**CEPC -Accelerator Technologies to Snowmass2021 AF7**

**CEPC Accelerator Study Group**

**Executive summary**

The discovery of the Higgs boson at CERN’s Large Hadron Collider (LHC) in July

2012 raised new opportunities for a large-scale accelerator. Due to the low mass of the

Higgs, it is possible to produce it in the relatively clean environment of a circular electron–positron collider with reasonable luminosity, technology, cost and power consumption. The Higgs boson is a crucial cornerstone of the Standard Model (SM). It is at the center of some of its biggest mysteries, such as the large hierarchy between the weak scale and the Planck scale, the nature of the electroweak phase transition, and many other related questions. Precise measurements of the properties of the Higgs boson serve as excellent tests of the underlying fundamental physics principles of the SM, and they are instrumental in explorations beyond the SM. In September 2012, Chinese scientists proposed a 240 GeV *Circular Electron Positron Collider* (CEPC), serving two large detectors for Higgs studies. The tunnel for such a machine could also host a *Super Proton Proton Collider* (SPPC) to reach energies beyond the LHC.

The CEPC Preliminary Conceptual Design Report (Pre-CDR, the *White Report*)[1]was published in March 2015, followed by a Progress Report (the *Yellow Report*)[2] in April 2017, where CEPC accelerator baseline choice was made. The Conceptual Design Report (CEPC Accelerator CDR, the *Blue Report*) [3] has been publically realsed in Nov. 2018, and also submitted to European High Energy Strategy in May, 2019 [4].

The CEPC is a circular *e+e-* collider located in a 100-km circumference tunnel beneath the ground. The accelerator complex consists of a linear accelerator (Linac), a damping ring (DR), the Booster, the Collider and several transfer lines. In the tunnel, space is reserved for a future *pp* collider, SPPC. The center-of-mass energy of the CEPC is set at 240 GeV, and at that collision energy CEPC will serve as a Higgs factory, generating more than one million Higgs particles. The design also allows for operation at 91 GeV as a Z factory and at 160 GeV as a W factory. The number of Z particles produced will be close to one trillion, and W+W-pairs close to 20 million. The heart of the CEPC is a double-ring collider (except at SCRF region, where electron and positron use common beam pipe). Electron and positron beams circulate in opposite directions in separate beam pipes but with the common SCRF system. They collide at two interaction points (IPs), where large detectors as described in detail in the CDR (Volume II) are located. The CEPC Booster is located in the same tunnel above the Collider. It is a synchrotron with a 10 GeV injection energy and extraction energy equal to the beam collision energy. The repetition cycle is 10 seconds. Top-up injection will be used to maintain constant luminosity. The 10 GeV Linac, injector to the Booster, built at ground level, accelerates both electrons and positrons. A 1.1 GeV damping ring reduces the positron emittance. Transport lines made of permanent magnets connect the Linac to the Booster. The tunnel size is large enough to accommodate the future SPPC without removing the CEPC collider ring. This opens up the exciting possibilities of *ep* and *e*-ion physics in addition to *ee* physics (CEPC) and *pp* and ion-ion physics (SPPC). In addition to particle physics, the Collider can operate simultaneously as a powerful synchrotron radiation (SR) light source. It will extend the usable SR spectrum into an unprecedented energy and brightness range. Two gamma-ray beamlines are included in the design. The circulating CEPC beams radiate large amount of SR power, 30 MW per beam. Reducing power consumption is an important criterion in the design. By using superconducting radio frequency (SCRF) cavities, high efficiency klystrons, 2-in-1 magnets, combined function magnets, large coil cross-section in the quadrupoles, the total facility power consumption is kept below 300 MW. The power conversion efficiency from the grid to the beam will be more than 20%, higher than other accelerator facilities. Prior to the construction will be a five-year R&D period (2018-2022). During this period, prototypes of key technical components will be built and infrastructure established for industrialization for manufacturing the large number of required components. There are numerous considerations in choosing the site. At this moment six sites have been considered and they all satisfy the technical requirements. A detailed cost estimate based on a Work Breakdown Structure (WBS) has been carried out. CEPC Construction is expected to start in 2022 and be completed in 2030. After commissioning, a tentative operation plan will be running 7 years for Higgs physics, followed by 2 years for operation in Z mode and 1 year for operation in W mode. The large number of particles produced makes the CEPC a powerful instrument not only for precision measurements on these important particles, but also in the search for new physics. The CEPC is an important part of the world plan for high-energy physics research. It will support a comprehensive research program by scientists from throughout the world. Physicists from many countries will work together to explore the science and technology frontier, and to bring a new level of our understanding of the fundamental nature of matter, energy and the Universe.

**Parameters and the optimization design**

According to the CEPC physics goals at the Higgs and Z-pole energies, the CEPC should provide e+e- collisions at the center-of-mass energy of 240 GeV and deliver a peak luminosity of 2×1034 cm-2s-1 at each interaction point. The CEPC has two IPs for e+e- collisions. At the Z-pole the luminosity is required to be larger than 1×1034 cm-2s-1 per IP. Its circumference is around 100 km in accordance with the SppC, which is designed to provide proton-proton collisions at 100 TeV center-of-mass energy using 16 Tesla superconducting dipole magnets.

The CEPC baseline design is a 100 km fully partial double ring scheme based on crab waist collision and 30 MW radiation power per beam at Higgs energy, with the shared RF system for both electron and positron beams. As an alternative option, Advanced Partial Double Ring (APDR) has been also studied systematically with the aim of comparing the luminosity potentials and saving cost.

The luminosities for Higgs and W operation are mainly limited by the SR power (30 MW). The luminosity at Higgs is 3 × 1034 cm-2s-1 with 242 bunches; the luminosity at the W is 1 × 1035 cm-2s-1 with 1524 bunches. At the Z pole, the luminosity for 3T detector solenoid is 1.7 × 1035 cm-2s-1 and is 3.2 × 1035 cm-2s-1 for 2T detector solenoid, both with 12,000 bunches. The limit of bunch number comes from the electron cloud instability of the positron beam. The minimum bunch separation for Z due to electron cloud effect is 25 ns and a 10% beam gap is left for cleaning. There is still some space for parameter optimization at z pole to get even higher luminosity. Beam-beam interaction in is one of the most important limitations to the CEPC performance, which is calculated both by analytical method and computer simulations to make optimized parameter design and choose optimum operating conditions. The crab-waist scheme increases the luminosity by suppressing vertical blow up, which is a must to reach high luminosity. Beamstrahlung is synchrotron radiation excited by the beam-beam force, which is a new phenomenon in a storage ring based collider. It will increase the energy spread, lengthen the bunch and may reduce the beam lifetime due to the long tail of the photon spectrum. The beam-beam limit at the W/Z is mainly determined by the coherent x-z instability instead of the beamstrahlung lifetime as in the Higgs mode. Longer bunch length will help to suppress the coherent instability.

The CEPC CDR design goals have been evaluated and checked from the point view of beam-beam interaction, which is feasible and achievable.

**CEPC SCRF technologies**

CEPC CDR will use a 650 MHz RF system with 240 2-cell superconducting cavities for the Collider and a 1.3 GHz RF system with 96 9-cell superconducting cavities for the Booster. The Collider is a partial double-ring with common cavities for electron and positron beams in Higgs operation mode and a full double ring with separate cavities for electron and positron beams in W and Z operation modes. Full installation of the same types of cavities and cryomodules for Higgs, W, and Z-pole modes without changing any hardware is the baseline configuration. The Collider SCRF system is optimized for the Higgs mode of 30 MW SR power per beam, with enough tunnel space and operating margin to allow higher RF voltage and/or SR power (50 MW SR power per beam) by adding cavities. Each Collider cavity has two detachable coaxial HOM couplers mounted on the cavity beam pipe with HOM power handling capacity of 1 kW. Each 11 m-long cryomodule consists of six cavities. Each cryomodule has two beamline HOM absorbers at room temperature outside the vacuum vessel with HOM power handling capacity of 5 kW each.

HOM power limit per cavity and the fast-growing longitudinal coupled-bunch instabilities (CBI) driven by both the fundamental and higher order modes impedance of the RF cavities determine to a large extent the highest beam current and luminosity obtainable in the Z mode. Transient beam loading is also a concern. For a higher luminosity Z upgrade, because of the high HOM power and the need to have the smallest number of cavities, KEKB / BEPCII type single cavity cryomodules with very high input coupler power will be needed.

The CEPC SCRF technical challenges that require R&D include: achieving the cavity gradient and high quality factor in the real cryomodule environment (Q0 > 4×1010 at 22 MV/m for the vertical acceptance test with nitrogen-doping or other high Q technology, and normal operation gradient below 20 MV/m with the lower limit of Q0 of 1.5×1010 for long term operation. In fact, the vertical test specification has been reached in June 2020 with Q0 = 6×1010 at 22 MV/m by BCP and nitrogen infusion on a 650 MHz 2-cell cavity. Magnetic field shielding and active cancellation of cavities with large bore radius and cryomodule in the north-south direction are critical to achieve high Q in the tunnel.), robust and variable high power (> 300 kW CW) input couplers that are design compatible with cavity clean assembly and low heat load, efficient and economical damping of the HOM power with minimum dynamic cryogenic heat load, and fast RF ramp and control of the Booster.

During the CEPC Technical Design Report (TDR) phase, to increase the Z-pole luminosity, a common 650 MHz single cell cavity design has been proposed with operation requirement of Q0 = 3×1010 at 40 MV/m for Higgs mode. The HOM power per cavity will be 2~3 kW at Z-pole mode with Q0 = 3×1010 at 3.6 MV/m. R&D has been carried out by using large grain Nb material.

As for SC cavity fabrication and surface treatment technologies, important progresses have been made in 2019-2020: average accelerating gradient of more than ten EP-treated single-cell 1.3 GHz fine grain cavities reached 42 MV/m, with maximum gradient of 46 MV/m and average Q0 above 1.5×1010 at 30 MV/m. In parallel with design and key R&D, extensive development of SCRF personnel, infrastructure and industrialization is essential for the successful realization of CEPC. This will have synergy with ongoing SCRF-based accelerator projects in China, such as SHINE (Shanghai HIgh repetition rate XFEL aNd Extreme light facility) in Shanghai (600 1.3 GHz 9-cell cavities of operational Q0 = 2.7×1010 at 16 MV/m) and ADANES (Accelerator Driven Advanced Nuclear Energy System) in Huizhou, etc. A large SRF infrastructure facility (PAPS-RF) is being built at the Huairou Science City near Beijing for the mass production (assembly and testing) of the cavities and cryomodules as well as frontier R&D.

**CEPC 650MHz high efficiency klystron (RF source)**

The CEPC two beam synchrotron radiation power is more than 60 MW, it needs high efficiency RF source to minimize CEPC AC power consumption. Considering the klystron operation lifetime and power redundancy, a single 650MHz 800 kW klystron amplifier will drive two of the collider ring SC cavities through a magic tee and two rated circulators and loads. The CEPC high efficiency 650MHz klystron design goals are to set the efficiency to be above 80% and successful industrialization. On March 10, a first single beam 650MHz 800kW klystron has been successfully tested with efficiency of 62% compared with 65% of designed valued. A high efficency 650MHz 800kW klystron has been designed with the 3D simulation designed efficiency of 81%. A prototype will be launched into fabrication at the end of 2020.

**CEPC linac injector (source)**

The CEPC linac injector to booster is a normal conducting S-band linac with frequency 2860 MHz providing electron and positron beams at an energy of up to 10 GeV at a repetition rate of 100 Hz. One-bunch-per-pulse is adopted and bunch charge should be larger than 1.5nC.

In the design of CEPC linac, the reliability and availability of the linac injector was emphasized because it is one of the indispensable facilities. The S-band linac has a robust design based on well proven technologies, and a 15% overhead of accelerating structure and klystron is foreseen to provide margins. The linear type layout of CEPC linac is adopted and one electron transport line at an energy of 4 GeV is designed to bypass the positron source and part accelerating section. All the lattice design and multi-particle simulations are conducted and the linac can meet all the requirements with errors.

A thermionic gun is adopted and can provide 11 nC electron beam for positron production. To keep the potential to meet higher requirements and possibility of updates in the future, the linac can provide bunch charge larger than 3 nC electron beam and positron beam. The positron source is a conventional design with a tungsten target of 15 mm in length and adiabatic matching device of 6 T in peak magnetic field. The energy of electron beam for positron production is 4 GeV and rms beam size is 0.5 mm.

A 1.1 GeV damping ring with 75.4 m circumference is adopted to reduce the transverse emittance of positron beam to suitably small value. An energy spread compressor system before damping ring and a bunch length compressor system after damping ring have been designed in the transport lines between the Linac and the damping ring. Both parameters and lattices for damping ring and transport lines have designed, which can meet the requirements.

    To increase CEPC booster injection energy from 10GeV to **45.5**GeV with the aim of increasing the the starting dipole field from 28Gauss to 126Gauss, a plasma injector backup scheme has been proposed, which boosts the CEPC S-band linac electron and positron energy **from** 10GeV to **45.**5GeV. Low emmittance and large charge rf  guns are needed together with a **400MeV** damping ring. Simulation results shows that the plasma injector could satisfy the injection requirement from booster. Experimental demonstration of electron acceleration by plasma will be conducted on Shanghai Soft-XFEL linac platform, and experiments will start in the fall of 2020. As for positron acceleration verification, SLAC **FACET-II** is appropriate platform. The CEPC booster injection requirement from the plasma injector are as follows: energy 45.5GeV, bunch charge 1nC, bunch length <10ps, bunch energy spread 0.2%, normalized emittance <3000μm ·rad, and bunch transever size <2000 μm. **CEPC plasma injector is based on** advanced accelerator science and technology, which need wide and close international collaboration.

**CEPC cost**

The CEPC CDR cost of 5 Billion US dollars contains mainly three parts, civil engineering, accelerator with two detectors. As cost repartition (without detectors, for example), civil engineering 40%; collider magnets 12%; booster magnets 6%, vacuum system 9%; RF power system 6%; SRF system 4%; mechanical system 5%; instrumentation 4%; cryogenic system 4%; linac injector 2.5%; and others.

**References:**

1. CEPC-SppC Pre-CDR, <http://cepc.ihep.ac.cn/preCDR/volume.html>, 2015.
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4. CEPC Accelerator submitted to European Strategy in 2019: ArXiv: 1901.03169.