DESIGN STUDY OF CEPC BOOSTER*

Bian Tian-Jian†, Gao Jie, Institute of High Energy Physics, Beijing, China
Cai Yun-Hai, Slac National Accelerator Laboratory, CA, USA
Michael Koratzinos, University of Geneva, GENEVA, Swiss
Zhang Chuang, Cui Xiao-Hao, Wang Yi-Wei, Bai Sha, Wang Dou, Su Feng, Xiao Ming,
Institute of High Energy Physics, Beijing, China

Abstract

CEPC is next generation circular collider proposed by China. The design of the full energy booster ring of the CEPC is especially challenging. The ejected beam energy is 120GeV, but the injected beam only 6GeV. In a conventional approach, the low magnetic field of the main dipole magnets creates problems. we have two ways to solve this problem, Firstly, we propose to operate the booster ring as a large wiggler at low beam energy and as a normal ring at high energies to avoid the problem of very low dipole magnet fields. Secondly, we implement the orbit correction and correct the earth field to make booster work.

INTRODUCTION

CEPC (Circular Electron and Positron Collider) was proposed as an electron and positron collider ring with a circumference of 50-100km to study the Higgs boson[1][2][3]. CEPCB(CEPC Booster) is a full energy booster ring with the same length of CEPC which ramp the beam from 6Gev to 120Gev. At the injected beam energy, the magnetic field of the main dipole is about 30Gs, the low magnetic field will create problems for magnet manufacturing[4].

In the Pre-CDR[5], a preliminary design is proposed, but the problems of earth field correction and dynamic aperture are not solved.

In this paper, we focus on those problems and find a reasonable solution. In the wiggler scheme, which split the normal dipole to several pieces with different magnet field direction to avoid the problem of very low dipole magnet fields[6][7][8], because low field magnet manufacture is difficult.

In the normal bend scheme, we implement the first turn orbit correction and closed orbit correction to correct the earth field effect.

An analytic map method(Differential algebra)[9] is used to derive the twiss functions of arbitrary order of energy spread, such as β function, phase advance function, dispersion function. Those functions are all analytic functions dependent of sextupole strength. Optimize the high order chromaticities, then a good dynamic aperture for both on-momentum and off-momentum particles are got.

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† biantj@ihep.ac.cn

DESIGN GOAL

At present, the emittance of CEPC is about $2.0 \times 10^{-9} m * rad$, it is much lower than the Pre-CDR because of the crab waist scheme. That makes the CEPCB harder to design because emittance of CEPCB at high energy is also reduced, which cause the chromaticities much stronger and pose challenges to our design at the same time.

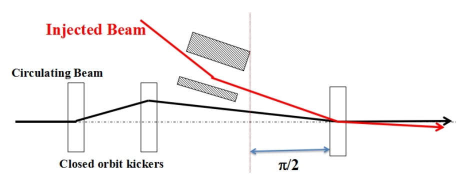

Figure 1: Injection scheme.

Fig. 1 shows the X direction injection scheme for mainring. Asume that the dynamic aperture of CEPC mainring at 0.5% energy spread is 15 times of sigma and the β function is about 200m.

The total space for injection:

$$\begin{aligned} & \sqrt{\epsilon_x \times \beta_x} \times 15 \\ = & \sqrt{2.0 \times 10^{-9} \times 200} \times 15 \\ = & 9.49(mm) \end{aligned}$$

5 sigma is retained for revolution beam to get enough quantum life time:

$$\begin{aligned} & \sqrt{\epsilon_x \times \beta_x} \times 5 \\ = & \sqrt{2.0 \times 10^{-9} \times 200} \times 5 \\ = & 3.16(mm) \end{aligned}$$

Asuming that the emittance of CEPCB at 120Gev is $3.5 \times 10^{-9} m * rad$, and 3 sigma is retained for injection beam to loss less particles:

$$\begin{aligned} & \sqrt{\epsilon_x \times \beta_x} \times 3 \\ = & \sqrt{3.5 \times 10^{-9} \times 200} \times 3 \\ = & 2.51(mm) \end{aligned}$$

The design goals of CEPCB are listed:

1. The emittance of CEPCB at 120Gev is about $3.5 \times 10^{-9} m * rad$.

2. 1% energy acceptance for enough quantum life time.

3. The dynamic aperture results must better than 6 sigma (Normalized by emittance, which is decided by the beam from linac) for both on-momentum and off-momentum(1%) particles.

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WIGGLER BEND SCHEME

Linear Lattice

The layout of CEPCB is show in Fig. 2. It is make up by 8 arcs and 8 straight section, and the total length is 63.8 km. The RF cavities are distributed in each straight section. The lattice for CEPCB has been chosen to use the standard FODO cells with 90 degrees phase advances in both transverse planes, which give us smaller emittance and clear phase relationship between sextupoles.

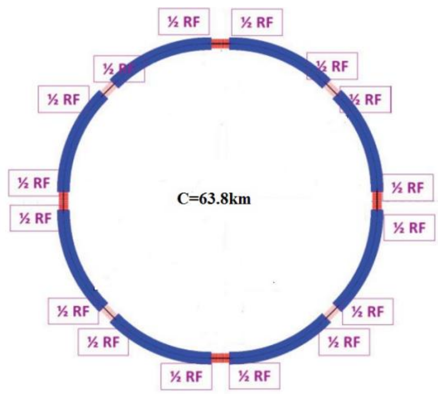

Figure 2: Layout of CEPCB.

A standard FODO cell with 90 degrees phase advance is shown in Fig. 3. The length of each bend is 30.4 m, the length of each quadrupole is 1.2 m, while the distance between each quadrupole and the adjacent bending magnet is 1.7 m. The total length of each cell is 70 m.

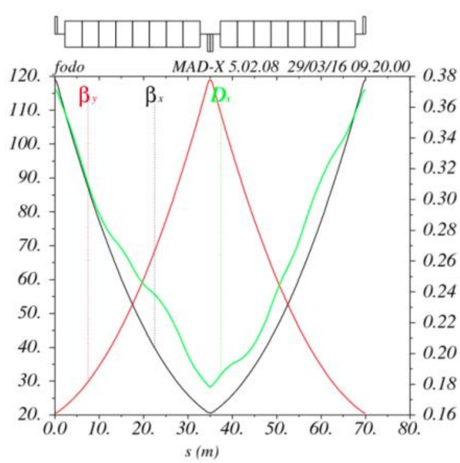

Figure 3: Beta functions and dispersion function of a standard FODO cell with 90/90 degrees phase advance in CEPCB.

In order to make the main dipole stronger to avoid the problem of low magnet field, we split the 30.4 m bend to 8 pieces. The adjacent dipole pieces have different magnet field direction but the integral field strength of dipole is the same as the normal dipole. And we call this scheme "wiggler scheme", as Fig. 4 shows. The orbit off-set(the red curve in Fig. 4) in dipole is became smaller as the beam ramping up until the negative dipole change it's field direction and all the dipole became normal bending magnet at 120 Gev. Fig. 5 shows the bending angle of positive and negative magnet as a function of ramping time.

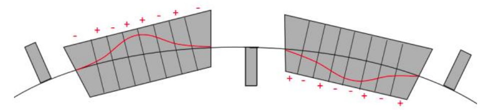

Figure 4: wiggler orbit in a FODO cell.

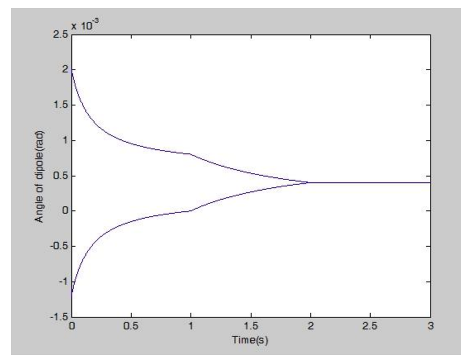

Figure 5: Positive and negative magnet as a function of ramping time.

Sextupole Scheme

The sextupole scheme of CEPCB is shown in Fig. 6. The long space means 180 degree phase advance and the short space means 90 degree phase advance. The FODO in Fig. 6 means to insert a FODO cell in the two repeated sextupole arrangement. In total, 8 families of sextupoles are used.

SF1	SF1 SF2	SF2 SF3	SF3 SF4	SF4
SD1	SD1 SD2	SD2 SD3	SD3 SD4	SD4
FODO				
SF1	SF1 SF2	SF2 SF3	SF3 SF4	SF4
SD1	SD1 SD2	SD2 SD3	SD3 SD4	SD4

Figure 6: Sextupole scheme of CEPCB.

In this scheme, geometric terms are minimized because of the non-interleaved sextupole scheme. Two identical sextupoles apart by 90 degree phase advance to cancel the beta-beat effect of off-momentum particles.

Our goal is reducing the 2^{nd} and 3^{rd} order chromaticities to enlarge the energy acceptance. An analytic map method (Differential algebra)[9] is used to derive the 2^{nd} and 3^{rd} order chromaticities analytically, which contain the information of the 8 sextupole families.

When we optimize the 8 sextupole families using the 2^{nd} and 3^{rd} order chromaticities we have derived, we find it is not enough to make the 2^{nd} and 3^{rd} order chromaticities as small as we expect. So tune shift between ARCs is considered. The analytic map method is also used in finding a right phase

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advance between two ARCs, and we find 43.3 degree is a good choice[7]. Fig. 7 shows the tune as a function of energy spread.

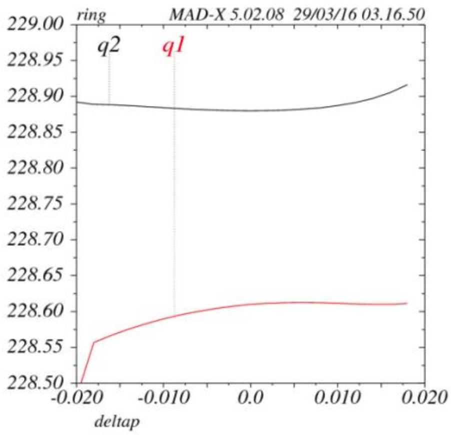

Figure 7: Tune as a function of energy spread.

Dynamic Aperture Results and CEPCB Parameters

To make the CEPCB closer to a real machine, mutipole errors are added. We estimate the error of CEPCB is in the same level as LEP[10], the Table 1 shows the error estimation.

Table 1: CEPCB Error Estimate

	Dipole	Quad	Sext
Bend	8×10^{-4}		
Quadrupole	2×10^{-4}	6×10^{-4}	
Sextupole	7×10^{-4}	5×10^{-4}	1.7×10^{-4}

Table 2: CEPCB Parameters@6GeVate

6GeV	Unit	Value
offset in bend	cm	1.20
Momentum compaction		2.02E-5
Strength of dipole	Gs	-129/180
NB/beam		50
Beam current/beam	mA	7.50E-1
Bunch population		2.00E10
RF voltage	GV	2.10E-1
RF frequency	GHz	1.30
Synchrotron oscillation		2.10E-1
Energy acceptance RF	%	5.93
SR loss/turn	GeV	5.42E-4
energy spread	%	1.47E-2
Horizontal emittance	m*rad	6.38E-11

The tune we are using here is: 0.61/0.88, because this tune avoid some strong resonance line. But it is just a rough estimation, tune scanning is needed to find a better tune.

Table 3: CEPCB Parameters@120GeV

120GeV	Unit	Value
offset in bend	cm	0
Momentum compaction		2.38E-5
Strength of dipole	Gs	516.71
NB/beam		50
Beam current/beam	mA	7.50E-1
Bunch population		2.00E10
RF voltage	GV	3.5
RF frequency	GHz	1.30
Synchrotron oscillation		1.4E-1
Energy acceptance RF	%	2.46
SR loss/turn	GeV	2.35
energy spread	%	1.20E-1
Horizontal emittance	m*rad	3.62E-9

Table 4: CEPCB Parameters@80GeV

80GeV	Unit	Value
offset in bend	cm	0
Momentum compaction		2.31E-5
Strength of dipole	Gs	344.74
NB/beam		50
Beam current/beam	mA	7.50E-1
Bunch population		2.00E10
RF voltage	GV	1.00
RF frequency	GHz	1.30
Synchrotron oscillation		0.10E-1
Energy acceptance RF	%	2.34
SR loss/turn	GeV	0.46
energy spread	%	7.80E-2
Horizontal emittance	m*rad	1.61E-9

With error, cavity on, 0% and 1% energy spread, the dynamic aperture results are shown in Fig. 8 and Fig. 9. In x direction, dynamic aperture is 0.06 m and 0.04 m, and in the y direction, dynamic aperture is 0.023m and 0.016 m for on-momentum and 1% off-momentum particles. Fig. 8 and Fig. 9 also plot the tune shift depending with amplitude on the tune map, which also constraint in a reasonable range without touch dangous resonance line. The parameters of CEPCB for 6GeV, 120GeV, 80GeV and 45.5GeV are listed in Table 2, Table 3, Table 4 and Table 5.

The normal form parameters for X direction and Y direction are listed in Table 6 and Table 7. Tune is a function of action J_x, J_y and energy spread δ, then Taylor expand it. The first column is the taylor coefficients of tune, the other columns are the exponent of J_x, J_y and δ. The normal form parameters are caculated by LEGO[11].

$$
\begin{aligned}
J_x &= \frac{x^2+px^2}{2} \\
J_y &= \frac{y^2+py^2}{2} \\
\delta &= \frac{p_0+\Delta p}{p_0}
\end{aligned}
$$

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Table 5: CEPCB Parameters@45.5GeV

120GeV	Unit	Value
offset in bend	cm	0
Momentum compaction		2.38E-5
Strength of dipole	Gs	195.91
NB/beam		50
Beam current/beam	mA	7.50E-1
Bunch population		2.00E10
RF voltage	GV	0.40
RF frequency	GHz	1.30
Synchrotron oscillation		8.80E-2
Energy acceptance RF	%	2.87
SR loss/turn	GeV	4.85E-2
energy spread	%	4.40E-2
Horizontal emittance	m*rad	5.21E-10

Table 6: CEPCB Normal form Parameters for X Direction

Coefficients	J_x	J_x	δ
6.099×10^{-1}	0	0	0
-2.807×10^{3}	1	0	0
-1.675×10^{3}	0	1	0
1.452	0	0	1
8.265×10^{5}	2	0	0
-7.245×10^{5}	1	1	0
-9.854×10^{6}	1	0	1
-6.698×10^{5}	0	2	0
-8.014×10^{6}	0	1	1
-1.580×10^{2}	0	0	2
-6.942×10^{8}	2	0	1
-2.486×10^{10}	1	1	1
5.529×10^{7}	1	0	2
1.149×10^{10}	0	2	1
-2.303×10^{7}	0	1	2
1.974×10^{3}	0	0	3
-6.144×10^{9}	1	0	3
-1.818×10^{9}	0	1	3
2.641×10^{5}	0	0	4
1.793×10^{7}	0	0	5

NORMAL BEND SCHEME

Earth Magnet Field Correction

In the normal bend scheme, sextupole scheme is the same with the wiggler bend scheme, and linear optics is also similar. The bend strength is very low, which is about 30Gs, because we ramp the beam from 6GeV to 120GeV. As we all know, the earth magnet field is about 0.5Gs. It is just like a big error added on the dipole, about 2 percent. So the earth magnet field must be shielded or corrected.

With the earth magnet field, the booster is a broken ring. The broken ring means the particles in the ring can not find a stable orbit, so the first turn orbit correction is needed. In the first turn orbit correction, we treat the broken ring as linac,

Table 7: CEPCB Normal form Parameters for Y Direction

Coefficients	J_x	J_x	δ
8.800×10^{-1}	0	0	0
-1.675×10^{3}	1	0	0
-1.114×10^{4}	0	1	0
-3.391×10^{-3}	0	0	1
-3.622×10^{5}	2	0	0
-1.340×10^{6}	1	1	0
-8.014×10^{6}	1	0	1
-2.520×10^{6}	0	2	0
-7.542×10^{6}	0	1	1
1.723×10^{2}	0	0	2
-1.243×10^{10}	2	0	1
2.297×10^{10}	1	1	1
-2.303×10^{7}	1	0	2
-4.064×10^{9}	0	2	1
2.119×10^{7}	0	1	2
2.195×10^{3}	0	0	3
-1.818×10^{9}	1	0	3
-2.907×10^{9}	0	1	3
2.725×10^{5}	0	0	4
2.381×10^{7}	0	0	5

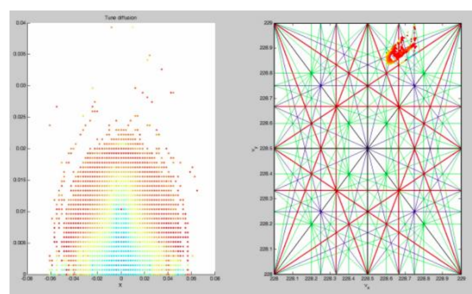

Figure 8: Wiggler bend scheme: Dynamic aperture and tune shift for the on-momentum particles.

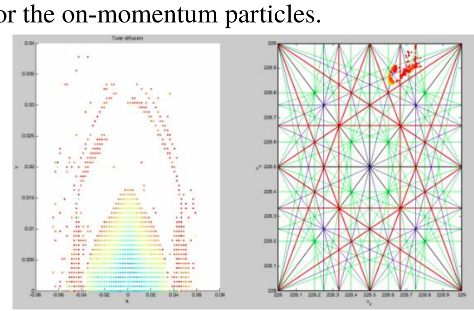

Figure 9: Wiggler bend scheme: Dynamic aperture and tune shift for the 1% off-momentum particles.

propagate the orbit and correct it part by part. As Fig. 10, Fig. 11, Fig. 12, Fig. 13 and Fig. 14 show, we divide the whole booster ring to 8 pieces, correct the orbit part by part. Fig. 14 shows the first turn orbit after whole ring correction.

After the first turn orbit correction, the closed orbit can be find, as Fig. 15 shows, and then we can implement the closed orbit correction. After all the corrections, the orbit

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distortion can be limited to 10 micron level. Fig. 16 shows the corrected orbit.

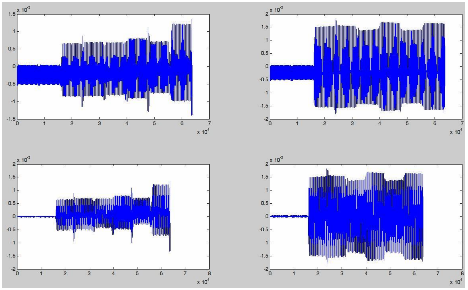

Figure 10: First turn orbit correction for the first part.

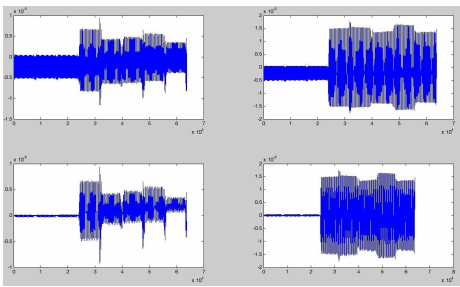

Figure 11: First turn orbit correction for the third part.

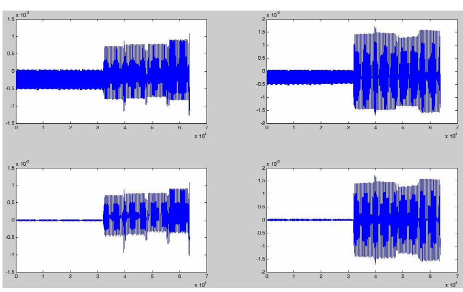

Figure 12: First turn orbit correction for the fourth part.

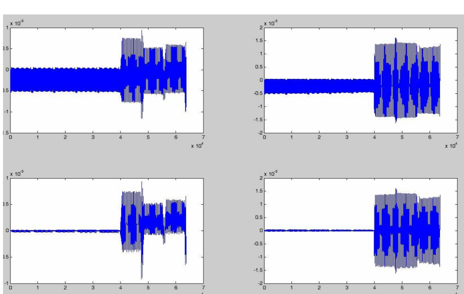

Figure 13: First turn orbit correction for the fifth part.

Dynamic Aperture Results and CEPCB Parameters

With error and orbit correction, Fig. 17 and Fig. 18 show the dynamic aperture result for on-momentum and off-momentum particles. Table 8 shows the wiggler bend scheme parameters at 6GeV.

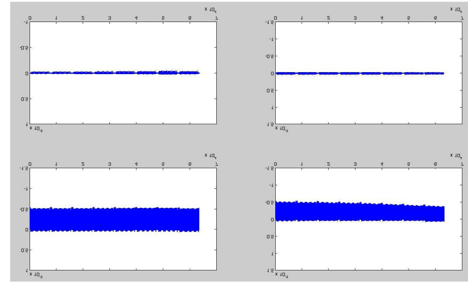

Figure 14: First turn orbit correction for the whole ring.

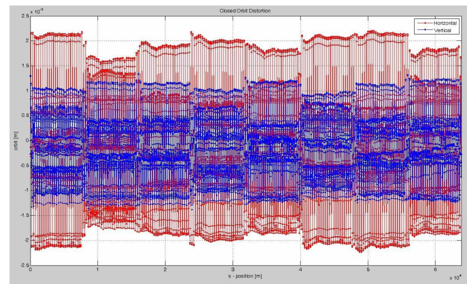

Figure 15: Closed orbit can be found after first turn orbit correction.

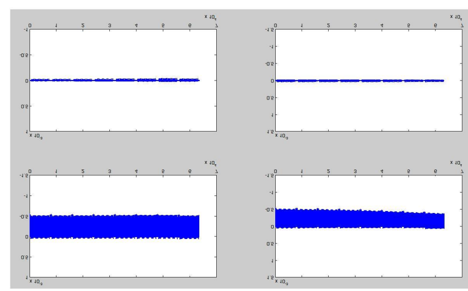

Figure 16: Closed orbit after all the corrections.

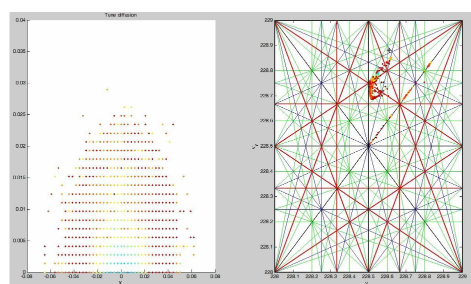

Figure 17: Normal bend scheme: Dynamic aperture and tune shift for the on-momentum particles.

SUMMARY

In this paper, two possible implementations for CEPCB are proposed. The low field problem are solved by the wiggler bend scheme and the method of correcting the earth magnet field is shown in normal bend scheme.

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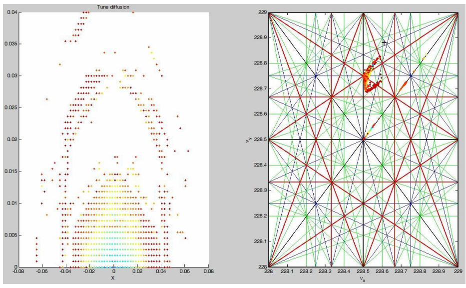

Figure 18: Normal bend scheme: Dynamic aperture and tune shift for the 1% off-momentum particles.

Table 8: CEPCB Parameters@6GeVate

6GeV	Unit	Value
offset in bend	cm	0
Momentum compaction		1.91E-5
Strength of dipole	Gs	25.80
NB/beam		50
Beam current/beam	mA	7.50E-1
Bunch population		2.00E10
RF voltage	GV	2.10E-1
RF frequency	GHz	1.30
Synchrotron oscillation		2.10E-1
Energy acceptance RF	%	4.99
SR loss/turn	GeV	1.47E-5
energy spread	%	7.47E-5
Horizontal emittance	m*rad	9.10E-12

Normal scheme:
With error, orbit correction, cavities on and tune 0.61/0.88, x direction dynamic aperture is 8.6 sigma, y direction dynamic aperture is 10.1 sigma @dp=0% for inject beam. With error, orbit correction, cavities on and tune 0.61/0.88, x direction dynamic aperture is 6.7 sigma, y direction dynamic aperture is 6.5 sigma @ dp=1% for inject beam.

Wiggler scheme:
With error, cavities on and tune 0.61/0.88, x direction dynamic aperture is 9.2 sigma, y direction dynamic aperture is 9.6 sigma @dp=0% for inject beam. With error, cavities on and tune 0.61/0.88, x direction dynamic aperture is 6.6 sigma, y direction dynamic aperture is 6.4 sigma @dp=1% for inject beam.

Contrast with the design goal we have proposed in previous section, both of the two design are reasonable and meet requirements.

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