HL-LHC Collaboration Meeting 2016: MCBXFB Short Orbit Corrector Prototype

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- Magnetic calculations.
- Mechanical calculations.
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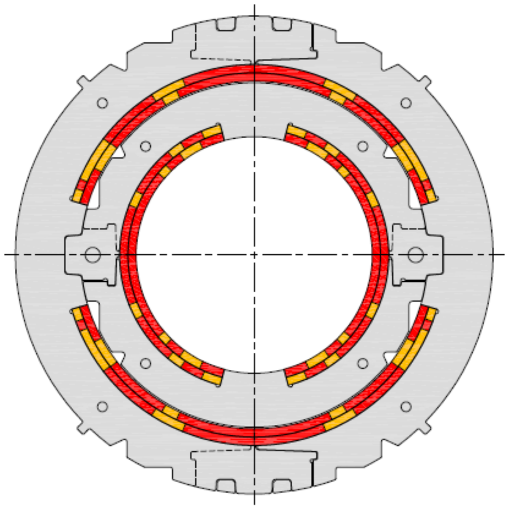
- Conclusions.

Magnet and cable specifications

MCBXFB Technical specifications	
Magnet configuration	Combined dipole (Operation in X-Y square)
Integrated field	2.5 Tm
Minimum free aperture	150 mm
Nominal current	< 2500 A
Radiation resistance	40 MGy
Physical length	< 1.505 m
Working temperature	1.9 K
Iron geometry	MQXF iron holes
Field quality	< 10 units (1E-4)
Fringe field	< 40 mT (Out of the Cryostat)

Radiation resistance requires mechanical clamping



Working point < 65%

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

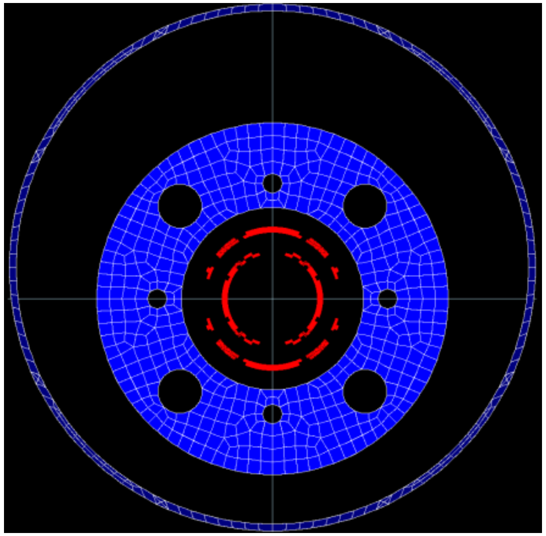
Magnetic calculations

Magnetic Design: Final design

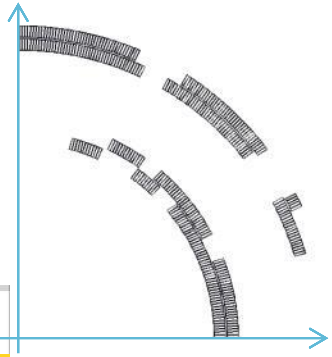
Inner Dipole (ID) & Outer Dipole (OD) parameters	Units	ID	OD
Nominal field	T	2.11	2.23*
Nominal Field (Combined)	T	3.07	
Nominal current	A	1600	1470
Coil peak field (Combined)	T	4.13 (ID)	
Working point (combined)	%	50.1	
Inductance/m	mH/m	46.77	99.1
Stored energy/m	KJ/m	59.87	107
Aperture	mm	156	230
Iron yoke Inner Diam.	mm	316	
Iron yoke Outer Diam.	mm	614	
Torque	Nm/m	1.2×10^5	
Max fringe field, 20 mm out of the cryostat	mT	29	
Total number of turns	-	139	187
Cable length needed for each pole/coil	m	362	485

Whole iron option is chosen:

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



* Higher field necessary to compensate the longer coil end at the outer dipole.



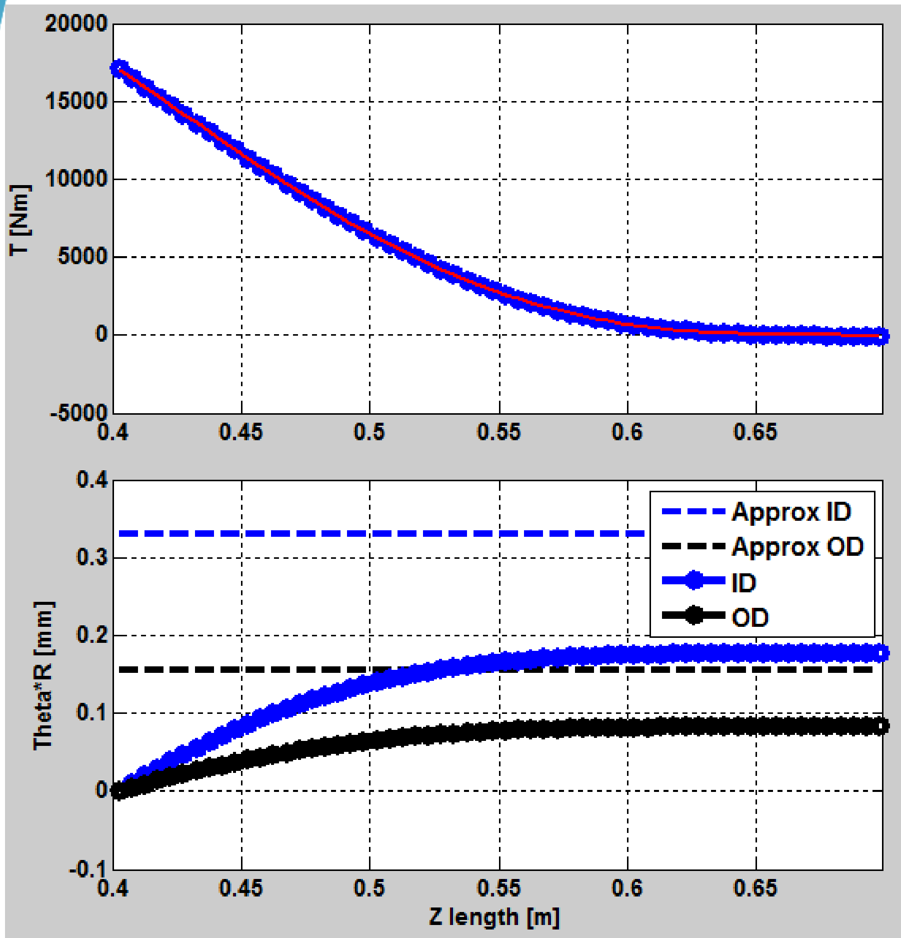
Difficult winding: 1 μm thinner cable yields

Δb3 ≅ - 5 units

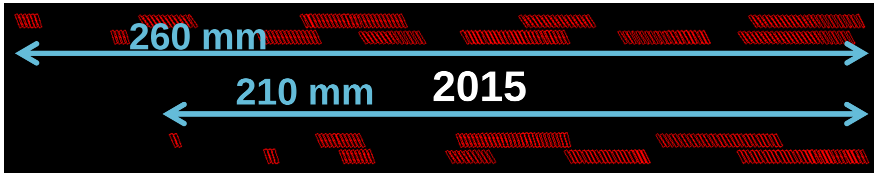
Δa3 ≅ + 0.8 units

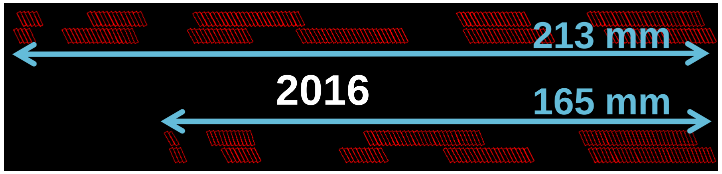
Magnetic Design Summary: Coil ends

Torsion estimations due to torque at coil ends

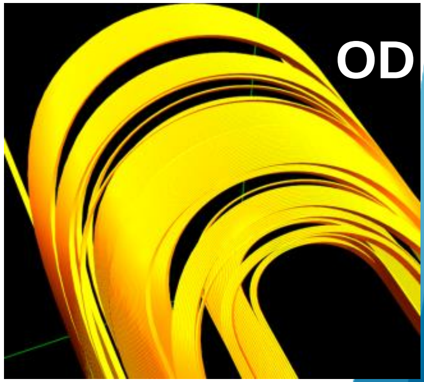


Coil ends were shortened to increase the coil length supported by collars:





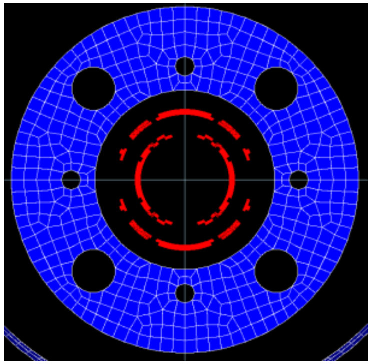
58 different spacers per magnet!

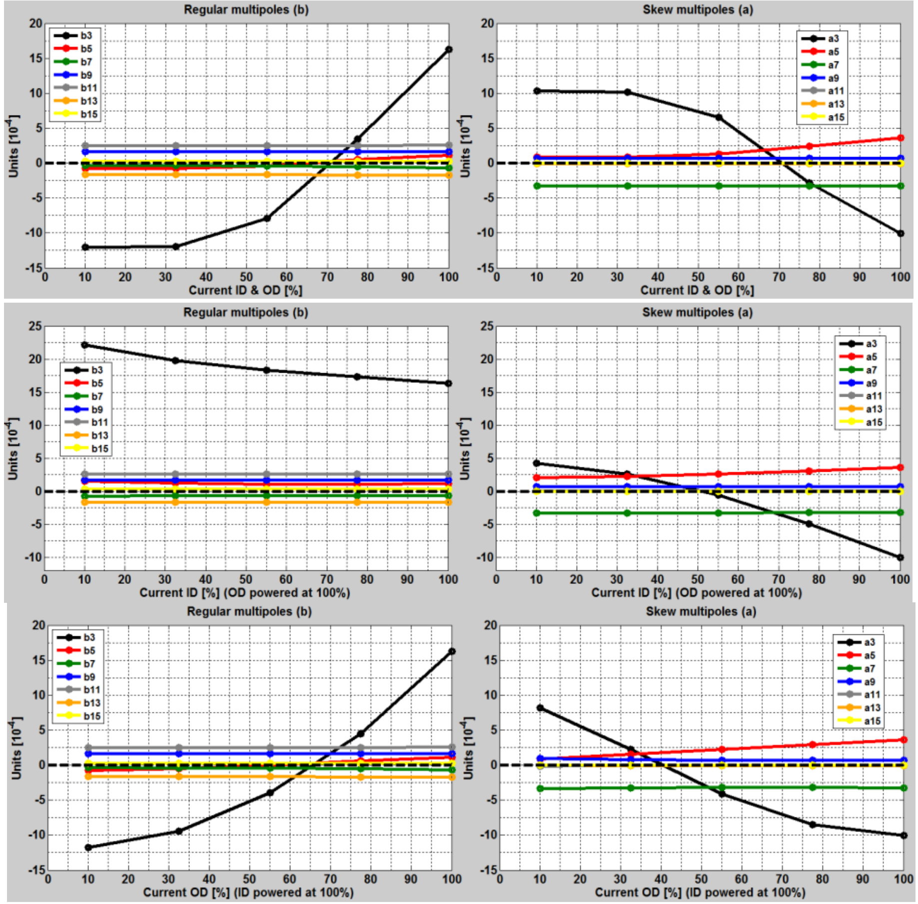


3-D magnetic re-design

Magnetic re-design was carried out taking into account:

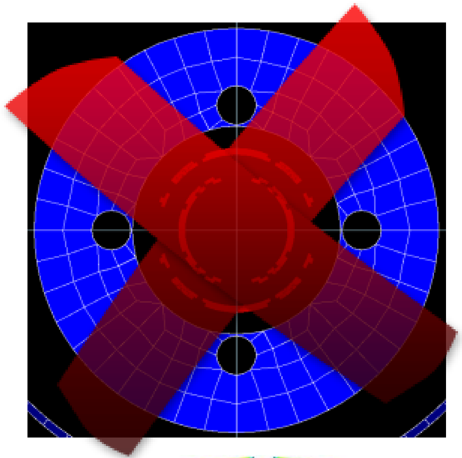
- Real cable and insulation measurements.
- Ground and interlayer insulation.
- MCBXFA is more relevant for the accelerator expected operation, so it is decided to centre its sextupole variation.
    - Different shimming schemes were planned for each one of the magnets.
    - All powering scenarios were studied for both magnets.
    - Choosing the best shimming scenario for both of them.
- Some high order multipoles were reduced. However b11 and a7 remains to be high.

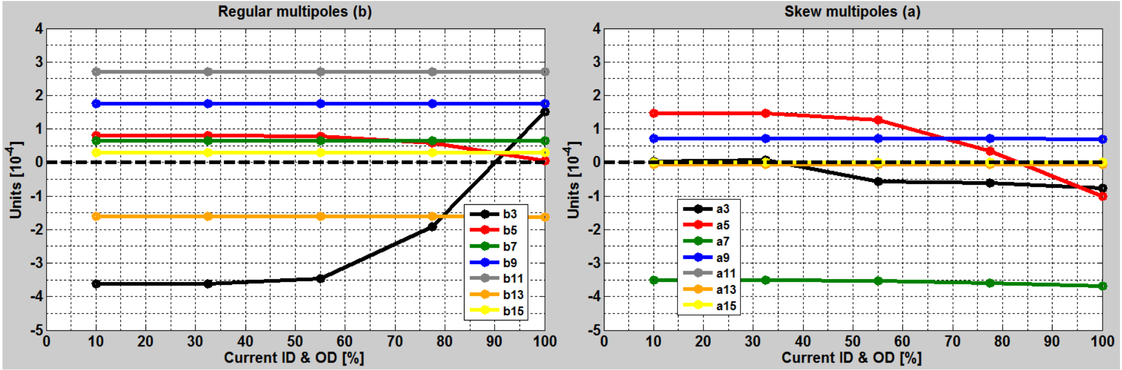




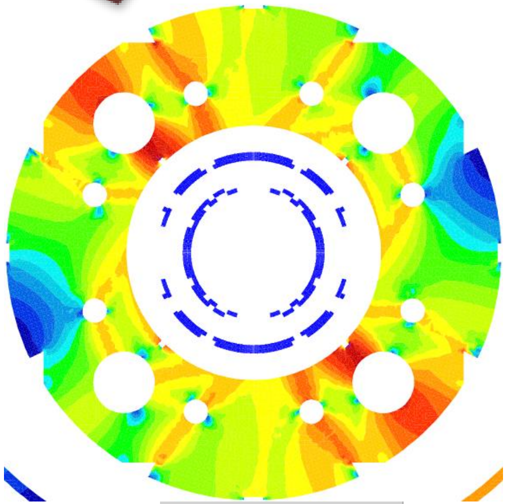
Magnetic Design: Same iron for A & B

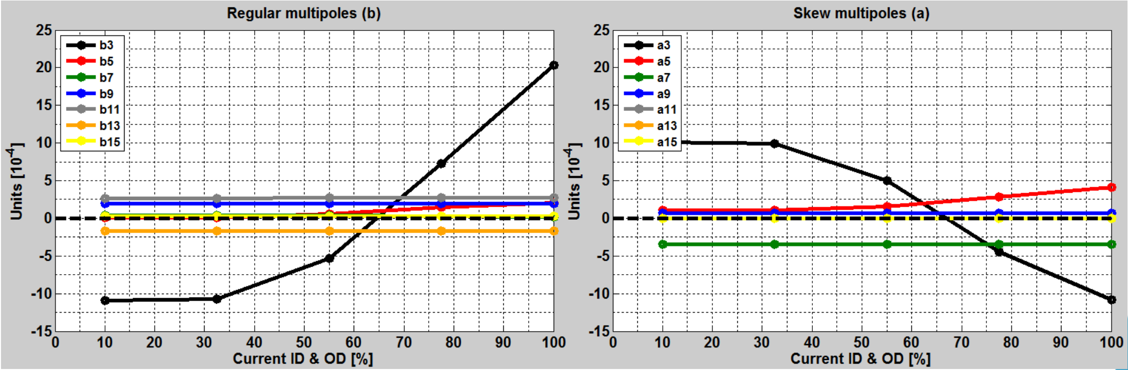
- The cooling pipes are aligned with the field when both dipoles are powered simultaneously.
- The impact on b3 variation with current is important: **from 6 units to 36.**
- It is accepted by beam dynamics calculations.





Integrated multipoles with iron holes at coordinate axes



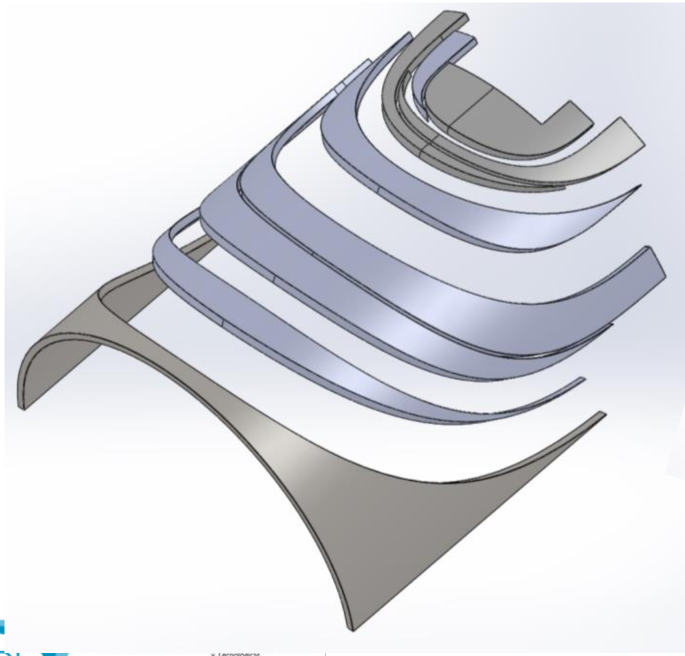


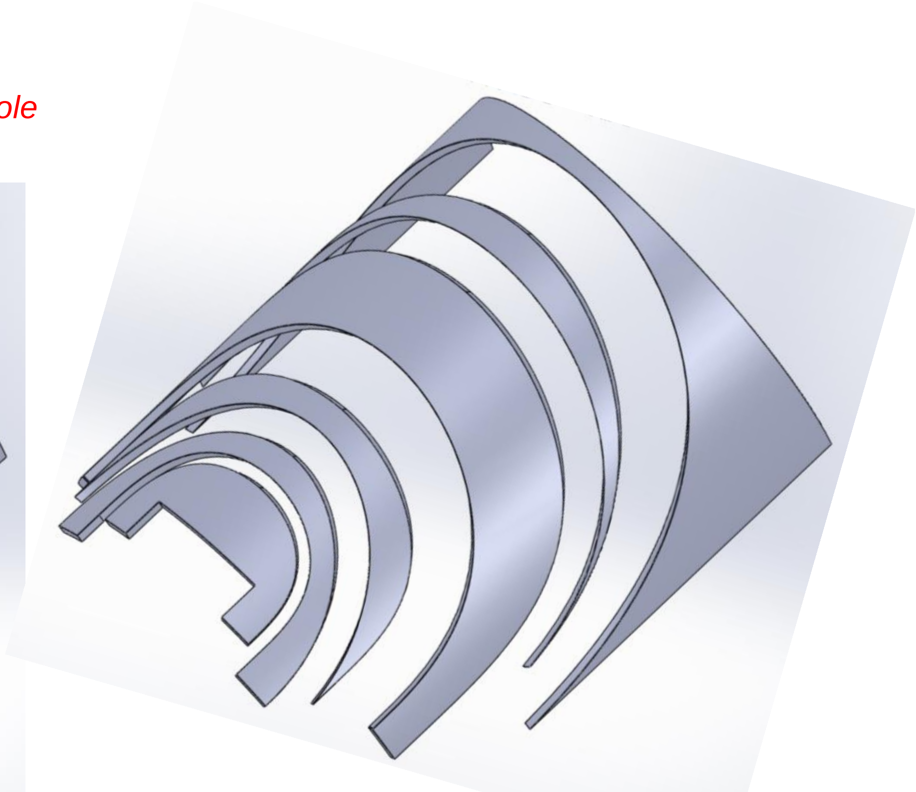
Integrated multipoles with iron holes aligned with maximum field

Magnetic Design Summary: Spacers

- Step files have been generated with CERN support (Susana Izquierdo Bermúdez & Benoit Lepoittevin).
- Ruled surfaces have been shifted by 0.23 mm to allow space for electrical insulation (glassfiber sheet).
- Edges have been rounded with 0.2 mm fillet radii.
- These drawings and 3-D models will be used for the cost estimate for the series.

Lead end spacers at the outer layer, outer dipole



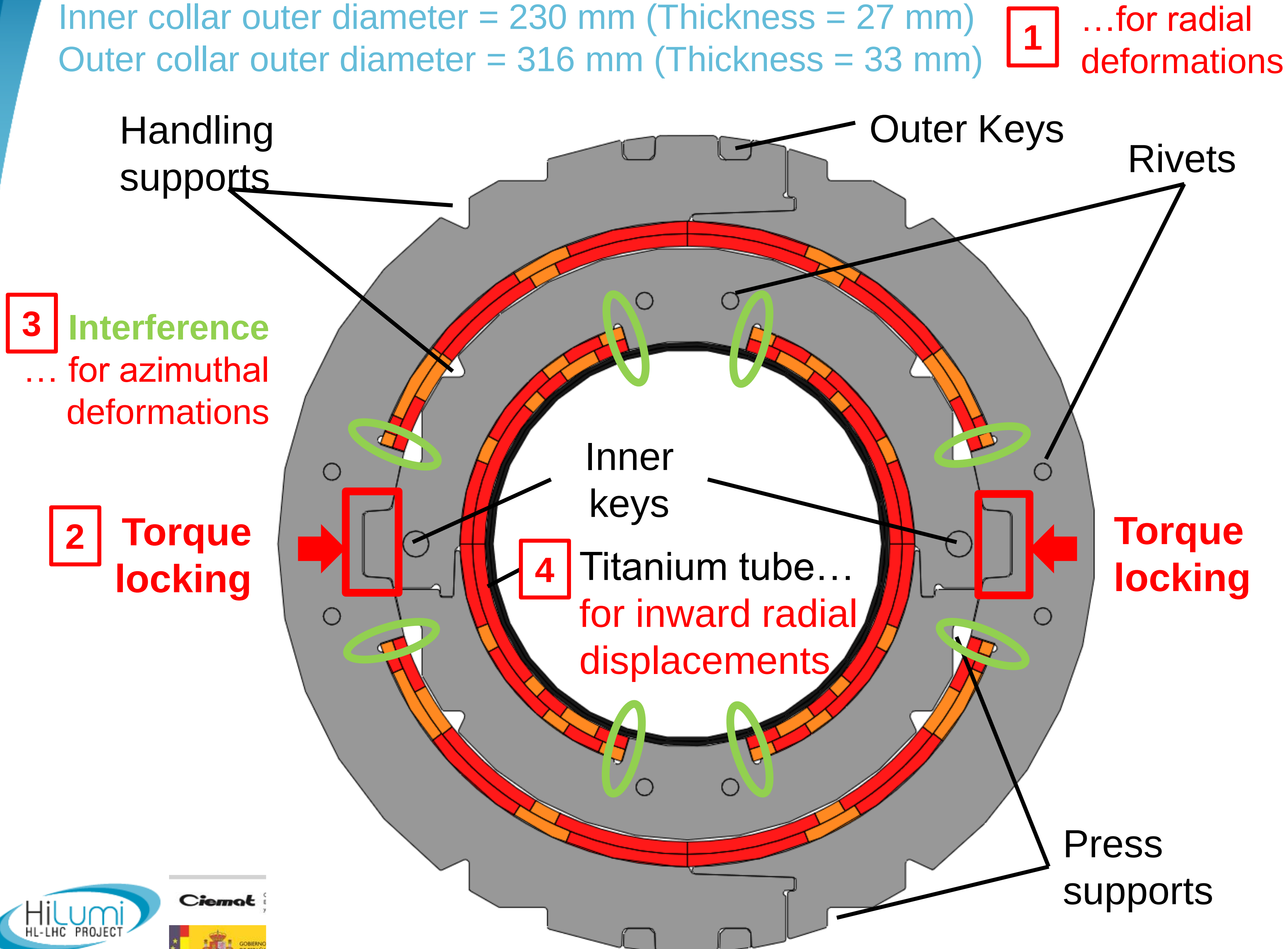


Return end spacers at the outer layer, outer dipole

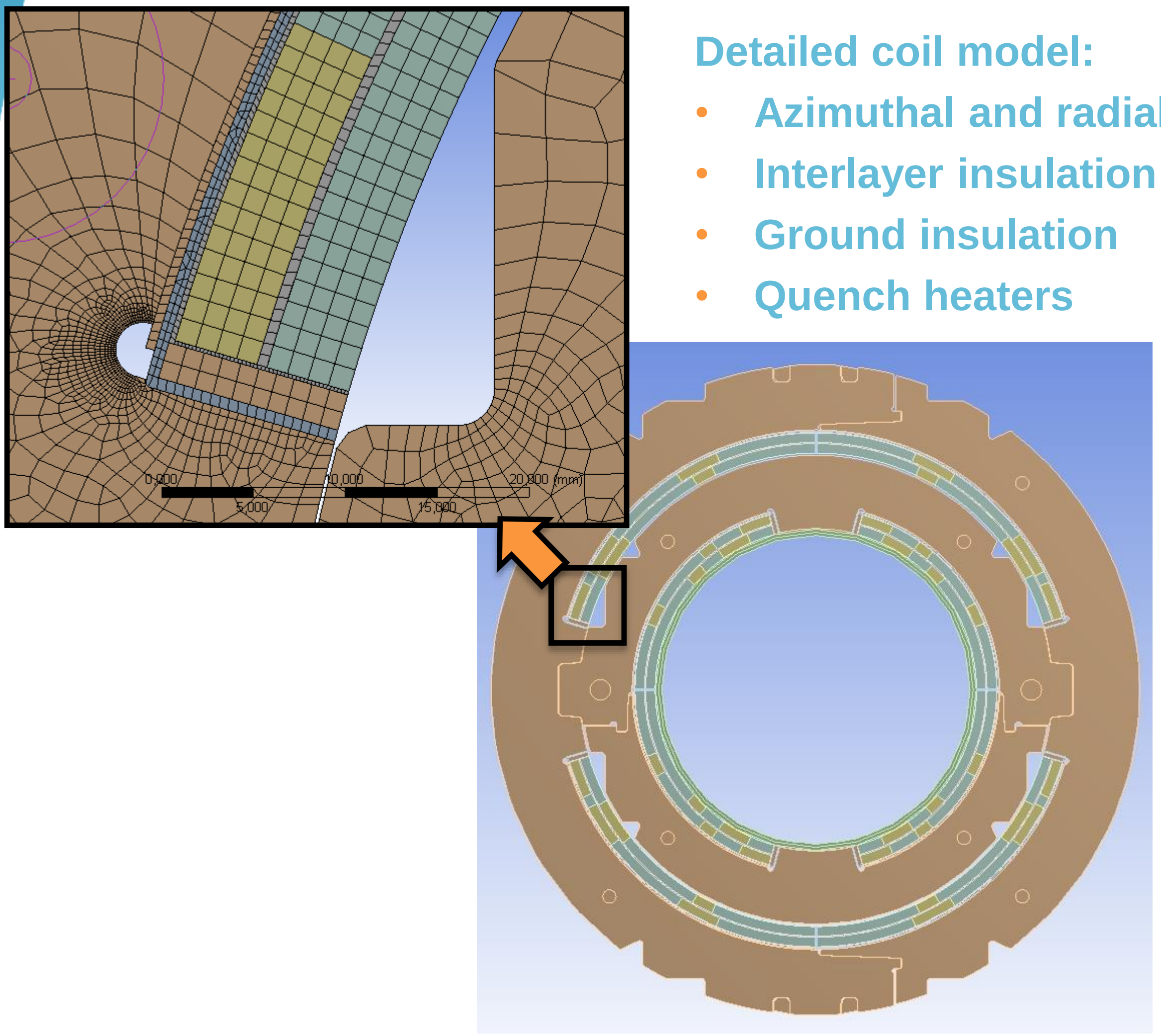
Mechanical calculations

Self-supporting collars

Inner collar outer diameter = 230 mm (Thickness = 27 mm)
Outer collar outer diameter = 316 mm (Thickness = 33 mm)



Mechanical design: Evolution



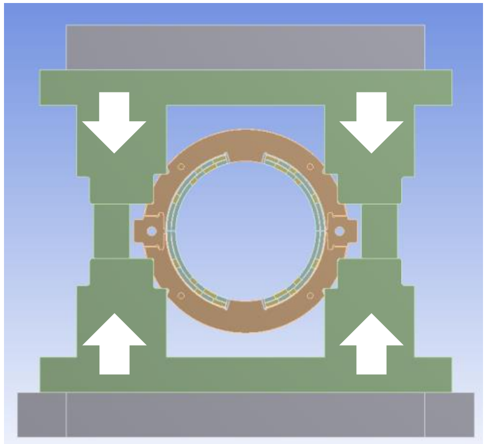
Detailed coil model:

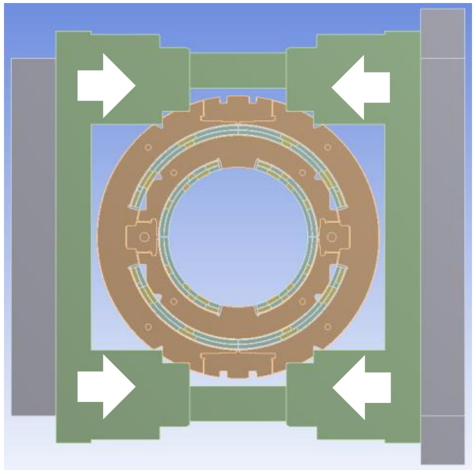
- Azimuthal and radial collaring shoes.
- Interlayer insulation
- Ground insulation
- Quench heaters

Difficulties to achieve convergence:

- No symmetry can be applied (longer times and difficult support definition).
- Many elements with different materials in contact.
- Take care of excessive penetration in contacts
- Difficult to mesh thin elements properly.

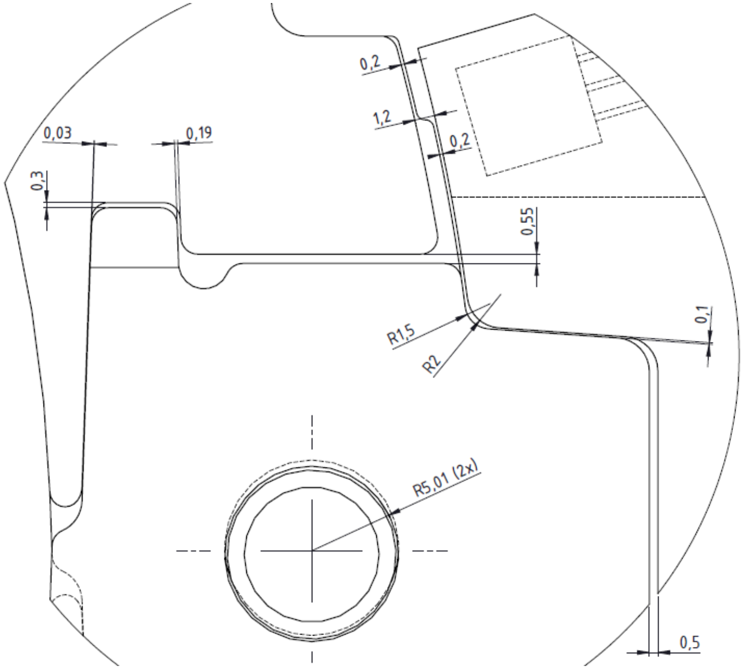
Mechanical design: Simulation of collaring



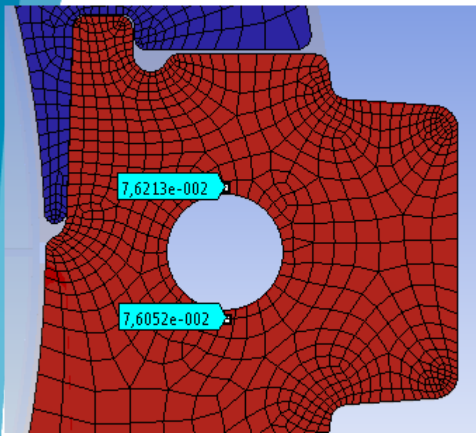


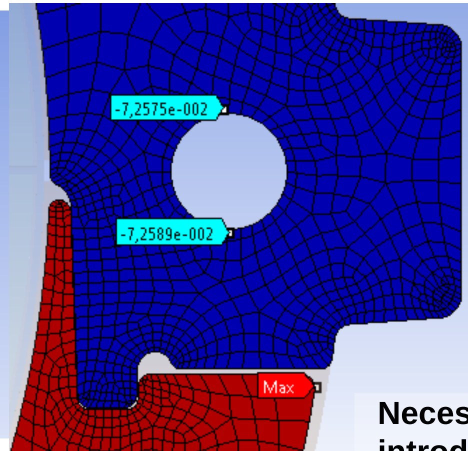
Achieved goals:

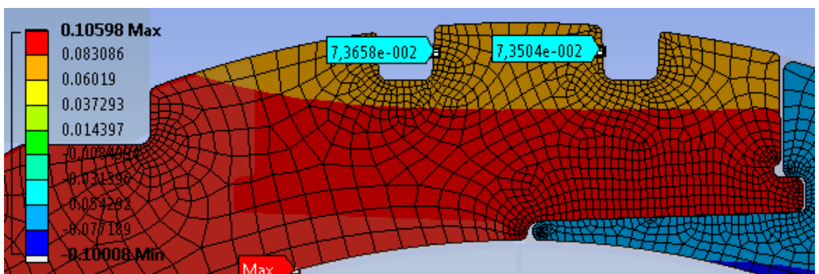
- Monitoring stress at the coils when the pins/keys are inserted.
- Sizing of the stoppers needed to limit the press displacement.
- Checking that all clearances are the correct ones in order to assure assembly.

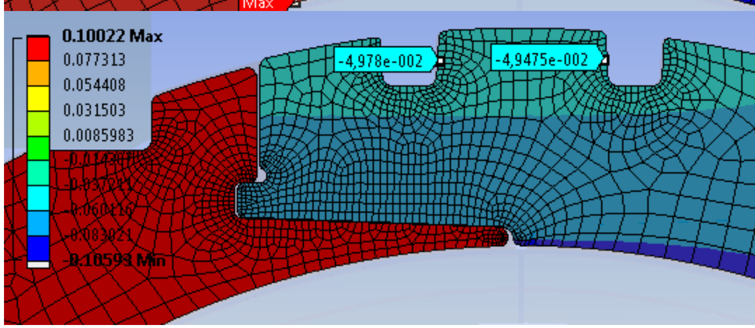


Mechanical design: Simulation of collaring

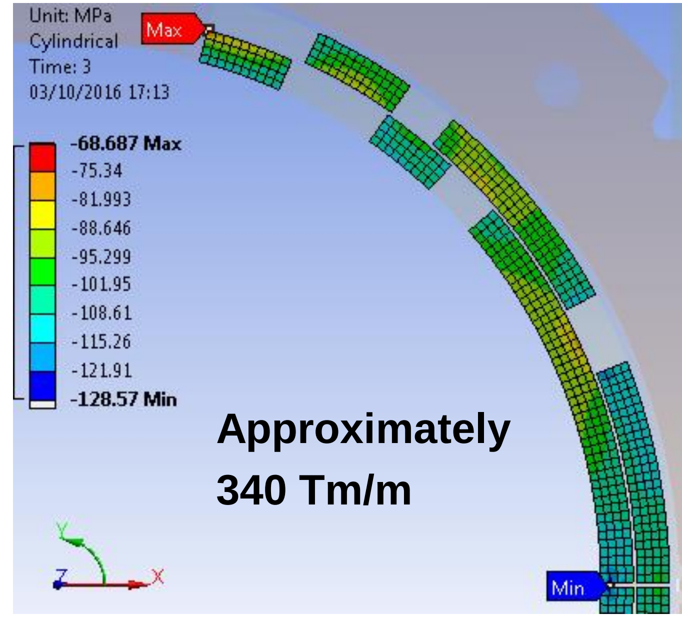








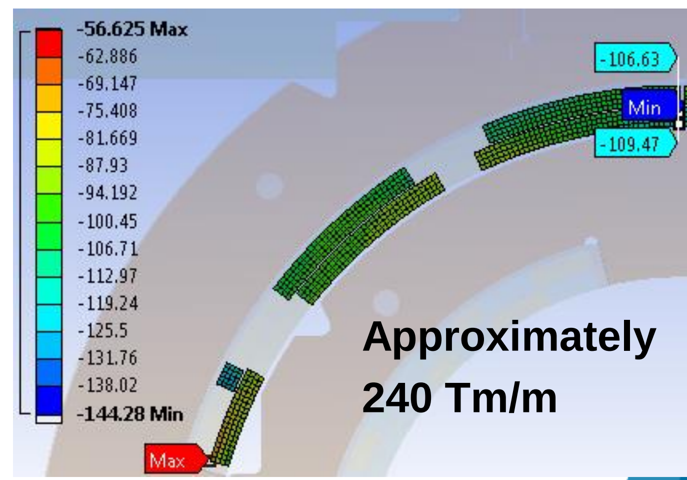
Inner Dipole



Approximately 340 Tm/m

Necessary play to introduce pins/keys (0.1 mm) is obtained for both sets of collars without stressing the coils excessively

Outer Dipole



Approximately 240 Tm/m

All assembly and operation scenarios have been simulated

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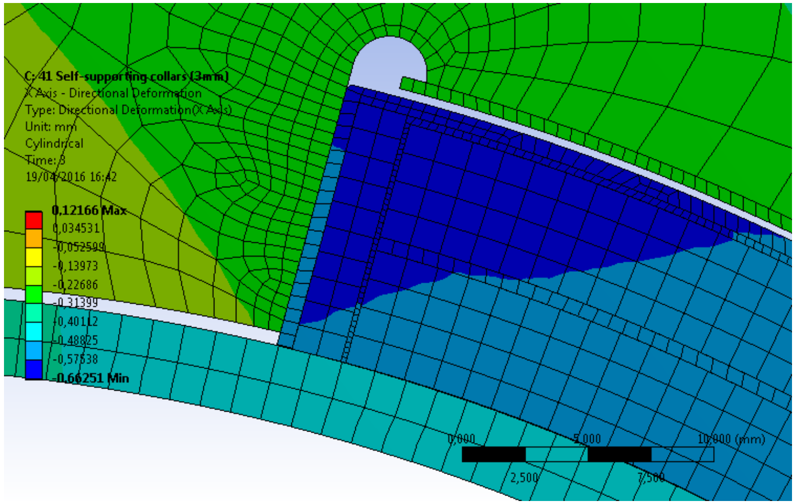
Mechanical design: Results

In this detailed model we obtained good results but…

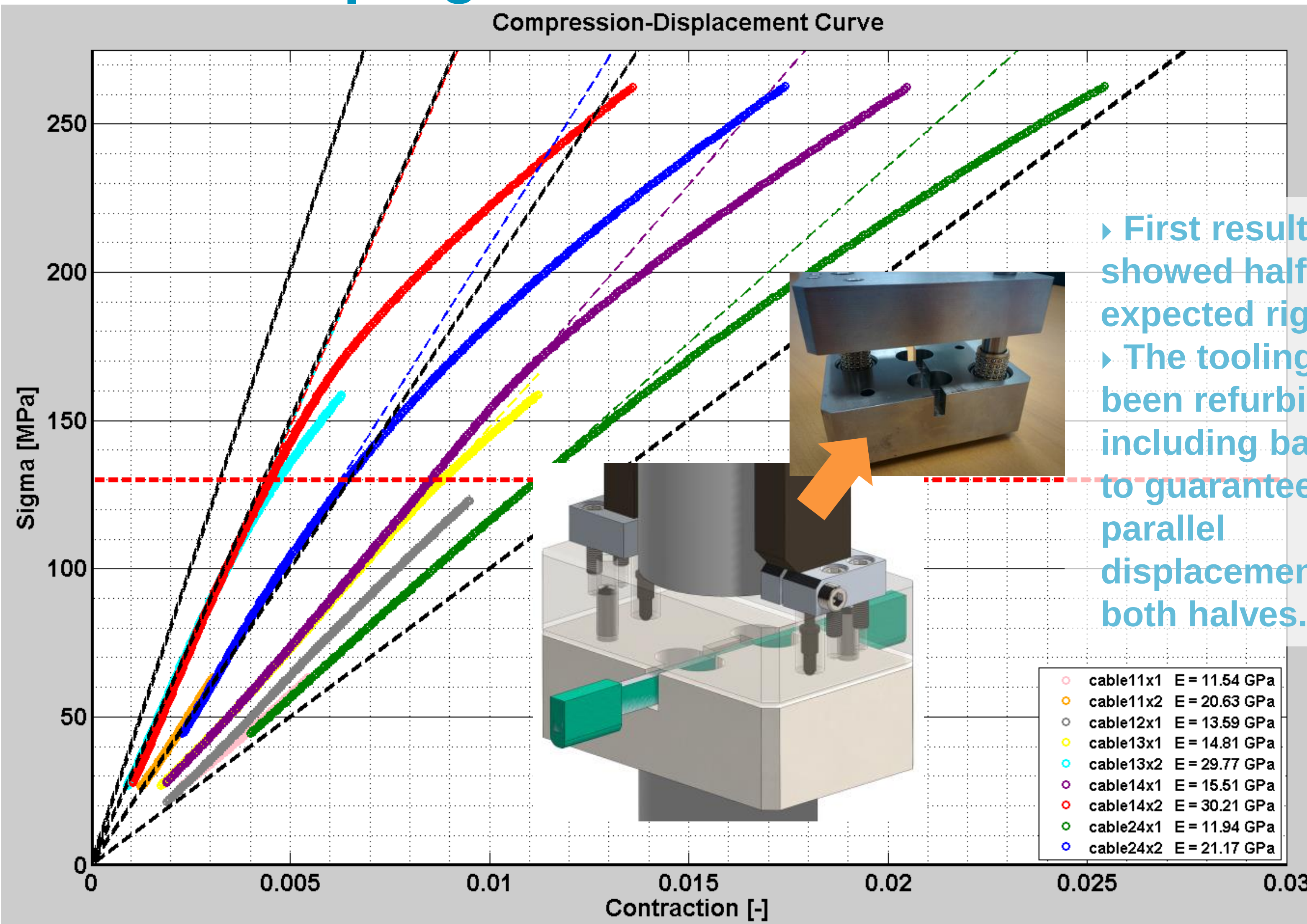
- Coils seem less stiff than in the previous model.
- The applied interference is not enough to keep the coils attached to the collars



We tend to trust more on the previous model as it is much simpler.

- MEASUREMENT OF THE ELASTIC MODEL OF THE TEN-CABLE STACK
- SHORT MECHANICAL MODEL

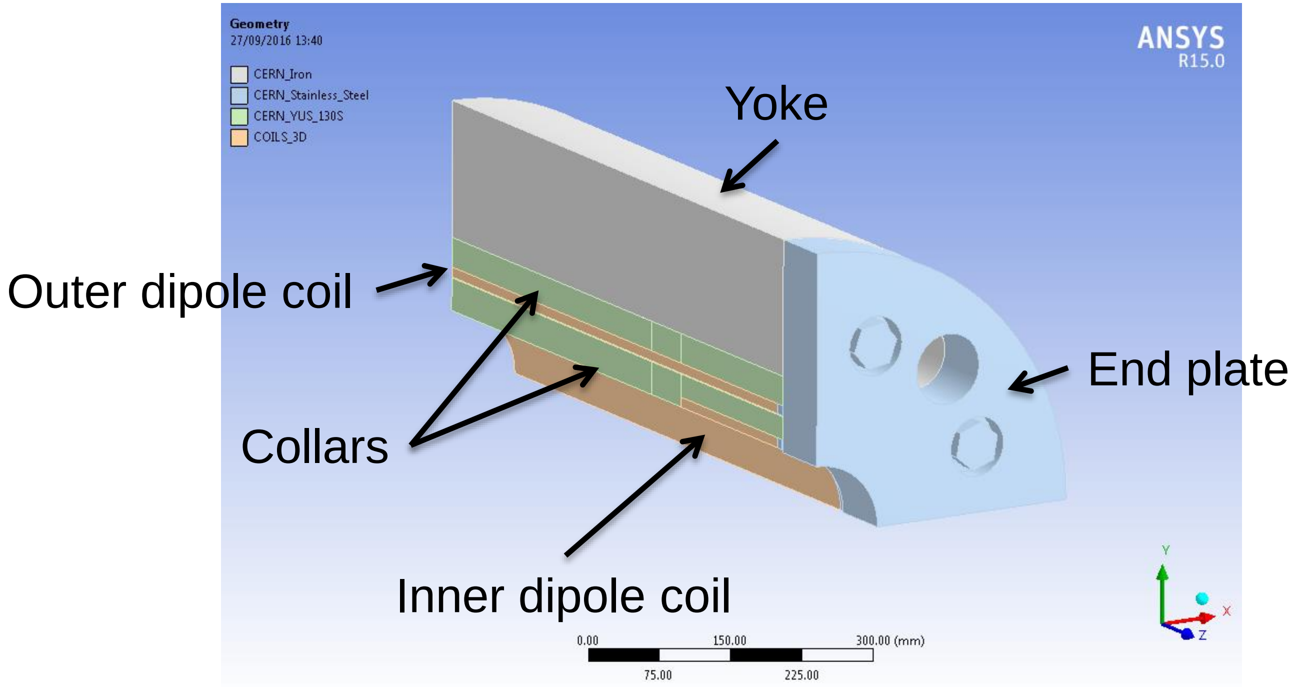
Measurement of the E-modulus of impregnated ten-cable stacks



- First results showed half the expected rigidity.
- The tooling has been refurbished including ball cages to guarantee a parallel displacement of both halves.

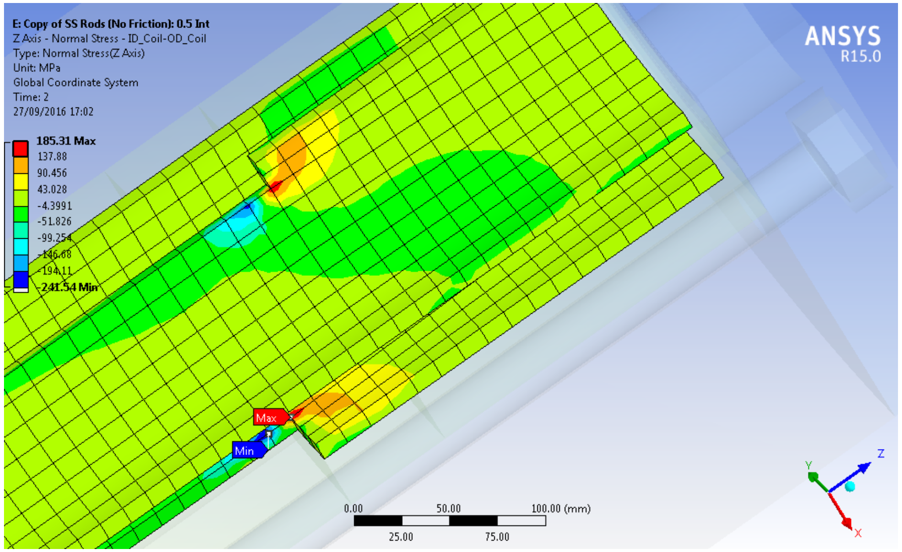
Mechanical Design: Longitudinal forces

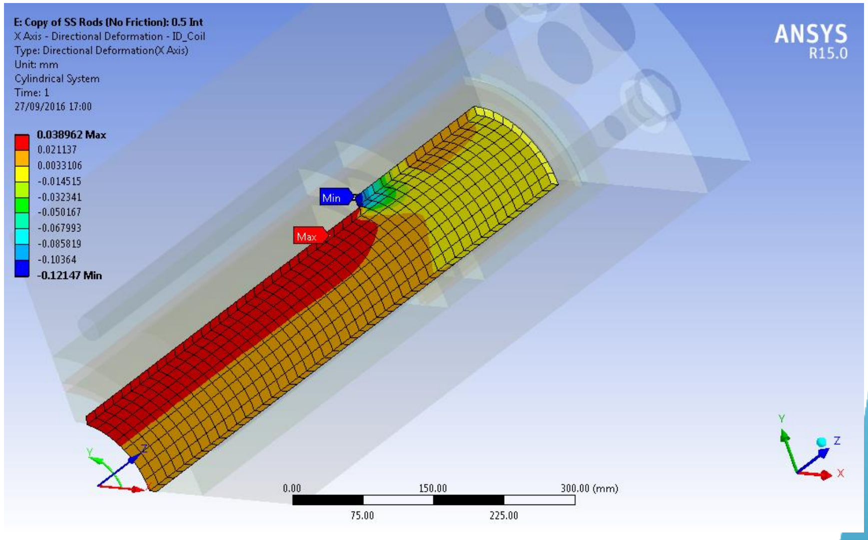
- We have no stainless steel around the iron yoke.
- Eight rods will take care of packing the iron yoke and holding the longitudinal Lorentz forces.
- We have started with an analytical model (simplified, one dimensional, no collars included): about 30 MPa of longitudinal pre-stress on coil ends would be enough not to lose contact at cold.
- Cross-check with a 3-D Ansys model is ongoing: collars are included (with friction as an option).



Mechanical Design: Longitudinal forces

- Results from Ansys model are under evaluation:
  - Uncertainty about mechanical properties of coil (Young modulus in longitudinal direction?).
  - Stress concentration at the collar nose edge and at the joint of central post and cables. Are they real?
  - Is there risk of buckling at the coil end under the initial pre-stress?



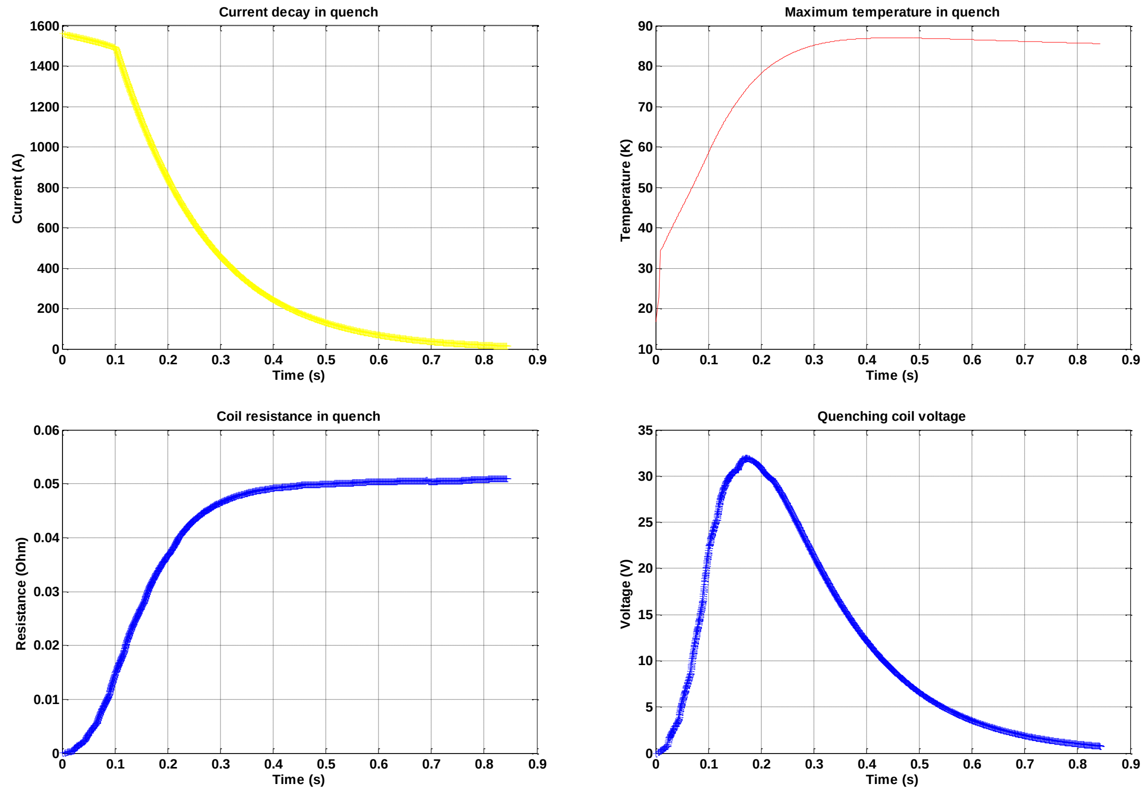


Quench protection

First approach: protection with dump resistors

First simulation using our in-house developed code showed good results:

A dump resistor was enough to protect the magnet

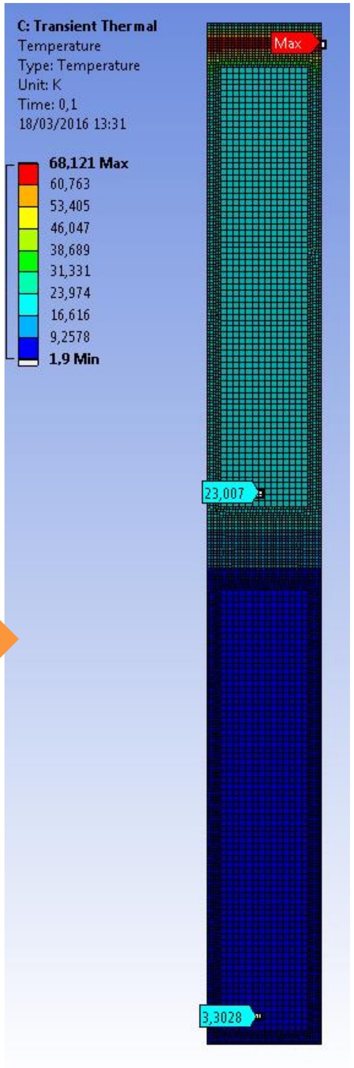


No quench heaters were necessary

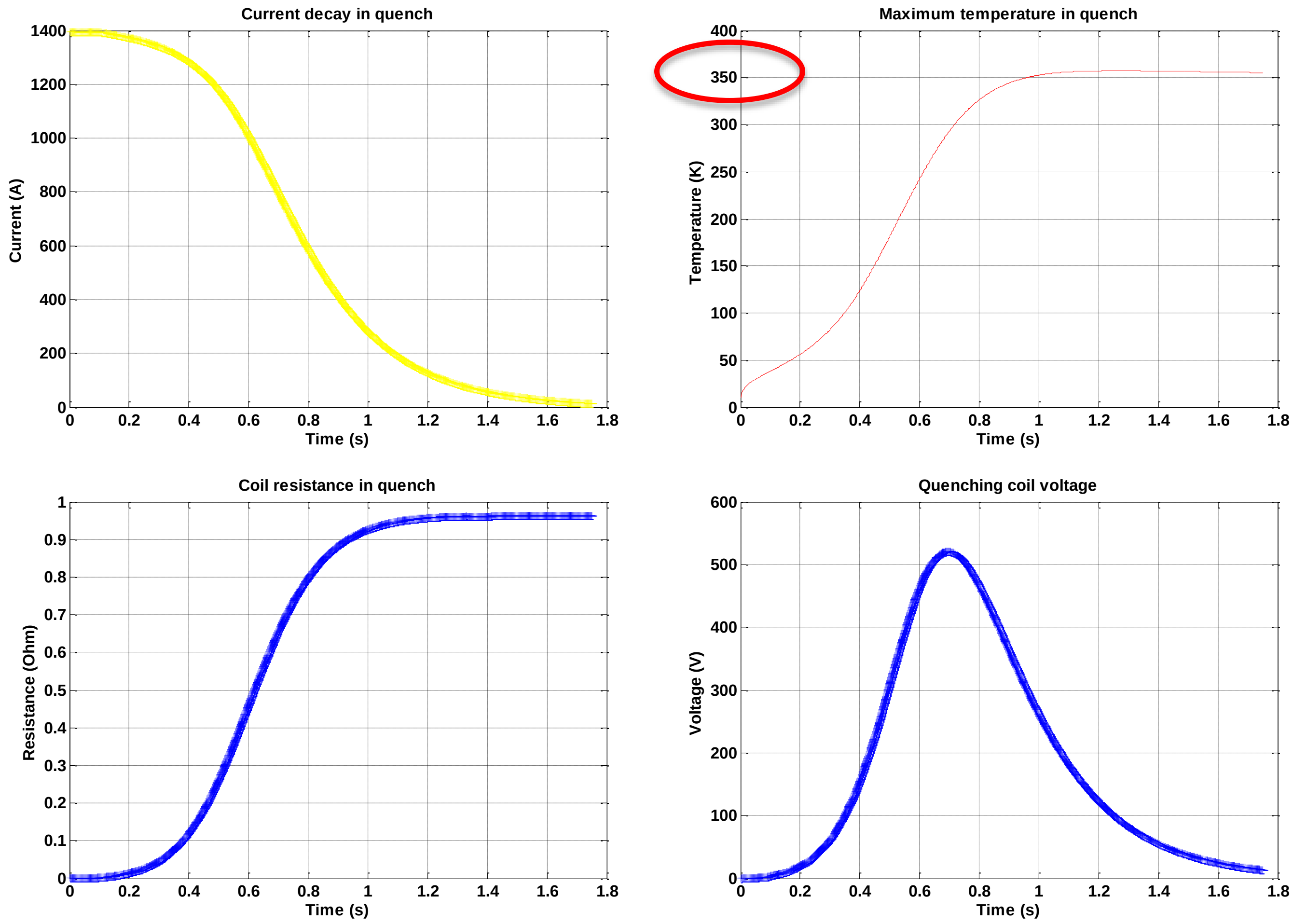
Protection: quench heaters evaluation

- Dump resistors are not the preferred option given the high cost of the switch.
- Quench heaters need to be considered.

- Our in-house code is improved to take into account spacers, layer jumps and quench heaters
- Quench heaters delay is obtained by means of a thermal simulation in Ansys (around 14 ms)

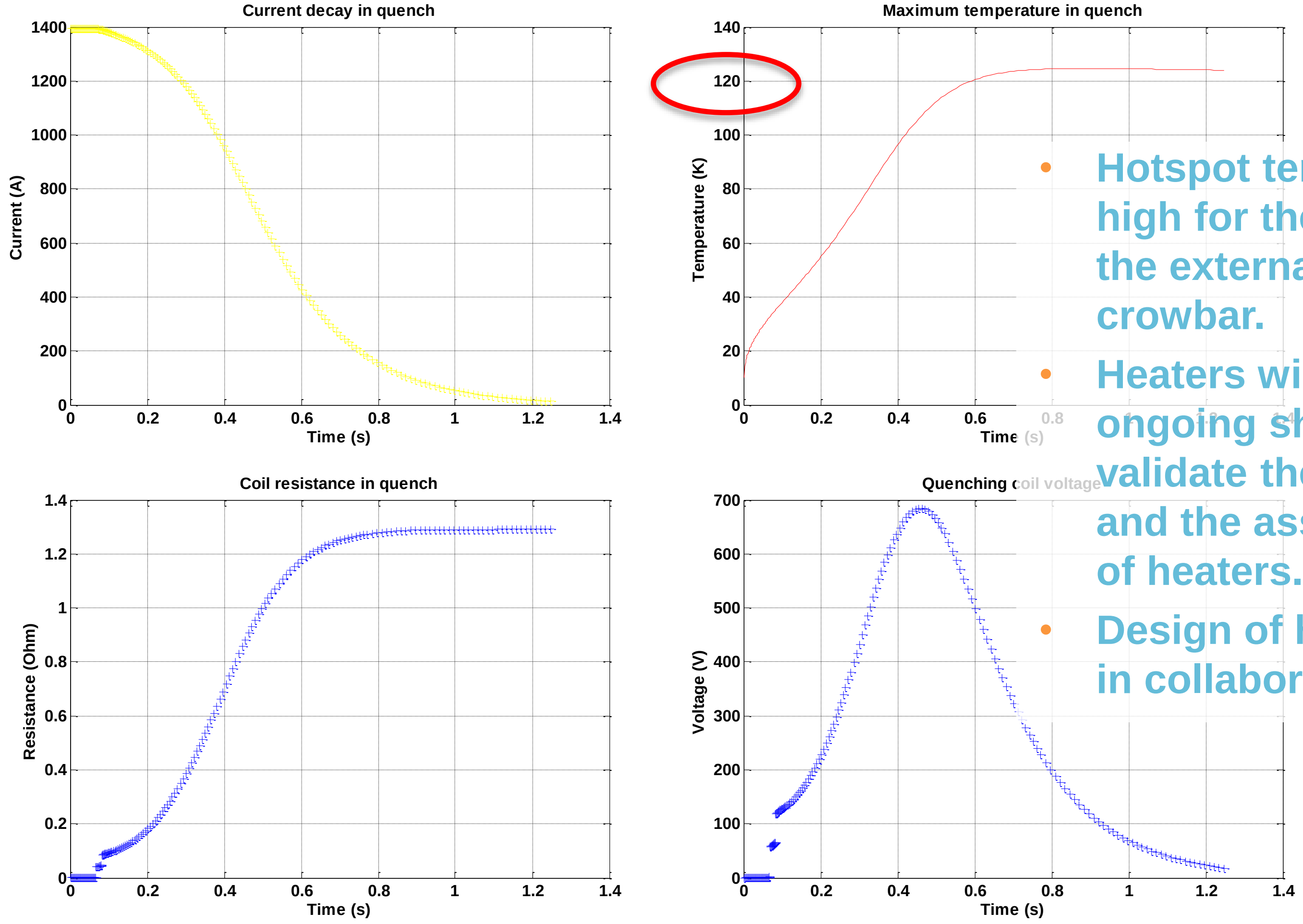


Protection with crowbar: simulation results



Long Magnet, Outer Dipole, Stand-alone powering (Crowbar resistance)

Protection with quench heaters: simulation



- Hotspot temperature is too high for the long magnet using the external resistance in the crowbar.
- Heaters will be included in the ongoing short prototype to validate the quench simulation and the assembly procedure of heaters.
- Design of heaters is ongoing in collaboration with CERN.

Long Magnet, Outer Dipole, Stand-alone powering (Quench Heater)

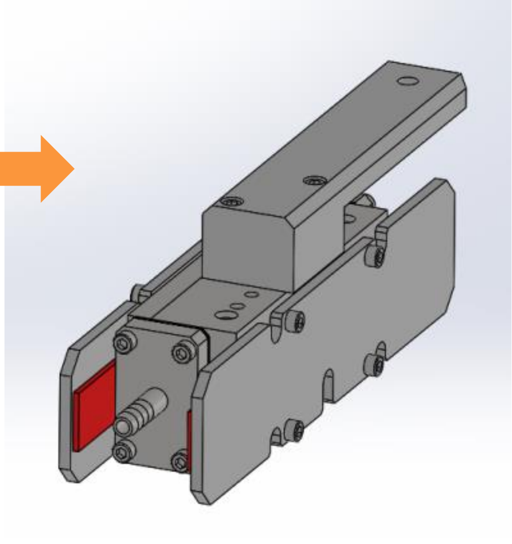
Fabrication

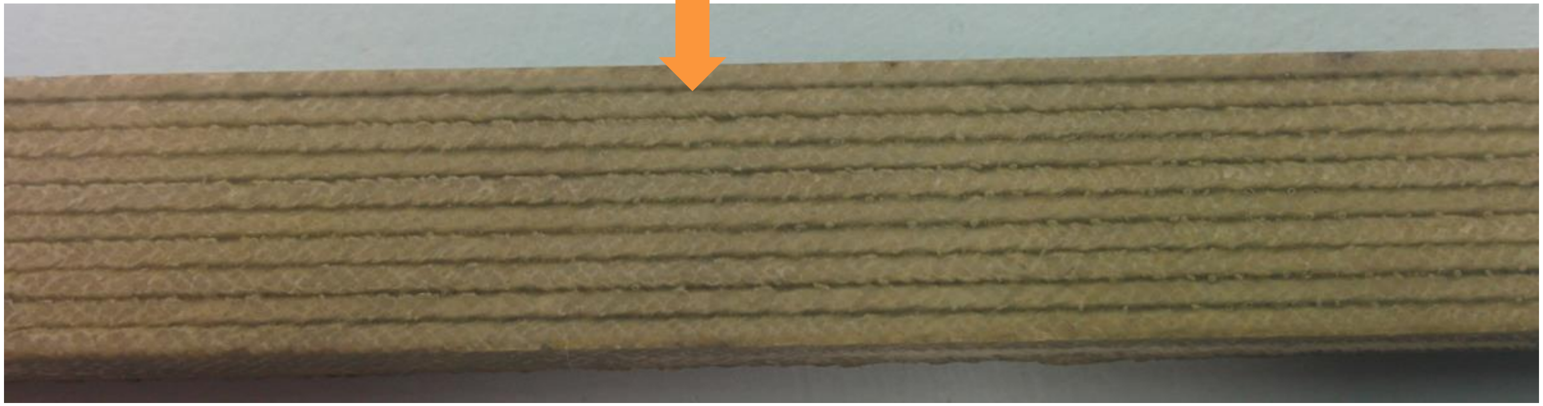
Manufacturing concept

- Double pancake coils of small Rutherford 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.
- Cable are insulated with braided S-2 glass fiber to ease 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.

Binder validation test

- Impregnation resin compatibility:
  - A mould for vacuum impregnation of ten-cable stack samples was fabricated.
  - Results seem to be good, no bubbles at first sight. No cracks with thermal cycling.
  - Nomex 411 is compatible with the resin.
  - Two different release agent have been checked: Araldit QZ13 and Loctite Frekote 770 NC.
  - Ongoing tests with a different thermal cycle.





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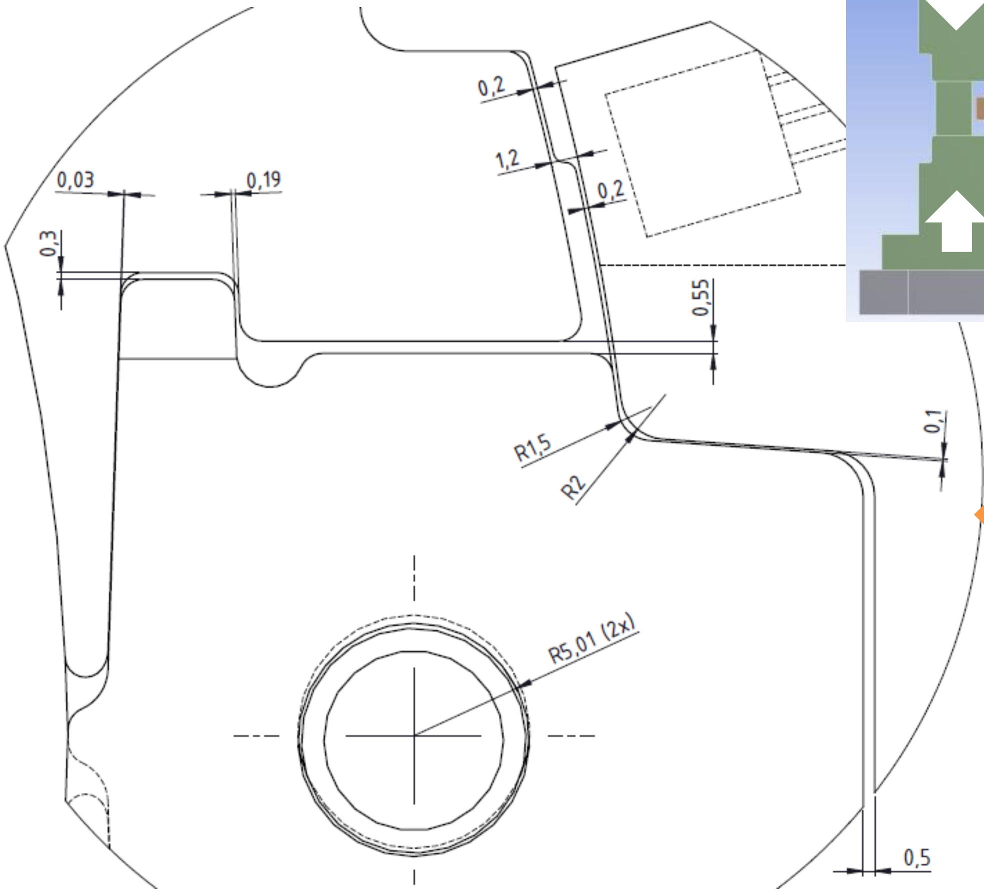
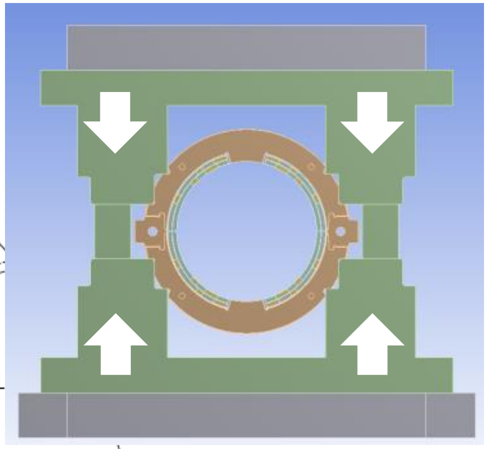
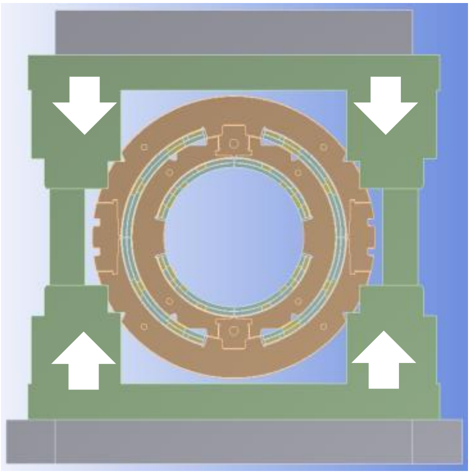
Short mechanical model: concept

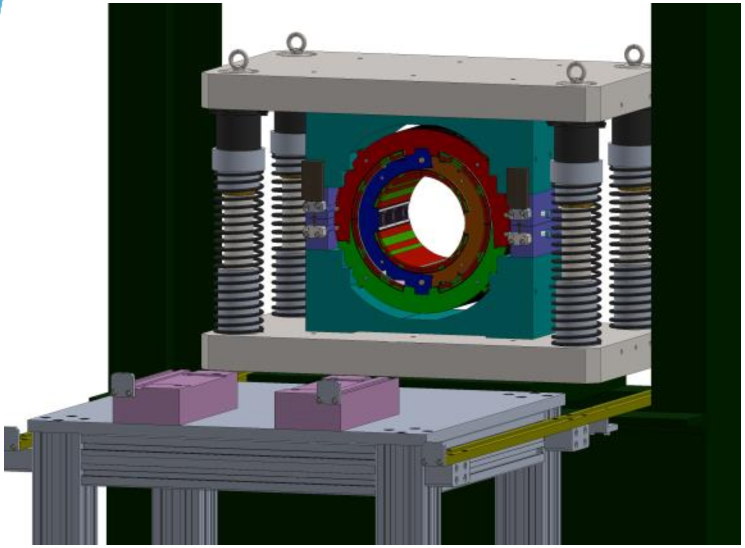






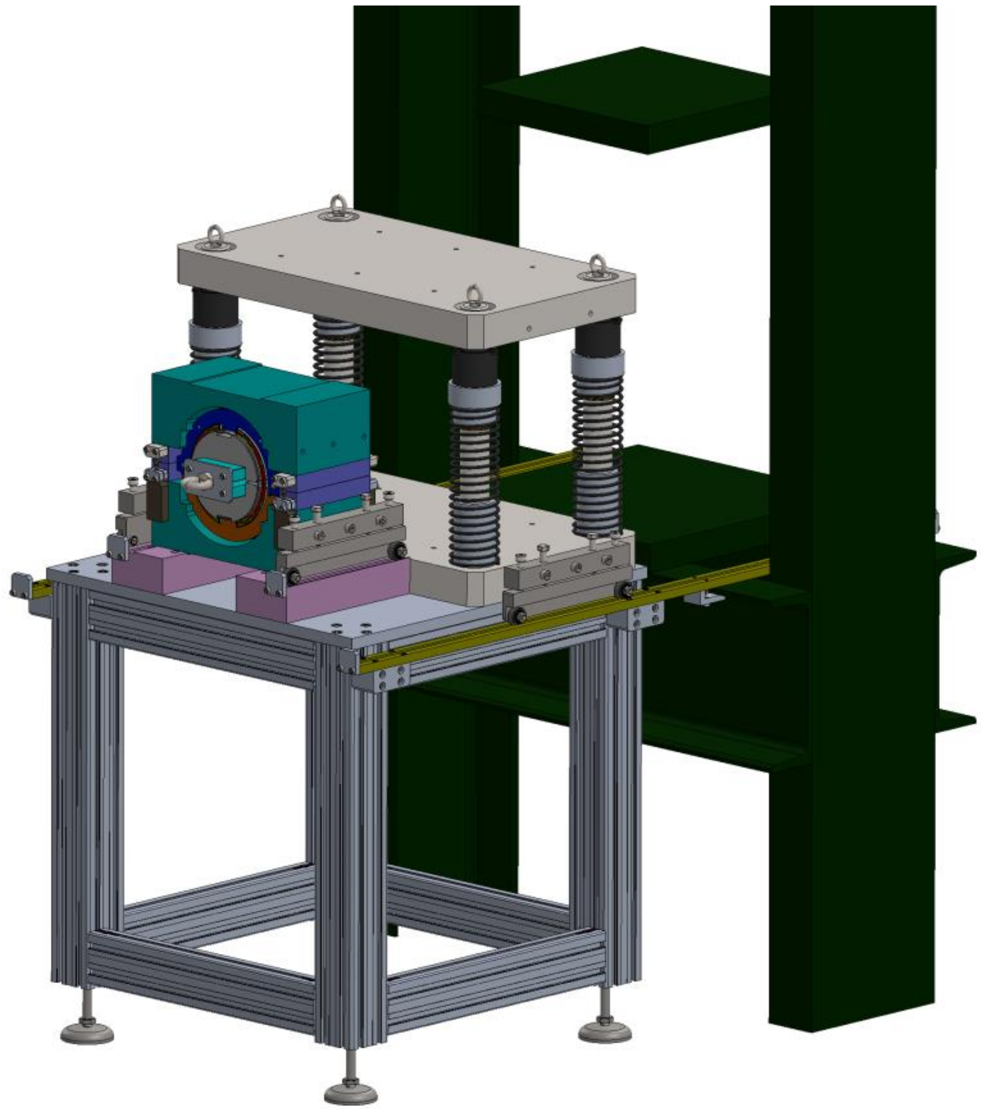
- Essential to validate the assembly process and the mechanical simulations.
- A 120 Tm press available at CIEMAT workshop will be used to this end.
- A 150-mm long set of collars will be closed. Aluminium dummy coils will be used for first tests.

Short mechanical model: design

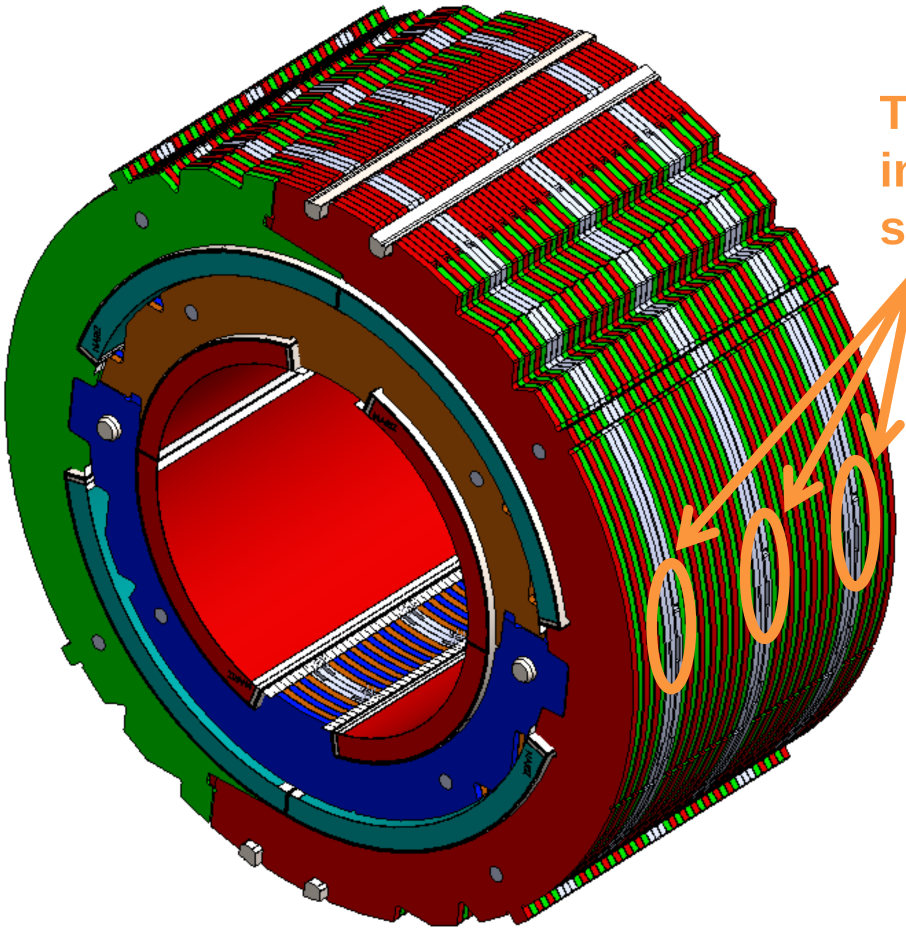


Outer collars tooling

Inner collar tooling

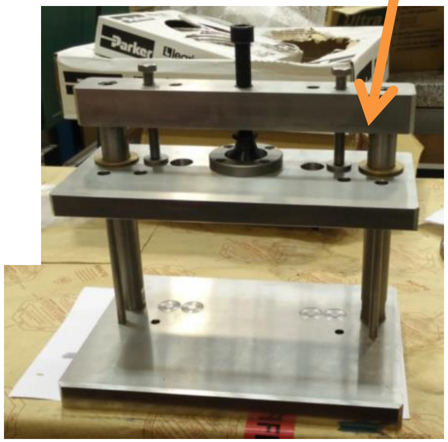


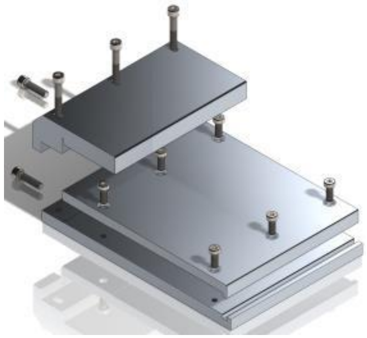
Ongoing Mock-ups and Tests: Short mechanical model



Three collars instrumented with strain gauges

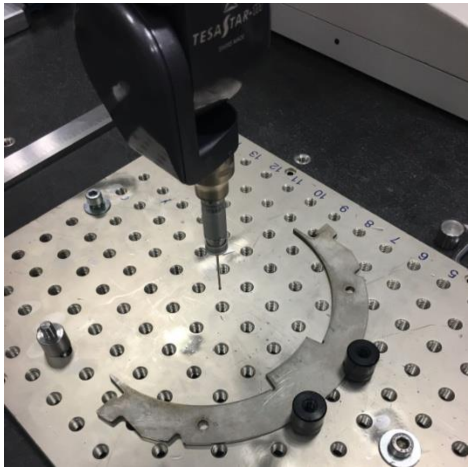
Auxiliary tooling in development/ production





Short mechanical model: fabrication

- All the parts are under fabrication.
- Some are already finished: main cage, tooling to pack collars, ancillary tools.
- Collar tips are deformed after EDM cut because of internal stresses:
  - A heat treatment at low temperature has been performed.
  - They are stacked taken into account the deformation.



Female collar, inner dipole

First tests: press calibration

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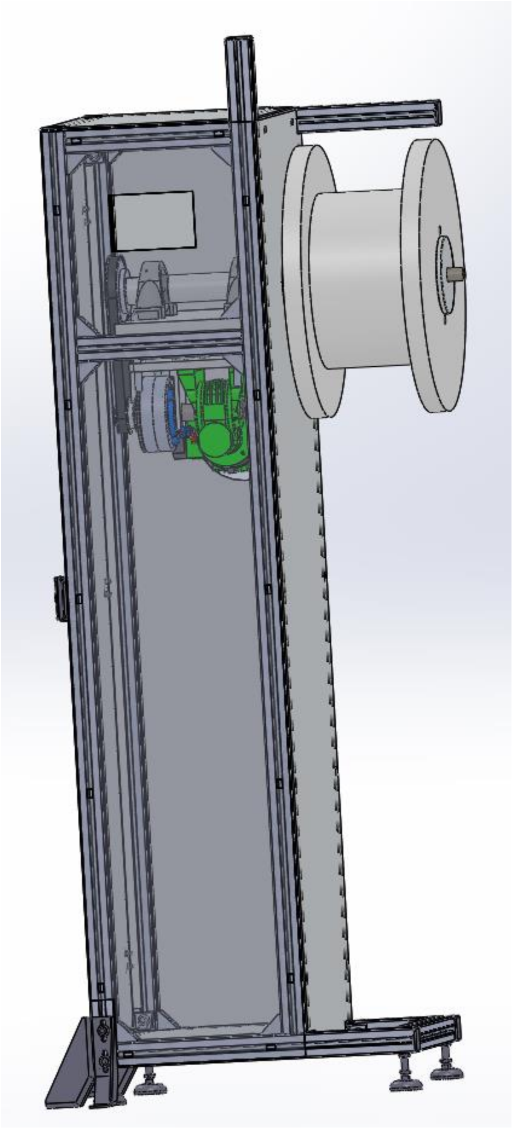
Winding machine

- Coils (winding and impregnation) will be done at CIEMAT facilities.

- Winding machine borrowed from CERN, some modifications pending:
  - Brake
  - Support beam and mandrel.
  - New actuator for the craddle movement.
  - Flag crane to hold the spool containing the second layer above the winding machine.

- Lead time of a commercial brake was too long and expensive. In-house development is ongoing.



Next steps

- Short mechanical model test: November/December
- Winding machine brake: November/December
- First winding test: December/January

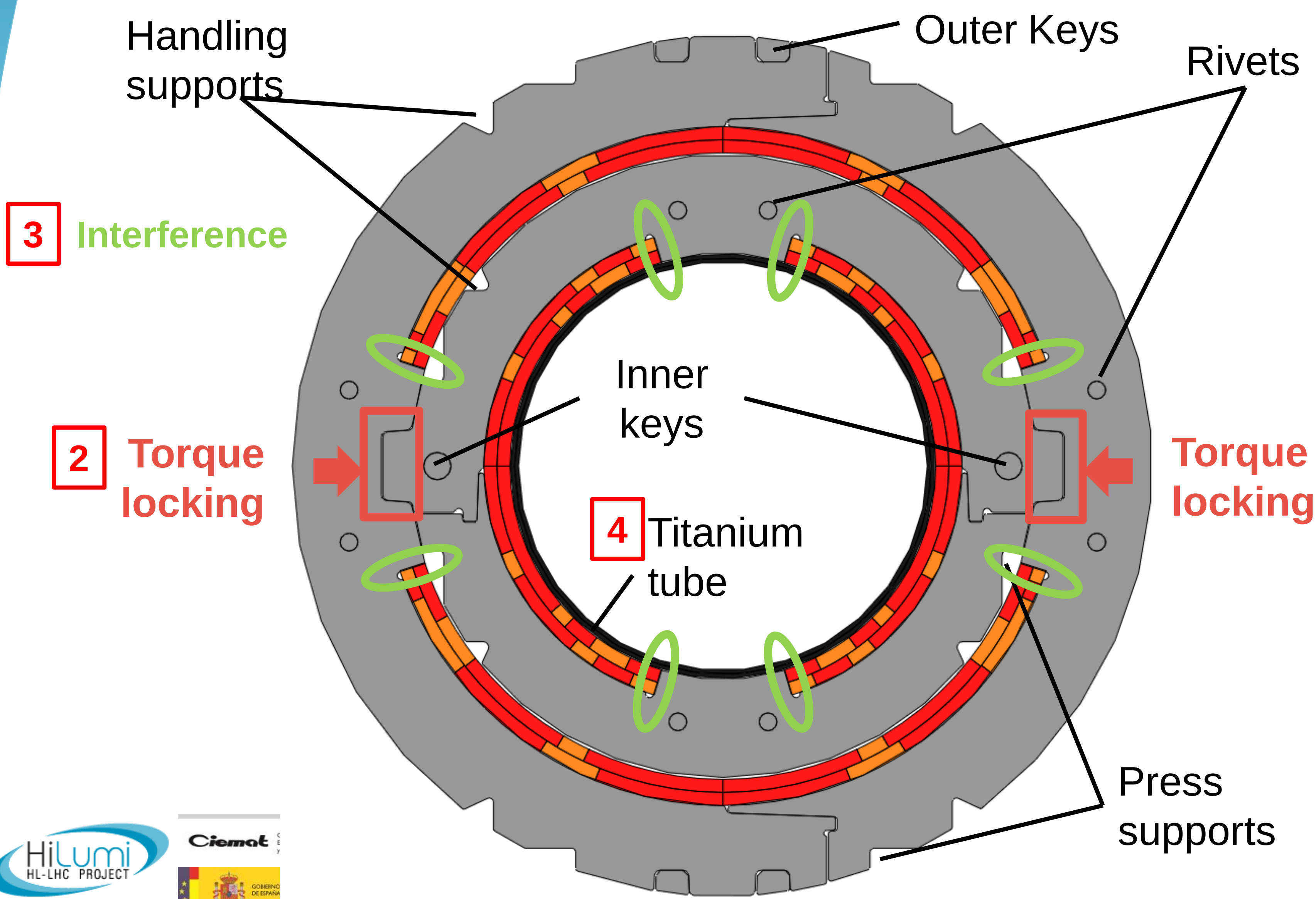
Conclusions

- Magnetic and mechanical design are close to be finished: only longitudinal mechanical model is ongoing.
- Manufacturing concepts are being validated through several mock-ups and tests.
- The short mechanical model is crucial to check if the assembly design is feasible and the mechanical simulations are trustable.
- We are working on the winding tools, to allow the first winding test in January.

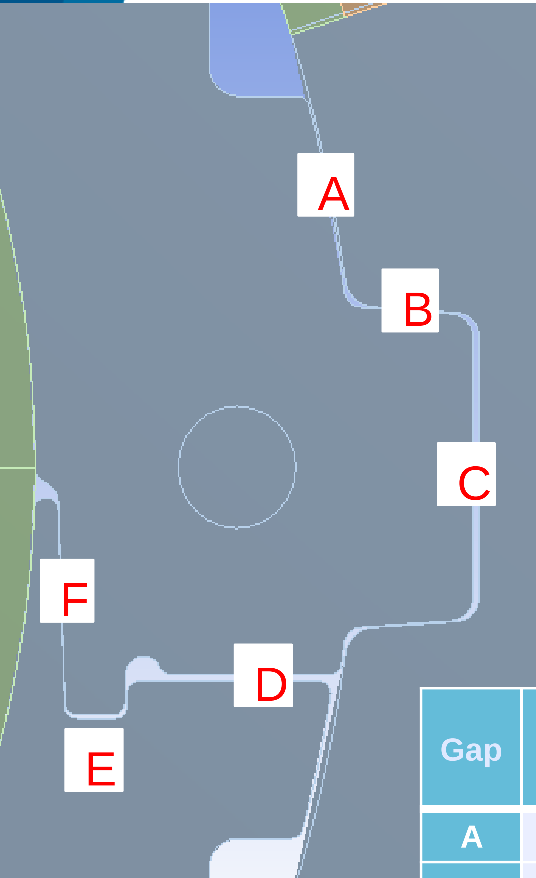
Back-up slides

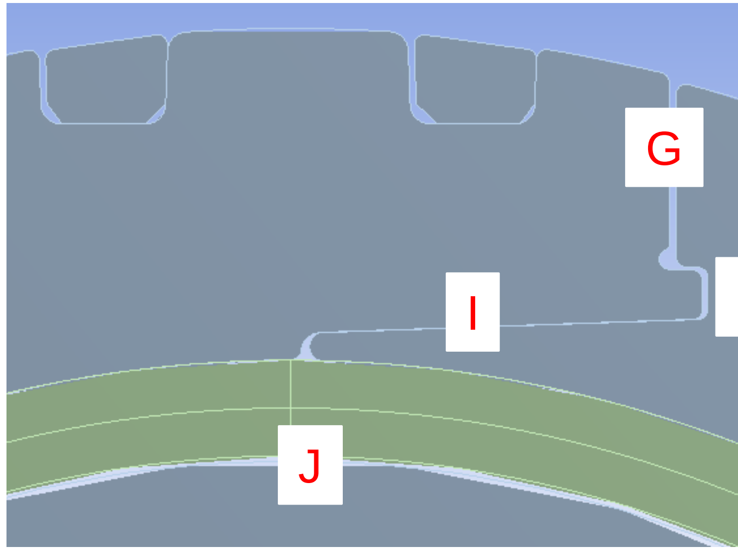
Self-supporting collars

Inner collar outer diameter = 230 mm (Thickness = 27 mm)
Outer collar outer diameter = 316 mm (Thickness = 33 mm)



Assembly gaps evolution





Inner collars play = 0,12 mm
Outer collars play = 0,1 mm

All values in mm

Gap	Original gap	ID Press	ID Spring Back	Before OD Press	OD Press	OD Spring back	Cool-down	108% Power.
A	0,2	-	-	opens	0,13	opens	opens	0,08
B	0,1	-	-	opens	0,08	0,08	0,085	contact
C	0,5	-	-	opens	0,47	opens	opens	0,4
D	0,55	0,42	opens	opens	opens	opens	opens	opens
E	0,3	0,18	opens	opens	opens	opens	opens	opens
F	0,03	≅0,03	contact	contact	contact	contact	contact	contact
G	0,7	-	-	opens	0,55	opens	opens	opens
H	0,6	-	-	opens	0,45	opens	opens	opens
I	0,03	-	-	contact	contact	contact	contact	contact
J	0,5	-	-	0,43	0,47	0,46	0,465	opens

HiLumi HL-LHC PROJECT

Ciemat

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