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CEPC ACCELERATOR TDR STATUS OVERVIEW

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Abstract

The Circular Electron-Positron Collider (CEPC) was proposed in the year of 2012, shortly after the observation of Higgs boson. After years of pre-studies, the CEPC study group has completed the Conceptual Design Report (CDR) in 2018. Since then a series of key technology R&D was carried out, and the accelerator design has been kept optimizing as well. The accelerator design can meet the scientific objectives by allowing the operation in different energies for W/Z, Higgs and ttbar with high luminosities. Key technologies required for the mass production have been developed, such as the superconducting accelerating cavities, high efficiency RF power source, magnets and vacuum systems etc. The accelerator Technical Design Report (TDR) is scheduled to be finished in the cross period of 2022-2023. All of the key technology R&D accomplishments will presented and the optimized accelerator parameters will be updated in it.

INTRODUCTION

The Higgs boson was discovered in July 2012. It plays an important role as the unique "elementary particle" in the SM. Chinese scientists proposed the Circular Electron-Positron Collider (CEPC) in September 2012. CEPC is an electron-positron Higgs factory which can produce 4 million Higgs bosons in a clean background, hence it will boost the precision of the Higgs by about 1 order of magnitude compare to HL-LHC. Except for Higgs, CEPC is expected to generate hundreds of millions W bosons, and 4 trillions of Z bosons with 4-5 orders of magnitude higher than that of the latest generation of the Large Electron Positron Collider. Moreover, CEPC can be upgraded in its center of mass energy to 360 GeV, and produces roughly 1 million top or anti-top quarks. Beyond the electron-positron collision, since the cross size of the CEPC tunnel is wide enough it can accommodate an independent proton-proton collider in the long term plan.

Since 2013, the CEPC has carried out design and key technology R&D. It has received total funding of roughly 260 million CNY from the MOST, the NSFC, the CAS, and some local governments. The Conceptual Design Report (CDR) was published in 2018 [1], followed by significant key technology achievements among the systems that require a high budget ratio in the accelerator construction. What's more, in the years after the CDR was released the design of CEPC was kept being optimized and its luminosity is competitive among the suggested Higgs factories in the world, as shown in Fig. 1.

CEPC aims at getting approved and then commencing the accelerator construction in the years between 2025-2030, thereby the machine operation and data collection can start in the decade of 2030's. Based on the achievements since the publication of CDR, the Technical Design Report (TDR) is planned to be finished in early 2023, in which the optimized accelerator design and the key technology R&D status will be presented in detail.

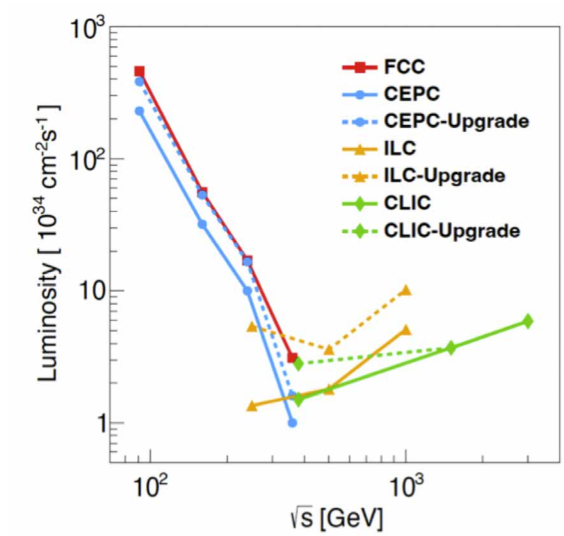

Figure 1: Comparison of the design luminosity of the CEPC and those of other electron-positron Higgs factories.

CEPC DESIGN

The majority CEPC accelerator complex consists of the 100 km collider and booster rings and the Linac including a positron damping ring as the injector. Table 1 lists the major parameters of CEPC at the power of 30 MW [2, 3].

Table 1: Margin Specifications

	Higgs	W	Z	top
Number of IPs	2	2	2	2
Circumference [km]	100	100	100	100
Energy [GeV]	120	80	45	180
Bunch number	249	1297	11951	35
Beam current [mA]	16.7	84.1	803.5	3.3
βx/βy at IP [m/mm]	0.33 /1	0.21 /1	0.13 /0.9	1.04 /2.7
Bunch length (SR/total) [mm]	2.3 /3.9	2.5 /4.9	2.5 /8.7	2.2 /2.9
Beam-beam parameters (ξx/ξy)	0.015 /0.11	0.012 /0.113	0.004 /0.127	0.071 /0.1
RF frequency [MHz]	650	650	650	650
Luminosity per IP [10^{34}/cm^2/s]	5.0	16	115	0.5

CEPC adopts a compatible design with the partial or full double-rings collider for electrons and positrons. A special

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bypass scheme is designed to allow an easy switch in various operations of Higgs, W and Z. As shown in Fig. 2, in the stage 1 the 2-cells 650 MHz SRF accelerator modules are divided into two parts. In the operation of Higgs, electron and positron beams pass both parts and the energy loss caused by the Synchrotron Radiation (SR) is compensated. In the lower energy operations of W and Z the electron and positron beams only pass one part of the accelerator modules since the needed energy compensation is lower. In stage 2 the high luminosity Z operation, not only the 2-cells but also the 1-cell cavities are used. The 2-cells SRF module are placed at the centre of the RF station and the 1-cell modules are placed on both sides. In the Higgs and Z energy operations the beams pass all SRF modules while in the high luminosity Z operation beams only pass through the 1-cell modules. In this way the side effect of HOM is mitigated. Finally, in the stage 3 the ttbar upgrade operation, the additional 5-cell cavities are induced adjacent to the 2-cell modules that the 180 GeV beam can be kept in the storage ring.

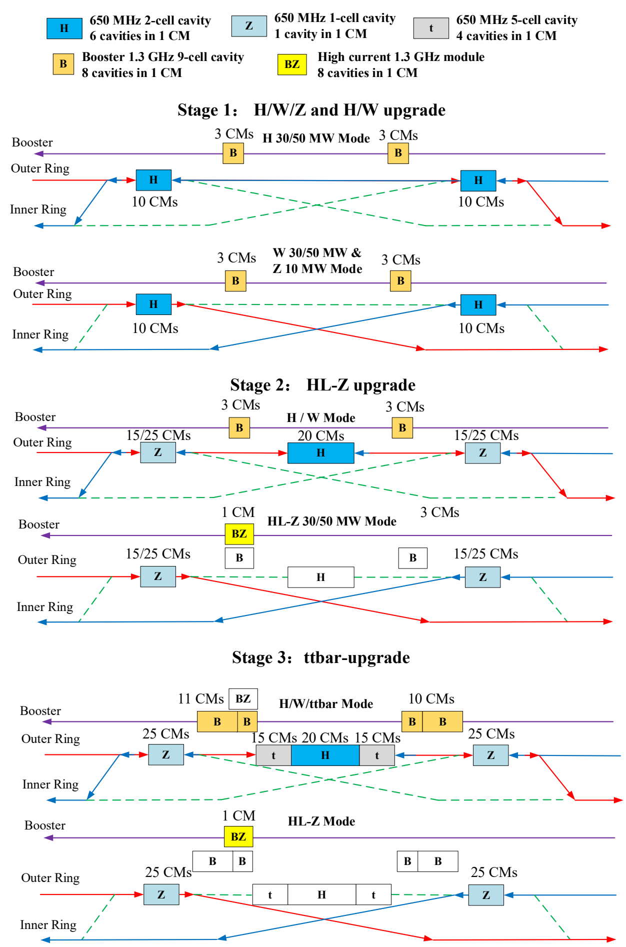

Figure 2: The bypass scheme for the RF station in different operations.

The optics is carefully optimized for all energies based on which high luminosities are expected [4]. The design of the interaction region provides local chromaticity and the crab-waist collision [5] is implemented. The FODO structure is applied to the arc region and the filling factor of dipoles in this region is maximized. In the operation of Higgs and ttbar the phase advance is 90/90 degrees and the aberration is cancelled. Whereas the phase advance in the operations of W and Z is 60/60 degrees. In the RF straight section a 75 m drift is reserved to transversely separate the electron/positron beams for about 10 cm. Two triplets are used to constrain the beta functions. The beams are further separated with dipoles outside of the drift space. The deflection of the outgoing beam is 35 cm in the Higgs mode while increasing to 1.0 m in the W and Z modes where the RF cryostat needs to be bypassed. The optics in half collider ring for all of the operation modes were designed and optimized. The beta and dispersion functions are shown in Fig. 3.

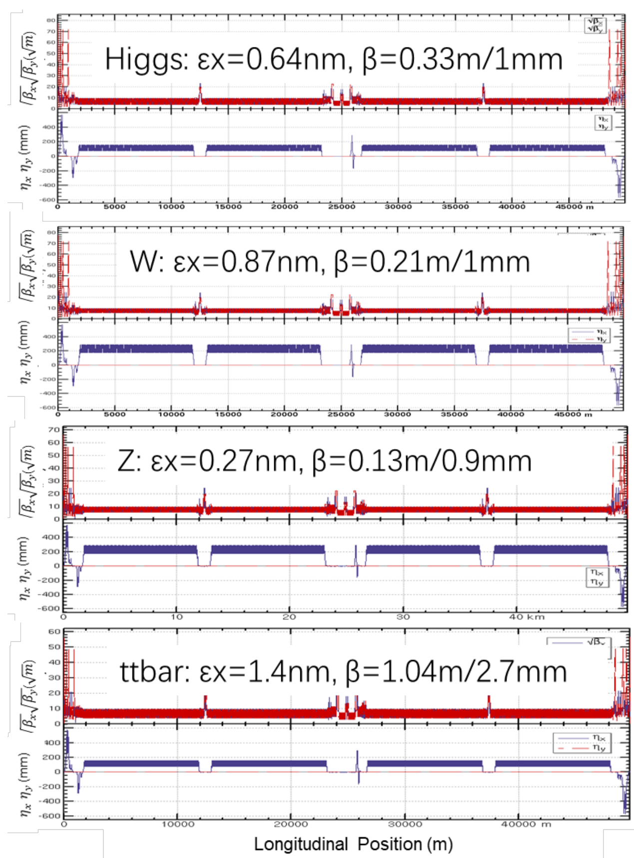

Figure 3: The half collider ring optics of all operation modes.

A certain Dynamic Aperture (DA) is required for the efficient injection and adequate beam life time. Systematic DA studies have been done for all operation modes. For example, The required DA for Higgs is $8\sigma_x \times 15\sigma_y \times$ 1.7%, event to the lattice with errors. Both magnet alignment and field errors were included for the simulations. By applying the closed orbit distortion correction and dispersion correction the errors are corrected and the required DA is feasible. Figure 4 shows the DA with bare lattice and with magnets errors.

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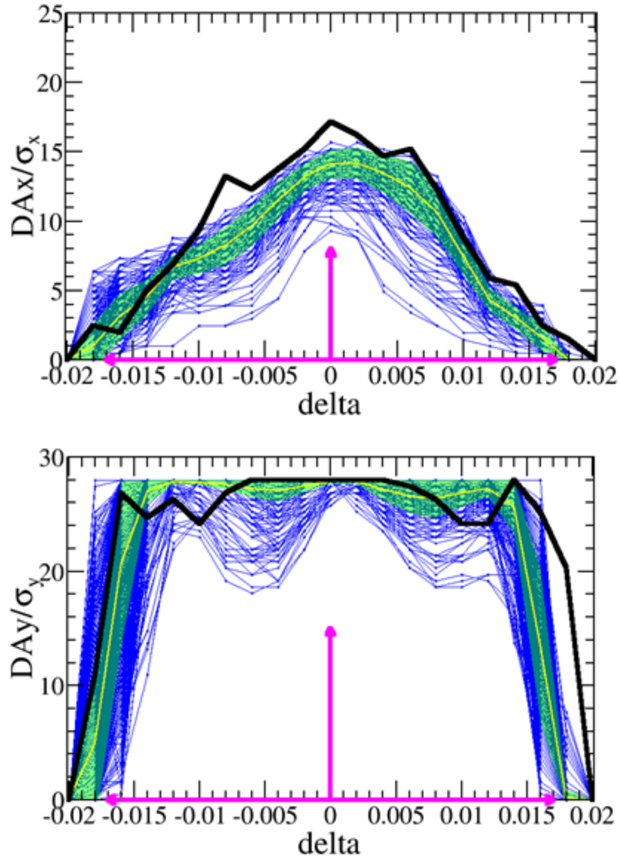

Figure 4: The Dynamic Apertures with respect to the energy deviation. The blue lines are DA with different simulated error seeds, yellow line is the mean value and the black line is the DA with bare lattice.

Beam-beam interactions impact the luminosity a lot. A number of beam parameters effect [6]. The comprehensive simulations were carried out. For example, the energy spread blows up and the bunch is lengthened due to the Beamstrahlung. Bunches are lengthened by the impedance as well which is also taken into accounted in the relevant simulations. For Higgs the beam-beam effect simulation is done with the luminosity of 5 x 10^{34}cm^{-2}s^{-1}. Figure 5 illustrates the luminosity and horizontal bunch size with respect to the horizontal tune. It is seen that the width of the stable tune area is 0.004, which satisfies the requirement.

Interaction of an intense charged particles with the vacuum chamber leads to collective instabilities. These instabilities degrade beam quality and expedite beam loss. The impedance thresholds for different operation modes are estimated. The limitation on the longitudinal broadband impedance mainly comes from the microwave instability and it results in bunch lengthening. Boussard or Keil-Schnell criteria is used to estimate the threshold of microwave instability. The limitation of the transverse broadband impedance mainly comes from the transverse mode coupling instability. Gaussian bunches are assumed and the threshold current is expressed with the transverse kick factor. The narrowband impedances are mainly contributed by the cavity alike structures. They induce coupled bunch instabilities in both longitudinal and transverse planes. The limitation on the shunt impedance of a HOM is evaluated in the resonant condition.

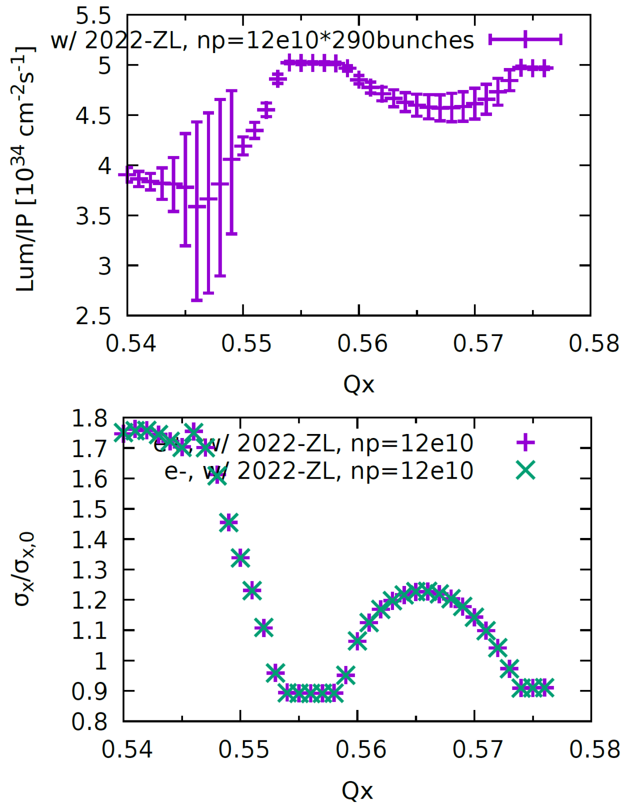

Figure 5: The luminosity and the beam size with respect to the horizontal tune.

According to the collider design, the impedance and wake are calculated both with formulas and with numerical codes. The microwave instability degrades the luminosity by lengthening the bunch and increasing the energy spread. The transverse mode coupling instability is estimated with the Eigen mode analysis which gives the dependence of the head-tail mode frequencies with respect to the bunch intensity. Careful simulations demonstrate that the transverse coupling effect is tolerable. To the narrow band instabilities one dominant contribution is the resonance of the transverse resistive wall impedance at zero frequency. The threshold exists at the high luminosity operation of Z pole where the most dangerous instability mode is about 2 ms much faster than the radiation damping of 840 ms. Therefore, an effective transverse feedback system is required for the correction. Another important narrow band impedance is contributed by the RF HOMs. The threshold value mainly depends on the actual tolerances of the cavity construction. With a HOM frequency scattering of 1 MHz, all the transverse and longitudinal modes below the cut-off frequency can be well damped for all operation scenarios. Other instabilities such as electron cloud effects, beam-ion instability were also investigated.

The booster raises the electron/positron output energy of the linac to different target collider operation energies

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(Higgs, W, Z and ttbar). In the high luminosity optimization, the linac extraction energy increases from 10 GeV, the CEPC-CDR baseline, to 30 GeV. The booster is accommodated in the same 100 km tunnel together with the collider, hanging on the tunnel ceiling. The booster not only fills the empty collider but also top-up injects bunches for the beam loss compensation in the collider. The on-axis scheme is used for the injection from the linac to booster and the Higgs injection from the booster to collider. The off-axis injection is adopted for the other energies from the booster to collider. The most sophisticated procedure is the top-up injection for Higgs: in the first step 240 bunches are injected from the linac, followed by the second step that 7 bunches are selected and extracted from collider to booster and the bunches from linac and collider merge by damping, then they are injected back to the collider. These steps iterate until all bunches in collider are full of charge.

In order to meet the beam dynamics requirement two types of lattice were investigated for the booster arc cells. One is FODO and the other is TME (Theoretical Minimum Emittance). It turns out that TME lattice brings larger DA and requires lower magnet cost. Thereby TME is chosen. The Dynamic Aperture is calculated and shown in Fig. 6. The thick solid lines are the DA with bare lattice at different energy deviations. The dot lines indicate the shrunken DA with 100 error seeds simulation of magnets misalignment and field imperfection where close orbit distortion and dispersion correction were applied. The centre half elliptical circle indicates the least requirement of DA and it is well satisfied.

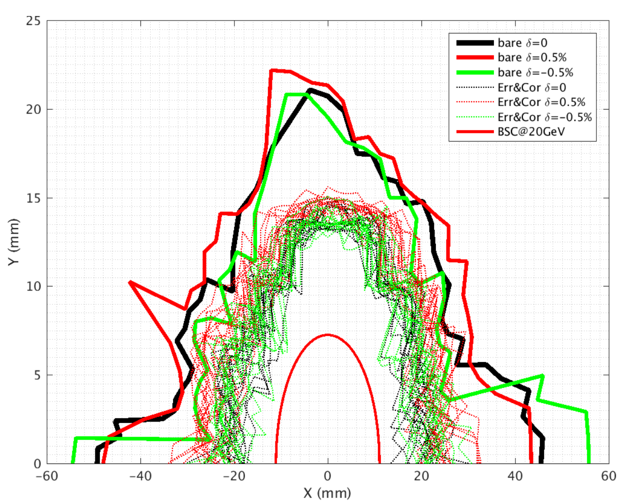

Figure 6: The booster DA with bare lattice and errors.

In the CEPC-CDR the linac uses normal conducting S-band cavities with the frequency of 2860 MHz to accelerate 10 GeV electron/positron energy. However, the correlated study for the booster dipole reveals that the economical iron-based magnet does not satisfy the quality requirement. It only works for the higher energy than 20 GeV. For this reason, the linac energy is increased from 10 to 30 GeV which allows the use of the diluted iron dipoles for the mass production. Moreover, the linac mainly uses C-band accelerator to increase the beam energy with high gradient.

KEY TECHNOLOGY R&D

Since 2013, the CEPC has carried out a series of key technology R&D. The fanatical support from various funding sources boosted the relevant studies in a wide range, covering most of the systems, such as RF power source, superconducting RF cavity, magnet system, vacuum chamber and so on. In addition, a significant part of the technology required by CEPC was validated in other large-scale accelerator facilities that the Institute of High Energy Physics (IHEP) is in charge of.

Among these key technology studies the high efficiency klystron is one of the most important exploration. The standard klystron energy transfer rate is about 60%. With an improved efficiency of 80% the P-band klystron along will save the operation fee more than 100 M CNY per year. Except for the economic benefit, the higher efficiency also makes CEPC an environmental friendly facility. For this purpose, the research team has planned three prototypes. The first one aims at a 650 MHz klystron with the standard 60% energy transfer rate. The second klystron aims at the high efficiency of 77% and the third one takes use for the Multi-Beam-Klystron (MBK) technology to reach the efficiency of 80%. The first prototype accomplished its commissioning in 2021 and the efficiency is 62%. The second prototype is still in the test and the efficiency already reached 70.5%. The third MBK prototype has been designed and is in the manufacture. Figure 7 shows the efficiency of the second klystron prototype with respect to the input voltage.

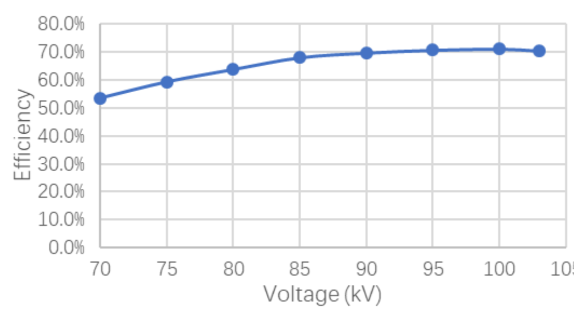

Figure 7: The 2nd klystron prototype efficiency *vs* input voltage.

CEPC relies on high quality superconducting RF cavity. Not only the widely used 9-cell 1.3 GHz but also the 1/2-cell 650 MHz superconducting RF cavities were developed in-house. Important technology breakthroughs have been achieved in the past years and the technology reaches states-of the-art level. As an example, Fig. 8 shows the test results of three 1-cell 650 MHz SRF cavities with different surface treatments such as EP and middle temperature annealing. The quality factor with respect to the acceleration field, voltage and the peak surface field is demonstrated, which exceed the specifications of CEPC. Efforts are continuously spent to reach even higher Q factor at high gradient.

The CEPC booster share the 100 km tunnel with the collider and lots of civil construction fee is saved. However, the ultra-long booster needs very weak dipoles to ramp up

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low energy beams: the minimum beam energy of 20 GeV asks for 56 Gs dipole field. It is very weak field and the prototype with anisotropic steel shows that the field homogeneity is better than 0.1% and fulfils the specification. With higher injection energy to the booster of 30 GeV, the cheaper isotropic steel can be used and can heavily reduce the construction fee. Figure 9 shows the weak field dipole cross section and the field distribution.

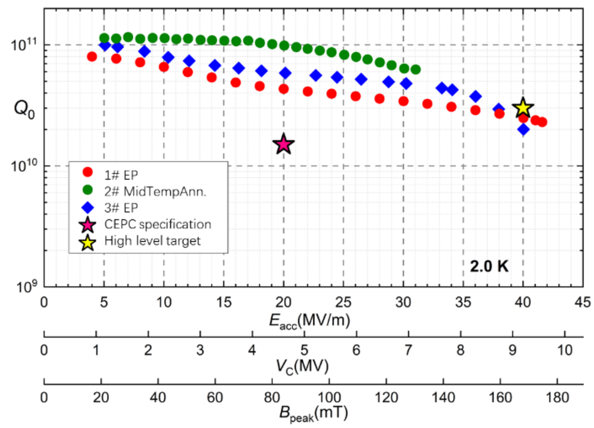

Figure 8: Q factor with respect to the acceleration field, voltage and peak field for three 650MHz 1-cell prototype.

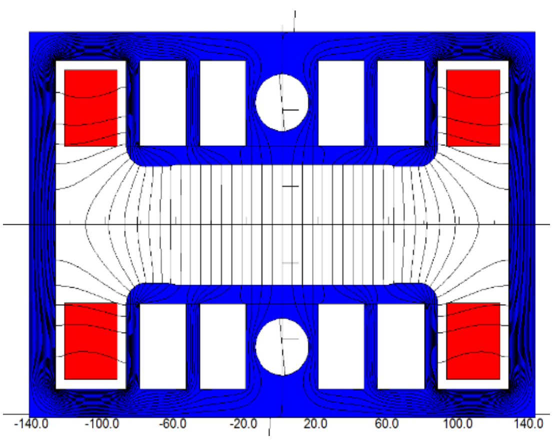

Figure 9: The cross section of the weak field dipole and its field distribution.

SUMMARY

Since the CEPC-TDR publication in 2018 the accelerator team has kept on the design optimization in a consistent way and the key technology R&D. The lattice and collision design were updated and higher luminosities at different energies are foreseen. The baseline SR power is 30 MW but the design is upgradable to the higher power of 50 MW. A series of key technology R&D has been carried out as well. The fruitful achievement of the pre-studies as well as the experience accumulated from other large-scale accelerator facilities undertook by IHEP guarantees the readiness of construction around the year of 2026.

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This overview paper is presented on behalf of the CEPC accelerator team. The relevant materials including the table data, plots etc. are collected from various talks given by the CEPC colleagues.

REFERENCES

[1] CEPC Study Group, "CEPC Accelerator CDR", arXiv:1809.00285 [physics.acc-ph], 2018. doi:10.48550/arXiv.1809.00285

[2] J. Gao, "CEPC and SppC Status from the completion of CDR towards TDR", *Int. J. Mod. Phys. A*, vol. 36, no. 22, p. 2142005, 2021. doi:10.1142/S0217751X21420057

[3] CEPC Accelerator Study Group, "Snowmass 2021 White Paper AF3-CEPC", arXiv:2203.09451[physics.acc-ph], 2022. doi:10.48550/arXiv.2203.09451

[4] Yiwei Wang *et al.*, "Lattice design for the CEPC double ring scheme", *Int. J. Mod. Phys. A*, vol. 33, no. 2, p. 1840001, 2018. doi:10.1142/S0217751X18400018

[5] M. Zobov *et al.*, "Test of "Crab-Waist" Collisions at the DAΦNE Φ Factory", *Phys. Rev. Lett.*, vol. 104, p. 174801, 2010. doi:10.1103/PhysRevLett.104.174801

[6] Yuan Zhang *et al.*, "Self-consistent simulations of beam-beam interaction in future e⁺e⁻ circular colliders including beamstrahlung and longitudinal coupling impedance", *Phys. Rev. Accel. Beams*, vol. 23, p. 104402, 2020. doi:10.1103/PhysRevAccelBeams.23.104402