A reference design of the Yoke System for the CEPC detector

Abstract:

XXX

1. Introduction:

The CEPC is a superb factory of Massive SM particles. According to its conceptual design report, the CEPC will produce 1 Million Higgs bosons, 100 Million W bosons, and almost 1 Trillion Z bosons in 10 years of operation. The CEPC could measure many of the major Higgs boson couplings with precisions about one order of magnitude better than those achievable at the High Luminosity-LHC. It is projected to improve the precisions of many of the electroweak observables by about one order of magnitude or more. Large quantities of the bottom quarks, charm quarks, and tau leptons will be produced from the Z boson decay, leading to rich flavor physics program at the CEPC. The clean collision environment also makes the CEPC an ideal facility to perform precision QCD measurements.

The rich physics program at the CEPC poses stringent requirements on its detector design. The CEPC detector should reconstruct all critical physics objects – those final state that massive bosons decay into – with high efficiency, high purity, and high precision. The CEPC detector should be stable enough to control the systematic uncertainties. To fulfill those physics requirement, several detector concepts are proposed and dedicated simulation and R&D program confirms these concepts fulfill the CEPC physics requirements.

The baseline detector is developed following the Particle Flow Principle. Emphasizing on the reconstruction of every final state particle, especially the separation of particles in the jets. It uses the TPC as its main tracker, the high granularity calorimeter system and a large volume solenoid that can host both ECAL and HCAL inside. This geometry is developed from the ILD detector geometry, one of the reference detectors for the linear collider studies.

Inherited from the ILD design, the current Yoke in the CEPC baseline has a thickness of 3 meter and a total weight exceed 10k tons. This solenoid is much larger than that at the LEP experiments, and close to the scale of CMS detector. The ILD detector needs this massive Yoke, mainly because the push-pull scenario at linear collider. As the linear collider has only one interaction point, the ILC hosts two detectors in the same experimental hall. Therefore, a sufficient shielding of the stray field from the detector solenoid became crucial for the operation. Meanwhile, the linear colliders could be operated at center of mass energies as high as 1 or even 3 TeV, a thick Yoke provides extra information for the muon identification, especially the jet muons.

Those two requirements are significantly weakened at the CEPC. As a circular collider, the CEPC can have multiple interaction points, each host only one large-scale detector. Meanwhile, the center of mass energy of the CEPC is much lower than that of the linear colliders. Therefore, the Yoke thickness could be significantly reduced with respect to the original design of the ILD, which leads to a significant reduction of the construction cost, and simplifies the design of interaction region.

The total thickness of the Yoke at the CEPC is mainly determined by the requirements from the accelerator operation and the physics performance. The former includes the stray field strength control at the beam delivery system and at the booster ring. Taking reference of the CMS stray field distribution. We designed a reference Yoke design. This reference Yoke design reduces the thickness and total weight by 70% and 85% w.r.t the original design. We estimated the stray field at the objective region and designed a conceptual, low-cost local shielding layout, and conclude this design is in principle valid for the accelerator operation. The physics requirement will be addressed in other studies. (I can say sth but not entirely quantitative at this moment…)

This manuscript is organized as following. Section 2 summarizes the Yoke design at the CEPC CDR and the new reference design, and calculates the corresponding stray field distribution. Section 3 briefly introduces the device layout and requirement on external B-Field strength of the BDS region and the nearby booster ring. Section 5 introduces the conceptual local shielding scenario. The conclusions are given in Section 6. (Slightly modified from the outline last week).

2. Yoke design at CEPC CDR and new design

2.1. Yoke design at CEPC Pre-CDR and CDR

The CEPC detector magnet is an iron-yoke-based solenoid to provide an axial magnetic field of 3 Tesla at the interaction point. A room temperature bore is required with 6.8 m in diameter and 8.3 m in length. The geometrical layout of magnet are shown in Figure 1.

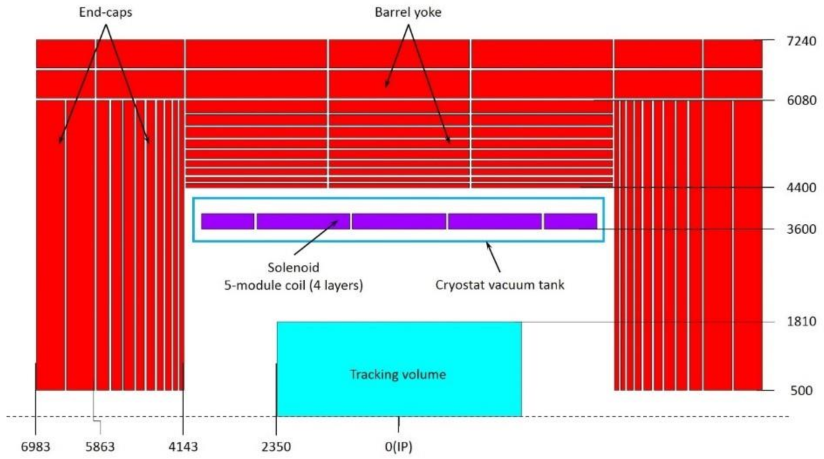


Figure 1. Geometrical layout of CEPC detector magnet.

The iron yoke serves as the magnetic flux return and the main mechanical structure of the sub-detectors. Therefore high permeability material with high mechanical strength is required for the yoke material. The gaps between yokes provide room for the muon detector, data cables, cooling pipes, gas pipes and etc. through the yoke. The yoke is divided into two main components, one cylindrical barrel yoke and two endcap yokes. The total weight of the yoke assembly is about 12,573 tons. Table 1 shows the yoke parameters of the CEPC original design.

Table 1. Yoke parameters of CEPC original design

Barrel yoke inner diameter (mm)	8800	Weight of barrel yoke (t)	5940
Barrel yoke outer diameter (mm)	14480	Weight of each end cap (t)	3316.6
Total length of yoke (mm)	13966	**Total weight of yoke (t)**	**12573**

The barrel yoke is a dodecagonal shape structure with a length of 8,206 mm (Figure 2). The outer diameter of the dodecagon and the inner diameter are 14,480 mm and 8,800 mm respectively. The barrel yoke is subdivided along the beam axis into 3 rings, with 11 radial layers in each ring. Each ring of the barrel yoke is composed of 12 azimuthal segments. 40 mm gap is designed between the rings and the layers for placing the muon detector and the electronics cables and services. From the inner to the outer, the layer thicknesses are 80 mm, 80 mm, 120 mm, 120 mm, 160 mm, 160 mm, 200 mm, 200 mm, 240 mm, 540 mm, 540 mm, respectively.

The endcap yokes are designed to dodecagonal structure with the out diameter of 14,480 mm. Each endcap yoke will consist of 11 radial layers (Figure 3). Each endcap yoke is composed of 12 azimuthal segments. The layer thicknesses are 80 mm, 80 mm, 120 mm, 120 mm, 160 mm, 160 mm, 200 mm, 200 mm, 240 mm, 540 mm, and 540 mm, respectively.

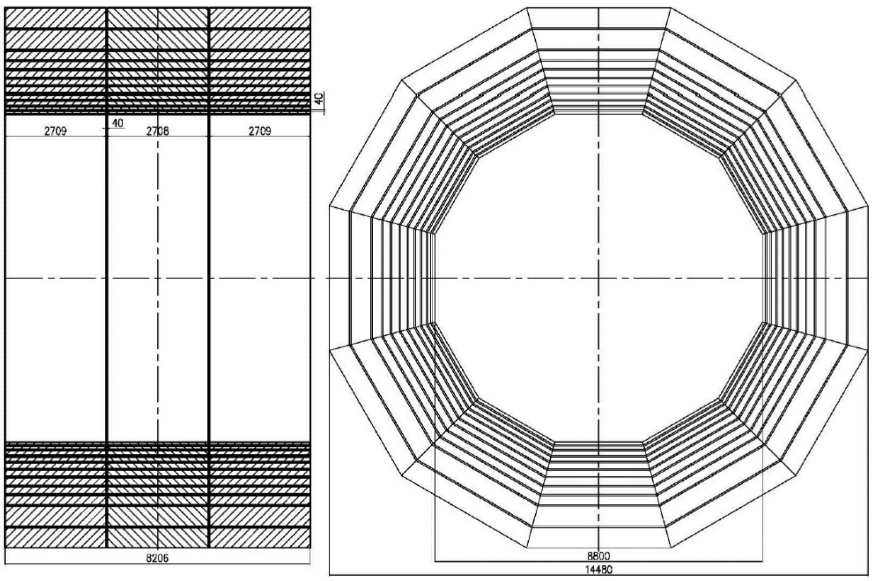


Figure 2. Barrel yoke of CEPC detector magnet.

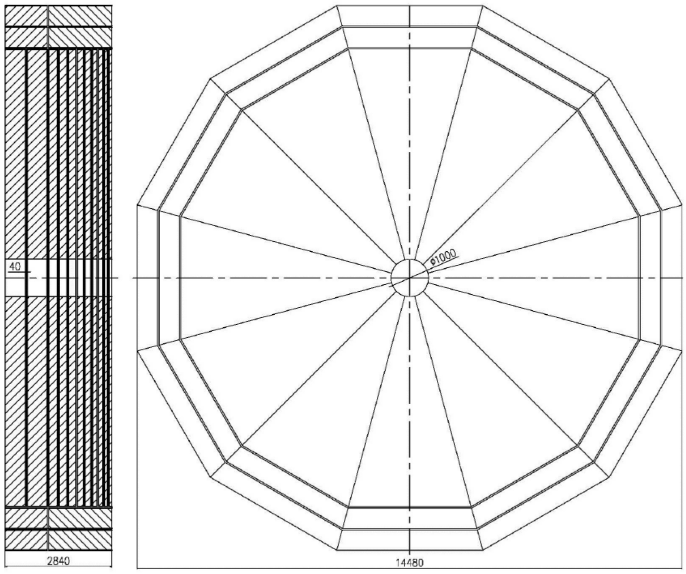


Figure 3. Endcap yokes of CEPC detector magnet.

2.2. Stray field of CEPC original design and CMS

Figure 4 gives the stray field 50 gauss and 100 gauss distributions of CEPC original design. There are two directions: Radial direction (R vertical) and Axial direction (Z horizontal).

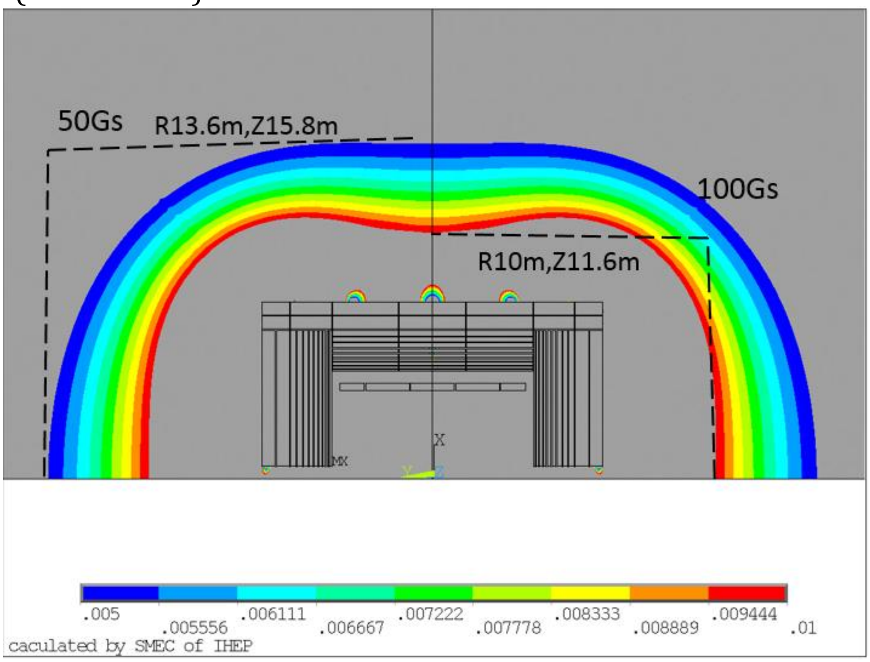


Figure 4. Stray field distribution of CEPC original design

Table 2. Location of 50 gauss and 100 gauss.

stray field		Location
50 Gs	R direction	13.6 m
	Z direction	15.8 m
100 Gs	R direction	10 m

	Z direction	11.6 m

The 1/4 Model of CMS magnet, purple part is the coil, red part is the yoke, the coil is divided into four parts, there are 200mm between each part, and the data is referenced from the TDR of CMS：

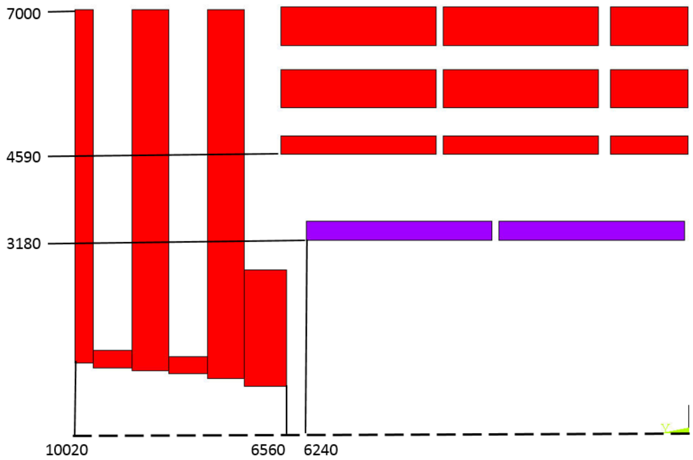


Figure 5. 1/4 model of CMS magnet

Stray field 50 gauss and 100 gauss distribution of CMS magnet, we can see the stray field of 50 gauss and 100 gauss at two directions, the blue part is 50 gauss and the red part is 100 gauss：

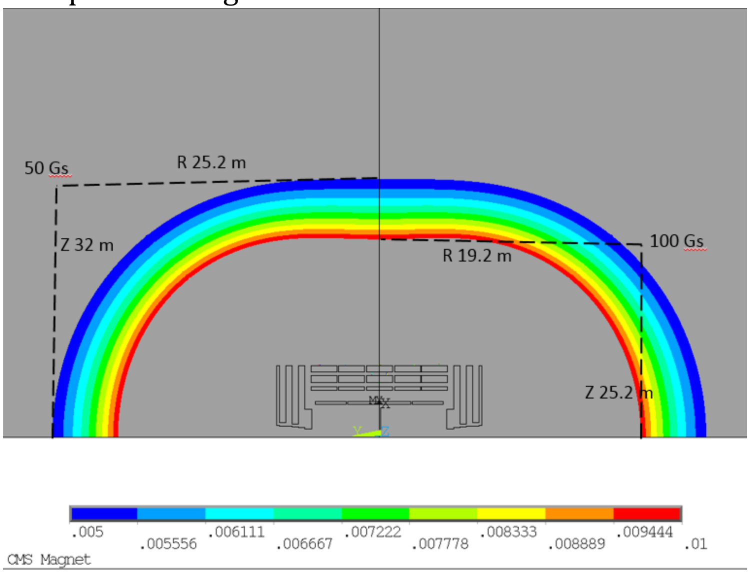


Figure 6. Stray field distribution of CEPC original design

Table 3. Location of 50 gauss and 100 gauss.

Stray field		Location
50 Gs	R direction	25.2 m
	Z direction	32 m

100 Gs	R direction	19.2 m
	Z direction	25.2 m

Table 4. Stray field comparison of CMS and CEPC original design:

Stray field		CMS	CEPC original
50 Gs	R direction	25.2 m	13.6 m
	Z direction	32 m	15.8 m
100 Gs	R direction	19.2 m	10 m
	Z direction	25.2 m	11.6 m

Table 5. Yoke weight and size comparison:

	CMS	CEPC original
Central field (T)	4	3
Inner diameter of coil (mm)	6360	7200
Length of coil (mm)	12480	7606
Barrel yoke inner diameter (mm)	9180	8800
Barrel yoke outer diameter (mm)	14000	14480
Total length of yoke (mm)	20040	13966
Weight of barrel yoke (t)	6000	5940
Weight of each end cap (t)	2000	3316.6
Total weight of yoke (t)	**10000**	**12573**

From Table3 to Table 5, we can get that the stray field of CEPC original design is much smaller than CMS. There are two reasons: first, the center magnetic field of CMS is 4 tesla, which is bigger than CEPC; second, CEPC uses too much yoke, even much heavier than CMS. Two much yoke brings many difficulties, such as the size of hole, crane, cost and so on.

According to the experience of CMS and physical reasons, the Yoke thickness could be significantly reduced, which leads to a significant reduction of the construction cost, and simplifies the design of interaction region.

2.3. The new design of yoke

2.3.1. Three layers yoke design

The layer of the yoke is decreased to three, other parameters are not changed. The range of stray field are controlled to similar to the CMS, then weight of yoke decreases a lot,. There are three layers of end cap and barrel yoke, the thickness of inner two layers is 200mm, the thickness of out layer is 300mm. Figure 7 shows the 1/4 model of CMS, CEPC original design and 3 layers yoke option.

Table 6 gives the yoke weight and size comparison between the CMS, CEPC original design and 3 layers yoke option. We can get that after lose weight, the stray field range is similar to CMS. The total weight of yoke changes from 12573 t to 2874.5 t. It's less than 1/4 of the original plan.

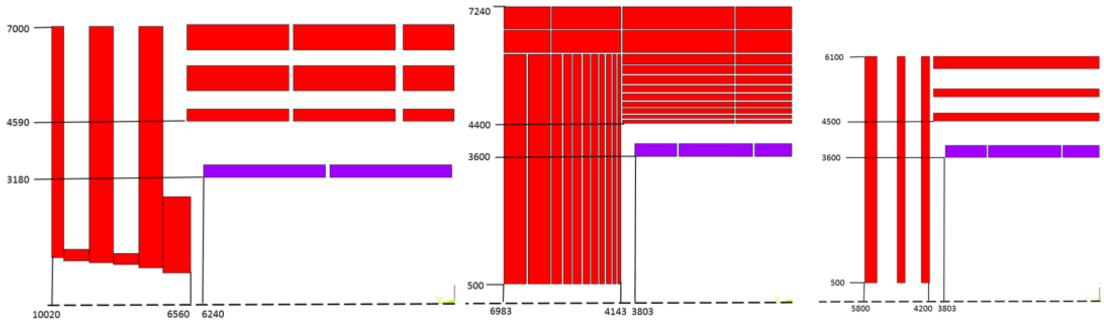


Figure 7. Shape and size comparison: purple part is the coil, red part is the yoke.

Table 6. Yoke weight and size comparison

	CMS	CEPC original	CEPC 3 layers yoke
Central field (T)	4	3	3
Diameter of coil (mm)	6360	7200	7200
Length of coil (mm)	12480	7606	7606
Barrel yoke inner diameter (mm)	9180	8800	9000
Barrel yoke outer diameter (mm)	14000	14480	12200
Total length of yoke (mm)	20040	13966	11600
Weight of barrel yoke (t)	6000	6122	1608
Weight of each end cap (t)	2000	3419	678
Total weight of yoke (t)	**10000**	**12573**	**2874.5**

2.3.2. The size of Superconducting Coil decrease design

After the optimization of inner detector design, the radius superconducting coil can be reduced 20 cm, and the length reduces 40 cm (Manqi, can you add some sentences why the coil is smaller?)

Then the yoke can be optimized. First the yoke is still 3 layers, just the radius of the coil is changed from 3600 mm to 3400 mm, and the length reduces from 7606 mm to 7238 mm; second the layer of the yoke is reduced to one, and the stray field is also limited to similar to the CMS. The structure of the yoke is simpler. Figure 8 shows the shape and size comparison of the different design model. Table 7 gives the yoke weight and size comparison of different design, from the table we can see that the weight of the yoke reduces a lot. Table 8 is the stray field distributions of different designs. The simplest structure design also has a similar stray field region to the CMS.

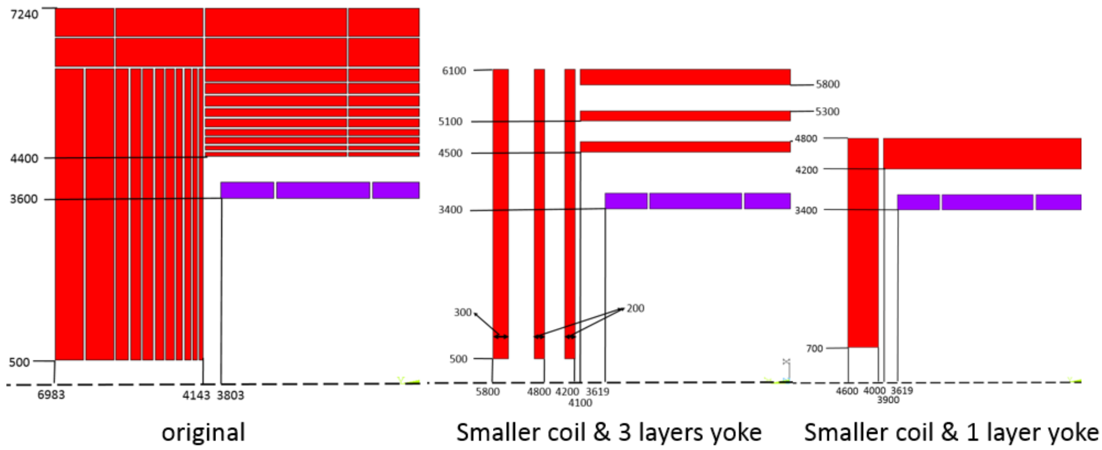


Figure 8. Shape and size comparison of different design model

Table 7. Yoke weight and size comparison of different design

	CMS	CEPC original	CEPC 3 layers yoke	Smaller coil & 3 layer yoke	Smaller coil & 1 layer yoke
Central field (T)	4	3	3	3	3
Inner diameter of coil (mm)	6360	7200	7200	6800	6800
Length of coil (mm)	12480	7606	7606	7238	7238
Barrel yoke inner diameter (mm)	9180	8800	9000	9000	8400
Barrel yoke outer diameter (mm)	14000	14480	12200	12200	9600
Total length of yoke (mm)	20040	13966	11600	11600	9200
Weight of barrel yoke (t)	6000	5940	1608	1560	1125
Weight of each end cap (t)	2000	3316.6	678	657	401
Total weight of yoke (t)	**10000**	**12573**	**2874.5**	**2874.5**	**1927**

Table 8. Stray field comparison.

Stray field		CMS	CEPC original	CEPC coil smaller& 3 layers yoke	CEPC coil smaller& 1 layers yoke
50 Gs	R direction	25.2 m	13.6 m	23.4 m	24.4m
	Z direction	32 m	15.8 m	28.6 m	30.4 m
100 Gs	R direction	19.2 m	10 m	18.4 m	19.2 m
	Z direction	25.2 m	11.6 m	22.7 m	24.2 m

2.4. Other reference: BES III and BELLE II

2.4.1. Detector magnet of BES III

The size of the BES III detector magnet is much smaller than the CEPC, and the magnet field is only 1 tesla. Figure 9 shows the size of the coil and yoke.

Table 9 gives the parameters of the magnet. The magnetic field distribution can be seen in Figure 10. From the figure, we can get than the magnetic field on the yoke is far from saturated, so the region of stray field can be limited to very small. More details can be seen in Figure 11 and Table 10.

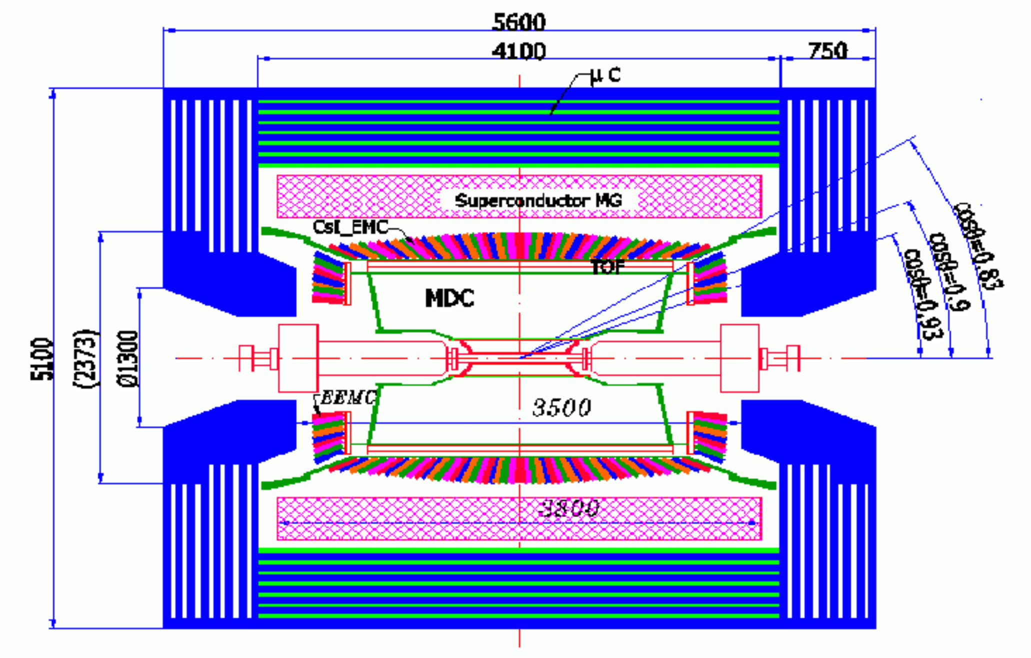


Figure 9. Dimension diagram of BES III detector magnet

Table 9. BES III detector magnet parameters:

Central magnetic field	1.0 T
Coil length	3.5 m
Internal diameter	1.49 m
Operating current	3.369 kA
Stored energy	11 MJ

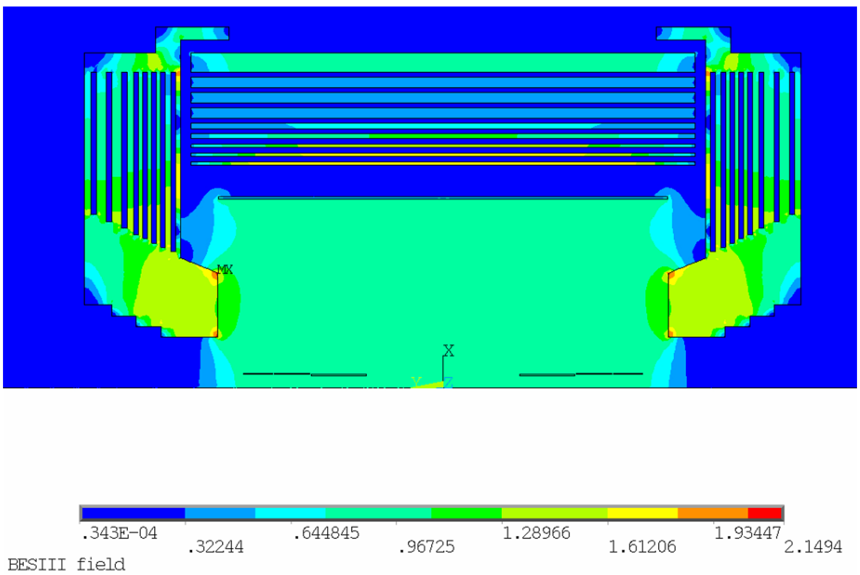


Figure 10. Magnetic field distribution of BES III detector magnet.

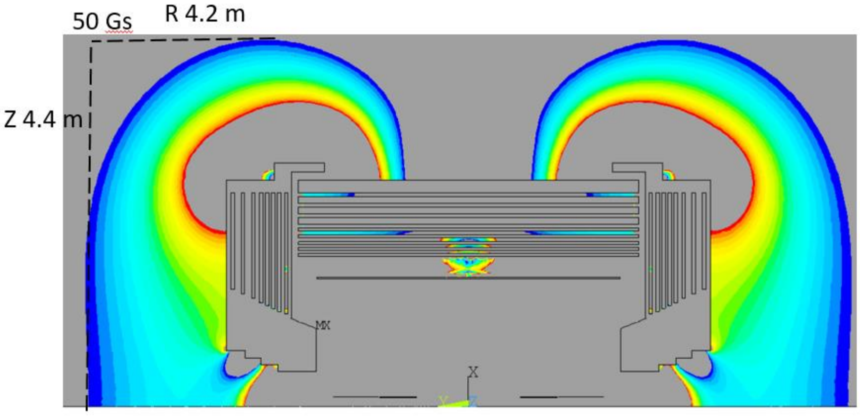


Figure 11. Stray field distribution of BES III detector magnet

Table 10. Location of 50 gauss.

Stray field		Location
50 Gs	R direction	4.2 m
	Z direction	4.4 m

2.4.2. Detector magnet of BELLE II

The data is referenced from the TDR of BELLE II. The size of the BELLE II magnet is a little larger than BES III, and the center magnetic field is 1.5 tesla. The maximum magnetic field is also a litter larger than 2 tesla. Figure 12 shows the 1/4 model of the magnet. Table 11 and 12 are the parameters of the magnet and yoke. Figure 13 and 14 are the magnetic field and stray field 50 gauss and 100 gauss distribution. The stray field is limited well.

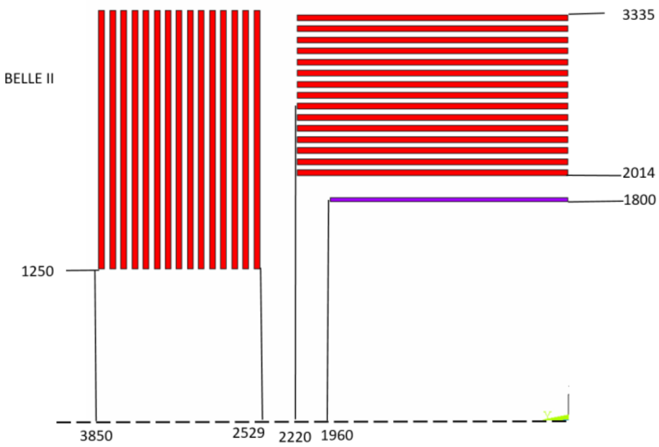


Figure 12. 1/4 model of Coil and yoke of BELLE II magnet

Table 11. Magnet parameters of BELLE II:

Central magnetic field	1.5 T
Coil length	4.440 m
Internal diameter	3.6 m
Operating current	4.4 kA
Stored energy	35 MJ

Table 12. Yoke parameters of BELLE II:

Items	Parameters
Belle Iron Yoke	
Height	9.57 m
Beam level	5.72 m
Total Weight	11740 kN
Barrel yoke	
Shapes	octagonal
Material	S10C iron
Height	7.7 m
Width	7.7 m
Length	4.4 m
Total Weight	6240 kN
Number of iron plates	15
Thickness of iron plate	47 mm
Thickness of gap	44 mm
End Yoke	
Material	S10C iron
Height	7.7 m
Width	7.7 m
Length in beam direction	1321 mm
Total Weight	5254 kN
Number of iron plates	15
Thickness of iron plate	47 mm
Thickness of gap	44 mm

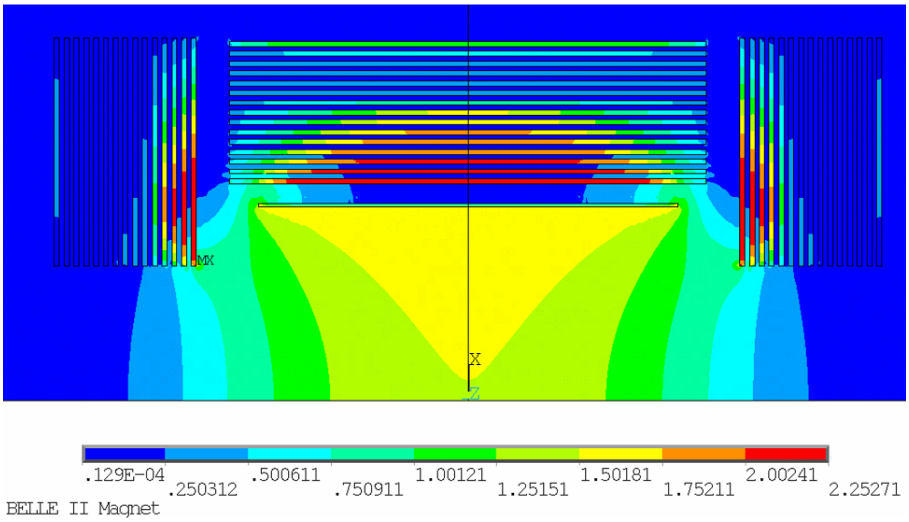


Figure 13. Magnetic field distribution of BELLE II detector magnet.

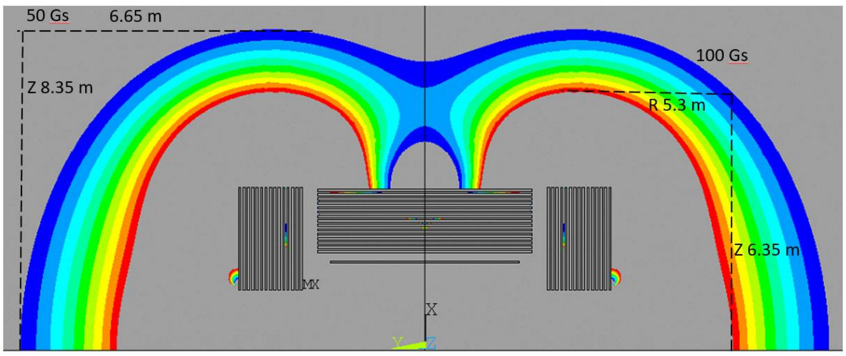


Figure 14. Stray field distribution of BELLE II detector magnet

Table 13. Location of 50 gauss and 100 gauss.

Stray field		Location
50 Gs	R direction	6.65 m
	Z direction	8.35 m
100 Gs	R direction	5.3 m
	Z direction	6.35 m

2.4.3. Stray comparison of BES III and BELLE II:

The magnetic field of the two detector magnets is 1 tesla and 1.5 tesla, and the maximum field is a little larger than 2 tesla. The magnetic field on the yoke is not saturated. Figure 15 shows the magnetic field distribution on the yoke of BES III and BELLE II, we can get that the magnetic field on the outer yoke is less than 1.5 tesla, so the magnetic flux can be limited in the yoke mostly.

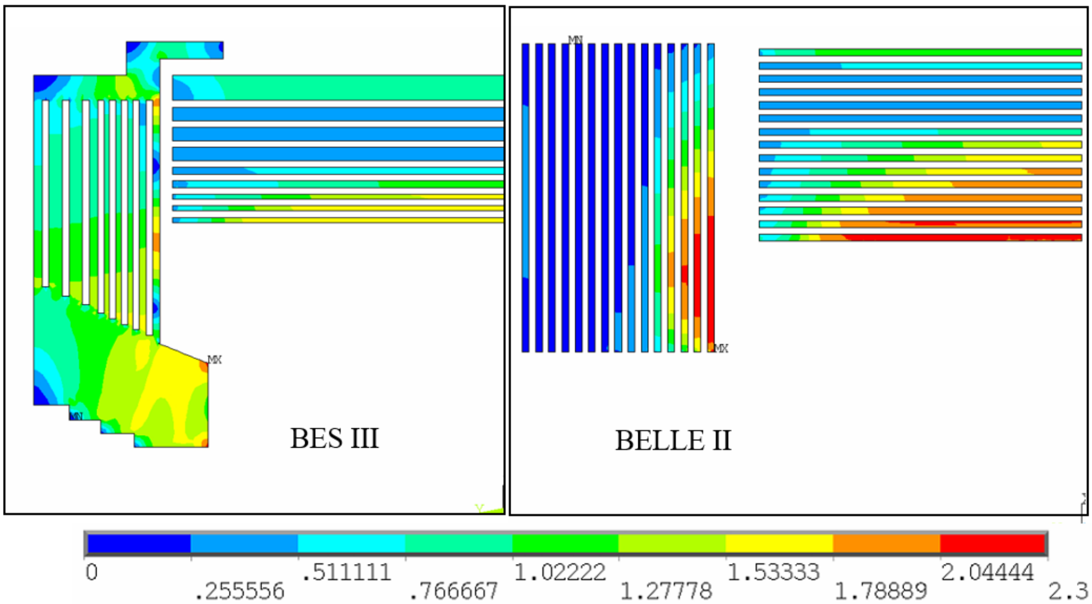


Figure 15. Magnetic field distribution on the yoke of BES III and BELLE II

Table 14. Location of 50 gauss and 100 gauss of BES III and BELLE II

Stray field		BES III	BELLE II
50 Gs	R direction	4.2 m	6.65 m
	Z direction	4.4 m	8.35 m
100 Gs	R direction		5.3 m
	Z direction		6.35 m

2.5. Final version yoke design

Considering the Muon detector, the yoke has to be divided into four parts, and there is a 40 mm gap between each part. This design bases on the smaller coil & 1 layer yoke version. Fig 16 shows the shape and size schematic diagram of the new design and based design version. Table 15 gives the yoke size and weight parameters.

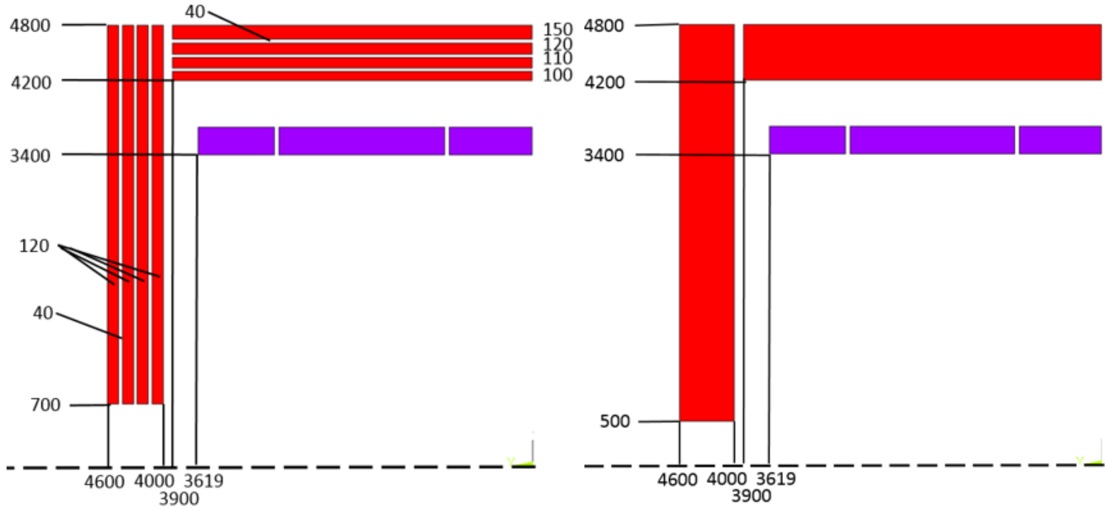


Fig 16. Shape and size schematic diagram of the two design plans

Table 15. Yoke weight and size comparison of different design

	Smaller coil & 1 layer yoke	Final version design
Central field (T)	3	3
Operating current (A)	17952.2	18314.7
Inner diameter of coil (mm)	6800	6800
Length of coil (mm)	7238	7238
Inner diameter of end yoke (mm)	500	700
Barrel yoke inner diameter (mm)	8400	8400
Barrel yoke outer diameter (mm)	9600	9600
Total length of yoke (mm)	9200	9200
Weight of barrel yoke (t)	1125	857
Weight of each end cap (t)	401	275
Total weight of yoke (t)	**1927**	**1407**

Magnetic field distribution

Figure 17 shows the 2D magnetic field distribution of this vision. The center field is 3 T. Figure 18 gives the axial magnetic field distribution from center to 20 meters.

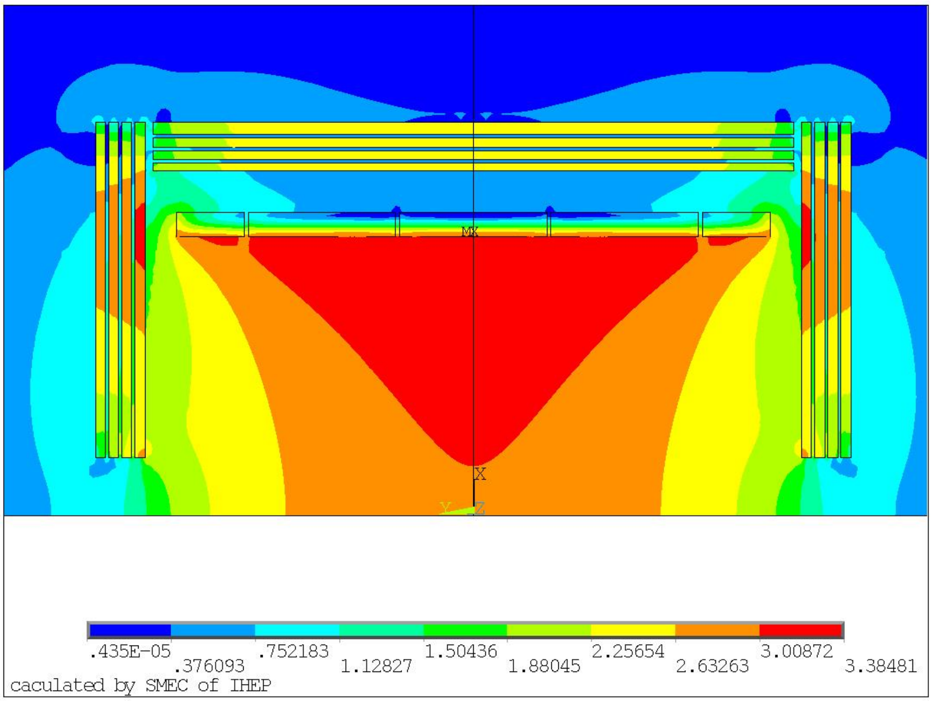


Figure 17. Magnetic field distribution

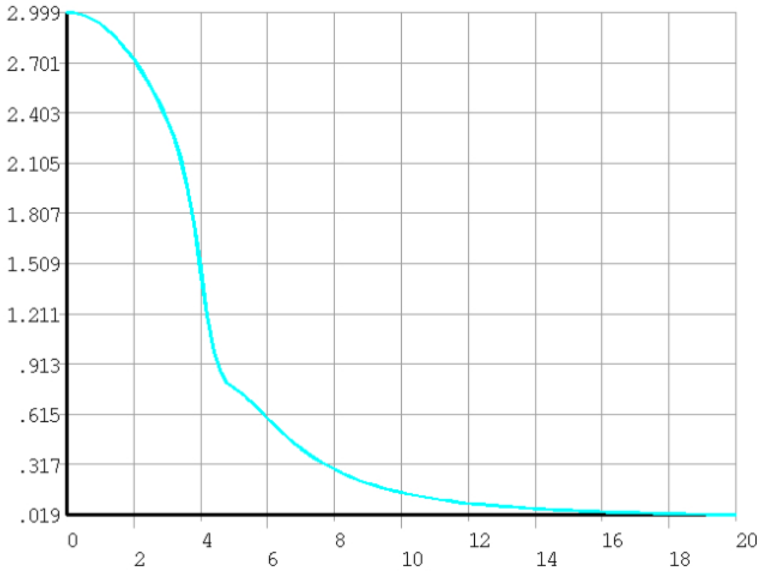


Figure 18. Magnetic field distribution along axial direction

Figure 19 and table 16 give the stray field 50 Gauss and 100 Gauss distribution of the plan. It is a little larger than that of one layer plan.

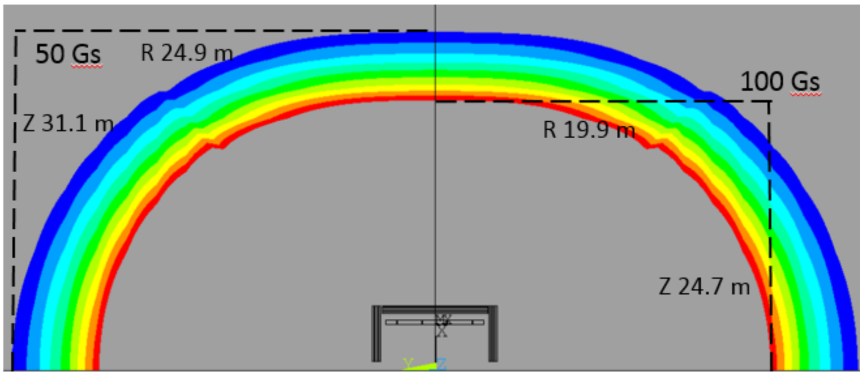


Figure 19. Stray field distribution of 3 layers yoke magnet

Table 16. Location of 50 gauss and 100 gauss.

Stray field		Location
50 Gs	R direction	24.9 m
	Z direction	31.1 m
100 Gs	R direction	19.9 m
	Z direction	24.7 m

Stress analysis of the yoke

There is magnetic force acting on the yoke. Because of the high field, the magnetic force is very large. This should be considered. Table 17 is the calculated result of the axial component magnetic force of the end yoke. Figure 20 and 21 show the contour distribution of the stress.

Table 17. Axial component Force on end yoke.

part	Force unit (N)
End yoke 1	-0.11236E+08
End yoke 2	-0.10123E+08
End yoke 3	-0.75674E+07
End yoke 4	-0.45802E+07

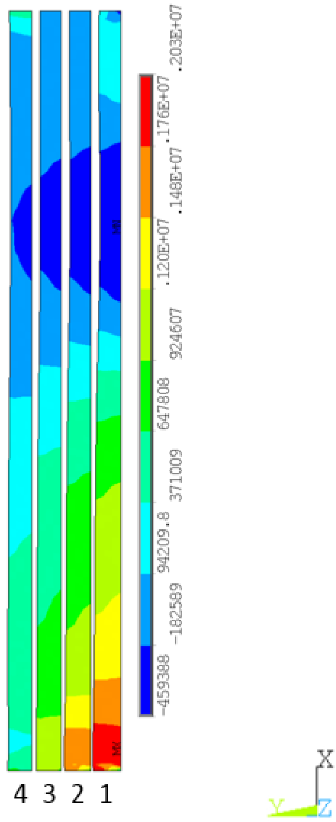


Figure 20, axial component stress of the end yoke

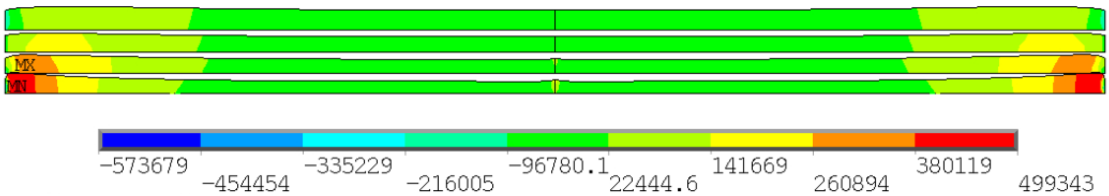


Figure 21, radial component stress of the barrel yoke

2.6. Summary of yoke design.

The original design of detector magnet has a very thick yoke. Taking reference of the CMS stray field distribution. We designed a reference yoke design. This reference yoke design reduces the thickness and total weight by 70% and 85% w.r.t the original design. This will take a lot of benefits, not only the magnet, but also the whole project.

3. Device layout and magnetic field strength at booster ring

The magnetic stray fields outside the iron return yokes of the detectors need to meet the requirements of the electronics, the accelerator components and the interventions for maintenance.

3.1. Device layout

3.2. Magnetic field strength at booster ring

The Booster tunnel located 25 m away from the beam line tunnel. The magnetic field strength is required to be less than 5 gauss. If the version of 3 layers thin yoke is used, the stray field strength at the booster location is about 50 gauss, so the stray field must be shield.

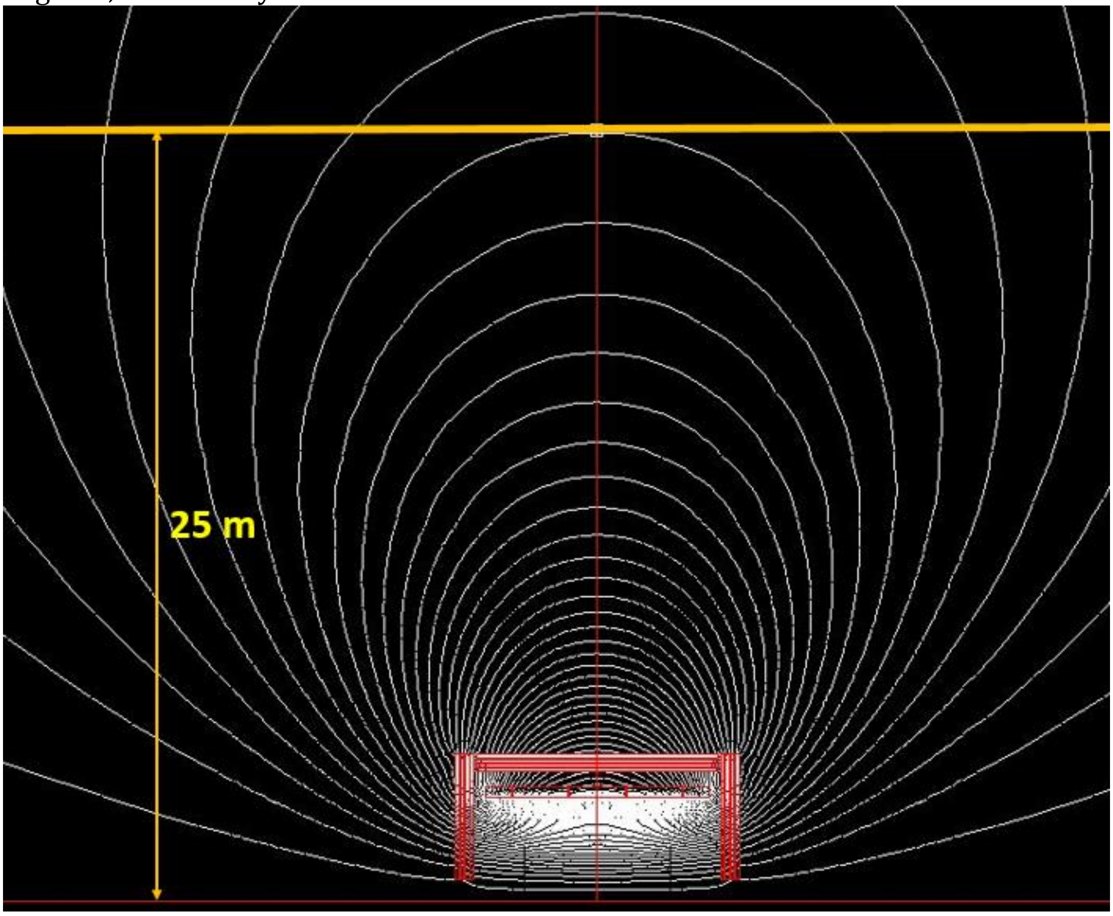


Figure 22, the location of booster ring

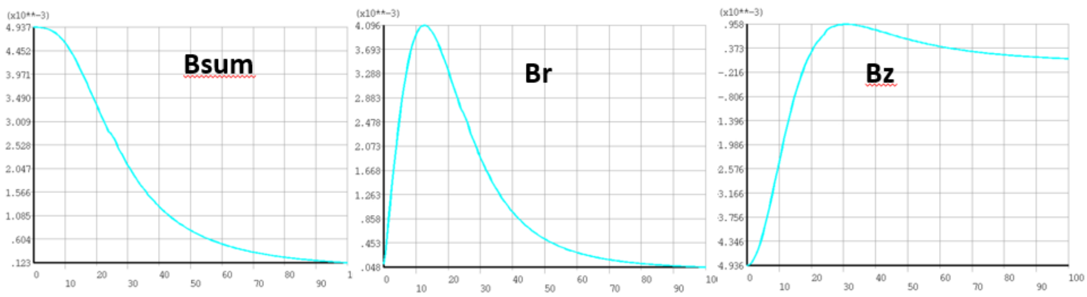
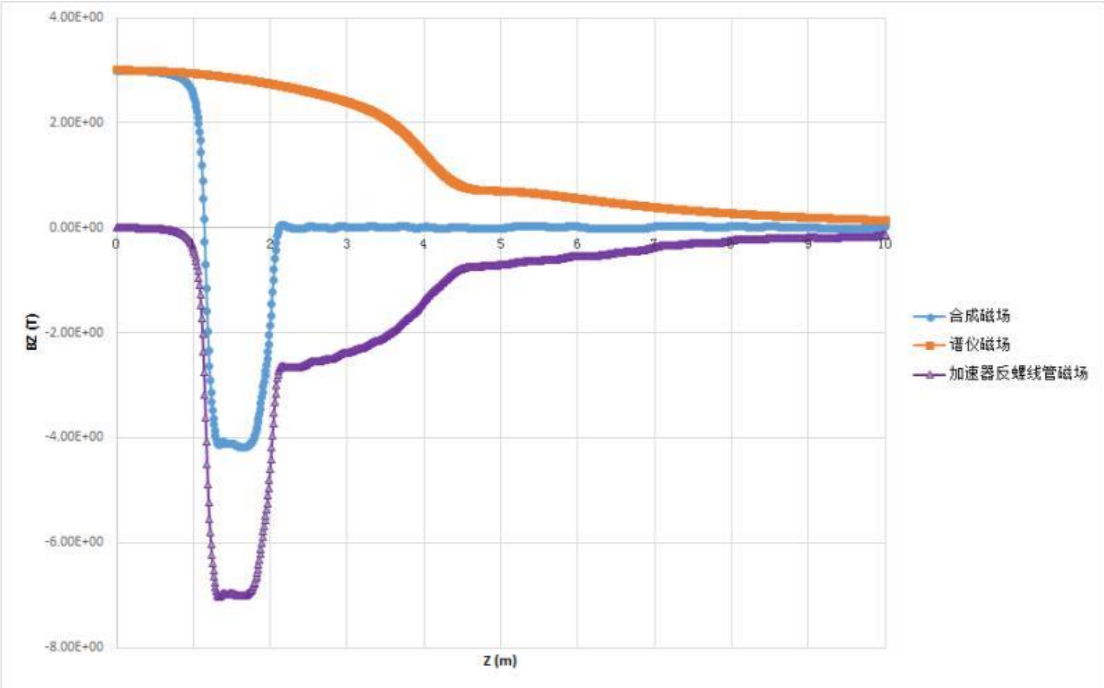


Figure 2 , the magnetic field distribution at Booster ring

3.3.

4. Conceptual local shielding scenario

The magnetic field at the electron-positron beam line in the detector need to be compensated.



5. Conclusion