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CEPC ACCELERATOR TDR STATUS AND AC POWER CONSUMPTIONS*

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Abstract

The discovery of the Higgs boson at Large Hadron Collider (LHC) of CERN in July 2012 raised new opportunities for a large-scale accelerator. The Higgs boson is the heart of the Standard Model (SM) and is at the center of many mysteries of universe. In Sept. 2012, Chinese scientists proposed a 240 GeV Circular Electron Positron Collider (CEPC), having two large detectors for Higgs studies as a Higgs Factory and other topical researches. The 100 km tunnel of CEPC could also host a Super proton proton Collider (SppC) to reach energies above 100 TeV. CEPC Conceptual Design Report (CDR) has been released in Nov. 2018, and CEPC Technical Design Report (TDR) will be completed at the end of 2022. in this paper, CEPC Technical Design Report (TDR) status, upgrade possibilities and AC power consumption have been reported.

INTRODUCTION

The discovery of the Higgs boson at CERN's Large Hadron Collider (LHC) in July 2012 raised new opportunities for large-scale accelerators. The Higgs boson is the heart of the Standard Model (SM), and is at the center of our understanding the mysteries of universe. Precise measurements of the properties of the Higgs boson serve as probes of the underlying fundamental physics principles of the SM and beyond. Due to the modest Higgs boson mass of 125 GeV, it is possible to produce it in the relatively clean environment of a circular electron–positron collider with high luminosity and multi detectors. In Sept. 2012, Chinese scientists proposed a 240 GeV Circular Electron Positron Collider (CEPC), serving two large detectors for Higgs studies and other topics as shown in Fig. 1. The 100 km tunnel for such a machine could also host a Super Proton Proton Collider (SPPC) to reach energies above 100 TeV.

CEPC is a Higgs factory composed of a linac injector (10 Gev for CDR, 30 GeV for TDR), 100 km circumference full energy booster and collider ring equipped with 2 detectors. In addition to operate at center of mass energy for Higgs of 240 GeV, CEPC could operate also at different energies, such as Z-pole of 45.5 GeV, W of 80 GeV, and as last phase upgrade possibility, ttbar of 180 GeV. The Conceptual Design Report (CEPC Accelerator CDR) [1] has been released in Nov. 2018. CEPC as a Chinese proposed international large science project, it participates the international high energy strategic planning and collaborations. In May 2019, CEPC accelerator document was submitted to European High Energy Physics Strategy workshop for worldwide discussions [2]. In 2022, CEPC accelerator document was submitted to the Particle Physics Community Planning Exercise (Snowmass'21) of USA [3].

CEPC TRD PARAMETERS

According to the CEPC TDR baseline 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 $5 \times 10^{34} cm^{-2}s^{-1}$ at each interaction point. The CEPC has two IPs (two detecors) for e+e- collisions and is compatible with four energy modes (Higgs, Z-pole, W, and ttbar). At the Z-pole energy the luminosity is required to be larger than $1 \times 10^{36} cm^{-2}s^{-1}$ per IP. The experiments at ttbar energy is an energy upgrade option at the last stage of CEPC.

The CEPC TDR baseline design is a 100 km double ring scheme based on crab waist collision and 30 MW radiation power per beam at four energy modes, with the shared RF system for Higgs/ttbar energies and independent RF system for W/ Z energies. The CEPC main parameters for TDR are listed in Table 2. The luminosity at Higgs energy is $5 \times 10^{34} cm^{-2}s^{-1}$. At the Z-pole, the luminosity is $1.15 \times 10^{36} cm^{-2}s^{-1}$ for 2T detector solenoid.

The CEPC TDR power upgrade parameters of 50 MW SR power/beam at Higgs, W, Z and ttbar energy operations and the luminosities are shown in Table 3. The luminosities at Higgs and the Z-pole energies are $8.3 \times 10^{34} cm^{-2}s^{-1}$ and $1.91 \times 10^{36} cm^{-2}s^{-1}$, respectively.

CEPC TDR DESIGN STATUS

Collider Ring

For CEPC collider design, 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 especially at high energy region. 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 tt/Higgs mode. A smaller phase advance of the FODO cell (60/60) for the collider ring optics is chosen at the W/Z mode to suppress the beam-beam instability when we consider the beam-beam effect and longitudinal impedance consistently. The CEPC TDR design goals have been evaluated and checked from the point view of beam-beam interaction, which are feasible and achievable.

MDI

The CEPC machine detector interface (MDI) is about 14 m (±7m from the IP) in length in the Interaction Region

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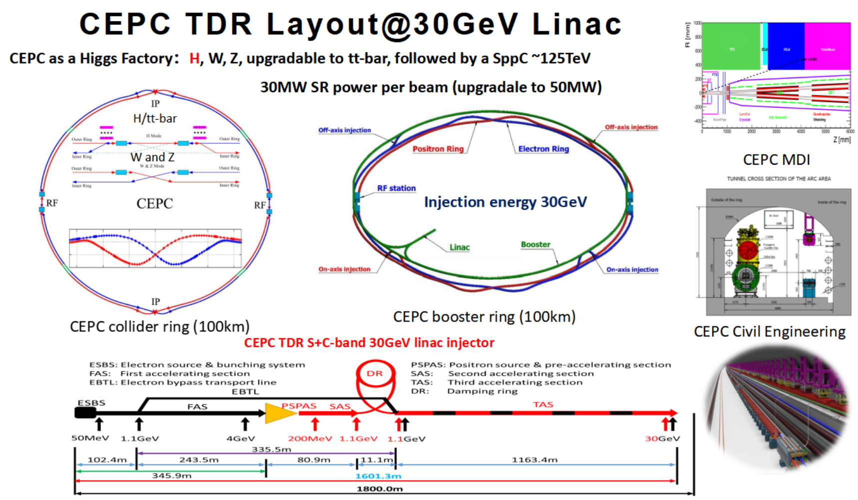

Figure 1: CEPC TDR layout.

(IR), where many elements from both detector system and accelerator components need to be installed including the detector solenoid, anti-solenoid, luminosity calorimeter (LumiCal), interaction region beam pipe, cryostat, beam position monitors (BPMs) and bellows. The cryostat includes the final doublet superconducting magnets and anti-solenoid. The CEPC detector consists of a cylindrical drift chamber surrounded by an electromagnetic calorimeter, which is immersed in a 2 to 3 T superconducting solenoid of 7.6 m in length. After optimization, the accelerator components inside the detector without shielding are within a conical space with an opening angle of 6.78 degrees. The crossing angle between electron and positron beams is 33 mrad in horizontal plane. The final focusing quadrupole is 1.9 m (L*) from the IP. A water cooling structure is required to control the heating problem of HOM in IR vacuum chamber. The diameters of beryllium pipe and the SC quadrupoles are 20 mm.

Booster

The booster provides electron and positron beams to the collider at different energies. The booster TDR design is consistent with the TDR parameters for four energy modes. The booster is in the same tunnel as the collider, placed above the collider ring except in the interaction region where there are bypasses to avoid the detectors. The injection system consists of a 30 GeV Linac, followed by a full-energy booster ring. Electron and positron beams are generated and accelerated to 30 GeV in the Linac. The beams are then accelerated to full-energy in the booster, and injected into the collider. For different beam energies of Higgs, W, Z and ttbar, experiments, there will be different particle bunch structures in the collider. The optics of booster is changed to TME structure and the emittance of booster is reduced significantly in order to match the lower emittance of collider and hence to reach higher luminosity goal in TDR. The CEPC booster TDR parameters at the injection and extraction are shown in Tables 4 and 5.

Collider and Booster SRF Systems

CEPC will use 650 MHz SCRF system for the collider and 1.3 GHz for the booster. For the first phase, CEPC will use 240 650 MHz 2-cell superconducting cavities for the collider and 96 1.3 GHz 9-cell superconducting cavities for the booster. The collider is a fully partial double-ring with common cavities for electron and positron beams in Higgs operation mode and a double ring for separate cavities for electron and positron beams in W and Z operation mode. The collider SRF system is optimized for the Higgs mode of 30 MW SR power per beam as the first priority, with enough tunnel space and operating margin to allow higher RF voltage (ttbar) and SR power (50 MW SR power per beam) by adding cavities.

RF staging and bypass scheme is proposed to unleash full potential of CEPC to reach highest luminosity at each energy and keep operational flexibility in the same time. RF staging of both the Collider and Booster is required for the CEPC power and energy upgrade. Cavity by-pass is needed to enable seamless operation mode switching, which is different from FCC-ee design.

Linac Injector

The CEPC linac injector is a normal conducting S-band and C-band linac with frequency of 2860 MHz and 5720 MHz, providing electron and positron beams at an energy of up to 30 GeV at a repetition rate of 100 Hz, as shown in Fig. 2. S-band accelerating structure is used in FAS with energy of 4 GeV and SAS with energy of 1.1 GeV and C-band accelerating structure is used in TAS form 1.1 GeV to 30 GeV. 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 positron damping ring of 1.1 GeV of circumference of 0.15 km has been design. The bunch charge is 1.5 nC and have the capability to reach 3 nC both for electron and positron beam. The linac length is 1.6 km

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and the linac tunnel length is 1.8 km with 0.2 km as reserved space. The CEPC linac injector parameters are shown in Table 1. 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 linac has a robust design based on well proven technologies, and about 15% backup of accelerating structures and klystrons are foreseen to reach high availability.

CEPC TDR TECHNOLOGY R&D STATUS

Intensive and full spectrum key technology R&D has been carried out during CDR and TDR periods, for example:

- CEPC 650 MHz 800 kW CW high efficiency klystrons (77 80%);
- CEPC 1.3 GHz and 650 MHz SRF accelerator systems, including SC cavities and cryomodule;
- SC quadrupole magnets including cryostate;
- High precision booster dipole magnets;
- Collider dual aperture dipole magnets, dual aperture qudrupole and sextupole magnets;
- Vacuum chamber system with NEG coating technology;
- Electrostatic-magnetic separators;
- High gradient S-band linac structures, pulse compressor, positron source, C-band linac and 80MW klystron;
- 18KW@4.5K cryoplant (Company);
- Plasma injector (alternative linac injector technology);
- SppC related high field superconducting magnets;
- Civil engineering designs in different sites; etc as shown in Fig. 2.

In synergy with other accelerator projects under construction, such as HEPS, a 6 GeV fourth generation light source by IHEP, all kinds of kickers and high precision magnets' power supplies have been developed. The CEPC TDR is scheduled to be completedat the end of 2022 and enter into Engineering Design Phase (EDR) started from 2023.

CEPC SITING STATUS

For CEPC site selection, the technical criteria are roughly quantified as follows: earthquake intensity less than seven on the Richter scale; earthquake acceleration less than 0.1 g; ground surface-vibration amplitude less than 20 nm at 1–100 Hz; granite bedrock around 50–100 m deep, and others. The site-selection process started in February 2015, preliminary studies of geological conditions for CEPC's potential site locations have been carried out in Qinhuangdao in Hebei province; Huangling county in Shanxi province; Huzhou in Zhejiang province; Changchun in Jilin province and Changsha, in Hunan province, etc. as shown in Fig. 3, and all these sites satisfies the CEPC construction requirements.

CEPC TIMELINE

CEPC has been firstly proposed by Chinese scientists in Sept. 2012 just after the Higgs Boson discovery at CERN. CEPC CDR has been completed in Nov. 2018, and accelerator TDR will be completed at the end of 2022. CEPC will enter EDR phase in 2023 and will be completed at the end of 2025. CEPC team will work closely with Chinese central government, international/industrial collaborations, and the local host government in EDR phase (2023-2025) towards the aim of putting CEPC into construction around 2027 (within the 15th five year plan of China), and into operation around 2035. At the end of CEPC operation, SppC could be put to construction, as shown in Fig. 4.

CEPC AC POWER CONSUMPTION

Corresponding to CEPC TDR parameters, the total AC powers for CEPC operation at Higgs energy with 30 MW and 50 MW SR power/beam are shown in Tables 6 and 7. The total AC power at Z-pole energy with 30 MW SR power/beam is shown in Table 8, and at ttbar energy with 50 MW SR power/beam is shown in Table 9. All these results have the rooms for further optimizations. In addition, economical using of green energies in future Higgs factories has been studied, and a 10MW solar power system has been developed at the site of the HEPS by IHEP.

CONCLUSIONS

CEPC as a Higss factory provides one of the future colliders for the high energy particle physics community and sciences in general worldwide. CEPC has developed on the timeline since it has been proposed in Sept. 2012, through pre-CDR, CDR, and TDR with international collaborations and industrial (CEPC Industrial Promotion Consortium, CIPC) participation. Continuous efforts are needed to progress forwards through CEPC EDR (2023-2025) with the aim of operating CEPC around 2035.

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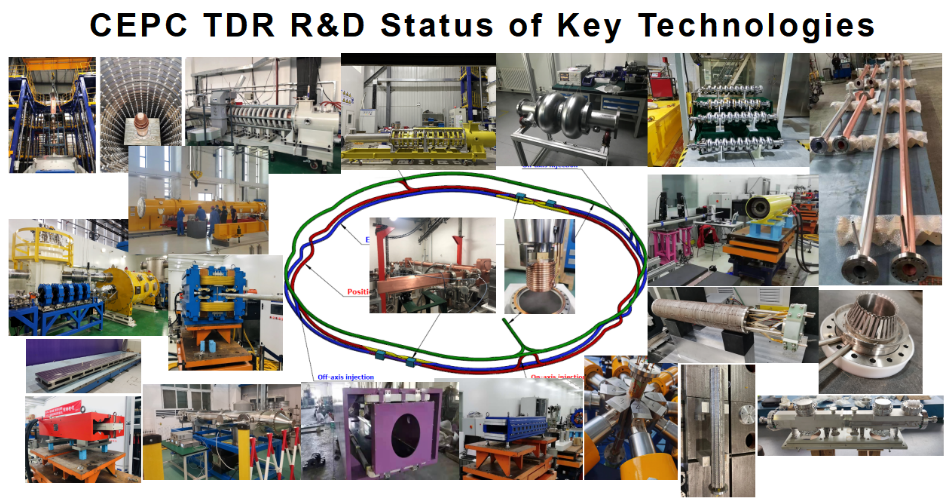

Figure 2: CEPC accelerator TDR key technology R&D status.

Figure 3: CEPC siting status.

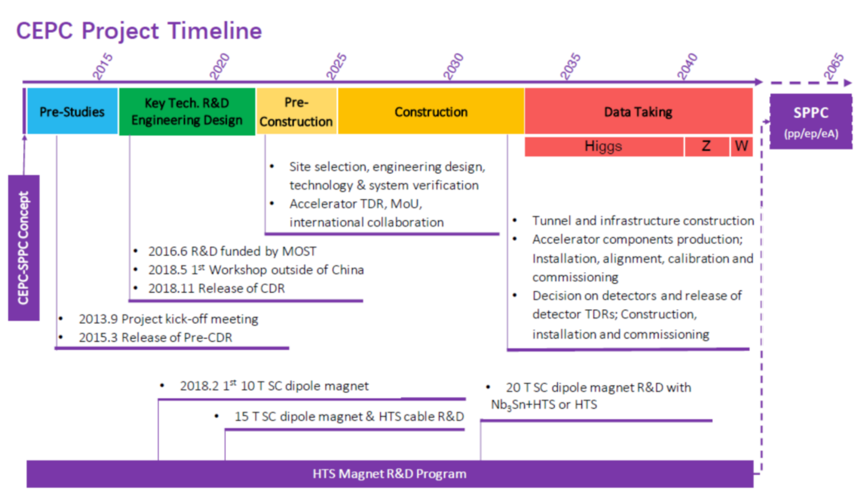

Figure 4: CEPC timeline.

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Table 1: The CEPC TDR 30 GeV Linac Injector Parameters

Parameter	**Unit**	**Value**	**Simulated Electron**		**Positron**	
Beam energy	GeV	30	31.3	30.8	31.1	30.8
Repetition rate	Hz	100	/			
Bunch charge	nC	1.5	1.5	3.0	1.5	3.0
Energy spread		1.5×10-3	1.4×10-3	1.7×10-3	1.4×10-3	1.9×10-3
Emittance	nm	6.5	1.4	1.5	3.3(H)/1.7(V)	3.5(H)/1.8(V)
Bunch length (RMS)	mm	/	0.4			

Table 2: The CEPC TDR Parameters with 30 MW SR Power/Beam

Parameter	**Higgs**	**Z**	**W**	**ttbar**
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	30			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	120	45.5	80	180
Energy loss per turn [GeV]	1.8	0.037	0.357	9.1
Piwinski angle	4.88	24.68	6.08	1.21
Bunch number	268	11934	1297	35
Bunch spacing [ns]	591 (53% gap)	23 (18% gap)	257	4524 (53% gap)
Bunch population [10^{10}]	13	14	13.5	20
Beam current [mA]	16.7	803.5	84.1	3.3
Momentum compaction [10^{-5}]	0.71	1.43	1.43	0.71
Beta functions at IP (bx/by) [m/mm]	0.3/1	0.13/0.9	0.21/1	1.04/2.7
Emittance (ex/ey) [nm/pm]	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam size at IP (sigx/sigy) [um/nm]	14/36	6/35	13/42	39/113
Bunch length (natural/total) [mm]	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Energy spread (natural/total) [%]	0.10/0.17	0.04/0.13	0.07/0.14	0.15/0.20
Energy acceptance (DA/RF) [%]	1.6/2.2	1.3/1.7	1.2/2.5	2.3/2.6
Beam-beam parameters (ksix/ksiy)	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF voltage [GV]	2.2	0.12	0.7	10
RF frequency [MHz]	650	650	650	650
Longitudinal tune Qs	0.049	0.035	0.062	0.078
Beam lifetime (bhabha/beamstrahlung)[min]	39/40	80/18000	60/700	81/23
Beam lifetime [min]	20	80	55	18
Hour glass Factor	0.9	0.97	0.9	0.89
Luminosity per IP[$10^{34}/cm^2$/s]	5.0	115	16	0.5

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Table 3: The CEPC TDR parameters with 50MW SR Power/Beam

Parameter	**Higgs**	**W**	**Z**	**ttbar**
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	50			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	120	80	45.5	180
Energy loss per turn [GeV]	1.8	0.357	0.037	9.1
Piwinski angle	4.88	6.08	24.68	1.21
Bunch number	415	2162	19918	58
Bunch spacing [ns]	385	154	15(10% gap)	2640
Bunch population [10^{10}]	14	13.5	14	20
Beam current [mA]	27.8	140.2	1339.2	5.5
Momentum compaction [10^{-5}]	0.71	1.43	1.43	0.71
Phase advance of arc FODOs [degree]	90	60	60	90
Beta functions at IP (bx/by) [m/mm]	0.33/1	0.21/1	0.13/0.9	1.04/2.7
Emittance (ex/ey) [nm/pm]	0.64/1.3	0.87/1.7	0.27/1.4	1.4/4.7
Beam size at IP (sx/sy) [um/nm]	15/36	13/42	6/35	39/113
Bunch length (SR/total) [mm]	2.3/3.9	2.5/4.9	2.5/8.7	2.2/2.9
Energy spread (SR/total) [%]	0.10/0.17	0.07/0.14	0.04/0.13	0.15/0.20
Energy acceptance (DA/RF) [%]	1.7/2.2	1.2/2.5	1.3/1.7	2.3/2.6
Beam-beam parameters (xx/xy)	0.015/0.11	0.012/0.113	0.004/0.127	0.071/0.1
RF voltage [GV]	2.2 (2cell)	0.7 (2cell)	0.12 (1cell)	10 (5cell)
RF frequency [MHz]	650			
Beam lifetime [min]	20	55	80	18
Luminosity per IP[$10^{34}/cm^2$/s]	8.3	26.6	191.7	0.8

Table 4: The CEPC TDR Booster Parameters at Injection

Parameter	**Unit**	**tt**	**H**	W	**Z**	
Beam energy	GeV	30				
Bunch number		35	268	1297	3978	5967
Threshold of single bunch current	mA	8.68	6.3	5.8		
Threshold of beam current (limited by coupled bunch instability)	mA	97	106	100	93	96
Bunch charge	nC	1.1	0.78	0.81	0.87	0.9
Single bunch current	mA	3.4	2.3	2.4	2.65	2.69
Beam current	mA	0.12	0.62	3.1	10.5	16.0
Growth time (coupled bunch instability)	ms	2530	530	100	29.1	18.7
Energy spread	%	0.025				
Synchrotron radiation loss/turn	MeV	6.5				
Momentum compaction factor	10-5	1.12				
Emittance	nm	0.076				
Natural chromaticity	H/V	-372/-269				
RF voltage	MV	761.0	346.0	300.0		
Betatron tune nx/ny		321.23/117.18				
Longitudinal tune		0.14	0.0943	0.0879		
RF energy acceptance	%	5.7	3.8	3.6		
Damping time	s	3.1				
Bunch length of linac beam	mm	0.4				
Energy spread of linac beam	%	0.15				
Emittance of linac beam	nm	6.5				

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Table 5: The CEPC TDR Booster Parameters at Extraction

Parameter	Unit	tt	H		W	Z	
		Off axis inj.	Off axis inj.	On axis inj.	Off axis inj.	Off axis inj.	
Beam energy	GeV	180	120		80	45.5	
Bunch number		35	268	261+7	1297	3978	5967
Maximum bunch charge	nC	0.99	0.7	20.3	0.73	0.8	0.81
Maximum single bunch current	mA	3.0	2.1	61.2	2.2	2.4	2.42
Threshold of single bunch current	mA	91.5	70		22.16	9.57	
Threshold of beam current (limited by RF system)	mA	0.3	1		4	16	
Beam current	mA	0.11	0.56	0.98	2.85	9.5	14.4
Growth time (coupled bunch instability)	ms	16611	2359	1215	297.8	49.5	31.6
Bunches per pulse of Linac		1	1		1	2	
Time for ramping up	s	7.1	4.3		2.4	1.0	
Injection duration for top-up (Both beams)	s	29.2	23.1	31.8	38.1	132.4	
Injection interval for top-up	s	65	38		155	153.5	
Current decay during injection interval		3%					
Energy spread	%	0.15	0.099		0.066	0.037	
Synchrotron radiation loss/turn	GeV	8.45	1.69		0.33	0.034	
Momentum compaction factor	10-5	1.12					
Emittance	nm	2.83	1.26		0.56	0.19	
Natural chromaticity	H/V	-372/-269					
Betatron tune nx/ny		321.27/117.19					
RF voltage	GV	9.7	2.17		0.87	0.46	
Longitudinal tune		0.14	0.0943		0.0879	0.0879	
RF energy acceptance	%	1.78	1.59		2.6	3.4	
Damping time	ms	14.2	47.6		160.8	879	
Natural bunch length	mm	1.8	1.85		1.3	0.75	
Full injection from empty ring	h	0.1	0.14	0.16	0.27	1.8	0.8

Table 6: The CEPC TDR AC Power Consumption (30 MW SR Power/Beam at Higgs Energy)

Parameter	Ring	Booster	LINAC	BTL	IR	Surface Building	TOTAL
RF Power Source	96.9	1.4	11.1				109.5
Cryogenic System	11.6	0.6	-		1.1		13.4
Vacuum System	1.0	3.8	1.8				6.5
Magnet Power Supplies	52.3	7.5	2.4	1.1	0.3		63.5
Instrumentation	1.3	0.7	0.2				2.2
Radiation Protection	0.3		0.1				0.4
Control System	1.0	0.6	0.2	0.0	0.0		1.8
Experimental devices					4.0		4.0
Utilities	31.8	3.5	2.0	0.6	1.2		39.1
General services	7.2		0.3	0.2	0.2	12.0	19.8
RF system			0.8				0.8
TOTAL	203.4	18.2	18.9	1.8	6.8	12.0	261.1

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Table 7: The CEPC TDR AC Power Consumption (50 MW SR Power/Beam at Higgs Energy)

Parameter	Ring	Booster	LINAC	BTL	IR	Surface Building	TOTAL
RF Power Source	161.5	1.4	11.1				174.1
Cryogenic System	15.5	0.6	-		1.7		17.9
Vacuum System	1.0	3.8	1.8				6.5
Magnet Power Supplies	52.3	7.5	2.4	1.1	0.3		63.5
Instrumentation	1.3	0.7	0.2				2.2
Radiation Protection	0.3		0.1				0.4
Control System	1.0	0.6	0.2	0.0	0.0		1.8
Experimental devices					4.0		4.0
Utilities	42.4	3.5	2.0	0.6	1.2		49.7
General services	7.2		0.3	0.2	0.2	12.0	19.8
RF system			0.8				0.8
TOTAL	282.4	18.2	18.9	1.8	7.4	12.0	340.7

Table 8: The CEPC TDR AC Power Consumption (30 MW SR Power/Beam at Z-pole Energy)

Parameter	Ring	Booster	LINAC	BTL	IR	Surface Building	TOTAL
RF Power Source	96.9	0.1	11.1				108.1
Cryogenic System	4.1	0.6	-		1.1		5.9
Vacuum System	1.0	3.8	1.8				6.5
Magnet Power Supplies	9.6	1.4	2.4	1.1	0.3		14.7
Instrumentation	1.3	0.7	0.2				2.2
Radiation Protection	0.3		0.1				0.4
Control System	1.0	0.6	0.2	0.0	0.0		1.8
Experimental devices					4.0		4.0
Utilities	28.1	3.5	2.0	0.6	1.2		35.5
General services	7.2		0.3	0.2	0.2	12.0	19.8
RF system			0.8				0.8
TOTAL	149.4	10.8	18.9	1.8	6.8	12.0	199.7

Table 9: The CEPC TDR AC Power Consumption (50 MW SR Power/Beam at ttbar Energy)

Parameter	Ring	Booster	LINAC	BTL	IR	Surface Building	TOTAL
RF Power Source	161.5	1.4	11.1				174.1
Cryogenic System	25.2	0.6	-		1.1		26.9
Vacuum System	2.0	3.8	1.8				7.6
Magnet Power Supplies	118.8	16.8	2.4	1.1	0.3		139.3
Instrumentation	1.3	0.7	0.2				2.2
Radiation Protection	0.3		0.1				0.4
Control System	1.0	0.6	0.2	0.0	0.0		1.8
Experimental devices					4.0		4.0
Utilities	44.7	3.5	2.0	0.6	1.2		52.0
General services	7.2		0.3	0.2	0.2	12.0	19.8
RF system			0.8				0.8
TOTAL	361.9	27.5	18.9	1.8	6.8	12.0	428.9