16 T dipole in common coil configuration: electromagnetic design

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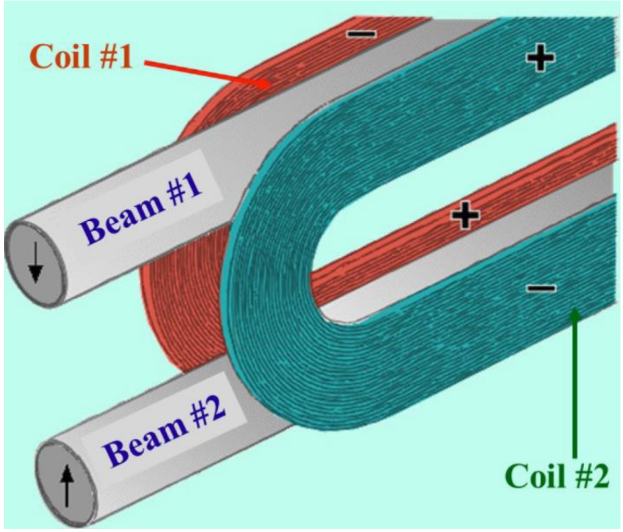
Outline

- Introduction
- 2-D magnetic design without ancillary coils
- 2-D magnetic design with ancillary coils
- Conclusions

Introduction (I)

- The common coil layout is based on two flat coils.
- A unique support structure for two apertures, placed at the same vertical plane.
- Main advantage: pure flat coils.
- Disadvantages: large stored energy and electromagnetic forces, complicated assembly.
- Traditionally, American labs (BNL, LBNL, Fermilab) have worked on this layout, also for high fields.
- Chinese colleagues (IHEP) are now working on a 20-Tesla dipole design based on common coils.
- In the framework of EuroCirCol project, CIEMAT is working on a 16-Tesla dipole design based on common coils.



Common coil layout
Courtesy: R. Gupta (BNL)

Introduction (II)

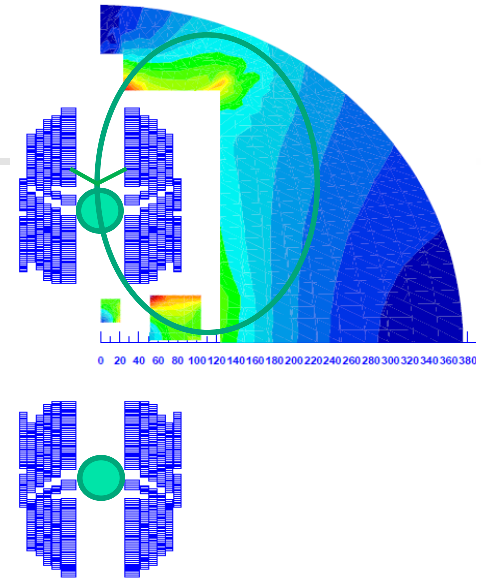
- The starting parameters are common for the three design options under study in the EuroCircol framework (cos-theta, block and common coil):

COMMON STARTING PARAMETERS FOR THE MAGNET OPTIMIZATION

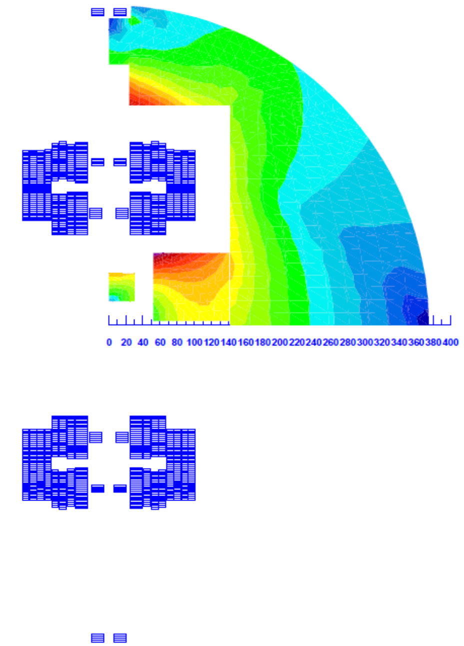
Dipole field at aperture	16	T
Aperture diameter	50	mm
Reference radius	17	mm
Beam-to-beam distance	250	mm
Outer diameter	800	mm
Cryostat outer diameter	1000	mm
Operating margin (nominal current is 90% on loadline)	≥10	%
Nominal current	≥9000	A
Working temperature	4.2	K
Cable insulation thickness	0.15	mm per conductor face
Inter-layer insulation thickness	0.5	mm
Minimum ground insulation thickness	2	mm
X-section multipoles (geometric)	A few 10^{-4}	units at reference radius
Overall coil length	14	m
Peak temperature	350	K (quench at 105% of nominal current)
Peak voltage to ground	2000	V (quench at 105% of nominal current)
Peak inter-turn voltage	100	V (quench at 105% of nominal current)
Protection circuit delay	40	ms

2-D magnetic design

- The influence of a number of parameters has been analyzed to optimize the 2-D magnetic design and to better understand the **sensitivity factors**:
  - Ancillary coils.
  - Intra-beam distance.
  - Iron outer diameter.
  - Strand diameter.
  - Number of coils.
  - Nominal current (intrinsically, cable size).
  - Internal splices.
  - Magnet protection.
- Main objective: **minimum volume of superconductor** while achieving the requirements in the previous Table.
- **Self field** is not included in these calculations. If included, working point on load line increases about 1%.
- Only double pancake coils are considered in this study.
- Field lines surround the coil blocks.



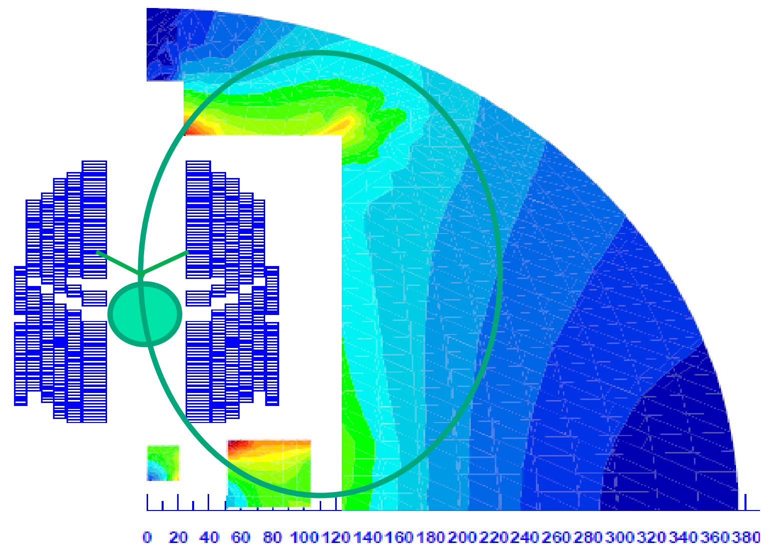
Common coil without ancillary coils

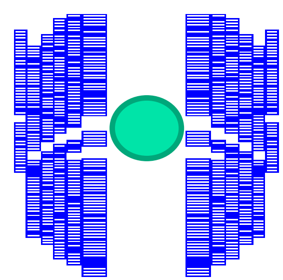


Common coil with ancillary coils

2-D magnetic design optimization **without** ancillary coils

- In a first stage, we have considered only the main coils.
- The main advantages would be:
  - Less coils to be produced, in order to save tooling and time of reaction.
  - Easier mechanical assembly:
    - Less parts to be assembled.
    - No forces on the coil blocks towards the aperture.





Sensitivity analysis of intra-beam distance

- A short intra-beam distance implies a strong cross-talk between apertures:
  - The superconductor efficiency decreases with the intra-beam distance.
  - The field quality is more difficult to achieve with short intra-beam distance.
- **Conclusion**: we keep **320 mm** as intra-beam distance.

Intra-beam distance	**280**	**320**	**360**	**mm**
Nominal current	8910	9030	9025	A
Intra-beam distance	280	320	360	mm
Iron outer diameter	750	750	750	mm
Strand area per magnet	290	266	260	cm^2
Total FCC SC weight	16157	14816	14485	ton
Strand area per magnet Cu:Sc=1	255	214	209	cm^2
Total FCC SC weight Cu:Sc=1	14197	11933	11679	ton
Margin on load line	89.4	89.7	89.4	%
Peak field	16.41	16.43	16.42	T
b3	5	0.1	2.6	units
b5	-8.6	-6.3	-3.1	units
b7	3.3	2.1	3.9	units
b9	1.7	0.8	1.4	units
a2	-2.1	-3.3	0.2	units
a4	5.4	-1.9	3.2	units
a6	-4.8	-9.8	7.1	units
a8	-3	-4.1	3.4	units
inc_b3	17	19	17	units
inc_a2	41	14	4	units
Stored energy	6.01	5.89	5.75	MJ/m
Static self inductance	151.4	144.5	141.2	mH/m
Sum_fx	19.27	20.08	19.88	MN/m
Sum_fy	3.67	1.82	1.15	MN/m
Stray field at 50 mm off iron yoke	0.78	1.1	1.25	T
Stray field at 1 m off magnet center	47	56	62	mT

Sensitivity analysis of iron outer diameter

- No significant saving of superconductor with more iron due to the strong saturation.
- Fringe field slightly decreases with more iron.
- It is better to use that space for the outer shell: increase stiffness of support structure.
- **Conclusion**: we keep **750 mm** as iron yoke outer radius.

Iron outer diameter	**750**	**800**	**mm**
Nominal current	9030	9030	A
Intra-beam distance	320	320	mm
Strand area per magnet	266	264	cm^2
Total FCC SC weight	14816	14723	ton
Strand area per magnet Cu:Sc=1	214	213	cm^2
Total FCC SC weight Cu:Sc=1	11933	11883	ton
margin on load line	89.7	90.3	%
#block	1	13	
peak field	16.43	16.42	T
b3	0.1	0.1	units
b5	-6.3	-6.9	units
b7	2.1	1.9	units
b9	0.8	0.8	units
a2	-3.3	-5	units
a4	-1.9	-1.9	units
a6	-9.8	-9.8	units
a8	-4.1	-4.2	units
inc_b3	19	20	units
inc_a2	14	22	units
Stored energy	5.89	5.83	MJ/m
Static self inductance	144.5	143.0	mH/m
Sum_fx	20.08	20.14	MN/m
Sum_fy	1.82	1.94	MN/m
Stray field 50 mm	1.1	0.93	T
Stray field 1 m	56	51	mT

Sensitivity analysis of strand diameter

- With larger strand diameter, the engineering current density is higher. Therefore, the superconductor efficiency increases.
- **Conclusion**: it is better to use a strand so large as possible (1.1 mm diameter).

Strand diameter	**1**	**1.1**	**mm**
Nominal current	9000	9030	A
Intra-beam distance	320	320	mm
Iron outer diameter	750	750	mm
Strand area per magnet	276	266	cm^2
Total FCC SC weight	15391	14816	ton
Strand area per magnet Cu:Sc=1	229	214	cm^2
Total FCC SC weight Cu:Sc=1	12773	11933	ton
margin on load line	90.3	89.7	%
#block	9	1	
peak field	16.49	16.43	T
b3	-1.7	0.1	units
b5	-4.5	-6.3	units
b7	5.3	2.1	units
b9	2.2	0.8	units
a2	-4	-3.3	units
a4	5.8	-1.9	units
a6	4.5	-9.8	units
a8	2.3	-4.1	units
inc_b3	16	19	units
inc_a2	15	14	units
Stored energy	6.14	5.89	MJ/m
Static self inductance	151.6	144.5	mH/m
Sum_fx	19.35	20.08	MN/m
Sum_fy	2.08	1.82	MN/m
Stray field 50 mm	1.1	1.1	T
Stray field 1 m	59	56	mT

Sensitivity analysis of nominal current

- If both layers of the high field coil are made with the same cable, the outer layer has a low working point on the load line. Inside the same cable, field is quite different between the strands. Field lines are quite parallel to the high field coil.
- The effect on magnet protection is not analyzed at this stage.
- **Conclusion**: it is better to stick to the minimum allowable current (9 kA).

Nominal current	**9030**	**10025**	**A**
Intra-beam distance	320	320	mm
Iron outer diameter	750	750	mm
Strand area per magnet	266	288	cm^2
Total FCC SC weight	14816	16079	ton
Strand area per magnet Cu:Sc=1	214	233	cm^2
Total FCC SC weight Cu:Sc=1	11933	13016	ton
margin on load line	89.7	90.9	%
#block	1	7	
peak field	16.43	16.41	T
b3	0.1	10.9	units
b5	-6.3	1.8	units
b7	2.1	6.4	units
b9	0.8	2.2	units
a2	-3.3	-5.6	units
a4	-1.9	-3.1	units
a6	-9.8	-4.5	units
a8	-4.1	-1.6	units
inc_b3	19	20	units
inc_a2	14	14	units
Stored energy	5.89	6.27	MJ/m
Static self inductance	144.5	124.8	mH/m
Sum_fx	20.08	19.89	MN/m
Sum_fy	1.82	2.14	MN/m
Stray field 50 mm	1.1	1.12	T
Stray field 1 m	56	59	mT

Sensitivity analysis of the number of coils

- Intrinsically, the current is larger for a two-coil layout. Without internal splices, the superconductor efficiency is poor in the outer layer.
- **Conclusion**: As expected, it is better to use **three coils**.

Number of coils	3	2	
Nominal current	9030	12780	A
Intra-beam distance	320	320	mm
Iron outer diameter	750	750	mm
Strand area per magnet	266	287	cm^2
Total FCC SC weight	14816	16016	ton
Strand area per magnet Cu:Sc=1	214	249	cm^2
Total FCC SC weight Cu:Sc=1	11933	13908	ton
margin on load line	89.7	90	%
#block	1	1	
peak field	16.43	16.3	T
b3	0.1	-0.1	units
b5	-6.3	0.5	units
b7	2.1	5.4	units
b9	0.8	1.9	units
a2	-3.3	-3.6	units
a4	-1.9	5.2	units
a6	-9.8	-6.8	units
a8	-4.1	-3.4	units
inc_b3	19	18	units
inc_a2	14	14	units
Stored energy	5.89	5.82	MJ/m
Static self inductance	144.5	71.3	mH/m
Sum_fx	20.08	20.32	MN/m
Sum_fy	1.82	1.85	MN/m
Stray field 50 mm	1.1	1.05	T
Stray field 1 m	56	55	mT

Sensitivity analysis of internal splices

- Superconductor efficiency increases noticeably if one uses different cable size for each layer of the high field coil.
- **Conclusion**: we will keep an **internal splice in the high field coil**.

Internal splice at high field coil	NO	YES	
Nominal current	9030	9025	A
Intra-beam distance	320	320	mm
Iron outer diameter	750	750	mm
Strand area per magnet	266	223	cm^2
Total FCC SC weight	14816	12438	ton
Strand area per magnet Cu:Sc=1	214	162	cm^2
Total FCC SC weight Cu:Sc=1	11933	9036	ton
margin on load line	89,7	90	%
#block	1	13	
peak field	16,43	16,49	T
b3	0,1	3,4	units
b5	-6,3	-1,7	units
b7	2,1	5,7	units
b9	0,8	2	units
a2	-3,3	-3,8	units
a4	-1,9	-0,6	units
a6	-9,8	-5,1	units
a8	-4,1	-2	units
inc_b3	19	17	units
inc_a2	14	11	units
Stored energy	5,89	5,18	MJ/m
Static self inductance	144,5	127,2	mH/m
Sum_fx	20,08	19,25	MN/m
Sum_fy	1,82	1,44	MN/m
Stray field 50 mm	1,1	0,86	T
Stray field 1 m	56	46	mT

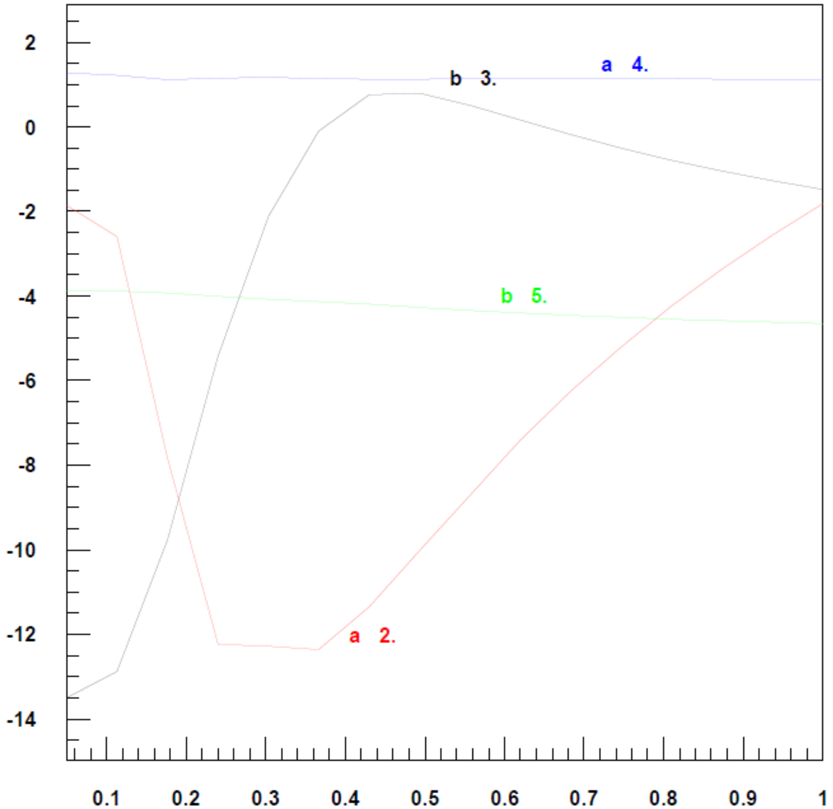
2-D magnetic design: magnet protection

- All the coils are quenched by heaters (see T. Salmi's talk). Thanks a lot to Tiina for the spreadsheet to compute hot-spot temperatures.
- Except the high field coil (minimum Cu:Sc ratio is 1), all the coils should reach a hotspot temperature as close as possible to 350 K: it helps to get a uniform temperature map. High temperature gradient at the high field cable interface.
- Voltages from coil to ground are high for 9 kA nominal current. Higher currents are possible but superconductor efficiency decreases.
- Quench heater assembly is very easy in these flat coils.
- **Conclusion**: hotspot temperature close to 350K in **all** the coils.

Nominal current	9025	9000	9000	A
1st coil				
#cables	76/71	75/72	76/75	
#strands	3112	3102	3026	
strand diameter	1,1	1,1	1.1/1.1	mm
Cu:Sc	1/1.5	1/1.7	1/1.3	
Cu current density	730/989	728/940	728/1196	A/mm^2
2nd coil				
#cables	143	142	139	
#strands	1716	1988	1668	
strand diameter	1,1	1,1	1,1	mm
Cu:Sc	3	3,8	2,4	
Cu current density	1055	854	1118	A/mm^2
3rd coil				
#cables	104	109	102	
#strands	1040	1308	1212	
strand diameter	1,1	1,1	1,1	mm
Cu:Sc	3	4	2,3	
Cu current density	1266	986	1132	A/mm^2
Strand area per magnet	223,061875	243,208909	224,506379	cm^2
Total FCC SC weight	12438	13561	12518	ton
Strand area per magnet Cu:Sc=1	162,042972	158,928418	165,058378	cm^2
Total FCC SC weight Cu:Sc=1	9036	8862	9204	ton
margin on load line	90	90	90,1	%
Stored energy	5,18	5,28	5,05	MJ/m
Static self inductance	127,2	130,4	124,7	mH/m
Hot spot temperature	450	350	370	K

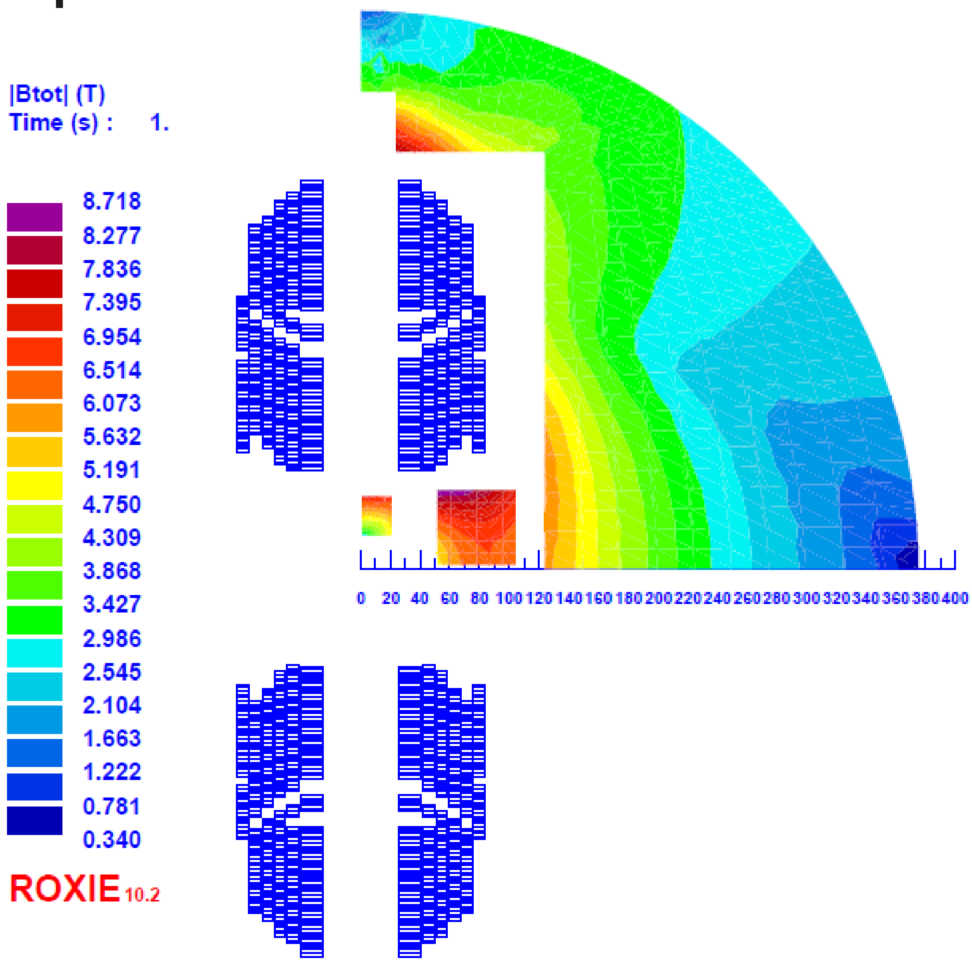
Optimal solution without ancillary coils

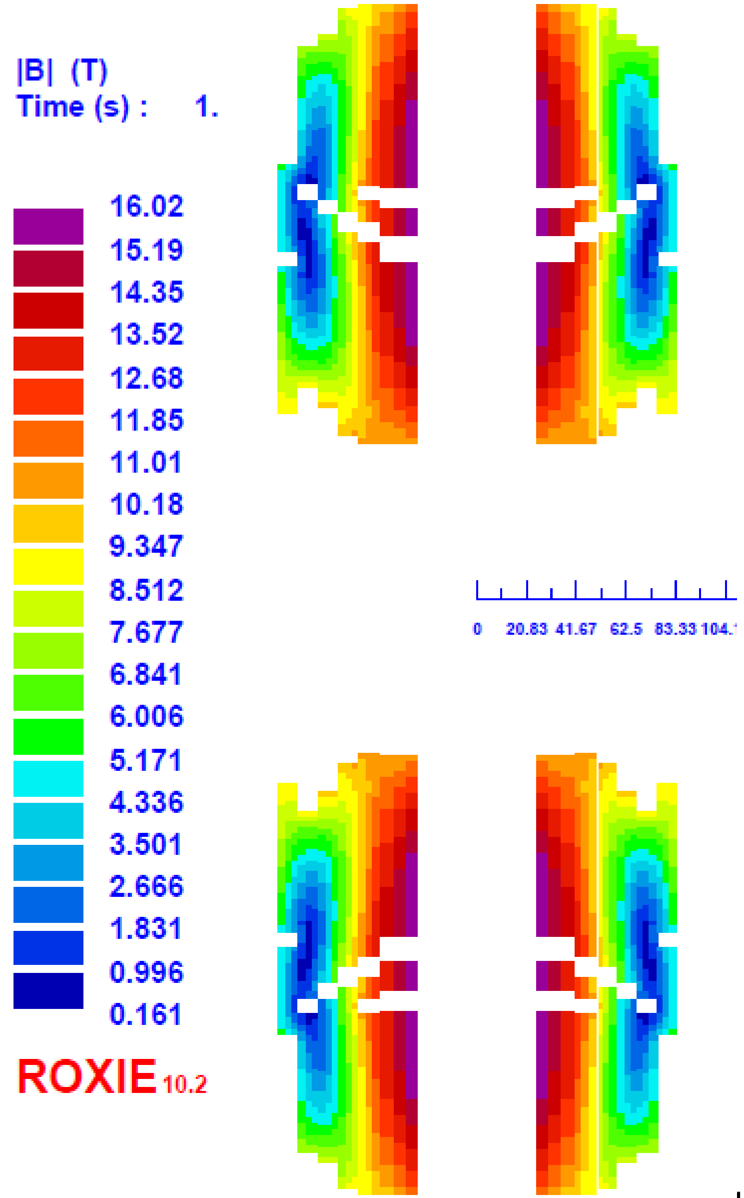
- **Summary**: 320 mm intra-beam distance, 750 mm iron outer diameter, 9 kA nominal current, three coils, internal splice at high field coil, hotspot temperature close to 350K in all the coils.
- Iron shape is customized to decrease the multipole field variation with current.



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

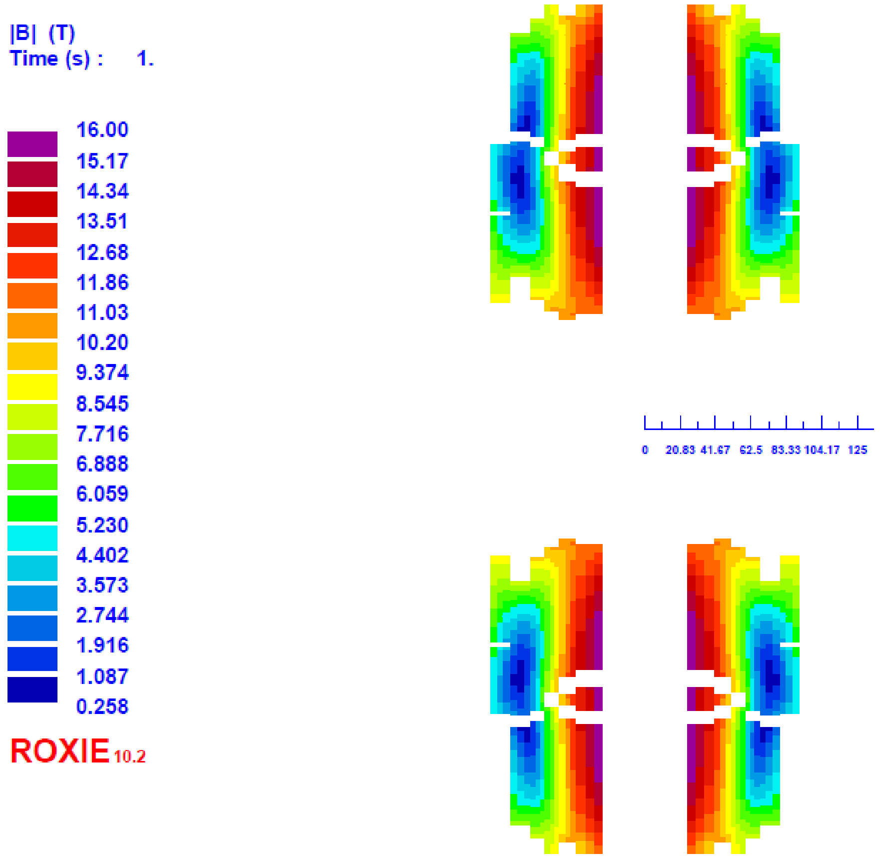
Optimal solution without ancillary coils





2-D magnetic design at 1.9 K

- The low field coil can be made with NbTi when working temperature is 1.9 K.
- In a Nb3Sn based design, about 12500 tons are necessary. In this alternative design, 10100 tons of Nb3Sn are needed, together with 3000 tons of NbTi.
- **Conclusion**: low field coil should be made in NbTi if working temperature is 1.9 K.



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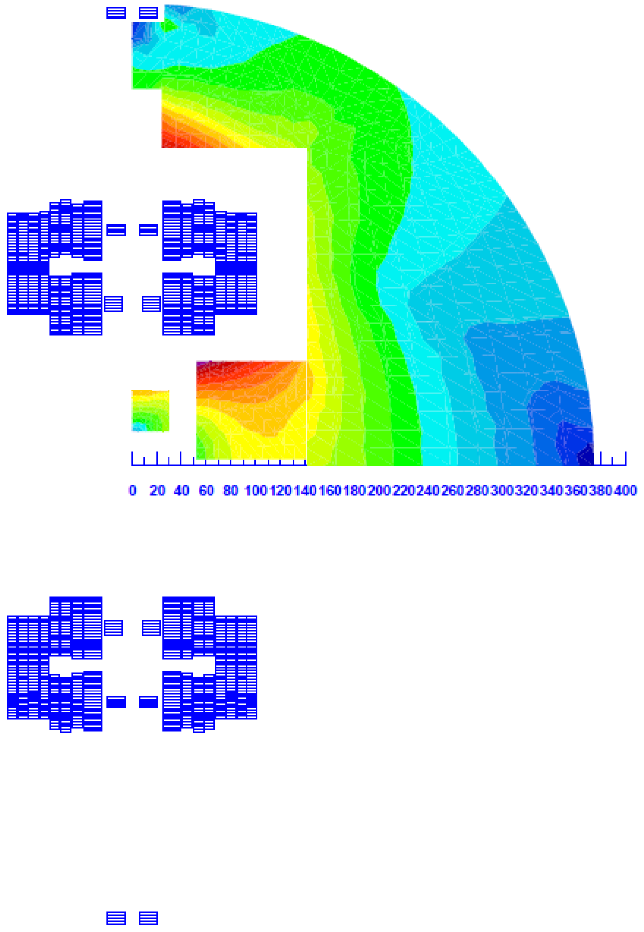
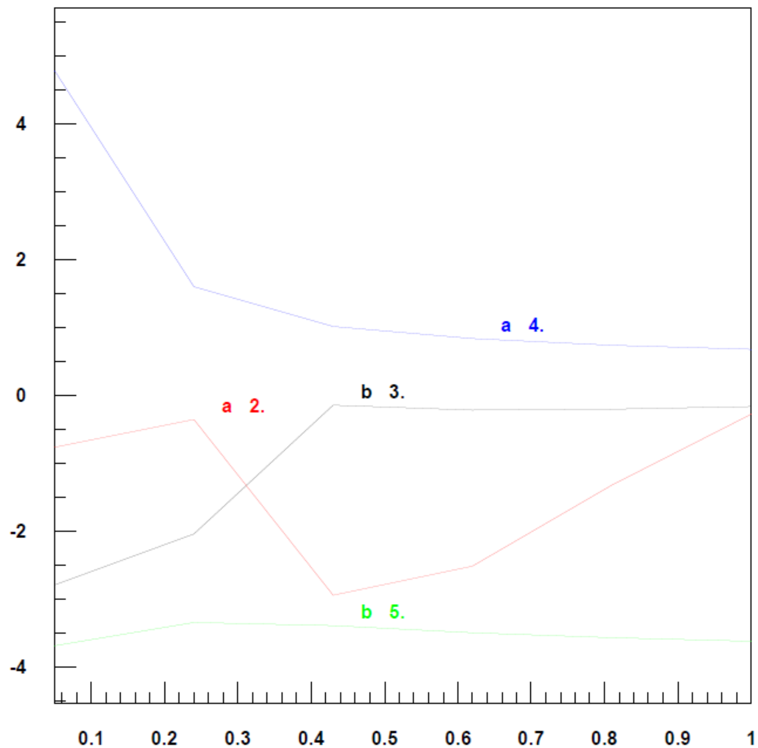
2-D magnetic design optimization **without** ancillary coils

- In this second stage, ancillary coils are included in the layout. They are flat, although flared ends are possible, saving two coils.
- It is strongly recommended by Ramesh Gupta (BNL) and Qingjin Xu (IHEP) during last FCC Week.
- Optimization is more efficient in Roxie when using absolute positions of coil blocks as design variables instead of relative ones (thanks to B. Auchmann).
- The main advantages of this layout would be:
  - Enhanced superconductor efficiency. Optimal aspect ratio of block is around 1.5 (width/height).
  - Shorter cable unit length (less turns per coil).
  - Cross-talk reduction: intra beam distance can be shortened.
  - Large bending radius: react and wind coils.
  - Outer iron radius could be reduced.



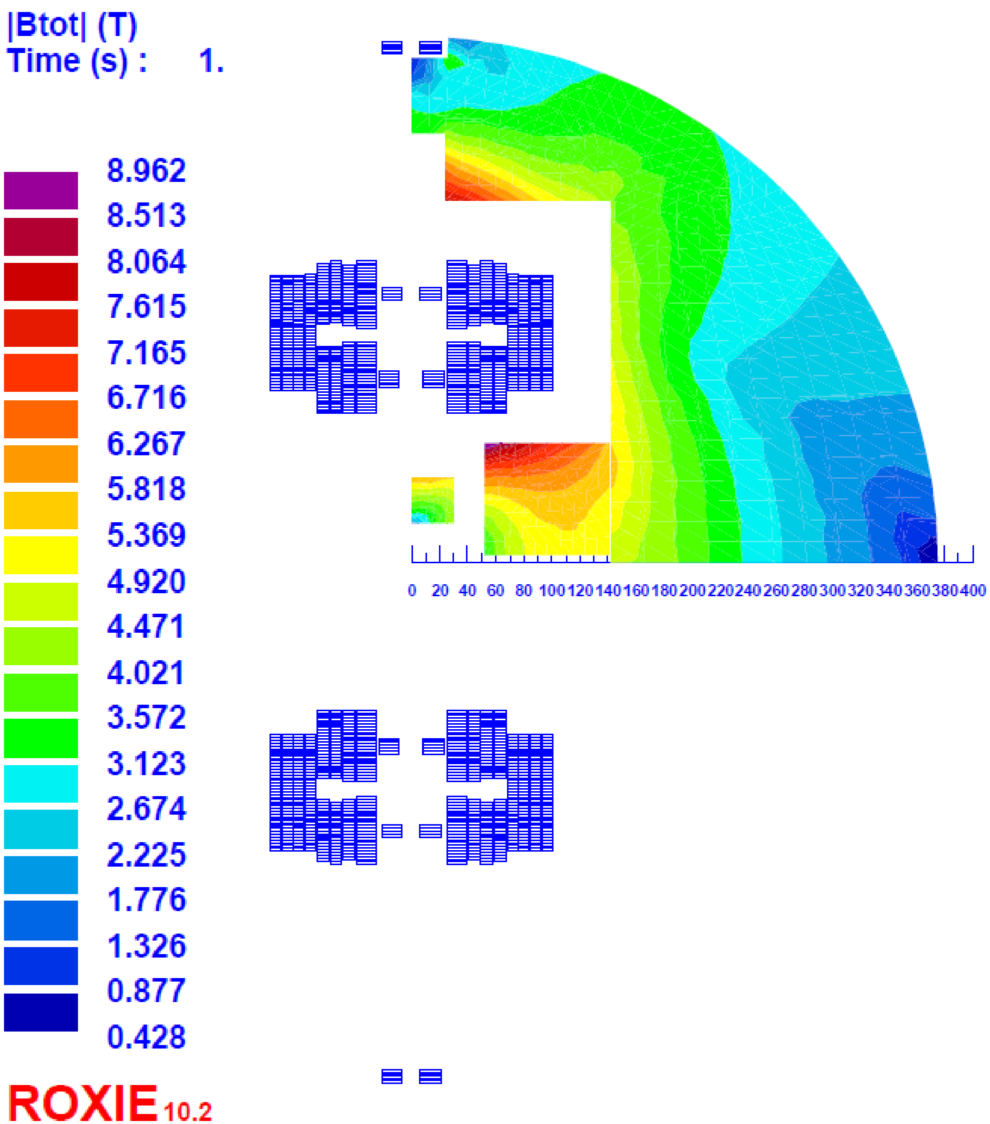
Optimal solution with ancillary coils

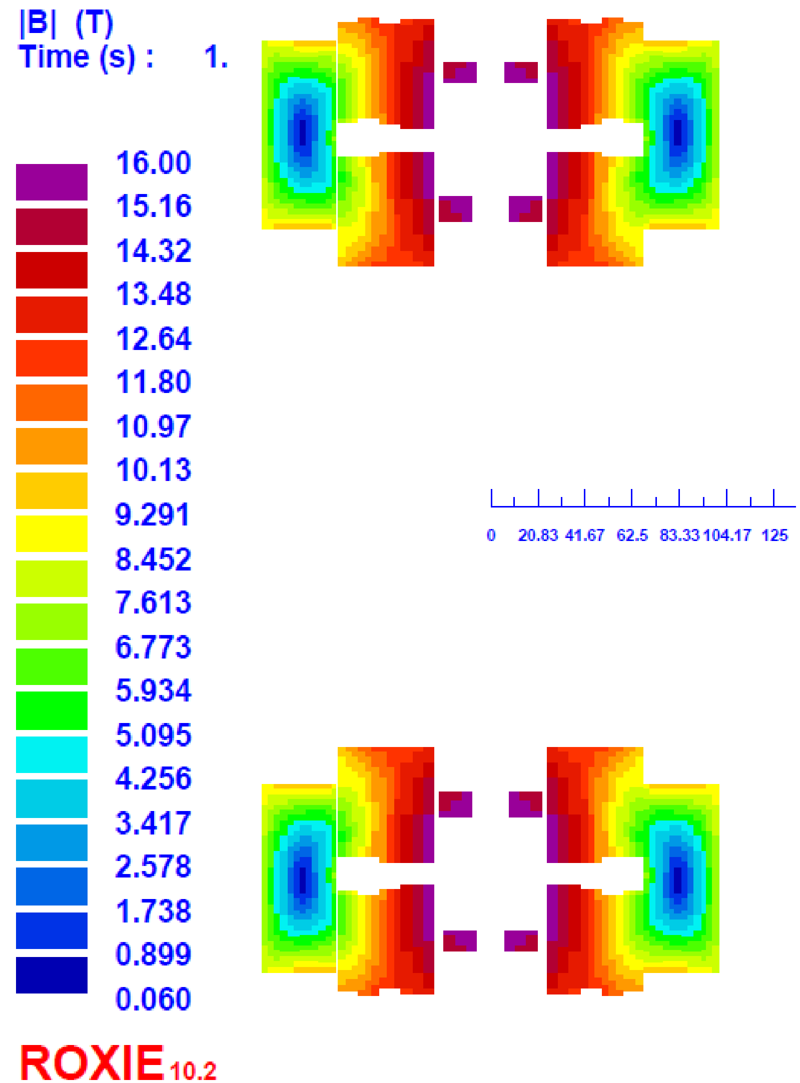
- **Summary**: 320 mm intra-beam distance, 750 mm iron outer diameter, 9 kA nominal current, four main coils, internal splice at high field coil, hotspot temperature close to 350K in all the coils.
- Iron shape is customized to decrease the multipole field variation with current.



Ancillary coils	NO	YES	
Nominal current	9000	9000	A
Intra-beam distance	320	320	mm
Iron outer diameter	750	750	mm
Strand area per magnet	224,5	177,5	cm^2
Total FCC SC weight	12518	9898	ton
Strand area per magnet Cu:Sc=1	165,1	131,2	cm^2
Total FCC SC weight Cu:Sc=1	9204	7315	ton
margin on load line	90,1	90	%
#block	4	2	
peak field	16,5	16,32	T
b3	-1,4	-0,1	units
b5	-4,1	-4,2	units
b7	5,4	-8,9	units
b9	2,2	-3,6	units
a2	-1,8	-0,3	units
a4	1,3	0,8	units
a6	3,9	3,6	units
a8	2,2	3,8	units
inc_b3	14	3	units
inc_a2	10	3	units
Stored energy	5,05	4,62	MJ/m
Static self inductance	124,7	114,1	mH/m
Sum_fx	19,11	14,71	MN/m
Sum_fy	1,5	0,79	MN/m
Stray field 50 mm	0,79	0,65	T
Stray field 1 m	43	46	mT

Optimal solution with ancillary coils





Magnetic design with ancillary coils: sensitivity analysis of intra beam distance

- Cross-talk between apertures is now weaker:
  - The superconductor efficiency slightly decreases with the intra-beam distance.
  - The field quality achievable with short intra-beam distance.
- **Conclusion**: **280 mm** could be the intra beam distance, with a smaller iron outer radius.

Intra-beam distance	**320**	**280**	**mm**
Nominal current	9000	9000	A
Iron outer diameter	750	700	mm
Strand area per magnet	177,5	177,4	cm^2
Total FCC SC weight	9898	9892	ton
Strand area per magnet Cu:Sc=1	131,2	134,7	cm^2
Total FCC SC weight Cu:Sc=1	7315	7512	ton
margin on load line	90	91	%
#block	2	6	
peak field	16,32	16,39	T
b3	-0,1	-3,2	units
b5	-4,2	-6	units
b7	-8,9	-3,9	units
b9	-3,6	-3,9	units
a2	-0,3	-5,9	units
a4	0,8	-0,1	units
a6	3,6	10,9	units
a8	3,8	7,1	units
inc_b3	3	8	units
inc_a2	3	16	units
Stored energy	4,62	4,7	MJ/m
Static self inductance	114,1	116,0	mH/m
Sum_fx	14,71	15,5	MN/m
Sum_fy	0,79	1,45	MN/m
Stray field 50 mm	0,65	0,49	T
Stray field 1 m	46	39	mT

Final considerations: how to go on?

- The cross section is very similar to the block design. The amount of superconductor to provide 16 T field is not very different from other layouts if using ancillary coils.
- The main advantage of the common coil layout is that all **the coils are flat**.
- The main disadvantage is the high **induced voltage during quench** (see T. Salmi's talk):
  - **Stored energy** is larger in the common coil than in the other layouts because there is not common flux between both apertures.
    - It does not decrease with the intrabeam distance, only with the coil size. Engineering current density should be increased: decrease safety margin.
  - **Current should be larger**: the best solution would be to increase the strand diameter or the current density (lower Cu to Sc ratio or safety margin). To increase the number of strands would decrease the superconductor efficiency.
  - Analyze the **connections** between coils to decrease the voltages.
- The thermal gradient between the high field layer and the rest of coils can be reduced by decreasing the Cu to Sc ratio in that cable or RRR (impact on stability??).

Conclusions

- 2-D magnetic optimization of common coil layout for a 16-T dipole has been done.
- Superconductor efficiency is lower than cos-theta or block configurations, but it can be kept moderate if implementing an internal splice at the high field coil, large strands and low nominal current.
- Superconductor efficiency is further enhanced by the use of ancillary coils, although the assembly is more difficult.
- With ancillary coils, the cross section is very similar to block layout. Only differs in the stored energy and the cross talk.
- Low field coil can be made in NbTi if working temperature is 1.9 K.
- High voltages to ground during quench could be decreased with larger currents or higher engineering current density.
- Sensitivity analysis is ongoing, to be used in the cost study: different values of nominal field, load margin and aperture.

Back-up slides

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Magnetic Design Study of the High-Field Common-Coil Dipole Magnet for High-Energy Accelerators

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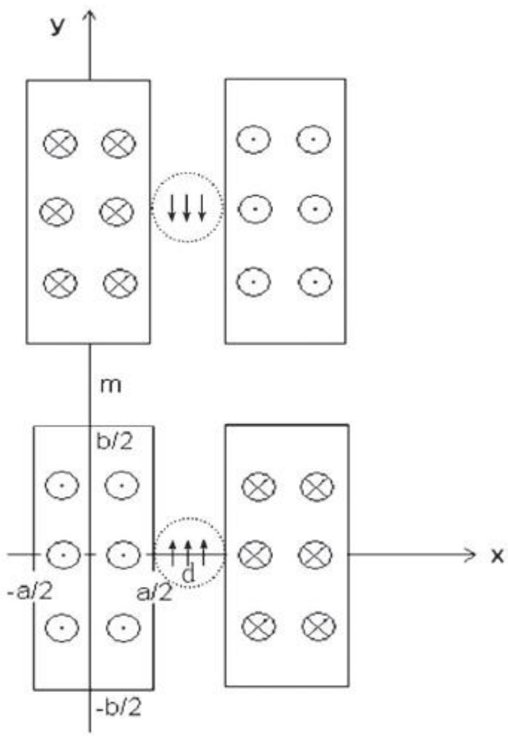

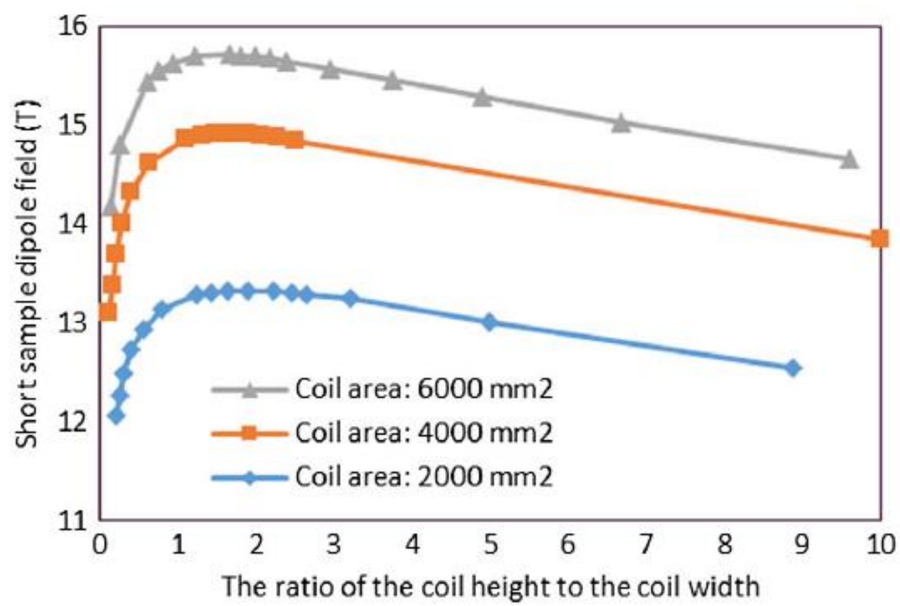

Fig. 2. Variation of the dipole field with different ratios of the coil height to the coil width (b/a in Fig. 1). Calculation results with (5) and (6).

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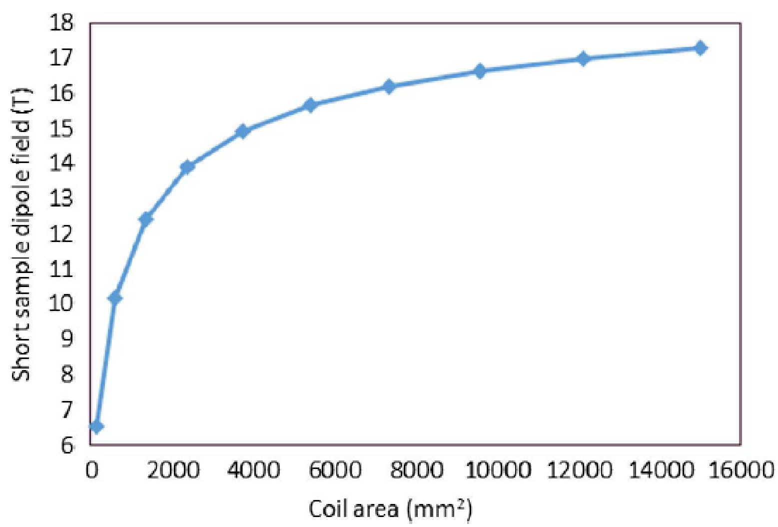


Fig. 3. Relationship between the short sample dipole field and the coil area for the common-coil magnet, assuming the ratio of the coil height to the coil width $b/a = 1.5$. Calculation results with (5) and (6).

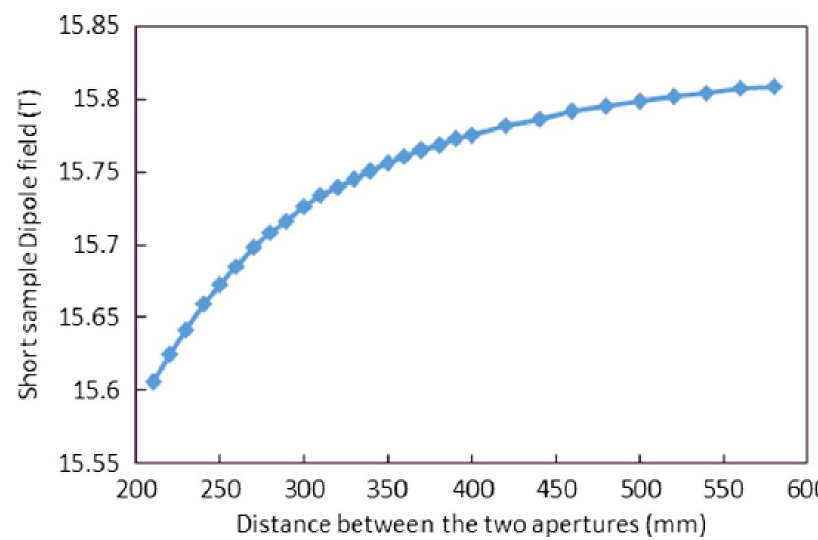


Fig. 4. The variation of the dipole field with different distances between the two apertures ($m + b$ in Fig. 1): Calculation results with (5) and (6).

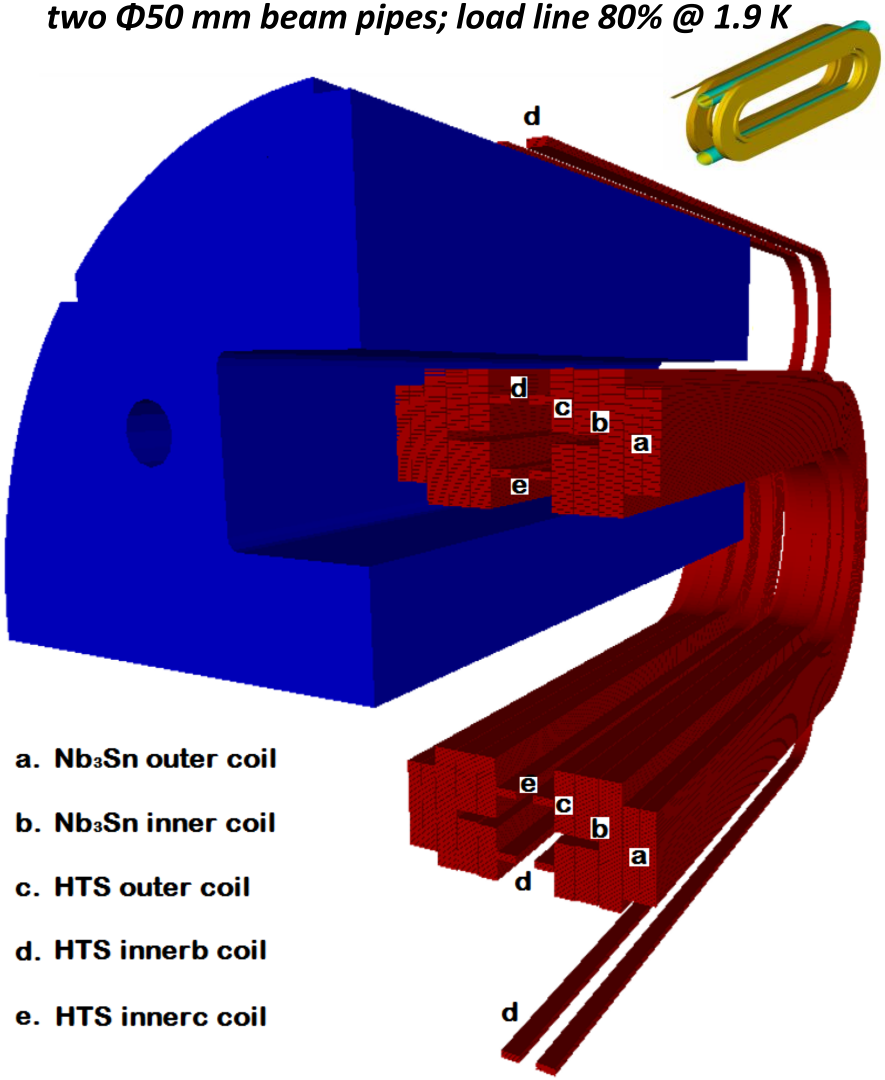
Design Study of the SPPC Dipole Magnet

Q. Xu, K. Zhang, C. Wang et al.

With common coil configuration

20-T dipole magnet with common coil configuration

two Φ50 mm beam pipes; load line 80% @ 1.9 K



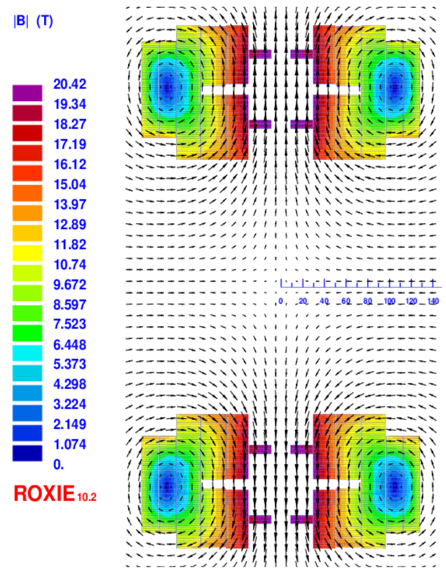
a. Nb_3Sn outer coil

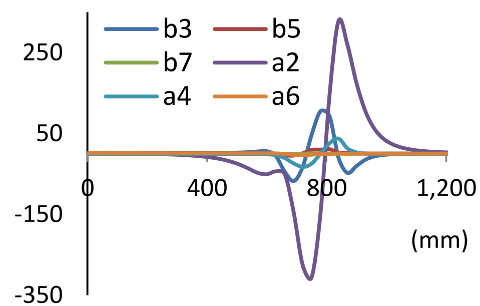
b. Nb_3Sn inner coil

c. HTS outer coil

d. HTS innerb coil

e. HTS innerc coil



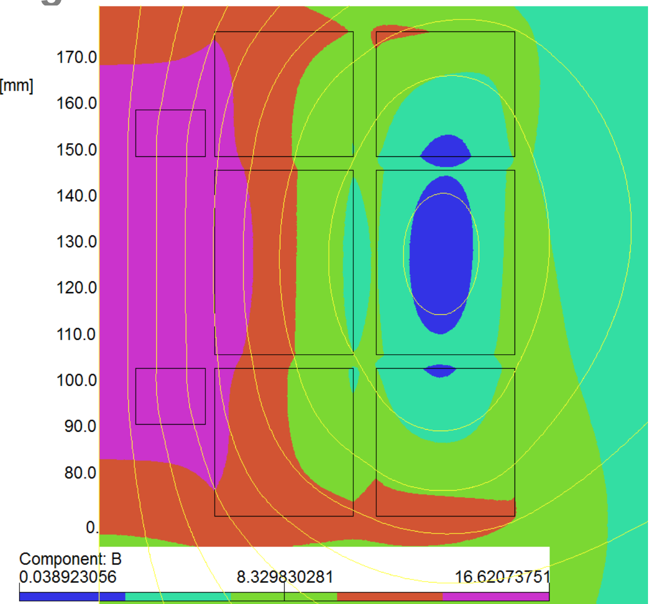


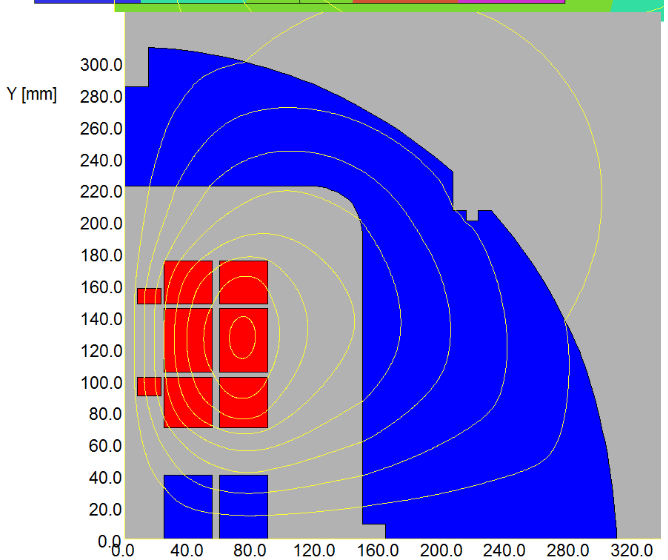
Integrated b_n/a_n	Value (10^{-4})
b3	0.14
b5	1.42
b7	-0.40
a2	-0.29
a4	-1.81
a6	0.03

Magnet		Number of apertures	2
		Aperture diameter (mm)	50
		Inter-aperture spacing (mm)	333
		Operating current (A)	14700
		Operating temperature (K)	4.2
		Operating field (T)	20
		Peak field (T)	20.4
		Margin along the load line (%)	11
		Stored magnetic energy (MJ/m)	7.8
		Inductance (mH/m)	72.1
		Yoke ID (mm)	260
		Yoke OD (mm)	800
		Weight per unit length (kg/m)	3200
		Energy density (coil volume) (MJ/m^3)	738
		Force per aperture – X / Y (MN/m)	23.5/4.4
		Peak stress in coil (MPa)	240
		Fringe Field @ r = 750 mm (T)	0.02
Coil	Nb_3Sn	Number of layers	2
	outer	Number of turns per layer	46
(2 Nb_3Sn		Bending radius (mm)	127.8
outer +	Nb_3Sn	Number of layers	2
2 Nb_3Sn	inner	Number of turns per layer	59/64
inner +		Bending radius (mm)	109.1
2 HTS	HTS	Number of layers	1
outer +	outer	Number of turns per layer	59
4 HTS		Bending radius (mm)	109.0
inner-b +	HTS	Number of layers	1
2 HTS	inner-b	Number of turns per layer	4
inner-c)		Bending radius (mm)	135.7
	HTS	Number of layers	1
	inner-c	Number of turns per layer	4
		Bending radius (mm)	100.9
Cable	Nb_3Sn	Number of strands	38
	outer	Cable dimension (mm^2)	15*1.5
(Nb_3Sn		Insulation thickness (mm)	0.15
outer	Nb_3Sn	Number of strands	56
+	inner	Cable dimension (mm^2)	22*1.5
Nb_3Sn		Insulation thickness (mm)	0.15
inner	HTS	Number of strands	50
+		Cable dimension (mm^2)	20*1.5
HTS cable)		Insulation thickness (mm)	0.15
Strand	Nb_3Sn	Diameter (mm)	0.82
		Copper/Superconductor ratio	1
(Nb_3Sn		Non-Cu J_c (A/mm^2 @15 T, 4.2 K)	1500
+		dJ_c/dB (A/T)	350
HTS)	HTS	Diameter (mm)	0.82
		Copper/Superconductor ratio	1
		Non-Cu J_c (A/mm^2 @20 T, 4.2 K)	1300
		dJ_c/dB (A/T)	13

Q. Xu, K. Zhang, C. Wang et. al., 20-T Dipole Magnet with Common Coil Configuration: Main Characteristics and Challenges, IEEE Trans. Appl. Supercond., VOL. 26, NO. 4, 2016， 4000404

A Few Parameters of Preliminary 16 T Common Coil PoP Dipole





Aperture : 50 mm

Bore Field: 16.05 T

Current: 10. 6 kA

Stored Energy (per aperture) : 1.8 MJ/m

Peak field : 16. 62 T

Peak Enhancement = 3.6%

Conductor: Same as used in FNAL design

15 T Dipole Outer Layer	40 x 0.7 mm	15043, 15044, 15045, 15244, 15245, 15290	108/127 (Ti)	374 m	1.251±0.001 x 14.71±0.01 mm², 16.8 deg	11.0 mm	Oct. 2013 1-pass
15 T Dipole Inner Layer	28 x 1 mm	16638, 16639, 16640	150/169 (Ti)	420 m	1.803±0.002 x 14.79±0.02 mm², 15.5 deg	11.0 mm	Dec 2015 1-pass

Fermilab

FNAL HFM and Nb3Sn conductor R&D 2/8/2016