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

Muons Magnets Working Group
https://indico.cern.ch/event/1455031/
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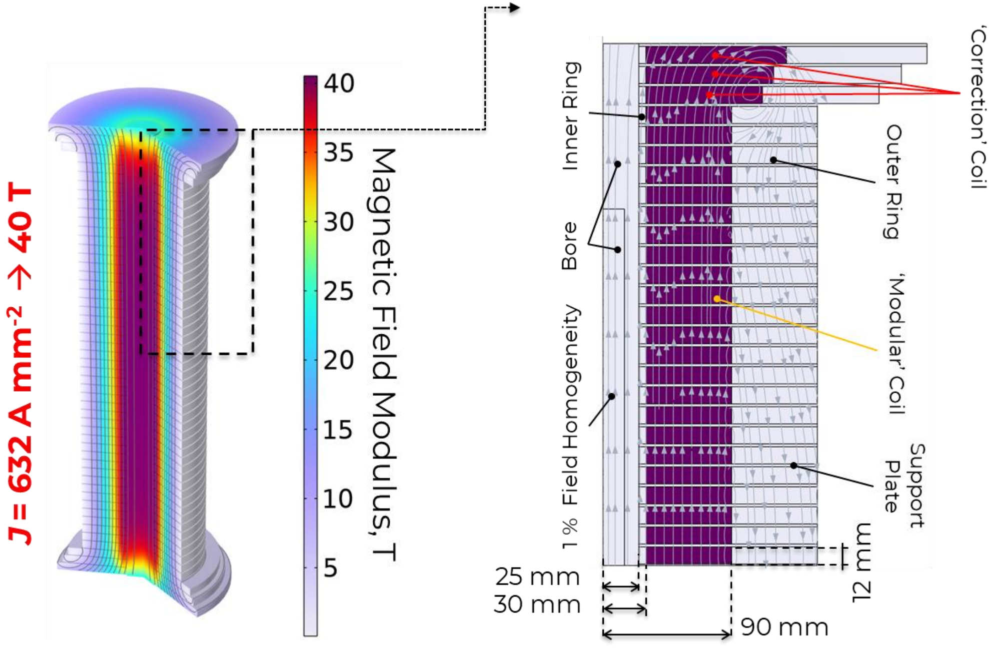
- 2D FEM model
- Alternative configurations
- 3D assembly
- Outlook and future activities

Introduction to the magnet design

- Conceptual design
  - Fully HTS
  - NI/Metal-insulated coil
  - Tens of ‘modular’ and a few ‘correction’ pancakes
  - 73 cm height 40 T solenoid 50 cm 1 % field homogeneity
  - Pre-compression disk to limit the hoop strain on the tape



Courtesy of B. Bordini

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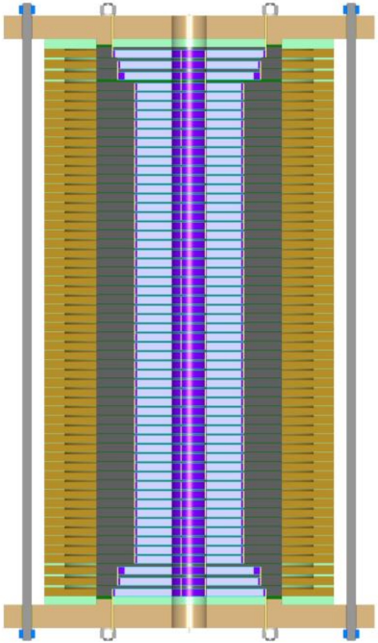
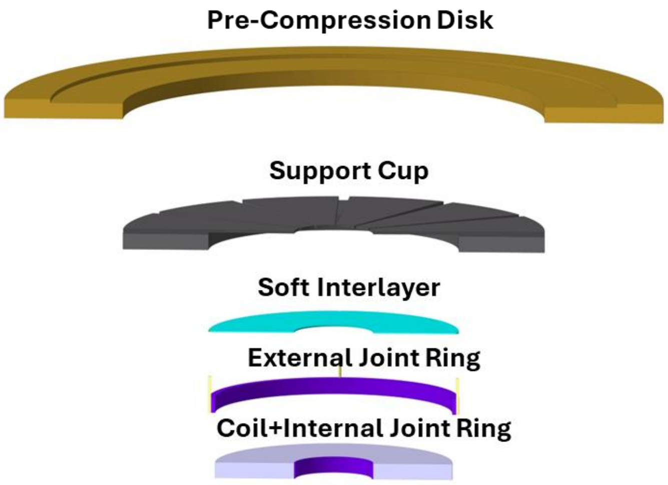
Introduction to the magnet design

- Conceptual design
  - Internal/External joint ring: SC coil not exposed and connected to the electrical connection between pancake
  - Soft interlayer to avoid transmission of axial force
  - Support cap: to apply first pre-compression and intercept axial force
  - Pre-compression-disk: to apply pre-compression





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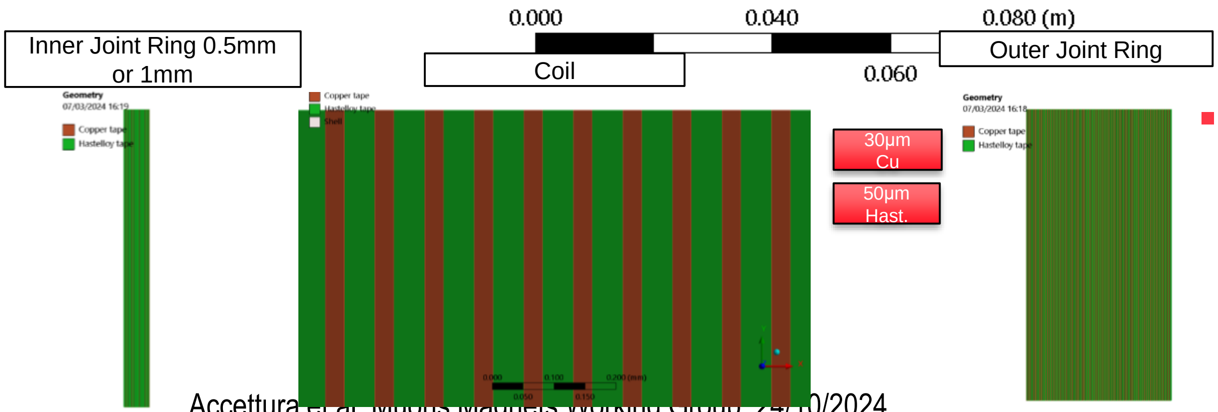
2D FEM model

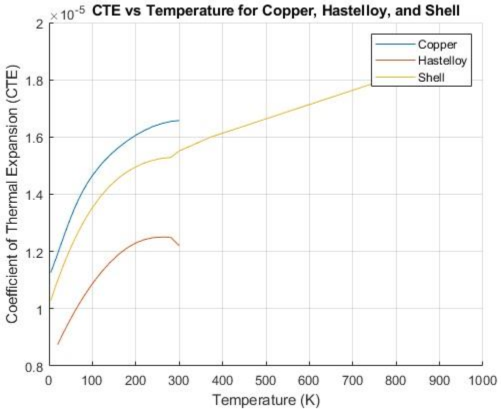
- 2D Mechanical Simulation of a modular coil: all 750 windings are represented
- The model accounts for: Cu yielding and; the thermal contractions of the different materials, inner and outer layer



- 3-steps simulations:
  1. Shrink fitting (shell 200°C→RT)
  2. Cool-down
  3. Energization

Reference model results-1

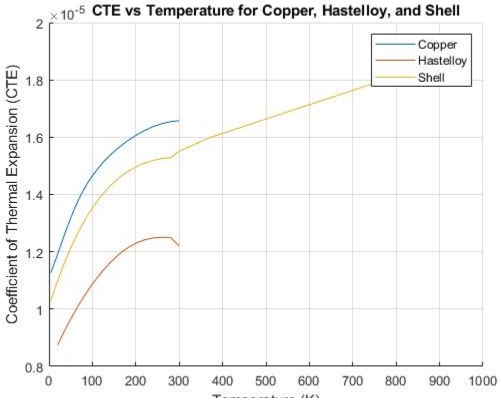
- External shell made of SS304/316:
  - 200MPa pre-compression reached at 200°C
  - Pre-compression decreased during cooldown



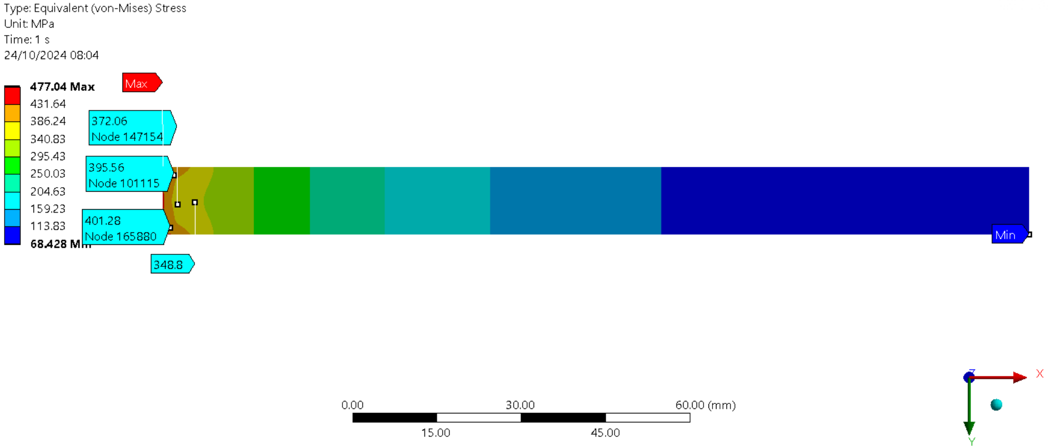
Inner Joint ring thickness [mm]	Pre-compression at cold [MPa]	Radial stress[MPa]			Hoop Strain [%]			Shear Stress [MPa]		
		Step 1	Step 2	Step 3	Step 1	Step 2	Step 3	Step 1	Step 2	Step 3
0.5	170	-205/-8	-190/-5	**-290/10**	**-0.25**/-0.10	-0.20/ -0.12	-0.04/**0.28**	6	4.5	4
	250	-318/-12	-258/-8	**-367/7**	**-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

Reference model results-2

- External shell made of SS304/316:
  - 200MPa pre-compression reached at 200°C
  - Pre-compression decreased during cooldown
  - High stress reached on the shell

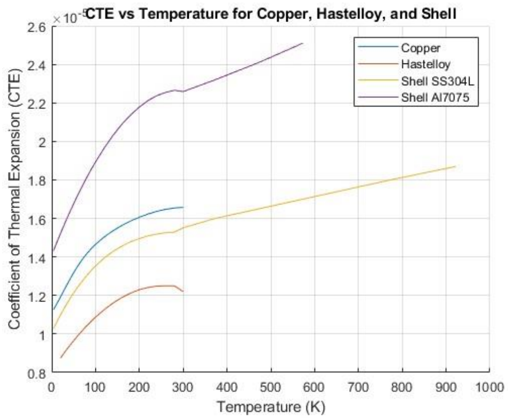


Equivalent stress in the shell MAX/AVE [MPa]		
Step 1	Step 2	Step 3
480/160	400/140	620/216



Alternative configurations-1

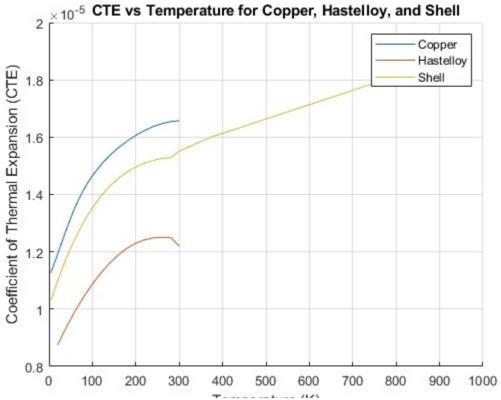
- External shell made of Al7075:
  - 130MPa pre-compression reached at 200°C
  - Pre-compression increased during cooldown
  - Shear stress comparable, buffer layer working well



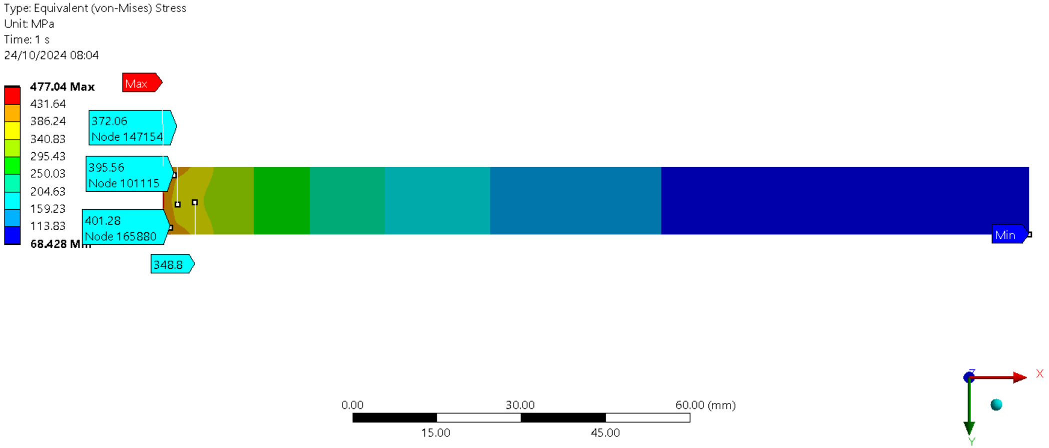
	Inner Joint ring thickness [mm]	Pre-compression at cold [MPa]	Radial stress[MPa]			Hoop Strain [%]			Shear Stress [MPa]		
			Step 1	Step 2	Step 3	Step 1	Step 2	Step 3	Step 1	Step 2	Step 3
Steel	1	170	-205/-14	-190/-10	-288/19	-0.25/-0.10	-0.2/-0.12	-0.05/0.29	6	4	5
Al7075	1	150	-144/-10	-172/8	-222/24	-0.17/-0.07	-0.18/-0.1	-0.01/0.38	6	4	5

Alternative configurations-2

- External shell made of Al7075:
  - 200MPa pre-compression reached at 200°C
  - Pre-compression decreased during cooldown
  - High stress reached on the shell

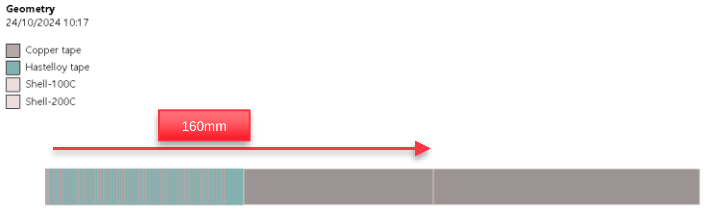


	Equivalent stress in the shell MAX/AVE [MPa]		
	Step 1	Step 2	Step 3
Steel	480/160	400/140	620/216
Al7075	324/110	355/124	460/160



Alternative configurations-3

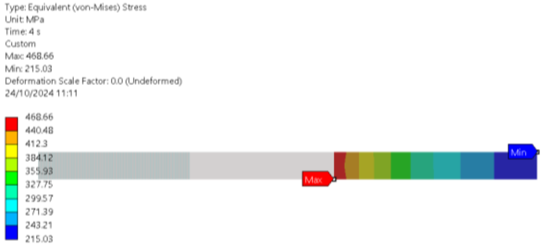
- Configuration 2 pre-compression disks:
  - Easier assembly of the support cup
  - Limited temperature close to the coil
  - Easier tolerances compensation

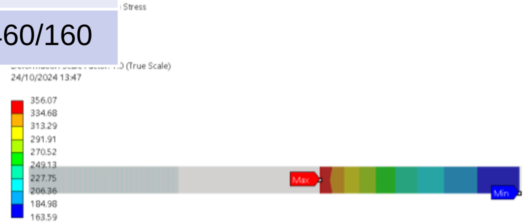


	Inner Joint ring thickness [mm]	Pre-compression at cold [MPa]	Radial stress[MPa]				Hoop Strain [%]			Shear Stress [MPa]		
			Step 0	Step 1	Step 2	Step 3	Step 1	Step 2	Step 3	Step 1	Step 2	Step 3
Steel	1	170	-	-205/-14	-190/-10	-288/19	-0.25/-0.10	-0.2/-0.12	-0.05/0.29	6	4	5
Al7075	1	150		-144/-10	-172/8	-222/24	-0.17/-0.07	-0.18/-0.1	-0.01/0.38	6	4	5
Steel/Steel	1	175	-70/-5	-208/-14	-185/-10	-294/18	-0.25/-0.11	-0.21/-0.12	-0.05/0.28	4	7	5
Steel/Al7075	1	154	-70/-5	-155/-11	-159/-8	-262/20	-0.19/-0.09	-0.18/-0.10	-0.03/0.32	4	4	5

Alternative configurations-4

	Equivalent stress in the shell MAX/AVE [MPa]		
	Step 1	Step 2	Step 3
Steel	480/160	400/140	620/216
Al7075	324/110	355/124	460/160



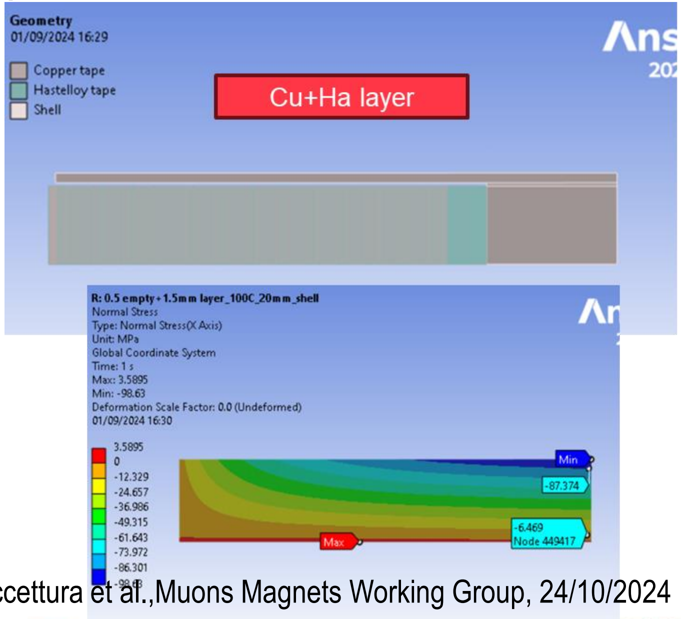


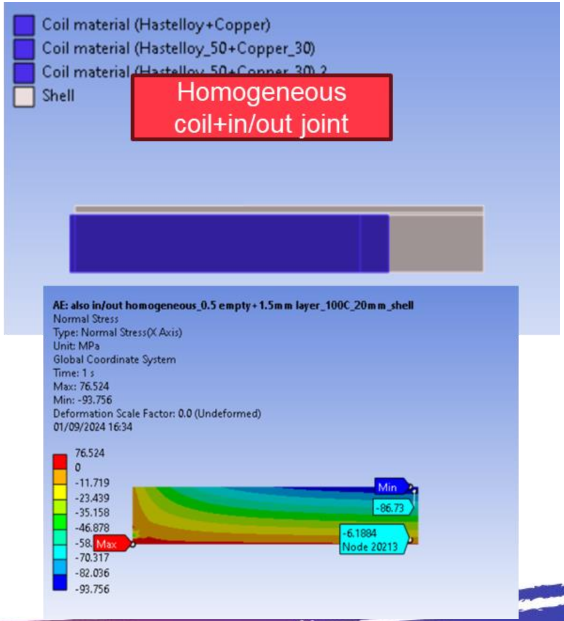
	Equivalent stress in the shell MAX/AVE [MPa]			
	Step 0	Step 1	Step 2	Step 3
IN-Steel	187/115	240/150	220/130	370/214
OUT-Steel	-	470/312	400/265	470/310

	Equivalent stress in the shell MAX/AVE [MPa]			
	Step 0	Step 1	Step 2	Step 3
IN-Steel	187/115	199/113	195/116	360/207
OUT-Al	-	290/195	325/217	356/240

3D assembly

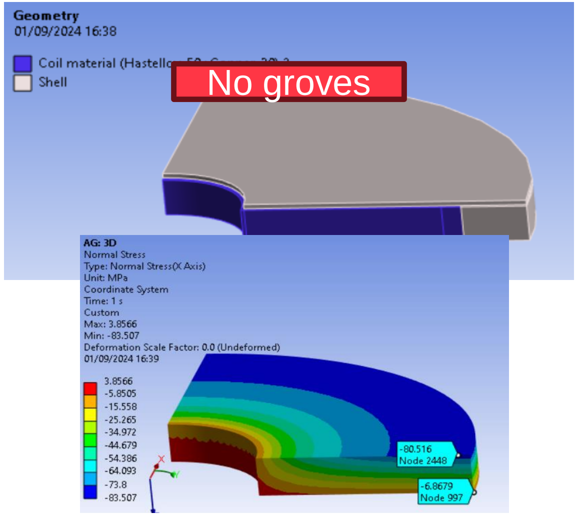
- We need to consider the shape of the support cup
  - Intermediate plate circumferential stiffness causes non-uniform pre-compression of the coil

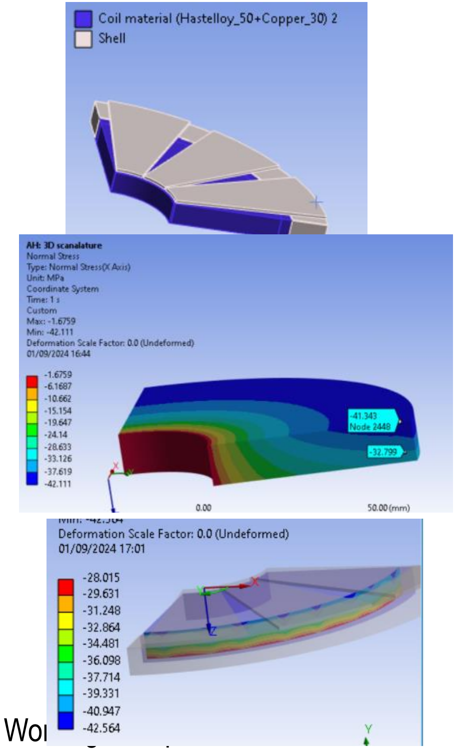


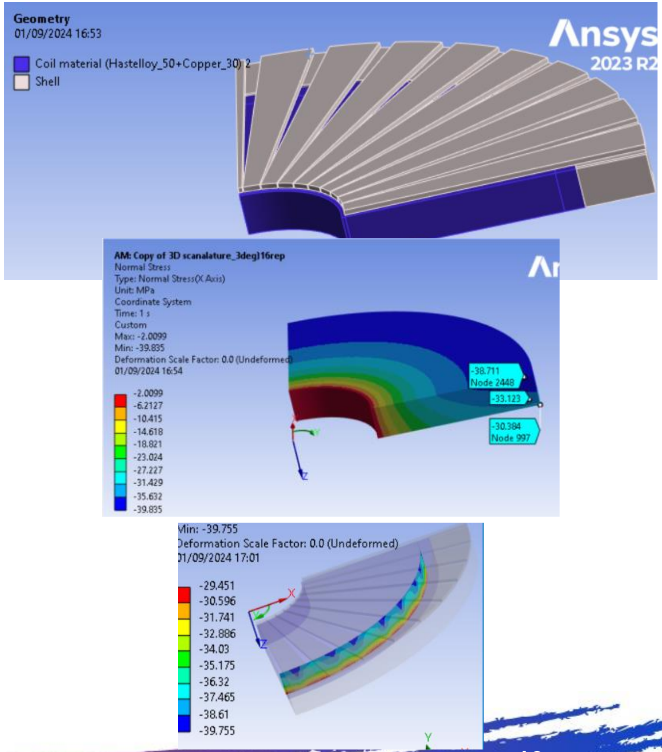


Groves optimization

- Groves introduced to reduce the stiffness







Outlook and future activities

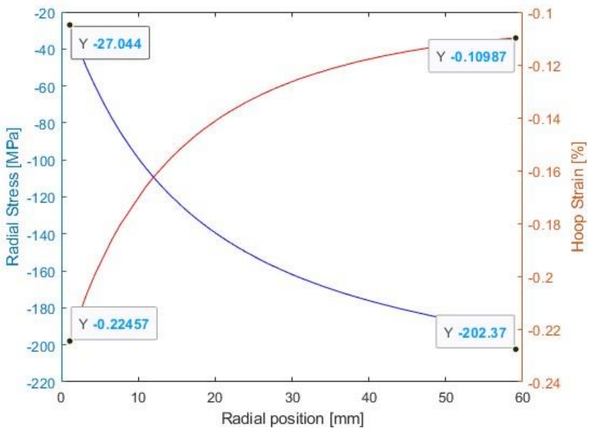
- The design of the shrink-fitting process has been reviewed to optimize the fabrication
  - A 2-shell concept is applicable and could facilitate the assembly
- A 3D modelling is required to simulate the final design. First studies indicate that the application of grooves on the support cup is needed to make the pre-compression uniform on the coil surface

Stress and Strain in the coil

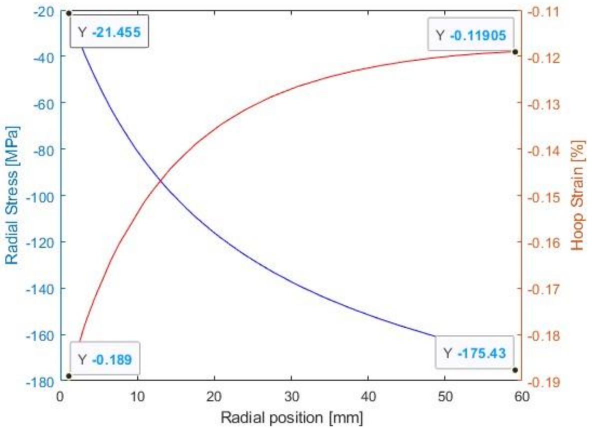
Pre-compression 170 MPa

Inner Joint ring 1 mm thick

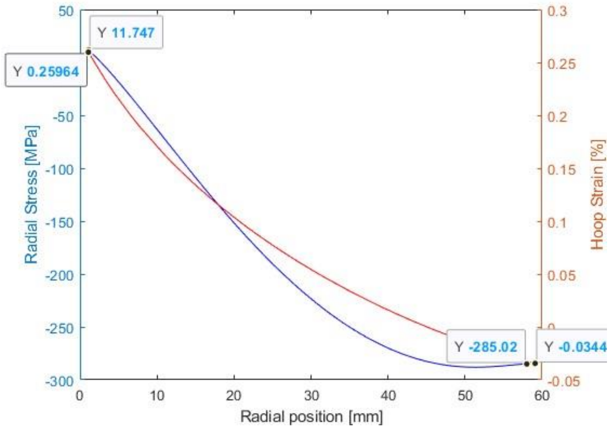
Step 1



Step 2

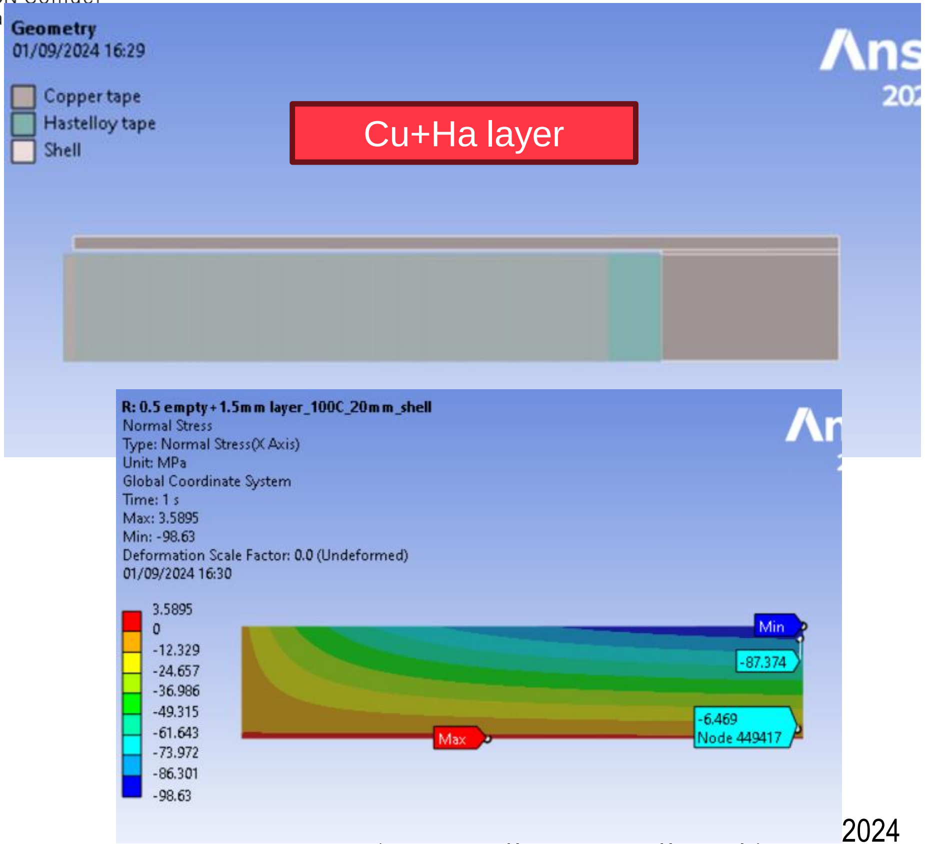


Step 3

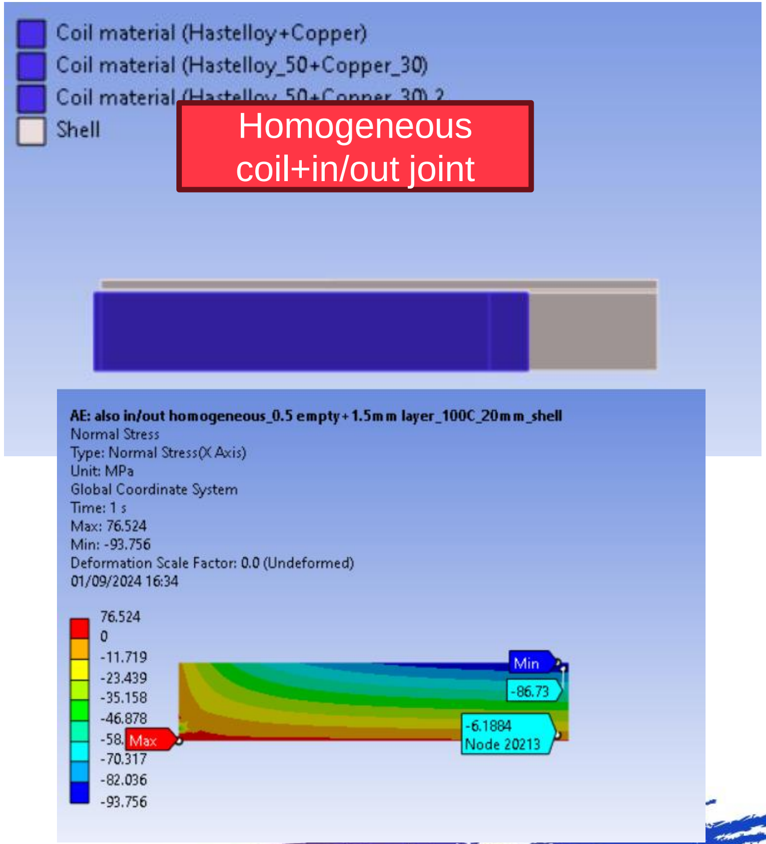


2D layered vs homogeneous

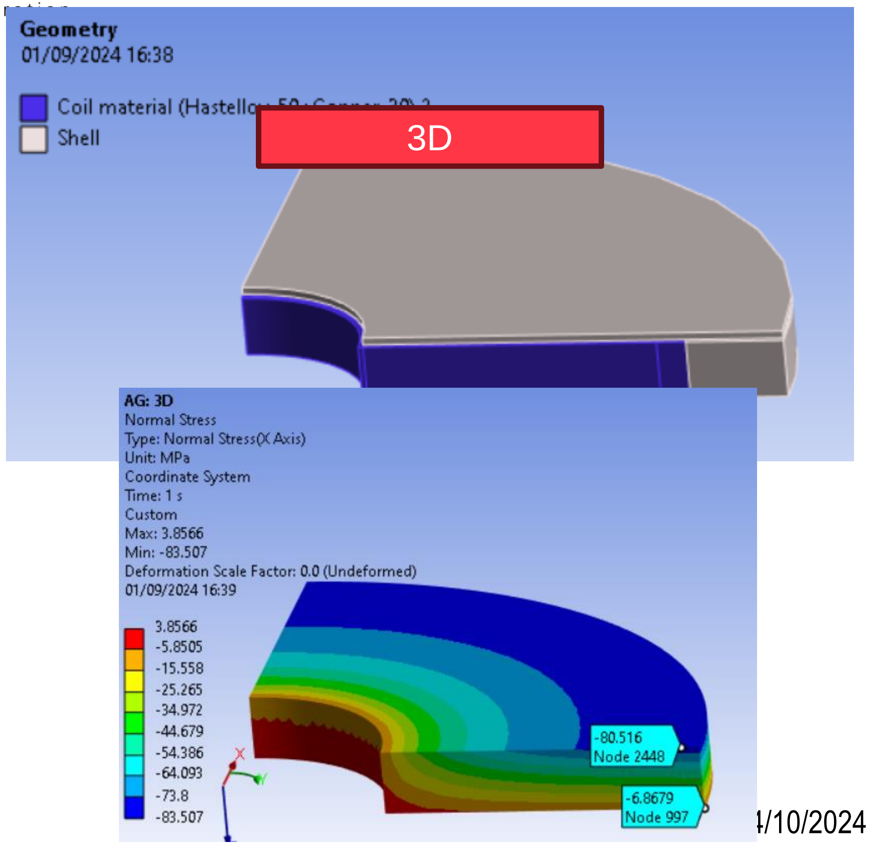
Cu+Ha layer



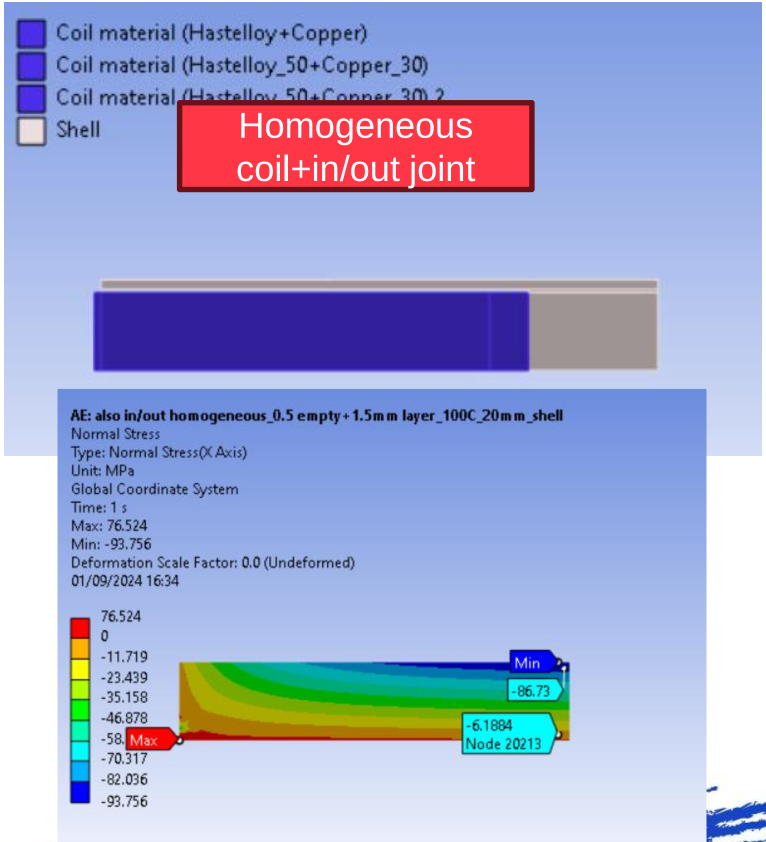
Homogeneous coil+in/out joint



3D vs 2D

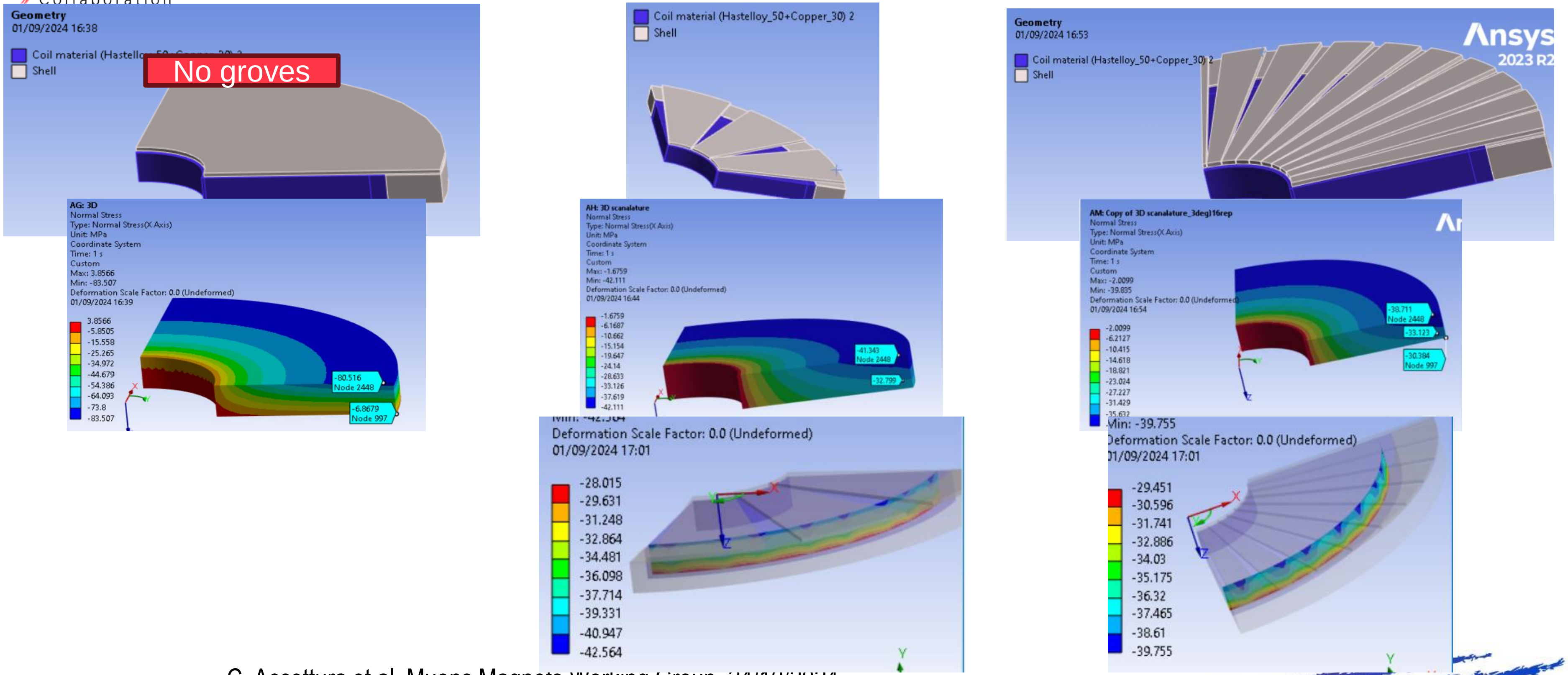


Geometry
01/09/2024 16:38
Shell
3D
AG: 3D
Normal Stress
Type: Normal Stress(X Axis)
Unit: MPa
Coordinate System
Time: 1 s
Custom
Max: 3.8566
Min: -83.507
Deformation Scale Factor: 0.0 (Undeformed)
01/09/2024 16:39
3.8566
-5.8505
-15.558
-25.265
-34.972
-44.679
-54.386
-64.093
-73.8
-83.507
-80.516
Node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

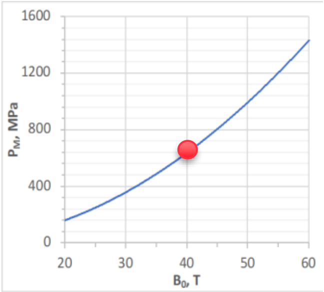
Groves optimization

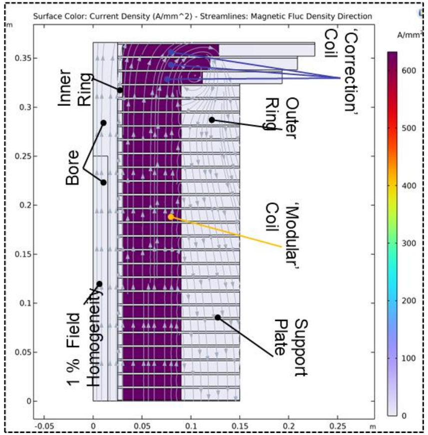


Introduction and Motivations

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

Magnetic pressure vs Field

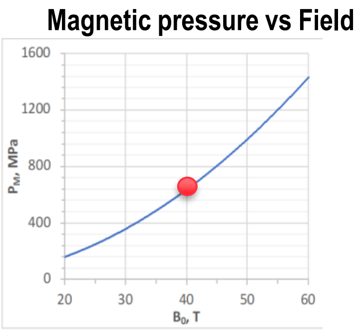


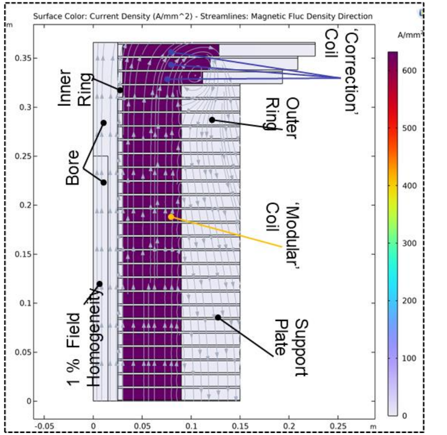


See B. Bordini, Technology options for the final cooling solenoids, IMCC Annual Meeting 2023, Orsay

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

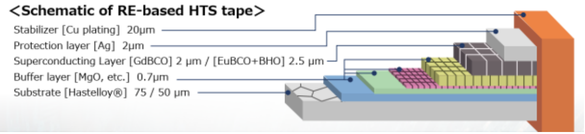




See B. Bordini, Technology options for the final cooling solenoids, IMCC Annual Meeting 2023, Orsay

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

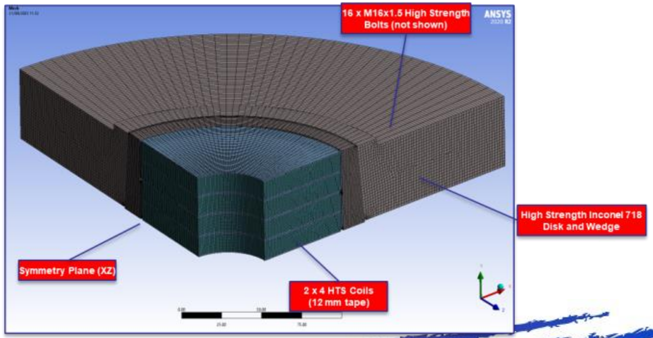
- A pre-compression of ~200MPa is need to remain below this value



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:**
  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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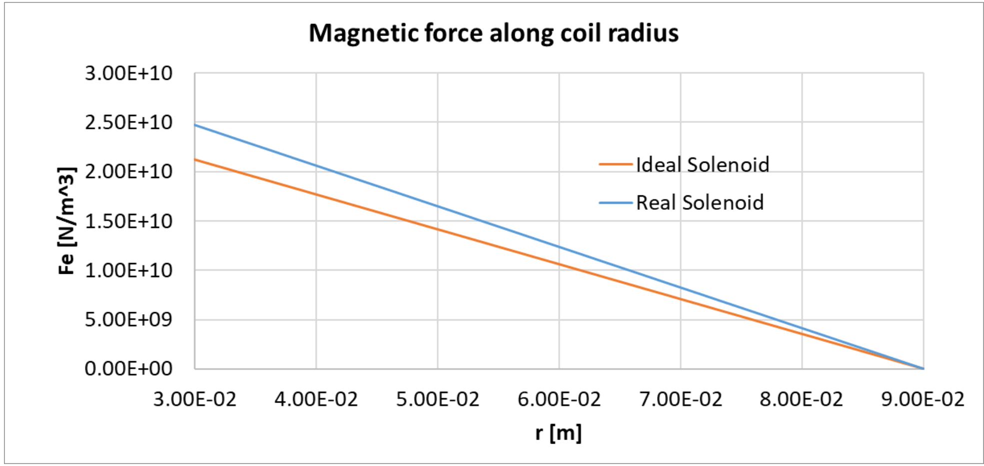
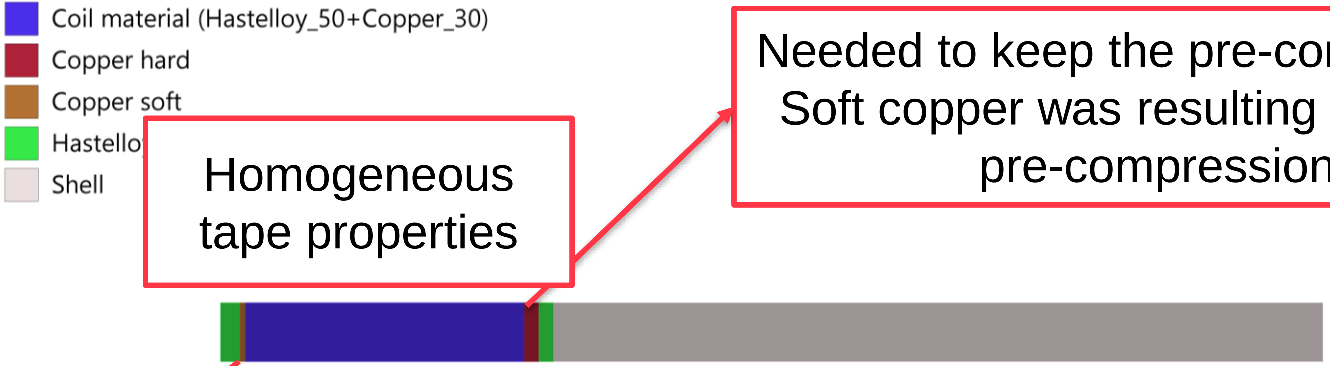
Assumptions

- 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)



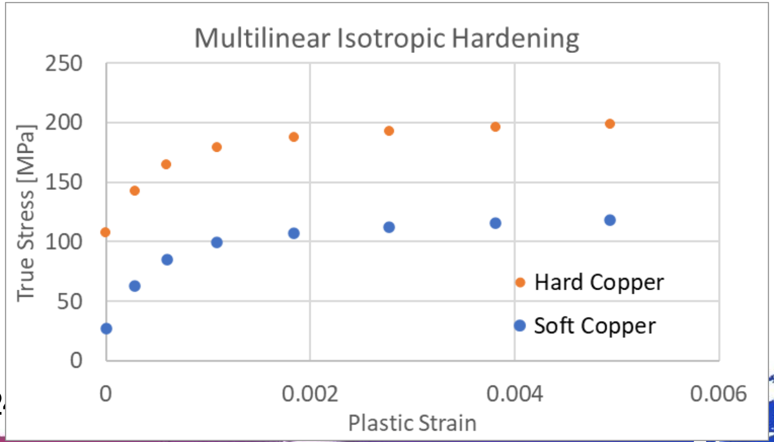
Reference model



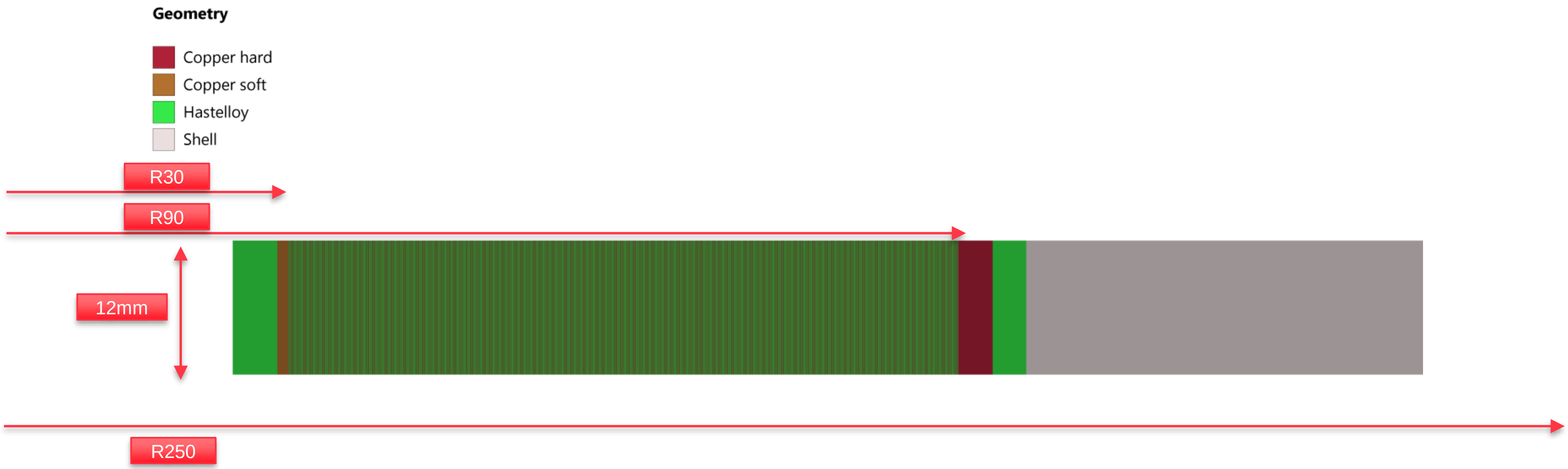
Homogeneous tape properties

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



Layered model



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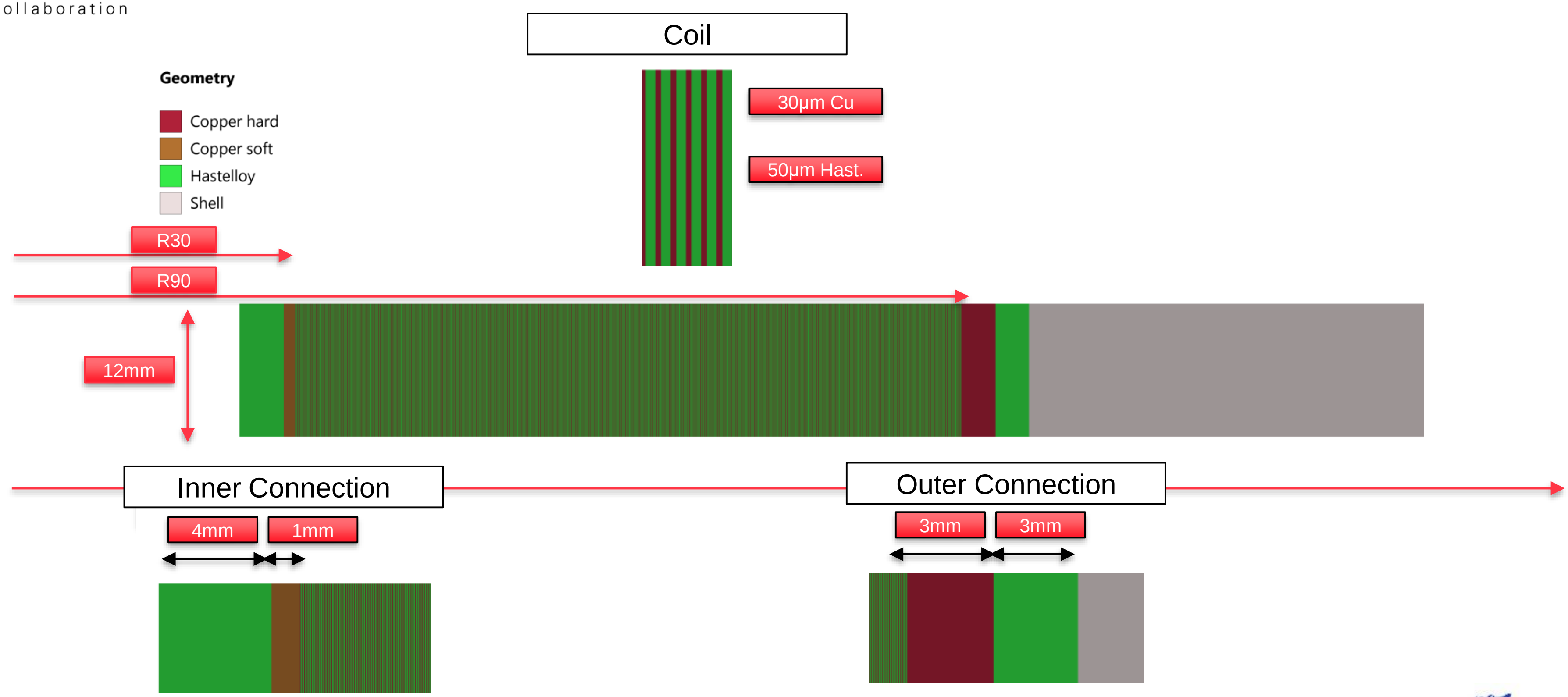
Geometry and Materials



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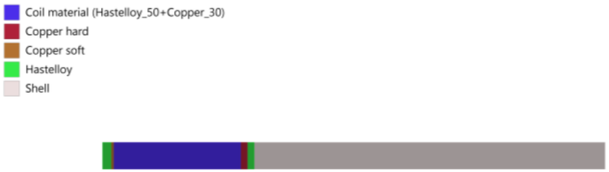
Validity of homogeneous model

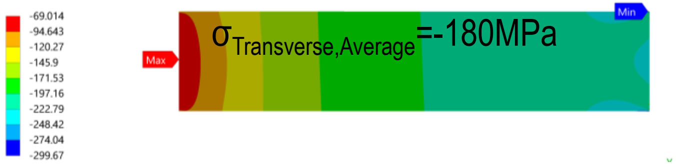


Step 1: Shrink fitting (T external shell =250°C)

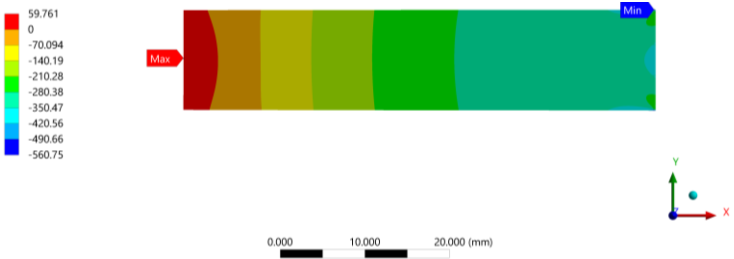
$\sigma_{Transverse,Average}$=-210MPa

Step 2: Cool-down

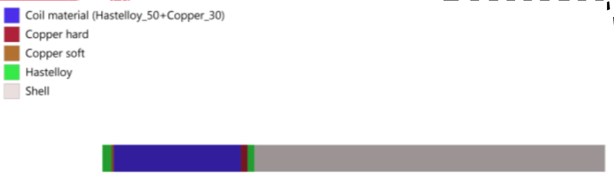
$\sigma_{Transverse,Average}$=-180MPa

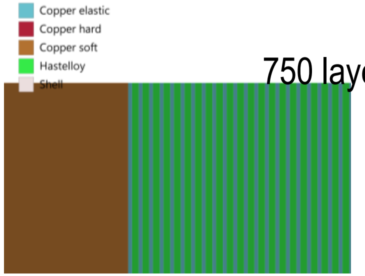


Step 3: Energization



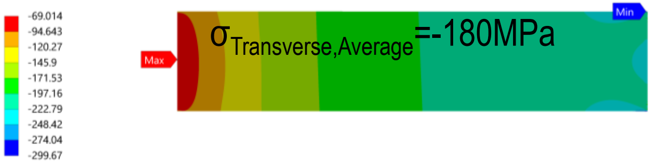
Validity of homogeneous model

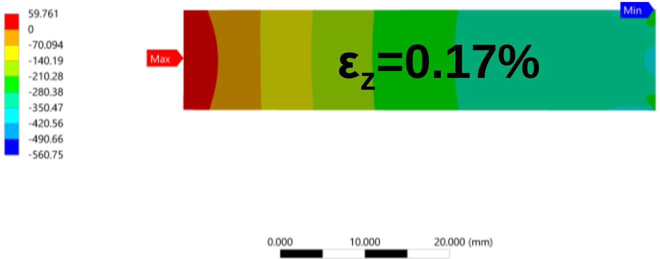


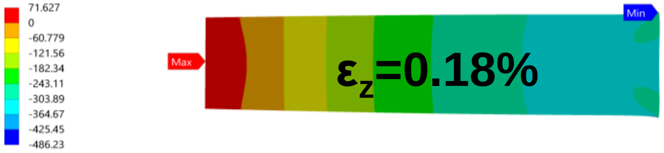


750 layers: 30µm+50 µm

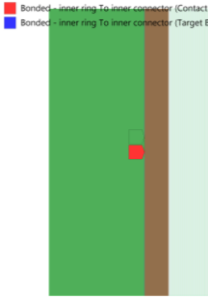
Homogeneous model	Layered model
Step 1: Shrink fitting	**Step 1: Shrink fitting**
$\sigma_{Transverse,Average}$=-210MPa	$\sigma_{Transverse,Average}$=-215MPa
Step 2: Cool-down	**Step 2: Cool-down**
$\sigma_{Transverse,Average}$=-180MPa	$\sigma_{Transverse,Average}$=-170MPa
Step 3: Energization	**Step 3: Energization**
ε_z=0.17%	ε_z=0.18%



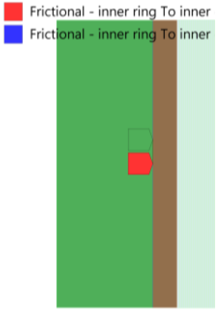


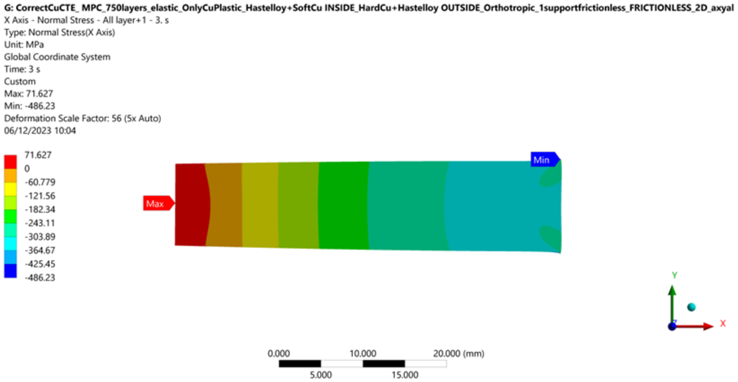


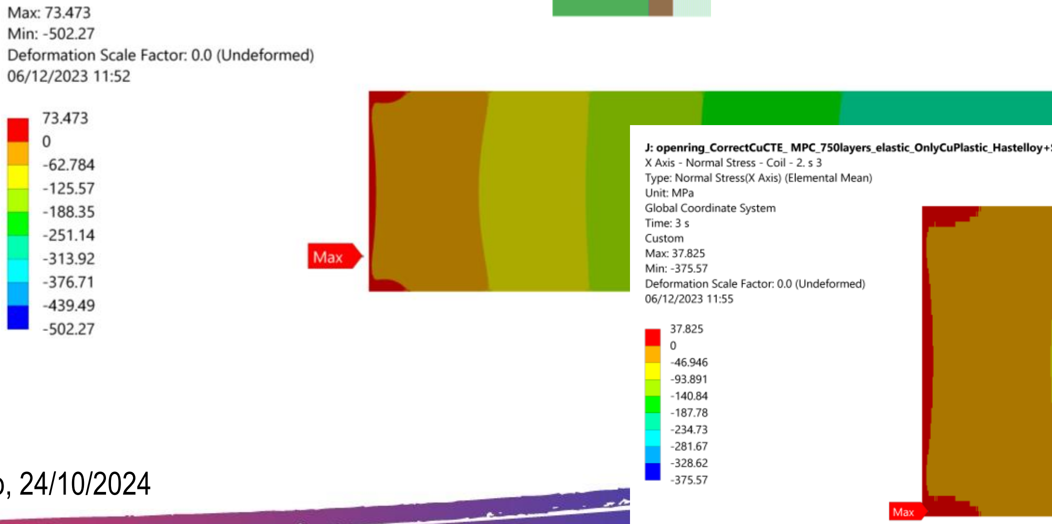
Effect of the inner joint properties



Let the ring detach to limit radial tensile stress







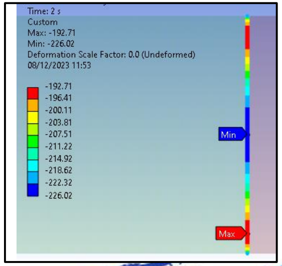
Effect of the tape plasticity

	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

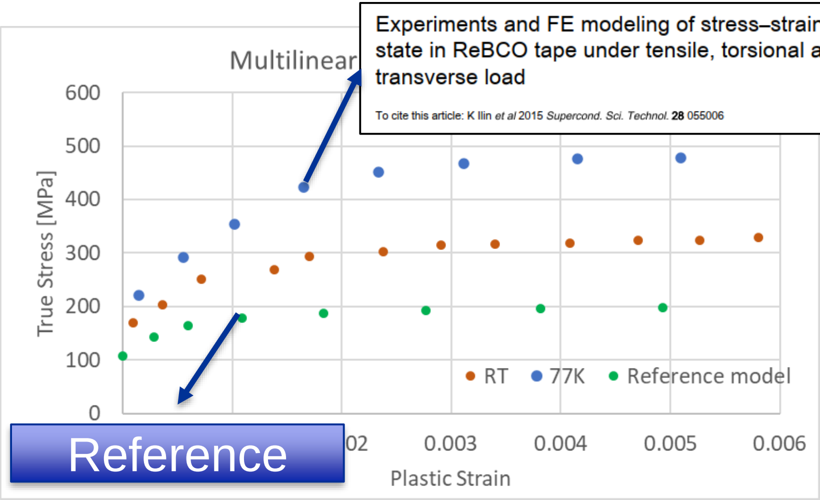
To cite this article: K Ilin *et al* 2015 *Supercond. Sci. Technol.* **28** 055006

Reference

Effect of the tape properties

	σ_x-radial[MPa]			ε_z-hoop
step	min	max	ave	max
1	-291	-55	-208	
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



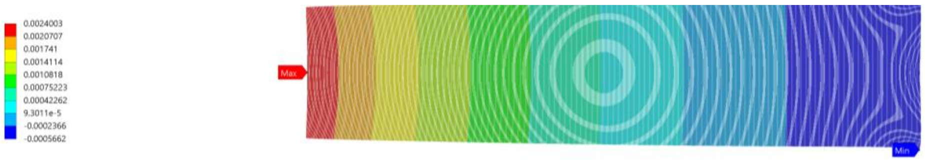
Effect of the tape properties

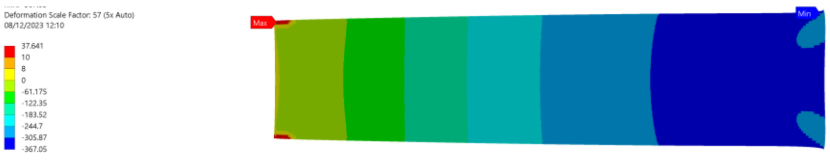
	σ_x-radial[MPa]			ε_z-hoop
step	min	max	ave	max
1	-291	-55	-208	
2	-264	-60	-171(215)	
3	-484	75*	-218	0.24%

*Localized effect

ε_z=0.24% ☑

σ_x~10MPa ☑



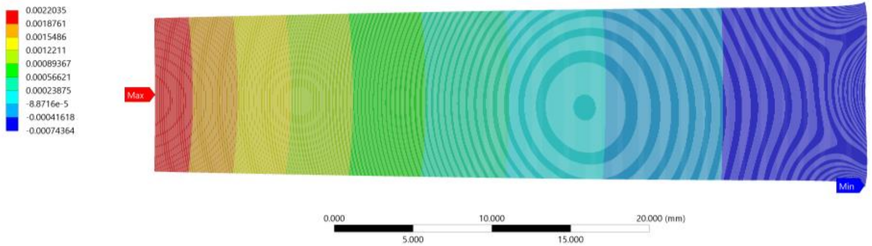


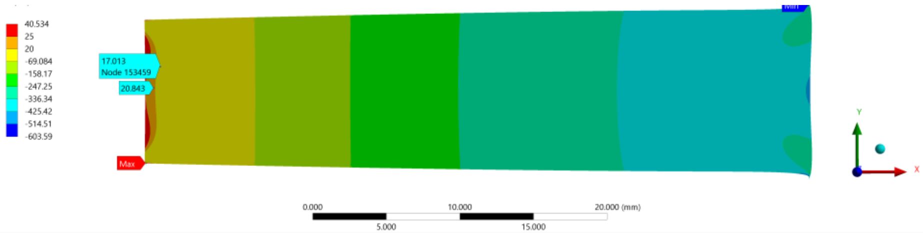
Alternative Inner Joint-1

Reduced Hastelloy (1mm-Bonded to Cu)

ε_z=0.22% ☑

σ_x~20MPa
(p~250MPa)



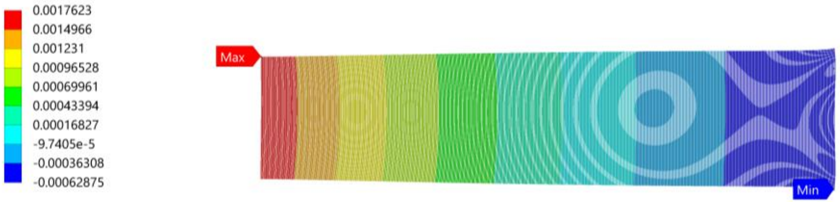


Alternative Inner Joint-2

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

ε_z=0.17% ☑

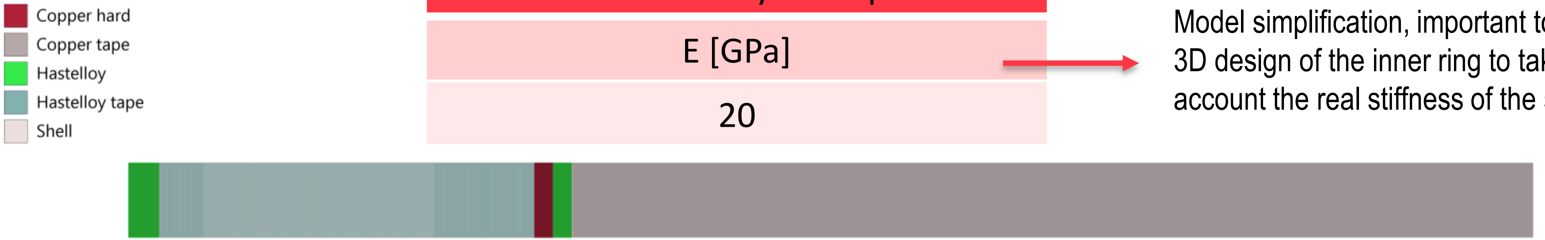
σ_x=80MPa ☒



Alternative Inner Joint-3

Soft Hastelloy isotropic
E [GPa]
20

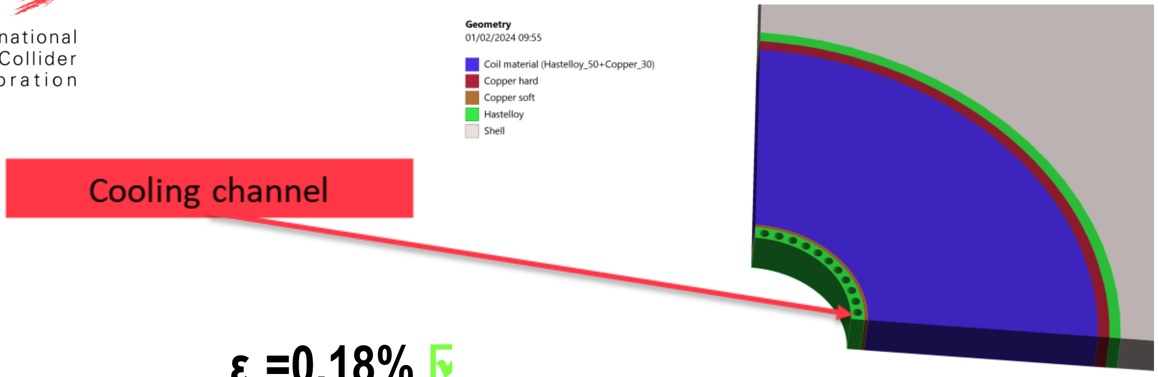
Model simplification, important to have a 3D design of the inner ring to take into account the real stiffness of the structure



ε_z=0.27% ☑

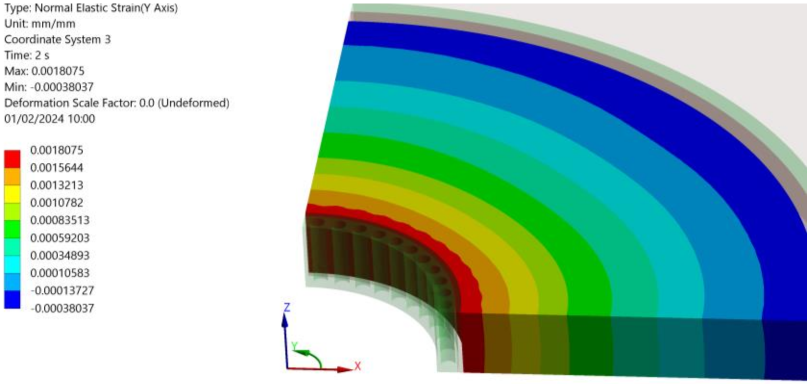
σ_x=12MPa ☑

Alternative Inner Joint-4

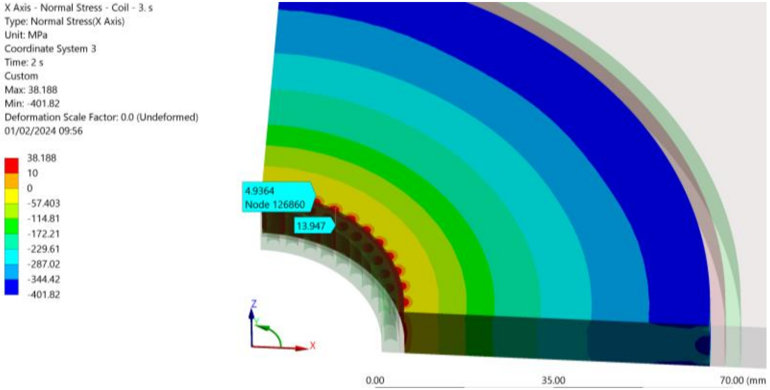


3D model more time-consuming, homogeneous material and mesh to be refined→ **INCREASE OF at least~50% expected**

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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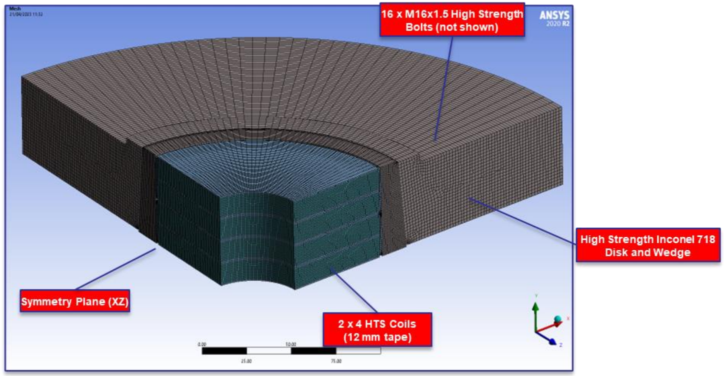
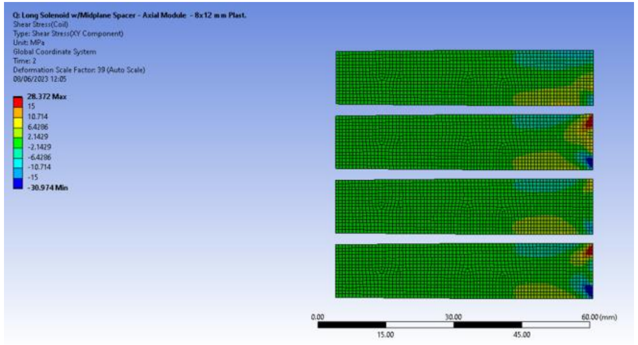
Mechanical considerations - Second concept

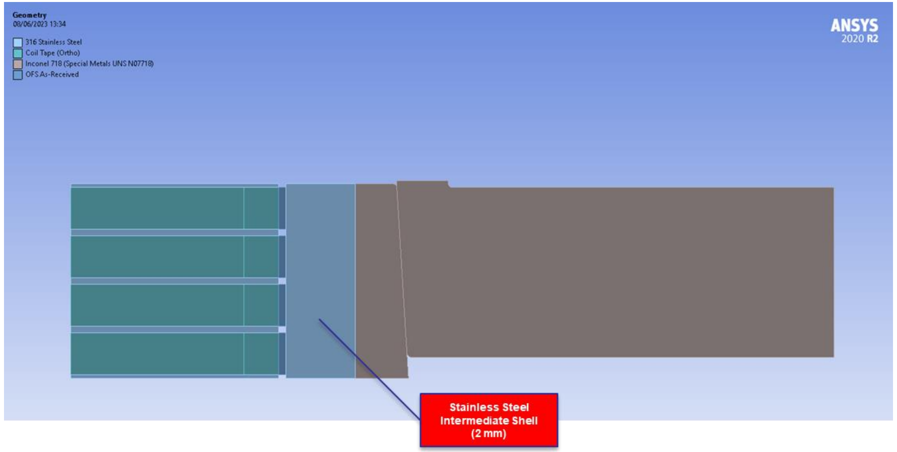
- 2 Load Steps:
  - Shrink Disk displacement (5 mm)
  - Energization
- Max. Hoop Stress (after energization): 620.4 MPa
- Max. Hoop Strain (after energization): 0.344 %
- Shear Stresses globally lower than 15 MPa
- However, locally they can reach after energization ~ |30| MPa





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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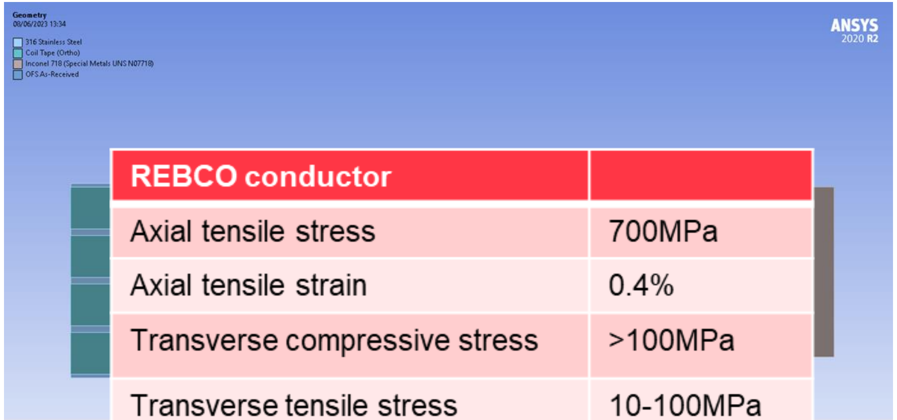

REBCO conductor	
Axial tensile stress	700MPa
Axial tensile strain	0.4%
Transverse compressive stress	>100MPa
Transverse tensile stress	10-100MPa
Max shear stress	>19MPa

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

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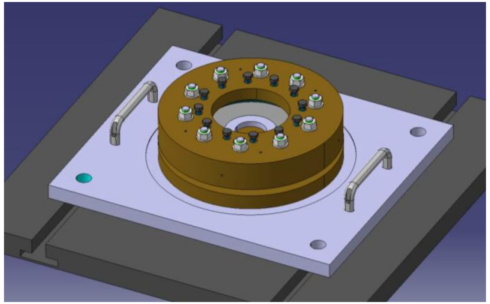
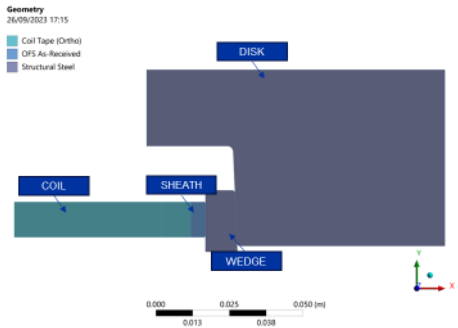
Testing



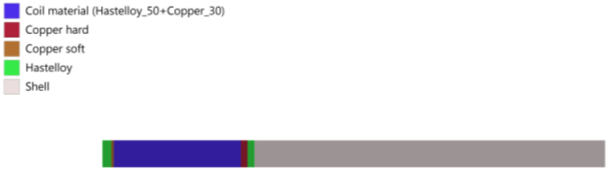


- σ_{hoop}~-600MPa reached on the inner radius of the coil
- The required compression is achieved with 10 M16 bolts
- System equipped with strain gauges and digital image correlation to characterize the coil

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

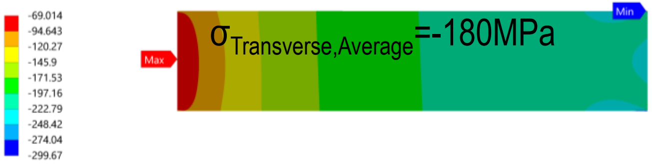
Validity of homogeneous model



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

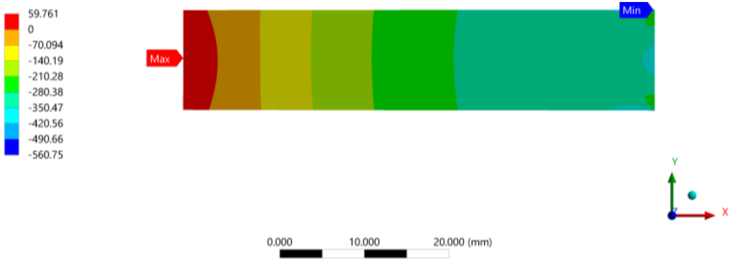
$\sigma_{Transverse,Average}$=-210MPa

Step 2: Cool-down

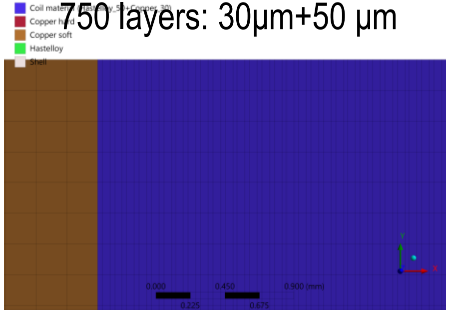


$\sigma_{Transverse,Average}$=-180MPa

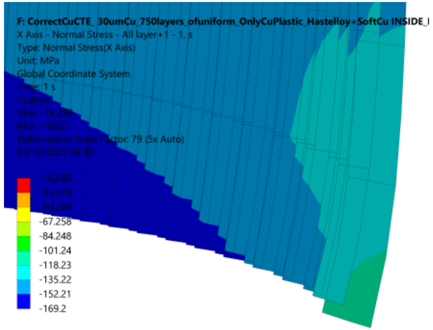
Step 3: Energization



750 layers: 30µm+50 µm



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



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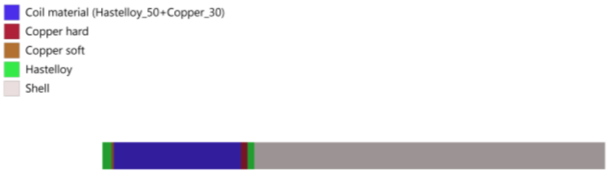

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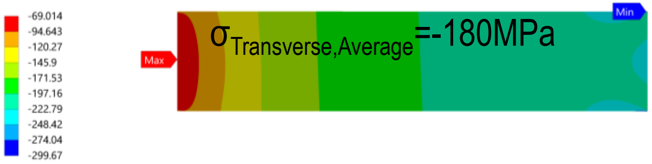

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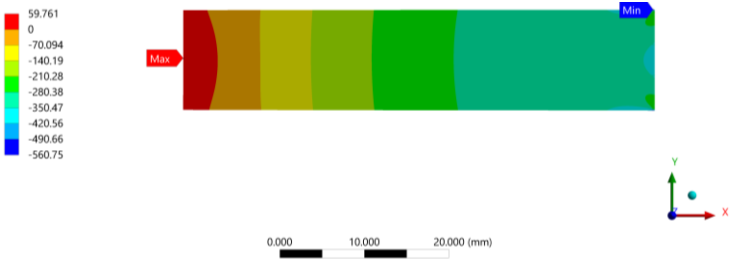

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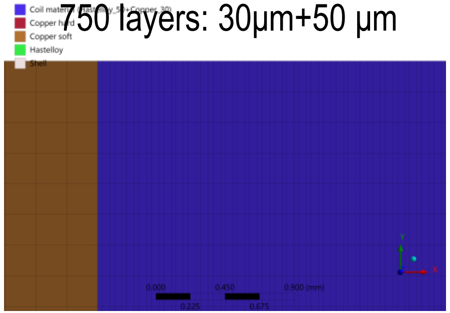
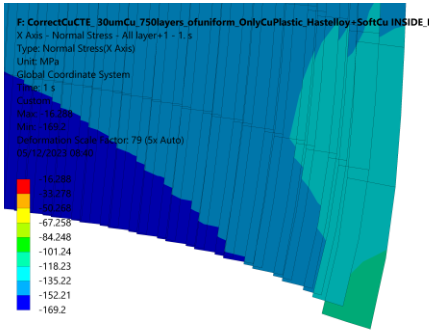
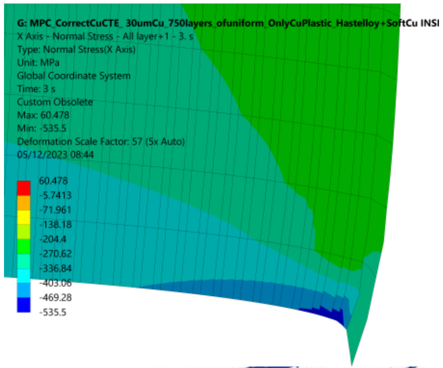




$\sigma_{Transverse,Average}$=-85MPa

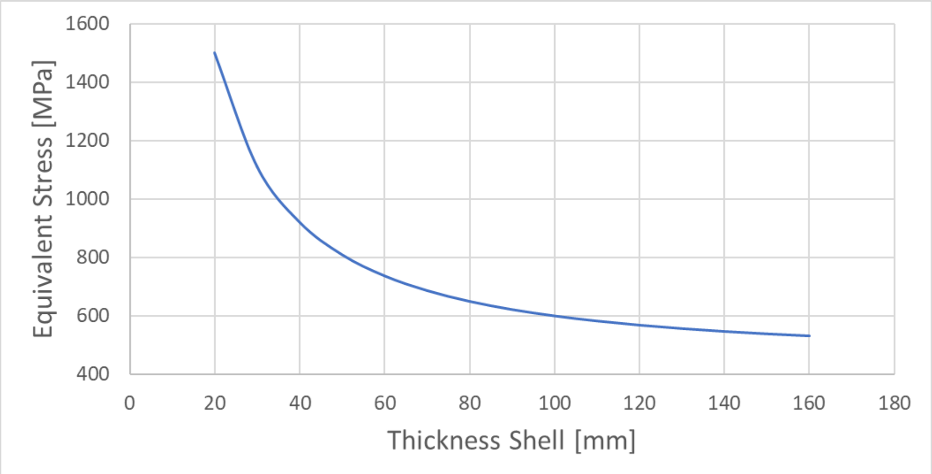
MPC CONTACT

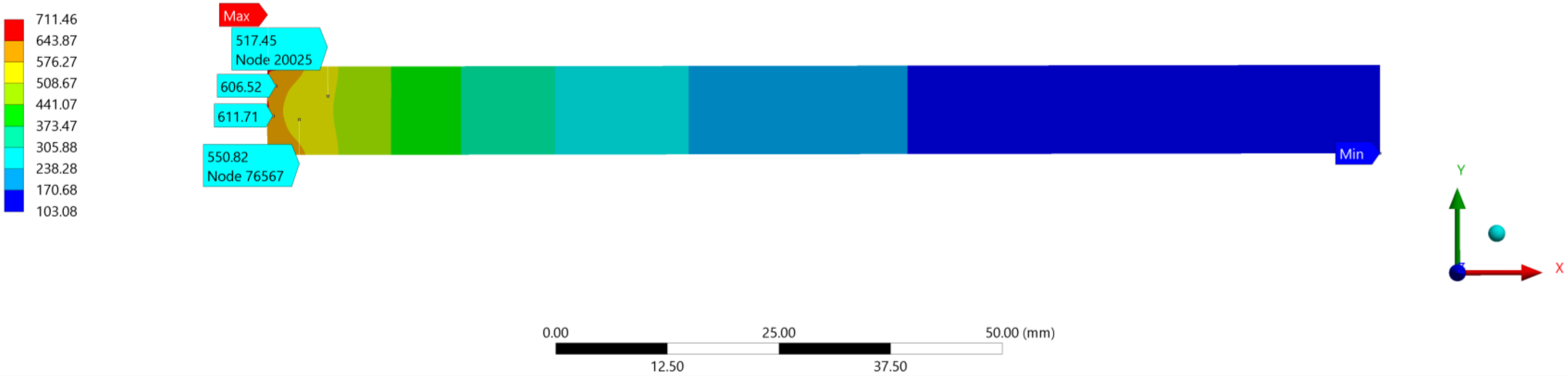
$\sigma_{Transverse,Average}$=-215MPa



Why thick shell?

Before energization



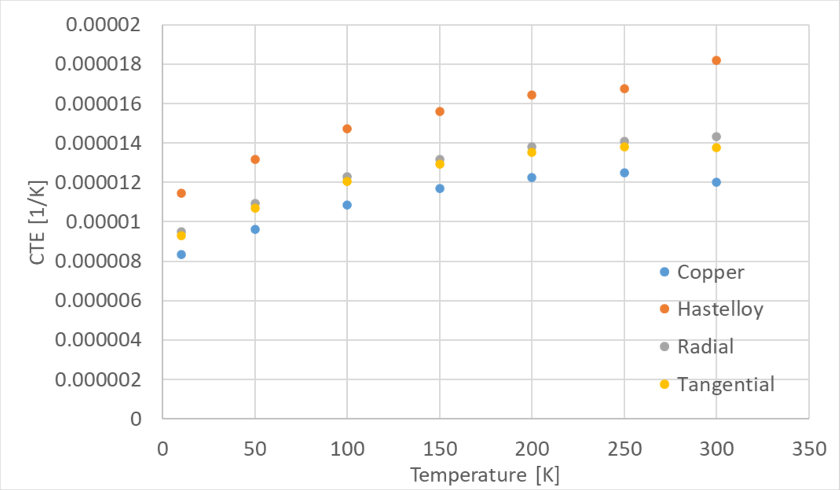


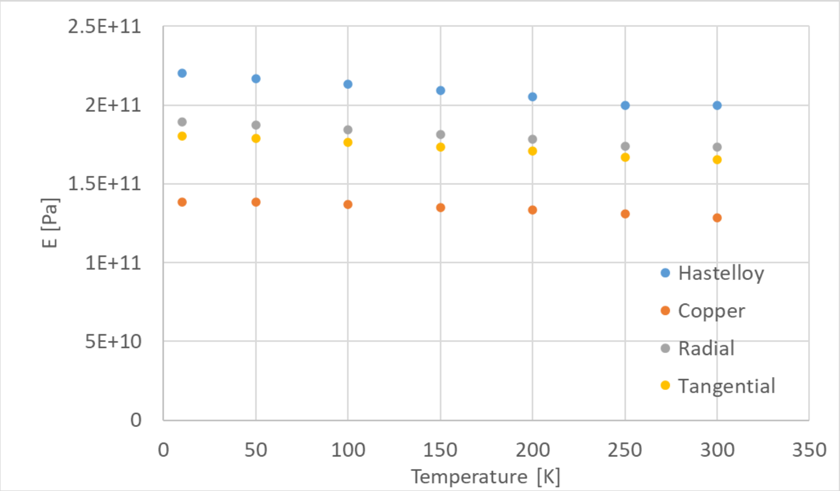
Homogeneization

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

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

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





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