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

International MUON Collider Collaboration

ASC 24 SALT LAKE CITY
SEPTEMBER 1 - 6
SALT PALACE CONVENTION CENTER

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

Funded by the European Union

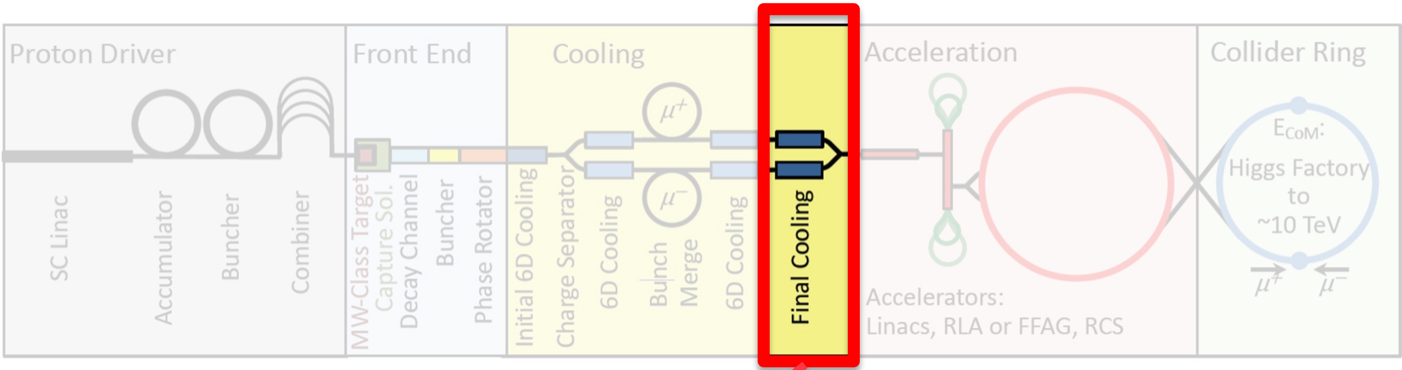
MuCol

B. Bordini, C. Accettura, A. Bertarelli, L. Bottura, A. Dudarev, M.A. Hafiz, A. Kolehmainen, T. Mulder, D. Rinaldoni, F. Sanda, G. Vernassa, A. Verweij, M. Wozniakc

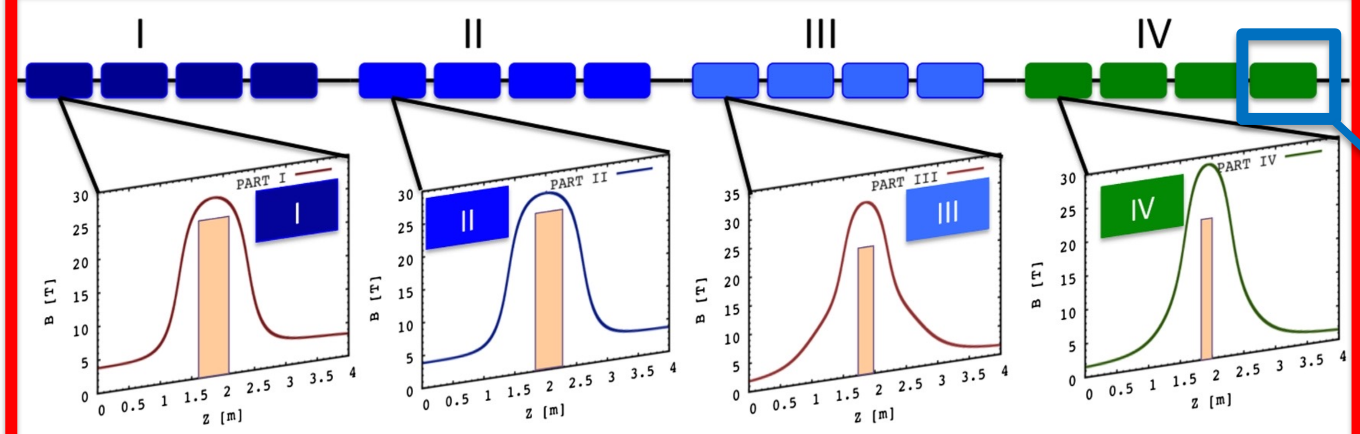
Outline

- **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

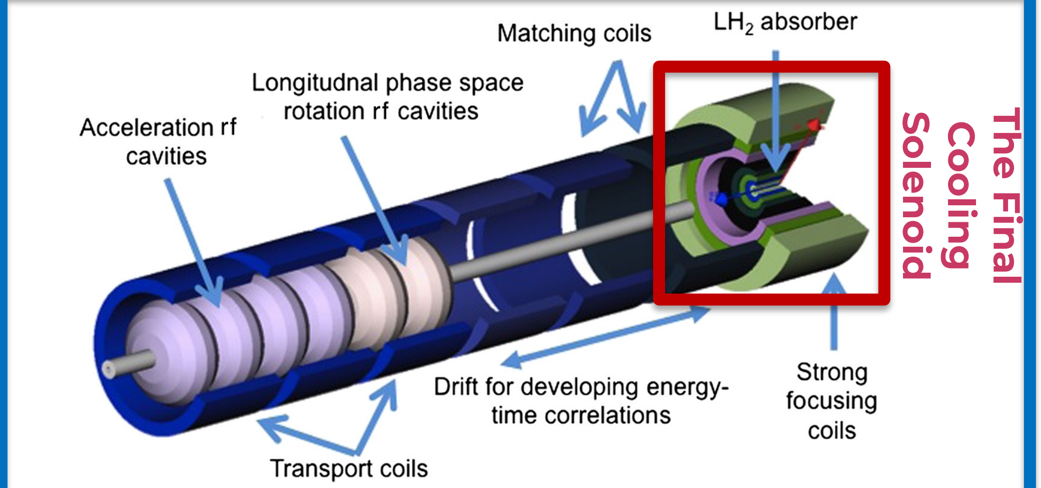
The Muon Collider
Final Cooling Channel



- 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



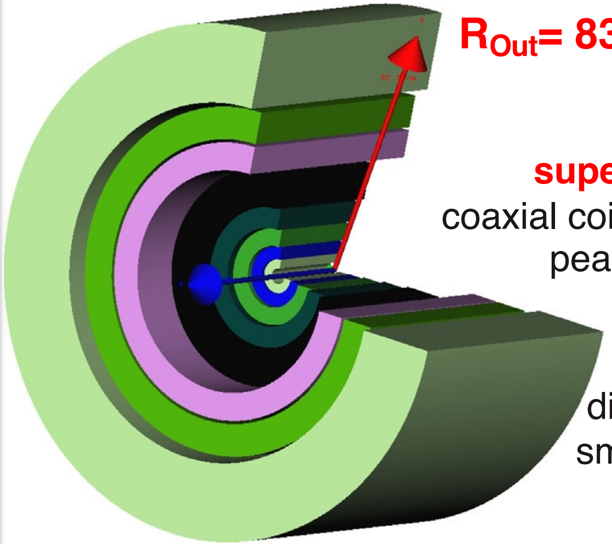
A layout schematic of **16 cells** of the **final cooling channel** defined by the MAP study (Sayed et al. Phys. Rev. ST Accel. Beams **18**, 091001). The coloured boxes in the top represent the **cooling cells.** The bottom figures show a sample of the on-axis field of the strong focusing solenoid;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

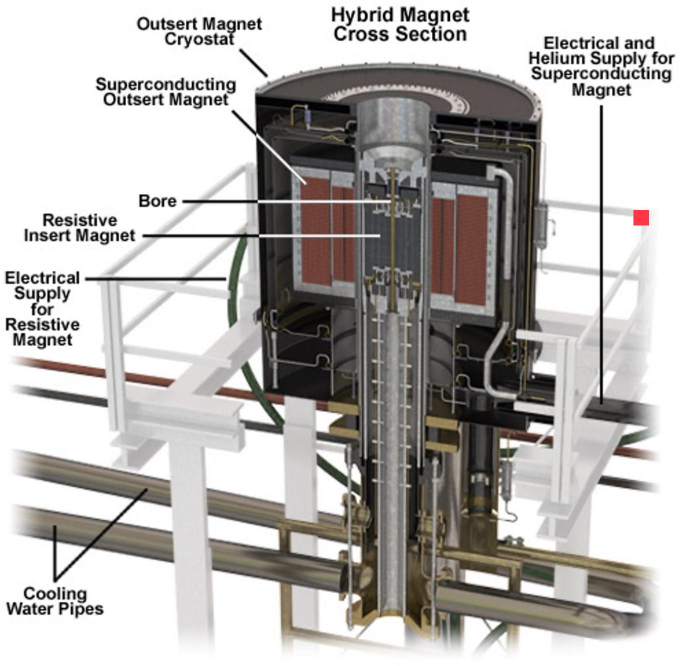
Design proposed by MAP



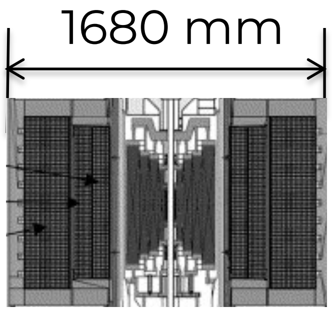
A set of eight **superconducting** coaxial coils providing a peak field of **50 T**

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

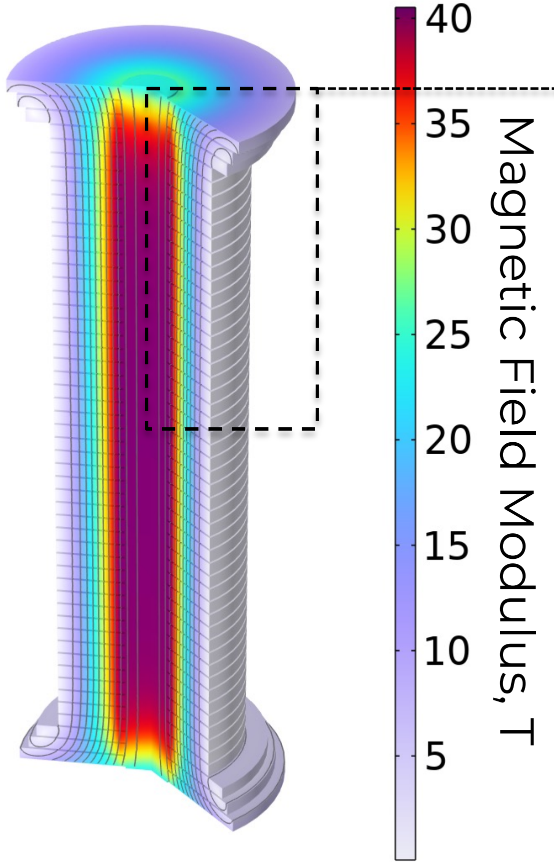
- **Main specs** used for the CERN conceptual design
  - **B ≥ 40 T**, aperture **ϕ ≥ 50 mm**,
  - field **homogeneity 1 % over 0.5 m**
  - **Energizing** time **6 hrs** and **persistency 0.1 Units/s**

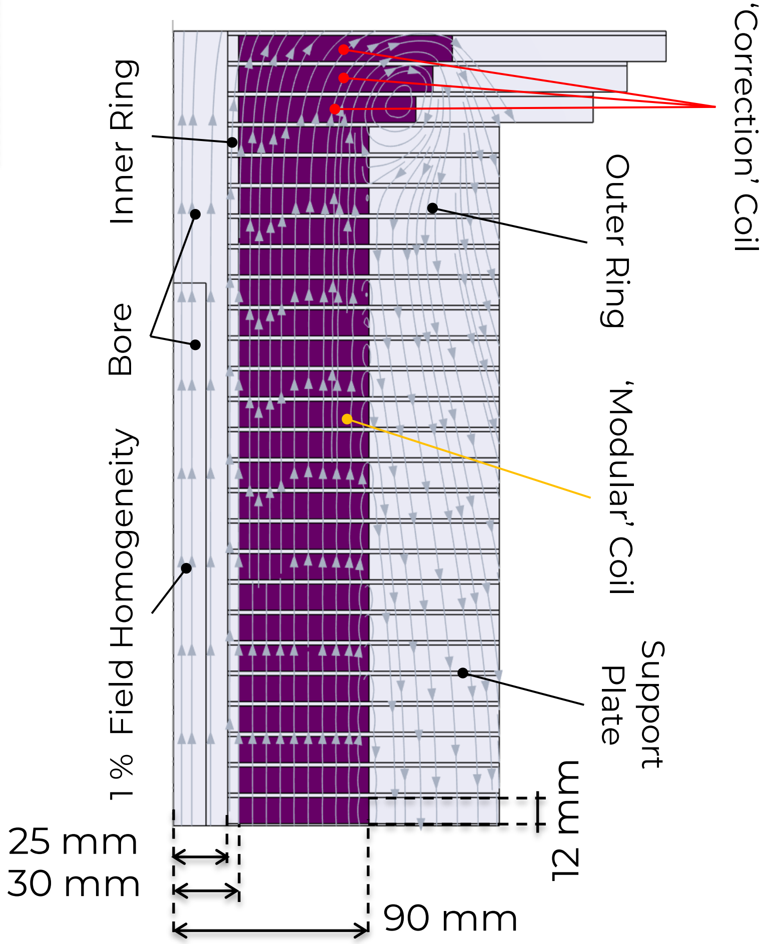
40^{+} T Conceptual design*

Ultra Compact Full ReBCO Solenoid

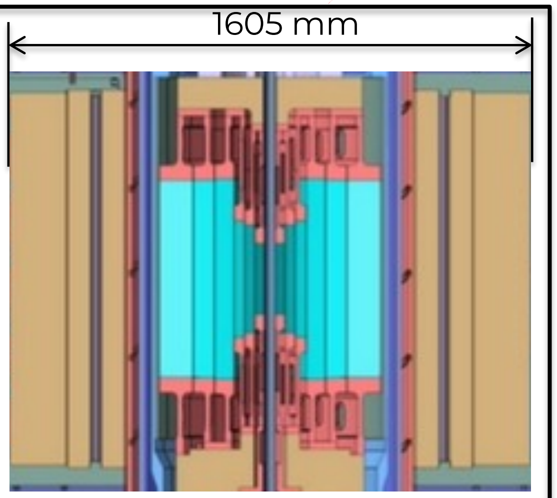
73 cm height 40 T solenoid
50 cm 1 % field homogeneity

J = 632 A mm^{-2} → 40 T

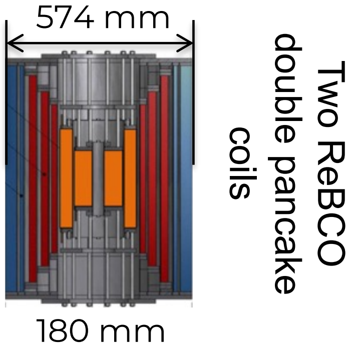




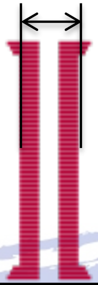
Windings of the **Hybrid** **45 T**, **32 mm** user facility solenoid at **CHMFL**



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

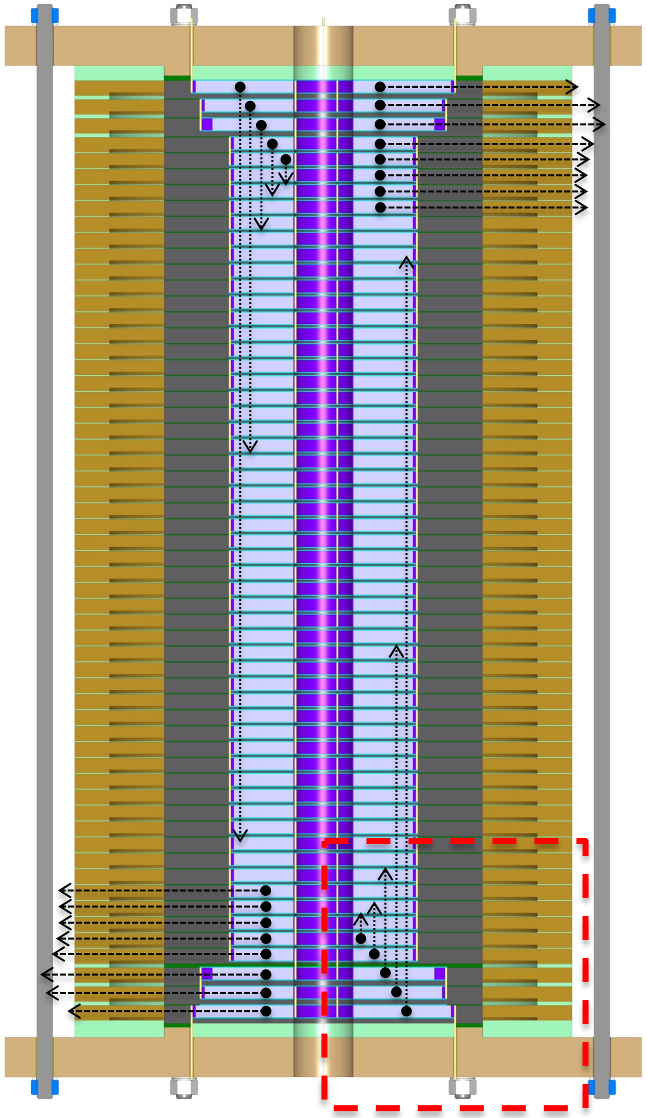


Winding of the **full ReBCO 40 T- 50 mm** solenoid proposed for the Final Cooling

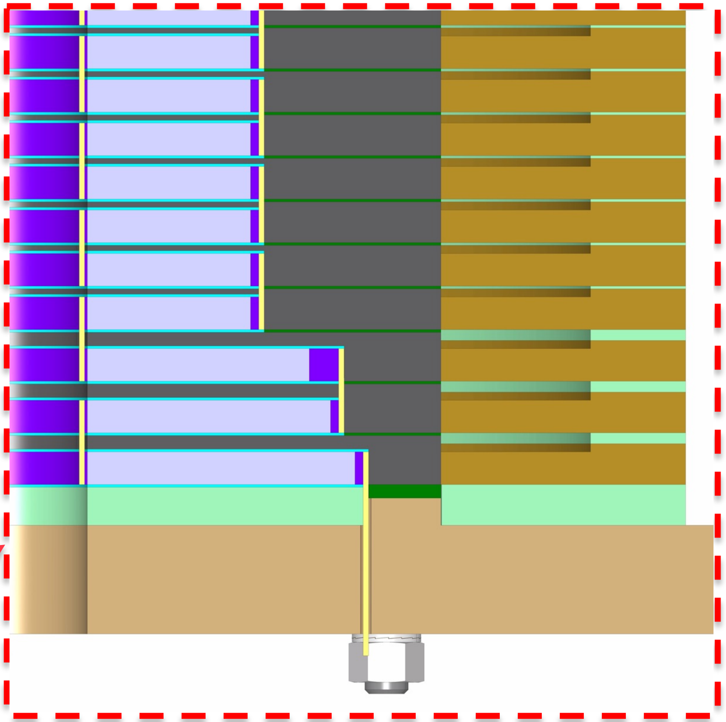


*B. Bordini *et al.*, "Conceptual Design of a ReBCO Non/Metal-Insulated Ultra-High Field Solenoid for the Muon Collider," in *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 3, pp. 1-10, May 2024

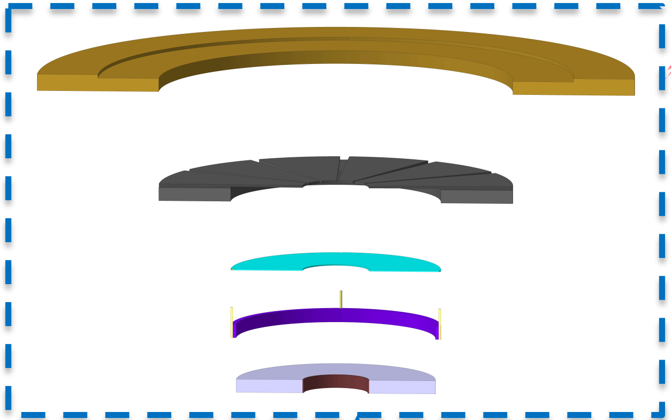
Advancing on the Engineering Design

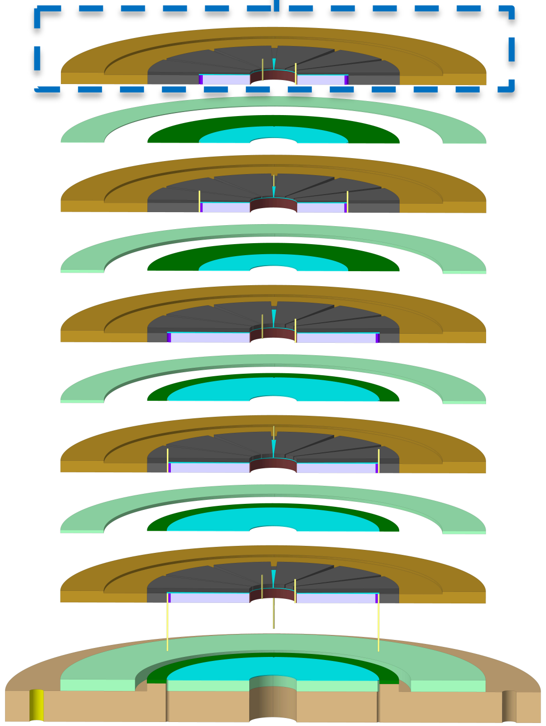


**F. Sanda, A. Kolehmainen,
C. Accettura, A. Bertarelli**



'Explosion' of the assembly of one pancake

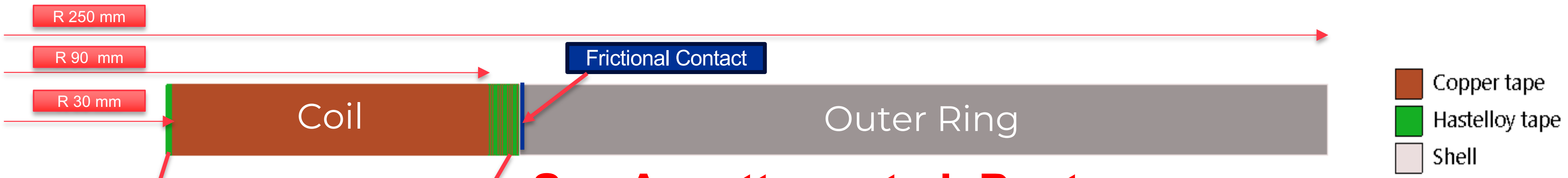




'Explosion' of the assembly of the first 5 pancakes from the bottom

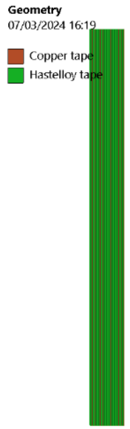
Mechanical Analysis
2 D FEM : geometry

- 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)**

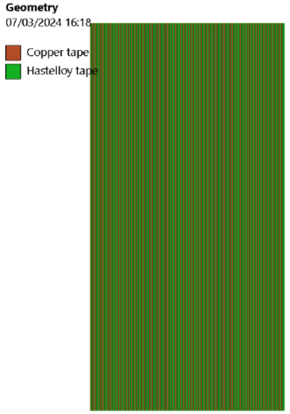


See Accettura et al. Poster 2LPo1B-03

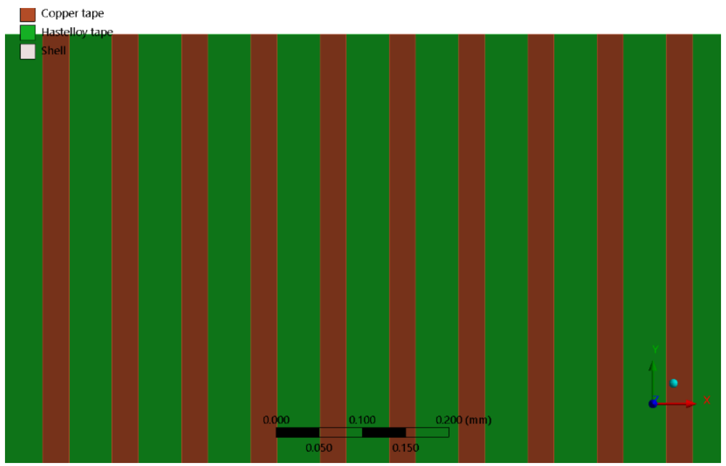
Inner Joint Ring 0.5mm or 1mm



Outer Joint Ring



Coil



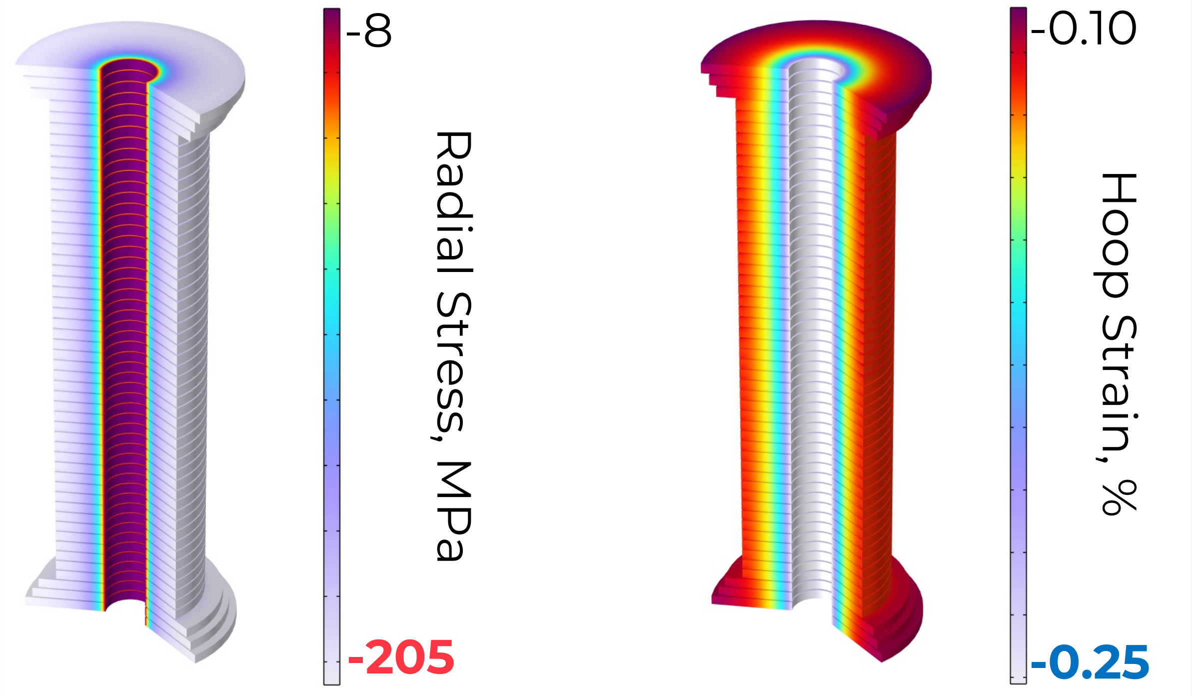
- **3** different **loading steps** simulated
  - ***I*** **pre-compression** via **shrink fitting**
    - the outer ring cools down to Room Temperature
  - ***II*** **cooldown from RT** to **4.2 K**;
  - ***III*** **energization** to 40 T
- The model accounts for
  - **Cu yielding**
  - **Thermal contractions**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

Mechanical Analysis

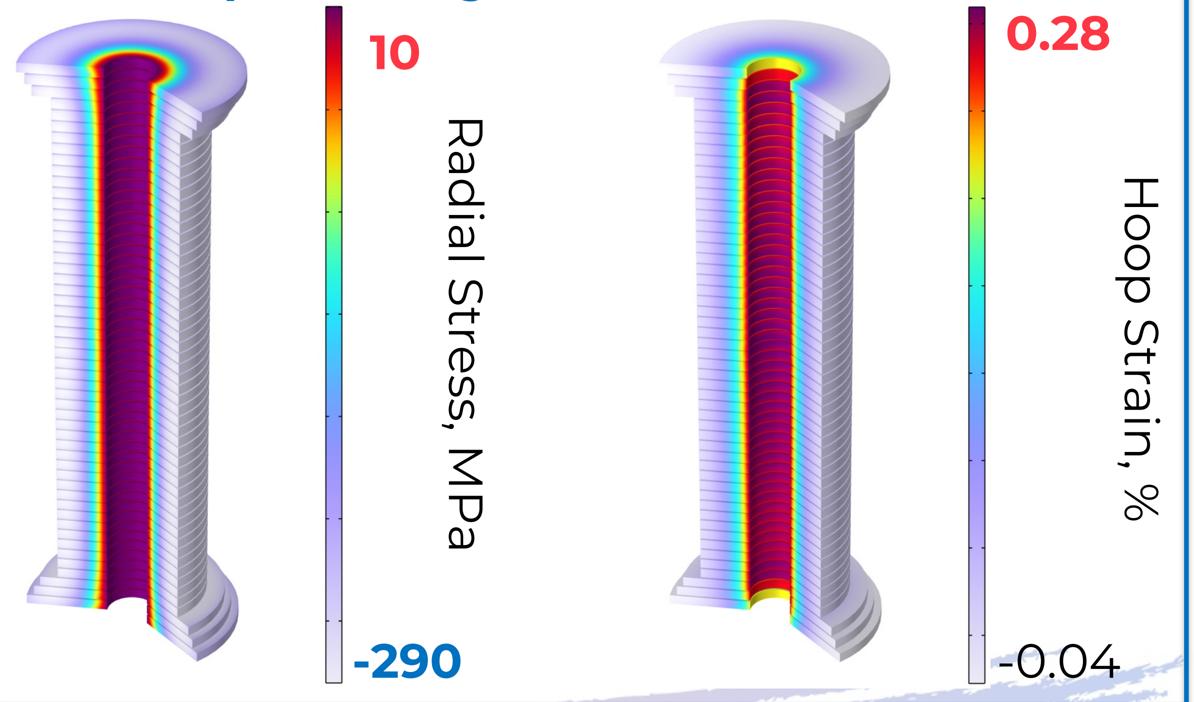
2 D FEM: ~200 MPa Pre-compression

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**

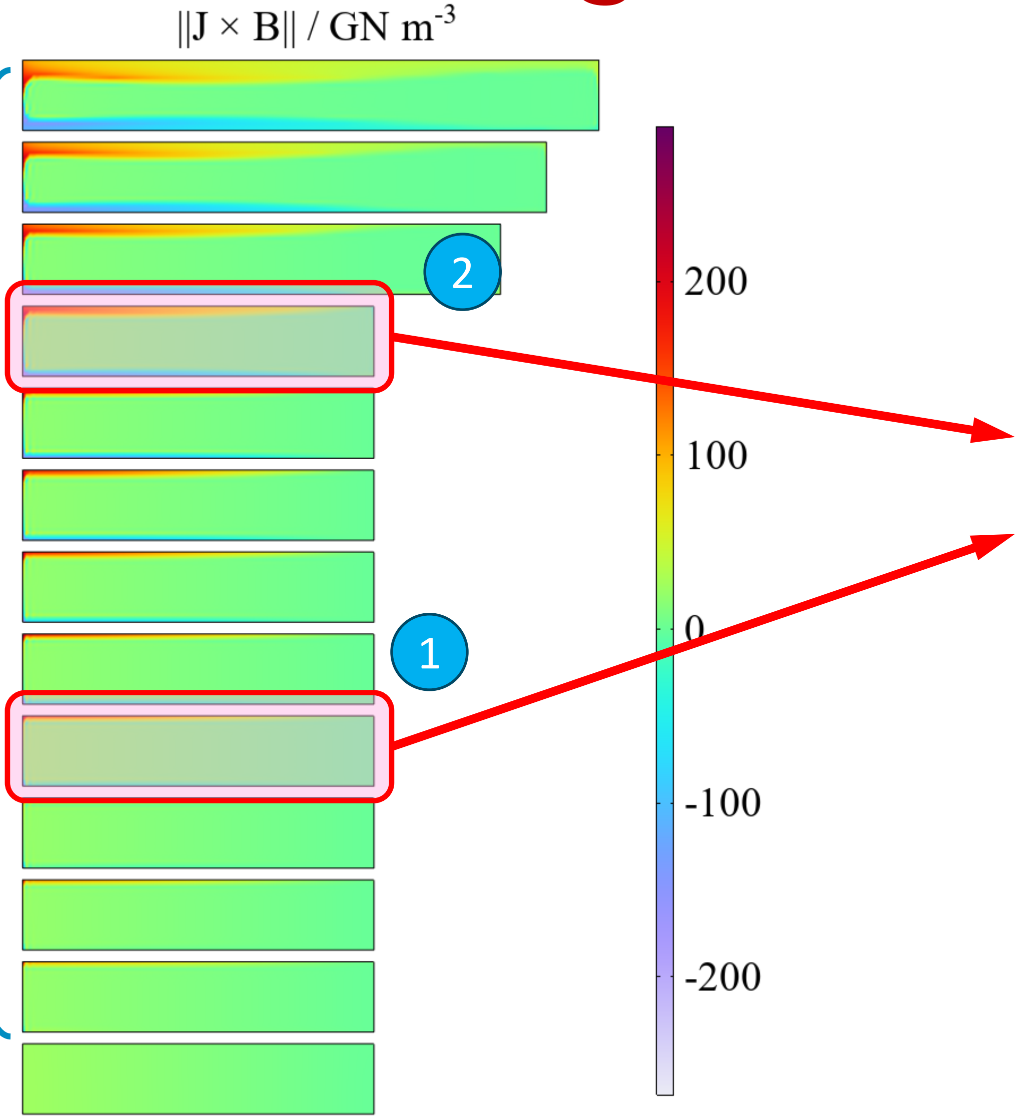
Mechanical **loads** are **under control** (in **stationary** operating **conditions** and **neglecting** the **solenoid heads** where the conductor get **magnetized**)

See Accetura et al. Poster
2LPo1B-03

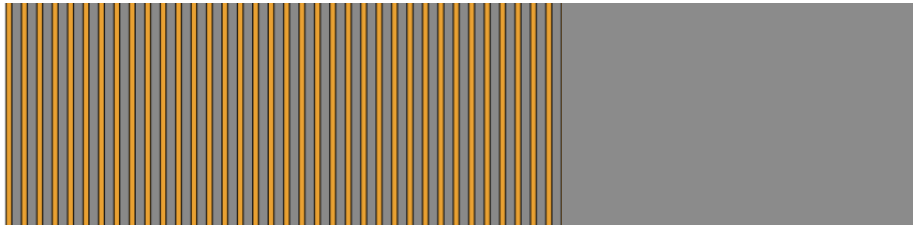
Electro-Mechanical Analysis

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

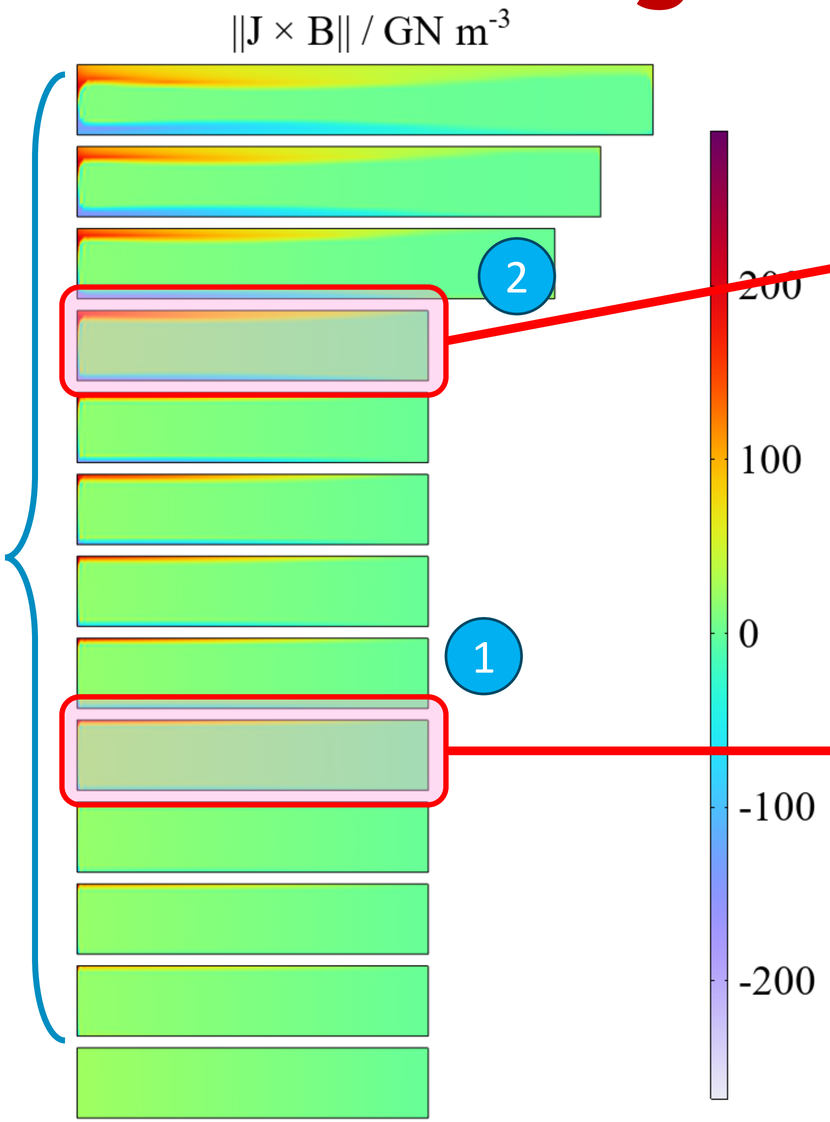


G. Vernassa

Electro-Mechanical Analysis

2 D FEM – Magnetization in Operation

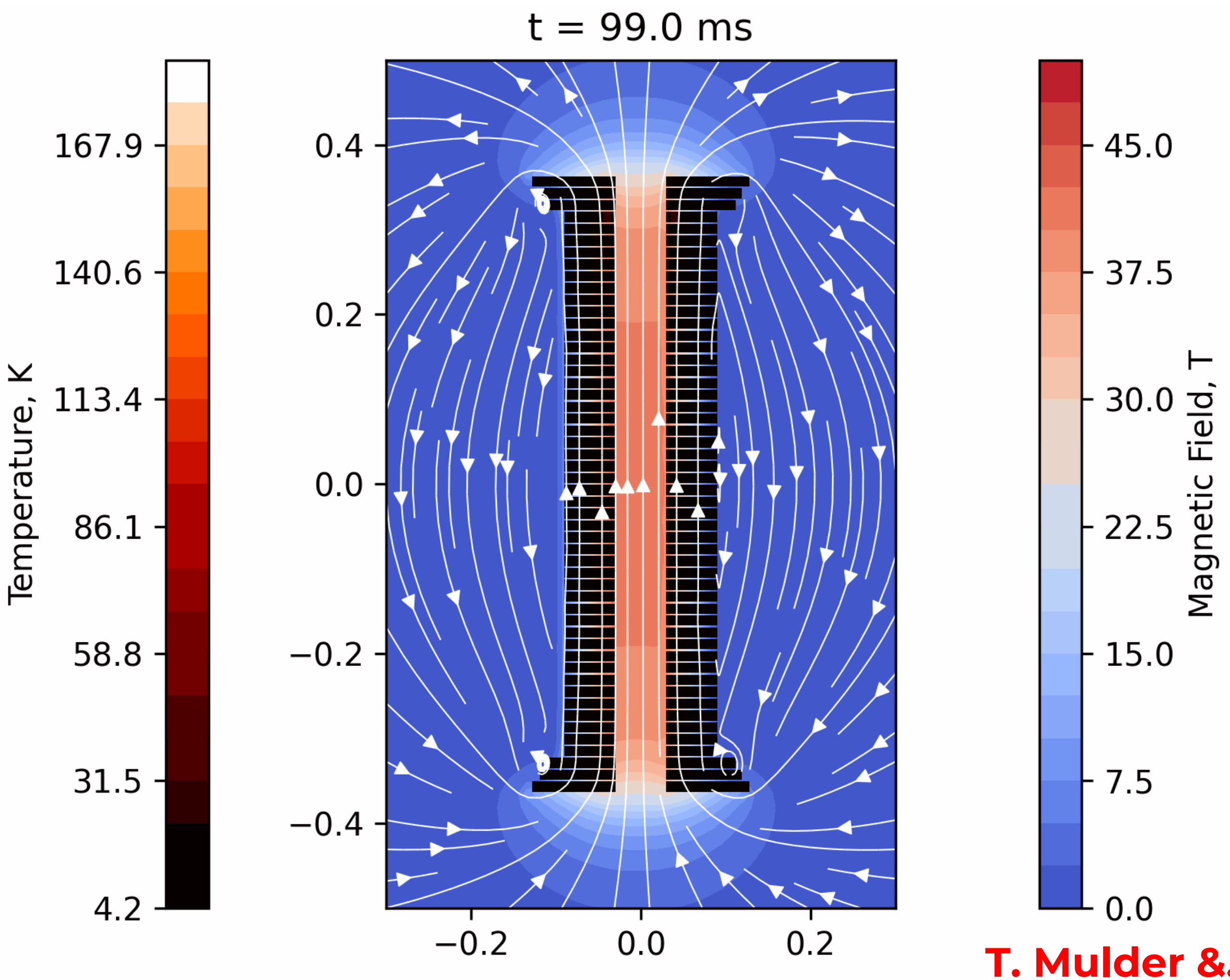
Coils Electro dynamics with T-A Formulation

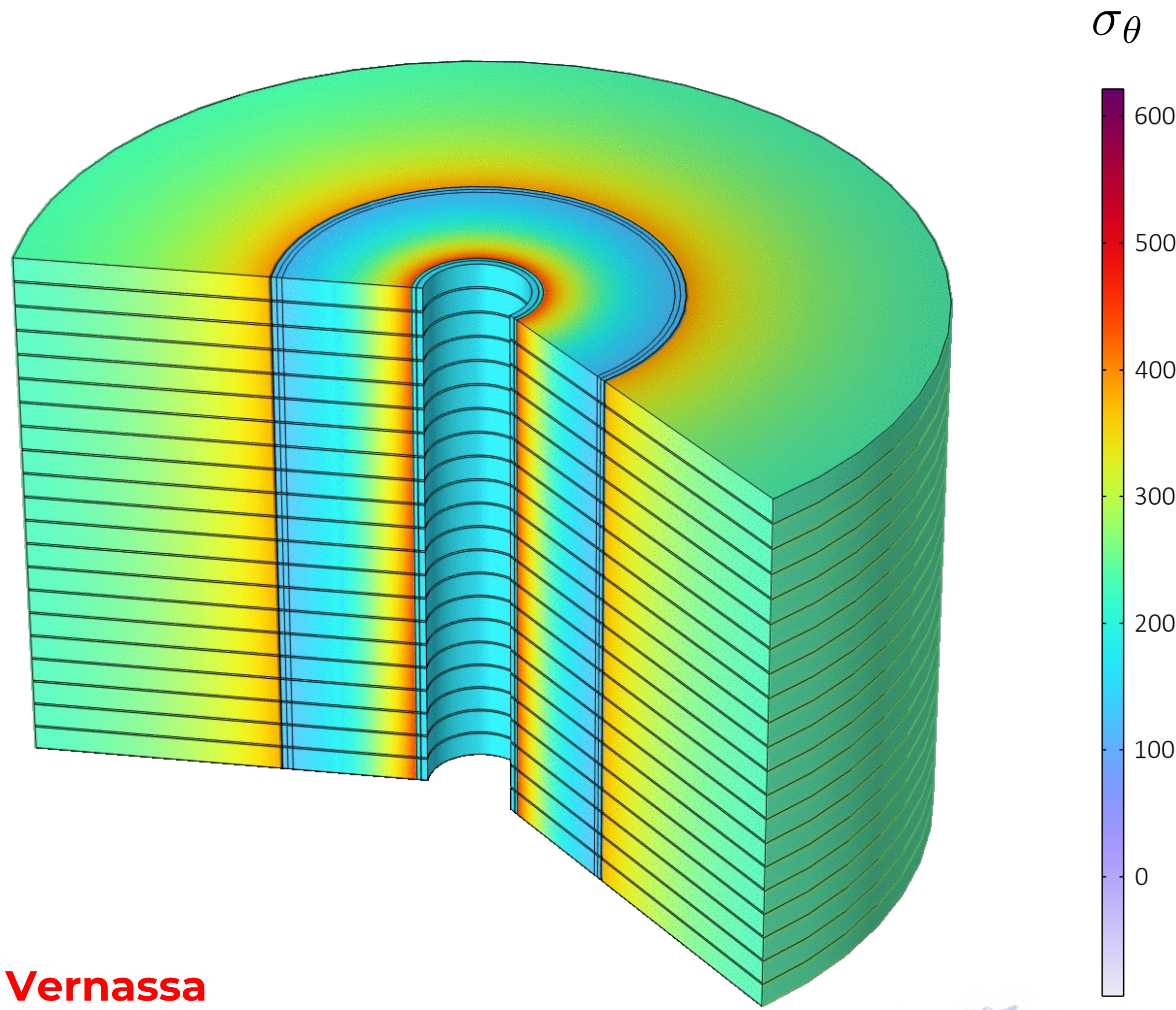


- Significant **Increase** of max **hoop strain ~30%**
  - to be considered striated tapes as in magnet heads
- **Increase** of max hoop strain **negligible** ~1%

G. Vernassa

Integrated Mechanical-Electrodynamic simulations

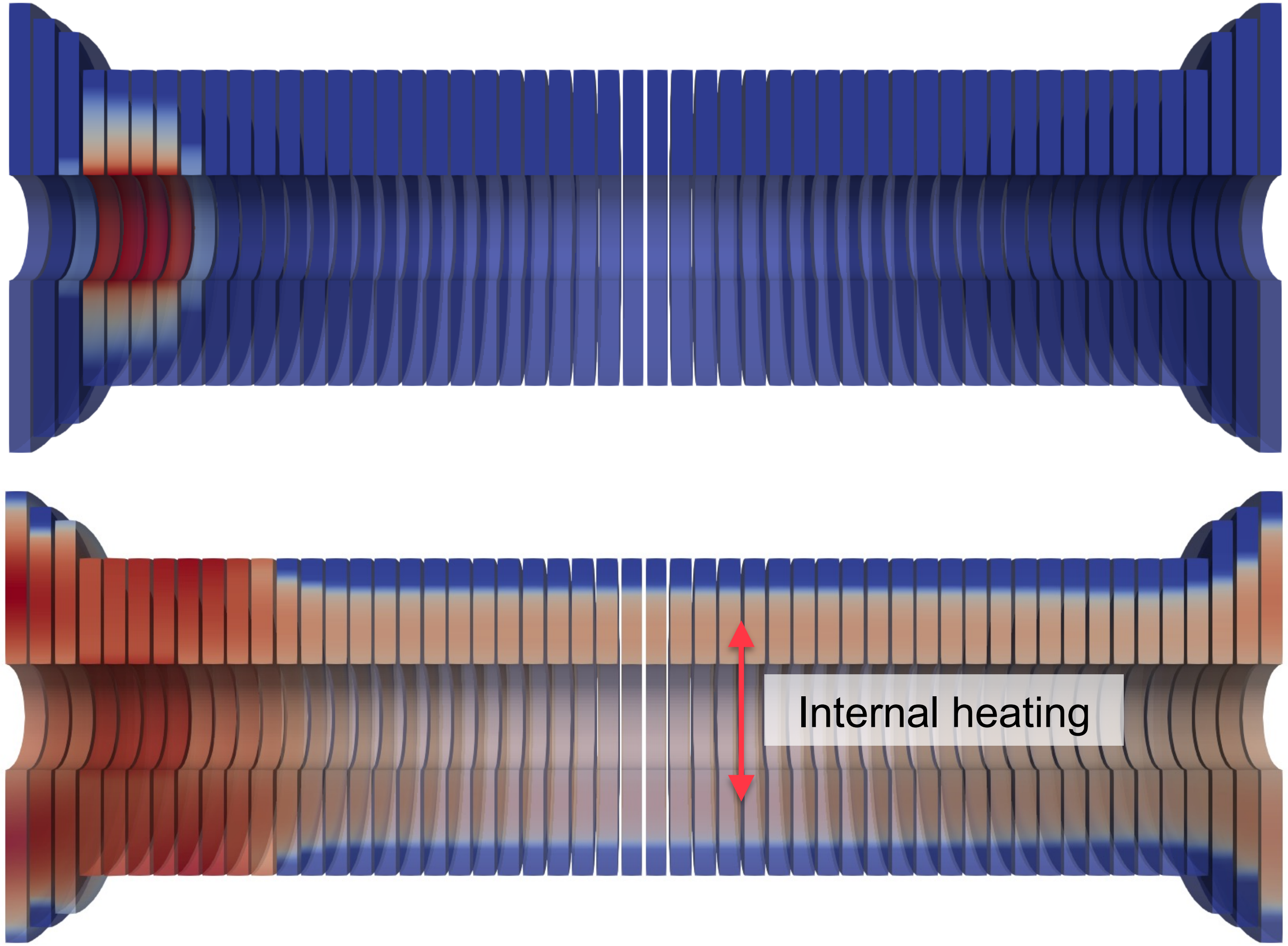


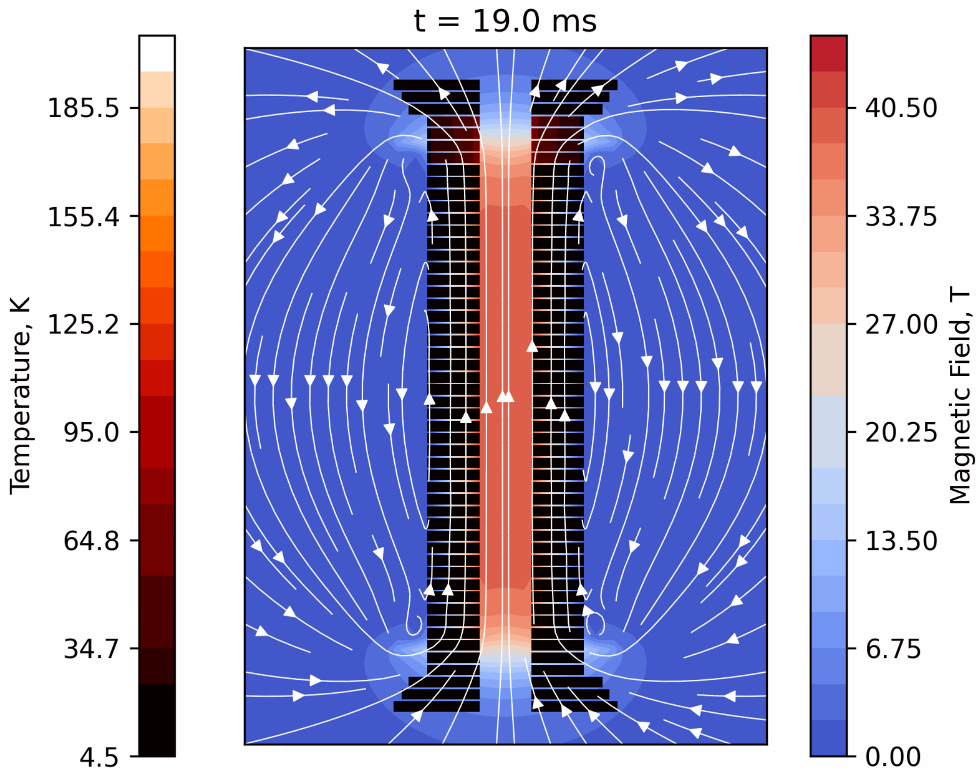


T. Mulder &. G. Vernassa

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.

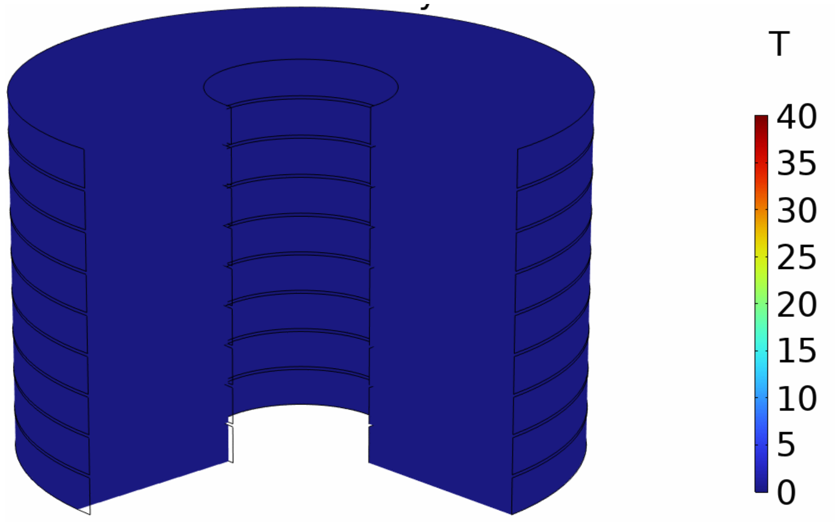
3D electrodynamic models
40 T Solenoid - Energization

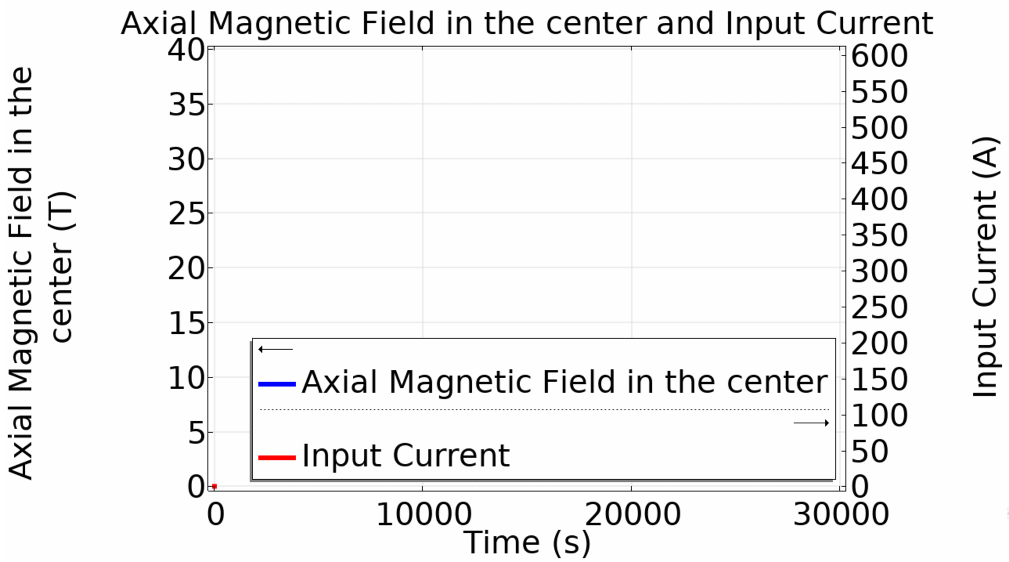
Assumptions:

- **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 !!!

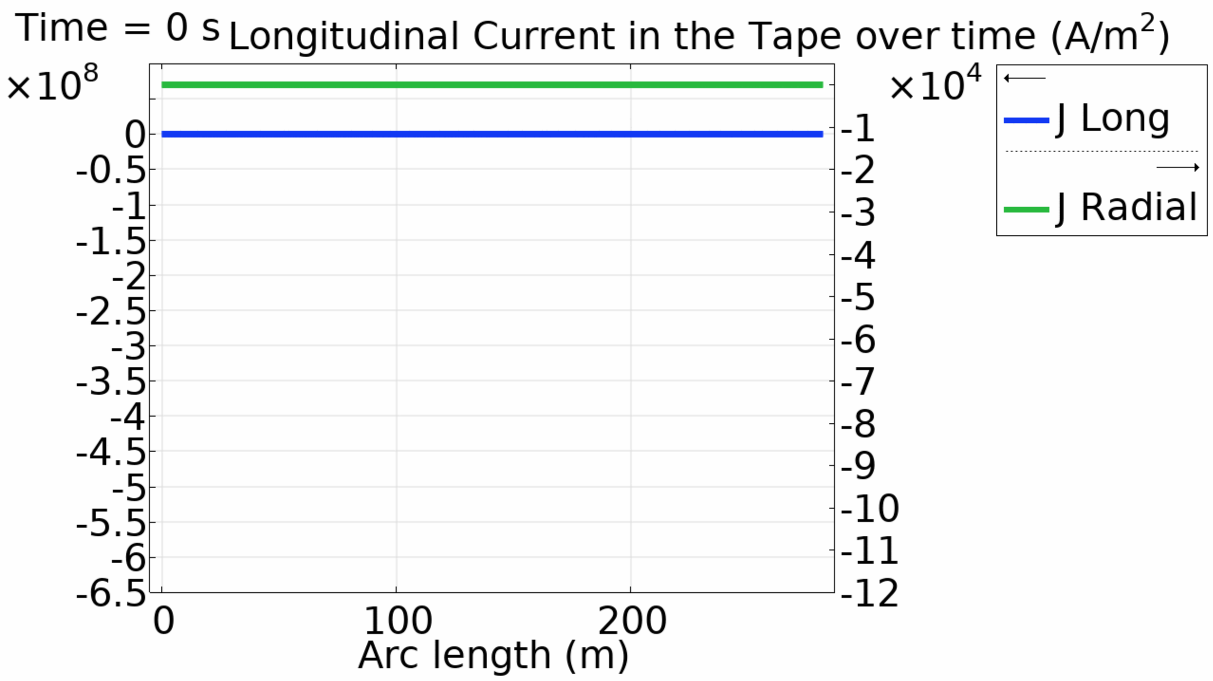
D. Rinaldoni

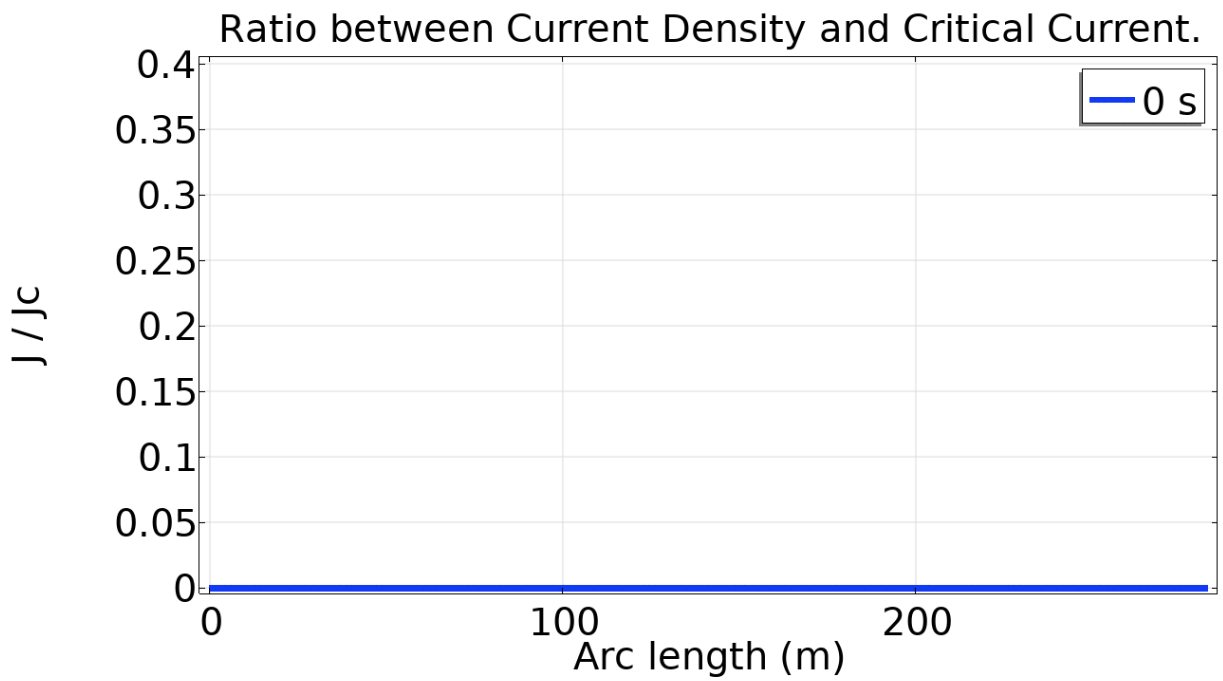




3D electrodynamic models

40 T Solenoid – Current Distribution

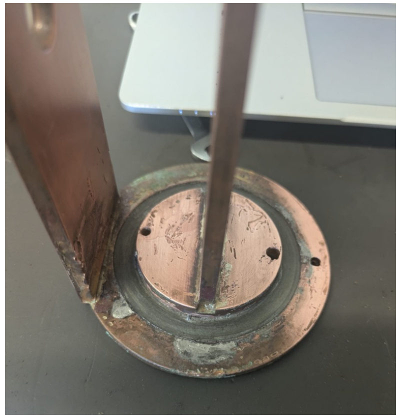


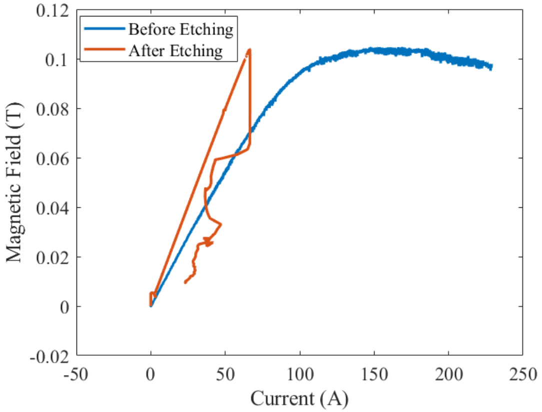


D. Rinaldoni

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

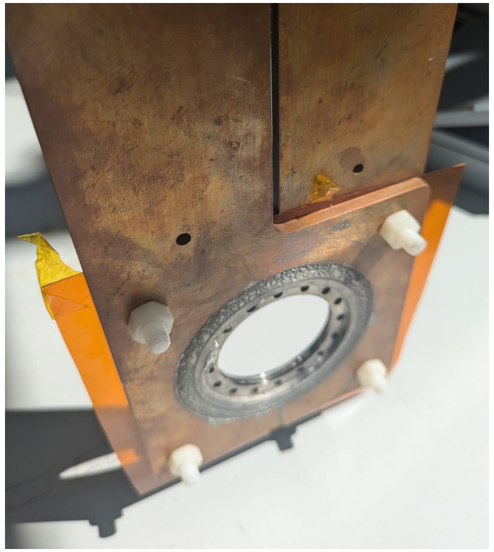
Technological Studies
Fully soldered pancake

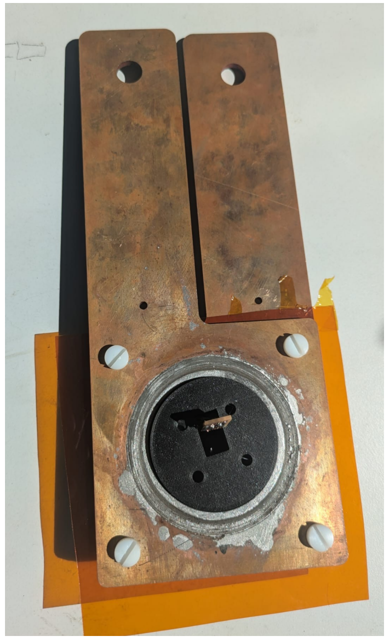




Energization Current	$\tau_c\ (s)$	
	Before Etching	After Etching
5 A	4.9	0.042
10 A	4.7	0.041
20 A	4.8	0.030
50 A	4.6	0.052

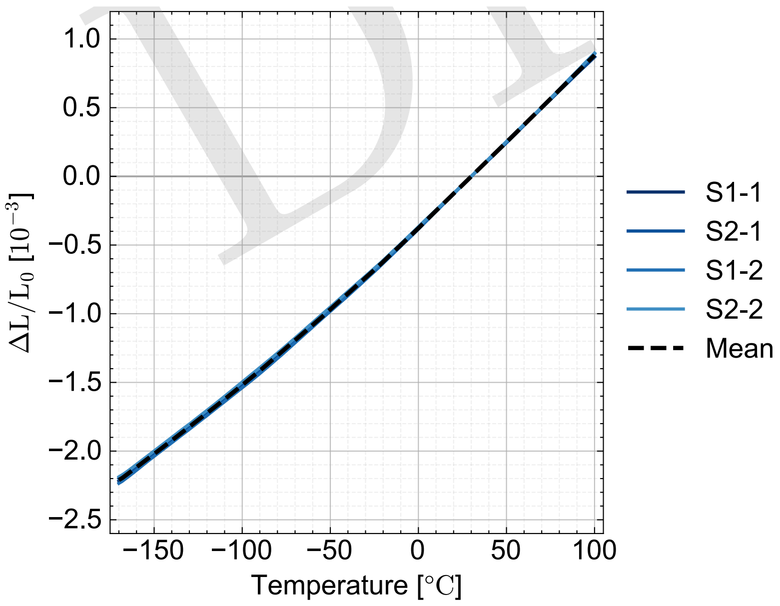
Single pancake



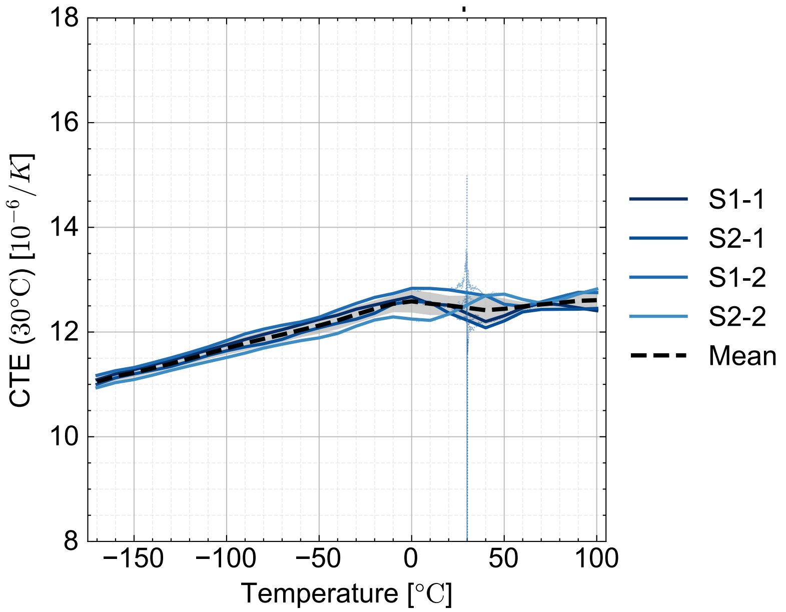


Double pancake configuration to be tested in the coming days

Macro-Mechanical Characterization

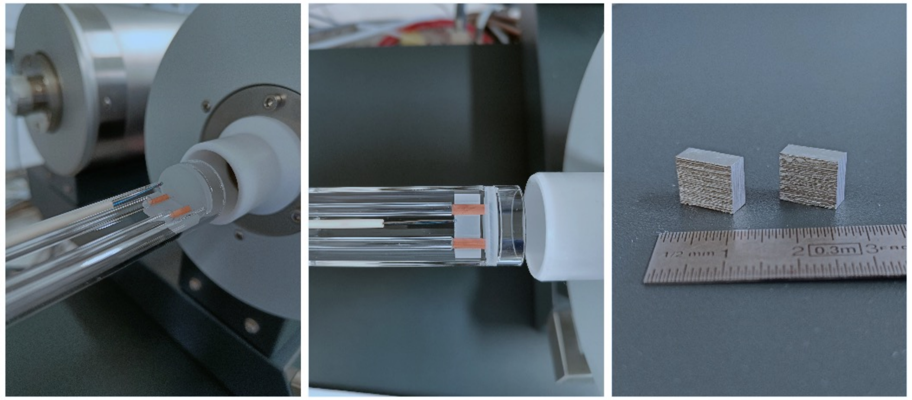


(a) Relative change in length



(b) Coefficient of thermal expansion

Stack Samples



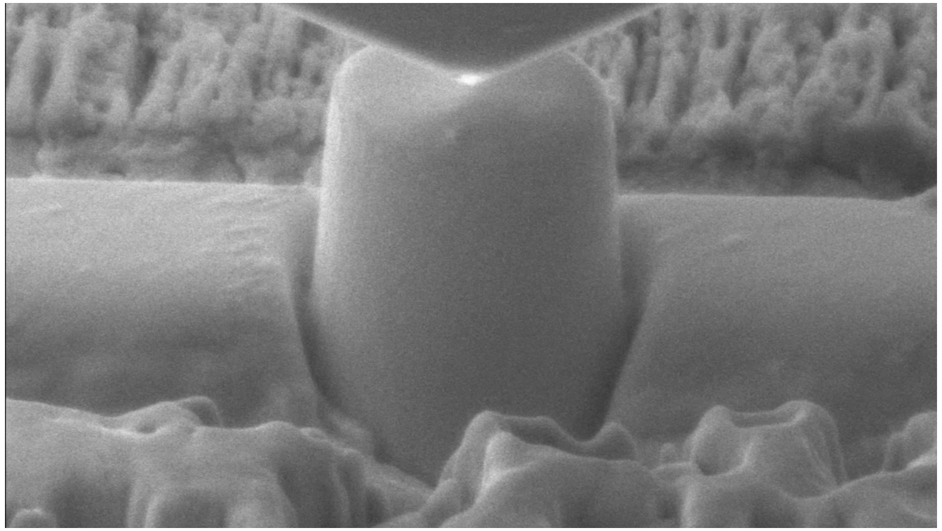
Sample holder including two samples of the Fujikura FESC-SCH04 tape

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

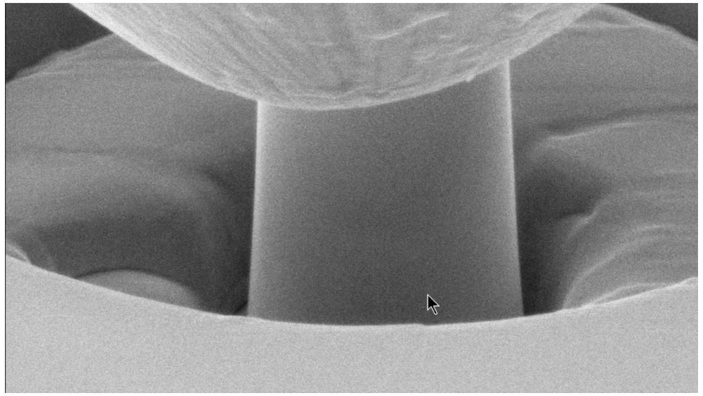


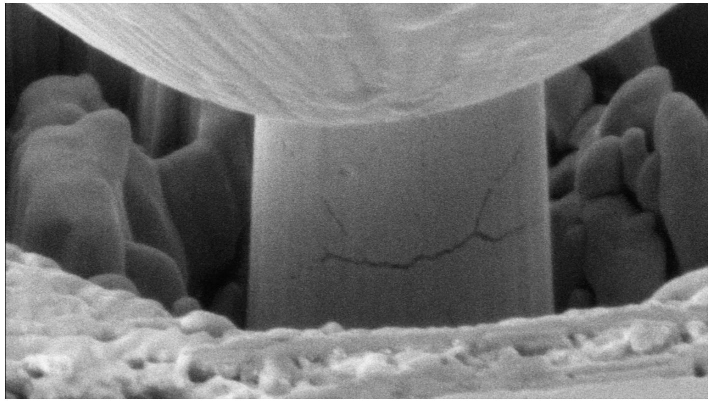
REBCO
K_c / MPa $m^{0.5}$
???*

*See Vernassa et al. Poster 2MPo2C-08

Hastelloy	Copper
σ^y / GPa	σ^y / GPa
???*	???*

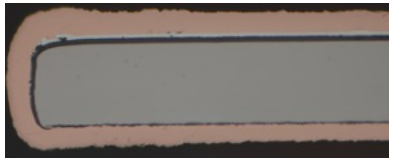
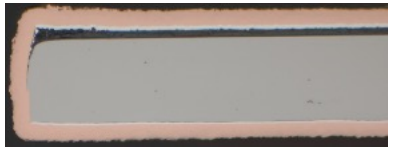
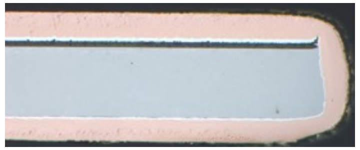
Micropillar compression on Hastelloy and Copper

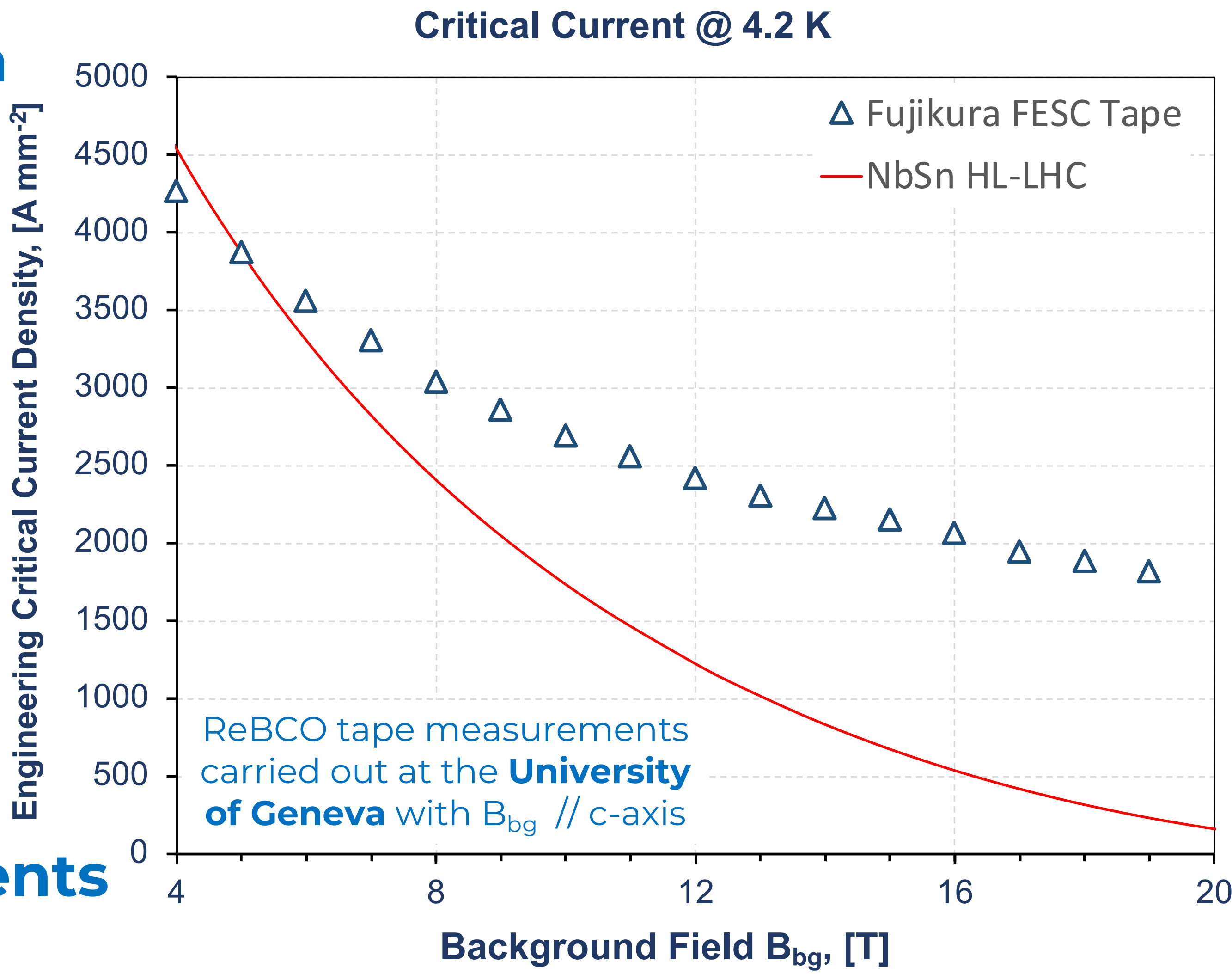




ReBCO Tape Procurement & Electrical Characterization

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

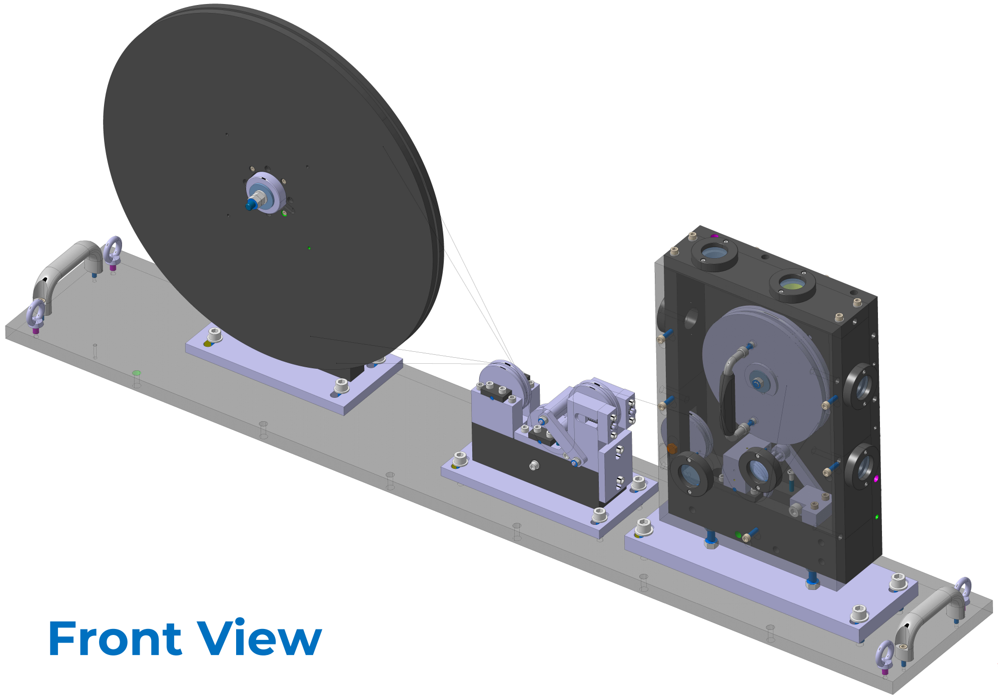


- Started **critical current measurements**

Ready to GO

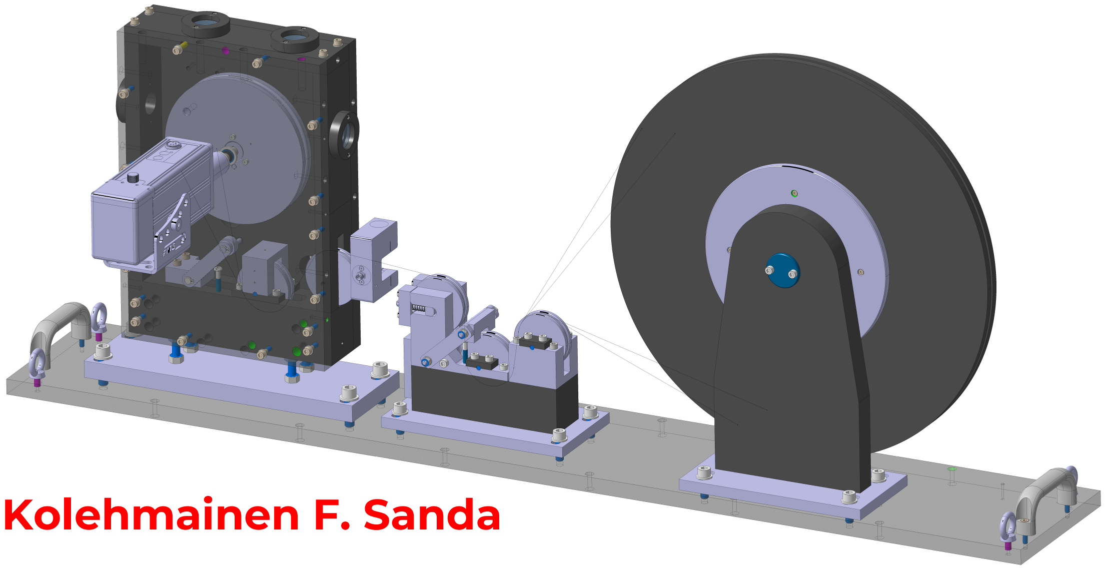
- **Designed** and **procured** the **components** of a **winding machine** allowing hot winding of soldered pancakes; **assembly** is expected starting **this week**

Ready to start manufacturing and testing pancakes in ‘series’ !!!



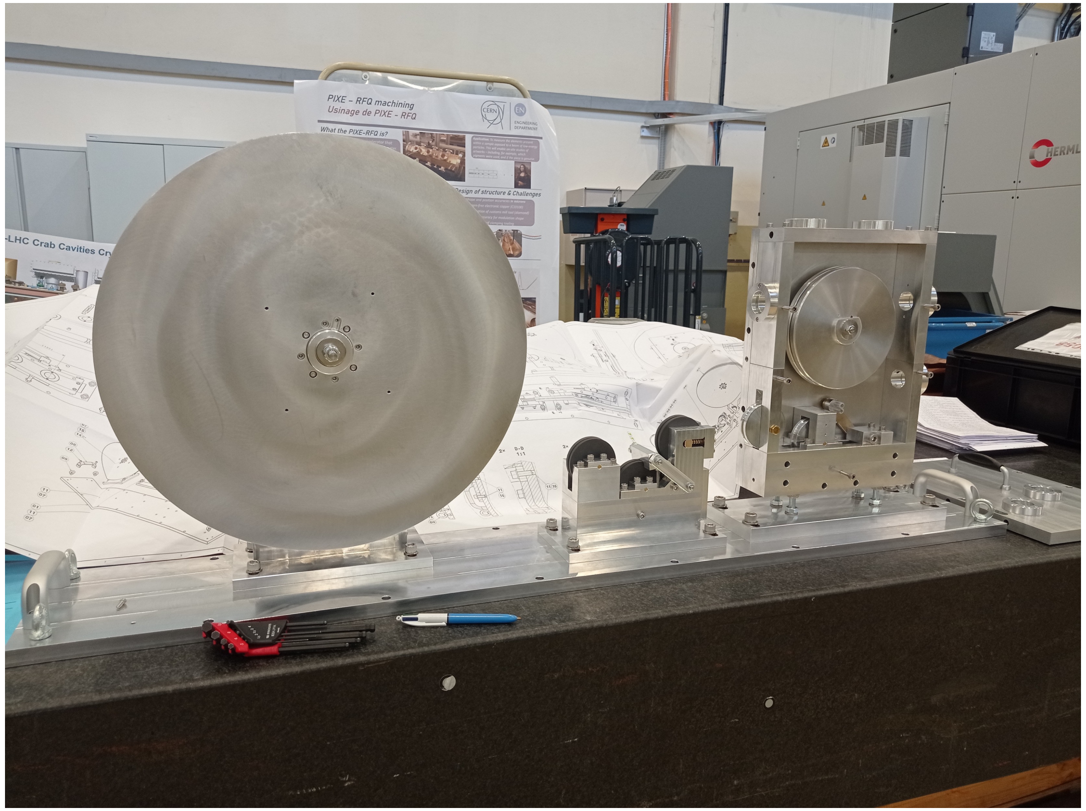
Front View

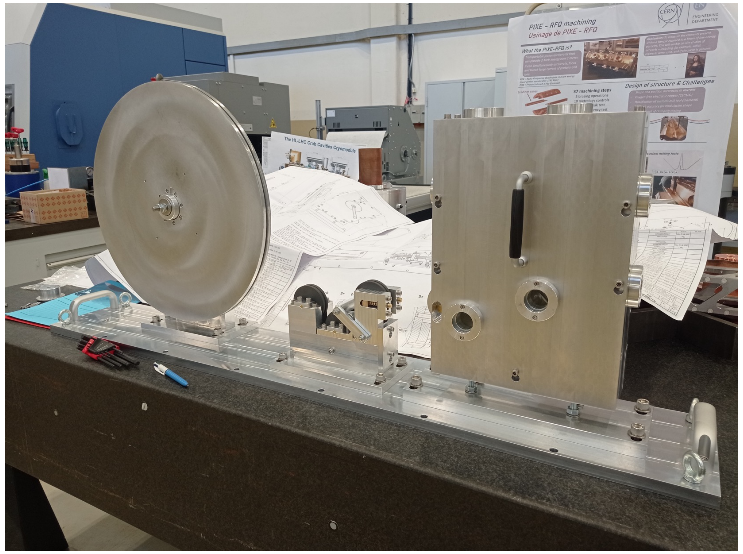
Rear View

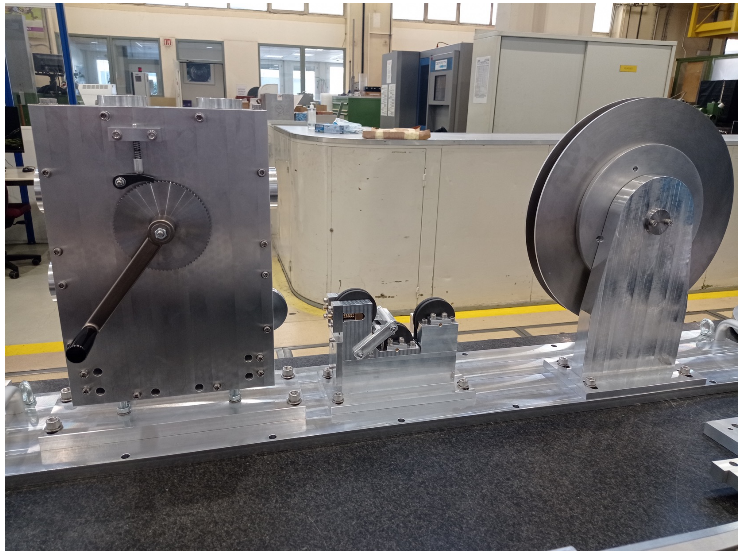


A. Dudarev , A. Kolehmainen F. Sanda

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