CEPC-SPPC ACCELERATOR STATUS*

J. Gao†, IHEP, Beijing 100049, China

Abstract

In this paper we will give an introduction to Circular Electron Positron Collider (CEPC). The scientific background, physics goal, the collider design requirements and the conceptual design principle of CEPC are described. On CEPC accelerator, the optimization of parameter designs for CEPC with different energies, machine lengthes, single ring and crab-waist collision partial double ring options, etc. have been discussed systematically. The subsystems of CEPC, such as collider main ring, booster, electron positron injector, etc. have been introduced. The detector and MDI design have been briefly mentioned. Finally, the optimization design of Super Proton-Proton Collider (SPPC), its energy and luminosity potentials, in the same tunnel of CEPC are also discuss. It is decided that CEPC-SppC CDR baseline will be of 100km circumference, and the corresponding designs are underway.

INTRODUCTION

With the discovery of the Higgs particle at the Large Hadron Collider at CERN in July 2012, after more than 50 years of searching, particle physics has finally entered the era of the Higgs, and the door for human beings to understand the unknown part of the Universe is wide open! Thanks to the low energy of Higgs, it is possible to produce clean Higgs with circular electron positron colliders in addition of linear colliders, such as ILC and CLIC, with reasonable luminosity, technology, cost, and power consumption.

In September 2012, Chinese scientists proposed a Circular Electron Positron Collider (CEPC) in China at 240 GeV centre of mass for Higgs studies with two detectors situated in a very long tunnel more than twice the size of the LHC at CERN. It could later be used to host a Super Proton Proton Collider (SppC) well beyond LHC energy potential to reach a new energy frontier in the same channel.

After ICFA Higgs Factory Workshop held at Fermi Laboratory in Nov 2012, CERN proposed also a similar one, Future Circular Collider (FCC) with a much longer tunnel than that of LHC. From 12 to 14 June 2013, the 464th Fragrant Hill Meeting was held in Beijing on the strategy of Chinese high energy physics development after Higgs discovery, and the following consensuses were reached: 1) support ILC and participate to ILC construction with in kind contributions, and request R&D fund from Chinese government; 2) as the next collider after BEPCII in China, a circular electron positron Higgs factory (CEPC) and a Super proton-proton Collier (SppC) afterwards in the same tunnel is an important option as a historical opportunity, and corresponding R&D is needed. ICFA has given two successive statements in Feb. and July of 2014, respectively, that ICFA supports studies of energy frontier circular colliders and encourages global coordination; ICFA continues to encourage international studies of circular colliders, with an ultimate goal of proton-proton collisions at energies much higher than those of the LHC. During the AsiaHEP and ACFA meeting in Kyoto in April 2016, a positive statement of AsiaHEP/ACFA Statement on ILC+CEPC/SppC has been made with strong endorsement of the ILC and encouraging the effort led by China on CEPC/SppC. On Sept 12, 2016, during the meeting of the Chinese High Energy Physics of Chinese Physics Society, a statement on the future Chinese high energy physics based on accelerator has been made that CEPC is the first option for future high energy accelerator project in China as a strategic action with the aim of making CEPC as a large international scientific project proposed by China. The 572th Fragrant Hill Meeting dedicated to CEPC has been held from Oct. 18-19, 2016, and it is concluded that CEPC has a solid physics reason to be built with big physics potential in SppC. The optimization design, relevant technologies and industry preparation could be ready after a five years dedicated R&D period before CEPC starts to be constructed around 2022 and completed around 2030. CEPC will operate 10 ten years with two detectors to accumulate one million Higgs and 100 million of Z particle.

In the beginning of 2015, Pre-Conceptual Design Reports (Pre-CDR) of CEPC-SppC [1] have been completed with international review. The International Advisory Committee (IAC) of CEPC was also established in 2015. At the end of 2016 a CDR Status Report will be finished before finishing of the CDR at the end of 2017. In 2016, Chinese Ministry of Science and Technology has allocated several tens of million RMB on CEPC R&D to start with.

Finally, it is decided that CEPC-SppC CDR baseline will be of 100km circumference, and the corresponding designs are underway.

CEPC ACCELERATOR DESIGN

According to the physics goal of CEPC at Higgs and Z-pole energy, it is required that the CEPC provides e^+e^- collisions at the center-of-mass energy of 240 GeV and delivers a peak luminosity of 2×10^{34} cm$^{-2}s^{-1}$ at each interaction point. CEPC has two IPs for e^+e^- collisions. At Z-pole energy the luminosity is required to be larger than 1×10^{34} cm$^{-2}s^{-1}$ per IP. Its circumference is around 60 k-

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† gaoj@ihep.ac.cn

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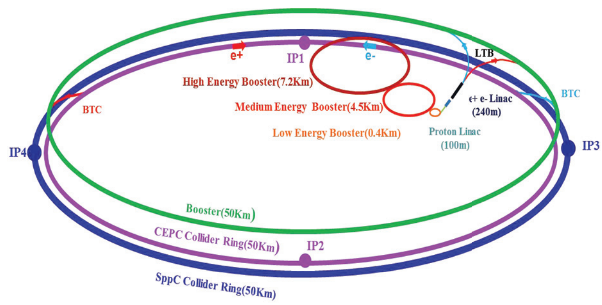

Figure 1: CEPC-SPPC schematic layout.

m in accordance with SppC, which has 70 TeV of center of mass proton proton collision and 20 Tesla superconduction magnet dipole field. The schematic layout of CEPC-SppC is shown in Fig. 1, and CEPC accelerator complex is composed of a 6 GeV electron and positron linac injector with a 1 GeV positron damping ring, a booster from 6 GeV to 120 GeV in the same channel of 120 GeV collider rings.

Main Parameters and Main Ring Designs

To make an optimization a collider, started from the goals, such as energy, luminosity/IP, number of IPs, etc, one has to consider very key beam physics limitations, such as beam-beam effects [2] and Beamstrahlung [3], and also take into account of economical and technical limitations, such synchrotron radiation power and high order mode power in each Superconducting rf cavity. By taking into account all these limitations in an analytical way, an analytical electron positron circular collider optimized design methods have been developed both head-on collision and crab-waist collision. The CEPC parameters of single ring head-on collision scheme as used in CEPC-SppC Pre-CDR and the crab-waist collision designs are shown in Tab. 1 [4].

In Pre-CDR, single ring head-on collision scheme has been studied with Pretzel scheme. The apparent low cost single ring Pretzel scheme has many problems, such as not flexible lattice solution, small dynamic aperture, low Z-pole energy luminosity (around 10^{32} cm$^{-2}s^{-1}$), and very high AC power consumption (around 500MW). To solve these critical problems, a Partial Double Ring (PDR) scheme has been proposed independently [5][6]. In Tab. 1 we could find that with crab wait collision, one could reduce synchrotron radiation power from 50 MW to about 30MW, and with Z-pole luminosity to satisfy the design requirement. In fact, in addition to single ring and partial double ring schemes, there are two other types of schemes, i.e. Advanced Partial Double Ring (APDR) [7] and Double Ring (DR) scheme [8]. In fact, in principle, the crab-waist CEPC parameters could be realized by PDR, APDR and DR schemes. PDR, APDR and DR are also called options to a crab-waist collision scheme. However, if one take synchrotron radiation effect and the collective effect of superconducting accelerator system taking into account, the three options are quite different from one from another. Apparently, DR is the most expensive and relative easy option, APDR as shown in Fig. 2(PDR is a special case of APDR, only two partial double ring sections at two IPs) is most possible economic option overcoming the difficulties from PDR, i.e., beam loading and sawtooth effects, which should be studied carefully before a reasonable choice among differen options.

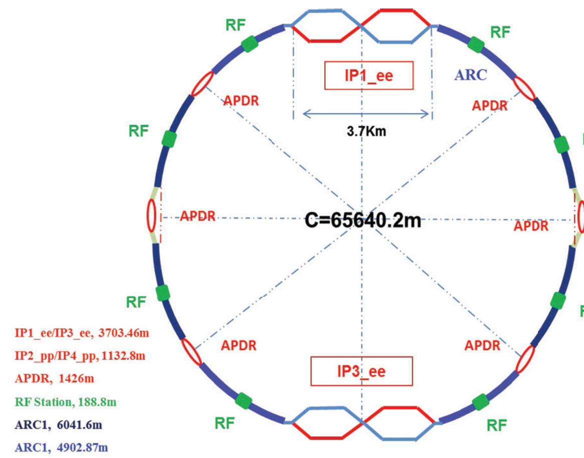

Figure 2: CEPC advanced partial double ring scheme.

As for PDR (APDR) lattice design, in the Arc region, the FODO cell structure is chosen to provide a large filling factor. The 90/90 degrees phase advances is chosen to achieve a very small emittance of 2 nm. The non-interleaved sextupole scheme [9] was selected due to its property of small tune shift. Considering the symmetry of two IPs and two beams, the lattice CEPC PDR scheme has a four-fold symmetry and the maximum number of sextupole families in the ARC region is 96 [10].

The CEPC interaction region (IR) was designed with modular sections including the final transformer, chromaticity correction for vertical plane, chromaticity correction for horizontal plane and matching transformer. To achieve a momentum acceptance as large as 2%, local correction of the large chromaticity from final doublet is necessary.

The dynamic aperture of the ring is optimized by SAD and goal is to have dynamic aperture in both transverse planes lager than 5σ including all effects with energy spread of from $+2\%$ to -2%.

The advantage of PDR and APDR over DR is the cost saving, if beam loading and sawtooth effects related to PDR (APDR) are not to be the showstoppers, which need detailed studies before making a final decision.

Injector

To reduce the cost of the whole system, the length of the Linac is chosen to be as short as possible, and a booster ring is used to ramp the beams from the Linac energy to the full injection energy of the main collider. Therefore, the whole CEPC system is composed of three parts: a linac, a booster, the main collider ring. The Linac injector system

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Table 1: Main parameters of CEPC

	Pre-CDR	*H-high lumi.*	*H-low power*	*W*	*Z*
Number of IPs	2	2	2	2	2
Energy (GeV)	120	120	120	80	45.5
Circumference (km)	54	61	61	61	61
SR loss/turn (GeV)	3.1	2.96	2.96	0.58	0.061
Half crossing angle (mrad)	0	15	15	15	15
Piwinski angle	0	1.88	1.84	5.2	6.4
N_e/bunch (10^{11})	3.79	2.0	1.98	1.16	0.78
Bunch number	50	107	70	400	1100
Beam current (mA)	16.6	16.9	11.0	36.5	67.6
SR power /beam (MW)	51.7	50	32.5	21.3	4.1
Bending radius (km)	6.1	6.2	6.2	6.2	6.2
Momentum compaction (10^{-5})	3.4	1.48	1.48	1.44	2.9
β_{IP} x/y (m)	0.8/0.0012	0.272/0.0013	0.275 /0.0013	0.1/0.001	0.1/0.001
Emittance x/y (nm)	6.12/0.018	2.05/0.0062	2.05 /0.0062	0.93/0.0078	0.88/0.008
Transverse σ_{IP} (um)	69.97/0.15	23.7/0.09	23.7/0.09	9.7/0.088	9.4/0.089
ξ_x/IP	0.118	0.041	0.042	0.013	0.01
ξ_y/IP	0.083	0.11	0.11	0.073	0.072
V_{RF} (GV)	6.87	3.48	3.51	0.74	0.11
f_{RF} (MHz)	650	650	650	650	650
Nature σ_z (mm)	2.14	2.7	2.7	2.95	3.78
Total σ_z (mm)	2.65	2.95	2.9	3.35	4.0
HOM power/cavity (kw)	3.6	0.74	0.48	0.88	0.99
Energy spread (%)	0.13	0.13	0.13	0.087	0.05
Energy acceptance (%)	2	2	2		
Energy acceptance by RF (%)	6	2.3	2.4	1.7	1.2
n_γ	0.23	0.35	0.34	0.49	0.34
Life time due to beamstrahlung_cal (minute)	47	37	37		
F (hour glass)	0.68	0.82	0.82	0.92	0.93
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.04	3.1	2.01	4.3	4.48

is composed of a 6 GeV S-band linac with positron source and a 1 GeV positron damping ring with two stage bunch compressors.

Booster The booster provides 120 GeV electron and positron beams to the CEPC collider for top-up injection at 0.1 Hz. The Booster is in the same tunnel as the collider, placed above the collider ring and has about same circumference. The design of the full energy booster ring of the CEPC is especially challenging due to the injected beam only 6GeV, which might cause difficulties. As an alternative design we studied also a wiggler dipole magnets to raise the initial magnetic field [11].

Detector and MDI

The CEPC conceptual detector takes the ILD detector as starting point [12][13]. Similar to the ILD, the core part of this conceptual detector is a solenoid with 3.5 Tesla Magnet Field. To minimize the dead zone, the entire ECAL, HCAL and the tracking system are installed inside the solenoid. The tracking system is composed of a large volume TPC as the main tracker and the silicon tracking system. The interaction region of the CEPC partial double ring consists of two beam pipes, of which the crossing angle is 30mrad, surrounded by silicon tracker, luminosity calorimeter and the final quadrupoles QD0 and QF1, with L* is 1.5m [14]. The inner radius of the vacuum chamber should be larger than the beam-stay-clear region. We chose 17 mm (2 mm for safety) both for QD0 and QF1. On the other hand, the collision environment of CEPC is significantly different from that of the linear colliders. Therefore, mandatory changes have been included into the CEPC conceptual detector design. The entire Machine Detector Interface (MDI) has been re-designed, to achieve the nominal luminosity and to keep the radiation at the IP at acceptable level for the electronics. The distance between the final focusing quadrupole magnet (QD0) and the interaction point have been changed from 3.5 meter to 1.5 meter. In the original design, the ILD uses extremely heavy Yoke system, to shield the B-field since Linear Collider requires the Push-Pull scenario. On the contrary, CEPC has 2 interaction points and a much thinner return Yoke could serve. Beside these changes, dedicated simulation and optimization studies has been established, to test new ideas and designs. Hopefully, these studies will eventually leads to a detector design that further balances the construction cost and physics performance.

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Table 2: SPPC parameter list

	SPPC (Pre-CDR)	SPPC 61Km	SPPC 100Km	SPPC 100Km	SPPC 82Km
Main parameters and geometrical aspects					
Beam energy[E_0]/TeV	35.6	35.0	50.0	64.0	50.0
Circumference[C_0]/km	54.7	61.0	100.0	100.0	82.0
Dipole field[B]/T	20	19.81	15.62	19.98	19.74
Dipole curvature radius[ρ]/m	5928	5889.64	10676.1	10676.1	8441.6
Bunch filling factor[f_2]	0.8	0.8	0.8	0.8	0.8
Arc filling factor[f_1]	0.79	0.78	0.78	0.78	0.78
Total dipole length [L_{Dipole}]/m	37246	37006	67080	67080	53040
Arc length[L_{ARC}]/m	47146	47443	86000	86000	68000
Straight section length[L_{ss}]/m	7554	13557	14000	14000	14000
Physics performance and beam parameters					
Peak luminosity per IP[L]/ $cm^{-2}s^{-1}$	1.1×10^{35}	1.20×10^{35}	1.52×10^{35}	1.02×10^{36}	1.52×10^{35}
Beta function at collision[β^*]/m	0.75	0.85	0.99	0.22	1.06
Max beam-beam tune shift per IP[ξ_y]	0.006	0.0065	0.0068	0.0079	0.0073
Number of IPs contribut to ΔQ	2	2	2	2	2
Max total beam-beam tune shift	0.012	0.0130	0.0136	0.0158	0.0146
Circulating beam current[I_b]/A	1.0	1.024	1.024	1.024	1.024
Bunch separation[Δt]/ns	25	25	25	25	25
Number of bunches[n_b]	5835	6506	10667	10667	8747
Bunch population[N_p] (10^{11})	2.0	2.0	2.0	2.0	2.0
Normalized RMS transverse emittance[ε]/μm	4.10	3.72	3.59	3.11	3.35
RMS IP spot size[σ^*]/μm	9.0	8.85	7.86	3.04	7.86
Beta at the 1st parasitic encounter[$\beta 1$]/m	19.5	18.67	16.26	69.35	15.31
RMS spot size at the 1st parasitic encounter[σ_1]/μm	45.9	43.13	33.10	56.19	31.03
RMS bunch length[σ_z]/mm	75.5	56.69	66.13	14.62	70.89
Full crossing angle[θ_c]/μrad	146	138.03	105.93	179.82	99.29
Reduction factor according to cross angle[F_{ca}]	0.8514	0.9257	0.9247	0.9283	0.9241
Reduction factor according to hour glass effect[F_h]	0.9975	0.9989	0.9989	0.9989	0.9989
Energy loss per turn[U_0]/MeV	2.10	1.98	4.55	12.23	5.76
Critical photon energy[E_c]/keV	2.73	2.61	4.20	8.81	5.32
SR power per ring[P_0]/MW	2.1	2.03	4.66	12.52	5.90
Transverse damping time [τ_x]/h	1.71	1.994	2.032	0.969	1.32
Longitudinal damping time [τ_ε]/h	0.85	0.997	1.016	0.4845	0.66

SPPC DESIGN

The design goal of the SPPC is about 70 TeV, using the same tunnel as the CEPC of 61 km, with SC dipole magnet field of about 20 Tesla of luminosity of $1.2{\times}10^{35}$/cm$^{-1}s^{-1}$. If 100km ring is adopted a proton beam of 128 TeV of luminosity of $1{\times}10^{36}$/cm$^{-1}s^{-1}$ at 20 Tesla could be obtained, and parameter choice and optimization process is given in Tab. 2 [15].

The injector chain pre-accelerates the beam to injection energy with the required beam properties such as bunch current, bunch structure, and emittance. The injection chain determines the beam fill period. To reach 2.1 TeV, we have designed a four-stage injector chain: a linac (p-Linac) to 1.2 GeV, a rapid cycling synchrotron (p-RCS) to 10 GeV, a medium-stage synchrotron (MSS) to 180 GeV, and finally the super synchrotron (SS) to 2.1 TeV. High repetition rates for the lower energy stages help reduce the SS cycling period. This is important because the SS uses superconducting magnets and also to reduce the beam fill period of the SPPC. The beams can also be used for other applications or research purposes when the accelerators are not preparing beam for injection into the SPPC.

As for the circumference of SppC is concerned, to explore a center-of-mass energy of 100 TeV while keeping the dipole field at 20 T, the circumference should be 82 km at least. With this condition, there is hardly any space to upgrade, so a 100 km SPPC is much better because the dipole field is then only 15.62 T.

CONCLUSIONS

In this paper we have briefly reviewed the CEPC-SppC projects history, design philosophy and actual status. A dedicated R&D program both on accelerator and detectors has started with support of Chinese MOST. The beam loading and sawtooth effects have to be studied carefully to before the final choice between partial double ring (PDR and APDR) and double ring schemes. It is decided that CEPC-SppC CDR baseline will be of 100km circumference, and the corresponding designs are underway.

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