HFM

High Field Magnets

ISAAC, a first common coil with RMC coils: features and plans

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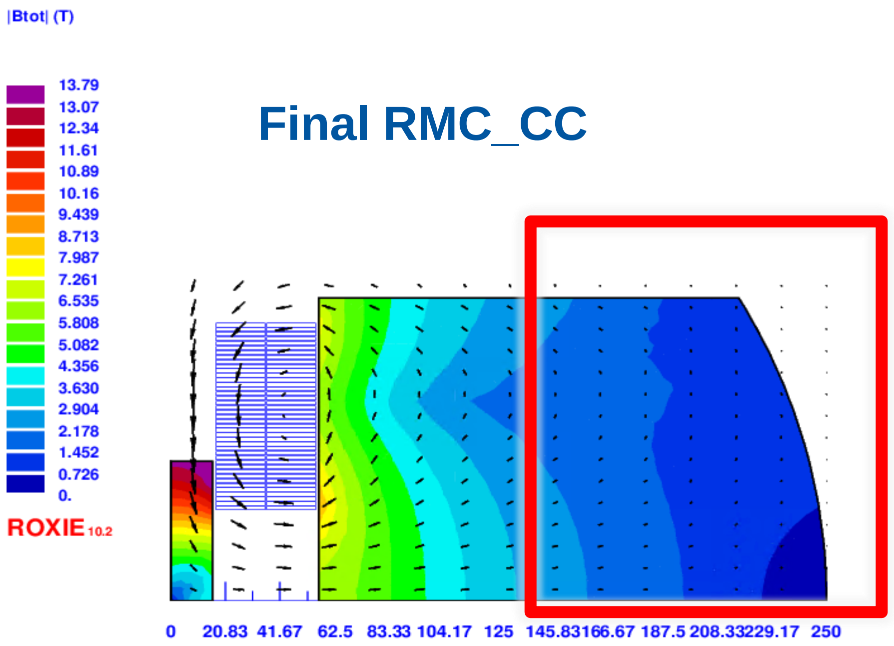
ISAAC magnetic design: goals & constraints

- Main goal: learn for the 14 T model with **existing coils**, mostly on **mechanics**
  - Existing RMC coils made at CERN with MQXF strand are selected. These coils have reached short sample conditions during their test campaign in block configuration: *H. Bajas, 'RMC_QXF: Test Results Report', presented at the RMC-QXF-PIT Test Results, CERN SM18, Prévessin-Moëns, France, Jun. 20, 2018. [Online]. Available: https://indico.cern.ch/event/738646/*
  - Provide ≈14 T in the aperture (100% load)
  - Decrease vertical Lorentz force F_y to achieve low vertical preload (free horizontal movement when coils are energized, without friction)
  - Mechanics & assembly as simple as possible
- **ISAAC**: **I**nvestigating **S**uperconducting **A**ssembly to **A**ddress **C**ommon coil mechanics

ISAAC magnetic design to provide 14T

- Yoke very close to the coil (only 1.2 mm distance).
- Intra-beam distance tuned to decrease *a2* multipole.
- Efficiency in common coil configuration is low due to the narrow pole window.
- Yoke geometry to decrease vertical repulsive forces on cables. The outer diameter could be reduced without significant impact on the aperture field
- **Protection** is possible using a dump resistor.



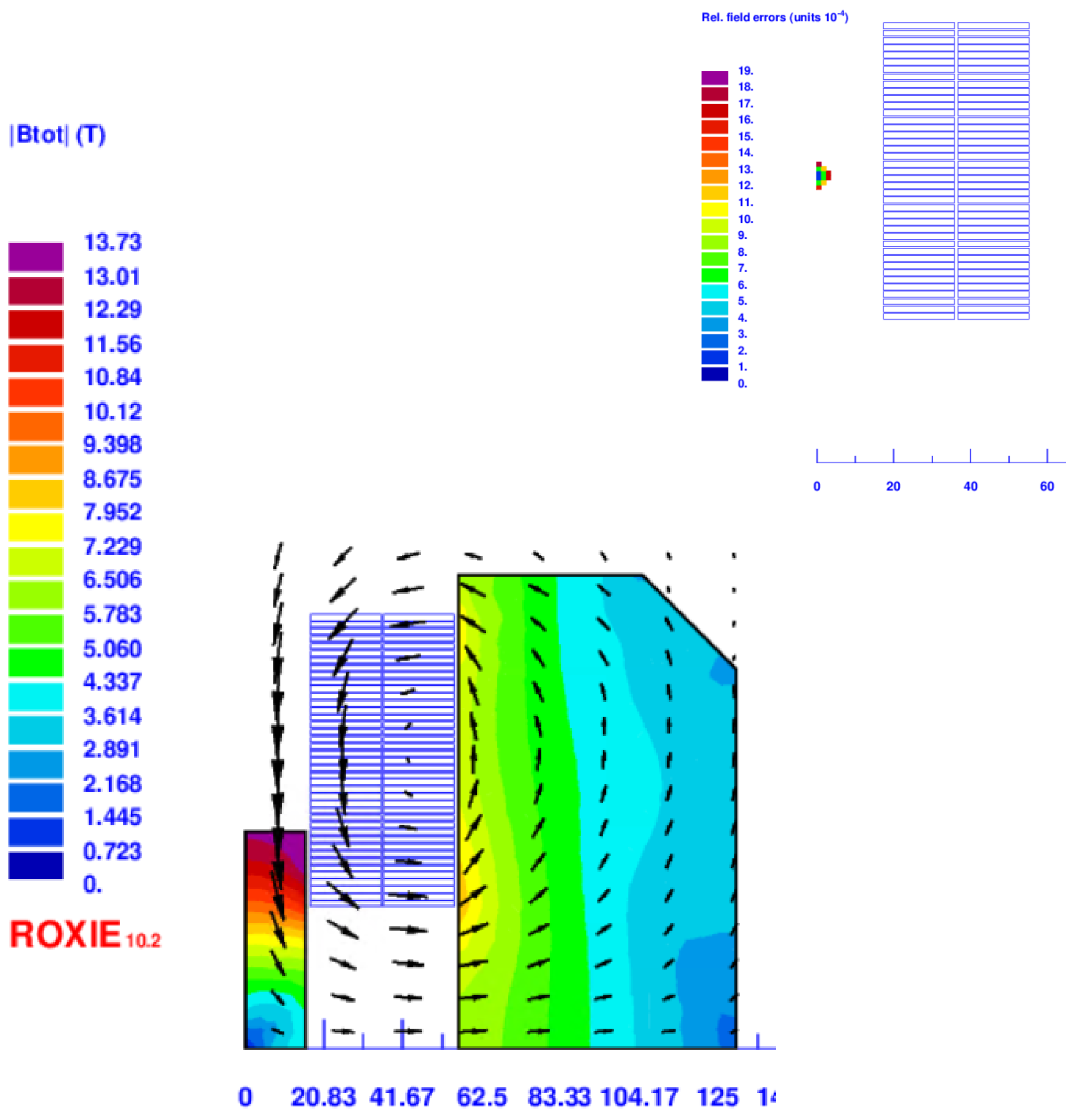
Design ID	ISAAC	Block	Eq. CC	Eq. CC (+100 mm intrabeam	Units
Aperture	34	74	74	74	mm
Intra-beam dist.	150	-	152	**252***	mm
I_nom	19083	14486	21353	20460	A
Yoke outer radius	250	246	246	246	mm
B	14	14	11.3	11.96	T
Peak field	14.8	16.16	14.27	14.51	T
Peak Field/B	1.0571	1.154	1.263	1.213	-
Load	99.99	99.99	100.2	100.36	%
Engineering J	537	408	601	576	A/mm^2
Copper J	1509	1145	1688	1618	A/mm^2
Superconductor J	1850	1404	2070	1984	A/mm^2
Stored energy	1038	1752	1701	1733	kJ/m
Static Self Induct.	5.7	16.7	7.46	8.28	mH/m
L*I	109	242	159	169	HA/m
Stray field (20 mm)	0.44	1.188	0.65	1.56	T
Sum Fx Q1	6.636	5.1	5.79	6.53	MN/m
Sum Fy Q1	0.474	-4.3	3.02	0.73	MN/m

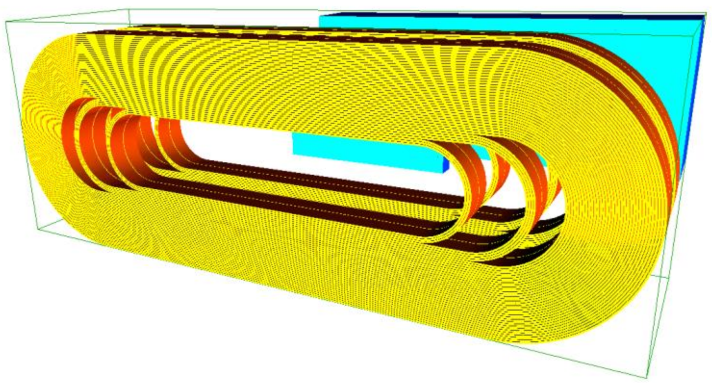
ISAAC 3D

- **All models available:**

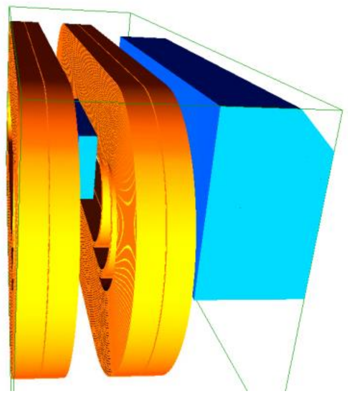
	Without iron	SS yoke only	Complete Yoke
Integrated field [Tm]	12.72	13.81	13.9
Magnetic length [m]	0.554	0.536	0.55

- **Magnetic length: 0.55 m**
  - Straight section = 0.3 m
  - Physical length = 0.65 m aprox.
- **3D peak fields are lower than 2D** ones
- Energy and longitudinal forces match



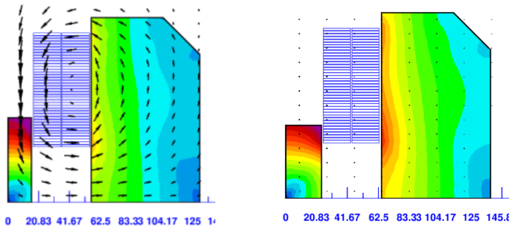


Iron yoke views



ISAAC 2D: Aperture comparison

- Both apertures are feasible: **34** and **50** mm
- Worse peak to bore **field ratio** in 50 mm aperture
- More stored **energy** in 50 mm aperture, but magnet protection is feasible



ISAAC: MAGNETIC DESIGN

Parameter	Conf. 1	Conf. 2	Units
Aperture	**34**	**50**	**mm**
Intra-beam distance	149.6	149.6	mm
Straight section length	0.3	0.3	m
Turns per coil	82	82	-
Copper area (1st quadrant)	1015	1015	mm^2
Superconductor area (1st quadrant)	846	846	mm^2
Nominal current (I)	19340	20728	A
Magnetic length	0.55	0.55	m
Aperture field	13.93	12.68	T
Peak Field	14.73	14.37	T
Peak/aperture field ratio	1.0577	1.1338	-
Load-line	100	100	%
Stored energy	1039	1350	kJ/m
Static self-inductance (L)	5.56	6.28	mH/m
L·I	107	130	HA/m
F_x (Q1)	6.38	5.86	MN/m
F_y (Q1)	0.42	0.81	MN/m
R_{dump}	45	45	mΩ
Detection delay	20	20	ms
Maximum voltage	914	979	V
MIITS	22	28	MAAS
Hot-spot temperature	209	292	K
Cu current density (J_{Cu})	1562	1674	A/mm^2
Superconductor current density (J_{SC})	1875	2009	A/mm^2
Engineering current density (J_{eng})	544	583	A/mm^2
Energy density	89.2	115.8	J/cm^3

Parameter	Value	Units
Strand type	Nb_3Sn	
Strand diameter	0.85	mm
Strand technology	PIT	
Number of Nb_3Sn filaments/Sub-elements	192	
Number of turns per layer	41	
Cu/SC	1.2	
RRR	100	
Non-Cu J_c (15 T, 4.2 K), no self-field corr.	1280	A/mm^2
Number of strands in cable	40 (2x20)	
Cable bare width (before/after HT)	18.15/18.5	mm
Cable bare thick. (before/after HT)	1.525/1.59	mm
Insulated cable width (after HT)	18.8	mm
Insulated cable thick. (after HT)	1.89	mm
Cable width expansion during HT	1.93	%
Cable mid-thick. expansion during HT	4.26	%
Pitch length	109	mm
Insulation type	S2-Glass Braiding	
Insulation thickness per side at 5 MPa	0.15	mm
Impregnation resin	CTD-101K	
Distance between layers	0.5	mm
dB/dt	~0.01	T/s

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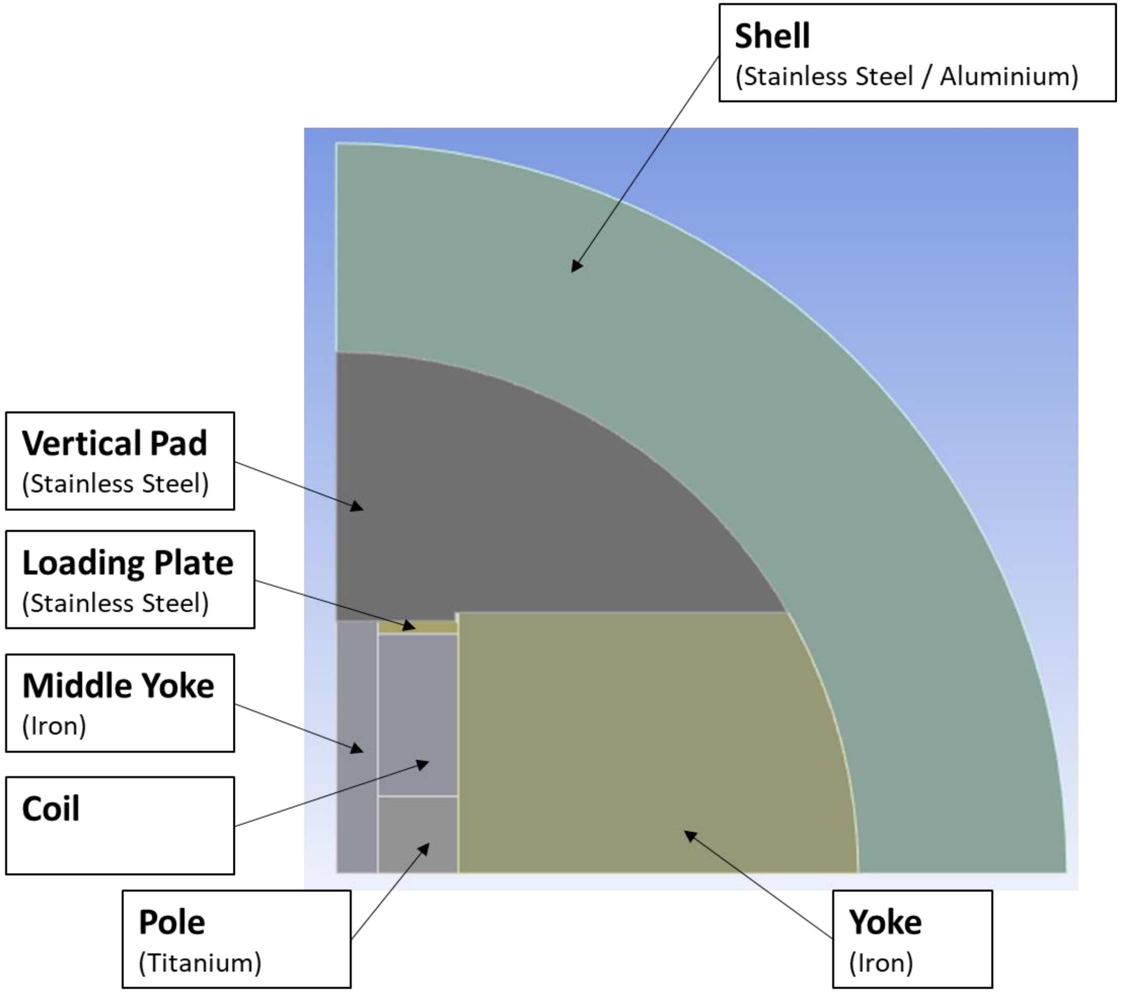
Mechanical design: initial layout

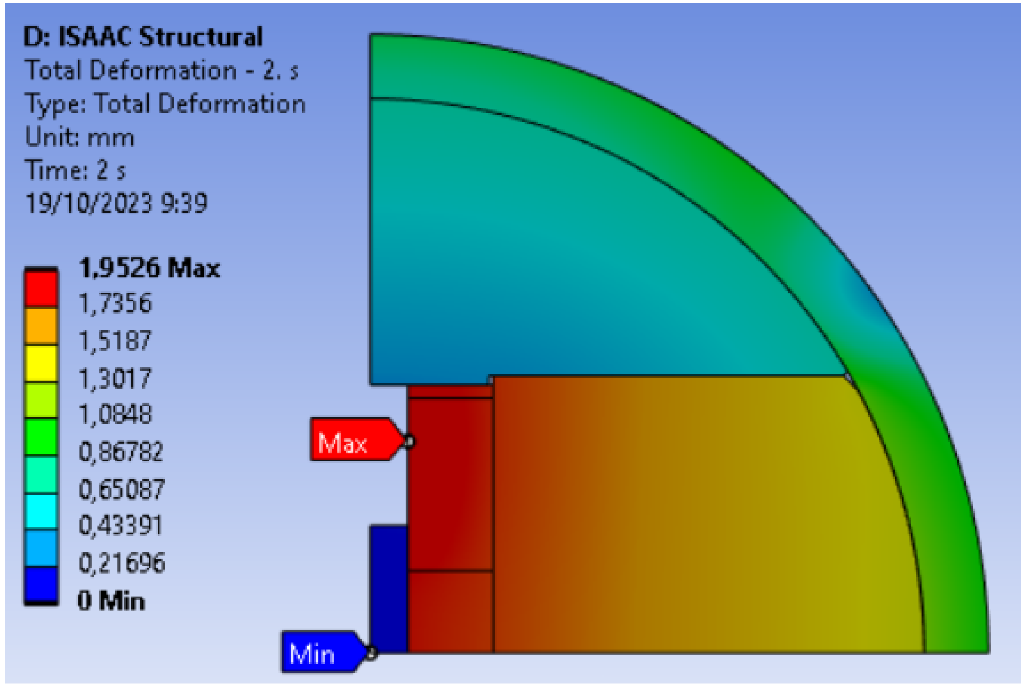
Main features:

- Parts in contact (without prestress) at room temperature
- Stainless steel vertical pad
- Cooling (from 295 K to 1.9 K)
- Electromagnetic forces



Mechanical design: goals

- Aluminium shell similar to SMC CERN block configuration:
  - Outer yoke radius: 250 mm
  - Shell thickness: 29 mm



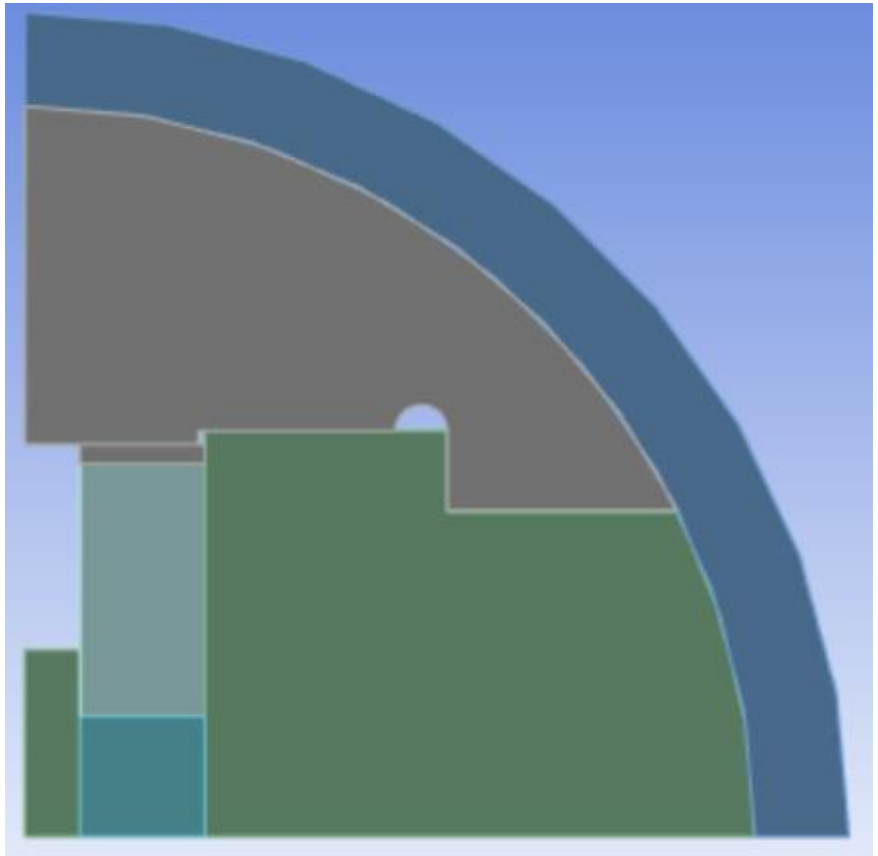
Goal: **Displacement of the coil below 1mm** in order to:

- Reduce the possibility of sudden coil movements
- Reduce the impact on field quality

First simulation shows a horizontal displacement of the coil close to **2 mm**!!

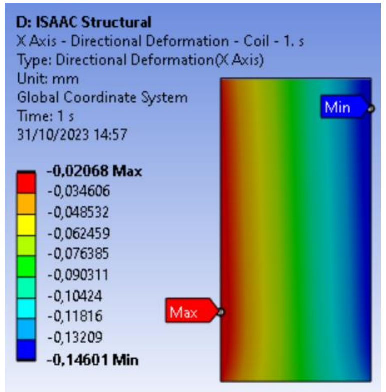
Mechanical design: stiff support structure

- Let's explore the use of yoke as **support structure**
- Upper part is made of **stainless steel**: it may help to contain the large Lorentz horizontal force
- **Aluminium shell** also contributes to hold the forces
- The coil would lose **contact** with this part during cooling down: it could move horizontally without friction
- Assembly with **bladder and keys** is not included in this model
- Slight **preload** just to keep contact between parts

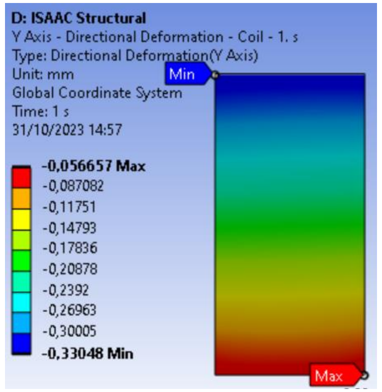


Mechanical design: coil displacement

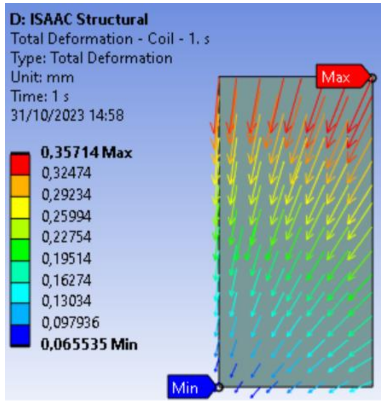
- Horizontal coil displacement below **0.5 mm**



X displacement



Y displacement

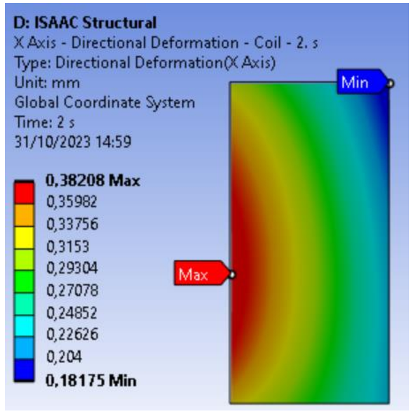


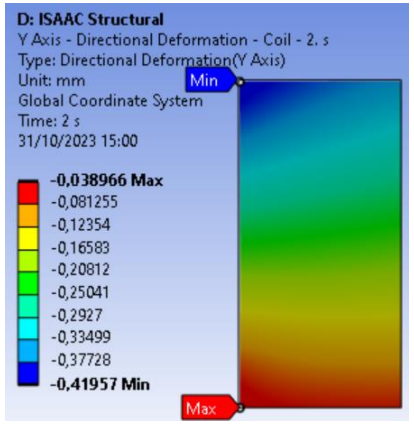
Total displacement

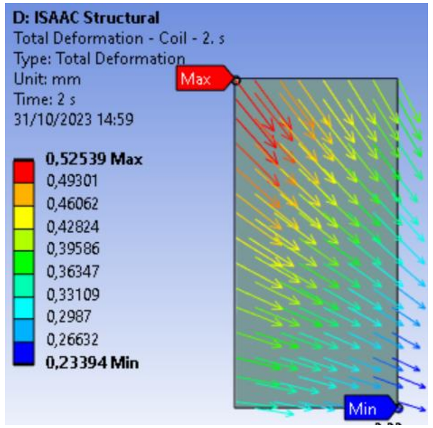
Coil X (Cold)	
Inner	**Outer**
-0,021 mm	-0,146 mm

COOLING

Coil X (EM)	
Inner	**Outer**
0,4054 mm	0,3298 mm





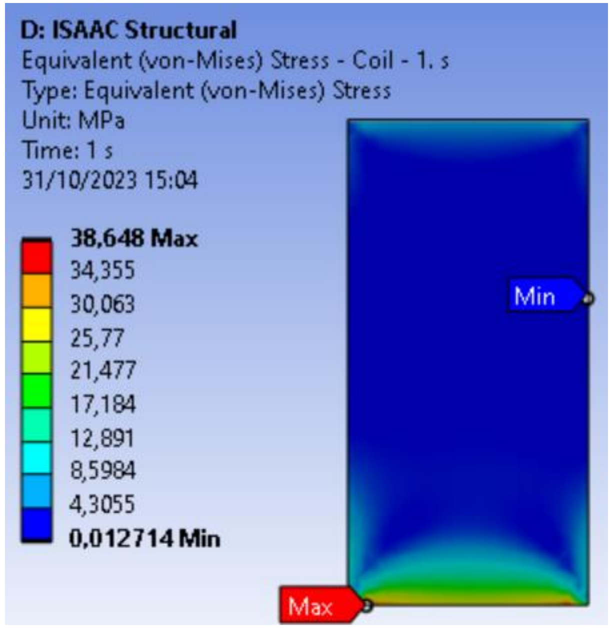


COOLING + EM

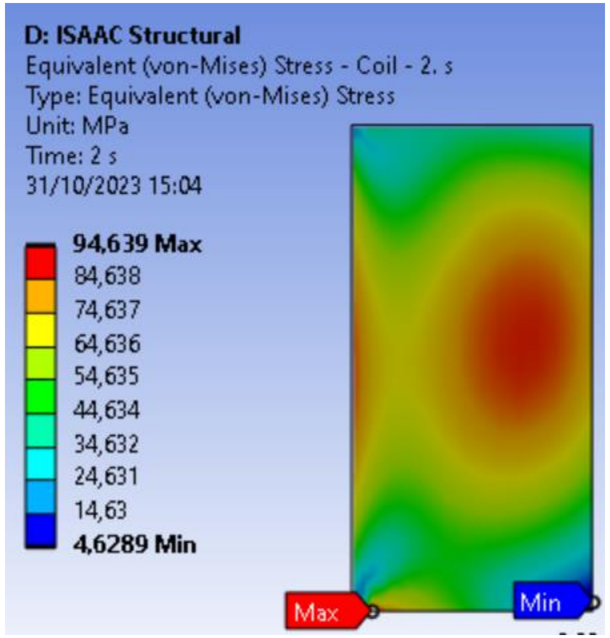
Coil X (Cold+EM)	
Inner	**Outer**
0,3848 mm	0,1838 mm

Mechanical design: stress distribution

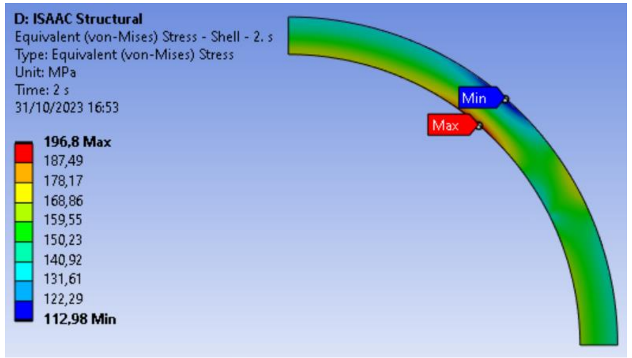
- Coil stress **below 95 MPa**!!
- No significant problems for the structural parts.
- Detailed design is ongoing.

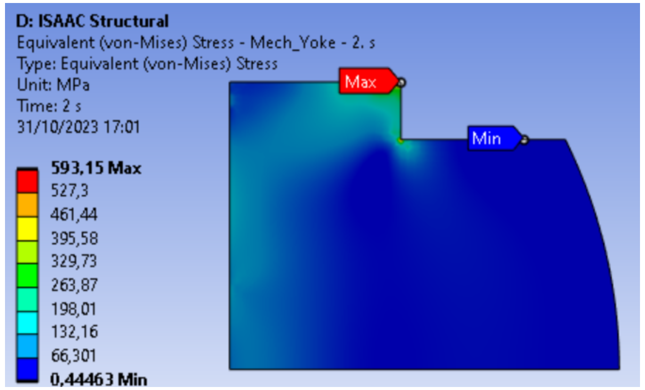


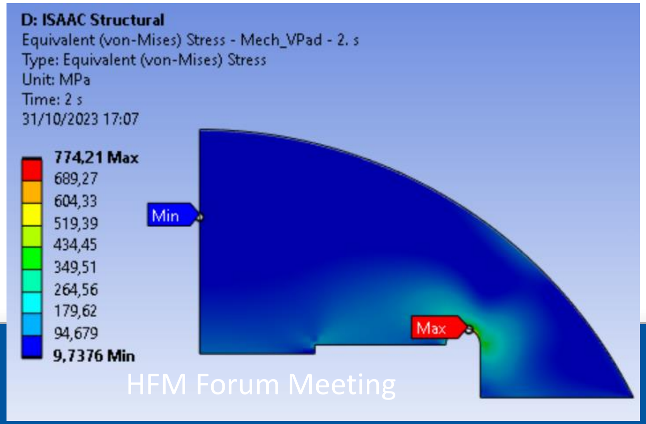
COOLING



COOLING + EM







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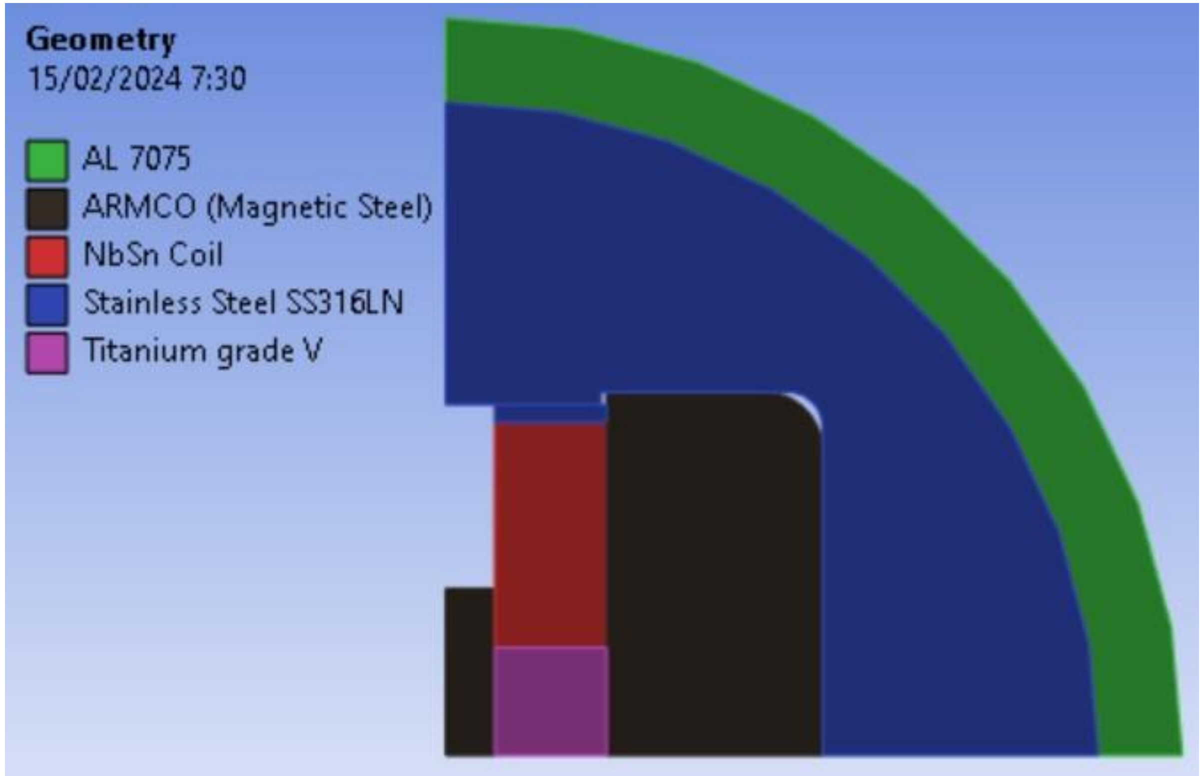
First design iteration: stiffer support structure

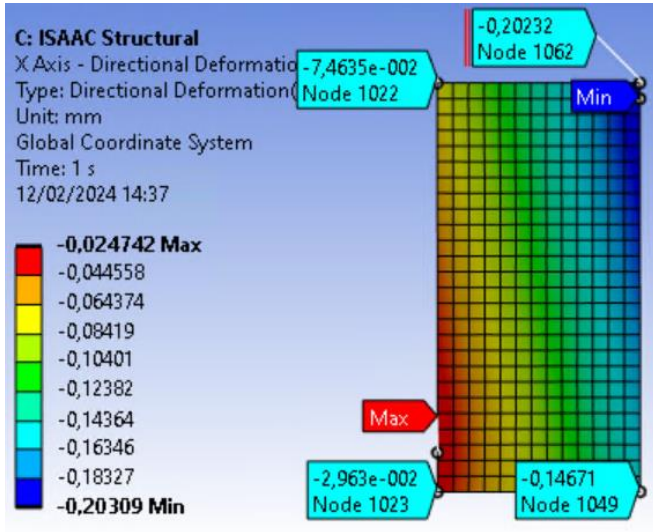
- The support structure is much more stiffer
- No bladder and keys included in this model



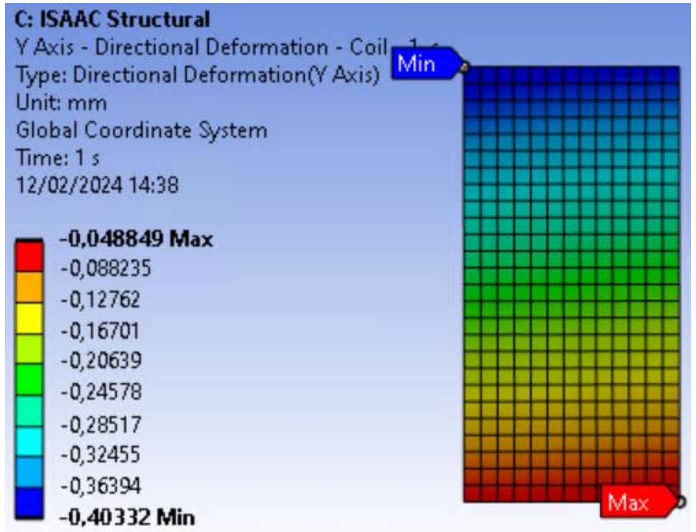
Material properties: A Review of the Mechanical Properties of Materials Used in Nb3Sn Magnets for Particle Accelerators (DOI 10.1109/TASC.2023.3248544)

Displacements @ Coil. COOLING + EM

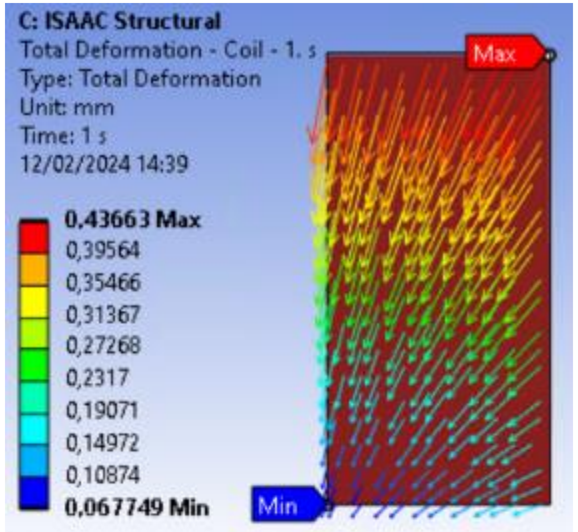
Without Bladder & Keys. Ti Pole – RMC



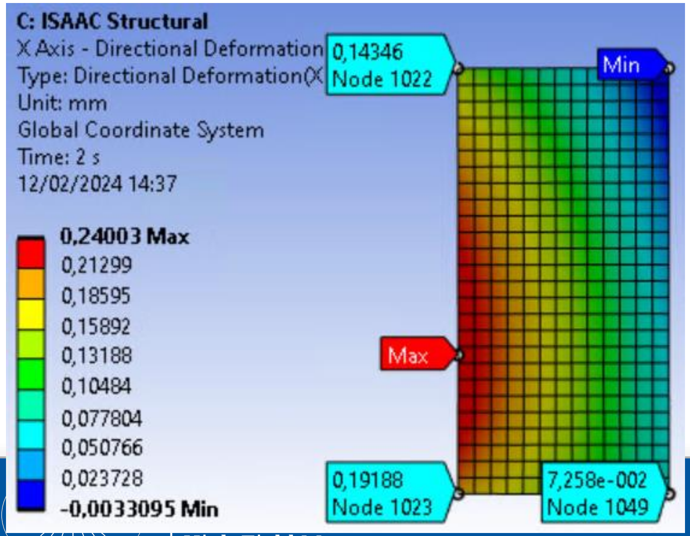
X displacement

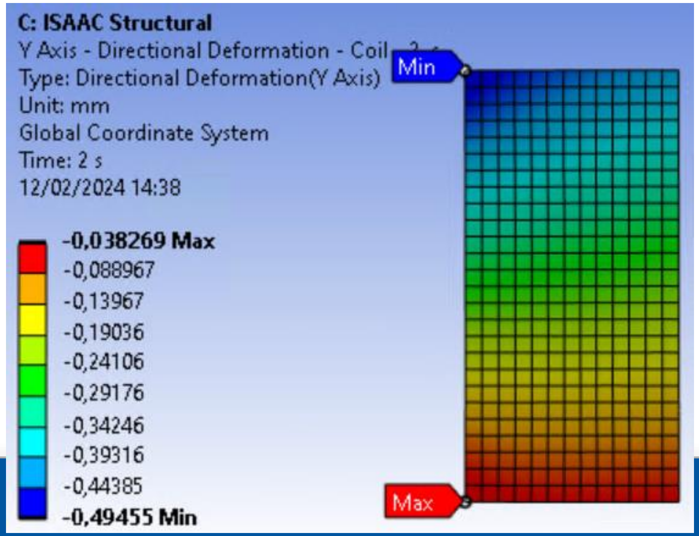


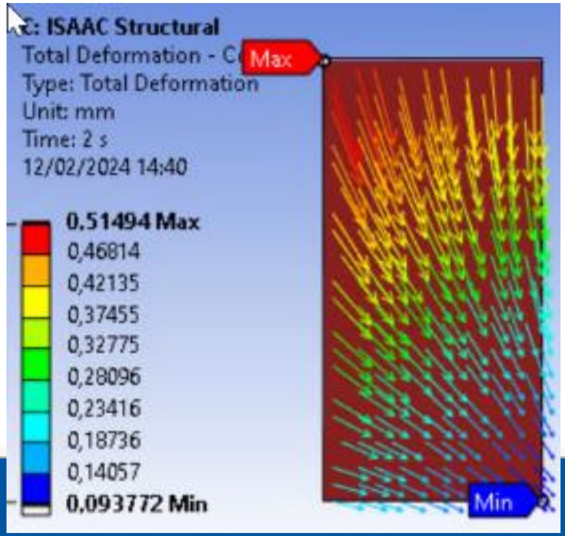
Y displacement



Total displacement







Coil X (Cold)	
Inner	Outer
-0,075 mm	-0,202 mm
-0,03 mm	-0,147 mm

COOLING

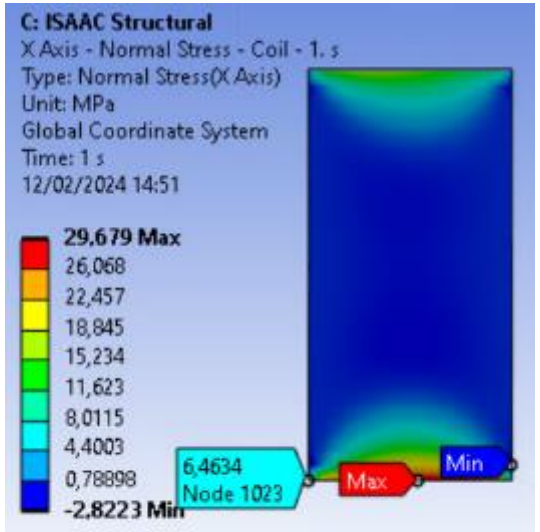
Coil X movement (EM)	
Inner	Outer
0,2181 mm	0,199 mm
0,2215 mm	0,0741 mm

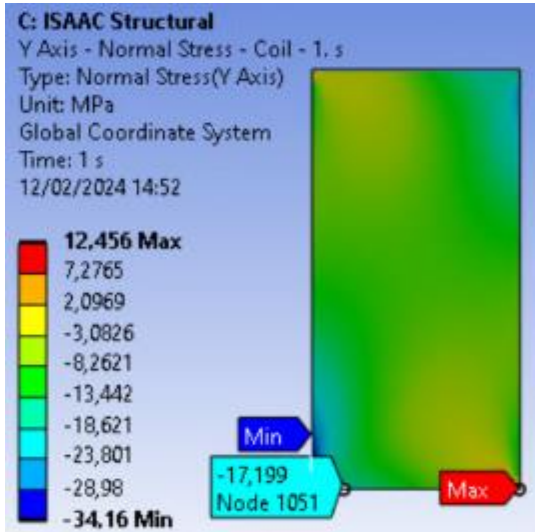
COOLING + EM

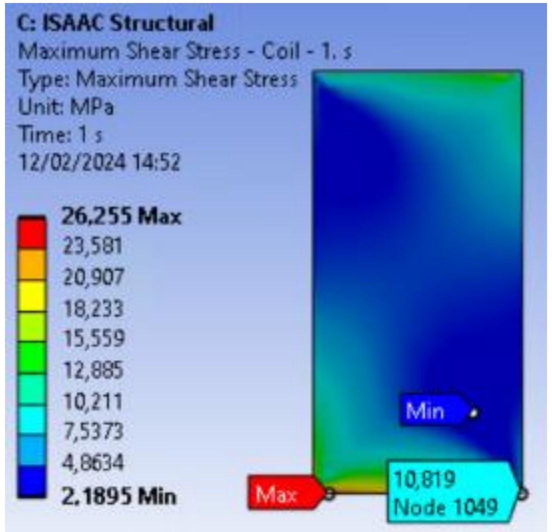
Coil X (Cold-EM)	
Inner	Outer
0,1435 mm	-0,003 mm
0,1919 mm	-0,073 mm

Stress @ Coil. COOLING + EM

Without Bladder & Keys. Ti Pole – RMC

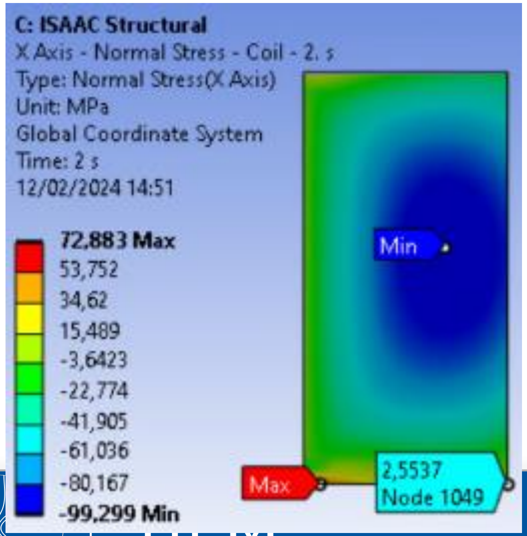


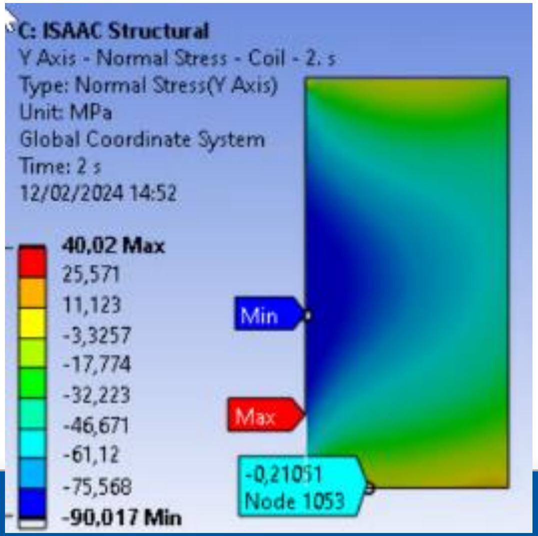


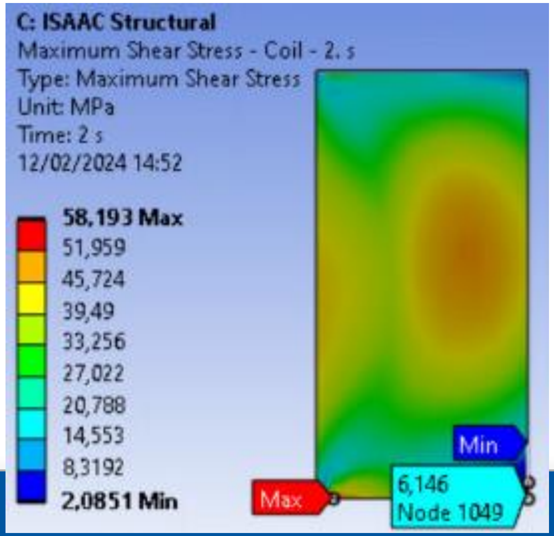


X normal stress | Y normal stress | Shear Stress

COOLING





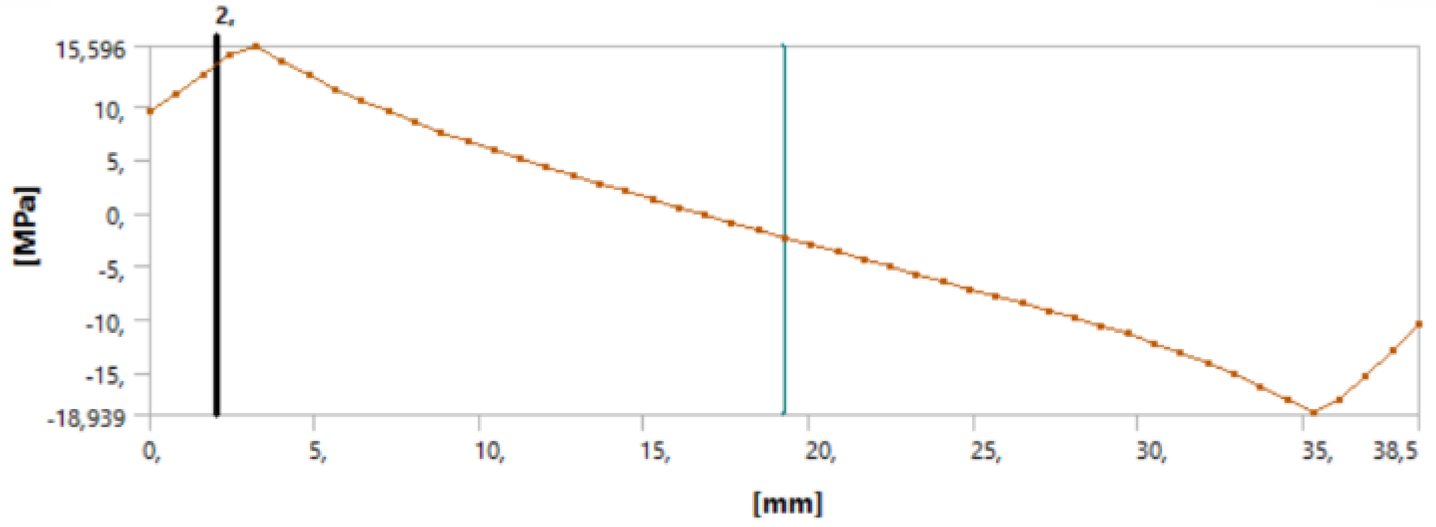


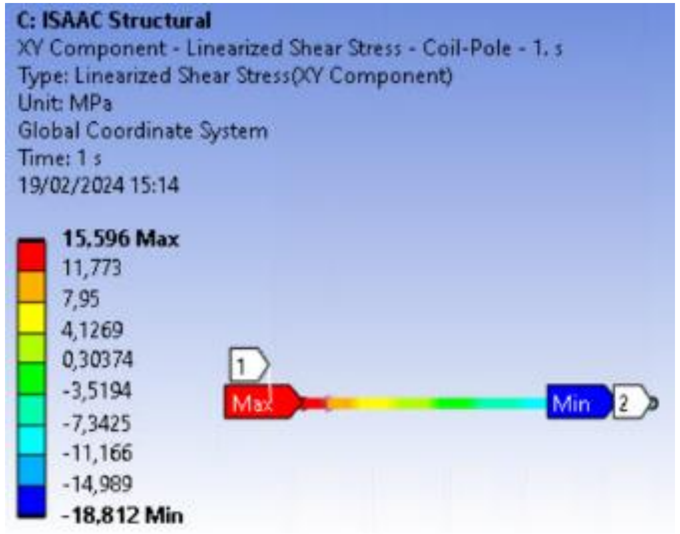
COOLING + EM

Shear stress @ Coil

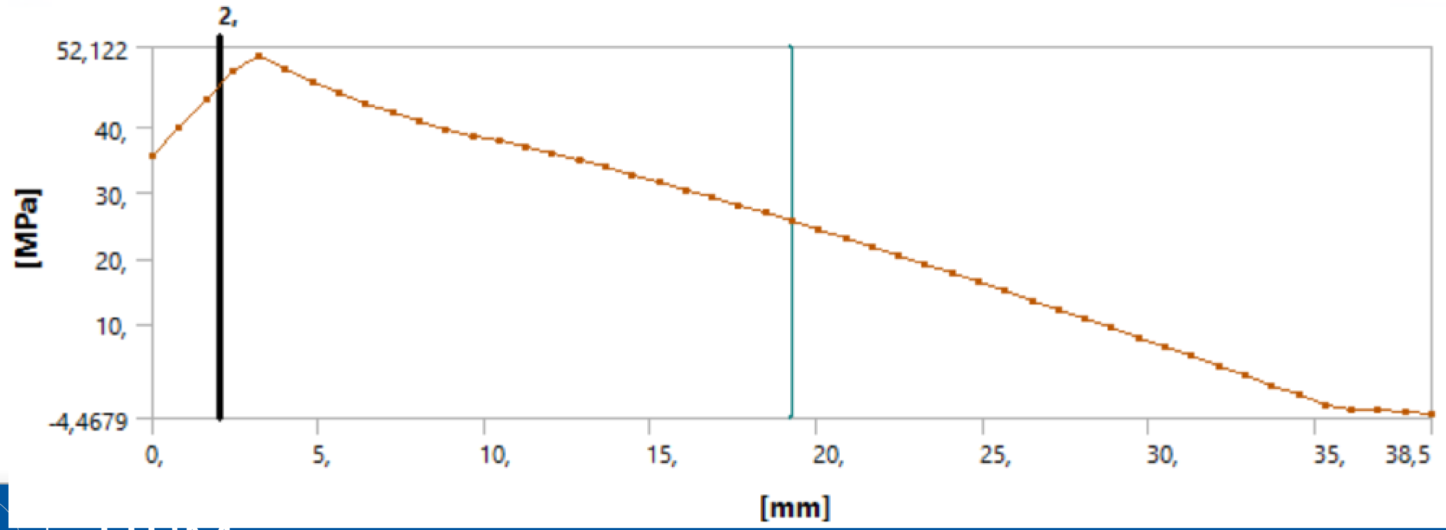
Without Bladder & Keys. Ti Pole – RMC

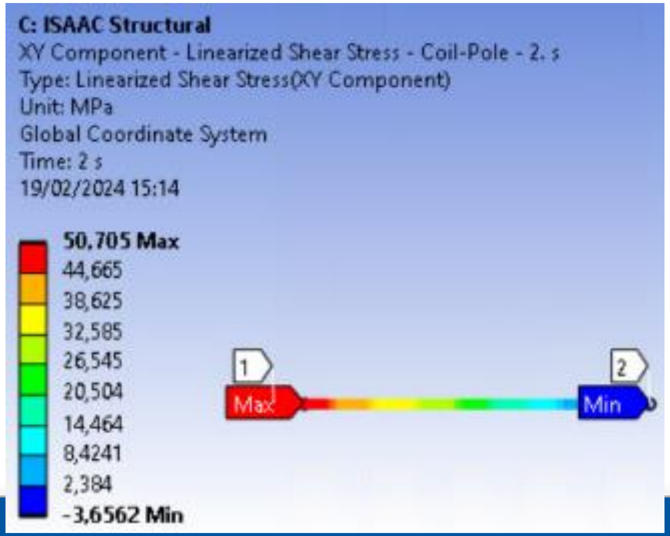
COOLING



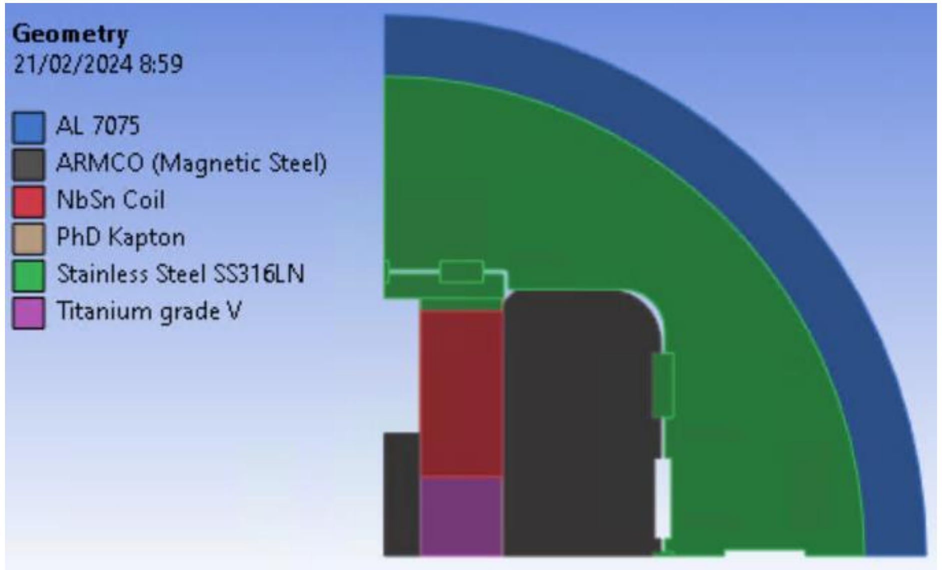


COOLING + EM

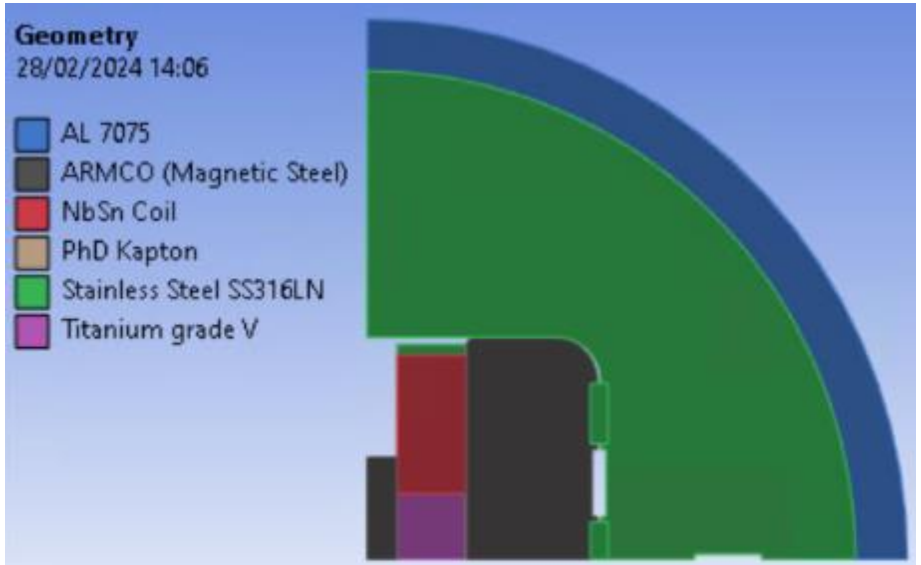




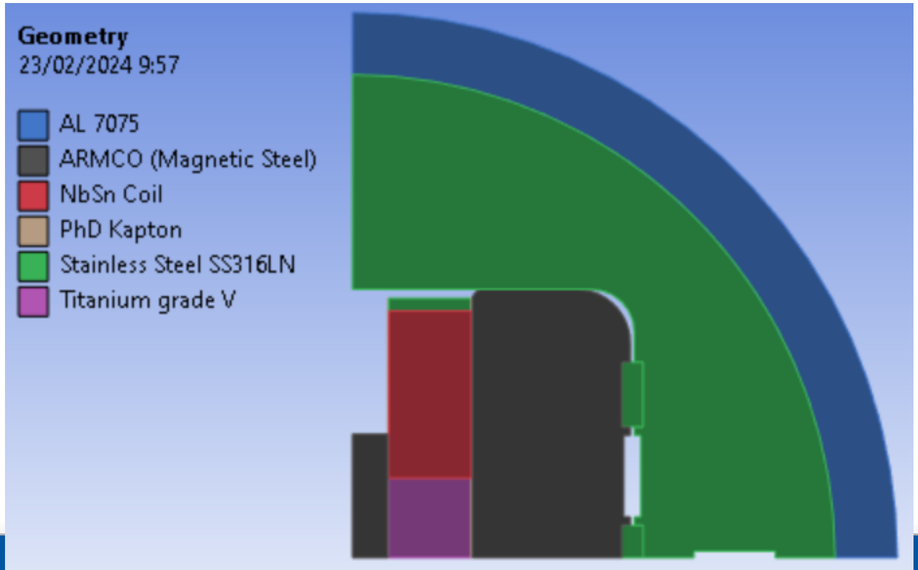
A number of configurations were unsuccessfully studied to reduce the shear stress…



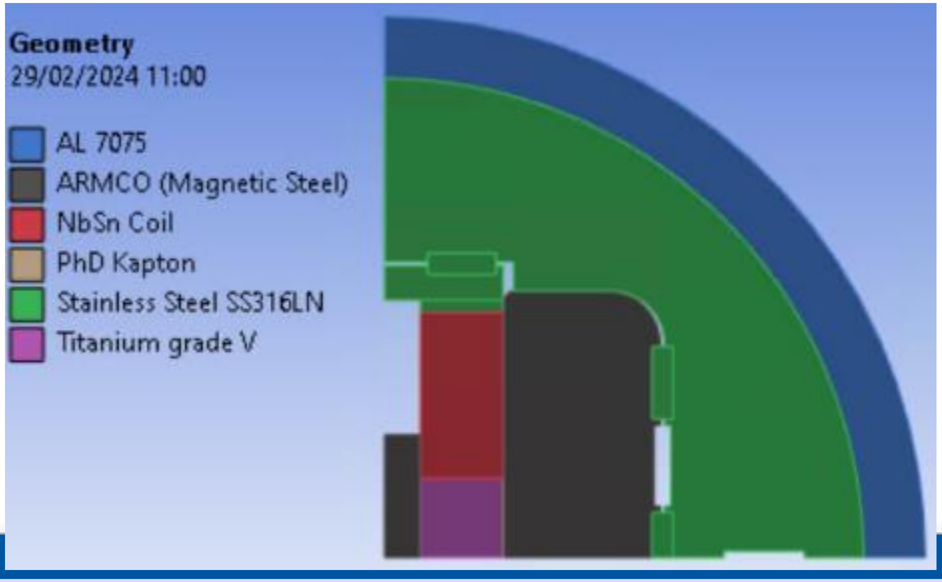
Bladder & Keys. Horizontal and Vertical



Bladder & Keys. Only Horizontal. + 50mm Shell Inner R



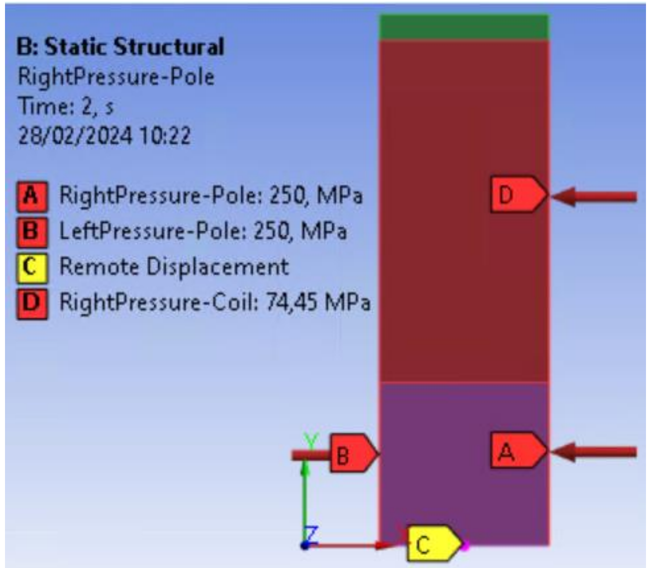
Bladder & Keys. Only Horizontal

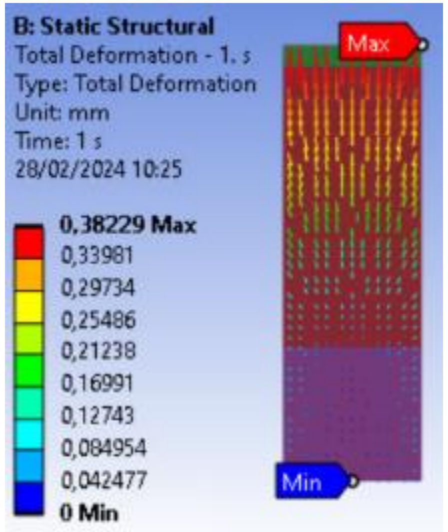


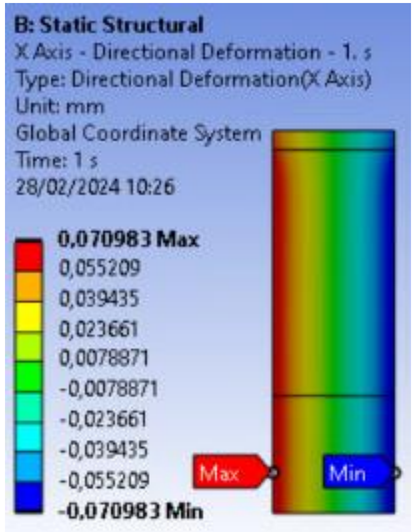
Bladder & Keys. Horizontal and Vertical (v2)

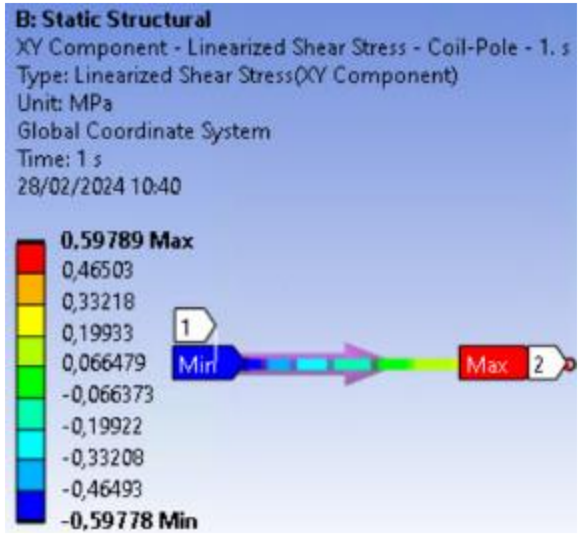
Only the coil is modeled: boundary conditions to minimize shear stress

COOLING









Total displacement

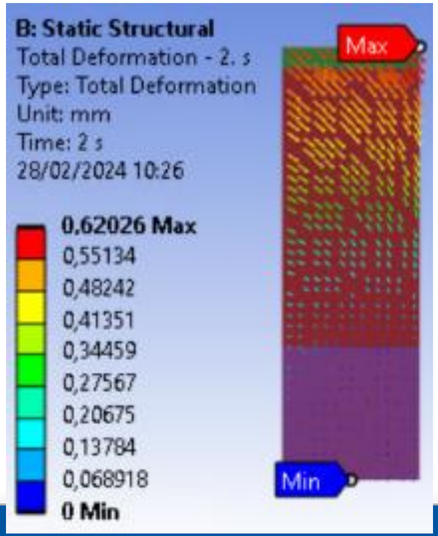
X displacement

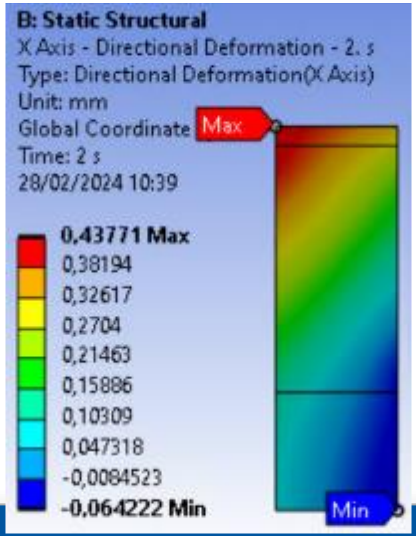
Shear stress

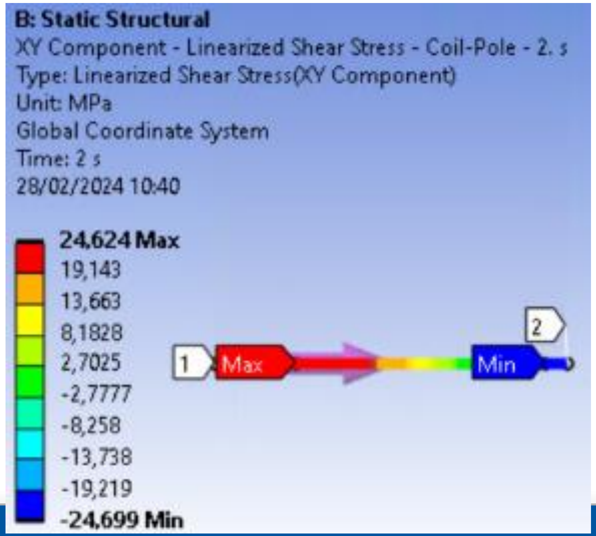
		Different Pressures Pole & Coil (X direction): B			
		Start (0s)	Cooling (1s)	Cool+EM (2s)	Ansys label
Pole (Left)		0 MPa	250 MPa	250 MPa	B
Pole (Right)		0 MPa	-250 MPa	-250 MPa	A
Coil (Right)		0 MPa	0 MPa	-74,45 MPa	D
LoadPlate (Right)		0 MPa	0 MPa	0 MPa	E

	Time [s]	Total - Force Reaction - Remote Displacement - 1. s (X) [N]
1	1,	8,2908e-007
2	2,	-3,143e+005

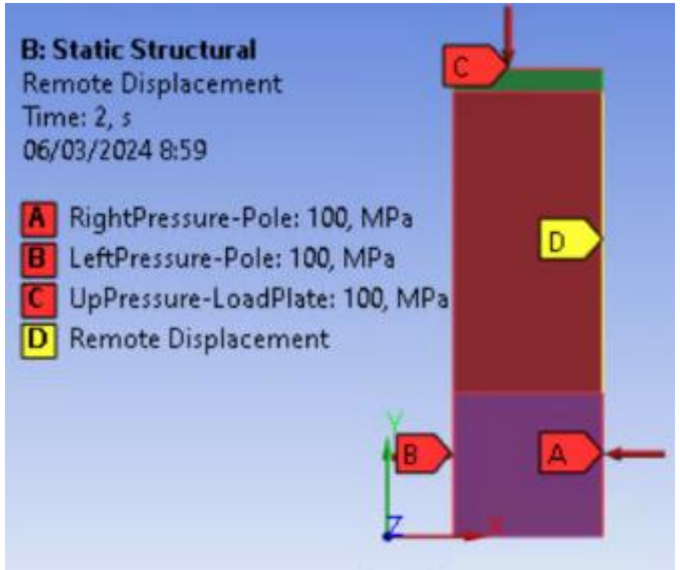
COOLING + EM







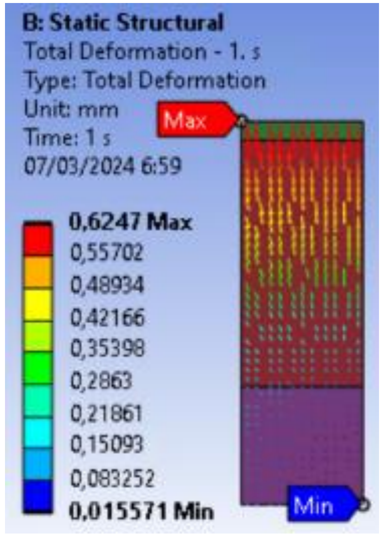
Shear stress cannot be reduced with moderate preload

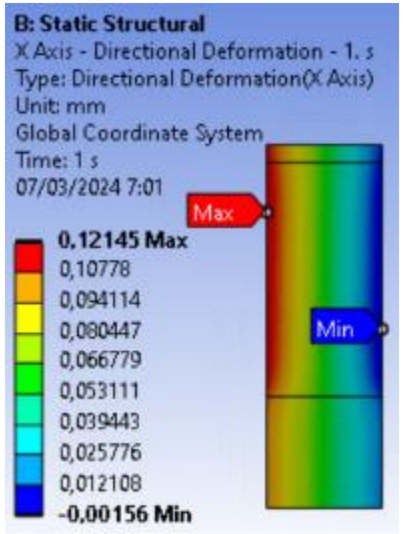


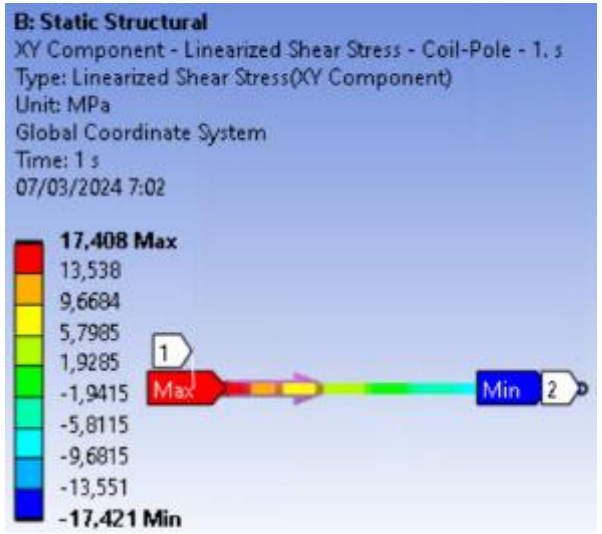
		Different Pressures Pole & Coil (X/Y direction): F			
		Start (0s)	Cooling (1s)	Cool+EM (2s)	Ansys label
Pole (Left)		0 MPa	100 MPa	100 MPa	B
Pole (Right)		0 MPa	-100 MPa	-100 MPa	A
Coil (Right)		0 MPa	0 MPa	0 MPa	D
LoadPlate (Right)		0 MPa	0 MPa	0 MPa	E
LoadPlate (Up)		0 MPa	-100 MPa	-100 MPa	F

	Time [s]	All - Force Reaction - Remote Displacement - End Time (X) [N]
1	1,	-1,7507e-003
2	2,	-6,1021e+006

COOLING



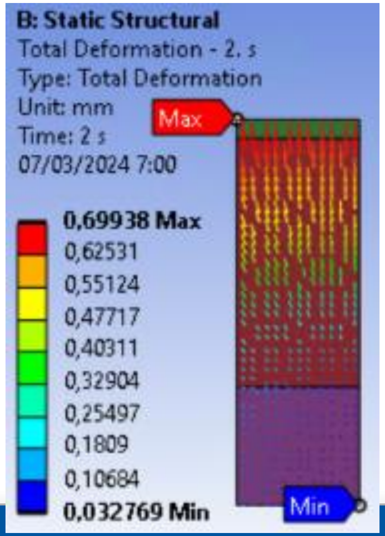


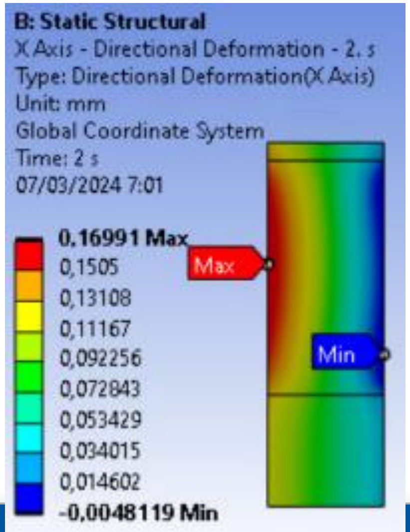


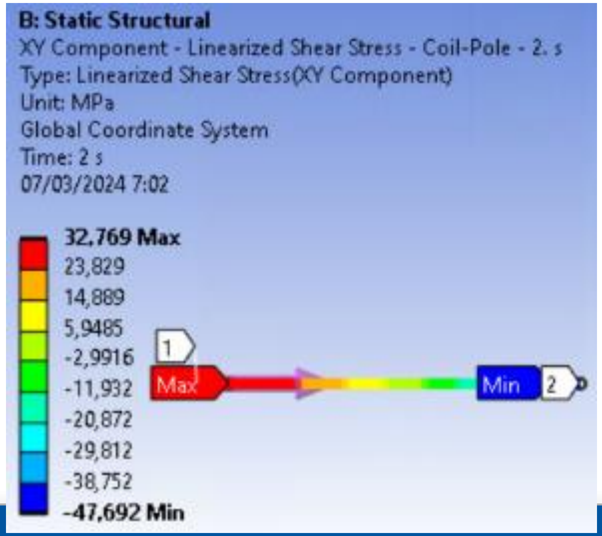
Total displacement

X displacement

Shear stress

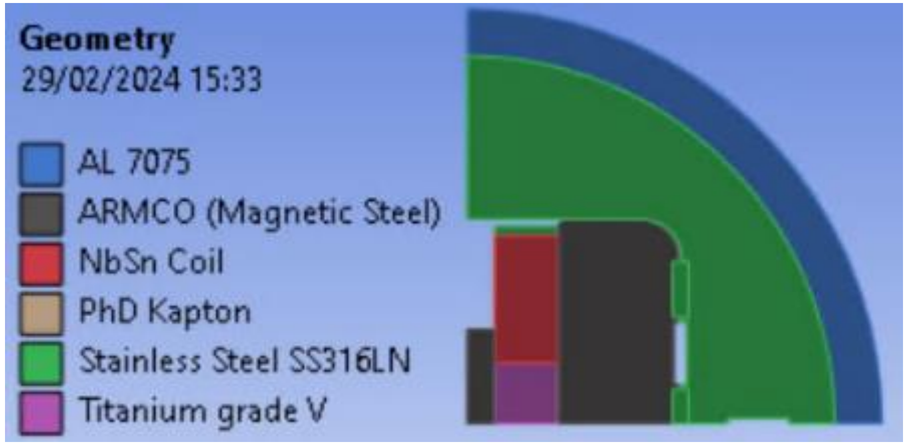






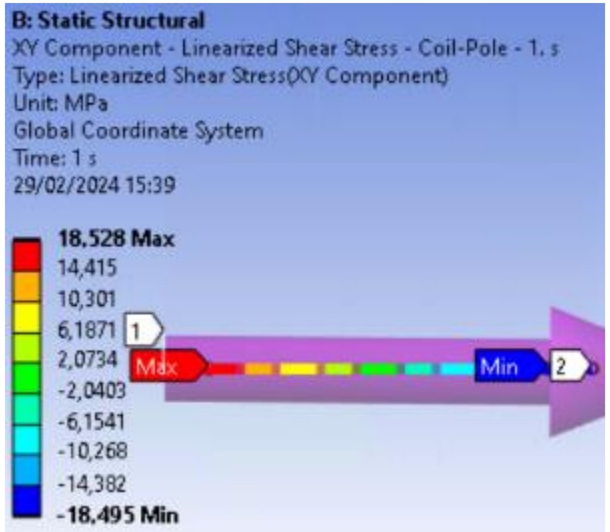
COOLING + EM

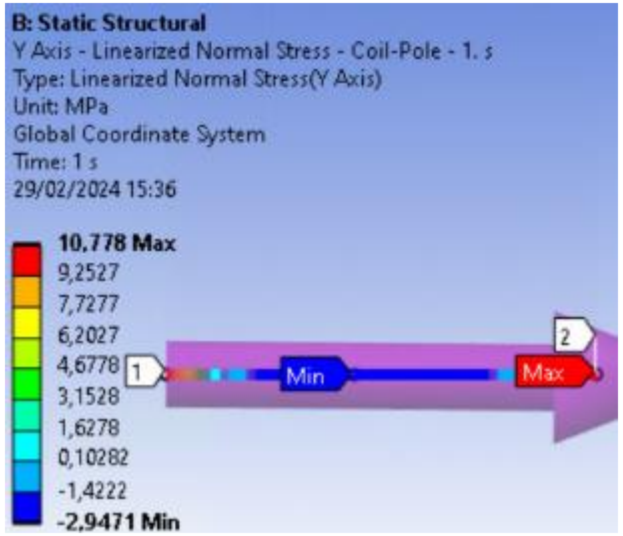
ISAAC Mechanical Design: conclusion



Upper Key: 0,12mm gap
Lower Key: contact

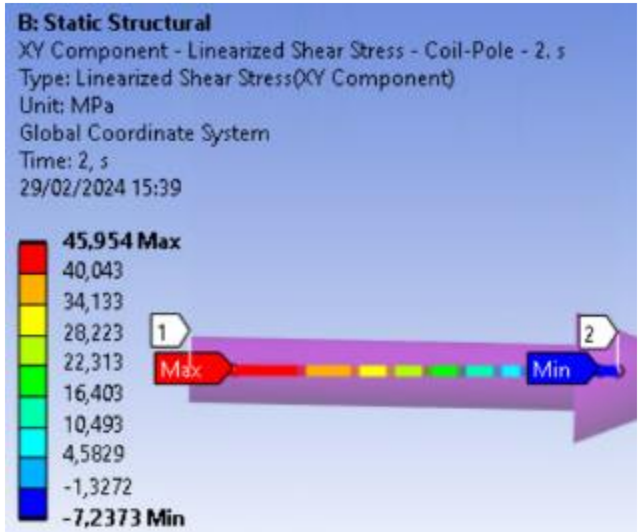
COOLING

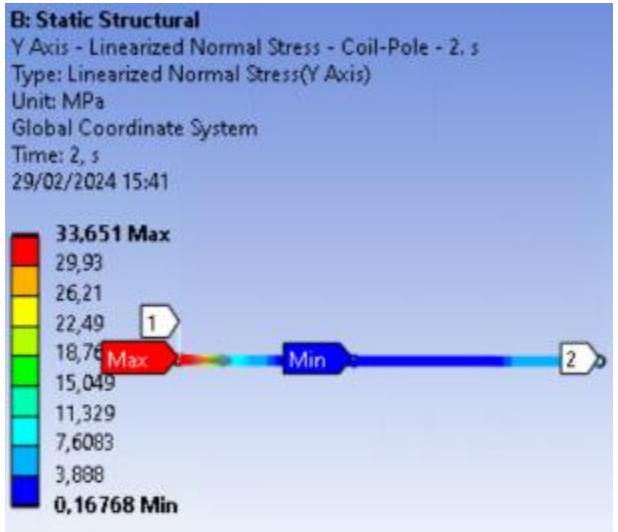




SHEAR STRESS

NORMAL STRESS (Y)



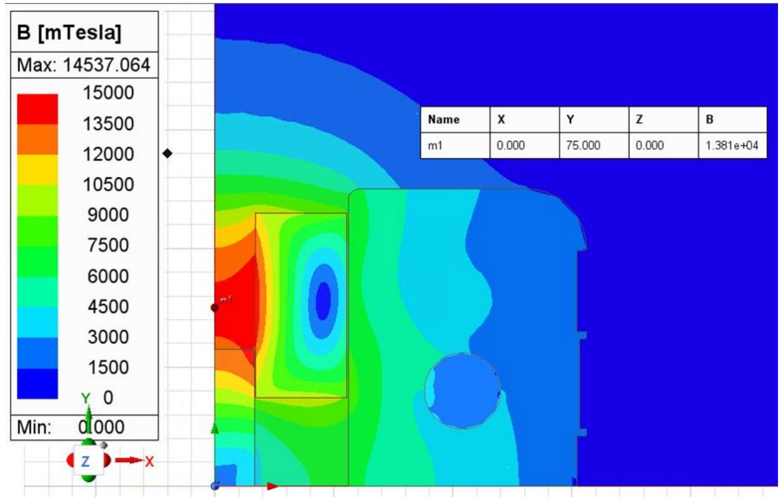


COOLING + EM

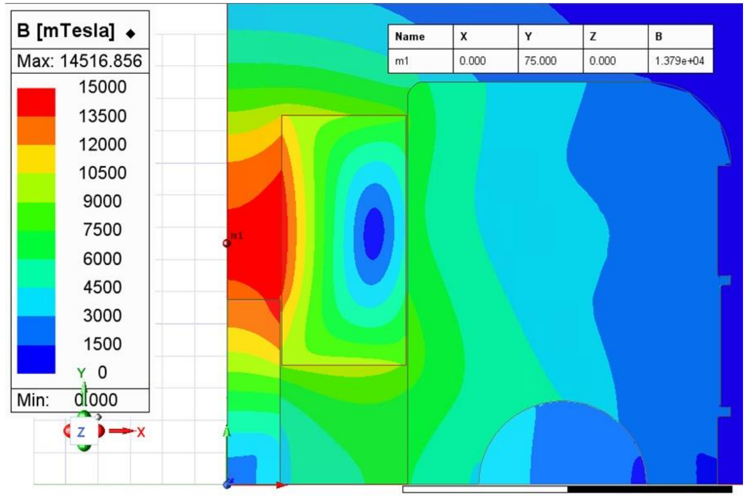
- No way to reduce the shear stress at the pole turn
- Only slight horizontal preload at assembly

Mechanical design: next steps

- **3D modeling** is ongoing
- Axial Lorentz forces will be kept by aluminium rods: they should be placed close to the coils, iron must be enlarged
- First priority is to freeze the shell diameter
- Main concern is the shear stress



30 mm rods



50 mm rod

Schedule

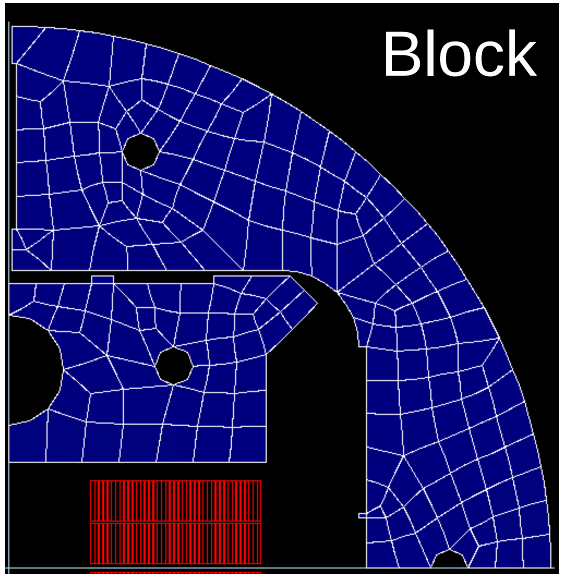
- Mechanical calculations: mid-May
- Engineering design: June
- Fabrication: September (shell is the bottle neck)
- Assembly: October
- Test: November

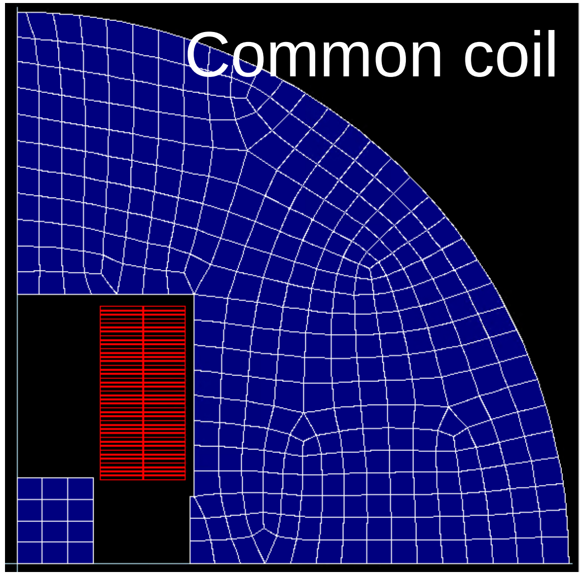
Conclusions

- The first stage of CIEMAT HFM program is the study of common coil mechanics using **existing RMC coils**
- The strategy is to let the coils **move horizontally**, due to the low impact on field quality: low coil stresses at any load condition
- Electromagnetic design has been made for **two apertures: 34 and 50 mm**
- A significant shear stress is induced at the pole turn due to the **glued titanium pole**
- No way has been found to reduce the **shear stress**. A balanced solution is found with slight horizontal preload at assembly, aluminium shell and stiff support structure.
- **3D mechanical design** is ongoing to study the behaviour of axial forces.
- The **bottleneck** for fabrication is the aluminium shell.
- In parallel, the electromagnetic design of a 14 T demonstrator magnet with 50 mm aperture is being done, based on **existing strands**

Block vs. common coil

- Same aperture, 100% load line, same yoke outer radius
- Same energy but half inductance in CC: easier to protect.
- Slightly larger horizontal forces but large repulsive vertical forces.
- More current required in CC: less field but two apertures.

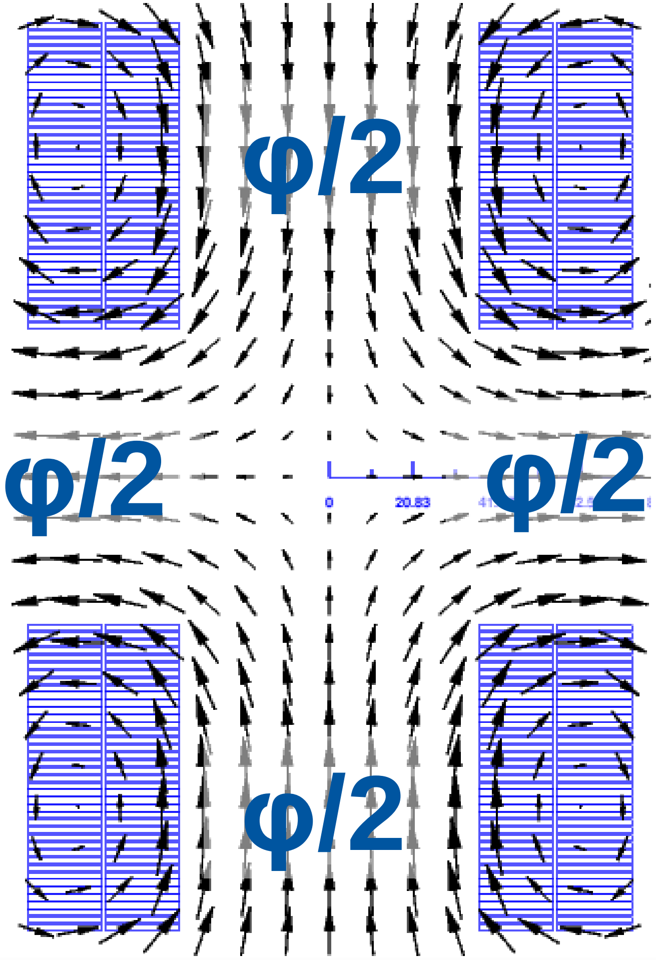


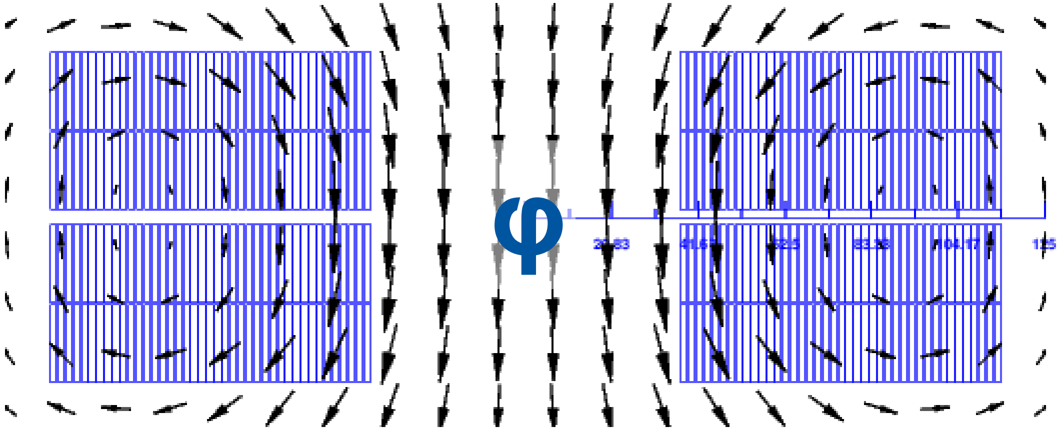


Design ID	Block	CC	Units
Aperture	74	74	mm
Intra-beam dist.	-	152	mm
I_nom	14486	21294	A
Yoke outer radius	246	246	mm
B	14	11.28	T
Peak field	16.16	14.24	T
Peak Field/B ratio	1.154	1.26	-
Stored energy	**1752**	**1692**	**kJ/m**
Static Self Induct.	**16.7**	**7.46**	**mH/m**
L*I	242	159	HA/m
Stray field (20 mm)	1.188	0.64	T
Sum Fx Q1	5.1	5.77	MN/m
Sum Fy Q1	**-4.3**	**3**	**MN/m**

Block vs. common coil

- Using the same coils, current and aperture, common coil field is about half the block coil field





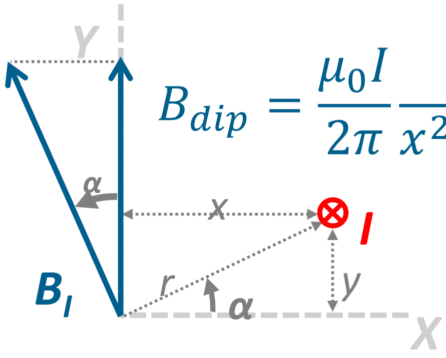
For $I_{CC} = I_{block}$

$$B_{CC} \approx \frac{B_{block}}{2}$$

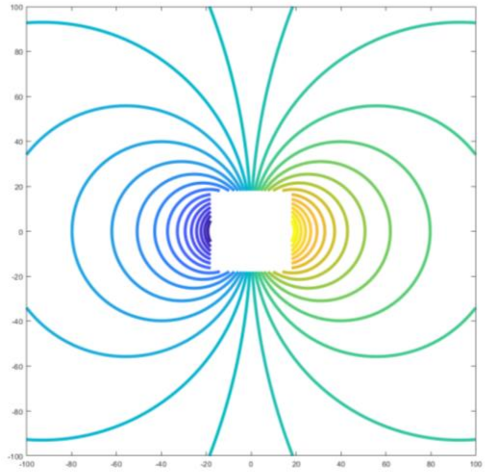
$$B_{CC} \approx \frac{\mu_0 I_{CC}}{\pi \cdot aperture} \qquad B_{block} \approx \frac{2\mu_0 I_{block}}{\pi \cdot aperture}$$

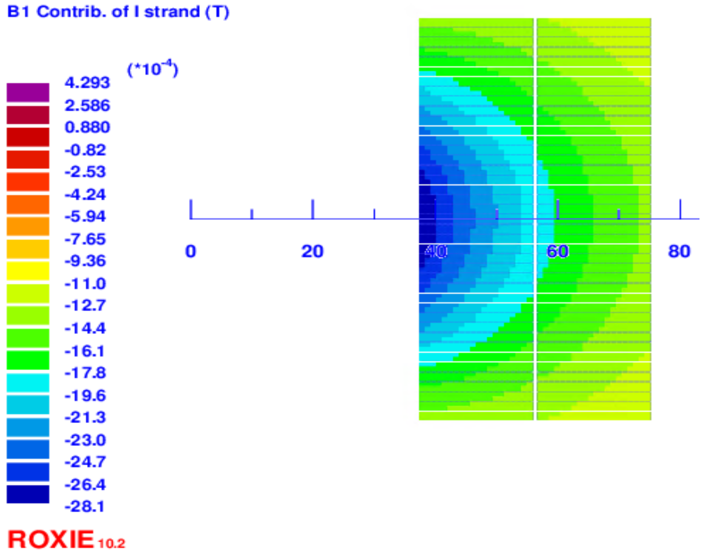
Block vs. common coil

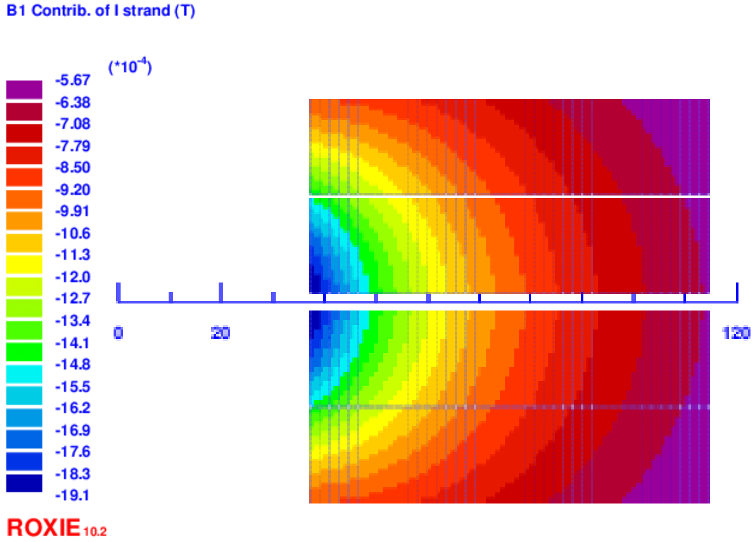
- Isolines for the dipole field contribution of a current line depending on its location
- In this particular case, the far cables of the block configuration are not efficient



$$B_{dip} = \frac{\mu_0 I}{2\pi} \frac{x}{x^2 + y^2}$$







Magnetic design: field quality vs coil position

- ISAAC magnet aperture: 34 mm
- A horizontal displacement of 0.5 mm:
  - decreases field about 1%
  - multipoles variation below 0.5 units unless a2 (1.5 units)

mm	T	units	units	units	units	units	units	units	units	%
Displ. X	**Aperture field**	**b3**	**b5**	**b7**	**b9**	**a2**	**a4**	**a6**	**a8**	**% B**
0	13.99	297.1	0.7	2.2	-0.5	3.0	-25.7	-1.5	1.4	**0**
0.5	13.86	297.0	1.1	2.2	-0.5	1.5	-25.9	-1.6	1.5	**-0.97**
1	13.73	296.8	1.4	2.2	-0.5	-0.0	-26.2	-1.6	1.5	**-1.92**
1.5	13.60	296.5	1.8	2.2	-0.5	-1.5	-26.5	-1.6	1.5	**-2.87**