Structural analysis of Final Cooling Solenoid Coil

C. Accettura,
With several contributions from A. Bertarelli, B. Bordini,L. Bottura, A. Dudarev, A. Kolehmainen, F. Sanda

Final Cooling Solenoid Design and Fabrication (19 September 2024) · Indico (cern.ch)
20/09/2024, CERN

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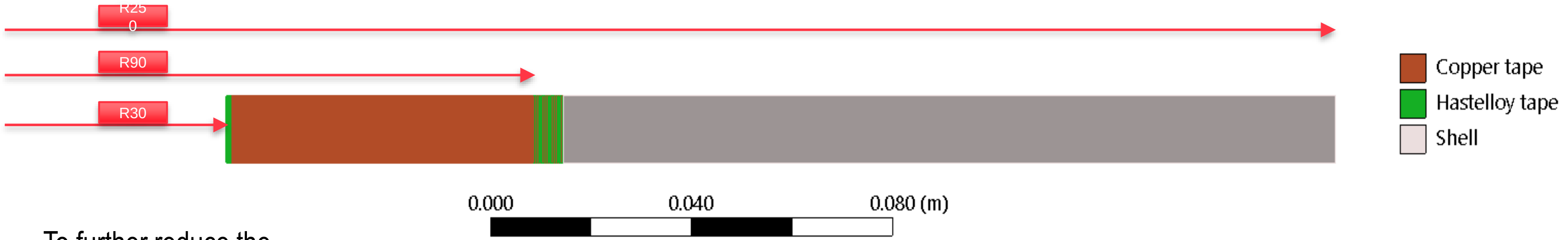
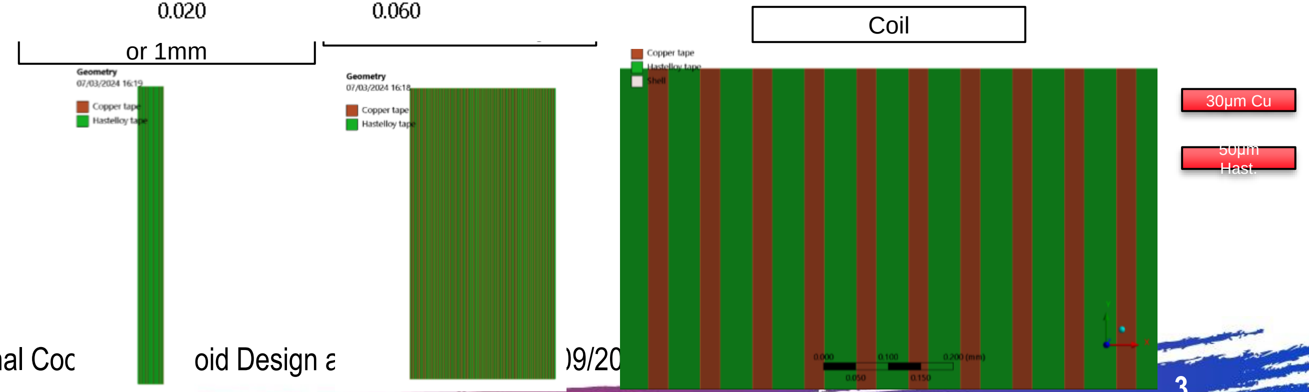
- Review of the model presented at the IMCC2024
- New model

Stress and Strain in the coil

- Mechanical Simulation of a modular coil: all 750 windings are represented
- The model accounts for: Cu yielding and; the thermal contractions of the different materials
  - $P_M = B_0^2 / 2\mu_0 \sim 600 MPa$
  - Hoop stress~ 1.4-2.2P_M (compact coil)



- To further reduce the stresses on the coils, a lower amount of Cu in the tape and a much larger outer-ring thickness

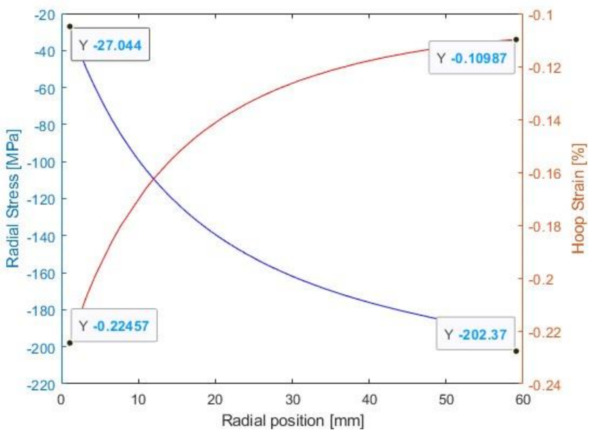


Stress and Strain in the coil

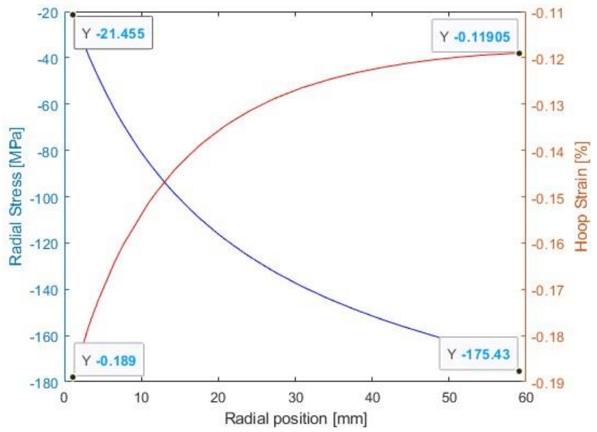
Pre-compression
170 MPa

Inner Joint ring
1 mm thick

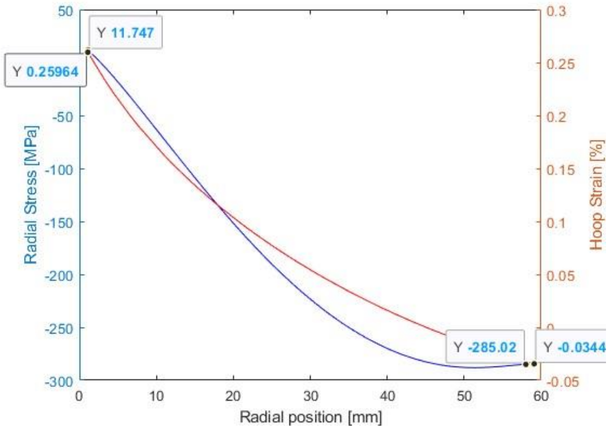
Step 1



Step 2



Step 3

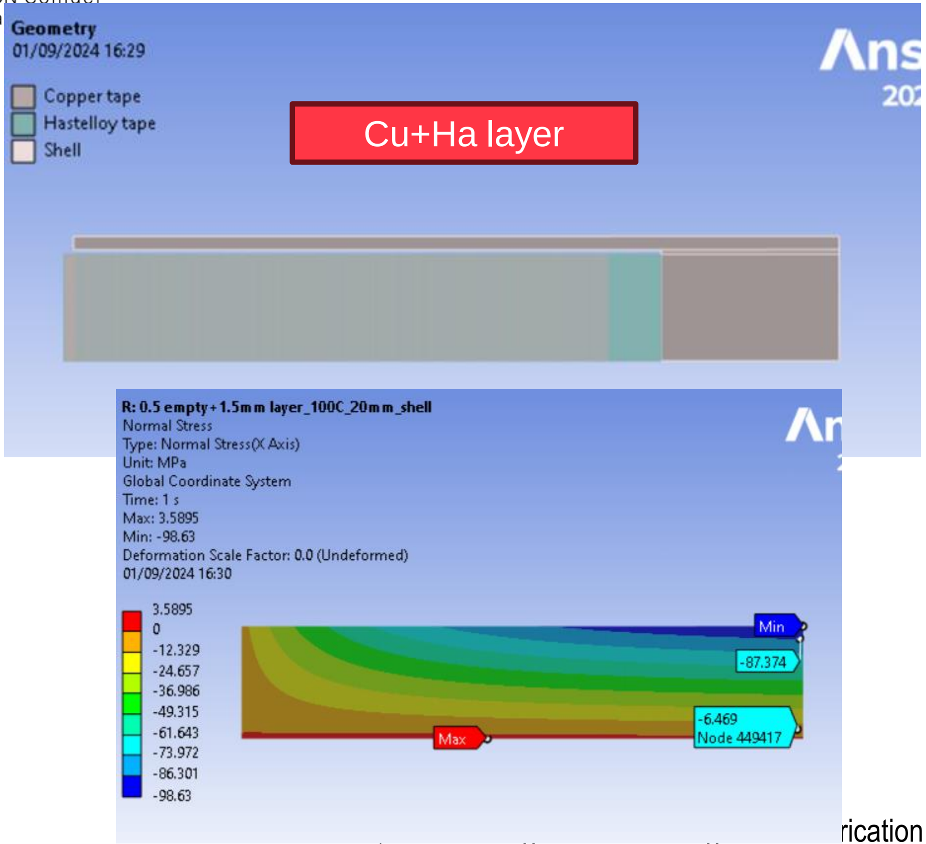


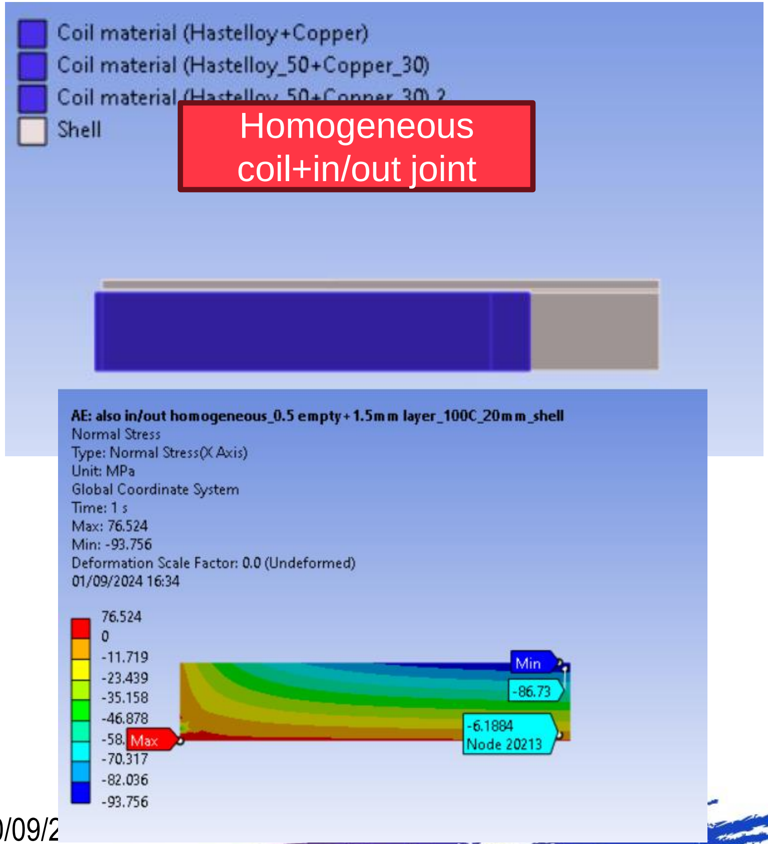
ɔol

Inner joint optimization

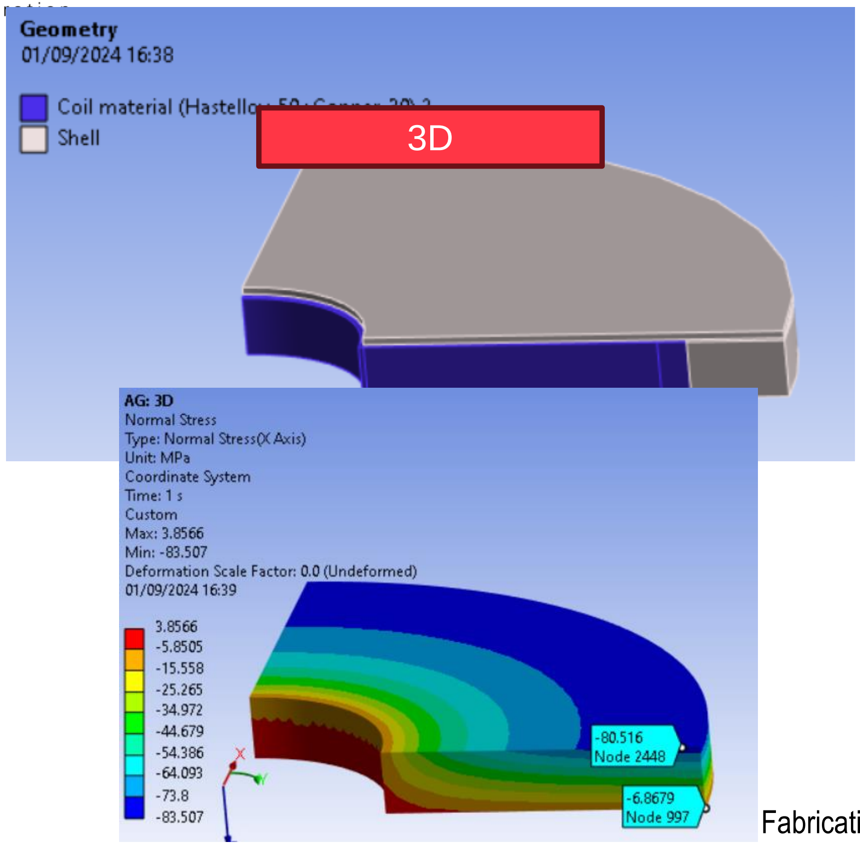
Inner Joint ring thickness [mm]	Pre-compression at cold [MPa]	Radial stress[MPa]			Hoop Strain [%]			Shear Stress [MPa]		
		Step 1	Step 2	Step 3	Step 1	Step 2	Step 3	1	2	3
0.5	170	-205/-8	-190/-5	**-290/10**	**-0.25**/-0.10	-0.20/ -0.12	-0.04/**0.28**	6	4.5	4
	250	-318/-12	-258/-8	**-367/7**	**-0.39**/-0.17	-0.31/-0.16	-0.09/**0.18**	10	6	5
1	170	-205/-14	-190/-10	**-288/19**	**-0.25**/-0.10	-0.2/-0.12	-0.05/**0.29**	6	4	5
	250	-320/-21	-259/-15	**-366/13**	**-0.39**/-0.17	-0.3/-0.16	-0.09/**0.18**	10	6	5

2D layered vs homogeneous

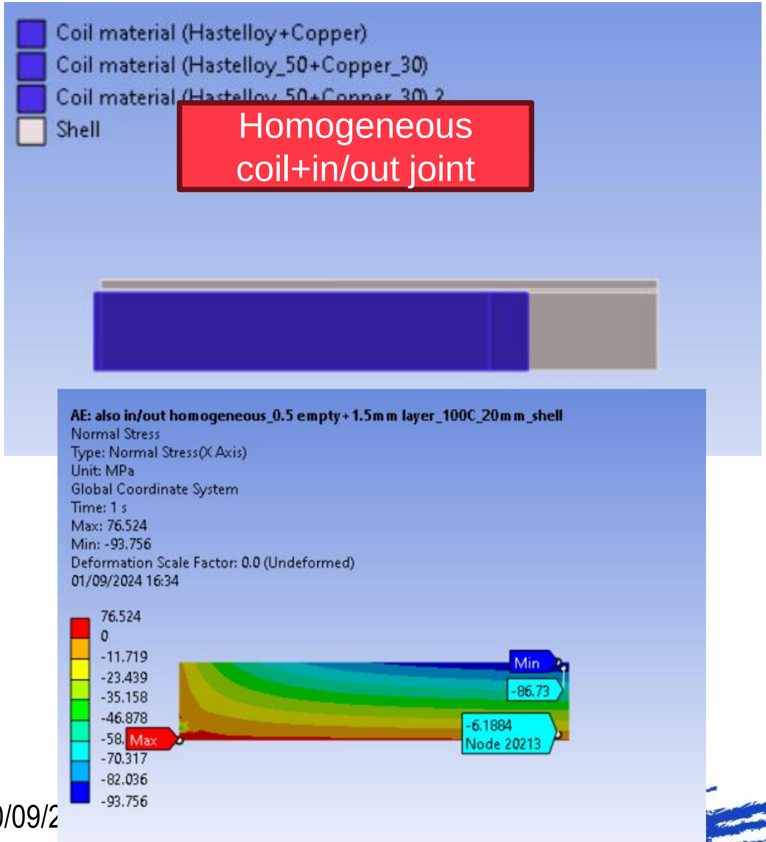




3D vs 2D

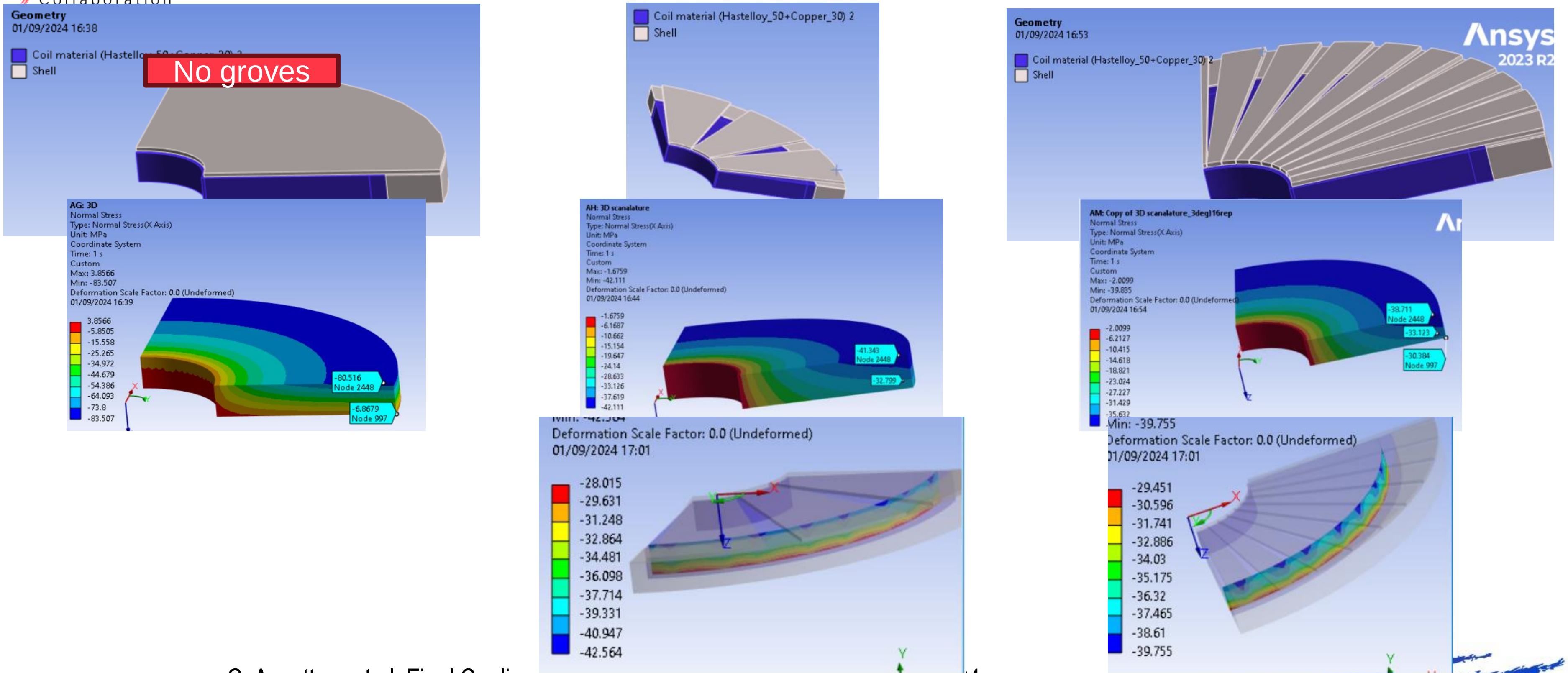


Geometry
01/09/2024 16:38
Shell
3D
AG: 3D
Normal Stress
Type: Normal Stress(X Axis)
Unit: MPa
Coordinate System
Time: 1 s
Custom
Max: 3.8566
Min: -83.507
Deformation Scale Factor: 0.0 (Undeformed)
01/09/2024 16:39
3.8566
-5.8505
-15.558
-25.265
-34.972
-44.679
-54.386
-64.093
-73.8
-83.507
-80.516
Node 2448
-6.8679
Node 997



Coil material (Hastelloy+Copper)
Coil material (Hastelloy_50+Copper_30)
Shell
Homogeneous
coil+in/out joint
AE: also in/out homogeneous_0.5 empty+1.5mm layer_100C_20mm_shell
Normal Stress
Type: Normal Stress(X Axis)
Unit: MPa
Global Coordinate System
Time: 1 s
Max: 76.524
Min: -93.756
Deformation Scale Factor: 0.0 (Undeformed)
01/09/2024 16:34
76.524
0
-11.719
-23.439
-35.158
-46.878
-70.317
-82.036
-93.756
Min
-86.73
Max
-6.1884
Node 20213

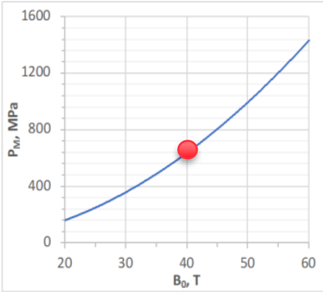
Groves optimization

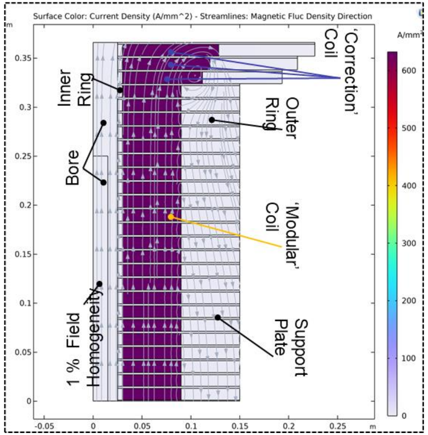


Introduction and Motivations

- Design proposed for the Final Cooling solenoid based on single and compact coil→ critical stress management:
  - $P_M = B_0^2/2\mu_0 \sim 600\text{MPa}$
  - Hoop stress~ 1.4-2.2P_M (compact coil)

Magnetic pressure vs Field



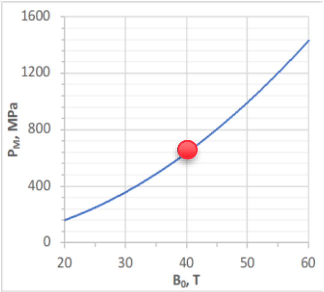


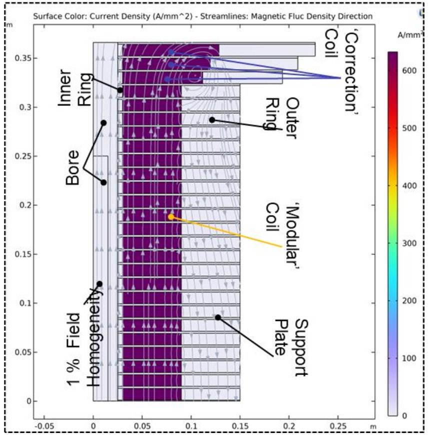
See [B. Bordini, Technology options for the final cooling solenoids, IMCC Annual Meeting 2023, Orsay]

Introduction and Motivations

- Design proposed for the Final Cooling solenoid based on single and compact coil→ critical stress management:
  - $P_M = B_0^2/2\mu_0 \sim 600MPa$
  - Hoop stress~ 1.4-2.2P_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





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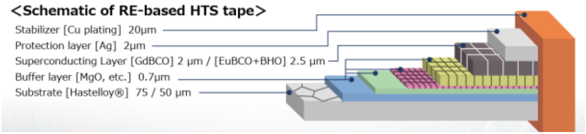


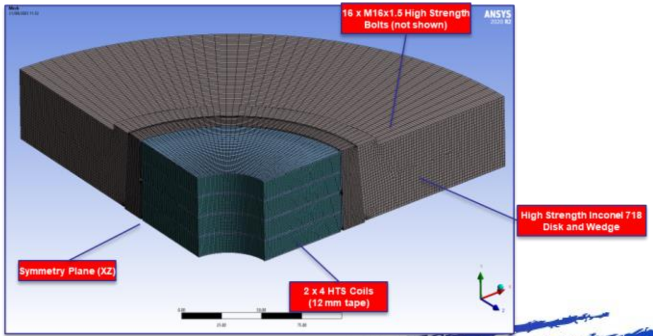
Reference Conductor Fujikura FESC-SH12.
https://www.fujikura.co.jp/eng/products/newbusiness/superconductors/01/superconductor.pdf

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

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

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:**
  1. Thermally-induced shrink fitting
  2. Adjustable shrink-discs with conical surfaces
  3. Hybrid solution (1+2)



Shrink Fitting

- Coil surrounded by a cylindrical shell with $r_{in\_shell} < r_{ext\_coil}$
- Shell is pre-heated→ fitting of the coil inside→ cool-down of the shell and thermal contraction
- Simple analytical evaluation: σ_{hoop}=-500MPa→200MPa→interference gap ~220µm→ Tshell~170°C

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

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

- Some practical aspects must be considered:
  - Differential contraction during cooldown
  - Strength of the cylinder
  - Impact of the joints
  - Plasticity
  - Mechanical tolerances: 1MPa/µm lost
  - Buckling
- FEA simulations at different levels of complexity

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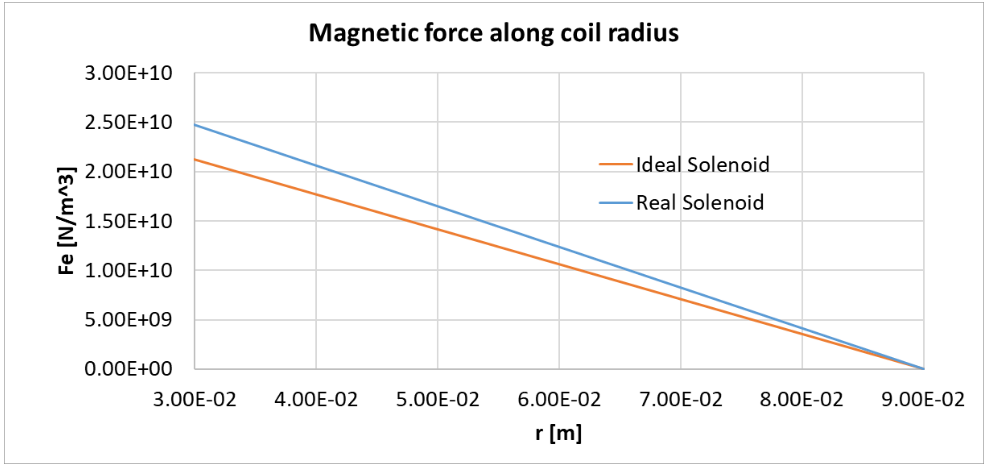
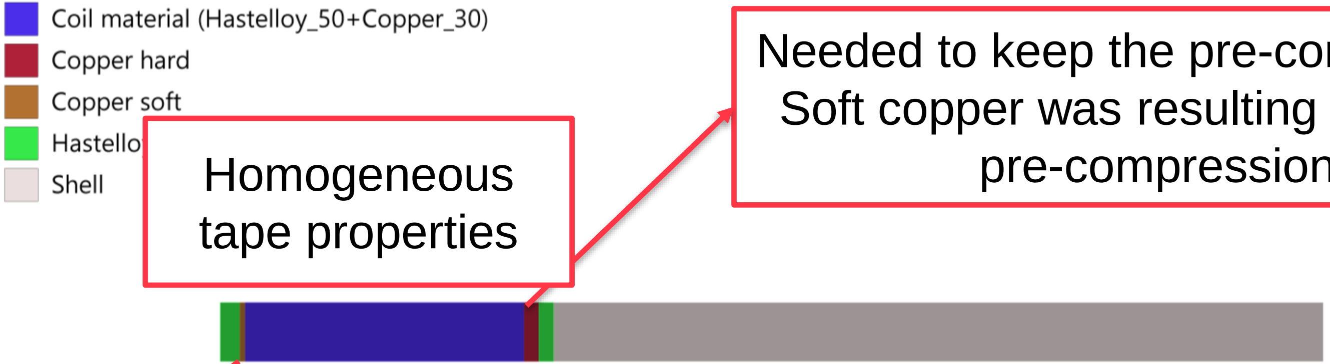
Assumptions

- 2D axisymmetric
- Electromagnetic Forces
  - Ideal Solenoid ($J_{ideal} = \frac{B_{MAX}}{\mu_0(r_{co} - r_{ci})}$ = 531 A/mm2)
  - Real Solenoid ($J_{real} = J_{ideal} \frac{t_{coil} + t_{supportplate}}{t_{coil}}$ = 620 A/mm2)



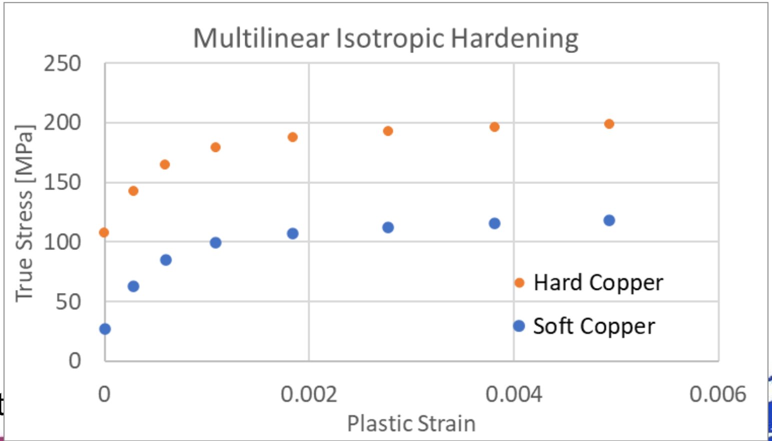
Reference model



Homogeneous tape properties

Needed to keep the pre-compression. Soft copper was resulting in a lower pre-compression

Ha to avoid radial tensile and shear stress after cooldown



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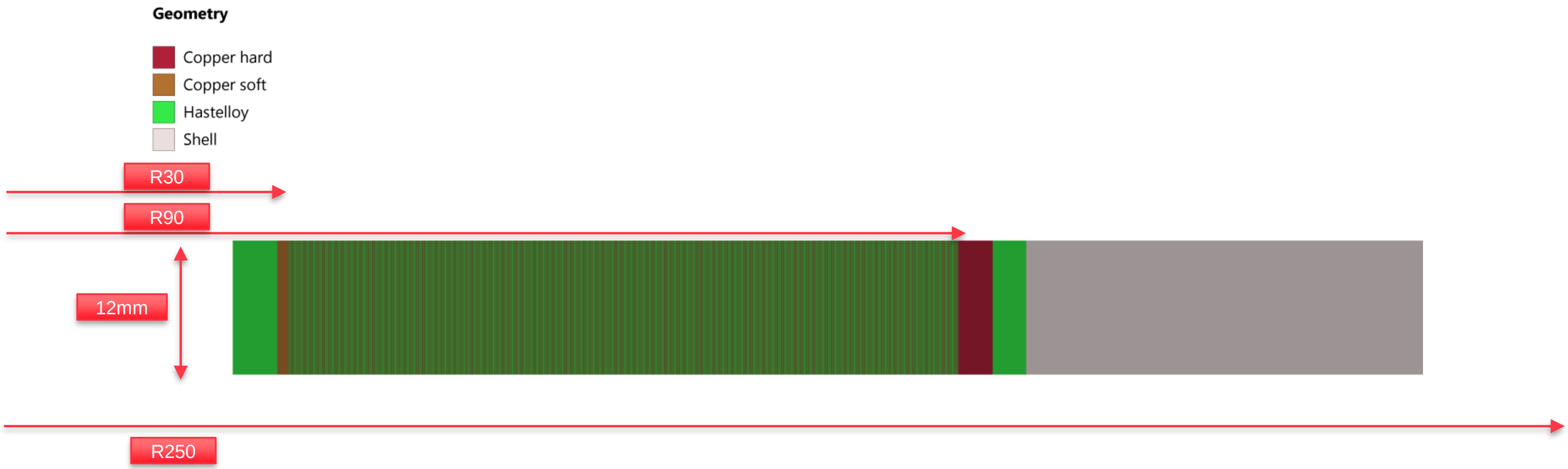
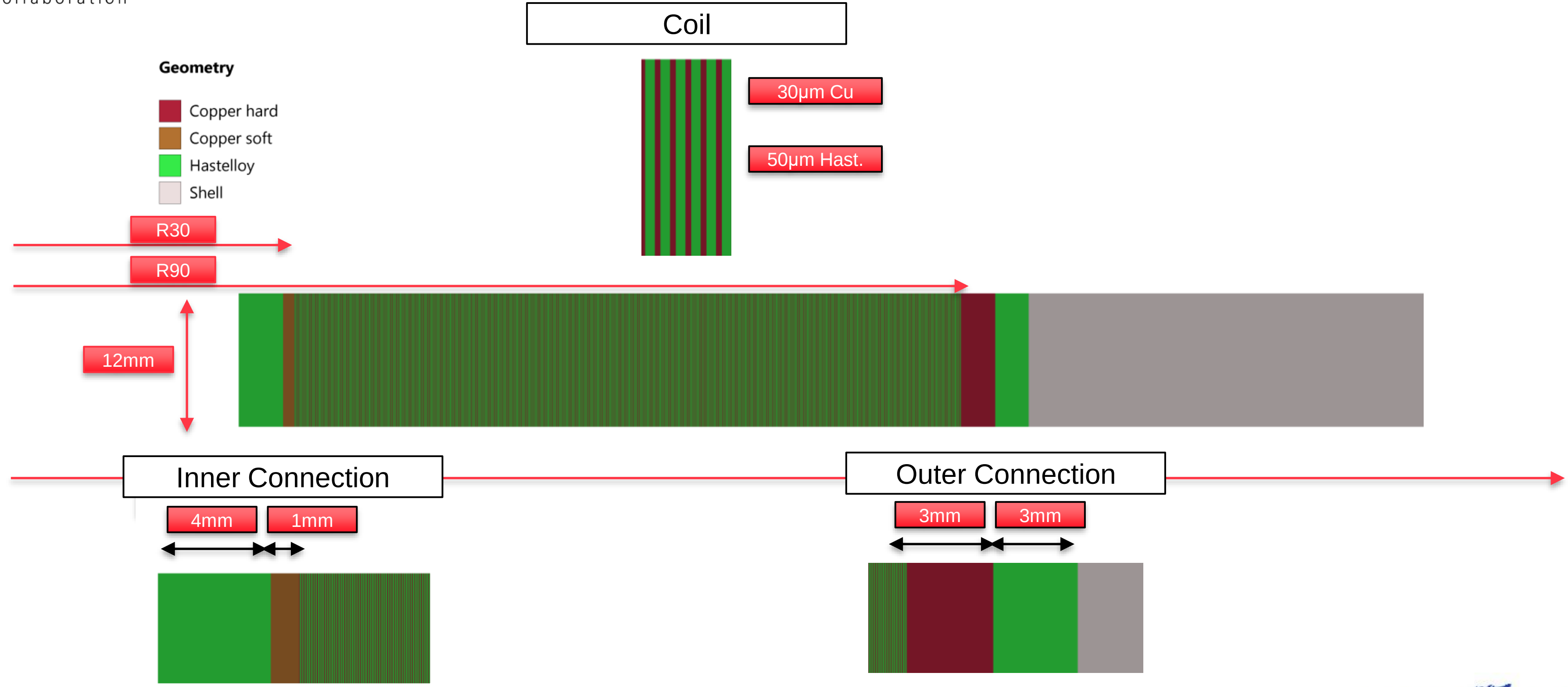
Layered model



Geometry and Materials



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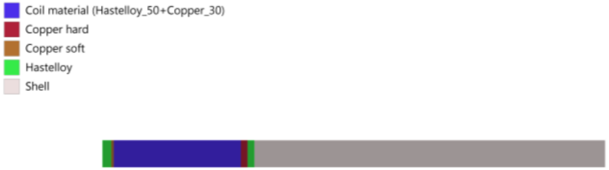
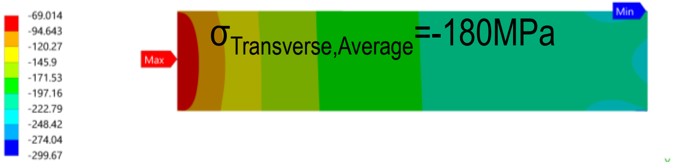
Validity of homogeneous model



Step 1: Shrink fitting (T external shell =250°C)

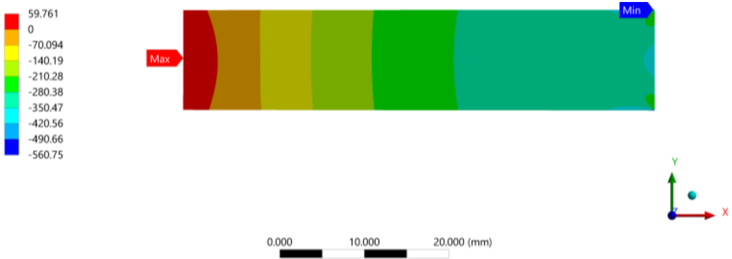
$\sigma_{Transverse,Average}$=-210MPa

Step 2: Cool-down

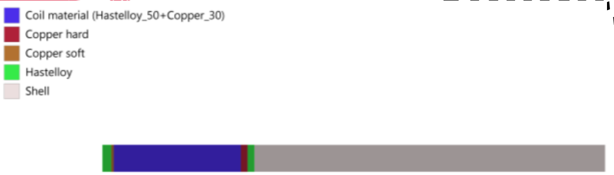


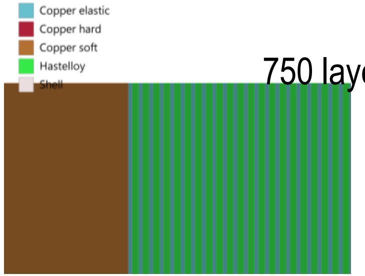
$\sigma_{Transverse,Average}$=-180MPa

Step 3: Energization



Validity of homogeneous model





750 layers: 30µm+50 µm

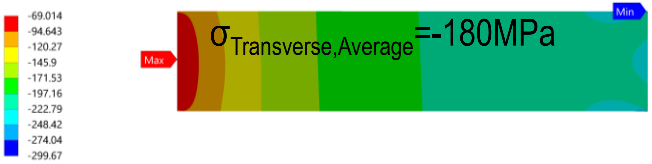
Step 1: Shrink fitting

$\sigma_{Transverse,Average}$=-210MPa

Step 1: Shrink fitting

$\sigma_{Transverse,Average}$=-215MPa

Step 2: Cool-down

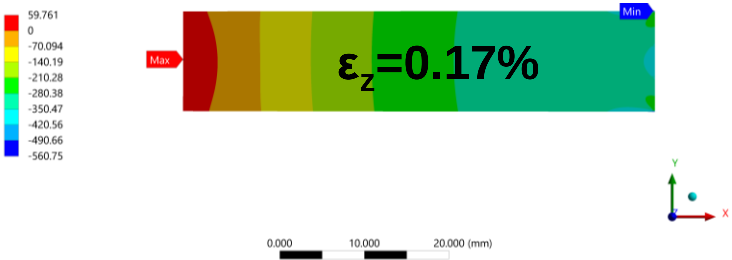


$\sigma_{Transverse,Average}$=-180MPa

Step 2: Cool-down

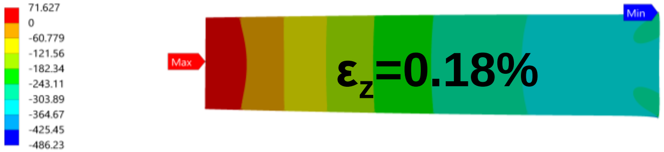
$\sigma_{Transverse,Average}$=-170MPa

Step 3: Energization



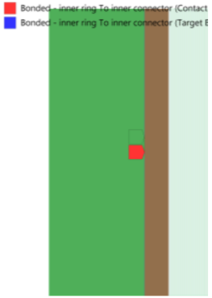
ε_z=0.17%

Step 3: Energization

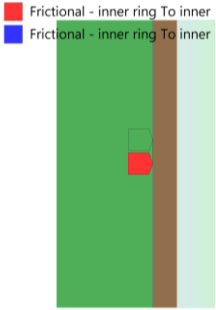


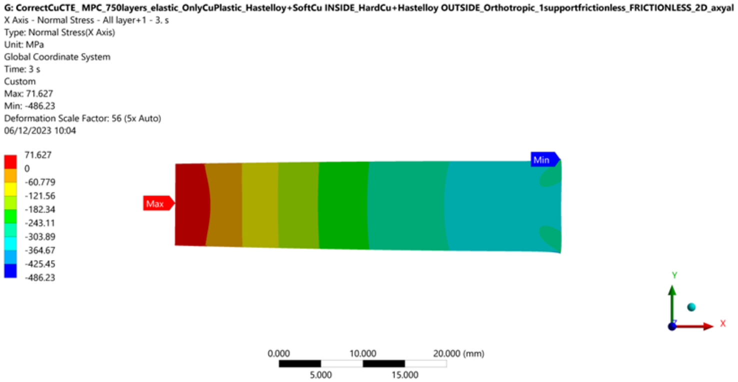
ε_z=0.18%

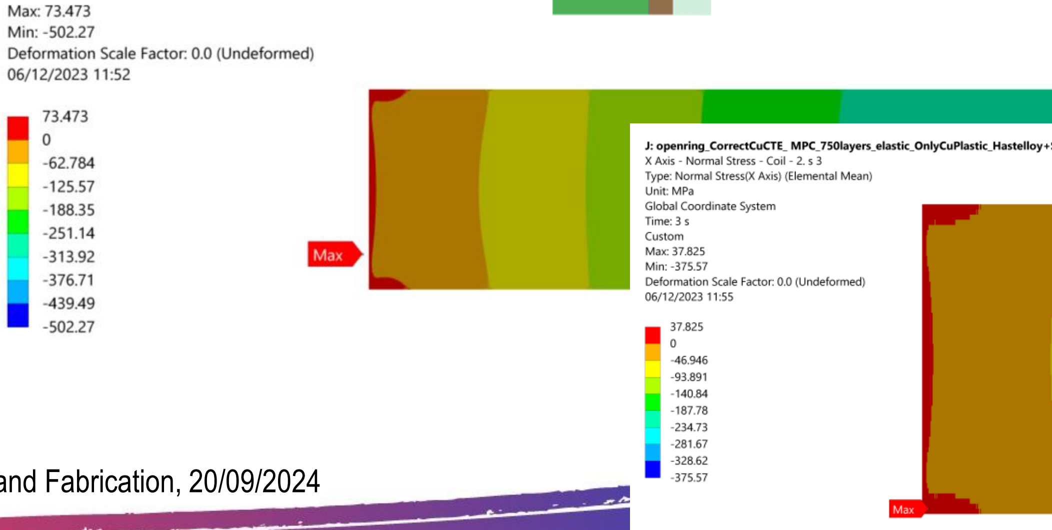
Effect of the inner joint properties



Let the ring detach to limit radial tensile stress







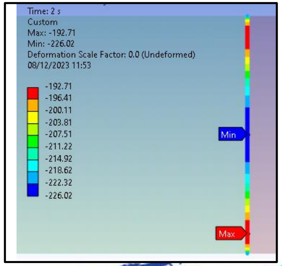
Effect of the tape plasticity

	σ_x-radial[MPa]			ε_z-hoop
step	min	max	ave	max
1	-289	-57	-210	
2	-224	-67	-164 (200*)	
3	-416	77	-213	0.30%
1	-308	-54	-214	
2	-272	-63	-171 (210*)	
3	-502	73	-224	0.22%

Plastic

Elastic

*Average on the external edge



Effect of the tape properties

	σ_x-radial[MPa]			ε_z-hoop
step	min	max	ave	max
1	-291	-55	-208	
2	-264	-60	-171 (215*)	
3	-484	75	-218	0.24%
1	-289	-57	-210	
2	-224	-67	-164 (200*)	
3	-416	77	-213	0.30%

*Average on the external edge

Experiments and FE modeling of stress–strain state in ReBCO tape under tensile, torsional and transverse load

To cite this article: K Ilin *et al* 2015 *Supercond. Sci. Technol.* **28** 055006

Reference

Effect of the tape properties

	σ_x-radial[MPa]			ε_z-hoop
step	min	max	ave	max
1	-291	-55	-208	
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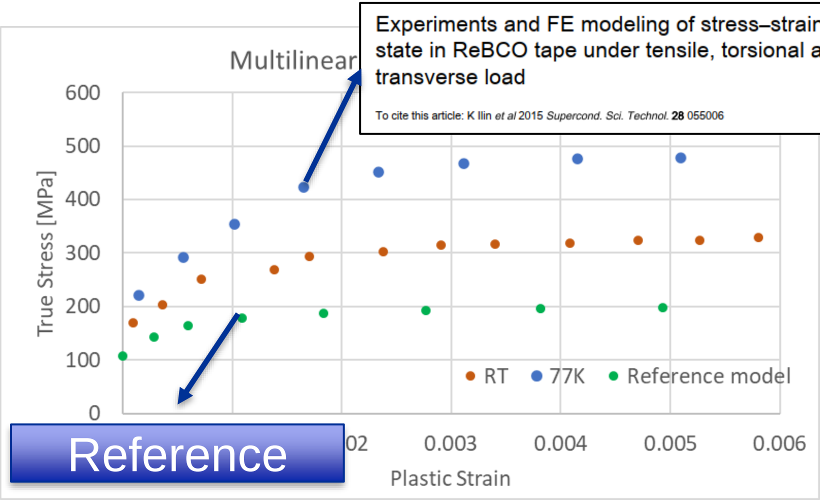
3	-416	77	-213	0.30%

*Average on the external edge



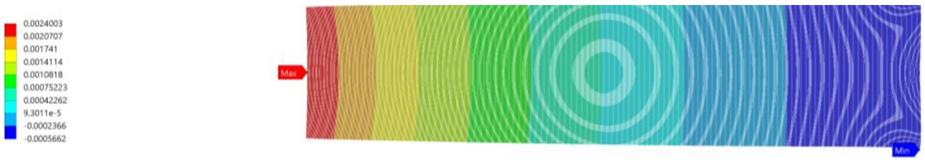
Effect of the tape properties

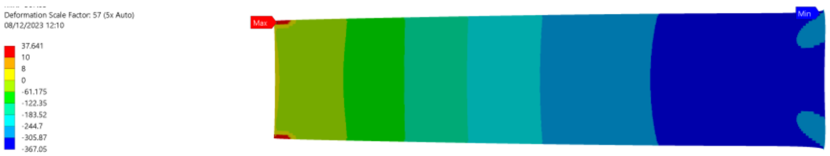
	σ_x-radial[MPa]			ε_z-hoop
step	min	max	ave	max
1	-291	-55	-208	
2	-264	-60	-171(215)	
3	-484	75*	-218	0.24%

*Localized effect

ε_z=0.24% ☑

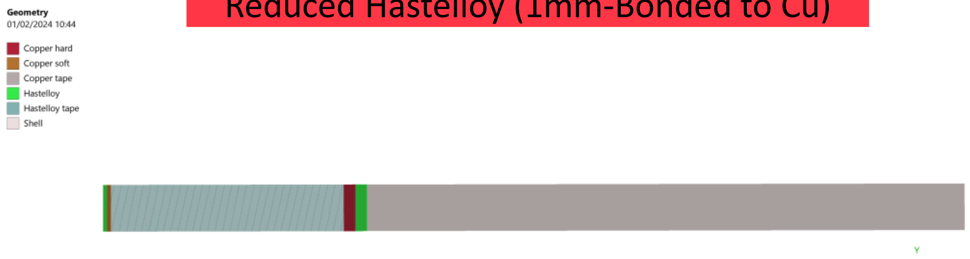
σ_x~10MPa ☑





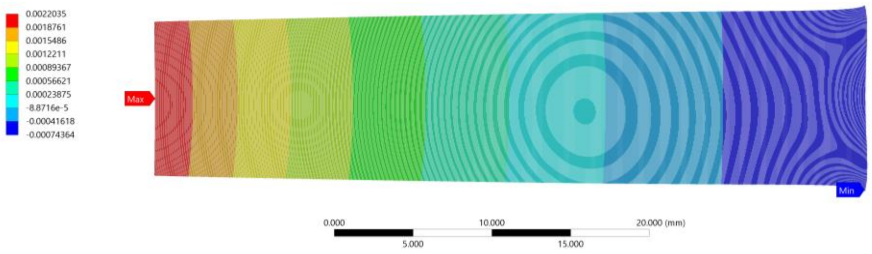
Alternative Inner Joint-1

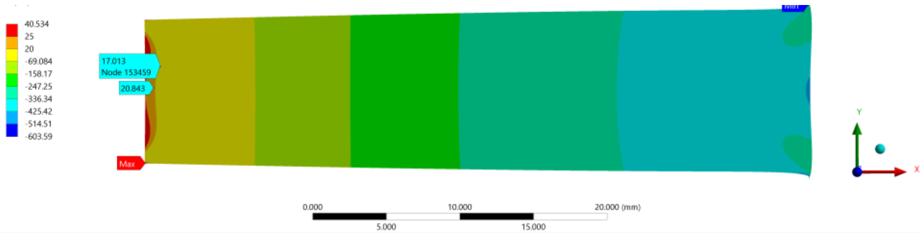
Reduced Hastelloy (1mm-Bonded to Cu)



ε_z=0.22% ☑

σ_x~20MPa (p~250MPa)



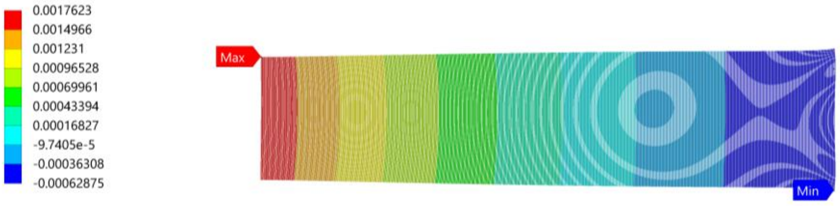


Alternative Inner Joint-2

Hastelloy orthotropic	
Ex-radial[GPa]	Ey,z-hoop[GPa]
100	200

ε_z=0.17% ☑

σ_x=80MPa ☒



Alternative Inner Joint-3

- Copper hard
- Copper tape
- Hastelloy
- Hastelloy tape
- Shell

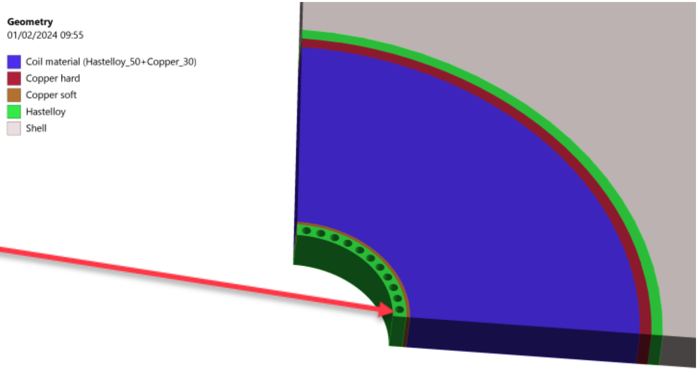
Soft Hastelloy isotropic
E [GPa]
20

Model simplification, important to have a 3D design of the inner ring to take into account the real stiffness of the structure

ε_z=0.27% ☑

σ_x=12MPa ☑

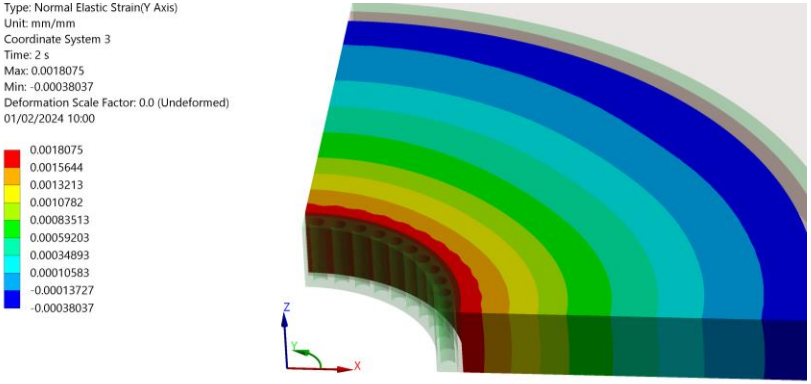
Alternative Inner Joint-4

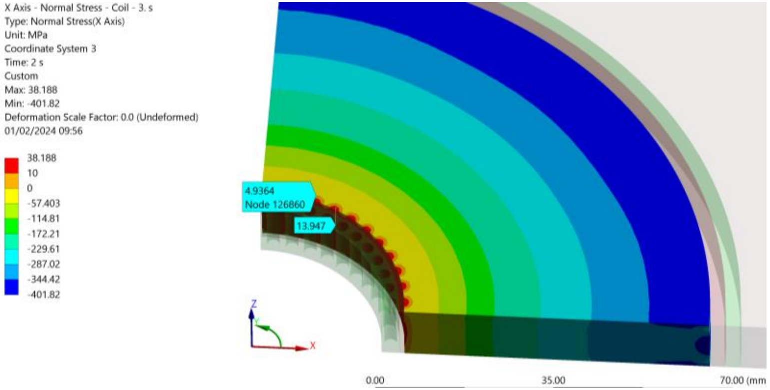


3D model more time-consuming, homogeneous material and mesh to be refined→ **INCREASE OF at least~50% expected**

ε_z=0.18% ✓

σ_x<20MPa





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

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

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

- 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

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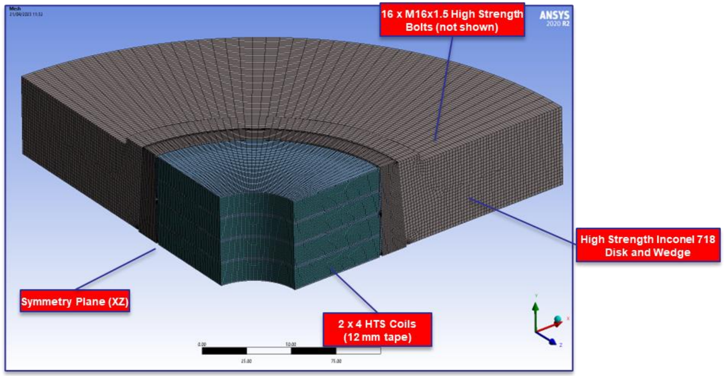
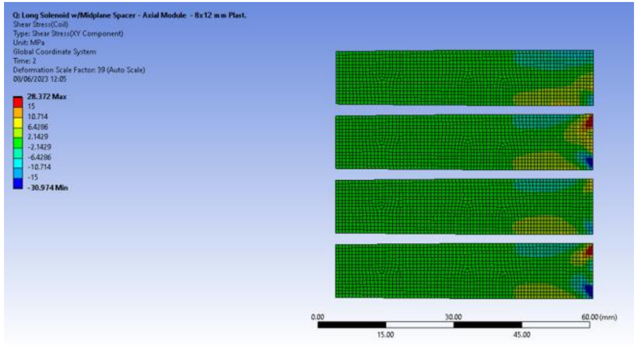
Mechanical considerations - Second concept

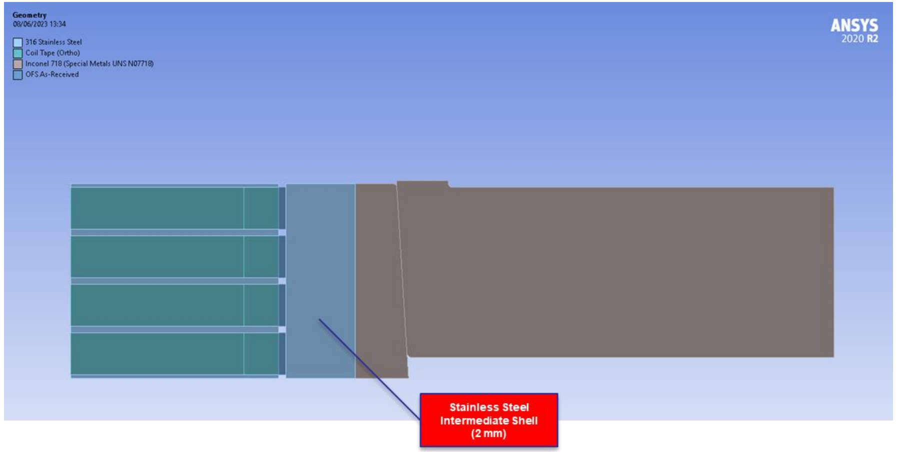
- 2 Load Steps:
  - Shrink Disk displacement (5 mm)
  - Energization
- Max. Hoop Stress (after energization): 620.4 MPa
- Max. Hoop Strain (after energization): 0.344 %
- Shear Stresses globally lower than 15 MPa
- However, locally they can reach after energization ~ |30| MPa





Mechanical considerations - Third concept

- To limit shear stresses, an intermediate steel shell is added (ID 184 mm; OD 224 mm)
- ~ 150 µm interference with coil pack created by differential heating
- 3 Load Steps: 1. Shell/Coil Interference; 2. Shrink Disk Displacement (2.2 mm); 3. Energization
- Min. Hoop Stress after shrinking: -426 MPa
- Max. Hoop Stress after energization: 598 MPa
- Max. Hoop Strain after energization: 0.332 %
- Local peak shear stress ~ 10 MPa
- Max Shear after energization |9.2| MPa



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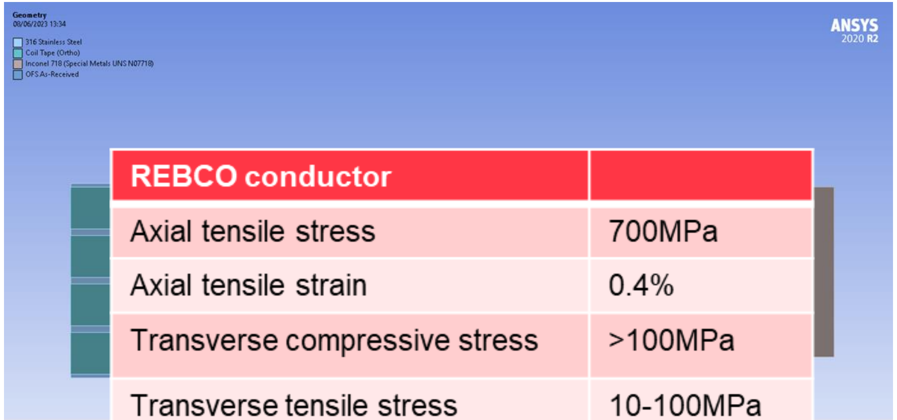
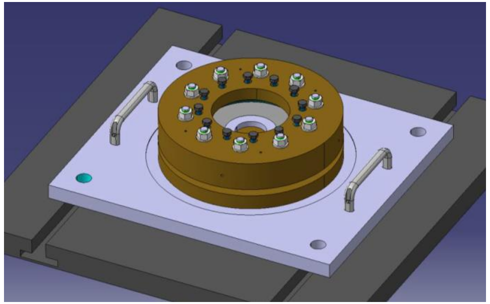
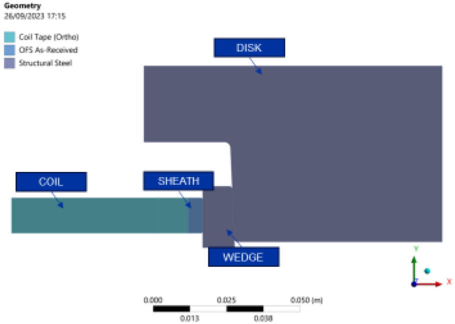


REBCO conductor	
Axial tensile stress	700MPa
Axial tensile strain	0.4%
Transverse compressive stress	>100MPa
Transverse tensile stress	10-100MPa
Max shear stress	>19MPa

- Preliminary is ok, but **limited safety margins**→ Fundamental to have a good understanding of the **material limits** and **failure mode**

Testing



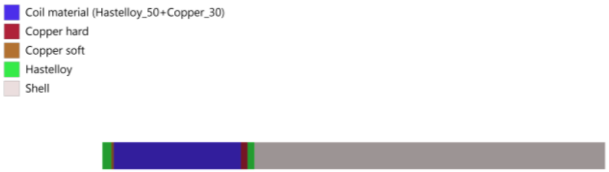


- σ_{hoop}~-600MPa reached on the inner radius of the coil
- The required compression is achieved with 10 M16 bolts
- System equipped with strain gauges and digital image correlation to characterize the coil

Conclusion and next step

- The final cooling solenoid requires a pre-compression to operate at 40T:
  - Shrink fitting, mechanical jigs or a combined solution can provide the required pre-compressions
  - Tape properties impacting the results→ important to benchmark them with experimental tests
  - The design of the inner and outer rings is critical: some possible solutions identified, more modelling work is needed to finalize the design
  - Different FEM models ready to investigate more options
  - Extensive work of design of the tooling for the experimental characterization of the tape

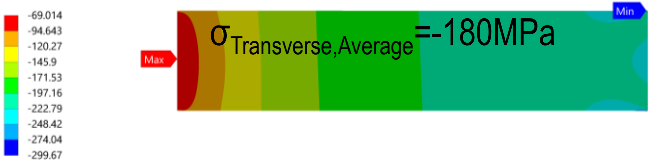
Validity of homogeneous model



Step 1: Shrink fitting (T external shell =250°C)

$\sigma_{Transverse,Average}$=-210MPa

Step 2: Cool-down



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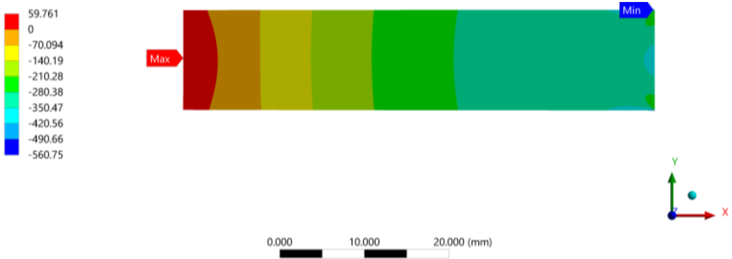
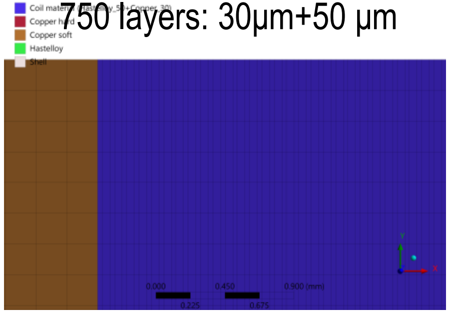
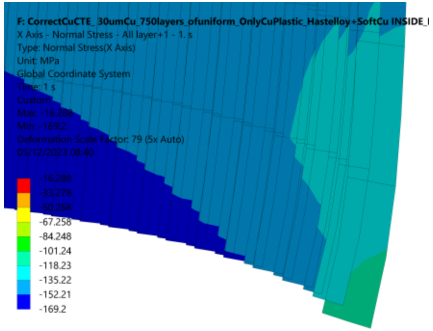


750 layers: 30μm+50 μm



$\sigma_{Transverse,Average}$=-85MPa



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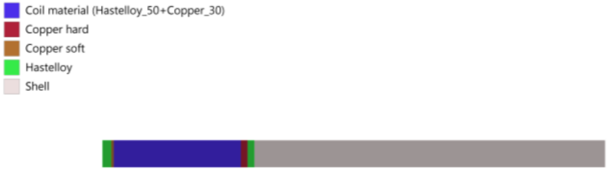

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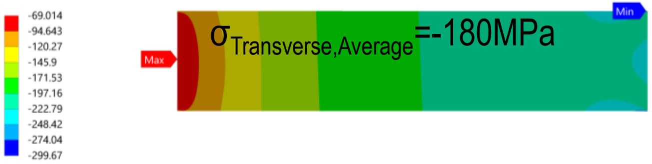

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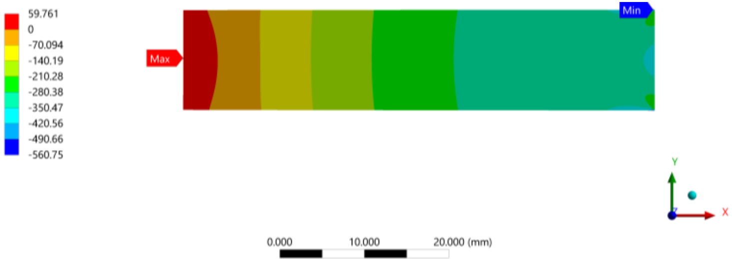

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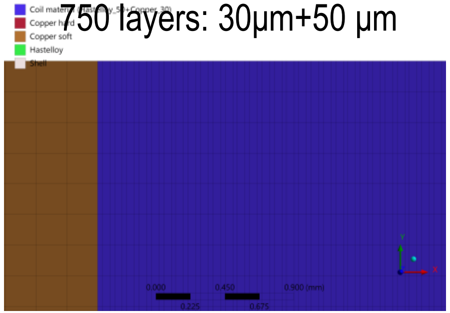

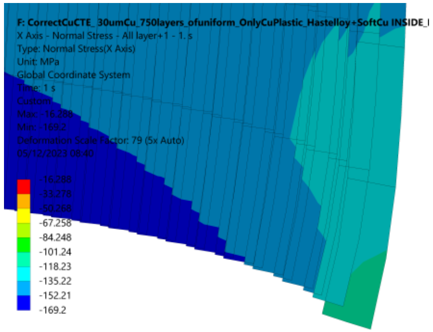

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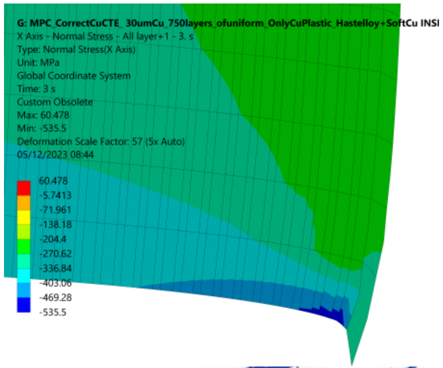
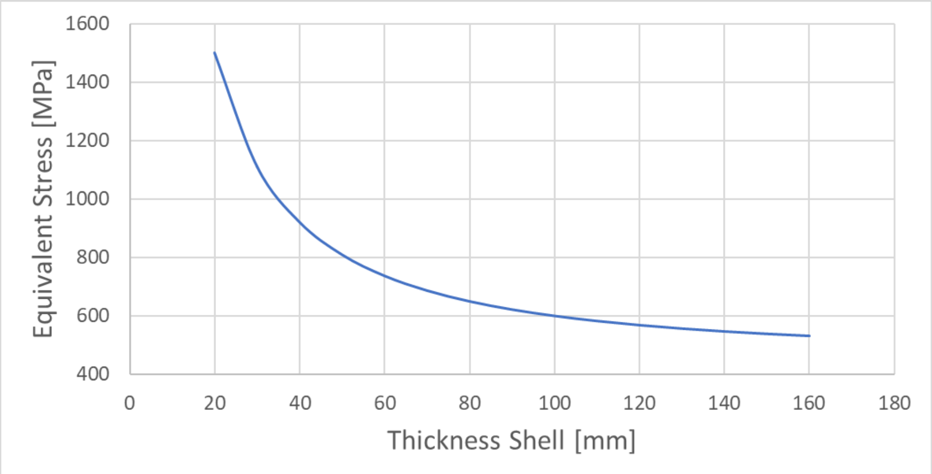
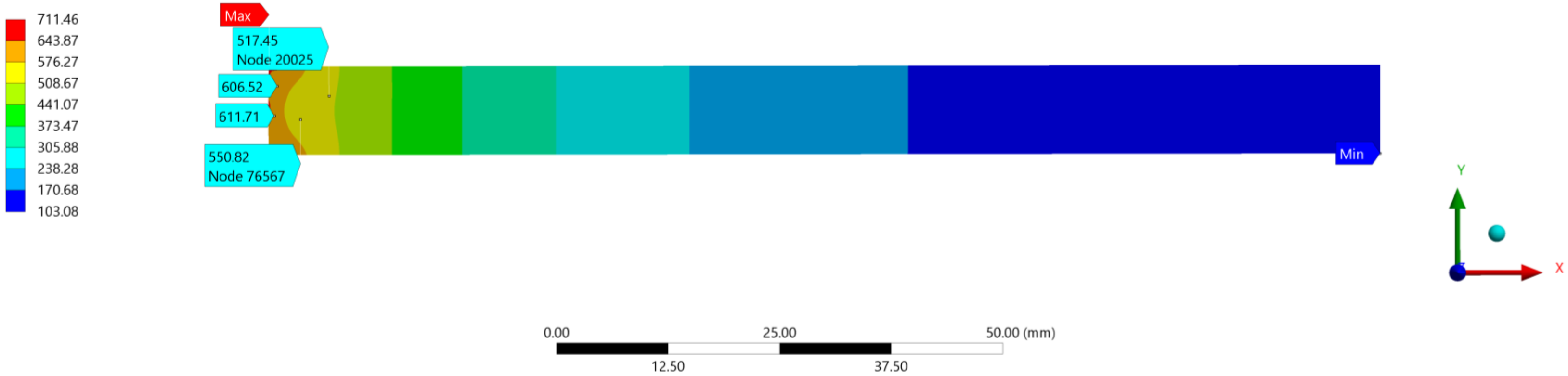
$\sigma_{Transverse,Average}$=-215MPa



Why thick shell?

Before energization



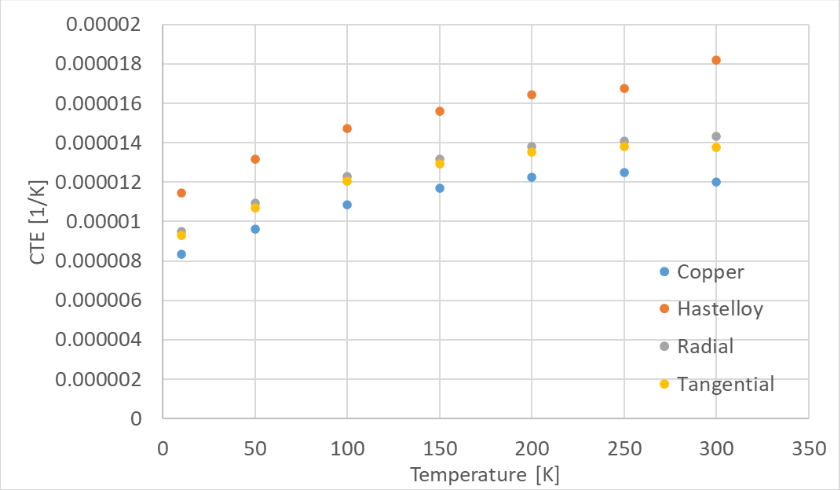


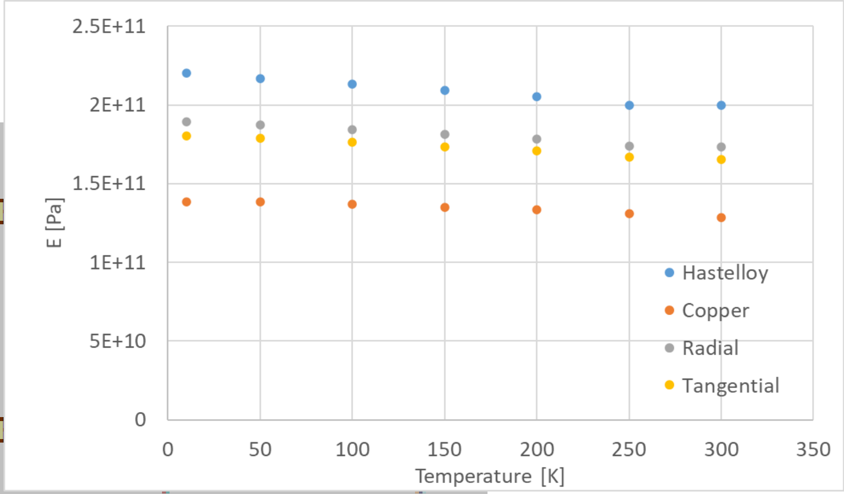
Homogeneization

- Radial direction→ springs in series
- Tangential direction→ springs in parallel

$$E_{radial} = \frac{E_{Cu} \cdot t_{Cu} + E_{Ha} \cdot t_{Ha}}{t_{tot}}$$

$$E_{tangential} = t_{tot} \cdot \left(\frac{t_{Cu}}{E_{Cu}} + \frac{t_{Ha}}{E_{Ha}} \right)^{-1}$$





C. Accettura et al.,Final Cooling Solenoid De