Status of Magnet R&D for CEPC Detector

Zhao Ling/Zhao Wei, IHEP

CEPC-SPPC Symposium, April 8-9, 2016

Outline

一 总体介绍

二 磁铁物理设计

三 磁铁技术 R&D

四 Summary

探测器磁铁研究总体介绍

Requirements:

Achieving the magnetic field;

Tracking volume within which *H* (*x, y, z*) is specified;

Magnet options:

Solenoid coil with iron yoke

Key Issues:

Design optimization：

- field homogeneity in the tracking volume
- the stray field distribution
- Iron yoke configuration and cost reduction

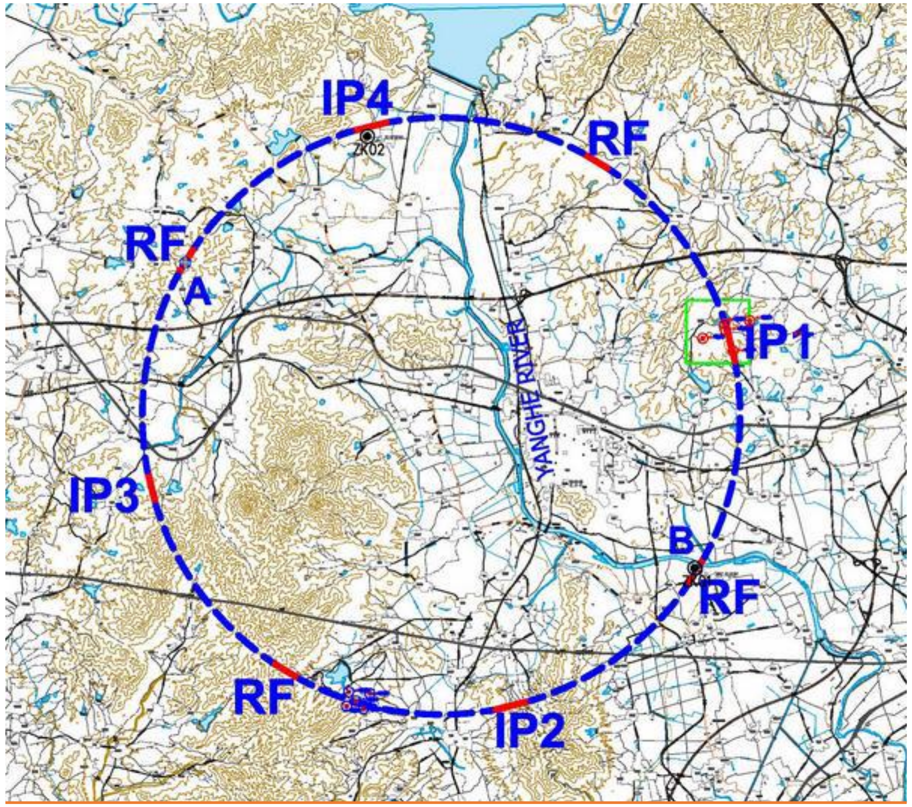
Conductor: Rutherford type cable 18.5kA ; mechanical reinforcement

Cryogenics: Thermal-siphon technology

Mechanical integrity

Protection

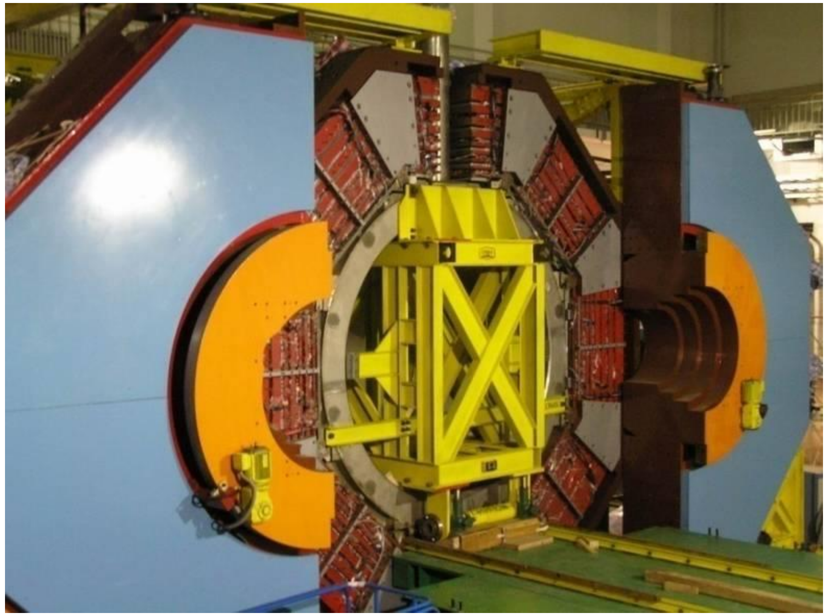
CEPC pre-CDR layout



	CEPC
Central field(T)	3.5
Max. field(T)	3.85
coil inner diameter (mm)	3600
Coil outer diameter (mm)	3900
Tracking volume(mm)	2350*1810

Superconducting Solenoid Magnet for BESIII detector

- An axial magnetic field of 1 T with a uniformity of 5% within the 3 m diameter volume of drift chamber for momentum measurement of charged secondary particles.
- The coil was indirectly cooled by forced flow of two-phase helium circulating inside tubes.



2001年7月，课题组开始调研BESIII超导磁体(SSM)方案。

国外厂家报价为5千万元，国内自主研制费用为2.5千万元，大幅度降低了制造费用。

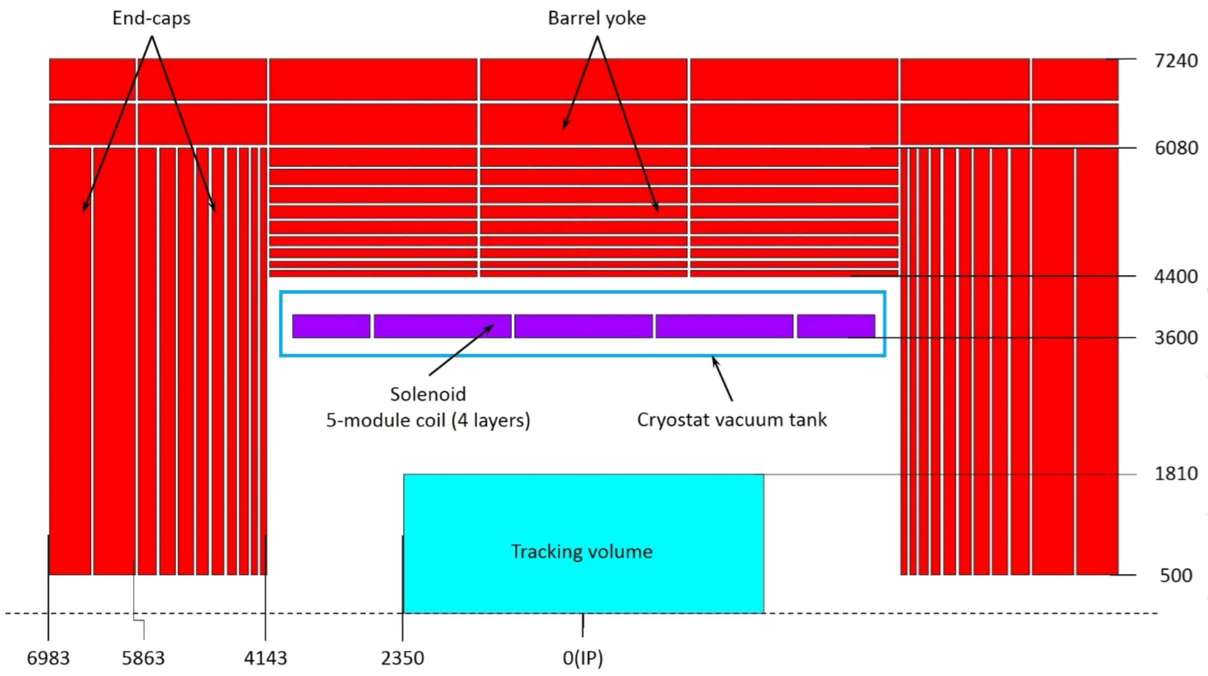
磁铁物理设计

- Design of solenoid coil with iron yoke

	CMS	SiD	CEPC
Central field(T)	4	5.0	3.5
Max. field(T)	4.6	5.6	3.85
coil inner diameter (mm)	3180	2731	3600
Coil outer diameter (mm)	3490	3112	3900
Coil length (mm)	12400	5586	7600
superconductor length(Km)		26.8	30.5
Dimension of superconductor(mm)	22×64	21.6×64	23×75
layers	4	6	4
Total turns	2168	1458	1288
Stroed energy(GJ)	2.69	1.7	1.8
Inductance(H)	14.2	10.7	10.4
Nominal current(A)	19200	17800	18600
Total weight(t)	10000	5218	12200

Field design and optimization

- The 7.4 m long coil is composed of 5 modules;
- Each middle module has 4 layers, with 78 turns per layer. Each end module also has 4 layers, but with 44 turns per layer.
- The nominal current is 18.5 kA for the design maximum central field of 3.5T.

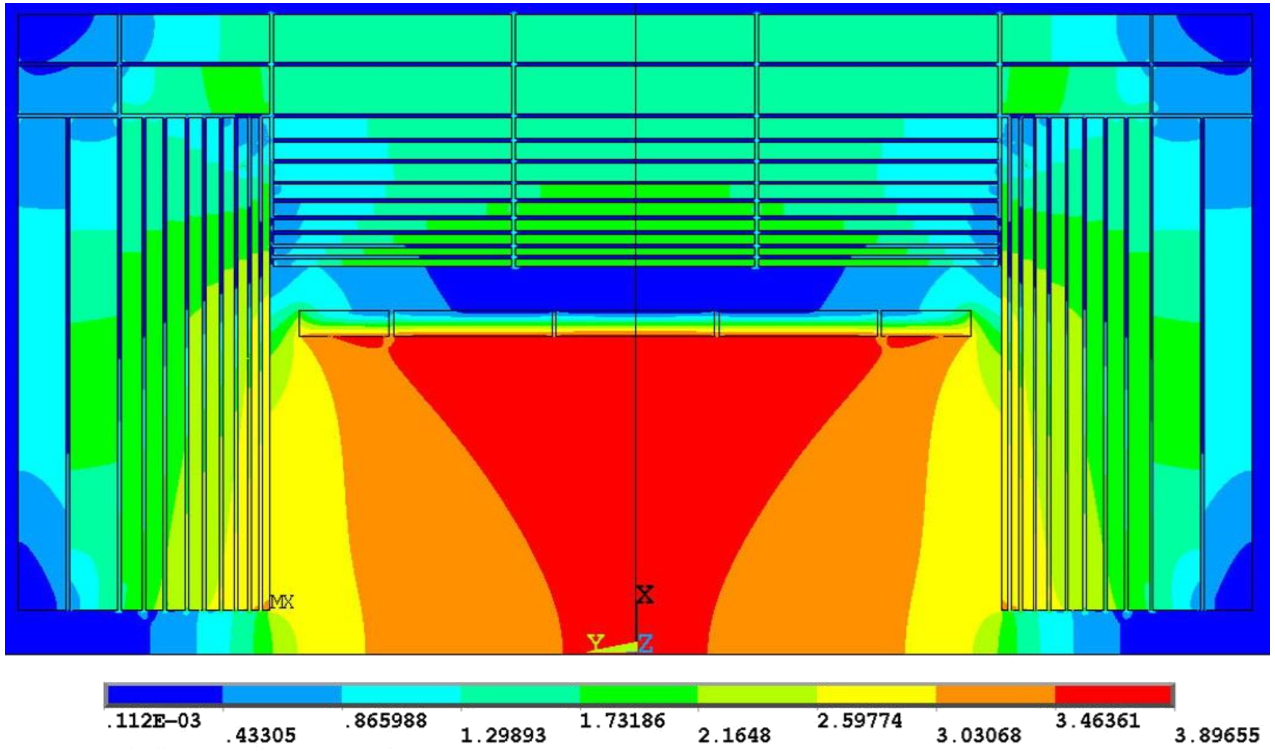


轭铁边沿6.983米

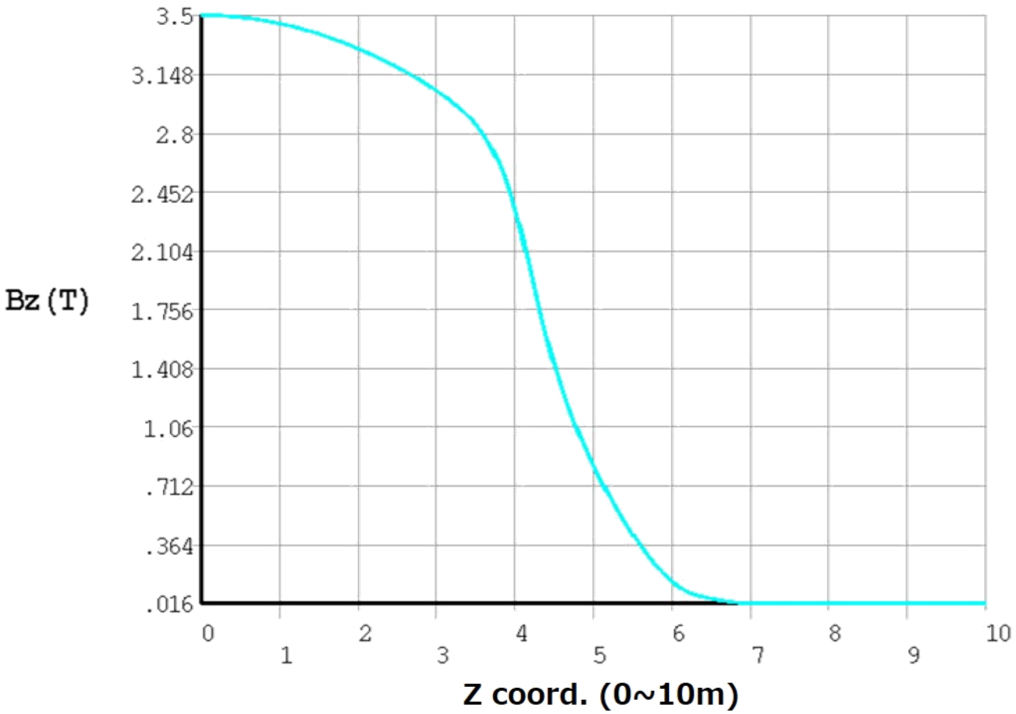
Main parameters of the CEPC detector magnet

Solenoid central field [T]	3.5	Nominal current [kA]	18.575
Maximum field on conductor [T]	3.85	Total ampere-turns of solenoid [MAt]	23.925
Coil inner radius [mm]	3600	Inductance [H]	10.4
Coil outer radius [mm]	3900	Stored energy [GJ]	1.8
Coil length [mm]	7600	Stored energy per unit of cold mass [KJ/kg]	10.91

• **Magnetic field distribution of the magnet**



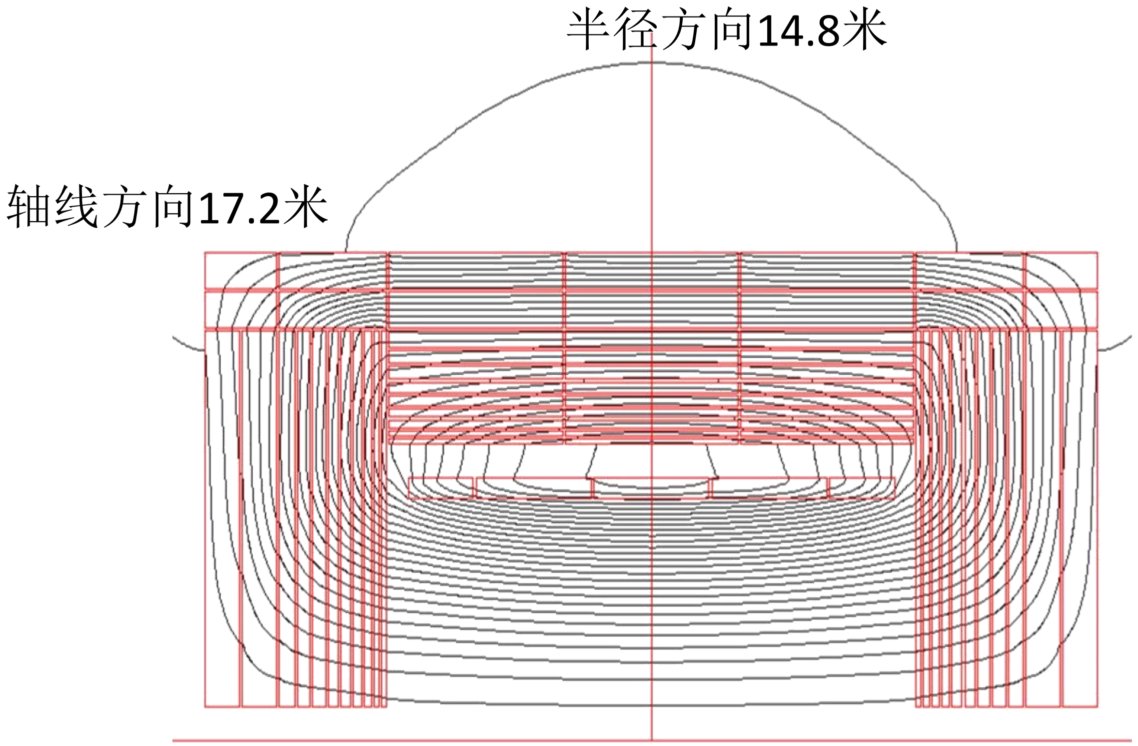
Field map of the magnet (T)



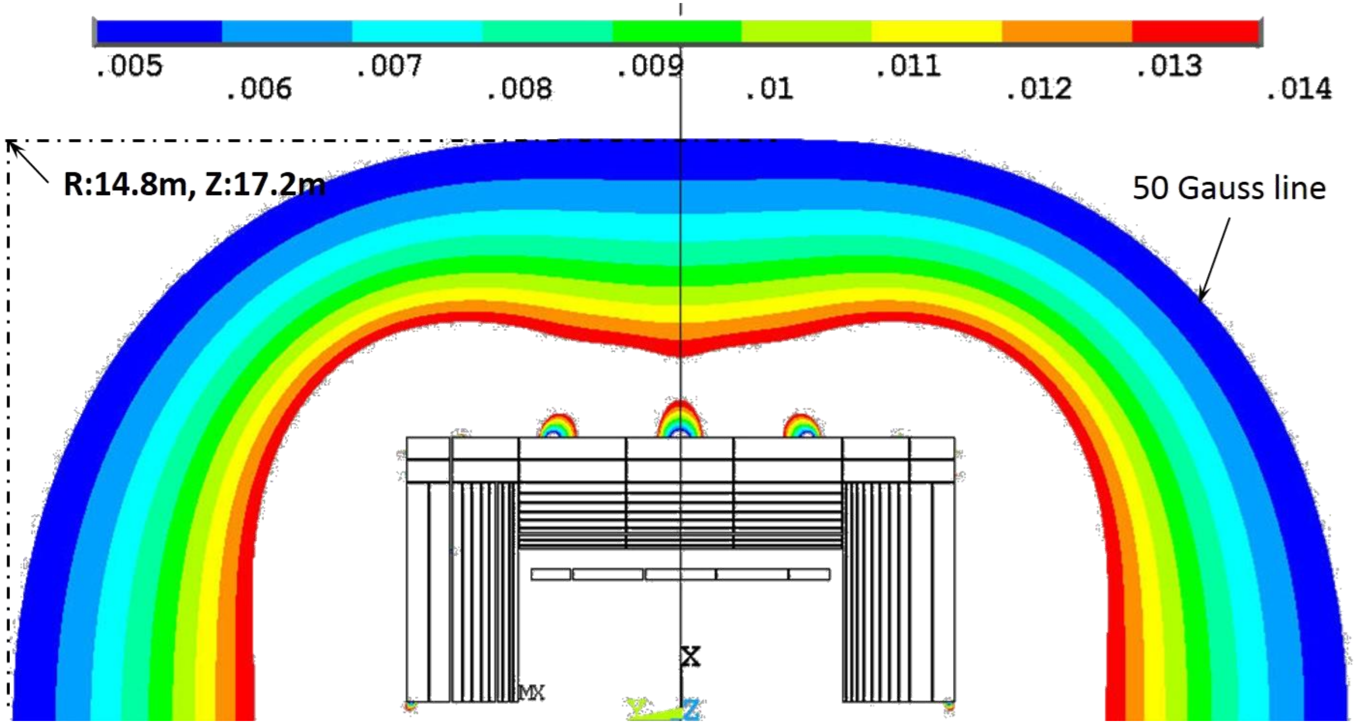
The calculated magnetic field Bz along the detector axis

$B_{center\ point} = 3.5T$; $B_{max\ coil} = 3.85T$

- **the stray field distribution outside the magnet**
  - **The 50 G line is at 14.8 m radial distance and 17.2 m axial distance with a total thickness of iron of 2.44 m both in the barrel and the two end-caps with the 3.5 T central field.**



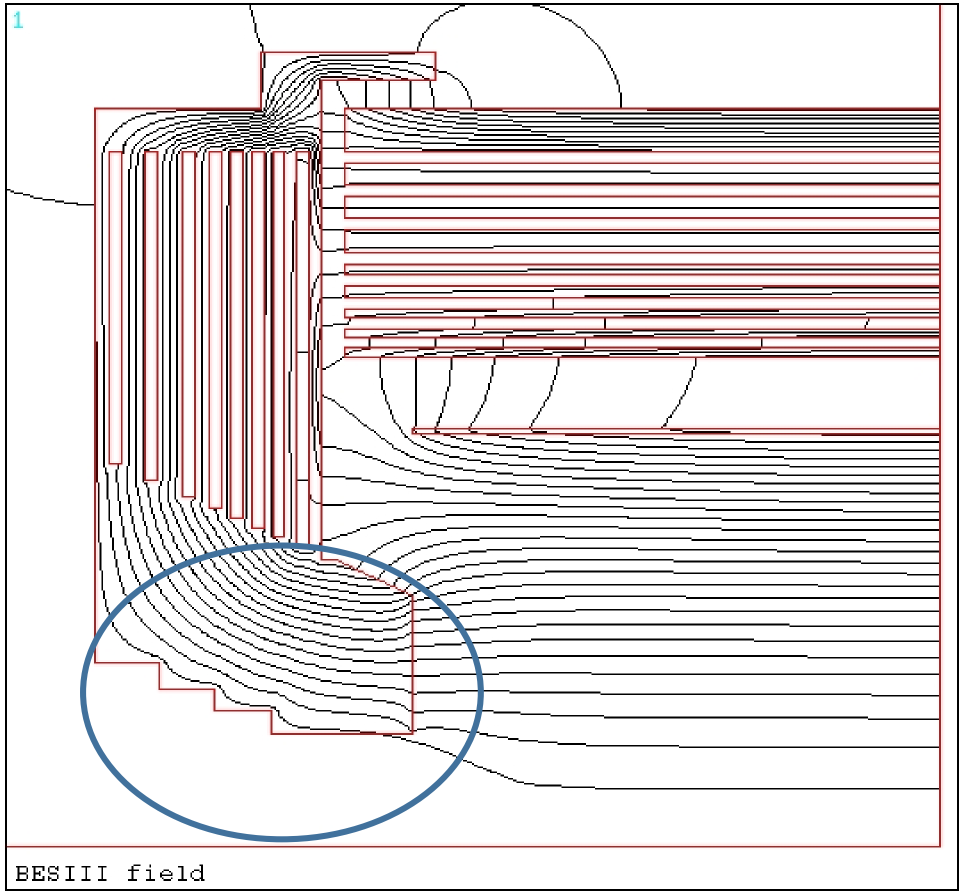
Magnetic flux line distribution of the magnet



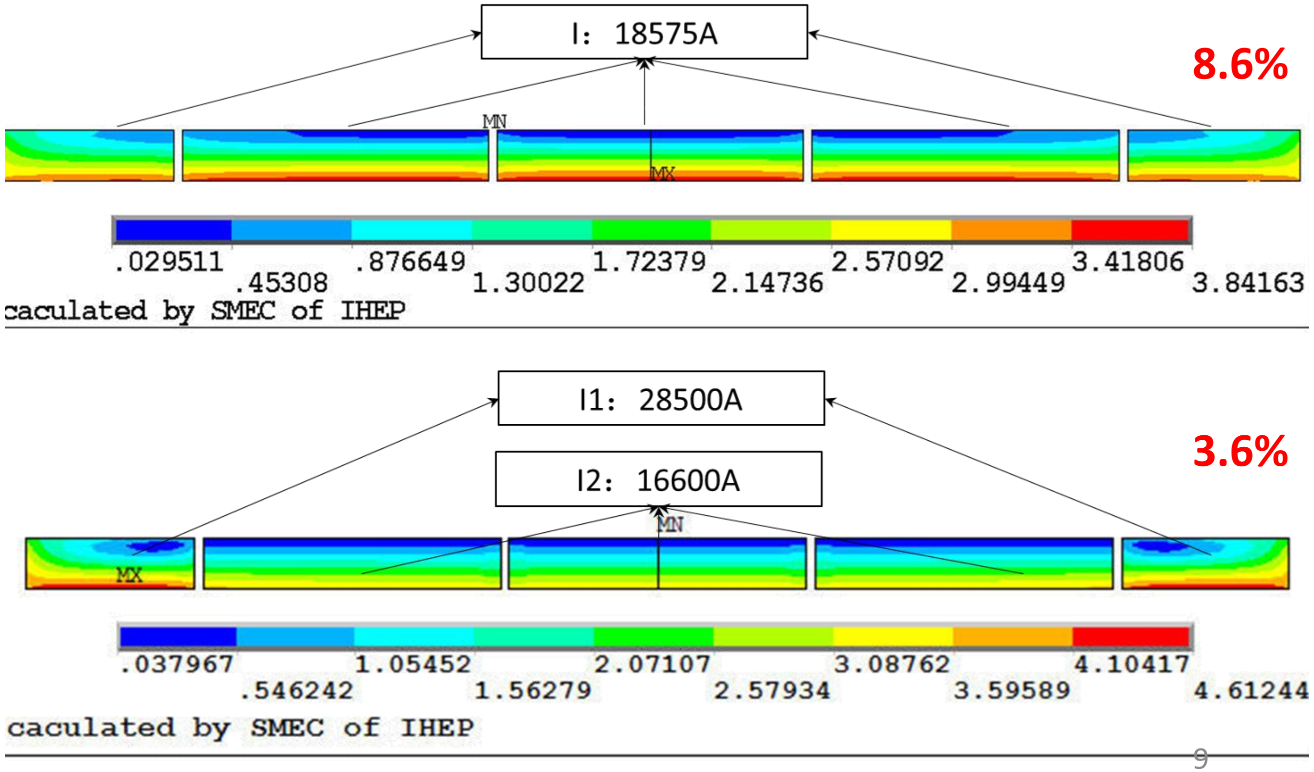
Stray field distribution outside the magnet (the field is given in T)

- **The way to Improve the field uniformity of the central area**
  - ➢ **Different current density in the coil**

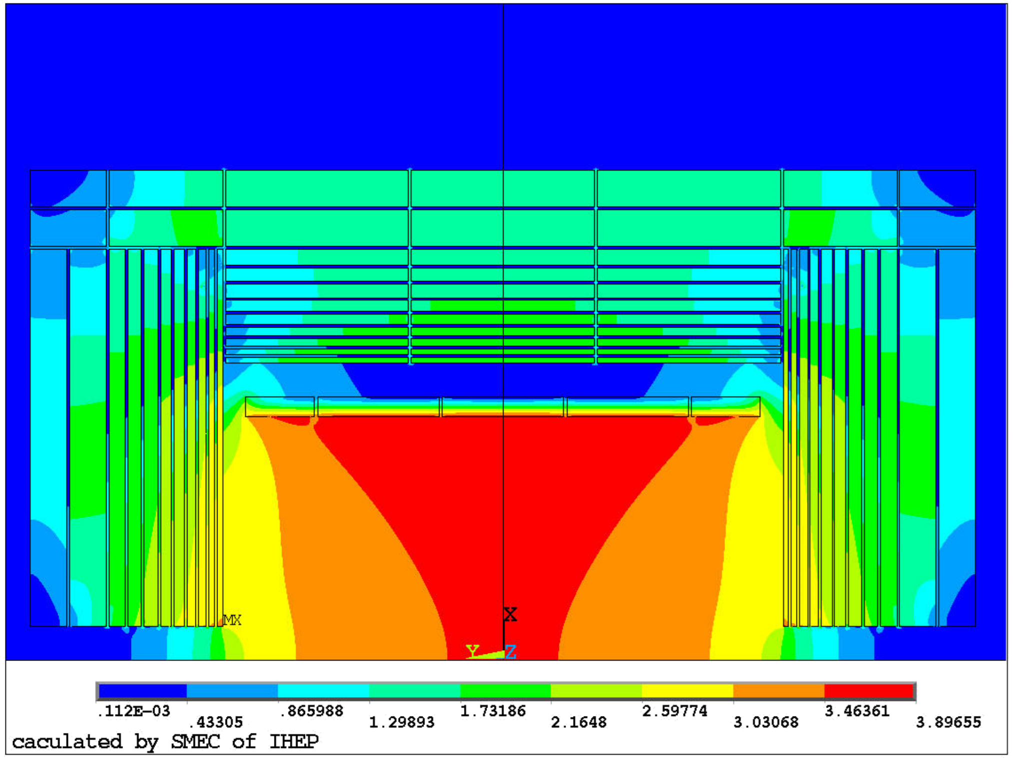
Magnetic deviation from the magnet center 0m to 2.35m along the axis direction:



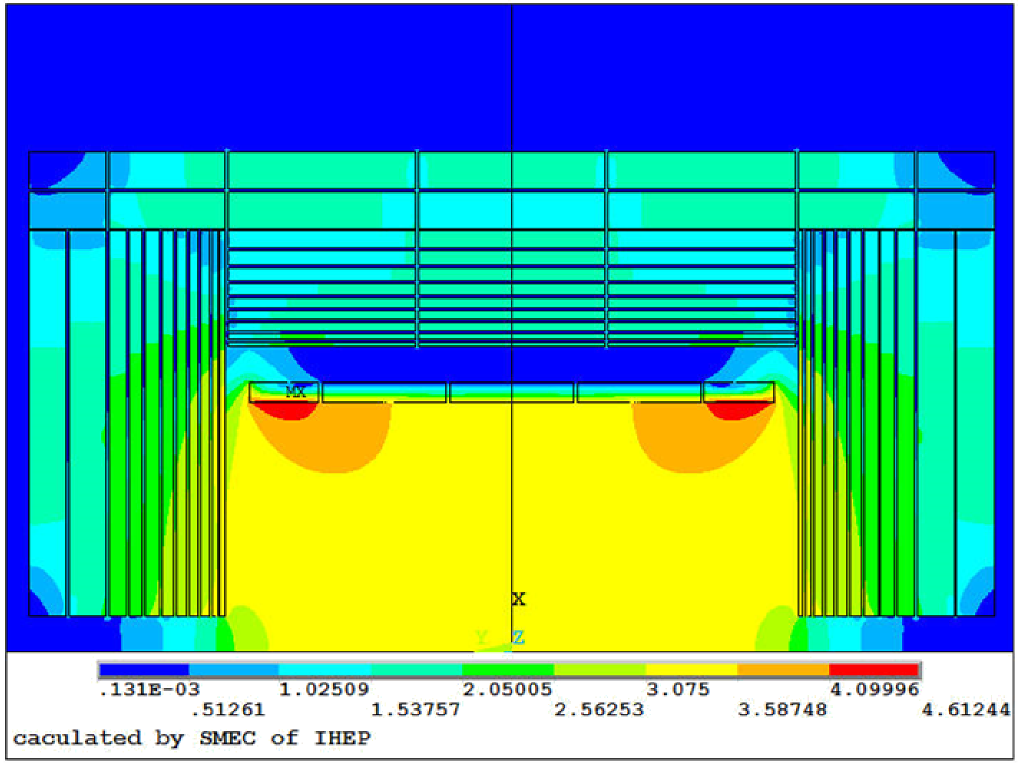
Current and field distribution in the coil



• **Comparison of magnetic field distribution**

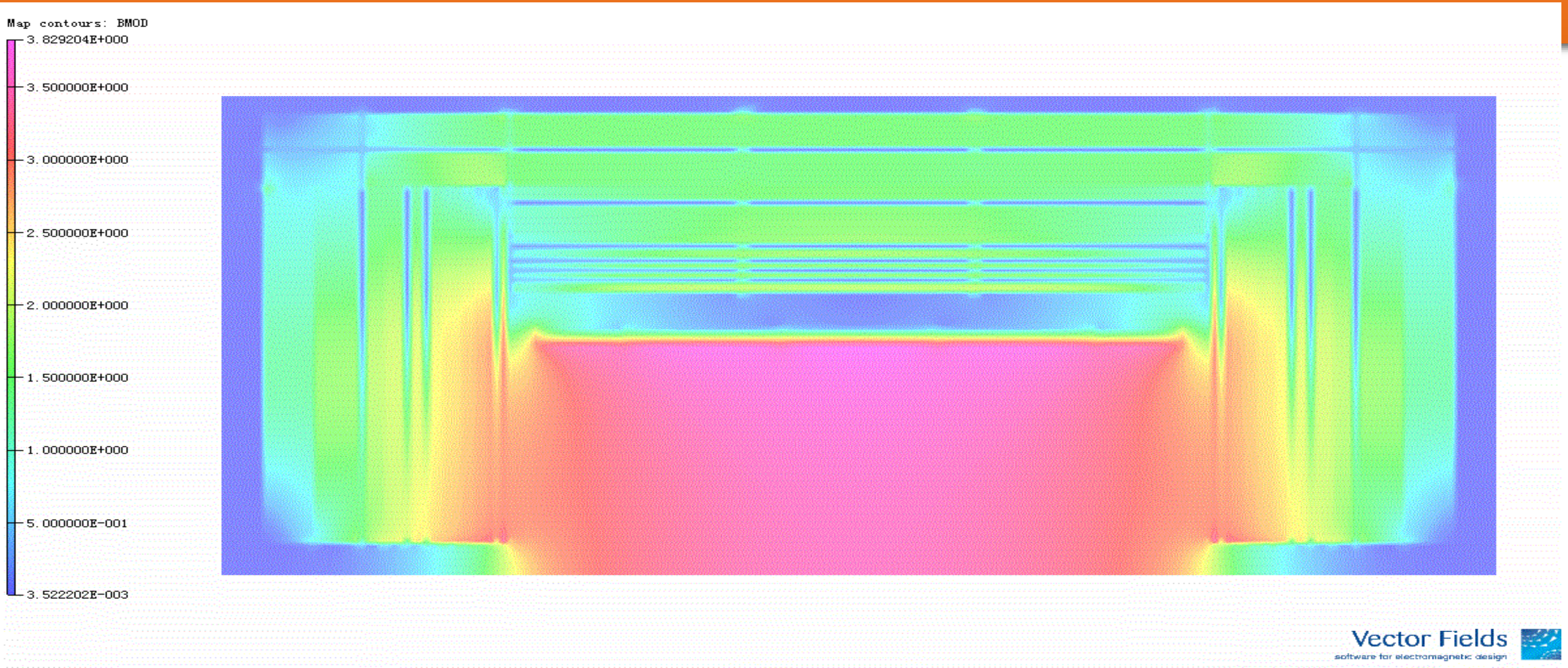


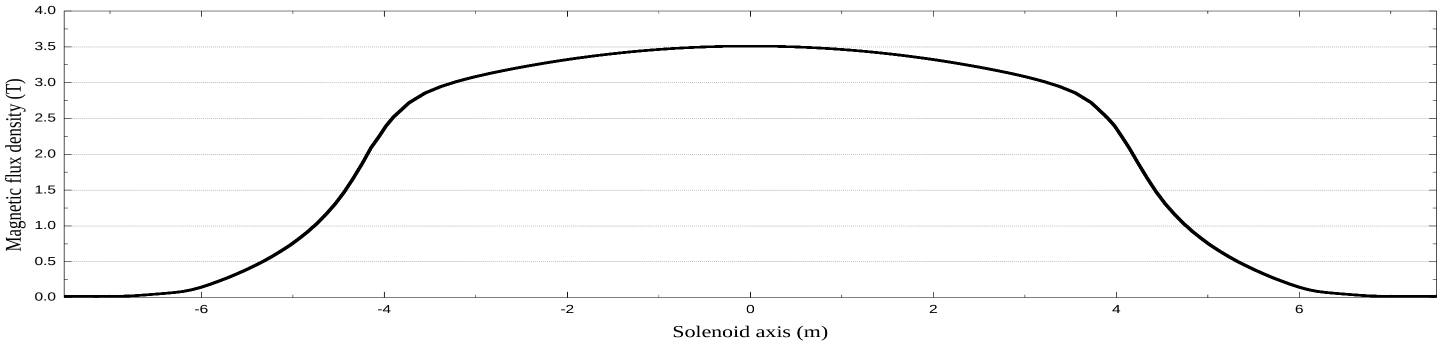
The same running current in the coil



Different running current in the coil

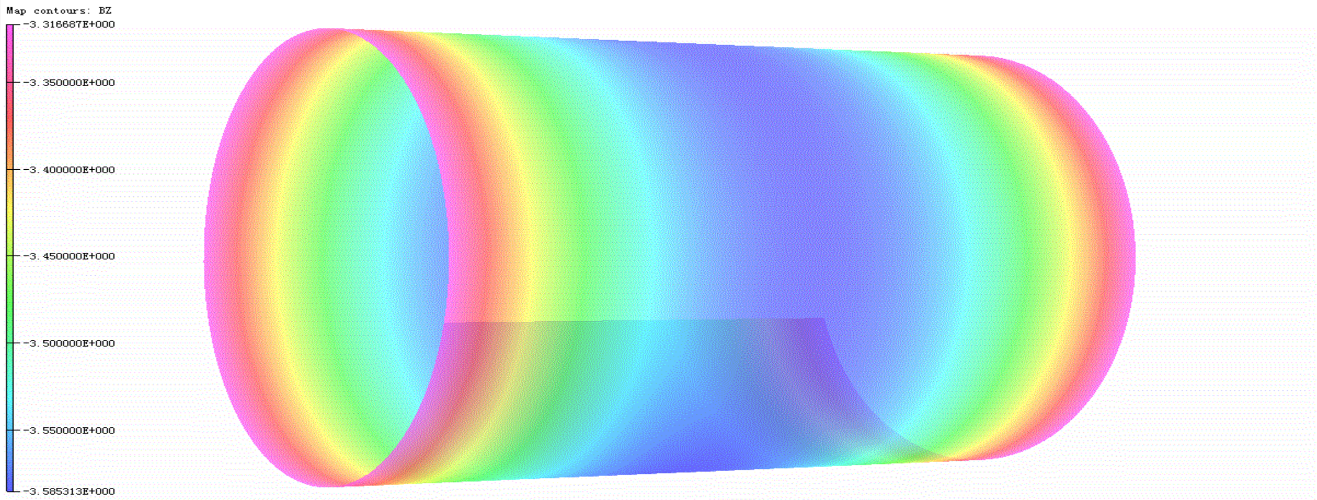
Magnetic Field Distribution

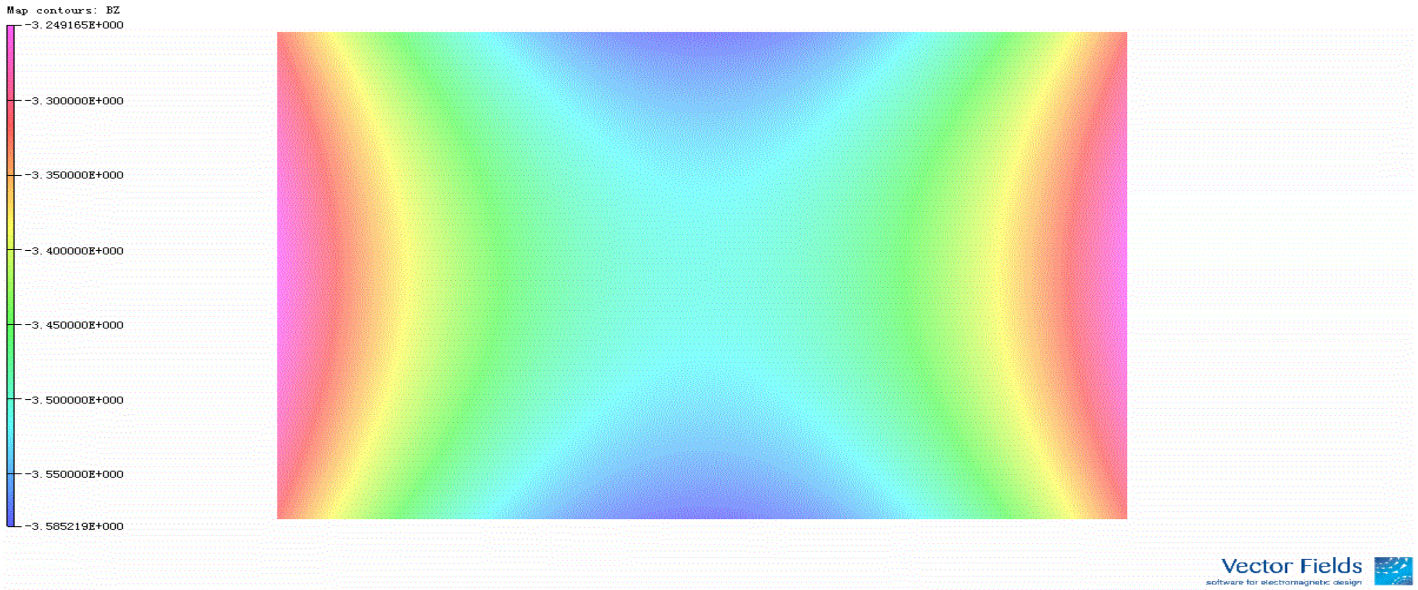




采用OPERA计算

Time Projection Chamber (TPC)



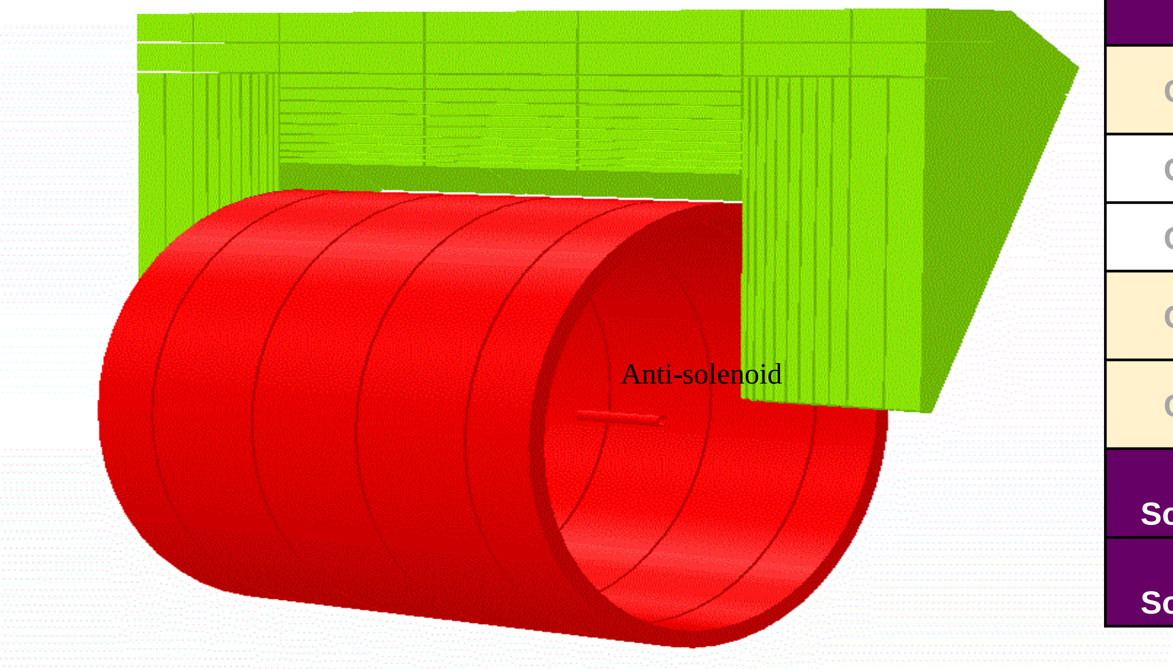


Item	Parameter	Unit
Length	4.7	m
Outer radius	1.8	m
Max. Field	3.58529	T
Min. Field	3.24917	T
Uniformity	9.4×10^{-2}	

采用OPERA计算

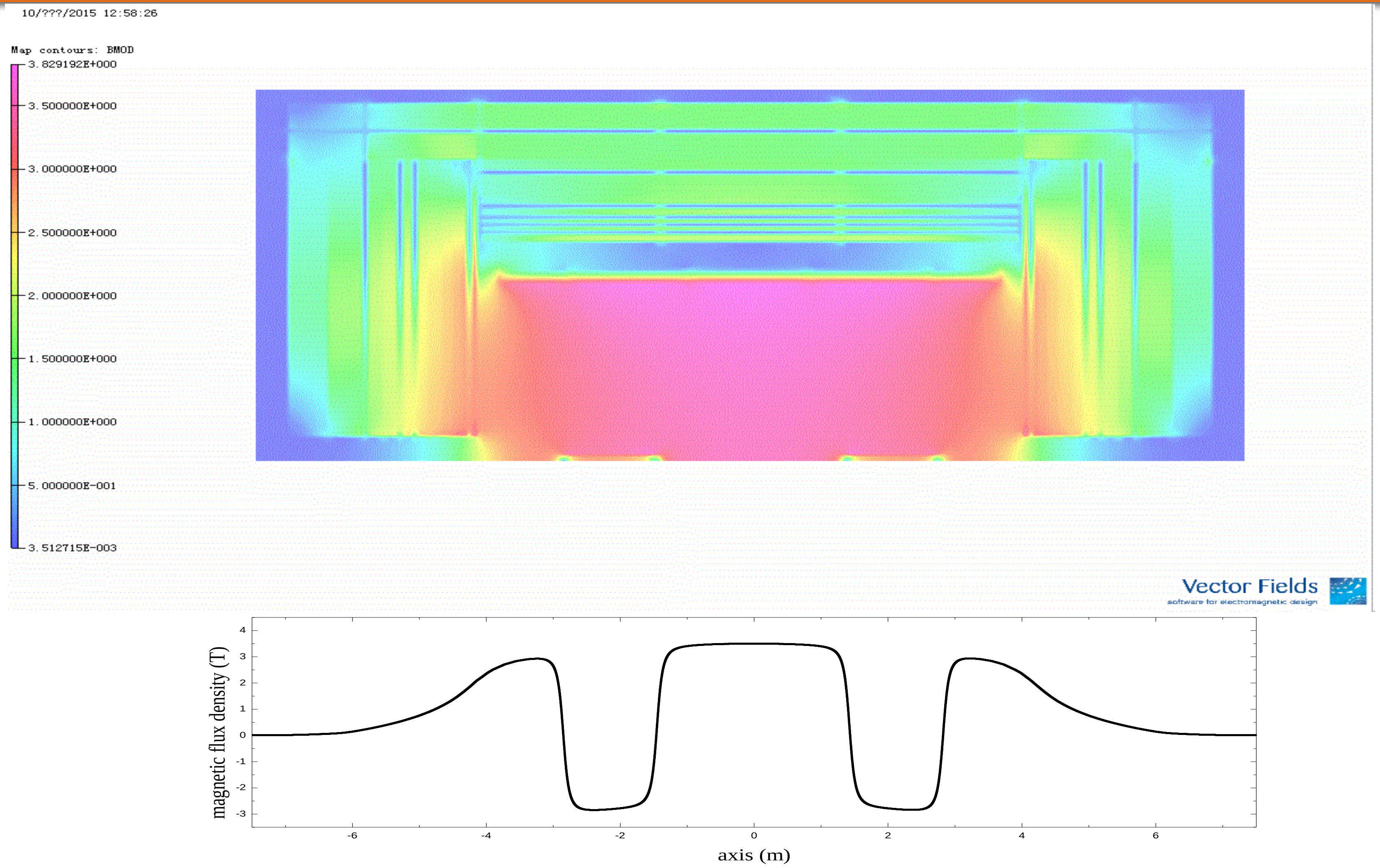
+Anti-solenoid (QD0)

加速器为了轴向积分磁场为零，需要抵消探测器的磁场，在靠近探测器端部添加反场线圈

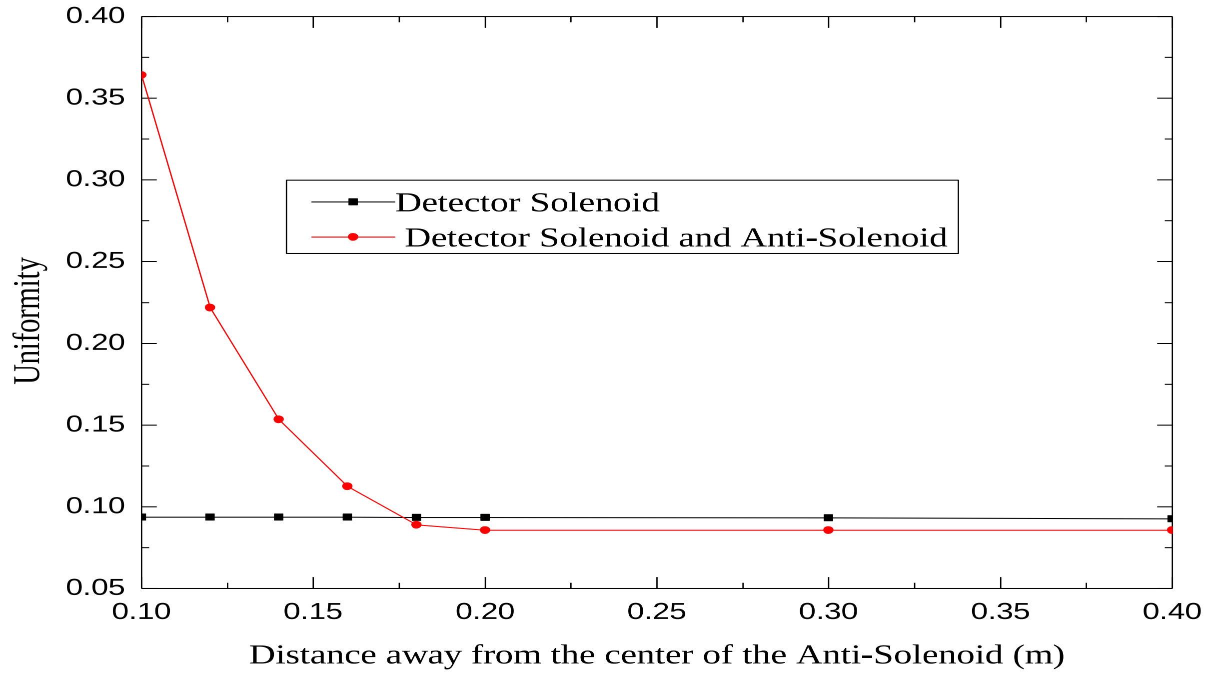


Coil ID	Coil Lengh	Inner Rad.	Coil Thicness	Z-Position	Current density
	[mm]	[mm]	[mm]	[mm]	[A/mm^2]
Coil-1	1794	3600	300	0	10.768
Coil-2	1794	3600	300	1844	10.768
Coil-3	1794	3600	300	-1844	10.768
Coil-4	1012	3600	300	3297	10.768
Coil-5	1012	3600	300	-3297	10.768
Anti-Solenoid	1400	80	20	2125	245
Anti-Solenoid	1400	80	20	-2125	245

Magnetic Field Distribution with Anti-Solenoid

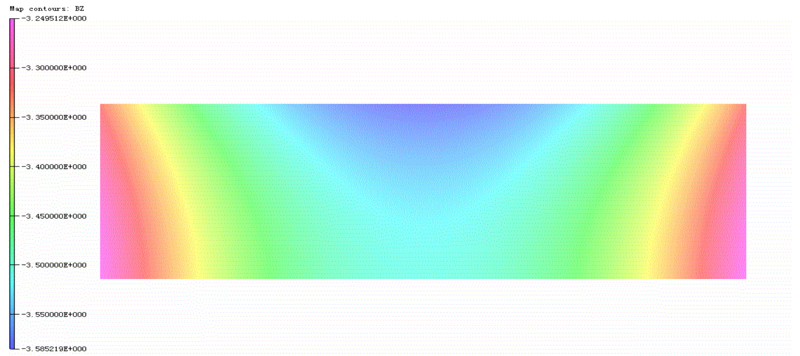


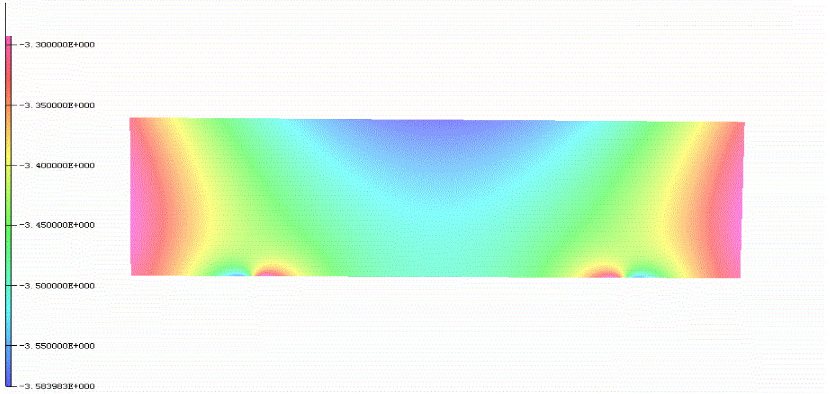
Uniformity of the TPC with Anti-Solenoid



There is a great effect around the Anti-Solenoid.

With the distance far away from the center of the Anti-Solenoid, the effect will become smaller





Iron yoke configuration and cost reduction

Table 6.1.1: SiD and CMS Superconducting Coil Comparison

Quantity	SiD	CMS	Units
Central Field	5.0	4.0	T
Stored Energy	1.59	2.69	GJ
Stored Energy Per Unit Cold Mass	12	11.6	kJ/kg
Operating Current	17.724	19.2	kA
Inductance	9.9	14.2	H
Fast Discharge Voltage to Ground	300	300	V
Number of Layers	6	4	
Total Number of Turns	1459	2168	
Peak Field on Superconductor	5.75	4.6	T
Number of CMS superconductor strands	40	32	
% of Short Sample	32	33	
Temperature Stability Margin	1.6	1.8	K
Total Cold Mass of Solenoid	130	220	tonne
Number of Winding Modules	2	5	
R_{min} Cryostat	2.591	2.97	m
R_{min} Coil	2.731	3.18	m
R_{max} Cryostat	3.392	3.78	m
R_{max} Coil	3.112	3.49	m
Z_{max} Cryostat	$\pm$ 3.033	$\pm$ 6.5	m
Z_{max} Coil	$\pm$ 2.793	$\pm$ 6.2	m
Operating Temperature	4.5	4.5	K
Cooling Method	Forced flow	Thermosiphon	

Eleven 20 cm thick iron plates with 4 cm gaps form both the barrel and end wall portions of the flux return. There is also a 5 cm gap between the barrel and door that is partially filled with barrel iron connecting plates. These connecting plates are also part of the solenoid axial restraint system. The door iron plates are held together with an iron cylinder on the ID and top plates on the OD.

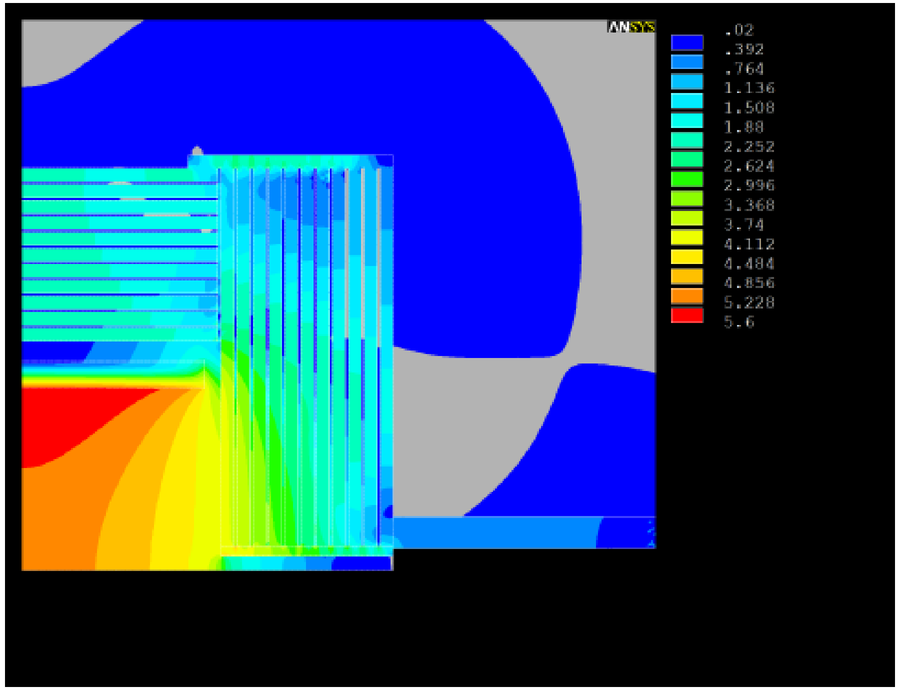
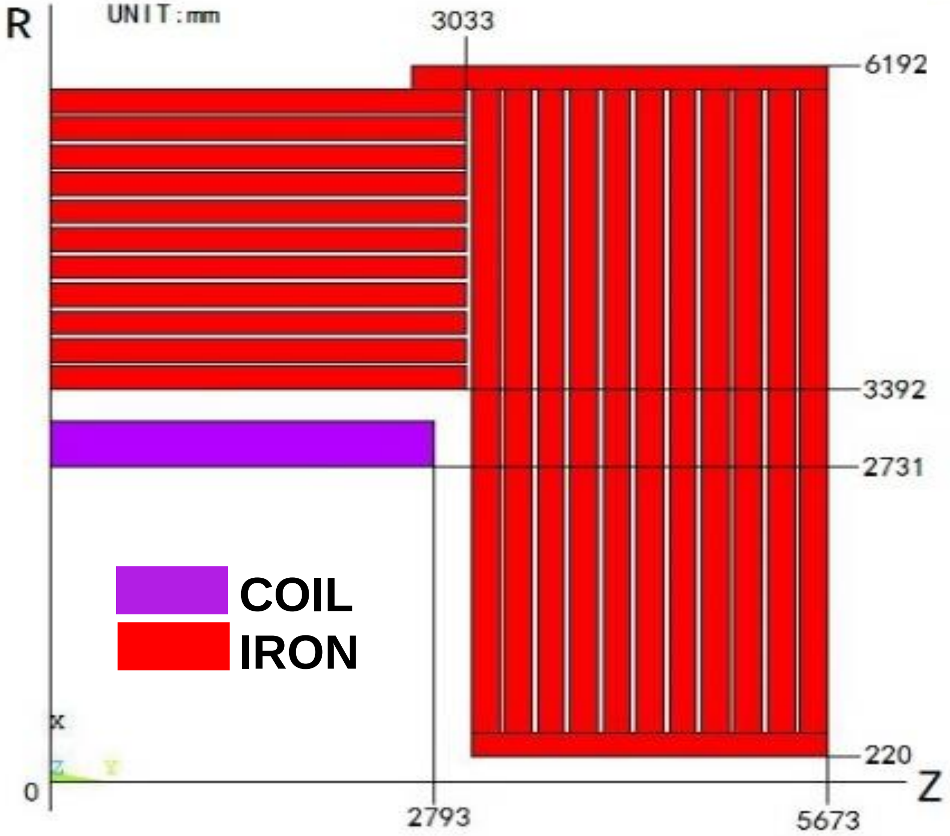
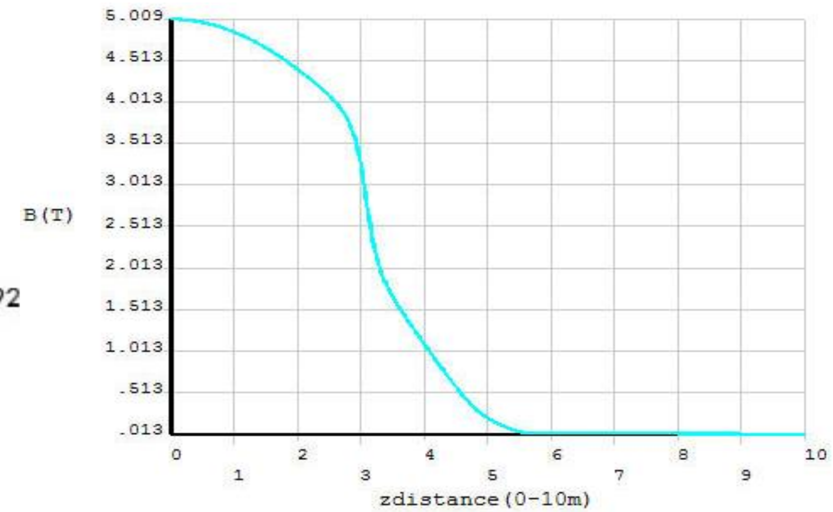


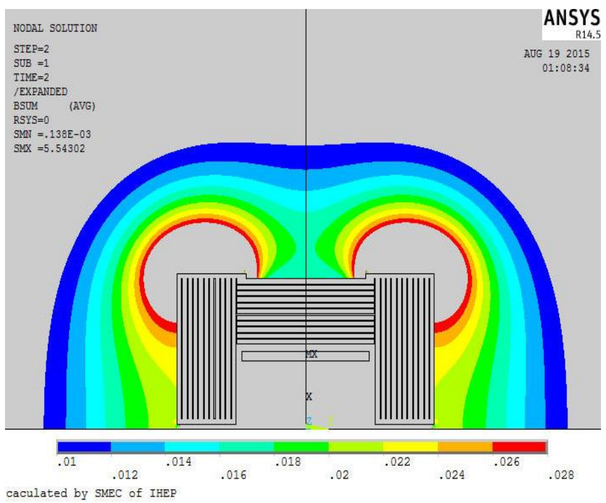
Figure 6.2.1: :2D Axisymmetric showing B_{max}. Only a small portion of the air is displayed. The gray/blue boundary is the 200 G line.

*SiD, DETAILED BASELINE DESIGN, DRAFT SUBMITTED TO THE PAC (REVISED), 10 DECEMBER 2012

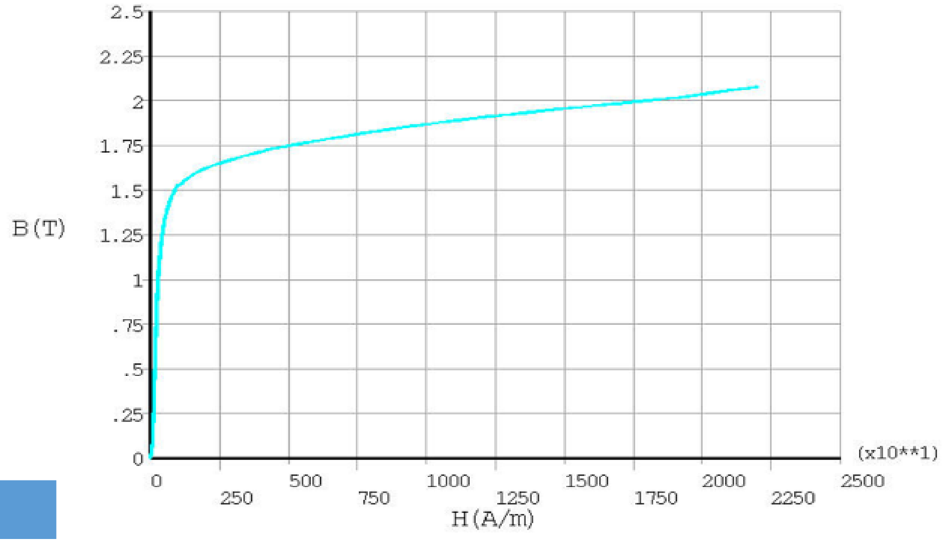
- Model and parameters







Item	End yoke	Barrel yoke	Sum
Weight(t)	2129.3	3088.4	5217.7



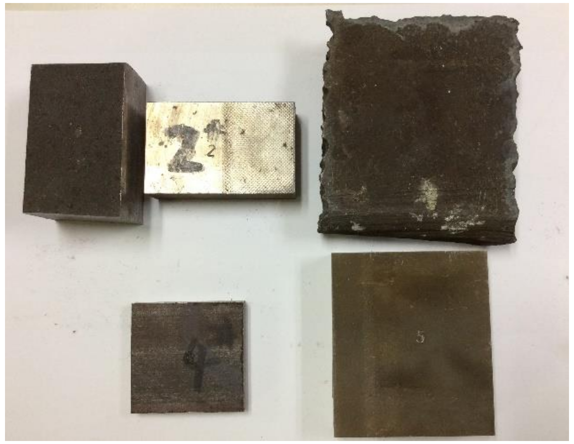
BH curve of 10 steel

(筒部、端部轭铁各11层，每层轭铁厚200mm；运行电流：17.8KA)

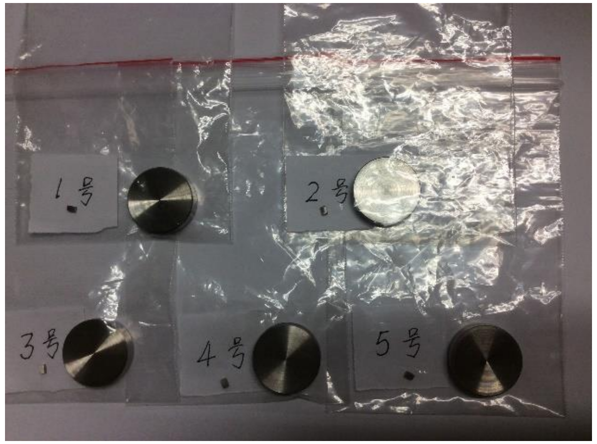
Iron yoke configuration and cost reduction

Manufacturing capability of iron yoke in China.

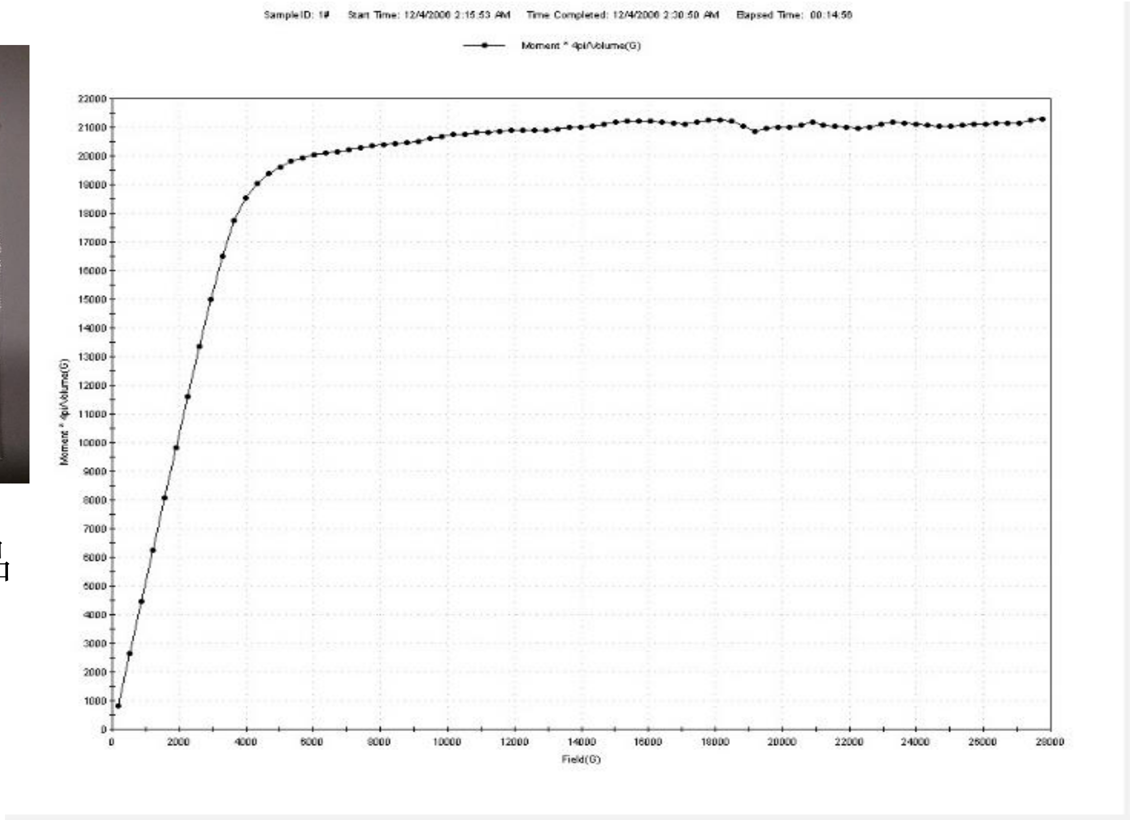
Research on magnetization curves of different materials and the material uniformity.



鞍钢铁磁性材料样品



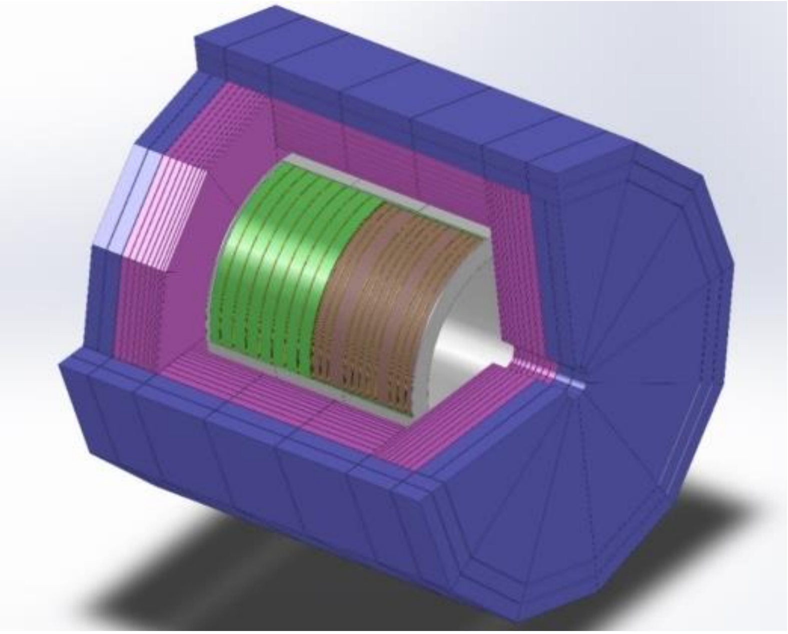
轭铁材料磁化曲线测量样品



轭铁材料样品1磁化曲线

Iron yoke configuration and cost reduction

Huge scale yoke
Total weight 12,200t



Barrel yoke:
Length: 8.2m
Outer diameter:14.5m
Max weight of segments: 100 tons

End yoke:
Thickness: 2.44m
Outer diameter:14.5m
Max weight of segments:200 tons

Magnetic flux return and main support structure for the whole detector

Manufacturing, Installation, Integration with sub-detectors, Moving;

Magnet technology R&D

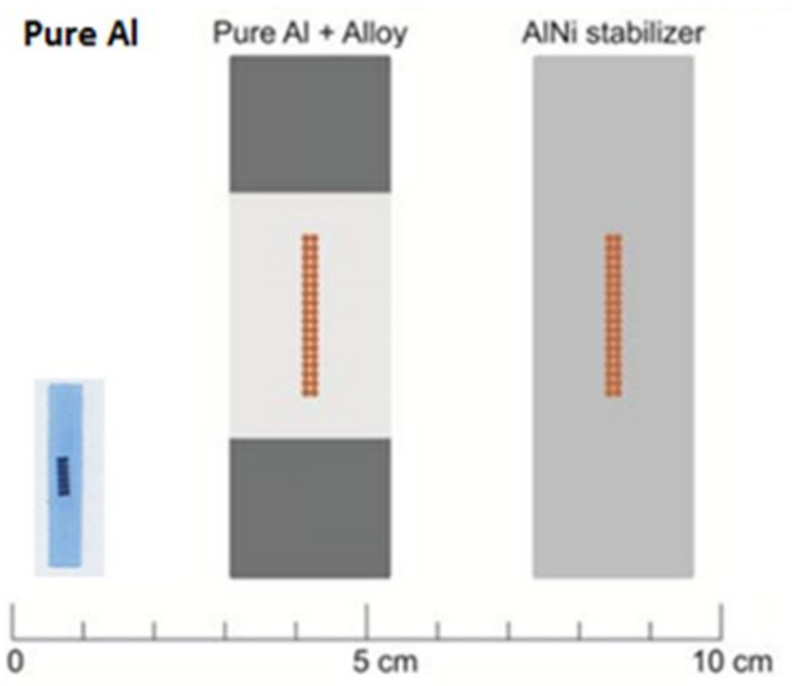
高能所创新经费支持（课题号：Y4545176Y2）

Superconductor

降低电感

18.5 kA超大电流 ➡ 卢瑟福电缆

Superconducting strand in virgin state	
Strand diameter	1.28 mm
Cu/NbTi	1.1
SC strand critical current density	3300A/mm^2 @4.2K,5T
Rutherford cable	
Number of strand	36
Cable transposition pitch	185 mm
Final conductor	
Bare dimensions	75*23 mm^2
SC strand critical current density	>2970A/mm^2 @4.2K,5T
Ic degradation during manufacturing	<10%



Cross section of Superconducting cable:
BESIII、 CMS、 ILD

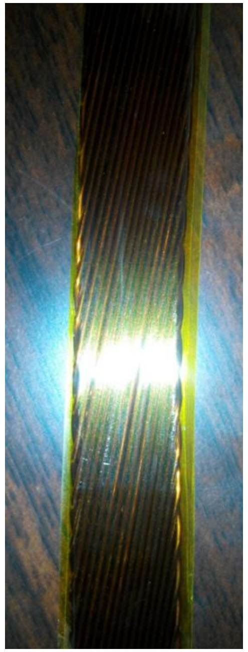
Rutherford type cable

2015年6月，与无锡统力电工有限公司建立战略合作关系。

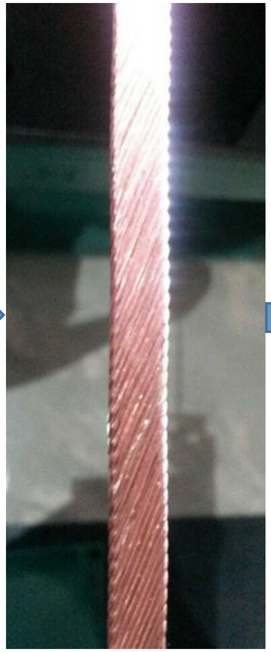
此前，与西部超导公司也建立了战略合作关系。

以此带动国内产业界对特种超导电缆的研发。

Progress in the Rutherford cable



Number of strands： 20
Strand diameter： 1.0mm
Materiel: Copper
Complete time:2015.5



Number of strands ： 17
Strand diameter ： 0.727mm
Materiel :Nb/Ti
Complete time:2015.7

Number of strands ： 24
Strand diameter ： 0.727mm
Materiel :Nb/Ti
Complete time:2015.8

Number of strands ： 18
Strand diameter ： 1.2mm
Materiel :Nb/Ti
Complete time:2016.2

Test results:

1.RRR value declined by about 1/3 after the stranding process.
2.The decrease of the critical current is less than 5%.

绞缆前后材料特性的变化

Conductor mechanical reinforcement

- Completed two rounds of insert process:
  Hollow aluminum alloy, Aluminum alloy + copper cable
- Result: Depression in the middle and the tooling needs to be improved.(2016.4)

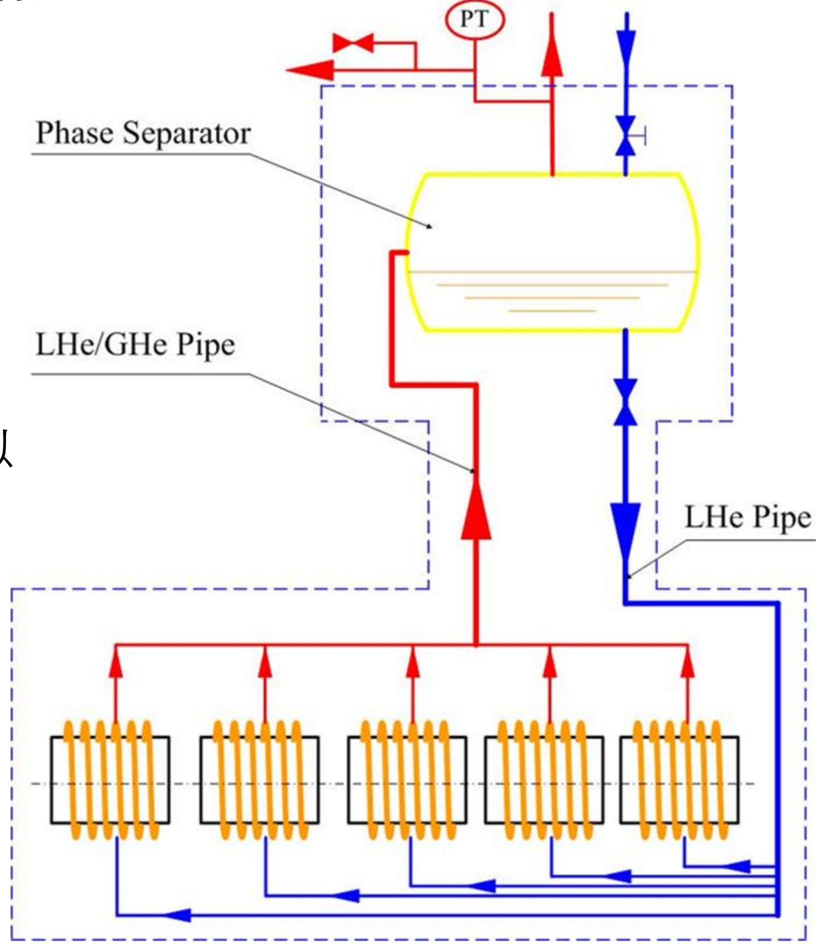
Hollow aluminum alloy
2016.1

Aluminum alloy + copper cable
2016.2

Cryogenics: Thermal-siphon technology

研究意义：
1、BESIII中采用迫流冷却（两相氦冷却），磁体冷却环路较长，两端温差大。在低温系统压力不稳定的情况下，温差过大而导致磁体失超。
2、CEPC探测器超导磁体采用虹吸冷却设计方案
（1）冷却环路内的温差较小
（2）提高磁体运行的稳定性，避免失超

研究内容：
（1）CEPC超导磁体虹吸冷却的具体设计方案。
（2）理论模拟内容：超导磁体冷却过程中虹吸管内液体流动的模拟；建立两相闭式热虹吸管及其换热器的理论模型；励磁和卸载过程中，交流损耗的存在和冷却条件的限制，都使磁体某些区域的运行温度裕度变的更小，更易导致磁体的失超，事实证明磁体失超总是从该区域的某一点开始。所以需要重点考虑在某些位置、某些工况下，热虹吸回路如何加强冷却，从而保证磁体的稳定条件。
（3）搭建原理验证、小尺寸及10:1尺寸三种虹吸环路实验平台。与理论计算结合，研究管路布置、液位变化、启动、沸腾限、换热系数等参数对传热效果的影响。



Thermal-siphon loop experiment（two phase Nitrogen)

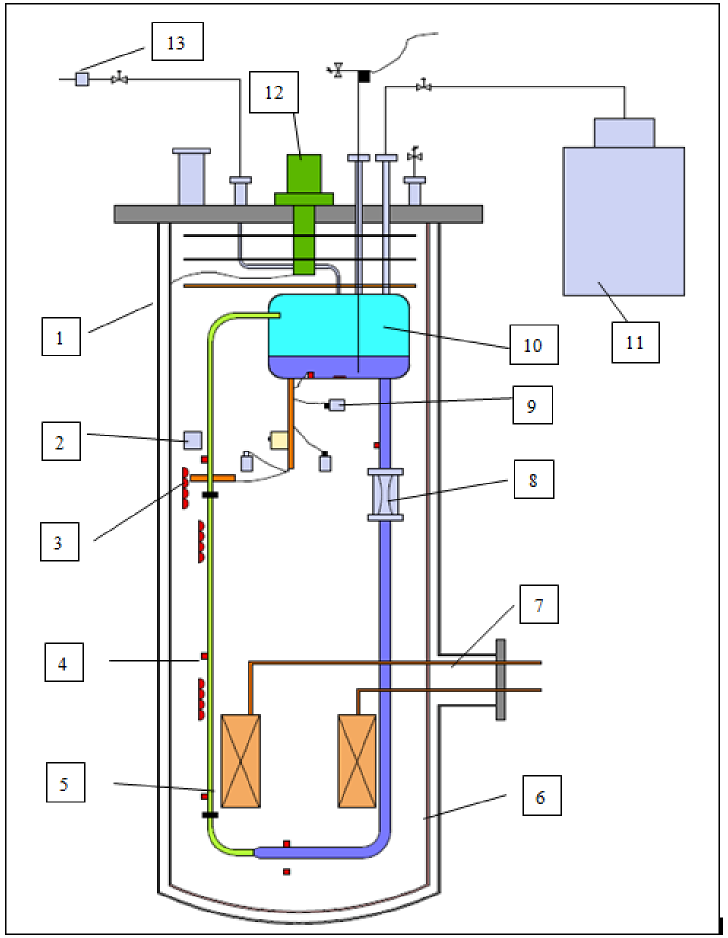
原理验证

热虹吸原理性实验平台

利用一台制冷机，减少液氦的使用

仪器仪表	型　　号
制冷机	GM 1.5W@4.2K
薄壁超导磁体	自制提供动态负载，模拟励磁、退磁过程中的温升速率、最高温度等
Validyne低温压力计	DP10-20，量程0.87kPa，精度±2Pa DP10-22，量程1.4kPa，精度±2Pa
液氮流量计	入口φ40mm，精度10%，量程20g/s
Brooks氮气流量计	SLA5853S
空隙率计	调研中
换热效率测试仪	调研中
温度计	Cernox／ｐｔ１００
水冷机组	7 to 10 liter / min

两相热虹吸环路实验平台示意图



1 – 真空容器 2-空隙率计 3-传热系数测试仪 4-温度计 5-超导磁体 6-冷屏 7-电流引线 8-质量流计 9-低温压力传感器 10-相分离器 11-液氮罐 12-制冷机 13-流量计

Summary

- Field design and optimization (cost reduction)
  - Coil configuration options
  - Field homogeneity in the tracking volume
  - Stray field distribution
  - Iron yoke configuration
- Superconductor:
  - Rutherford cable development (RRR value and current loss)
- Cryogenics:
  - Thermal-siphon experiment (results)

Thanks!