# UHF solenoid construction solutions

J. Guardia-Valenzuela, R. Unterrainer, C. Accettura,
A. Jade Ventura, F. Sanda, O. Sacristán, B. Bordini (CERN)

On behalf of the 40⁺ T team

Workshop on ultra-high-field solenoids, CERN – 26/11/2025
https://indico.cern.ch/event/1572785/

Funded by the European Union

# Outline

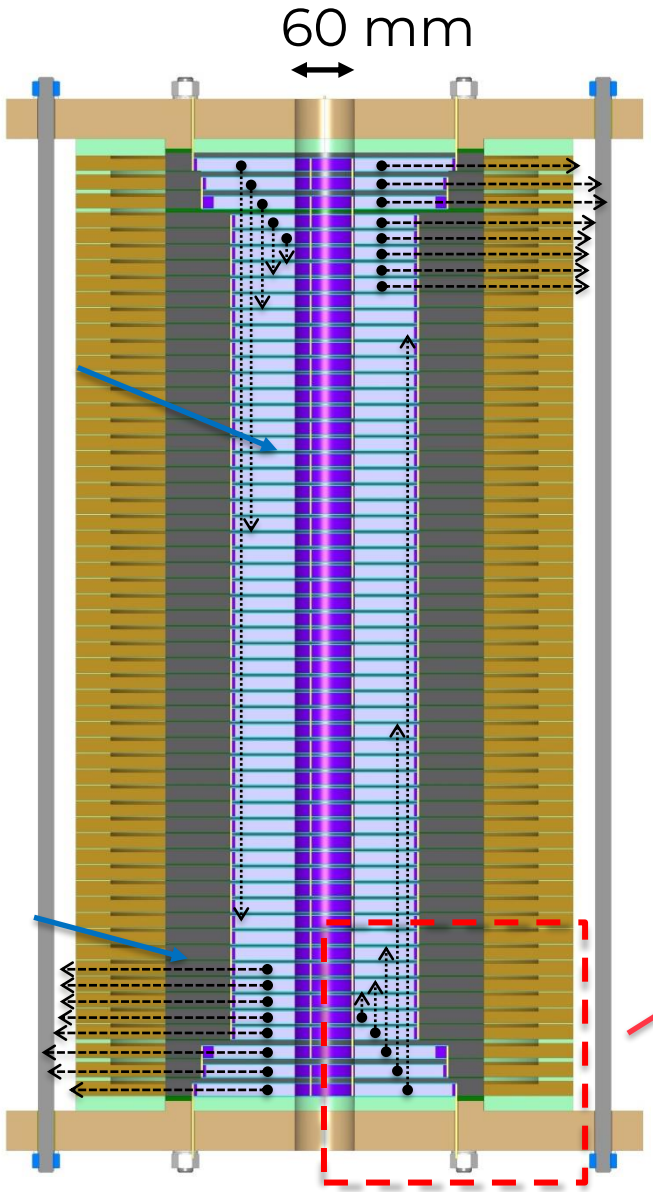
- **Introduction**
  - The 40 T FC Solenoid
  - Mechanical studies
- **Advancing development**
  - Winding machine
  - Pancake coil mechanical & thermo-physical characterisation
  - Shrink fitting tool
  - Pancake joining highlights
- **Conclusions**

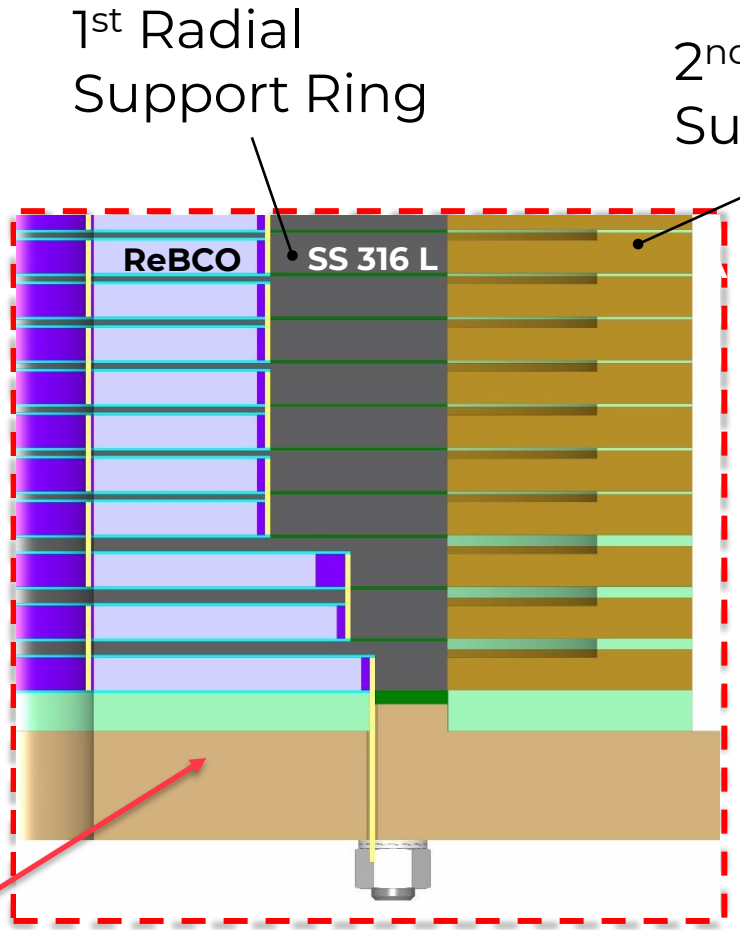
This presentation: Focus on **mechanical** studies, **tooling design & fabrication**, and **mechanical & thermo-physical characterisation.**

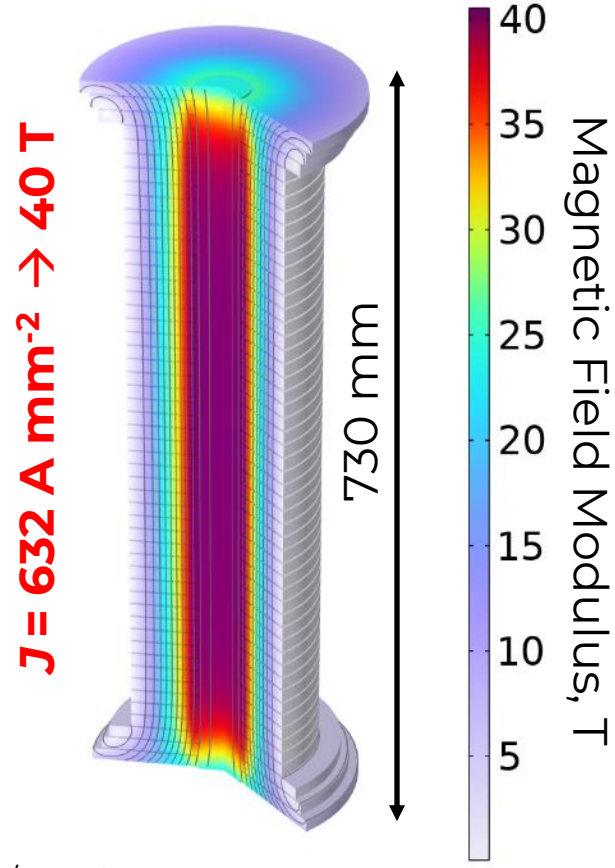
See also R. Unterrainer's presentation (25.11.2025) for pancake production & electro-magnetic characterisation.

# A Preliminary Engineering Design

**Radial** Lorentz Forces **scaled down** by a **factor** of **3** with **respect** to **axial** forces



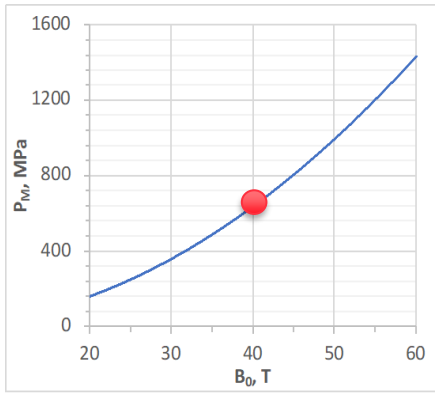

B. Bordini *et al.*, "Development of a ReBCO Non/Metal-Insulated 40 T Solenoid for a Muon Collider," TAS 2025

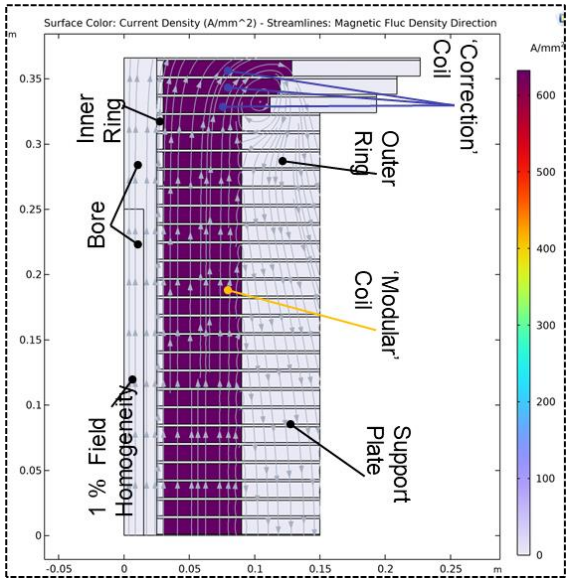
C. Accettura *et al.*, "Mechanical Design of a ReBCO Non/Metal-Insulated 40 T Solenoid for the Muon Collider," TAS 2025

# Introduction and Motivations

- Design proposed for the Final Cooling solenoid based on single and compact coil
  → critical stress management:
  - $P_M=B_0^2/2\mu_0$~600 MPa (radial)
  - Hoop stress~ 1.4-2.2$P_M$ (compact coil)
- Non-homogeneous and anisotropic material:
  - Maximum allowable stress very weak in certain direction
  - Scarce literature
  - Reduced safety margin

**Magnetic pressure vs Field**



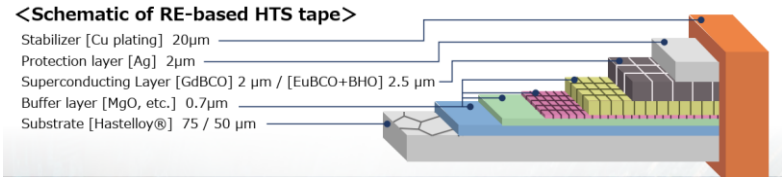




See B. Bordini, Technology options for the final cooling solenoids, IMCC Annual Meeting 2023, Orsay

| REBCO conductor | |
|---|---|
| Axial tensile stress | 700 MPa |
| Axial tensile strain | 0.4 % |
| Transverse compressive stress | >100 MPa |
| Transverse tensile stress | 10-100 MPa |
| Max shear stress | >19 MPa |

A pre-compression of ~200 MPa is need to remain below this value

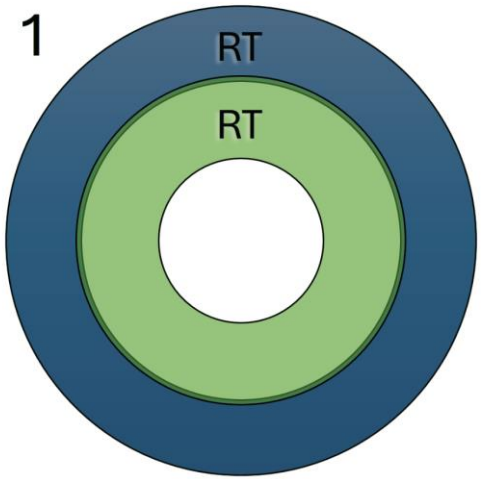
**Courtesy: C. Accettura**

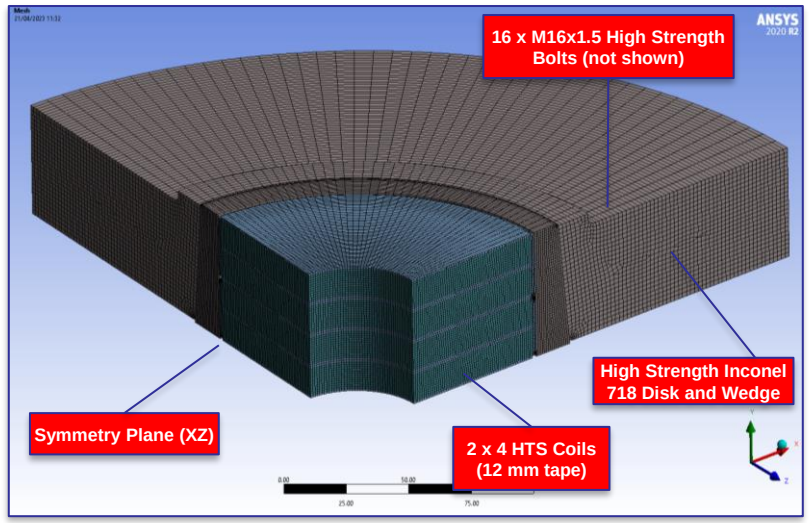


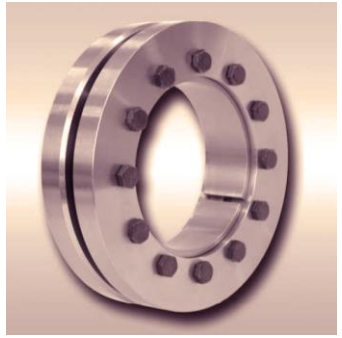

Reference Conductor Fujikura FESC-SH12.
*https://www.fujikura.co.jp/eng/products/newbusiness/superconductors/01/superconductor.pdf*

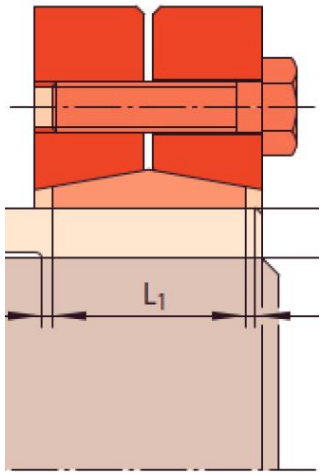
# Pre-compression

- How to obtain the pre-compression?
- Mechanical concept is based on **encapsulating** HTS pancake coils in **an external structure**, generating high **radial compressive stresses. Three concepts analysed:**
  - A. Thermally-induced shrink fitting
  - B. Adjustable shrink-discs with conical surfaces
  - C. Hybrid solution (A+B)

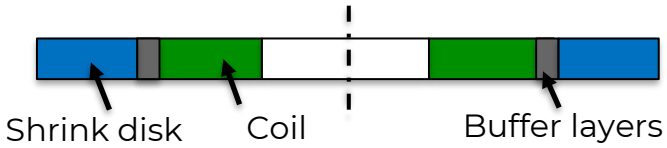





Enormous shear stress expected if the pancake is directly in contact with a rigid shrink disk
→ **Buffer layers needed**



# Mechanical Studies

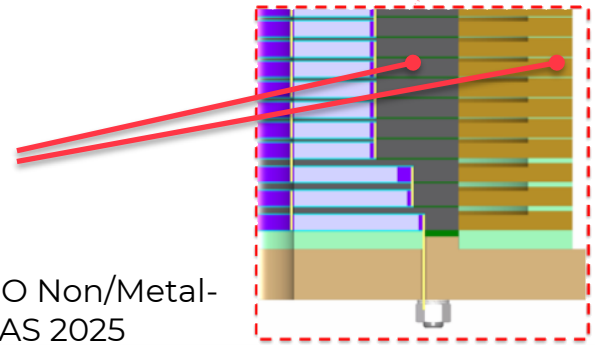
## Homogeneous Current Density distribution

**3** different **loading steps** simulated

***1*** **pre-compression** at RT via **shrink fitting** of the two outer rings

***2*** **cooldown from RT** to **4.2 K**;

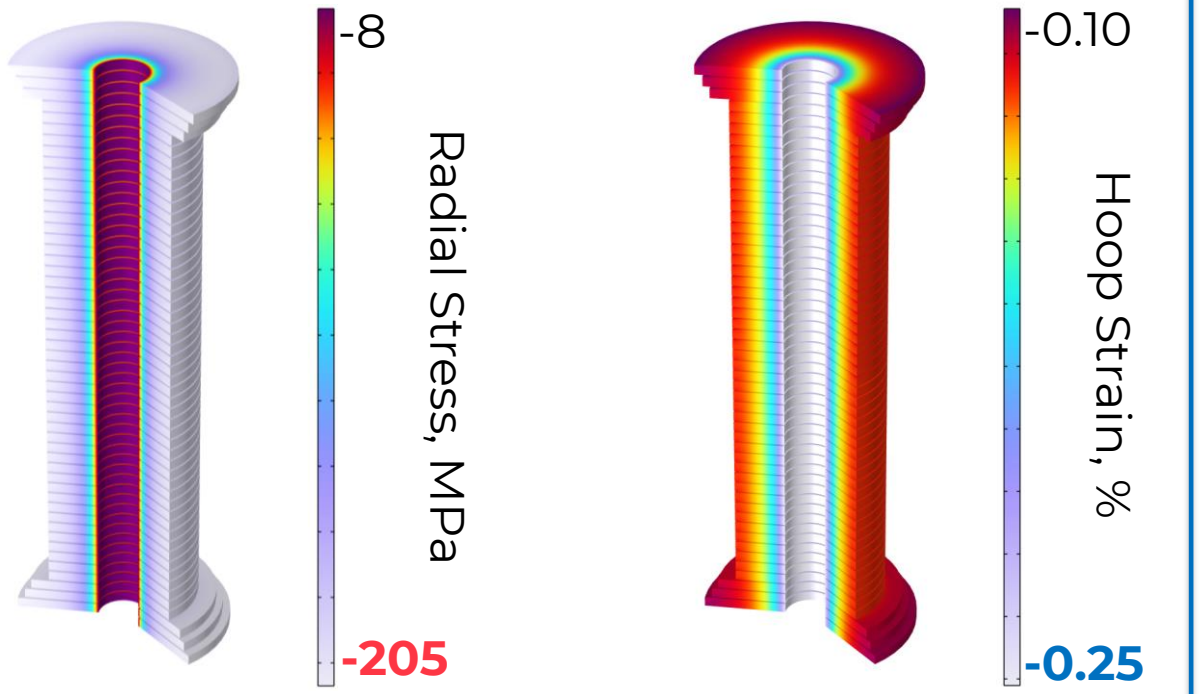
***3*** **energization** to 40 T



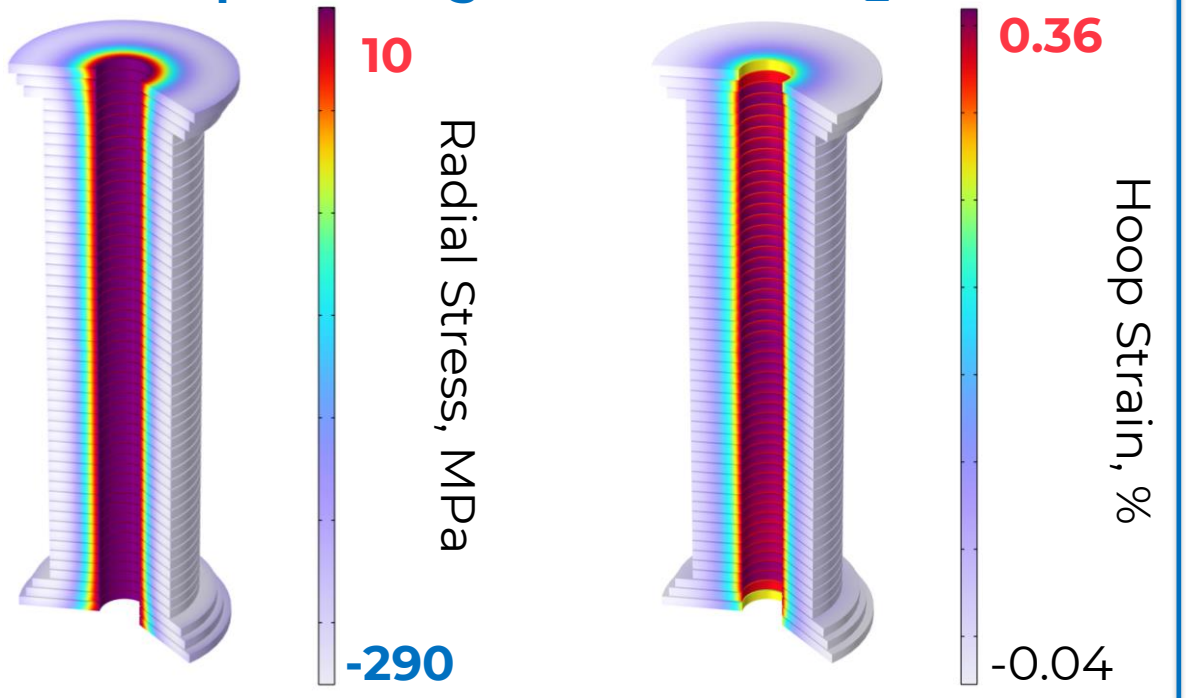
**Courtesy: C. Accettura**

C. Accettura *et al.*, "Mechanical Design of a ReBCO Non/Metal-Insulated 40 T Solenoid for the Muon Collider," TAS 2025

**Step 1 : Precompression at Room Temperature**

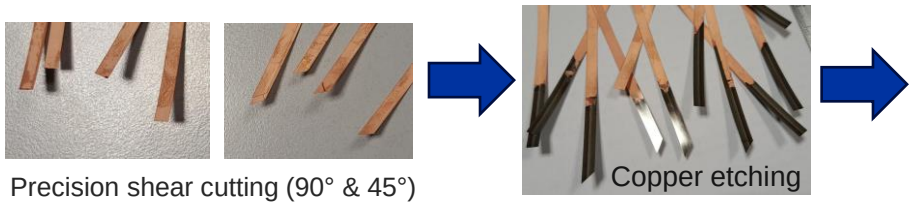



**Step 3 : Energization to 40 T @ 4.2 K**

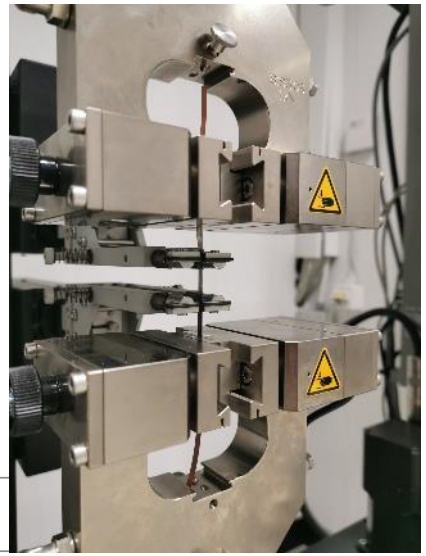


# Head-to-head laser welding of ReBCO tapes


## 80 µm-thick 4 mm-wide tapes




Precision shear cutting (90° & 45°)

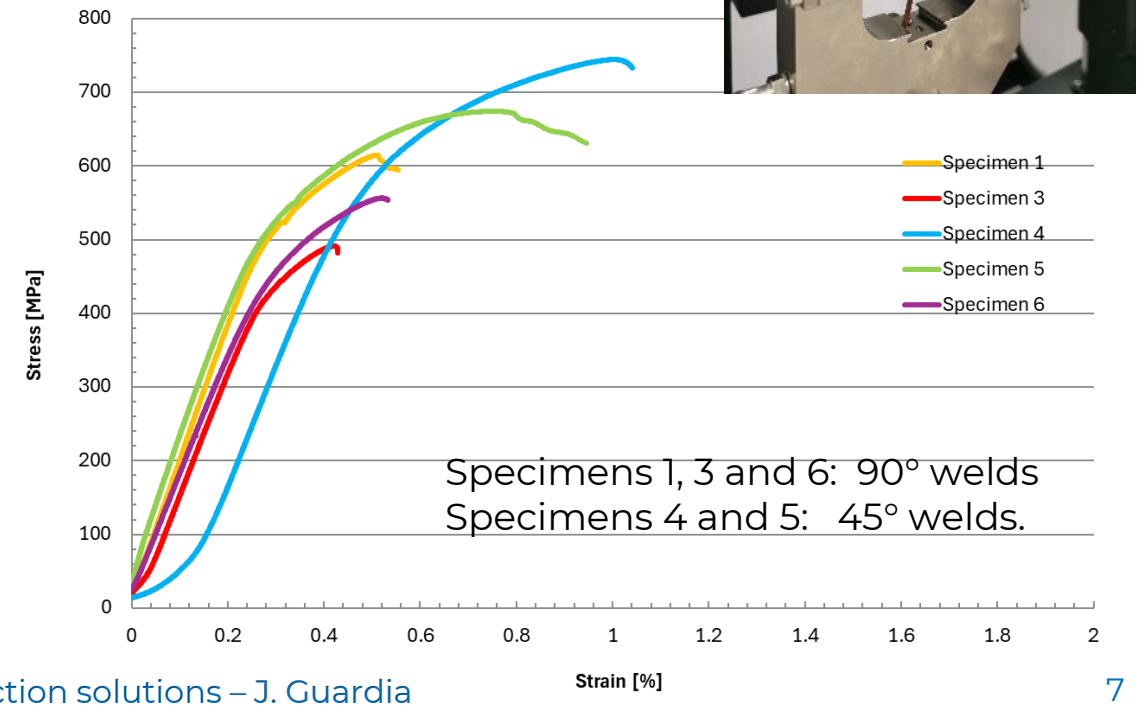


| | Rp0.2 (min.) [N] | Rm (min.) [N] |
|---|---|---|
| 90° welds | 74.3 | 114.7 |
| 45° welds | 93.6 | 154.5 |

154.5 N is ~85% of bulk material resistance!

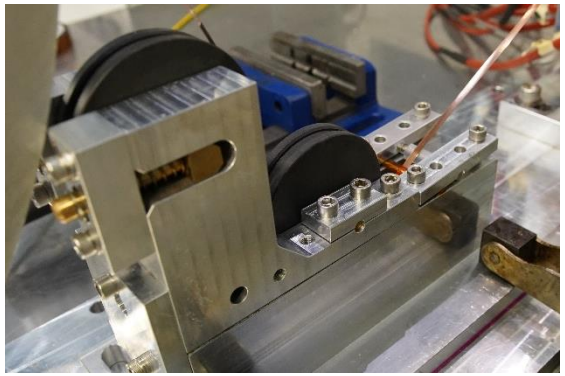
Hastelloy C-276 Rm=792 MPa [1] with cross-section 0.23 mm², **Rm=182.2 N**

[1] Haynes Hastelloy® C-276 alloy, solution heat treated flat products, thickness 2 mm, 20°C, Matweb.com




**Courtesy: L. GIEZENDANNER, J. GUARDIA, M. CROUVIZIER**

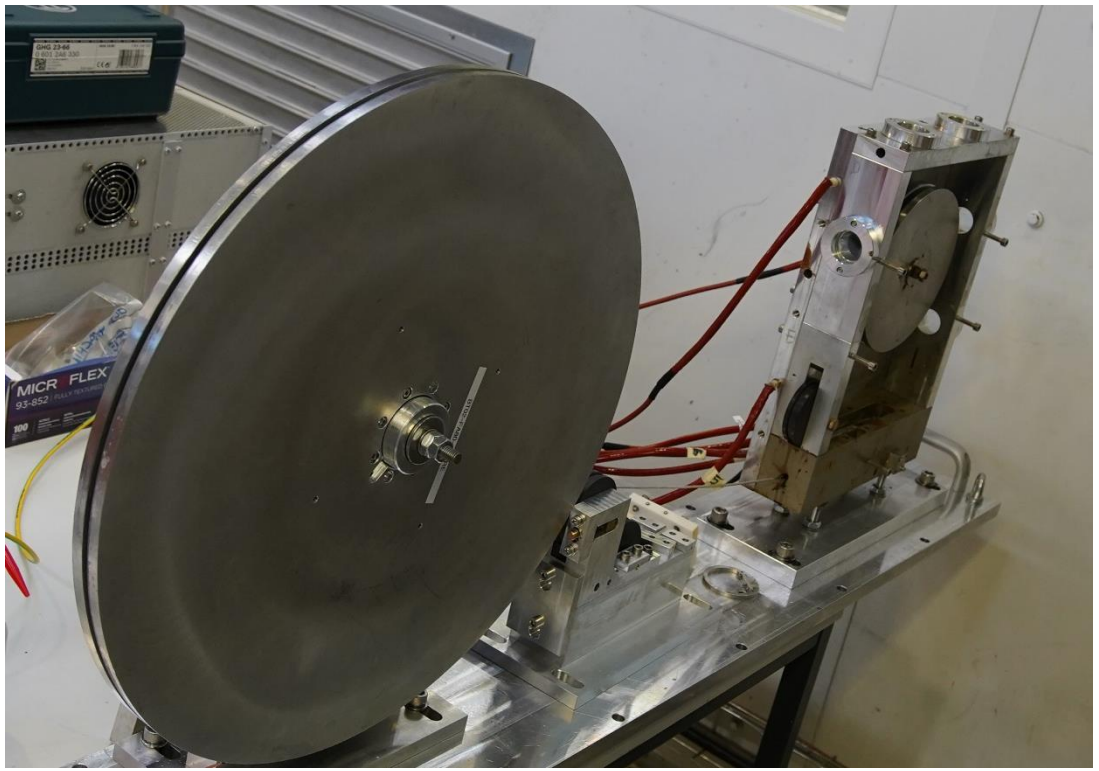
# Winding machine

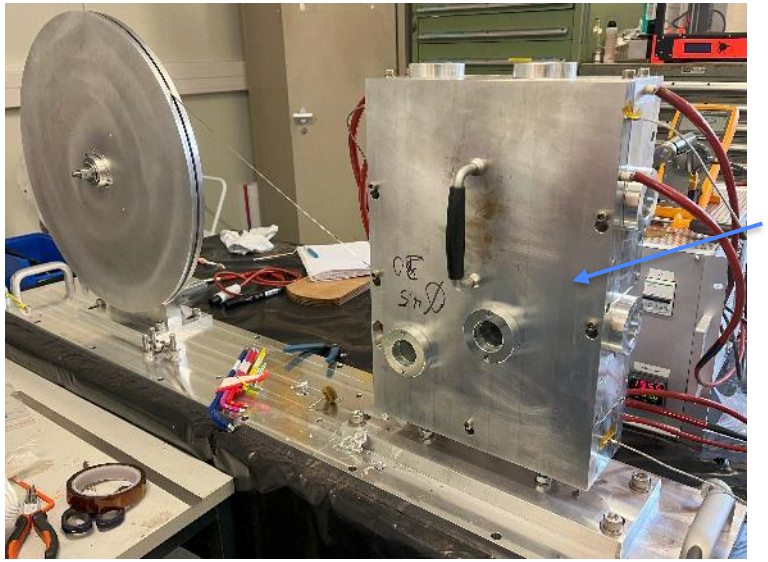





**Courtesy: A. Dudarev , M. A. Hafiz, A. Kolehmainen, F. Sanda, Y. S. Farys , P. L. Bouvier, A. Dallocchio, M. Garlasche**

# Winding machine





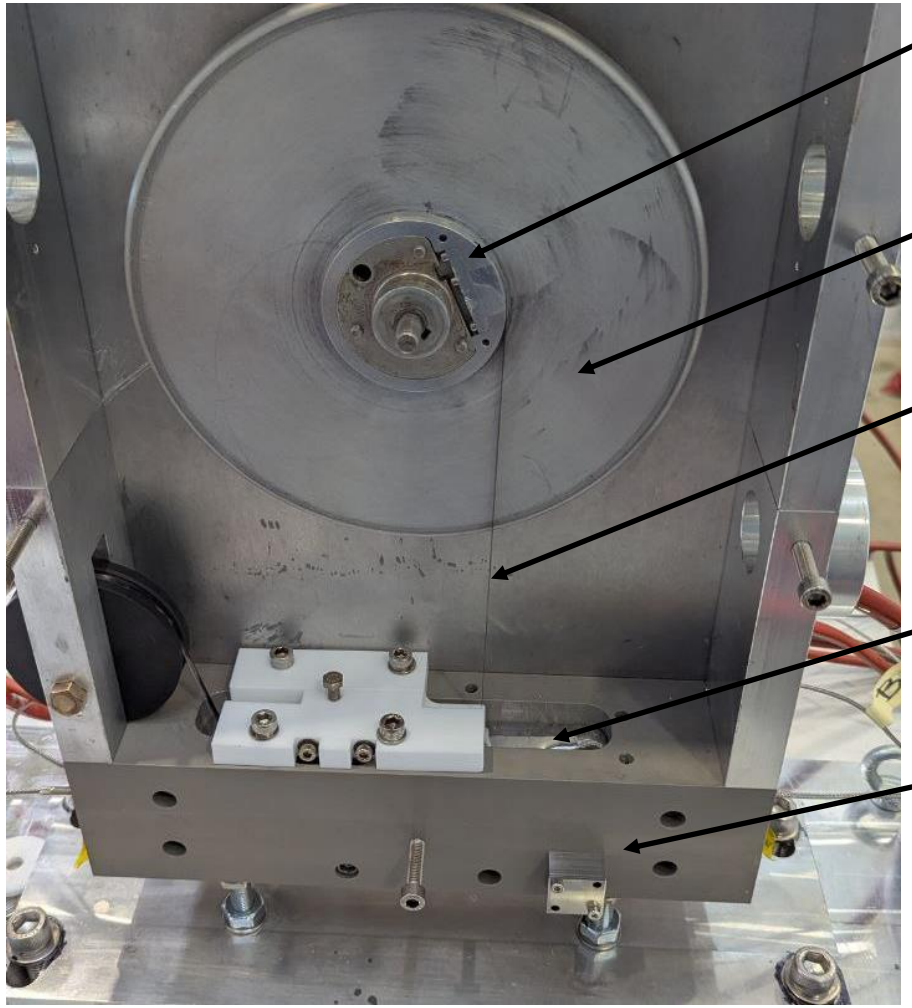
Hot box enclosure:
10 heaters installed,
4 temperature probes.

Sub-coil Geometry – dimensions of the superconducting pancake:
6 cm ID, 10 cm OD, 4 mm high

**Courtesy: M. A. Hafiz & G. Scarantino**

More details on pancake production in R. Unterrainer's presentation

# Winding machine



Mandrel (winding core)

Winding wheels (restrain tape)

Tape

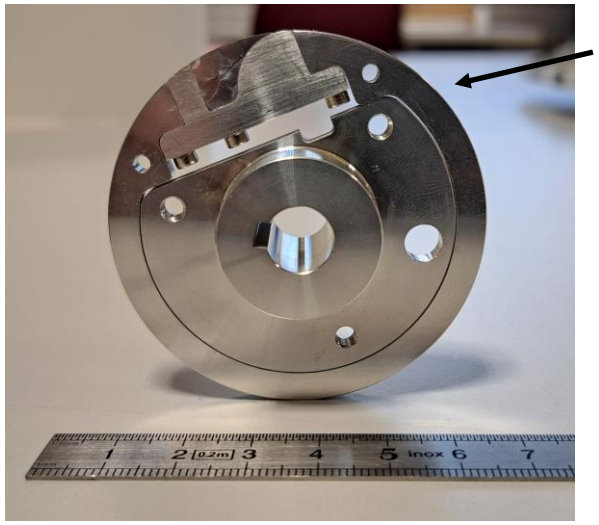
Solder

Ematal (Ti-Al oxide) anodised aluminium solder bath

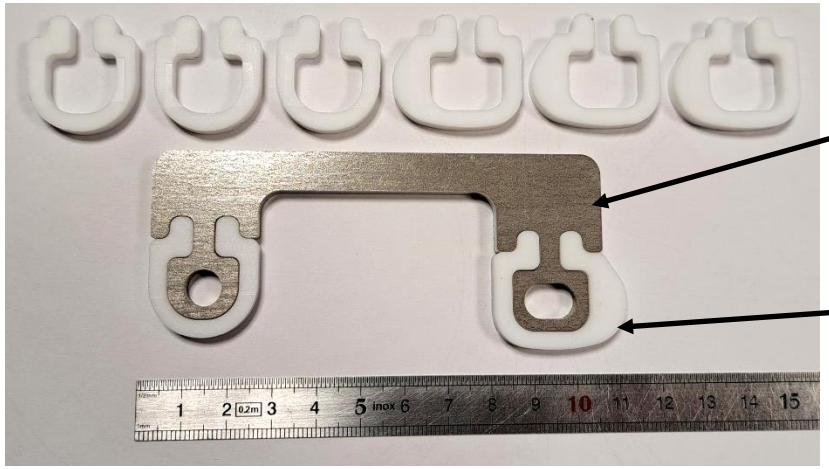
New PTFE coated aluminium solder bath with argon heating circuit

# Winding machine

Stainless steel winding plates

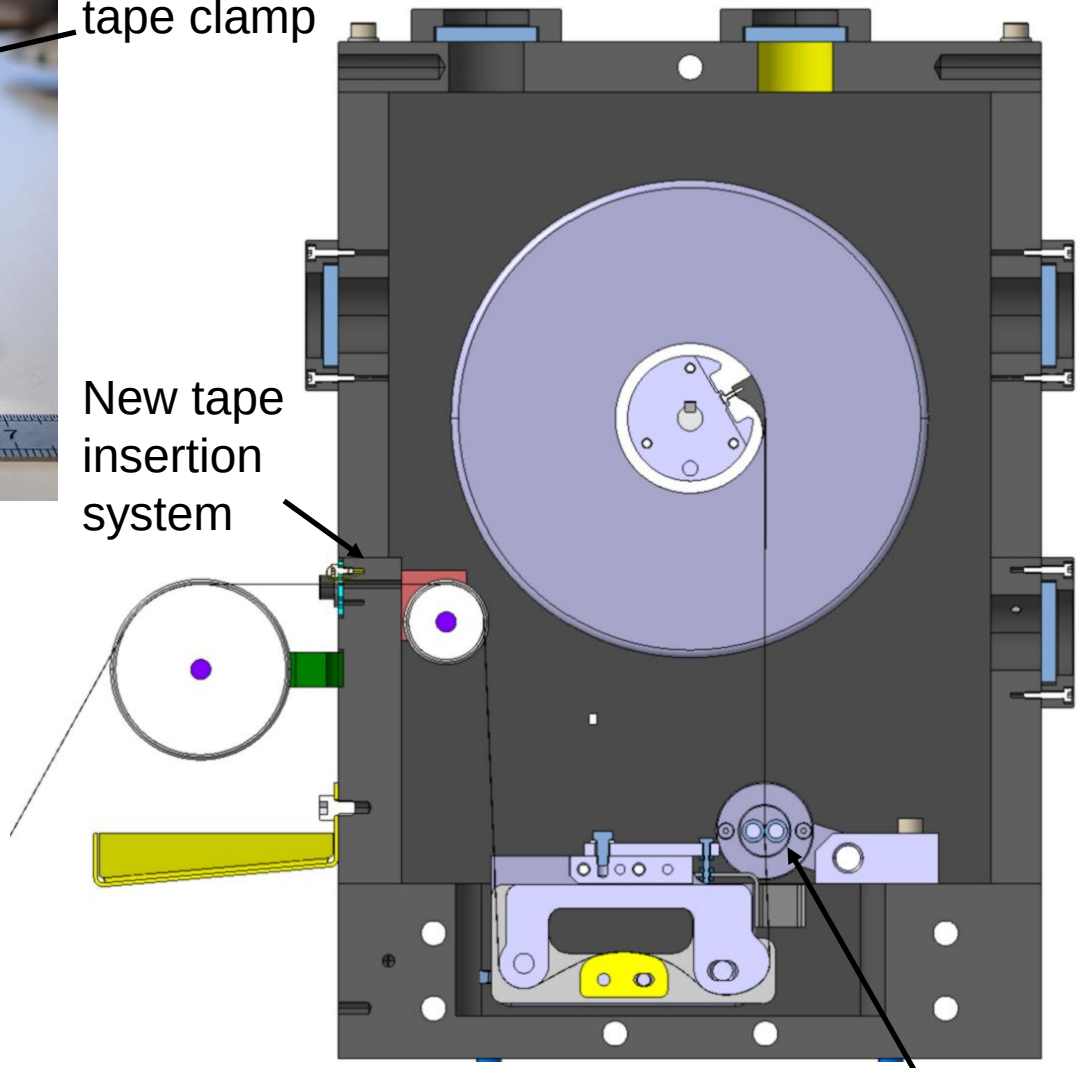


Hot winding mandrel with tape clamp



Stainless steel support

PTFE tape guides

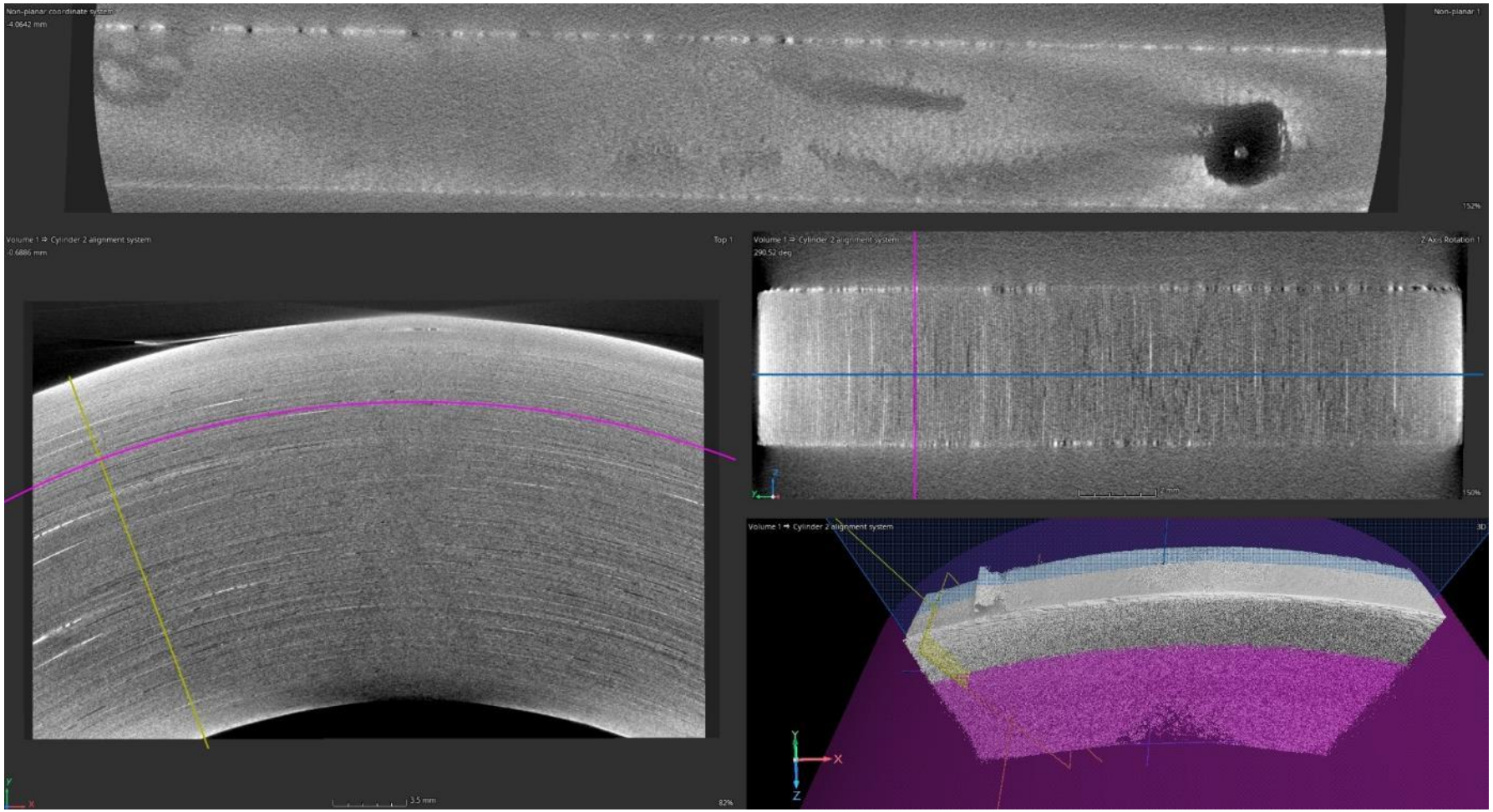


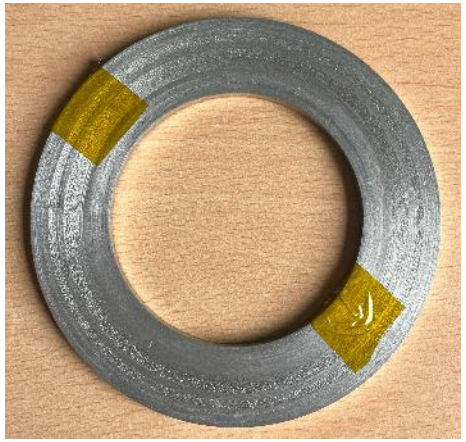
New tape insertion system

Solder wipes

# Sub-coils Characterization

## μ-computed tomography

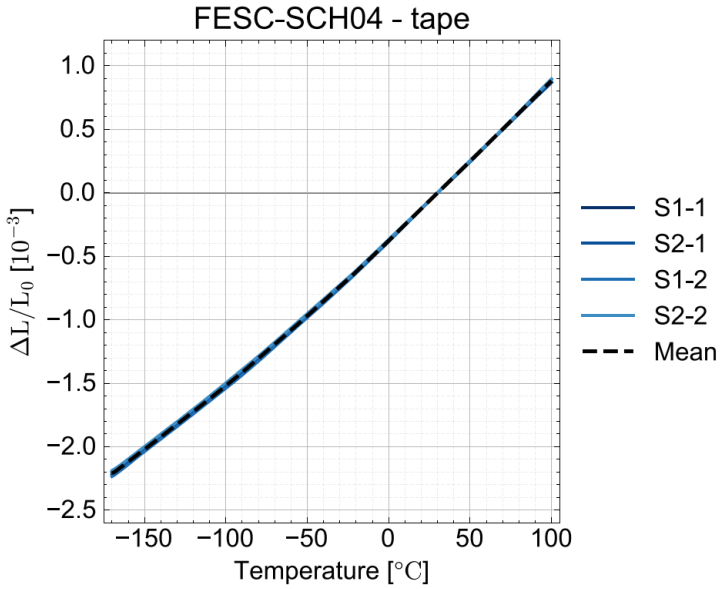




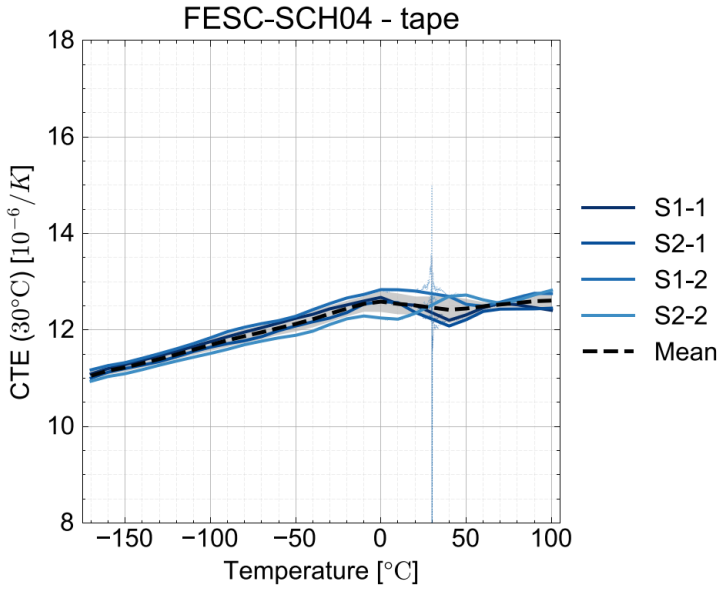
Assessing **porosity**, interface quality, and **geometric consistency**.

More details in R. Unterrainer's presentation (25.11.2025)

# Mechanical & thermo-physical characterisation




(a) Relative change in length




(b) Coefficient of thermal expansion

Thermal expansion measurements

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

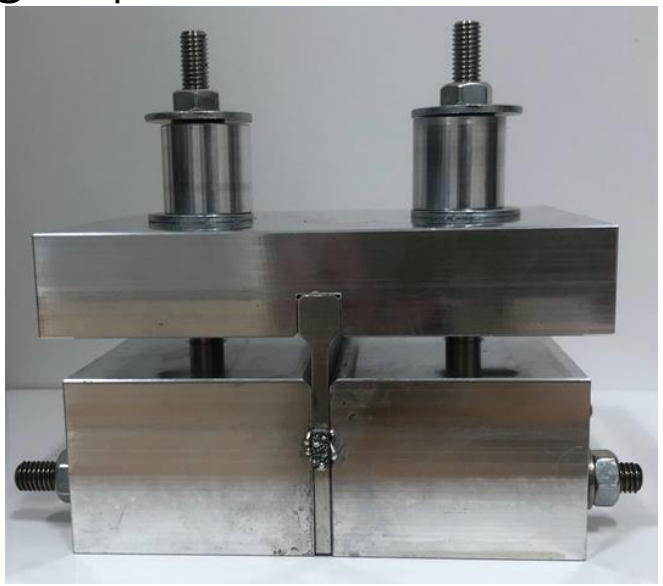
Measurements of two Fujikura FESC-SCH04-tape samples

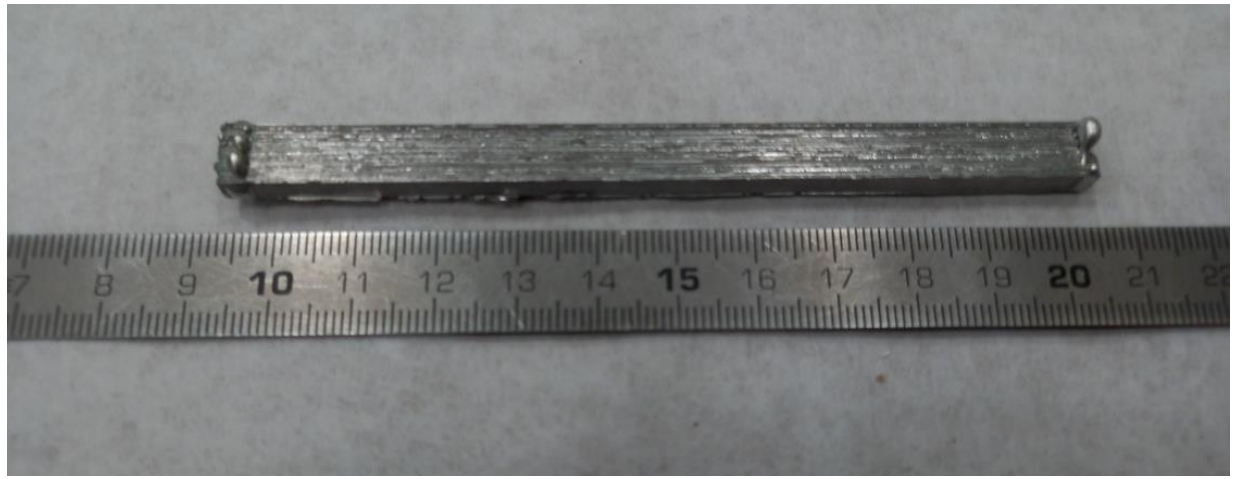
CTE measurements on tape ✔

**Courtesy of S. Hoell & O. Sacristan**

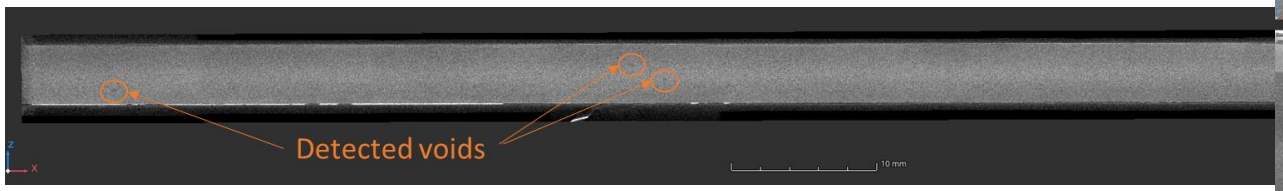
# Mechanical & thermo-physical characterisation

Tooling to produce stacks:





Micro-computed tomography test:




*Courtesy of M. Celuch*

Sample considered representative enough
to start thermo-mechanical characterization

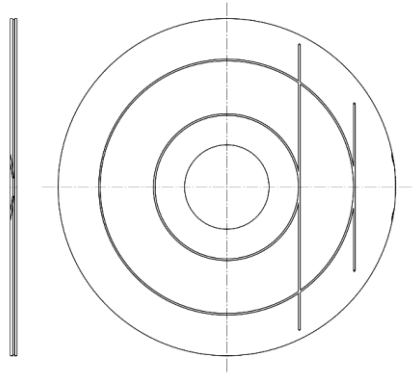
CTE & mechanical measurements on stacks ongoing

# Pancake compression test

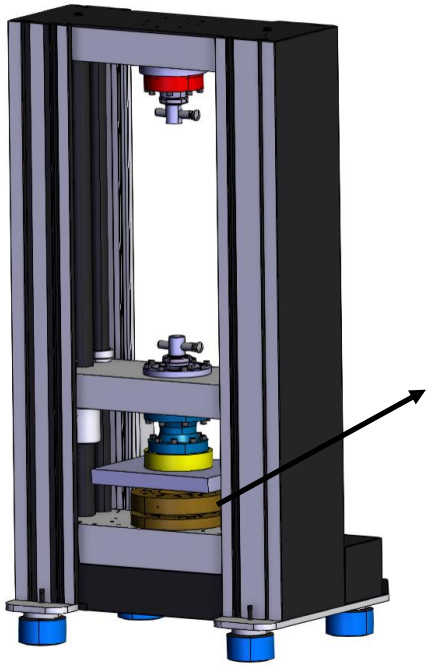
- Mechanics are the magnet limiting factor
- Experimentally validate pre-compression stresses
- Measure the mechanical (elastic) properties of pancakes and fine-tune FEM models

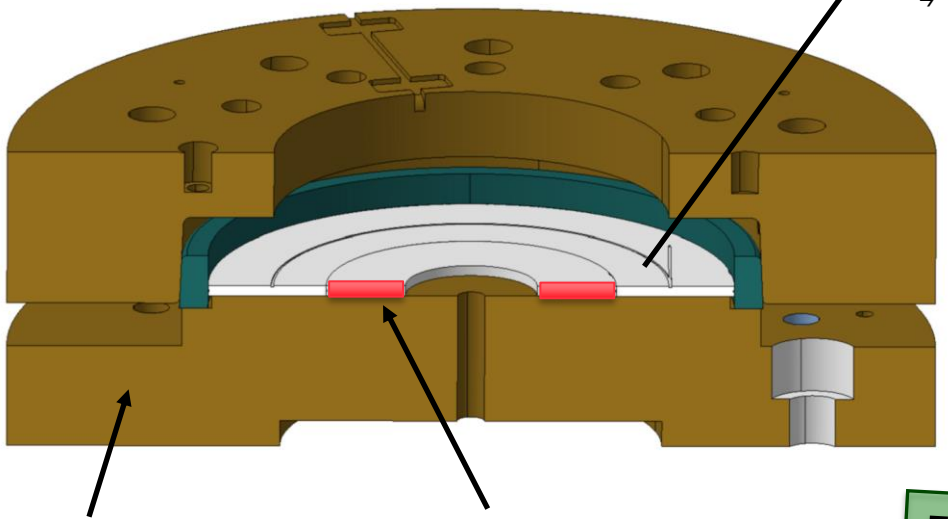
Compression rings

Dummy coils for test bench calibration



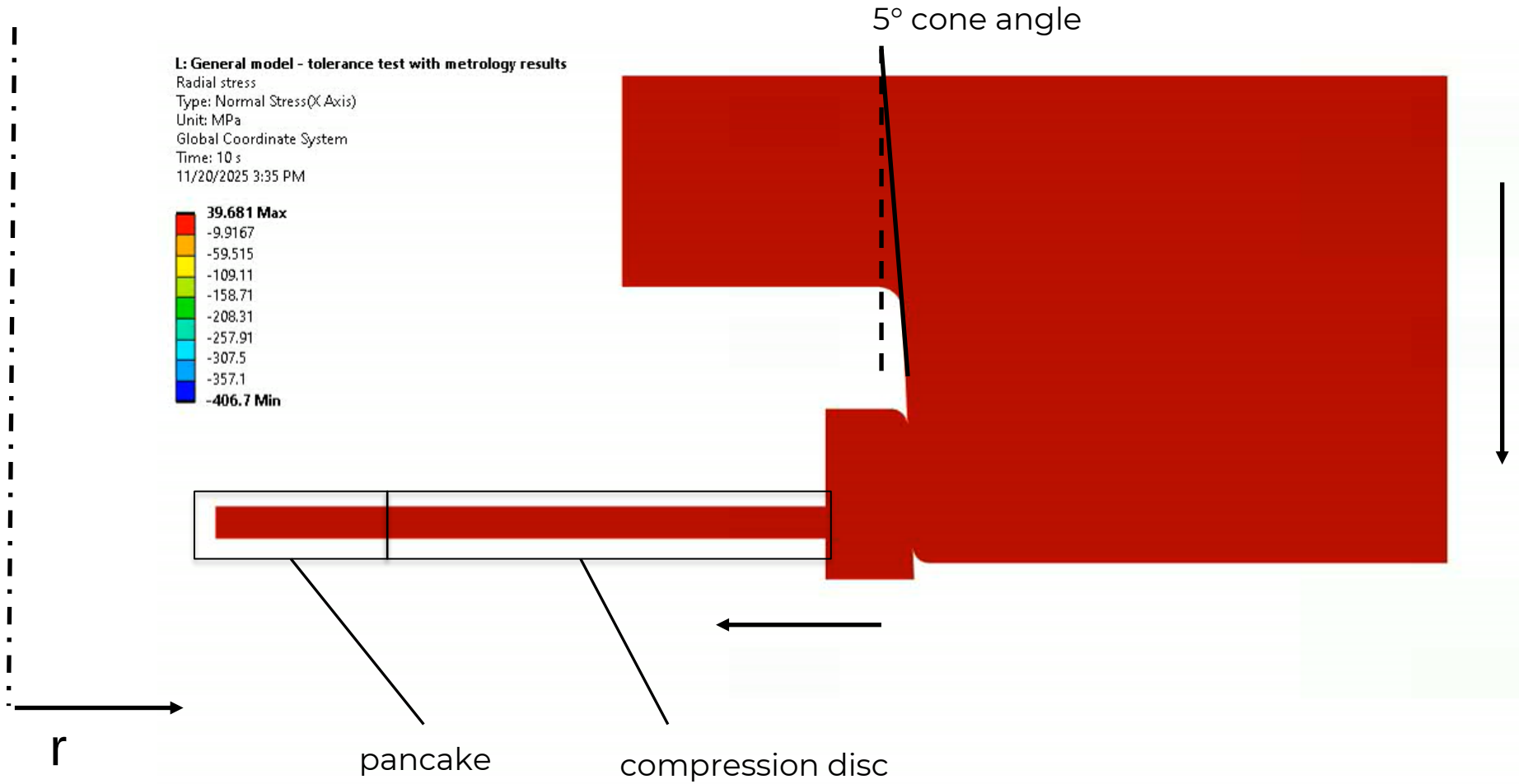
→ Equipped with Fiber Bragg Grating for strain measurements





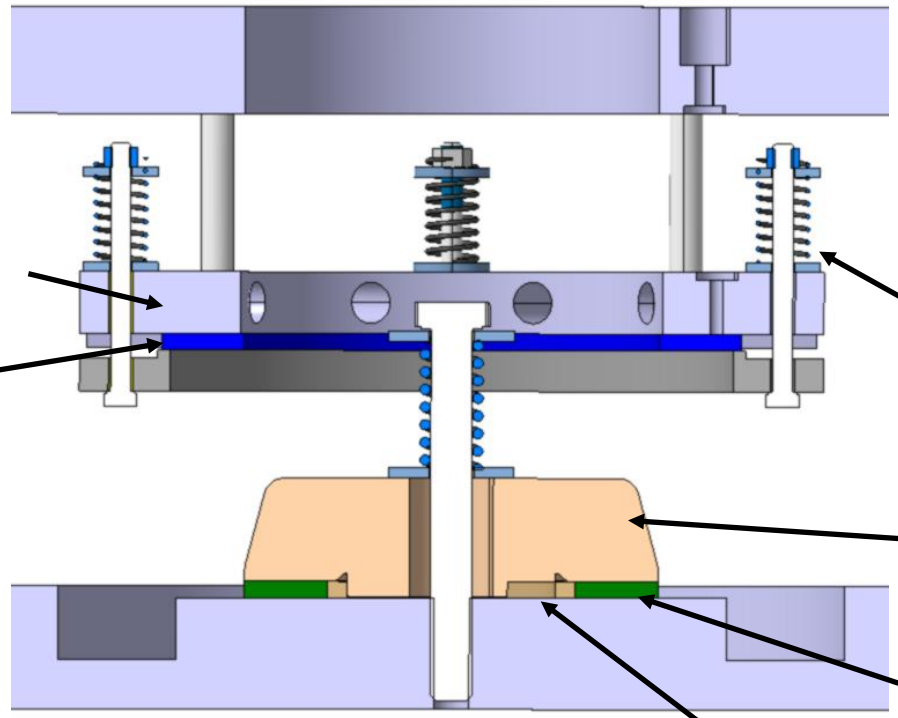

Engineering, design & fabrication completed ✔
Mechanical testing ongoing

# Pancake compression test

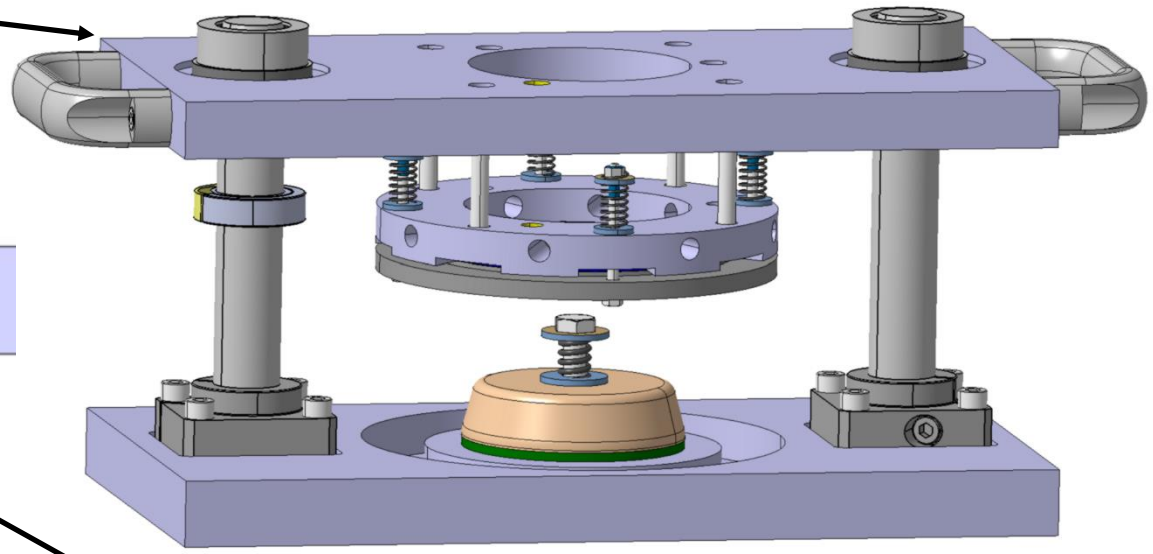



**Courtesy: A. Jade Ventura**

# Shrink fitting tooling




Sliding table (RT)



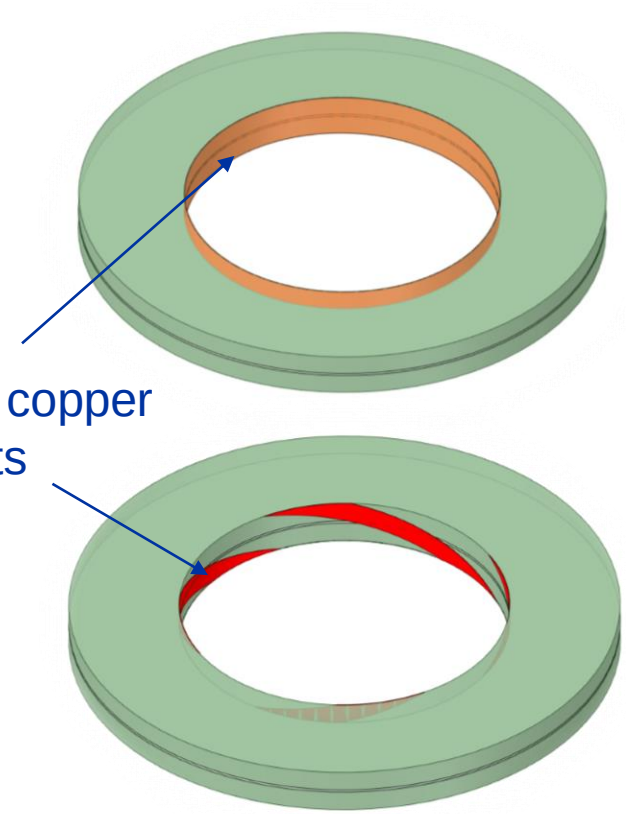
Spring supports to allow differential thermal expansion

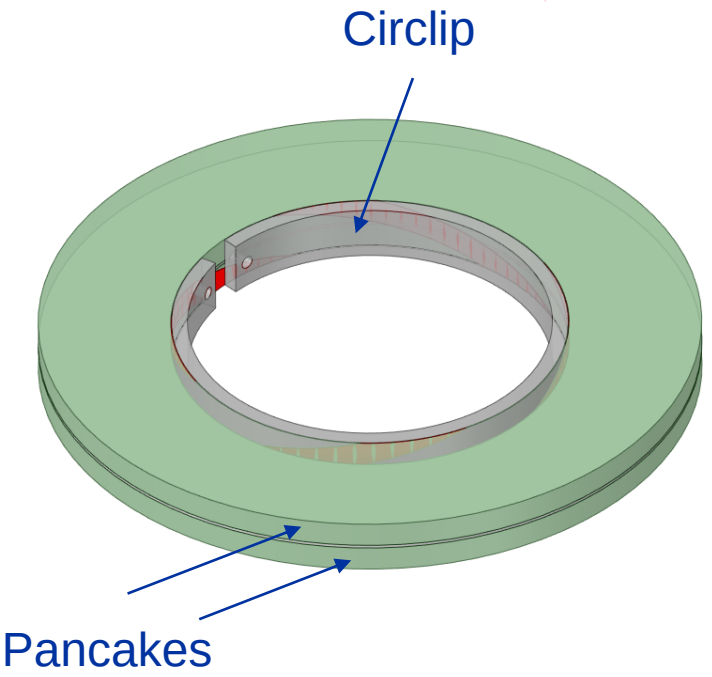
Design being finalised
Fabrication to follow

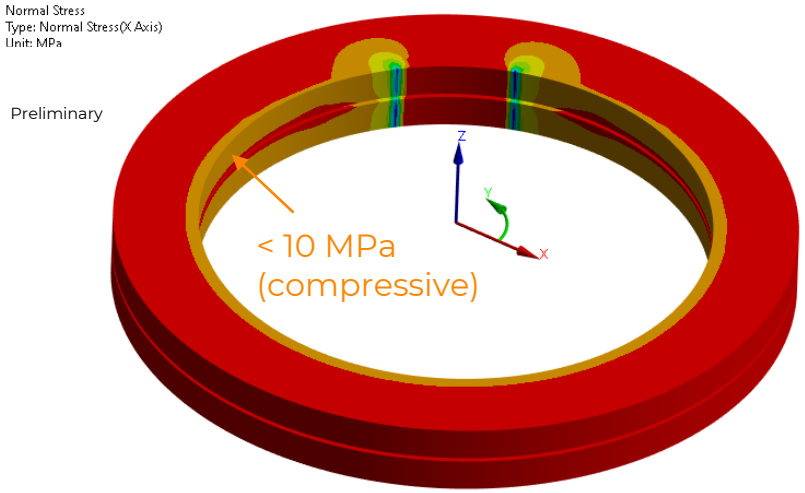
# Pancake joining highlights

Radial spring (circlip):

- Apply pressure during joints soldering
- Mechanical support during energization




Engineering & design ongoing to dimension the joints and the circlip spring → evaluate reaction stresses on the coils at room and cryogenic temperatures

# Conclusions

- During the past year, made **significant progress** in the **development** of the **40 T FC Solenoid**. Efforts have covered **multiple challenges**, including:
  - Winding machine
  - Pancake coil mechanical & thermo-physical characterisation
  - Shrink fitting tool
  - Pancake joining

- In the **coming year**, substantial efforts will **focus** on the **manufacturing** and **testing** of **sub-scale coils**

# Thank You For the Attention

Acknowledgements:

A. Bertarelli, A. Dallocchio, A. Dudarev, A. Jade Ventura, A. Kario, A. Kolehmainen, A. Moros, A. Verweij, B. Bordini, C. Accettura, D. Irbe, F. Sanda, G.A. Dubois, G. Scarantino, J. Guardia-Valenzula, L. Bottura, L. Fiscarelli, M. Buzio, M. Dalemir, M. Garlasche, M. Mentink, M. Wozniak, M.D. Crouvizier, O. Sacristan De Frutos, S. Hoell, T. Mulder, W. Walinga

Funded by the European Union

# Backup slides

# Shrink Fitting

- Coil surrounded by a cylindrical shell with rin<rext_coil
- Shell is pre-heated→ fitting of the coil inside→ cool-down of the shell and thermal contraction
- Simple analytical evaluation: 600MPa→200MPa→interference gap ~300μm→ ~250°C

(Hoop) (Radial)

$$\sigma_\theta = -\frac{\rho^2+\beta^2}{\rho^2}\frac{1}{1-\beta^2}p_e$$

$$\delta = \delta_{i2} - \delta_{e1} = \left[\frac{1}{E_2}\left(\frac{1+\beta_2^2}{1-\beta_2^2}+\nu_2\right)+\frac{1}{E_1}\left(\frac{1+\beta_1^2}{1-\beta_1^2}-\nu_1\right)\right]r_{e1}p_f$$

- Some practical aspects must be considered:
  - Differential contraction during cooldown
  - Strength of the cylinder
  - Impact of the joints
  - Plasticity
  - **Mechanical tolerances: 2MPa/μm lost**
  - **Buckling**

- FEM simulations at different levels of complexity

Courtesy of C. Accettura et al. (Final Cooling Solenoid Design and Fabrication, 20/09/2024)