Proceedings of the CERN-BINP Workshop for Young Scientists in e^+e^- Colliders, Geneva, Switzerland, 22 – 25 August 2016, edited by V. Brancolini ans L. Linssen, CERN Proceedings, Vol. 1/2017, CERN-Proceedings-2017-001 (CERN, Geneva, 2017)

Design study of CEPC Alternating Magnetic Field Booster*

T. Bian[*1], *J. Gao*[1], *Y. Cai*[2], *M. Koratzinos*[3], *C. Zhang*[1], *X. Cui*[1], *Y. Wang*[1], *S. Bai*[1], *D. Wang*[1], *F. Su*[1], *M. Xiao*[1]

[1]Institute of High Energy Physics, Beijing, China, [2]SLAC National Accelerator Laboratory, CA, USA, [3]University of Geneva, Geneva, Switzerland

Abstract

The CEPC is a next generation circular $e^+ e^-$ collider proposed by China. The design of the full energy booster ring of the CEPC is especially challenging. The ejected beam energy is 120 GeV, but that of the injected beam is only 6 GeV. In a conventional approach, the low magnetic field of the main dipole magnets creates problems. We propose operating the booster ring as a large wiggler at low beam energies and as a normal ring at high energies to avoid the problem of very low dipole magnet fields.

Keywords

CEPC; Booster; Alternating Magnetic Field; style.

1 Introduction

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

A preliminary design has been proposed in the Pre-CDR [5], but the problems of low field of the main dipole and dynamic aperture are not solved.

In this paper, we focus on these problems and find a reasonable solution. The wiggler scheme, which splits a normal dipole into several pieces with different magnet field direction, is adopted to avoid the problem of very low dipole magnet fields [6-8]. An analytic map method (Differential algebra) [9] is used to derive the Twiss functions of arbitrary order of the energy spread, such as β function, phase advance function or dispersion function. These functions are analytic functions dependent on the sextupole strength. First optimization of the high order chromaticities is done, and then a good dynamic aperture for both on-momentum and off-momentum particles is obtained.

2 Design goal

At present, the emittance of the CEPC is about $2.0\times10^{-9}\, m\cdot rad$, which is much lower than that in the Pre-CDR because of the crab waist. This makes the CEPCB harder to design because the emittance of the CEPCB at high energy is also reduced, which causes much stronger chromaticities and poses challenges to our design at the same time.

* Corresponding author: biantj@ihep.ac.cn

2518-315X– © the Author/s, 2017. Published by CERN under the Creative Common Attribution CC BY 4.0 Licence.
https://doi.org/10.23727/CERN-Proceedings-2017-001.145

Figure 1 shows the x direction injection scheme. It assumes that the dynamic aperture of the CEPC at a 0.5% energy spread is 20-fold sigma and the beta function is 590 m.

The total space for injection:

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

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

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

6 sigma is retained for the injection beam to lose fewer particles:

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

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

Below are listed the design goals of the CEPCB:

The emittance of the 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 be better than 6 sigma (normalized by an emittance of $3\times10^{-7}\,m\cdot rad$, which is determined by the beam from the linac) for both on-momentum and off-momentum (1%) particles.

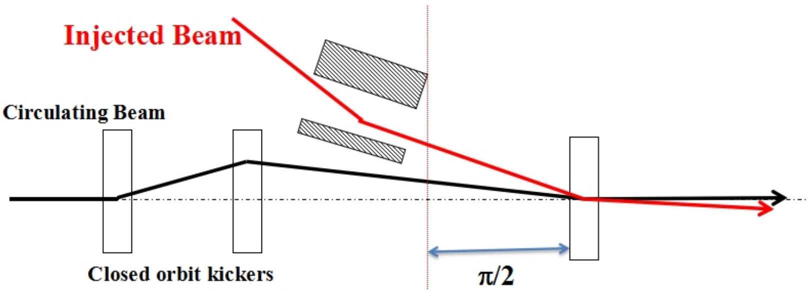

Fig. 1: Injection scheme

2.1 Linear lattice

The layout of the CEPCB is shown in Fig. 2. It is composed of 8 arcs and 8 straight sections with a total length of 63.8 km. The RF cavities are distributed in each straight section. The lattice for the CEPCB has been chosen to use the standard FODO cells with 90-degree phase advances in both transverse planes, which gives us a smaller emittance and a clear phase relationship between the sextupoles.

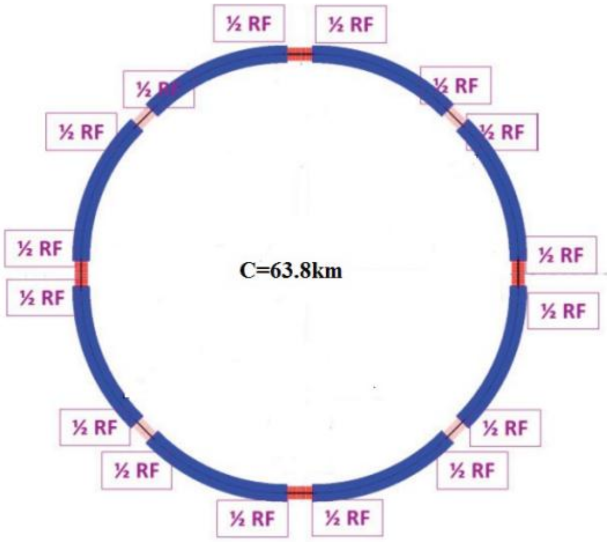

Fig. 2: Layout of CEPCB

A standard FODO cell with a 90-degree 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.

In order to make the main dipole stronger to avoid the problem of low magnetic field, we split the 30.4 m bend into 8 pieces. Adjacent dipoles in the pieces have different magnetic field directions, but the integral field strength of dipoles is the same as that of the normal dipole. We call this scheme the "wiggler scheme", as shown in Fig. 4. The orbit off-set (the red curve in Fig. 4) in the dipoles decreases during the beam ramp up until the negative dipole changes the sign of the field and all the dipoles become normal bending magnets at 120 GeV. Figure 5 shows the bending angle of positive and negative magnets as a function of the ramping time.

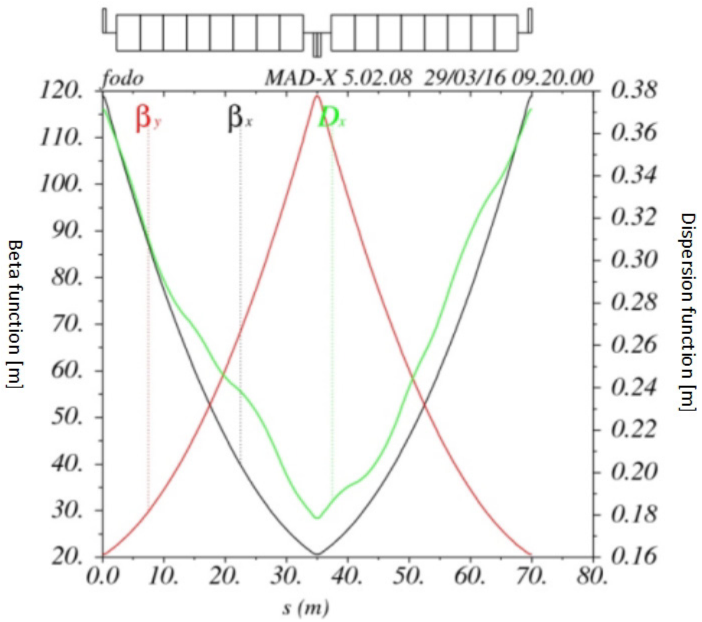

Fig. 3: Beta functions and dispersion function of a standard FODO cell with a 90/90-degree phase advance in the CEPCB.

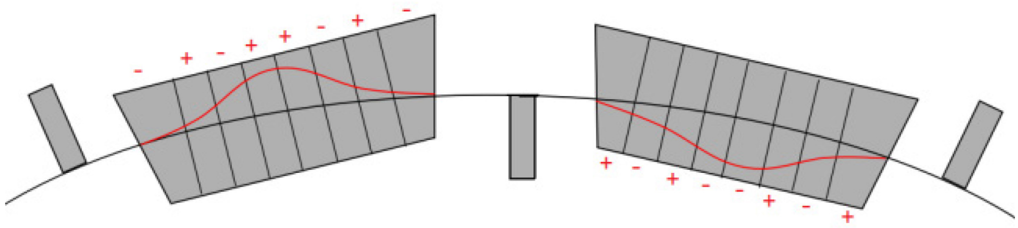

Fig.4: Twisted orbit in a FODO cell

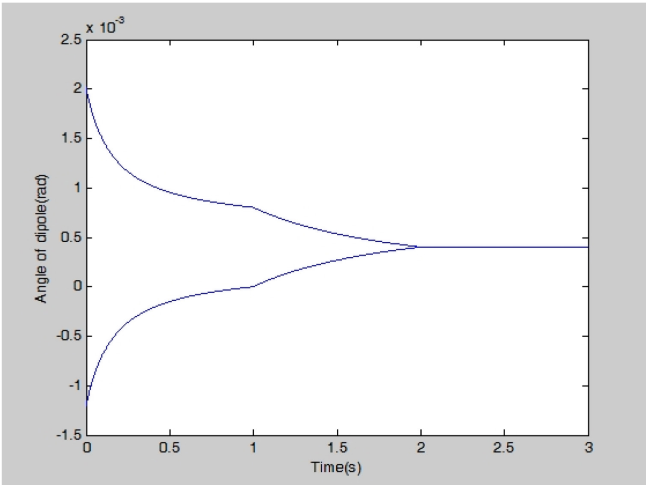

Fig. 5: Bending angle of the positive and negative magnet as a function of the ramping time

3 Sextupole scheme

The sextupole scheme of the CEPCB is shown in Fig. 6. "SF" and "SD" means focusing and defocusing sextupole. The long space means a 180-degree phase advance and the short space means a 90-degree phase advance. The "--" indicates a 45-degree phase advance between the focusing and defocusing sextupole. The FODO in Fig. 6 means that a FODO cell is inserted between two repeated sextupole arrangements. 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

Fig. 6: Sextupole scheme of CEPCB

In this scheme, the geometric terms are minimized because of the non-interleaved sextupole scheme. Two identical sextupoles stand apart by a 90-degree phase advance to cancel the beta-beat effect of off-momentum particles. Our goal is reducing the 2nd and 3rd order chromaticities to enlarge the energy acceptance. The analytic map method (Differential algebra) [9] is used to derive the 2nd and 3rd 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 that it is not enough to make the 2nd and 3rd order chromaticities as small as we expect. So, a 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 the 43.3 degree is a good choice [7]. Figure 7 shows the tune as a function of the energy spread.

4 Dynamic aperture results and CEPCB parameters

To make the CEPCB more real, multi-pole errors are added. We estimate that the error of the CEPCB is at the same level as that of the LEP [10]; Table 1 shows the error estimation.

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

With the error, cavity on and 0% and 1% energy spread, the dynamic aperture result is shown in Figs. 8 and 9. In the x direction, the dynamic aperture is 0.06 m and 0.04 m, and in the y direction, the dynamic aperture is 0.023 m and 0.016 m for on-momentum and 1% off-momentum particles. Figures 8 and 9 also show the tune shift depending on the amplitude, which is also constrained in a reasonable range. The parameters of the CEPCB are listed in Table 2.

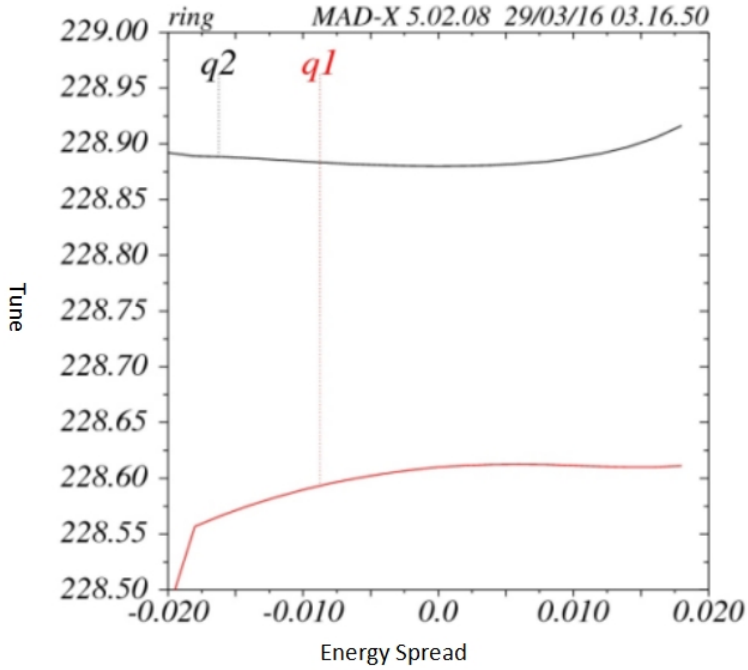

Fig. 7: Tune as a function of energy spread

Table 1: CEPCB multi-pole error estimate

	Bend	Quad	Sext
Quadrupole	8×10^{-4}		
Sextupole	2×10^{-4}	6×10^{-4}	
Octupole	7×10^{-5}	5×10^{-4}	1.7×10^{-3}

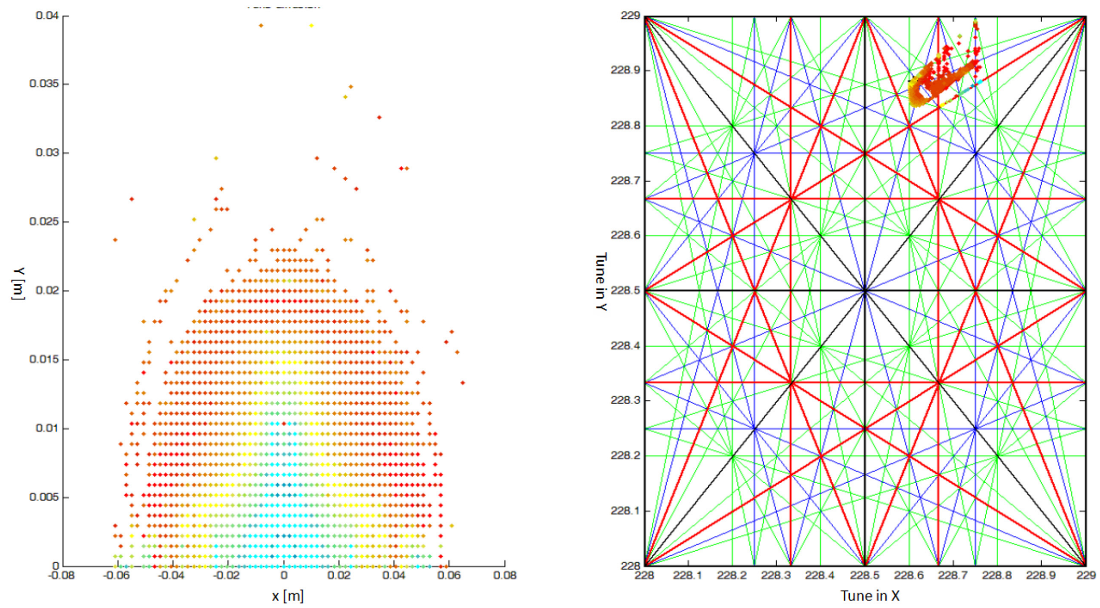

Fig. 8: Dynamic aperture and tune shift for the on-momentum particles

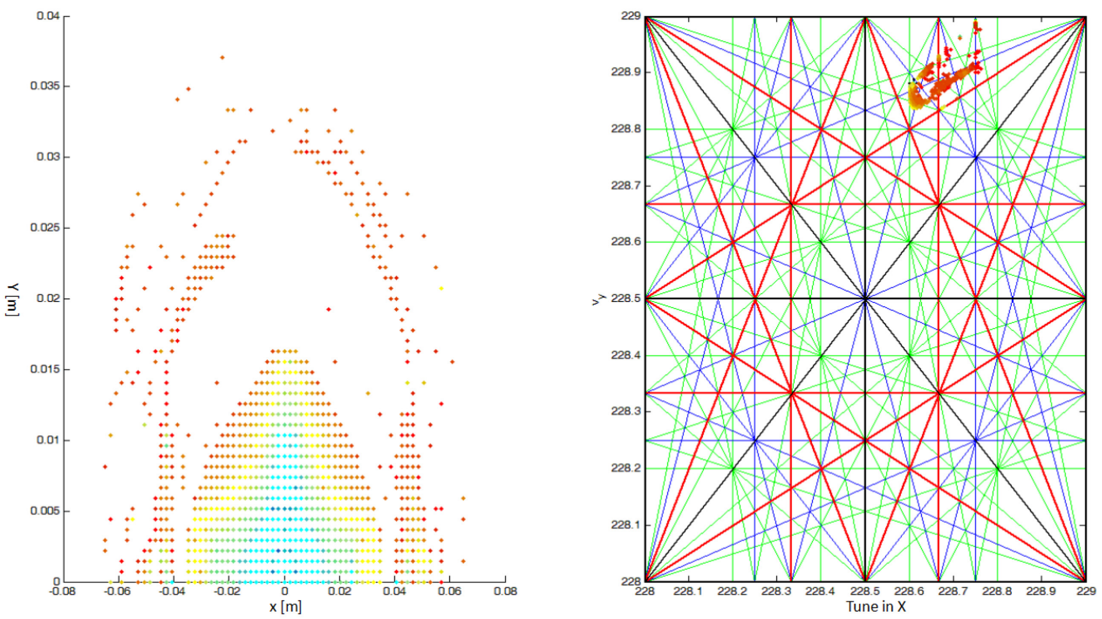

Fig. 9: Dynamic aperture and tune shift for the 1% off-momentum particles

Table 2: CEPCB parameters

6 GeV	Unit	Value	120 GeV	Unit	Value
Beam off-set in bend	cm	1.20	**Beam off-set in bend**	cm	0
Momentum compaction factor		2.33×10^{-5}	**Momentum compaction factor**		2.54×10^{-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		2.0×10^{10}	**Bunch population**		2.0×10^{10}
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	5.42×10^{-4}	**SR loss / turn**	GeV	2.34
equilibrium Energy spread	%	0.0147	**equilibrium Energy spread**	%	0.12
Horizontal emittance equilibrium	m*rad	6.38×10^{-11}	**Horizontal emittance equilibrium**	m*rad	3.61×10^{-9}

5 Summary

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

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

In contrast to the design goal we proposed in the second section, this design is reasonable and meets the requirements. Further studies are required to include the effect of the earth magnetic field; shielding or correcting is needed.

References

[1] G. Jie, Review of some important beam physics issues in electron–positron collider designs, *Modern Physics Letters A* **30 (11)** (2015) 1530006.

[2] W. Dou *et al*., Optimization parameter design of a circular e+ e- Higgs factory. *Chinese Physics C* **37 (9)** (2013) 097003.

[3] *S. Feng et al.*, Method study of parameter choice for a circular proton-proton collider. *Chinese Physics C* **40 (1)** (2015) 17001-017001.

[4] K. Wen, Some Design Considerations and R&D of CEPCB Dipole Magnet, IHEP, Beijing, Apr. 2016.

[5] The CEPC-SPPC Study Group, CEPC-SPPC Preliminary conceptual Design Report, IHEP, Beijing, IHEP-AC-2015-01, March. 2015.

[6] M. Koratzinos, private communication, Dec. 2015.

[7] Y. Cai, private communication, Feb. 2016.

[8] G. Xu, private communication, Feb. 2016.

[9] Y. Cai, Symplectic maps and chromatic optics in particle accelerators, *Nucl. Instr. Meth.* **797** (2015) 172-181.

[10] S. Bai, CEPC magnet error study summary, IHEP, Beijing, Dec. 2015.