Common coil configuration: electromagnetic design

J. Munilla, F. Toral - CIEMAT

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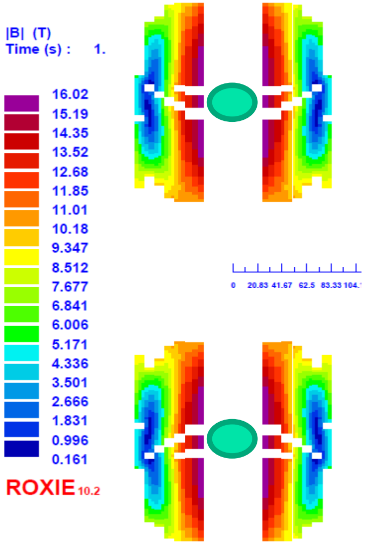
Outline

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

Optimal solution in 1st Review (2016)

- **Summary**: 320 mm intra-beam distance, 750 mm iron outer diameter, 9 kA nominal current, three coils, internal splice at high field coil, hotspot temperature close to 350K in all the coils.
- Iron shape is customized to decrease the multipole field variation with current.



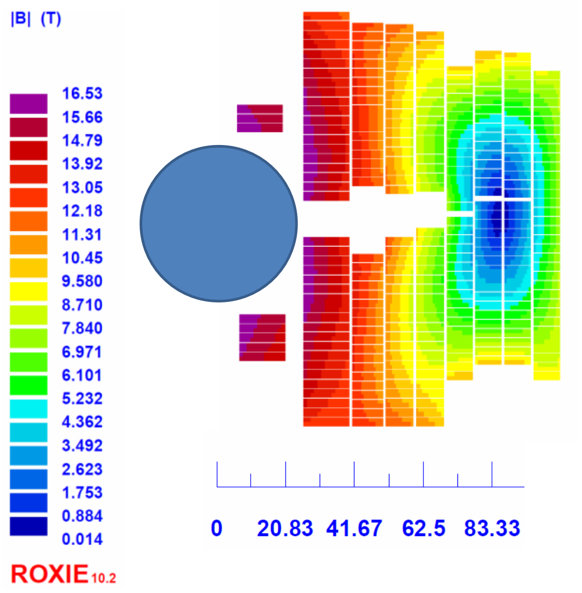
Nominal current		9000	A
Intra-beam distance		320	mm
Iron outer diameter		750	mm
1st coil			
#cables		76/75	
#strands		3026	
strand diameter		1.1/1.1	mm
Cu:Sc		1/1.3	
Cu current density		728/1196	A/mm^2
2nd coil			
#cables		139	
#strands		1668	
strand diameter		1,1	mm
Cu:Sc		2,4	
Cu current density		1118	A/mm^2
3rd coil			
#cables		102	
#strands		1212	
strand diameter		1,1	mm
Cu:Sc		2,3	
Cu current density		1132	A/mm^2
Strand area per magnet		224,506379	cm^2
Total FCC SC weight		12518	ton
Strand area per magnet Cu:Sc=1		165,058378	cm^2
Total FCC SC weight Cu:Sc=1		9204	ton
margin on load line		90,1	%
#block		4	
peak field		16,5	T
b3		-1,4	units
b5		-4,1	units
b7		5,4	units
b9		2,2	units
a2		-1,8	units
a4		1,3	units
a6		3,9	units
a8		2,2	units
inc_b3		14	units
inc_a2		10	units
Stored energy		5,05	MJ/m
Static self inductance		124,7	mH/m
Sum_fx		19,11	MN/m
Sum_fy		1,5	MN/m
Stray field 50 mm		0,79	T
Stray field 1 m		43	mT

New input parameters

- Ramesh Gupta (BNL) and Qingjin Xu (IHEP) strongly recommended the introduction of pole coils in FCC week 2016.
- New design parameters have been assumed by our EuroCirCol Working Group after the panel review in May 2016:
  - Working temperature 1.9 K
  - Safety margin 14% on load line
  - Critical current density 2300 A/mm2 @ 16T, 1.9 K (including cabling degradation 3%, self field)
  - Strand diameter up to 1.2 mm
  - Cu/Sc ratio down to 0.8
  - Magnet length 14.3 m
- It was also recommended to increase the nominal current in order to reduce the product L*I:
  - Benefits: lower induced quench voltages, easier power circuits
  - Drawbacks: lower superconductor efficiency, larger cable

Optimal solution with 9kA nominal current (ASC 2016)

- **Strategy**: The use of pole coils, enhanced cable properties and lower margin decreases the cable needs from 12518 to 8592 tons!!
- **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

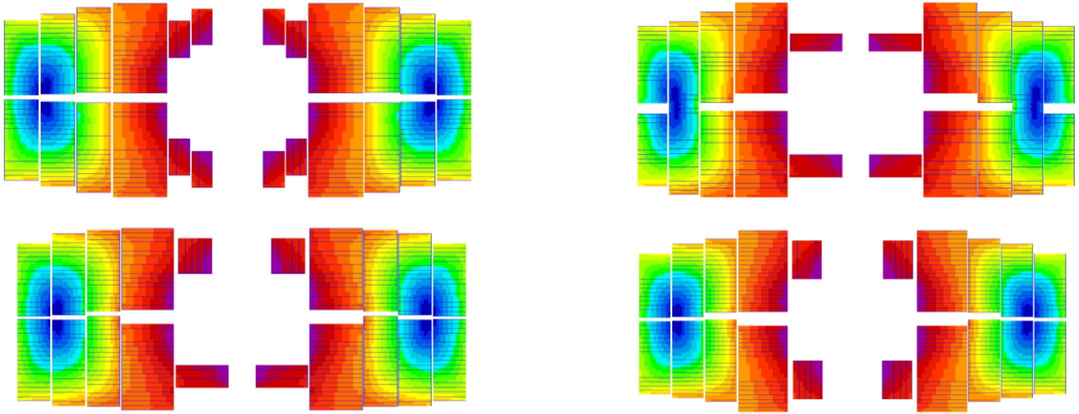
Nominal current	9170	A
Intra-beam distance	320	mm
Iron outer diameter	750	mm
1st coil		
#cables	40/37	
#strands	1164	
strand diameter	1.2/1.15	mm
Cu:Sc	1/1.5	
2nd coil		
#cables	76	
#strands	760	
strand diameter	1,2	mm
Cu:Sc	2,2	
3rd & 4th coils		
#cables	136	
#strands	1360	
strand diameter	1,15	mm
Cu:Sc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

Increase of nominal current

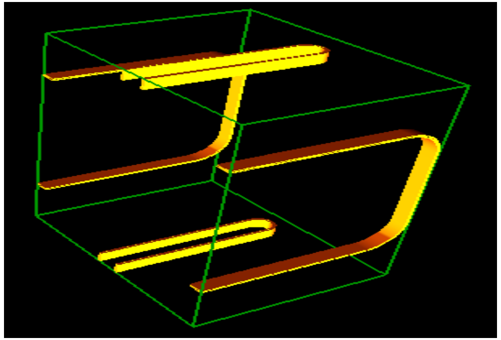
- Obviously, a higher nominal current would help to decrease the voltages during quench.
- A good compromise value is around 16 kA:
  - It allows reducing the number of main coils from four to two, for a constant number of ampereturns. Grading will be less effective.
  - It is the maximum current that 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.

Configuration of 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 while allowing a thicker mechanical support around the beam pipe.



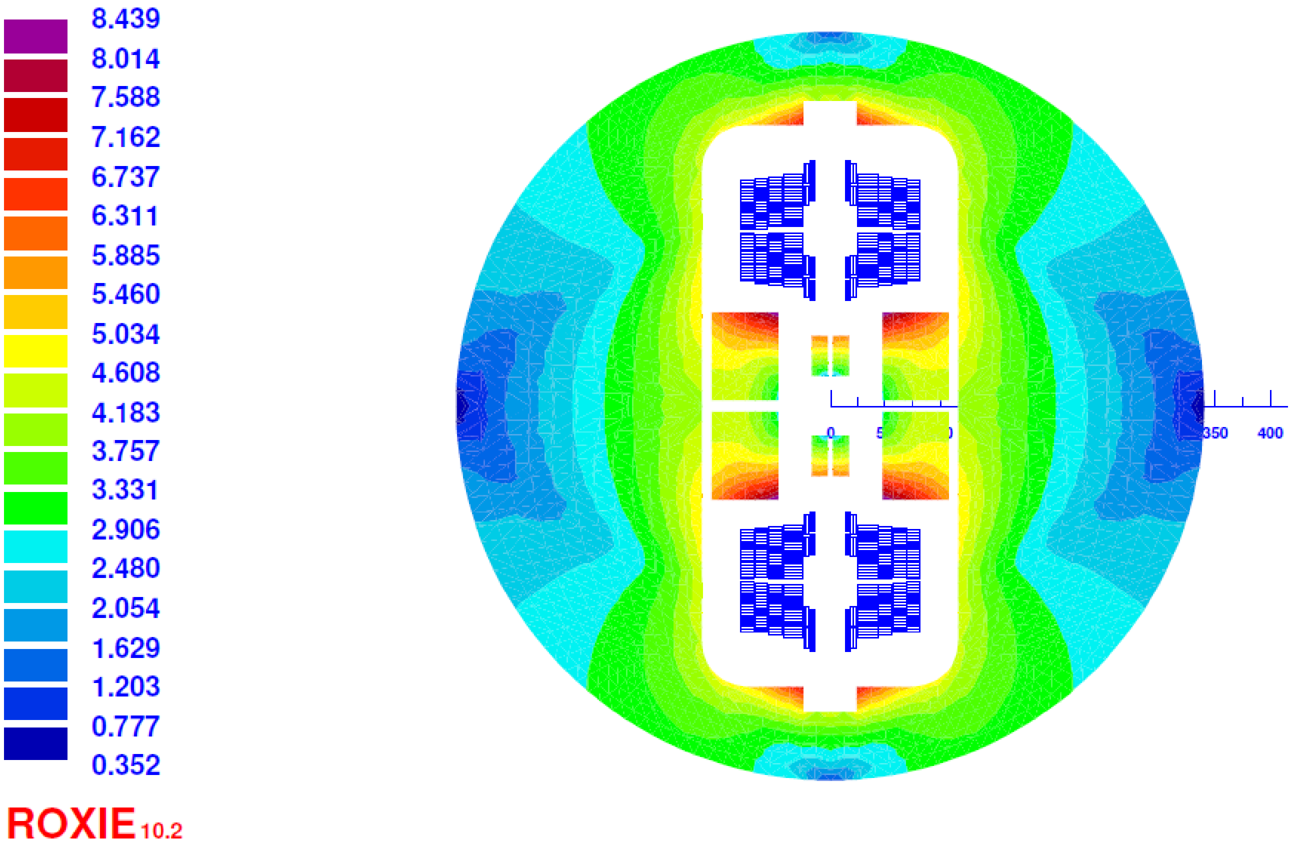
Summary of 2-D magnetic results

- 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). A large intra-beam distance would be very convenient for react-and-wind coils.

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

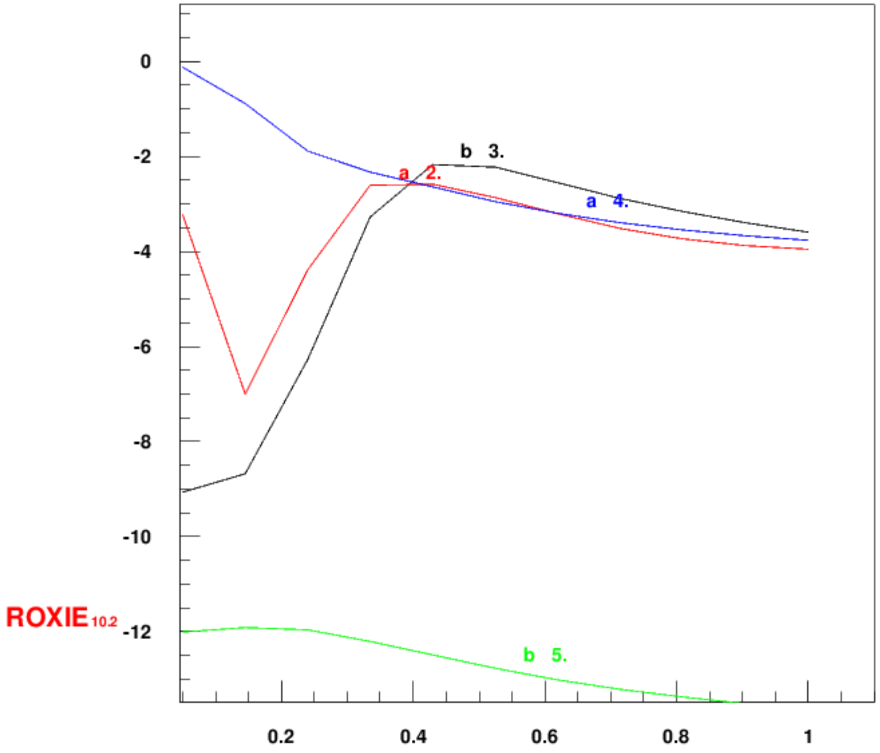


Electromagnetic design: Design #12

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	

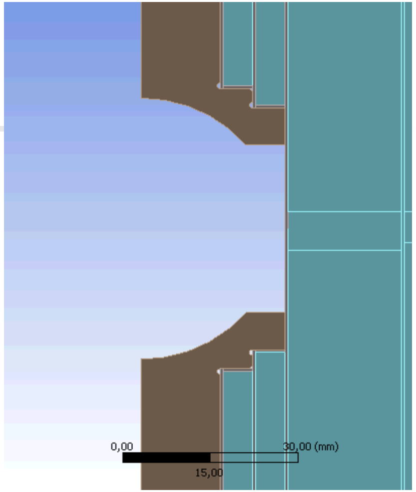
Total FCC SC weight	8951	ton
margin on load line	13,95	%
peak field	16,67	T
b3	-3,6	units
b5	-13,6	units
b7	-4	units
b9	-3,9	units
a2	-3,9	units
a4	-3,8	units
a6	-1,4	units
a8	-0,5	units
inc_b3	7,1	units
inc_a2	4,4	units
Stored energy	2,93	MJ/m
Static self inductance	22,6	mH/m
L*I	364,0	HA/m
Sum_fx	14,4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

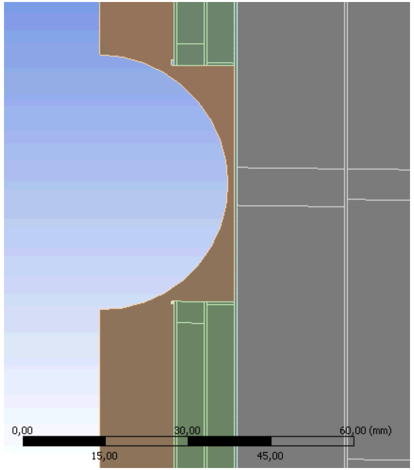
Electromagnetic design: Design #12



Electromagnetic design with mechanical support around beam pipe

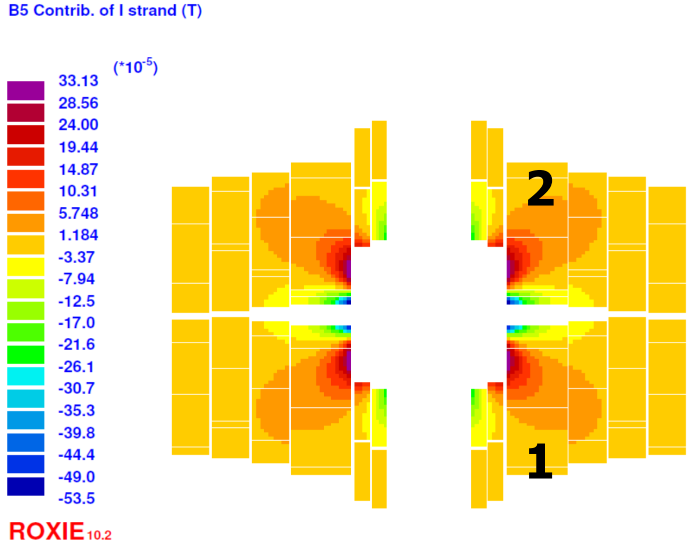
- There are two possibilities to hold the large horizontal Lorentz forces:
  - To let the main coils move and hold the pole coils with a cantilevered support.
  - To pre-compress the main coils against a closed structure around the beam pipe, which also holds the pole coils.
- The first option needs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





Electromagnetic design: optimization strategy

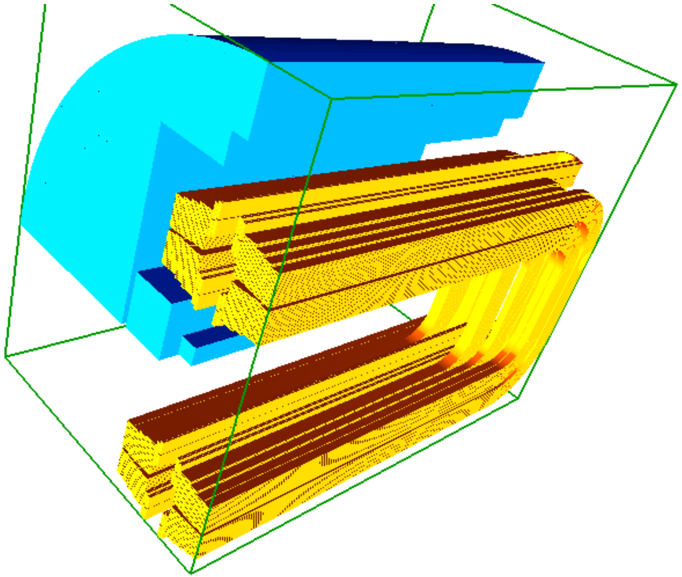
- Common coil ideal cross section is similar to a block magnet.
- The optimization algorithms are not always looking into the right direction. It is better to constrain the range of variation.
- It is good to understand the sensitivity of the design variables to find a good starting solution.



- **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.



Conclusions

- Common coil layout is studied by CIEMAT as one of the options for the 16 T dipoles demanded by future colliders.
- Several 2-D 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.
- Some further calculations are still needed: cooling holes at iron, magnetization effects, use of Invar... but the key to success is mechanics! Let’s see next presentation…