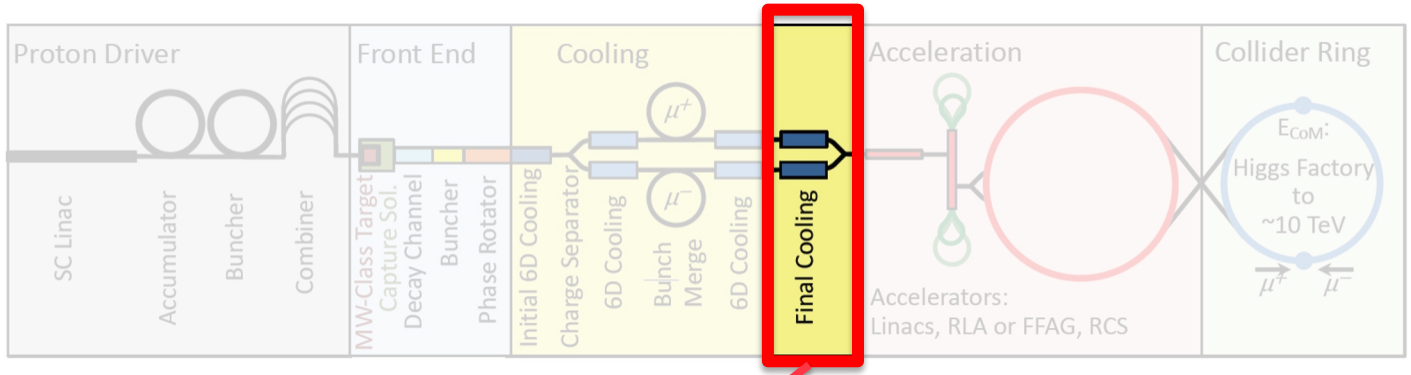
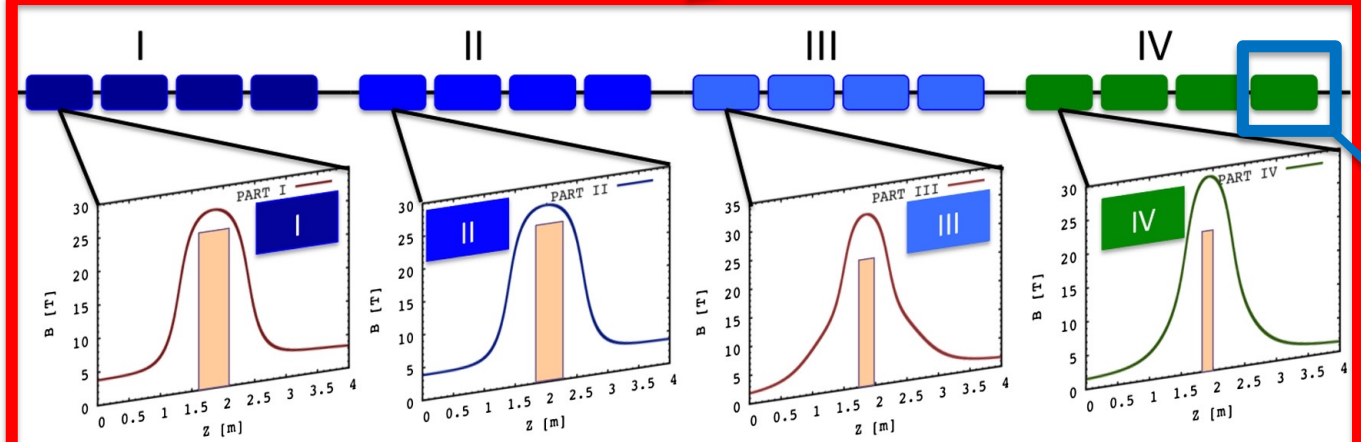
Outline

- **Introduction**
  - The Muon Collider & its Final Cooling Channel
  - The Final Cooling Solenoids and the proposed conceptual design
- **Design and studies for the final cooling solenoid**
  - Advancing on the: engineering Design and; mechanical analysis
  - Studying the effects of magnetization and quenches on mechanics
  - Protection studies and development of new electrodynamics models
- **Some Experimental Activities**
  - Technological Studies
  - Macro & Micro mechanical characterizations
  - Critical current measurements on procured ReBCO tapes

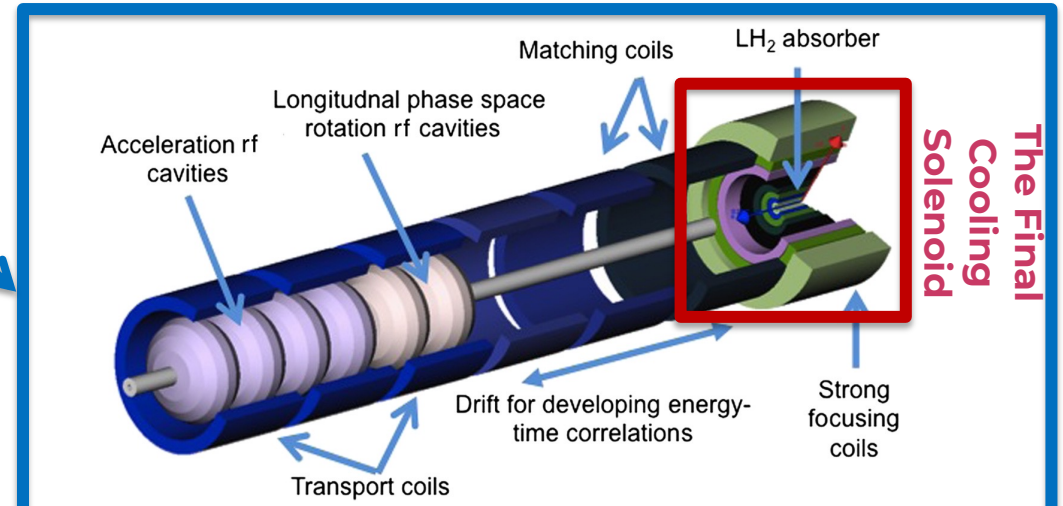
The Muon Collider
Final Cooling Channel



- The final cooling solenoids are part of the **final cooling channel**, which is constituted by several **cooling cells**
  - **16** were proposed by the MAP study



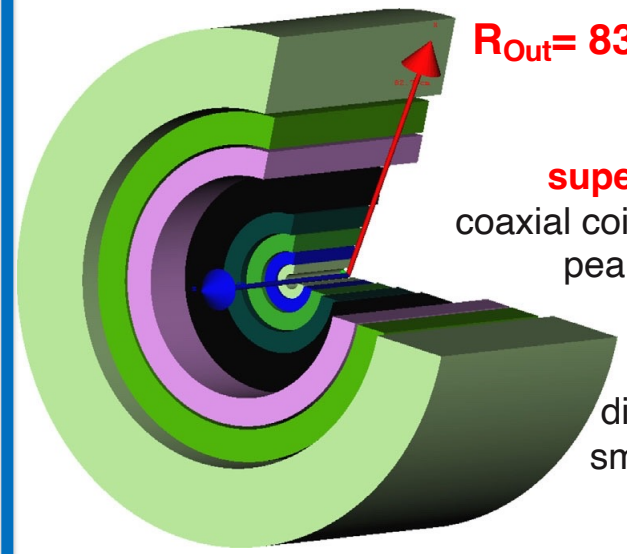
A layout schematic of **16 cells** of the **final cooling channel** defined by the MAP study (Sayed et al. Phys. Rev. ST Accel. Beams **18**, 091001). The coloured boxes in the top represent the **cooling cells.** The bottom figures show a sample of the on-axis field of the strong focusing solenoid; the shaded areas show the corresponding absorbers lengths.



Schematic of the elements of one ionization **cooling cell**, Sayed et al. Phys. Rev. ST Accel. Beams **18**, 091001

The Final Cooling (FC) Solenoid

Design proposed by MAP

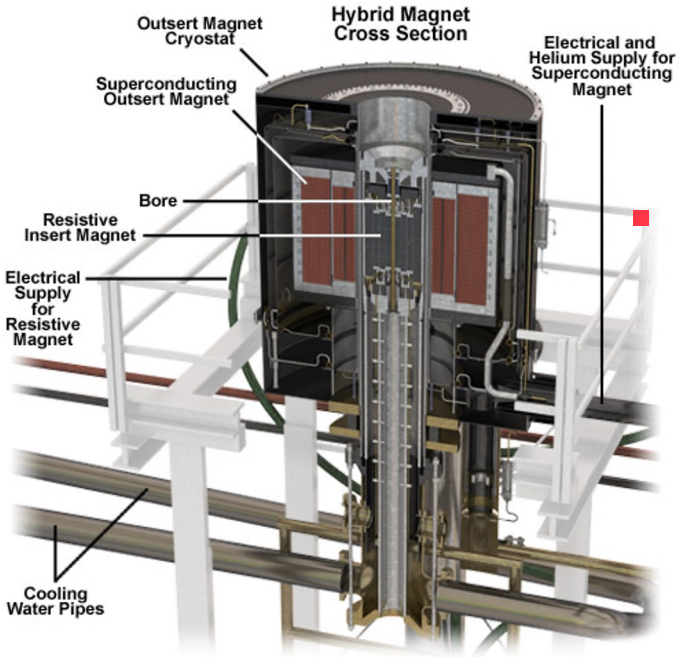


R_{Out}= 83 cm

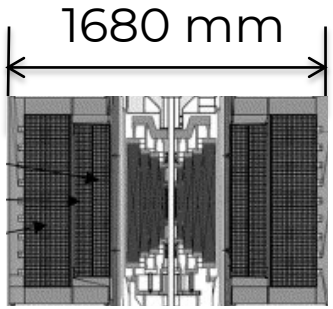
A set of eight **superconducting** coaxial coils providing a peak field of **50 T**

The inner diameter of the smallest coils is **50 mm**.

Sayed et al. Phys. Rev. ST Accel. Beams 18, 091001



Cross section of 45 T, **32 mm** **NHFML** user facility solenoid



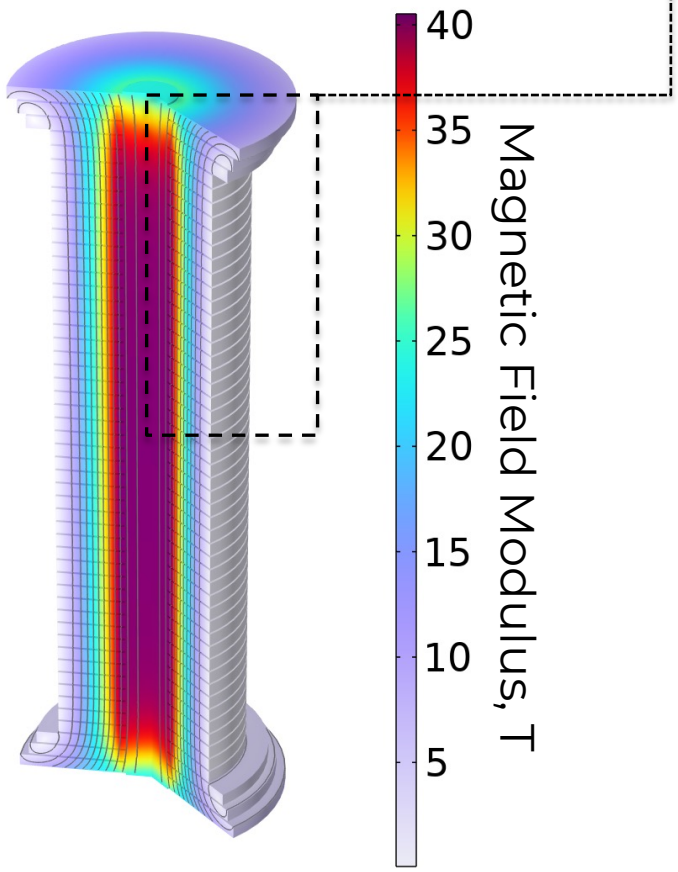
In the world, only **two solenoids** (at **NHFML** and **CHFML**) **B ≥ 40 T** in a **free bore aperture** (32 mm) **comparable** with what needed for **FC** solenoids

- For both, outermost winding diameter **~1.7 m**
- **Hybrid Magnets**: **33.5/29 T** from **resistive** insert, **11.5/11 T** by **superconducting** outsert
- their **large power consumption** (20-30 MW) is **unacceptable** for accelerator magnets

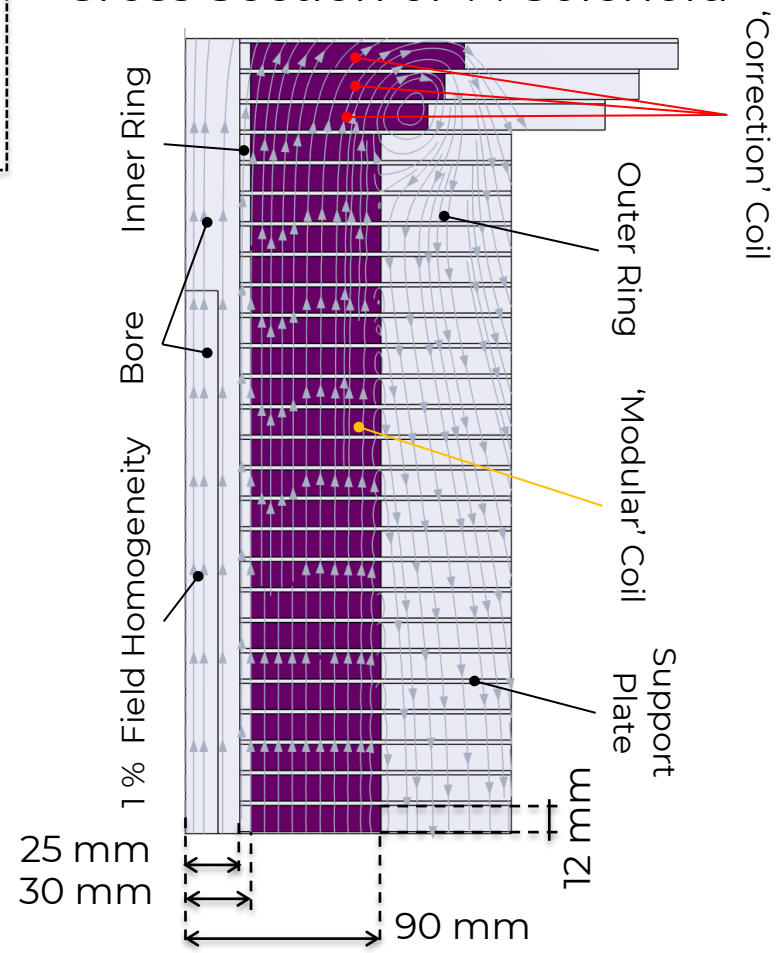
- **Main specs** used for the CERN conceptual design
  - **B ≥ 40 T**, aperture $\phi \geq$ **50 mm**,
  - field **homogeneity 1 %** over **0.5 m**
  - **Energizing** time **6 hrs** and **persistency 0.1 Units/s**

40+ T Conceptual design*
Ultra Compact Full ReBCO Solenoid

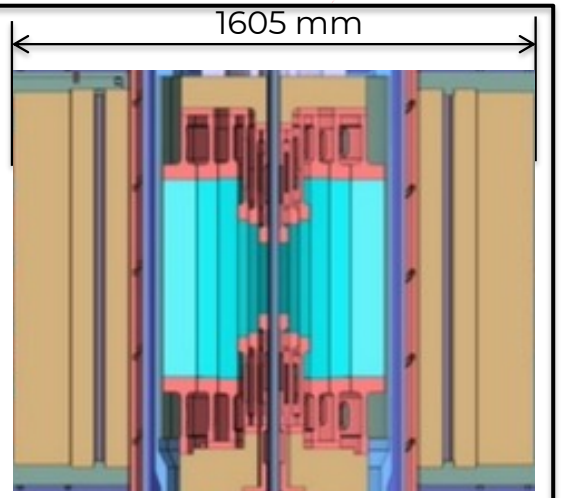
73 cm height 40 T solenoid
50 cm 1 % field homogeneity



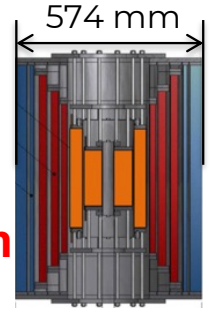
Cross Section of ¼ Solenoid



Windings of the **Hybrid 45 T, 32 mm** user facility solenoid at **CHMFL**



Winding of the **full superconducting** (15 T LTS, 17 T ReBCO) **32 T, 32 mm** user facility solenoid

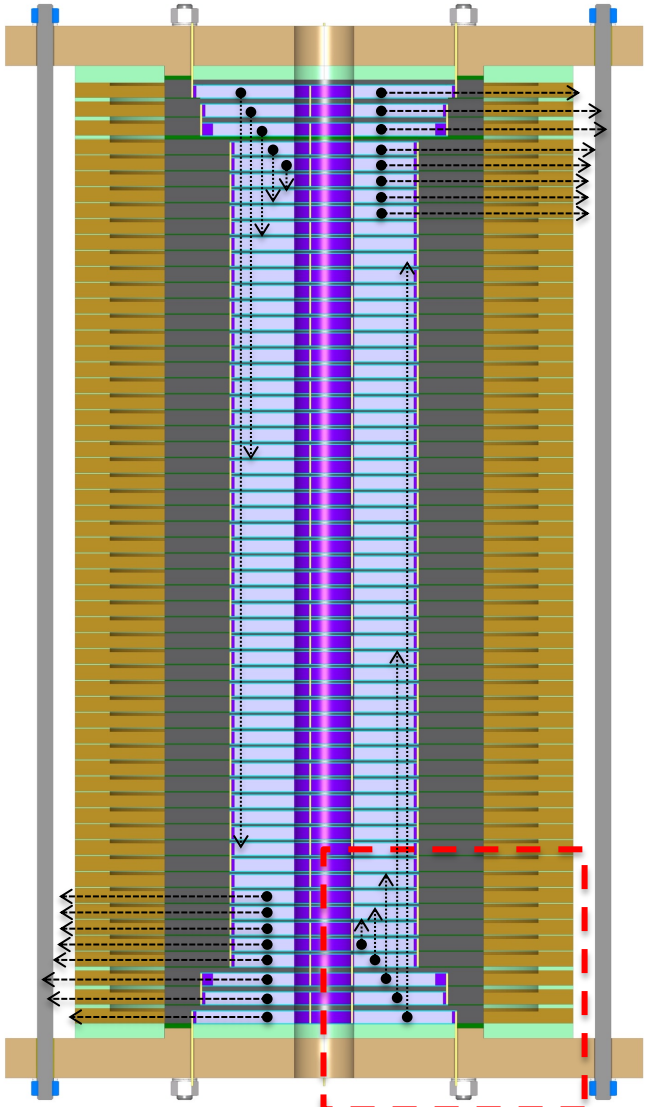


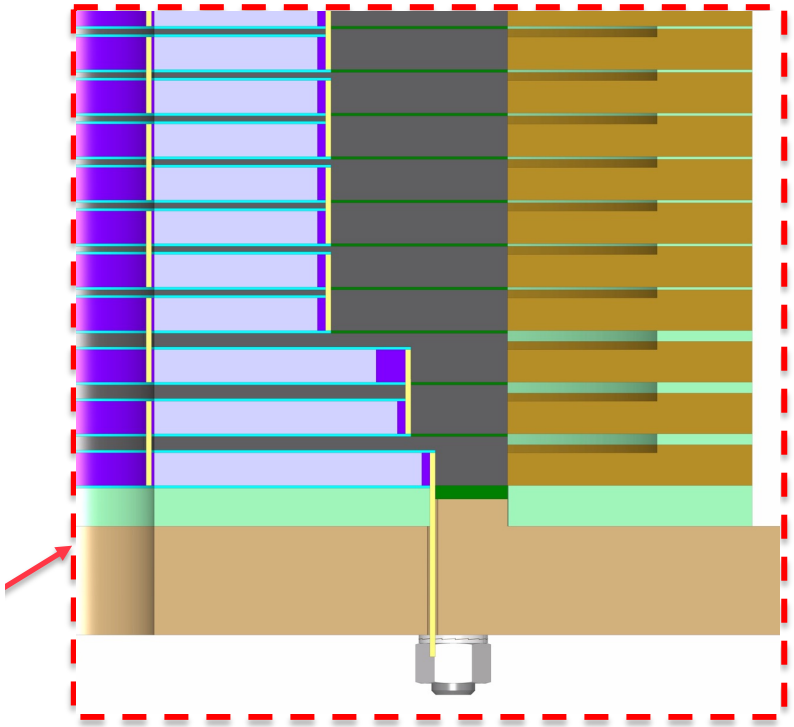
Winding of the **full ReBCO 40 T- 50 mm** solenoid proposed for the Final Cooling

*B. Bordini *et al.*, "Conceptual Design of a ReBCO Non/Metal-Insulated Ultra-High Field Solenoid for the Muon Collider," in *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 3, pp. 1-10, May 2024

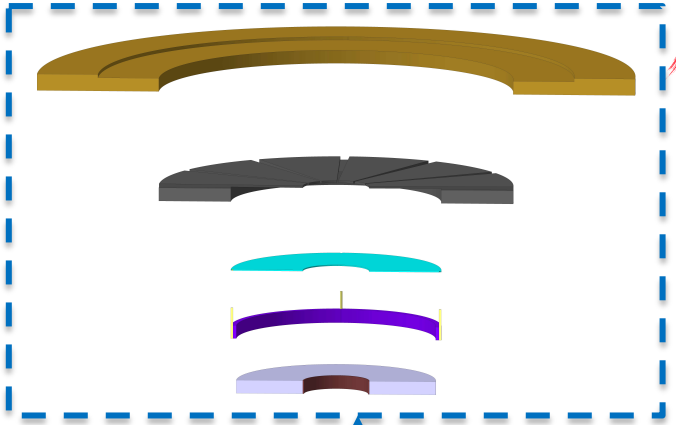
Advancing on the Engineering Design

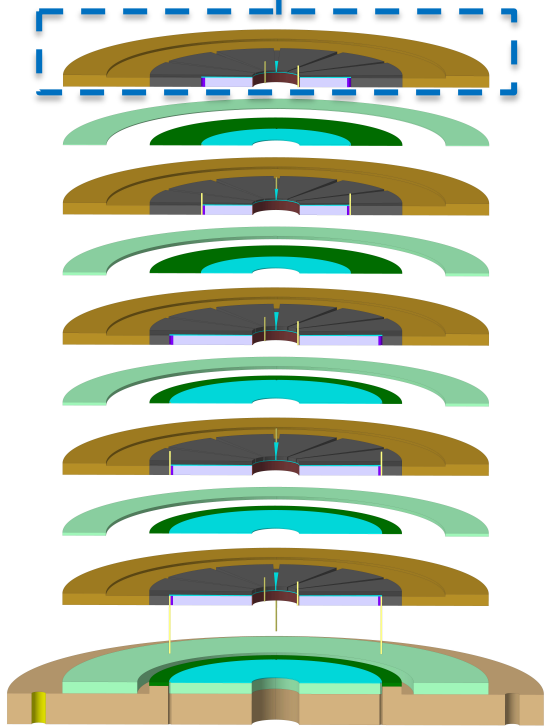
F. Sanda, A. Kolehmainen,
C. Accettura, A. Bertarelli





‘Explosion’ of the assembly of one pancake

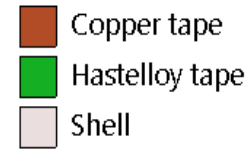




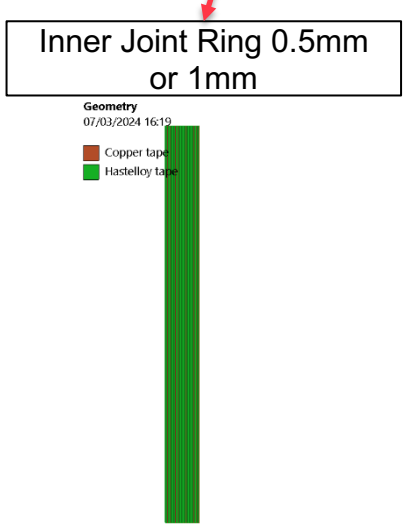
‘Explosion’ of the assembly of the first 5 pancakes from the bottom

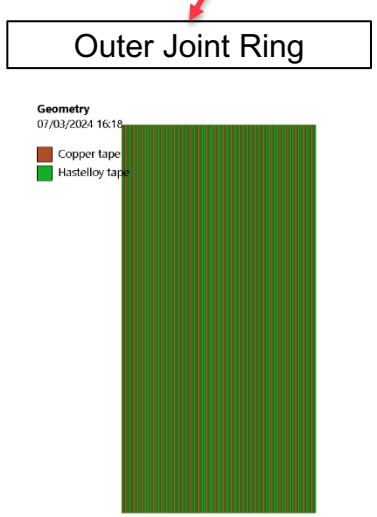
Mechanical Analysis
2 D FEM : geometry

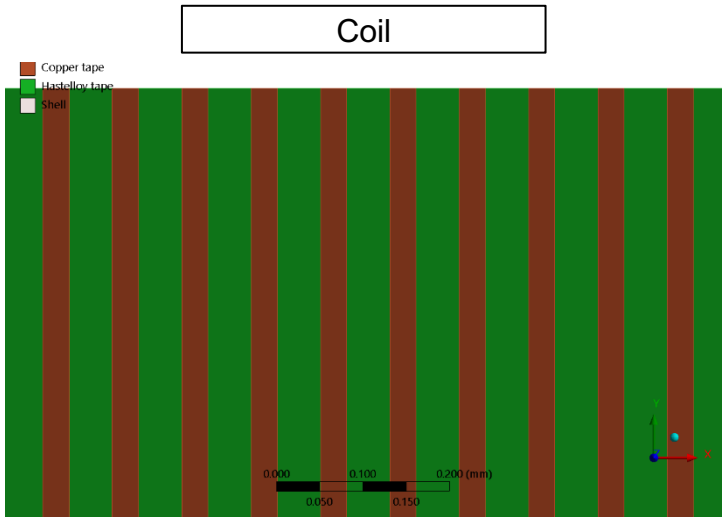
- Mechanical **Simulation** of a **modular coil: all 750** coil **windings** are **represented**
- The **Joint rings** and the **coil** are **wound** with **80 µm** thick **tapes** (**50 µm Hastelloy, 30 µm Cu)**



See Accettura et al. Poster 2LPo1B-03







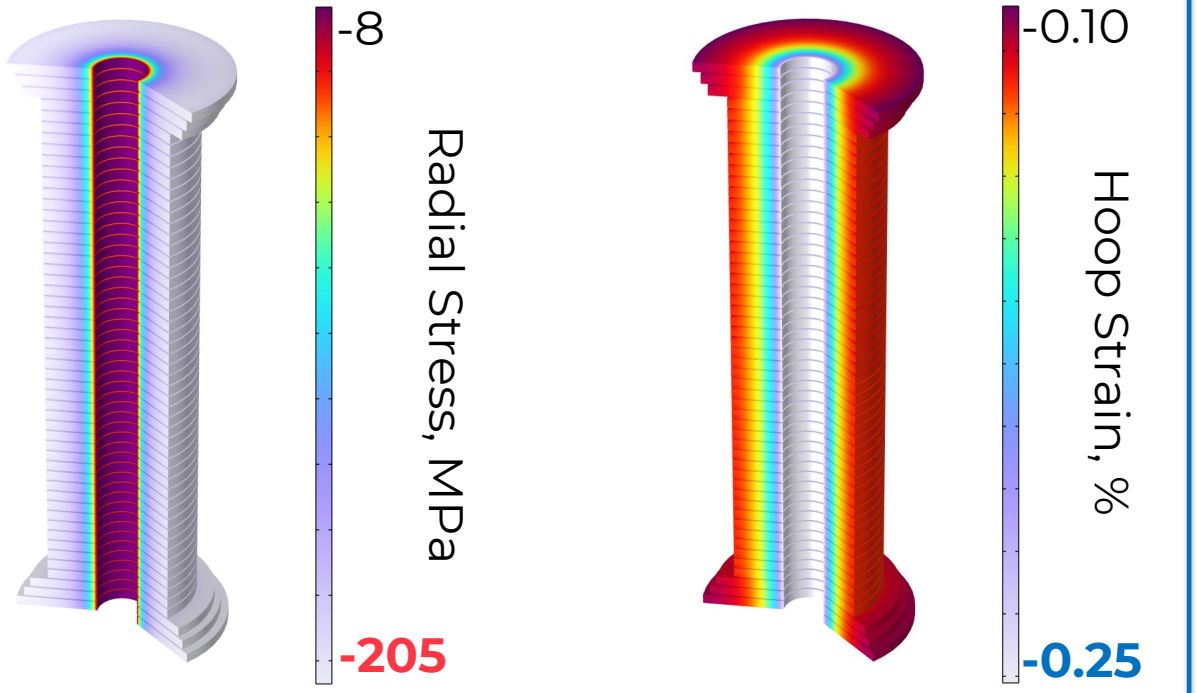
- **3** different **loading steps** simulated
  - ***I* pre-compression** via **shrink fitting**
    - the outer ring cools down to Room Temperature
  - ***II* cooldown from RT** to **4.2 K**;
  - ***III* energization** to 40 T
- The model accounts for
  - **Cu yielding**
  - **Thermal contractions** of the different materials

Mechanical Analysis

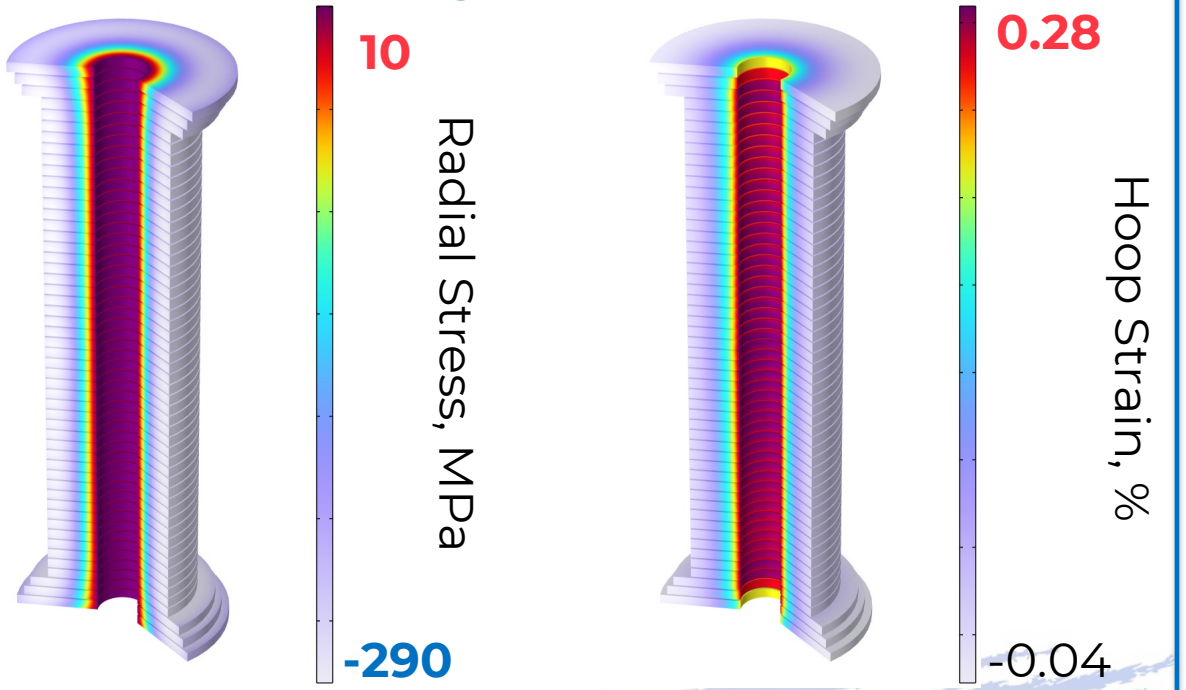
2 D FEM: ~200 MPa Pre-compression

Inner Joint ring thickness [mm]	Pre-compression at cold [MPa]	Min/Max *Radial* stress [MPa]			Min/Max *Hoop* Strain [%]		
		Step 1	Step 2	Step 3	Step 1	Step 2	Step 3
0.5	170						

Step 1 : Precompression at Room Temperature



Step 3 : Energization to 40 T @ 4.2 K



Mechanical Analysis
2 D FEM : four Case Studies

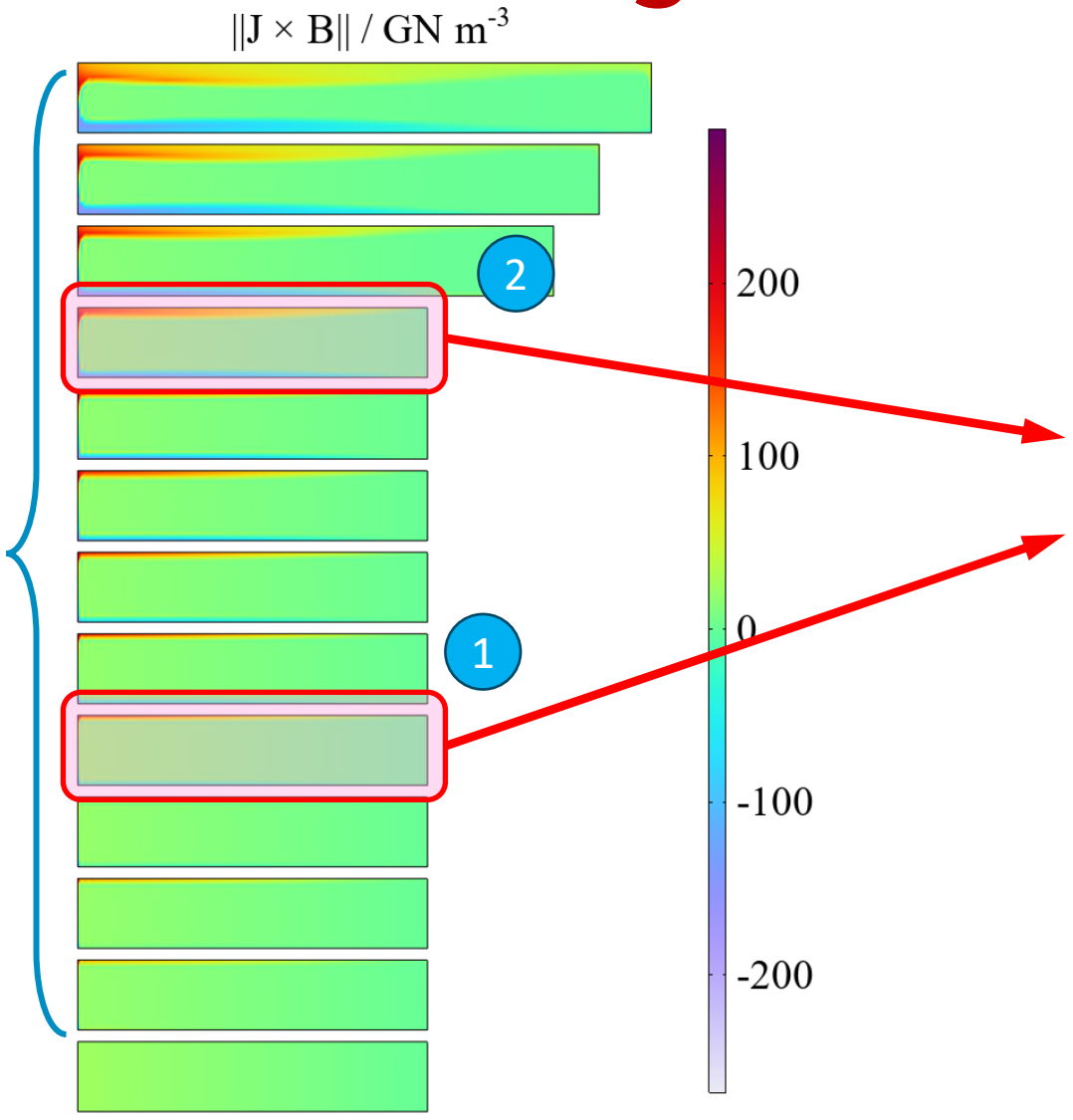
Inner Joint ring thickness [mm]	Pre-compression at cold [MPa]	Min/Max *Radial* stress [MPa]			Min/Max *Hoop* Strain [%]		
		Step 1	Step 2	Step 3	Step 1	Step 2	Step 3
0.5	170	-205/-8	-190/-5	**-290** /**10**	**-0.25**/-0.10	-0.20 /-0.12	-0.04/**0.28**
	250	-318/-12	-258/-8	**-367**/**7**	**-0.39**/-0.17	-0.31 /-0.16	-0.09/**0.18**
1	170	-205/-14	-190/-10	**-288**/**19**	**-0.25**/-0.10	-0.2 /-0.12	-0.05/**0.29**
	250	-320/-21	-259/-15	**-366**/**13**	**-0.39**/-0.17	-0.3 /-0.16	-0.09/**0.18**

Mechanical **loads** are **under control** (in **stationary** operating **conditions** and **neglecting** the **solenoid heads** where the conductor get **magnetized**)

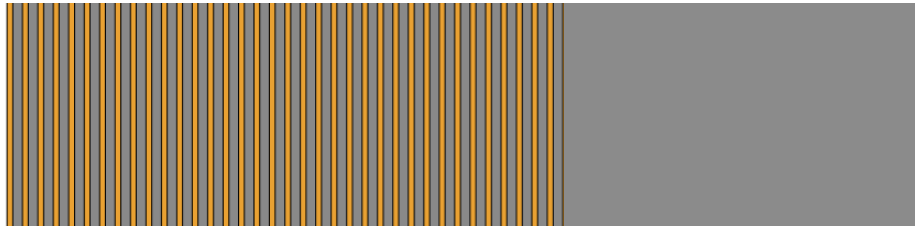
See Accetura et al. Poster
2LPo1B-03

Electro-Mechanical Analysis
2 D FEM – Magnetization in Operation

Coils Electro dynamics with T-A Formulation



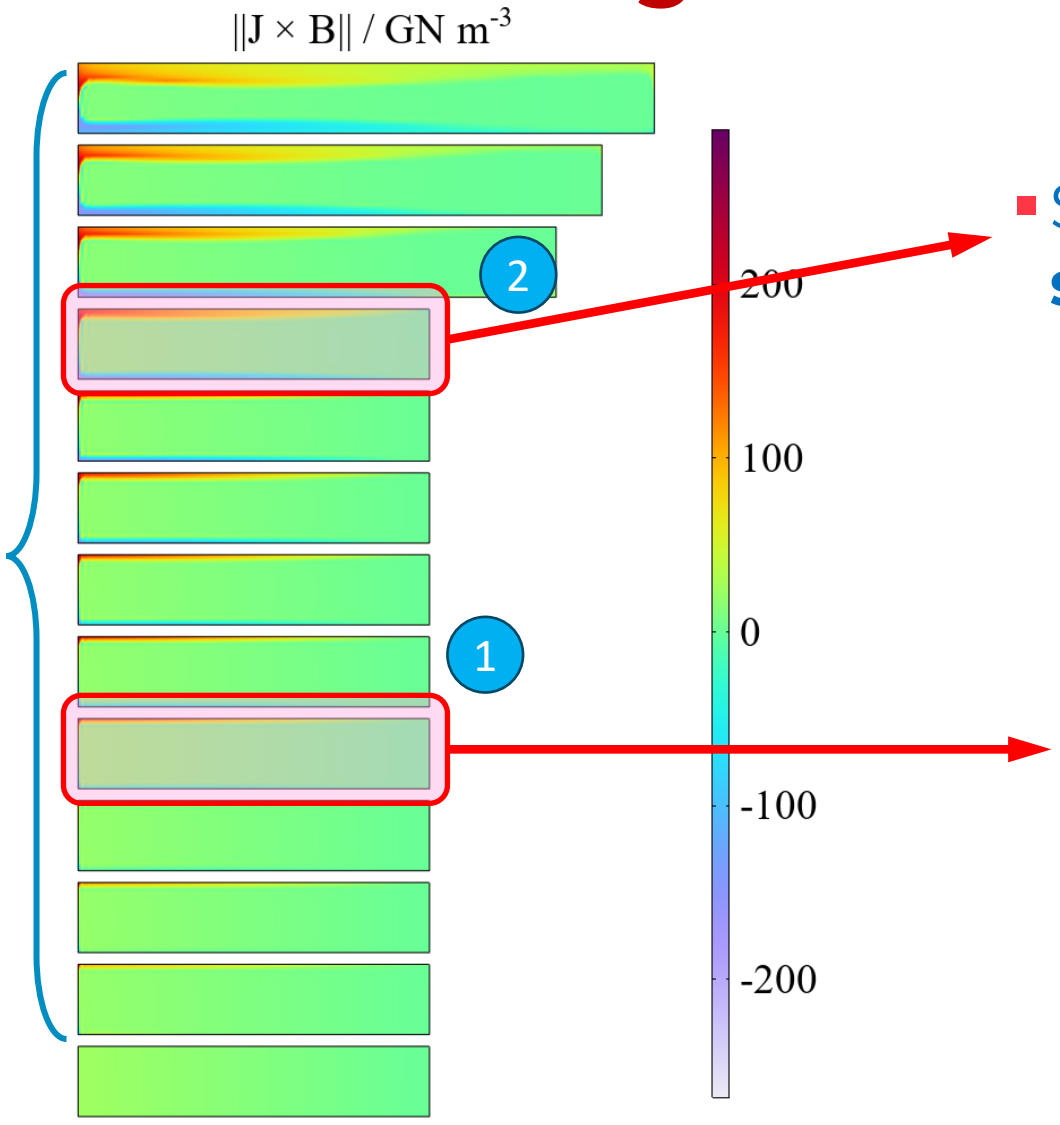
We study the mechanic,
with a detailed model to the tapes' scale



G. Vernassa

Electro-Mechanical Analysis
2 D FEM – Magnetization in Operation

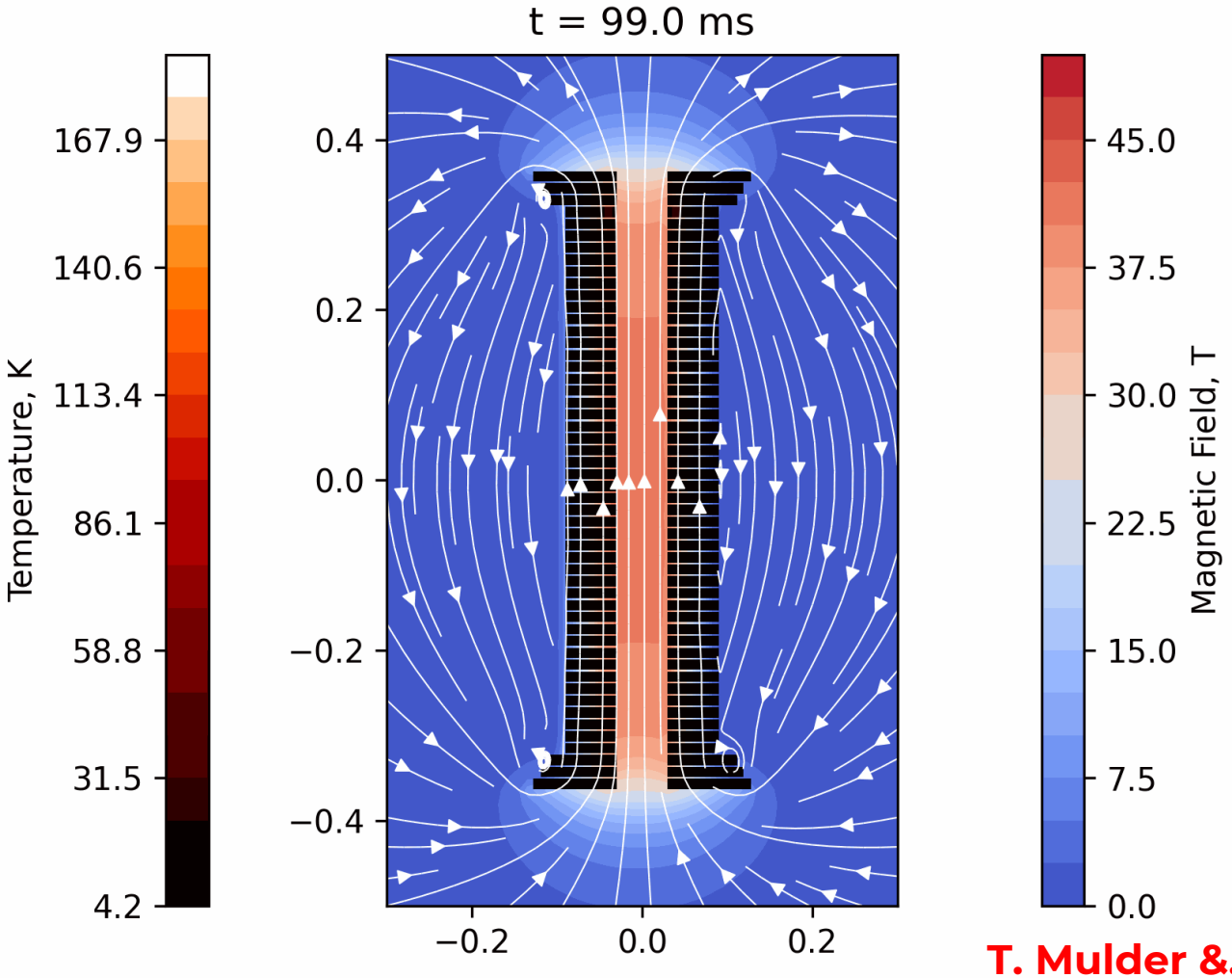
Coils Electro dynamics with T-A Formulation

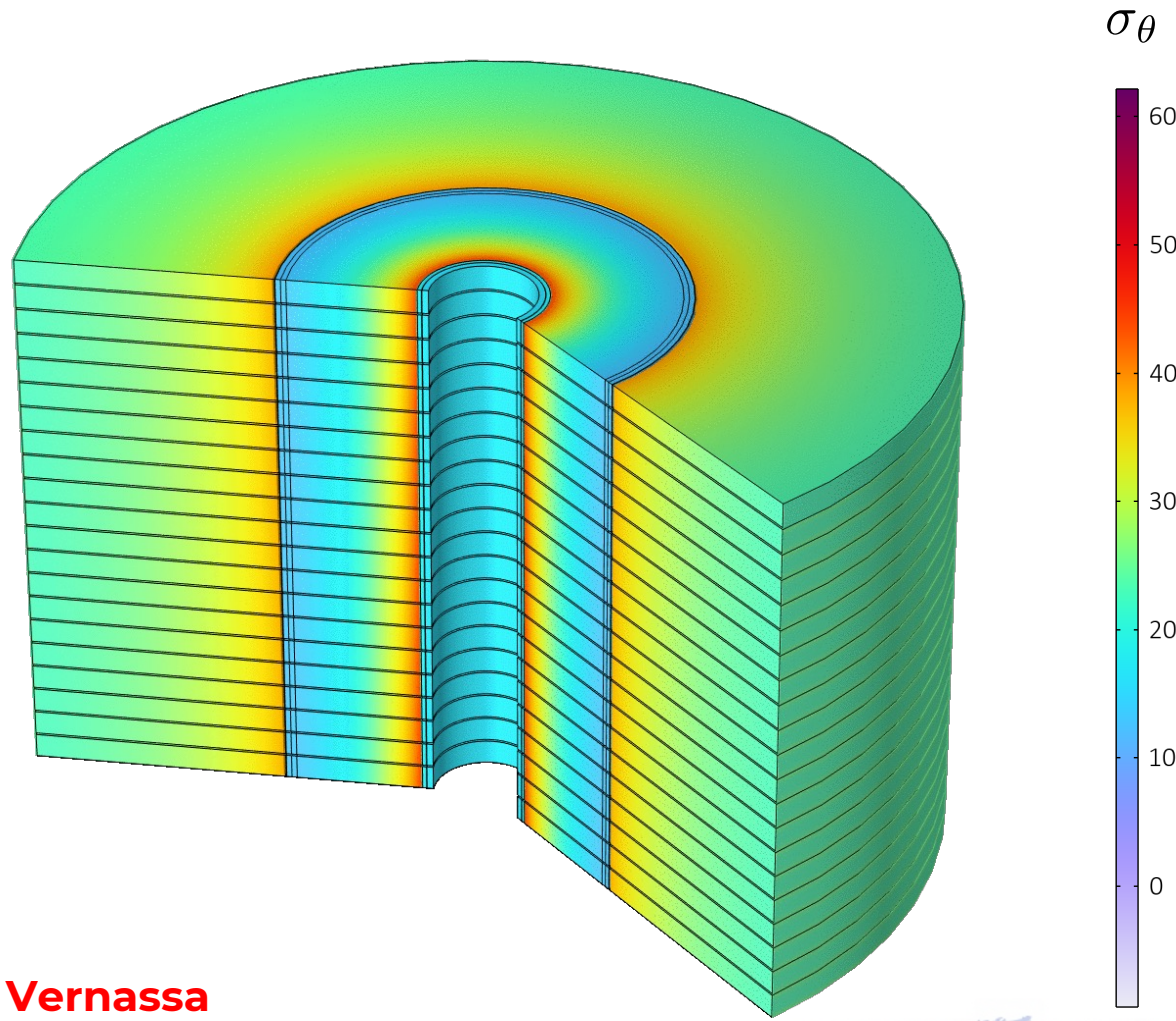


- Significant **Increase** of max **hoop strain ~30%**
  - to be considered striated tapes as in magnet heads
- **Increase** of max hoop strain **negligible** ~1%

G. Vernassa

Integrated Mechanical-Electrodynamic simulations

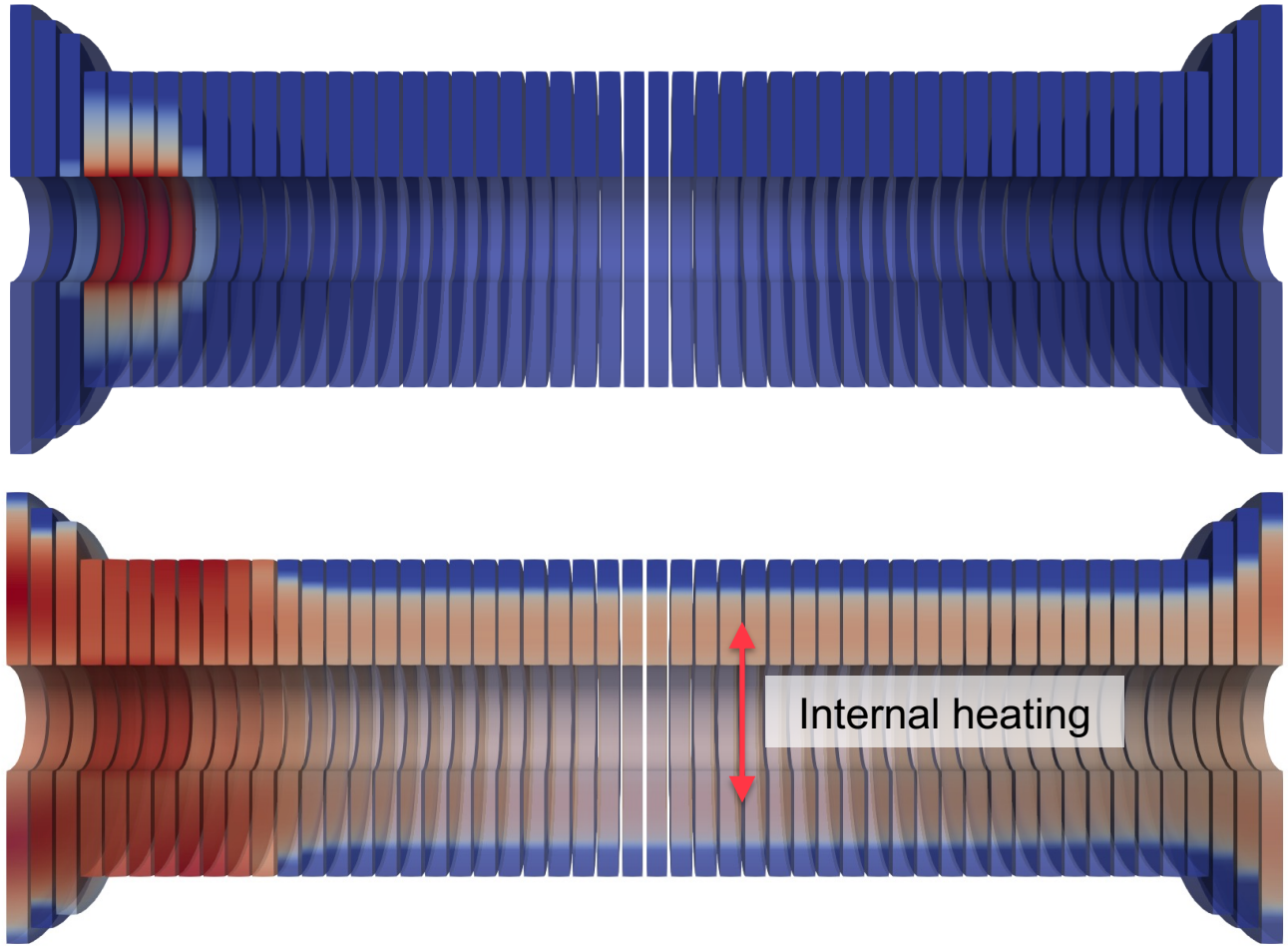


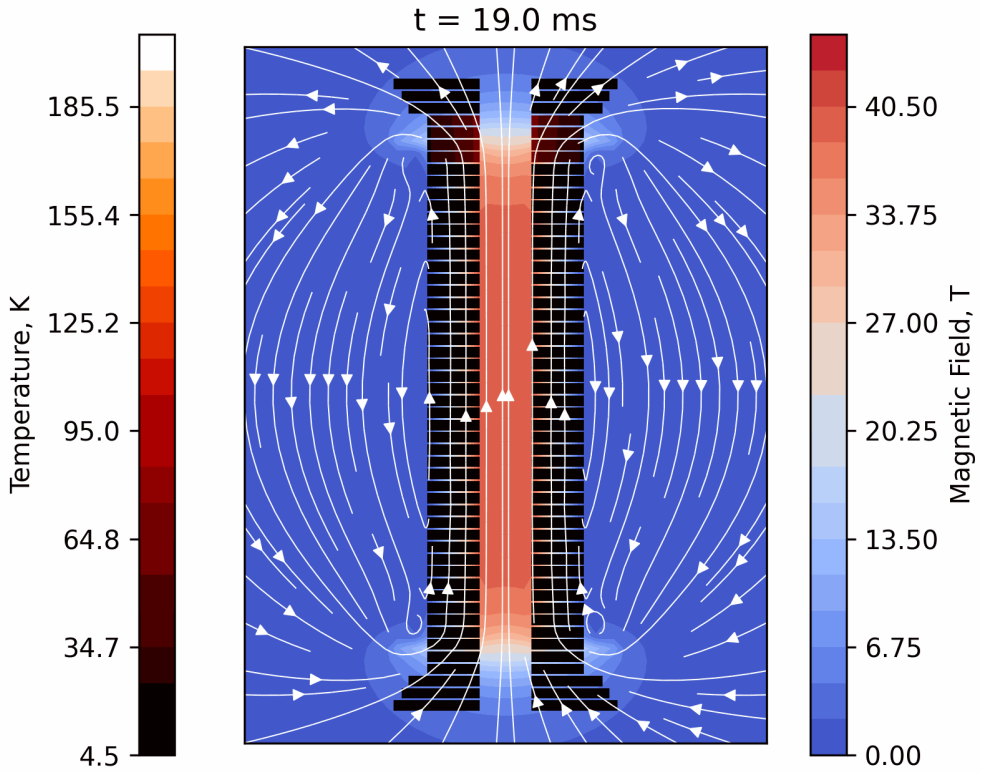


T. Mulder &. G. Vernassa

Protection Studies

See Mulder et al. Presentation 3J-ML-Or2A-04





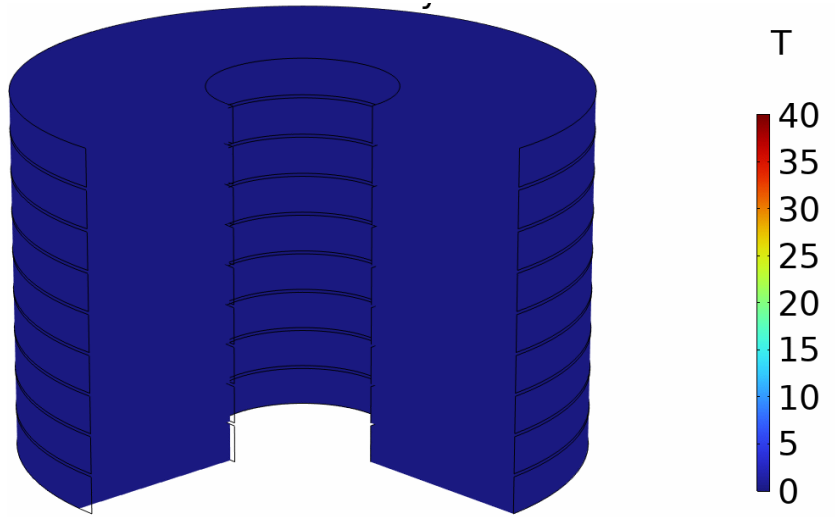
✓Magnet's turn-to-turn resistance used as internal quench heater.
✓Good distribution of dissipated stored energy and a resulting peak temperature of below 200 K.
✓No large induced currents, mechanically favorable solution.

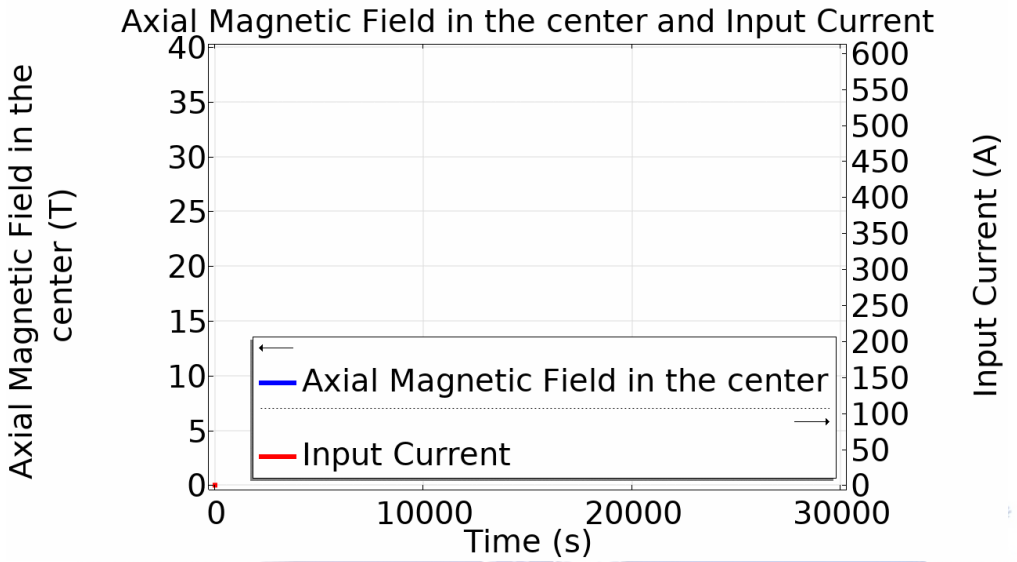
3D electrodynamic models
40 T Solenoid - Energization

Assumptions:

- **Infinite** number of identical **3D** pancakes
- Coil winding thickness **6 cm**
- **Conductor** made of **two tapes** (total thickness 160 μm)
- **750 layers** of conductor
- Tape width **12 mm**
- contact resistance, **10 μΩ cm²**
- **2 mm** of air between coils

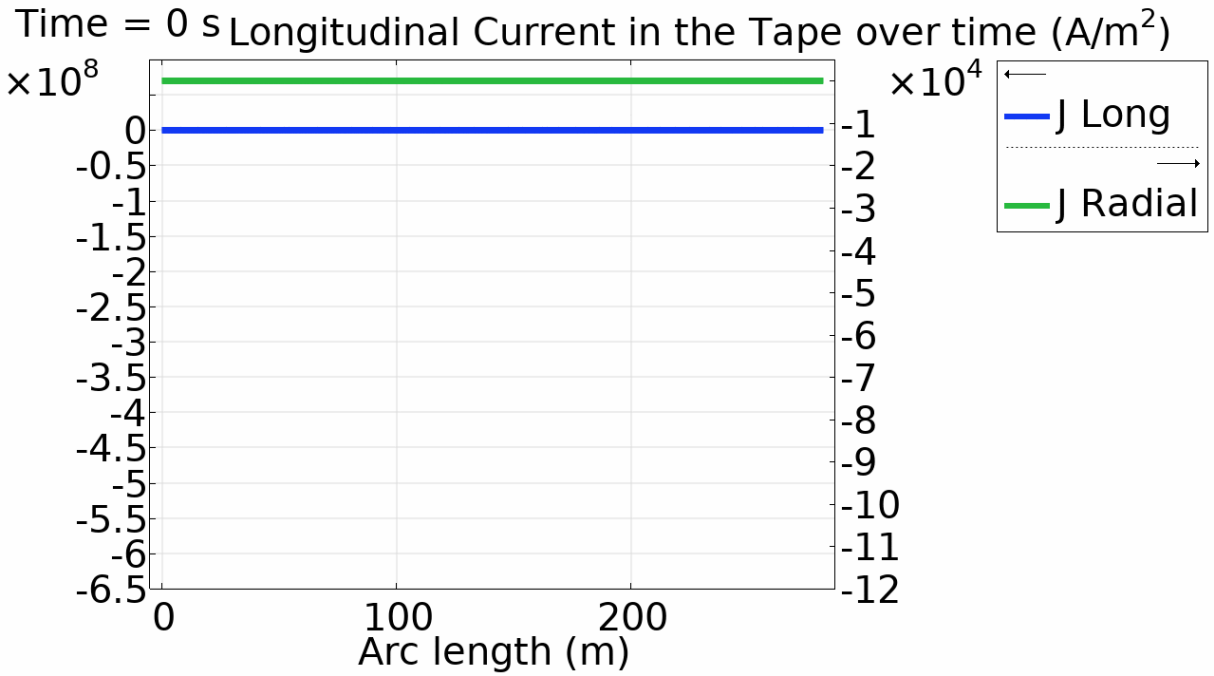
Only 1 hour computational time in a 2 k$ PC !!!

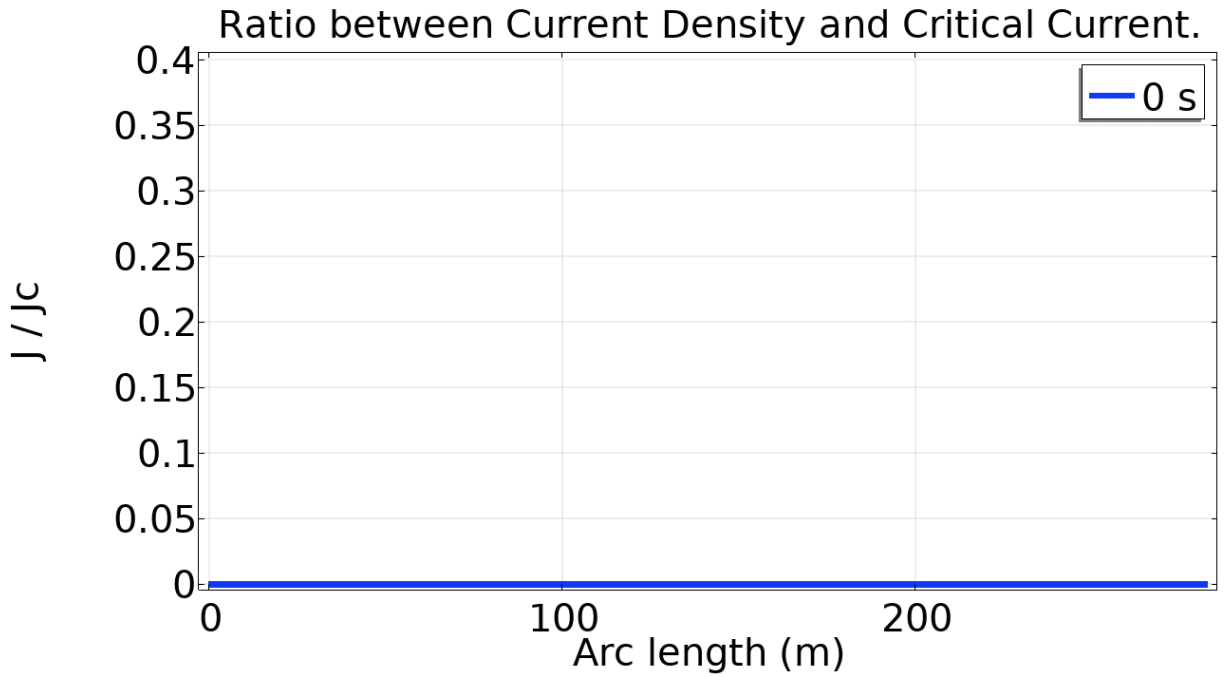




D. Rinaldoni

3D electrodynamic models
40 T Solenoid – Current Distribution



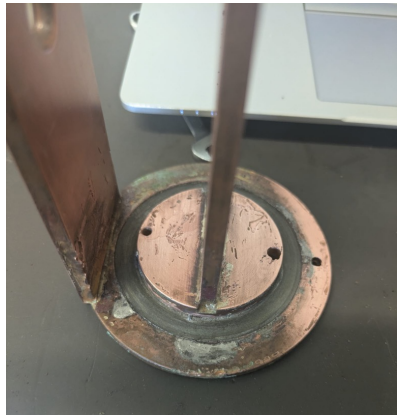


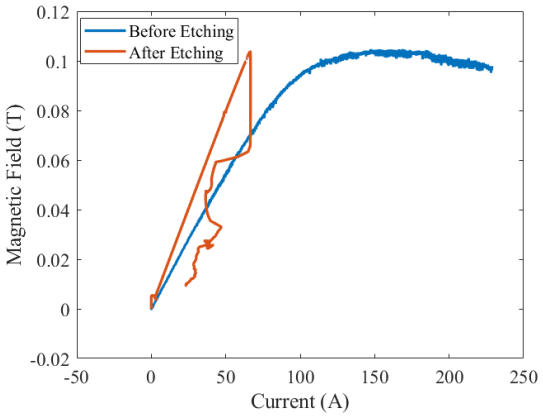
D. Rinaldoni

- **Large Current margin**: the current density along the superconductor is less then **40 %** of the **critical current**

Technological Studies
Fully soldered pancake

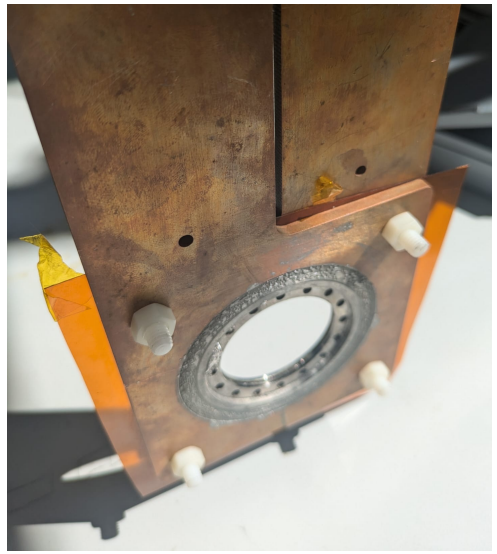
M. A. Hafiz

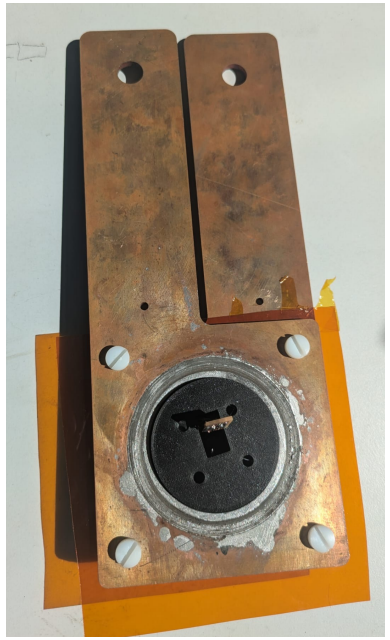




Energization Current	$\tau_c\ (s)$	
	Before Etching	After Etching
5 A	4.9	0.042
10 A	4.7	0.041
20 A	4.8	0.030
50 A	4.6	0.052

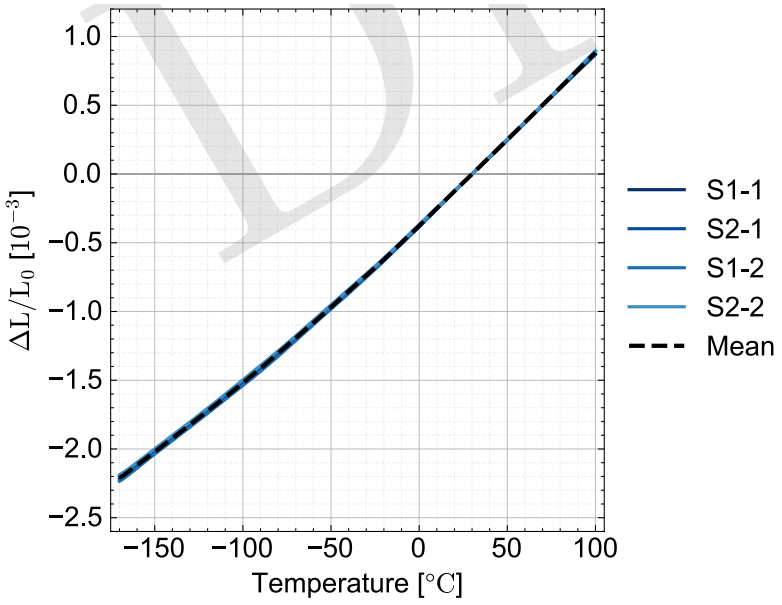
Single pancake



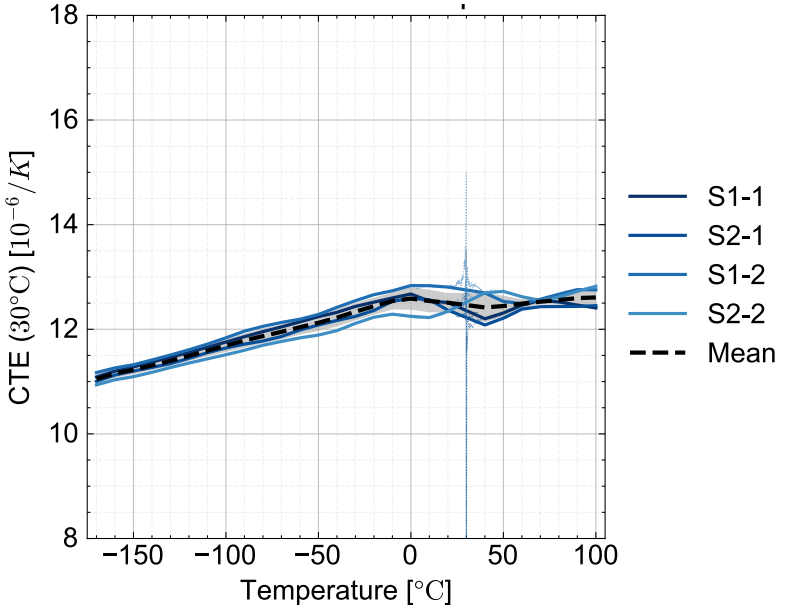


Double pancake configuration to be tested in the coming days

Macro-Mechanical Characterization

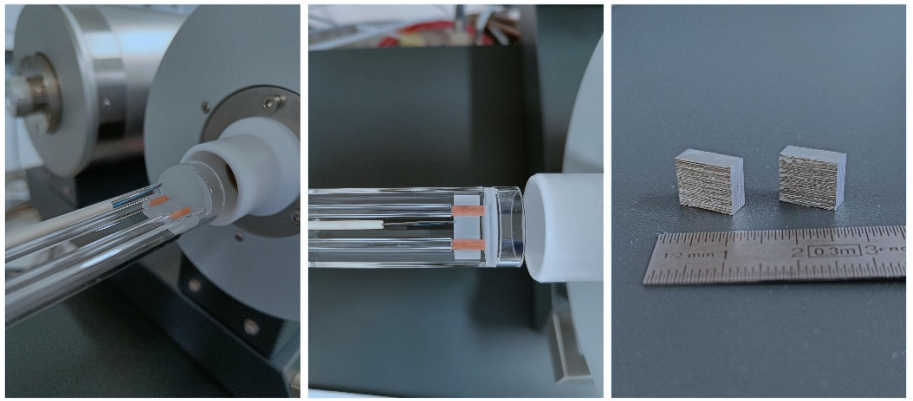


(a) Relative change in length



(b) Coefficient of thermal expansion

Stack Samples



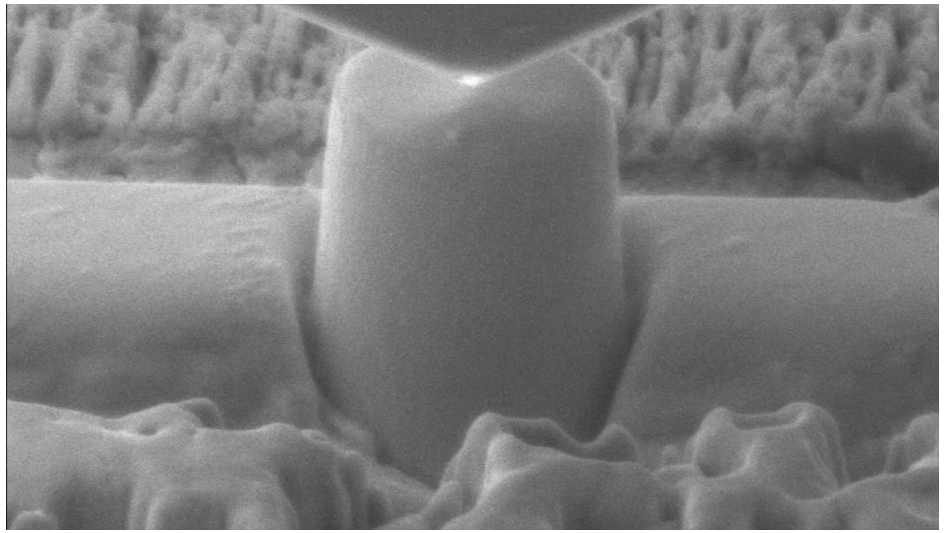
Sample holder including two samples of the Fujikura FESC-SCH04 tape

Thermal expansion measured for two samples of the Fujikura FESC-SCH04 tape

Courtesy of Stefan Hoell & Oscar Sacristian de Frutos, CERN

Micro-Mechanical Characterization

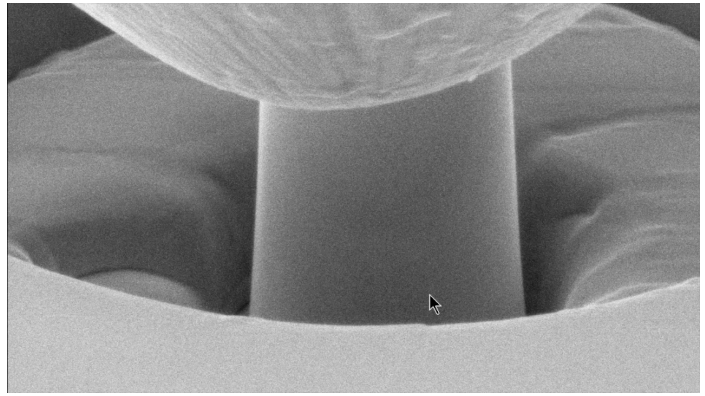
Micropillars Splitting at 300 K

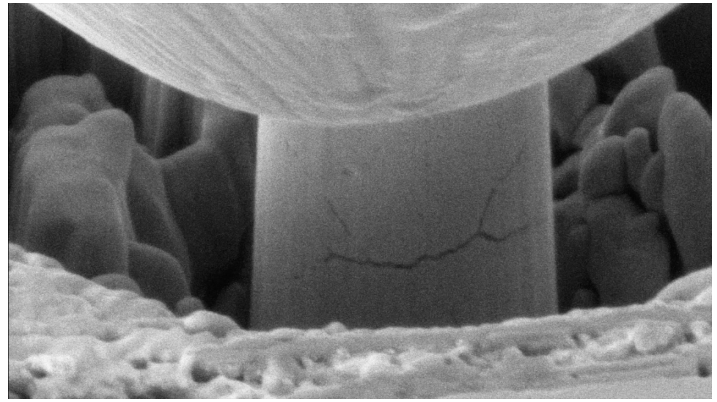


*See Vernassa et al. Poster 2MPo2C-08

Hastelloy	Copper
σ^y / GPa	σ^y / GPa
1.2 – 1.4	**0.4 – 0.6**

Micropillar compression on Hastelloy and Copper

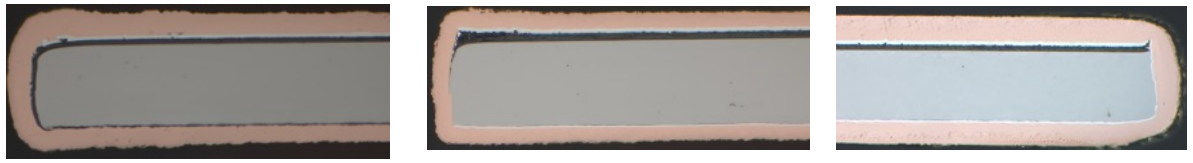


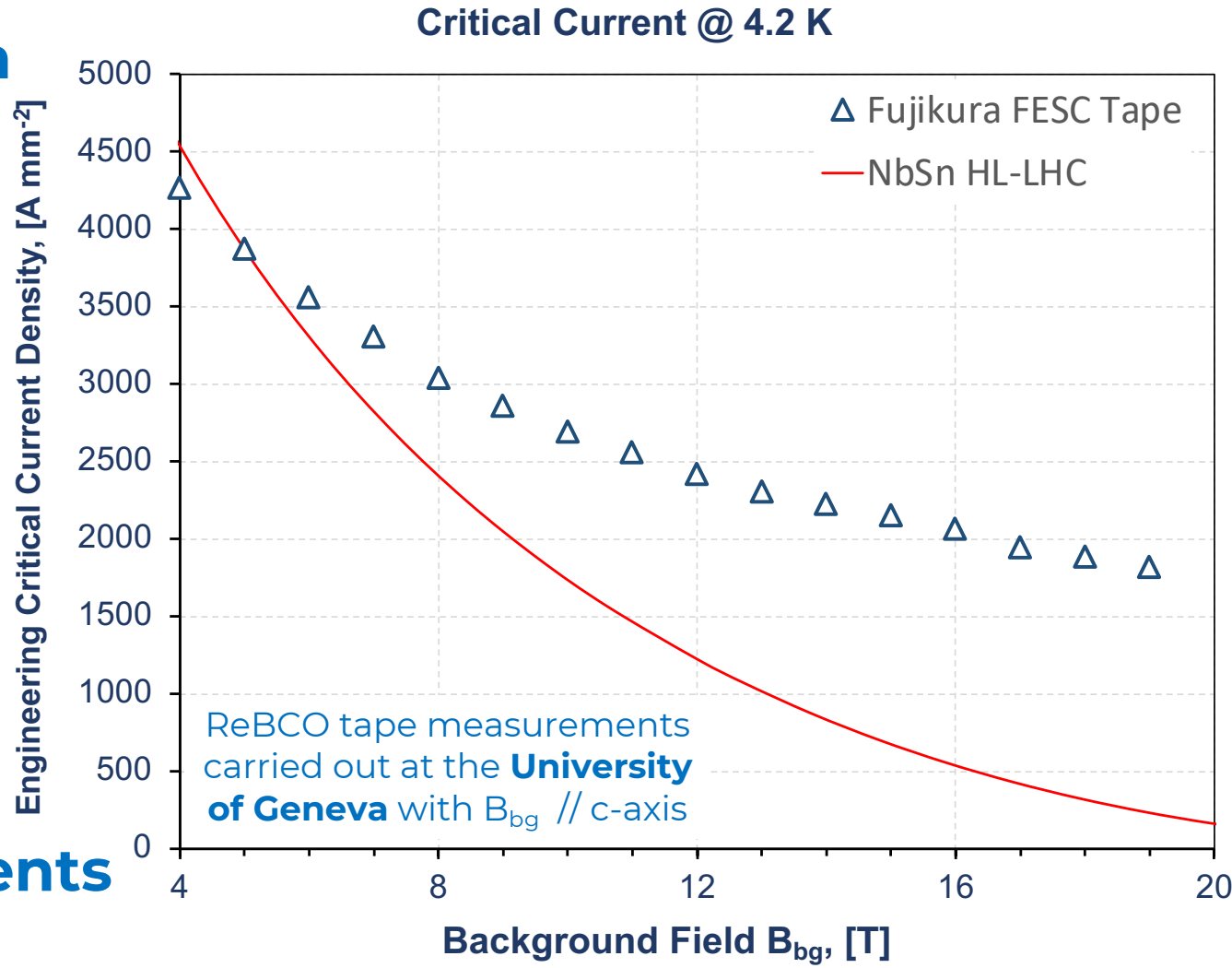


REBCO
K_c / MPa $m^{0.5}$
1.34 ± 0.12

ReBCO Tape Procurement & Electrical Characterization

- **Procured** more then **10 km** of **4 mm** tape from 3 different companies
  - Fujikura
  - SST
  - Faraday



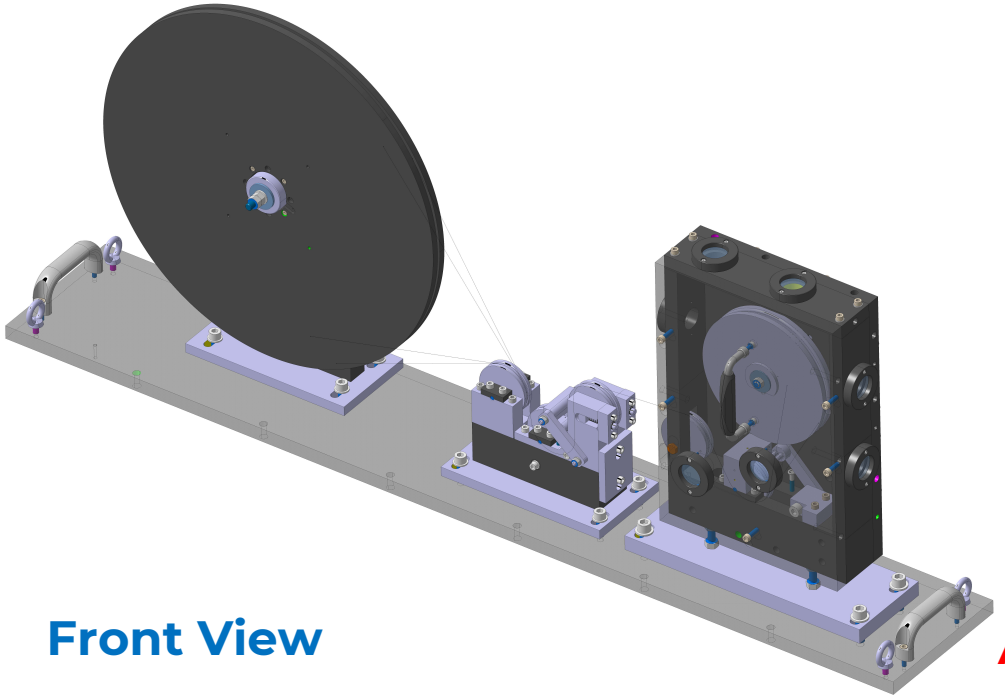


- Started **critical current measurements**

Ready to GO

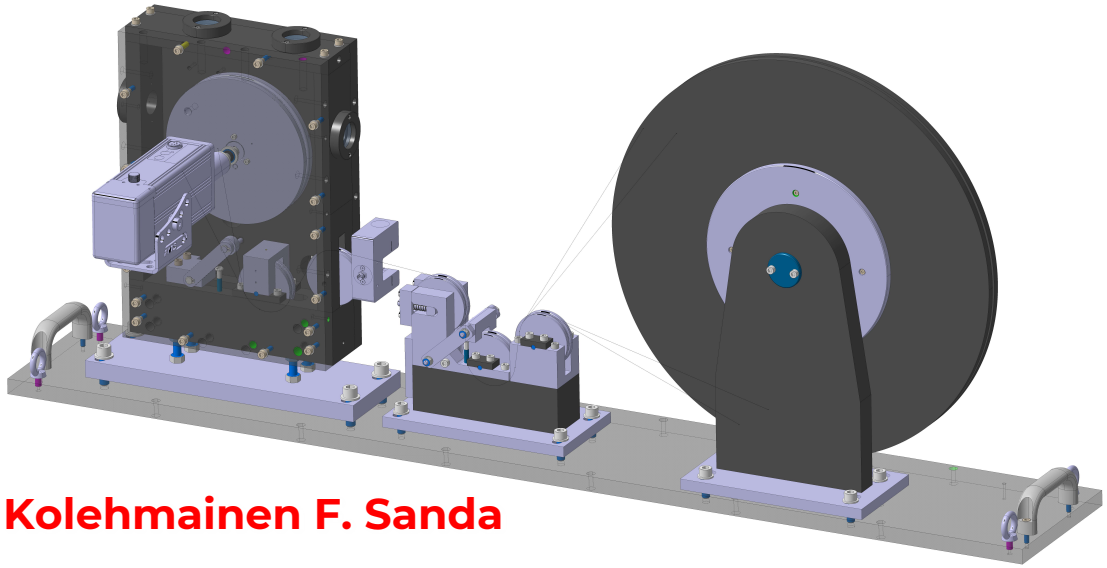
- **Designed** and **procured** the **components** of a **winding machine** allowing hot winding of soldered pancakes; **assembly** is expected starting **this week**

Ready to start manufacturing and testing pancakes in 'series' !!!



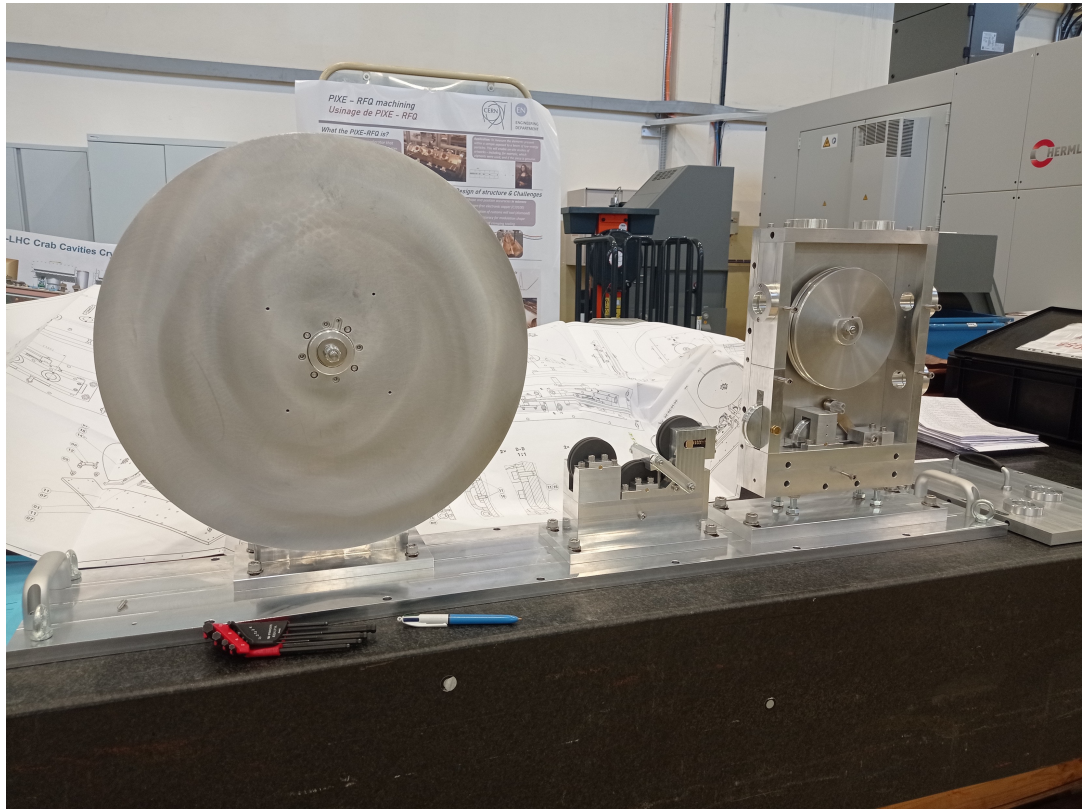
Front View

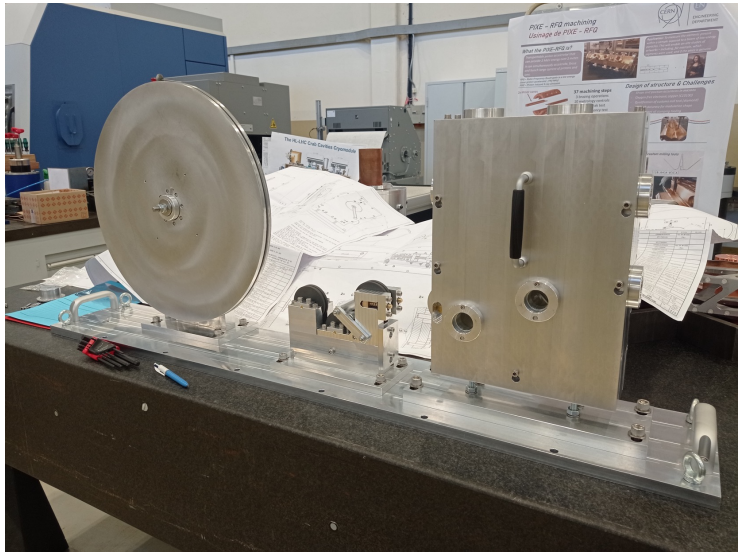
Rear View

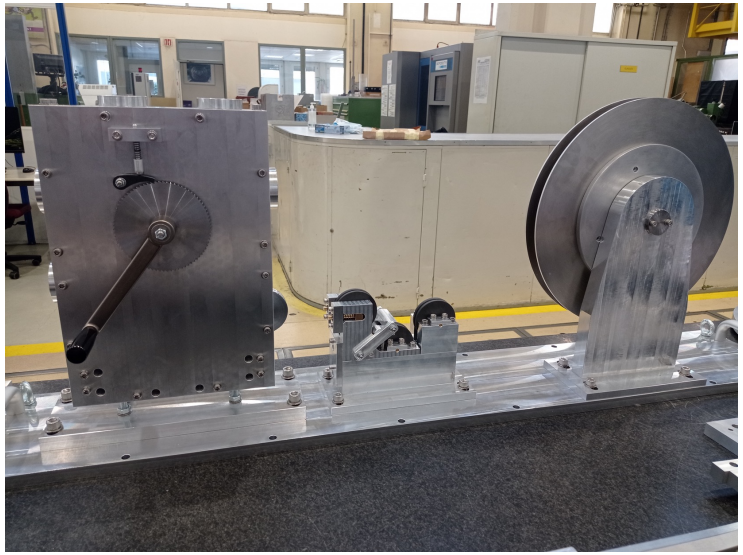


A. Dudarev , A. Kolehmainen F. Sanda

And now 27-09-24 … GO !







Y. S. Farys , Patrick Louis Bouvier, A. Dallocchio, M. Garlasche

Conclusions & Next Steps

- Many activities on going, mostly focusing on the main **identified criticalities**:
  - The **electro-mechanical** design → **stresses** on the **conductor** are very large
  - The **electrodynamics** and **protection** of the magnet → **complex transients** to control
- The project is **challenging** but **no show-stoppers** appeared **so far** and we are a **growing team** strongly **motivated**
- With the arrival of the winding machine, **experimental activities** and the **manufacturing** & **testing** of **pancakes** will significantly **increase**

Thank You For the Attention