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

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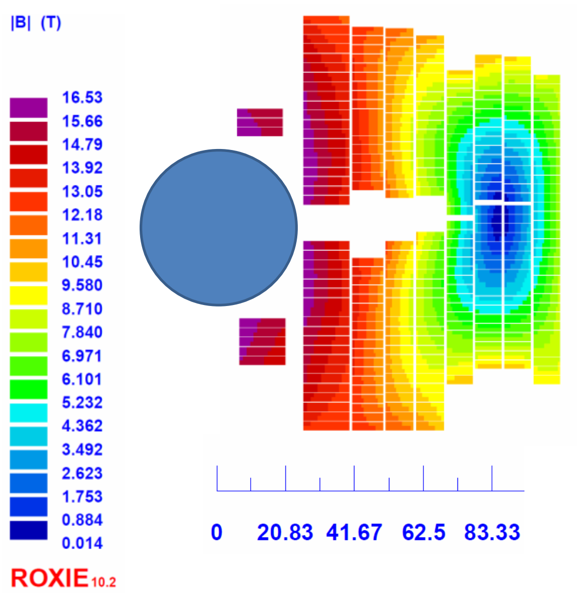
Outline

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

Introduction: optimal solution in ASC 2016

- **Strategy**: 320 mm intra-beam distance, 750 mm iron outer diameter, 9 kA nominal current, internal splice at high field coil, hotspot temperature close to 350K in all the coils.
- **Problem**: high voltage during quench propagation (3.2 kV).



Total FCC SC weight	8592	ton
margin on load line	86	%
peak field	16,51	T
b3	-2,5	units
b5	-4,2	units
b7	-11	units
b9	-4,6	units
a2	-1	units
a4	1	units
a6	2,1	units
a8	0,5	units
inc_b3	7	units
inc_a2	8	units
Stored energy	3,47	MJ/m
Static self inductance	82,5	mH/m
L*I	756,8	HA/m
Sum_fx	14,71	MN/m
Sum_fy	0,73	MN/m
Peak temperature (Excel)	396	K

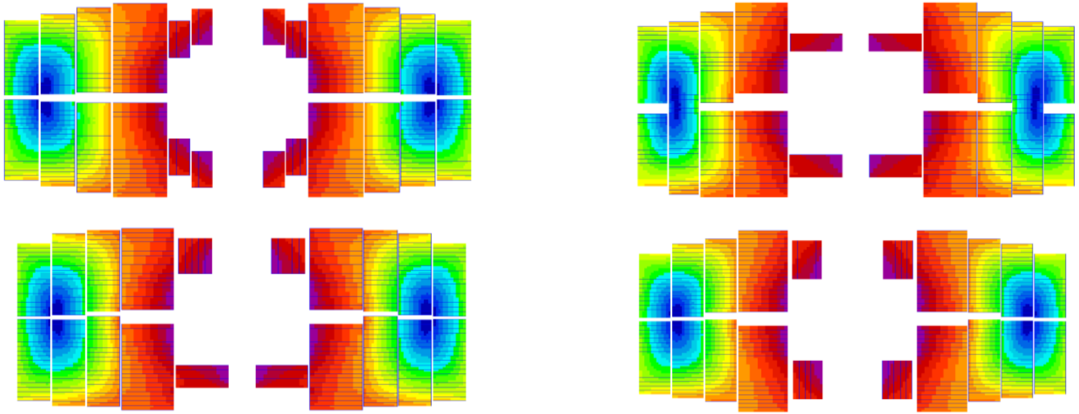
Nominal current	9170	A
Intra-beam distance	320	mm
Iron outer diameter	750	mm
1st coil		
#cables	40/37	
#strands	1164	
strand diameter	1.2/1.15	mm
Cu:Sc	1/1.5	
2nd coil		
#cables	76	
#strands	760	
strand diameter	1,2	mm
Cu:Sc	2,2	
3rd & 4th coils		
#cables	136	
#strands	1360	
strand diameter	1,15	mm
Cu:Sc	3,5	
Pole coils		
#cables	11	
#strands	198	
strand diameter	1,2	mm
Cu:Sc	1	

2-D electromagnetic design: nominal current

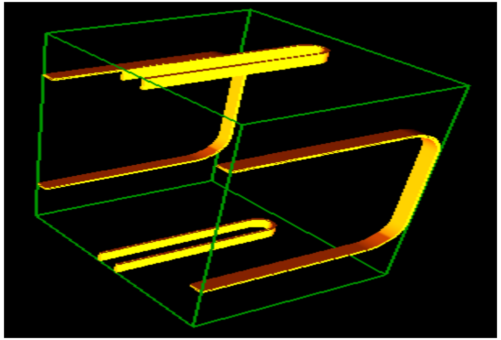
- Obviously, a higher nominal current would help to decrease the voltages during quench.
- A good compromise value is around 16 kA:
  - It allows reducing the number of main coils from four to two, for a constant number of ampereturns. Grading will be less effective.
  - It is the maximum current that a cable with 1.2 mm strands can carry in a background field of 16 T when used for a pole coil parallel to the main coils.
  - It is nearly twice the nominal current of Design #10 (ASC 2016), which means about one quarter of the self-inductance, for the same number of ampere-turns.

2-D electromagnetic design: pole coils

- We have studied different configurations of the ancillary coils.



- We have chosen the upper left one because:
  - The coils are flat or slightly flared.
  - It provides better field quality for a thicker mechanical support around the beam pipe.



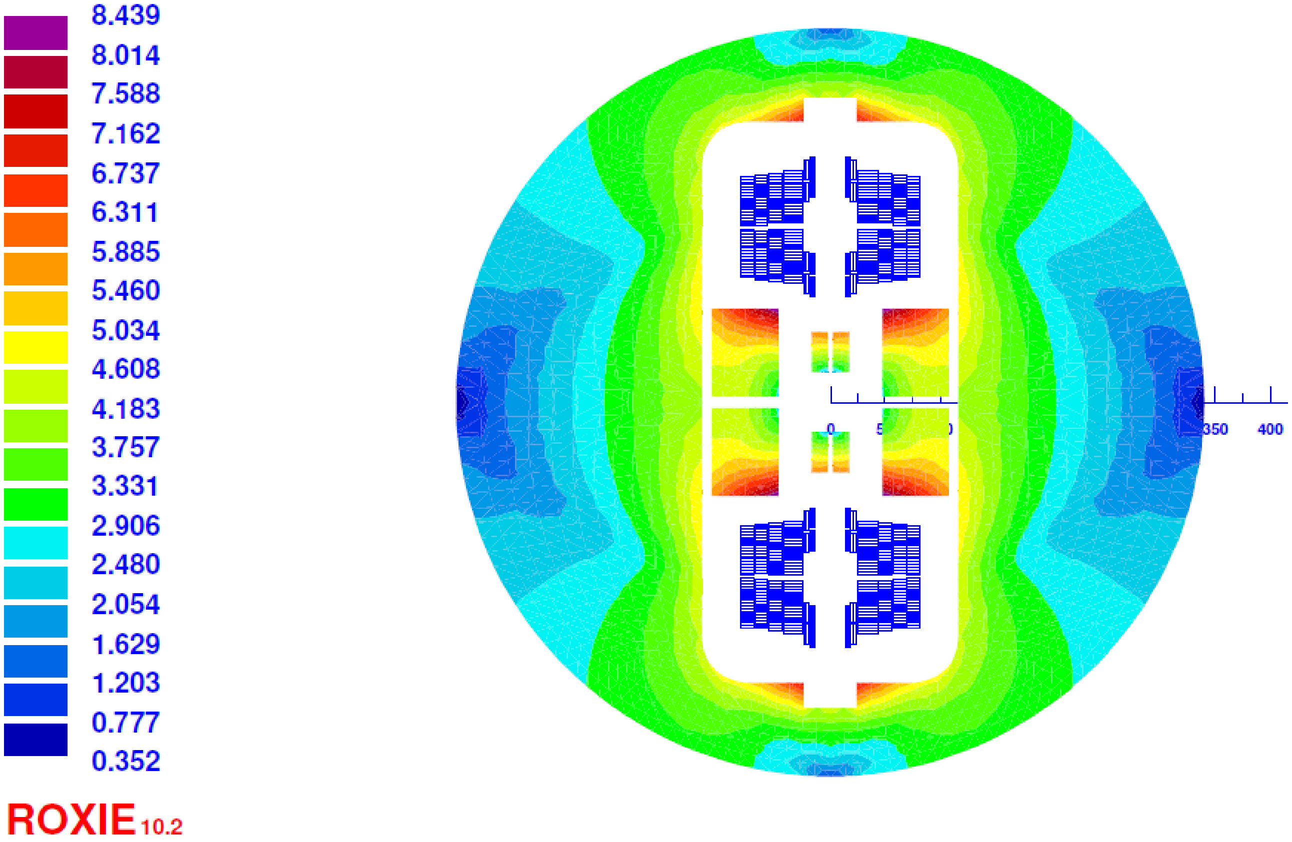
2-D magnetic results

- Design #11 needs more superconductor, but fulfils all requests.
- 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

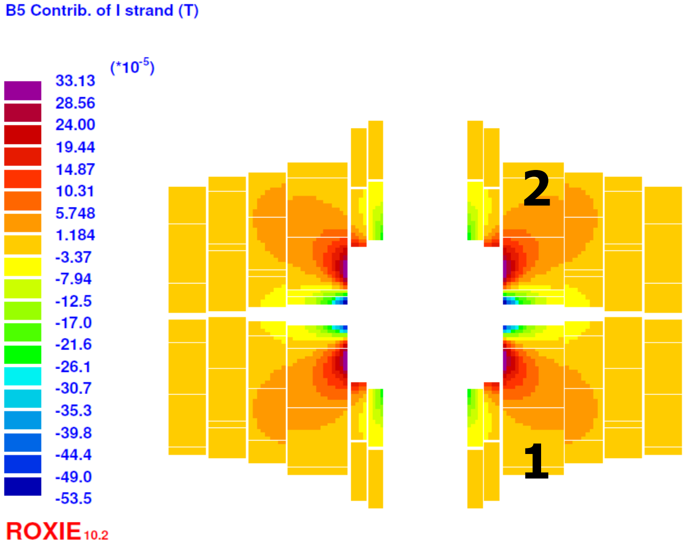
Design Id.	#10	#11	#12	#13	#14	Units
Nominal current *I*	9.17	16.1	16.1	16.1	16.1	kA
Minimum Cu:Sc ratio	1	1	0.8	1	1	
Intra-beam distance	320	320	320	320	280	mm
Iron outer diameter	750	750	750	650	650	mm
Stored magnetic energy	3.47	3.04	2.93	3.05	3.16	MJ/m
*L*I*	757	378	364	379	392	H·A/m
Vertical Lorentz 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: optimization strategy

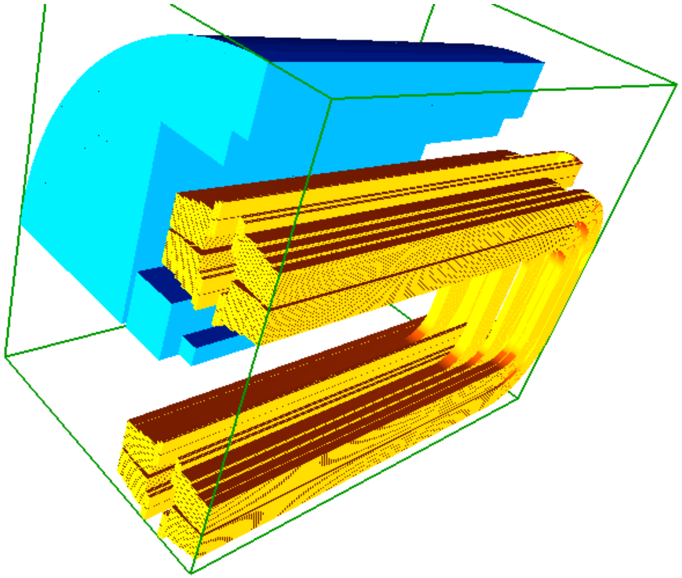
- Common coil ideal cross section is similar to a block magnet.
- The optimization algorithms are not always looking into the right direction. It is better to constrain the range of variation.
- It is good to understand the sensitivity of the design variables to find a good starting solution.



- **B3**: gap at midplane, outermost turns of blocks 1&2, ancillary coils
- **B5**: pole coils and midplane gap
- **B7**: pole coils
- **A2**: vertical position of the main coils respect the aperture (symmetry with aperture)
- **A4**: vertical position of blocks 1&2
- **Peak field**: ancillary coils in vertical position help to decrease Bpeak/Bnom

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.



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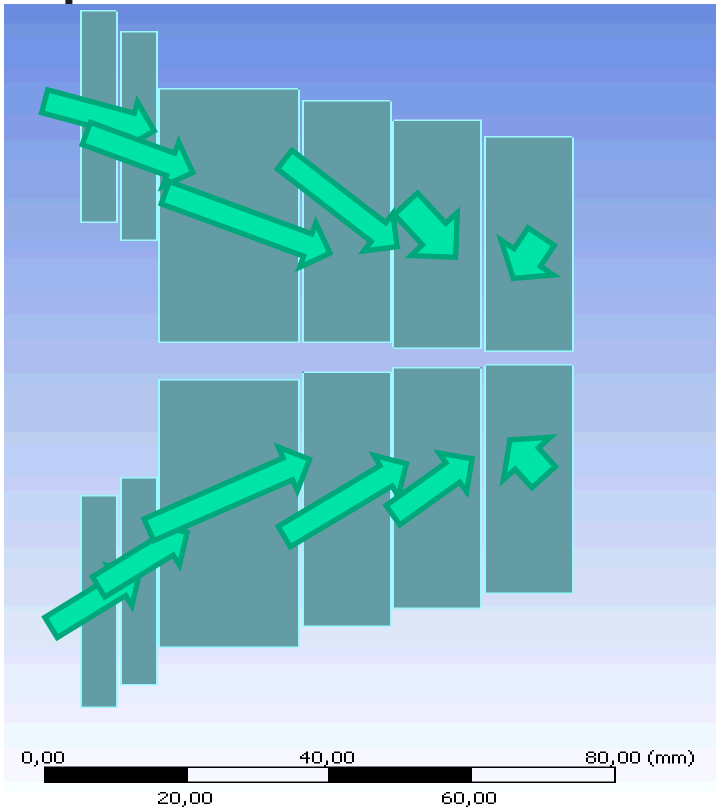
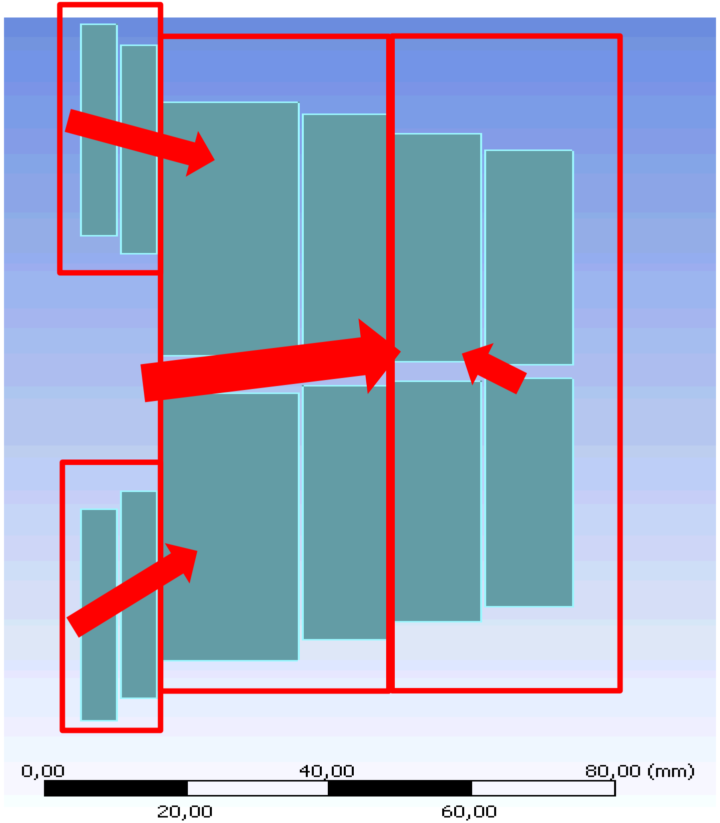
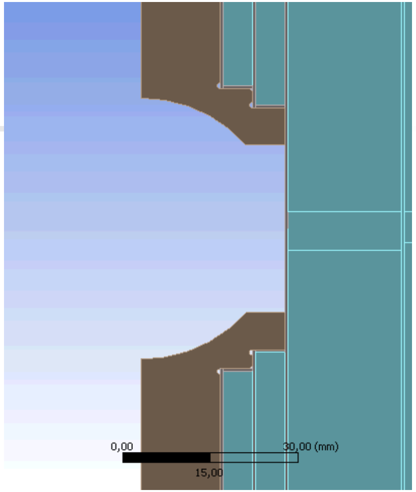
Common Coil Dipole: Forces at coils

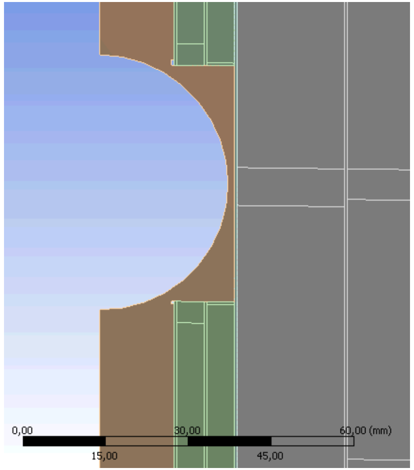




2-D mechanical support

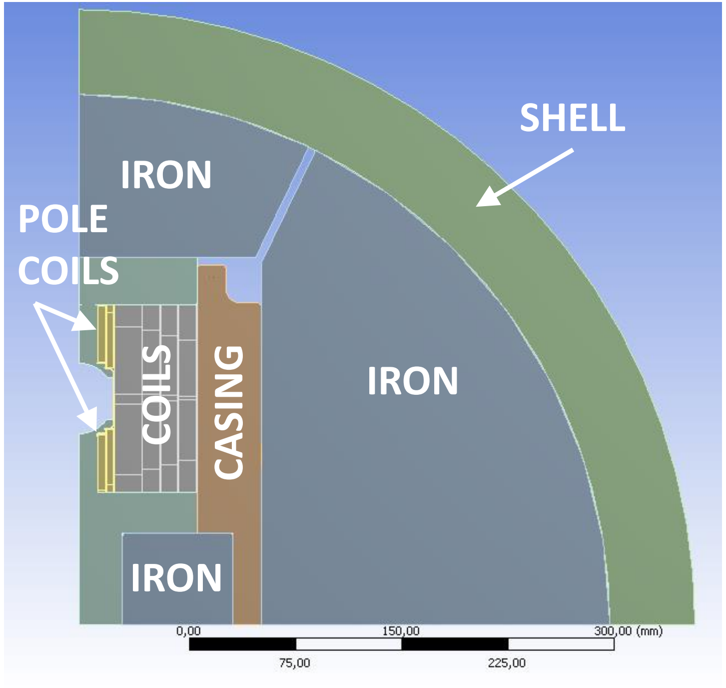
- There are two possibilities to hold the large horizontal Lorentz forces:
  - To let the main coils move and hold the pole coils with a cantilevered support.
  - To pre-compress the main coils against a closed structure around the beam pipe, which also holds the pole coils.
- Only the first option has been studied by now, since it needs less superconductor. When the main coils are shifted by 2.5 mm, the magnet needs 4% more cable and stores 10% more energy.





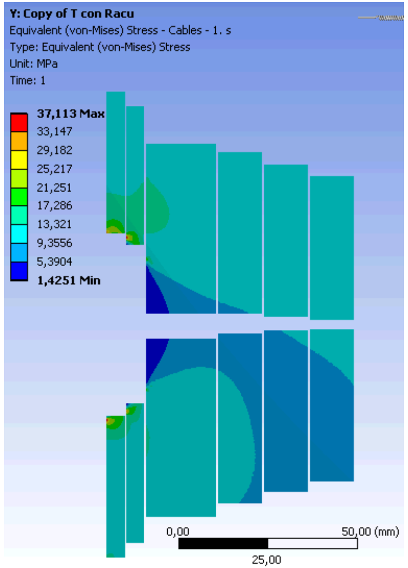
2-D mechanical model

- All the pieces are continuous at the other side of the symmetry axes.
- A 60 mm thick stainless steel shell holds the large horizontal Lorentz forces.
- The main coils are glued. They have copper spacers to perform equal width. 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.

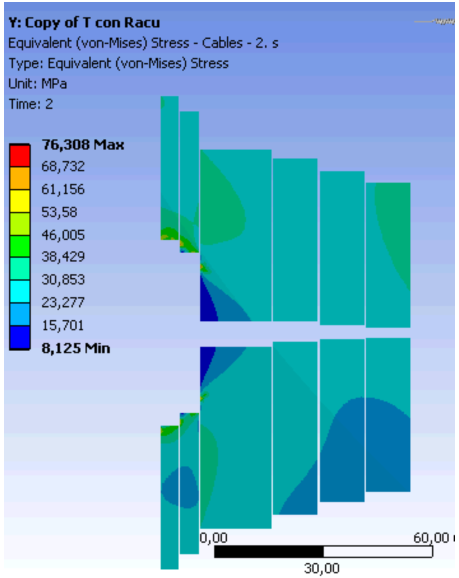


2-D FEM results: coil stresses

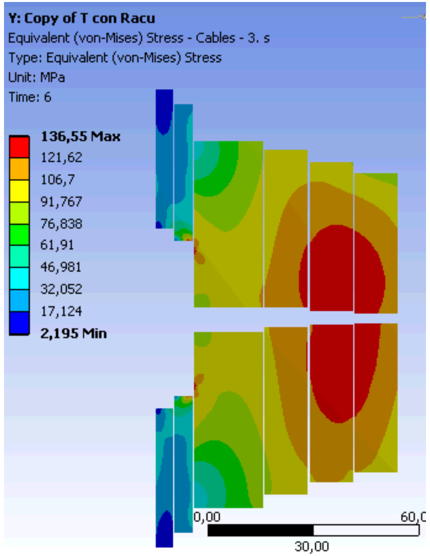
- The stresses on the coils are moderate for a high field magnet at all the load steps: assembly, cool-down and energizing. It is the consequence of not using pre-compression.



Assembly: Max 36 MPa



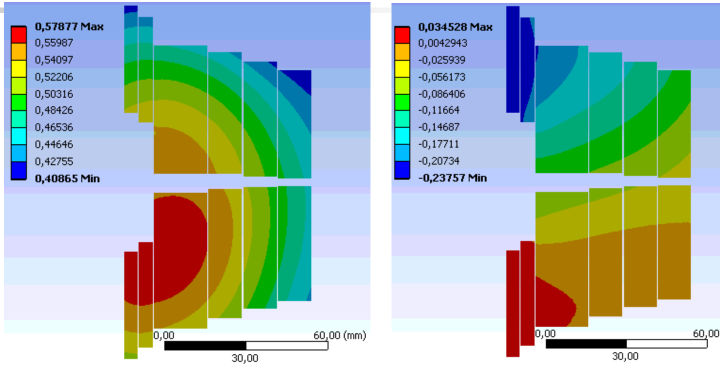
Cool down: Max 76 MPa



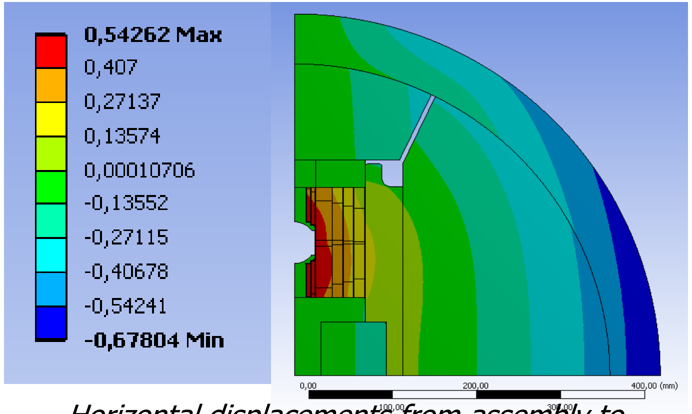
16 T: Max 136 MPa

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 (up to 0.5 mm) 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.
- This feature needs further investigation. Other structures providing pre-compression are under study.



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



Horizontal displacements from assembly to nominal field

2-D mechanical model results: summary

	Assembly	Cold	16T
σ_{VM} COIL (MPa)	36	76	136
σ_x COIL (MPa)	+4,5 / -38	+2,6 / -78	+1 / -140
σ_y COIL (MPa)	+2,3 / -20	+0,2 / -66	+1 / -155
Displ. X COILS (mm)			0,58 / 0,40
Displ. Y COILS (mm)			0,03 / -0,23
σ_{VM} Support (MPa)			527
σ_{VM} Iron (MPa)			418
σ_1 Iron (MPa)			82

Conclusions

- Common coil layout is studied by CIEMAT as one of the options for the 16 T dipoles demanded by future colliders.
- In this paper, several magnetic designs have achieved all the requests while using a moderate amount of superconductor.
- 3-D magnetic computations show that coil end design also fulfils requirements.
- Mechanical analysis has been done on a support structure which minimizes the stored elastic energy and the coil stresses, but some concerns arise due to the coil sliding respect casing. Further calculations are ongoing and other types of structures providing pre-compression will be considered.