HFM
High Field Magnets

WP3.7 - Nb3Sn ultimate performance common coil dipole demonstrator

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High field magnet program at CIEMAT

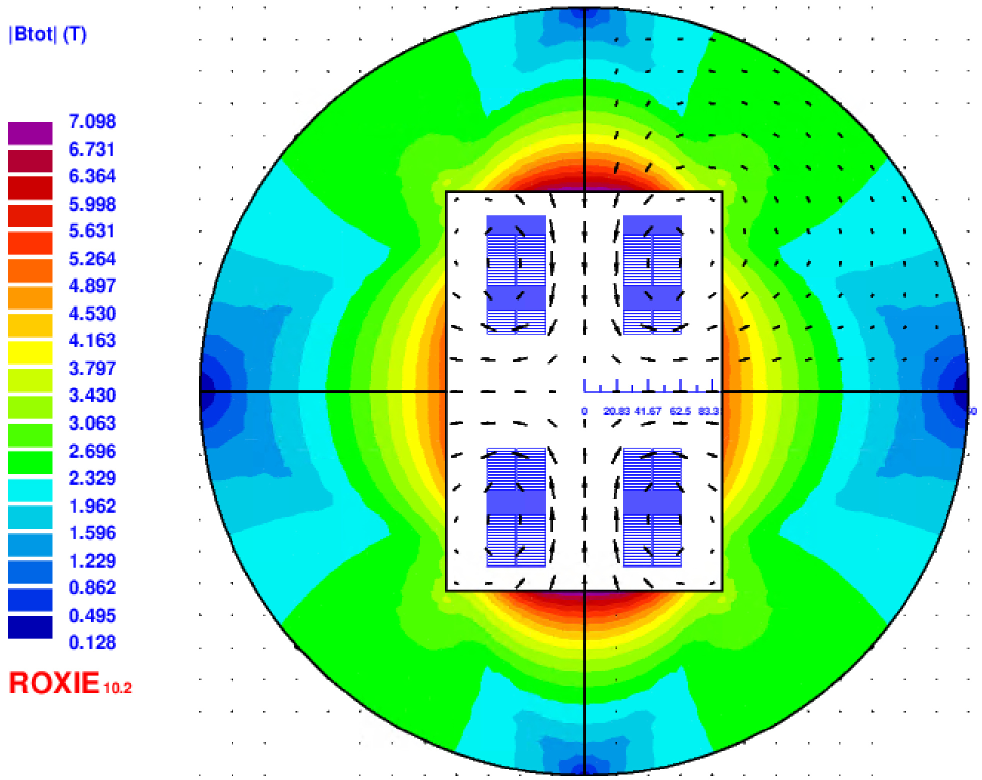
- Initial constraints for the research on high field magnets at CIEMAT:
  - Some delay in starting the activity due to the workload driven by MCBXF magnets.
  - The new laboratory will not be fully operational till Summer 2024: see Carla's talk tomorrow.

- Our strategy is based on the following steps:
  1. Model magnet using RMC coils in common coil configuration (ISAAC: Investigating Superconducting Assembly to Address Common coil mechanics).
  2. Research on fabrication techniques: detachable poles, react-and-wind coils.
  3. Prototype of a high field magnet in common coil configuration.

	HIGH FIELD SC MAGNET MODELS FOR FCC	2022				2023				2024				2025				2026				2027			
UM-IO-1.1	Provision of building and services	■	■	■	■	■																			
UM-IO-1.2	Set-up and commissioning of laboratory				■	■	■	■	■	■															
UM-IO-2.1	Production of tooling and structure for ERMC and RMM					■	■	■	■	■	■														
UM-IO-2.2	Production of practice coils						■	■	■	■	■	■	■												
UM-IO-3.1	High field demonstrator: detailed design								■	■	■	■	■	■	■										
UM-IO-3.2	High field demonstrator: design and procurement of the tooling												■	■	■	■	■								
UM-IO-3.3	High field demonstrator: manufacturing of the coils															■	■	■	■						
UM-IO-3.4	High field demonstrator: magnets assembly and participation to cold tests & analysis																			■	■				

ISAAC magnetic design: goals & constraints

- Main goal: learn for the 14 T model with **existing coils**, mostly on **mechanics**
  - Provide 14 T in the aperture (100% load required)
  - Decrease vertical Lorentz force F_y: low vertical preload (free horizontal movement, without friction)
  - Mechanics & assembly as easy as possible

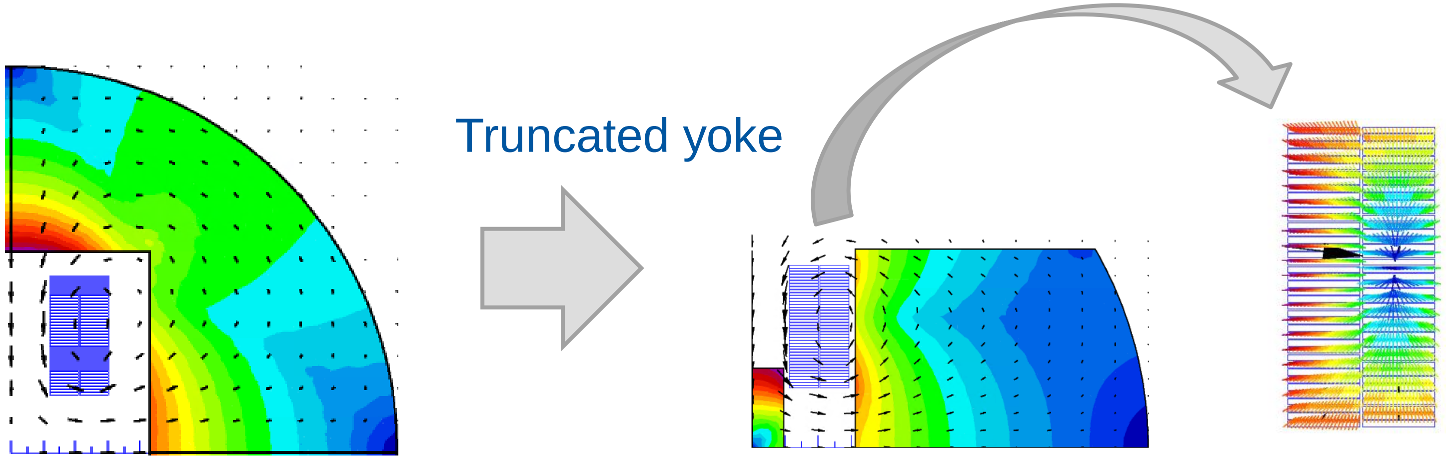


Initial base case

Design ID	2D_V0_80	Units
Aperture	50	mm
Intra-beam dist.	152	mm
I_nom	16	kA
Yoke inner X	90	mm
Yoke inner Y	130	mm
Yoke outer diam.	500	mm
B	10.25	T
Peak field	11.68	T
Load	80.2	%
Stored energy	855	kJ/m
Static Self Induct.	6.68	mH/m
L*I	106.86	HA/m
Stray field (20 mm)	0.29	T
Sum Fx Q1	4.19	MN/m
Sum Fy Q1	1.54	MN/m
Total F	4.47	MN/m

ISAAC magnetic design: decreasing F_y

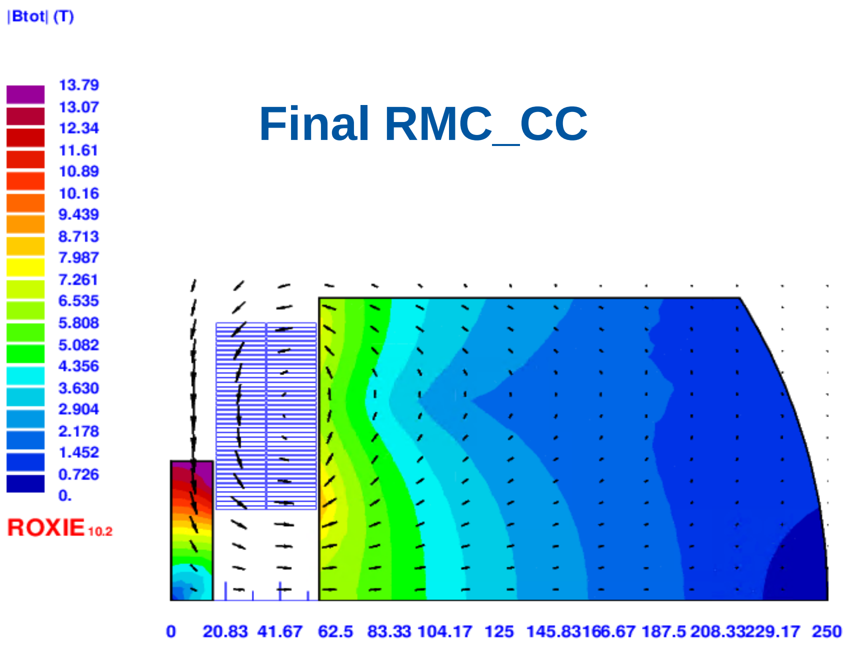
- Vertical Lorentz forces inside the coil need to be **balanced**: return conductors vs. iron
- Yoke is used to pull the field lines in the desired direction
- Yoke is truncated above the coil to provide good side support to coil
- Middle yoke helps to decrease F_y significantly and enhances bore field



Units	T	MN/m	MN/m	MN/m	-
Design ID	B	Total F	Sum Fx Q1	Sum Fy Q1	Ratio Fy/Fx
2D_V0_80_Apert46_MY20x50: **Full iron + Middle Yoke**	10.85	4.45	4.25	**1.31**	0.31
2D_V5_wo_MY: **Truncated iron without middle yoke**	10.28	4.33	4.28	**0.63**	0.15
2D_V5_MY20x50: **Truncated iron + middle yoke**	10.52	4.21	4.18	**0.47**	0.11

ISAAC magnetic design to provide 14T

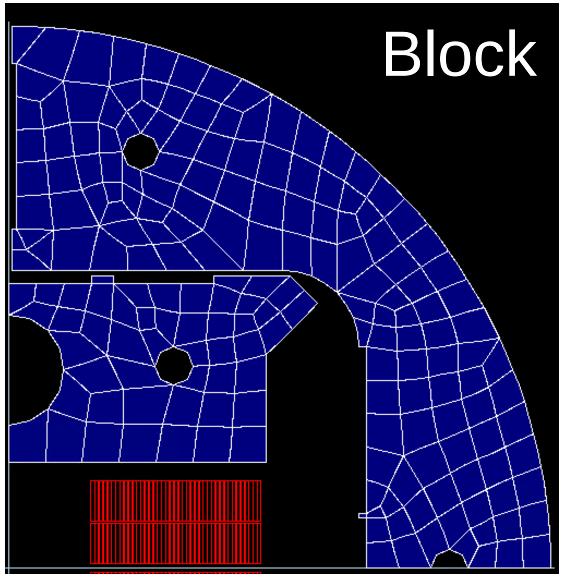
- Aperture decreased from 50 to **34 mm**
- Yoke very close to the coil (only 1.2 mm distance)
- Intra-beam distance tuned to decrease *a2*
- Middle yoke has a strong influence despite its assembly could be not straightforward
- **Protection** is possible using a dump resistor according to first simulations: R_{dump} = 45 mΩ yields a hotspot temperature of 286K and 900V voltage (adiabatic simulation)

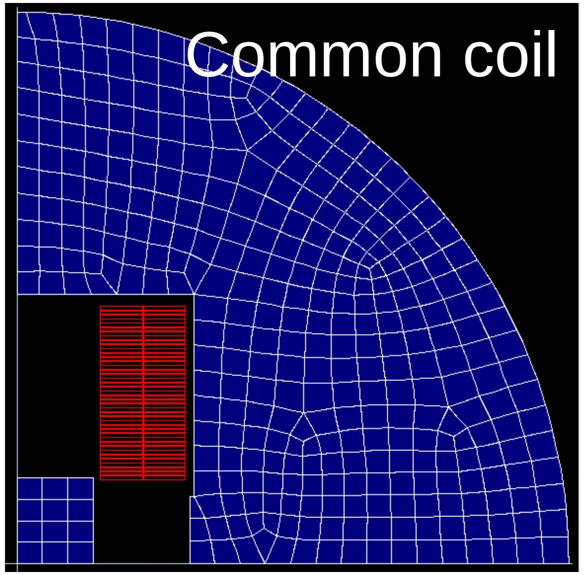


Design ID	Block	Final RMC_CC	CC	CC*	Units
Aperture	74	34	74	74	mm
Intra-beam dist.	-	150	152	252	mm
I_nom	14486	19083	21353	20460	A
Yoke outer radius	246	250	246	246	mm
B	14	14	11.3	11.96	T
Peak field	16.16	14.8	14.27	14.51	T
Peak Field/B	1.154	1.0571	1.263	1.213	-
Load	99.99	99.99	100.2	100.36	%
Stored energy	1752	1038	1701	1733	kJ/m
Static Self Induct.	16.7	5.7	7.46	8.28	mH/m
L*I	242	109	159	169	HA/m
Stray field (20 mm)	1.188	0.44	0.65	1.56	T
Sum Fx Q1	5.1	6.636	5.79	6.53	MN/m
Sum Fy Q1	-4.3	0.474	3.02	0.73	MN/m

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.

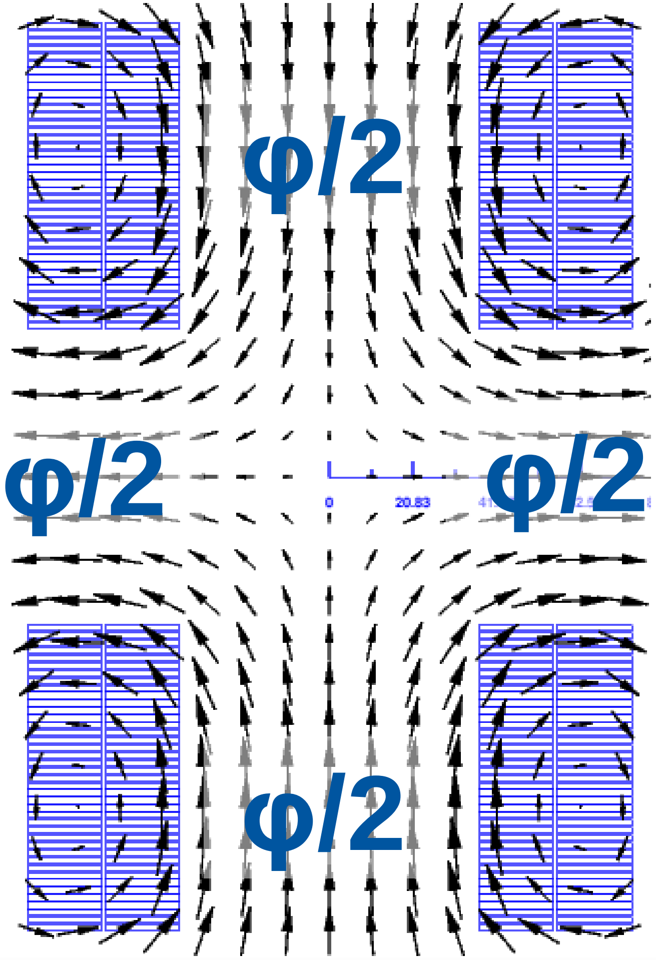


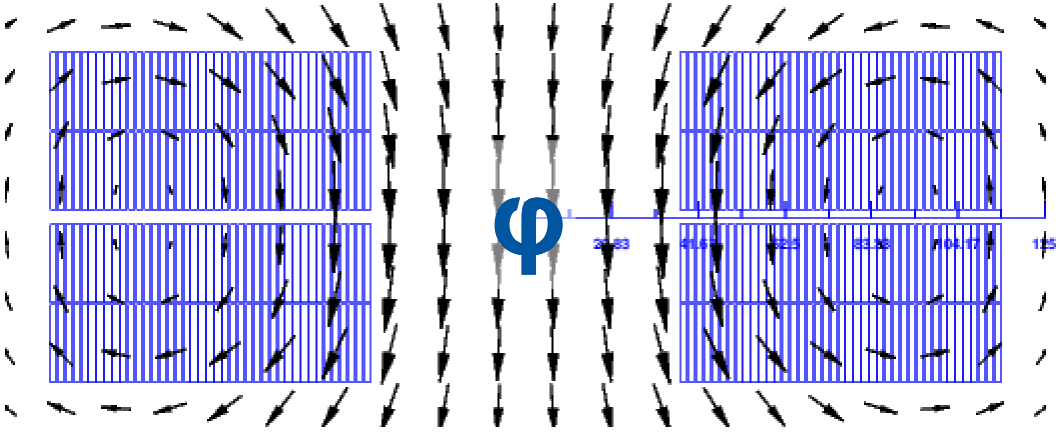


Design ID	Block	CC	Units
Aperture	74	74	mm
Intra-beam dist.	-	152	mm
I_nom	14486	21294	A
Yoke outer radius	246	246	mm
B	14	11.28	T
Peak field	16.16	14.24	T
Peak Field/B ratio	1.154	1.26	-
Stored energy	**1752**	**1692**	**kJ/m**
Static Self Induct.	**16.7**	**7.46**	**mH/m**
L*I	242	159	HA/m
Stray field (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 and aperture, common coil field is about half the block coil field





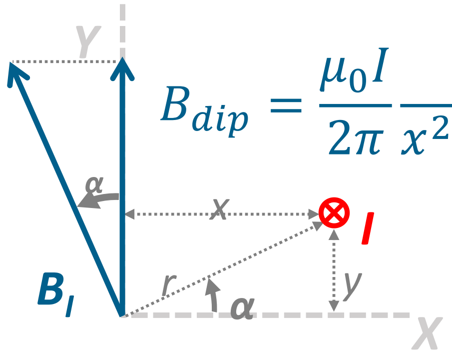
For $I_{CC} = I_{block}$

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

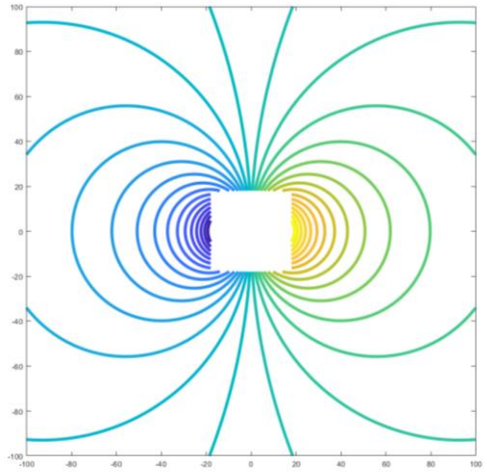
$$B_{CC} \approx \frac{\mu_0 I_{CC}}{\pi \cdot aperture} \qquad B_{block} \approx \frac{2\mu_0 I_{block}}{\pi \cdot aperture}$$

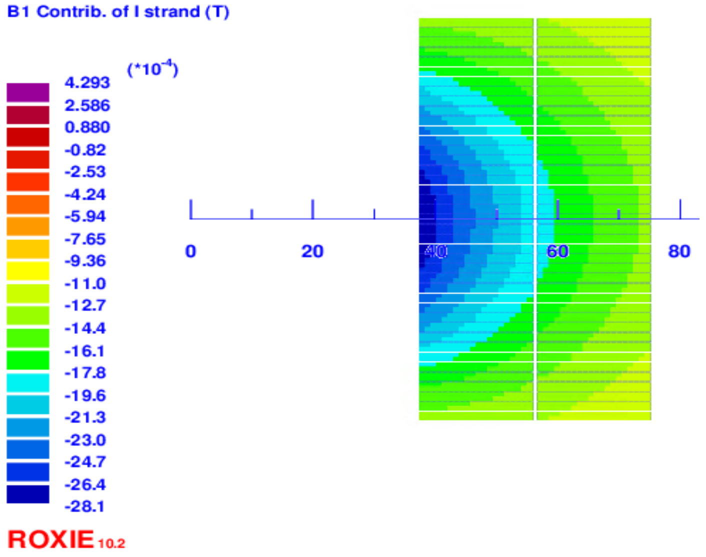
Block vs. common coil

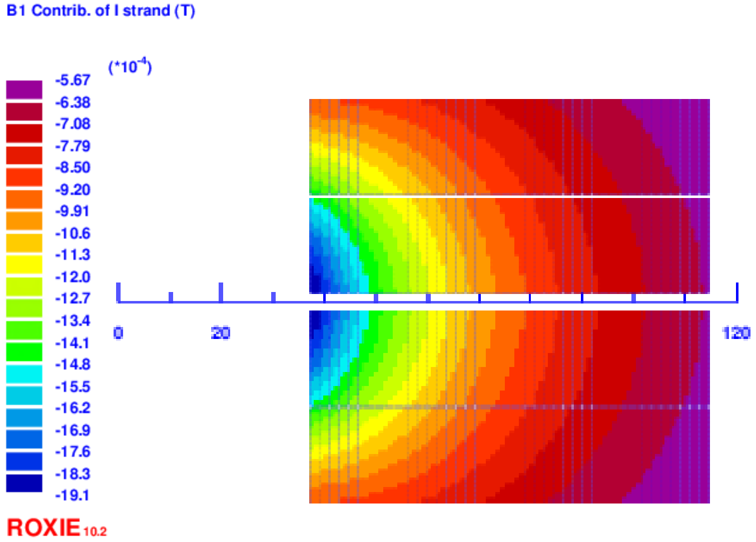
- Isolines for the dipole field contribution of a current line depending on its location
- In this particular case, the far cables of the block configuration are not efficient



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







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**

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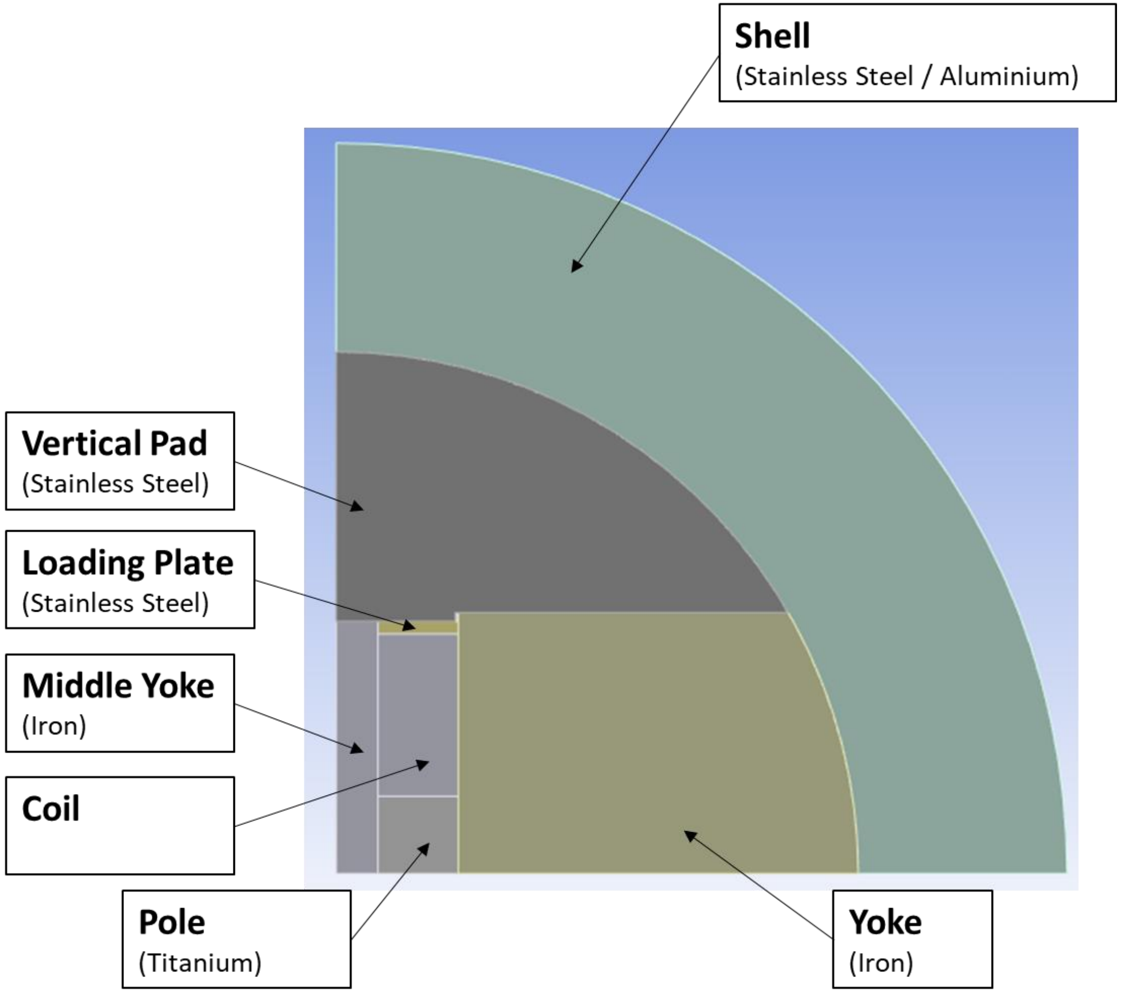
Mechanical design: layout

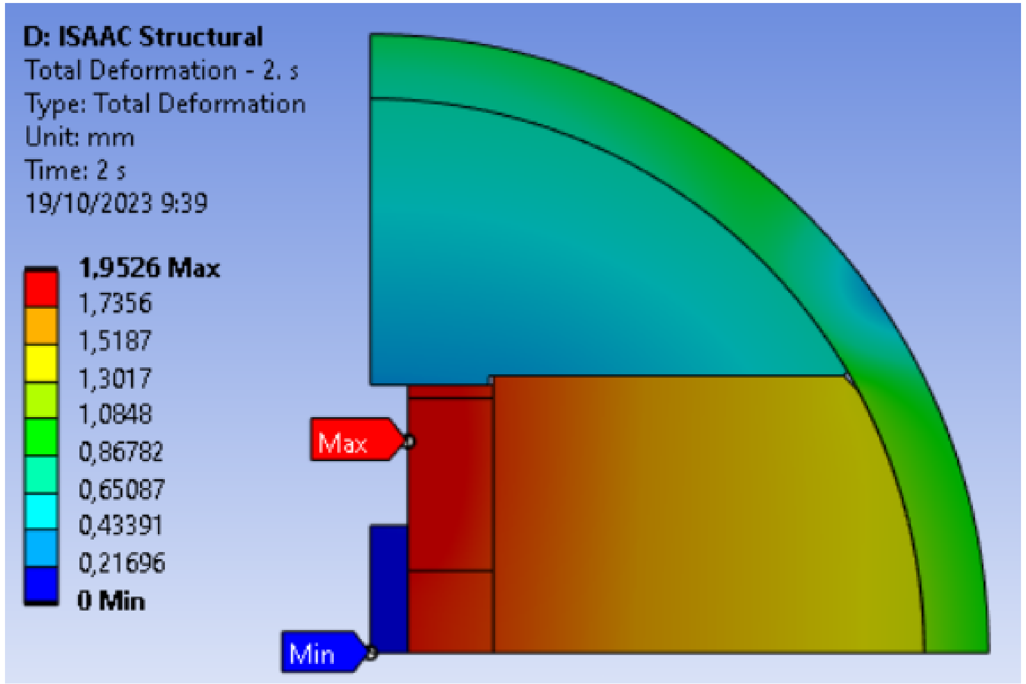
Main features:

- Parts in contact (without prestress) at room temperature
- Stainless steel vertical pad
- Cooling (from 295.15K to 1.9K)
- Electromagnetic Forces



Mechanical design: goals

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



Goal: **Coil displacement below 1mm** (after cooling) in order to:

- Reduce the possibility of sudden coil movements
- Aperture field over 13.7T

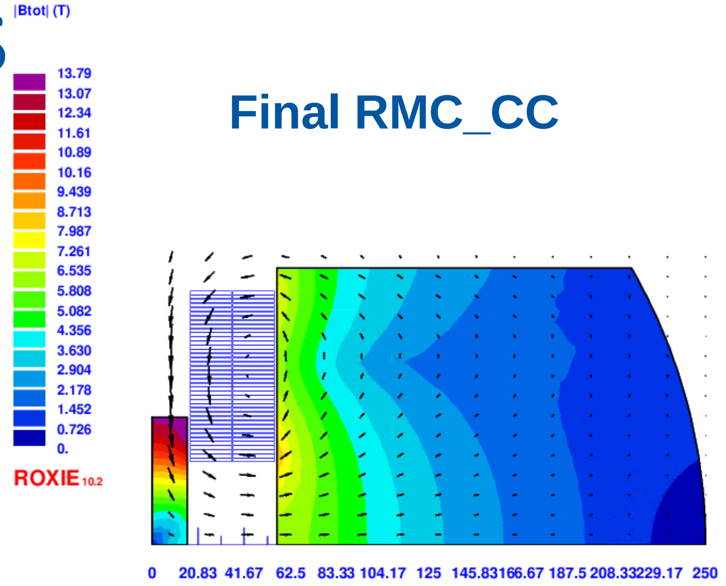
First simulation shows a horizontal displacement of coil close to **2 mm**!!

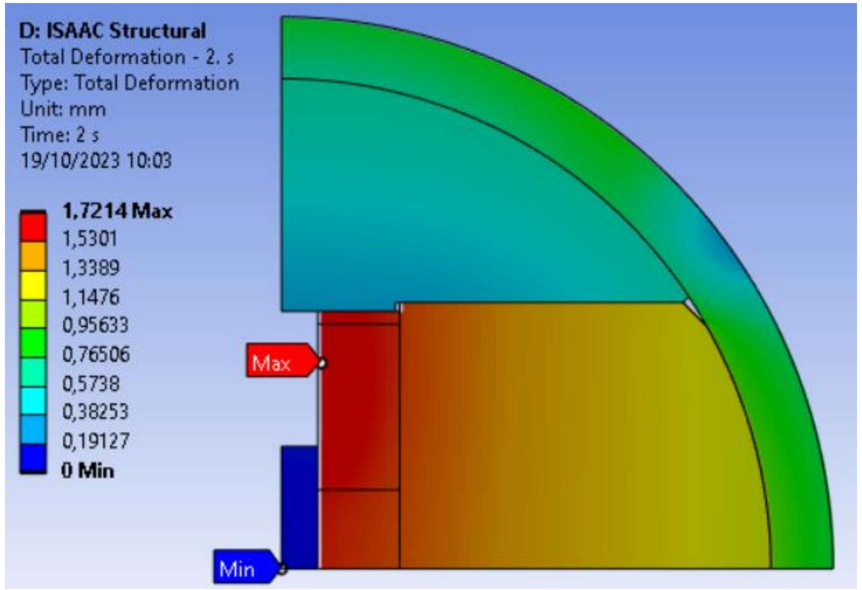
Mechanical design: first iterations

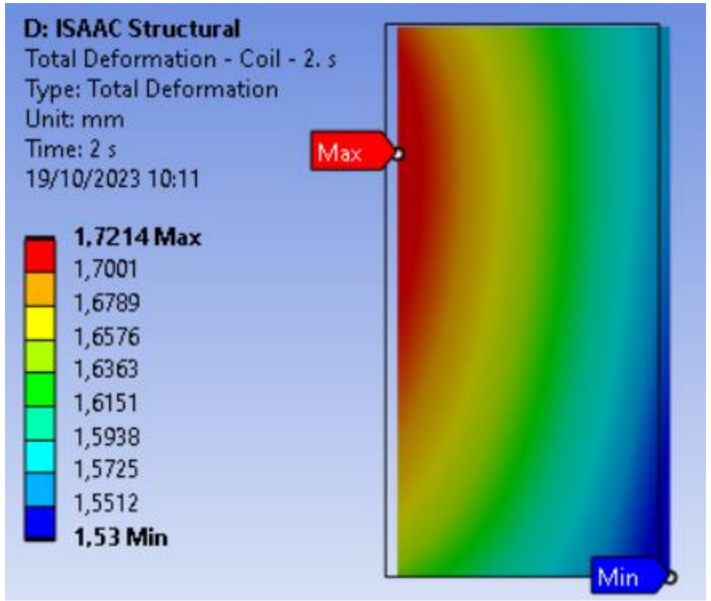
- Aluminium shell inner radius from 250mm to 230mm:
  - Very similar magnetic field (14T => 13.98T)
  - Coil displacement reduced (1,95mm => 1,72mm)

	R230	R250		Dif.
Peak field B	14,553	14,559	T	-0,04%
B (aperture)	13,980	14,000	T	-0,14%

Final RMC_CC



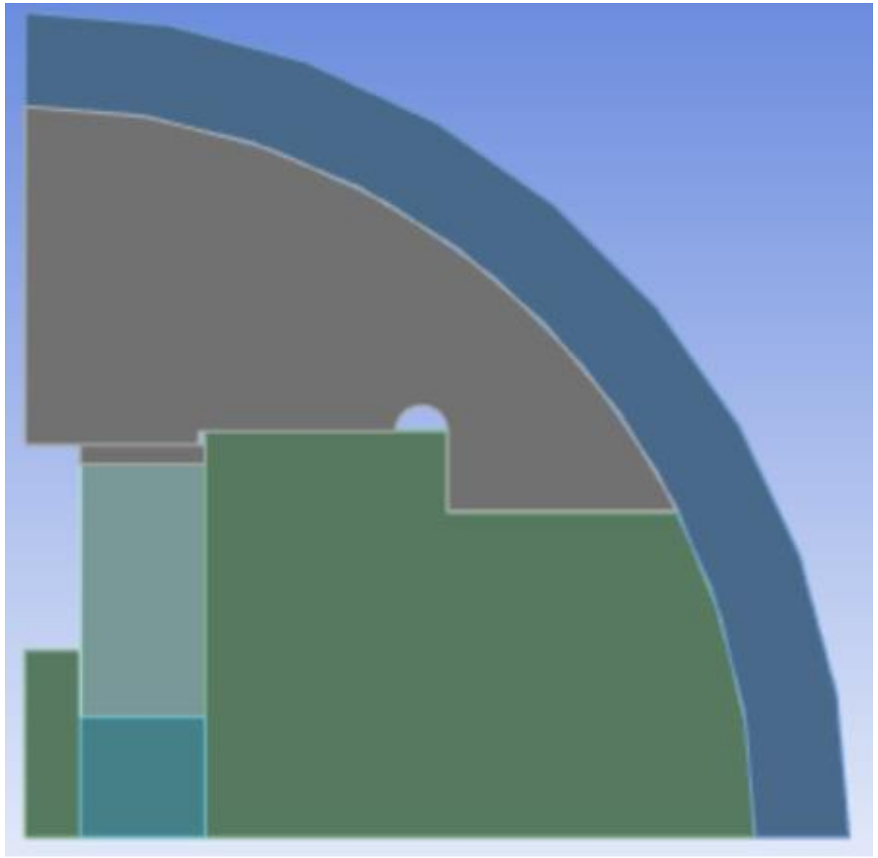




Increasing the thickness or using a stainless steel shell complicate considerably the magnet fabrication without a significant reduction of coil movement

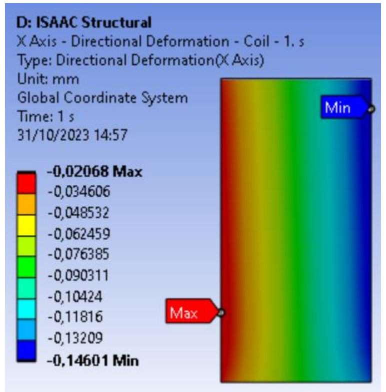
Mechanical design: stiff support structure

- Let's explore the use of yoke as **support structure**
- Upper part is made in **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 modeled yet
- Slight **preload** just to keep contact between parts

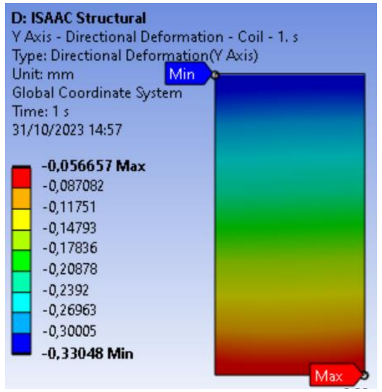


Mechanical design: coil displacement

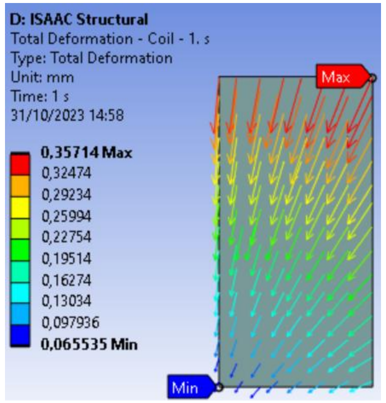
- Horizontal coil displacement below **0.5 mm**



X displacement



Y displacement

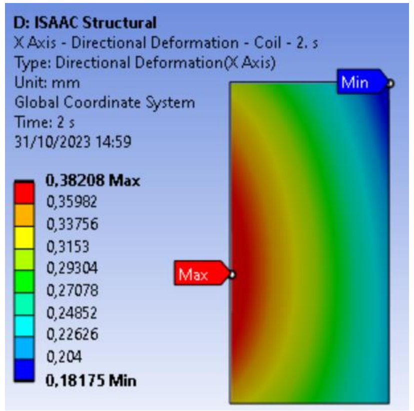


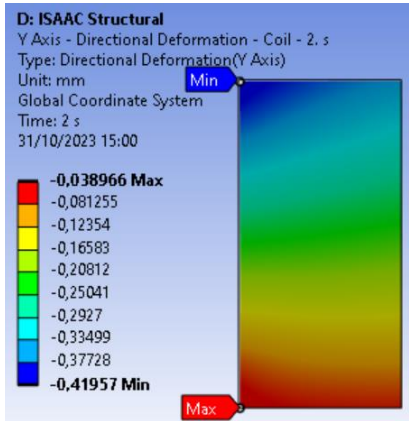
Total displacement

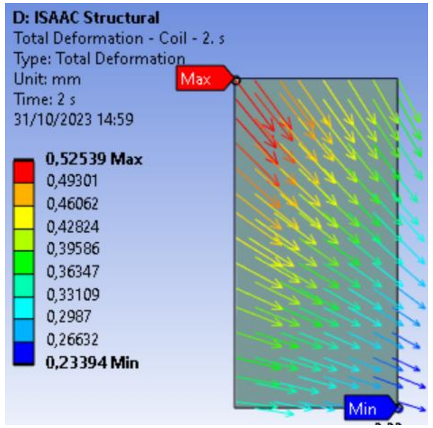
Coil X (Cold)	
Inner	**Outer**
-0,021 mm	-0,146 mm

COOLING

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





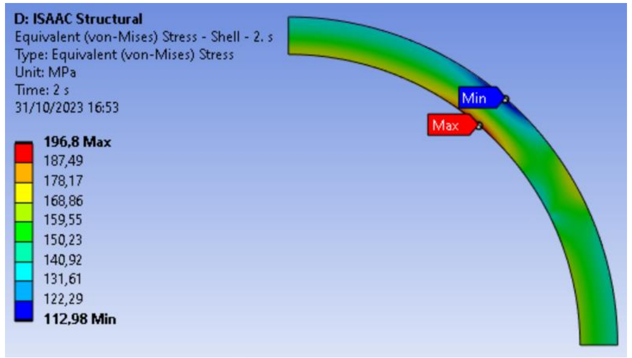


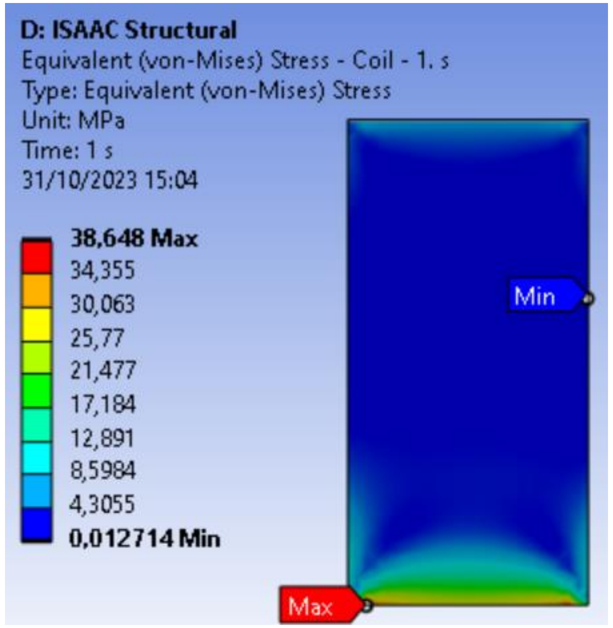
COOLING + EM

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

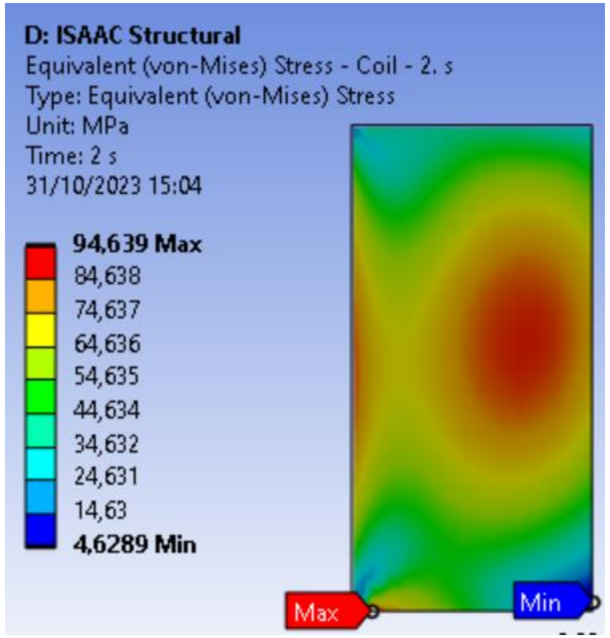
Mechanical design: stress distribution

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

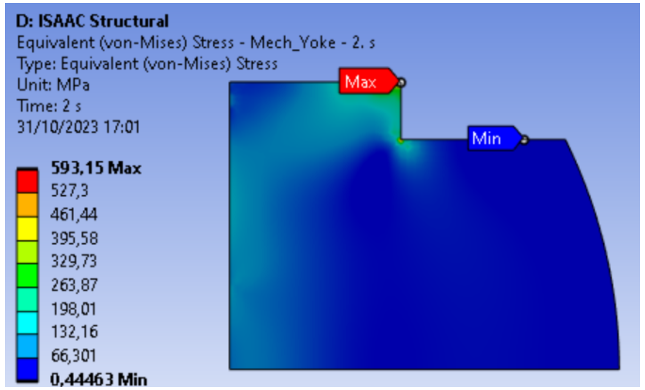


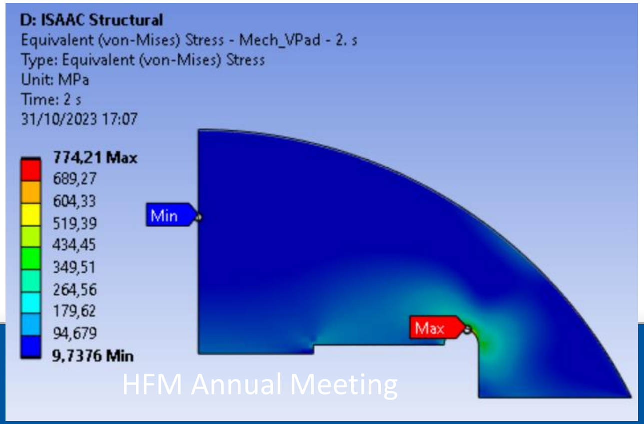


COOLING



COOLING + EM





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 **moving horizontally**, due to the low impact on field quality: low coil stresses at any load condition
- A promising design based on the use of yoke as support structure is being analysed in detail
- **Next step** is the engineering design: drawings and fabrication of parts
- In parallel, the electromagnetic design of a 14 T demonstrator magnet with 50 mm aperture will be done, based on **existing strands**