International
MUON Collider
Collaboration

Challenges of the final cooling solenoid

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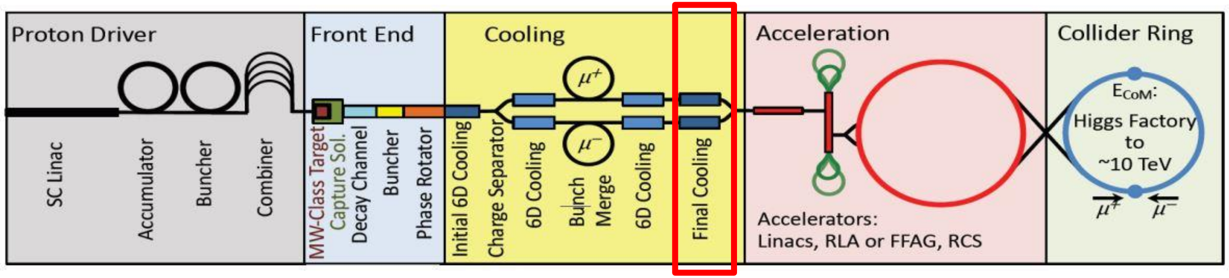
IMCC Annual Meeting
22/06/2023, IJCLab (Orsay, France)

Outline

1. Introduction and requirements
2. Which technology?
3. Main Challenges
4. Conceptual design
5. Mechanical considerations
6. Roadmap and planning
7. Societal impact of HTS UHF magnets
8. Conclusions

Introduction and requirements

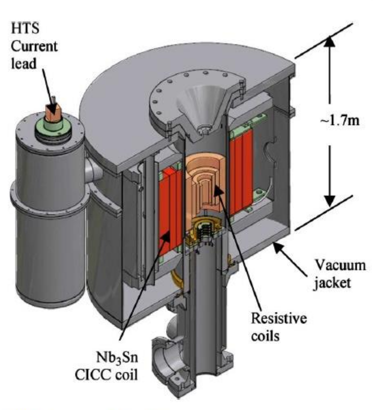


- Final cooling is part of the cooling system
- The final cooling channel is made of several stages (~14), each stage starts with a focusing solenoid
- Main solenoid specifications:
  - Ultra-High-Field (UHF) solenoid (>40T)
  - Homogeneity ~1% over 0.5m
  - Bore~50mm

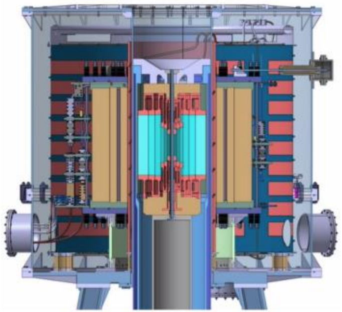
Which technology?

Technology	Pro's	Con's
Hybrid SC (LTS) + resistive	Known technology (TRL 9)	Large dimension and mass Electric power consumption

Cross section of 45 T, **32 mm**
NHFML user facility solenoid
Hybrid Magnet 33.5 T from resistive insert, 11.5 T by superconducting outsert
30 MW power comsumption
https://nationalmaglab.org/user-facilities/dc-field/magnets-instruments/



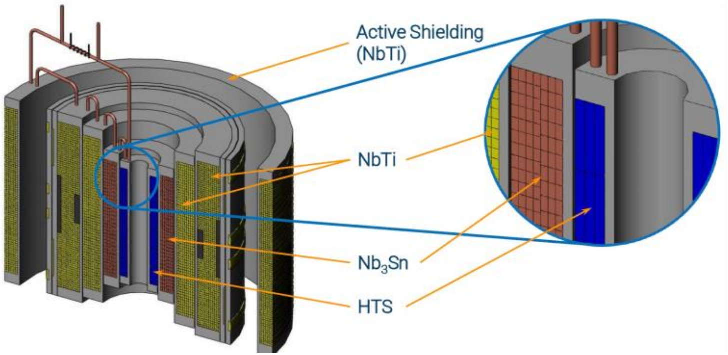
Tallahassee magnet system.



Cross section of **40*/37 T**, **32/50 mm**
CHMFL user facility solenoid
Hybrid Magnet 29/26 T from resistive insert, 11 T by superconducting Nb3Sn CICC outsert
20 MW power comsumption
http://english.hmfl.cas.cn/uf/ms/202202/t20220224_301451.html

Which technology?

Technology	Pro's	Con's
Hybrid SC (LTS) + resistive	Known technology (TRL 9)	Large dimension and mass Electric power consumption
Hybrid SC (LTS) + SC (HTS) Insulated	Known design principles Synergy with other fields of science application Can profit from development by others (e.g. NHMFL)	Large dimension and mass Developmental technology (TRL 6/7)



1.2 GHz-NMR (Bruker) 28.19 T – 54 mm RT

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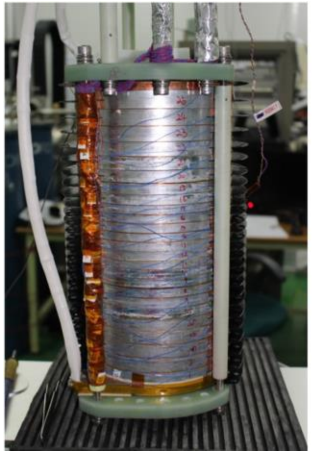
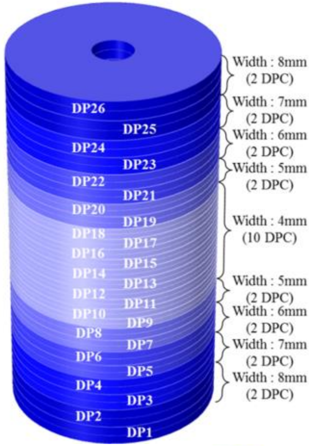
Hybrid SC (LTS) + SC (HTS) Insulated	Known design principles Synergy with other fields of science application Can profit from development by others (e.g. NHMFL)	Large dimension and mass Developmental technology (TRL 6/7)
All-SC (HTS) Insulated	More compact than LTS/HTS Allows for operation at higher temperature	R&D at low readiness (TRL 4/5)
All-SC (HTS) Non-insulated	Most compact magnet winding Synergies with other fields of science/societal applications Can profit from development by others (e.g. NHMFL)	R&D at low readiness (TRL 3/4/5) Ramping time and field stability need to be demonstrated

Sunam NI one-body
ReBCO magnet
26.4 T in 35 mm, J central pancake 404 A mm^{-2}
(26.4 T HTS multi-width)
overall diameter and height: 172 and 327 mm
S. Yoon et al. Supercond. Sci. Technol. 29 (2016) 04LT04





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Which technology for the final cooling solenoid?

- **Large coil are expensive**
- **More components (nested coils) could complicate construction**

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

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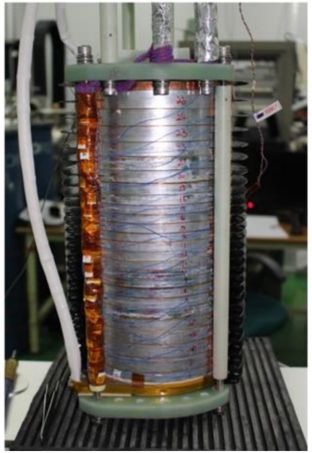

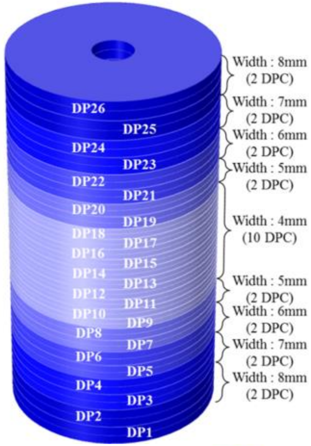

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Which technology for the final cooling solenoid?

- ✓ **All-SC (HTS)**
- ✓ **Non-insulated**
- ✓ **High uniform J**
- ✓ **Single coil**

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

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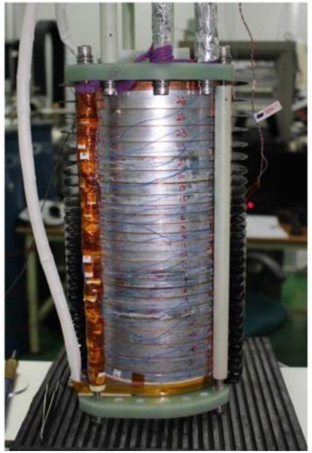
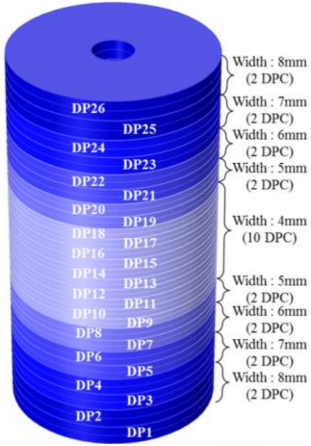
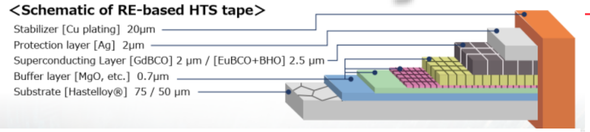




Main challenges-1

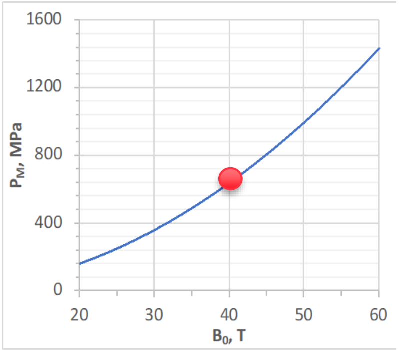
- Mechanics and Material Science
  - **High stress management:**
    - $P_M = B_0^2/2\mu_0 \sim 600MPa$
    - Hoop stress~ $1.4\text{-}2.2P_M$ (compact coil)
  - **Non- homogeneous and anisotropic material:**
  - Maximum allowable stress very weak in certain direction
  - Scarce literature
  - Reduced safety margin

Need of experimental campaign!

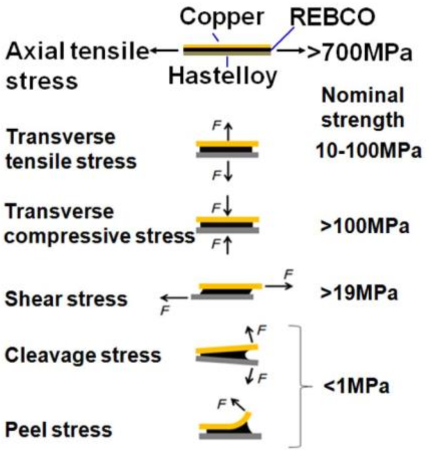


Reference Conductor Fujikura FESC-SH12. *https://www.fujikura.co.jp/eng/products/newbusiness/superconductors/01/superconductor.pdf*

Magnetic pressure vs Field

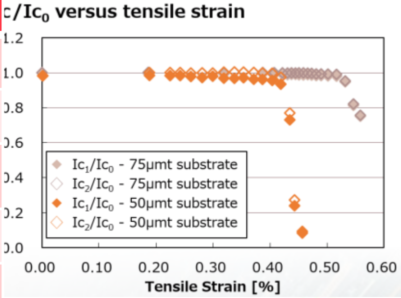


REBCO conductor



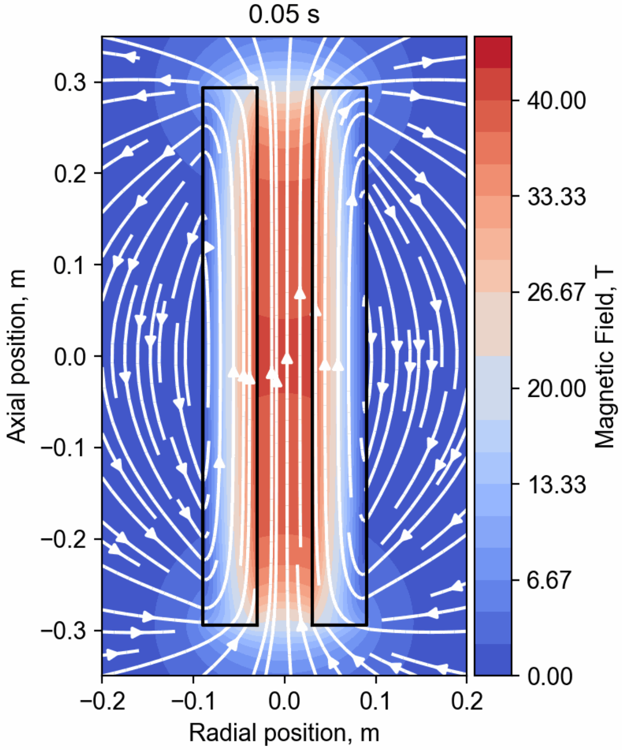
Hideaki Maeda and Yoshinori Yanagisawa IEEE TAS, VOL. 24, NO. 3, JUNE 2014.

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



Main challenges-2

- Mechanics and Material Science
  - **Detailed analysis of fast transients in Not/Metal Insulated coils are essential for their protection (and operation)**
  - CERN started to work on it
  - Several experts on quench dynamics and SC magnets protection
  - In house software (STEAM) validated on numerous LTS magnet tests/experiments
  - Development of new tools dedicated to the transient analysis on ReBCO not/metal insulated coils
  - Availability of and competences on FEM software (Comsol Multiphysics and GetDP) running on CERN clusters



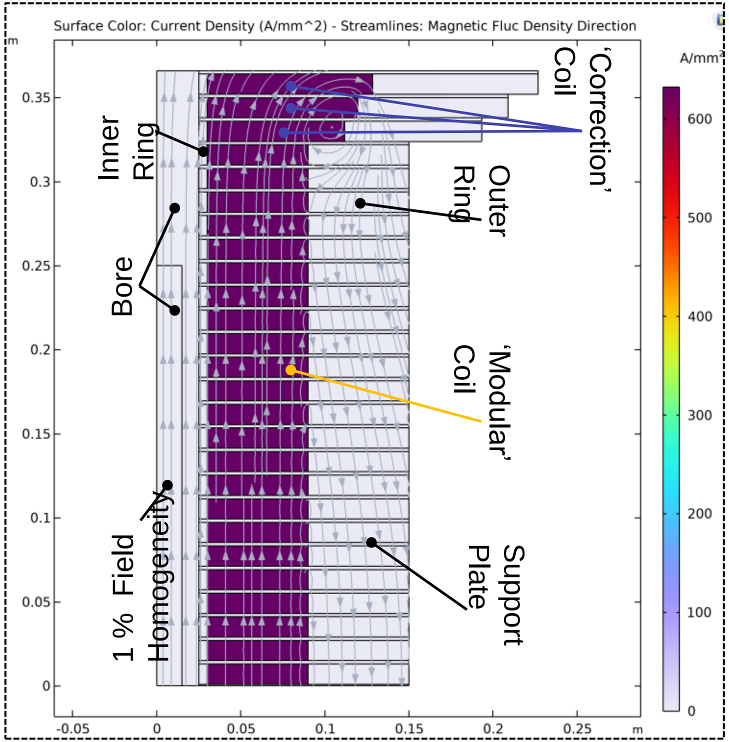
Simulation and Animation courtesy of Tim Mulder

Conceptual design

- High Je (> 650 A mm^{-2}, to limit costs and dimensions)
- Non/metal-insulated coils (protection, mechanical robustness)
- Modular single layer pancakes (design simple and flexible)
- Use as wide as possible tapes (12 mm, to limit the number of pancakes

- Current/tape~760A<1000 A < estimated Ic (4.2 K, B// =50 T)
- **Radially support each coil via an outer ring that could eventually apply a precompression on the coil (limit the hoop stress and to avoid tensile radial stresses)**

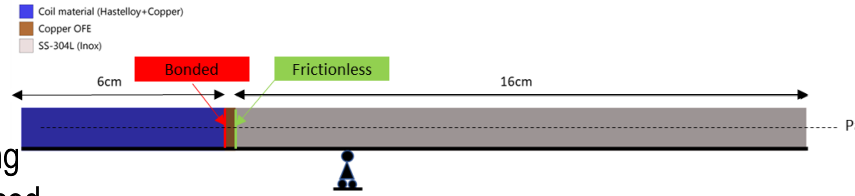
See B. Bordini, Conceptual Design Study of a 40+ T ReBCO Solenoid for the MUON Collider, IMCC Annual Meeting 2022



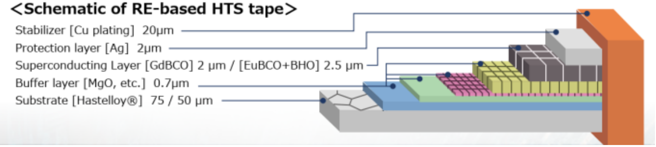
Mechanical considerations

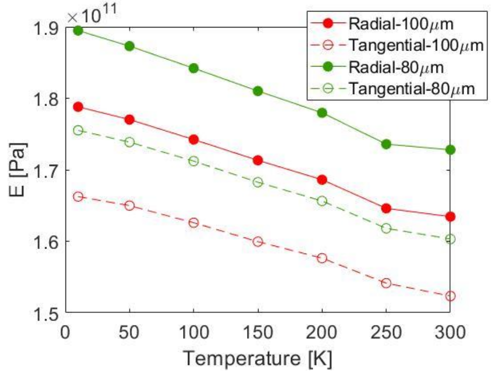
- A **high radial compression** is necessary to reduce hoop stresses and prevent tensile radial stresses on the HTS coil (~200MPa)
- Mechanical concept is based on **encapsulating** HTS pancake coils in **an external structure**, generating high **radial compressive stresses. Three concepts analysed:**
  1. Thermally-induced shrink fitting
  2. Adjustable shrink-discs with conical surfaces
  3. Hybrid solution (1+2)

Mechanical considerations - First concept

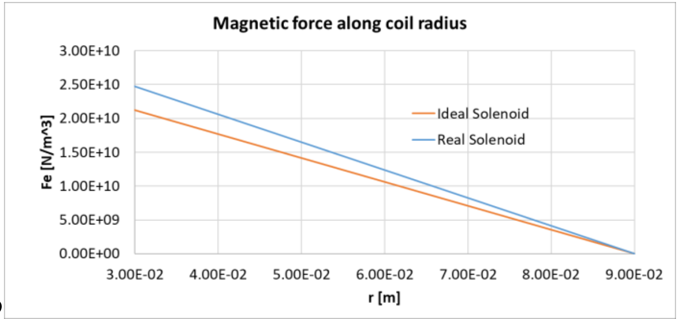


- FEA of single pancake. The baseline concept is based on encapsulating HTS pancake coils in a thick cylindrical shell, relying on thermally-induced shrink fitting.
- Linear Elastic Materials; orthotropic, homogenized HTS properties, properties function of temperature
- Two options studied
  - 20 µm of Cu (750 turns)
  - 40 µm of Cu (600 turns)



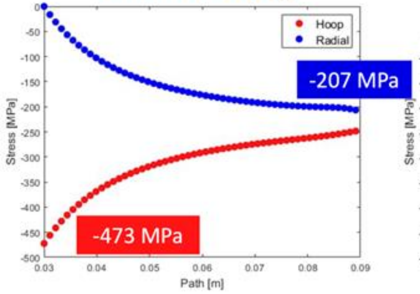


- Thermal condition
  - ΔTshell = 200 °C
- Electromagnetic Forces
  - Ideal Solenoid ($J_{ideal} = \frac{B_{MAX}}{\mu_0(r_{co}-r_{ci})}$ = 531 A/mm2)
  - Real Solenoid ($J_{real} = J_{ideal}\frac{t_{coil}+t_{supportplate}}{t_{coil}}$ = 620 A/mm2)

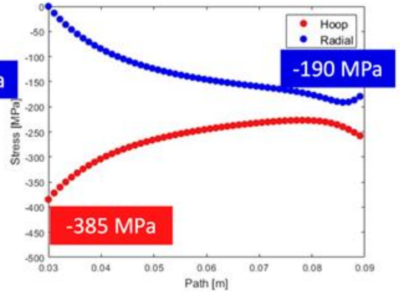


Mechanical considerations - First concept

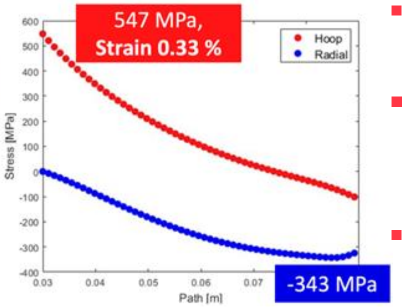
Room Temperature after shrink fitting



Cryogenic Temperature



Energization at 40 T

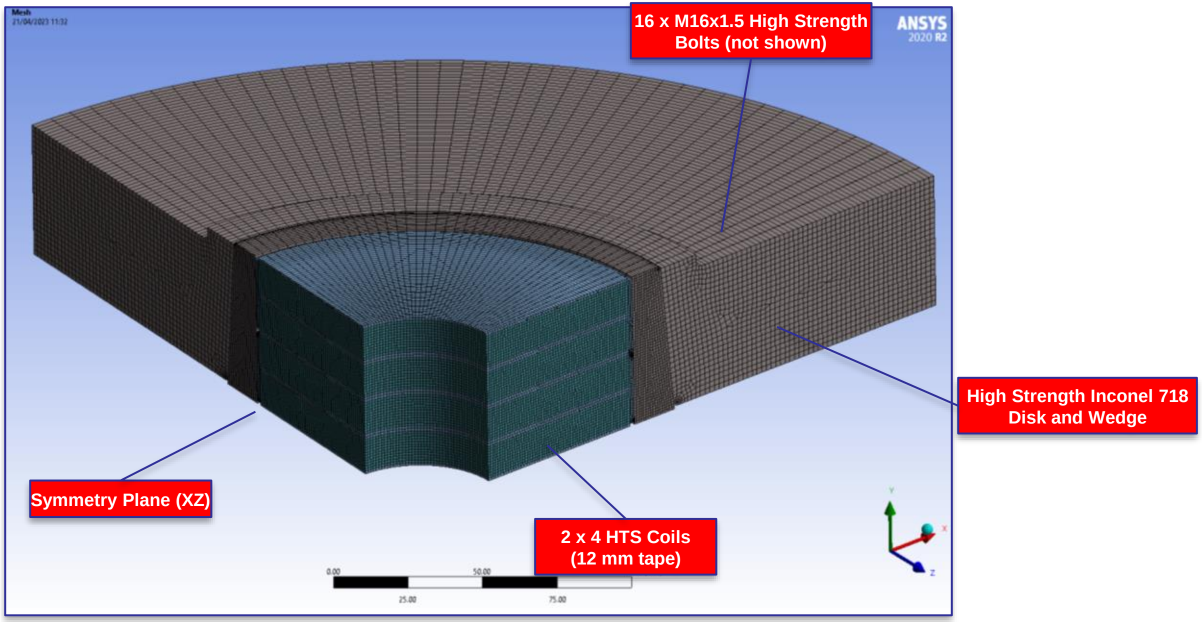


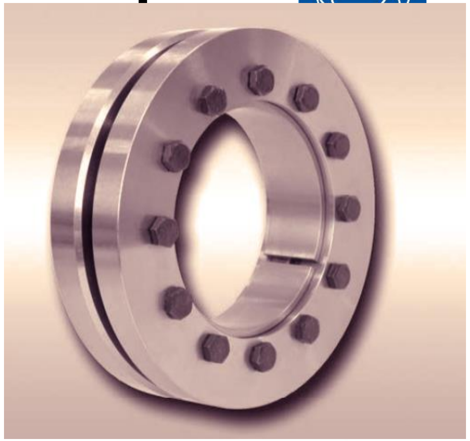
- A pre-compression of ~200MPa is achievable with thermally-induced shrink fitting (ΔTshell = 200 °C)
- Stress/strain below the limits, but tight safety factor→ **important to verify the material limits**
- The Cu fraction in the tape does not significantly impact the peak stresses (simulations accounting for Cu yielding on going)
- The max hoop strain strongly depends on the thickness of the plates between the modular coils

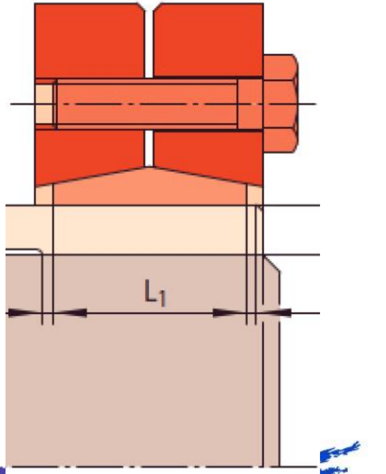
				Stress (MPa) at RT		Stress (MPa) at 4.2 K		Stress (MPa) and Strain (%) at 40 T		
Case	Copper in the tape (%)	Distance between 'modular' coils (mm)	J_e (A/mm^2)	Min Hoop	Min Radial	Min Hoop	Min Radial	Max Hoop Stress	Min Radial Stress	Max Hoop Strain
1	40	2	632	-473	-207	-385	-190	547	-343	0.33
2	20			-484	-211	-413	-193	529	-352	0.3
3	40	0	542	-473	-207	-385	-190	412	-320	0.25
4	20			-484	-211	-413	-193	393	-330	0.22

Mechanical considerations - Second concept

- Alternative concept is based on a pair of adjustable shrink-discs with conical surfaces
- Thicker coils packs can be assembled (up to 8 x 12 mm coils)



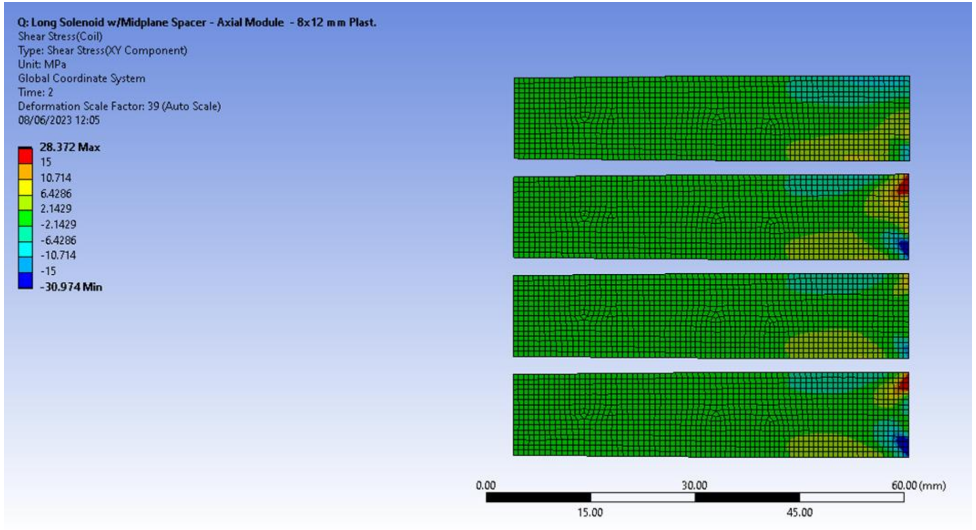




C. Accettura et al., Challenges of final cooling solenoid, IMCC Annual Meeting - 22/06/2023

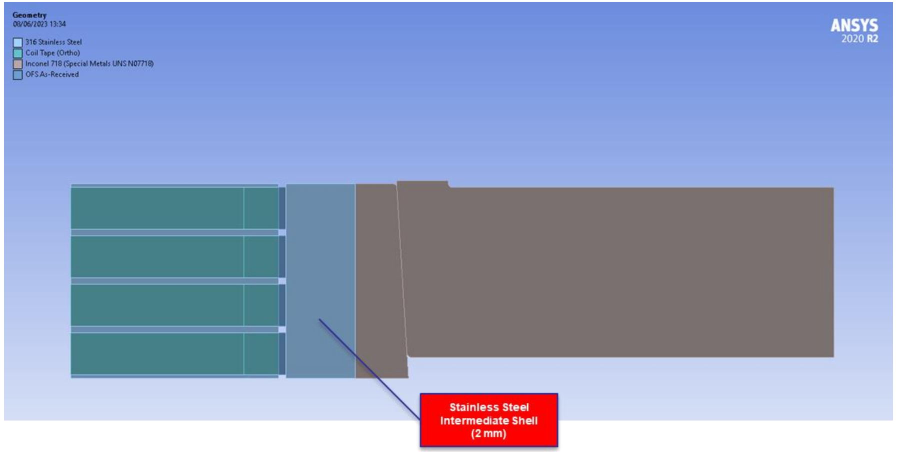
Mechanical considerations - Second concept

- 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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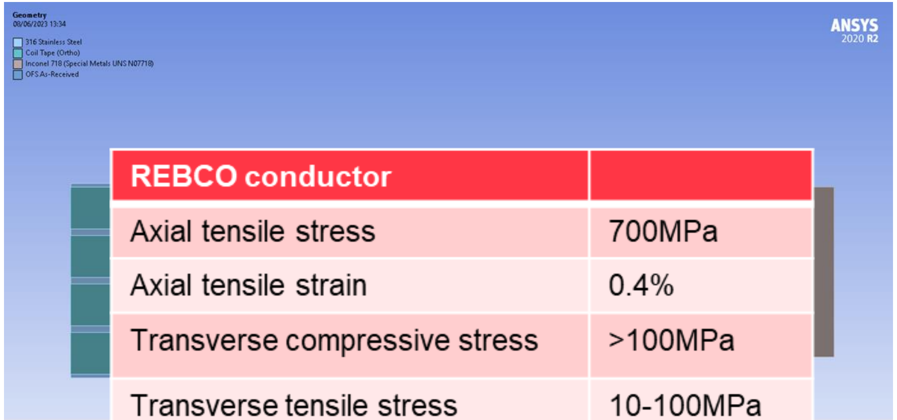
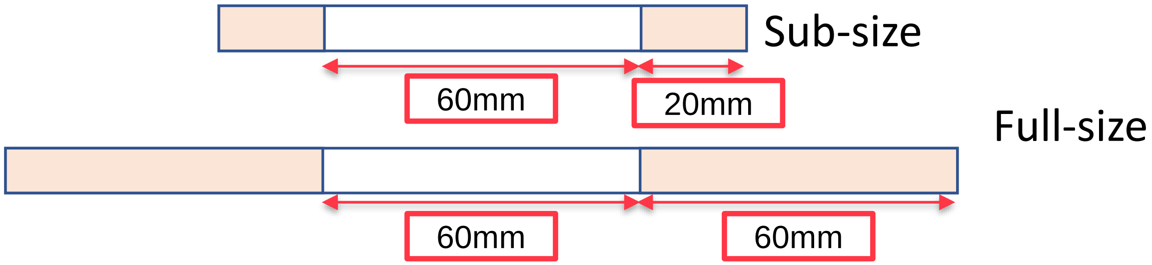


REBCO conductor	
Axial tensile stress	700MPa
Axial tensile strain	0.4%
Transverse compressive stress	>100MPa
Transverse tensile stress	10-100MPa
Max shear stress	>19MPa

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

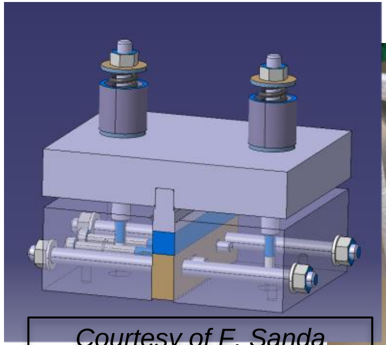
Roadmap and planning

- How to tackle these challenges?
  - The proposed design is pushing at the limit the HTS performance → Fundamental to **characterize the HTS tape** (also for more detailed simulations)
  - Evaluate the **impact of the manufacturing process** on the **coil final performance**
- What can we test?
  - Tape stacks
  - Small-size coil
  - Full-size coil
  - Pancakes stacked in mini-coils

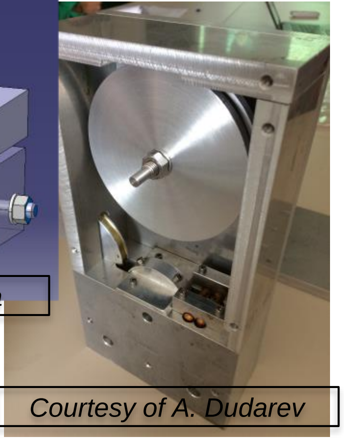


Roadmap and planning

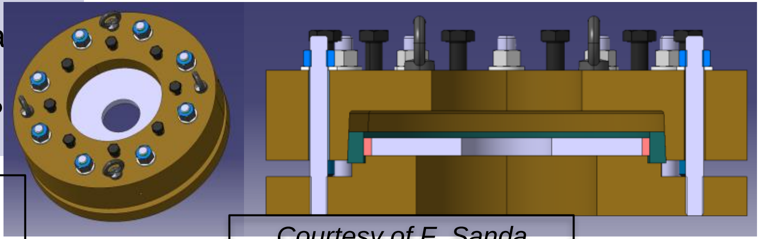
	Configuration	Objective	Test description
Material Characterization & Fabrication	Tape stacks	Characterize the thermo-physical and mechanical properties of the tape.	IET, dilatometer.
	Sub-size Full-size Dummy	Characterize the mechanical behavior of coil during pre-compression.	Compressive jig with controlled compressive force with DIC and strain gauges.
		Tape degradation during coil manufacturing.	Test Ic before/a winding at 77 which type??



Courtesy of F. Sanda



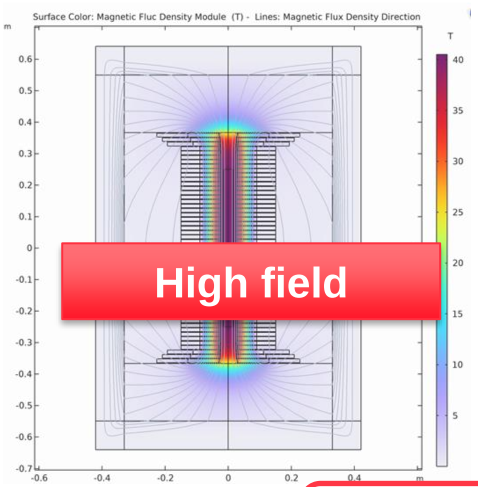
Courtesy of A. Dudarev



Courtesy of F. Sanda

+ test of inter-turn resistance, joint design, protection and performance

Societal impact of HTS UHF magnets



High field + **Cost saving** + **Sustainability**

Compact winding

- Reduce the amount of SC

→ Cost saving

Full HTS

- HTS development beneficial for lower-B magnet→ operation at 10K

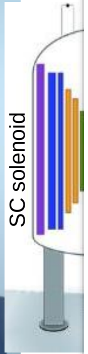
→ Sustainability

Very attractive for several applications

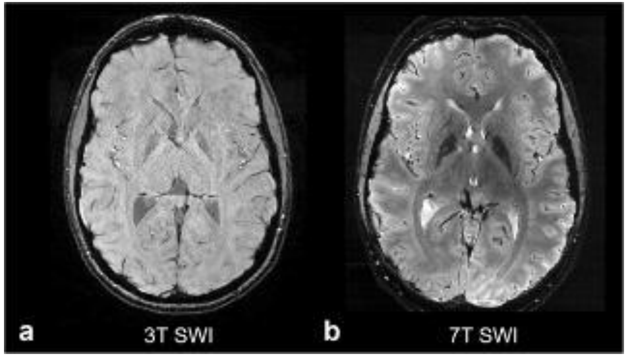
Societal impact of HTS UHF magnets

Nuclear Magnetic Resor

$$\Delta\nu \approx \frac{1}{\gamma B}$$



Magnetic Resonance Imaging



14 T HTS MRI
800 mm

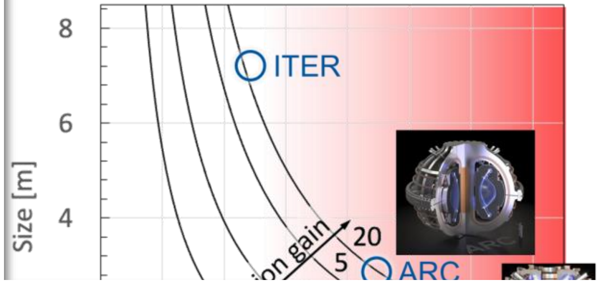
HEALTH TECH SCIENCE 14 TESLA MRI SCANNER MRI RADBOUD UNIVERSITY » MORE TAGS SHARE THIS:

MONDAY, 20 FEBRUARY 2023 - 13:05

Strongest MRI in the world to be built in Netherlands

The Netherlands will soon house the strongest MRI scanner in the world with a magnetic field strength of 14 Tesla. A consortium of seven partners, led by Radboud University's Donders Institute for Brain, Cognition, and Behavior, will build the MRI scanner in Nijmegen with a 19 million euros Roadmap grant received from NWO.

Fusion



Generator for wind turbine

AMSC SeaTitan
10 MW
HTS DD

Conclusions

- A conceptual design of the final cooling solenoid has been studied:
  - 40 T
  - All-SC (HTS)
  - Non-insulated
  - High uniform J
  - Single coil
- The main challenges are related to the mechanics and the material limits: 3 concepts have been proposed to apply the required pre-compression to the coil and to limit the stresses.
- The analysis shows that we are operating at the limit of the HTS performance→ fundamental to verify the material behaviour and the failure modes.
- **If successful, it can have a great impact on science and societal applications!**

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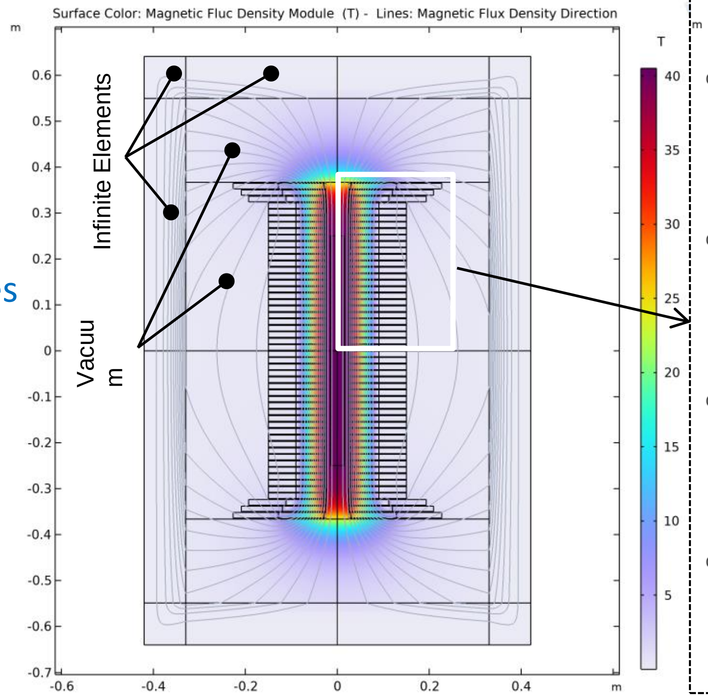
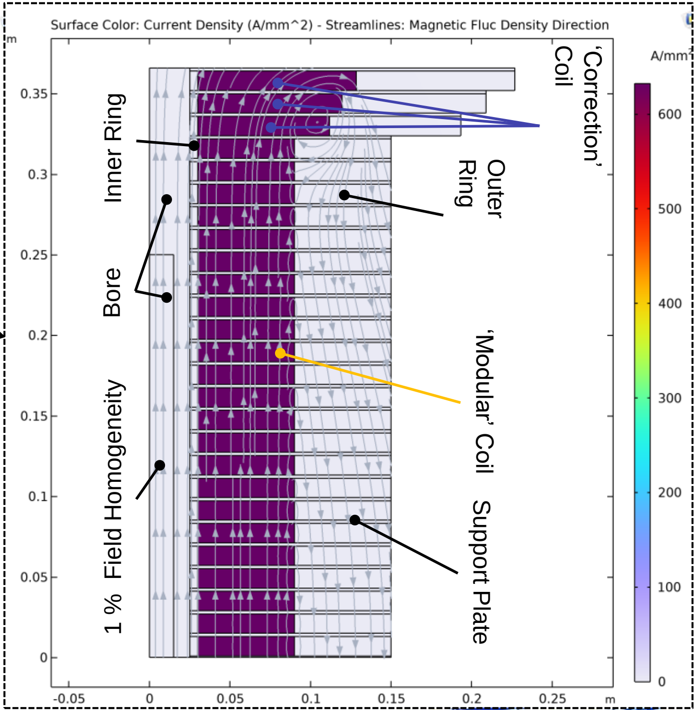
Thank you
for your attention!
Your questions please?

40+ T Conceptual design

- **46** identical **'modular'** and **6 'correction'** pancakes
- **'modular'** pancake:
  - **6 cm** (6-8) **thick** coil
  - J_e **632 A mm^{-2}** (>500)
  - **12 mm** wide **tape**
  - **Outer ring** thickness x times (>1) coil thickness
  - Inner ring 5 mm thick
  - Support Plate 2 mm (less?) thick
  - Bore **aperture 50 mm**
  - Bore Field = **40 T**





Principles Guiding the study 1/2

- $J_e > 500$ A mm^{-2}
  - limit **costs** and **dimensions**
- **Modular Single** coil **pancakes** (not nested coils)
  - **simplify** the **design**, the magnet **system** and the **protection**
- **Non/metal insulated** coils
  - **protection**, mechanical **robustness**, high J_e
- **Avoid tensile radial stresses** and limit the **hoop strain** to values **lower** than **0.4 %**
  - **minimize** the **risk** of I_c **degradation**

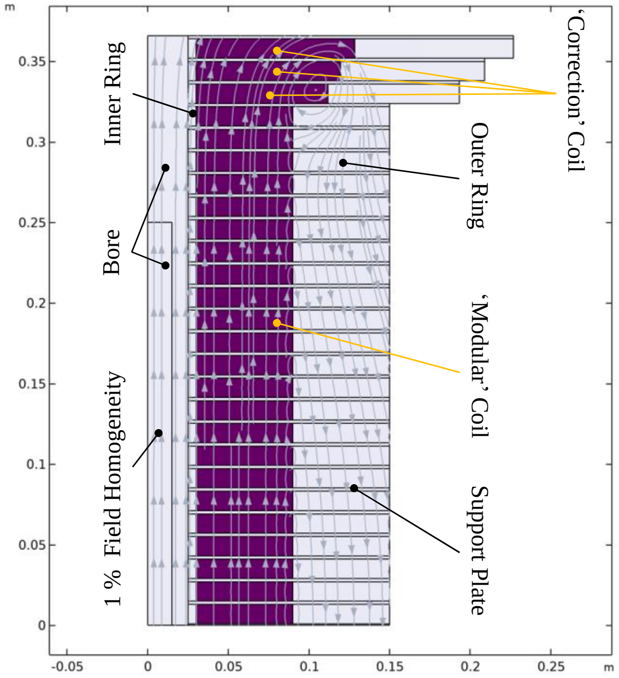


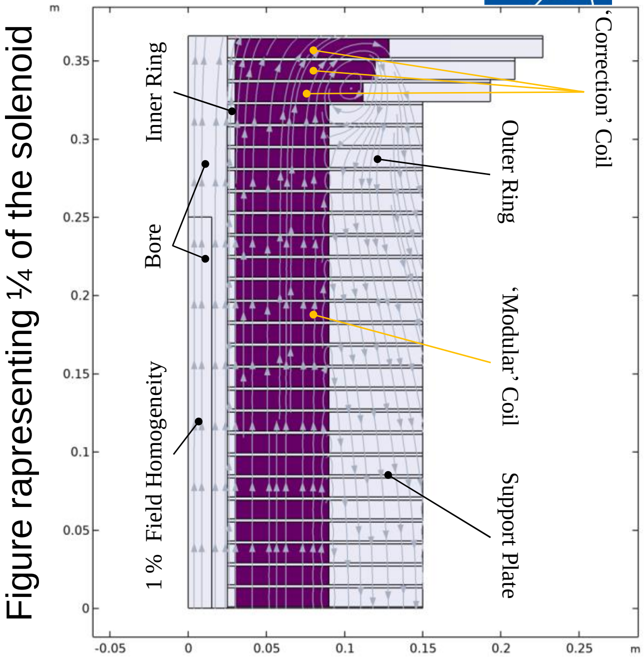
Figure rapresenting ¼ of the solenoid

- **Radially support** each pancake **via** a stiff **outer ring** that also applies a radial **precompression** on the coils
  - **limit** the **hoop strain** and **avoid tensile radial** stresses

Principles Guiding the study 2/2

International UON Collider Collaboration

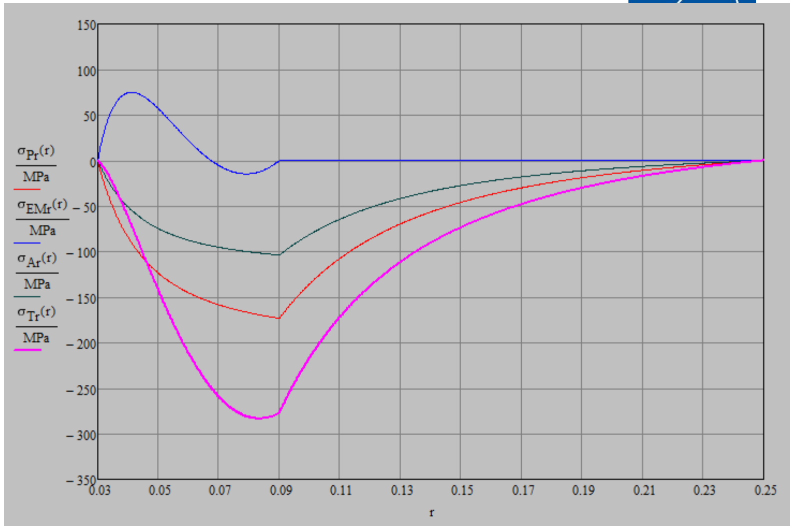
- Maintain the magnetic **field lines** practically **parallel** to the **tapes** in the **'modular'** coils
  - **minimize axial** Lorentz **forces** and **maximize I_c**
- **Intercept axial** Lorentz **forces** between pancakes via **support plates**
  - **minimize** the pancakes **mechanical interactions**, **avoid** the **accumulation** of axial forces
- Use as **wide** as possible **tapes**, 12 mm
  - to **limit** the number of **pancakes**



- **Robust design** for the **'correction'** coils, to **account** for the not negligible **axial forces** experience (significant radial fields) and the conductor **magnetization** (tape striations ?)
  - **protection**, mechanical **robustness**

Mechanical considerations

- Step 1: Analytical estimation
- Analytical calculations of stresses and deformations performed for an inner cylinder submitted to EM forces and radial preload from an external thick cylindrical shell, linearly superposing effects of preload, EM forces (and restoration of Boundary Conditions)
- Assumptions
  - Axial symmetry, plain strain (i.e. infinitely long solenoid)
  - Linear elasticity. Homogeneous material. Both isotropic and orthotropic cases studied.
  - Ideal, uniform current distribution
- Main parameters and material properties:
  - Magnetic Field $B_{max} = 40\ \mathrm{T}$
  - Coil Dimensions : Inner Radius $a_c = 30\ \mathrm{mm}$ Outer Radius $b_c = 90\ \mathrm{mm}$
  - Current density $J = \frac{B_{max}}{\mu_0(b_c - a_c)} = 531\ \mathrm{A\ mm^{-2}}$
  - Shell Properties $a_s = 90\ \mathrm{mm}$, $b_s = 250\ \mathrm{mm}, E_s = 210\ \mathrm{GPa}$ (Steel Outer Shell)
  - HTS Tape Geometry: width 12 mm; thickness $t_w = 75\ \mathrm{\mu m}$
  - Wire Elastic properties from rule of mixtures with 50 µm Hastelloy, 10+10 µm Copper plating, 5 µm Silver
    $\Rightarrow E_r = 171\ \mathrm{GPa}, E_\theta = 180\ \mathrm{GPa}, \mathrm{R} = \frac{E_\theta}{E_r} = 1.054$
  - Interference (thermally induced) between Coil and Shell $\delta_r = \sim 180\ \mu m$



- Radial effects
  - Shrink Fitting Pressure (at cold) $p_\delta = 170\ \mathrm{MPa}$
  - Coil Radial stresses are always compressive, both for shri energization
  - Min coil radial stress at energization $\sigma_{Trc} = -284\ \mathrm{MPa}$ OD. Final pressure $p_T = 278\ \mathrm{MPa}$

Mechanical considerations

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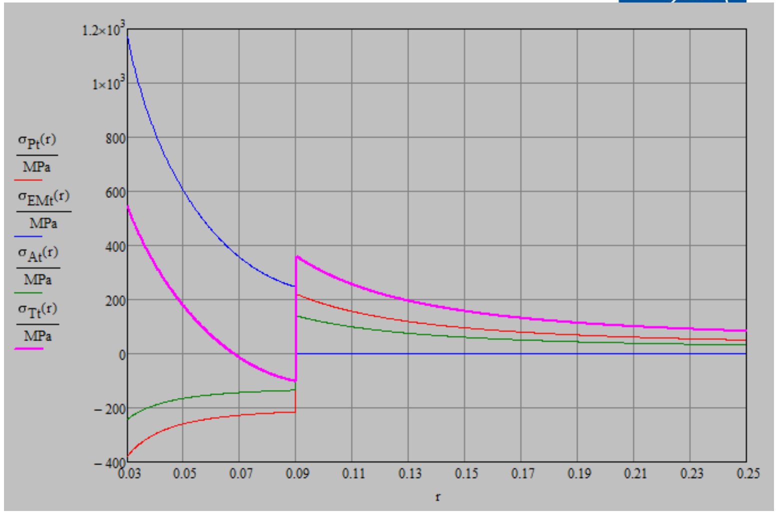
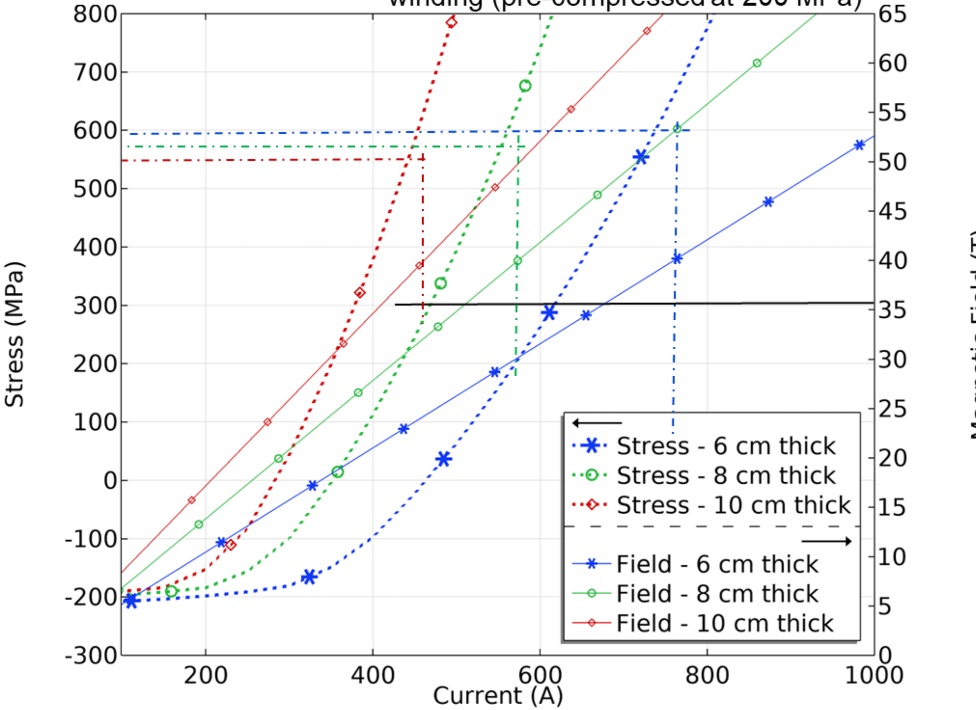


- Hoop Stresses
  - Min coil hoop stress (ID) after shrink fitting (at cold) $\sigma_{P\theta c}(a_c) = -37$
  - Max shell hoop stress (ID) after shrink fitting (at cold) $\sigma_{P\theta s}(a_s) = 22$
  - Max coil hoop stress (ID) at energization (total) $\sigma_{T\theta c}(a_c) = 548\ \mathrm{MPa}$
  - Max shell hoop stress (ID) at energization (total) $\sigma_{T\theta a}(a_s) = 360\ \mathrm{MPa}$

Mechanical considerations

- A precompression of about 200 MPa is essential to limit the conductor hoop stress to acceptable values
- Even with a 200 MPa precompression, the coil thickness must be smaller than ~8 cm to avoid radial tensile stress
- The maximum field achievable with this design (based on pancakes made of a single coil) is about 40 T
- Most of the axial Lorentz forces act on the last 2 pancakes of each extremity about 3 and 1.5 MN on average ~30 and 15 MPa applied on the respective support plates the axial force acting on the 4th coil is more than one order of magnitude lower

Max Hoop stress and load line for different thickness of the modular coil winding (pre-compressed at 200 MPa)

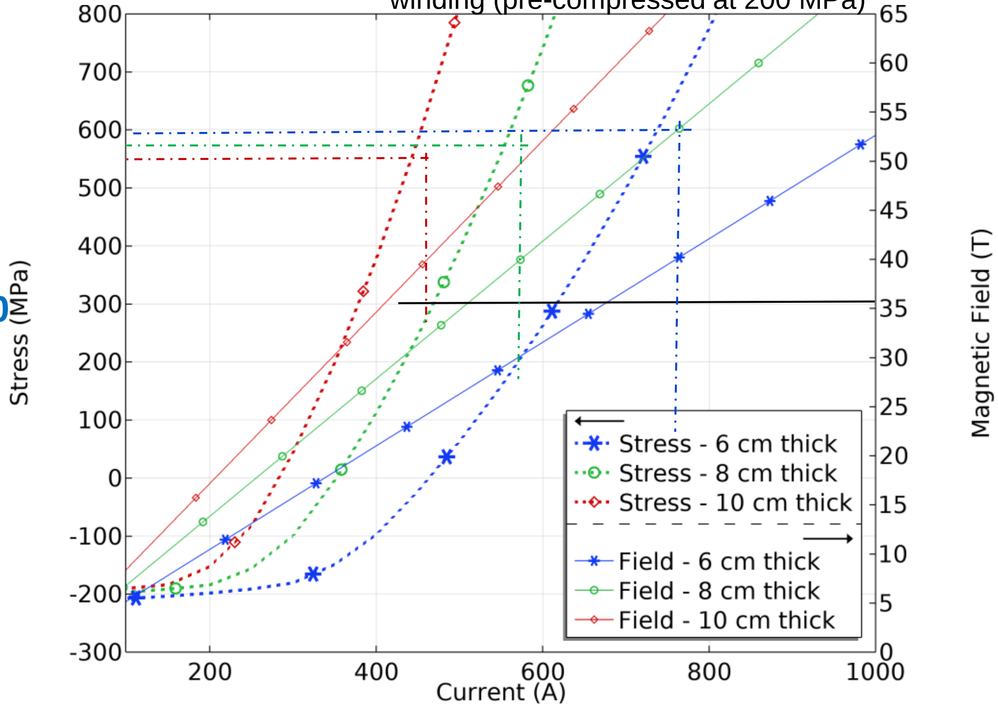


C. Accettura et al., Challenges of final cooling solenoid, IMCC Annual Meeting - 22/06/2023

Mechanical Analysis I *
main findings

- A **precompression** of about **200 MPa** is **essential** to limit the conductor hoop stress to acceptable values
- **Even** with a **200 MPa** precompression, the coil **thickness** must be **smaller** than **~8 cm** to avoid radial tensile stress
- The **maximum field** achievable with this design (based on pancakes made of a **single coil**) is **about 40 T**
- **Most** of the **axial** Lorentz **forces** act on the **last 2 pancakes** of each extremity
  - about 3 and 1.5 MN → on average ~30 and 15 MPa applied on the respective support plates
  - the axial force acting on the 4th coil is more than one order of magnitude lower

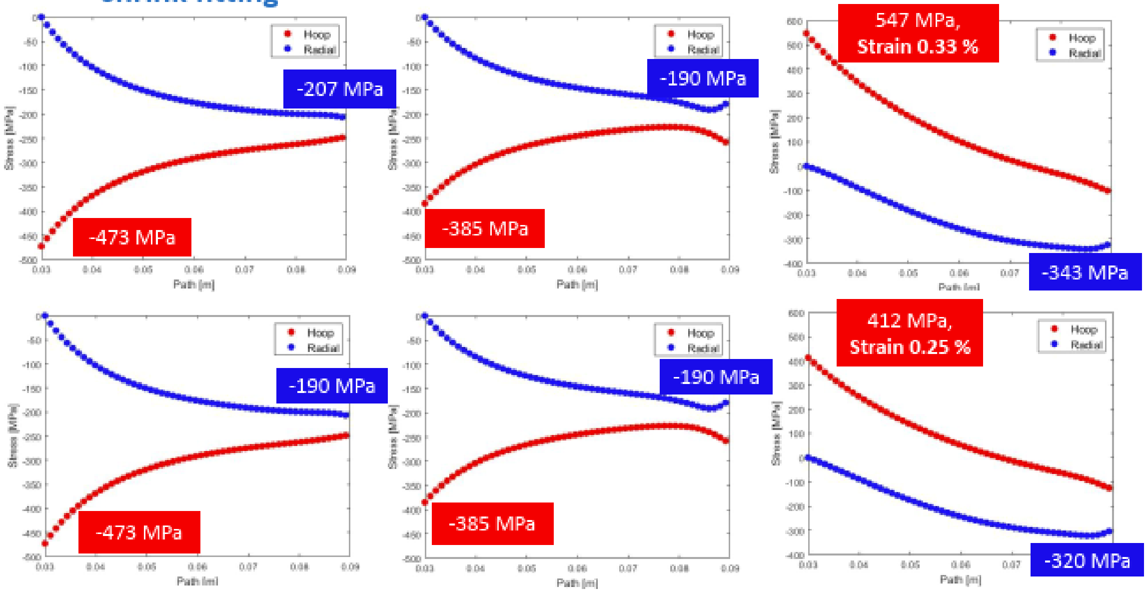
Max Hoop stress and load line for different thickness of the modular coil winding (pre-compressed at 200 MPa)



*Assumption in appendix

Mechanical considerations - First concept

Room Temperature after shrink fitting | Cryogenic Temperature | Energization at 40 T | Case

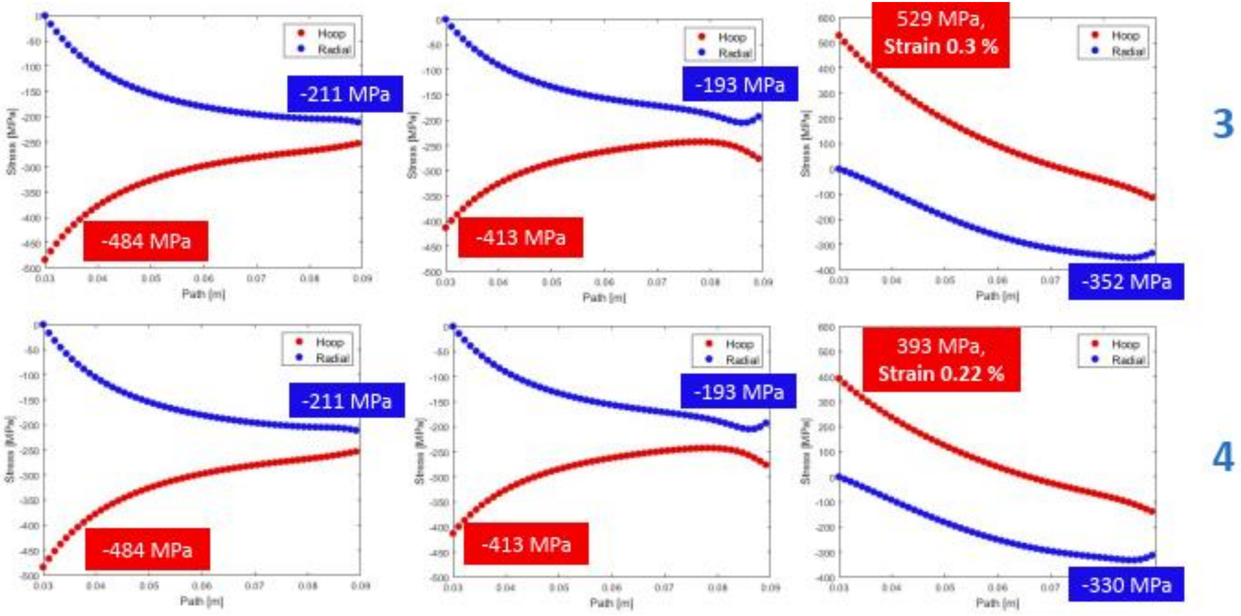


1

2

- Case 1 : **100-µm**-thick tape (40 µm Cu), 600 turns, **2-mm distance** between adjacent pancakes, J_e= 632 A/mm²
- Case 2 : **100-µm**-thick tape (40 µm Cu), 600 turns, **no distance** between adjacent pancakes, J_e= 542 A/mm²

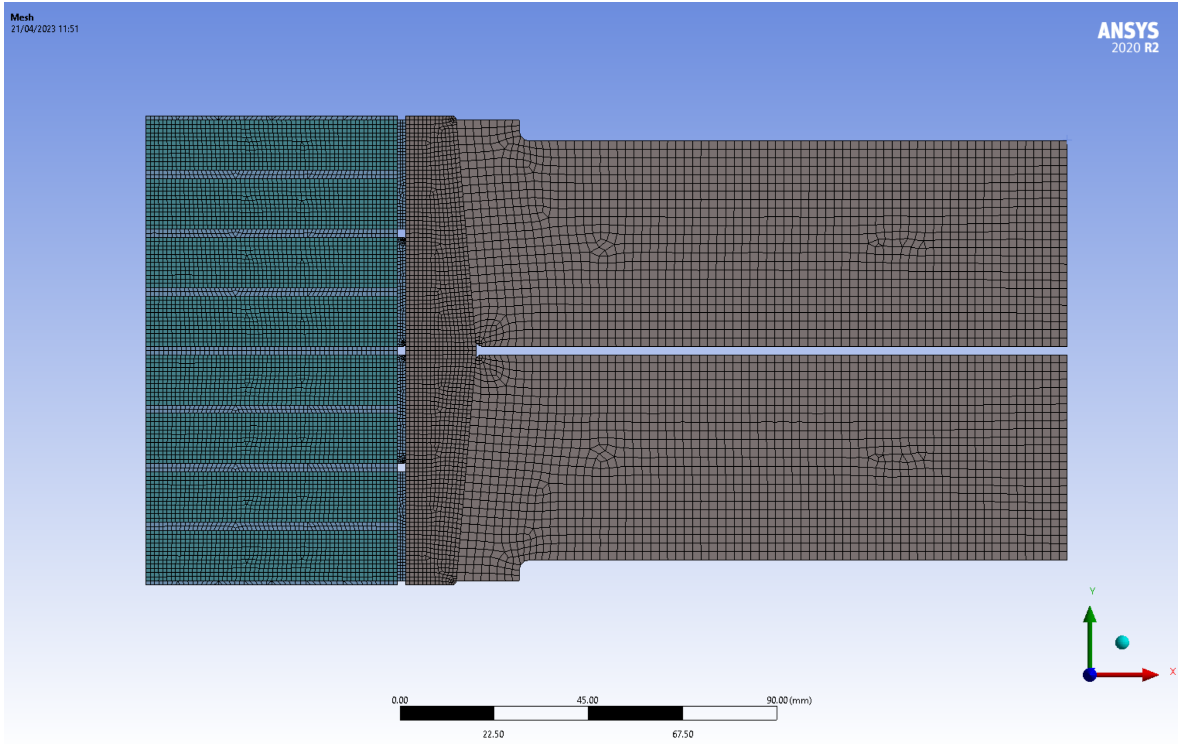
Mechanical considerations - First concept

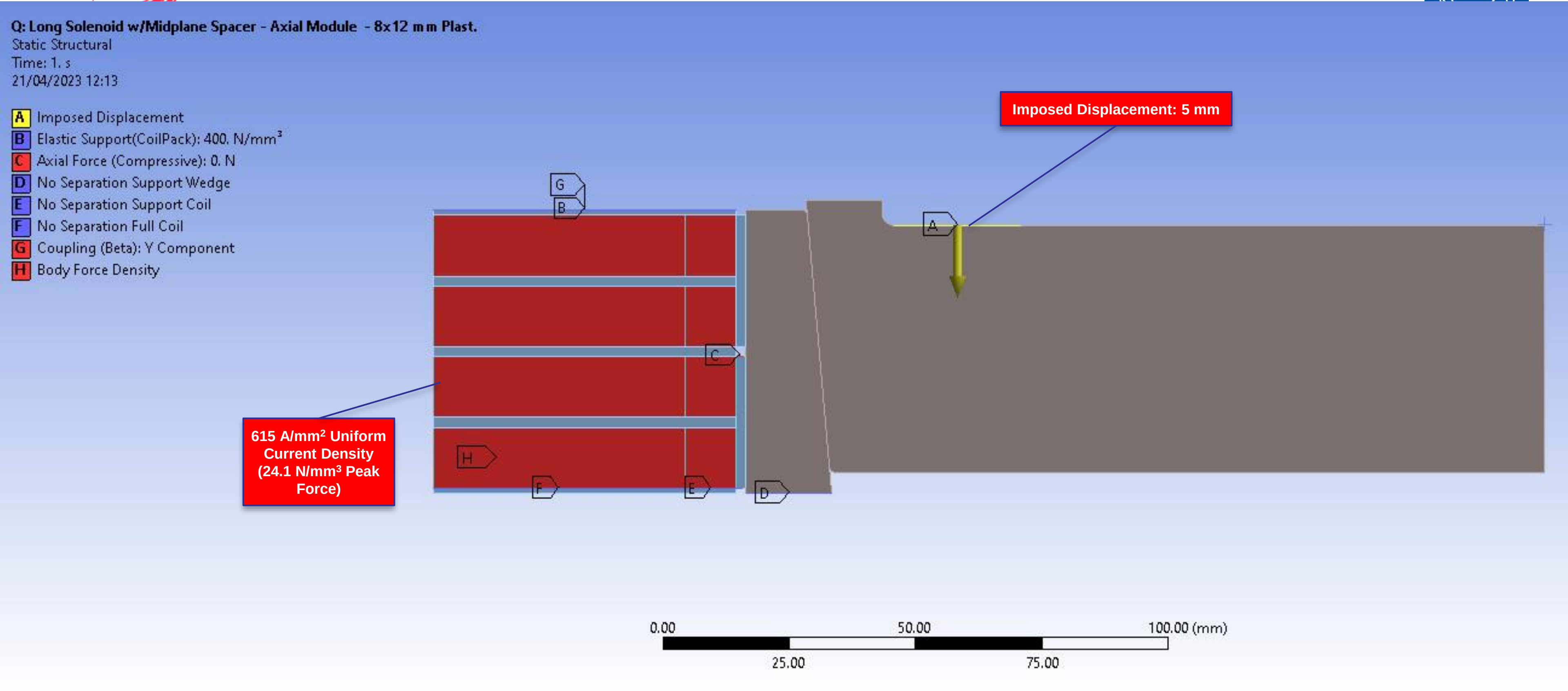


- Cas2 **3** : **80-µm**-thick tape (20 µm Cu), 720 turns, **2-mm distance** between adjacent pancakes, J_e= 632 A/mm²
- Case **4** : **80-µm**-thick tape (20 µm Cu), 720 turns, **no distance** between adjacent pancakes, J_e= 542 A/mm²

Mechanical considerations

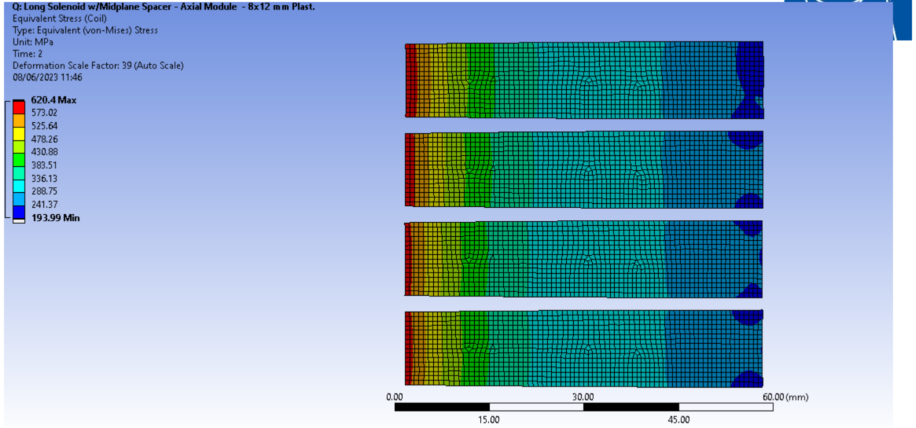
Main Dimensions
- **Coil ID 60 mm**
- **Coil OD 180 mm**
- **Disc OD 500 mm**
- **Coil Pack Height 112 mm**

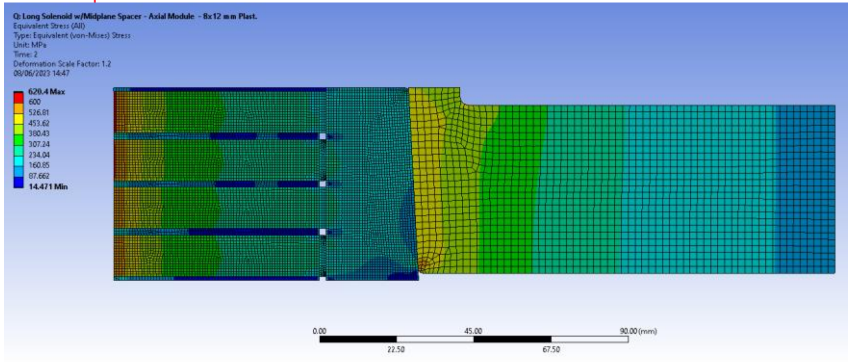


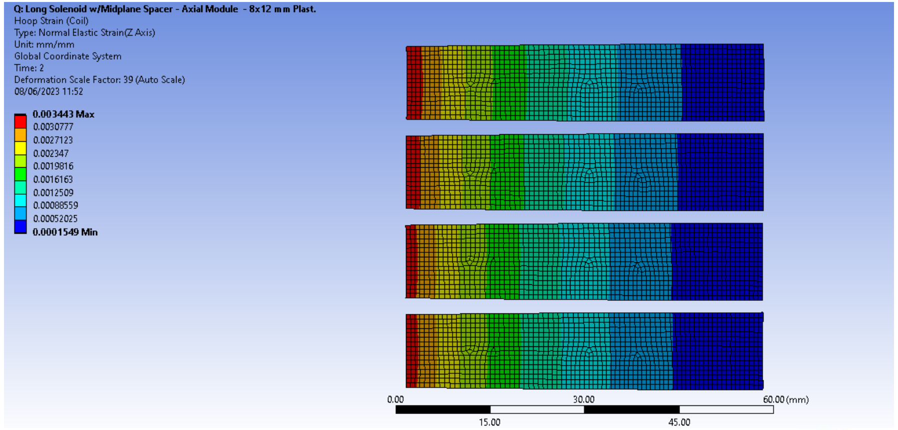

Q: Long Solenoid w/Midplane Spacer - Axial Module - 8x12 mm Plast.
Static Structural
Time: 1. s
21/04/2023 12:13
A Imposed Displacement
B Elastic Support(CoilPack): 400. N/mm³
C Axial Force (Compressive): 0. N
D No Separation Support Wedge
E No Separation Support Coil
F No Separation Full Coil
G Coupling (Beta): Y Component
H Body Force Density
Imposed Displacement: 5 mm
615 A/mm² Uniform Current Density (24.1 N/mm³ Peak Force)
0.00
25.00
50.00
75.00
100.00 (mm)

Concept 2 – Conical shrink disk: Hoop Stresses and Strains

- 2 Load Steps:
  1. Shrink Disk displacement (5 mm)
  2. Energization
- Max. Hoop Stress (after energization): 620.4 MPa
- Max. Hoop Strain (after energization): 0.344 %

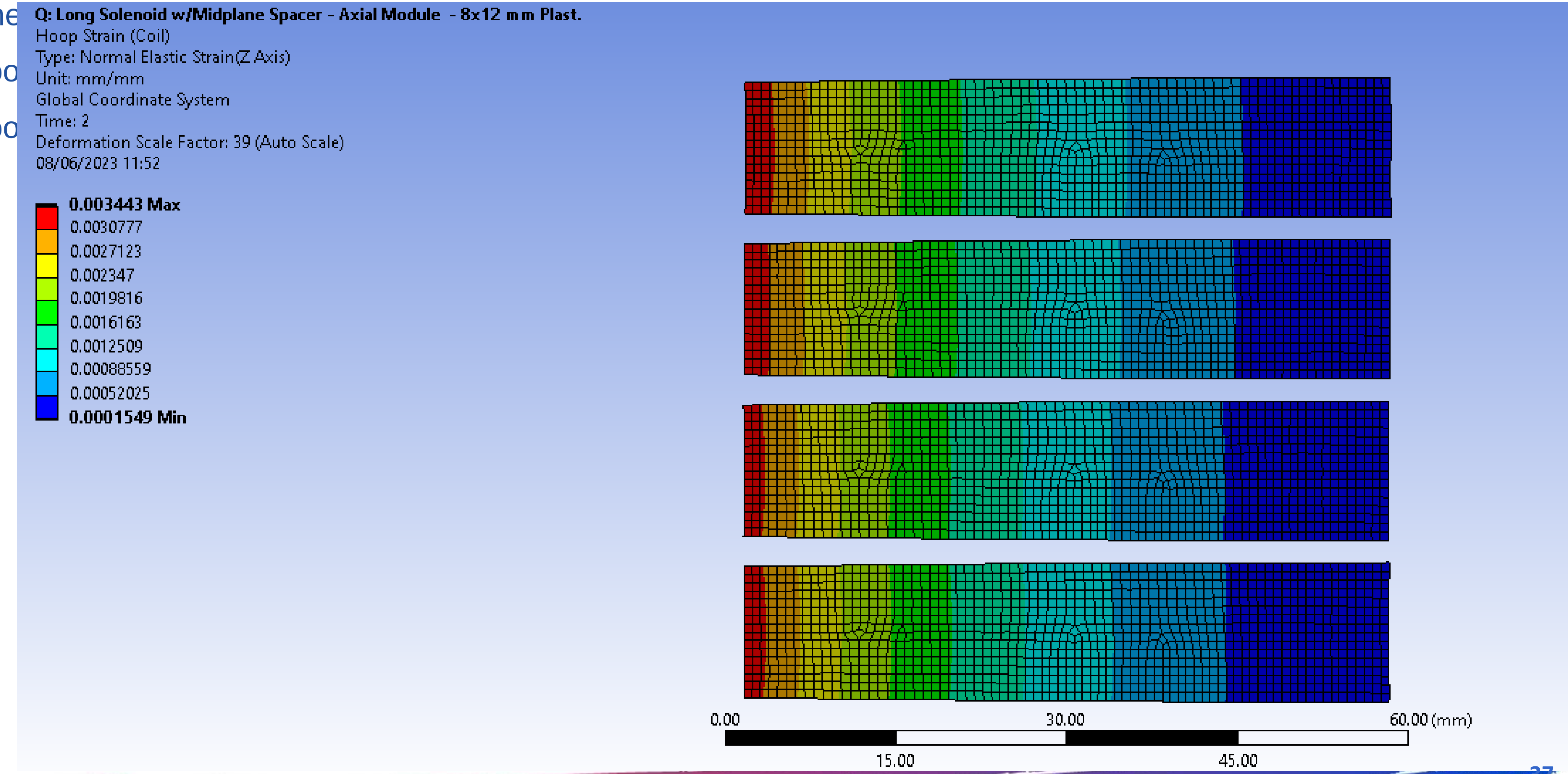






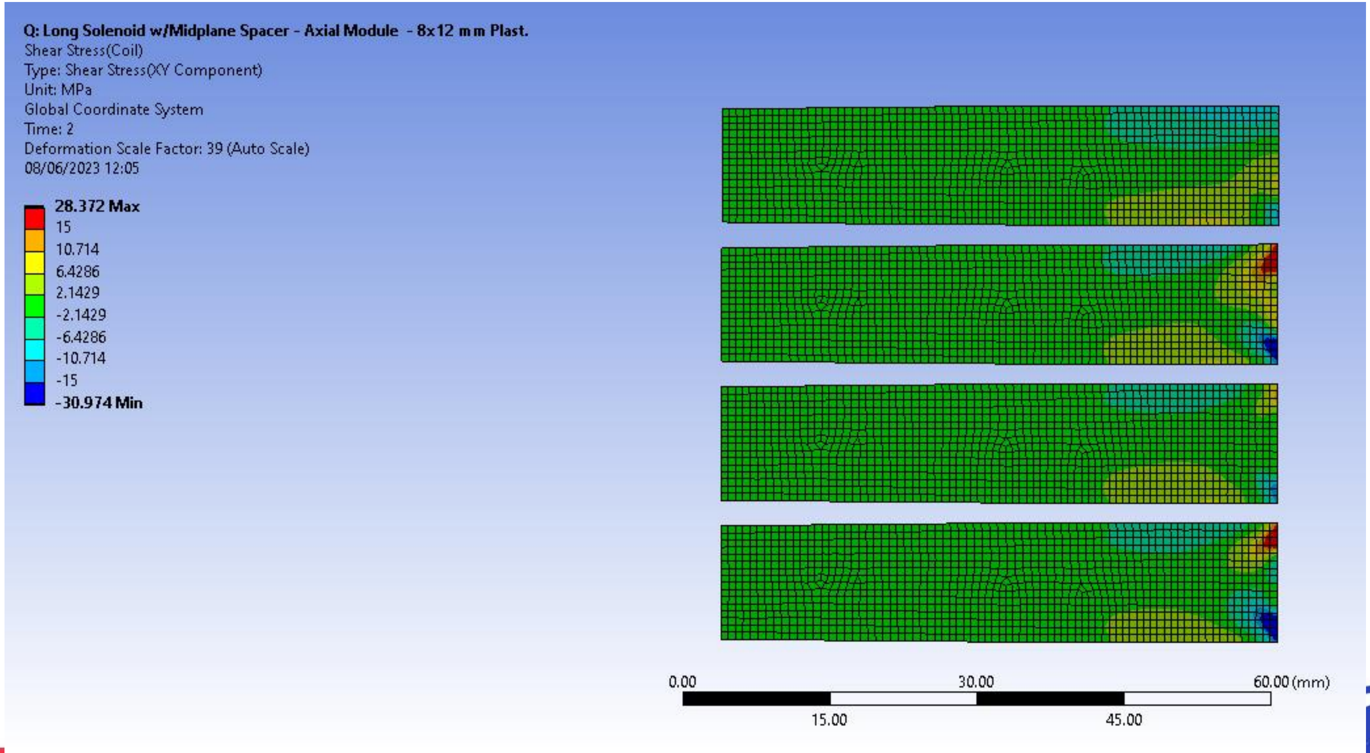
Concept 2 – Conical shrink disk: Hoop Stresses and Strains

- 2 Load Steps:
  1. Shrink Disk displacement (5 mm)
  2. Ene
- Max. Hoo
- Max. Hoo



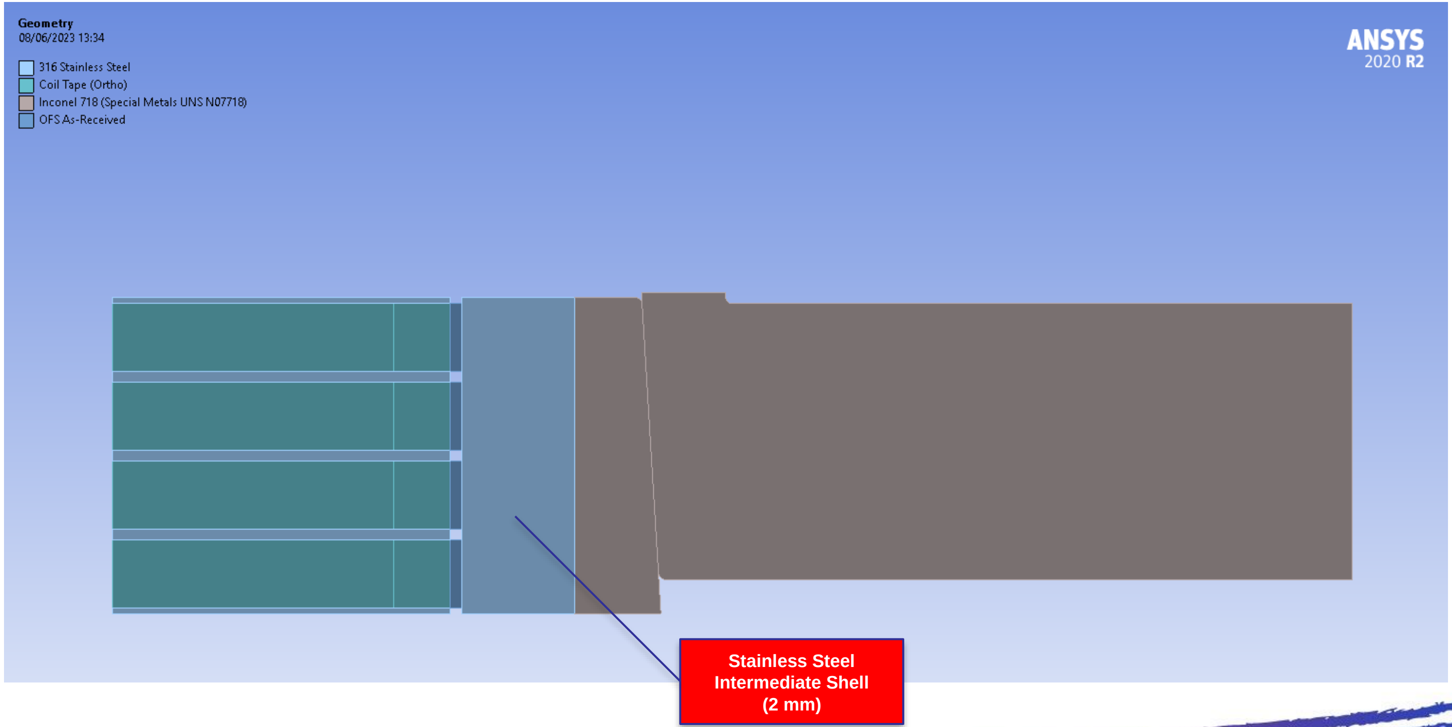
esses

- Shear Stresses globally lower than 15 MPa
- However, locally they can reach after energization ~ |30| MPa

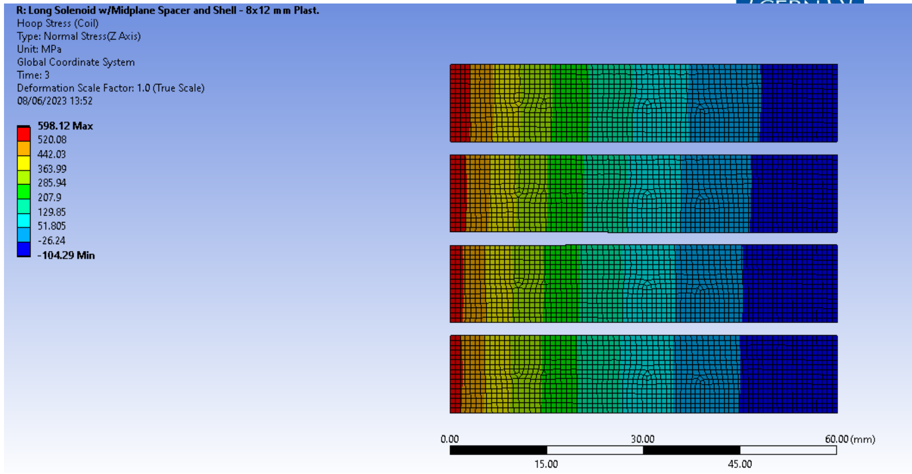


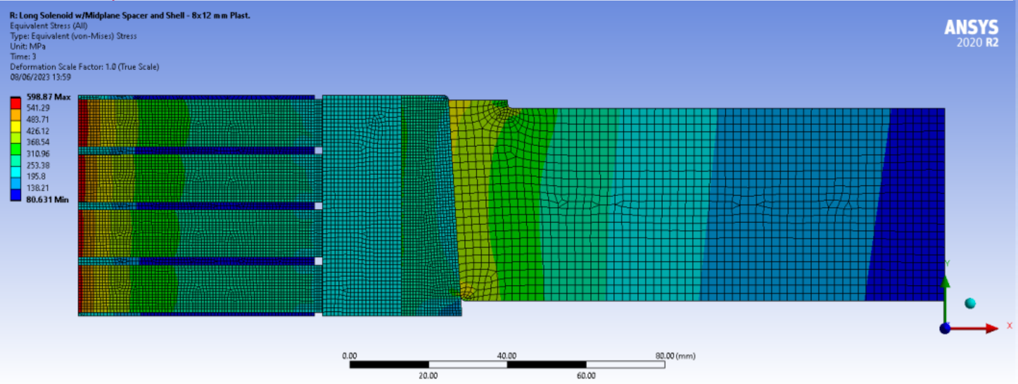
DISK)

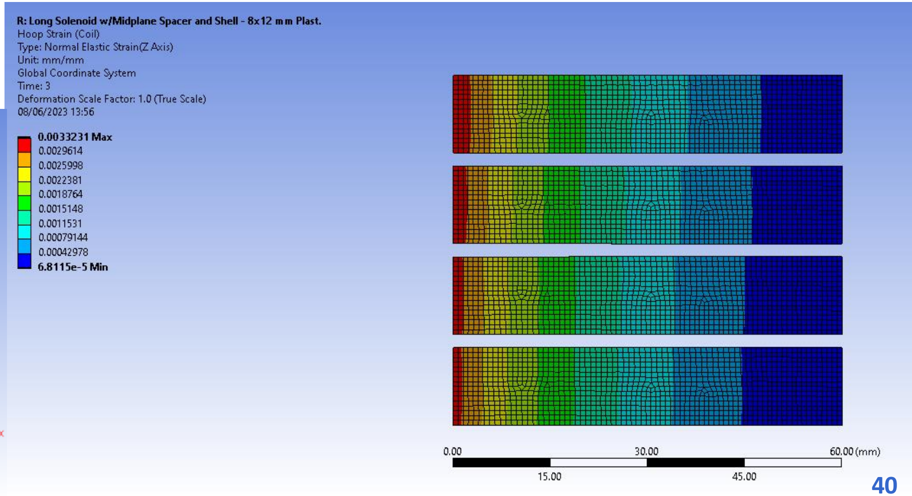
- To limit shear stresses, an intermediate steel shell is added (ID 184 mm; OD 224 mm)
- ~150 µm interference with coil pack created by differential heating
- 3 Load Steps: 1. Shell/Coil Interference; 2. Shrink Disk Displacement (2.2 mm); 3. Energization



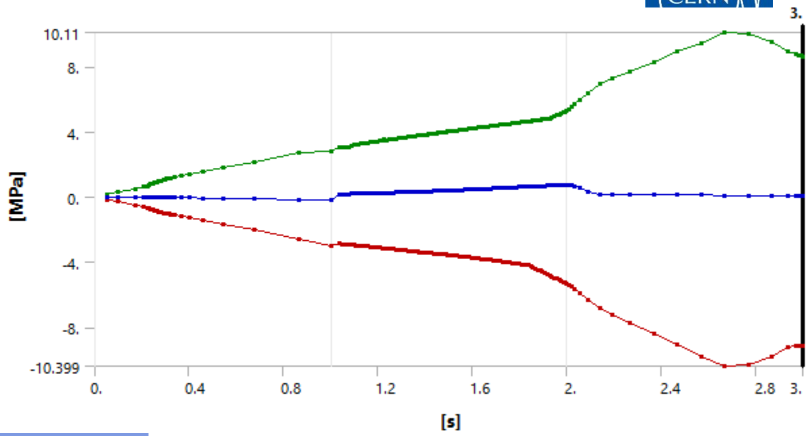
- Min. Hoop Stress after shrinking: -426 MPa
- Max. Hoop Stress after energization: 598 MPa
- Max. Hoop Strain after energization: 0.332 %

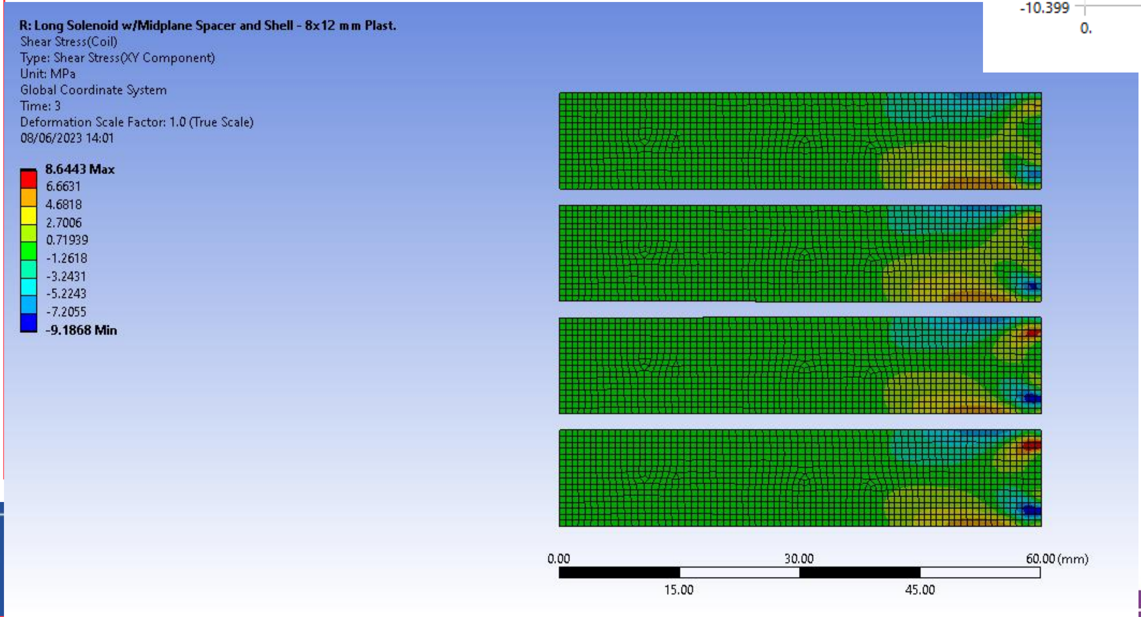






- Local peak shear stress ~ 10 MPa
- Max Shear after energization |9.2| MPa

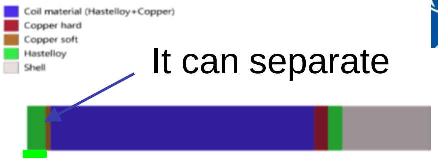


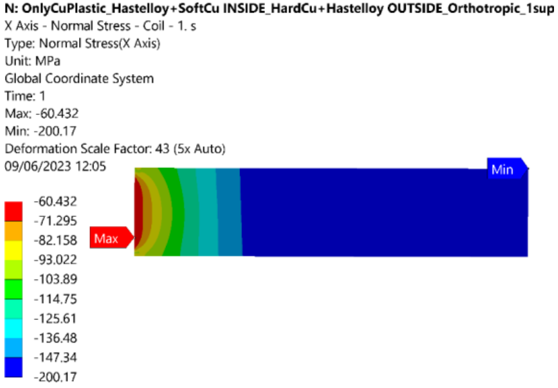


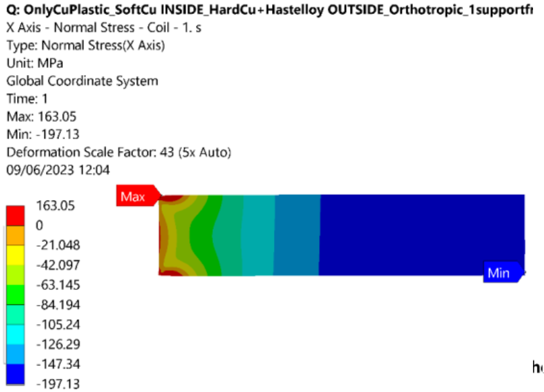
Mechanical considerations - Comparison

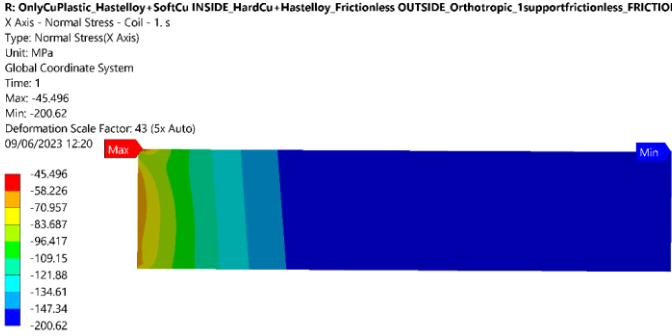
Concept	Pros	Cons
Thermally-induced shrink fitting	• Simple • Limit shear stress	• Requires tight tolerances (~ 2 MPa/µm) • Cannot be adjusted • Several coaxial shells necessary to limit Tmax on Coil (if overheating is applied)
Adjustable shrink-discs with conical surfaces	• Easily adjustable • Tolerances less critical • Thicker coil packs can be assembled (up to 8 × 12 mm coils)	• High shear stresses locally induced • Requires control of friction coefficient between conical surfaces ⇒ if lubrication not admissible, hard coatings likely required
Intermediate shell for thermally-induced shrink fitting+Adjustable shrink-discs with conical surfaces	• As concept 2 with limited shear stresses	Somehow similar to concept one, though lower temperatures and less tight tolerances are required (thanks to adjustment

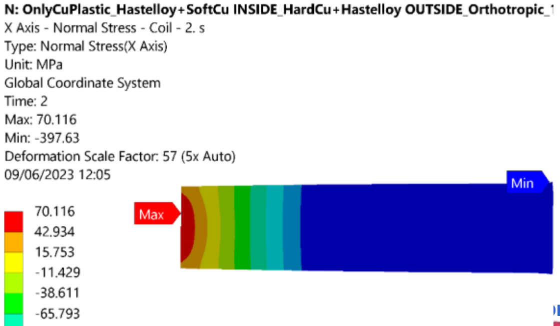
It can separate

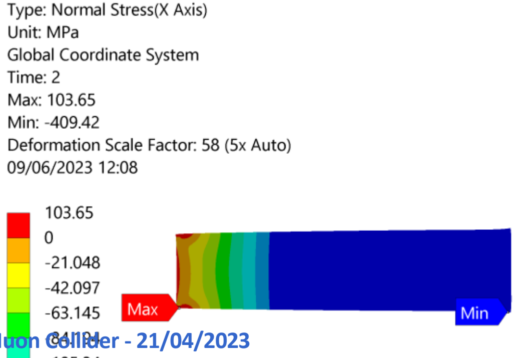


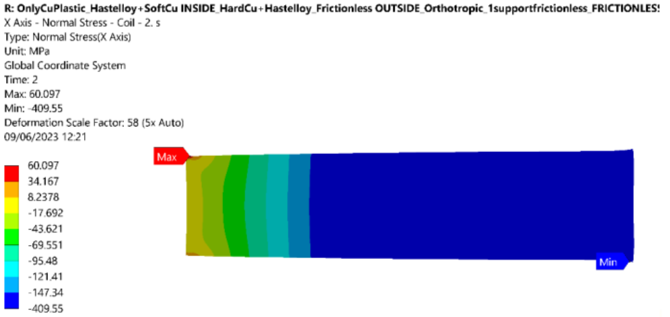












Roadmap and planning

	Configuration	Objective	Test description
Inter-turn resistance	Sub-size Full-size Dummy	Inter-turn resistance control and variants.	Produce baseline windings (e.g. soldered, no insulation control) and variants introducing intrinsic and extrinsic resistance control.
Joint design		Joints resistance and stability.	Produce test configuration for pancake joints and unit electrical/mechanical test. Integrate joints in pancakes and test resistance and stability (force and thermal cycles).
Protection		Quench detection.	Introduce and test diagnostics in above tests. Select baseline (voltage ?) for comparison.
		Quench protection.	Test energy release and temperature increase in provoked and spontaneous quenches.
Performance		Coil dynamic force.	Test mini-coil stacks of pancakes.
		Reaching field/sub-optimal performance.	Use pancakes to test performance (force and thermal cycles) and compare to expected performance from characterized tapes (NOTE: need of complete Ic(B,T,angle) scaling).

Scheduling

- A preliminary **Gantt chart** has been defined

Author: Siara Fabbri

Today: 15/6/2023

2023				2024				2025				2026			
Jan 1	Apr 1	Jul 1	Oct 1	Jan 1	Apr 1	Jul 1	Oct 1	Jan 1	Apr 1	Jul 1	Oct 1	Jan 1	Apr 1	Jul 1	Oct 1
S	S	S	S	M	M	M	T	W	T	T	W	T	W	W	T

TASK	OBJECTIVES (can be in Parallel)	COLLABORATORS	PROGRESS	MONTHS	START	END
2.2	– Design and demonstrate UHF HTS solenoids using NI/PI technique for final cooling	Institutes: INFN, CERN, PSI, CEA, LNSMI, Utwente, Usouthampton, SO'TON Persons: A. Dudarev, B. Bordini, T. Mulder, A. Bertarelli, C. Accettura, M. Statera, S. Fabbri, L. Bottura, Y. Tang				
1	Define performance specifications (beam physics), and initiate meetings with beam/shield/absorber/cryo/vacuum/ on these specs (First draft - 2023, final draft - 2025)	S. Fabbri, L. Bottura, M. Statera	0%	9.0	1-Jan-23	30-Sep-23
2	Define reference geometries and estimate material needs for technology R&D	M. Statera, L. Bottura	0%	4.0	1-Jan-23	30-Apr-23
3	CERN - Engineering design of final cooling solenoid, 40 T (or higher), 50 mm bore, 500 mm length, stand-alone (First concept 2023, Final Concept 2025)	A. Dudarev, B. Bordini, T. Mulder, A. Bertarelli, C. Accettura	0%	9.0	1-Jan-23	30-Sep-23
4	CERN - R&D pancakes manufacturing and test at CERN, geometry and loading alternatives, resistance control, mechanical testing, powering test	A. Dudarev, B. Bordini, T. Mulder, A. Bertarelli, C. Accettura		36.0		
	Design and tooling		0%	12.0	1-Jan-23	31-Dec-23
	Mechanical tests		0%	18.0	1-Jan-24	31-Dec-24
	Manufacturing start		0%	18.0	1-Jun-24	1-Jun-25
	Testing		0%	24.0	1-Jan-25	31-Dec-26
5	INFN - R&D pancakes manufacturing and test at INFN, small coils having different configurations and characteristics (insulated, non-insulated, dimensions,...). Proposal: Provide test windings for characterization and test at collaborators	M. Statera, S. Sorti		36.0		
	Start construction		0%	12.0	1-Jul-23	1-Jul-24
	Start testing		0%	24.0	1-Jan-24	31-Dec-25
6	(SO'TON) – R&D pancakes manufacturing with insulation/potting technology as tested in EuCARD2 (timeline TBD)	Y. Tang				
7	Testing of small R&D pancakes in background field (10 T, 100 mm maximum) at variable temperature in gaseous helium, for currents up to 1500 A - first tests mid 2024	Y. Tang	0%	12.0	1-Jun-23	30-Jun-24
8	PROPOSAL: PSI - R&D pancakes manufacturing and test at PSI. Share advances and make available small windings for characterization and test at collaborators	J. Kosse (PSI), B. Auchmann (PSI)				
9	PROPOSAL: CEA/LNCMI – Testing of small R&D pancakes in background field (20 T, 120 mm maximum)	X. Chaud (LNCMI), L. Quettier (CEA)				