



MCBXF design

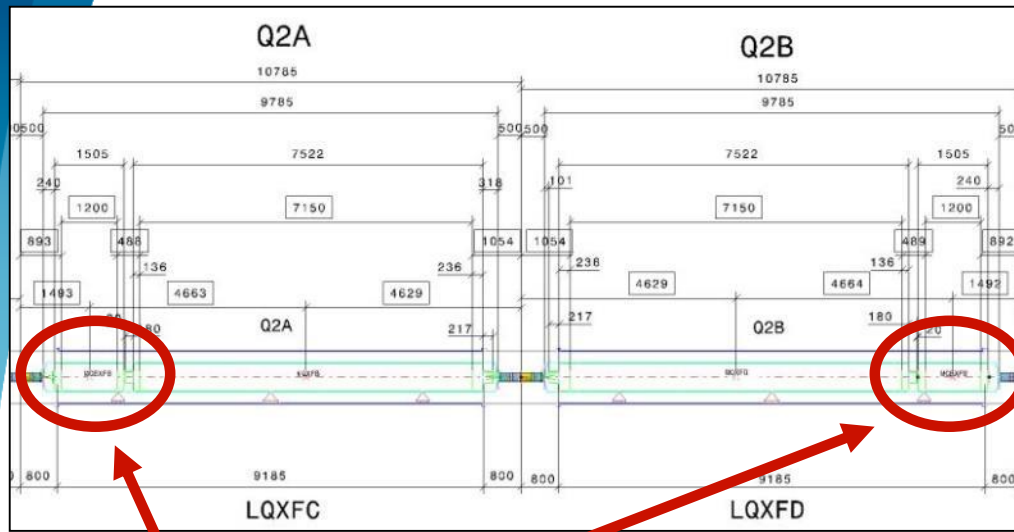
Fernando Toral (CIEMAT)

On behalf of MCBXF CERN-CIEMAT Collaboration

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MCBXF Orbit Correctors

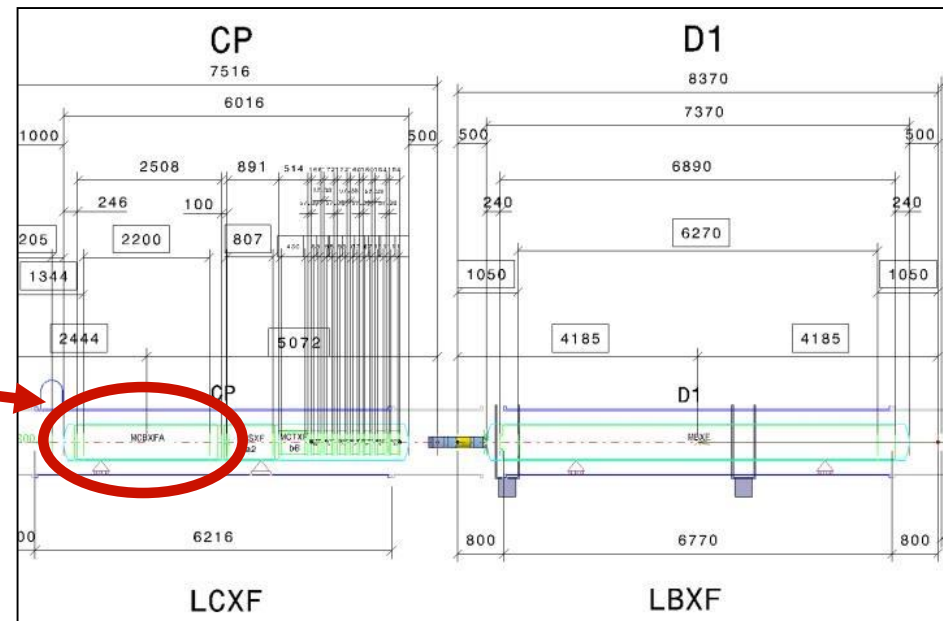


MCBXFB (2.5 T·m)

Ciemat

Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

**MCBXFA
(4.5 T·m)**



Magnet and cable specifications

MCBXF Technical specifications

Magnet configuration	Combined dipole (Operation in X-Y square)
Integrated field	4.5 (A) / 2.5 (B) Tm
Minimum free aperture	150 mm
Nominal current	< 2000 A
Radiation resistance	35 MGv
Physical length	< 2.5 (A) / 1.505 (B) m
Working temperature	1.9 K
Iron geometry	MQXFB iron holes
Field quality	< 5 units (1E-4) ($b_3 < 20$)
Fringe field	< 40 mT (Out of the Cryostat)

Vertical
dipole
field
(2.1 T)

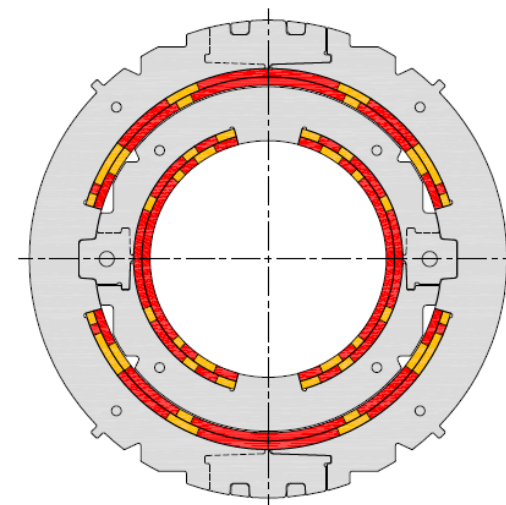
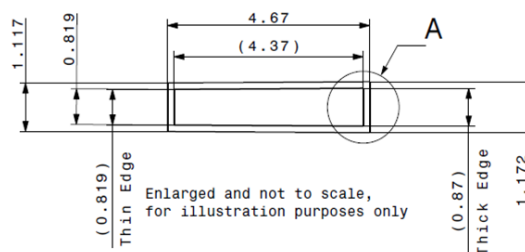
Combined
dipole field
(Variable
orientation)

Horizontal
dipole field
(2.1 T)

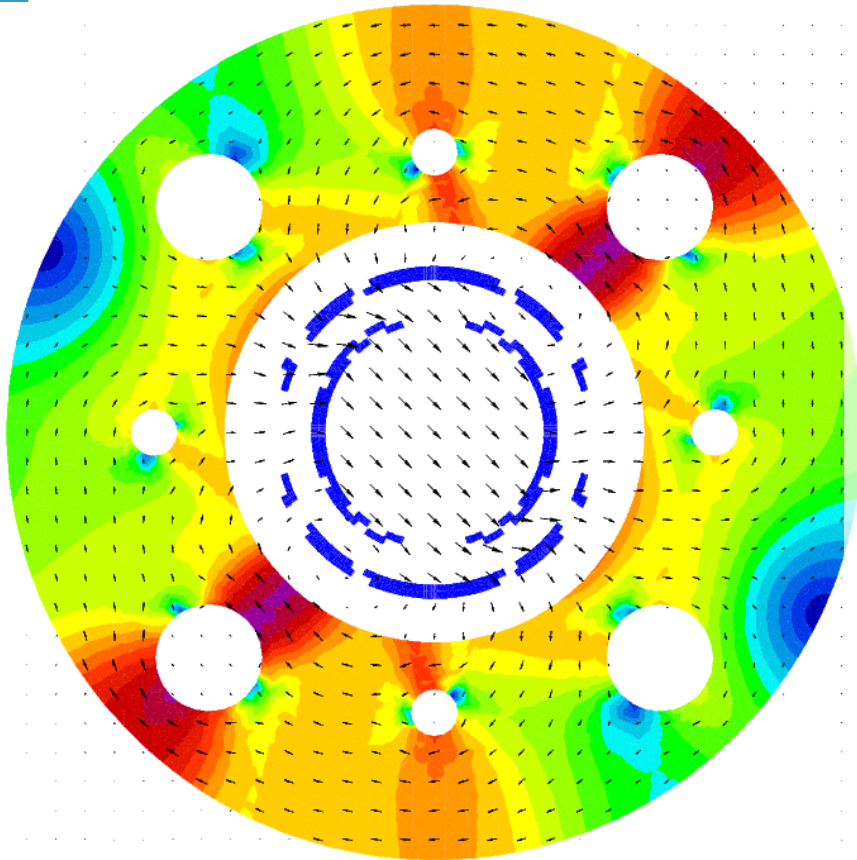
Radiation resistance
requires mechanical
clamping

Cable Parameters

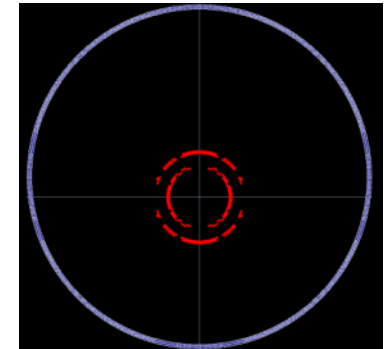
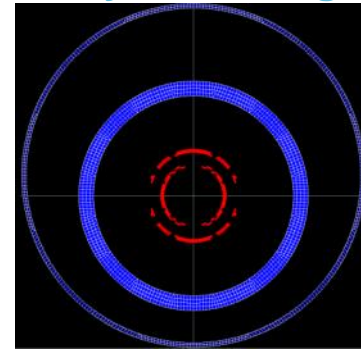
No. of strands	18
Strand diameter	0.48 mm
Cable thickness	0.845 mm
Cable width	4.37 mm
Key-stone angle	0.67°
Cu:Sc	1.75



Magnetic Design: Iron saturation



- ▶ Iron saturation causes the variation of sextupoles with the current (up to 30 units in the worst case)
- ▶ The difficulty arises because the field changes in two ways depending on the powering scenario: Orientation and intensity.
- ▶ Other yoke configurations are tested...



... but they do not meet the fringe field requirement: Dipole field decays with $1/r^2$.

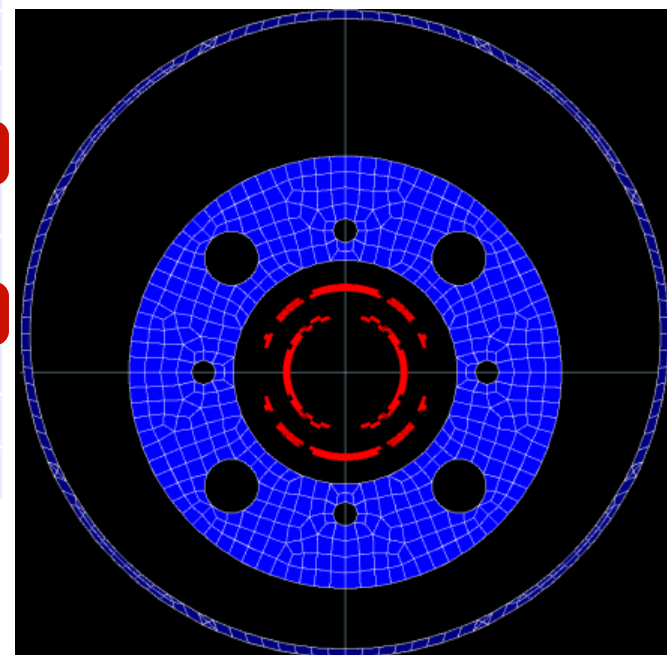
- **Therefore, we have to choose between:**
 - **High fringe field or**
 - **High variation of the multipoles with the current.**

Magnetic Design: Final 2D design

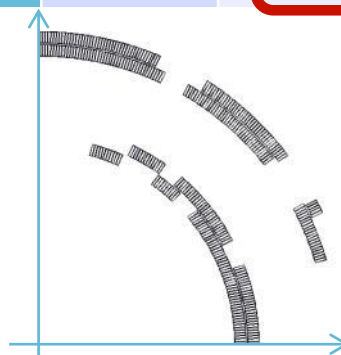
Inner Dipole (ID) & Outer Dipole (OD) parameters	Units	ID	OD
Nominal field	T	2.15	2.26
Nominal Field (Combined)	T	3.12	
Nominal current (short)	A	1625*	1474*
Nominal current (long)	A	1584*	1402*
Coil peak field (Combined)	T	4.13 (ID)	
Working point (combined)	%	50.1	
Differential self inductance at Inom / m	mH/m	48.7	104
Stored energy/m	KJ/m	64	119.3
Aperture	mm	156.2	230
Iron yoke Inner Diam.	mm	317.2	
Iron yoke Outer Diam.	mm	614	
Torque	Nm/m	1.4×10^5	
Max fringe field, 20 mm out of the cryostat	mT	29	
Total number of turns	-	140	191
Cable length needed for each pole/coil	m	360	487

Whole iron option is chosen:

- It meets fringe field requirement.
- It has smaller Lorentz forces.

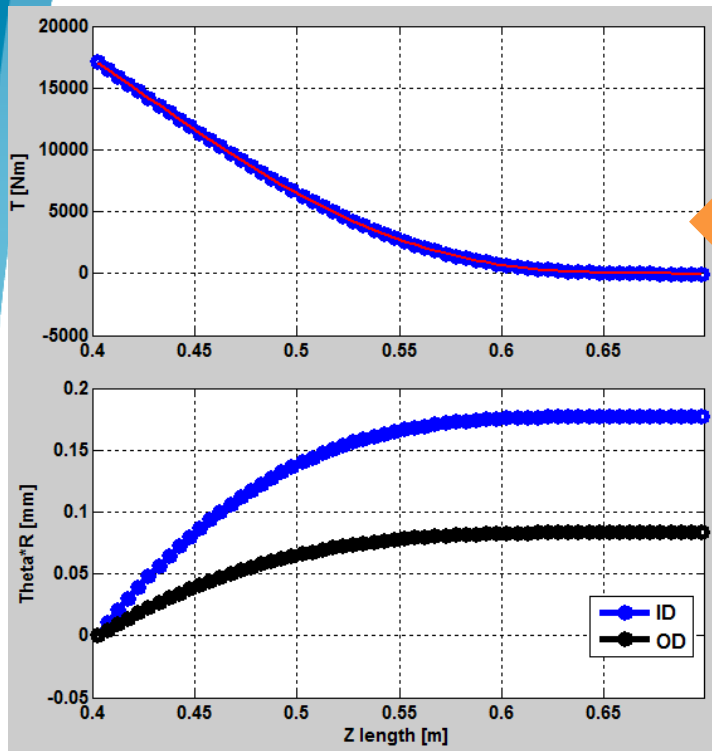


* To be updated according to MCBXFB01 test results.

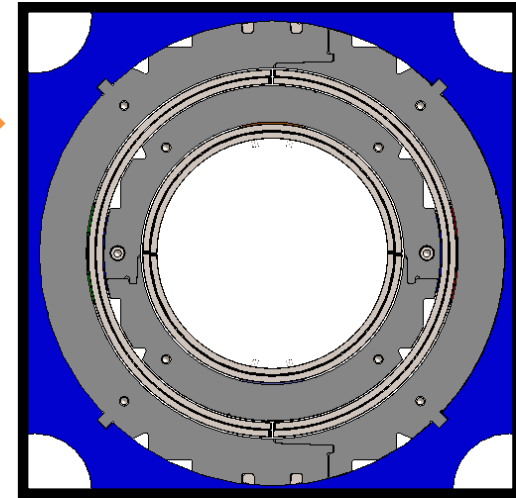


Difficult winding

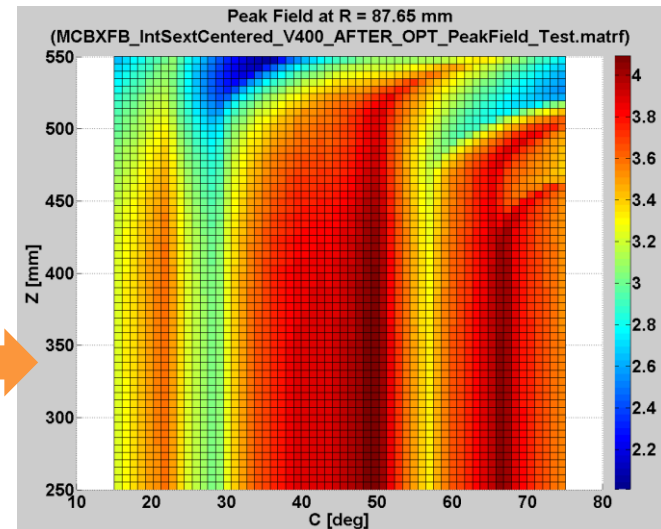
Detailed magnetic design: Torque and peak field at coil ends



- Torque cannot be azimuthally locked at coil ends.
- Coil ends should be shortened to improve the torque clamping.
- Look out endspacer design not to be too slender.

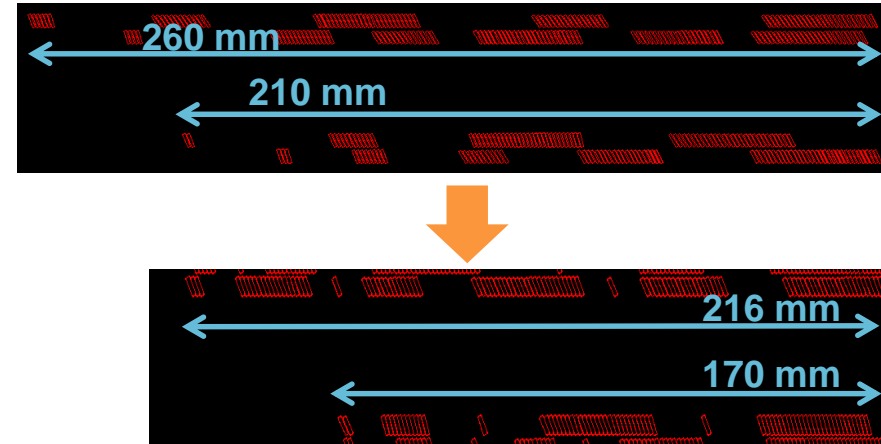
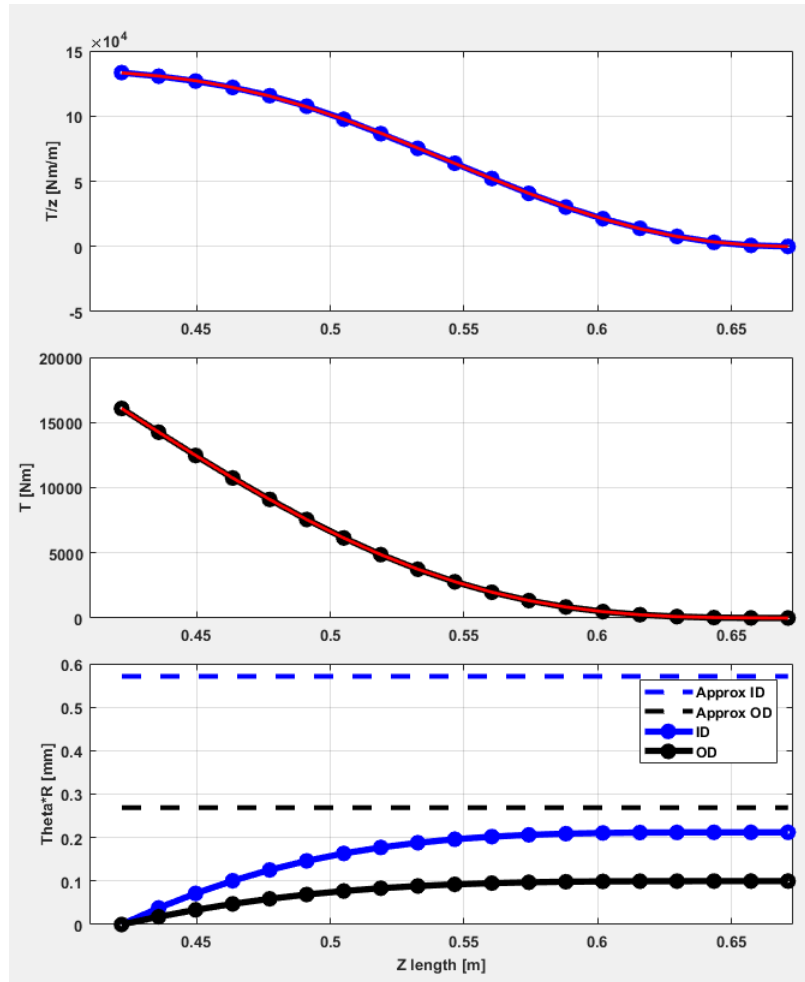


- Field is not aligned with coil poles at nominal current (45° orientation)
- Peak field is always at the straight section.



3-D Magnetic Design: Shorten coil ends

Torsion estimations due to torque at coil ends



- Coil ends were shortened to increase the coil length supported by collars.
- The optimization is very slow:
 - More than 100 design variables are used and their range have to be carefully controlled
 - Endspacers can not be too slim.
 - Block jumps conductors have to be carefully placed to avoid cable distortions.

**Around 50
different endspacers, specially
slender for the outer coils**

Magnetic Design: Sensitivity analysis

- Small changes in the conductor positioning or dimensions, specially in the inner dipole, causes great changes in the multipole values.

0.3 mm thinner
interlayer



$\Delta b_3 \cong - 5 \text{ units}$
 $\Delta a_3 \cong + 0.8 \text{ units}$

(3D)

0.001 mm
thinner cable

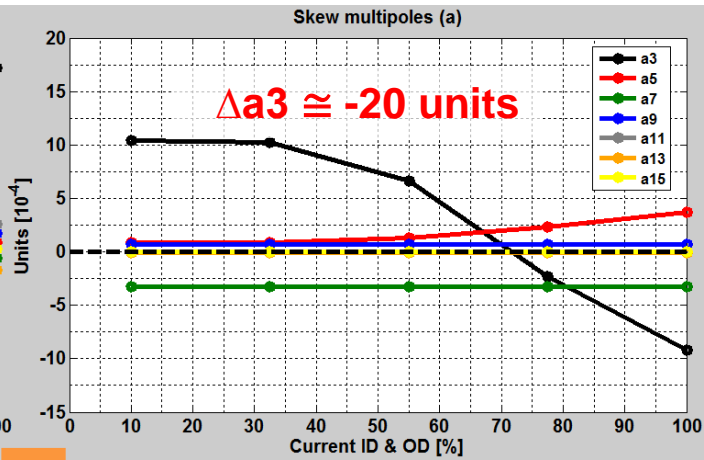
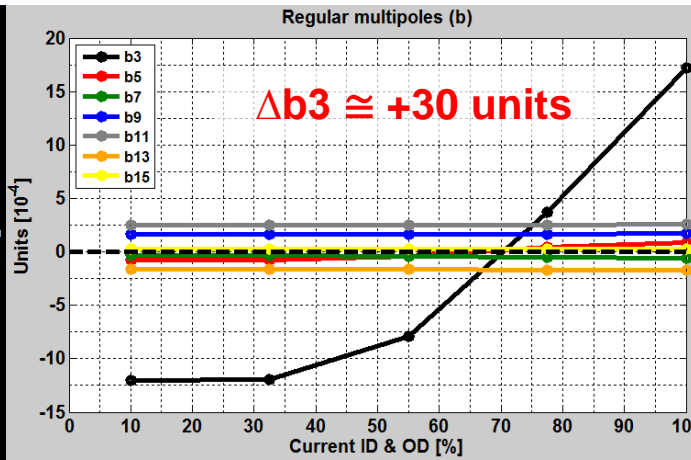
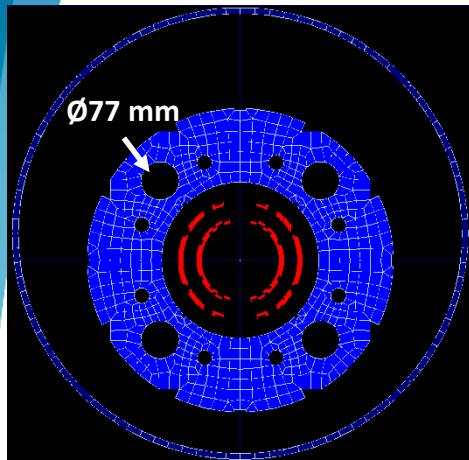


$\Delta b_3 \cong + 3 \text{ units}$
 $\Delta a_3 \cong - 1.25 \text{ units}$

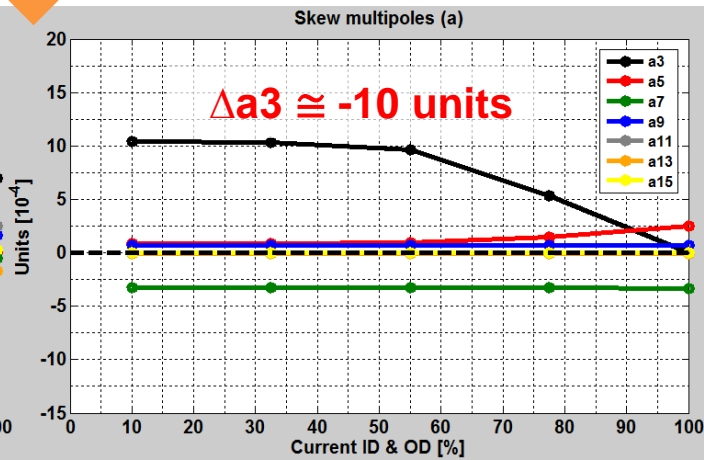
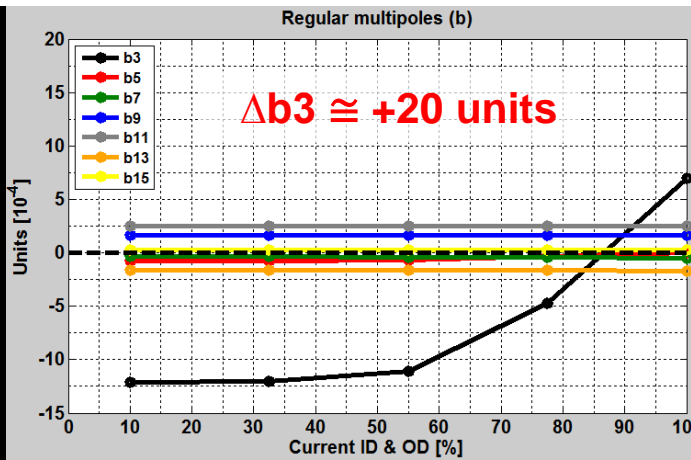
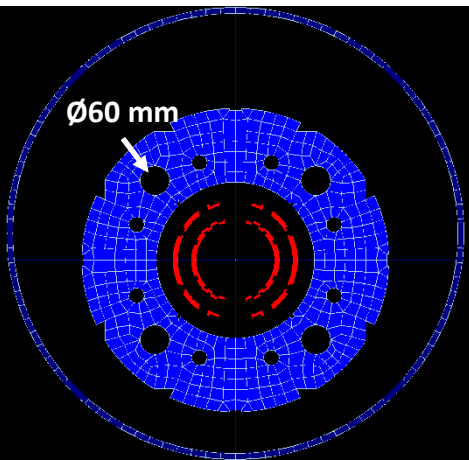
(2D)

- Coil deformation due to collaring is not included in the 3D magnetic simulations. The potential field errors will be compensated later, after learning from magnetic measurements on the prototype.

Magnetic design: *MCBXFA Ø77 VS Ø60 mm



10 units less of variation!!!



* Plots for both dipoles ramping simultaneously (Same results ramping ID or OD)

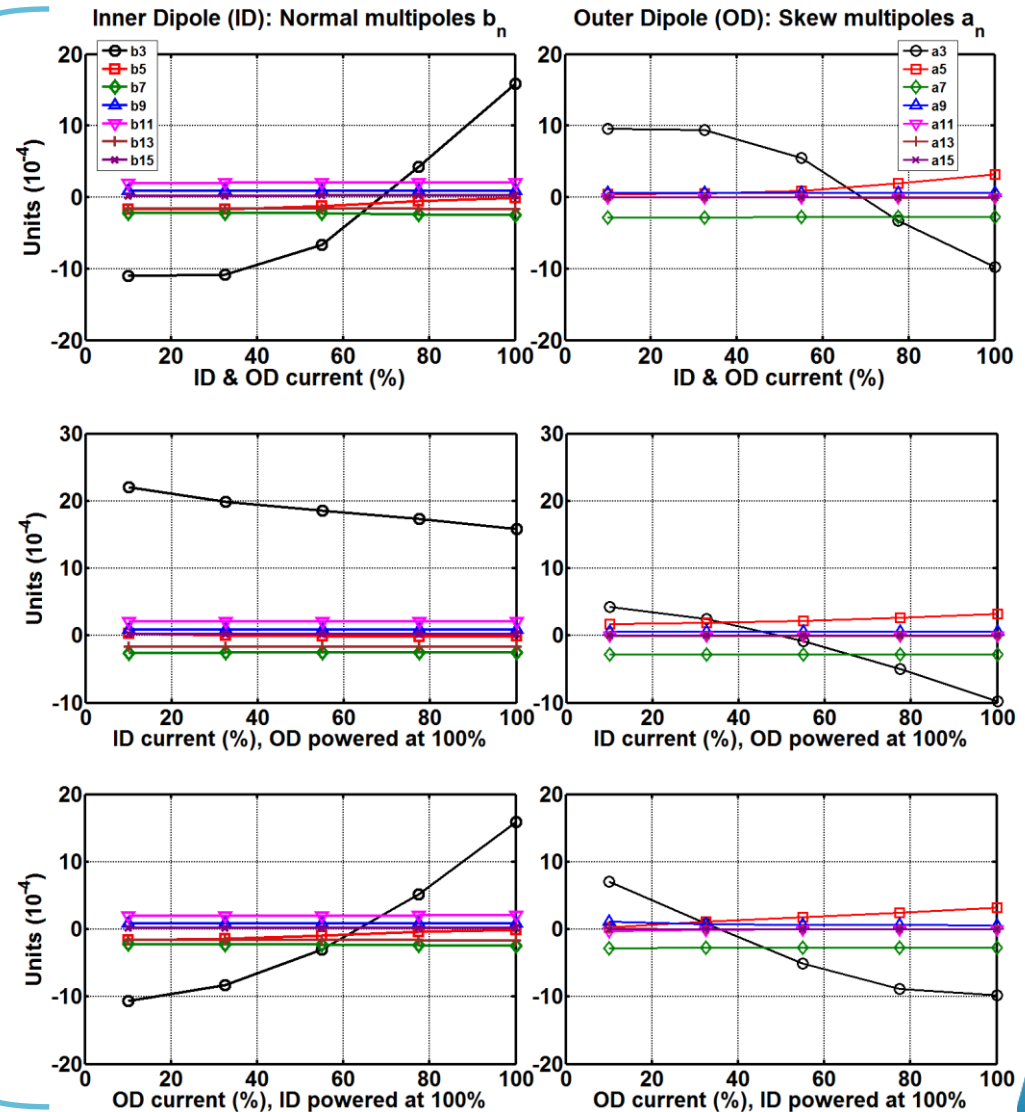
Detailed 3D magnetic design: Computation strategy and field quality

Optimization needed
for any powering
scenario
(infinite cases)
Each case takes like
an hour to compute
(3D iron)

Reduced to
only **three**
powering
scenarios

The optimization is performed
without iron.
The objectives are shifted to
take it into account.

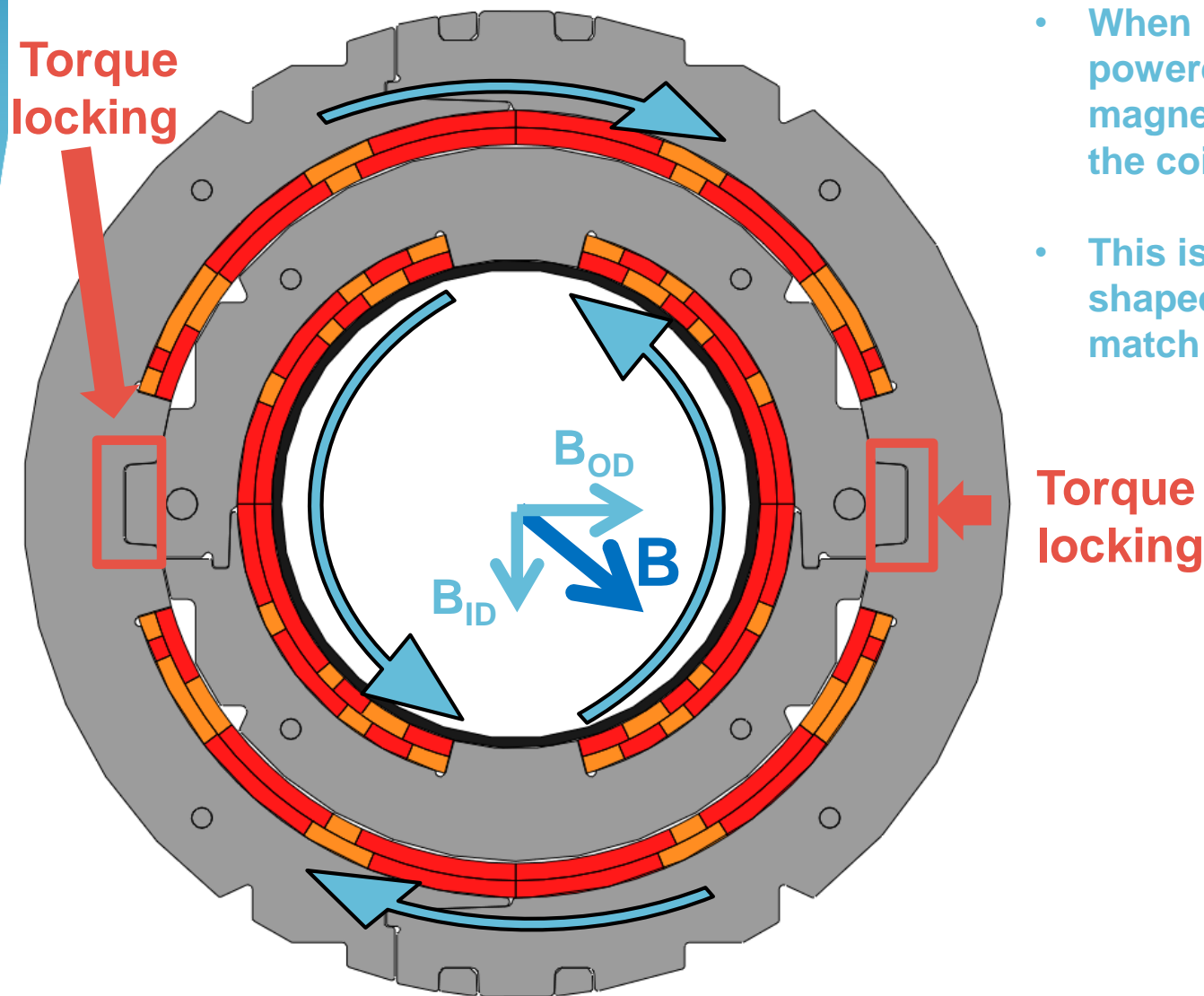
$b_3 < \pm 20$ units required
rest $< \pm 5$ units required



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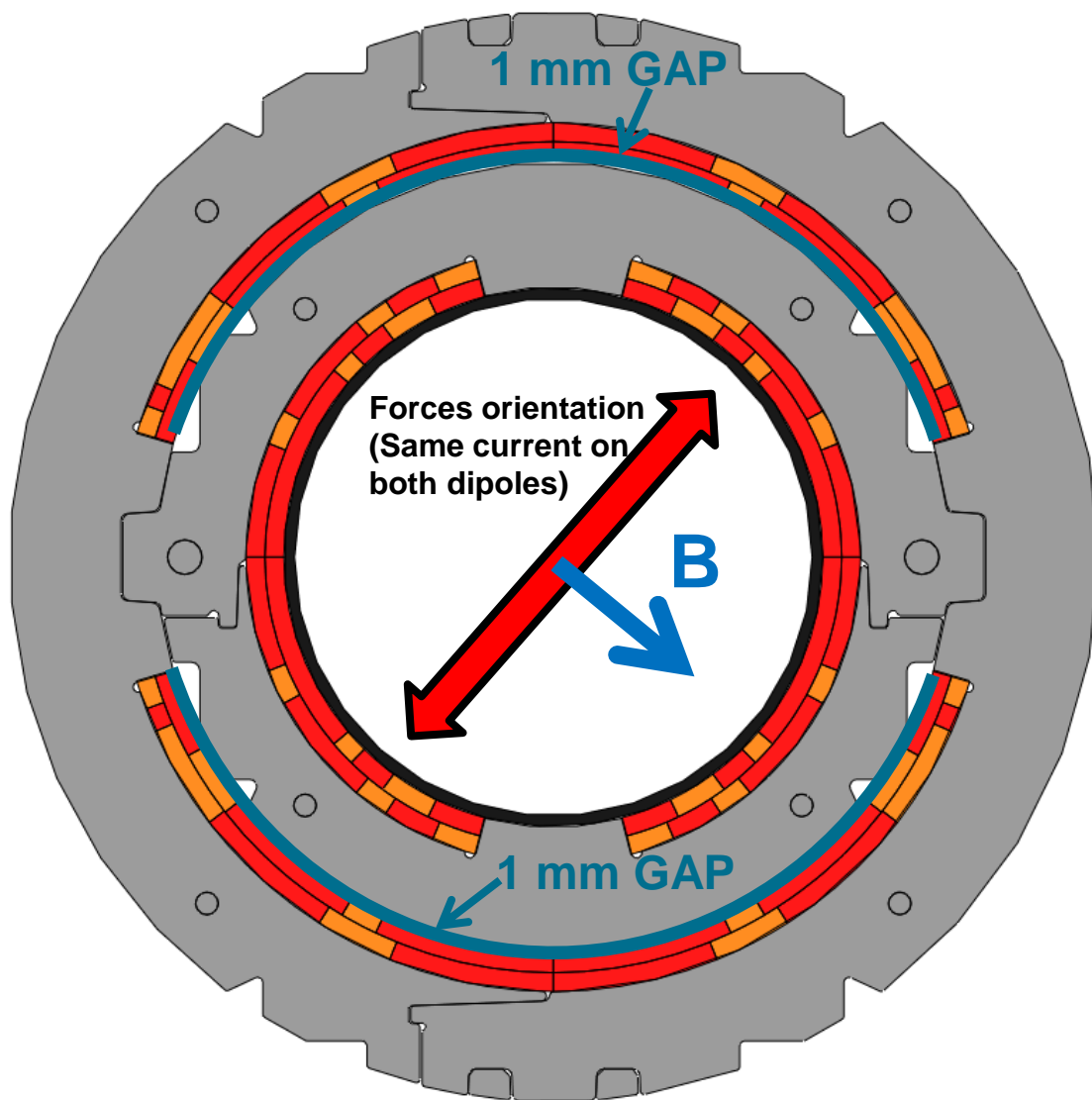
Mechanical design: Torque locking



- When both dipoles are powered their perpendicular magnetic fields try to align the coils.
- This is avoided through key-shaped inner collars which match into the outer ones.

Torque locking

Mechanical design: Radial deformations



The action of an external shell or increasing the outer collars thickness do not reach the inner coils, given the assembly gap between inner collars and outer coils.

The only way to decrease the inner dipole deformation is to increase inner collars thickness.



Self Supporting collars:

- Inner collar outer diam.= 230 mm (Thickness = 27 mm)
- Outer collar outer diam. = 316 mm (Thickness = 33 mm)

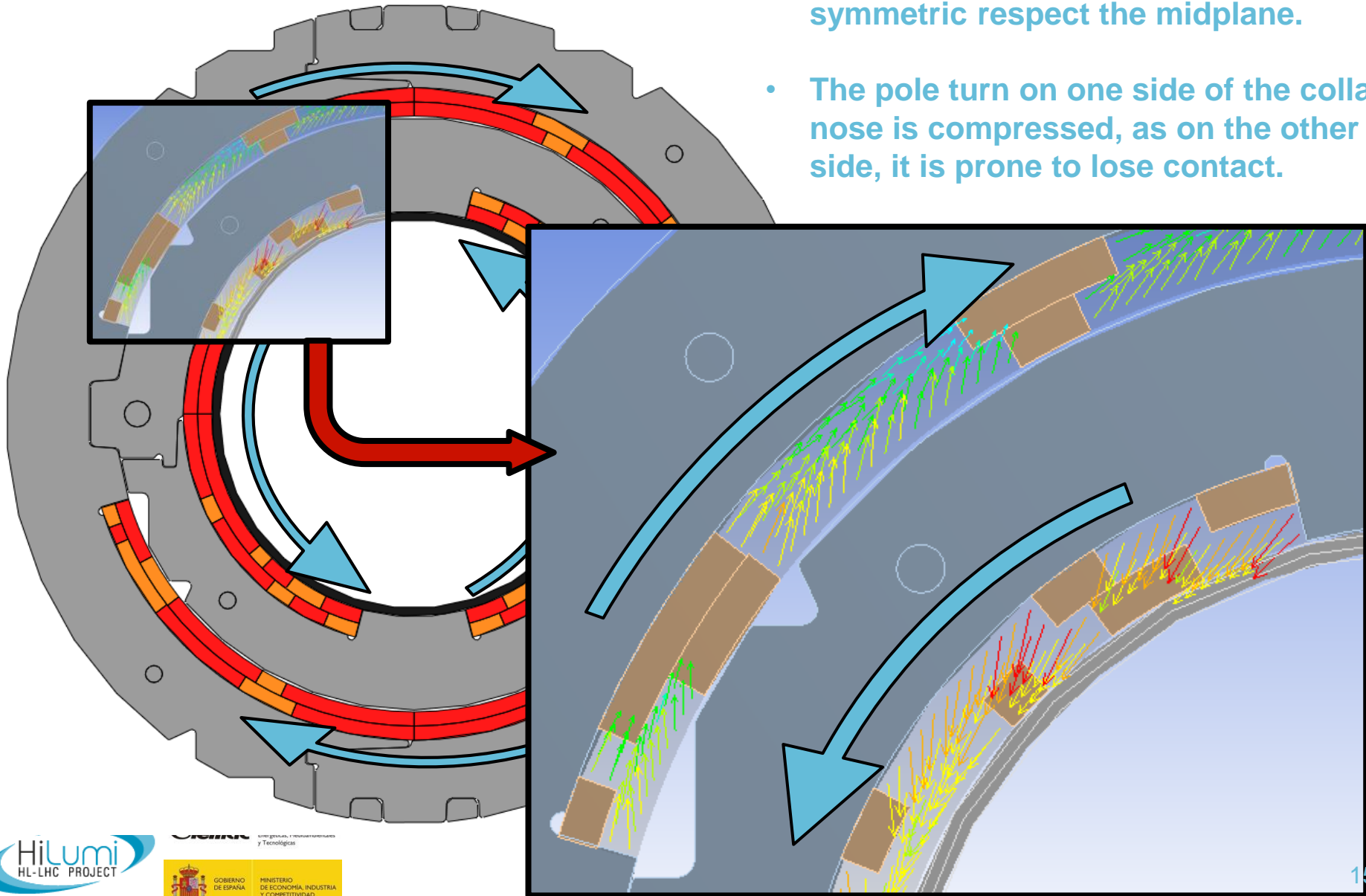


Differences between the axis of the elliptical shape of the coils (108% IN):

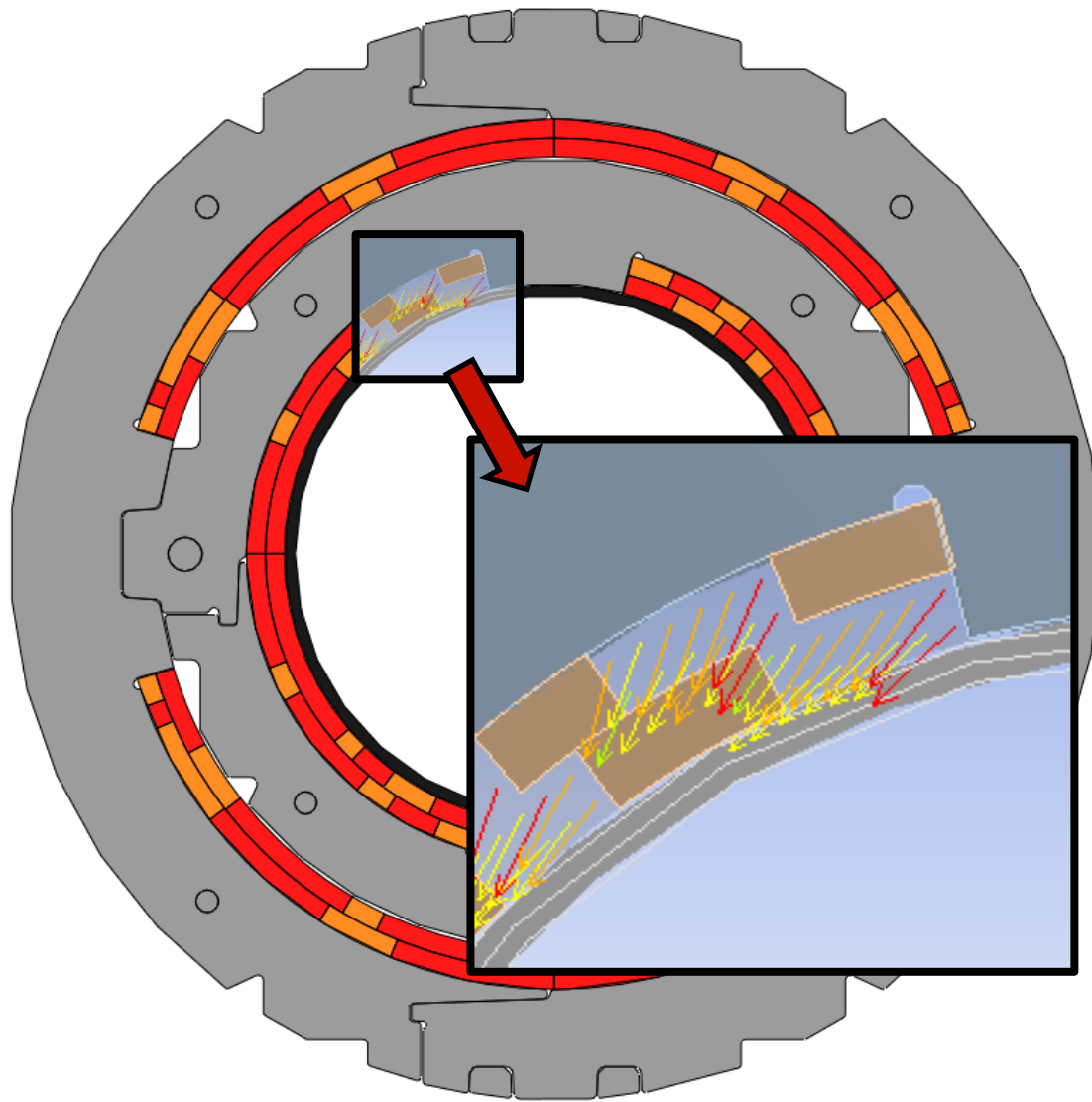
- Inner dipole = 0.6 mm
- Outer Dipole = 1 mm

Mechanical design: Azimuthal deformations

- Azimuthal coil displacements are not symmetric respect the midplane.
- The pole turn on one side of the collar nose is compressed, as on the other side, it is prone to lose contact.



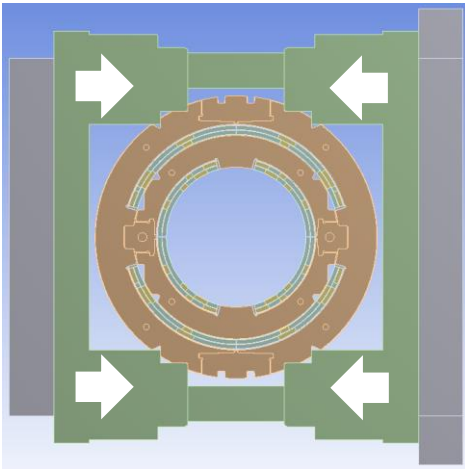
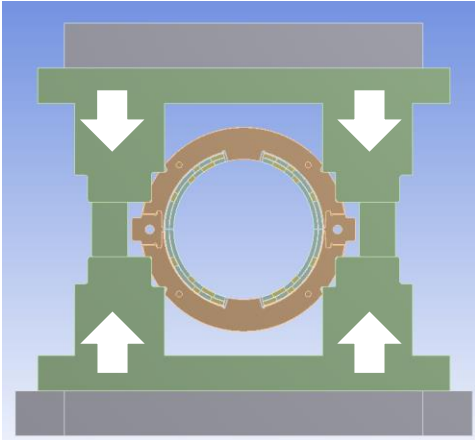
Mechanical design: Radial inward forces



Due to the nested dipole configuration, inner coils tend to deform into the aperture (0,1 mm without friction).

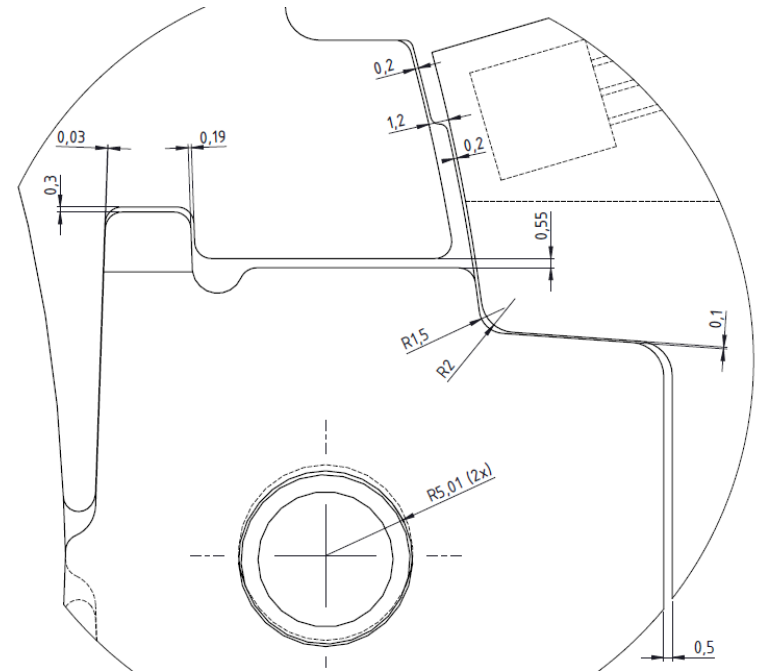
Some space (3 mm) is kept for a Ti tube to be inserted if necessary (we hope not!).

Mechanical design: Simulation of collaring



Achieved goals:

- Monitoring stress at the coils when the pins/keys are inserted.
- Sizing of the stoppers needed to limit the press displacement.
- Checking that all clearances are the correct ones in order to assure assembly.



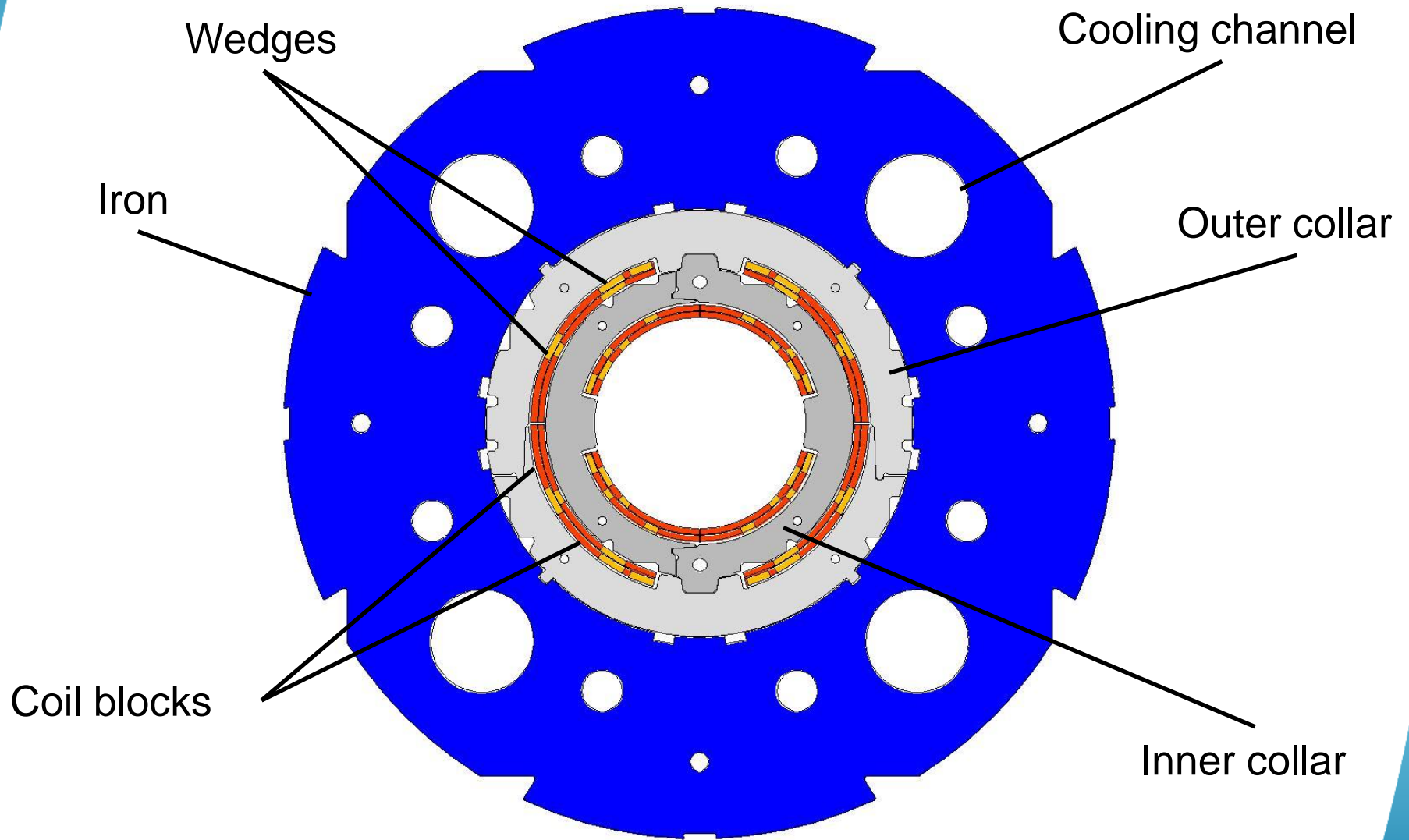
Mechanical design: material properties and results

Part	Material	Young's modulus (GPa) 2 K / 293 K	Thermal expansion coefficient (K ⁻¹)
Coil Blocks	Impregnated fiber glass insulated cables (NbTi)	40 / 40	1.1×10^{-5}
Wedge	Copper	138 / 128	1.064×10^{-5}
Interlayer and fiber glass insulation	Impregnated Nomex and fiber glass	30 / 30	2.44×10^{-5}
Ground insulation	Kapton foil	2.5 / 2.5	1.98×10^{-5}
Collars	Stainless Steel YUS 130S	202 / 194	8.93×10^{-6}
Loading plate, keys and rivets	Stainless Stell 316 L	210 / 193	9.83×10^{-6}

Dipole	Turn	Collaring	Spring- back	Cool down	Nominal current
Inner	Pole	146	105	44	16
	Midplane	140	111	47	75
Outer	Pole	160	123	57	22
	Midplane	155	133	41	79

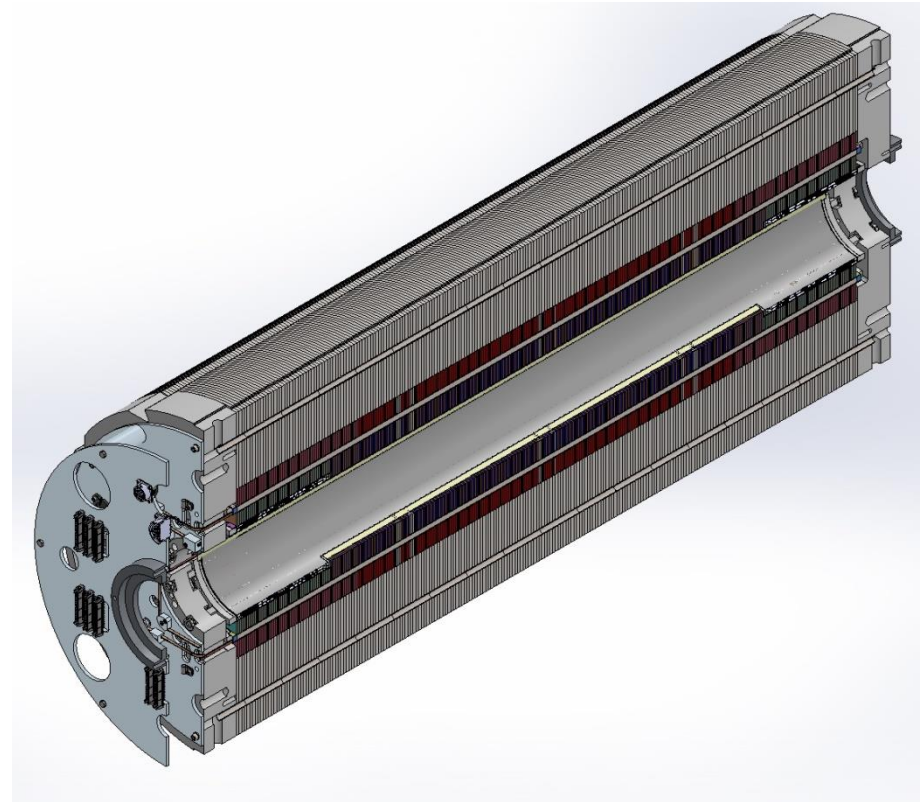
Compressive azimuthal stress (MPa)

Iron yoke



Endplates design

- There is no shell or inertia tube.
- Two **endplates** with eight stainless steel **rods** compress the iron laminations and hold the axial Lorentz forces.
- There is no contact between the collars and the endplates.
- The endplates are 70 mm thick but they cannot be considered as infinitely rigid.
- We want to apply the **axial pre-stress** just to guarantee contact at the coil ends when cooled-down.

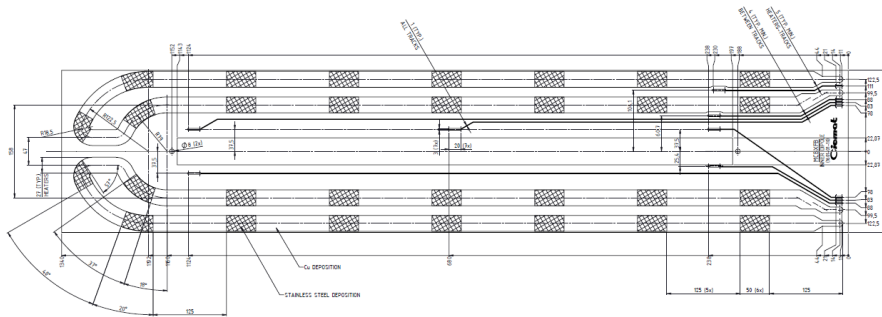


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Protection (2016)

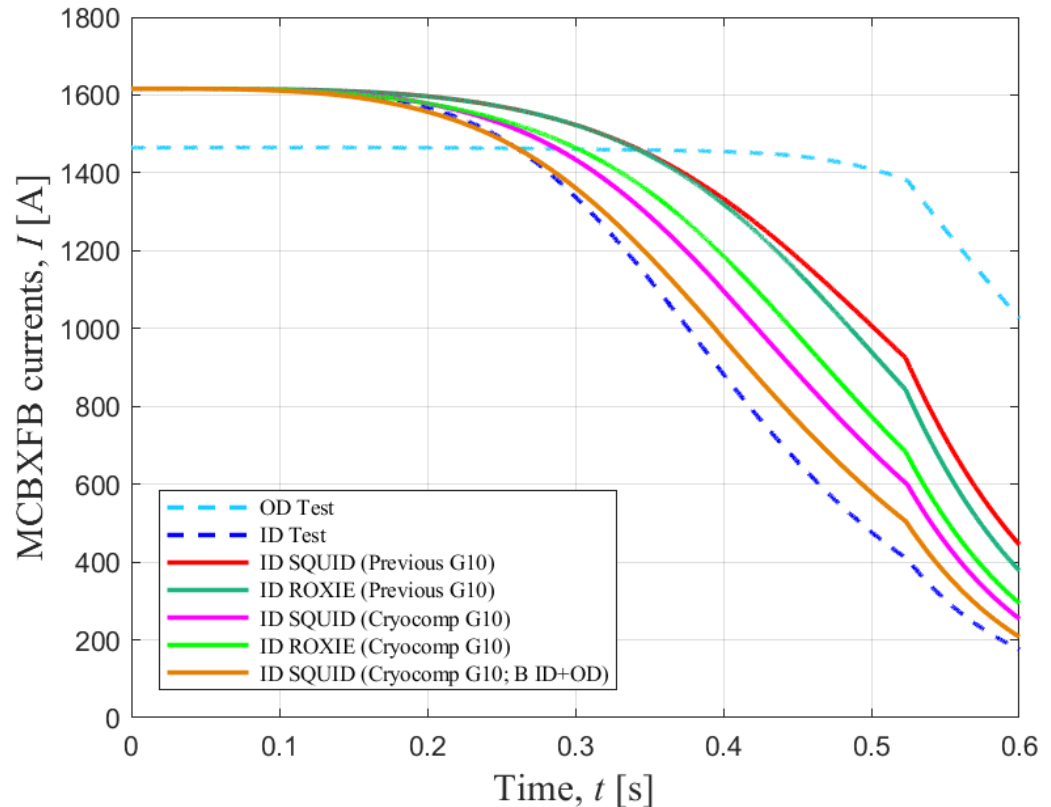
- Quench simulation with CIEMAT code **SQUID**, based on finite difference method.
- Baseline strategy is: short magnet is self-protected, long one is protected by dump resistor.
- Heaters are being implemented in the short prototype for **validation**. If successful, they will be likely implemented instead dump resistor.
- Heaters produced by **927** team.
- One **voltage tap** per cable block and at both sides of the layer jump.



	Current	Dipole	Protection	Tmax (K)	Vmax (V)	Energy dissipated in magnet (kJ)	
MCBXFA	Nominal	Inner	Heaters ON	126	393	121	
			Heater OFF	242	389	121	
			Dump resistor 0.3 ohm	65	480	5	
		Outer	Heaters ON	133	643	215	
			Heater OFF	284	618	215	
			Dump resistor 0.3 ohm	106	441	26	
		110% nominal	Inner	Heaters ON	154	519	146
				Heater OFF	274	504	146
				Dump resistor 0.3 ohm	80	528	9
	Outer		Heaters ON	160	847	260	
			Heater OFF	322	798	260	
			Dump resistor 0.3 ohm	141	485	46	
	MCBXFB	Nominal	Inner	Heaters ON	129	234	72
				Heater OFF	177	235	72
				Dump resistor 0.3 ohm	50	480	2
			Outer	Heaters ON	137	383	129
				Heater OFF	211	376	129
				Dump resistor 0.3 ohm	65	441	7
110% nominal			Inner	Heaters ON	154	311	88
				Heater OFF	198	308	88
				Dump resistor 0.3 ohm	57	528	3
	Outer	Heaters ON	163	504	156		
		Heater OFF	243	489	156		
		Dump resistor 0.3 ohm	79	485	11		

a058: ID quench at 1616 A with dump resistor delayed 500 ms

- Quench in the midplane of the Inner Dipole at 1616 A, around nominal current with OD at 1465 A.
- $t=0$ at the initial quench. 13 ms for quench detection plus 10 ms for quench validation.
- 0.3 Ohm dump resistor with 500 ms delay from validated quench.
- Good agreement between SQUID and ROXIE with the previous G10 properties, but very conservative compared to measurements.
- Agreement improved in both models with the Cryocomp G10 properties. ROXIE is more conservative than SQUID (differences in the magnetic field implementation).



- Very good agreement of the SQUID model with Cryocomp G10 properties to measurements taking into account the combined magnetic field.**

MCBXFB in combined operation.

Dipole quenched	Case	MIIts (MA ² s)	Hot-spot temperature (K)	Maximum voltage (V)
ID	Inom=1625 A Self protected (no dump)	0.96	252	245
ID	Inom=1625 A Dump resistor 0.3 Ohm	0.34	67	489
ID	Inom=1625 A Dump resistor 0.2 Ohm	0.45	80	327
ID	Inom=1625 A Dump resistor 0.15 Ohm	0.55	96	246
OD	Inom=1474 A Self protected (no dump)	1.04	306	370
OD	Inom=1474 A Dump resistor 0.3 Ohm	0.50	89	443
OD	Inom=1474 A Dump resistor 0.2 Ohm	0.66	124	296
OD	Inom=1474 A Dump resistor 0.15 Ohm	0.77	159	222

- Note that the calculated voltage is the resistive magnet voltage plus the voltage across the dump resistor.

MCBXFA in combined operation

Dipole quenched	Case	MIIts (MA ² s)	Hot-spot temperature (K)	Maximum voltage (V)
ID	Inom=1584 A Self protected (no dump)	1.08	311	411
ID	Inom=1584 A Dump resistor 0.3 Ohm	0.52	81	476
ID	Inom=1584 A Dump resistor 0.2 Ohm	0.69	118	318
ID	Inom=1584 A Dump resistor 0.15 Ohm	0.8	155	239
OD	Inom=1402 A Self protected (no dump)	1.14	354	586
OD	Inom=1402 A Dump resistor 0.3 Ohm	0.74	132	422
OD	Inom=1402 A Dump resistor 0.2 Ohm	0.89	194	282
OD	Inom=1402 A Dump resistor 0.15 Ohm	0.96	233	212

- Note that the calculated voltage is the resistive magnet voltage plus the voltage across the dump resistor.

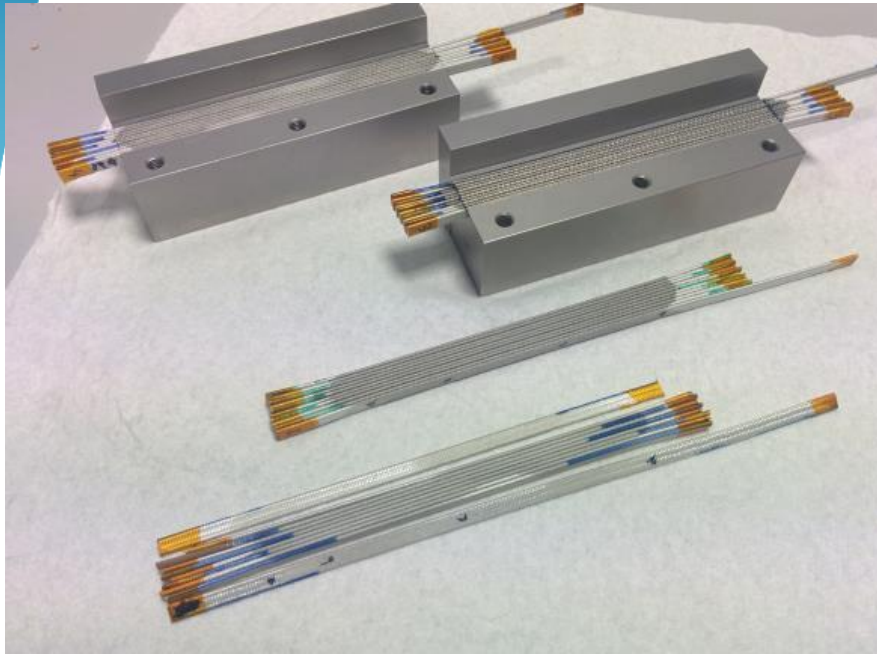
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Manufacturing concept

- Double pancake coils of small NbTi cable with large aperture: **large number of turns**.
- Traditional coils made with polyimide insulated cables would be too **spongy**: dimension control would be very challenging.
- **Fully impregnated coils** would ease the dimension accuracy.
- Resin should be **radiation hard** and have a good mechanical behaviour.
- Cable should be insulated with a **glass-fiber sleeve** to ease the impregnation.
- A **binder** is necessary to hold the first layer while winding the second one.
- The binder must be compatible with the **resin**.
- **Coil pre-stress** will be provided by self-supported stainless steel collars.
- **Iron yoke** will be laminated and will not provide additional mechanical support.

Validation Tests: Binder curing



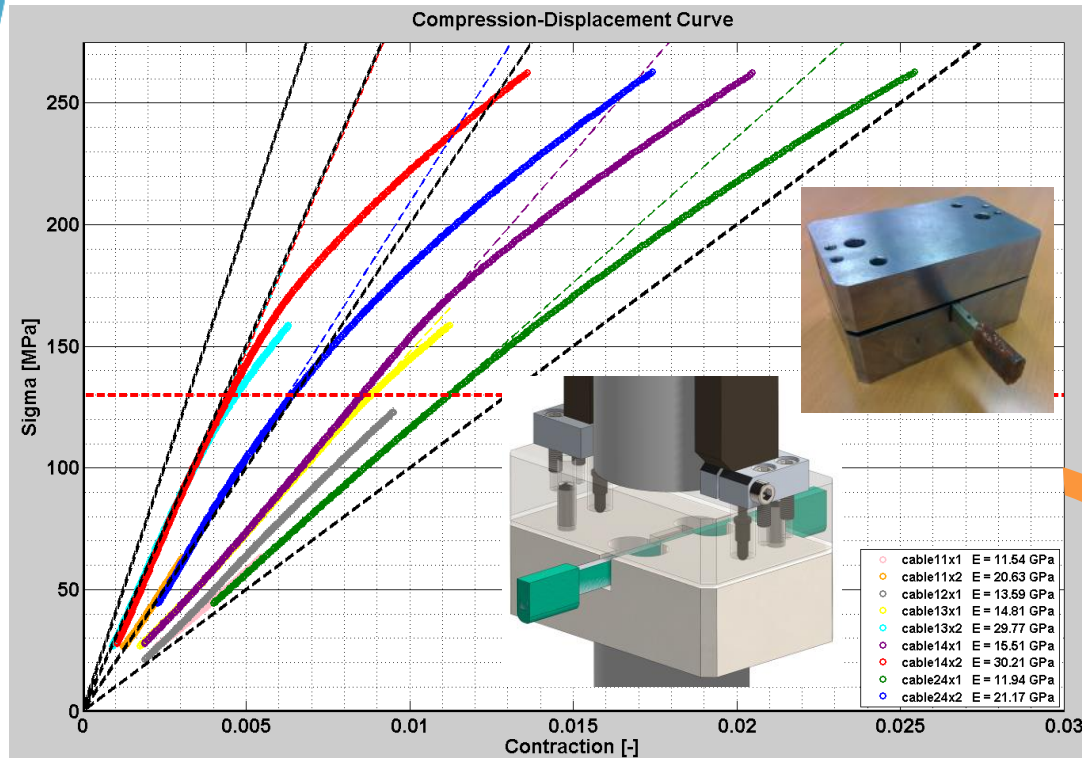
- Winding and impregnation process needs to be validated
 - Binder needs to be stiff enough to hold properly the first layer while winding the second one.
 - Binder needs also to be compatible with the impregnation resin.
- A battery of test were carried out in collaboration with CERN Polymer Lab, using two candidate binders. Finally, **0.7 g of a 50/50 solution of CTD 1.1 and butanone for a 10 cable stack of 120 mm.**
- However, the dimensions of the cable stack were not stable...
- Test applying heating during curing were carried out at CIEMAT in order to assure the complete evaporation of solvent.
- First tests end up concluding that after a **curing cycle of 150°C during 10 hours the cable stack is stable**. They keep their dimensions over time.
- After additional tests, a lower temperature treatment will be applied to the real coils, using just **120°C during 18 hours**.

Validation Tests: Impregnation



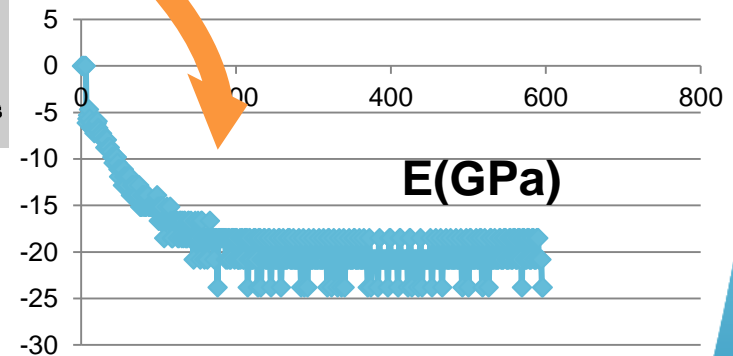
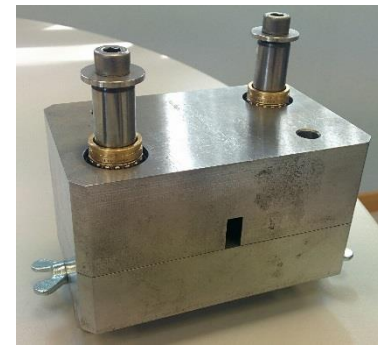
- Despite CTD 422 resin was validated for its use in combination with CTD 1.1 binder, it has been decided to switch to CTD 101K instead.
- There were some doubts about the mechanical resilience of 422. The training of the octupole made at CIEMAT in 2013 was slow. It is more secure to use the CTD 101K that has been widely tested in other magnets.
- The initial reason to use 422 was its higher radiation resistance, however MCBXF magnets are placed right next to other magnets (MQXF) with similar exposure and impregnated with 101K.
- CTD 101K has been validated in combination with CTD 1.1 binder and Nomex in several tests with ten cable stacks.

Validation Tests: Coil Young modulus



Custom tooling was used to obtain the Young modulus of ten-cable stack impregnated samples. First results showed half the expected rigidity.

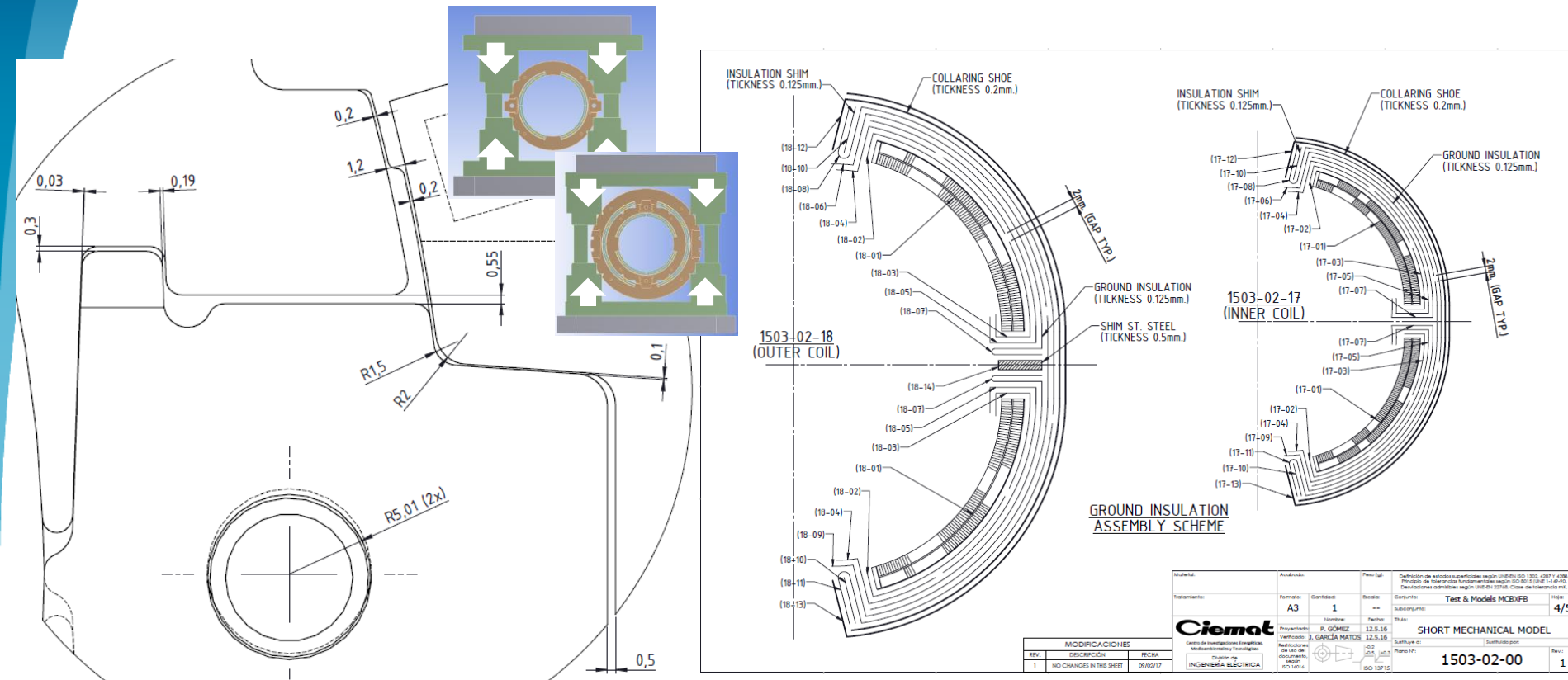
After improving the tooling, the tests confirms that Young modulus of the coils is close to **20 GPa**.



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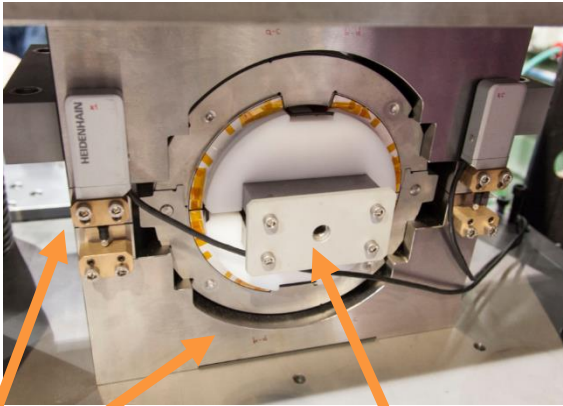
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Short mechanical model: Motivation



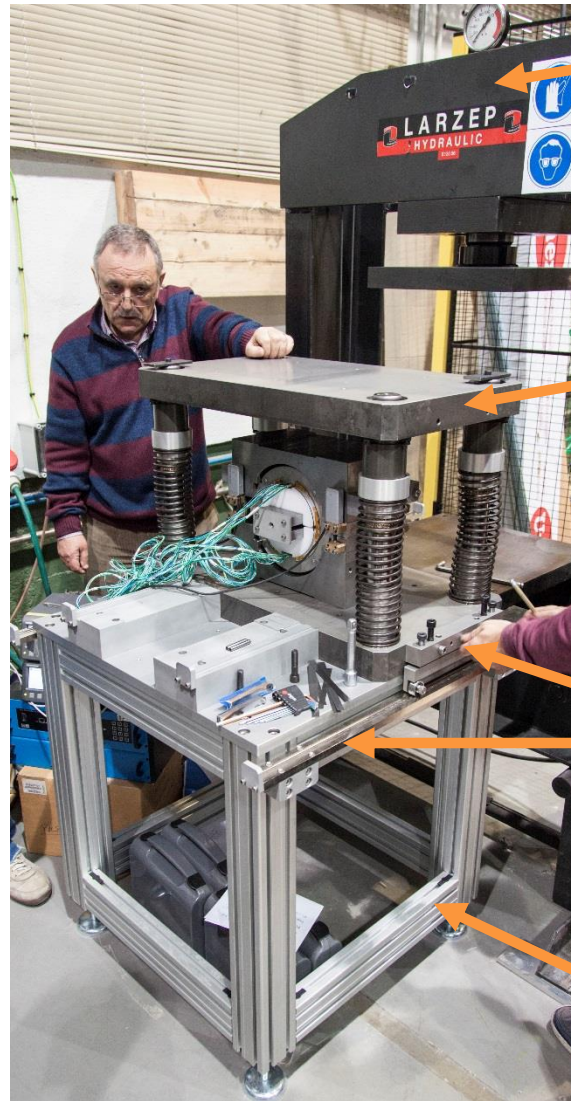
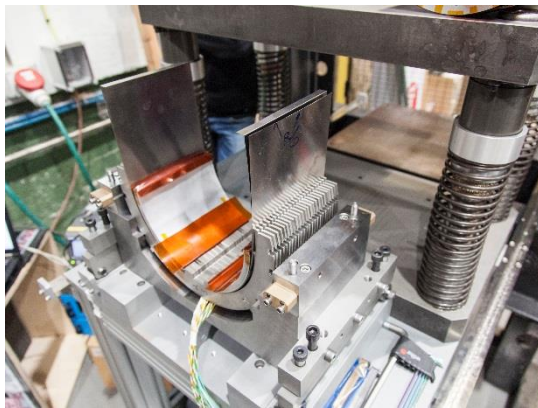
- A short mechanical model, as close as possible to the real magnet, becomes essential to:
 - Validate the assembly process of the nested dipoles: feasibility, gaps, ground insulation, collaring shoes...
 - Test part of the tooling to be used in the prototype assembly.
 - Validate the FEM mechanical model.

Short mechanical model: Assembly



Pressing cradles and stoppers

Inner collapsible mandrel



120 Ton press refurbishing and calibration

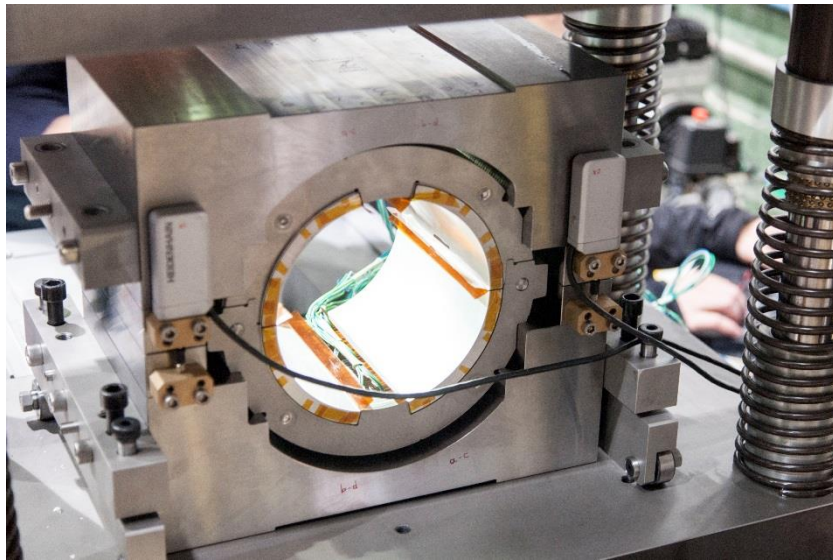
Alignment cage

Handling/sliding system

Support/assembly table

Short mechanical model: Inner Dipole Results

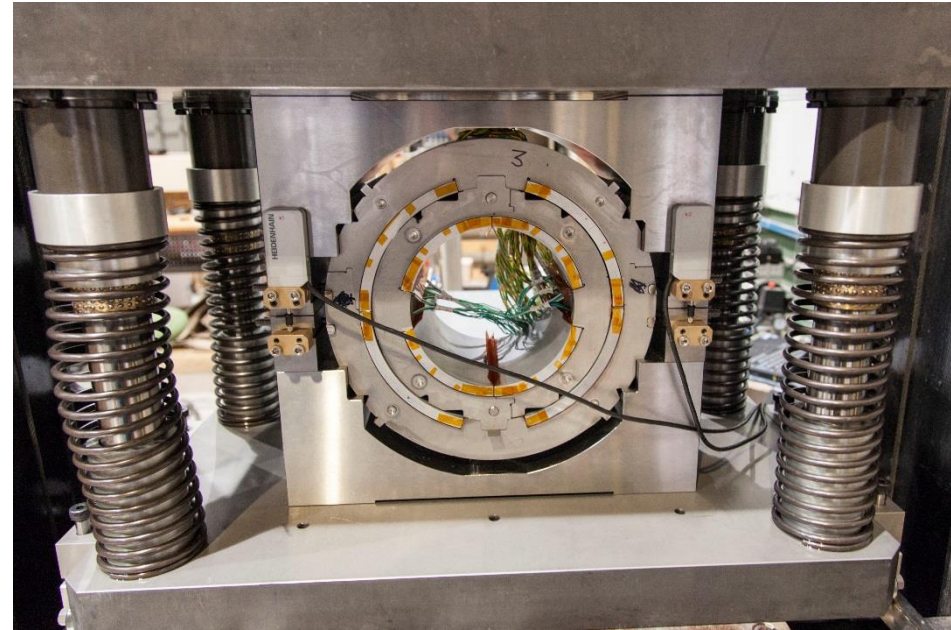
Shim [mm]	Average displacement gauge [mm]	Average strain gauge [$\mu\epsilon$]	Average stress [MPa]	Press force [ton]
0.7	0.45~0.51	100	21	-
0.6	0.1	189	40	28
0.5	0.2	247	52	26
0.4	0.3	337	71	34
0.3	0.4	429	90	40
0.2	0.5	507	106	40
Spring back	N/A	343	72	N/A



- At the minimum gap of 0.2 mm, expected strain at the collar nose was about 530 $\mu\epsilon$, very close to the average of the measurements of the gauges (507 $\mu\epsilon$).
- When the pressure is relieved, the inner dipole is left in its “spring-back” position. Calculated strain was 350 $\mu\epsilon$ and the average of all measures is 343 $\mu\epsilon$.
- The collapsible mandrel is retired without effort from the inner dipole aperture.

Short mechanical model: Outer Dipole Results

Shim [mm]	Average displacement gauge [mm]	Average strain gauge [$\mu\epsilon$]	Average stress [MPa]	Press force [ton]
1.4	0.25	32	7	4
1	0.4	109	23	-
0.7	0.69	234	49	22
0.5	0.9	367	77	35
0.4	0.98	416	87	30
0.5	0.9	361	76	33
0.4	1	427	90	38
0.3	1.095	502	105	40
0.2	1.18	590	124	40
Spring back	N/A	424	89	N/A



- At the minimum gap of 0.2 mm, expected strain at the collar nose was about 590 $\mu\epsilon$, not far from the average of the measurements (507). However, gauges in the lower half measured about one half of the upper ones.
- The coils have not tried to collapse inwards. Gaps are correct.
- Strain gauges are not equilibrated at the “spring back” position. Lower/male gauges indicate approximately twice the pressure than the upper/female ones. However the average is 424 $\mu\epsilon$, very close to the 385 $\mu\epsilon$ expected from the simulation results.

Short mechanical model: 2nd Outer Dipole Test

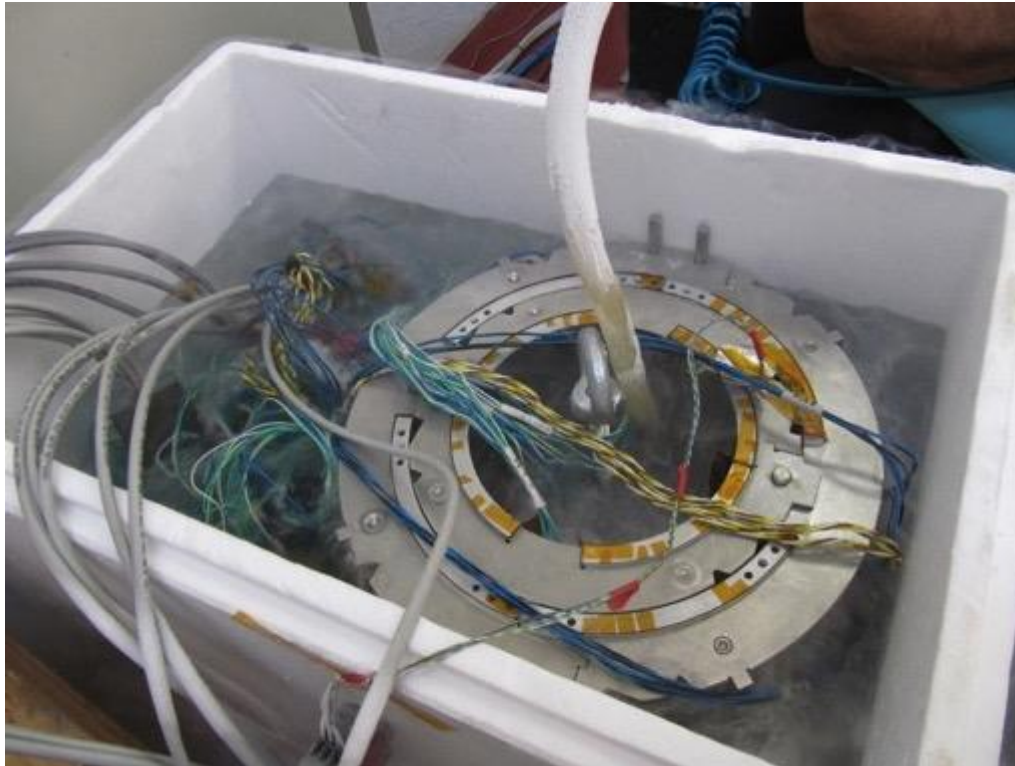
Shim [mm]	Average displacement gauge [mm]	Average strain gauge [$\mu\epsilon$]	Average stress [MPa]	Press force [ton]
1	0	0	0	10
0.7	0.27	98	20	-
0.5	0.47	181	38	-
0.5	0.45	189	41	-
0.3	0.68	322	67	40
0.2	0.78	398	83	50
0.2	0.78	405	85	50
Spring back	-N/A	272	57	N/A

- Surprisingly, the strain gauges measure similar values this time.
- Assembly procedure was a bit different, which could explain the difference.

- Additional activities:
 - Disassemble again the collar packs and repeat the test. Same results.
 - New outer male collars with right geometry were launched to production and tests were repeated with same results.

Short mechanical model: cold test

- The short mechanical model has been cooled down in a liquid nitrogen bath. Average measurements are very close to FEM results ($250\text{ }\mu\text{E}$).



ID-edge	OD-edge	ID-center	OD center	Average
359	197	230	228	254

Measured deformations at collar noses from room to liquid nitrogen temperature (μE)

Conclusions

- MCBXF orbit correctors have been designed at CIEMAT.
- The main challenge of the electromagnetic calculations is the variation of field quality with iron saturation.
- The torque is hold by clamped nested collars. The coil ends are short to reduce the unsupported coil length.
- Both dipoles are protected with a 0.15 ohm dump resistor.
- The coils are fully impregnated, made with a NbTi Rutherford cable insulated with braided glass fiber.
- Validation tests have been made to check the cable modulus of elasticity and to characterize the compatibility of binder and resin.
- A short mechanical model has been produced to prove the feasibility of the nested collared assembly.
- A fine tuning of the inner dipole design is ongoing (see Ezio's talk) to improve the training under inversions of torque direction.



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Thank you for your attention

Back up slides

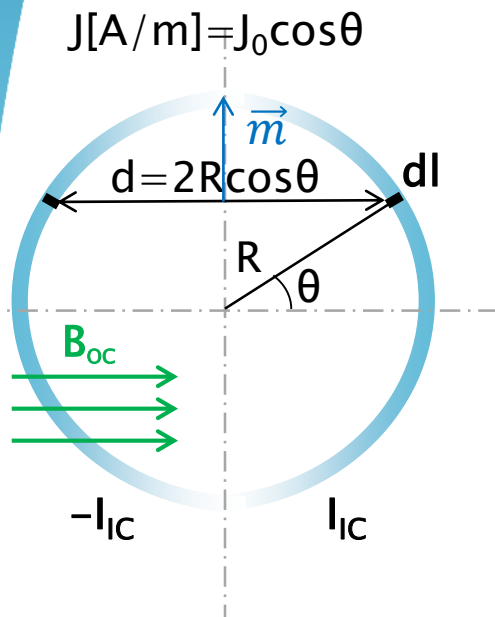
Magnet configuration

- Cosine theta:
 - Winding and assembly procedures are well-known.
 - Long coil ends (similar to the aperture diameter).
 - High number of turns (large aperture and small cable).
- Superferric:
 - Field quality is not achievable within the available space (iron saturation and large aperture).
 - Very simple configuration.
- Canted cosine theta:
 - Magnet protection in case of quench.
 - Large radial forces (same as cosine theta case). Stiffness of mandrel? Long training?
 - Long coil ends due to the large aperture.
 - Azimuthal forces support and good field quality.

Single layer & Double layer designs VS old MCBX (same central field comparison)

Inner coil (ID) & Outer Coil (OD) parameters	Units	Single layer design	Double Layer design (Small Collars)	Double Layer design (Large Collars)	Old MCBX (Series Model, both coils powered)
Nominal field 100% (ID)	T	2.13	2.13	2.13	2.13
Nominal field 100% (OD)	T	2.11	2.12	2.12	2.12
Nominal current (ID)	A	2450	1250	1560	362.5x8=2900
Nominal current (OD)	A	2150	1036	1340	331.25x8=2650
Coil peak field	T	4.27	3.95	3.93	3.817
Working point	%	60%	44.7%	48.1%	39.54%
Torque	10 ⁵ Nm/m	0.92	0.98	1.19	-0.455
Conductors height (h)	mm	4.37	2x4.37	2x4.37	13.2 (8)
Mean stress at the coil and collar nose interface	MPa	135	70	82	38
Aperture (ID)	mm	Ø150	Ø150	Ø156,2	Ø90
Aperture (OD)	mm	Ø180	Ø200	Ø218	Ø116.8
Iron yoke Inner Diam.	mm	Ø230	Ø250	Ø300	Ø180
Iron yoke Outer Diam.	mm	Ø540	Ø540	Ø610	Ø330
Number of conductors used (1 st quad)	-	162	357	324	800

Some useful expressions to understand where mechanical stresses come from



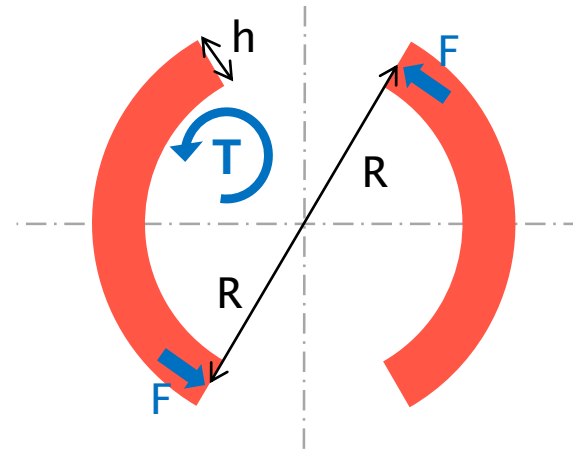
$$I_T = \int_{-\pi/2}^{\pi/2} J dl = \int_{-\pi/2}^{\pi/2} J_0 \cos \theta R d\theta = 2J_0 R \rightarrow J_0 = I_{IC} / 2R$$

$$\frac{T}{l} = \frac{\vec{m} \times \vec{B}}{l} = \frac{B_{0c}}{l} \int_{-\pi/2}^{\pi/2} S \cdot I = B_{0c} \int_{-\pi/2}^{\pi/2} 2R_{IC} \cos \theta J_0 \cos \theta R_{IC} d\theta$$

$$T/l^* = \frac{\mu_0 \pi}{8} I_{IC} I_{OC} \frac{R_{IC}}{R_{OC}} \left(\frac{R_Y^2 + R_{OC}^2}{R_Y^2} \right) \leftarrow T/l = \frac{\pi}{2} R_{IC} B_{0c} I_{IC}$$

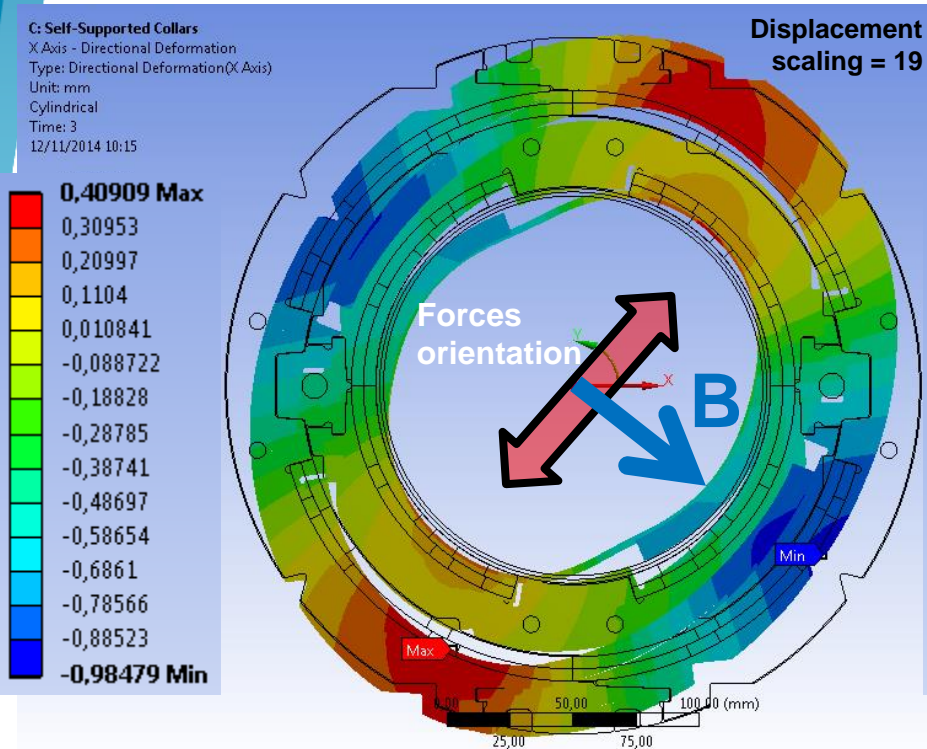
* Linear Iron

$$\sigma_{\theta cond} = \frac{F}{A} = \frac{T/2R}{lh} = \frac{T/l}{2Rh}$$



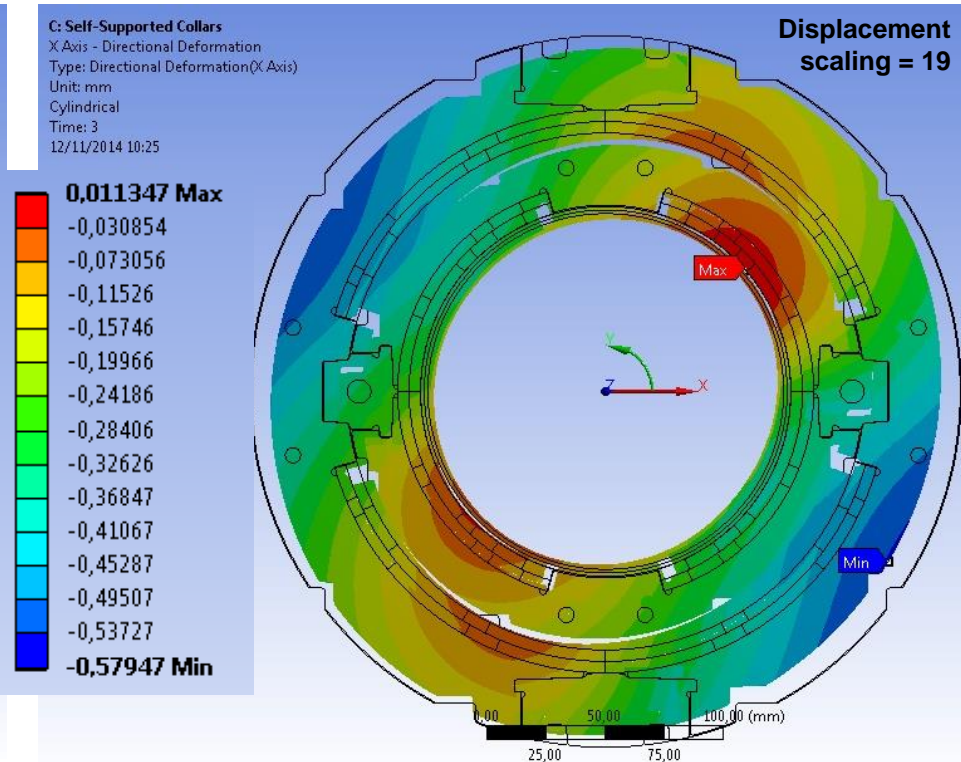
Results: Large radial collar deformations

Outer Collar Diam.= 275 mm



Ellipticity \cong 1.4 mm

Outer Collar Diam.= 300 mm



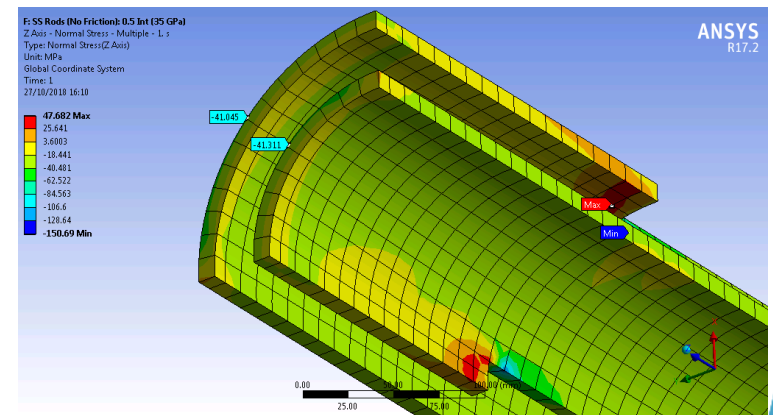
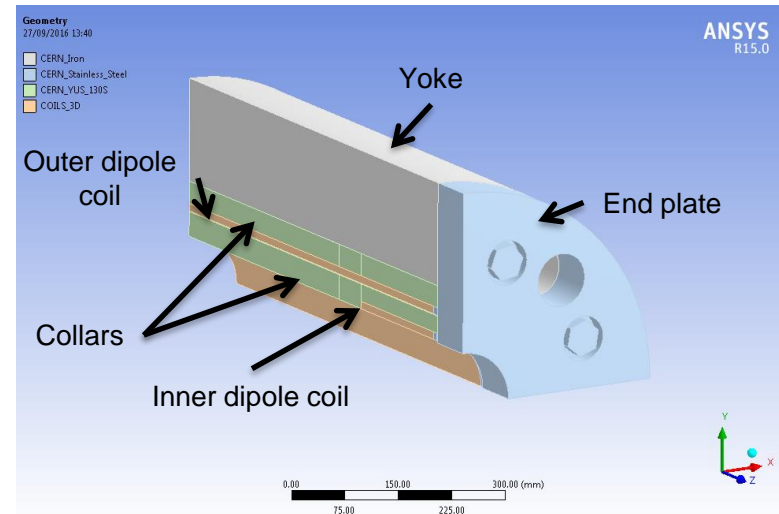
Ellipticity \cong 0.6 mm

Field quality effect (Ansys2Roxie) :

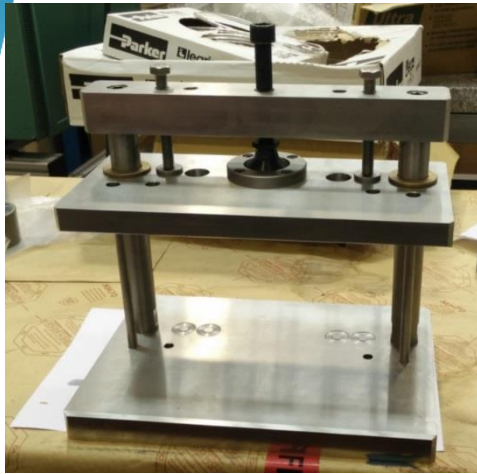
- $\Delta b_3 = 9$ units
- $\Delta a_3 = 6$ units

Magnet engineering design: endplates (II)

- **Two models** have been developed to analyze the mechanical problem:
 - Analytical based on Roark's formulas
 - 3-D finite element model
- Friction is neglected. All materials are assumed as isotropic in a first approach. Three load steps: assembly, cool-down and energization.
- Both models agree on the results. For the first load step, to provide a pressure of 40 MPa on the coil ends, the analytical model needs 69 MPa at the rods and the numerical one, 60 MPa.
- However, we are assuming an isotropic **iron yoke**. The axial modulus of elasticity should be measured during assembly to decide the value of the axial coil pre-stress.

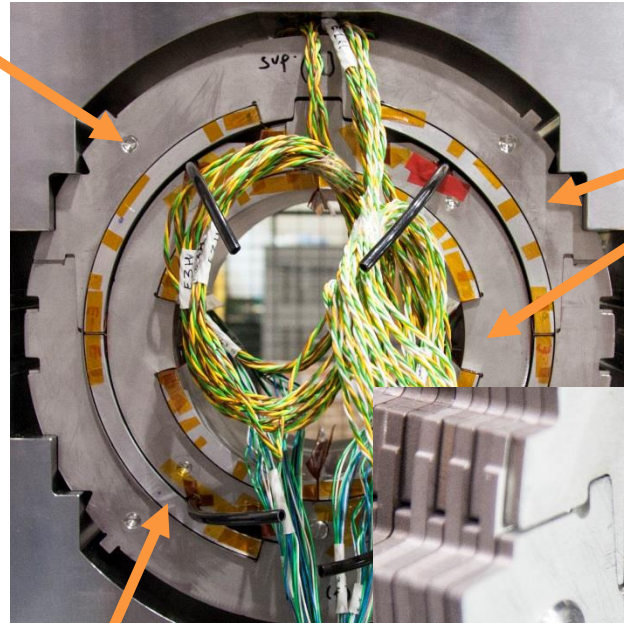
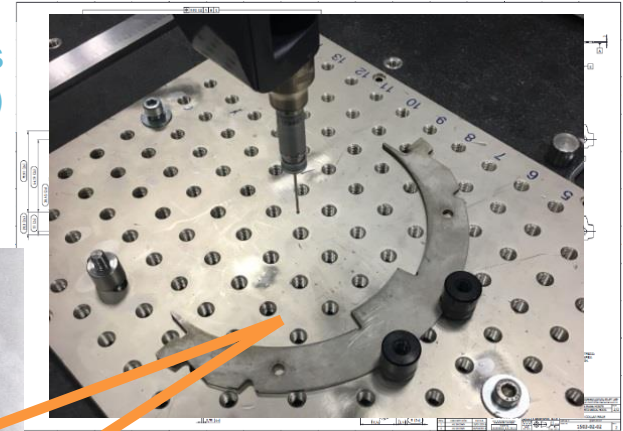


Short mechanical model: Fabrication

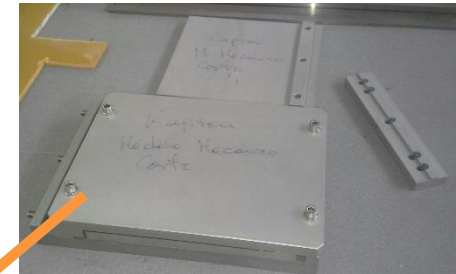


Rivets insertion tool (ID & OD)

Collars
(Laser + EDM)



Aluminium
dummy coils



Kapton bending
tooling



Handling scissors (ID & OD)

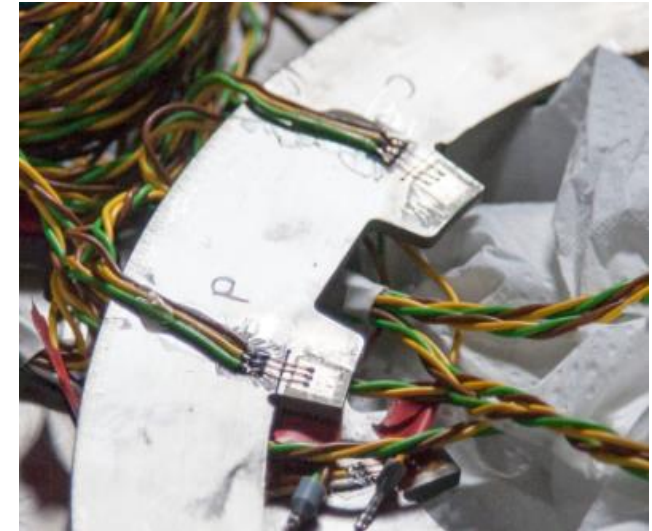
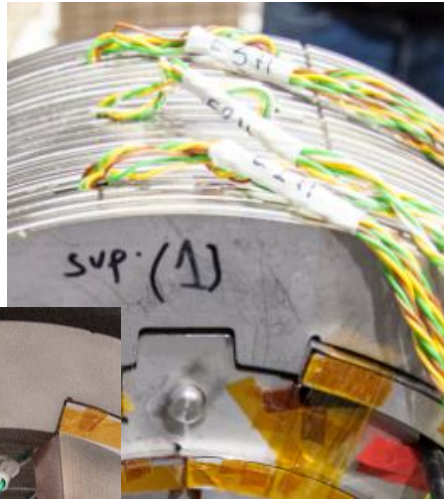


Collaring shoe
preforming
tooling

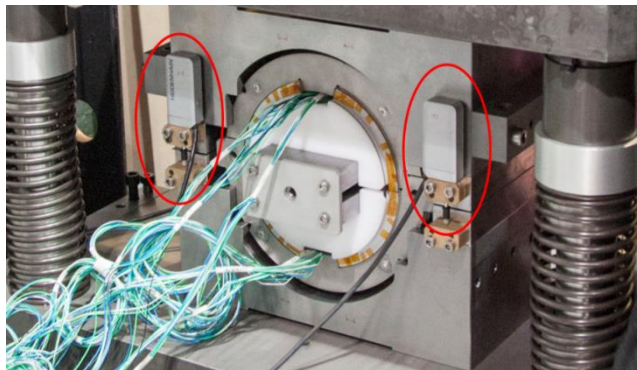


Short mechanical model: Instrumentation

Three sections
are monitored
by strain gauges
(ID & OD)



Four strain gauges per collar: on both
sides of the collars and noses



Four displacement
gauges: micrometric
precision

**All gauges configuration,
installation, cabling and data
acquisition have been
developed in-house**