International MUON Collider Collaboration

MuCol

Cooling Cell Integration Issues

Lucio Rossi – Marco Statera – Giuseppe Scarantino – Mattia Castoldi WP8 & WP7

Dario Giove WP8 & WP6

Univ. of Milan & INFN-Milan-LASA

Roberto Losito – Siara Fabbri & Luca Bottura CERN WP7 – WP8

Funded by the European Union

INFN Istituto Nazionale di Fisica Nucleare

CERN

Funded by the European Union (EU). Views and opinions expressed are however those of the author only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

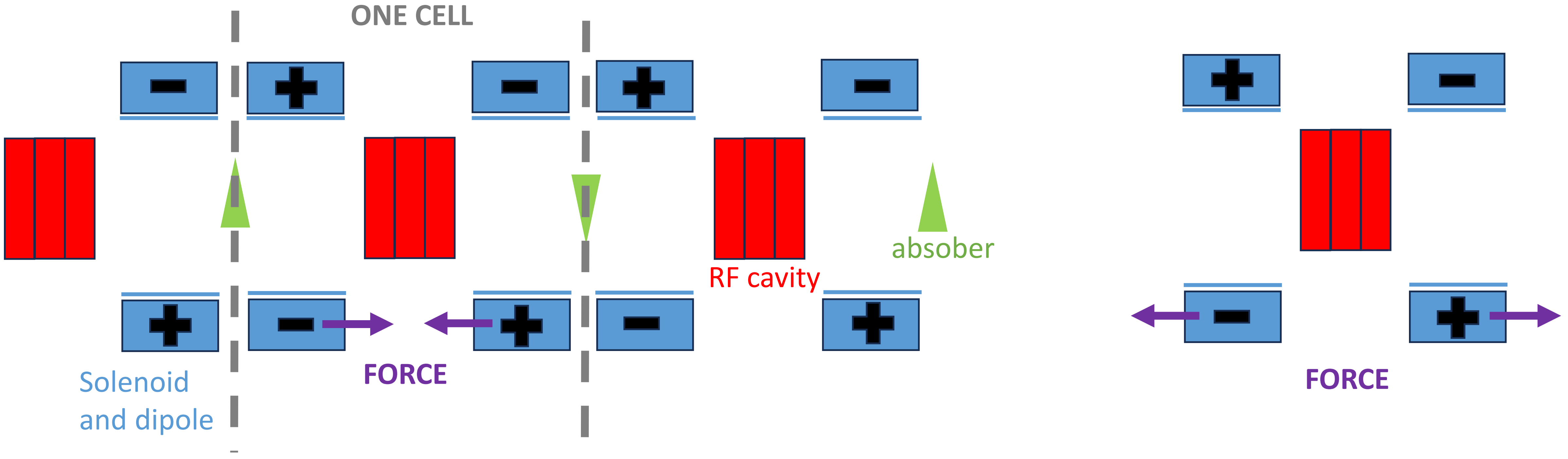
Content

- Recap Fermilab Workshop outcome
- New magnetic configuration studies
- Cryostat integration choice
- Memory shape alloys solution
- Integration RF cavities
- Selected Magnetic configuration
- Cell Integration and assembly status

Lattice operation of a cell and stand alone operation

LATTICE OPERATION

SINGLE CELL



Operating mode

Lattice mode

- Normal one during beam operation
- Designing for this solution only is simpler

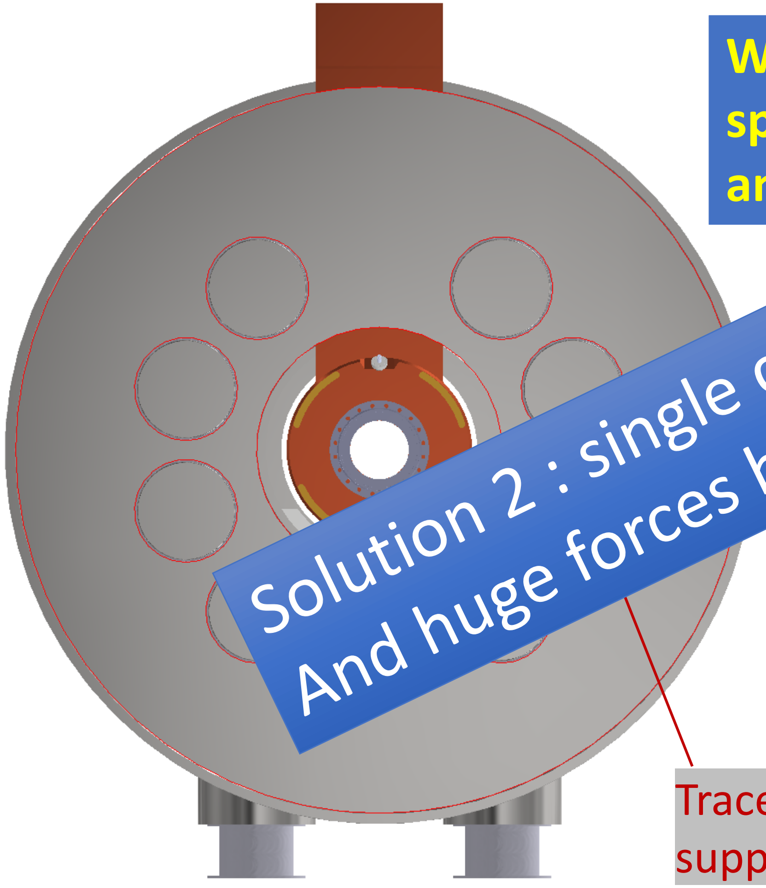
Stand alone

- Test of each cell at full field is mandatory.
  → Can this be challenged?
  → We think no…
- A magnet can always fail with faster discharge than the adjacent one. → we ask to support 10% of the nominal force on half cell coil
- The first cell and the last one of a stage have different “weaker or stronger” neighbors. Or even none.

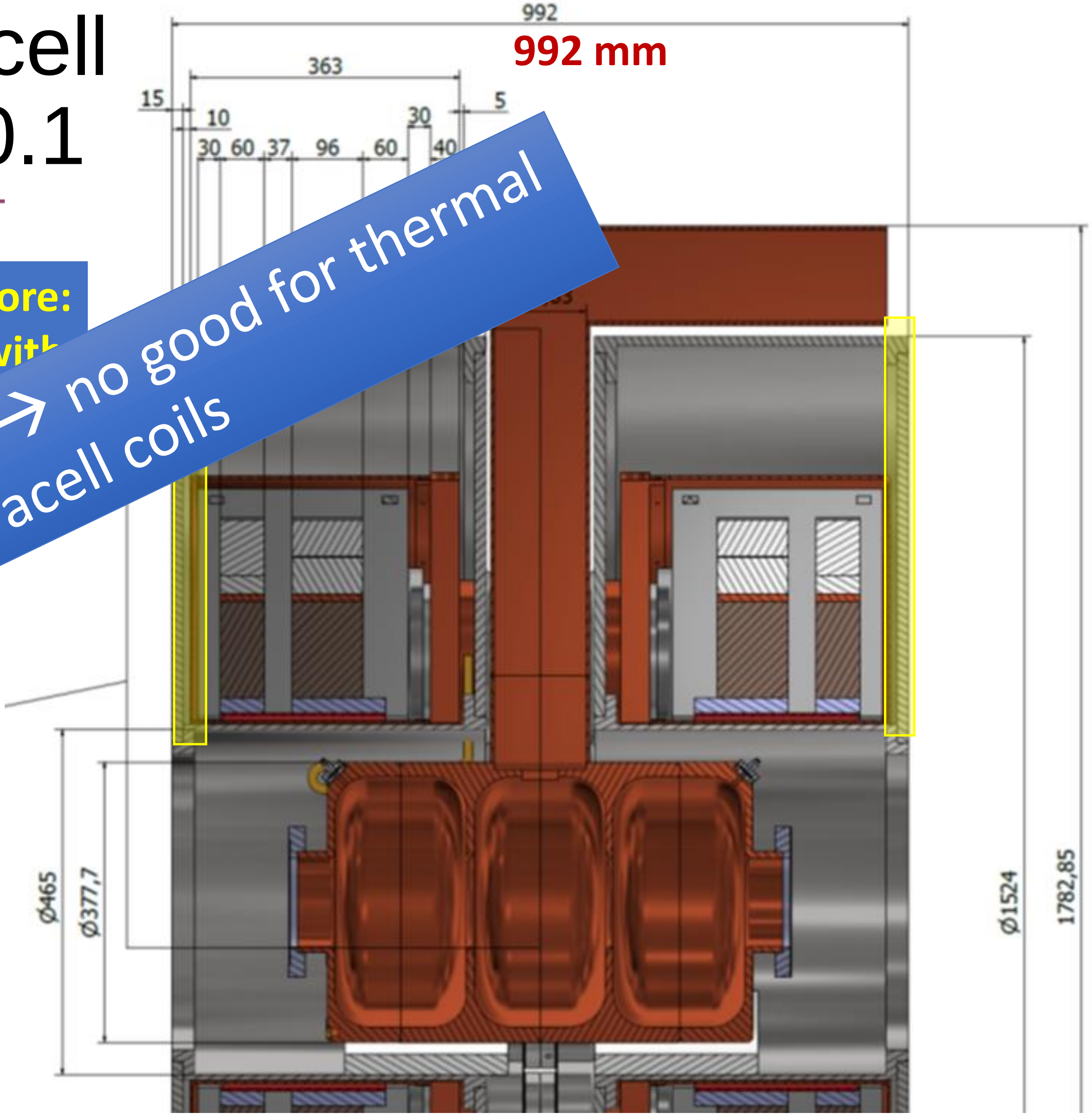
S5-like demo cell Integration V0.1

Where to gain more:
space removed with
an intercell cr

Solution 2 : single cell cryostat → no good for thermal
And huge forces between intracell coils



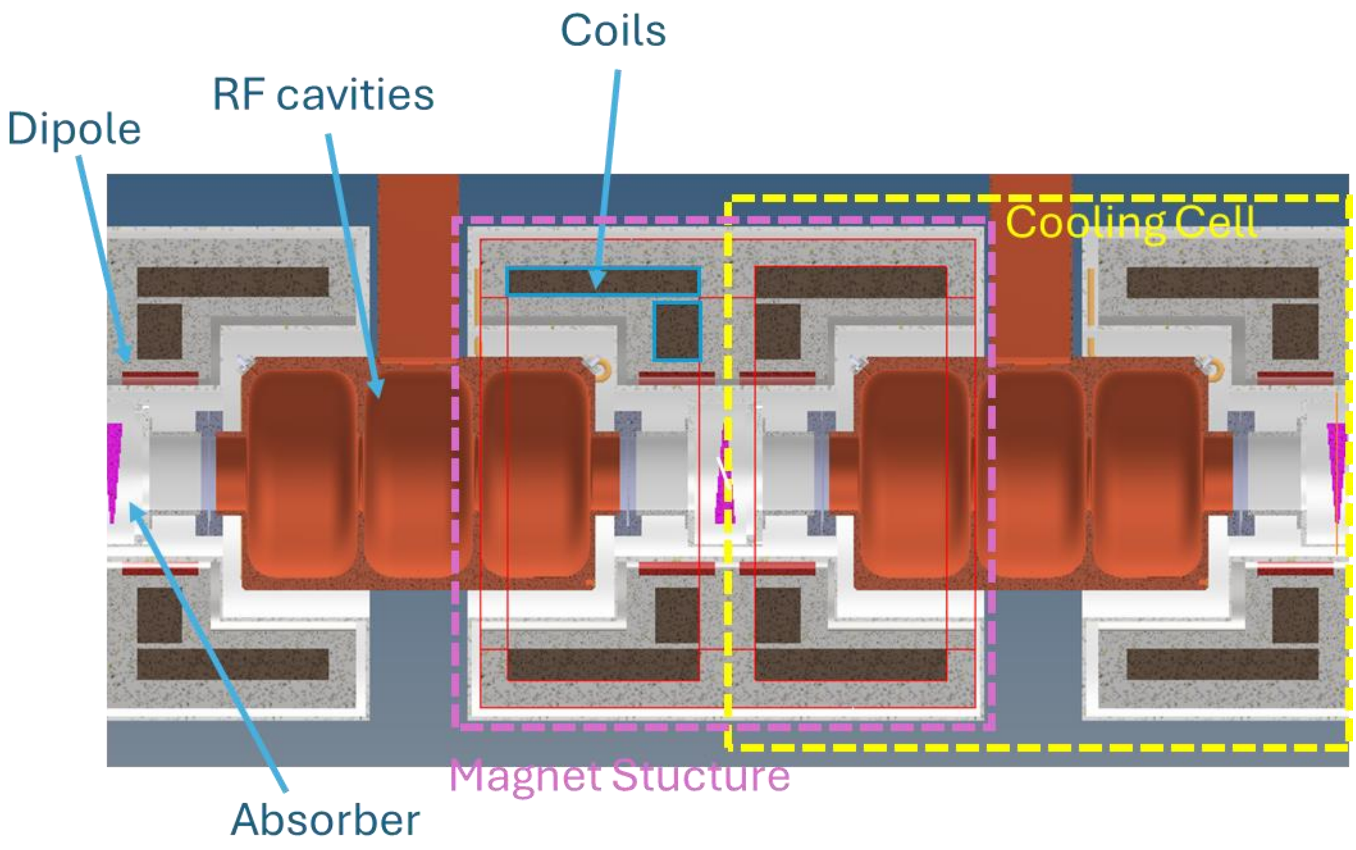
Traces of the 8 support rods



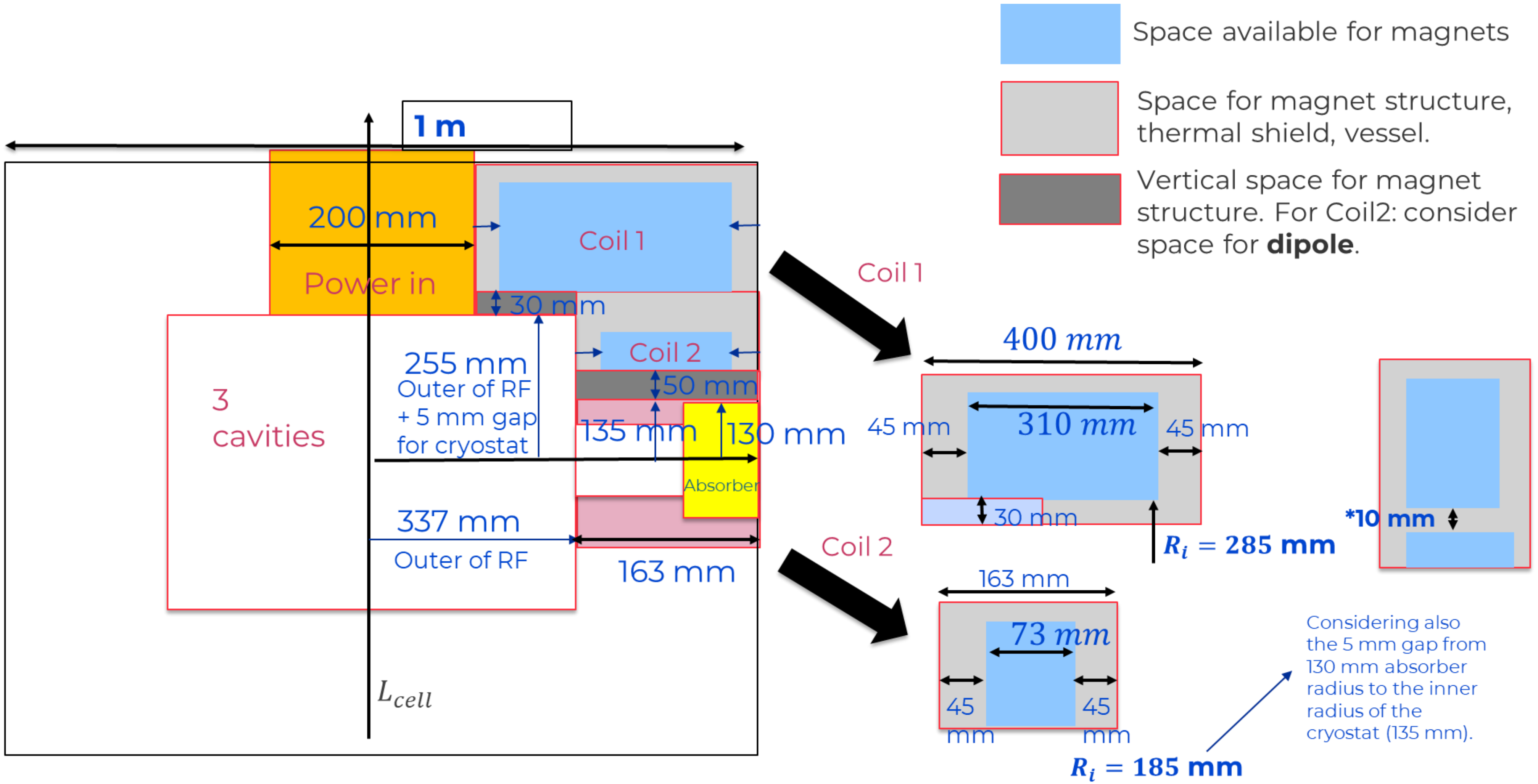
Solution pursued for lattice operation
Intercell cryostat

The magnet crystat would be simply slided over the RF structure from both sides of RF coupler

- **Plus**
- RF structure fully assembled independently on the rest
- Makes easy assembly and access to RF for maintenance
- The coils of a cell can be pushed as near the cell border as wanted
- **Minus**
- The forces between coils of the same cell needs to be reacted though RT gap
- This generates enormous heat load at 20 K since gap is short and forces enormous (>> than the RFMFTF)
- A single cell is not representative of the whole. For a single cell one needs to build also adjacent magnets (and forces are not balanced on aside coils)

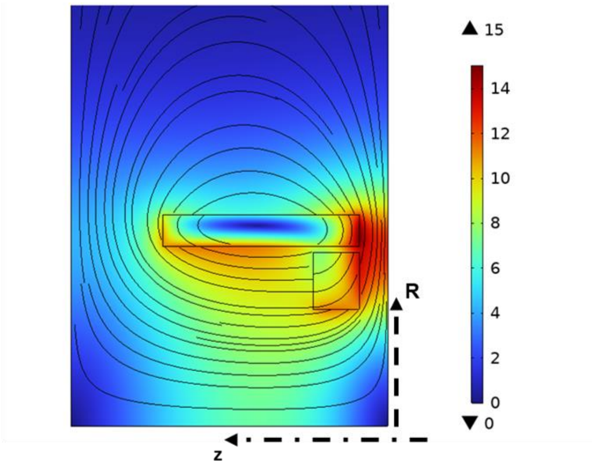


New Magnet Optimization: parameter space

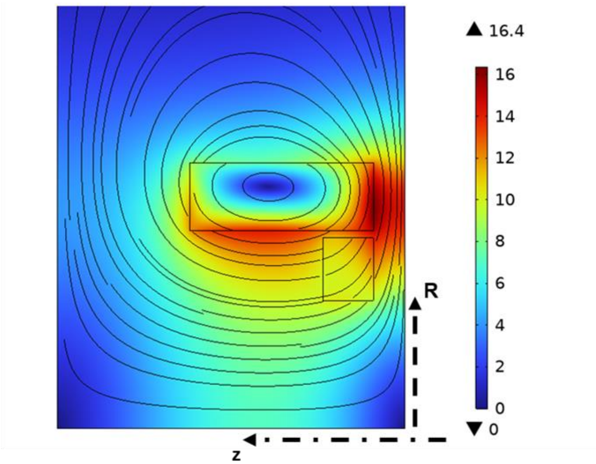


(Recap) Results Presented @ FNAL Workshop

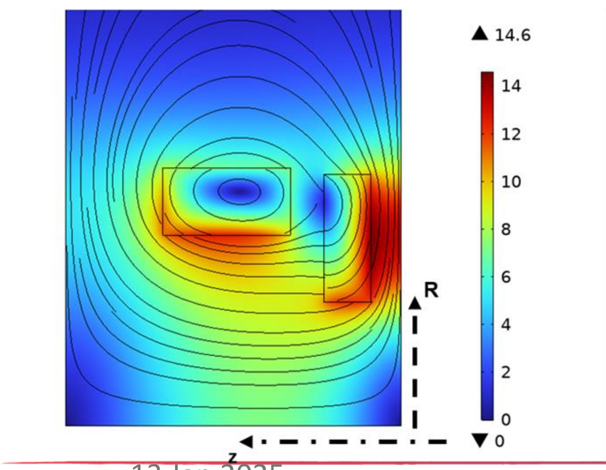
Option 17MN – 10mm gap
“Min Net Axial Force”



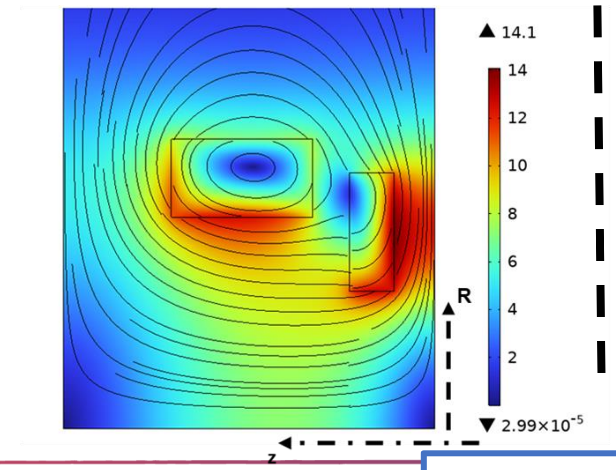
Option 27MN – 10mm gap
“Min Axial Force on Coil2”



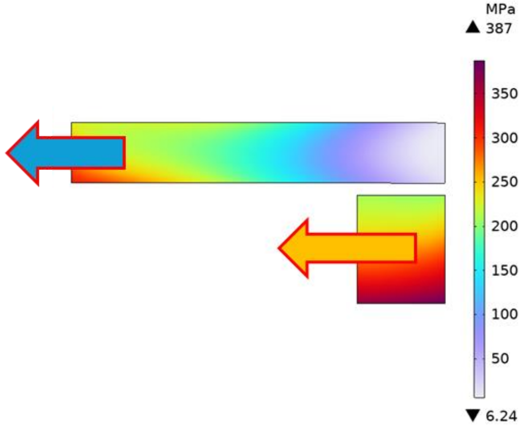
Option 21MN – Optim. Tool
“Min hoop stress on Coil2”



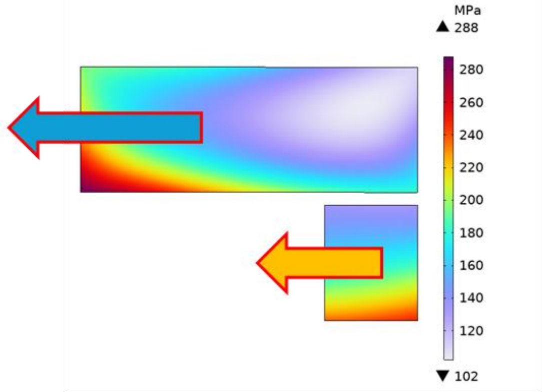
Option 15MN – Optim. Tool
“Min Coil Volume”



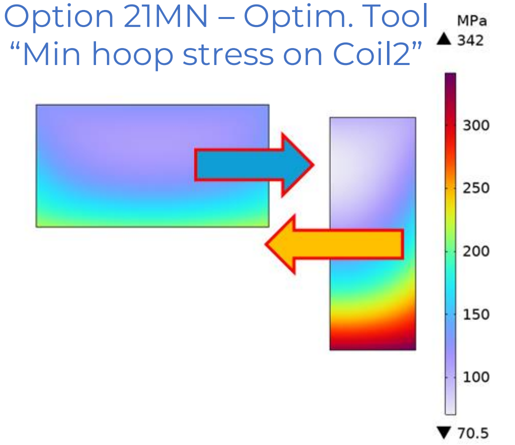
Option 17MN – 10mm gap
“Min Net Axial Force”



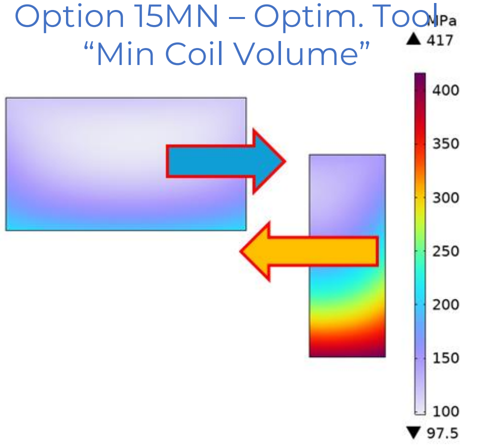
Option 27MN – 10mm gap
“Min Axial Force on Coil2”



Option 21MN – Optim. Tool
“Min hoop stress on Coil2”



Option 15MN – Optim. Tool
“Min Coil Volume”



Lattice operation

(Recap) Results Presented @ FNAL Workshop (II)

Configuration	B2/B1 (%)	Focusing Strength per cell length (T^2 m)	Max Hoop Stress (MPa)	Max Tensile Radial Stress (MPa)	Axial Force on Coil#1/Coil #2 (MN)	Net Axial Force (MN)	Total Torque (MN m)	Total Magnetic Energy Density in cell (MJ/m^3)	Coil Volume (half cell) (dm^3)	Coil Current Coil#1/Coil#2
Option 17MN - 10mm gap	14.4	24.42	387	15.3	+7 +10	+17	0.14	152.4	39.7	1035 575
Option 27MN - 10mm gap	14.2	[illegible]	[illegible]	[illegible]	+20.5 +6.5	+27	0.51	135.6	63.8	768 334
Option 21MN - Optim. Tool	13.6	[illegible]	[illegible]	[illegible]	-12.3 +33.1	+20.8	1.25	138.0	63.4	686 720
Option 15MN - Optim. Tool	13.5	26.37	417	6.08	-10.6 +25.1	14.5	1.29	125.0	58	674 847
"S5test_demo_28T peak_1" 25% current reduction	5.03	38.88	672 (422 with prestress)	0.14	-27 +67	50	--	292.1	43.31	1253

Minimum coil volume (**cost**) option: selected for more detailed EM and mechanical analyses

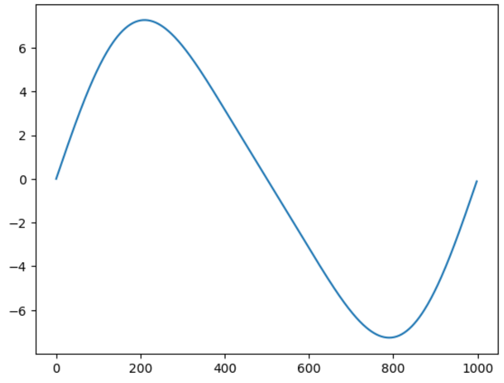
Lattice operation

Coil Search Scheme for Cell Demonstrator

- Two approaches were considered for the search of the optimal coil configuration:
  - **Optimization tool** (S. Fabbri presentation),
  - **Coil parameters scan in operating conditions**.
- In this presentation I will focus on the coil configuration scan approach.
- **MATLAB** + **FEMM** script solving the magnetostatic problem in lattice conditions.
- Scan the coil geometrical parameters and current densities: 10 parameters.
- Results compared to the target field harmonics required by the cooling lattice.
- Select the optimal configuration based on your design parameters.

- Cons: **computational cost.** Choose the initial set of parameters and use discrete steps!

Target field on axis for a 1 m cell



Target field harmonics

- **$B1 = 7 \pm 0.2$ T**
- $B2 = 1 \pm 0.02$ T
- $B3 = \pm 0.4$ T

Target design parameters:

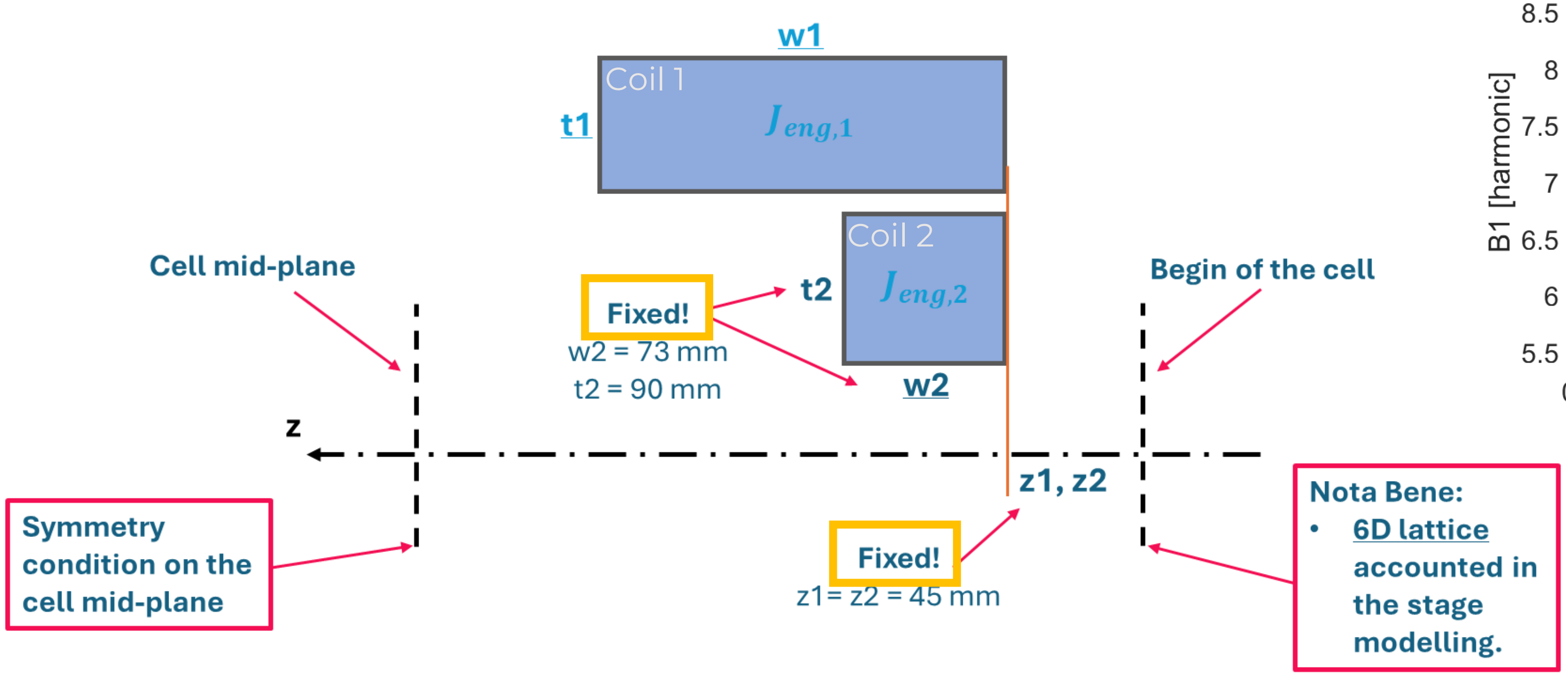
- Minimize axial force (**feasibility**).
- Minimize conductor volume (**cost**).
- Minimize stored magnetic energy (**protection**).

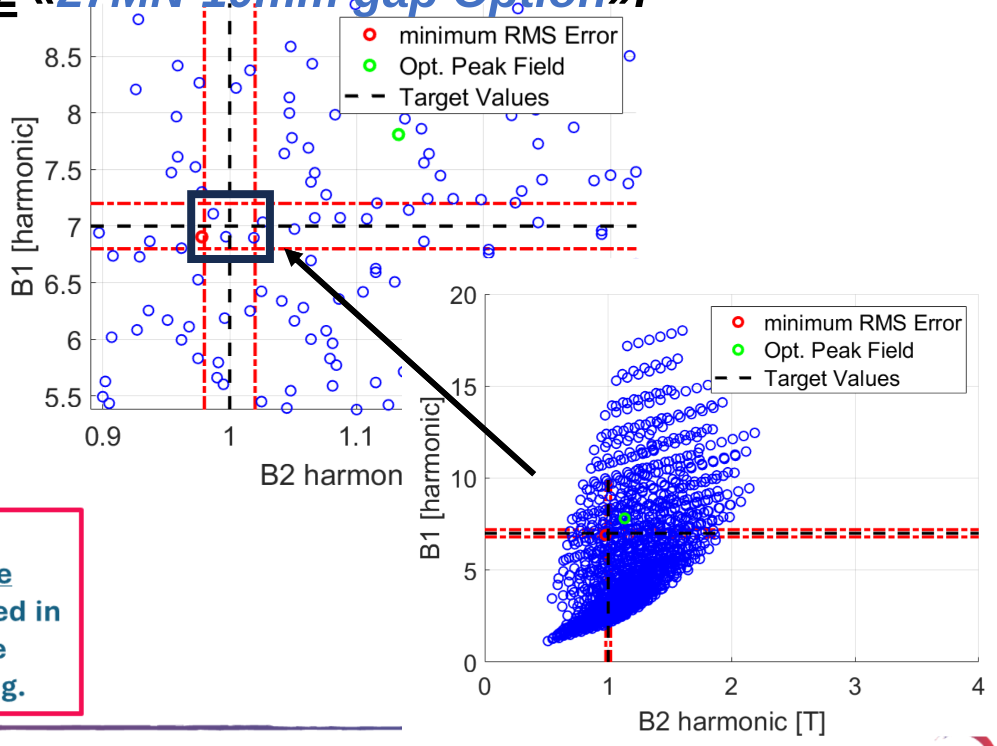
Coil Search Scheme – Setup#1

- Geometry of coil#2 is fixed. Four free parameters considered: $\mathbf{J_{eng,1}}$, $\mathbf{J_{eng,2}}$, coil#1 **axial** and **radial length**.
- Parameters scan within the reported geometrical constraints.
- Five **configurations within** the **target field harmonic tolerances** have been identified.
- Configuration selected**: minimum net axial force** and **minimum coil volume**
- «*17MN-10mm gap Option*», **minimum axial force on Coil#2** «*27MN-10mm gap Option*».

4^6 **configurations scanned**

Coil scheme & parameters considered:



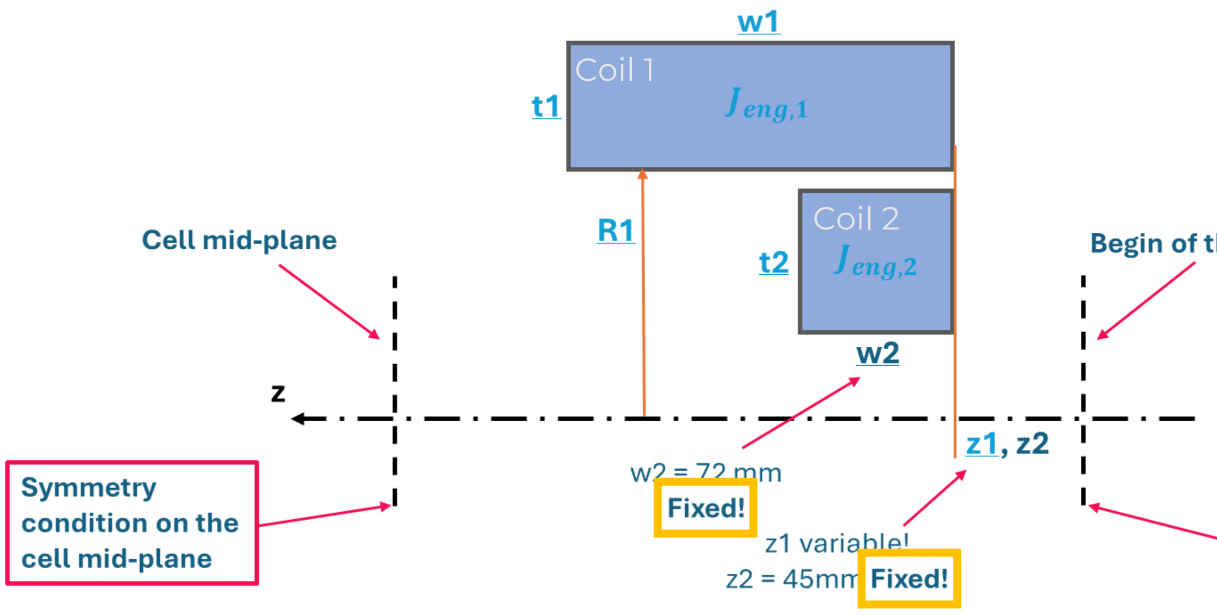


Coil Search Scheme – Setup#2
(with step between coil start)

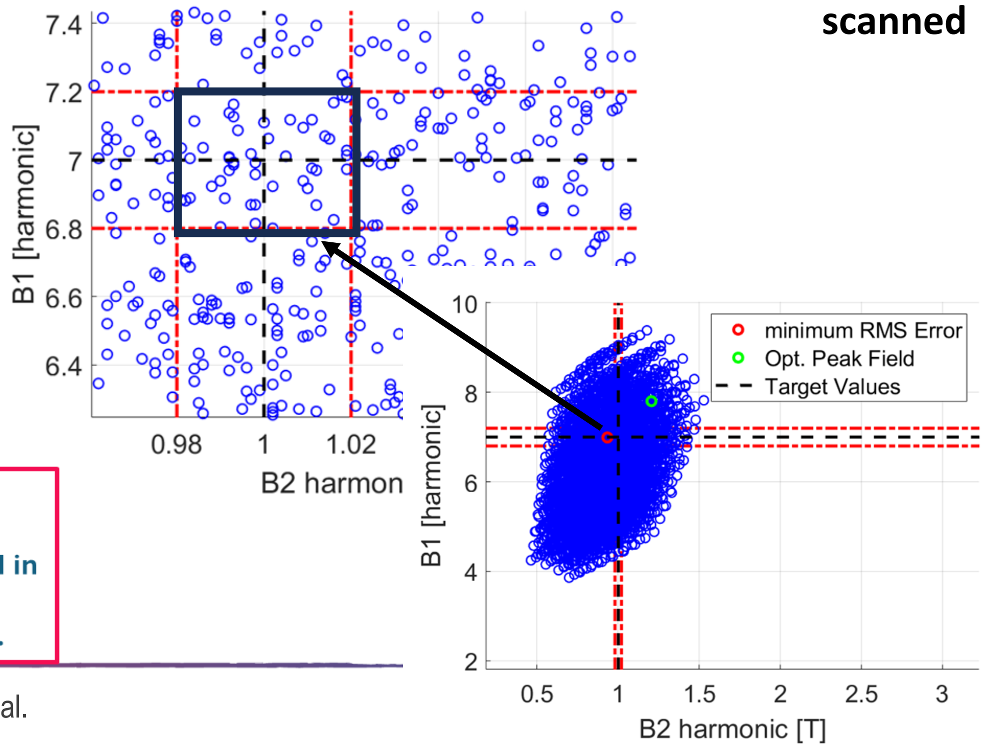
- From the analysis of the “*17MN-10mm gap*” configuration, the coil search scheme has been refined to scan a finer parameters space, relaxing previously constrained parameters.
- **Seven** free parameters considered: $\mathbf{J_{eng,1}}$, $\mathbf{J_{eng,2}}$, coil#1 **radius**, **axial position** and **axial/radial length**, coil#2 **radial length**.
- **O(100) configurations within** the **target field harmonic tolerances** have been identified.
- Two optimal configurations selected**: «*11MN-20mm gap – min volume*»**, **«*11MN-20mm gap*».**

around 5000 configurations scanned

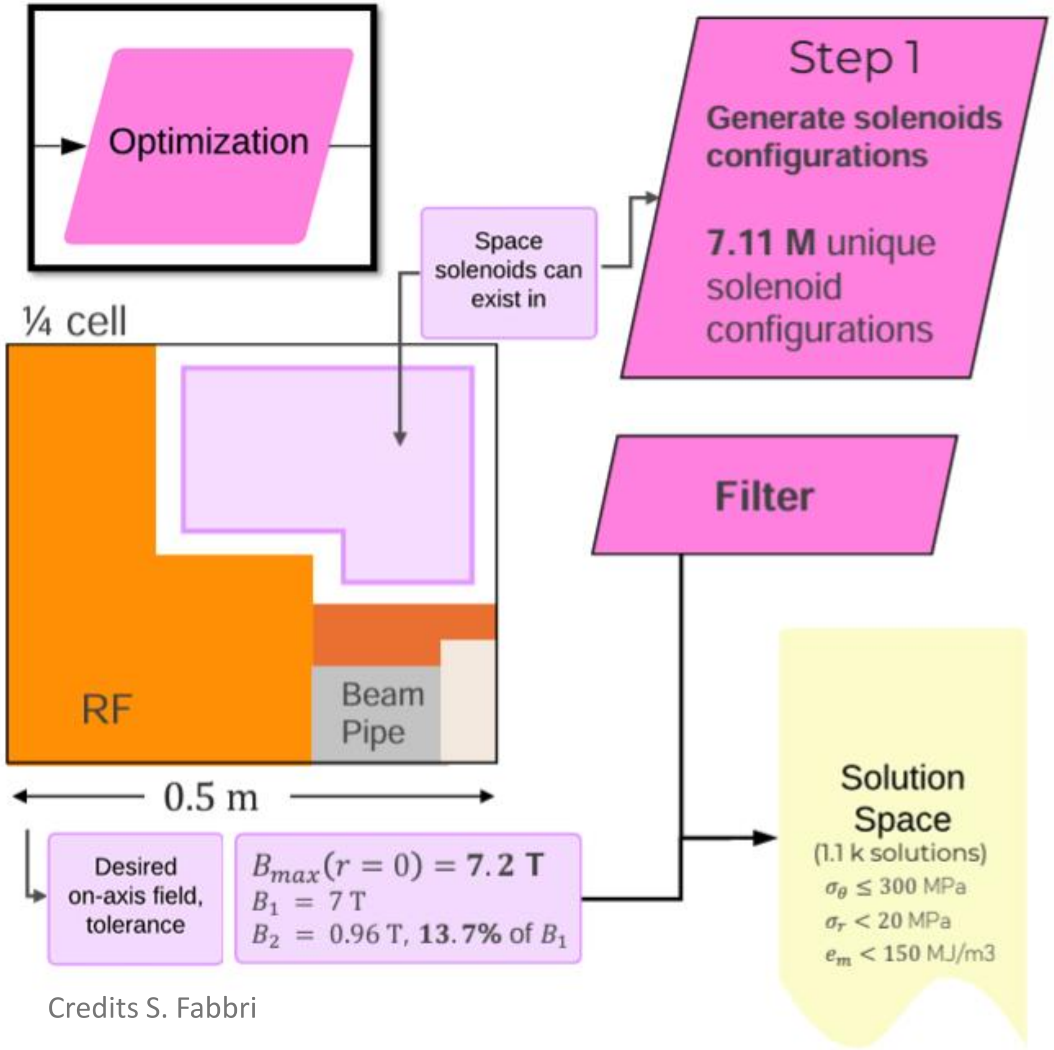
Coil scheme & parameters considered:



Nota Bene:
- **6D lattice accounted in the stage modelling.**



Optimization Tool: Analytical Framework (S. Fabbri)



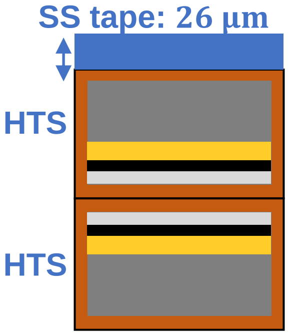
Credits S. Fabbri

Configurations found:

- **Option 21MN – Optim. Tool "Min hoop stress on Coil2".**
- **Option 15MN – Optim. Tool "Min Coil Volume".**

Winding Discretization

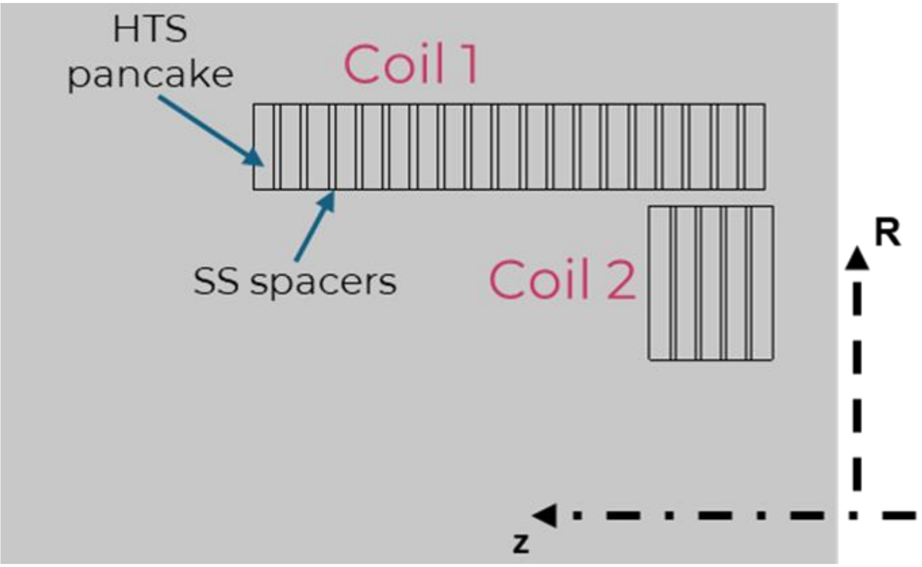
- Winding scheme: 2x HTS tapes + SS tape co-wound (ESMA-derived).
- Dimensions: **HTS**(12mm X 0.0656mm), **SS**(12mm X 0.026mm).
- Divide the homogenized coil section in pancakes separated by SS spacers.
- **Inter-pancake spacers** dimensions?
  - Find the best compromise in terms of field (B1, B2, focusing strength), margins (Ic) and **mechanics**.



Selected spacer dimensions:

- **Coil1: 4mm spacer**
- **Coil2: 3mm spacer**

This configuration maximize the number of pancakes in the stacks, given the total coil dimensions for «Option1»



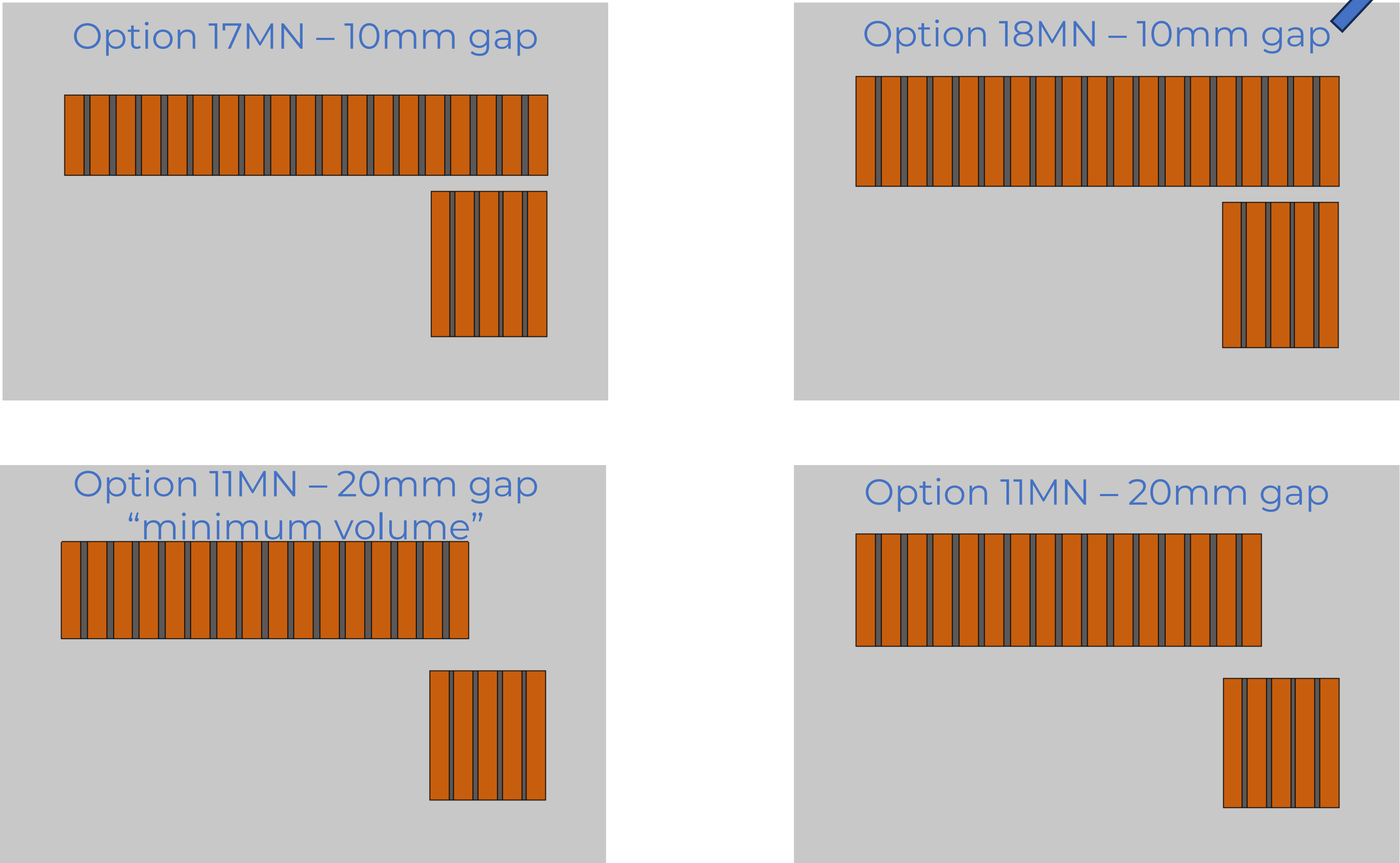
Configurations studied

Configuration derived from "Option 17MN-10mm gap" for Ampere-turns conservation and increased margins

Setup#1

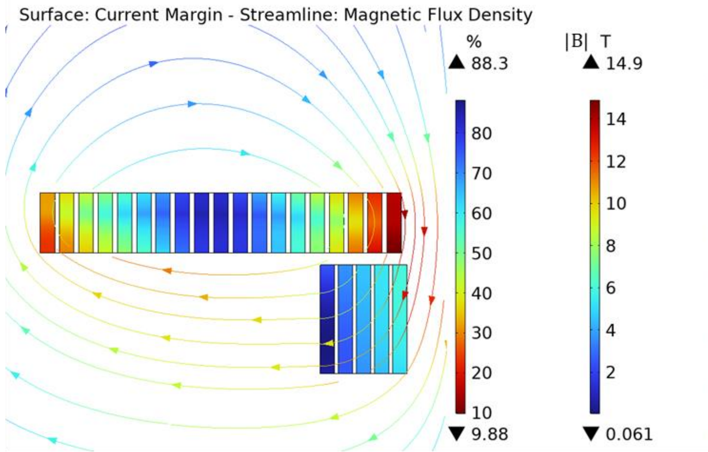
Optimized versions of "Option 17MN-10mm gap"

Setup#2

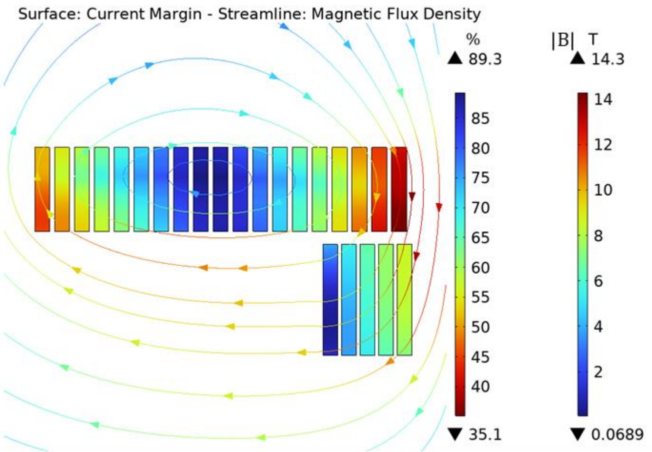


EM Analysis Results: Coil Margins

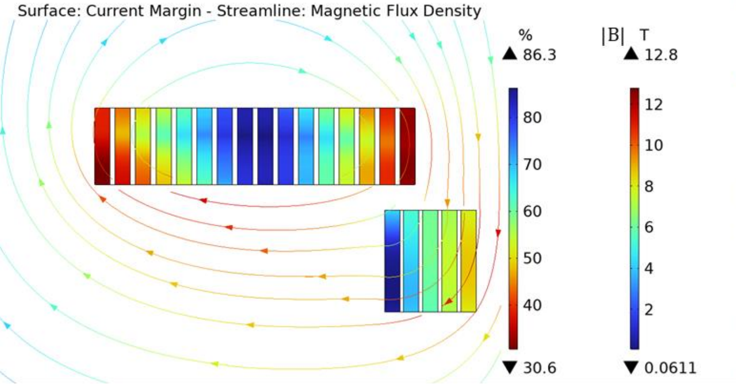
Option 17MN – 10mm gap



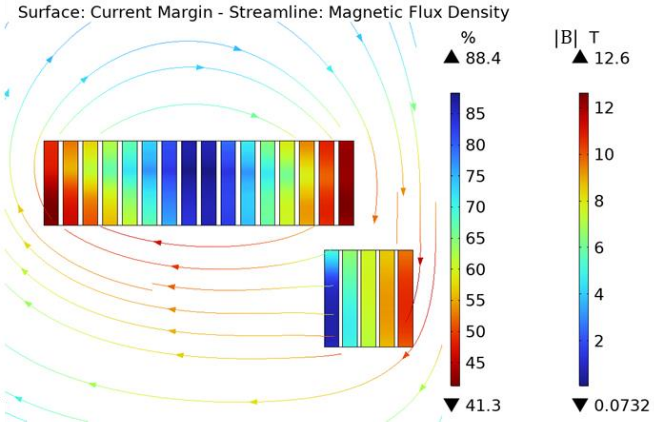
Option 18MN – 10mm gap



Option 11MN – 20mm gap
"minimum volume"



Option 11MN – 20mm gap



	Current Margin (%)	Temperature Margin (K)	Load-line Margin (%)
Option 17MN-10mm gap	9.9	4.8	3.8
Option 18MN-10mm gap	35.1	14.1	22.3
Option 11MN – 20mm gap "min volume"	30.6	11.5	17.0
Option 11MN – 20mm gap	41.3	15.5	25.5

Lattice operation

Summary Table

Configuration considered to study the mechanics of the coil assembly

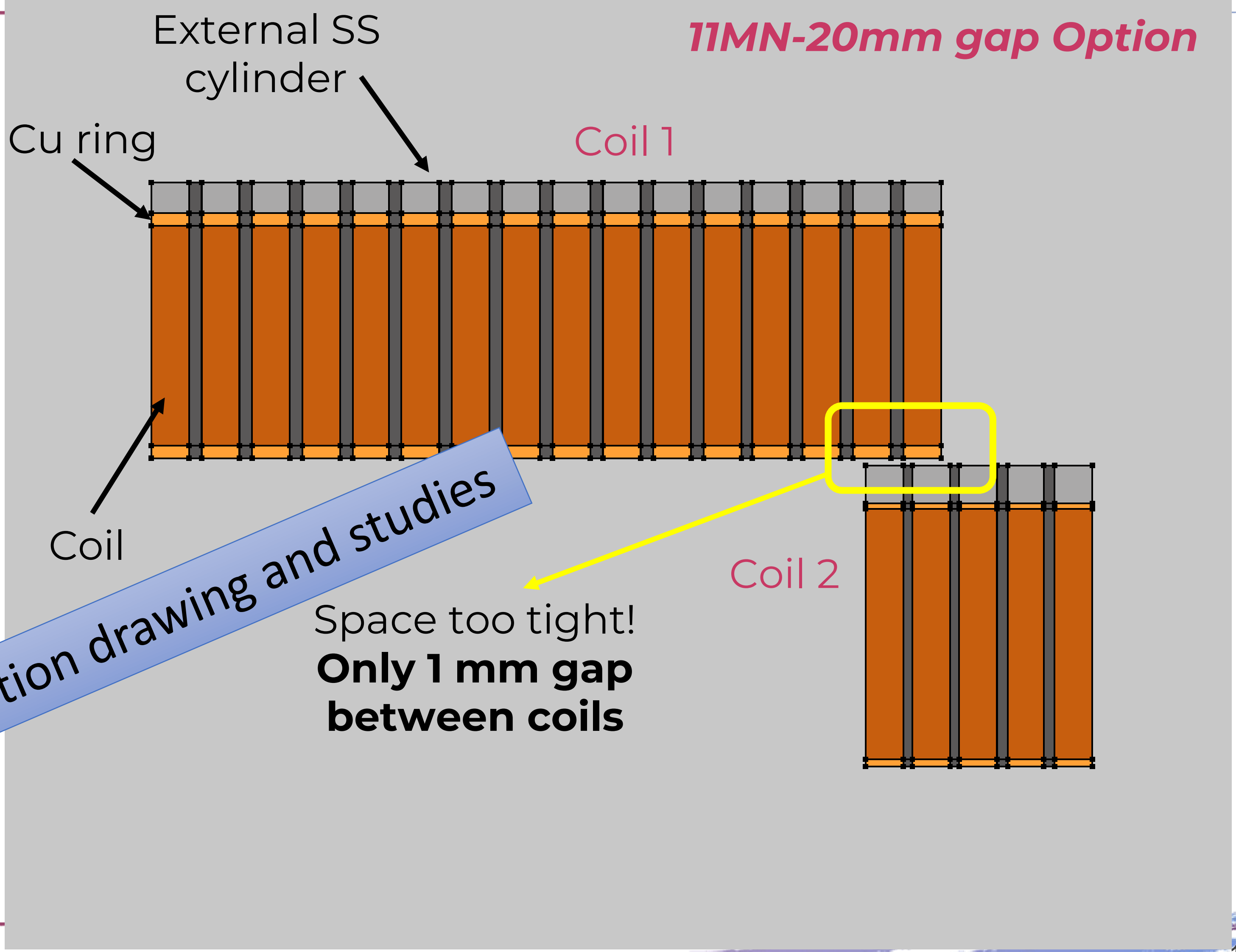
"*11MN-20mm gap*" configuration provides highest margins, low magnetic energy density and forces, with 9 km increase of the total HTS length .

Lattice operation

	J_eng Coil1/Coil2 (A/mm^2)	B2/B1 (%)	Focus. Strength per cell length (T^2*m/m)	Axial Force on Coil1/Coil2 (MN)	Net Axial Force (MN)	Net Torque applied on centroid of forces (MN*m)	Peak Hoop Stress on Coil1/Coil2 (MPa)	Peak Positive Radial Stress on Coil1/Coil2 (MPa)	Peak Von Mises Stress on SS spacers (MPa)	Total Magnetic Energy Density in cell (MJ/m^3)	Total HTS length (full cell) (km)	Coil Current Coil1/2 (A)
Option 17MN-10mm gap	421.5 209.1	14.7	24.7	+6.7 +10.4	+17.1	-0.597	+294 +397	+1.96 +14.5	+499 +465	159.4	66	795 394
Option 18MN-10mm gap	322.9 209.1	14.5	24.6	+8.0 +10.3	+18.3	-0.652	+230 +358	+0.91 +14.1	+390 +459	130.0	85.6	609 394
Option 11MN – 20mm gap "min. vol."	380.3 263.9	14.7	24.4	+0.4 +11.0	+11.4	-0.540	+260 +349	+3.45 +8.97	+377 +460	155.3	62.8	717.4 497.2
Option 11MN – 20mm gap	328.3 263.9	14.8	23.7	+0.7 +10.8	+11.5	-0.562	+222 +344	+2.95 +8.84	+323 +454	136.2	71.6	619.4 497.9

Coil Assembly Study

- A mechanical analysis of the coil assembly has been performed.
- The **Cu rings** (4mm Coil1, 2mm Coil2) have been dimensioned to **limit** the **Joule losses below 10 mW.**
- The **SS ring thicknesses** were **limited** by the **space available for Coil2**. 12mm thick rings were considered in Coil2 and 10mm rings in Coil1 (since the highest radial stresses and coil radial thickness are in Coil2).
- The SS spacers have been extended to contain the Cu/SS rings.

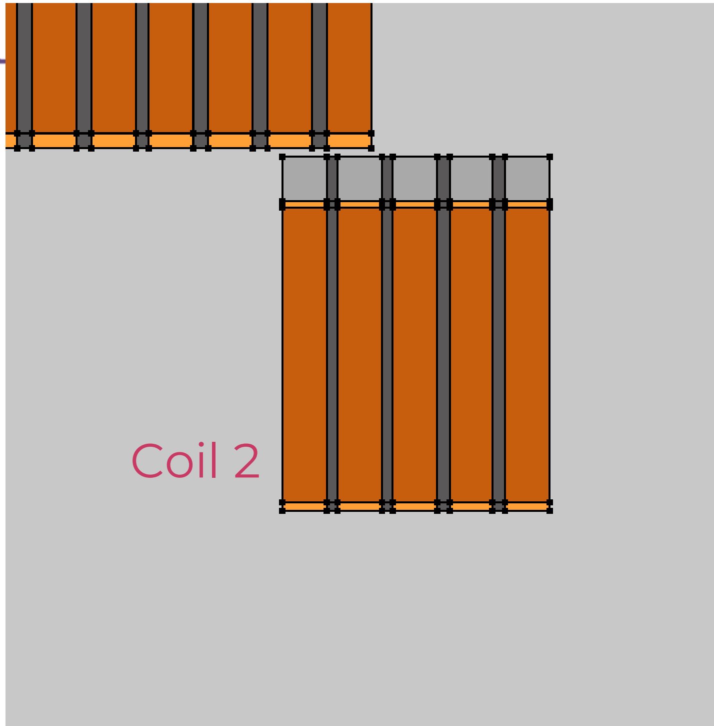


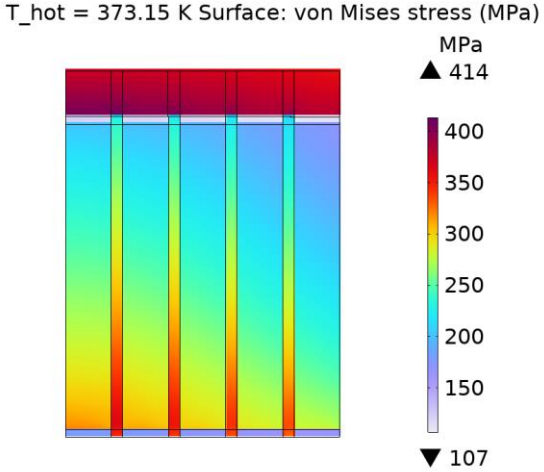
USED for Integration drawing and studies

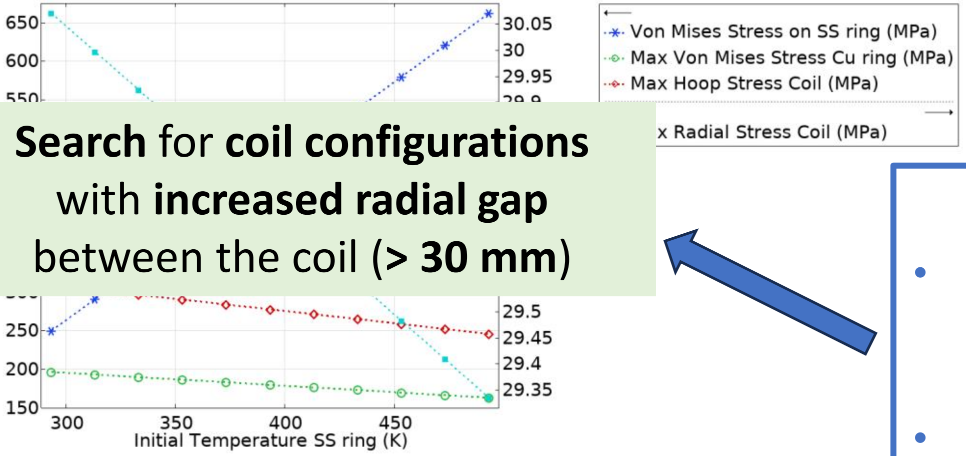
Shrink-fitting Evaluation on Coil2

- In the proposed configuration, **Coil2** presents the challenge of **high radial/hoop stresses** to be **contained by SS rings of relatively thin radial thickness**.
- From a simplified analysis, the **radial pressure** applied on the external coil boundaries in lattice operation must be at least **16MPa on Coil 1**, **80MPa on Coil 2**.

- This study serves to answer the question on the **maximum applicable stress via shrink fitting** and the **associated hot temperature**.







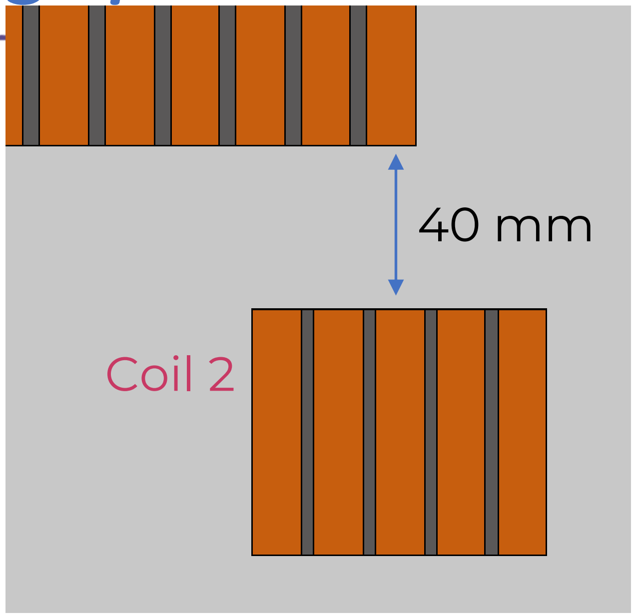
Search for **coil configurations** with **increased radial gap** between the coil (**> 30 mm**)

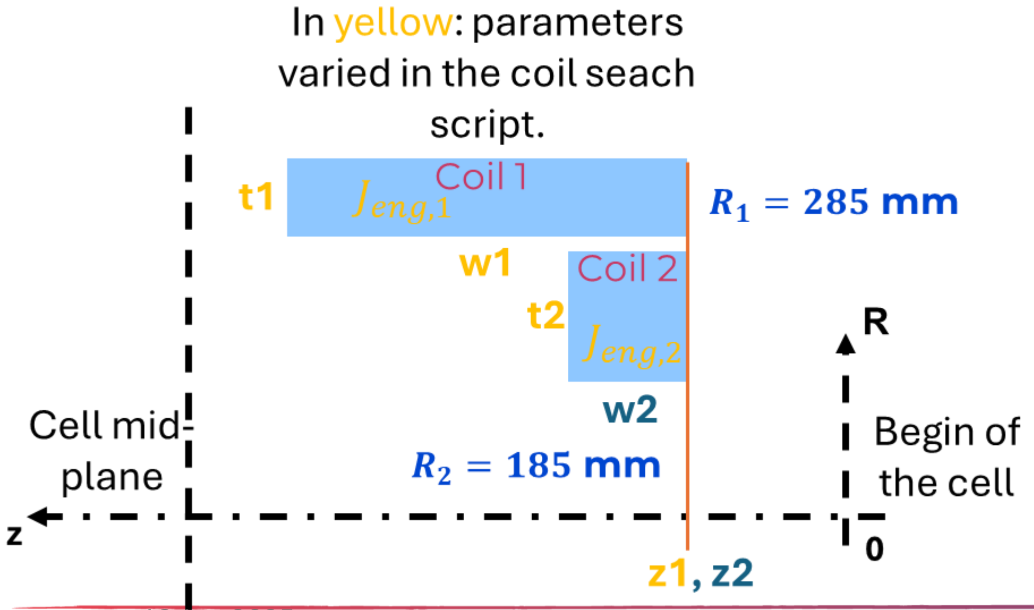
This solution is **not feasible:**

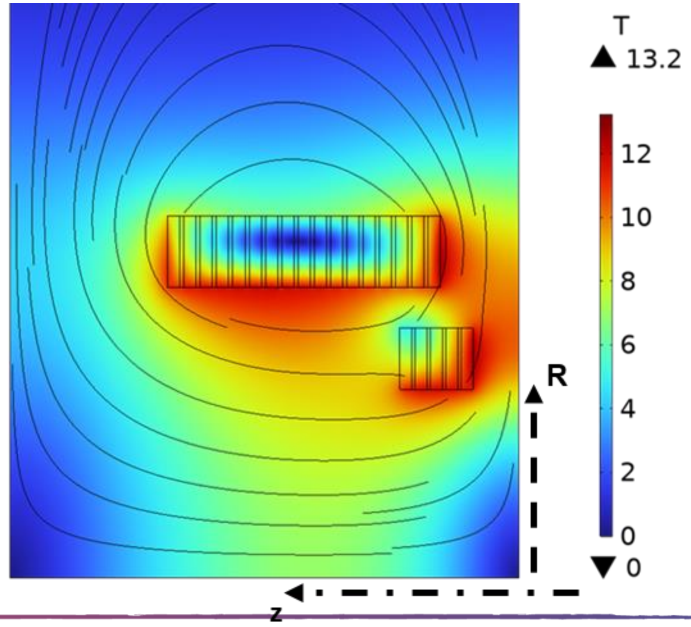
- **SS ring thickness too small to provide the required pre-compression on Coil2.**
- **Too small radial gap between coils.**

New configuration for integration studies + mechanics: *Option 12MN-40mm gap !!!*

- From a new scan of the **coil search scheme**, with the **new constraint** on the **minimum radial gap between the two coils**, we found the here reported solution: *"**Option 12MN-40mm gap**"*.
- This solution offers **minimum differences** with the ***12MN-20mm gap* option**, with the **advantage of increased radial gap** between coils.

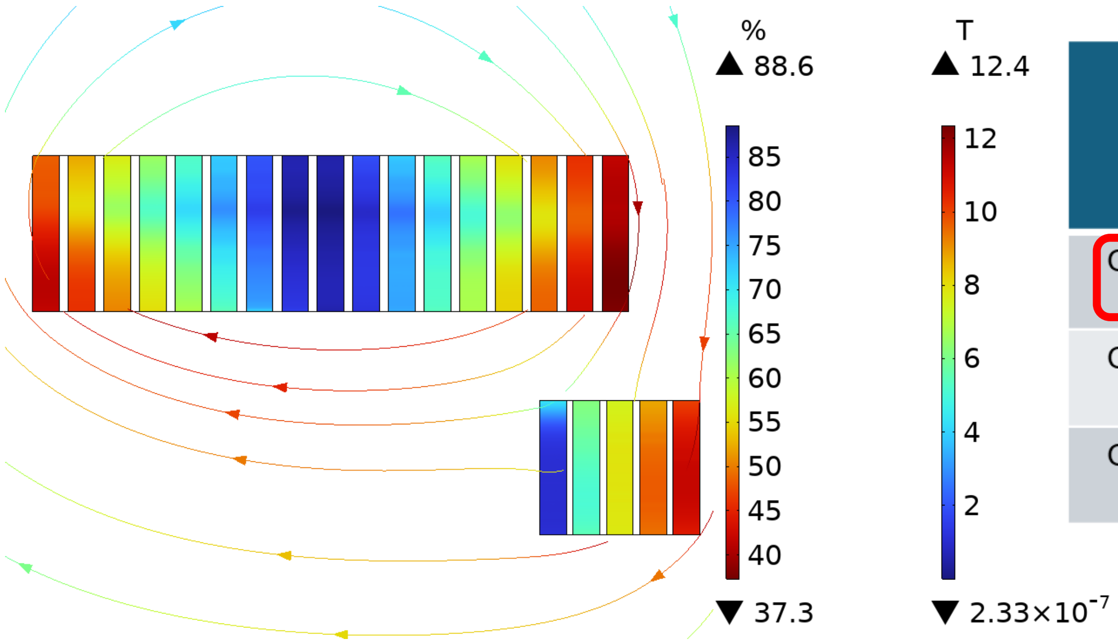






Solutions comparison - Margins

Option 12MN – 40mm gap



Margins are too low

	Current Margin (%)	Temperature Margin (K)	Load-line Margin (%)
Option 17MN-10mm gap	9.9	4.8	3.8
Option 11MN-20mm gap	41.3	15.5	25.5
Option 12MN-40mm gap	37.3	14.5	23.5

Lattice operation

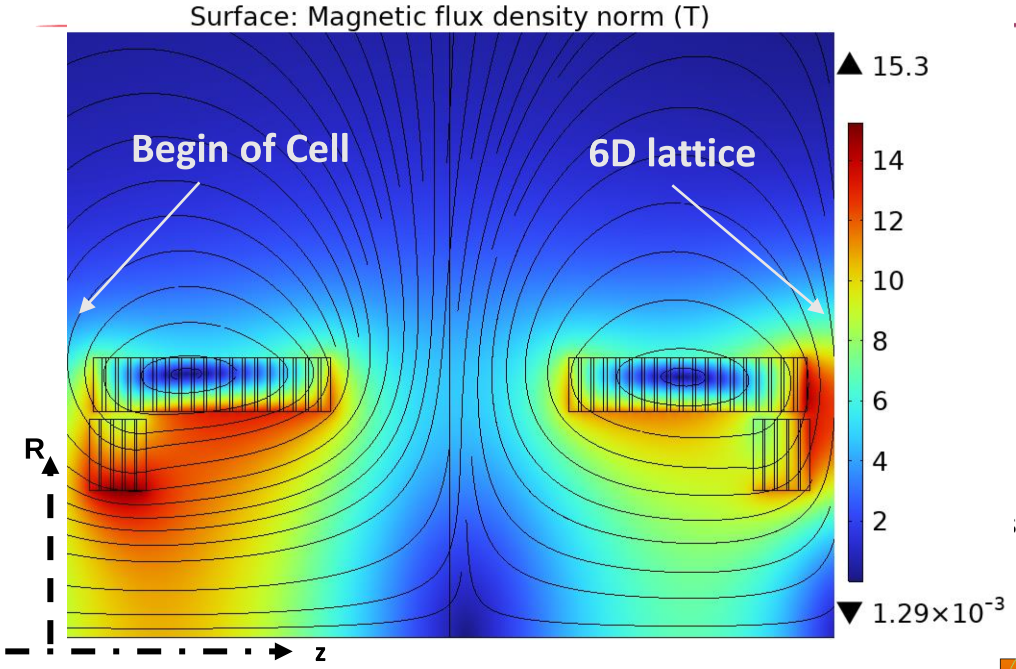
Summary Table

Lattice operation

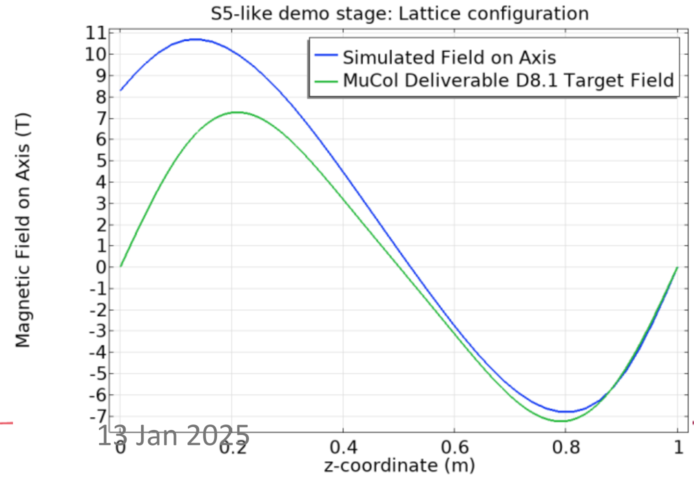
	J_eng Coil1/Coil2 (A/mm^2)	B2/B1 (%)	Focus. Strength per cell length (T^2*m/m)	Axial Force on Coil1/Coil2 (MN)	Net Axial Force (MN)	Net Torque applied on centroid of forces (MN*m)	Peak Hoop Stress on Coil1/Coil2 (MPa)	Peak Positive Radial Stress on Coil1/Coil2 (MPa)	Peak Von Mises Stress on SS spacers (MPa)	Total Magnetic Energy Density in cell (MJ/m^3)	Total HTS length (full cell) (km)	Coil Current Coil1/2 (A)
Option 17MN-10mm gap	421.5 209.1	14.7	24.7	+6.7 +10.4	+17.1	-0.597	+294 +397	+1.96 +14.5	+499 +465	159.4	66	795 394
Option 11MN-20mm gap	328.3 263.9	14.8	23.7	+0.7 +10.8	+11.5	-0.562	+222 +344	+2.95 +8.84	+323 +454	136.2	71.6	619.4 497.9
Option 12MN-40mm gap	328.6 299.8	14.9	24.0	+4.12 +8.25	+12.4	-0.558	+231 +374	+1.77 +9.48	+353 +508	140.4	71.2	620.0 565.4

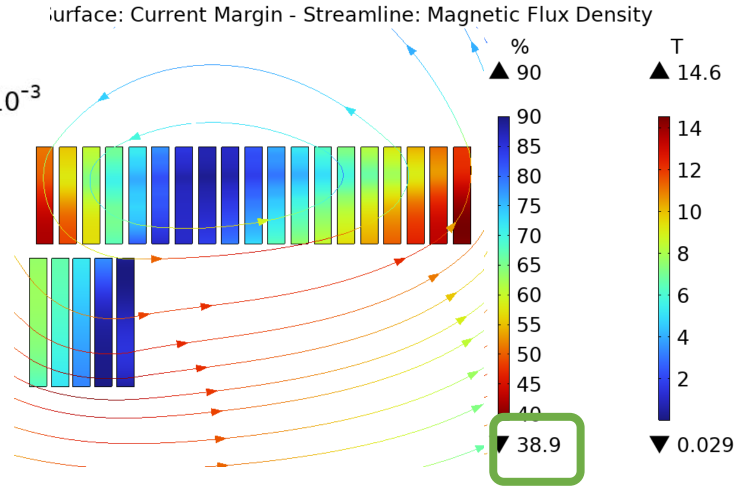
Note: Beg/End Stage Field Analysis

To be validated by Optics!

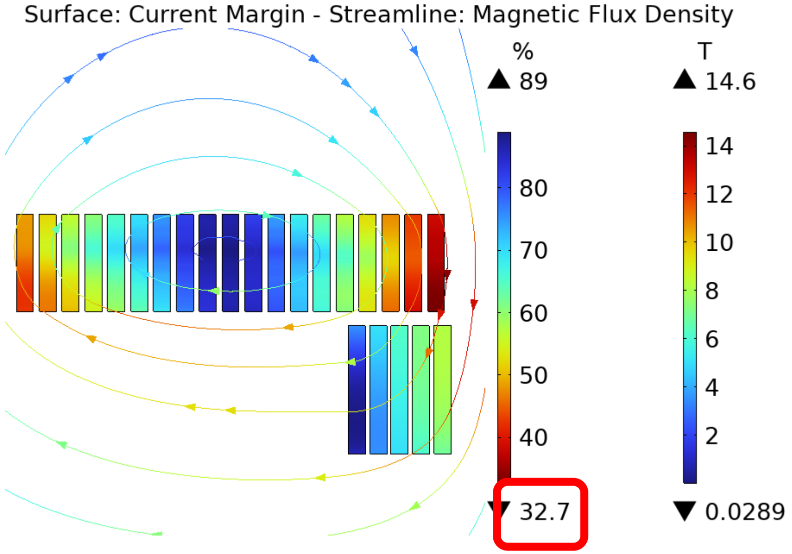


- In lattice operation, the magnets of the first and last cells of the array are subjected to different operating conditions.
- The **margins** are **not critical**. A slight improve of the current margins is observed.
- Instead, attention must be given to the **stresses!**

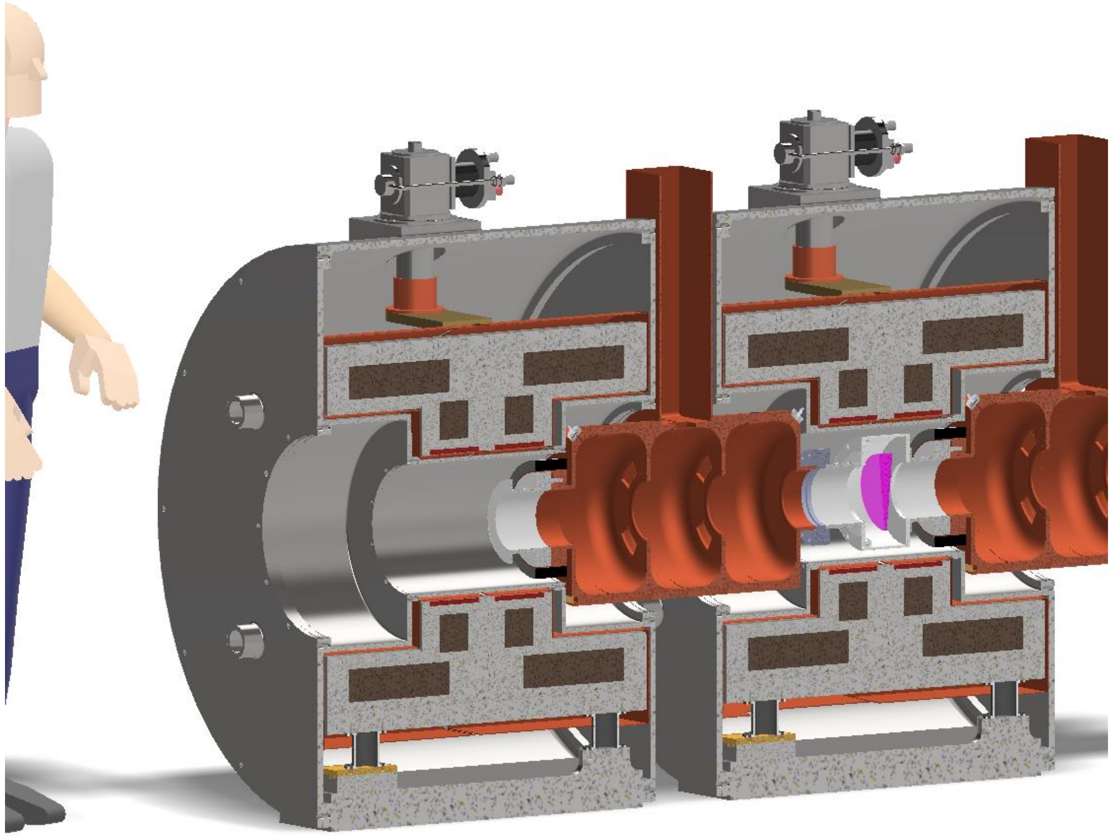


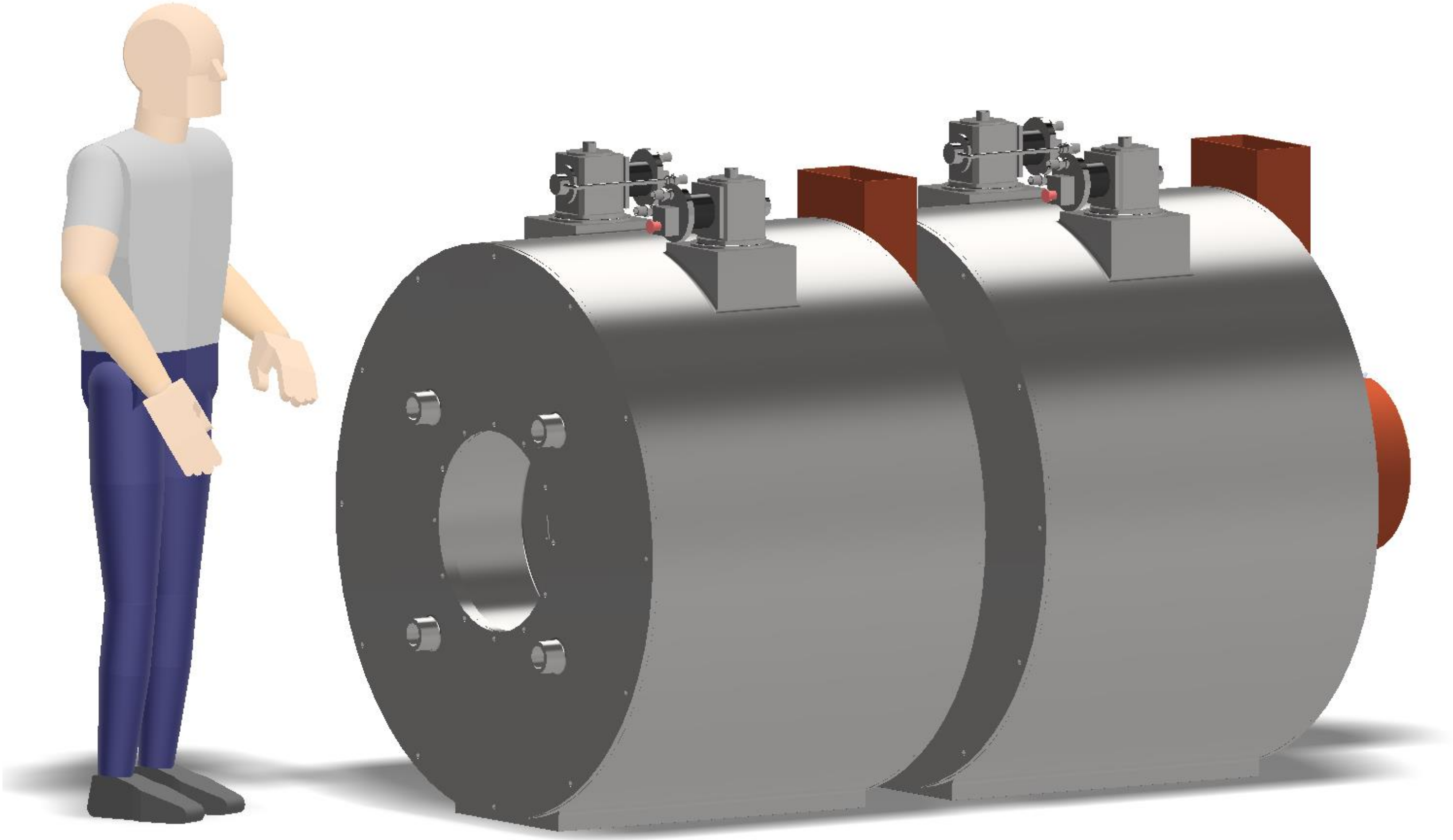


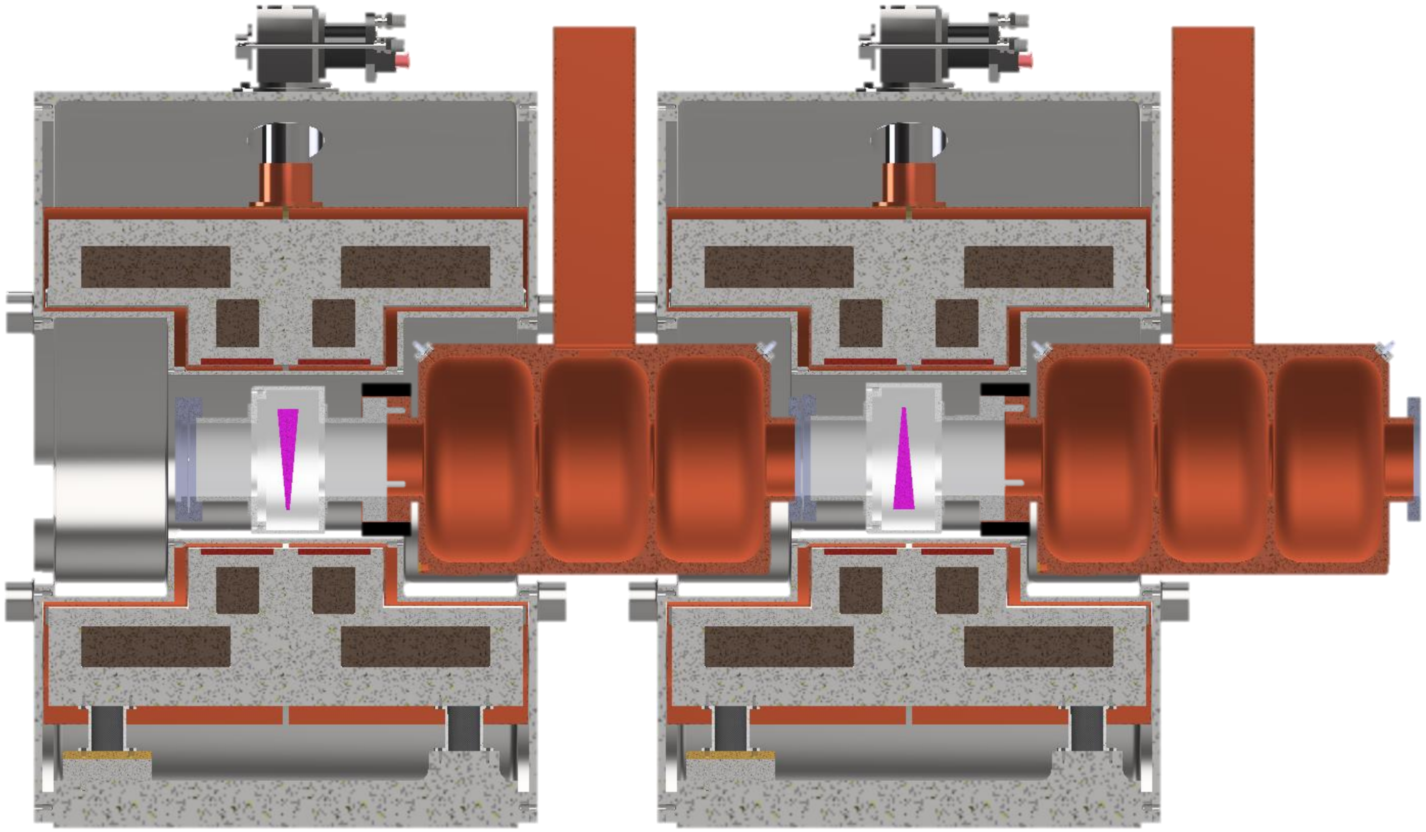
Magnet facing the "begin of cell" side.



Magnet facing the lattice side.







Thank you

International
MUON Collider
Collaboration

MuCol

Funded by
the European Union

Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.