RHIC Electron Lens Beam Transport System Design Considerations

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To apply head-on beam-beam compensation for RHIC, two electron lenses are designed and will be installed at IP6 and IP8. Each electron lens has several sub-systems, including electron gun, electron collector, superconducting main solenoid (SM), diagnostics system and power supply system. In addition to these systems, beam transport system which can transport electron beam from electron gun side to collector side is also needed.

In this note, the design considerations for this beam transport system are reported.

Introduction

To design electron lens beam transport system, the most important thing is to control electron beam trajectories and make them follow the center line of superconducting main magnet.

Six magnets are used for this purpose. Fig. 1 is the layout of one electron lens, which has gun side, SM and collector side. Each side of one electron lens has three magnets, they are GS1, GS2 and GSB on left side, and CS1, CS2 and CSB on right side.

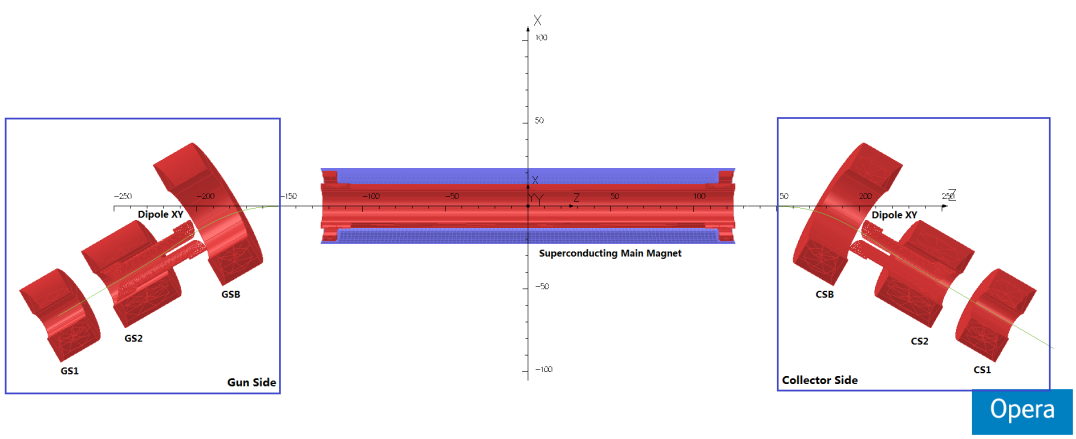

Fig. 1 Layout of E lens

For our electron lens beam transport system, the second important thing is to steer beam position inside SM magnet with 5 mm change in horizontal and vertical plane. To satisfy this requirement, two dipole magnets (Dipole X and Dipole Y) are designed for each side of two lenses.

During electron lens design period, running cost also should be taken for considerations. How to reduce power consumption used in transport system is the third important thing.

After that, some other design considerations, such as two electron lens simulations, power stability, iron thickness (for superconducting main magnet) and realistic solenoid simulations are also discussed in this note.

Electron Beam Center Trajectory Control

With electron lens default operation configuration, electron beam comes out from electron gun first, and then goes through GS1, GS2 and GSB. After that, it starts to enter the SM magnet, passes SM along the center line of this magnet. Then, it is transported from CSB, CS2 and CS1. Finally, it is dumped into a collector. This procedure is also shown as the green line in Fig. 1, which starts from gun side to collector side.

With default operation configuration, dipole magnet should be shut down, and the magnetic field along this line should be greater than 3000 Gauss.

There are several parameters that can be used for beam trajectories control, such as the strength of GSB and SM magnetic field, the angle between GSB and z axis and the distance between GSB and SM. Table 1 lists all parameters which can be used for trajectory control, and gives how beam trajectories move when these parameters are applied.

Table1 the Parameters Can be Used for Beam Center Trajectory Control

Parameters	Shift Up (+X)	Shift Down(-X)
GSB current	Increase	Decrease
GSB angle	Increase	Decrease
GSB position	Shift up	Shift down
GS1 and GS2 angle	Decrease	Increase
GS1 and GS2 position	shift to left	shift to right
GSB, GS1 and GS2 position	Shift to left	Shift to right
GSB Local Shift	Shift up	Shift down
GS1 and GS2 current	No change	

After tuning these parameters, we can control the beam trajectories as we expected.

Table 2 is our electron lens beam transport system design specifications. The first part in this table includes the position and angle of GS1, GS2 and GSB. The second part of this table is the conductor parameters and the geometry of these magnets. The third part that listed in this table is the power

consumption, temperature increase and magnetic field which are caused by these solenoids, and they are given with two different cases, normal optimization case and normal plus 40% current case.

Table 2 E-lens Beam Transport system Design Specifications

	E-lens Beam Transport System Design Specification					
		GS1	GS2	GSB	GSX	GSY
			Position and Angle			
Global Position	L_*_GCS (mm)	-1690	-1690	-1850	-1690	-1690
Local Position	L_*_LCS (mm)	1320	820	100	660	660
Angle	Theta (degree)	30	30	30	30	30
			Solenoid Parameters			
Conductor	h_cond (mm)	14	14	14	6.35	6.35
	ID_water(mm)	9	9	9	4.75	4.75
	b_insul (mm)	0.3	0.3	0.3	0.65	0.65
Size	ID(mm)	173.48	234	480	194	210
	OD(mm)	553.08	526	859.6	208	224
	Length(mm)	262.8	379.6	262.8	500	500
	N_Layer	13	10	13	12	12
	N_pan	9	13	9		
	Inductance (Henry)	0.017	0.018	0.043		
	Resistance (ohm)	0.03926	0.04798	0.07611	0.023	0.024
			Optimization			
Power	Power (kW)	58.3	25.6	45	1.4	1.7
	Current(A)	1188	731	769	258	271
Water	Temp_Delta (°C)	13.4	3.6	14.2	5.9	6.9
	Pressure_Drop(Bar)	1.5	1.5	1.5	1.5	1.5
Field	(Gauss)	8000.26	4468	3202	-	-
			Plus 40% Current			
Power	Power (kW)	114	50	88	2.9	3.4
	Current(A)	1663	1023	1077	361	383
Water	Temp_Delta (°C)	26.2	7.05	27.87	11.55	13.54
	Pressure_Drop(Bar)	1.5	1.5	1.5	1.5	1.5
Field	(Gauss)	11200	6256	4482	-	-

Because CS1, CS2 and CSB have the same configuration as GS1, GS2 and GSB respectively, they are not listed in this table.

Fig. 2 shows the position definitions that are listed in table 2. GS1 and GS2 have the same global position, which is L_GS12_GCS. GSB has its own global position L_GSB_GCS. But all of them have the same 30 degree angle. And they have their different local positions. From the global position and along 30 degree line, they are moved with the distance L_GS1_LCS, L_GS2_LCS and L_GSB_LCS.

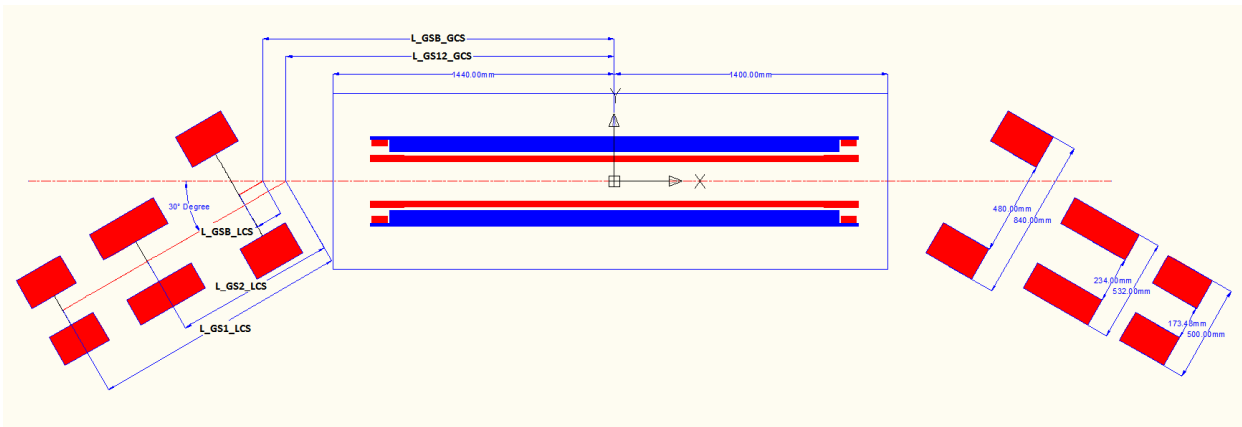

Fig. 2 Position Definitions in Table 2

At last, when electron beam passes this beam transport system, with the parameters listed in table 2, it can go through SM magnet along its center line. Fig. 3 is the plot of beam trajectory which is controlled along the center line of SM magnet

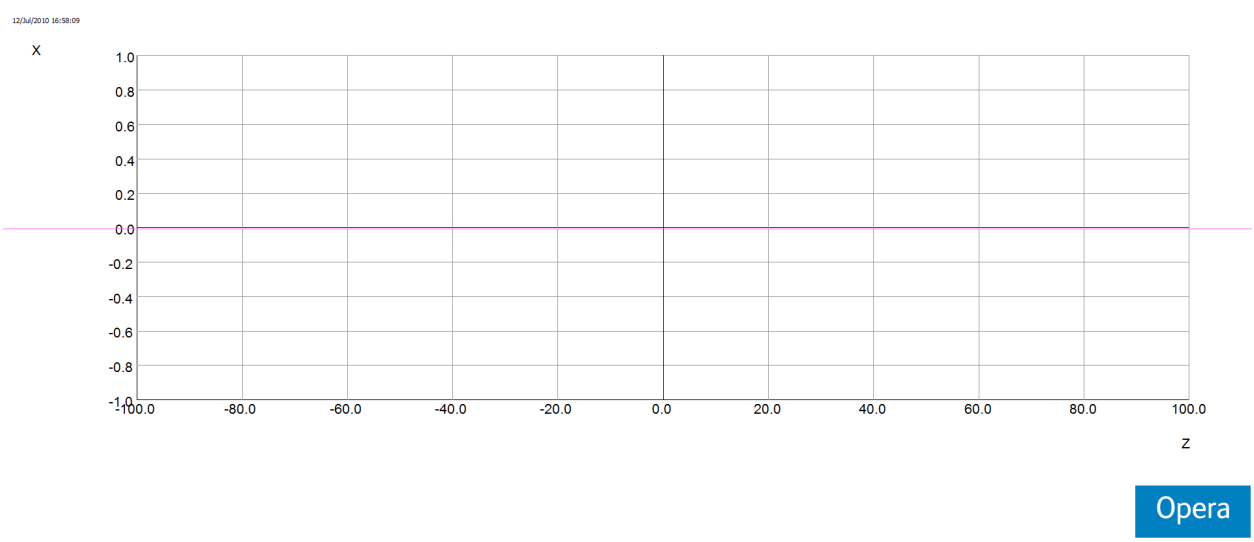

Fig. 3 Beam trajectory at the center of SM magnet

Meanwhile, the magnetic field along the center line (the green line in Fig. 1) was also plot as Fig. 4. The vertical unit is Gauss and horizontal unit is centimeter.

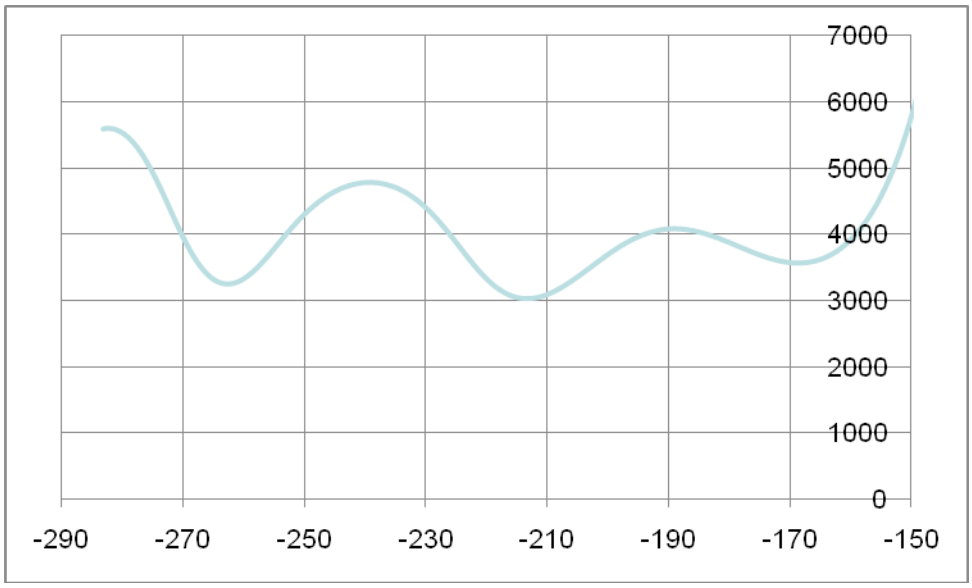

Fig. 4 Magnetic field distribution along center trajectory line

From Fig. 4, we can find that all positions that electron beam passes, its magnetic field is greater than 3000 Gauss.

Fig. 5 is the magnetic field map distribution around gun side, which shows the area that the amplitude of magnetic field is greater than 3000 Gauss.

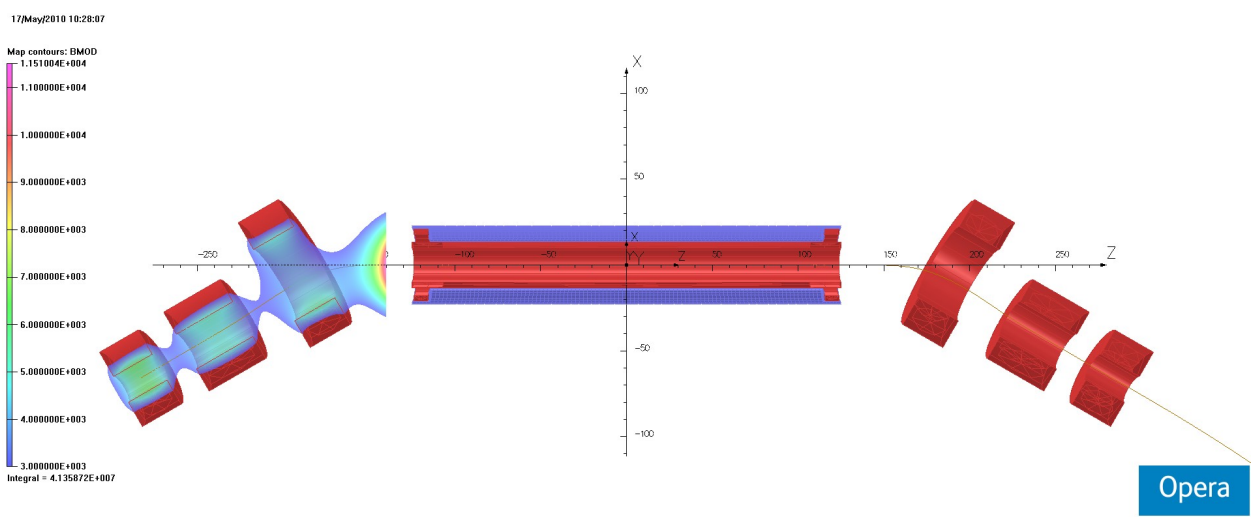

Fig. 5 Magnetic field distribution around gun side

3. Dipole Magnet Design for Beam Off-set

For electron lens, electron beam should head on collide with proton beam at IP 6 or IP 8. So, it is very important to align electron beam with proton beam.

And for this alignment, steer electron beam to approach proton beam is easier than to adjust proton beam. Because of this, the electron beam should have the capability to shift 5 mm around the center line in horizontal and vertical plane.

Dipole magnet X and Y are designed for this purpose (Fig. 1). They are placed inside of GS2 and CS2. Their parameters are also listed in Table 2. Fig. 6 is the geometry of one dipole X, and Fig. 7 is its magnetic field distribution. In Fig. 7, the vertical unit is Gauss and horizontal unit is centimeter.

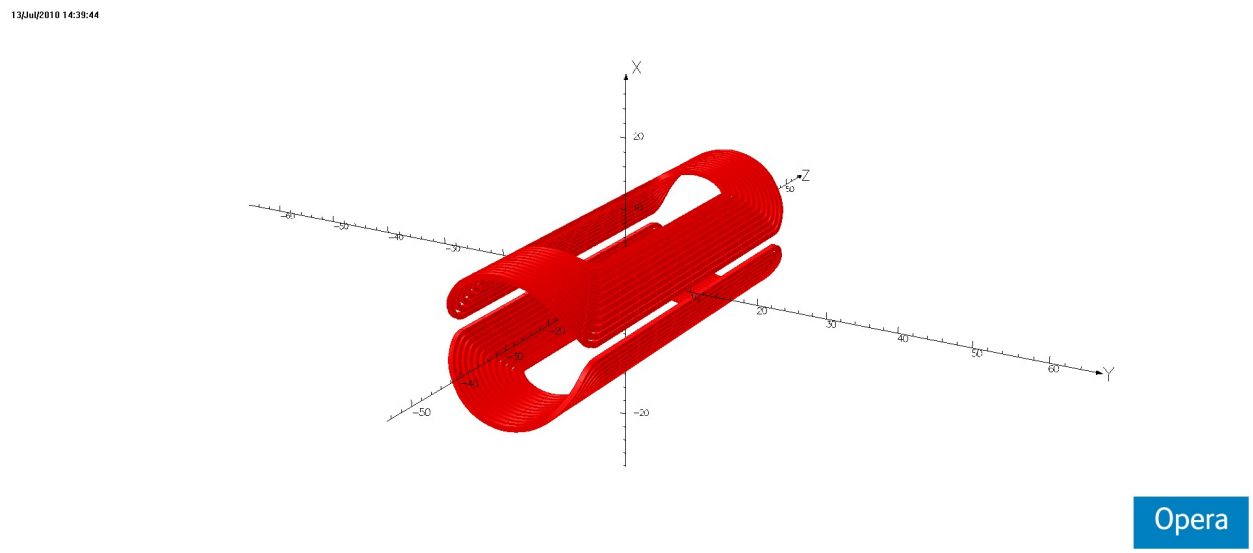

Fig. 6 Geometry of Dipole X

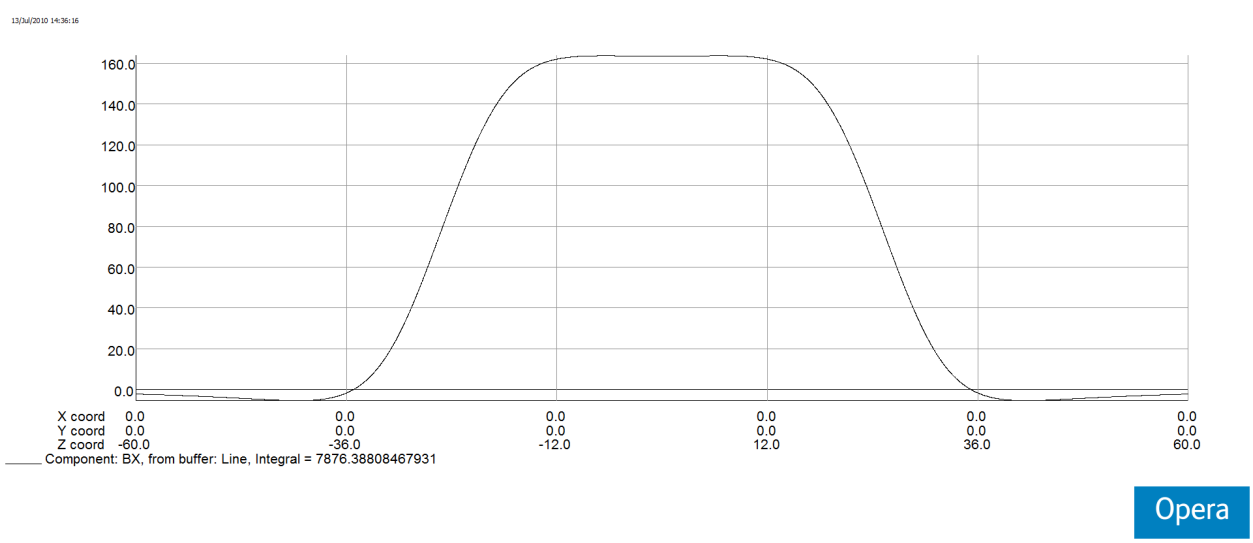

Fig. 7 the Magnetic Field Distribution (Bx) Produced by Dipole X

Fig. 8 is the beam trajectories inside of SM magnet with 5 mm shift after dipole X and dipole Y power on.

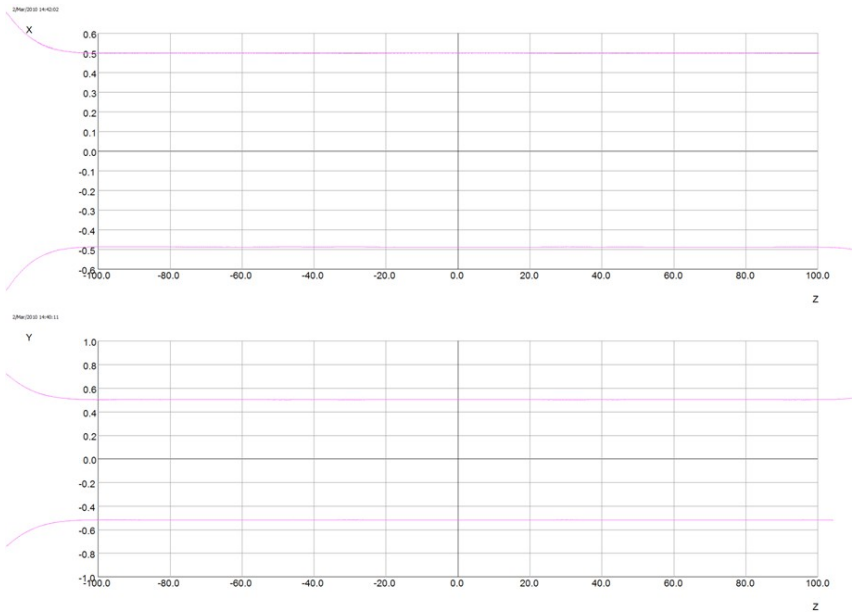

Fig. 8 Beam Trajectory 5 mm Off-set in Vertical and Horizontal Plane

Fig. 9 is the beam trajectories envelope after using dipole magnet with the center beam trajectory 5 mm shift. In Fig. 9, when the upper line was plot, the electron comes from upper side of cathode and beam was shifted up 5mm. The lower line was plot with the electron produced by lower side of cathode and with beam 5 mm shift down.

According to Fig. 9, we can optimize the tube inner diameter so that the electron beam will not touch its inner side. Tube inner size should also be careful design by technician at last.

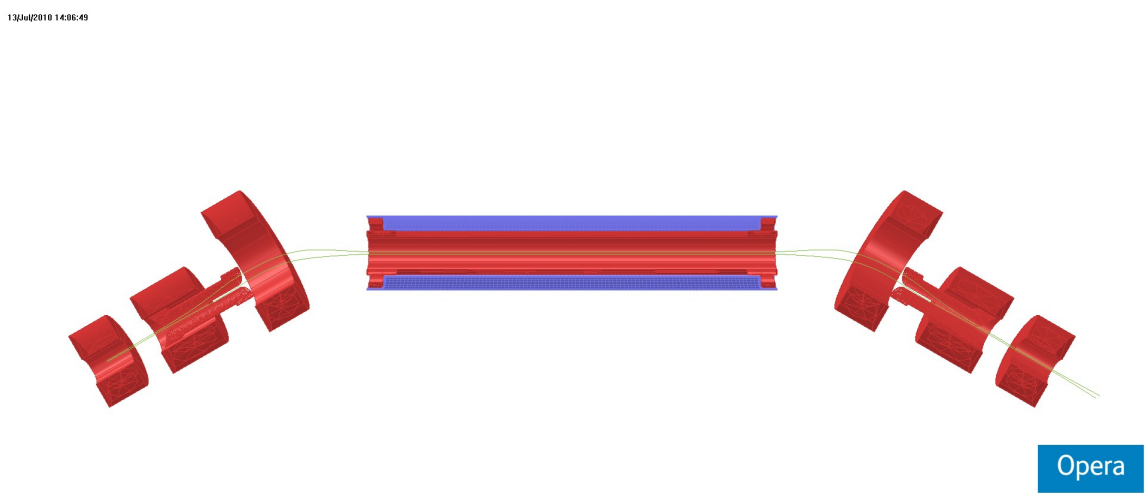

Fig. 9 Horizontal Beam Trajectory Envelope with 5mm Shift Up and Down)

4. Power Consumption Optimization

For power consumption, there are several ways to optimize it. Firstly, we can optimize the conductor parameters.

Table 3 lists some conductors and their power consumptions, currents and space factor. Space factor equals to the conductor intersection area divided by total intersection area. All these conductors are the conductor with square outside and round hole inside. H_Cond is the out size and D_water is the inner diameter of water cooling hole.

Table 3 Conductor and Power Consumption

Conductor	H_Cond	D_Water	P (kW)	Current (A)	Space Factor λ
1	9.7	7.9	77.88	418	0.425
2	11	8.8	77.58	557	0.447
3	6	4.5	72.94	175	0.461
4	6.35	4.75	73.6	198	0.468
5	10	7.5	71.58	480	0.497
6	7	5	68.27	240	0.509
7	8	5.5	64.35	311	0.544
8	13	9	65.78	837	0.569
9	9.52	6.35	59.26	418	0.576
10	14	9	54.5	846	0.62

Fig. 10 is the power consumptions with different conductors that listed in table 3. Its vertical unit is Kilowatt. At last, the conductor with number 10 is used for our solenoids magnet design, and the conductor 4 is used for dipole magnet design.

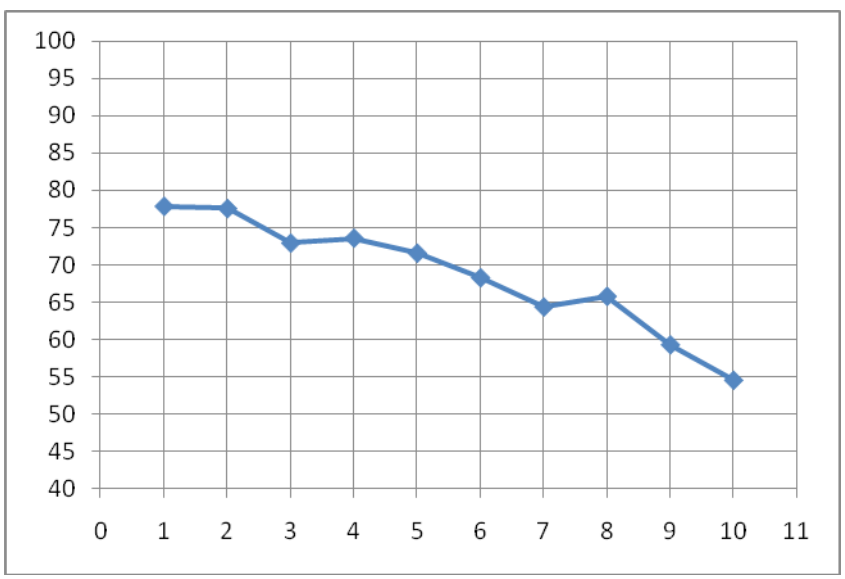

Fig. 10 Power Consumption with Different Conductor

With 8k Gauss GS1 and 4k Gauss CS1, the total power consumption is about 214 kW for one electron lens.

The second way to reduce power cost is to use different operating configuration. For our default operating model, we tune the current of GSB to control beam trajectories. Dipole magnets are turned off at this moment. After finishing electron lens commissioning, if it is possible to decrease the minimum magnetic field, from 3k Gauss to 1.5k Gauss for example, maybe we can reduce the GSB current while increase dipole magnet X current for beam position control.

The case C in the Table 4 is one example (not the realistic one) which operated with dipole magnet X. Compared with case A (default operating model) and case C, we can reduce power consumption about 30 kW.

Table 4 Power Consumption for Different Operating Model

	Dipole X Current Density(A/cm^2)	GSB Current Density(A/cm^2)	Beam Position(cm)	Dipole X Power(kW)	GSB Power(kW)
A	0	365	~ 0	0	~ 45
B	0	180	~ -0.48	0	~ 11
C	350	180	~ -0.02	0.3	~ 11

Thirdly, we also did some power consumption optimizations for magnets themselves. Fig. 11 is the power optimization for GS1 solenoid. The red curve is the power consumption change with different number of pancakes while number of layer is 13. The blue curve is the power change with layer number, while keep pancake number same as 9.

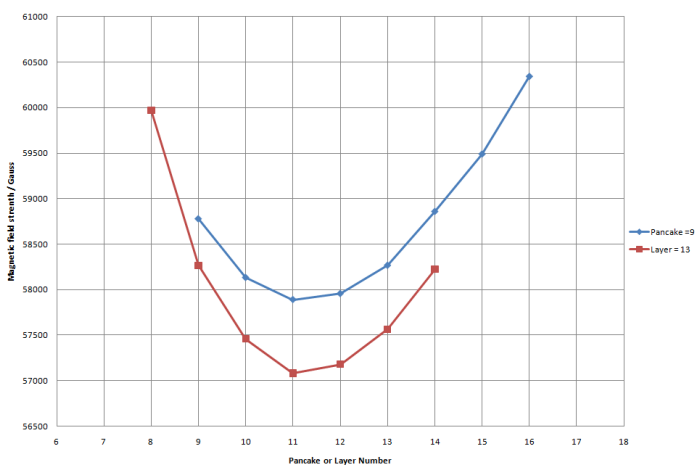

Fig. 11 Power Consumption with Different Conductor

From Fig. 11, solenoid GS1 with 11 pancakes and 13 layers has the minimum power consumption 57.08 kW, that is slightly lower than present parameter (9 pancake and 13 layers) 58.26 kW.

5. Two Electron Lenses Simulations

Usually, head-on beam compensation system should have two electron lenses. Fig. 12 is the layout of two symmetrical electron lenses system.

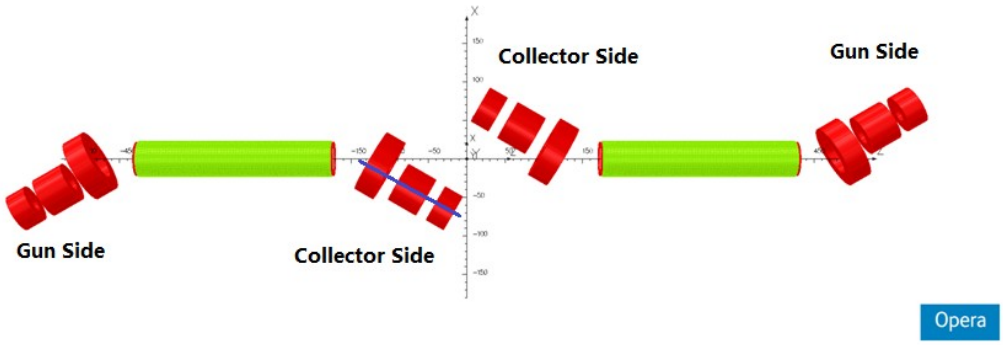

Fig. 12 Layout of Two Electron Lenses

For this two lenses system, the distance between them is another important thing. If we put them too close, their magnetic field on their collector side will affect each other, and electron beam trajectories maybe change too much beam trajectories control.

500 cm and 600cm distances between these two electron lenses were investigated when we carried out our simulations. Fig. 13 is their magnetic fields which were plot along the blue line in Fig. 12. With right side electron lens power off and power on, the magnetic field change 77 Gauss and 37 Gauss for 500 cm and 600 cm distance respectively.

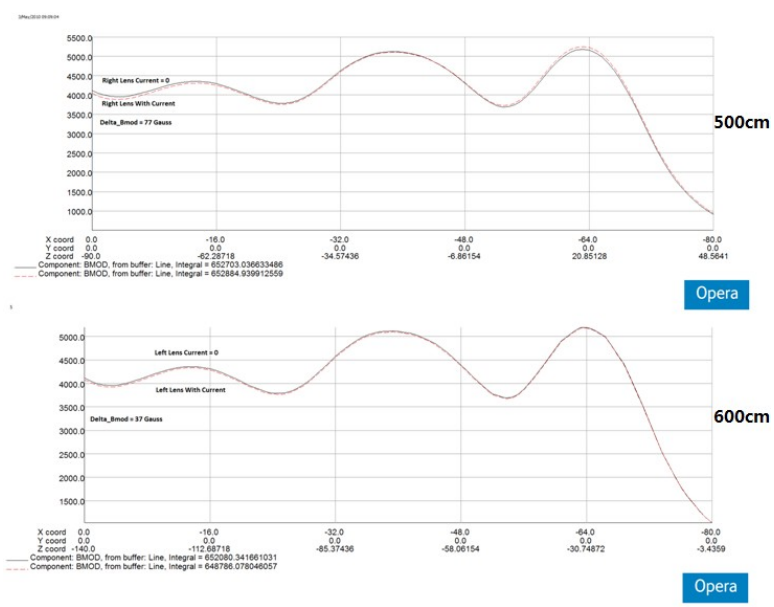

Fig. 13 Magnetic Field change for Two Electron Lens Configurations

Because magnetic field changed, the beam trajectories that located at the center point between CS1 and CS2 also changed. Fig. 14 is the electron beam trajectories change, which is about 48 mm and 12 mm for 500 cm and 600 cm distance respectively.

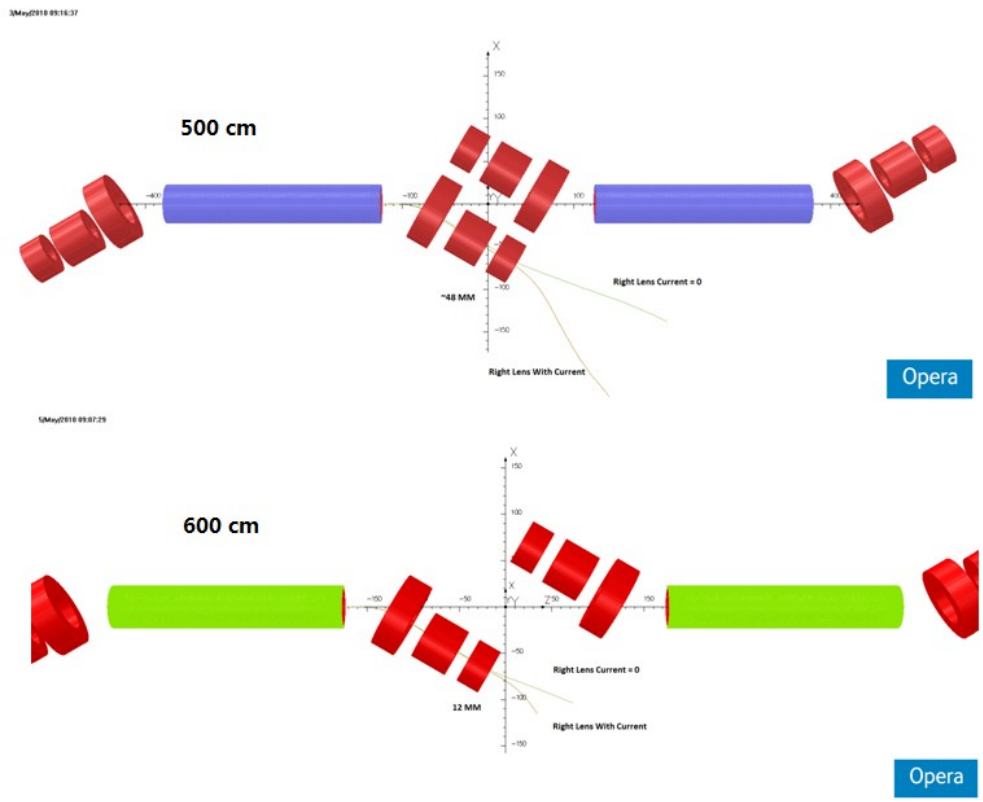

Fig. 14 Magnetic Field change for Two Electron Lens Configurations

During beam transport system design period, magnetic force calculation is another essential problem. Table 5 is the force calculation for left electron lens with 500 cm and 600 cm distance between the two lenses.

Table 5 Force Calculation with Different Lens Distance

Magnet	500 CM			600 CM		
	X (kN)	Y (kN)	Z (kN)	X (kN)	Y (kN)	Z (kN)
GSB	-2.4	0	6.7	-2.5	0	6.9
GS2	2.0	0	2.2	2.0	0	2.1
GS1	1.9	0	3.5	1.9	0	3.3
CSB	-2.8	0	-6.8	-2.7	0	-6.9
CS2	1.7	0	-2.0	1.9	0	-2.1
CS1	2.2	0	-3.0	1.8	0	-3.3

6. Power Stability Calculation

To estimate the power stability, we change GSB current and record the beam position (at the center of SM magnet) change, then plot GSB current as the function of Beam position in Fig. 15 and fit this plot with linear line.

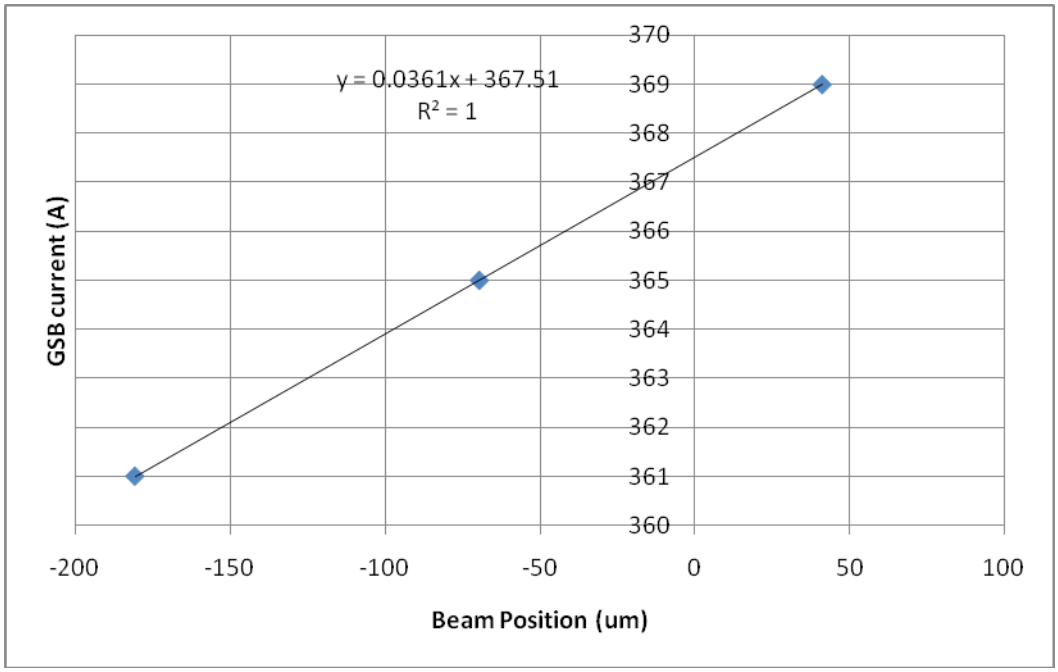

Fig. 15 Power Stability Calculation

At last, we get the function:

Y (A) = 0.0361* X (um) + 367.51

According to our requirement, the beam position vibration should be less than 10 um, that means power supply stability should better than 0.361 A. The power supply system with 10^{-3} stability should satisfy our requirement.

7. Iron Thickness Estimate for SM Magnet

In electron lens system, the superconducting main magnet will produce 6 Tesla magnetic fields. If there is no any iron to shield its field, its strong magnetic field may affect the outside instruments or was affected by outside field such as GSB, GS2 and so forth. In this instance, it is difficult to get a uniform field inside of this SM magnet.

To avoid this problem, an iron shield is placed at the outside of superconducting conductor. But the thickness of this iron should be carefully design. It should be compromise between cost and field uniform.

In order to estimate the thickness of iron, we put another straight iron cross over the center of SM magnet. Fig. 16 is the geometry we used for iron thickness estimate. The length of this straight iron line is 100 cm, and the distance between the center of SM and this straight iron line is also 100 cm.

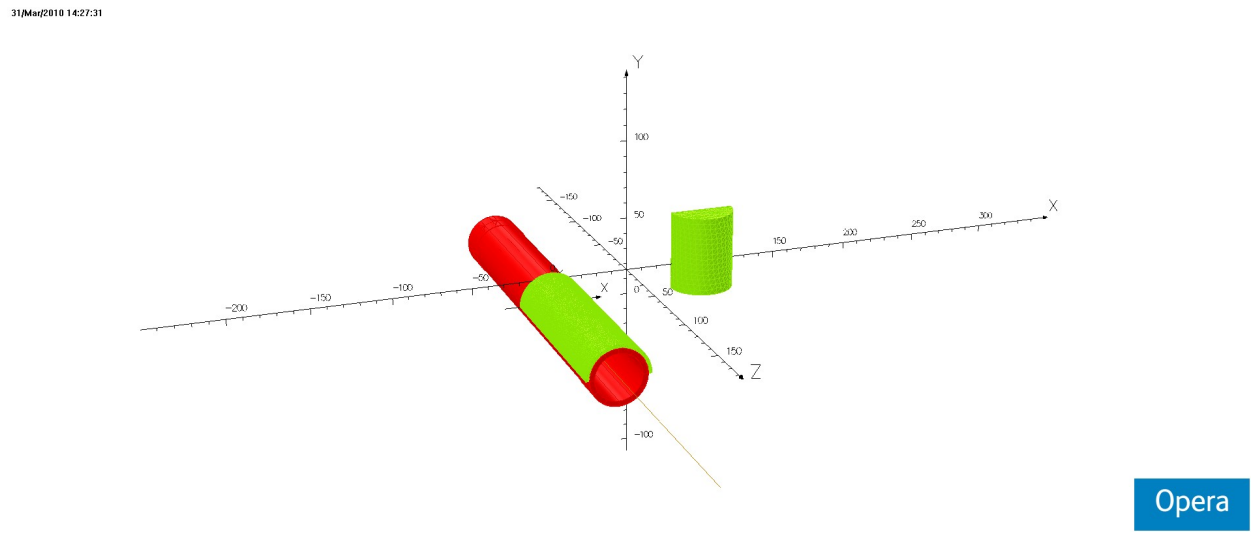

Fig. 16 Simulation Geometry for Iron Thickness Estimate

When we carried our simulation, the diameter of that straight iron and thickness of shield iron were changed. The iron thickness that was used is 2cm, 4cm, 6cm and 8 cm and the diameter of this straight iron line is 40 cm and 15 cm.

Then the electron beam trajectories were recorded and compared with and without this straight iron line. Their deviations and some other parameters are listed in table 6.

Table 6 Iron Thickness Simulation

Thickness of Shield Iron	Deviation with 40 cm Diameter	Deviation with 15 cm Diameter
2 (cm)	~ 30 um	~ 1.8 um
4 (cm)	~ 18 um	-
6 (cm)	~ 17 um	-
8 (cm)	~ 7 um	-

Fig. 17 was the deviation plotted with different thickness of superconducting shield iron. The initial beam position locates at -120 cm on z axis.

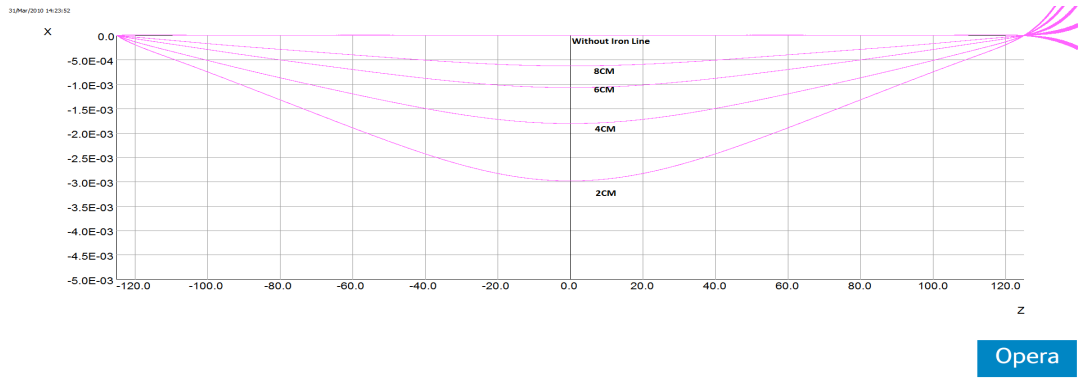

Fig. 17 Deviation Simulation with Different Iron Thickness

Fig. 18 is the electron beam trajectories with different thickness (9 and 12 cm) shield iron. When Fig. 18 was plotted, 10 cm diameter and 100 cm length straight iron was placed at 80 cm from the center of SM magnet.

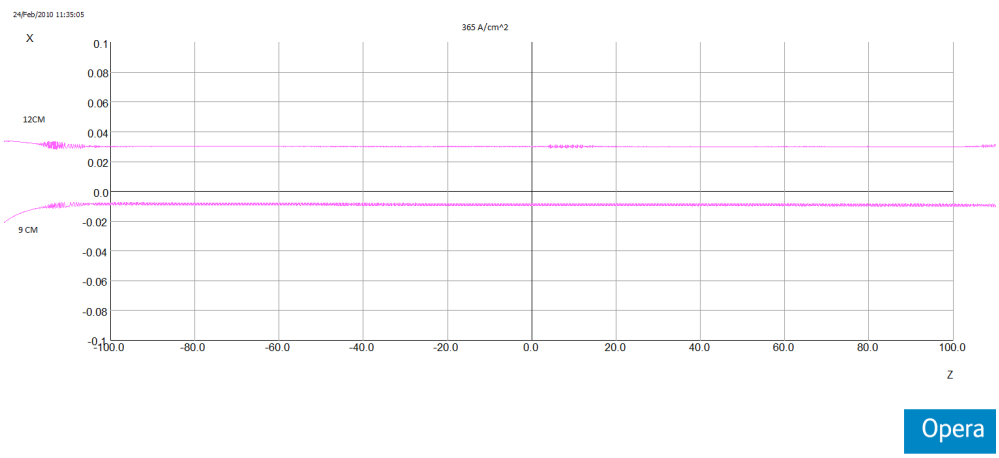

Fig. 18 Beam Trajectories with Different Thickness Iron

In addition to beam position change, if compared without this straight iron line, the magnetic field at the center of SM magnet also changes 0.25 Gauss and 0.08 Gauss for 9 and 12 cm thickness respectively.

The thickness of shield iron will be finally designed by superconducting magnet group according to its cost and magnetic field saturation.

8. Realistic Solenoid Simulation

Usually, we use idealistic solenoid model in our simulations. The idealistic solenoid has perfect magnetic field flux that is symmetry parallel to the center axis of solenoid. But in fact, the realistic solenoid must have some errors when we make it. These errors will tilt the main magnetic field flux and

cause high order magnetic field. Then, this distorted magnetic field will also defect and distort beam trajectories. So, it is also very important to investigate beam behavior after using the realistic solenoids.

After constructing two realistic magnets GS1 and GS2, we put them together with two configurations Case A and Case B, which are shown as Fig. 19. For Case A, GS1 and GS2 have the some leads directions. In Case B, GS1 and GS2 have opposite leads directions.

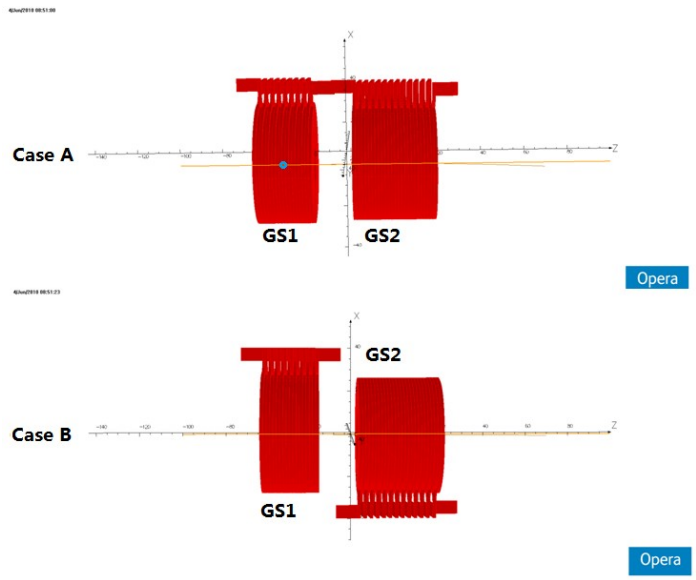

Fig. 19 Realistic Magnet Simulation with GS1 and GS2

The initial electron beam starts from the center of GS1 and go through GS2 from left to right. Then the beam trajectories are plotted as Fig. 20.

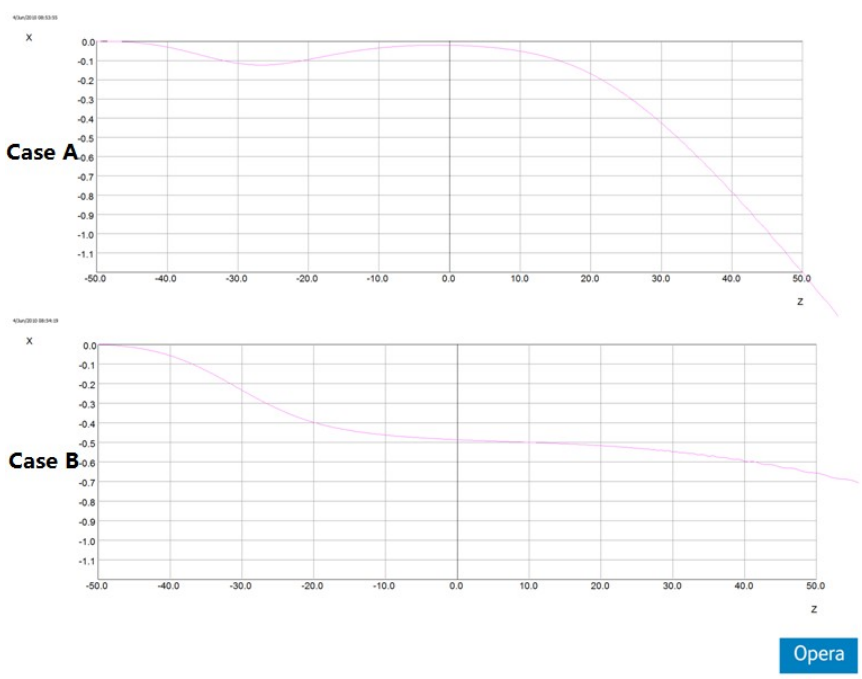

Fig. 20 Beam Trajectories Calculation by Realistic Magnet

Firstly, from Fig. 20 we can find that electron beam trajectories do not go along the center line of magnet. They were deflected away from the center line.

Secondly, we can know that Case A has a better result that Case B. That means the leads of all solenoids should be placed with the same direction if we use more than one solenoid at same time. The magnetic field component Bx for Case A and B are plotted in Fig. 21.

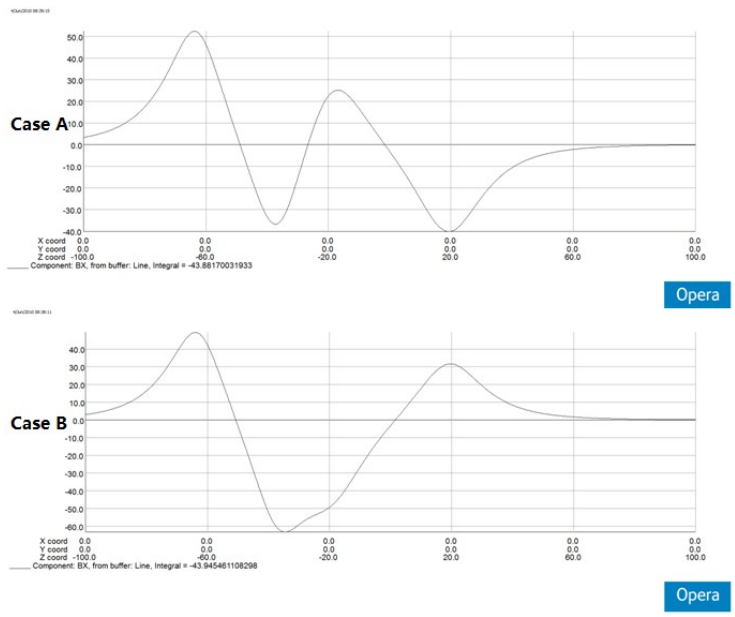

Fig. 21 Bx Component of Two Realistic Magnet Configurations

Furthermore, this beam trajectory change can also be found in our electron beam transport system.

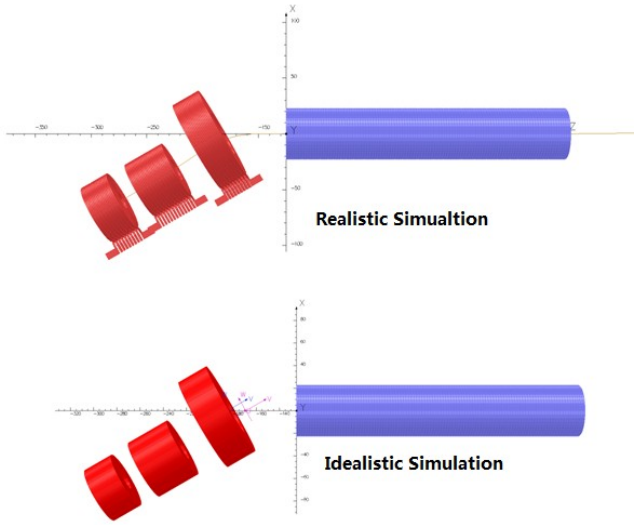

Fig. 22 Realistic Magnet Simulation for Electron Lens

In Fig. 22, after replacing idealistic GS1, GS2 and GSB with realistic magnets, the beam position at the center of SM magnet changes from (-0.01, -0.01) cm to (0.08, 0.05) cm in horizontal and vertical direction.

9. Discussion

Until now, we finished the most important parts of electron lens beam transport system design. For beam position control, the fringe coil in superconducting main magnet may be also used for this purpose.

In this note, we also discussed about some important issues about electron lens project, including two electron lens simulation, realistic magnet simulation and etc. These preparations will make us closer to the success of RHIC electron lens project.