3.6 Design study of CEPC Alternating Magnetic Field Booster*

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3.6.1 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 low field of the main dipole and dynamic aperture are not solved.

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

3.6.2 Design Goal

At present, the emittance of CEPC is about $2.0\times10^{-9}\,m\cdot rad$, it is much lower than the Pre-CDR because of crab waist. 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 shows the X direction injection scheme. Asume that the dynamic aperture of CEPC at 0.5% energy spread is 20 times of sigma and the beta function is 590m.

The total space for injection:

$$\sqrt{2.0\times10^{-9}\times590}\times20=0.0217(\mathrm{m})$$

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

$$\sqrt{2.0\times10^{-9}\times590}\times8=0.0087(\mathrm{m})$$

6 sigma is retained for injection beam to loss less particles:

$$\sqrt{3.5\times10^{-9}\times590}\times6=0.0086(\mathrm{m})$$

In that condition, 4mm is retained for septum. So $3.5\times10^{-9}m\cdot rad$ seems a reasonable option for the emittance of CEPCB at 120Gev.

The design goals of CEPCB are listed:

The emittance of CEPCB at 120Gev is about $3.5\times10^{-9}m\cdot rad$.

1% energy acceptance for enough quantum life time.

The dynamic aperture results must better than 6 sigma (Normalized by emittance $3\times10^{-7}m\cdot rad$, which is decided by the beam from linac) for both on-momentum and off-momentum(1%) particles.

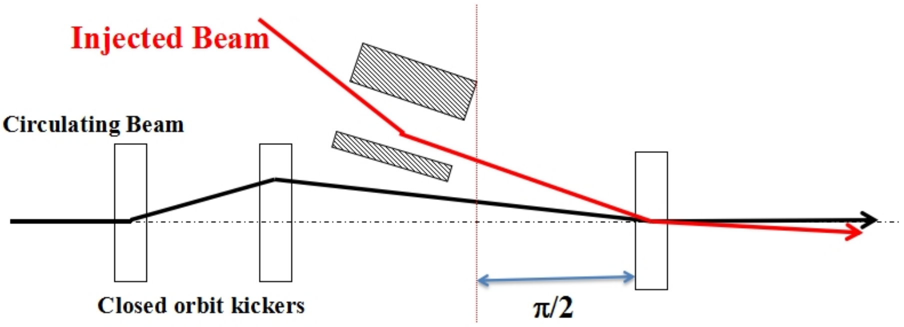

Figure 1: Injection scheme.

3.6.3 Linear Lattice

The layout of CEPCB is show in Figure 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.

A standard FODO cell with 90 degrees phase advance is shown in Figure 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.

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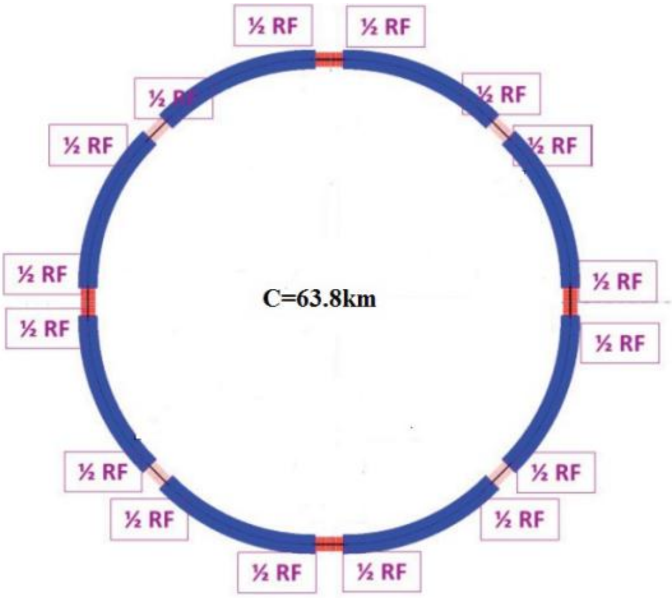

Figure 2: Layout of CEPCB.

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 figure 4 shows. The orbit off-set(the red curve in figure 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. Figure 5 shows the bending angle of positive and negative magnet as a function of ramping time.

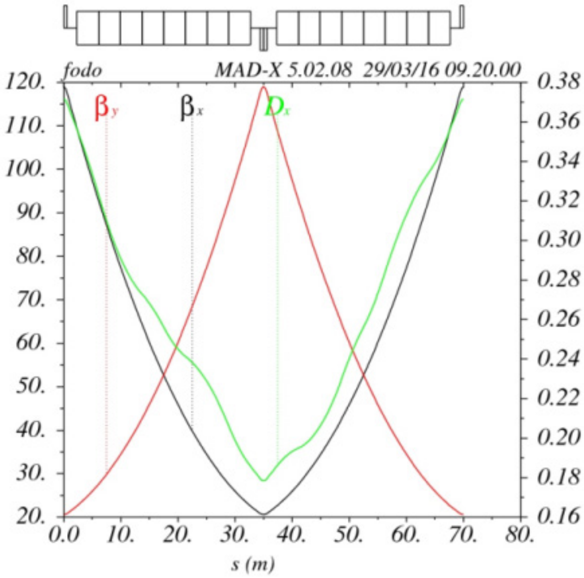

Figure 3: Beta functions and dispersion function of a standard FODO cell with 90/90 degrees phase advance in CEPCB.

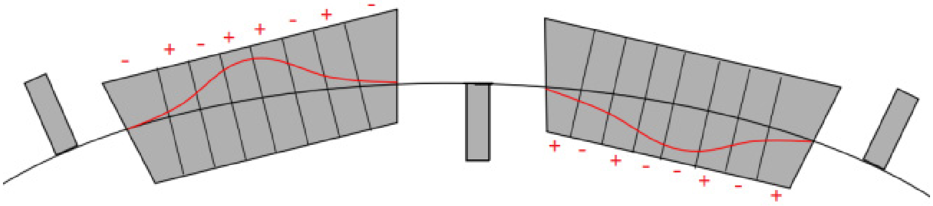

Figure 4: Twisted orbit in a FODO.

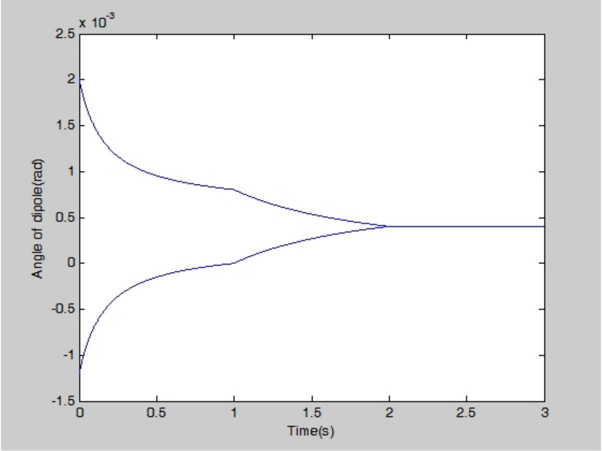

Figure 5: Positive and negative magnet as a function of ramping time.

3.6.4 Sextupole Scheme

The sextupole scheme of CEPCB is shown in Figure 6. The long space means 180 degree phase advance and the short space means 90 degree phase advance. The FODO in Figure 6 means to insert a FODO cell in 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 2th and 3rd 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 2nd and 3rd order chromaticities we have derived, we find it is not enough to make the 2nd and 3rd 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 advance between two ARCs, and we find 43.3 degree is a good choice[7]. Figure 7 shows the tune as a function of energy spread.

3.6.5 Dynamic Aperture Results and CEPCB Parameters

To make the CEPCB more real, 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.

The tune we are using is: 0.61/0.88, because it avoids some strong resonance line. This tune a rough estimation, tune scanning is needed to find a better tune.

With error, cavity on and 0% and 1% energy spread, the dynamic aperture result is shown in figure 8 and figure 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. Figure 8 and Figure 9 also shows the tune shift depending on amplitude, which also constraint in a reasonable rang e. The parameters of CEPCB are listed in table 2.

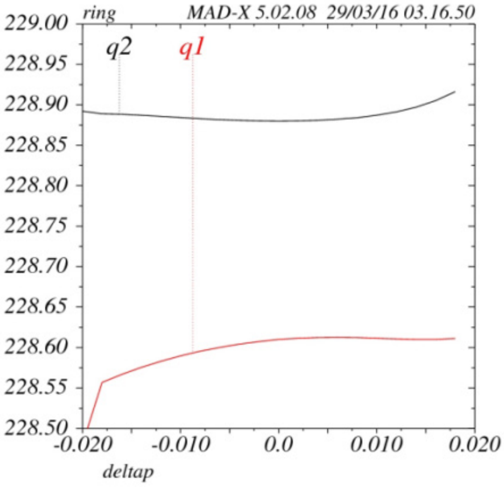

Figure 7: Tune as a function of energy spread.

Table 1: CEPCB error estimate

Parameter	***bend***	***quad***	***sext***
quadrupole	8e-4	…	…
sextupole	2e-4	6e-4	…
octupole	7e-5	5e-4	1.7e-3

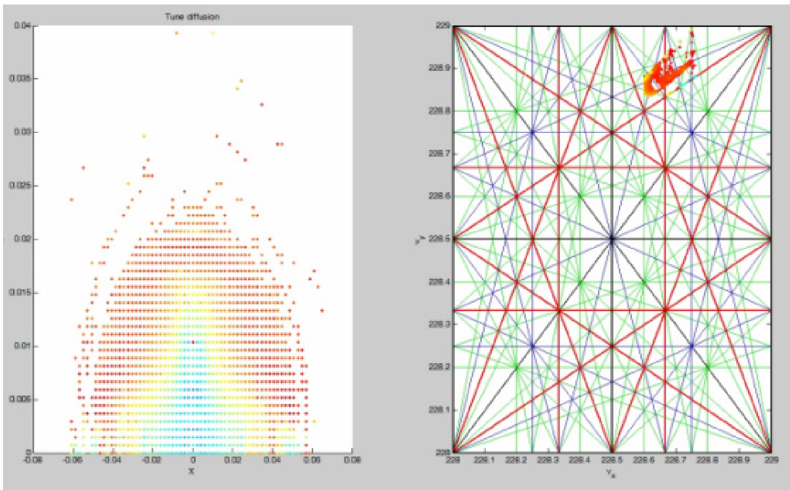

Figure 8: Dynamic aperture and tune shift for the on-momentum particles.

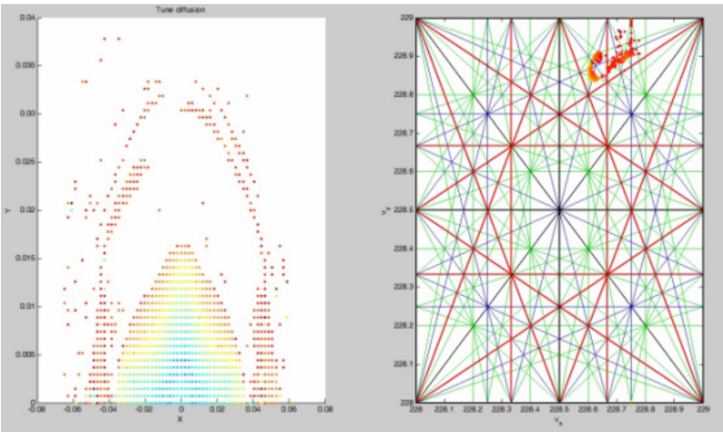

Figure 9: Dynamic aperture and tune shift for the 1% off-momentum particles.

Table 2: CEPCB parameters

6Gev	***unit***	***value***	***120Gev***	***unit***	***value***
Beam off-set in bend	cm	1.20	Beam off-set in bend	cm	0
Momentum compaction factor		2.33e-5	Momentum compaction factor		2.54e-5
Strength of dipole	Gs	-129/180	Strength of dipole	Gs	516.71
NB/beam		50	NB/beam		50
Beam current / beam	mA	0.92	Beam current / beam	mA	0.92
Bunch population		0.92	Bunch population		0.92
RF voltage	GV	0.21	RF voltage	GV	6
RF frequency	GHz	1.3	RF frequency	GHz	1.3
Synchrotron oscillation tune		0.21	Synchrotron oscillation tune		0.21
Energy acceptance RF	%	5.93	Energy acceptance RF	%	4.57
SR loss / turn	Gev	5.42e-4	SR loss / turn	Gev	2.34
equilibrium Energy spread	%	0.0147	equilibrium Energy spread	%	0.12
Horizontal emittance equilibrium	m*rad	6.38e-11	Horizontal emittance equilibrium	m*rad	3.61e-9

3.6.6 **Summary**

In this paper, a possible implementation for CEPCB is proposed. The low field problem is solved by the wiggler scheme. The strength of main dipole increase from 30Gs to -129.18/+180.84 Gs. Damping times are much shorter, which is 4.7 seconds.

With error, cavity on and 0% and 1% energy spread, dynamic aperture is 9.2 sigma and 6.6 sigma in x direction; And 9.6 sigma and 6.4 sigma in y direction.

Contrast with the design goal we have proposed in previous section, this design is reasonable and meet requirements. What we should do next is considering the effect of earth field, shielding or correcting is needed.

3.6.7 References

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3.7 Collider-Related Lattice Design Efforts at Fermilab

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3.7.1 Introduction

Historically the design of circular hadron collider lattices has been very much an art form, utilizing periodicity, symmetry, and anti-symmetry to help guide the development of the focusing structure of these large-scale synchrotrons. As energies and circumferences continue to climb as well as demands for ever-higher luminosities, new elements such as beam-beam tune shift limits, energy deposition rates, and synchrotron radiation effects have become primary factors as opposed to secondary considerations. Rather than the high periodicity typical of many lower-energy synchrotrons, designs for high-energy hadron colliders today tend toward large arcs with “clustered” straight