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ISSUES RELATED TO CEPC e+/e- INJECTION*

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Abstract

Circular Electron-Positron Collider (CEPC) is a 100 km ring collider as a Higgs factory. It consists of a double ring collider, a full energy booster, a Linac and several transport lines. The Linac is a normal conducting S-band and C-band linear accelerator and provide electron and positron beam at an energy up to 30 GeV with repetition frequency of 100 Hz. After a conventional positron source, there is a 1.1 GeV damping ring to reduce the emittance of positron beam. C-band accelerating structures are adopted to accelerate electron and positron beam from 1.1 GeV to 30 GeV. For Z mode, in order to obtain higher injection speed, the Linac operates in double-bunch acceleration mode. The physics design and dynamic simulation results of the Linac will be detailed presented in this paper.

INTRODUCTION

The Higgs boson was discovery at the ATLAS and CMS experiments of the Large Hadron Collider at CERN in July 2012 [1, 2]. In Autumn 2012, Chinese scientists proposed a Circular Electron Positron Collider (CEPC) at 240 GeV centre of mass for Higgs studies [3]. The CEPC is a 100 km ring collider as a Higgs factory and it could later be used to host a Super Proton Proton Collider (SppC) as a machine for new physics and discovery. The CEPC accelerator comprises a double ring collider, a booster, a Linac and several transport lines. The booster and the collider ring are placed in the same tunnel and have the same circumference, which is about 100 m underground. In addition to the Higgs mode (120 GeV), CEPC will also run in W (80 GeV), Z (45.5 GeV), and ttbar mode (180 GeV).

From the pre-CDR stage to TDR stage, the CEPC Linac has undergone several iterations [4, 5] and evolution of parameters is shown in Fig. 1. For the 100 km booster with maximum extraction energy of 180 GeV, the dipole magnetic field is low at the injection energy and high at the maximum extraction energy. So, the design of booster dipole magnet and power supply is very difficult. In order to solve the problem, we choose the injection energy as 20 GeV and used iron-corn magnet which material is oriented silicon steel sheet. However, non-oriented silicon steel sheet is very expensive. If the Linac energy is increased from 20 GeV to 30 GeV, booster dipole magnet material can use non-oriented silicon steel sheet instead of oriented silicon steel sheet. Comprehensively considering the cost of the injector, the Linac energy was determined to be 30 GeV. Currently, for the latest scheme of Linac, the energy is 30 GeV, emittance is 6.5 nm and the bunch charge is 1.5 nC. Considering maintaining the potential to meet high requirements and future upgrades, the maximum bunch charge is 3 nC. At the Z mode with large bunch number in collider ring, the Linac run in double-bunch acceleration mode to speed up the injection speed.

Stage			PreCDR	CDR									TDR					
Parameter		Unit	V1	V2			V3								V4		
				V2.1	V2.2	V2.3	V3.1	V3.2	V3.3	V3.4	V3.5	V3.6	V3.7	V3.8	V4.1	V4.2	V4.3
Beam energy (e+/e-)	E_{e-}/E_{e+}	GeV	6	10					4	10			20	10/20	20		30
Repetition rate	f_{rep}	Hz	50					100									
Bunch number per pulse			1													1&2	
Bunch population (e+/e-)	N_{e-}/N_{e+}	$\times10^9$	20				6.25			6.25(18.8)	9.4 (18.8)						
		nC	3.2				1			1(3)	1.5 (3)						
Energy spread (e^+/e^-)	σ_E	$\times10^{-3}$	1				2								1.5		
e^- bunch charge at target		nC	10														
e^- beam energy at target		GeV	4						2	4							
Emittance	ε	nm	300								120		60	40	10		6.5
Damping Ring			Yes			No					Yes	Yes			Yes		
	E_{e+}	GeV	1.1								1.1	1.1			1.1		
	C	m	58.5								58.5	75.4			147		
	ε_0	mm-mrad	287								287	377			94		
Bunch compressor			No							Yes	No		Yes				
Accelerating strucutre			S-band										S-band+C-band				
RF frequency	f_{RF}	MHz	2856.75									2860	2860/5720				
Accelerating gradient		MV/m	15/27	18/27 or. 18/21			21						22 & 27/45				
Klystron-to-ACC.Struc.			1-t-2	1-t-2 or. 1-t-4			1-t-4						1-t-4 & 1-t-2(S)/1-t-2(C)				
Shared Linac Energy range		MeV	200-1100		No												
Linac tunnel length		km	600	1200					500	1200			1400				1800
Collider circumference		km	54 & 61	61			100										
Layout			shared Linac	3 layout schemes			TGB or EBTL		Pre-BST	EBTL							
Date			Apr-16	Nov-16			Dec-16	Apr-17	Aug-17	Oct-17	Dec-17	Jul-18	Mar-19	Sep-19	May-21	Mar-22	Jun-22

Figure 1: Evolution of the CEPC Linac parameters.

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LAYOUT

The CEPC Linac can provide electron and positron beams with energy up to 30 GeV. The Linac is composed of an electron source and bunching system (ESBS), a first accelerating section (FAS) where electron beam is accelerated to 4 GeV, a positron source and pre-accelerating section (PSPAS) where positron beam is produced and accelerated to 200 MeV, a second accelerating section (SAS) where positron beam is accelerated to 1.1 GeV, a third accelerating section (TAS) where electron beam and positron beam are accelerated from 1.1 GeV to 30 GeV, a 1.1 GeV electron bypass transport line (EBTL) where electron beam is bypassed in electron mode and a 1.1 GeV damping ring (DR) where positron beam is damped to reduce the emittance. In order to avoid the interference with energy analysing station, waveguide, positron source, transport lines between Linac and damping ring, and so on, the deflection direction of the EBTL is vertical and the separation distance is 1.2 m. The Linac layout is shown in Fig. 2. For the FAS, the bunch charge is about 10 nC for positron production, we use S-band accelerating structure to suppress the Wakefield effect. For the SAS, the emittance of positron beam is very large, so we use S-band accelerating structure, For the TAS, we use C-band accelerating structure to reduce Linac size and save cost. The Linac length is 1.6 km and there is about 200 m as reserved space, so the Linac tunnel length is about 1.8 km.

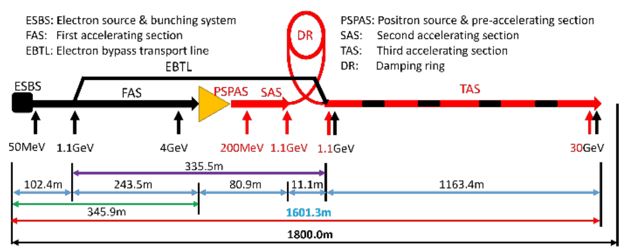

Figure 2: The layout of Linac.

Table 1: Main Parameters of Accelerating Structures

Parameter	Unit	S-band		C-band
Frequency	MHz	2860		5720
Length	m	3.1	2.0	1.8
Cavity mode		2π/3		3π/4
Aperture	mm	19~24	25	11.8~16
Gradient		22/27	22	45
Cells		85	55	89

BASIC CONSIDERATION

Wakefield

Main parameters of accelerating structures are shown in Table 1. For periodic structure, the high frequency longitudinal impedance was found by R. Gluckstern [6], with a modification by K. Yokoya and K.L.F. Bane [7], and the short-range dipole wake was given by K.L.F. Bane [8]. The Wakefields of S-band and C-band accelerating structure are shown in Fig. 3.

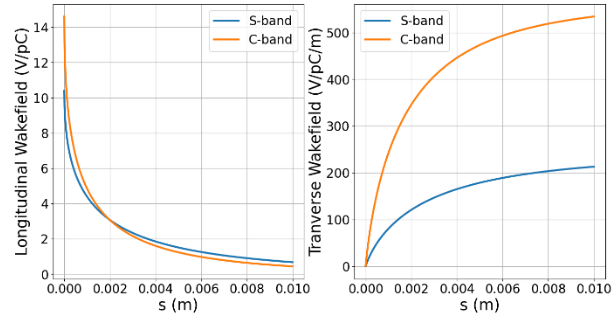

Figure 3: Wakefields of accelerating structure.

Bunch Length

We scan the bunch charge and bunch length and simulated the energy spread for the TAS, which is shown in Fig. 4. In order to meet the requirement of energy spread, we choose the bunch length as 0.4 mm. So, at the beginning of the TAS, we need a bunch compressor.

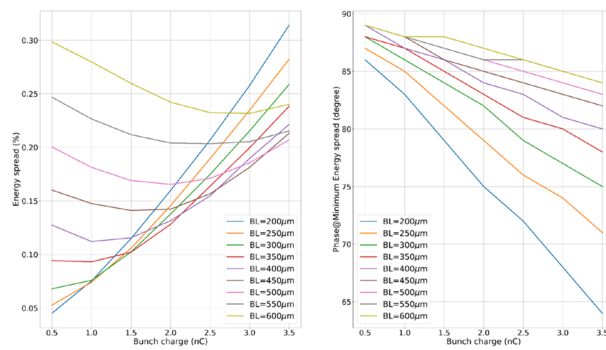

Figure 4: Energy spread with different bunch charge and bunch length.

Bunch Compressor

Generally, one bunch compressor system includes one RF cavity system providing a momentum chirp and a chicane compressing bunch length, which of the layout is shown in Fig. 5.

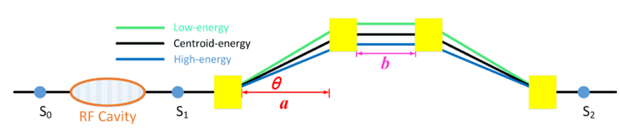

Figure 5: Layout of bunch compressor.

where *0*, *1*, *2* represent the position of the entrance of RF cavity, the entrance of and the exit of chicane, z is the longitudinal position deviation from bunch center, δ is the energy spread, E is the centroid energy, φ_0 is the synchronous phase of RF cavity. We can get the phase and voltage of RF cavity and R_{56} of chicane from the following equation:

$$F = \frac{\langle z_0^2\rangle - \langle z_2^2\rangle}{\langle z_0^2\rangle\langle z_2^2\rangle}\langle \delta_0^2\rangle \quad (1)$$

$$k = \frac{2\pi f}{c} \quad (2)$$

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$$f = \sqrt{\frac{\langle z_2^2 \rangle}{\langle z_0^2 \rangle}} \tag{3}$$

$$\varphi_0 = \arctan\left(\sqrt{\frac{k^2}{4F} - 3} - \frac{k}{2\sqrt{F}}\right) \tag{3}$$

$$V = \frac{\sqrt{F} E_0}{k \cos \varphi_0} \tag{4}$$

$$R_{56}^{ch} = \frac{(f^2-1)}{\sqrt{F}}\left(1 + \frac{\sqrt{F}\tan\varphi_0}{k}\right). \tag{5}$$

ELECTRON LINAC

The electron Linac includes ESBS, a part of FAS with energy of 1.1 GeV, EBTL and TAS. The ESBS comprise a thermal cathode electron gun, two subharmonic bunchers, a buncher, and an accelerating structure [4]. ESBS can provide electron beam with bunch charge of 10 nC. The EBTL is a local achromatic design. The electron Linac is well matched. In the last part of TAS, the period phase advance is gradually smaller to reduce the strength requirements for the quadrupole magnet. The simulation results of electron Linac are shown in Fig. 6 and Table 2, which can meet the requirements.

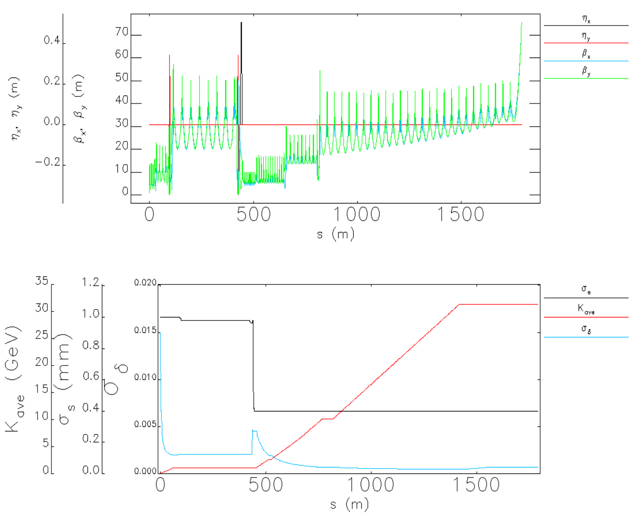

Figure 6: Dynamic results of electron Linac.

Table 2: Simulation Results of Electron Linac

Parameter	Unit	Value	Simulation	
			Electron	
Beam energy	GeV	30	31.3	30.8
Repetition rate	Hz	100	/	
Bunch charge	nC	1.5	1.5	3.0
Energy spread		1.5×10^{-3}	0.68×10^{-3}	1.37×10^{-3}
Emittance(x/y)	nm	6.5	1.35/1.33	1.4/1.6
Bunch length	mm	/	0.4	0.4

POSITRON LINAC

The Positron Linac includes electron beam part of ESBS and FAS and positron beam part of PSPAS, SAS and TAS. S-band accelerating structures are used in FAS and the dynamic results are shown in Fig. 7. The PSPAS [9] is composed of a target, a flux concentrator which is an adiabatic matching device (AMD), 6 larger aperture S-band constant-impedance accelerating structures and a beam separation system. A schematic layout of the positron source is shown in Fig. 8. For SAS, there are 10 larger aperture accelerating structures with gradient of 22 MV/m and 8 normal S-band accelerating structures with gradient of 27 MV/m. Triplet structure is outside each accelerating structure. According to the start-to-end simulation of PAPAPAS and SAS, the positron yield is 0.45 positron particle per electron particle at energy of 1.1 GeV. Optics function of the SAS is shown in Fig. 9. After the damping ring, the positron beam is accelerated from 1.1 GeV to 30 GeV in the TAS and simulation results are shown in Fig. 10 and Table 3.

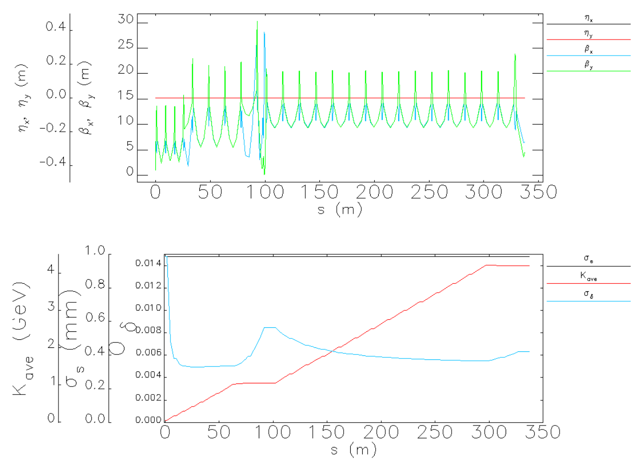

Figure 7: Dynamic results of FAS.

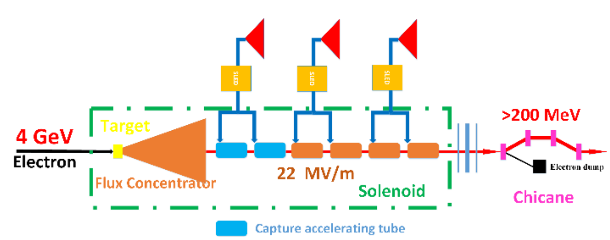

Figure 8: The layout of CEPC positron source.

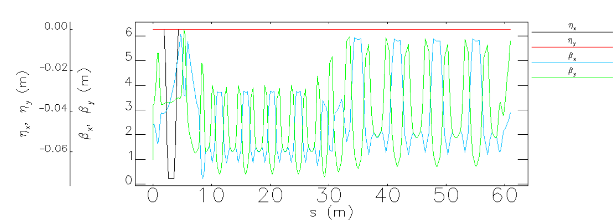

Figure 9: Optics function of SAS.

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Table 3: Simulation Results of Positron Linac

Parameter	Unit	Value	Simulation Electron	
Beam energy	GeV	30	31.3	30.8
Repetition rate	Hz	100	/	
Bunch charge	nC	1.5	1.5	3.0
Energy spread		1.5×10^{-3}	1.29×10^{-3}	2.16×10^{-3}
Emittance(x/y)	nm	6.5	3.29/1.64	3.80/1.66
Bunch length	mm	/	0.4	0.4

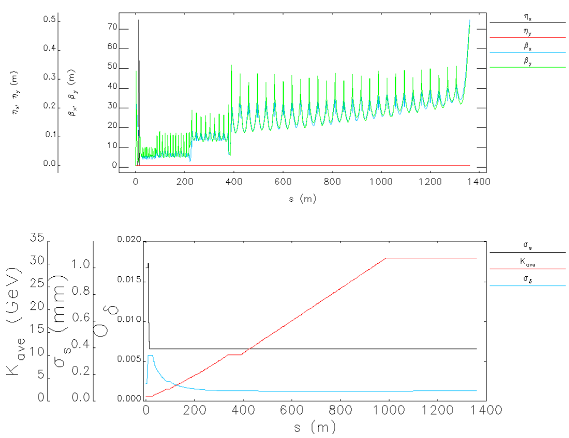

Figure 10: Dynamic results of TAS.

DOUBLE-BUNCH ACCELERATION

The repetition rate of the Linac is 100 Hz. In order to meet the injection speed requirement for Z mode, the Linac need to double the bunch repetition rate. A simpler scheme is increasing the repetition rate to 200 Hz, but it will increase the cost greatly. At last, we chose double-bunch acceleration mode. In this case, the most important issues are the frequency relationship. Considering the RF frequency of each accelerator and the time resolution ability of the detector, we give the timing related parameters and the harmonic number and beam pattern information of the collider ring, which are shown in Table 4. In order to get more flexible injection scheme and have better compatibility potential, we also consider use a RF gun. The bunch spacing in the Linac is about 70 ns, it is not too large and still can use pulse compressor even for C-band accelerating structure.

Table 4: Parameters of Timing System and Bunch Pattern Information

Parameter	Unit	High luminosity Z mode Baseline scheme	RF gun scheme
Repetition frequency	Hz	100	
Common frequency	MHz	130	
Linac common frequency	MHz	14.44	43.33
Bunch frequency	MHz	14.44	43.33
SHB1 RF frequency	MHz	158.89	/
SHB2 RF frequency	MHz	476.67	/
LINAC RF frequency	MHz	2860.00	
	MHz	5720.00	
Damping ring RF frequency	MHz	650.00	
Booster RF frequency	MHz	1300.00	
Ring RF frequency	MHz	650.00	
Bunch spacing @Collider	ns	23.08	23.08
Bunch spacing @Linac	ns	69.23	23.08
Injection scheme		bunch-by-bunch	pulse-by-pulse bunch-by-bunch
Harmonic number		45*(2k) + [10, 20, 40] 45*(2k+1) + [5, 25]	5(2k)+ [2,4] 5(2k+1) + [1,3]
Bunch number per train		6n	2n

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CONCLUSION

The CEPC Linac is a normal conduction S-band and C-band linear accelerator with repetition rate of 100 Hz and can provide electron and positron beam with energy of 30 GeV. One conventional positron source is adopted with electron beam energy of 4 GeV. For Z mode, the Linac will run in double-bunch acceleration mode to double the injection speed. Simulation results of all the Linac was present and the design of Linac can meet the requirement.

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