OVERVIEW OF HIGH ENERGY e^+e^- FACTORIES

K. Oide*, KEK, Oho, Tsukuba, Ibaraki, Japan

Abstract

Designs of e^+e^- colliders from the Z-pole and above are introduced. Two projects, CEPC and FCC-ee, are discussed. If we compare their schemes, a partial double ring (CEPC) and a full double ring (FCC-ee), find several important differences that affect the performance. On the other hand, there are a number of similarities in both designs, such as the crab-waist scheme, crossing angle, optimization of the dynamic aperture, etc.

INTRODUCTION

At least there are two plans have been studied for high energy e^+e^- circular collider factories. One is CEPC in China, which consists of a circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel. Another is FCC-ee, which is an e^+e^- collider as potential intermediate step or a possible first step for a 100 TeV pp-collider (FCC-hh). The design of CEPC has been considering several schemes: single-ring with pretzel, partial double-ring (PDR), and full double-ring. Although CEPC has not decided the scheme yet, the main efforts have been focused on the PDR scheme in this year. Thus we pick PDR for CEPC in this article. On the other hand, FCC-ee has chosen a full double ring scheme.

DESIGN PARAMETERS

Table 1 compares important design parameters of two machines at several beam energies. The parameters are as of this workshop.

PROGRESS

As for FCC-ee, a baseline beam optics [1] has been chosen, characterized by:

- A highest-energy circular e^+e^- collider ultra-low β^* of 1 mm and more than ±2% dynamic momentum acceptance.
- Features a local chromatic correction for the vertical plane. The dynamic aperture was optimized by varying the strengths of about 300 independent $-I$ sextupole pairs in the arcs.
- A crab-waist scheme was implemented by reducing the strength of an existing sextupole in the chromatic correction section with proper betatron phases, instead of adding another dedicated sextupoles.
- Synchrotron radiation is accommodated by tapering the magnet strengths in the arcs, and by a novel asymmetric IR/final-focus layout.
- The RF system is concentrated in two straight sections. A common system provides maximum voltage for $t\bar{t}$ running, where operation requires only few bunches. Two separate RF systems, one for either beam, are used at lower beam energies.
- The optics was designed to match the footprint of a future hadron collider (FCC-hh) along the arcs. Due to the asymmetric interaction region (IR) layout the e^+e^- interaction point (IP) is displaced transversely by about

Table 1: Design Parameters of FCC-ee and CEPC(PDR) together with LEP2. SR: synchrotron radiation, BS: beamstrahlung. FCC-ee has two options at Z.

	FCC-ee				CEPC(PDR)		LEP2
Beam energy [GeV]	45.6		120	175	45.6	120	105
Beam current [mA]	1450		30	6.6	67.6	16.9	3
Bunches/beam	91500	30180	770	78	1100	107	4
Energy loss/turn [GeV]	0.03		1.67	7.55	0.061	2.96	3.34
SR power for two beams [MW]	100				8.2	100	22
RF voltage [GV]	0.2	0.4	3	10	0.11	3.48	3.5
Bunch length (SR) [mm]	1.6	1.2	2.0	2.1	3.78	2.7	12
Bunch length (+BS) [mm]	3.8	6.7	2.4	2.5	4.0	2.95	12
Emittance $\varepsilon_{x,y}$ [nm, pm]	0.1, 1	0.2, 1	0.6, 1	1.3, 2.5	0.88, 8	2.05, 6.2	22, 250
$\beta^*_{x,y}$ [m, mm]	1, 2	0.5, 1	1, 2	1, 2	0.1, 1	0.27, 1.3	1.5, 50
Long. damping turns	1320		72	23	748	41	31
Crossing angle [mrad]	30				30		0
Beam lifetime [min]	185	94	67	57	79	20	434
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	70	207	5.1	1.3	4.5	3.1	0.0012

* Katsunobu.Oide@kek.jp

ISBN 978-3-95450-187-8

9 m from the hadron IP. This allows a lepton detector to be installed in the same cavern.

- The optics, the footprint, and the dynamic aperture are compatible with a top-up injection mode of operation based on a full-energy booster ring installed in the same tunnel and, in the IR, following the path of the hadron collider ring.

Figure 1 shows the obtained dynamic aperture for FCC-ee.

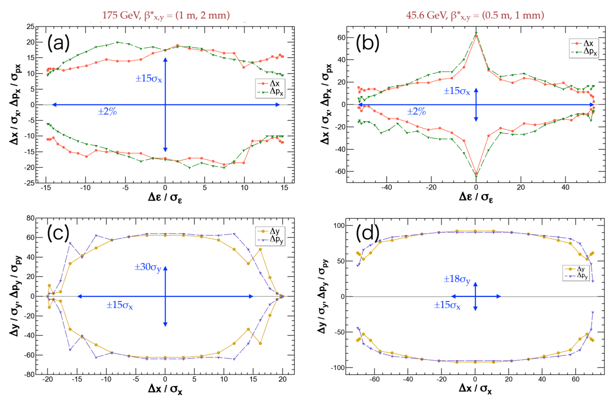

Figure 1: Dynamic apertures after an optimization of sextupoles via particle tracking. (a, c): $\beta^*_{x,y}$ =(1 m, 2mm), 50 turns at $t\bar{t}$, (b, d): $\beta^*_{x,y}$ =(0.5 m, 1mm), 2,650 turns at Z. (a, b): z-x plane with $J_y/J_x = 0.2\%$ for (a) and 0.5% for (b). (c, d): x-y plane with $\delta = \Delta\varepsilon = 0$. The aperture was searched both in (a,b) x and p_x or (c,d) y and p_y directions. The number of turns is chosen to correspond to about 2 longitudinal damping times at each energy. The blue lines show the DAs required for the beamstrahlung and the top-up injection. Effects in Table 2 are taken into account except for the radiation fluctuation and the beam-beam effect.

The design of CEPC has made significant progress [2] with the partial double-ring scheme:

- Integrated optics with the arc, interaction region (IR), RF are designed with the PDR scheme.
- Difficulties of the single ring scheme such as long-range beam-beam effect, dynamic aperture due to pretzel orbit, high HOM loss due to a short bunch, etc., have been totally removed.
- The local chromaticity corrections system (LCCS) has been designed for both planes. The crab sextupoles are incorporated in the vertical LCCS sextupoles.
- 90°/90° FODO cells are employed in the arc with non-interleaved sextupole pairs.
- The dynamic aperture has been optimized by varying up to 192 sextupole families in the arc to provide nearly sufficient momentum acceptance. Almost all effects have been included except for the energy-sawtooth.

Table 2: Effects Taken into Account in the Estimation of the Dynamic Aperture for FCC-ee.

Effect	Included?	Significance at $t\bar{t}$
Synchrotron motion	Yes	**Essential**
Radiation loss in dipoles	Yes	**Essential** – improves the aperture
Radiation loss in quadrupoles	Yes	**Essential** – reduces the aperture
Radiation fluctuation [a]	Yes	**Essential**
Tapering	Yes	**Essential**
Crab waist	Yes	transverse aperture is reduced by ~ 20%
Solenoids	Yes	minimal, if locally compensated
Maxwellian fringes	Yes	small
Kinematical terms	Yes	small
Higher order fields/errors/misalignm	No	**Essential**, development of correction/tuning scheme is necessary

[a] not included in the optimization

- Advanced algorithms such as Multi-objective optimization have been developed and applied for the design.

Figure 2 shows the obtained dynamic aperture for CEPC PDR.

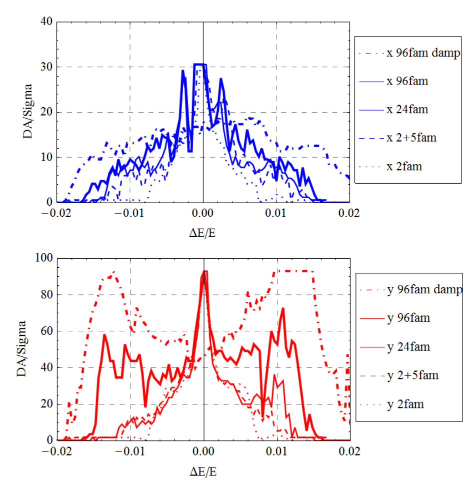

Figure 2: The dynamic apertures of CEPC PDR [2] in x-z (top) and y-z planes (bottom). The lines show the difference between the number of sextupole families. The largest ones include synchrotron radiation damping, and are approaching the goal momentum aperture ±2%.

ISBN 978-3-95450-187-8

Table 3: Major Differences in the Design of CEPC(PDR) and FCC-ee.

	CEPC(PDR)	FCC-ee
Scheme	Partial Double Ring	Full Double Ring
Circumference [km]	61	100
$\mathcal{L}$ at H [10^{34} cm^{-2}s^{-1}]	3	5
$\mathcal{L}$ at Z [10^{34} cm^{-2}s^{-1}]	3.6	200
Energy sawtooth effect	uncorrectable, can be reduced by inserting more RF sects.	completely correctable
SR to IP	190 keV @ H	100 keV @ $t\bar{t}$
$\beta^*_{x,y}$ @ Z [m, mm]	0.1, 1	0.5, 1
Strong-strong beam-beam instability	may be weaker than FCC-ee due to smaller β^*_x	luminosity reduced by ~50% @ Z if it occurs
Local chromaticity correction	X & Y	Y
Dynamic aperture	In progress	OK without machine errors
Hadron machine	can co-exist	removes the ee machine

SIMILARITIES

Both designs for CEPC and FCC-ee are obtaining similarities, by employing the PDR scheme for CEPC:

- 2 IPs/ring, with 30 mrad crossing angle and crab waist.
- Vertical local chromaticity correction system incorporated with crab sextupoles.
- $90^\circ/90^\circ$ FODO cells in the arc.
- Non-interleaved sextupole pairs with $-I$ transformation.
- Optimization of dynamic aperture with hundreds of sextupole families.

DIFFERENCES

An apparent difference between their designs are in their circumferences: around 61 km for CEPC and 100 km for FCC-ee. The energy reach of CEPC is limited to Higgs due to the circumference, no matter which scheme is chosen. This is a choice of the project, and not an issu of the design scheme. Besides the circumference, there are important differences between two designs. Table 3 compares these differences. The major issues are:

- CEPC's luminosity is roughly 1/40 of FCC-ee's at Z. This is a main limitation by the PDR scheme, just depends on the length of the double-ring part.
- The level of synchrotron radiation toward the IP: CEPC is ~2x higher than FCC-ee.
- Tapering is not possible in PDR. Thus the effect of the energy sawtooth on the dynamic aperture must be studied.
- CEPC has smaller β^*_x, which is 1/5 of FCC-ee's. It may mitigate the strong-string beam-beam instability [3].
- CEPC has a local chromaticity correction for both planes, which enables the smaller β^*_x.

ACKNOWLEDGEMENT

The author thank Huiping Geng, Qing Qin, Dou Wang, Yiwei Wang, and Yuan Zhang for providing materials of CEPC. Also thank M. Benedikt, A. Blondel, A. Bogomyagkov, M. Koratzinos, E. Levitchev, J. Wenninger, F. Zimmermann, and all contributors for the design of FCC-ee beam optics.

REFERENCES

[1] K. Oide, et al, arXiv:1610.07170(2016).

[2] H.P. Geng *et al.*, presented at eeFACT2016, Daresbury, UK, September 2016, paper MOT3BH3.

[3] K. Ohmi, presented at eeFACT2016, Daresbury, UK, September 2016, paper TUT1BH2.

ISBN 978-3-95450-187-8