Chapter 21
Circular Colliders in China

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Abstract The project of the Circular Electron-Positron Collider, CEPC, proposed by the Institute for High Energy Physics, Beijing, IHEP, is illustrated.

It is a great honour and pleasure for me to speak at the 100 years Memorial Symposium of Bruno Touschek. The concept of colliders, and the famous Touschek effect are text I learned in books, but now I have the fortune to hear his stories, and give a presentation with his colleagues and students in the same room, although virtual. This is a remarkable memory for me and I appreciate very much the opportunity. Now let me contribute a report about colliders in China.

Accelerator development started in China in early 50s. The first attempt was a 2.5 MeV proton electrostatic accelerator, followed by a 30 MeV electron LINAC in '60s. A number of accelerators for high energy physics, mostly protons on fixed target was proposed in '60–'80s but never approved except a 30 MeV proton LINAC as an exercise.

At the beginning of '80s, the Beijing Electron–Positron Collider (BEPC) was proposed and finally approved. The construction started in 1984 and the first collision was seen in the fall of 1988. BEPC was designed and achieved to have the highest luminosity at the 2–5 GeV energy region for tau and charm physics, a special domain for its abundant resonances, gluon rich environment, being a bridge for pQCD and non-pQCD, and advantages of quantum entanglement of pair production at the threshold. BEPC was a great start for particle physics and synchrotron radiation in China, for its rich physics outcome, and for its training of physicists and engineers on both experimental physics and accelerators. Its success led to a major upgrade in 2004–2008, called BEPCII, which replaced the existing single-ring e^+e^- collider to a factory-type of double-ring machine in the same tunnel to increase the luminosity by a factor of 100. Figure 21.1 shows the luminosity evolution of colliders at 2–5 GeV

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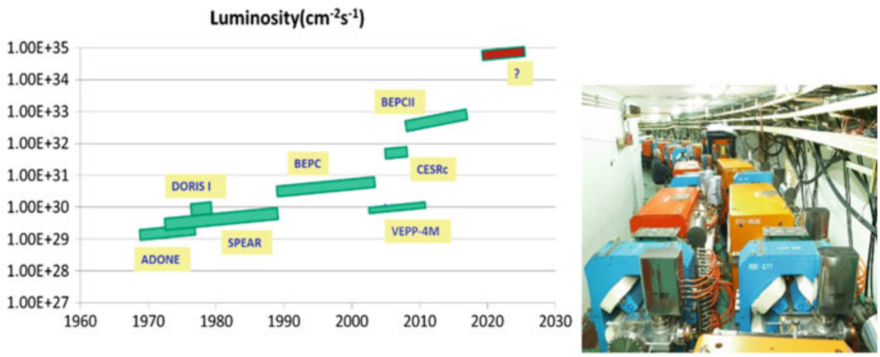

Fig. 21.1 Evolution of the luminosity of e^+e^- colliders at 2–5 GeV energy region, and the BEPCII in the BEPC tunnel (photo IHEP)

energy region and the BEPCII in the BEPC tunnel. It is clear that BEPC and its upgrade, BEPCII, maintained their leadership role in the last 40 years.

The newly built detector, BESIII, has a collaboration with more than 500 members from 17 countries, including 3 institutions from Italy. Its physics program covers light hadron spectroscopy, exotic hadron states, charm and charmonium physics, QCD studies, tau physics and new physics searches [1]. Up to now, more than 380 papers have been published at leading international journals, and a possible 4-quark state, $Z_c^{\pm}(3900)$ was discovered, together with its companion particles, $Z_c^0(3900)$, $Z_c^{\pm}(4020)$, and $Z_c^0(4020)$. Other XYZ particles and their new decay modes, new light hadron resonances and possible glueball candidates were also observed [2].

Even the luminosity of BEPCII reached its design value and after 12 years of data taking, the rich physics program of BESIII still requires 40 fb^{-1} more data, corresponding to another 15 years of data taking [3]. A further upgrade of BEPCII was thus proposed and approved recently by the Chinese Academy of Sciences. The first upgrade item is to increase the luminosity by a factor of 3 at 2.3 GeV for XYZ particle studies (Fig. 21.2), by squeezing the beam size after adding a new RF cavity per beam. The second item is to increase the maximum beam energy from 2.45 to 2.8 GeV for charmed baryons, by replacing the two superconducting quadrupole focusing magnets near the interaction point with higher field strengths. Such an upgrade is also a technology exercise for the future Circular Electron–Positron Collider (CEPC), which will be discussed later. The upgrade is planned to be completed in 2024 and the machine will at least be operational until 2030.

In the mean time we realize that BEPCII cannot be a machine forever and a more ambitious program is desired. Further future of a high energy physics machine after BEPCII has been a topic for discussion since 2005 in the community of China. Various options such as the super-tau-charm factory, super-Flavor factory, even Higgs factory have been talked about in the following years. Joining international projects like ILC was also an option. At a meeting in Sep. 2012, the idea of a Circular Electron–Positron

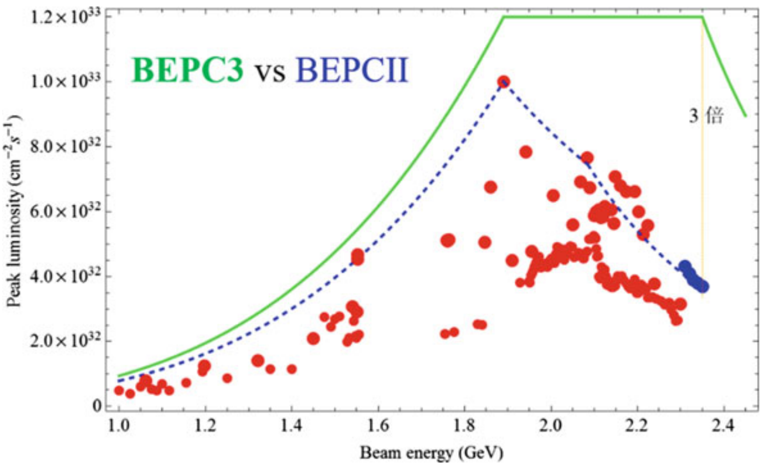

Fig. 21.2 Luminosity upgrade of BEPCII

Collider (CEPC) as a Higgs factory, followed by a very high energy Super Proton-Proton Collider (SPPC) in the same tunnel was proposed. The possibility to re-use the tunnel like LEP-LHC and its advantages over the International Linear Collider (ILC) with a higher luminosity and synchrotron radiation applications quickly gained support in China. The concept, as the first one of its type in the world, was reported in Oct. 2012 at the Fermilab Higgs Factory Workshop [4] and well accepted in the world. Soon after similar ideas such as FCC in Europe appeared and gained momentum.

Higgs factory as the next machine after LHC has a very rich physics potential, as already studied extensively for ILC. If LHC does not find anything new beyond the Standard Model (SM), a Higgs Factory shall be the first choice to discover new physics indirectly beyond the SM. If LHC does find anything new, a Higgs factory is still the first choice to study new physics. Indeed, Higgs is the best window to new physics since it is very special with non-gauge interactions and with a potential similar to that of Landau-Ginzburg which originated from a Cooper pair, an interesting analogy for Higgs being a composite particle. The shape of the Higgs potential also affects the electroweak phase transition at the very beginning of the Universe. Many other inconsistencies and incompleteness of the SM are also Higgs-related, such as the meta-stable vacuum, coupling with dark matter particles, and even the origin of the Higgs mass. An independent study by European physics community also concluded in 2020 that a Higgs Factory is the highest priority for the future of high energy physics [5].

At Higgs factories, couplings of Higgs with fermions and intermediate bosons can be measured to a precision better than 1%, even up to 0.1% with Z. Such a precision can probe new physics up to an energy scale of about 10 TeV, almost a factor of 10 better than that at LHC. If no new physics are found up to this energy scale, the principle of Naturalness is no longer valid which can even be a more important discovery. In addition, comprehensive and high precision tests of the electroweak

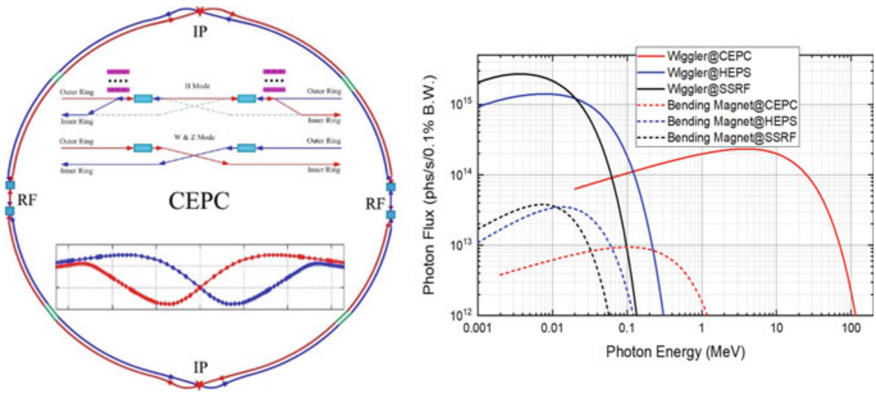

Fig. 21.3 Conceptual design of CEPC, and its photon flux of the synchrotron radiation versus other dedicated synchrotron radiation facilities

theory and QCD studies at Z and W resonances, and flavor physics studies at Z resonances can be performed at circular Higgs factories. Detailed physics potentials are still under study although some have been published [6].

The baseline design of CEPC is 100 km circumference, 30 MW beam power, upgradable to 50 MW beam power and 180 GeV beam energy for ttbar, and compatible with the future pp collider (SPPC) in the same tunnel. Figure 21.3 shows the main ring design and the flux of synchrotron radiation photons. Detailed physics design of the accelerator has been continuously improved since the publication of the "Conceptual Design Report of CEPC" (CDR) in 2018 [7]. Effects such the dynamic aperture with component production errors, beam-beam effects, impedance, electron clouds, etc. have been taken into accounts. Table 21.1 lists the latest key parameters of the CEPC baseline design at Higgs and Z energies, which have been improved dramatically over the CDR with 70% increase of the luminosity at Higgs.

Key components R&D and prototyping have been started since 2014 with funding support from the Ministry of Science and Technology (MoST), Chinese Academy of Sciences (CAS), and National Natural Science Foundation of China (NSFC). Many of the R&D programs were jointly supported with other projects such as the ILC, LHC, High Energy Photon Source (HEPS) in Beijing, China Spallation Neutron Sources (CSNS) as well as startup funds of newly recruited talents and generic R&D. A major progress is the development of Superconducting RF (SRF) cavities. An advanced infrastructure for SRF cavity production, inner surface treatment, QC&QA and testing facilities was established with funding from the Beijing Municipal government and great results have been obtained. Figure 21.4 shows testing results of cavity prototypes for the booster (1.3 GHz) and the main ring (650 MHz) which already satisfied the CEPC design specifications. In fact, the 1.3 GHz cavities which are also applicable to the Shanghai Free Electron Laser Facility and other international projects have already achieved world's best Q-values, thanks to the

Table 21.1 Key parameters of CEPC and its luminosity

	Higgs (high_lum.)	Z (high_lum.)
Number of IPs	2	2
Beam energy (GeV)	120	45.5
Circumference (km)	100	100
Synchrotron radiation loss/turn (GeV)	1.8	0.036
Crossing angle at IP (mrad)	16.5	16.5
Piwinski angle	4.87	18.0
Number of particles/bunch N_e (10^{10})	16.3	16.1
Bunch number (bunch spacing)	214 (0.7us)	10,870 (27 ns)
Beam current (mA)	16.8	841.0
Synchrotron radiation power /beam (MW)	30	**30**
Bending radius (km)	10.2	10.7
Momentum compact (10^{-5})	7.34	2.23
β function at IP β_x*/ β_y* (m)	0.33/0.001	0.15/0.001
Emittance e_x/e_y (nm)	0.68/0.0014	0.52/0.0016
Beam size at IP σ_x /σ_y (μm)	15.0/0.037	8.8/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.115	0.0048/0.129
RF voltage V_{RF} (GV)	2.27	0.13
RF frequency f_{RF} (MHz)	650	650
Natural bunch length σ_z (mm)	2.25	2.93
Bunch length σ_z (mm)	4.42	9.6
Energy spread (%)	0.19	0.12
Energy acceptance requirement (%)	1.7	1.4
Energy acceptance by RF (%)	2.5	1.5
Beamstruhlung lifetime/quantum lifetime (min)	41	–
Lifetime (hour)	21	1.8
Luminosity/IP L (10^{34} cm^{-2} s^{-1})	**5.0**	**101.1**

mid-temperature baking technology. Further R&D to allow the new design of 1-cell 650 MHz applicable to all beam energies of Higgs, Z, and W studies is still on-going.

Other prototypes, including electron guns, all types of magnets, beam diagnostics, vacuum beam pipes with NEG coating, electro-static separators, alignment apparatus, as well as high efficiency klystrons have been in progress. Many were already tested to have satisfied design specifications, as shown in Fig. 21.5.

Design and R&D of detectors have been also progressing well. A new detector concept other than those suggested for ILC, CLIC and FCC have been proposed recently, as shown in Fig. 21.6. A gaseous detector (drift chamber or TPC) in the

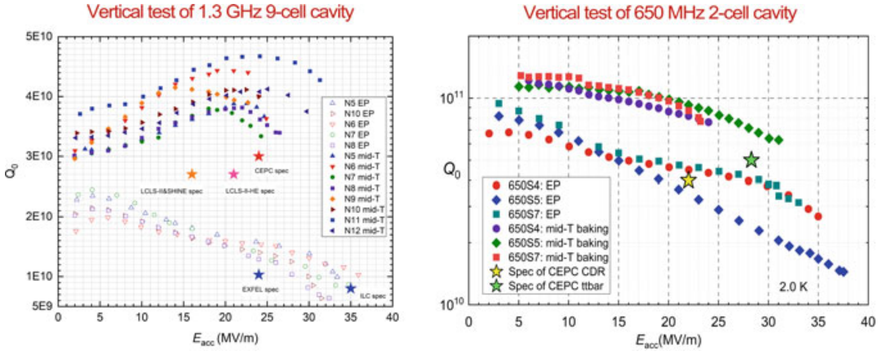

Fig. 21.4 Vertical test results of RF cavities. Left: 1.3 GHz for the booster ring; Right: 650 MHz for the main storage ring

Fig. 21.5 Prototypes of magnets, electro-static separator, Klystrons, vacuum pipes with NEG coating, etc. for CEPC (photos IHEP)

middle of the silicon tracker can improve the track reconstruction, momentum resolution and serve for the particle ID using its dE/dx(or dN/dx) capabilities. A BGO-based crystal electromagnetic (EM) calorimeter with PFA capabilities will have the best energy resolution not only for jets as needed by the Higgs physics, but also for photons needed by the flavor physics. Crystals are arranged in both the x- and y- directions perpendicular to particles from the interaction point. The position of the energy deposition along the crystal bar is obtained from the measured timing difference between two ends of the crystal using SiPMs. Simulation of such a 3D calorimeter shows that ghost hits can be mostly removed and EM showers with a distance more than 4 cm can be well separated. The jet energy and direction can be easily reconstructed and their invariant mass can be obtained with a precision better

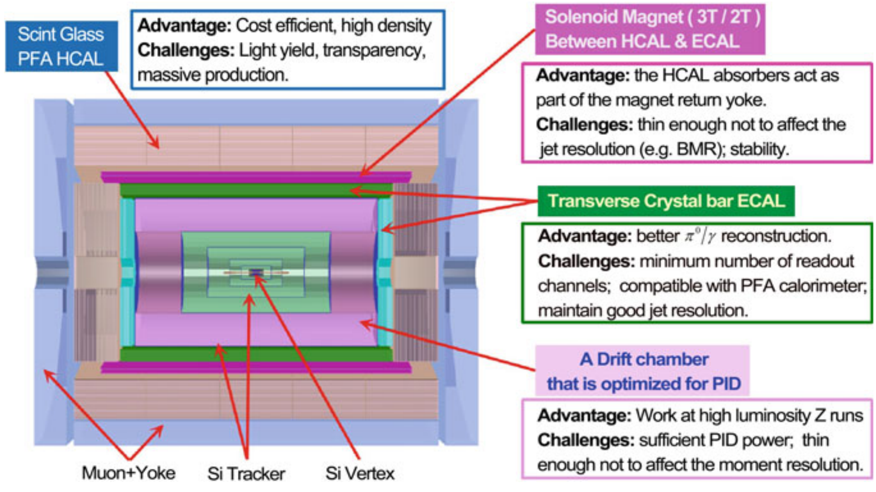

Fig. 21.6 Design of a new detector concept for CEPC

than any other technologies. A very thin solenoid magnet in between the crystal and hadron calorimeter with a field strength of 3 T for Higgs and 2 T for Z physics can be built using high Tc superconducting cables. In order to increase the sampling ratio, the sensitive material of the hadron calorimeter is chosen to use scintillating glass with a density more than 6 g/cm^3, placed in between steel plate. Although it is almost impossible to produce large size glass bars for a total absorption hadron calorimeter, as was suggested years ago, small piece (~4 × 4 × 1 cm^3) of glass with a high light yield (>1000 photons/MeV) is feasible and cost effective. Simulation shows that the stochastic term of the energy resolution for hadrons can be improved from ~50% using traditional technologies to <40% using scintillating glass with a proper sampling ratio.

For the long run, R&D of high Tc superconducting magnets for SPPC is a very important and interesting subject with possible applications to the society. For reasons of cost and applications in the higher magnetic field, Iron-Based Superconducting (IBS) material seems the best choice. A large collaboration with other research institutions, universities and industries has been formed with funding support from CAS, and interesting results have been reported [8]. Another very interesting topic of R&D is the use of the plasma wake-field acceleration (PWA) as the injector of CEPC. By using traditional accelerators before and after the PWA to compensate shortfalls of each other's technology, the injector will be satisfactory and can be very cost-effective. Indeed, an innovative idea to accelerate positrons was proposed [9] recently which may pave the way for e^+e^- colliders using PWA technologies.

The CEPC project obtained substantial support from all funding agencies in China, even though the construction is still under discussion. Our plan is to complete the TDR by the end of this year, and the full construction may start at around 2025. The site selection has been on going for almost 10 years, taking into account issues like geology for tunneling, power supply and other infrastructure capabilities, cultural environment and transportation easiness for foreigners, local economy and possible government support, etc. At this moment, 5 cities are running at the front: Qing-Huang-Dao, Chang-Sha, Chang-Chun, Hu-Zhou and Xi'an. Geological investigations and the detailed arrangement of experimental facilities are still under study and the final choice of the site will happen when the project is approved for construction.

We acknowledge that CEPC has a lot of similarities with FCC-ee at CERN, even though the two machines are designed somewhat differently, and running plans are not the same. Their synergies shall be explored more profoundly and the collaboration is much desired. In fact, CEPC will be an international project given its size and the government announced plan to support "China initiated large science projects". We will certainly coordinate with CERN and the international community to move forward with the hope that at least one of the Higgs factories will be realized.

In summary, China has been working on circular e^+e^- colliders for 40 years, and a large science and engineer team has been assembled, together with relevant knowledges and experiences obtained with great efforts. We are eager to make more significant contributions to the high energy physics in the world, and CEPC is a rare opportunity for us. We will work with the international community towards the next phase of the particle physics.

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