PROCEEDINGS OF SCIENCE

Status of the CEPC Project

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The discovery of the Higgs boson marked the beginning of a new era in HEP. Precision measurement of the Higgs boson properties and exploring new physics beyond the Standard Model using Higgs as a tool become a natural next step beyond the LHC and HL-LHC. Among the proposed Higgs factories worldwide, the Circular Electron Positron Collider (CEPC) with 100km circumference was proposed by the Chinese HEP community in 2012. CEPC is an e^+e^- Higgs factory to produce Higgs/W/Z bosons and top quarks which aims to measure Higgs, EW, flavour physics and QCD with unprecedented precision and to probe new physics beyond the SM. With the official release of CEPC Accelerator Technical Design Report (TDR) in December 2023, we are intensively preparing accelerator Engineering Design Report (EDR) and reference detector TDR. The purpose is to submit CEPC proposal to Chinese government for approval and start construction within the "15th five-year plan (2026-2030)" upon approval. In the proceedings, the overview and global aspects of the CEPC project, highlights of CEPC physics, accelerator and detector R&D are presented.

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1. Introduction

The discovery of the Higgs boson in 2012 by the ATLAS and CMS Collaborations [1, 2] at the Large Hadron Collider (LHC) at CERN has ushered a new era in particle physics. The Higgs boson is a crucial cornerstone of the Standard Model (SM). It is at the center of the biggest mysteries of modern particle physics, such as the large hierarchy between the weak and Planck scales and the nature of the electroweak phase transition. Precise measurements of the properties of the Higgs boson along with those of the W and Z bosons, heavy flavor physics, will provide critical tests of the underlying fundamental physics principles of the SM. These measurements are also vital in the exploration of physics beyond the SM (BSM). Such a comprehensive physics program will be a critical component of any road map for particle physics in the coming decades.

Due to the modest Higgs boson mass of about 125 GeV, it is possible to produce the Higgs boson in the relatively clean collision environment of electron–positron colliders with high luminosity and affordable cost. The advantages of linear electron-positron colliders are that they have great potential to reach the center of mass energy up to 1TeV and beyond, such as ILC and CLIC. As for the circular electron positron colliders such as CEPC and FCC-ee, they have great advantages of higher luminosities at Higgs, WW and Z energies which will greatly benefit the ultimate precision measurements of SM and exploration of BSM physics (see Figure 1).

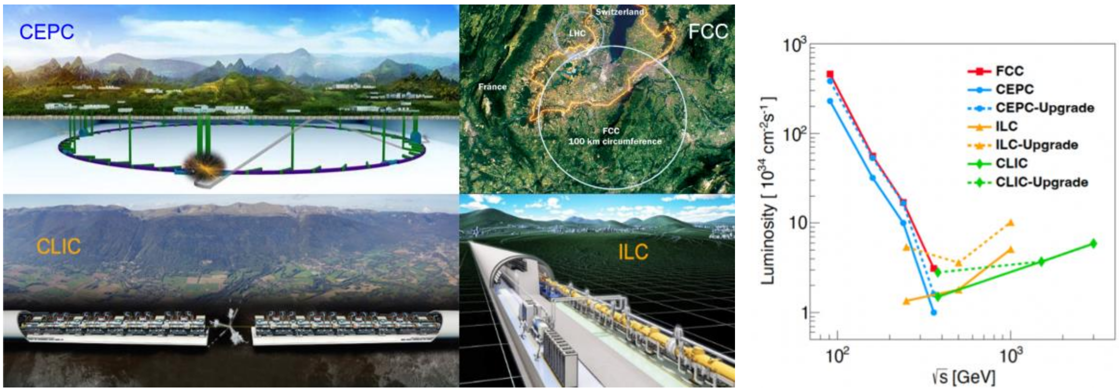

Figure 1: The luminosity comparison of different electron-positron colliders. (arXiv:2203.09451)

There is global consensus on the Higgs factories after years of feasibility studies. In 2013 and 2016, China Xiangshan Science Conferences concluded that "CEPC is the best approach and a major historical opportunity for the national development of accelerator-based high energy physics program". In 2020, European Strategy for Particle Physics Update (ESPPU) stated that "An electron-positron Higgs factory is the highest priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy". In 2022, International Committee for Future Accelerator (ICFA) reconfirmed "the international consensus on the importance of a Higgs factory as the highest priority for realizing the scientific goals of particle physics" and expressed strong support for the above-mentioned Higgs factory proposals. In 2023, US P5 report recommended to convene a targeted panel to consider the level and nature of US contribution in a specific Higgs factory etc. Apparently, the scientific importance and strategic value of electron-positron Higgs factories is clearly identified by international High Energy Physics community.

2. CEPC Project

The Circular Electron Positron Collider (CEPC) is a large international scientific project initiated by Chinese scientists in September 2012, right after the discovery of the Higgs boson. The CEPC was firstly presented to the international community at the ICFA Workshop "Accelerators for a Higgs Factory: Linear vs. Circular" (HF2012) in November 2012 at Fermilab [3]. A Preliminary Conceptual Design Report (Pre-CDR) was published in March 2015 [4], followed by the public release of CEPC Conceptual Design Report (CDR) in November 2018 [5]. In December 2023, the Technical Design Report (TDR) of the CEPC accelerator design was officially released after a series of international and cost reviews [6].

The collider with a circumference of 100 km is designed to operate at center-of-mass energies of 240 GeV (Higgs factory), around 91.2 GeV (Z factory), around 160 GeV (WW threshold scan), and possible upgrade to 360 GeV (top quark pair). It is anticipated to produce large samples of Higgs (~4M), WW(~20M) and Z(~ 4T) bosons which allow their properties measurements at unprecedented accuracy and explore BSM physics up to 10 TeV [7] (Table 1, 2 and Figure 2).

The tunnel could also host a Super Proton-Proton Collider (SppC) to reach center-of-mass energy about 100 TeV with 20 Tesla high temperature superconducting magnet technology.

Operation mode		ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]		~240	~91	~160	~360
Run Time [years]		10	2	1	5
30 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.6
	Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
50 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**8.3**	**192**	**26.7**	**0.8**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	22	100	6.9	1
	Event yields [2 IPs]	4.3×10^6	4.1×10^{12}	2.1×10^8	6×10^5

Table 1: The CEPC operation modes, luminosities and event yields at different energies.

Higgs		
Observable	HL-LHC Projection	CEPC Precision
M_H	20 MeV	3 MeV
Γ_H	20%	1.7%
$\sigma(ZH)$	4.2%	0.26%
$B(H\to bb)$	4.4%	0.14%
$B(H\to cc)$	-	2.0%
$B(H\to gg)$	-	0.81%
$B(H\to WW)$	2.8%	0.53%
$B(H\to ZZ)$	2.9%	4.2%
$B(H\to \tau\tau)$	2.9%	0.42%
$B(H\to \gamma\gamma)$	2.6%	3.0%
$B(H\to \mu\mu)$	8.2%	6.4%
$B(H\to Z\gamma)$	20%	8.5%
$B_{upper}(H\to inv.)$	2.5%	0.07%

W, Z and Top		
Observable	Current Precision	CEPC Precision
M_W	9 MeV	0.5 MeV
Γ_W	49 MeV	2 MeV
M_{top}	760 MeV	O(10) MeV
M_Z	2.1 MeV	0.1 MeV
Γ_Z	2.3 MeV	0.025 MeV
R_b	3×10^{-3}	2×10^{-4}
R_c	1.7×10^{-2}	1×10^{-3}
R_μ	2×10^{-3}	1×10^{-4}
R_τ	1.7×10^{-2}	1×10^{-4}
A_μ	1.5×10^{-2}	3.5×10^{-5}
A_τ	4.3×10^{-3}	7.0×10^{-5}
A_b	2×10^{-2}	2×10^{-4}
N_ν	2.5×10^{-3}	2×10^{-4}

Table 2: Expected precision of parameters at the CEPC, where the results of Higgs are estimated with 20 ab-1 integrated luminosity at CEPC and 3000 fb-1 at HL-LHC.

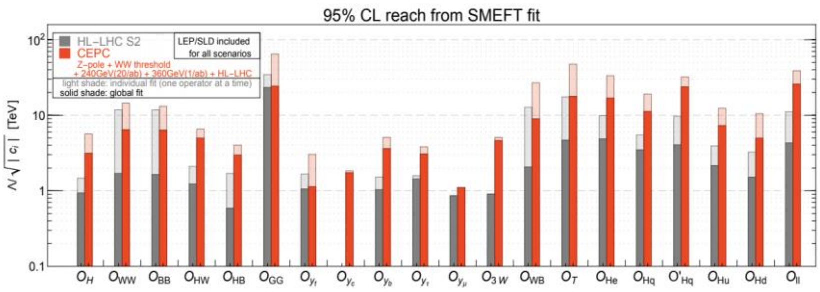

Figure 2: Expected limits of new physics energy scale to be explored from SMEFT fit.

PoS(ICHEP2024)821

3. CEPC Accelerator

The CEPC accelerator design and tunnel cross section are shown in Figure 3. It is 100 km double ring design with 30 MW synchrotron radiation power as baseline, it is upgradable to 50 MW and operate at higher center-of-mass energy up to 360 GeV for top quark pair production. The tunnel cross section is 6-meter wide and 5-meter height which can accommodate booster, CEPC and SppC in the same tunnel. The CEPC accelerator is optimized to switch the Higgs, WW, Z and tt modes freely through bypass scheme without changing hardwares (Figure 3).

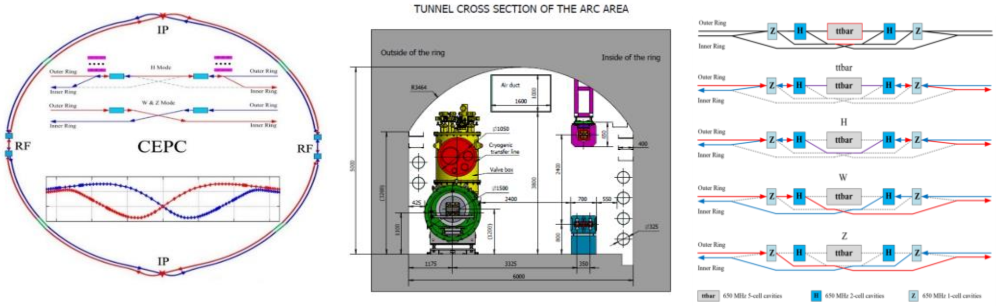

Figure 3: CEPC accelerator (left), tunnel cross section (middle) and bypass scheme (right)

The CEPC TDR cost is 36.4 billion RMB (about 4.6 billion Euro), the distribution of the CEPC cost includes accelerator (52%), conventional facilities (28%), experiments (11%), gamma-ray beam lines (0.8%), project management (0.8%) and contingency (7.4%).

CEPC accelerator key technologies R&D span over all components listed in CDR (Figure 4), about 90% of the accelerator components (in term of cost fraction) have prototypes specifications already met the CEPC requirements, including superconducting radio frequency cavities, klystron, magnets, cryogenics, vacuum, magnet power supplies, mechanics, linac and positron sources etc. The remaining 10% of components (eg. RF power source, survey and alignment, machine integration) have prototypes manufactured and to be completed by 2026.

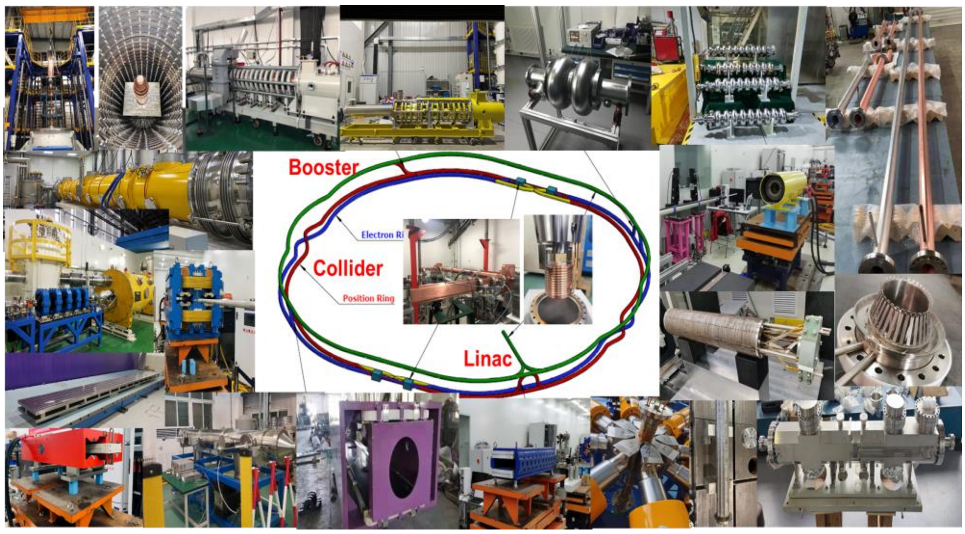

Figure 4: CEPC accelerator key technologies R&D

With completion of the accelerator TDR, the CEPC accelerator team started the engineering design phase in 2024. About 35 dedicated working groups are formed aiming for key issues related to accelerator engineering aspects. For instance, engineering design of a full size module with six

650 MHz 2-cell SRF cavities, high efficiency klystrons, magnets automatic production lines, massive production line of NEG coating vacuum chambers, alignment and installation plan, detector coil development, machine and detector interface, a 60-meter long tunnel mockup, including parts of arc section and part of RF section, to demonstrate the insider tunnel alignment and installation, especially for booster installation on the roof of the tunnel. The CEPC accelerator engineering design report (EDR) is expected to complete in 2027.

4. CEPC Detector

The CEPC detector concept are based on the stringent performance requirements needed to deliver a precision physics program that tests the SM and searches for new physics over a wide range of center of mass energies and at high beam luminosities. These specifications include large and precisely defined solid angle coverage, excellent particle identification, precise particle energy and momentum measurements, efficient vertex reconstruction, excellent jet reconstruction and flavor tagging. The physics program demands that all possible final states from the decays of the intermediate vector bosons, W and Z, and the Higgs bosons need to be separately identified and reconstructed with high resolution. In particular, to clearly discriminate the $H \rightarrow ZZ^* \rightarrow 4j$ and $H \rightarrow WW \rightarrow 4j$ final states, the energy resolution of the CEPC calorimetry system for hadronic jets needs to be pushed quite beyond today's limits. The Higgs decays into two photons and the search for Higgs invisible decays impose additional requirements on energy and missing energy measurement resolutions. To measure the coupling of the Higgs boson to the charm quark, the CEPC detectors are required to efficiently distinguish b-jets, c-jets, and light jets from each other. To achieve excellent sensitivity for the Higgs decays to muon pair, the momentum resolution is required to achieve a per-mille level relative accuracy. The latter two requirements drive the performance of the vertex detector and tracking systems.

CEPC detector key technologies R&D have been carried out in the past decade, including a series of silicon pixel sensors (position resolution is 3-5 microns) for CEPC vertex and tracker system, TPC prototype with low power readout electronics, drift chamber with cluster counting method, particle flow algorithm (PFA) based electromagnetic calorimeter prototype (ECAL, $\sim 16\%/\sqrt{E}$) with plastic scintillator and SiPM as active material and tungsten as absorber, hadronic calorimeter prototype (HCAL, $\sim 56\%/\sqrt{E}$) prototype with plastic scintillator and SiPM as active material and stainless steel as absorber. These prototypes had test beams at CERN and/or at DESY for performance studies, test results are promising, mostly reach the designed performance.

Based on feasibility studies of three CEPC detector designs presented in the CDR, we proposed a novel detector design (Figure 5) based on PFA calorimeters aiming at further improving boson mass resolution from 4% to 3%. The basic idea is to employ long crystal bars for ECAL to obtain significantly better electromagnetic resolution ($\sim 3\%/\sqrt{E}$), and to use high density scintillating glass as active material of HCAL to achieve better sampling ratio and hence better hadronic energy resolution ($\sim 40\%/\sqrt{E}$). The main goal of the PFA calorimeters system is to achieve jet energy resolution about $30\text{-}40\%/\sqrt{E}$ to fulfil the physics requirement. The combination of silicon tracker with TPC or DC helps to improve the momentum resolution of charged tracks and to achieve better particle identification ($\sim 3\sigma$ π/K separation for momentum up to 20 GeV/c). Currently, we are converging technology options and intensively performing study towards a CEPC reference detector TDR which will be available in June 2025.

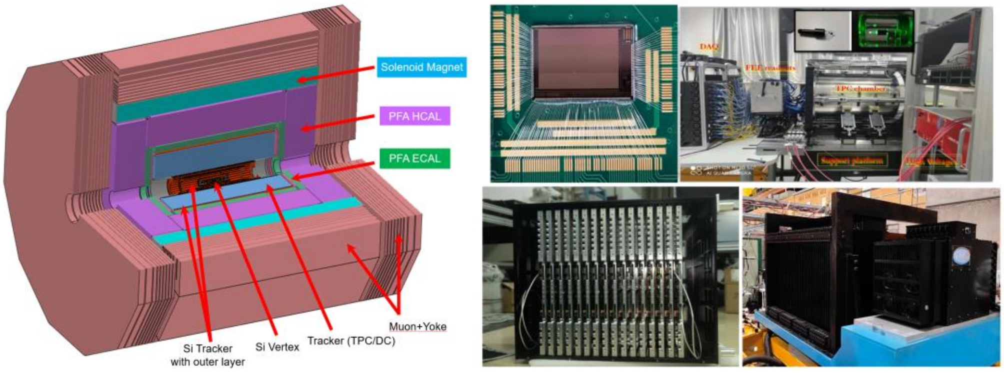

Figure 5: CEPC Detector Design (left), prototypes of silicon pixel sensor, TPC, ECAL and HCAL.

5. Summary and Future Plan

The CEPC project made significant progress on accelerator TDR and related key technologies R&D in the past decade. The CEPC proposal will be submitted to the Chinese government for approval in 2025 by following schedule of the 15th five-year plan. We will establish at least two international collaborations on experiments and prepare for detector TDRs. The CEPC accelerator EDR is expected to complete in 2027. Upon approval, the CEPC project construction will start immediately and will complete around 2035 under ideal timeline.

The CEPC is an important part of the world plan for high energy particle physics research. CEPC will offer the worldwide HEP community early Higgs/Z/W factories. It will support comprehensive research programs by scientists from all over the world. Physicists from many countries will work together to explore physics at high energy frontier and high luminosity frontier, and to bring a new level of understanding of the fundamental nature of matter, energy and the universe in the coming decades.

6. Acknowledgement

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