NEW CIRCULAR e^+e^- ACCELERATORS AT THE ENERGY FRONTIER*

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In recent years, the idea of construction of a new circular e^+e^- collider collecting data at the energy frontier has been materialised in two proposals: the FCC-ee at CERN and CEPC in China. Both projects are reviewed and the selected highlights of their physics programme are presented.

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1. Introduction

With the landmark discovery of the Higgs boson, the detailed elucidation of the properties of this new state(s) is now of highest priority. The new, giant circular collider working at the energy frontier would comprise an ideal tool to reach this goal. Moreover, the physics programme of such accelerator would encompass also top-quark studies, W and Z physics, precise determination of electroweak observables and searches for New Physics. Two new circular colliders have been proposed recently. They are now at early stage of engineering design and will be briefly discussed below together with their physics programme. The first accelerator, called FCC-ee (Future Circular Collider) is considered at CERN [1] while the second one, the CEPC (Circular Electron Positron Collider), is planned in China near the city Qinhuangdao [2].

On the eve of the 21$^{\text{st}}$ century, with the decommissioning of the LEP collider [3], the largest circular electron–positron accelerator ever built, the plans for any new such machines, yielding collisions at center-of-mass (CMS)

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energies higher than LEP ones, seemed to be sentenced to death. The reason was the rapid growth of the beam energy losses due to bremsstrahlung with the beam energy. However, the last decade witnessed a remarkable progress in acceleration techniques of electrons and positron in a circular geometry. Most of these new developments have been applied successfully *e.g.* in the KEKB collider [4]. As a result, the β_y^* parameter, which provides a measure of the envelope of all trajectories of the particles in the accelerator's lattice in the vertical direction, can now be squeezed to 1 mm which marks the gain by a factor of 50 to compare with LEP parameters. The other qualitative improvement is due to the scheme of top-up continuous injection from the additional, so-called booster ring. With the application of these novel but mature techniques, it is now feasible to reach an improvement of over three orders of magnitude in luminosity to compare with LEP, while keeping constrained the energy losses due to bremsstrahlung. Since the luminosity is proportional to the radius of accelerator's ring, one can expect a further gain in this parameter by constructing rings of bigger circumference, to compare with the value of 27 km at LEP. Such accelerator tunnel would be also a very natural and desirable host for a next generation proton–proton collider.

2. The FCC-ee and CEPC projects

The FCC-ee collider is expected to collect data at four working points, which are crucial for physics studies. They correspond to the following approximate CMS energies: 90 GeV[1] (Z peak), 160 GeV (WW threshold), 240 GeV (ZH threshold), 350 GeV ($t\bar{t}$ threshold). For the CEPC accelerator, the single working point at $\sqrt{s} = 250$ GeV is envisioned with the option of additional runs at the Z peak. The most relevant parameters of the FCC-ee and CEPC accelerators are collected in Table I. The two projects differ, in particular, in the beam pipe structure. Here the FCC-ee envisiones separate beam pipes for electrons and positrons, while the CEPC plans to host both beams in the single beam pipe. The latter option is less costly but more troublesome, in particular due to potential parasiting crossings and orbit instabilities.

The timeline of the FCC-ee and CEPC projects is presented in Table II. At the moment, they are both in the early stage of engineering design. The CEPC Collaboration issued Preliminary Conceptual Design Reports (pre CDRs) concerning both the accelerator [5] as well as physics and detector [6] issues in spring 2015 and submitted the R&D funding request to the Chinese government. The short-term goal of the FCC-ee Collaboration is the preparation of the CDR encompassing also the cost estimate by 2018. This date coincides with the update of the European Strategy of High Energy

[1] Natural units ($c = 1$) are used here.

Physics. Here, an important recent milestone was the first Annual Meeting of the Future Circular Collider study which took place in March 2015 in Washington D.C. [7].

TABLE I

Parameters of the FCC-ee and CEPC accelerators. The LEP2 characteristics have been supplemented for comparison. The following parameters are presented: E_b — beam energy, number of Interaction Points (IPs), I — beam current, number of bunches, $\beta^*_x(\beta^*_y)$ — horizontal (vertical) beta function at the IP, $\epsilon_x(\epsilon_y)$ — horizontal (vertical) emittance, P_SR — synchrotron radiation power and L — luminosity.

Parameter	LEP2	FCC-ee				CEPC
E_b [GeV]	104	45	80	120	175	125
Number of IPs	4	4	4	4	4	2
I [mA]	4	1400	152	30	7	16.6
Number of bunches	4	16700	4490	1330	98	50
β^*_x [mm]	1500	500	500	500	1000	800
β^*_y [mm]	50	1	1	1	1	1.2
ϵ_x [nm]	30–50	29	3.3	1	2	6.8
ϵ_y [pm]	250	60	7	2	2	20
P_SR [MW]	22	100	100	100	100	100
L $\left[10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}/\mathrm{IP}\right]$	0.012	28	12	6.0	1.8	1.8

TABLE II

Timeline of the FCC-ee and CEPC projects.

Phase	FCC-ee	CEPC
Pre-studies, engineering design, R&D studies	2014–2022	2014–2021
Preparatory phase	2022–2027	
Construction	2027–2037	2021–2027
Data taking	2037–2045	2028–2036

In parallel to the above-mentioned proposals of circular e^+e^- accelerators, two projects of linear colliders are being considered. These are the International Linear Collider (ILC) [8] with the proposed location in Japan and the Compact Linear Collider (CLIC) [9] at CERN. Figure 1 clearly illustrates the symbiosis between a circular and linear geometry of potential future e^+e^- accelerators. While the former offer the best option of collecting an enormous number of relevant events in the region between the Z peak and the $t\bar{t}$ threshold, the latter provide a better performance in this respect for the CMS energies above 400 GeV.

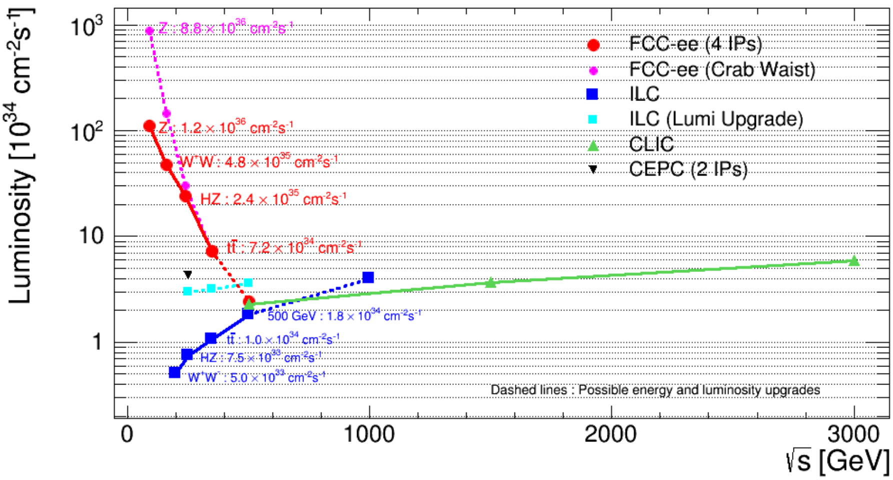

Fig. 1. Luminosities foreseen for FCC-ee, CEPC, ILC and CLIC colliders as a function of the CMS energy. Also shown are the FCC-ee possible improvements in luminosity using the crab-waist scheme [10] as well as a potential ILC upgrade due to the reconfiguration of the radiofrequency power sources [11].

3. Selected topics of the physics programme of new circular colliders

Both FCC-ee and CEPC accelerators offer a very attractive opportunity to collect enormous samples of ZH events: 2×10^6 and 1×10^6, respectively. Using the recoil mass technique [6], which is unique for e^+e^- environment, this allows for a very precise determination of the Higgs mass and width, at the level of precision exceeding 10(3) MeV, respectively [6, 12]. Higgs boson couplings to fermion and intermediate-boson pairs are expected to be measured with the precision reaching for some modes few per mille [6, 13] (*cf.* Table III). Thus, linear dependence of the couplings *versus* mass can be tested with the accuracy exceeding 1%. Moreover, upon observation of deviations from the Standard Model expectations, their pattern acts like a barcode for New Physics models.

Runs at the Z peak would yield 10^{12} (2×10^9) events, respectively (to compare with 2×10^7 events collected at LEP). As a result, most electroweak observables will be measured with the precision exceeding the current one by at least one order of magnitude and the main limitation of the accuracy will be due to systematic uncertainties [6, 14] (*cf.* Table IV).

The FCC-ee (CEPC) expects to harvest $10^8(10^7)$ WW pairs, respectively (to compare with 4×10^3 picked up at LEP2). The resulting precision on the determination of the W mass is to be of (1–3) MeV [6, 14].

TABLE III

Precision of determination of Higgs couplings at the FCC-ee and CEPC accelerators.

Uncertainty	FCC-ee	CEPC
$\sqrt{s}$ [GeV]	240	250
$\sigma(ZH)$	0.40	0.51
$\sigma(ZH) \times \mathrm{BR}\left(H \to b\bar{b}\right)$	0.20	0.28
$\sigma(ZH) \times \mathrm{BR}\left(H \to c\bar{c}\right)$	1.2	2.2
$\sigma(ZH) \times \mathrm{BR}\left(H \to \tau^+\tau^-\right)$	0.7	1.2
$\sigma(ZH) \times \mathrm{BR}\left(H \to \mu^+\mu^-\right)$	13	17.0
$\sigma(ZH) \times \mathrm{BR}\left(H \to gg\right)$	1.4	1.6
$\sigma(ZH) \times \mathrm{BR}\left(H \to WW\right)$	0.9	1.5
$\sigma(ZH) \times \mathrm{BR}\left(H \to ZZ\right)$	3.1	4.3
$\sigma(ZH) \times \mathrm{BR}\left(H \to \gamma\gamma\right)$	3.0	9.0

TABLE IV

Precision of determination of selected electroweak observables at the FCC-ee and CEPC accelerators.

Parameter	Current precision	FCC-ee stat. (syst.)	CEPC stat. only
M_Z [MeV]	91187.6 ± 2.1	0.005 $(< \pm 0.1)$	0.1
Γ_Z [MeV]	2495.2 ± 2.3	0.008 $(< \pm 0.1)$	0.2
R_l	20.767 ± 0.025	0.0001 $\binom{0.002}{0.0002}$	0.001
R_b	0.21629 ± 0.00066	0.000003 $(< \pm 0.00004)$	0.00018
N_ν	2.984 ± 0.008	0.00008 $(< \pm 0.004)$	0.003

The top-quark properties could be studied very precisely at the FCC-ee collider, profiting from the fact that the $t\bar{t}$ pairs are produced in a precisely defined leptonic state through electroweak processes. Moreover, in the threshold region ($\sqrt{s} \approx 350$ GeV), the dependence of the cross section *versus* the top-quark mass is computable to high precision. Using 10^6 $t\bar{t}$ pairs, the FCC-ee estimated the expected statistical uncertainty on the top-quark mass determination at the level of 10 MeV [14].

For the sake of completeness, the relevant information about the potential of physics studies at linear e^+e^- colliders can be retrieved from [15–17].

4. Summary

The circular electron–positron collider working in the CMS energy range between the Z peak and $t\bar{t}$ threshold would provide an extremely attractive physics programme in full synergy with the LHC achievements, in particular, the precise studies of Higgs, W and Z bosons and top-quark properties, together with an extensive searches for new phenomena. The proposals of two such colliders: FCC-ee at CERN and CEPC in China have been recently put forward.

I would like to thank Organizers for warm reception and hospitality.

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