S5-like Demo Cell
Update on Solenoid Design

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MuCol-WP8 integration meeting

Outline

→ *MuCol Deliverable Report D8.1* solenoid data

→ Study of the engineering limits of *D8.1* configuration

→ Solenoids design optimization strategy

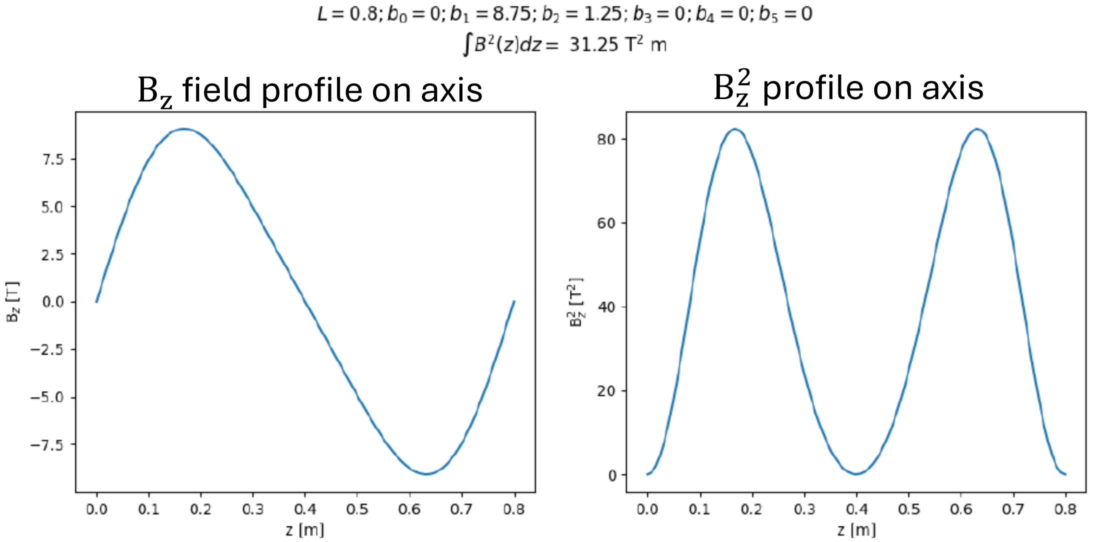
→ Minimum focusing strength error configuration analysis

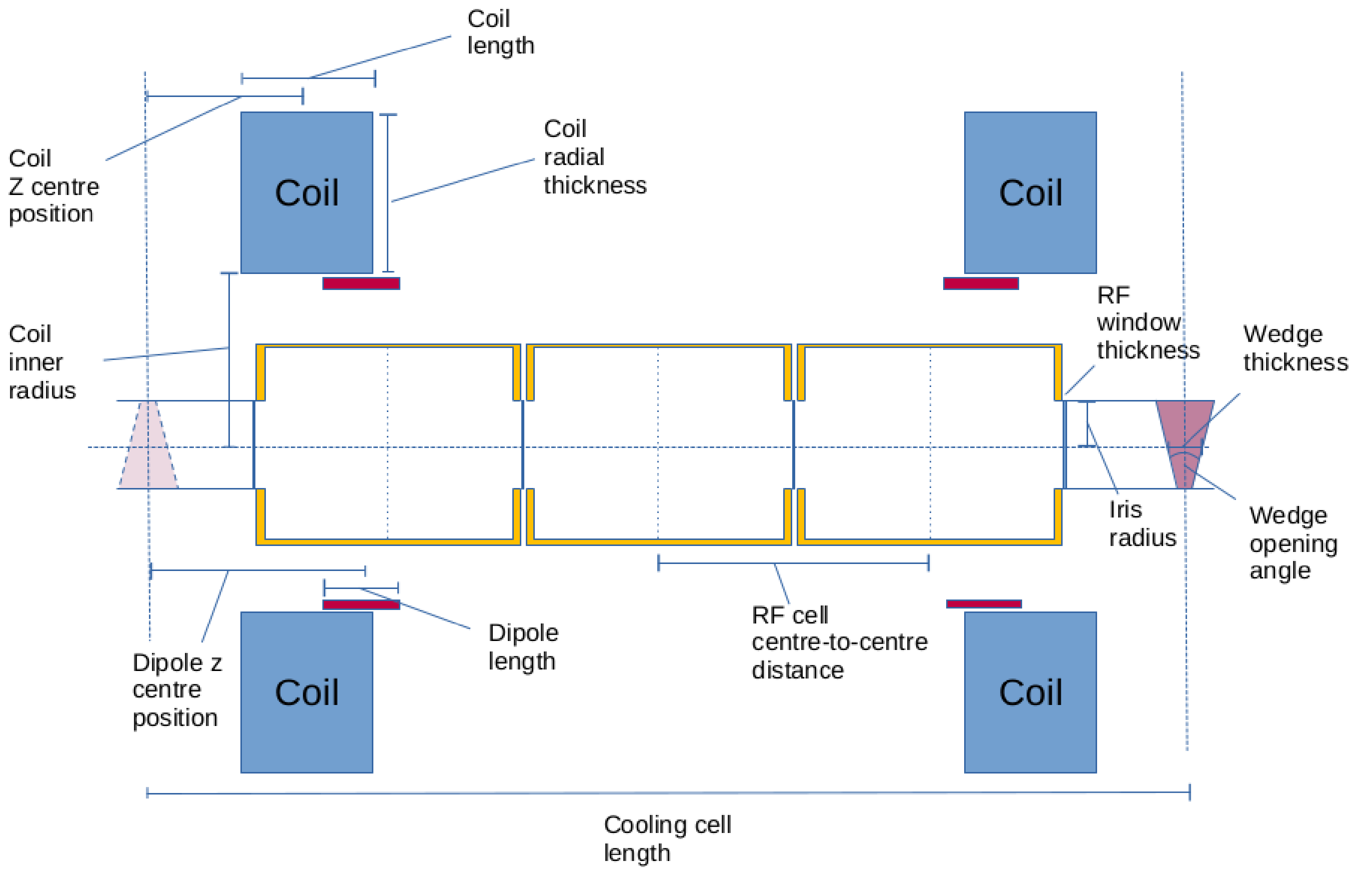
→ Mechanical analyses: *stand-alone* and *lattice* operational modes

→ Reduced-current configuration analysis

S5 demo cell analysis: *MuCol Deliverable Report D8.1*

- Beam optic studies on S5 cell assumed **ideal** solenoids and dipoles.
- Results presented in the *Deliverable Report D8.1*.
- An **engineering design of the stage magnets** is needed.





S5 demo cell: magnets design

- → Design for the target field required by the optics.
- → Magnets must be optimized starting from the proposed solenoid configuration.
- → Motivation: excessive peak field values on the coil section.

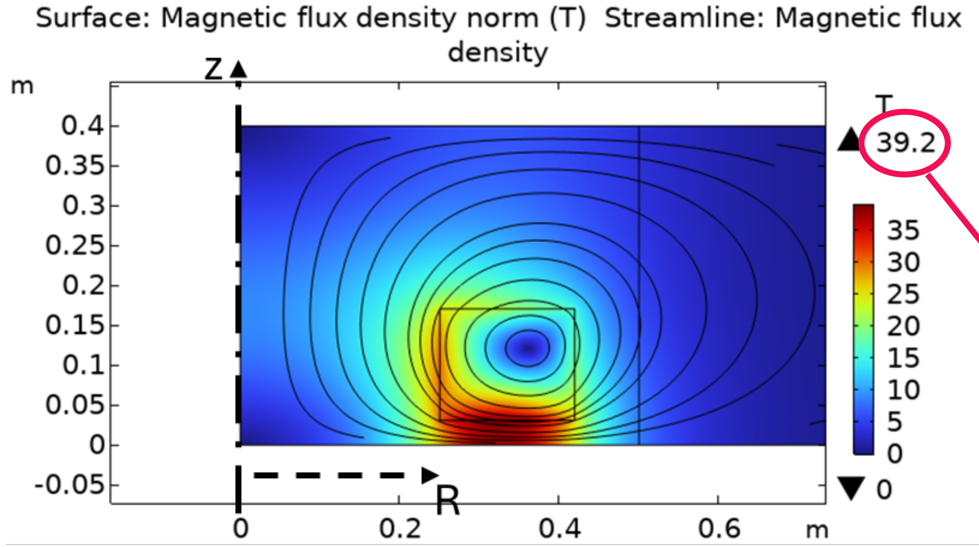
MuCol deliverable report D8.1 parameters

Simulated coil geometry	
Coil inner radius	250 mm
Coil length	140 mm
Coil radial thickness	169.3 mm
Coil z centre position	100.7 mm
Current Density	500 A/mm^2

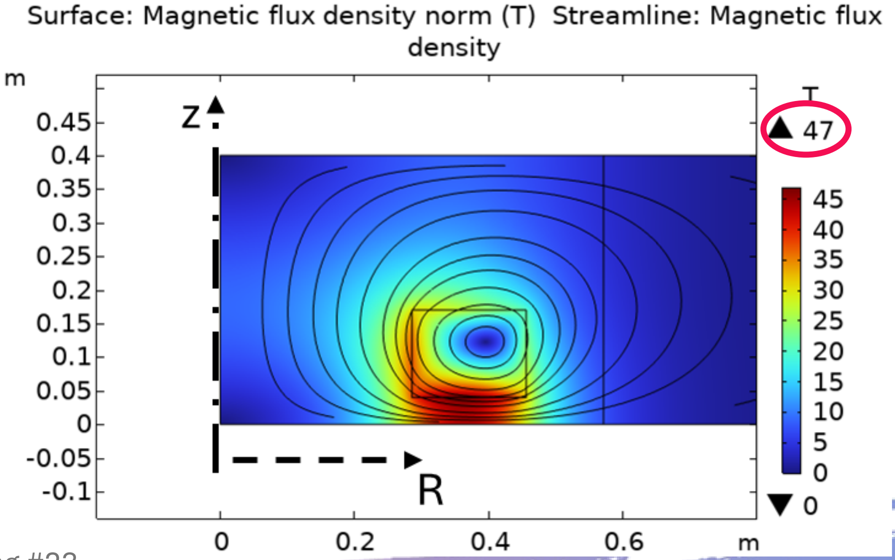
Geometrical radial constraints **not** satisfied*. (RF cavity aperture, cryostat thickness, **dipole radial thickness**)

***Same solenoid shifted to larger radius**, increasing current to keep same profile

Simulated coil geometry	
Coil inner radius	285 mm
Coil length	130 mm
Coil radial thicknes	170 mm
Coil z centre position	105 mm
Current Density	650 A/mm2



Excessive field at the coil section!!



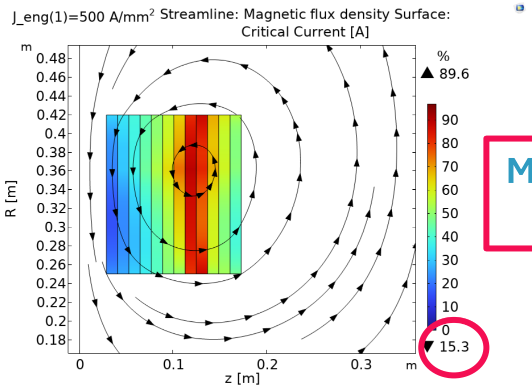
MuCol D8.1 Report configuration: excessive stresses

→ The engineering limits were investigated on the S5 cell solenoid parameters reported in the MuCol Deliverable Report D8.1.

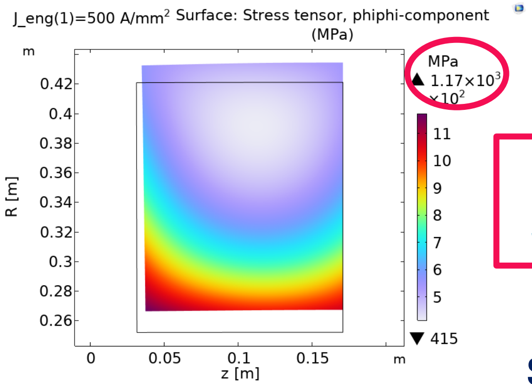
→ Limit for a feasible solenoid design:

MuCol deliverable report D8.1 parameters

$J_{eng} = 250\ A/mm^2$

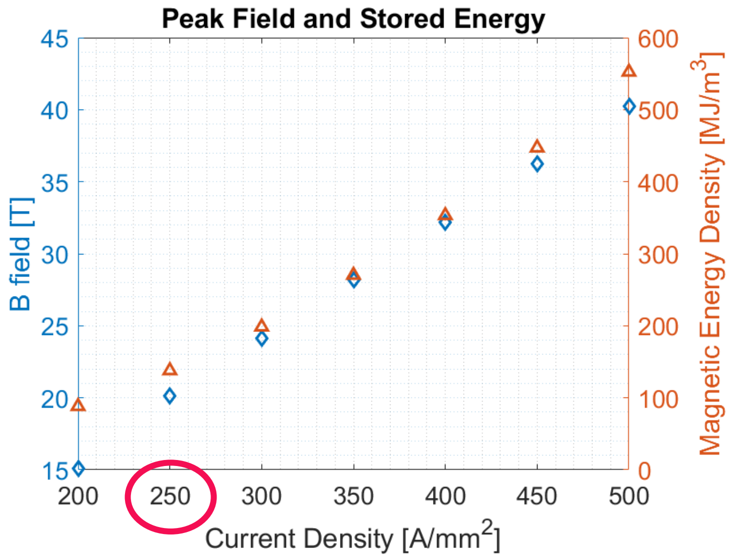


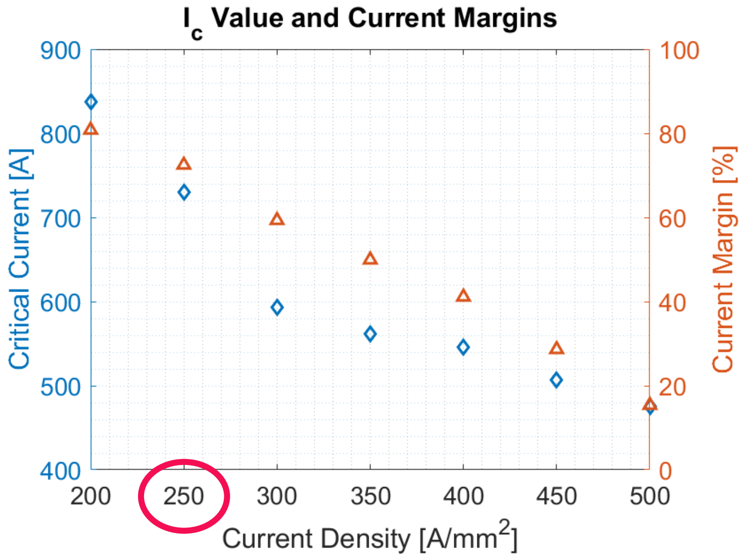
Minimum Current Margin: 15.3%

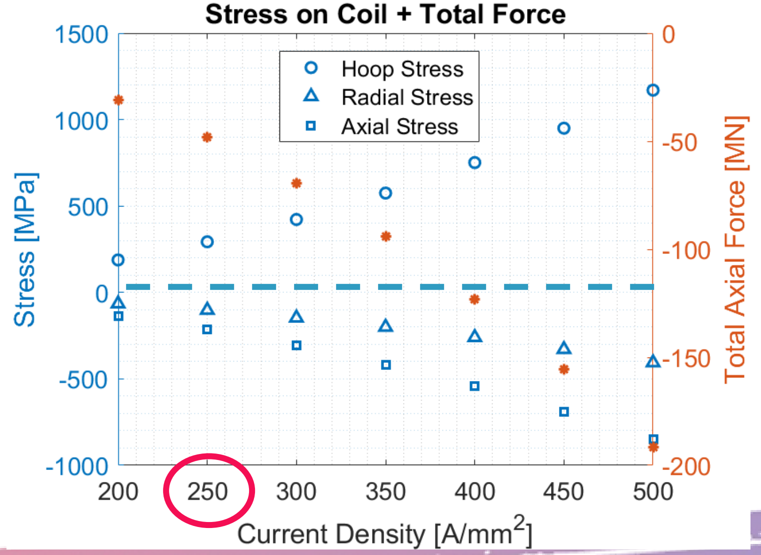


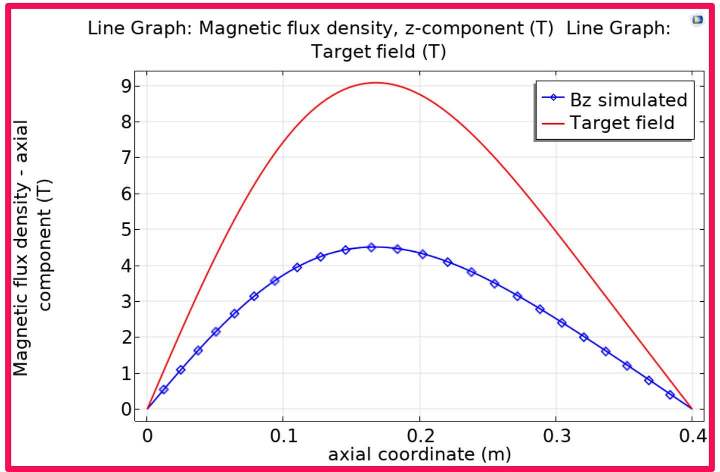
Max Hoop Stress: 1.2 GPa

Stresses are the limit!





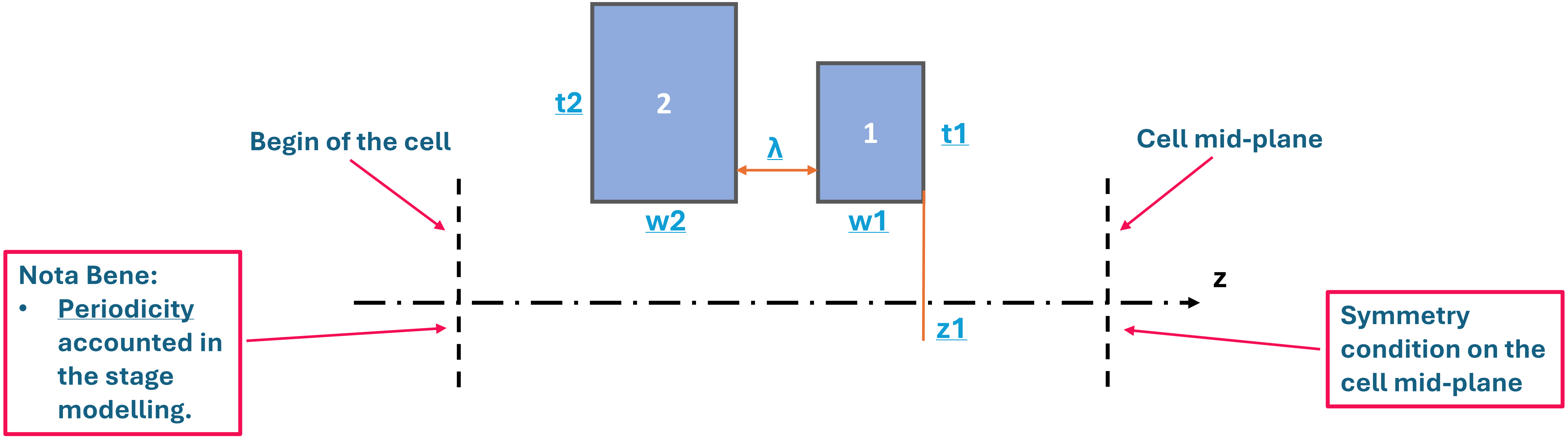




Solenoids optimization strategy: lattice configuration

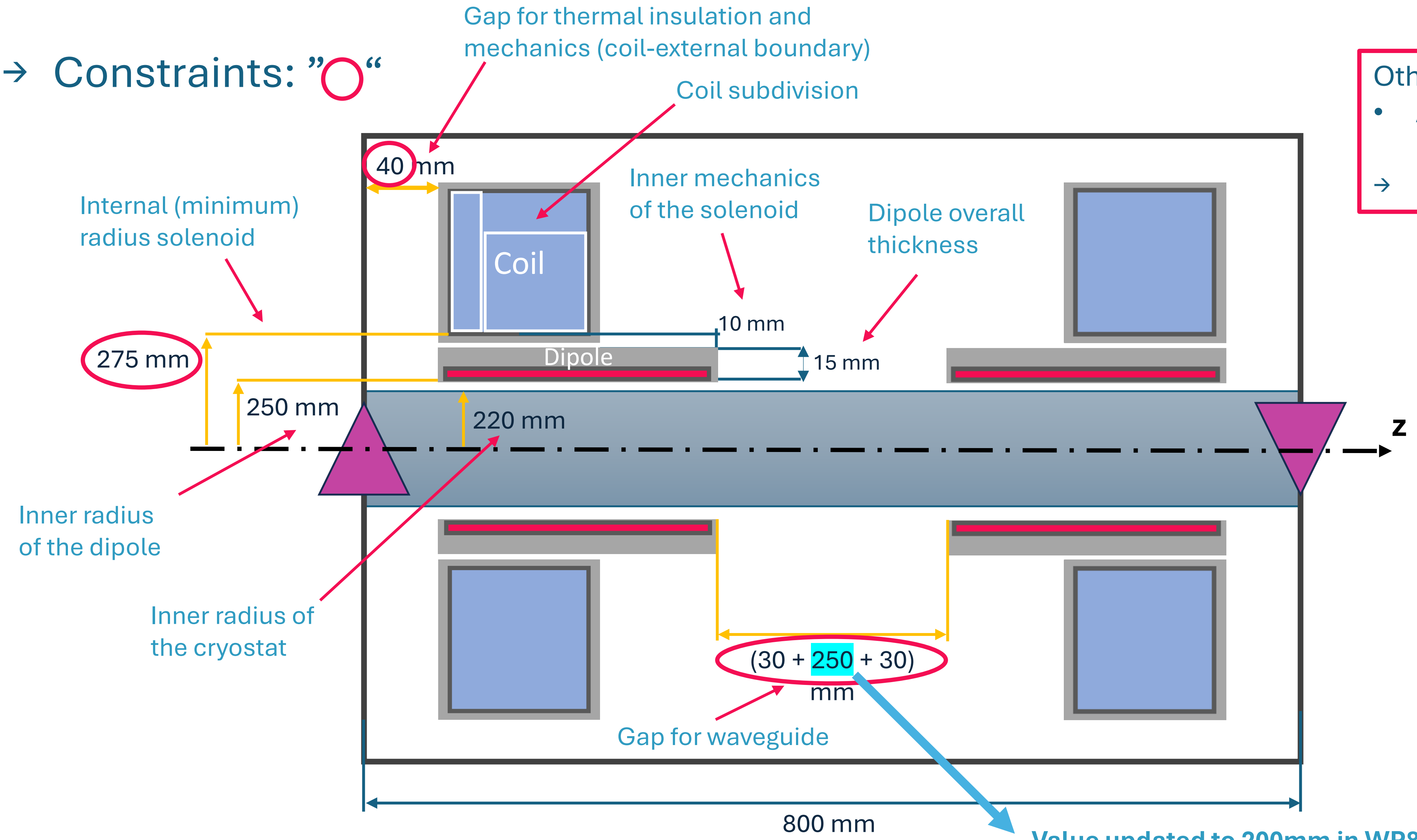
- → Divide the coil section in two to reduce the peak field and optimize their shape to produce the same target field.
- → Parametric sweep of the coil geometrical parameters: 6^4 combinations.

Coil scheme & geom. parameters considered:



Constraints

→ Constraints: "◯"



Other constraint:
- Aspect ratio of the coil section:

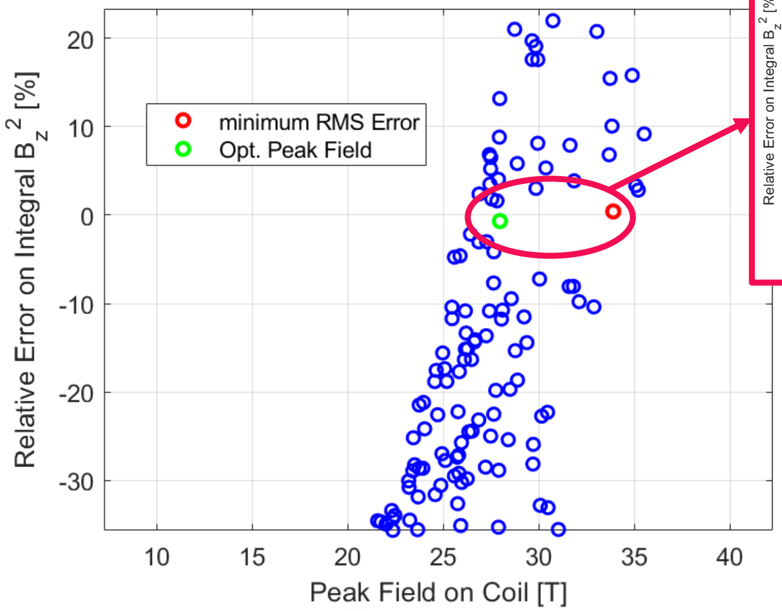
→ 1/3 < wx/tx < 3

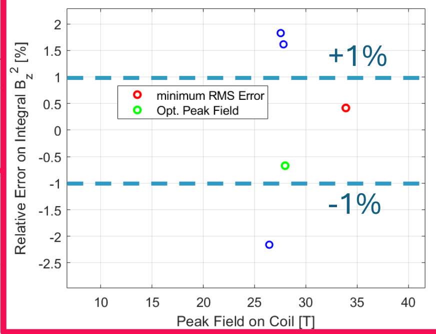
Value updated to 200mm in WP8 meeting #22

Optimization targets

- The search of the **optimal solenoid configuration** should target the following:
  - → Minimum peak field on the coil section.
  - → Minimum RMS error of the axial field w.r.t. the target field expansion.
  - → Minimum error on the focusing strength on the cell length (integral of B_z^2 along the cell axis).
  - → From results considerations: maximum B2 field harmonic component.

2 configuration found:
- **Minimum RMSE.**
- **Optimized: lower peak field.**

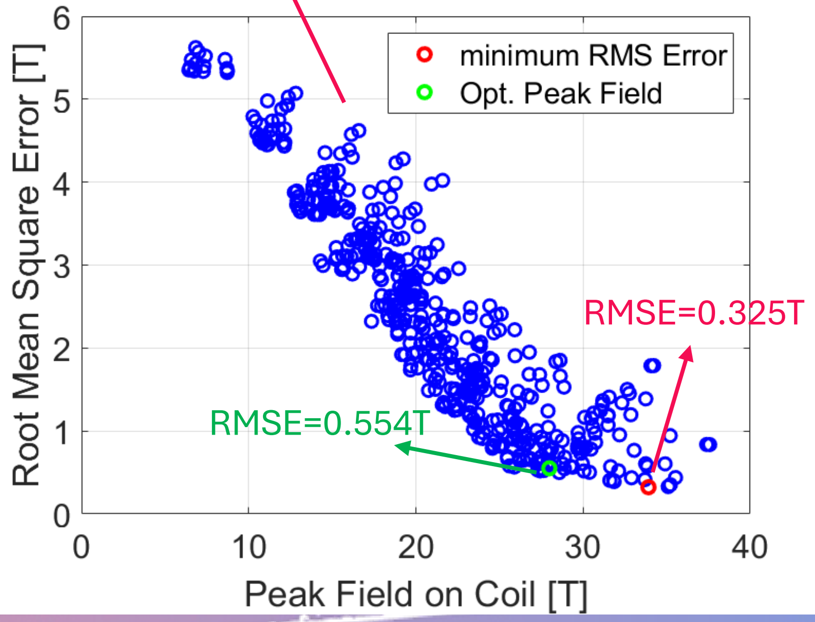




Focusing Strength error within **1%**

Each point corresponds to a unique combination of the geometrical parameters

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} \|y(i) - \hat{y}(i)\|^2}{N}},$$



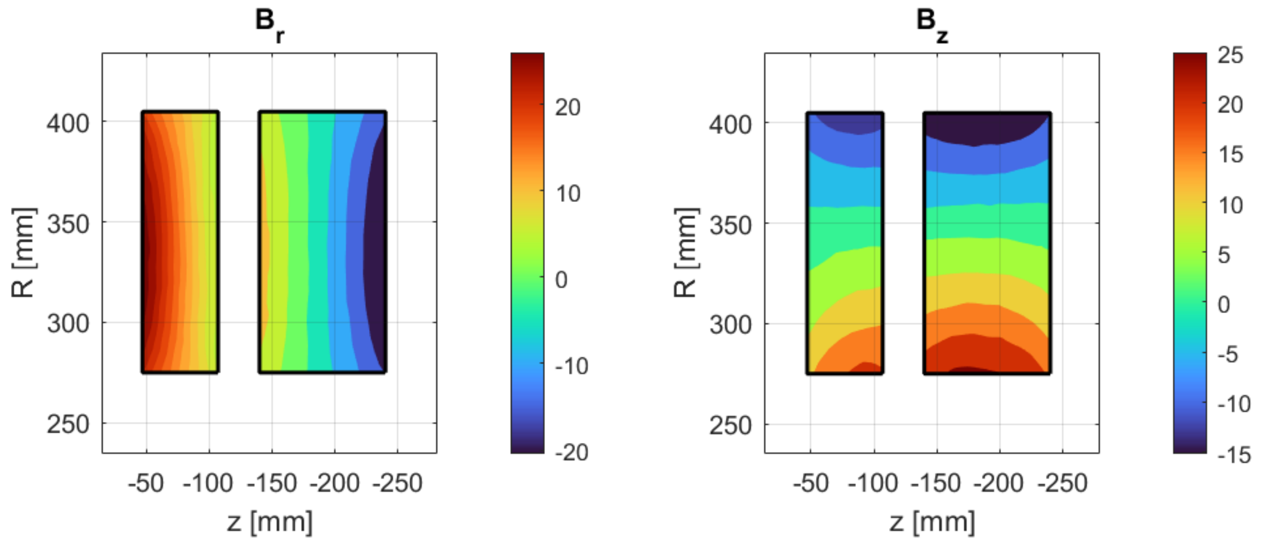
Results

$J_{eng} = 500\ A/mm^2$

→ Lower peak field configuration: RMSE = 0.554 T.

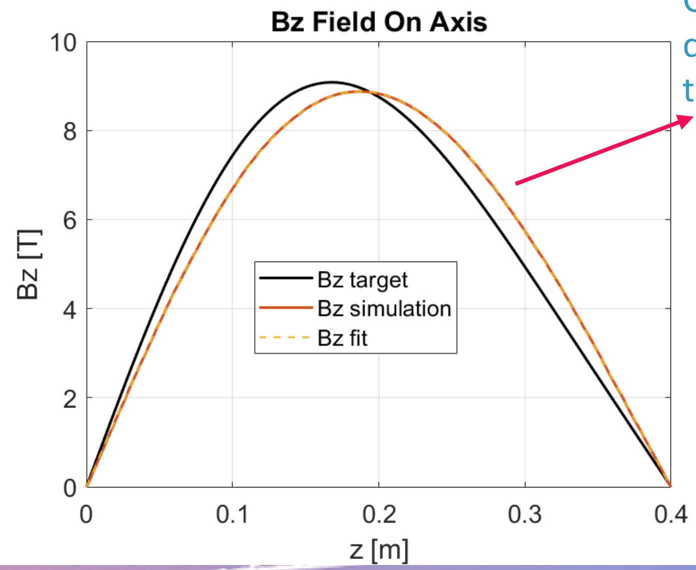
Simulated coil geometry	
z1	240 mm
w1	100 mm
t1	130 mm
z2	107 mm
w2	60 mm
t2	130 mm

N.B: 6D stage **lattice** considered!



Peak field still high, but improved w.r.t. single coil stack (>40T)!

Coil Parameters	
Current Margin [%]	30.9
Minimum Critical current [A]	582
Temperature Margin [K]	27.2
Total magnetic energy in cell [MJ]	47.4



Computed field disaligned w.r.t. the target…

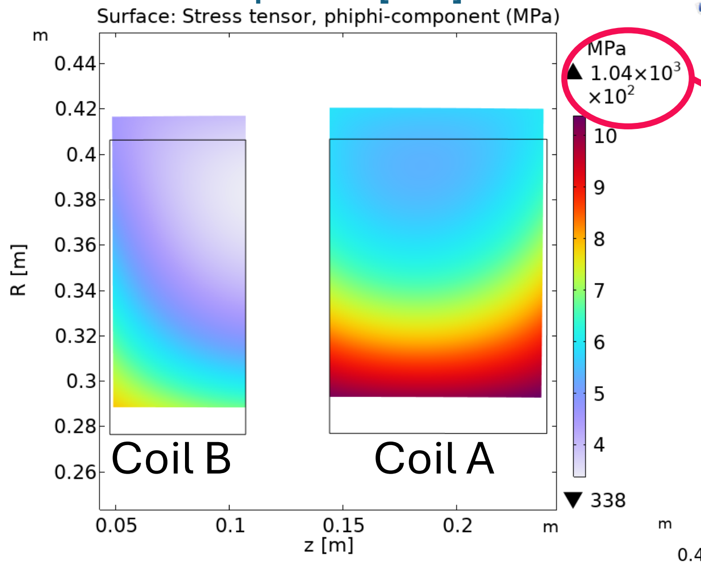
Mechanical Analysis: No prestress, no radial constraints

→ Mechanical analysis of the **free-expanding coils**.

→ **Limiting hoop stress values**!

→ Resulting force on the coils points towards the center of the cell (**attractive force**).

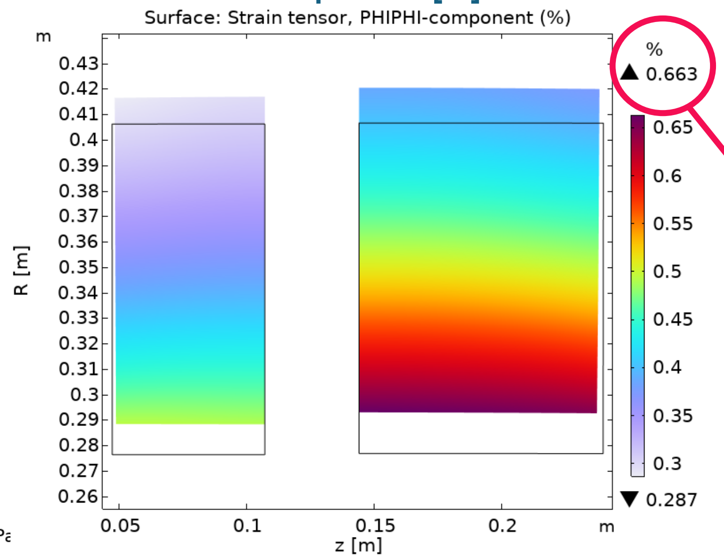
Hoop Stress [MPa]



No radial constraints applied.

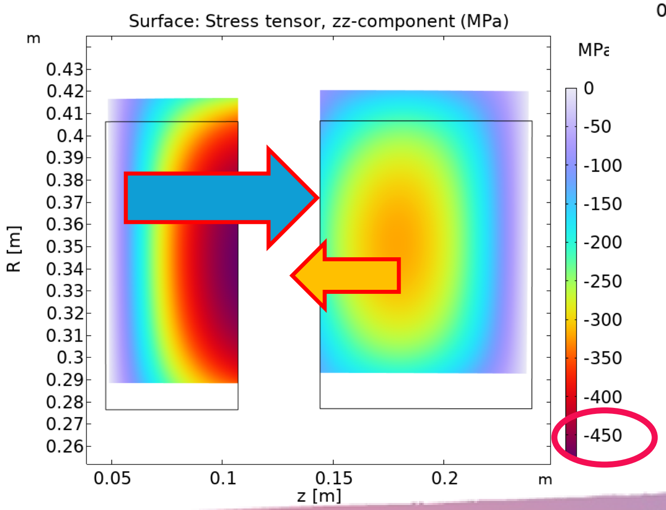
→ The coils are **not self-sustaining**

Hoop Strain [%]



>> Limit value of **0.3 %**

Axial Stress [MPa]



Coil Axial Forces:

→ Coil A: **47.5 MN**

→ Coil B: **-119 MN**

Net Force:

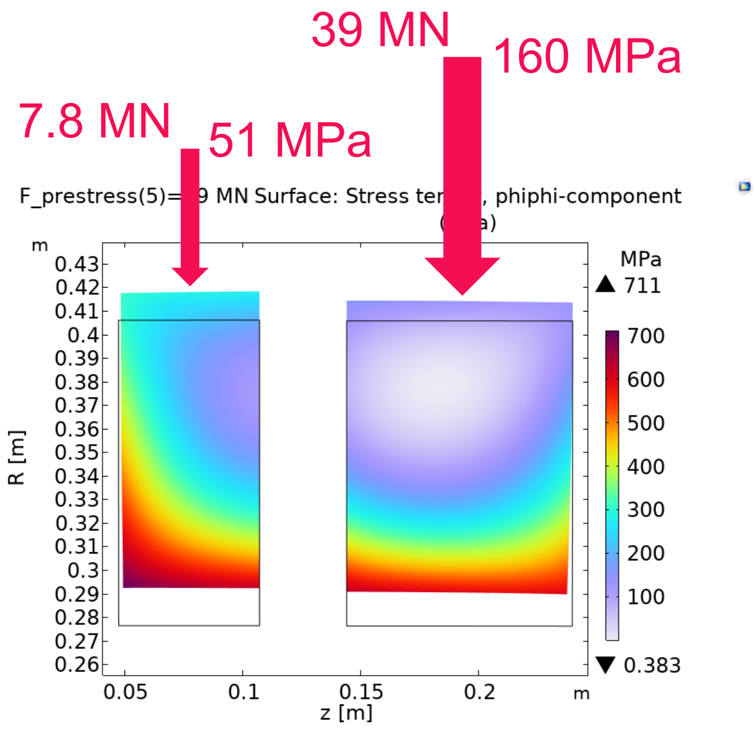
→ **-71.5 MN**

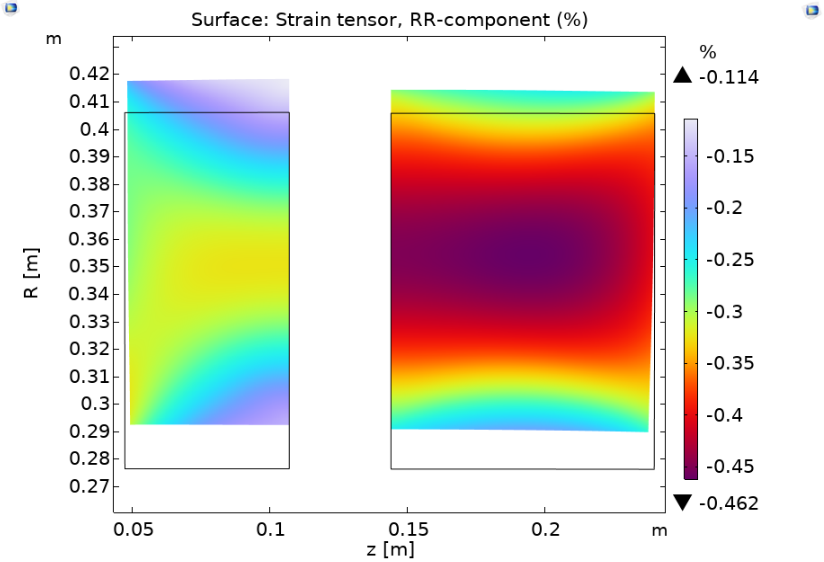
N.B:
6D stage **lattice** considered!

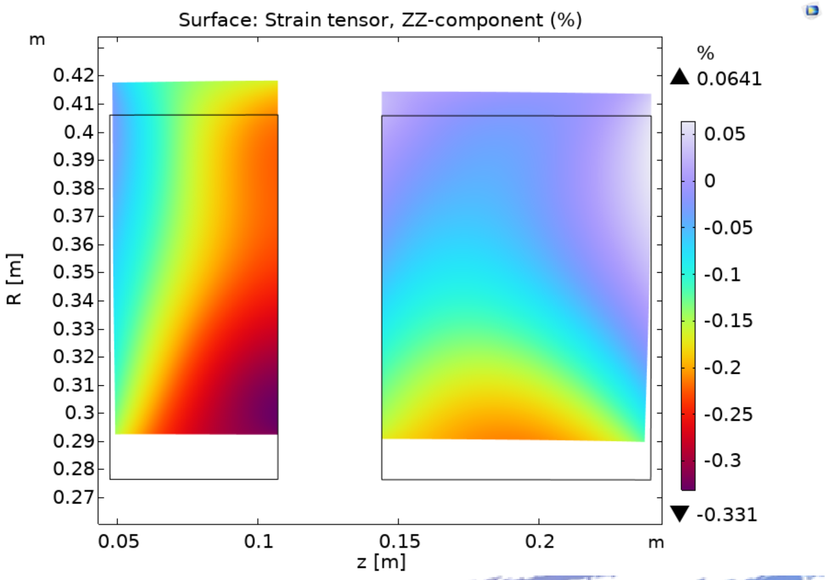
Prestress Study: Pressure on free boundary (I)

- Free radial expansion, pre-stress added as an external uniform pressure acting on the $R = R_{ext}$ plane.
- Parametric sweep of the applied force on the boundary stopped when hoop stress started to get negative values. Last step: 39 MN on Coil1, 7.8 MN on Coil2.
- Max hoop stress still **>700 MPa** ☹. Max hoop strain 0.5% > limit hoop strain!☹

First approach: **avoid negative hoop stress** values!







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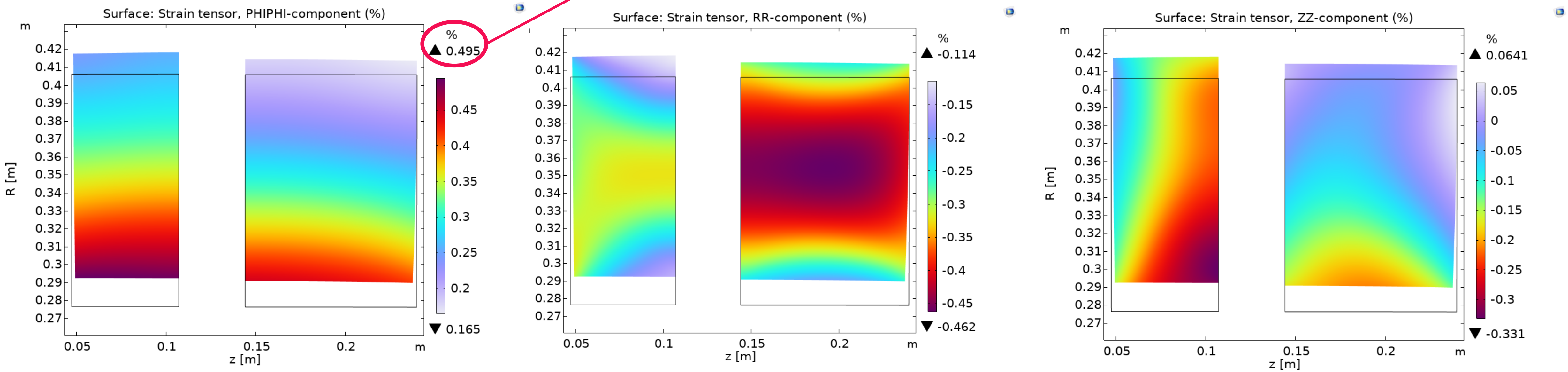
Max hoop strain > 0.3 %...

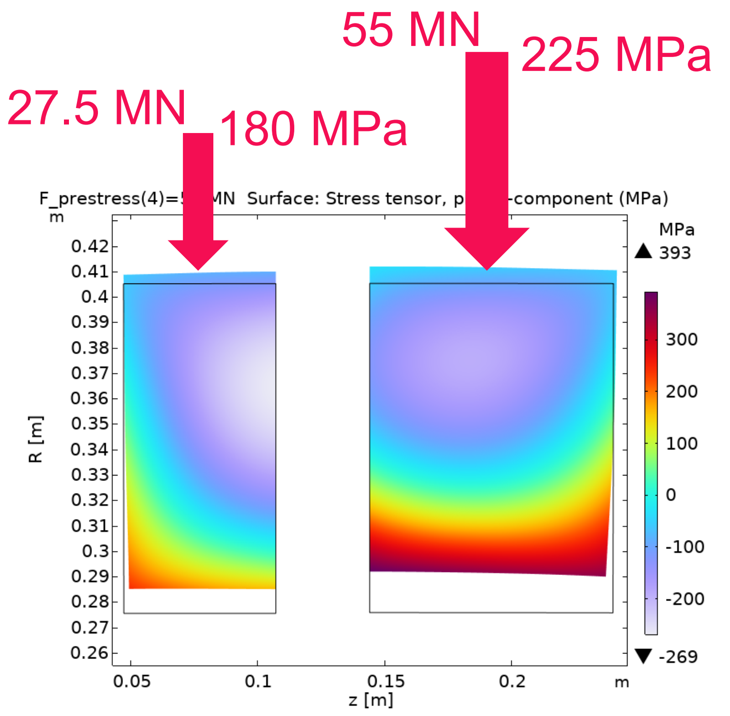


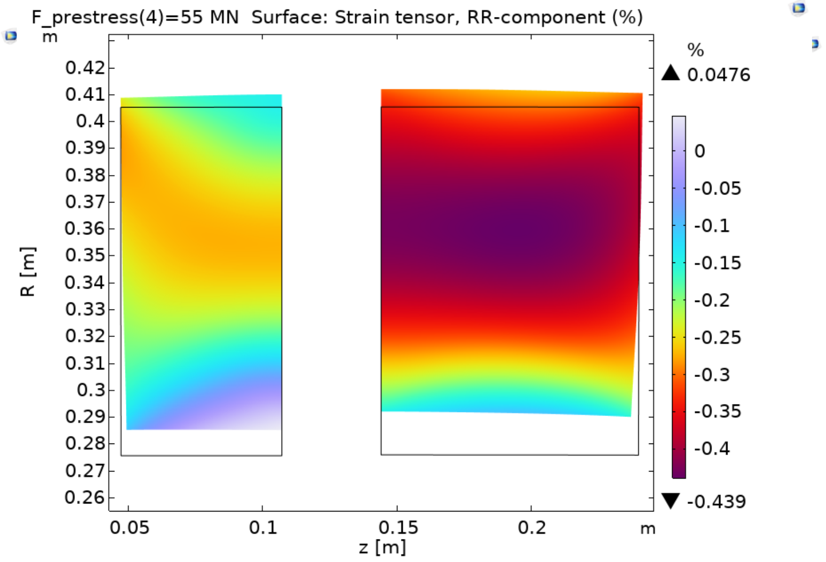
N.B: 6D stage **lattice** considered!

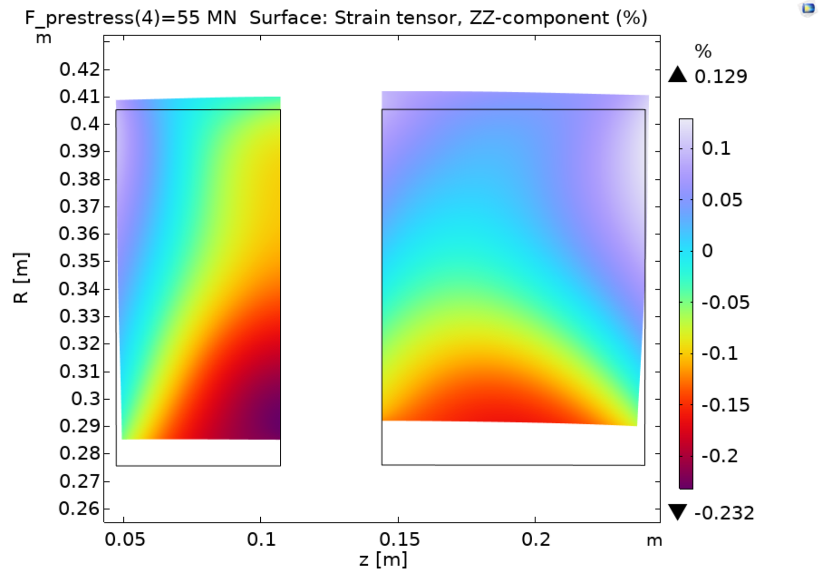
Prestress Study: Pressure on free boundary (II)

- Free radial expansion, pre-stress added as an external uniform pressure acting on the $R = R_{ext}$ plane.
- Parametric sweep of the applied force on the boundary stopped when hoop strain < 0.3% reached… BUT negative hoop stress. → Last step: 55 MN on Coil1, 27.5 MN on Coil2.
- Max **hoop stress 393 MPa / -269 MPa**. Max hoop strain 0.28% < limit hoop strain!

Approach: **hoop strain < 0.3% !!**







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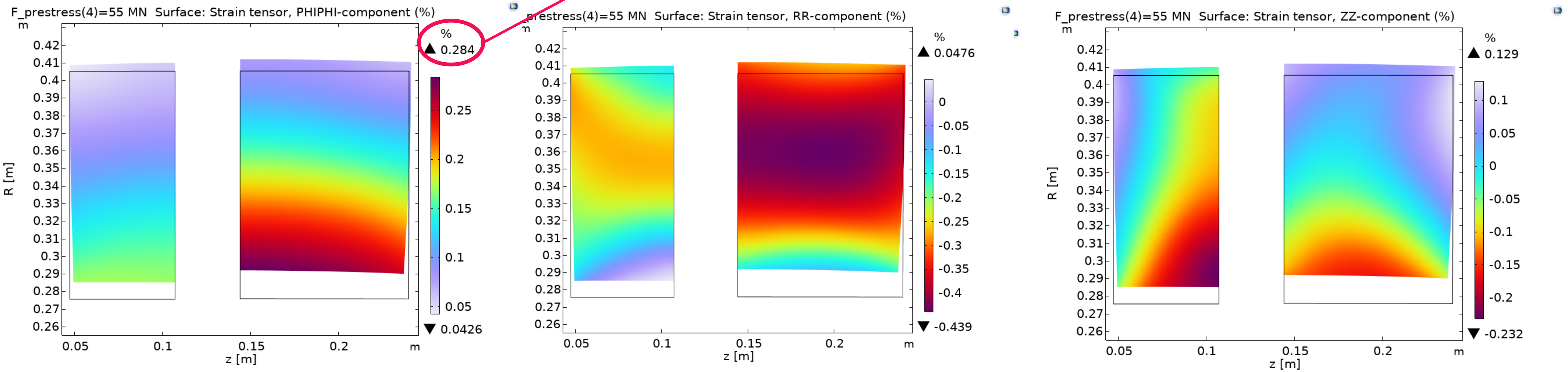
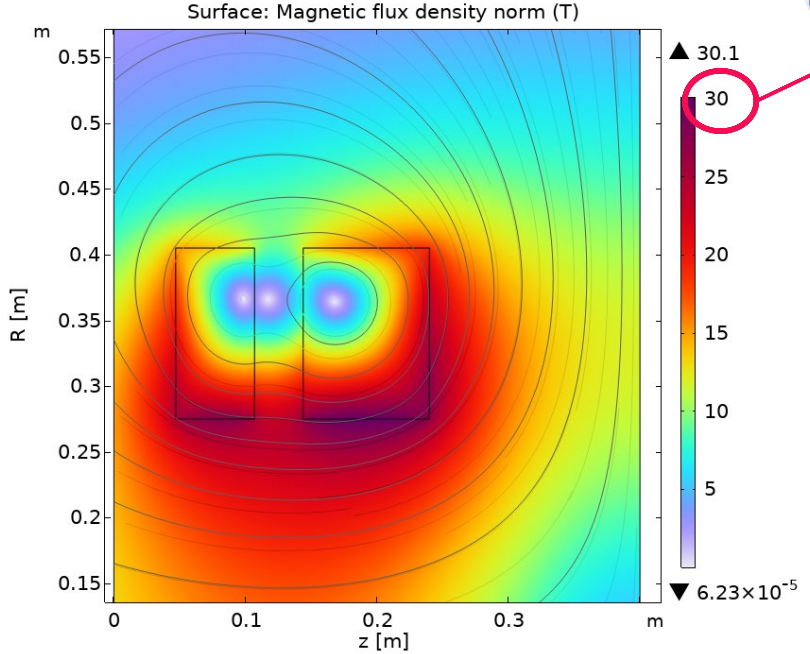


N.B: 6D stage **lattice** considered!

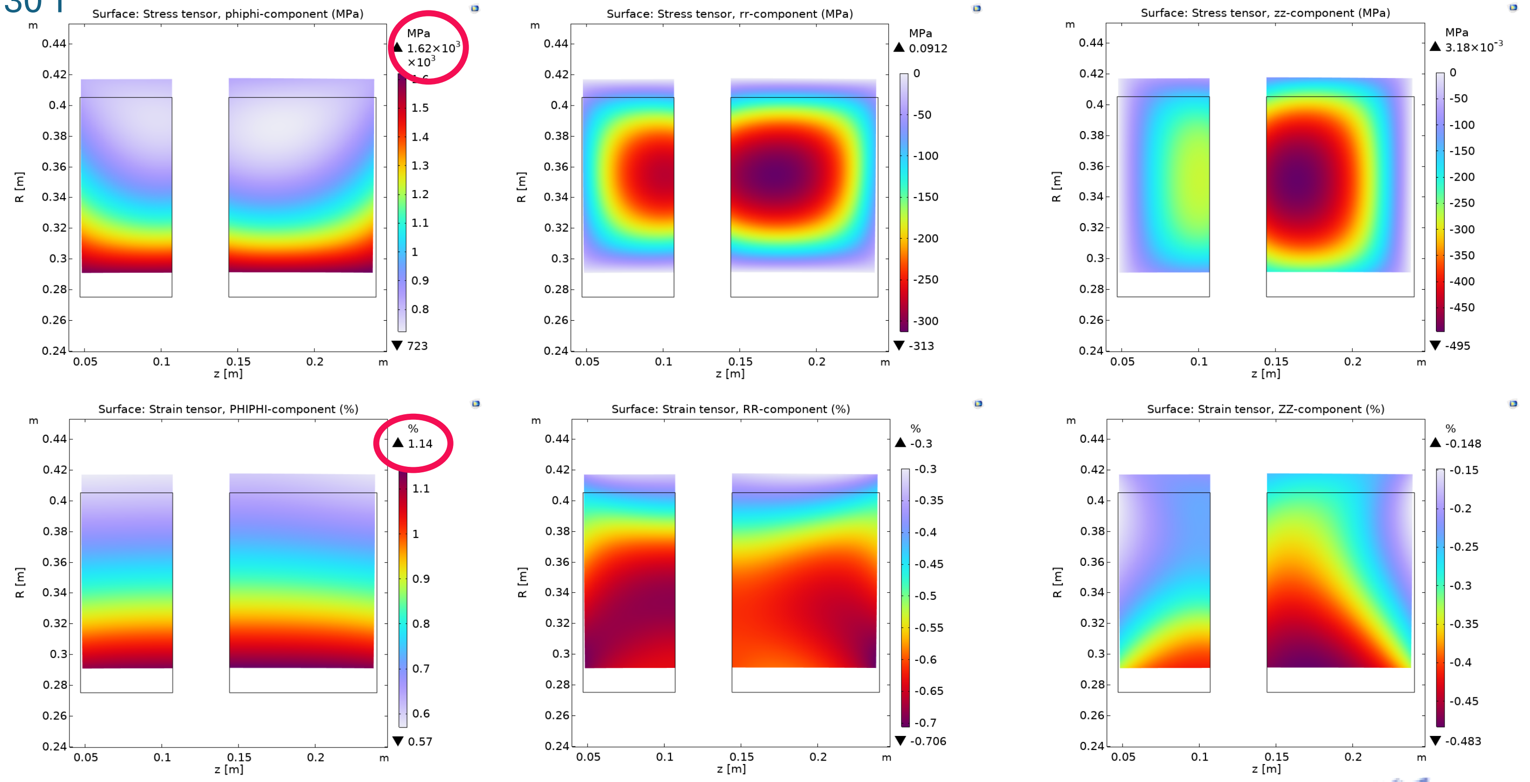
Mechanical Analysis:stand-alone demonstrator

- Results for the **stand-alone** demonstrator stage.
- This case is representative of the steady-state condition on an S5 stage following a fault shutdown on subsequent stages.



- Peak field increased to 30 T

Test: no prestress, no radial constraints.



Applied prestress needs to be increased:
- Apply **85 MN** on **Coil1** and **51 MN** on **Coil2** to have a peak hoop strain value of **0.29%**. Still **negative hoop stress** regions.

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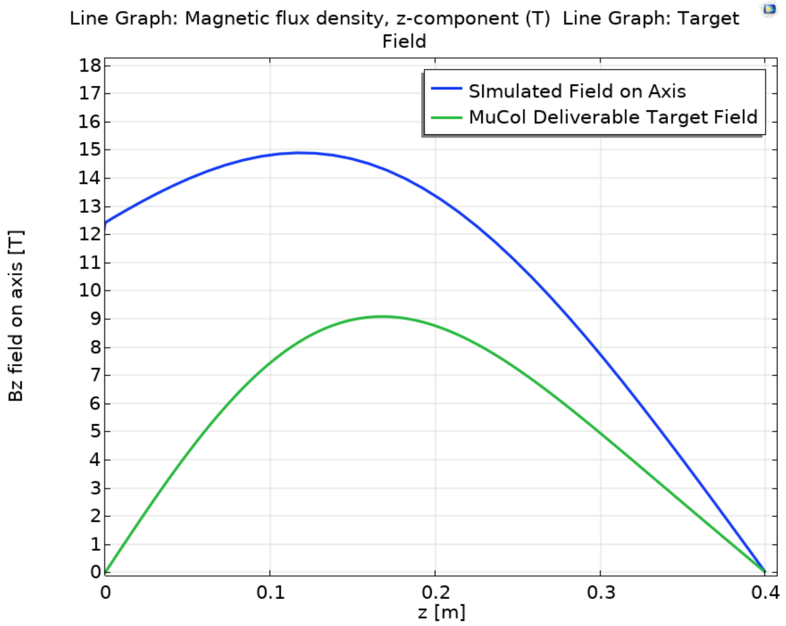

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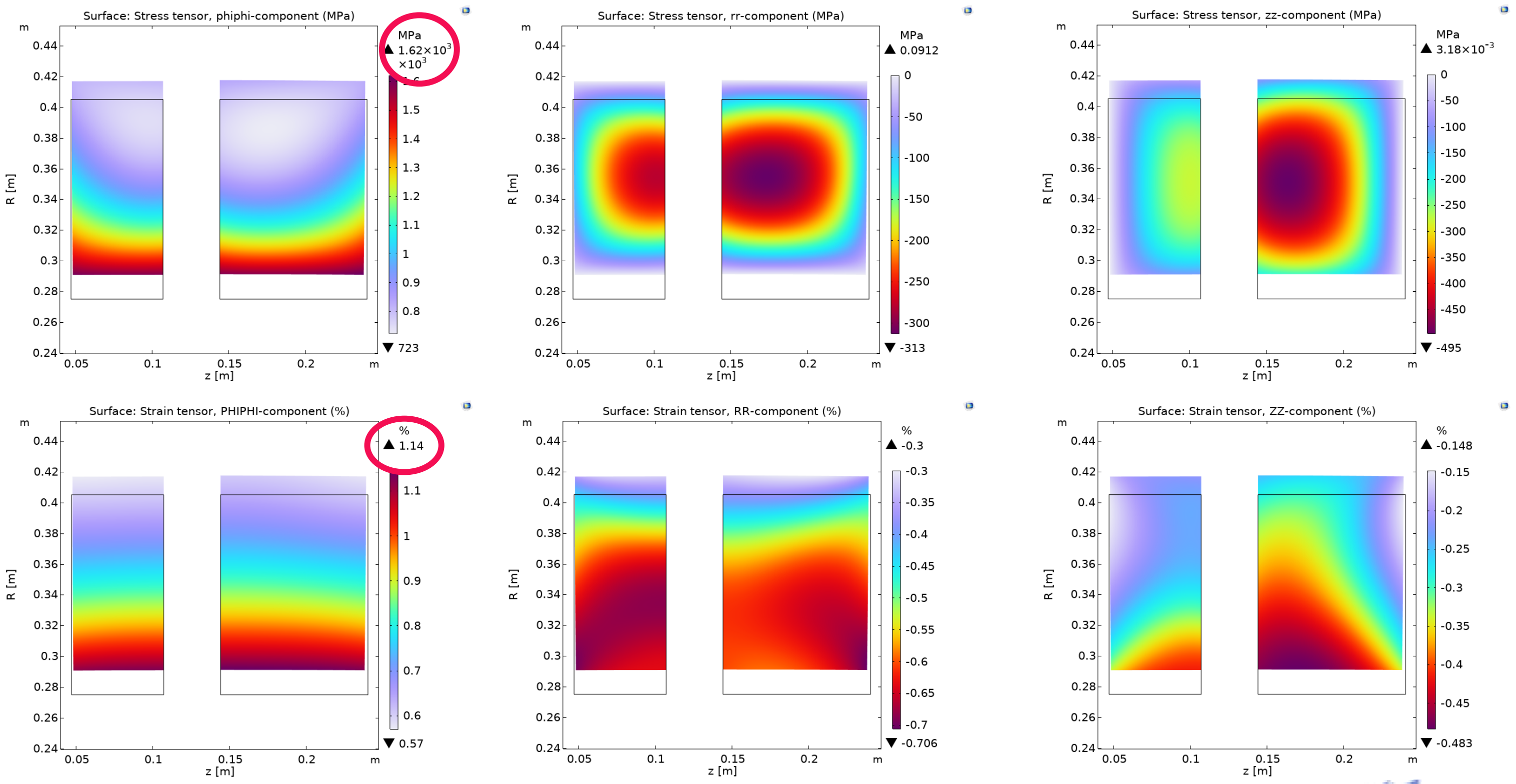

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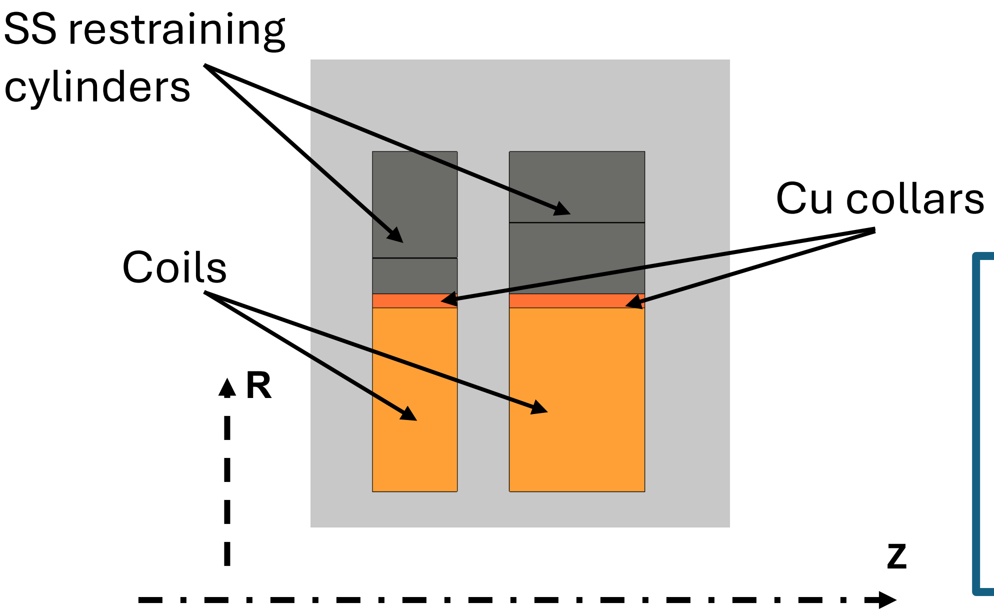
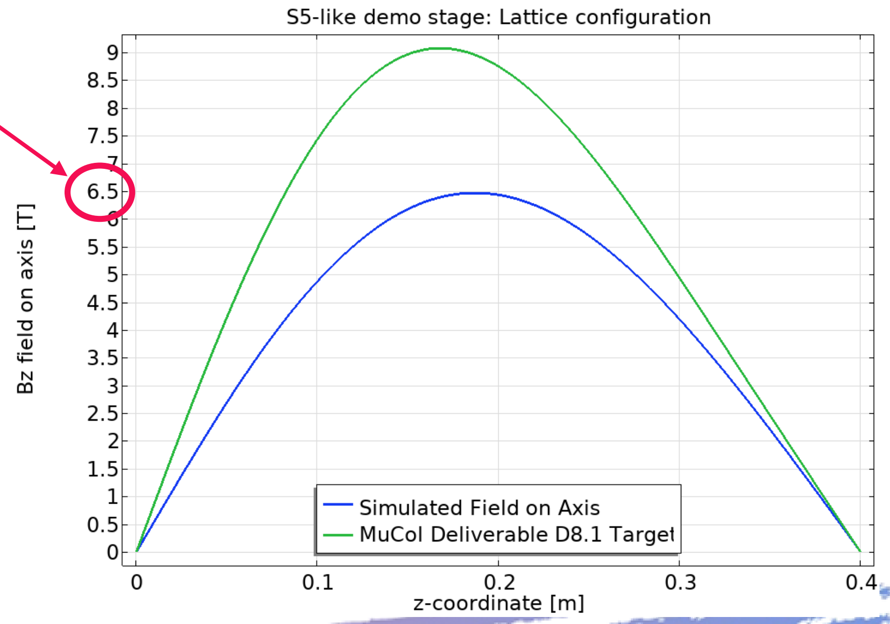
Reduced-current solenoid for first integration excercise

- Considering the required field targets, the **proposed solenoid configuration still does not respect the mechanical limits** of HTS-based coils.
- A **reduced-current configuration** has been studied: $\mathbf{J_{eng} = 375\ A/mm^2}$ (25% reduction).
- The **magnet design** and **cell integration** has been conducted on this configuration. The displayed **results does not meet the requested field targets on the beam axis**.
- Both configurations (***stand-alone***, ***lattice***) has been considered in the mechanical design.



Two separated AISI 316LN steel restraining collars has been added: in case of stand-alone stage operation, the coil-structure deformation will be contained by the most external SS ring.

Reduced peak field on axis: 6.5 T.



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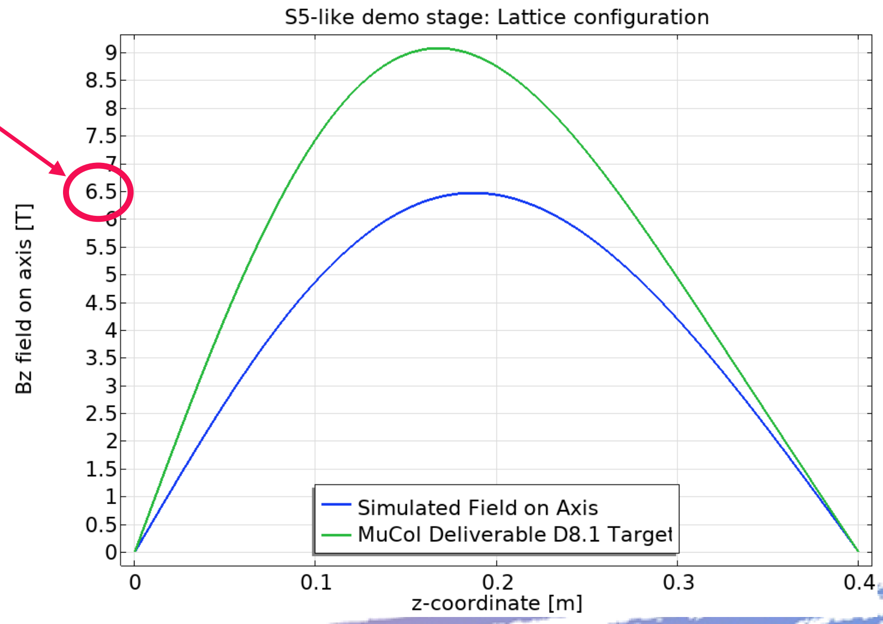
Figures of Merit	Value
RMS difference [T]	1.67
Reduction on Integral B_z^2 along the axis [%]	47.03

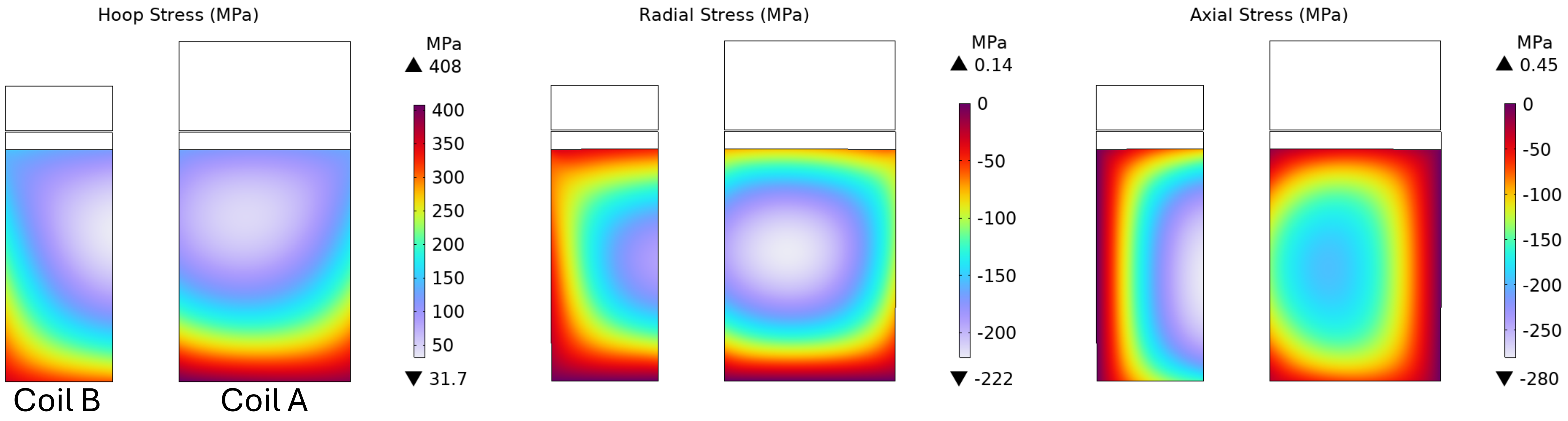
Reduced peak field on axis: 6.5 T.



Reduced-current solenoid design: lattice operation (I)

- The mechanical design of the S5-like solenoids converged to a **25% reduced current configuration.**
- To limit the stresses in the solenoids in lattice operation, SS collars must be fit on the **10 mm Cu rings** containing the coils. A **50 mm SS collar** is needed for **coil A**, **25 mm SS collar** for **coil B**.
- A **0.8 mm interference** between the two collars is **required** to contain the stresses in a **self-sustaining coil configuration**.

Coil stress components: lattice configuration



Stresses are within the mechanical limits!

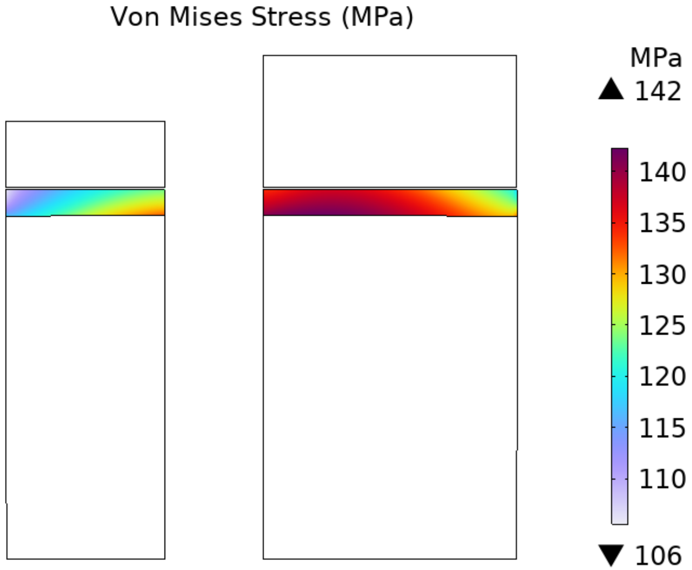
Reduced-current solenoid design: lattice operation (II)

→ The **Von Mises stress** was assessed in the **Cu collars** and **SS restraining rings**.

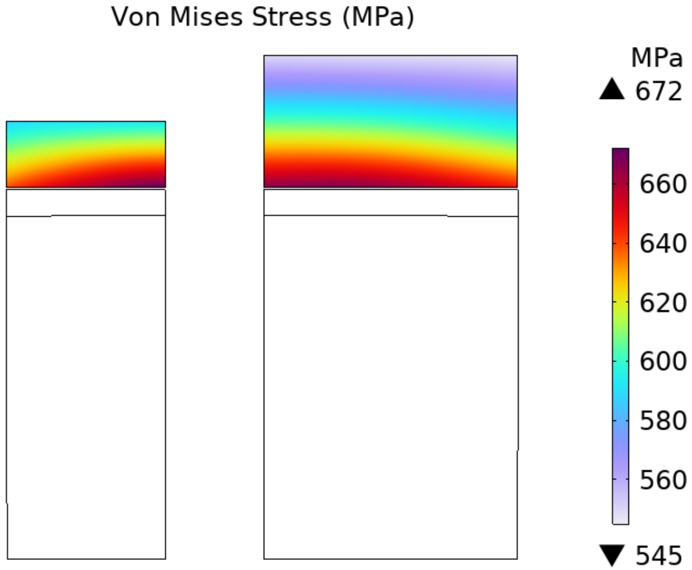
→ The resulting stresses are **compatible with the elastic limits of the materials** considered.

→ The **total radial displacement** is needed to determine the radial gap with the external SS ring required for the stand-alone cell operation.

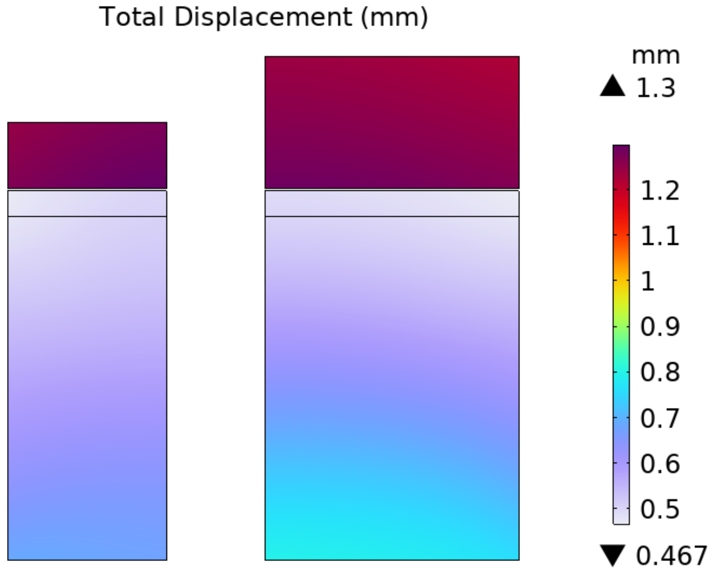
Cu collars



SS restraining rings



Total displacement

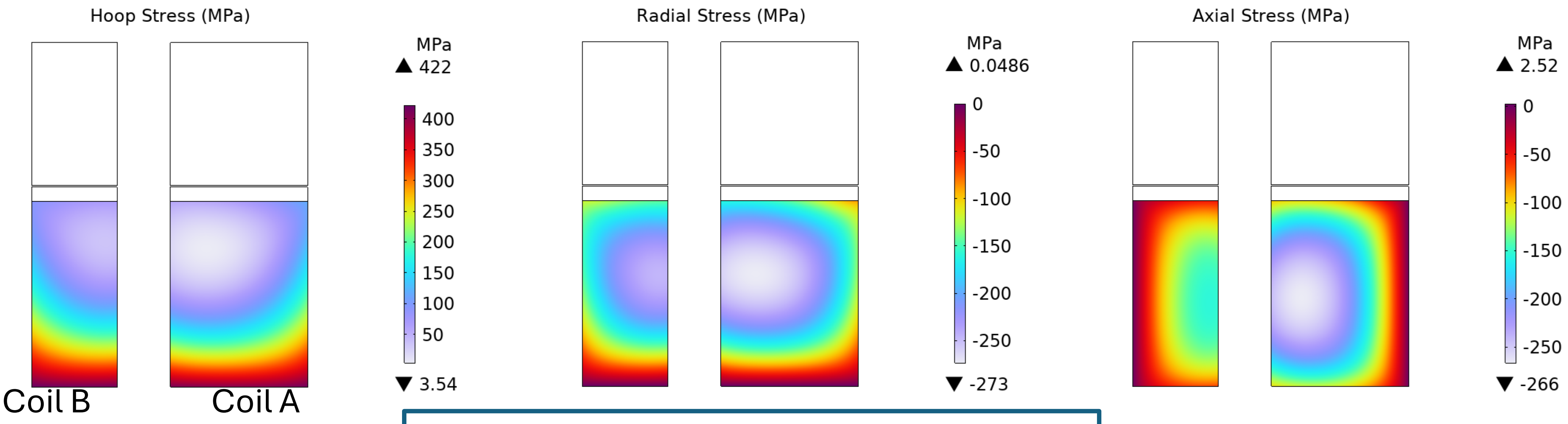


Stresses are within the mechanical limits!

Reduced-current design: stand-alone operation (I)

- The load conditions in the stand-alone cell operation are remarkably different to the analyzed lattice configuration.
- To limit the stresses in stand-alone operation, **additional SS collars must be fit** on the coils structure. Addittional **50 mm SS collar** is needed for **coil A, 75 mm SS collar** for **coil B**.
- A **0.8 mm interference** between the two collars is **assumed**.

Coil stress components: lattice configuration



Stresses are within the mechanical limits!

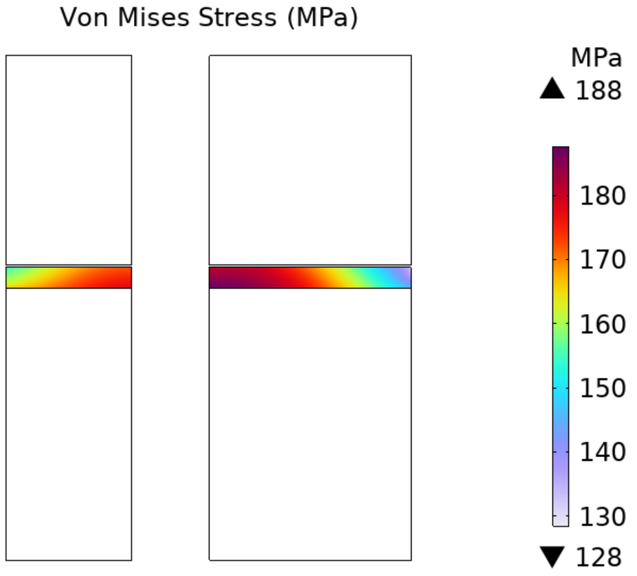
Reduced-current design: stand-alone operation (II)

→ The **Von Mises stress** was assessed in the **Cu collars** and **SS restraining rings**.

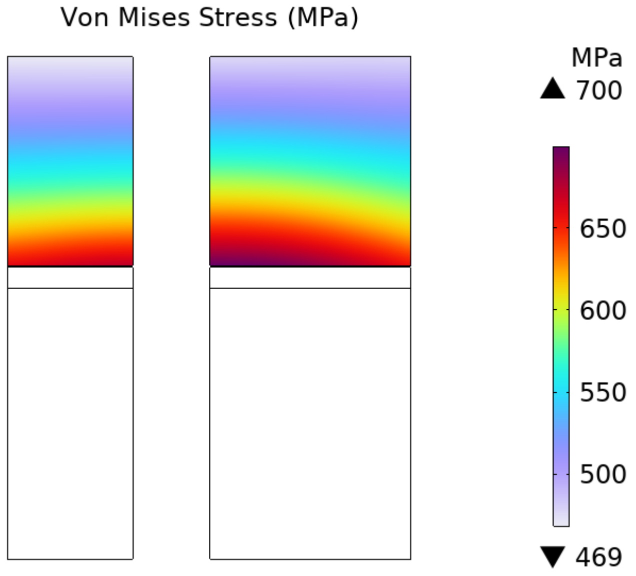
→ The resulting stresses are **compatible with the elastic limits of the materials** considered.

→ The **total radial displacement** has been assessed on the structure.

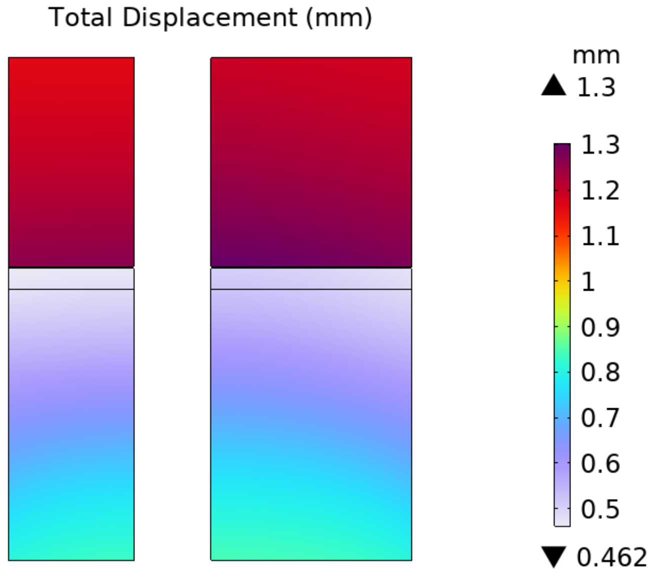
Cu collars



SS restraining rings



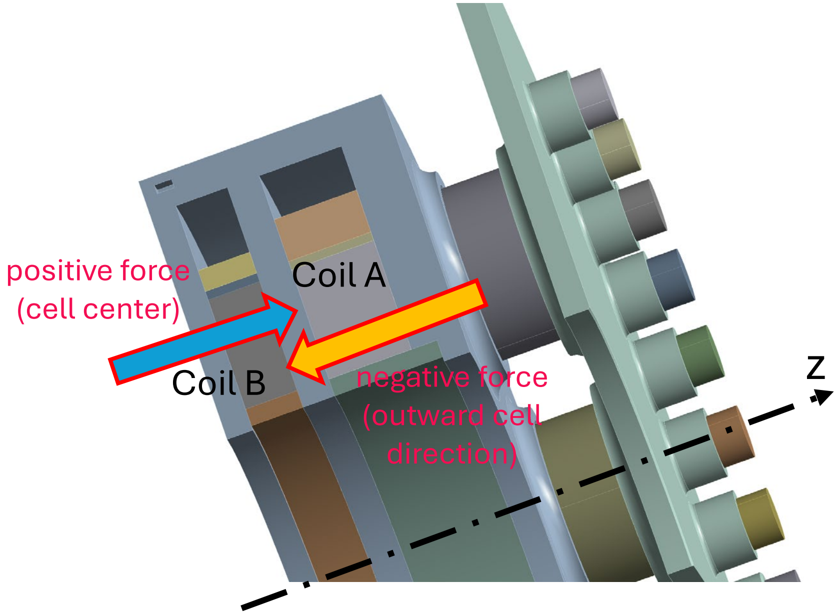
Total displacement



Stresses are within the mechanical limits!

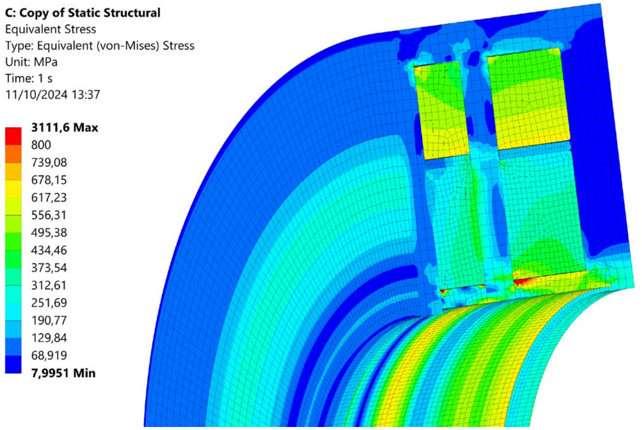
Reduced-current design: support structure design

- The coil support structure has been designed to sustain the coil axial forces in the two configurations: ***stand-alone***, ***lattice***.
- Thick AISI 316LN shell is needed to sustain the axial forces in normal out-of-cell direction.
- Even in the reduced-current configuration, **the mechanical design of the support structure is not trivial.**

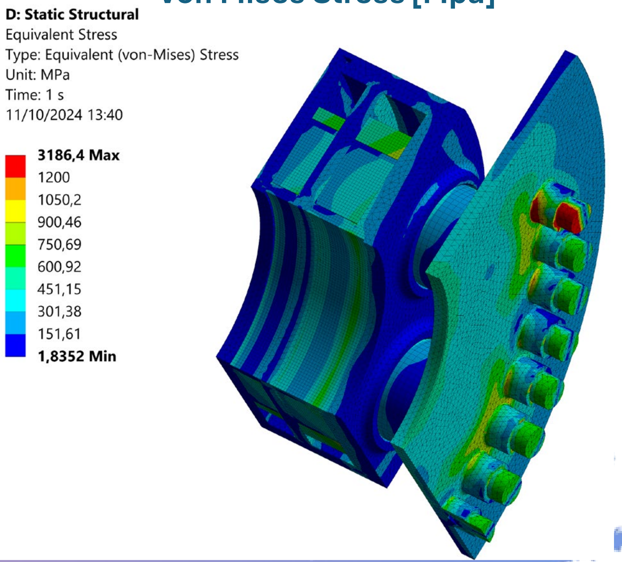


Coil Axial Forces	Coil A/Coil B Value [MN]	Net Force Value [MN]
Lattice configuration	-27 / +67	+50
Stand-alone configuration	-55 / +35	-20

Stand-alone configuration: Von Mises Stress [Mpa]



Lattice configuration: Von Mises Stress [Mpa]



Summary and next steps

- → The magnet design for the S5-like demonstrator cell looks challenging, in particular from a mechanical point of view.
- → The **search for an optimized solenoid configuration**, respecting the required focusing strength, converged to the two-coil-subdivision configuration presented.
- → The **mechanical limits** of the materials constituting the assembly are **not respected**, thus a reduced-current configuration has been studied.
- → A **25% coil current reduction** (from $500\ \mathrm{A/mm^2}$ to $375\ \mathrm{A/mm^2}$) decrease the coil stresses within their mechanical limits: a **collar** and **support structure design** has been **proposed**.
- → The **support structure** design **still presents criticalities** to be solved, the stresses appear excessive, requiring 60 mm Inconel bolts and a thick shell (with **associated increased cost** and **manufacturing complications**…).

- → **Further iterations are needed**, both on the **magnets design** and on the **cell integration** study!

Thank you for your attention!