Common coil configuration: electromagnetic calculations

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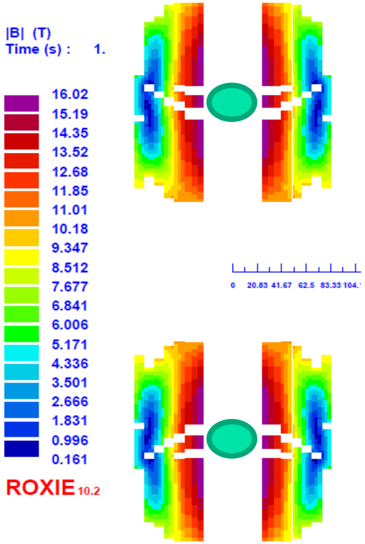
Thanks to R. Gupta (BNL) for his suggestions and help

Outline

- 2-D electromagnetic design at FCC week 2016
- Update on 2-D electromagnetic design
- 3-D electromagnetic calculations
- Conclusions

Optimal solution in FCC week 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

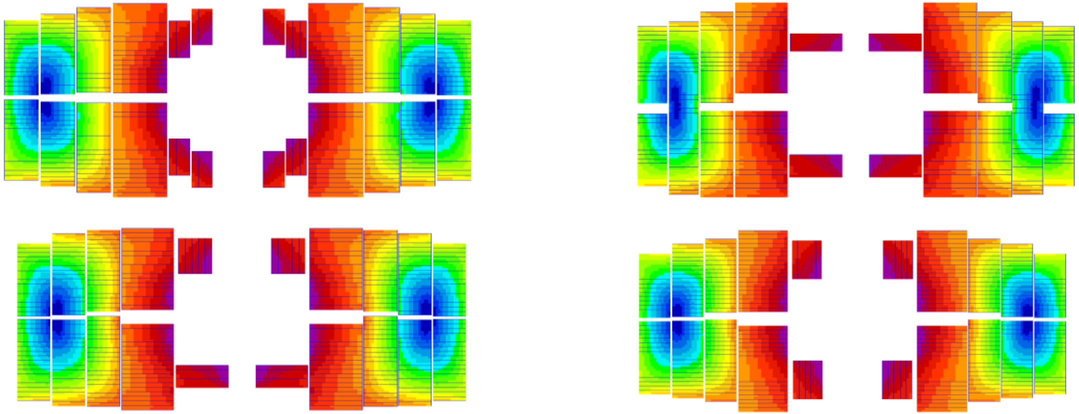
Solution space

- The use of pole coils decreases the cable needs from 12518 to 10110 tons!!
- The enhanced cable properties and lower margin allow an additional saving: only 9175 tons are necessary.
- The increase of the nominal current to about 15 kA, decreases the self-inductance to one third of the previous value, and the product L*I to one half. However, the cable need increases to 10018 tons.

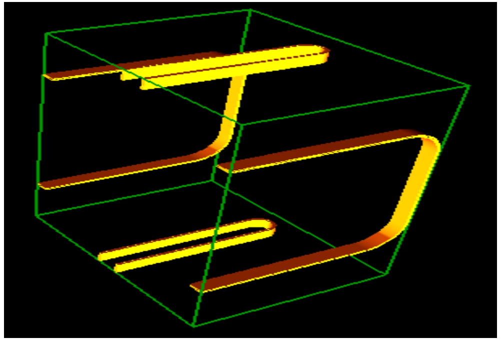
		may-16	jul-16	
Design Id.		5coils_v5	v1h_ecc1	v1h2
Nominal current	A	9000	9000	15180
1st coil				
#cables		43/41	42/42	38/38
#strands		1734	1596	1824
strand diameter	mm	1,1	1.05/1.1	1,2
Cu:Sc		1/1.5	1/1.2	1/2.1
Cu current density	A/mm^2	789/1127	866/1240	894/1100
2nd coil				
#cables		84	80	71
#strands		1176	960	1278
strand diameter	mm	1,05	1,1	1,2
Cu:Sc		2	2,2	2,1
Cu current density	A/mm^2	1113	1148	1100
3rd coil				
#cables		144	136	36
#strands		1680	1632	576
strand diameter	mm	1,1	1,05	1,2
Cu:Sc		2,6	3,5	3,9
Cu current density	A/mm^2	1081	1113	1054
4th coil (aux)				
#cables		13	13	7
#strands		312	312	210
strand diameter	mm	1,1	1,05	1,2
Cu:Sc		1	1	1
Cu current density	A/mm^2	789	866	894
Strand area per magnet	cm^2	177,5	161,1	175,9
Total FCC SC weight	ton	10110	9175	10018
Strand area per magnet Cu:Sc=1	cm^2	131,2	114,0	129,0
Total FCC SC weight Cu:Sc=1	ton	7315	6355	7191
margin on load line	%	90	86	
#block		2	9	
peak field	T	16,32	16,61	16,59
Stored energy	MJ/m	3,9	3,68	3,76
Static self inductance	mH/m	96,3	90,9	32,6
L*I	HA/m	866,7	817,8	495,4
Sum_fx	MN/m	14,71	14,5	14,73
Sum_fy	MN/m	0,79	0,8	0,84
Stray field 50 mm	T	0,65	0,56	0,62
Stray field 1 m	mT	46	40	43
Peak temperature (Excel)	K	382	394	394

Ancillary coils layout

- We have studied different configurations of the ancillary coils.

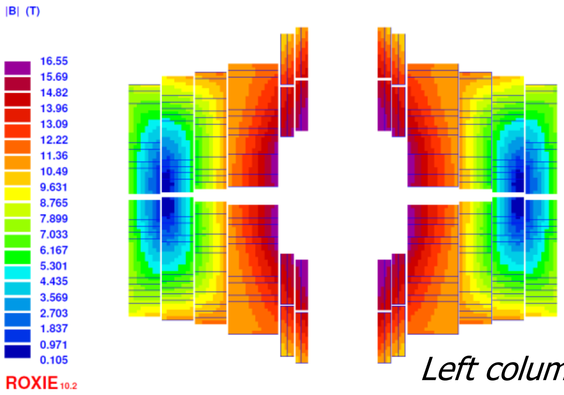


- We have chosen the upper left one because:
  - It allows flat coils with an acceptable bending radius.
  - It provides better field quality for a thicker mechanical support around the beam pipe.



Last results

- Left column model: two main coils with optimized pole coils, it only needs 8977 tons of cable.
- Central column model: coil aperture is 54 mm to allow space for inner support in case of **pre-compressed coils**. 300 tons of additional cable are needed. B5 is easier to be minimized.
- Right column model (**HE-LHC**): outer iron diameter is reduced from 750 to 650 mm. 9234 tons of cable.

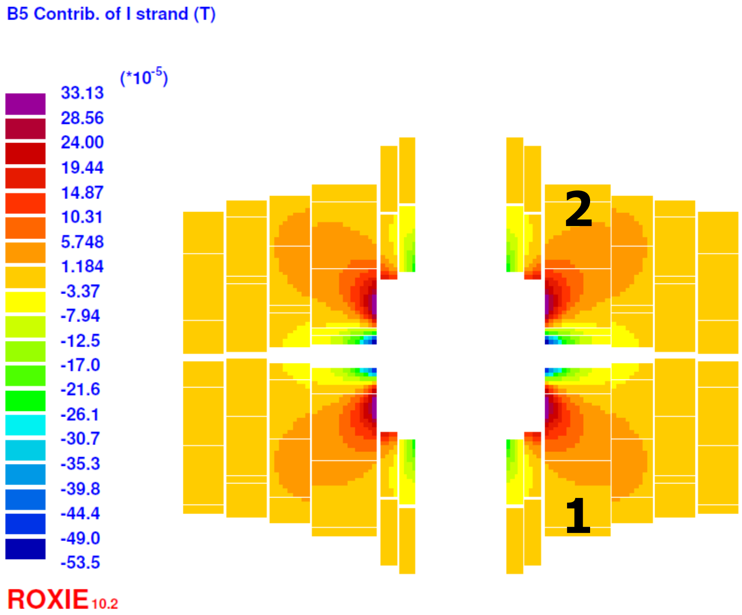


Left column model

Design Id.	v1h2_2ac7	v1h2_pre1	v1h2_helhc
Nominal current	16100	16100	16100
Intra-beam distance	320	320	280
Iron outer diameter	750	750	650
1st coil			
#cables	39/37	41/40	39/39
#strands	1836	1950	1872
strand diameter	1,2	1,2	1,2
Cu:Sc	1/2.5	1/2.5	1/2.5
Cu current density	949/1107	949/1107	949/1107
2nd coil			
#cables	73	73	77
#strands	1168	1168	1232
strand diameter	1,2	1,2	1,2
Cu:Sc	2,5	2,5	2,5
Cu current density	1107	1107	1107
Pole coils			
#cables	16	16	16
#strands	480	480	480
strand diameter	1,2	1,2	1,2
Cu:Sc	1	1	1
Cu current density	949	949	949
Strand area per magnet	157,6	162,8	162,1
Total FCC SC weight	8977	9271	9234
Strand area per magnet Cu:	128,9	133,6	131,9
Total FCC SC weight Cu:Sc=	7190	7450	7355
margin on load line	86,11	86,22	86,14
#block	9	10	9
peak field	16,56	16,59	16,56
b3	1	-3,7	-2,8
b5	-12,2	-1,2	-15,1
b7	-3,8	-0,5	-4,1
b9	-3,9	-2,7	-3,7
a2	3,3	0,8	-0,9
a4	-1,9	0,3	-1,6
a6	-0,7	-0,8	-0,6
a8	-0,4	-0,6	0,5
inc_b3	5	5	10
inc_a2	4	4	5
Stored energy	3,04	3,26	3,16
Static self inductance	23,5	25,2	24,4
L*I	377,6	405,0	392,5
Sum_fx	14,6	15,2	14,45
Sum_fy	0,57	0,62	0,92
Stray field 50 mm	0,46	0,5	0,76
Stray field 1 m	29	32	30
Peak temperature (Excel)	358	367	360

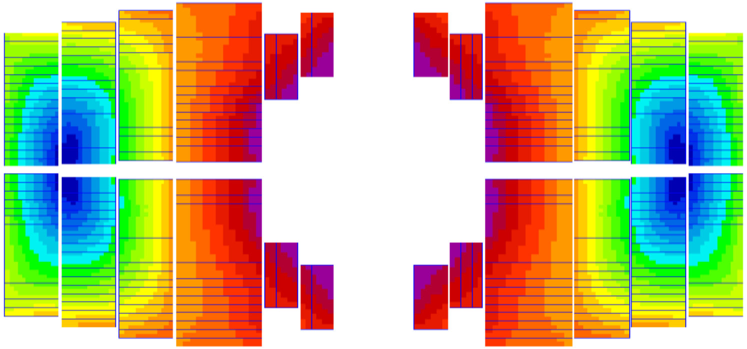
Electromagnetic design: field quality

- We have tried to understand the sensitivity of the field harmonics with the design variables. The optimization algorithms are not always looking into the right direction.



- **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

Electromagnetic design: remarks



- It is worth to notice that the common coil design has some intrinsic advantages:
  - All coils are flat. Cable is also flat.
  - The magnetic field density map fits nicely with a graded coil. Internal splice can be done at the coil end (low field region, straight cable).
  - The pole turns are not necessarily glued to the main turns.
  - Field quality is not very sensitive to horizontal displacement of the main coils.

3-D electromagnetic design

- The magnet has been modeled in 3-D.
- Field quality is quite good after few iterations.
- Peak field enhancement at coil ends is significant with the compact configuration shown in the picture. Optimization is ongoing.

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    3D REFERENCE MAIN FIELD (T) .........................      -7.8618
    REFERENCE MAGNET STRENGTH (T/(m^(n-1)) ............      -7.8618
    MAGNETIC LENGTH (mm) ...............................    1199.7082

    NORMAL 3D INTEGRAL RELATIVE MULTIPOLES (1.D-4):
    b 1:  10000.00000  b 2:     -0.00000  b 3:     -5.43722
    b 4:      0.00000  b 5:     -8.07379  b 6:      0.00000
    b 7:     -2.19095  b 8:     -0.00000  b 9:     -3.21681
    b10:      0.00000  b11:     -0.64045  b12:     -0.00000
    b13:     -0.14759  b14:     -0.00000  b15:     -0.05205
    b16:     -0.00000  b17:     -0.01473  b18:      0.00000
Version 1.29/04 of HIGZ started
    b19:     -0.00485  b20:     -0.00000  b

    SKEW 3D INTEGRAL RELATIVE MULTIPOLES (1.D-4):
    a 1:      0.00000  a 2:      2.50853  a 3:      0.00000
    a 4:     -9.82705  a 5:     -0.00000  a 6:     -2.53255
    a 7:     -0.00000  a 8:     -0.72099  a 9:      0.00000
    a10:     -0.24427  a11:     -0.00000  a12:     -0.08240
    a13:      0.00000  a14:     -0.02711  a15:      0.00000
    a16:     -0.00852  a17:     -0.00000  a18:     -0.00252
    a19:      0.00000  a20:     -0.00067  a
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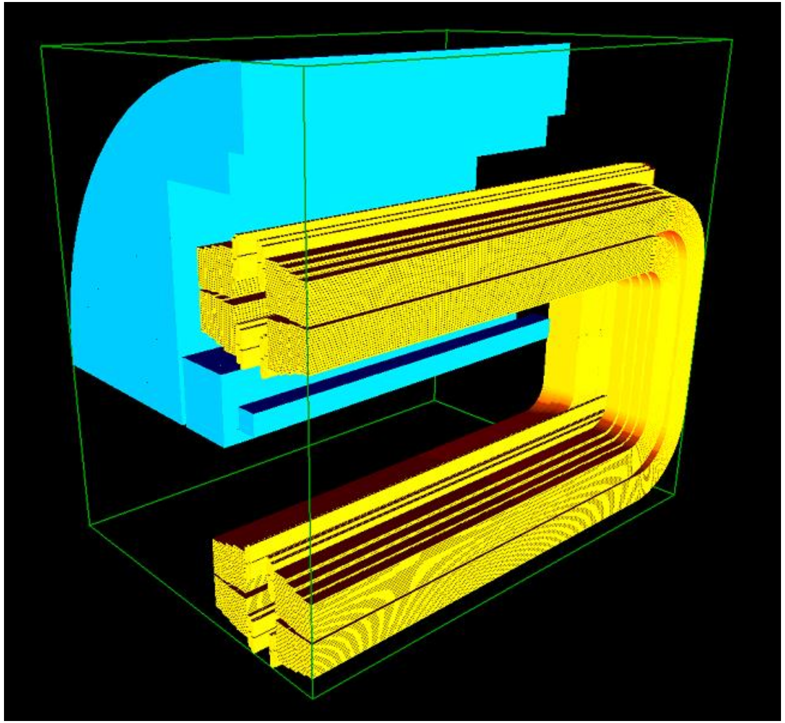

Conclusions

- 2-D electromagnetic calculations are finished: the design variables have been identified. The superconductor efficiency is noticeable. All coils are flat.
- 3-D electromagnetic calculations are ongoing. No problems are detected by now.