Preliminary Design Study of the High Field Dipole Magnets for CEPC-SppC

Qingjin XU
On behalf of the SppC magnet working group

Institute of High Energy Physics (IHEP)
Chinese Academy of Sciences (CAS)
Beijing, China

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Outline

- Background: SppC and the main dipole requirements
- Why started with the common coil ?
- Analytical modeling of the common coil configuration
- Preliminary design study of a 20-T common coil dipole
- Summary

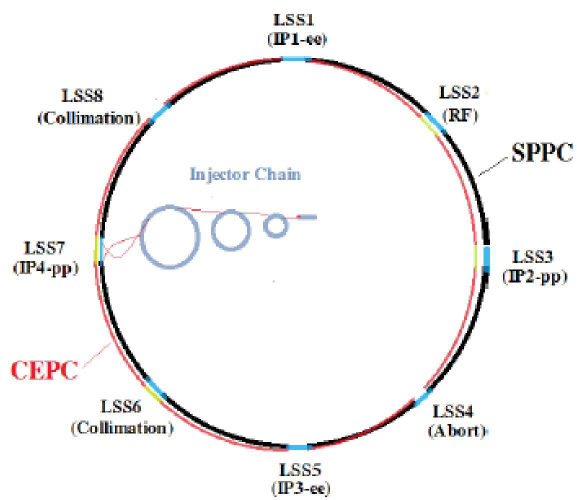
SppC and the main dipole requirements

SppC
- *50/100 km in circumference*
- *C.M. energy 70 TeV or higher*
- *Timeline*

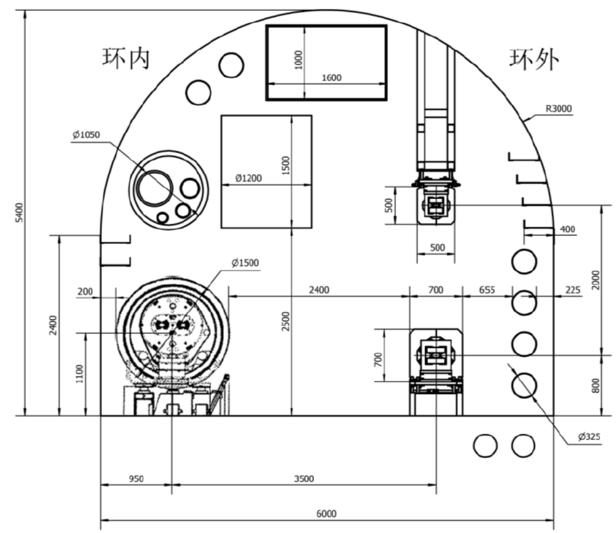
Pre-study:	*2013-2020*
R&D:	*2020-2030*
Eng. Design:	*2030-2035*
Construction:	*2035-2042*

Main dipoles
- *Field strength: 20 Tesla*
- *Aperture diameter: 40~50 mm*
- *Field quality: 10^{-4} at the 2/3 aperture radius*
- *Outer diameter: 900 mm in a 1.5 m cryostat*
- *Tunnel cross section: 6 m wide and 5.4 m high*

The CEPC-SPPC ring sited in Qinhuangdao, 50 km and 100 km options .



SPPC accelerator complex



6-m Tunnel for CEPC-SppC. Left: SPPC collider. Right: CEPC collider (bottom) and Booster (top)

CEPC-SppC Pre-CDR, Mar. 2015

R&D plan of the 20-T magnet technology

2015-2020

Development of a 12-T operational field Nb_3Sn twin-aperture dipole with 10^{-4} field quality; Fabrication and test of 2~3 T HTS (Bi-2212 or YBCO) coils in a 12-T background field and basic study on tape superconductors for accelerator magnets (field quality, fabrication method, quench protection).

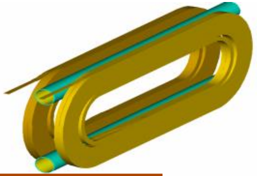
2020-2025

Development of 15-T Nb_3Sn twin-aperture dipole and quadrupole with 10^{-4} field uniformity; Fabrication and test of 4~5 T HTS (Bi-2212 or YBCO) coils in a 15-T background field.

2025-2030

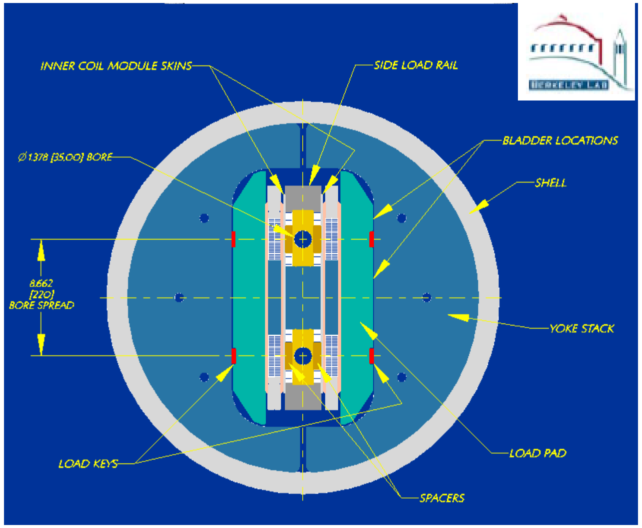
Nb_3Sn coils + HTS coils (*or only one of them*) to realize the 20-T dipole and quadrupole with 10^{-4} field uniformity; Development of the prototype SppC dipole/quadrupole and infrastructure build-up.

Why started with the common coil ?

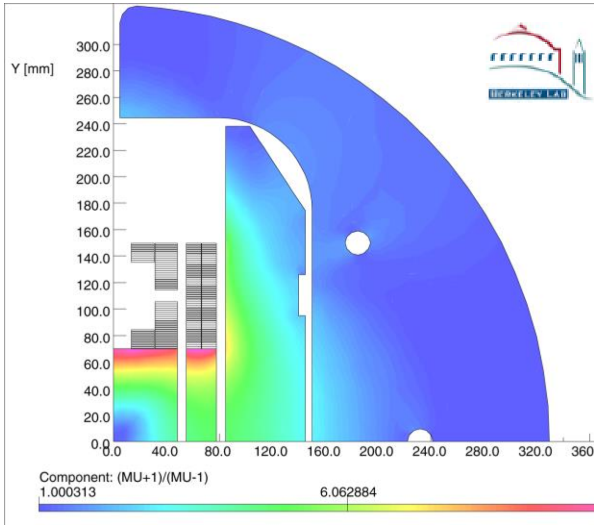


- *Simplest geometry, easy to fabricate;*
- *Good configuration to generate high field for technology demonstration;*
- *Twin-aperture configuration close to the final design for pp colliders;*
- *Much larger bending radius provides possibility for react & wind fabrication method;*
- *Common coil magnet development has taken place at LBNL, BNL, FNAL but scope was limited to technology tests, still need to answer critical questions on field quality and efficiency.*

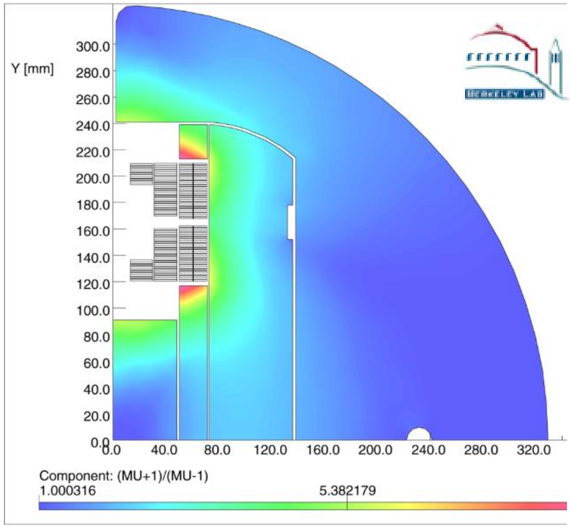
10 T RD3C done



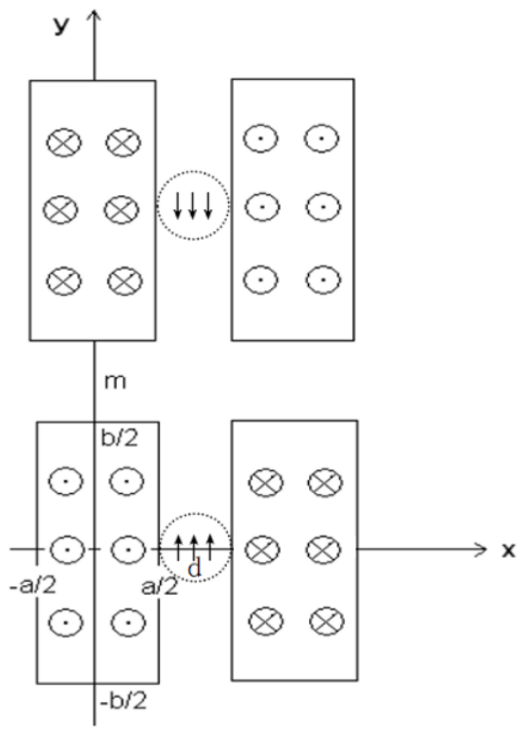
13 T RD4 stopped



15 T RD5 stopped



Analytical modeling of the common coil dipole



The four blocks represent the two racetrack coils with opposite current directions.

a: ***coil width;***

b: ***coil height;***

d: ***aperture diameter;***

m/2: ***bending radius of the racetrack coils.***

The magnetic field generated by a current-carrying wire located at (x_0, y_0) fulfils the Biot-Savart Law in Cartesian coordinates

$$B_y = \frac{\mu_0 I}{2\pi}\frac{x - x_0}{(x-x_0)^2 + (y-y_0)^2}$$

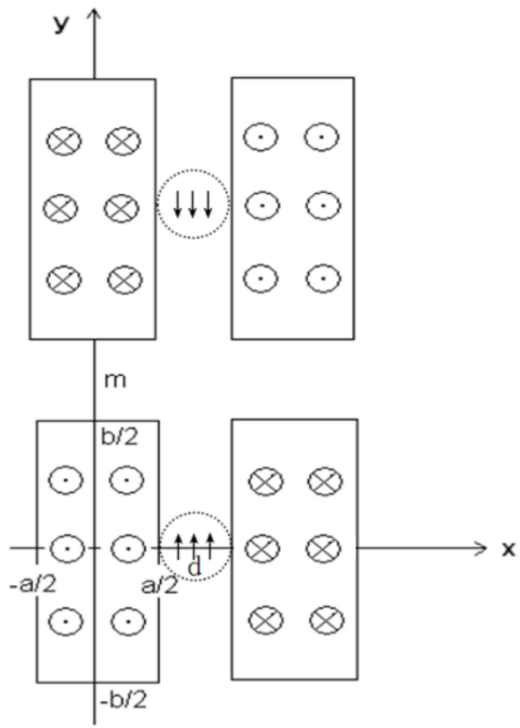
By integrating Biot-Savart Law in the four current-carrying blocks*, the magnetic field in the twin-aperture can be derived as*

$$\begin{aligned}B_y = \frac{\mu_0 J}{4\pi}\Bigg[&\int_{-\frac{b}{2}}^{\frac{b}{2}} \ln\frac{\left(x+\frac{a}{2}\right)^2+(y-y_0)^2}{\left(x-\frac{a}{2}\right)^2+(y-y_0)^2}\,dy_0 \\ &+\int_{-\frac{b}{2}}^{\frac{b}{2}} \ln\frac{\left(\frac{3a}{2}+d-x\right)^2+(y-y_0)^2}{\left(\frac{a}{2}+d-x\right)^2+(y-y_0)^2}\,dy_0 \\ &-\int_{-\frac{b}{2}}^{\frac{b}{2}} \ln\frac{\left(x+\frac{a}{2}\right)^2+(m+b-y-y_0)^2}{\left(x-\frac{a}{2}\right)^2+(m+b-y-y_0)^2}\,dy_0 \\ &-\int_{-\frac{b}{2}}^{\frac{b}{2}} \ln\frac{\left(\frac{3a}{2}+d-x\right)^2+(m+b-y-y_0)^2}{\left(\frac{a}{2}+d-x\right)^2+(m+b-y-y_0)^2}\,dy_0\Bigg]\end{aligned}$$

Replacing x with (a + d)/2 and y with 0 in above equation, we get the main dipole field of the common-coil configuration as

$$B_y = \frac{\mu_0 J}{2\pi}\int_{-\frac{b}{2}}^{\frac{b}{2}} \ln\left(\frac{\left(a+\frac{d}{2}\right)^2+y_0^2}{\left(\frac{d}{2}\right)^2+y_0^2} * \frac{\left(\frac{d}{2}\right)^2+(m+b-y_0)^2}{\left(a+\frac{d}{2}\right)^2+(m+b-y_0)^2}\right)dy_0$$

Analytical modeling of the common coil dipole



The four blocks represent the two racetrack coils with opposite current directions.

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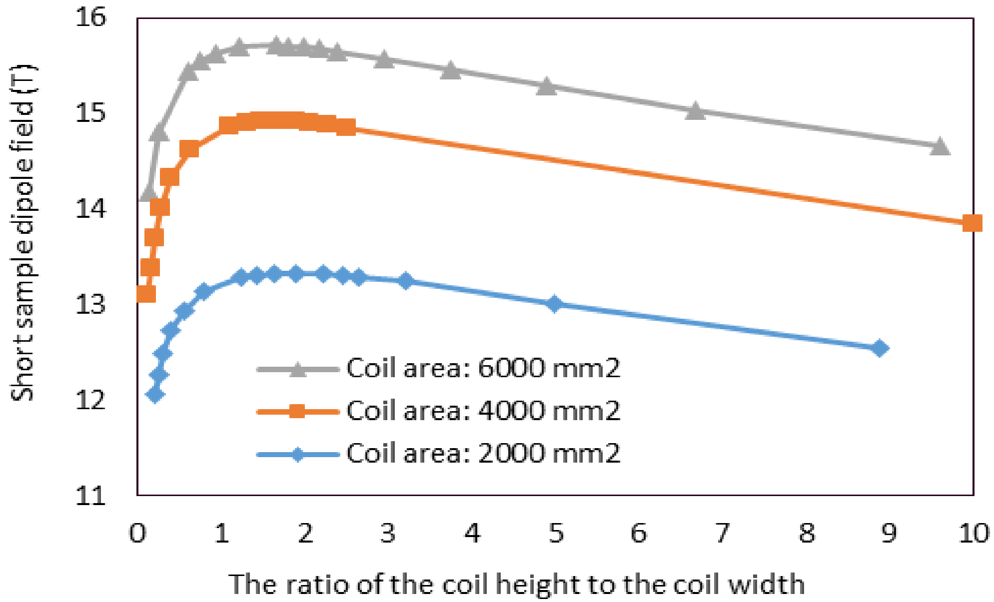
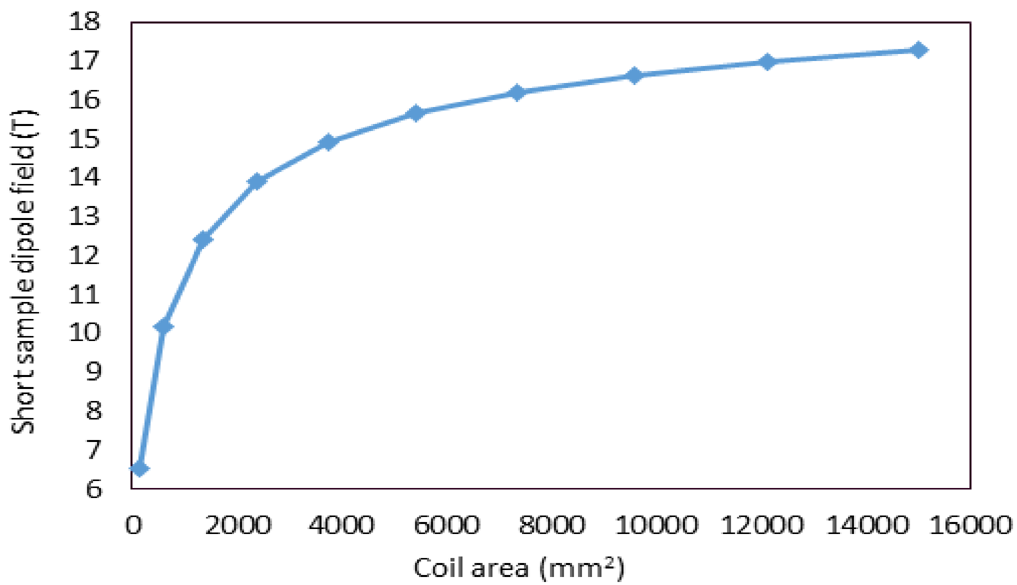
m/2: ***bending radius of the racetrack coils.***

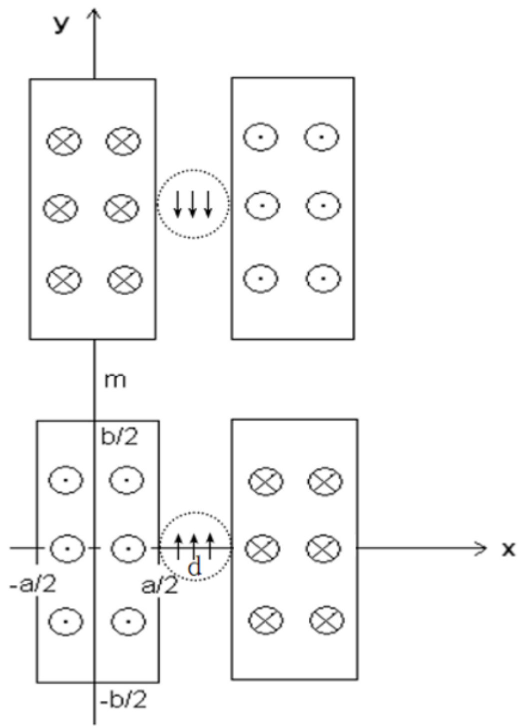
B_s vs. b/a



B_s vs. $b*a$



Analytical modeling of the common coil dipole



The four blocks represent the two racetrack coils with opposite current directions.

a: ***coil width;***

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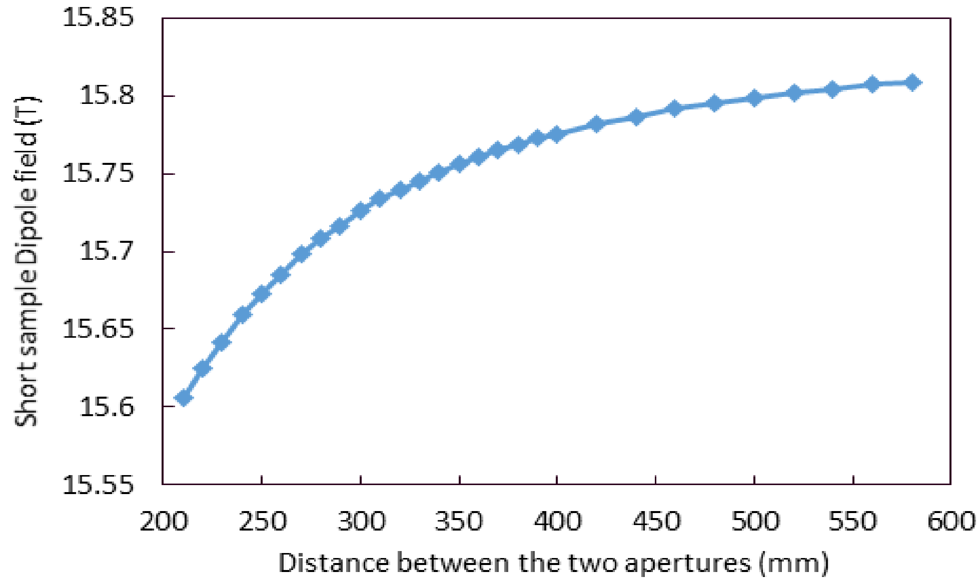
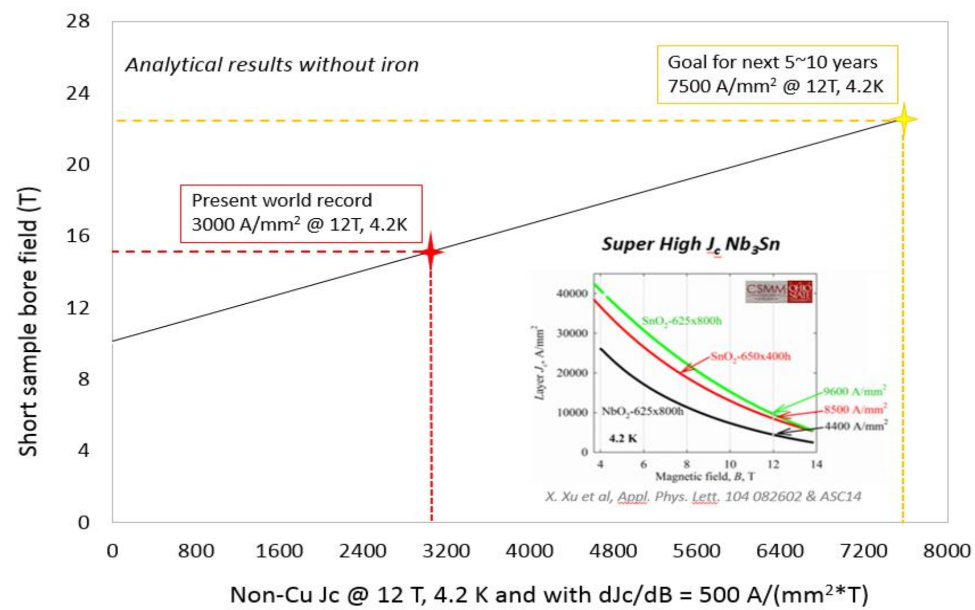
B_s vs. $m+b$



B_s vs. J_c

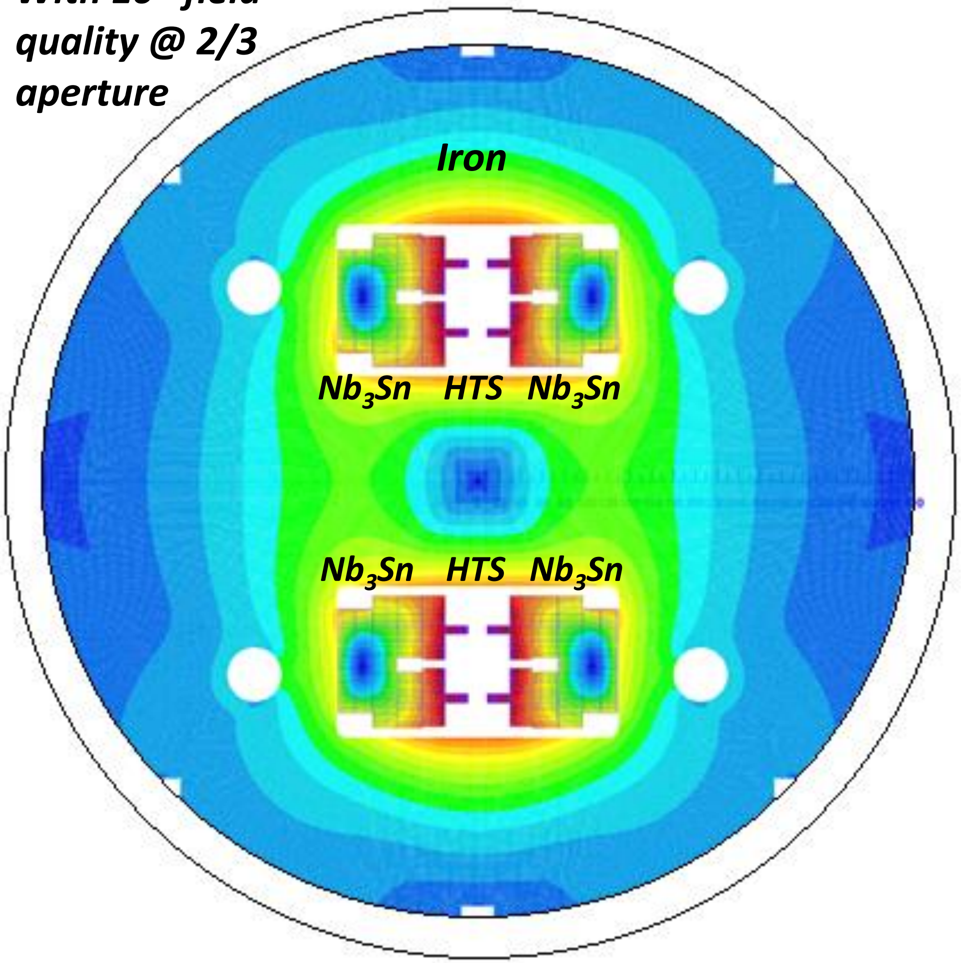


Preliminary Design study of a 20-T dipole

20-T Nb_3Sn + HTS common coil dipole for SppC

Space for beam pipes: 2 * Φ50 mm, with the load line ratio of ~80% @ 1.9 K and the yoke diameter of 800 mm

With 10^{-4} field quality @ 2/3 aperture

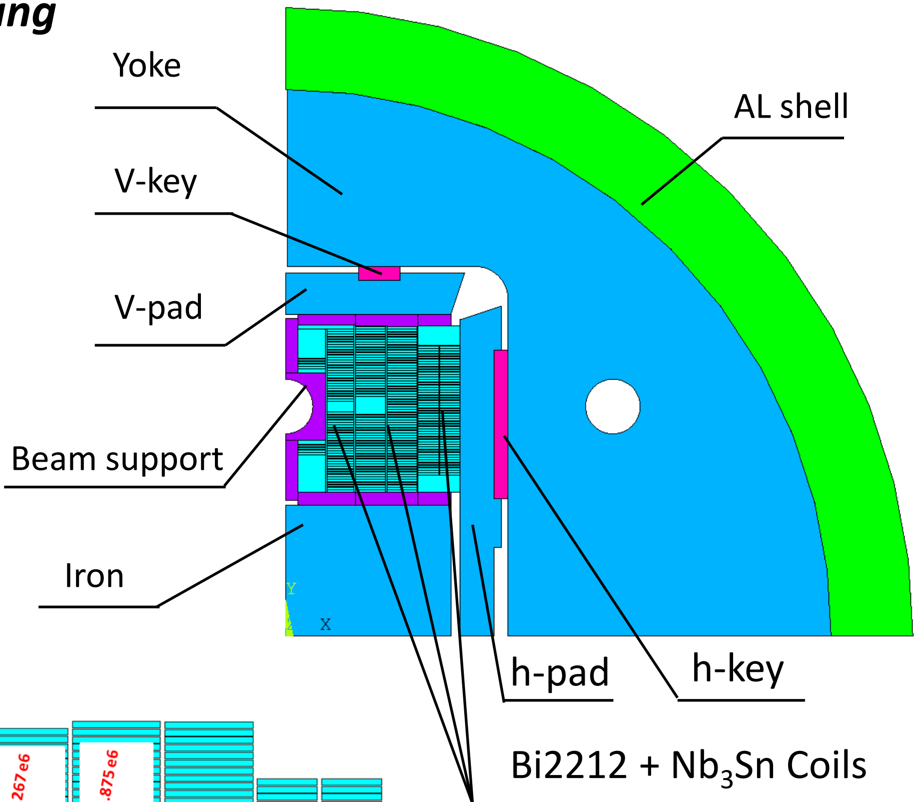


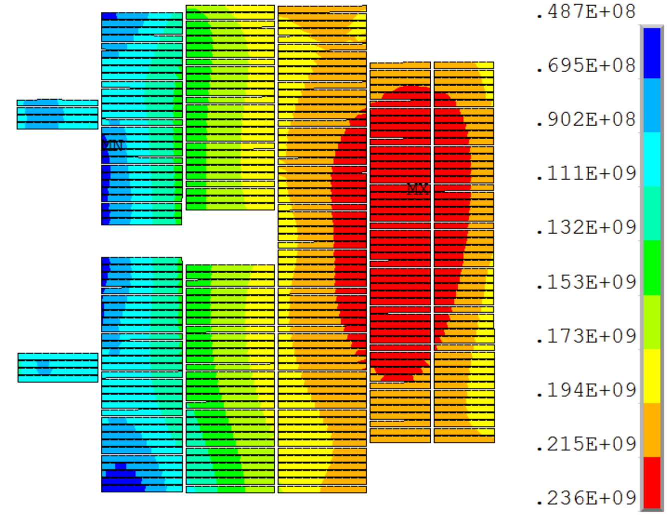
Main Design Parameters

Number of apertures	(-)	2
Aperture diameter	(mm)	50
Inter-aperture spacing	(mm)	330
Operating current	(A)	14700
Operating temperature	(K)	1.9
Operating field	(T)	20
Peak field	(T)	20.4
Margin along the loadline	(%)	~20
Stored magnetic energy	(MJ/m)	7.8
Inductance (magnet)	(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
Winding pack current density	(A/mm^2)	400
Force per aperture – X/Y	**(MN/m)**	**23.4/2.4**
Peak stress in coil	**(MPa)**	**240**
Fringe Field @ r = 750 mm	(T)	0.02

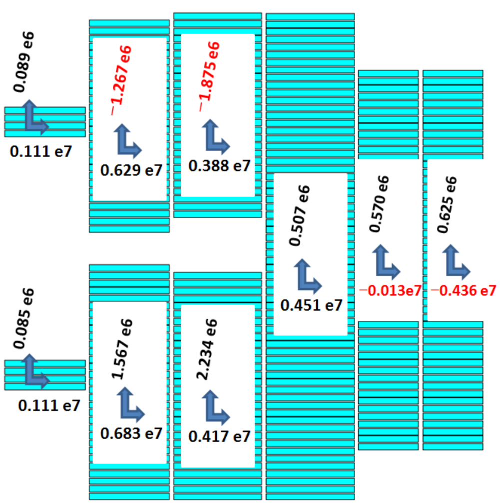
Preliminary Design study of a 20-T dipole

Kai Zhang





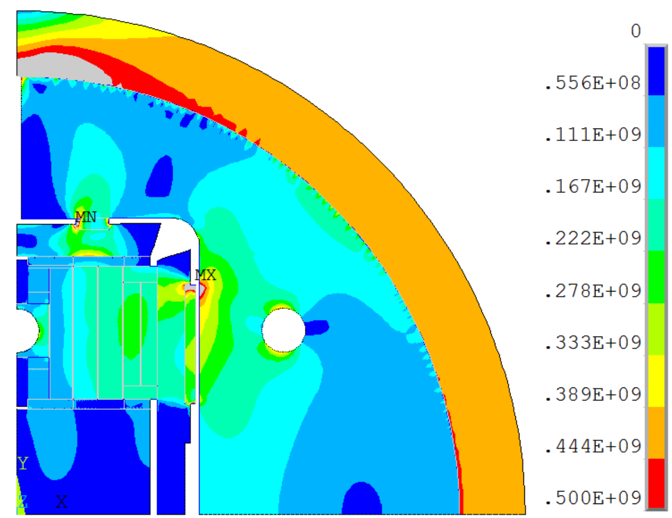
Stress in coil after excitation



Total lorentz force per aperture:

Fmag_x=23.4 MN/m

Fmag_y=2.38 MN/m



Stress in shell after excitation

Preliminary Design study of a 20-T dipole

Kai Zhang

	AL Shell thickness (mm)	Inteference (mm)	Fx1 ($\times 10^7$N/m)	Fx2 ($\times 10^7$N/m)	Fx3 ($\times 10^7$N/m)	$\overline{\sigma_{AL}}$ (MPa)
1	40	5.0	1.9168	2.3978	2.4680	626.3
2	50	4.0	1.8655	2.3821	2.4663	501.0
3	60	3.4	1.8091	2.3954	2.4896	423.4
4	80	2.6	1.6816	2.3888	2.5033	321.6
5	100	2.1	1.5592	2.3654	2.4991	258.8

Fx1: horizontal force transmitted by h-key after load 1;

Fx2: horizontal force transmitted by h-key after load 2;

Fx3: horizontal force transmitted by h-key after load 3;

$\overline{\sigma_{AL}}$: average von mises stress on AL shell after load 3.

Large interference is required by applying the preload with water pressurized bladder because the AL shell is not that rigid and the horizontal magnetic force is so large.

Preliminary Design study of a 20-T dipole

Kai Zhang

Material	Yield strength （MPa）			Young's modulus (GPa)
	300K	77K	4K	
316LN annealed	310	607	815	200
304L annealed	400	460	550	200
AL 6061-T6	300	360	380	
AL 7075-T6	502	589	648	63.2-74.4
AL 7475-T761	460	549	572	66.3-76.4
AL 2219-T87	397	484	539	67.8-77.9
AL 2090-T8E41	488	551	614	74.0-84.1

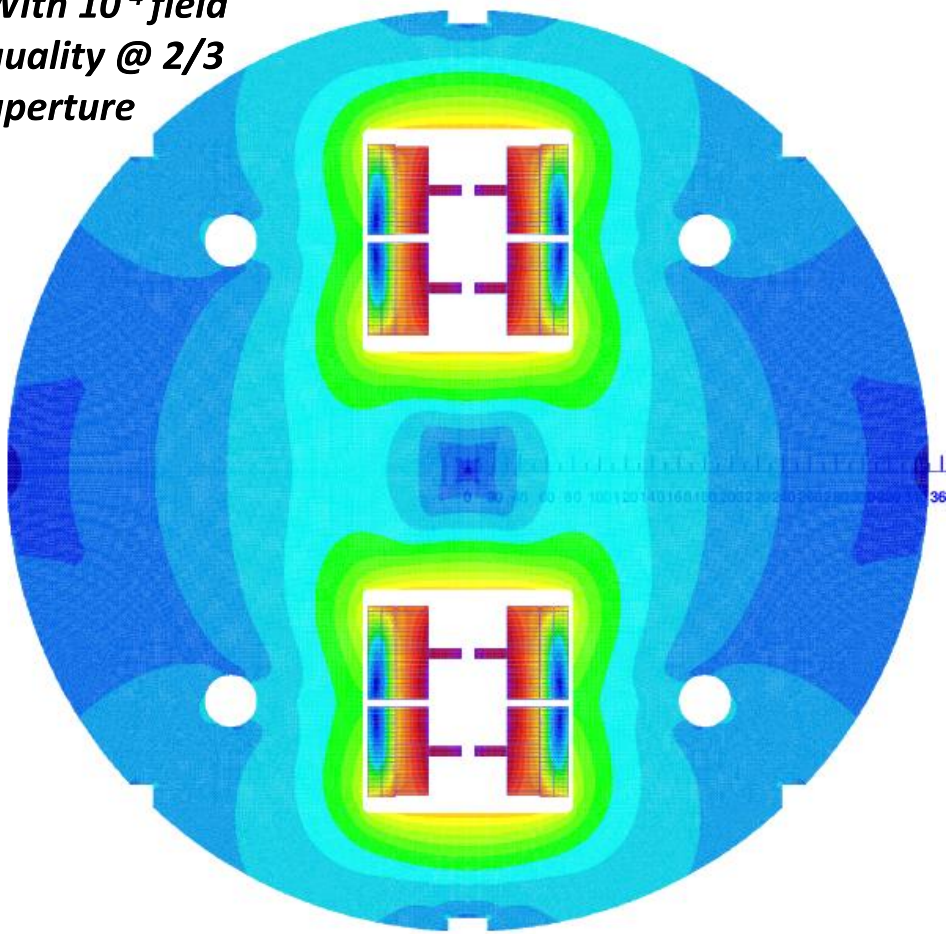
Design study of a 16-T common coil dipole

(Homework for FCC Magnet Study)

16-T Nb_3Sn common coil dipole

Space for beam pipes: 2 * Φ50 mm, with the load line ratio of ~83% @ 1.9 K and the yoke diameter of 700 mm

With 10^{-4} field quality @ 2/3 aperture



Main Design Parameters

Number of apertures	(-)	2
Aperture	(mm)	50
Inter-aperture spacing	(mm)	350
Operating current	(A)	13200
Operating temperature	(K)	1.9
Operating field	(T)	16
Peak field	(T)	16.4
Margin along the loadline	(%)	~20
Stored magnetic energy	(MJ/m)	3.6
Inductance (magnet)	(mH/m)	41
Yoke ID	(mm)	160
Yoke OD	(mm)	700
Weight per unit length	(kg/m)	2500
Energy density (coil volume)	(MJ/m^3)	808
Winding pack current density	(A/mm^2)	670
Force per aperture – X/Y	(MN/m)	17.4/0.4
Peak stress in coil	(MPa)	180
Fringe Field @ r = 750 mm	(T)	0.01

Summary

- *R&D of high field accelerator magnets has started in China from last year. To achieve the challenging 20-T target required by CEPC-SppC, a 15-year long term R&D plan is under discussion.*
- *Preliminary design study of the 20-T level dipoles is ongoing with the common coil configuration. The other coil configurations (block type, cos-theta, canted cos-theta) are also candidates for study in future.*
- *Main advantages of the common coil configuration*

  a) Simplest geometry for twin-aperture dipole, easy to fabricate;

  b) Large bending radius allows for react & wind fabrication method;

  c) Without any hard-way bending lower strain level in coils;
- *Disadvantages of the common coil configuration*

  a) Inefficiency comparing with cos-theta & block type configuration;

  b) needs double the support strength for the twin-aperture dipoles;

  c) a bit longer coil ends.

Study is still ongoing…

Interested with CEPC-SppC ?

The CEPC-SppC accelerator preCDR is available here:
http://cepc.ihep.ac.cn/preCDR/volume.html

Interested with a long term 20-T magnet R&D ?

An
ICFA mini-workshop on high field magnets for pp colliders
will be held in Shanghai from June 15th to 17th
Detail information can be found here:
http://indico.ihep.ac.cn/e/hfm2015

Thanks for everything!