OVERVIEW OF THE CEPC ACCELERATOR

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Abstract

A circular electron positron collider (CEPC) was proposed in IHEP after the Higgs boson was discovered at LHC two years ago. In the meantime, some possible ring-based Higgs factories, were also proposed in different labs around the world. In these two years, studies focusing on the preliminary design of the ring, and the considerations on injectors, were carried out in IHEP. Some results on beam physics and hardware will be given in this paper.

INTRODUCTION

Two years ago, CERN declared the discovery of the 126 GeV/c^2 Higgs boson, which is much less than expected before, causing the big possibility to build ring-based Higgs factory for further fine measurement of the new particle. Although muon collider, γ-γ collider, and linear collider were proposed to be the candidates of Higgs factory more than 10 years ago, some ring-based Higgs factories, such as LEP3 [1], TLEP [2], Super-Tristan [3], FNAL site-filter [4], etc., were suggested in different labs due to the relatively mature accelerator technology of circular machine. IHEP also proposed a circular e^+e^- collider (CEPC) as a Higgs factory in September 2012 [5], which can be converted to a super proton-proton collider (SppC) in the future as a machine for new physics and discovery, shown as Figure 1 [6].

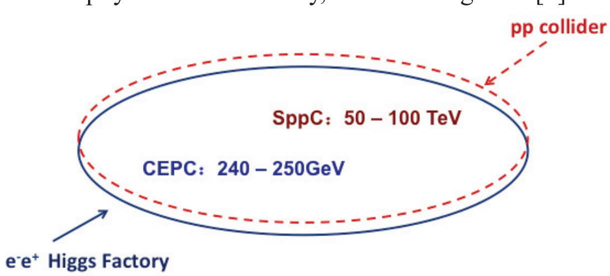

Figure 1: Schematic graph of the CEPC + SppC.

In the CEPC, the electron beam energy can be 120-125 GeV, and in the SppC, the proton beam energy can reach 25-50 TeV. The CEPC then can be thought as a natural extension of the BEPC, Beijing electron positron collider, which was built in 1980's and upgraded as BEPCII 10 years ago. From the BEPC and BEPCII, experiences on lepton machine's design, construction and operation are gradually accumulated. Accelerator technologies are also developed in IHEP, and other Chinese labs as well. Thus the CEPC becomes a very important direction in the field of high energy physics in China, and is the one we can do as a future high energy facility. In recent two years, we did some studies on the CEPC machine design, aiming on the pre-CDR to be finished by the end of 2014.

The current IHEP site is too small to accommodate the future CEPC and its auxiliary facilities. A candidate site for such a big machine is Funing of Qinhuangdao, a coast city northeast of Beijing and 300 km in between, shown in Figure 2.

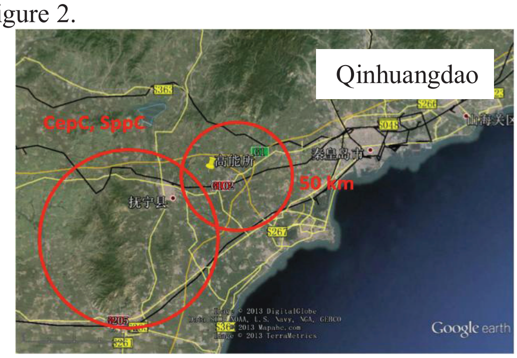

Figure 2: Possible location for future CEPC and SppC.

In this paper, the main studies on accelerator physics, such as main parameter determination, lattice design, final focus system, dynamic aperture simulation, beam-beam effect, injection chains, collective effects, etc., and some hardware system considerations of CEPC, are discussed. A preliminary overall time schedule will be given, and a summary of all studies is given at last.

MAIN PARAMETERS AND LAYOUT

Since the energy loss due to synchrotron radiation is proportional to the fourth power of beam energy, a relatively low beam energy will save the RF power and make the ring more flexible. Beam energy of 120 GeV is thus chosen, because the cross-section of Higgs at that energy is similar as that of 125 GeV. The beam power compensated by the RF will be limited as 50 MW in a general design of such a big ring. Such a large amount synchrotron radiation also causes a strong beamstrahlung [7], which makes the bunch size at the interaction point (IP) diluted and the beam energy spread enlarged. Finally, it brings the beam lifetime to reduce dramatically, and the luminosity decrease as well. General speaking, if we keep the beam power unchanged, the bigger the ring, the more the beam current can be stored, and thus the higher the peak luminosity. Considering a possible p-p collider in the same tunnel of the CEPC in the future for much high energy of proton beams, at least 50 km is necessary for the circumference of the CEPC ring. As a Higgs factory, a peak luminosity of $1\times10^{34}cm^{-2}s^{-1}$ is the lower limit to fit the physics requirement of CEPC.

ISBN 978-3-95450-172-4

A linac is supposed to be the main injector of the CEPC. A booster is considered to be in the same tunnel of the main ring to save budget, and connect with transport lines to the ring and the linac, shown as Figure 3. For the time being, pretzel orbit scheme is applied in the main ring.

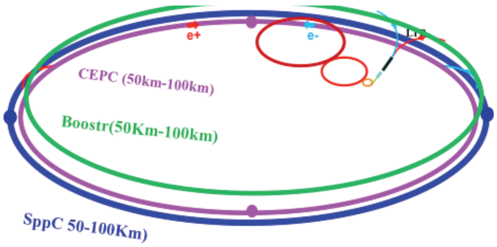

Figure 3: Accelerator chain of CEPC and future SppC.

In Figure 3, the SppC is also plotted as a future machine. The two small boosters inside the big rings are thought to be the boosters of SppC. So the design of the tunnel, the layout of the CEPC, and the interaction regions for all two machines, should be taken into account all together.

To design a high luminosity collider, the β function at the IP in vertical, and beam-beam parameters are of an importance that we need to take them more seriously. Combining the existing machine experiences and the future one, we choose β_y^*=1.2mm, and vertical beam-beam parameter ξ_y as large as 0.1. The accurate ξ_y will be got from the beam-beam simulation. Accordingly, the horizontal β at the IP is 0.8m. To get a high luminosity, the horizontal tune should be located very close to the half integer for each IP. So for 2 IPs, the horizontal tune of the whole ring is chosen to be just above the integer but very close to the integer.

Beamstrahlung effect should be carefully considered when other important parameters, such as beam current, emitance, momentum compaction, RF frequency, etc., are determined, as shown in [8] and [9].

Table 1 lists the main parameters of the CEPC ring, after the preliminary lattice design, which will be given in the following parts.

Table 1: Main Design Parameters of the CEPC Ring

Para.	Unit	Value	Para.	Unit	Value
Energy	GeV	120	Circum.	km	54.752
N_e	10^{11}	3.79	N_b/beam		50
Beam current	mA	16.6	SR power /beam	MW	51.7
ε (x/y)	nm	6.12/ 0.018	Bending radius	km	6.094
β_{IP} (x/y)	mm	200/1	σ_x/σ_y (@IP)	μm	70/0.15
$\xi_{x,y}$		0.118/ 0.083	SR loss /turn	GeV	3.11
α_p	10^{-4}	0.336	σ_z	mm	2.88
V_{rf}	GV	6.87	No. of IP		2
ν_s		0.181	f_{rf}	GHz	0.65
δ_{SR}		0.0013	Harm. No.		118712
δ_{BS}		0.0008	$\delta_{BS,\ tot}$		0.00177
n_γ		0.23	τ_{BS}	hr	12.2
F_H		0.692	L /IP	/cm^2/s	2.0×10^{34}

Since the beam loss due to synchrotron radiation is so large that RF cavities have to be distributed in nearly all the straight sections around the ring, compensating the energy saw-tooth effect. Figure 4 shows the IPs, straight sections, and RF sections all around the CEPC ring. In the figure, IP1 and IP3 are for the CEPC, while IP2 and IP4 are for the future SppC.

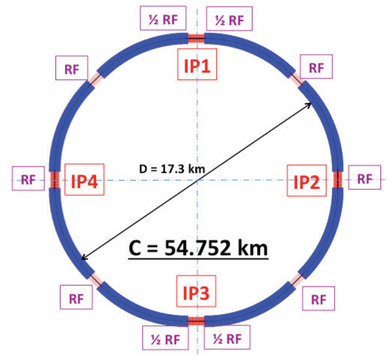

Figure 4: CEPC lattice and RF sections around the ring.

ACCELERATOR PHYSICS

Accelerator physics design, consisting of lattice design, final focusing system (FFS), dynamic aperture study, beam-beam simulation, collective effect, etc., is the basic design of the whole machine.

Lattice Design

The whole ring of the CEPC is divided into 8 arcs and 8 long straight sections (LSS). To be simple, a FODO cell is adopted in each arc, and the LSS as well. Both the horizontal and vertical phase advances in each cell are 60 degree. Figure 5 shows the Twiss functions in an arc.

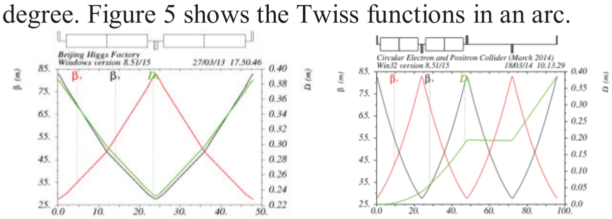

Figure 5: Twiss functions of a standard 60 degree cell (left) and a dispersion suppressor (right).

For more details of the lattice design, see [10].

FFS Design

FFS plays an important rule in a collider, especially in the factory-like machine with very small vertical β at the IP. It is the main source of the huge chromaticity, and need to be corrected by local chromaticity correction. The FFS is very critical to the machine-detector interface (MDI), and the background to the detector.

Some special lattice designs were developed for factory-like machine. Here, Cai's FFS design [11] was adopted. But different L_0 and other constraints made it to be optimized to fit the whole ring. In our design, L^*=1.5m. The total length of the FFS in one side of the IP is 341 m. Figure 6 shows the linear lattice of the FFS of CEPC.

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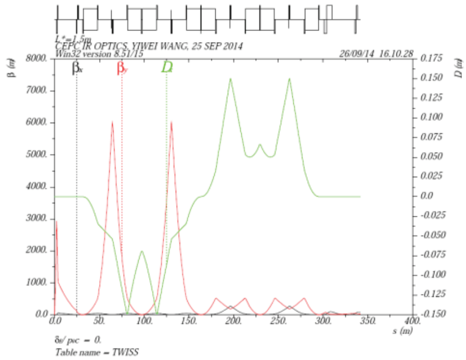

Figure 6: Twiss function of the FFS in the IR of CEPC.

How to design a good FFS is very critical to the dynamic aperture of the whole ring.

Dynamic Aperture

In a big machine, such as the CEPC storage ring, both small β function at IP and small emittance, will cause very large natural chromaticities in transverse directions. Furthermore, since the horizontal tune is very close to half integer for higher luminosity, natural chromaticity is very difficult to correct to be positive with a small anharmonicity. Strong non-linearity from FFS will cause the dynamic aperture to decrease dramatically. To correct the natural chromaticity globally, 2 sets of sextupole are used in the arcs. Other 4 sets of sextupole in the IR are devoted to correct chromaticity locally. MAD [12] and SAD [13] are used to do the dynamic aperture tracking. Figure 7 shows the tune and β_{IP} variations as functions of particle momentum deviation. Figure 8 gives the results of dynamic aperture tracking for a damping time. More details of dynamic aperture study can be found in [14]. Magnetic error effect will be studied in the near future.

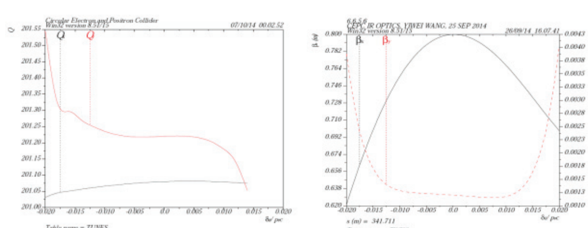

Figure 7: Tune and β function at IP as functions of momentum deviation (left: tunes, right: β function at IP).

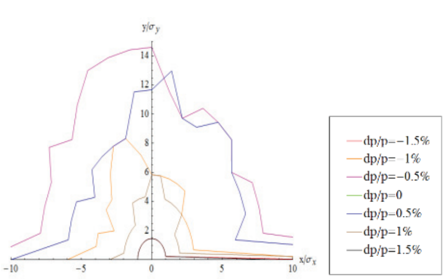

Figure 8: Dynamic aperture at different momentum deviations.

Beam-beam Simulation

Beam-beam interaction is the most important issue to study in accelerator physics of a collider. Simulations with the codes of Y. Zhang in IHEP, and other codes of Ohmi and Shtatilov, give the results of tune scan with beamstrahlung effect, shown in Figure 9. The transverse tunes for better luminosity locate at [0.54, 0.61].

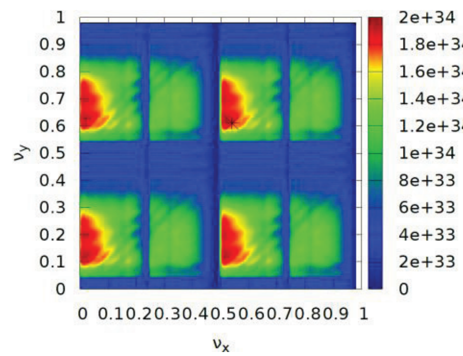

Figure 9: Beam-beam simulation for the tune scan.

Beam lifetime is also simulated with beamstrahlung effect. A quasi strong-strong model of beam-beam interaction gives the beam lifetime to be 1 to 3 hours with different simulation codes. More studies on beam-beam, such as luminosity as a function of bunch size, bunch current, and beam-beam parameters evaluated with equilibrium beam parameters, are also carried out [15].

Collective Effect

Bunch lengthening is the main single bunch instability in lepton colliders. Multi-bunch instability also occurs when single bunch current or bunch spacing exceeds a threshold. These impedance-induced instabilities should be checked in the design. At current stage, since the hardware of the ring is far from fixed, especially the vacuum chamber and other vacuum parts, it is not easy to estimate the coupling impedance. Only the wake field and impedance of resistive wall and RF cavity around the ring are calculated, shown in Table 2.

Table 2: Impedance Estimation

	R (kΩ)	L(nH)	k(V/pC)	$\lvert Z_{//}/n\rvert_{eff}$(Ω)
Resistive wall (Al)	9.5	124.4	301.3	0.0044
RF cavity	28.1	-	893.9	-
Total	37.6	124.4	1195.2	0.0044

The longitudinal wake is fitted with an analytical model of $W(s) = -Rc\lambda(s) - Lc^2\lambda'(s)$, where R is the resistance of the ring, L the inductance, k the loss factor, and $\lvert Z_{//}/n\rvert_{eff}$ the low frequency effective impedance, to estimate the bunch lengthening.

ISBN 978-3-95450-172-4

If the bunch lengthening is estimated by scaling the SuperKEKB's geometric wake, the bunch length will increase at least ~10 %.

In addition, transverse mode coupling instability and coherent synchrotron radiation are not serious with the current impedance budget. Ion effects, such as electron cloud instability and ion trapping, are expected less affected due to the counter-rotating beam in the same ring. But the pretzel orbit the ions cannot be cleaned by positron beam, and will still have effect on electron beam.

The beam tilt due to transverse wake fields happens when beams pass through the vacuum chamber with a transverse offset, and the tail particles in a bunch will get a transverse kick, which causes a transverse displacement of the bunch tail at IP. It will reduce the luminosity in a big collider. In the CEPC case, closed orbit and additional pretzel orbit will make the beam tilt effect stronger.

More detailed calculations are given in [16].

Pretzel Scheme

To save budget, one ring with pretzel orbits is adopted to the collision. Two sets of electrostatic separator are installed in each arc to separate two beams at the parasitic crossing points. Figure 10 shows the pretzel orbits produced with electrostatic separators and the phase advances between separators in the arcs. Some beam parameters are changed due to the pretzel orbits.

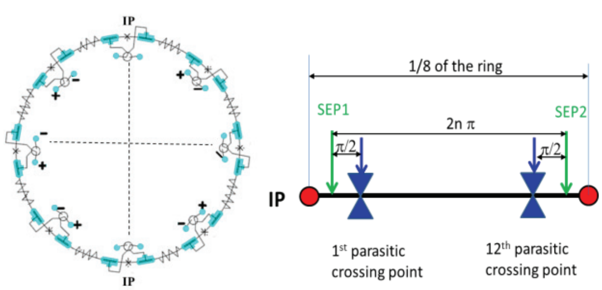

Figure 10: Pretzel orbit (left) and phase advance between two parasitic crossing points in one arc (right).

For the two IPs (IP2 and IP4 shown in Figure 4) of future possible SppC, we need to separate two beams to avoid collisions. More details on pretzel scheme study of CEPC are in [17].

Up to now, although we did some work on beam dynamics issues, we still have a lot of problems to be solved. Magnetic errors and their effects on beam, orbit correction, detailed impedance budget, synchrotron radiation heating, etc., need more studies.

INJECTION

As shown in Figure 2, the whole injector of the CEPC contains a linac and a booster for the time being. In the current design, the booster is supposed to be in the same tunnel of the main ring.

Design of Booster

The booster will be located in the same tunnel as the main ring of CEPC, and the future SppC ring as well. So one option to install the booster is up the main ring of CEPC, hanging on the roof of the tunnel. The layout and the circumference should be the same as those of the main ring of CEPC.

The booster is designed to supply beams to the collider with top-up injection rate of 0.1 Hz. The lattice functions of the cell and arc in the booster are shown in Figure 11. Table 3 gives the main parameters of the whole booster.

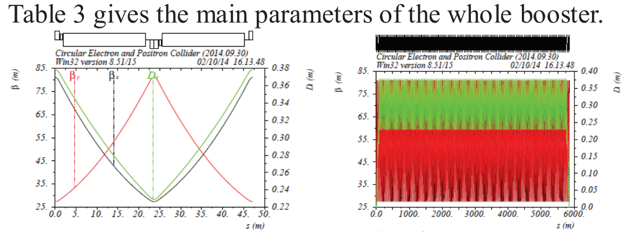

Figure 11: Twiss functions of a cell and an arc of the booster (left: FODO cell, right: arc).

Table 3: Main Parameters of the Booster

Circumference	km	54.752
Bending radius	km	6.519
Horizontal/vertical tunes		127.18/127.28
No. of FODO structures		768
FODO cell length	m	71.665
Phase advance/cell (H/V)		60°/60°
Maximum hori./verti. β	m	123.84/122.97
Maximum dispersion function	m	0.879
Length of bypass	m	2×752.482
Width of bypass	m	13.0

The dipole field of the booster is 614 Gs at 120 GeV; but only 30.7 Gs at 6 GeV for injection. Such a low field makes the perturbation of the earth field be taken into account. One way to increase the bending field is to have another booster between the current booster and the linac. Test on the low field stability was done in IHEP with the BEPC dipole and a very small driven current to be given to the dipole. Detailed results of the test and other design studies can be found in [18].

Top-up injection is supposed to be used for the beam injection from the booster to the main ring. Injection calculations can be found in [19]. Simulation on injection is needed for further study.

Linac

A normal conducting linac will be designed as the first injector of the CEPC. There are two scenarios for the linac with unpolarized beams. One is that both electron and positron beams are accelerated to 6 GeV, but the positron beam is produced or bombed the convertor with the 5 GeV electron beam. The positron beam is then transported back to the mid of linac and to be accelerated to 6 GeV, shown in Figure 12. Figure 13 shows another case of linac, but both two beams can be accelerated to 10 GeV. Polarized beam is also considered if physics requirement is proposed. But the polarized electron gun needs R&D.

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More detailed design of linac will be given in the near future for the pre-CDR study.

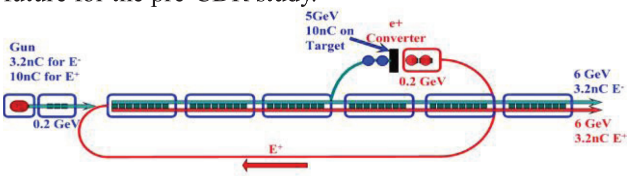

Figure 12: 6-GeV linac with unpolarized beams.

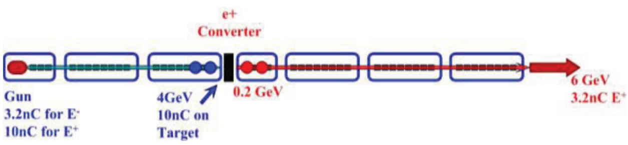

Figure 13: 10-GeV linac with unpolarized beams.

TECHNICAL SYSTEM

Nearly all the technical systems have been looked at for the pre-CDR study. As the key technology and the most expensive system, superconducting RF system is more than concerned and will be seriously considered for its R&D.

RF system provides power to accelerator beams to the design energy and compensates the energy loss due to SR around the ring. Superconducting RF (SRF) system will have higher efficiency and lower the HOM loss due to cavity. But the cost of superconducting system and the necessary cryogenic system will be one of the major fractions of the whole machine. Table 4 lists the main parameters of the SRF of the CEPC and the booster.

Table 4: Main Parameters of the SRF System of CEPC

	Main ring	Booster	LEP2
Cavity Type	650 MHz 5-cell Ni-doped Nb	1.3 GHz 9-cell Ni-doped Nb	352 MHz 4-cell Nb/Cu
Cavity number	384	256	288
V_{cav} / V_{RF} (MV/GV)	18 MV / 6.87 GV	20 MV / 5.04 GV	12 MV / 3.46 GV
E_{acc} (MV/m)	15.5	19	6 ~ 7.5
Q_0	2E10@2K	2E10@ 2K	3.2E9@ 4.2K
Cryo AC power(MW)	25	2.5 (22% DF)	6.1
Cryomodule number	96 (4 cav. / module)	32 (8 cav. / module)	72 (4 cav)
RF input power/ cav. (kW)	260	20	125
No. of RF source	384(300 kW klys.)	256 (25 kW SSA)	36 (1.2 MW)
AC power (MW)	200	2.4 (22% DF)	85
HOM damper power (W)	10k ferrite +1k hook	50 (hook+ ceramic)	300 (hook)

Although some kinds of SRF cavity, such as 1.3 GHz 9-cell cavity for ILC, 650 MHz β=0.82 5-cell cavity, and 500 MHz one-cell cavity with all cryomodule, coupler and other auxiliaries. Vertical and horizontal tests for 500 MHz cavity can be done in IHEP. But for high Q value with high acceleration gradient SRF cavity, we still need R&D in the near future. Some new techniques of coating at the inner surface of the cavity will be developed.

Other technical systems, like magnet, vacuum, beam instrumentation, mechanics, etc. needs R&D for their key parts of each system.

PLAN IN THE NEAR FUTURE

The pre-CDR study of CEPC started from the end of 2012 in IHEP. The pre-CDR is expected to finish by the end of 2014. In the meantime, R&D items of some key technical systems are being put forward to, and are willing to be proposed as an R&D project in the period of 2016-2020. The technical design report (TDR) of CEPC will be hoped to finish during this 5 years if everything goes smoothly. The construction of the CEPC then will start from 2021 and will last for 8-10 years, if the government can approve the project.

When the CEPC is in its R&D and construction stages, the pre-study and R&D of the key technologies of SppC, are hopeful to carry on, and the similar R&D and other work to be done as that of CEPC as well.

SUMMARY

The CEPC is the main high energy physics machine in the next decades around the world. Nearly all the aspects of the machine design have been touched. As the basis of the machine, accelerator physics studies of the CEPC main ring, is being carried on and getting progresses. But a lot of important issues of accelerator physics, the background to detector, machine detector interface, magnetic error effect, pretzel orbit induced physics or technical problems, etc., needs more studies in the near future. Thus, parameters of the main ring, booster, linac, etc., may be evolved or changed with the further study. The first stable version as a pre-CDR will be finished by the end of this year. Technical issues are being considered and some key technologies are proposed as the R&D project.

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