Magnetic and Mechanical Design of a 16 T Common Coil Dipole for FCC

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Thanks to R. Gupta (BNL), Q. Xu (IHEP), T. Salmi (TUT) and S. Izquierdo-Bermúdez (CERN) for their suggestions and help

Outline

- Introduction
- 2-D electromagnetic design
- 3-D electromagnetic design
- 2-D mechanical design
- Conclusion

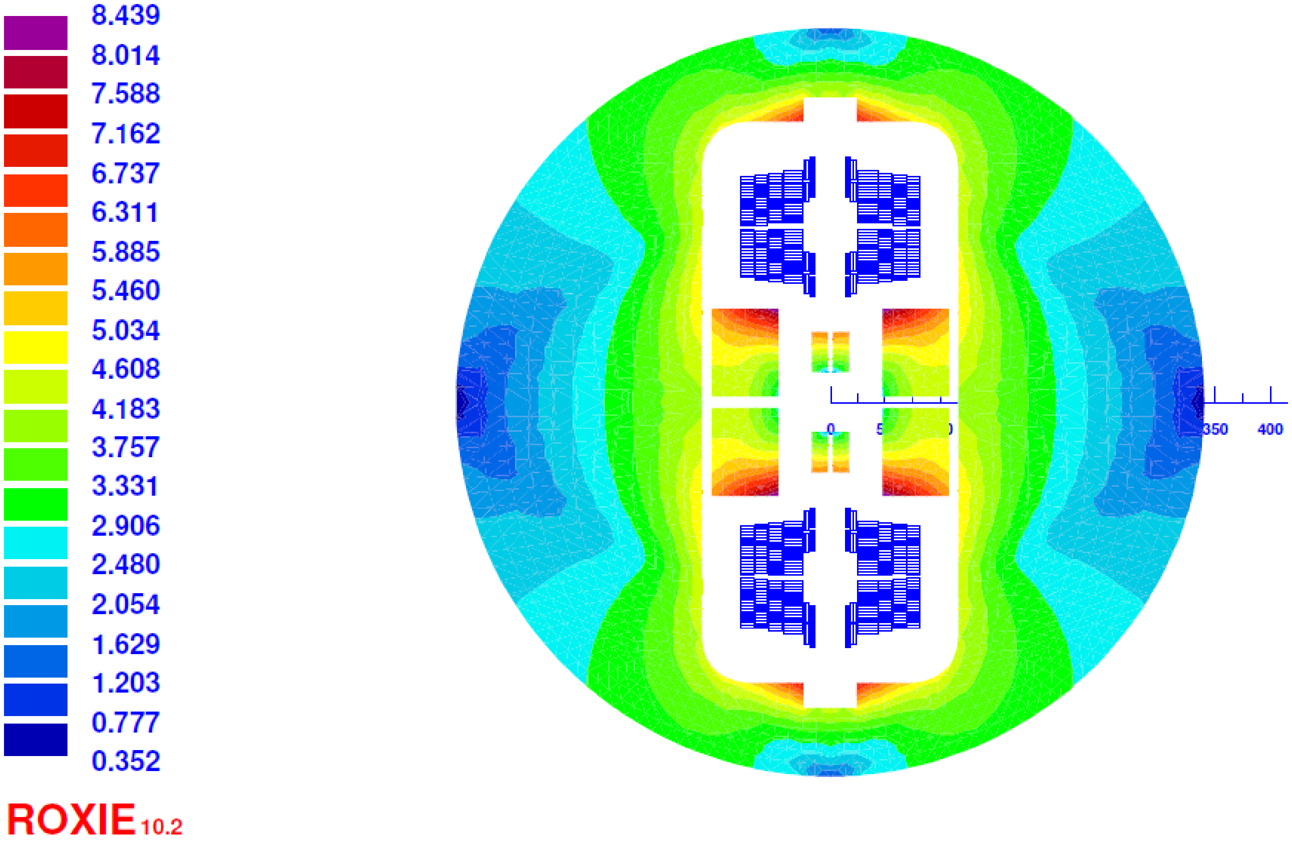
2-D magnetic results summary

- Design #11 needs less superconductor, but has problems with peak voltages during quench.
- Design #11 needs more superconductor, but fulfils all requests with a well balanced design.
- Design #12 is even better, but cable fabrication is more challenging (Cu:Sc=0.8).
- Design #13 and #14 are valid for an upgrade of LHC (650 mm outer iron diameter). They need more superconductor, specially when reducing the intra-beam distance (which also reduces the fringe field).

TABLE I
COMPARISON OF 2-D MAGNETIC DESIGNS

Design Id.	#10	#11	#12	#13	#14	Units
Nominal current *I*	9.17	16.1	16.1	16.1	16.1	kA
Minimum Cu:Sc ratio	1	1	0.8	1	1	
Intra-beam distance	320	320	320	320	280	mm
Iron outer diameter	750	750	750	650	650	mm
Stored magnetic energy	3.47	3.04	2.93	3.05	3.16	MJ/m
*L*I*	757	378	364	379	392	H·A/m
Vertical Lorentz force	0.73	0.57	0.43	0.34	0.92	MN/m
Horizontal Lorentz force	14.7	14.6	14.4	14.4	14.5	MN/m
Maximum stray field (600 mm radius)	0.19	0.15	0.17	0.19	0.15	T
FCC bare cable weight	8592	9353	8951	9446	9631	ton

Electromagnetic design: Design #12

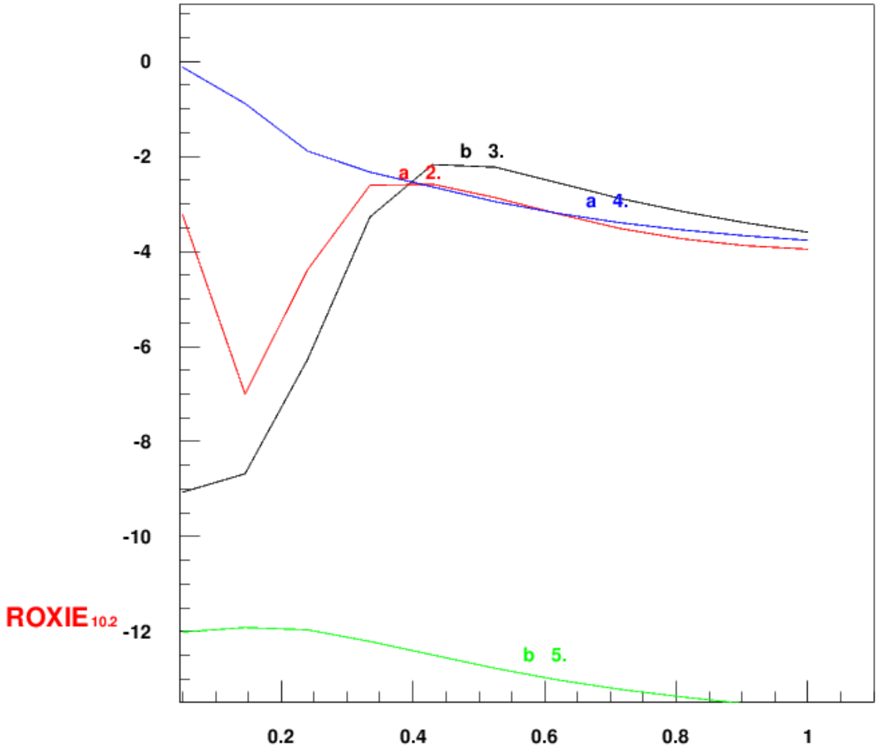


Electromagnetic design: Design #12

Nominal current	16100	A
Intra-beam distance	320	mm
Iron outer diameter	750	mm
1st coil		
#cables	38/37	
#strands	1730	
strand diameter	1,2	mm
Cu:Sc	0.8/2.5	
2nd coil		
#cables	72	
#strands	1296	
strand diameter	1,2	mm
Cu:Sc	2,5	
Pole coils		
#cables	16	
#strands	448	
strand diameter	1,2	mm
Cu:Sc	0,8	

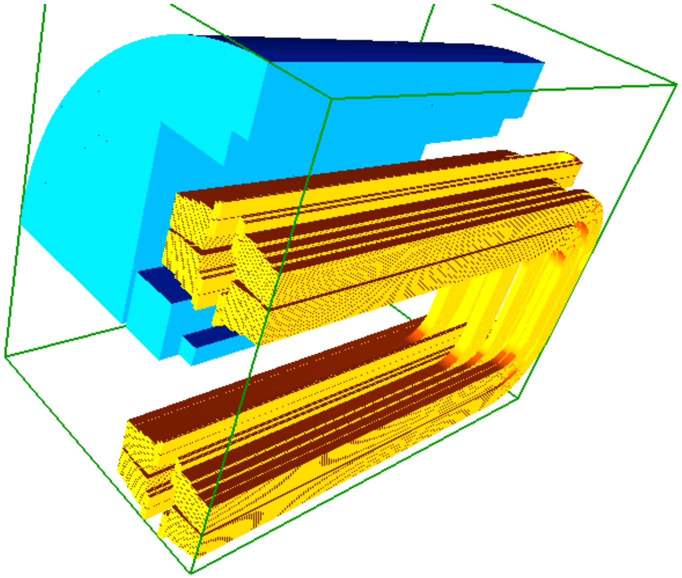
Total FCC SC weight	8951	ton
margin on load line	13,95	%
peak field	16,67	T
b3	-3,6	units
b5	-13,6	units
b7	-4	units
b9	-3,9	units
a2	-3,9	units
a4	-3,8	units
a6	-1,4	units
a8	-0,5	units
inc_b3	7,1	units
inc_a2	4,4	units
Stored energy	2,93	MJ/m
Static self inductance	22,6	mH/m
L*I	364,0	HA/m
Sum_fx	14,4	MN/m
Sum_fy	0,43	MN/m
Peak temperature (Excel	332	K

Electromagnetic design: Design #12



3-D electromagnetic design

- Peak field at coil end is similar to cross section:
  - The iron does not cover coil ends.
  - The coils have different lengths and bending radii.
- The iron is shaped to decrease the variation of field harmonics with current (b3 and a2 below 5 units, the rest is negligible).
- Each coil end is 255 mm long. The coils are 14.5 m long to provide a magnetic length of 14.3 m.
- The internal splice in the high field coil can be done at the coil ends, where the field is low.



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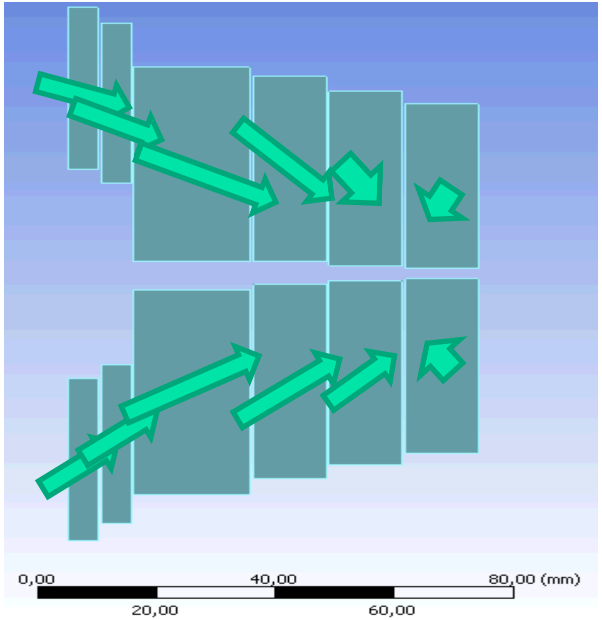
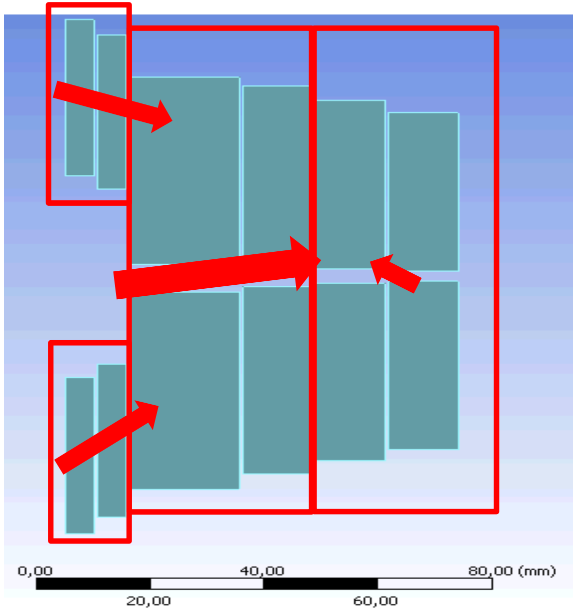
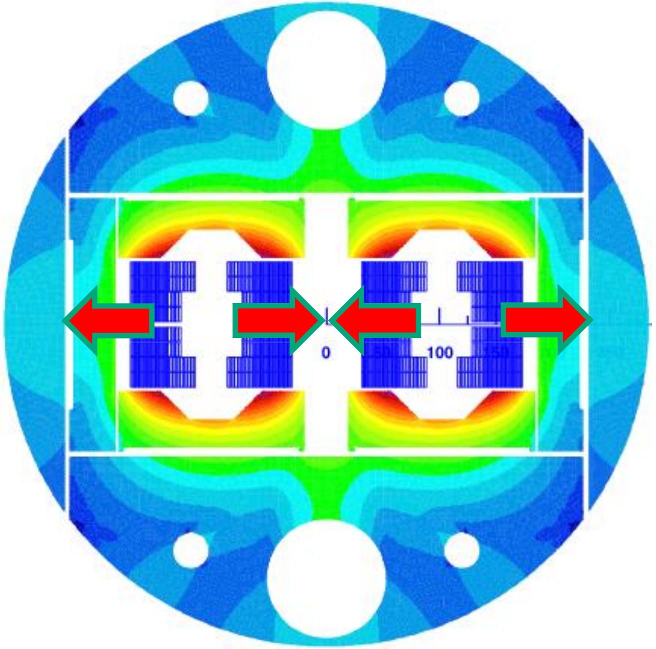
Common Coil Dipole: Forces at coils

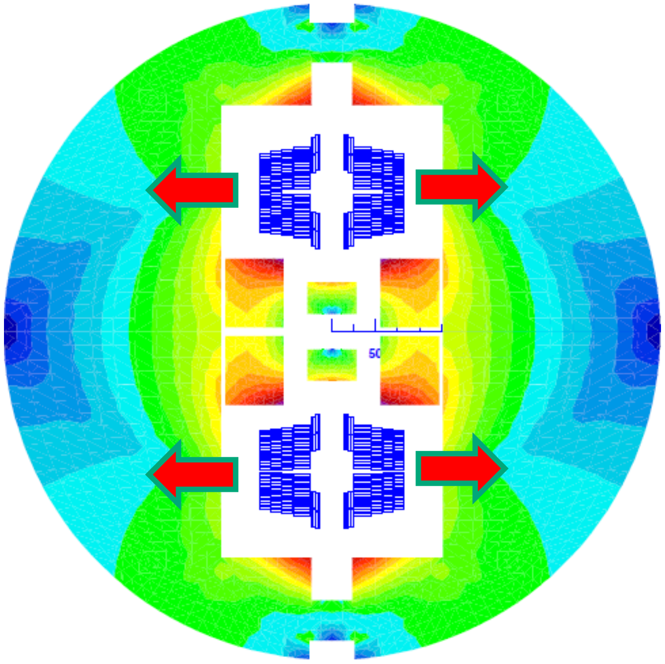




The forces per coil are similar for the block and common coil designs. In the case of the common coil, there is a **vertical repulsive force** between both apertures.

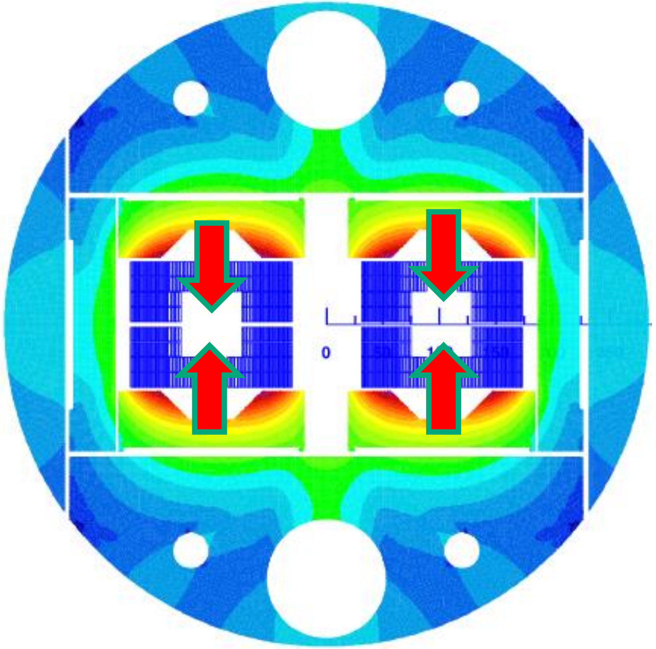
Common Coil Dipole: Support structure

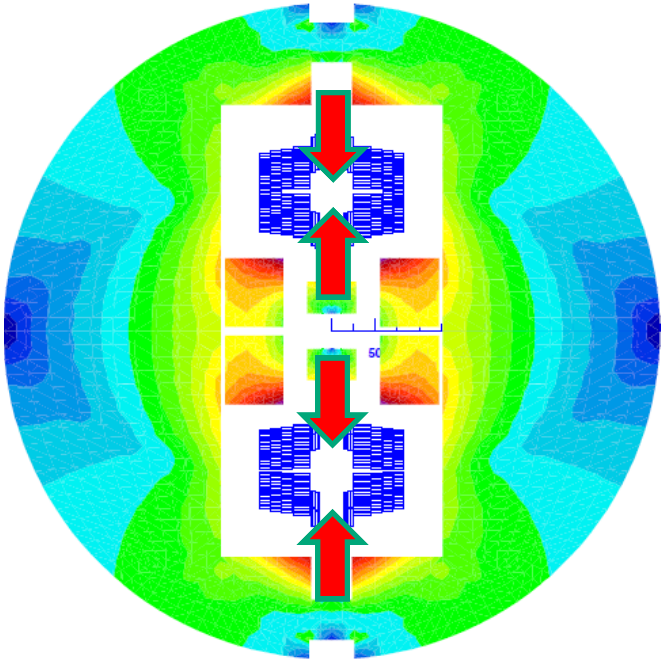




The forces per quadrant are similar for the block and common coil designs. However, the **external support structure** needs to hold **twice** the force in the case of the common coil magnet.

Common Coil Dipole: Vertical pre-stress

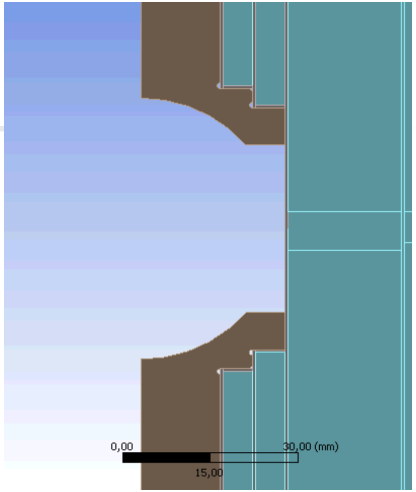


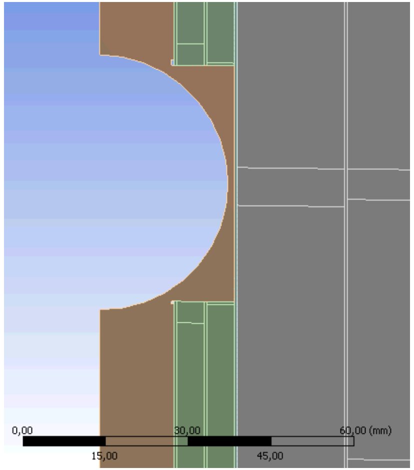


In a block dipole, the shell can apply a direct vertical pre-stress on coils.
In the common coil, most of the vertical pre-stress is lost because of vertical Lorentz forces and thermal contraction of support structure at the magnet mid-plane.

2-D mechanical support

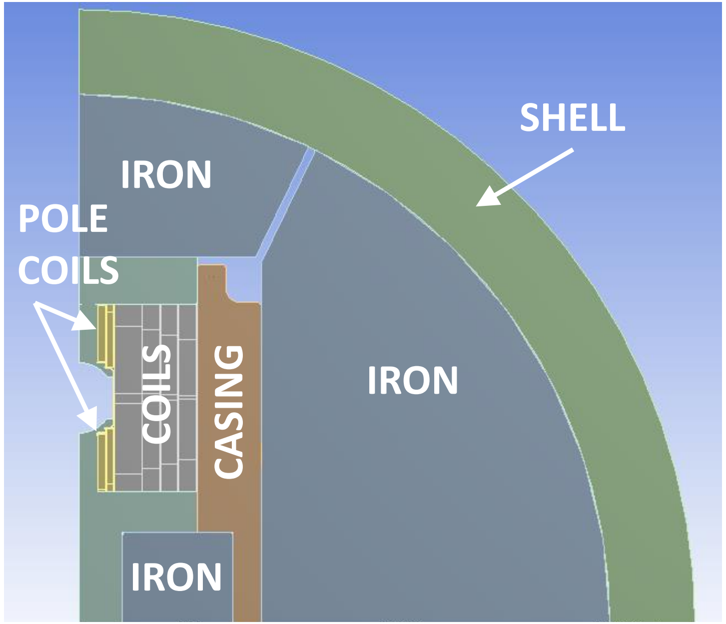
- There are two possibilities to hold the large horizontal Lorentz forces:
  - To let the main coils move and hold the pole coils with a cantilevered support. That is, a small coil pre-compression at cold.
  - To pre-compress the main coils against a closed structure around the beam pipe, which also holds the pole coils.
- The first option needs less superconductor. When the main coils are shifted by 2.5 mm, the magnet needs 4% more cable and stores 10% more energy.





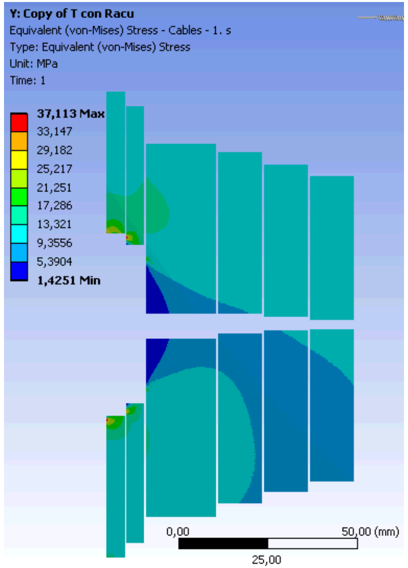
Open beam pipe support model

- All the pieces are continuous at the other side of the symmetry axes.
- A 40 mm thick stainless steel shell holds the large horizontal Lorentz forces.
- The main coils are glued. They have copper spacers to perform equal height. Copper spacers and cable blocks are modeled as different materials.
- The pole coils are glued to a 0.5 mm thick aluminium foil. They are hold by stainless steel pieces, bolted to a vertical plate to constitute a casing around the main coils. Those screws hold partially the horizontal Lorentz forces.
- No bladders. Small radial gap for assembly.

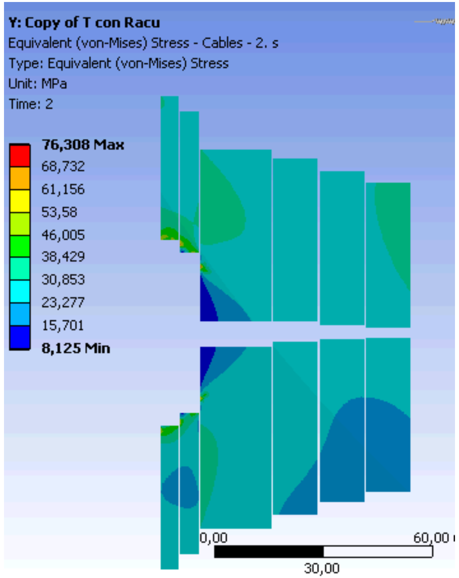


2-D FEM results: coil stresses

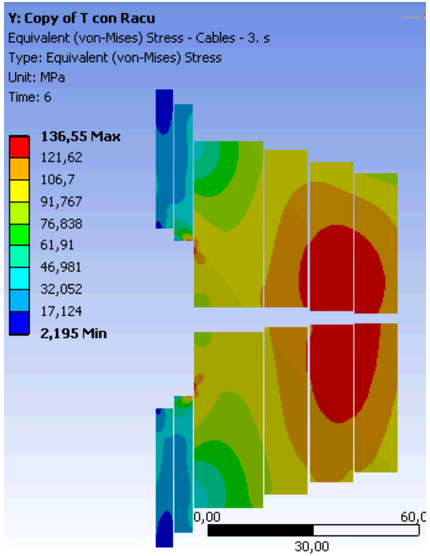
- The stresses on the coils are moderate for a high field magnet at all the load steps: assembly, cool-down and energizing. It is the consequence of not using pre-compression.



Assembly: Max 36 MPa



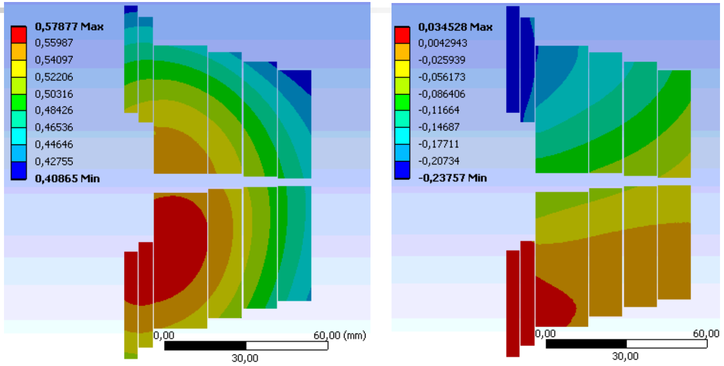
Cool down: Max 76 MPa



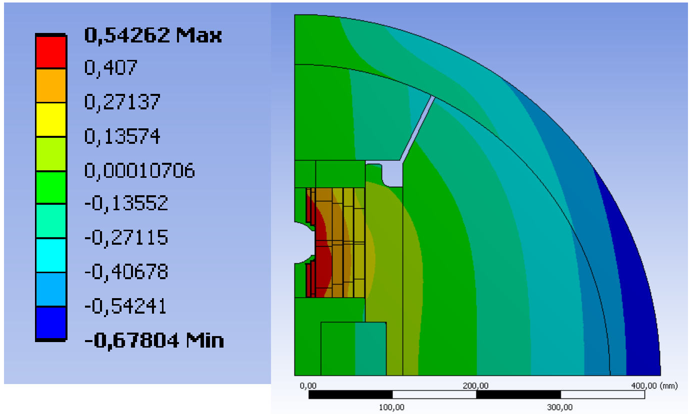
16 T: Max 136 MPa

2-D mechanical model results: displacements

- The coils move quite uniformly about 0.5 mm in horizontal direction:
  - The impact on field quality is moderate: 5.5 units on b3, 1 unit on b7, 0.8 on a2, less than 0.2 in the rest of multipoles.
  - There is sliding between coils and casing, because friction under vertical force is not enough to hold the horizontal Lorentz force. The dissipation heat appears at the copper spacer, not at the cables surface.
- Less stored elastic energy without pre-compression.
- This model needs further investigation using a prototype.



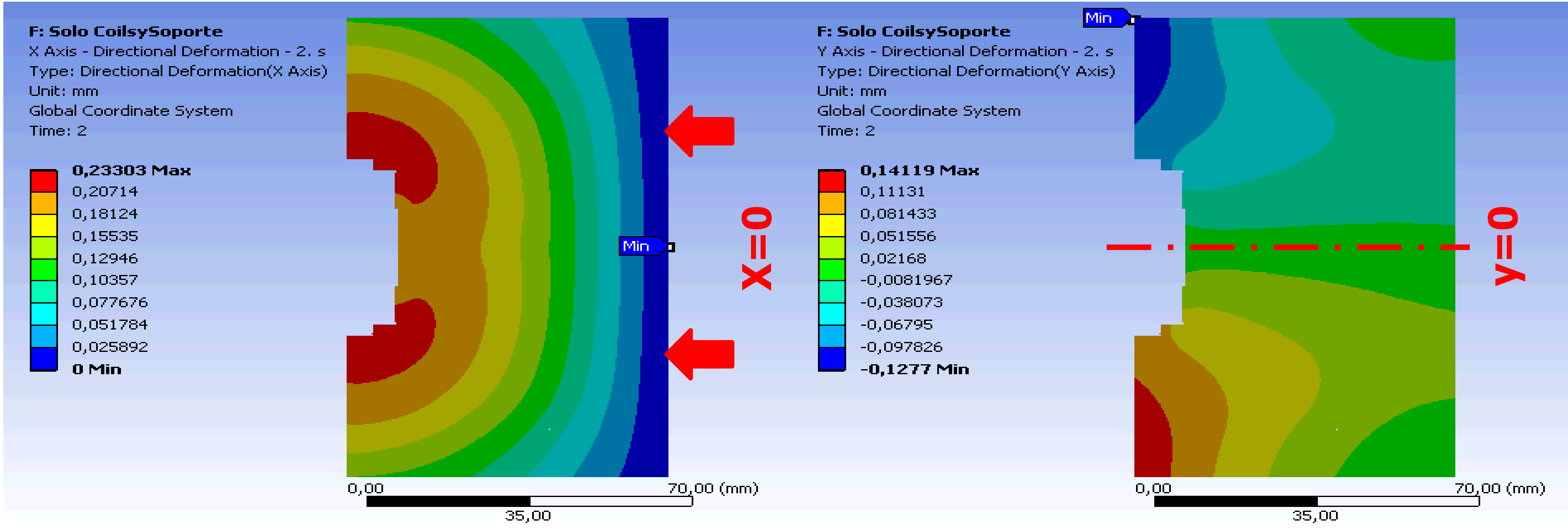
Horizontal (left) and vertical (right) displacements during energizing



Horizontal displacements from assembly to nominal field

Coil deformation under Lorentz forces

JUST COILS: Horizontal movement is blocked at the iron interface

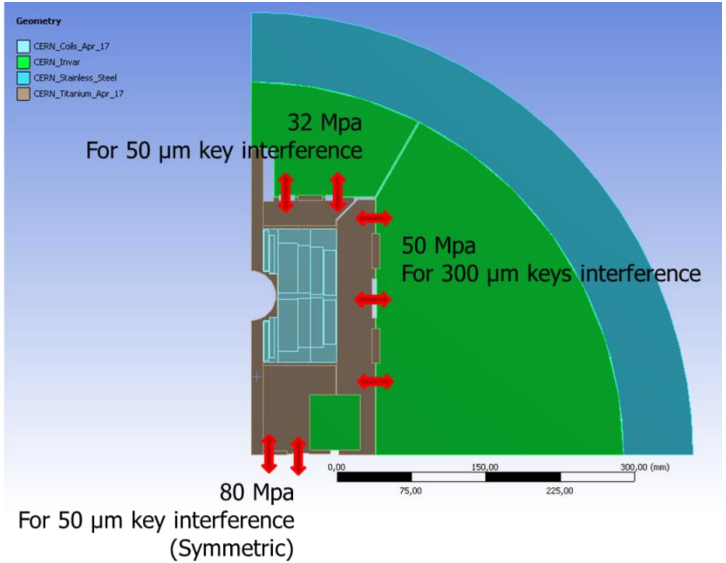


Horizontal force: +14,5 MN/m
Vertical force: +0,6 MN/m

Horizontal displacement: +0,23 mm
Vertical displacement: -0,13 / +0,14 mm

Closed beam pipe support model

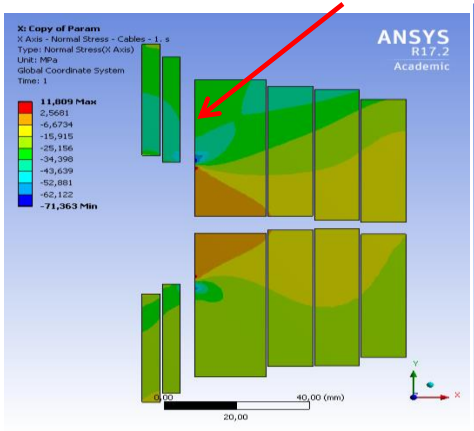
- An outer shell of stainless steel (70 mm) holds the horizontal Lorentz forces.
- Yoke is cut in 4 pieces. Invar to increase pre-stress. Magnetic simulation was made considering iron yoke, then changed to invar at structural analysis.
- Main coils are impregnated together, but NONE of them are bonded to supporting structure.
- Bladder and keys with large pressure.
- Friction coeffient of 0.2.

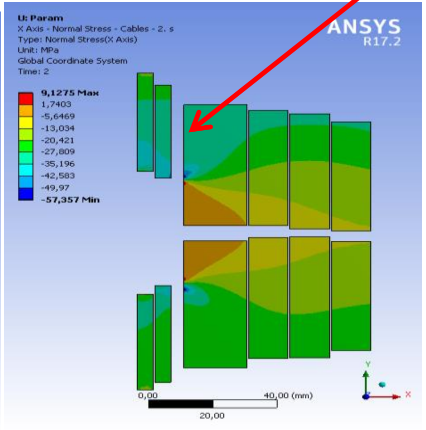


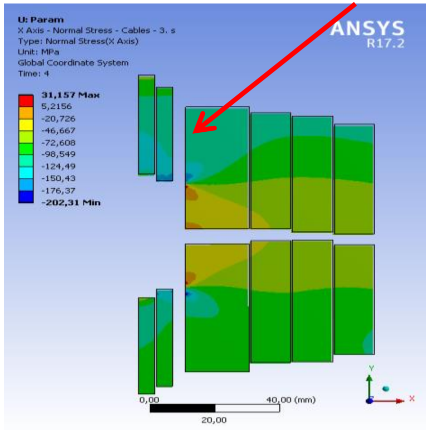
Coils X stress

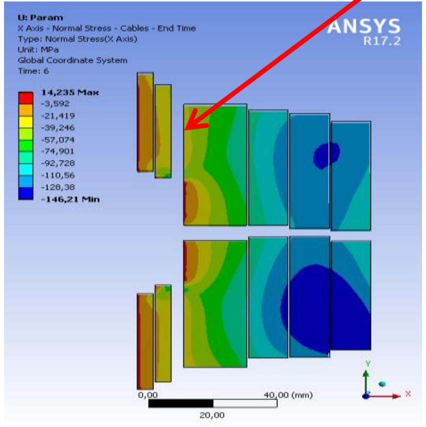
- “azimuthal” stress for Ancillary coils
- “radial” stress for main coils

Contact pressure *-35 MPa* *-28 MPa* *-120 MPa* *-25 MPa*









Assembly
Peaks +11/-71 Mpa

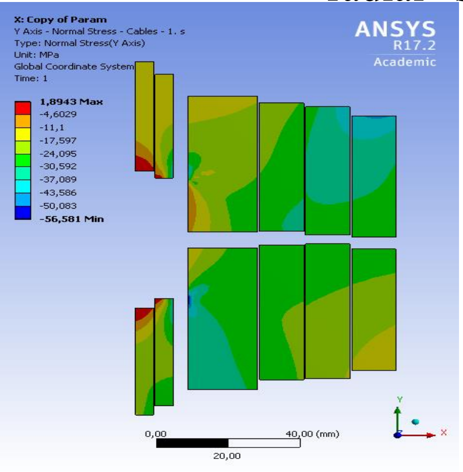
Keys in
Peaks +9/-57 Mpa

Cool down
Peaks +31/-202 MPa

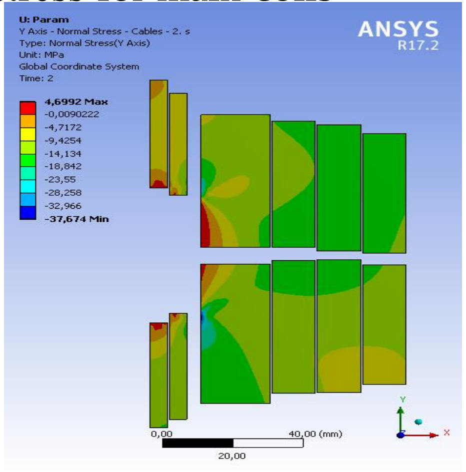
16 T
Peaks +14/-146 MPa

Coils Y stress

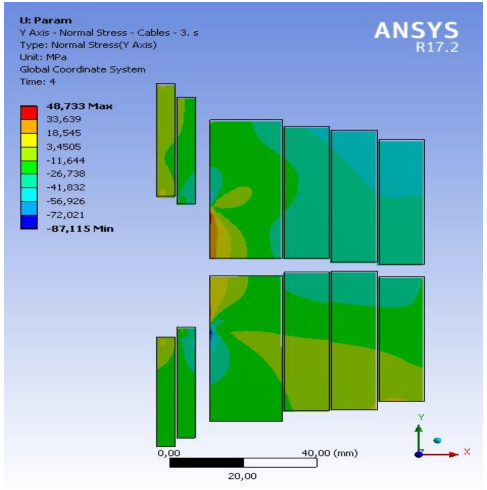
- “azimuthal” stress for Ancillary coils
- “radial” stress for main coils



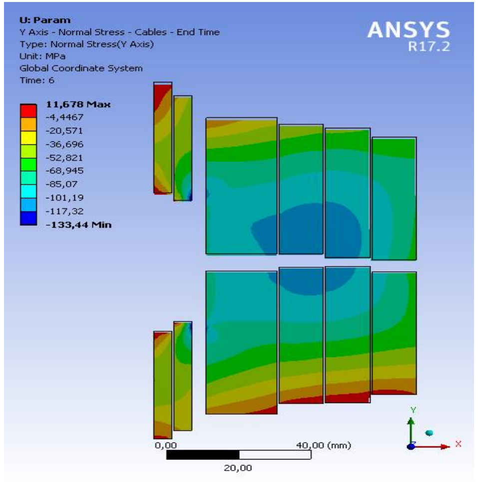
Assembly
Peaks +1/-56 Mpa



Keys in
Peaks +4/-37 Mpa



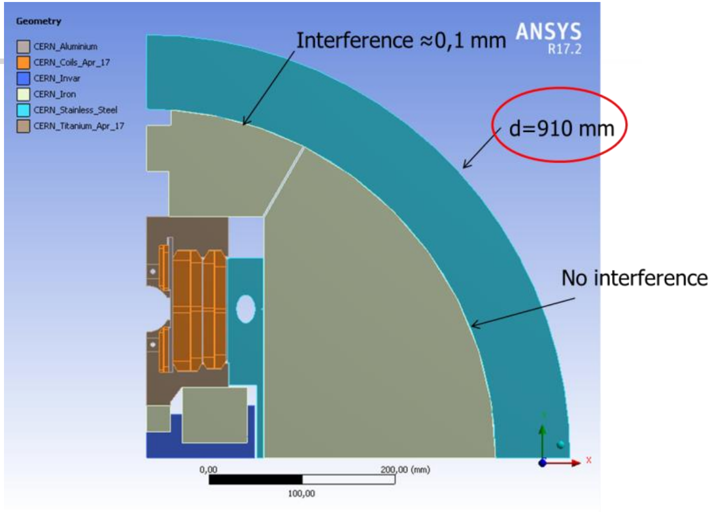
Cool down
Peaks +48/-87 MPa

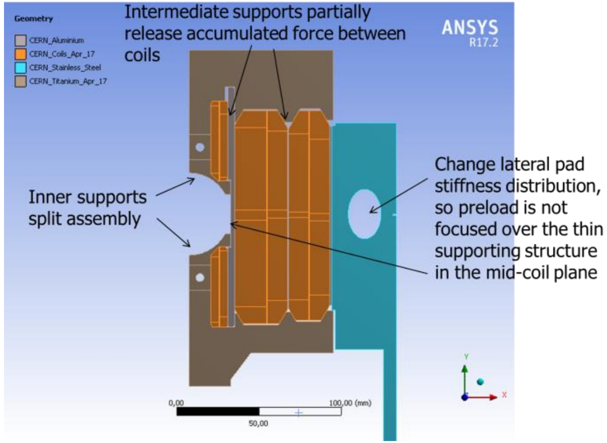


16 T
Peaks +11/-133 MPa

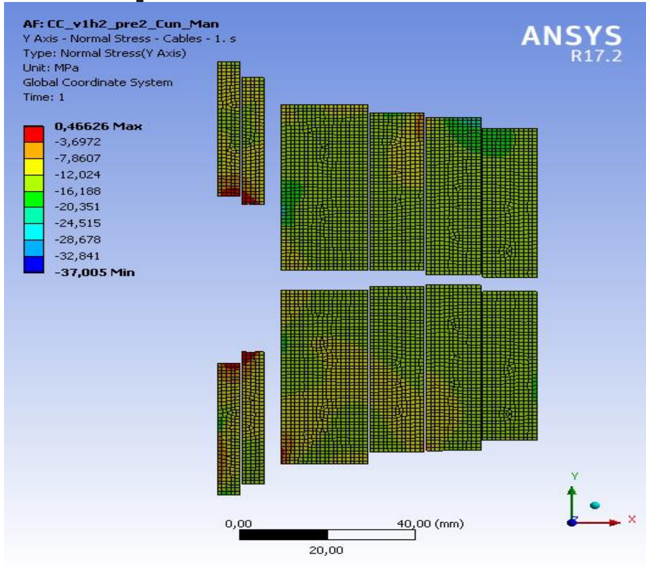
Closed beam pipe support model with limited pre-stress

- An outer shell of stainless steel (80 mm) holds the horizontal Lorentz forces.
- Yoke is cut in 4 pieces. Invar to increase pre-stress only at magnet mid-plane.
- No bladders.
- Coils are not bonded to support structure. Intermediate supports in between the main coils to change the stress distribution.
- Friction coeffient of 0.2.

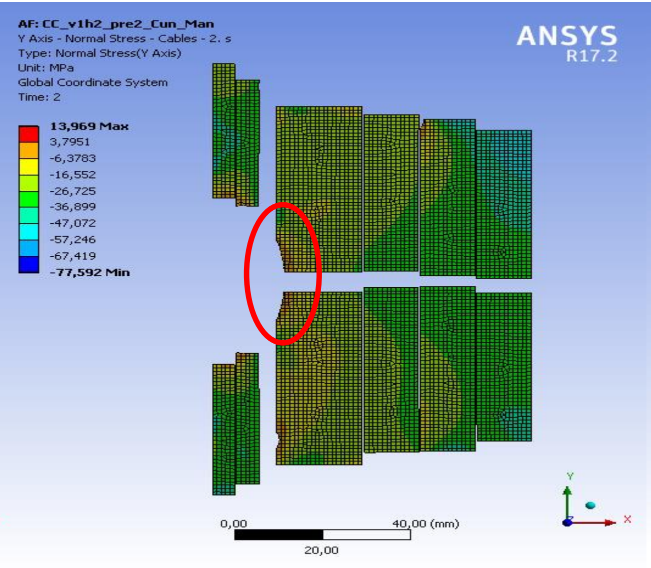




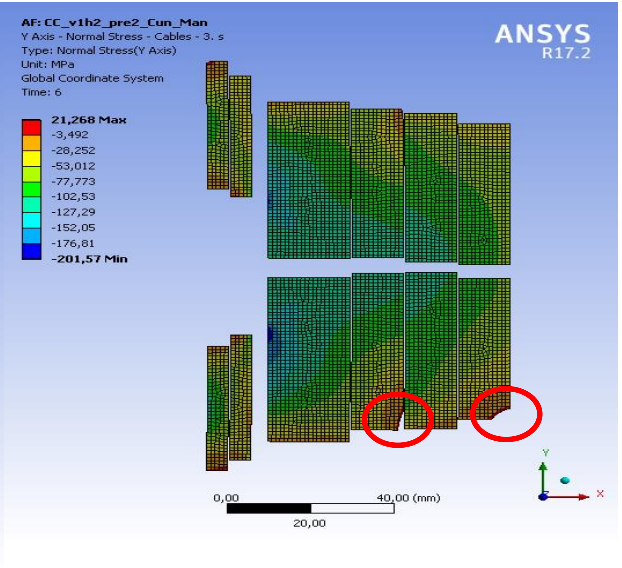
Results: Vertical Stress



Assembly



Cold



16 T

Less than +10 Mpa for local tensile stress values

Summary of mechanical results

OPEN SUPPORT (16T)	
Displ. X COILS (mm)	0,58 / 0,40
Displ. Y COILS (mm)	0,03 / -0,23
σ_{VM} Support (MPa)	527

CLOSED SUPPORT (KEYS) (16T)	
Displ. X COILS (mm)	0,275 / 0,11
Displ. Y COILS (mm)	0,05 / -0,25
σ_{VM} Support (MPa)	1059

CLOSED SUPPORT (LIMITED PRELOAD) (16T)	
Displ. X COILS (mm)	0,42 / 0,25
Displ. Y COILS (mm)	0,05 / -0,25
σ_{VM} Support (MPa)	650

Conclusions

- Common coil layout is studied by CIEMAT as one of the options for the 16 T dipoles demanded by future colliders.
- We have found a sound 2-D electromagnetic design: it needs more superconductor than other designs, but uses flat coils.
- 3-D magnetic computations show that coil end design also fulfils requirements.
- Main challenges of 2-D mechanical design have been analyzed. Several support structures have been modeled. Further investigation is necessary building prototypes.
- We are working on the signature of a Collaboration Agreement to develop support structures for some flat coils produced by CERN to study the different options shown in this presentation.