Status of the CEPC Project

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Abstract. In this article we give a brief historical review of particle physics achievement through e+e- colliders and proton accelerators in the last half century and perspective for the next half century with worldwide consensus. The Circular Electron Positron Collider (CEPC) is a Higgs factory proposed by Chinese scientists in 2012, and its Technical Design Report (TDR) has been completed in Dec. 2023. Since 2024 CEPC has entered into Engineering Design Report (EDR) phase and been planned to be put into construction during China's 15^{th} five-year plan (2026-2030) and completed around 2035. The TDR results and EDR status and plan will be presented.

1 Introduction

Uncovering the fundamental laws of the universe and its evolution is a great endeavour for humanity. The most effective way to achieve this goal in particle physics is via powerful, high-energy accelerators. In the last half century, many fundamental particles have been found by electron-positron colliders and hadron accelerators, such as charm quark in 1974, bottom quark in 1977, W and Z bosons in 1983, top quark in 1995. And the corresponding " factories" have been built to make detailed studies, such as BEPC/BEPC-II/VEPP-4 for tau-charm factories , LEP/SLC for Z factories, LEP-II for Z and W factories, and KEKB/PEP-II/SuperKEKB for bottom factories, etc.

On July 4, 2012, with the discovery of the Higgs boson with a mass of around 125 GeV at the Large Hadron Collider (LHC) at CERN, human being entered the new era of the "Higgs boson" and the door to the unknown part of the universe is wide open. The Higgs boson is the unique "elementary particle" that has zero-spin and participates in multiple non-gauge interactions in the SM. The Higgs boson has a natural and profound connection to the SM "questions" and "defects", for example the dark matter and the antimatter asymmetry in the universe, and offers one of the best windows to explore the new physics. It is natural, important and urgent to construct Higgs factories somewhere in the world to echo these very fundamental physics research demands. For these future large accelerators, we need new paradigm/theory, new colliders equipped with advanced detectors.

In Sept. 2012, Circular Electron Positron Collider (CEPC) as a Higgs factory constructed in China was proposed by Chinese scientists. As a staging possibility, a Super proton-proton Collider (SppC) was proposed also to be constructed in the same tunnel beside the CEPC, with the later ep and eA collision possibilities to explore the physics experimental potential in an maximum way of CEPC-SppC collider complex. In addition to CEPC, CERN has

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proposed Future Circular Collider (FCCee and FCChh); Japan Association of High Energy Physicists (JAHEP) proposes to construct a 250 GeV center-of-mass ILC promptly as a Higgs factory with energy upgrade potential to 1TeV; US has proposed C3 Higgs factory and envisaged in future a 10TeV muon collider. The particle physics community worldwide reached a consensus that Higgs factories must be constructed to guarantee the brave exploration to understand the origine of universe and its evolution in general.

Among circular and linear Higgs factories, they are quite in complementary in luminosities and energy reach potentials. The common challenges for these future large collider proposals are physics problem researches, advanced accelerator and detector technologies, such as SC accelerator technologies, positron source, damping ring, final focus, MDI, cryogenic system, sustainability, industrial promotion and participation, and outreach activities, etc. Apart from the healthy competitions among different proposals, common efforts and collaborations are needed to stimulate each other to strive towards the common goal.

2 CEPC general status

The CEPC accelerator complex comprises four accelerators: a 30 GeV Linac, a 1.1 GeV Damping Ring, a Booster capable of achieving energies up to 180 GeV, and a Collider operating at varying energy modes (Z, W, H and top pair). The Linac and the Damping ring are situated on the surface, while the Booster and Collider are housed in a 100 km circumference underground tunnel, strategically accommodating future expansion with provisions for a potential Super proton-proton Collider (SppC), as shown in Fig. 1. The CEPC primarily serves as a Higgs factory. In its baseline design the synchrotron radiation power of 30 MW per beam, it can achieve a luminosity of $5\times10^{34} cm^{-2} s^{-1}$ per interactions point (IP), producing an integrated luminosity of 13 ab^{-1} for two IPs over a decade, corresponding to 2.6 million Higgs boson events. If the single beam power is increased to 50 MW the CEPC's capability will expand to produce 4.3 million Higgs events, facilitating expected measurements of Higgs coupling at sub-percent levels, exceeding the precision expected from the HL-LHC by an order of magnitude for many final states of the Higgs.

After the completion of the Conceptual Design of the accelerator and the detectors [1,2] in 2018, the CEPC accelerator Technical Design Report (TDR) [3] was finalized in December, 2023, following comprehensive reviews in technical systems in June, and the cost review in Septembers by two separate groups of leading international experts, respectively. The designs and the costs of civil engineering were presented to a review committee consisting of domestic experts, the outcome of which was reported to an international panel which in turn briefed the international cost review committee and the CEPC international advisory committee (IAC). The TDR has been approved by all the review committees and endorsed by the IAC. This TDR details the machine's layout, performance metrics, physical design and analysis, technical systems design, R&D and prototyping efforts, and associated civil engineering aspects. Also the cost estimates (36.4B RMB, ~5B USD) and a preliminary construction timeline are included. The CEPC is planned to be ready for construction around 2027 and completed by 2035. The completed CEPC accelerator TDR is the first for circular Higgs factory proposals [4], and it has drawn the international attentions [5].

The CEPC group is working on a reference technical design (TDR_ref) of a detector system for the CEPC experiments. The TDR_ref is mainly intended for project review and approval in China to complete the overall CEPC complex. Once the project is approved, calls for letter of intents will be initiated to form genuine international collaboration and the formal TDR of the detectors will be worked on by the detector collaborations. This TDR_ref is expected to be completed by mid-2025 and will be included in the proposal for CEPC in China's 15^{th} Five Year Plan (FYP).

In the last decade, the CEPC R&D program covered the designs, all critical technologies and components in accelerators, detectors and instrumentation, software and physics performance study, progresses have been steady and much helped by the construction of a 4th generation high performance light source by IHEP at its Huairou campus, as well various detector upgrade projects participated by the CEPC collaborators.

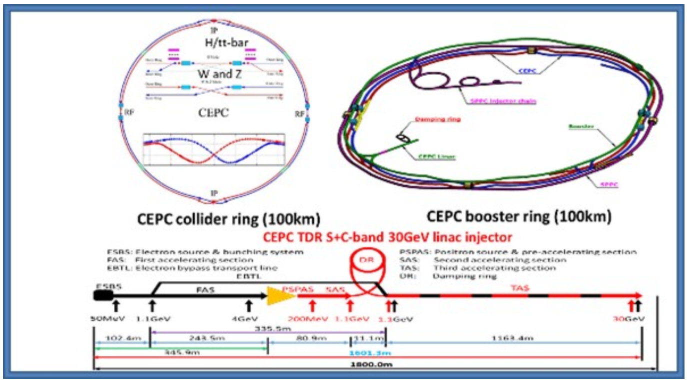

Figure 1. CEPC-SppC layout.

3 CEPC key technology development in TDR

A full spectrum of CEPC accelerator key technologies have been developed during CEPC accelerator TDR phase, and many important progresses have been made, and several examples are shown below. Firstly, the booster 1.3GHz full size cryomodule with average Q_0 @ 23.1 MV/m reaching 3.4×10^{10}, as shown in Fig. 2.

Figure 2. CEPC 1.3GHz full size cryomodule.

Secondly, CEPC collider ring 650MHz high power and high efficiency klystron has reached the design goal of 77% efficiency @800kW CW mode, as shown in Fig. 3. A multi-beam 650MHz klystron of designed efficiency of 80.3% is under fabrication. The CEPC 5720MHz klystron of 80MW for C-band linac will be constructed in 2025.

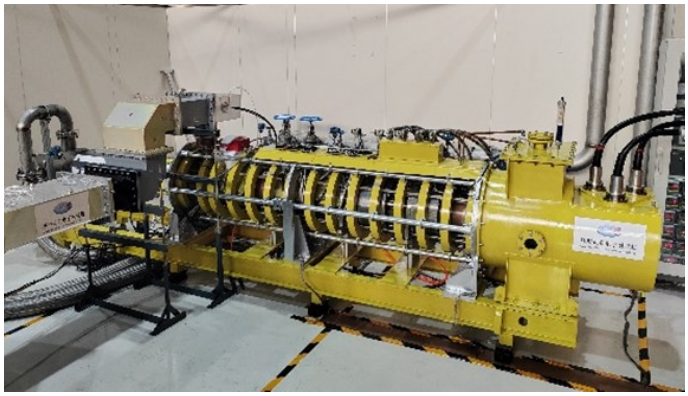

Figure 3. CEPC 650MHz 800kW CW high efficiency klystron.

Thirdly, CEPC has a large amount of normal conduction high precision magnets filling the most part of the 100km tunnel both for booster and collider ring. With the 30GeV injection energy from the linac, the CEPC booster dipole magnet has been demonstrated to reach the design goal with dipole magnet's economical iron core materials, as shown in Fig. 4.

Figure 4. CEPC booster full size dipole magnet.

And finally, the CEPC required 18kW@4K cryogenic refrigerator has been studied and developed jointly by the Institute of TIPC, CAS, and Beijing Sinoscience Fullcryo Technology CO., Ltd. company. In June of 2024, China's first 18kW@4K cryogenic refrigerator (also the largest in the world) has been successfully fabricated, as shown in Fig. 5.

With the full spectrum of TDR technology development, CEPC accelerator completed its TDR and entered into Engineering Design Report (EDR) phase before construction.

Concerning CEPC detector TDR reference design, many progresses have been made in pixel vertex detector, tracker & PID, calorimeters, muon detector, high field detector SC magnet, lumical, MDI, software, TDAQ, detector mechanics, etc., as shown in Fig. 6. Some of the sub-detectors, such as vertex detector and calorimeters, have been beam tested at DESY and CERN test beam stations in 2022, 2023 and 2024, respectively. The formal completion of CEPC detector TDR reference design report will be by the mid of 2025.

Figure 5. CEPC 18kW@4K cryogenic refrigerator.

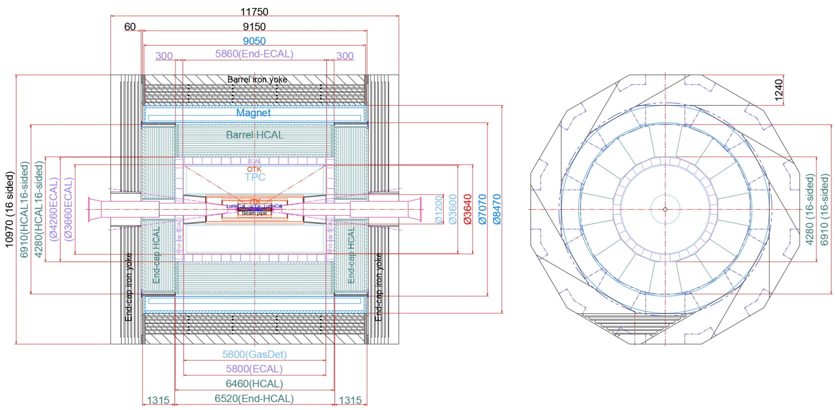

Figure 6. CEPC TDR detector reference design layout.

4 CEPC alternative technologies development

Plasma acceleration is a very promising strategic technology for future high energy physics thanks to its accelerating gradient as high as more than three order of magnitude compared with that of the conventional radio frequency accelerator technology. Since last 40 years, plasma acceleration has made enormous progresses, between laser driven and beam driven plasma acceleration technologies, the later one has important advantage of much high efficiency from AC power to the accelerated beam which is vital for high energy colliders. Apart from the beam driven plasma acceleration, the staging and positron acceleration are other key technologies need to be demonstrated with the required high beam qualities in practical applications. In 2023, IHEP started a beam driven plasma acceleration experiment test facility development with the financial support from CAS by using the BEPC-II electron and positron injection linac of 2GeV. To demonstrate staging and positron acceleration technologies, a new beam line of high bunch charge equipped with an L-band photo cathode RF gun parallel to BEPCII linac will be constructed. Positron beam will be accelerated by using hollow channel plasma. The intermediate application of such a beam driven plasma accelerator is a CEPC plasma injector for booster.

Polarization beam technology in high energy colliders is very challenging, both for linear collider and circular collider, but especially for circular one. In circular colliders, such as

CEPC, 5%∼10% transversely polarized beam can be used to precisely measure the beam energy, and the ∼50% longitudinal colliding beam could be vital for some specific experimental channels. For weak transverse polarized beams, self-polarization scheme can be used in the collider ring by using special unsymmetrical wigglers without polarization injection from the booster. For longitudinal collision polarized beams, one needs polarized beam source from the linac injector. Due to the large circumference of CEPC booster, it is found that during the energy ramping, it is not necessary to use Siberian snakes to avoid the depolarization resonances, and preliminary studies show that for Z and W energies, both the transverse and longitudinal polarization beams could be achieved, and the Higgs energy case is still under study.

5 Development for 15^{th} FYP

The Chinese Academy of Sciences (CAS) have organized various high level preparatory groups to prepare for the 15^{th} FYP (2026-30), among which new particle/nuclear physics projects were evaluated and reviewed in a combined group. The CEPC project has been ranked first by each of the three review committees (the international advisory committees, the domestic senior scientist group, the HEP association). The outcome of the preparation has been documented and submitted to CAS.

6 The SppC

The SppC presented in the TDR consists of two IPs with center-of-mass energy reaching 125 TeV in pp collision with 20T high field dipole magnets with a luminosity target of $10^{35} cm^{-2} s^{-1}$ per IP. The main progresses for SppC are with the long term and persistent development of High Field Magnet (HFM) particularly in the areas of the Iron Based High Temperature Superconducting (HTS) material and the magnet dipole, and the design consistency of the CEPC Higgs factory with the future requirement of the SppC, especially in the tunnel layout and access routes in the accelerator TDR. For the former the group and its collaborators have achieved a highest quenched field of 14T@4.2K with the model dipole magnet with the Nb3Sn+HTS combinations in 2023. A 16T@4.2K model dipole is under development.

7 CEPC EDR plan

The CEPC engineering design (EDR, 2024-2027) process has begun and the scope and the working plan have been defined. International committees will evaluate and guide the activities in September, 2024. Among the EDR programs, the automation of the production of high volume and expensive components of high consistency is a very important area. The CEPC SRF industrial production technology, the on-site automatic production of CEPC magnets and the massive automatic production line of the NEG coating vacuum chamber are a few examples. The positive results from these efforts have the potential to benefit other HEP projects in future. During EDR phase, a CEPC EDR site will be fully explored and in close synergy with local government and civil engineering design. A CEPC proposal will be submitted to central government in 2025 with the aim of CEPC be included into China's 15^{th} FYP.

8 CEPC international and industrial collaborations

CEPC has always been envisioned as an international big-science project and the international colleagues played a significant role in the study of CEPC CDR and TDR. A total of 1143 authors from 221 institutes (including 144 foreign institutes) across 24 countries and regions co-signed the CEPC CDR and a total of 1114 authors from 278 institutes (including 159 foreign institutes) across 38 countries and regions co-signed the CEPC accelerator TDR. The CEPC study group has signed more than 20 MoUs with institutes and universities from Europe, Asia, the Americas, Africa, and Oceania. The CEPC team organizes CEPC international workshops and European/US versions with significant international participations. The CEPC's development has been operated in an international way and guided by international committees, such as International Advisory Committee (IAC), the International Accelerator and Detector Review Committees. Concerning industrial collaboration, since November 2017, CEPC Industrial Promotion Consortium (CIPC) has been established and more than 100 companies have joined. CIPC members have played important roles in CEPC CDR and TDR, for example, Beijing Sinoscience Fullcryo Technology CO., Ltd. company as CIPC member has developed successfully 18kW@4K cryogenic refrigerator which is vital for CEPC construction and SppC as well.

9 CEPC in synergy with other accelerator projects in China

Since last six years, China has started many accelerator based projects in terms of electron positron collider upgrade (BEPCII-U); 4^{th} generation light sources, such as HEPS, SAPS (to be approved), and HALF; XFELs, such as SHINE, S3XFEL, and DALS; nuclear physics facilities, such as HIAF and CiADS; spallation neutron source upgrade (CSNS-II), etc. The total investment has reached 39B RMB (~5.6B USD) which is higher than the CEPC TDR cost of 36.4B RMB (~5.2B USD). These massive accelerator project investments have laid a solid foundation for the industry capability and accelerator personnel expertise increasing, which is very important for the CEPC construction related industrial and human resource environment in general.

10 Summary

The CEPC is on the path to converge into a complete package. The present EDR process will help reduce the project cost and improve the consistency of the critical components which would bridge the TDR technologies to industrialization and bring benefits to the HEP community. The CEPC has received a great deal of help from international collaborating scientists and labs, and the project is committed to maximize international collaboration and contribution. The CEPC Study Group is making strong effort to complete a proposal in 2025 to the Chinese government for approval. If successful the CEPC will offer the worldwide community an early Higgs factory.

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