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STATUS OF CIRCULAR ELECTRON-POSITRON COLLIDER AND SUPER PROTON-PROTON COLLIDER

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Abstract

Circular electron-positron collider (CEPC) is a dedicated project proposed by China to research the Higgs boson. The collider ring provides e+ e- collision at two interaction points (IP). The luminosity for the Higgs mode at the beam energy of 120GeV is 3×10^{34} cm^{-2}s^{-1} at each IP while the synchrotron radiation (SR) power per beam is 30MW. Furthermore, CEPC is compatible with W and Z experiments, for which the beam energies are 80 GeV and 45.5 GeV respectively. The luminosity at the Z mode is higher than 1.7×10^{35} cm^{-2}s^{-1} per IP. Top-up operation is available during the data taking of high energy physics. Super Proton-Proton Collider (SPPC) is envisioned to be an extremely powerful machine, with centre mass energy of 75 TeV, a nominal luminosity of 1.0×10^{35} cm^{-2}s^{-1} per IP, and an integrated luminosity of 30 ab^{-1} assuming 2 interaction points and ten years of running. The status of CEPC and SPPC will be introduced in detail in this paper.

MACHINE LAYOUT

CEPC [1] which aims at researching Higgs boson is a double ring scheme optimized at the beam energy of 120 GeV. SPPC will be the next project after the operation of CEPC in the future. The circumference of CEPC is 100km while matching the geometry of SPPC as much as possible. The circumference is determined by the requirements of SPPC so that the SPPC bending magnets can be designed and manufactured. The arc regions of the SPPC collider ring, the CEPC collider ring and the CEPC booster ring are in the same tunnel. The cross section of the tunnel in the arc region is shown in Fig. 1.

The interaction region of SPPC is located in the same long straight sections where the CEPC RF cavities are placed. The collimation region of SPPC with length of about 4km is located in the interaction region of CEPC. Due to the special collision orbit at the IP and the very large size of detector, bypass geometry or independent tunnel for SPPC and CEPC in the two regions is needed. The layout design of CEPC in the RF region and interaction region follows the space constraints. However, it still will be potential space conflict in the two regions during the geometry optimization of SPPC in the future. Since the operation of CEPC will be much earlier than SPPC. So SPPC and CEPC are arranged in the outside and inside respectively. SPPC team can optimize SPPC geometry with relatively lower magnetic field of bending magnet especially in the bypass region. The design of CEPC can keep fixed during the modification of SPPC. The booster ring of CEPC shown in Fig. 1 is located above collider ring with the distance of 2.4 m. The distance is sufficient to avoid the magnetic interference between the collider ring and the booster ring.

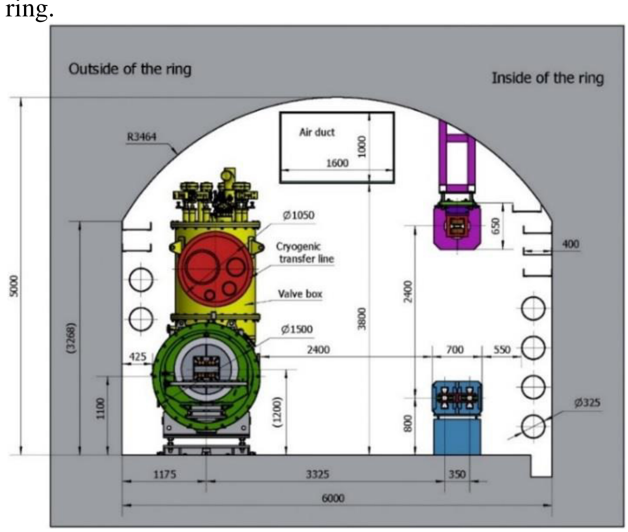

Figure 1: The cross section of the tunnel in the arc region.

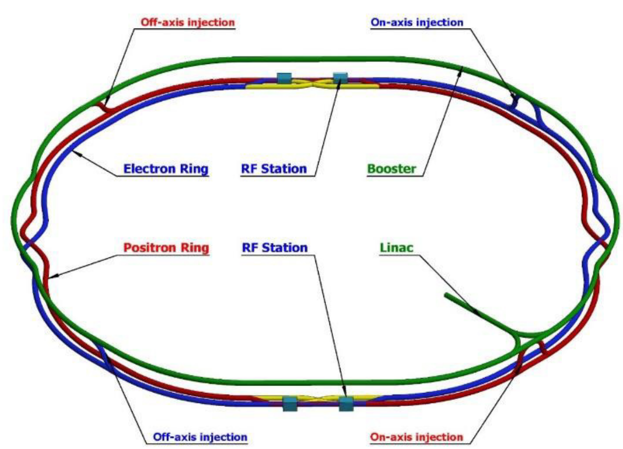

Figure 2: The layout of CEPC.

The layout of CEPC including Linac, transfer lines, booster ring and collider ring is shown in Fig. 2. The Linac is located at ground level with length of 1200 m. The Booster is underground at a depth of approximately 100 m. The Linac and Booster are connected by two transfer lines for e^+ and e^- respectively. These lines have a slope of 1:10. There are 8 straight sections in the collider ring. They are 2 interaction regions, 2 RF regions and 4 injection regions.

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Among them, two off-axis injection regions are the function regions for the operation of Higgs, W and Z. The two on-axis injection regions are used only during operation in the Higgs mode.

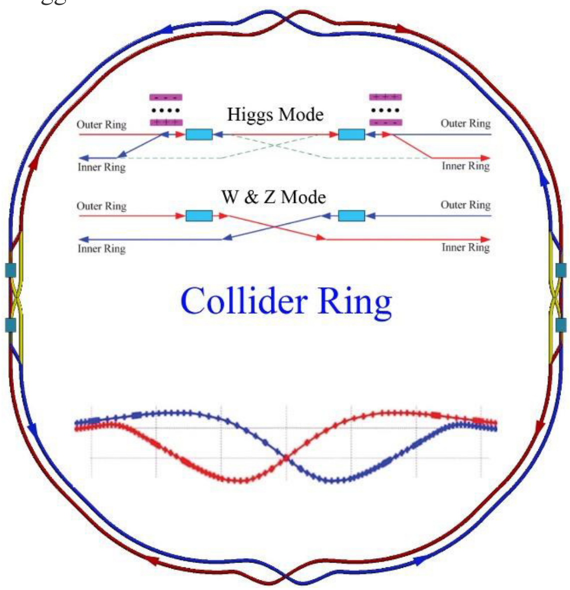

Figure 3: The layout of CEPC collider ring.

Fig. 3 shows the layout of CEPC collider ring. The design of collider ring is optimized at Higgs mode with 650 MHz two cell RF cavities. There are two dedicated surveys in the RF region for the Higgs, W and Z modes. During the operation of Higgs mode all the RF cavities are shared by both e+ and e- beams using combining magnets [2][3] near the RF cavities. Each beam is filled in half ring so that all e+ and e- bunches can pass the RF cavities in turn. This filling scheme in Higgs mode with half the ring won't reduce the luminosity because the required bunch number is relatively small and the bunch spacing is quite large. For the W and Z modes the surveys of e+ and e- rings in the RF region are designed independently by turning off the combined magnets so that all bunches can be filled along the whole e+ and e- rings. The beam current during the operation of W and Z modes is made as much as possible to improve the luminosity. W and Z modes use the same RF cavities which are used in Higgs mode to save cost. Half number of the cavities are distributed in e+ and e- rings respectively for the W and Z modes. The machine parameters for the Z mode do not increase the budget which is based on operation as a Higgs factory.

The central part of the interaction region is shown in Fig. 4. There is a Be pipe of length 14 cm and inner diameter 28 mm. The final focusing magnet is 2.2 m away from the IP. The horizontal crossing angle at the IP is 33 mrad to allow enough space for the superconducting quadrupole coils in a two-in-one type with space for a room temperature vacuum chamber. The accelerator components inside the detector are distributed within a conical space with an opening angle of 13.6˚.

Twin-aperture dipoles and quadrupoles [4] are in the arc region. The distance between the two beams is 0.35 m. The magnets in the other regions and all the sextupoles are independently powered for flexibility of the optics.

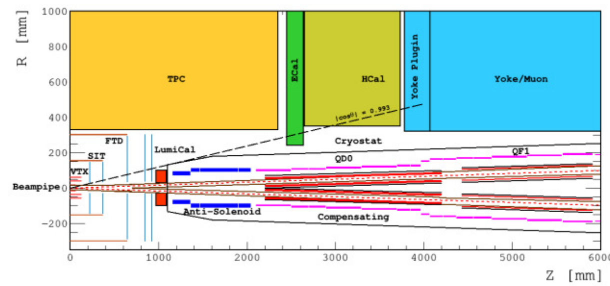

Figure 4: The central part of the interaction region.

PARAMETERS OF CEPC COLLIDER

The beam stay clear region is defined as ± (18 σ_x + 3 mm) and ± (22 σ_y + 3 mm) in the horizontal and vertical directions respectively. Coupling is 1%. The synchrotron radiation (SR) power per beam is limited to 30 MW. The high-energy physics goals of CEPC are to provide e^+e^- collisions at a beam energy of 120 GeV and attain a luminosity of 3×10^{34} cm^{-2}s^{-1} at each IP for operation in the Higgs mode. Furthermore, the CEPC should be able to run at 80 GeV and 45.5 GeV for experiments running in the W and Z modes respectively. The luminosity in Z mode is 1.7×10^{35} cm^{-2}s^{-1} per IP, and in W mode 1×10^{35} cm^{-2}s^{-1} per IP.

Main parameters of CEPC collider ring is shown in Table 1. The detector solenoid is 3 T with a length of 7.6 m as the baseline design. There are 22 anti-solenoid sections with different inner diameters within the final doublet region at each side of the IP to compensate for the effects on the beam of the strong detector solenoid [5]. For the Higgs mode, with the constraint of 30 MW, the design luminosity per IP is 3×10^{34} cm^{-2}s^{-1} with 242 bunches and beam current of 17.4 mA. The horizontal and vertical β functions at the IP are 0.36 m and 1.5 mm respectively. Operation is in top-up mode. The energy acceptance in Higgs mode is 1.35%. The beam lifetime with the beam-beam effect is greater than 26 minutes.

The Collider lattice in W mode is the same as in the Higgs mode. The design luminosity per IP is 1×10^{35} cm^{-2}s^{-1} with 1524 bunches and beam current of 87.9 mA, again with the constraint of 30 MW beam power.

For the Z mode, the horizontal and vertical β functions at the IP are 0.2 m and 1.5 mm respectively to avoid the strong coherent beam-beam instability [6] with the detector solenoid at 3T. The design luminosity per IP is 1.7×10^{35} cm^{-2}s^{-1} with 12000 bunches and beam current of 461 mA. During operation in the Z mode the synchrotron radiation power of each beam can only reach 16.5 MW due to the limitation of HOM heating in the RF cavities and the electron cloud instability in the positron ring. The coupling in Z mode is 2.2% which is much larger than expected because the strong fringe field of solenoids leads to a serious coupling growth of both beams. If the detector solenoid could be 2 T, the coupling can be controlled and the vertical β function at the IP can be reduced from 1.5 mm to 1.0mm so that the luminosity in Z mode per IP can reach 3.2×10^{35} cm^{-2}s^{-1}.

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Table 1: Main Parameters of CEPC Collider Ring

	Higgs	W	Z（3T）	Z（2T）
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5 × 2			
Piwinski angle	3.48	7.0	23.8	
Particles /bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number	242	1524	12000 (10% gap)	
Bunch spacing (ns)	680	210	25	
Beam current (mA)	17.4	87.9	461.0	
Synch. radiation power (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compaction (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance x/y (nm)	1.21/0.0024	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.109	0.013/0.123	0.004/0.06	0.004/0.079
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz)	650			
Harmonic number	216816			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	4.4	5.9	8.5	
Damping time $\tau_x/\tau_y/\tau_E$ (ms)	46.5/46.5/23.5	156.4/156.4/74.5	849.5/849.5/425.0	
Natural Chromaticity	-468/-1161	-468/-1161	-491/-1161	-513/-1594
Betatron tune ν_x/ν_y	363.10 / 365.22			
Synchrotron tune ν_s	0.065	0.040	0.028	
HOM power/cavity (2 cell) (kw)	0.46	0.75	1.94	
Natural energy spread (%)	0.100	0.066	0.038	
Energy spread (%)	0.134	0.098	0.080	
Energy acceptance requirement (%)	1.35	0.90	0.49	
Energy acceptance by RF (%)	2.06	1.47	1.70	
Photon number due to beamstrahlung	0.082	0.050	0.023	
Beamstruhlung /quantum lifetime (min)	80/80	>400		
Lifetime (hour)	0.43	1.4	4.6	2.5
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP (10^{34} cm^{-2}s^{-1})	3	10	17	32

THE DESIGN OF CEPC INJECTION

The beam stay clear region for the Booster is defined as ± (4 σ + 5 mm) in both horizontal and vertical directions with a round beam and emittance of 120 nm. This provides sufficient beam lifetime and transfer efficiency during injection and energy ramping. The diameter of the inner aperture of the vacuum chamber is chosen to be 40 mm from considerations of impedance.

The Booster uses 1.3 GHz 9-cell superconducting RF cavities. At the injection energy of 10 GeV from the Linac, the threshold of the single bunch current is 25.7 μA and the

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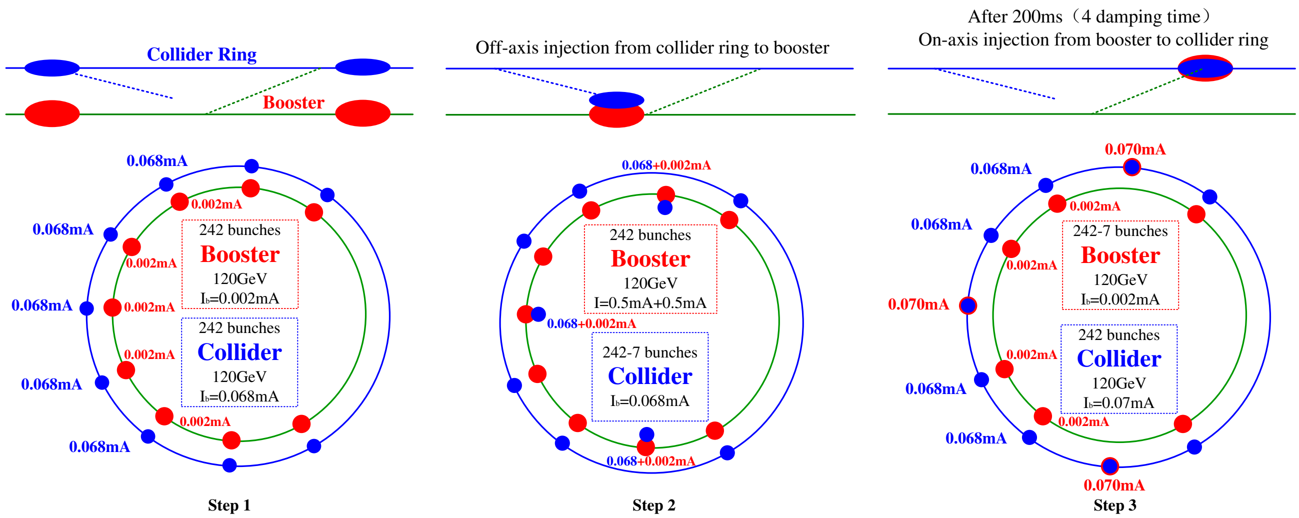

Figure 5: On-axis injection scheme only for Higgs operation.

threshold of beam current limited by RF power is 1.0 mA. The on-axis injection scheme is shown in Fig. 5. The Linac bunches are injected into the Booster by horizontal on-axis injection at an energy of 10 GeV. At the extraction energies when operating in W and Z modes the circulating bunches of the Booster will be injected into the Collider by horizontal off-axis injection. However, in order to keep a sufficient margin in dynamic aperture, especially with machine errors included, at the extraction energy during Higgs mode operation a special on-axis injection scheme is used, which can significantly relax the requirements on dynamic aperture compared with conventional off-axis injection schemes. First, several circulating bunches from the Collider are extracted to the Booster while the energy is 120 GeV and the beam current limited to 1 mA. The Booster circulating bunches are then merged with the injected bunches from the Collider after 4 damping times. Then, the merged bunches in the Booster are injected back into the Collider by vertical on-axis injection. This procedure will be repeated several times so that all the circulating bunches in the Booster can be accumulated into the Collider. The simulation result indicates that the collision of the stored bunches and the injected bunches is stable. The beam loading effect in the Booster RF system with the same bunch density as the Collider during the on-axis injection procedure in Higgs mode is weak. The maximum cavity voltage drop is 0.48% and the maximum phase shift is 0.63 degree. The peak HOM power per RF cavity is 62 W which is acceptable for the Booster RF system. The dynamic aperture in the Booster is sufficient for vertical off-axis injection from the Collider. The injection duration of both beams during top-up operation are 35.4 s, 45.8 s and 275.2 s for Higgs, W mode and Z mode respectively. The injection intervals with current decay of 3% are 47 s, 153 s and 504 s for Higgs, W mode and Z mode based on beam lifetime. The injection duration from an empty ring are 0.17 h, 0.25 h and 2.2 h for Higgs, W mode and Z mode respectively.

The requirements for sufficient injection efficiency are electron and positron bunch charge of 1.5 nC and repetition rate of 100 Hz. The total beam transfer efficiency from transfer line to the injection point of the Collider is greater than 90% with beam emittance of 120 nm and energy spread of 0.2% at the exit of the Linac. The transfer efficiency can be made much higher with a damping ring of energy 1.1 GeV while the beam emittance of Linac can be reduced to 40 nm. The Linac beam energy is 10 GeV so that magnetic field of Booster dipoles could be 30 Gauss at the injection energy. This is the minimum at which a good quality magnetic field can be obtained.

Table 2: Main Parameters of SPPC Collider Ring

Parameters	Values
Beam energy	37.5 TeV
Dipole field	12 T
Beam current	910 mA
Bunch current	9.8 mA
Circumference	100 km
Number of IP	2
β function at IP	0.75 m
Beam Current	0.73 A
Bunch number	10080
Bunch population	1.5×10^{11}
Beam lifetime	14.2 h
Bunch spacing	25 ns
Bunch length	75.5 mm
Injection energy	2.1 TeV
Full crossing angle	110 μrad
Stored energy per beam	9.1 GJ
Synchrotron radiation power	1.1 MW
Energy loss per turn	1.48 MeV
Normalized emittance	2.4 μm
Arc length	83.9 km
Arc filling factor	78%
SR heating load per aperture	13 W/m
Luminosity per IP	$1.0\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

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PARAMETERS OF SPPC COLLIDER

Within the tunnel of 100 km circumference, we will try to achieve 75 GeV center of mass energy in proton-proton collision with the anticipated accelerator technologies in the 2030's, but a more ambitious goal to go higher energy is possible [1]. The magnetic field of dipole is 12 T with iron-based high-temperature superconductors (Fe-HTS) for the initial SPPC and 20-24 T also using Fe-HTS magnets in an upgrade plan. Taking into account the expected evolution in detector technology we can expect the nominal luminosity of 1.0×10^{35} $cm^{-2}s^{-1}$ with a circulating beam current of about 0.73 A and small beta functions β^* of 0.75 m at the interaction point. Some key parameters of SPPC collider ring are shown in Table 2.

Table 3: Main Parameters of Higgs Luminosity Upgrade

Parameters	Values
Beam energy	120 GeV
Synchrotron radiation loss/turn	1.68 GeV
Beam current	17.8 mA
Synchrotron radiation power	30 MW
Beam-beam parameters ξ_x/ξ_y	0.024/0.113
Number of particles/bunch	1.7×10^{11}
Bunch number	218
β function at IP β_x/β_y	0.33 m/1.0 mm
Emittance $\varepsilon_x/\varepsilon_y$	0.89/0.0018 nm
Natural bunch length	2.2 mm
Bunch length	3.93 mm
Energy spread	0.19%
Energy acceptance requirement	1.7%
RF voltage	2.4 GV
HOM power/cavity	0.58 kW
Energy acceptance by RF	3.0%
Beamstrahlung photon number	0.104
Beamstruhlung lifetime	30 min
Quantum lifetime	50 min
Beam lifetime	13 min
Piwinski angle	3.78
Beam-beam parameters ξ_x/ξ_y	0.024/0.113
Luminosity /IP	$5.2\times10^{34}cm^{-2}s^{-1}$

To avoid parasitic collisions near the IPs producing background for the experiments, it is important to separate the two beams, except at the IPs, using a crossing angle. The crossing angle is chosen to avoid the beams overlapping at the first parasitic encounters at 3.75 m from the IPs when the bunch spacing is 25 ns. At these locations the separation is greater than 12 times the rms beam size. At the SPPC, this crossing angle at the collision energy is about 110 μrad. Compared to head-on collisions, this bunch crossing angle will result in a luminosity reduction of about 15%. With a smaller bunch separation, the crossing angle must be larger, and the luminosity reduction would be greater, but luminosity loss with crossing angles can be recovered when crab cavities are used. The crossing angle may be different at injection due to different lattice settings and larger emittance.

LUMINOSITY UPGRADE OF CEPC

For the Higgs mode, a luminosity upgrade scheme is considered. The constraint of beam power is still 30 MW, the design luminosity per IP is 5.2×10^{34} $cm^{-2}s^{-1}$ with 218 bunches and beam current of 17.8 mA. The horizontal and vertical β functions at the IP are 0.33 m and 1.0 mm respectively. Comparing to CDR scheme much longer quadrupoles for both interaction region and arc region are adopted to reduce the synchrotron radiation which is an important constraint for the dynamic aperture optimization. The bending filling factor is increased to reduce synchrotron radiation loss so that the beam current can be higher slightly. The emittance is chosen as 0.89 nm to satisfy the requirements of beam stay clear region within the final focussing magnets. The energy acceptance of Higgs mode is 1.7%. The beam lifetime with the beam-beam effect is greater than 13 minutes. Main parameters of luminosity upgrade scheme for the Higgs mode are shown in Table 3.

The optimization of dynamic aperture and the design of IR mechanics system for the new scheme are in progress.

CONCLUSION

The status of CEPC and SPPC is introduced in detail in this paper. The design of CEPC accelerator physics can meet the luminosity requirements at Higgs, W and Z. The finalization of the beam parameters and the specifications of special magnets have been finished. The hardware devices are all reasonable. Preliminary lattice design of SPPC collider ring has been finished and 10 σ dynamic aperture has reached. The developments on the key anticipated accelerator technologies such as superconducting RF cavity, high efficiency klystron and iron-based superconducting dipole are carrying out. The optimization to reduce machine cost and improve the beam performance is always under studying.

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