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DESIGN AND BEAM DYNAMICS OF THE CEPC BOOSTER*

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Abstract

The CEPC booster needs to provide electron and positron beams to the collider at different energy with required injection speed. A 10 GeV linac is adopted as the injector for CDR. Then the beam energy is accelerated to specific energy according to three modes of CEPC collider ring (H, W and Z). The geometry of booster is designed carefully in order to share the same tunnel with collider. The design status of booster including parameters, optics and dynamic aperture is discussed in this paper.

INTRODUCTION

The CEPC baseline design for CDR is a 100km double ring scheme with a same size booster whose energy starts from 10 GeV [1]. The booster provides electron and positron beams to the collider at different energies. Both the injection from zero current and the top-up injection should be fulfilled. Figure 1 shows the overall layout of CEPC injection chain. 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 two detectors on collider ring.

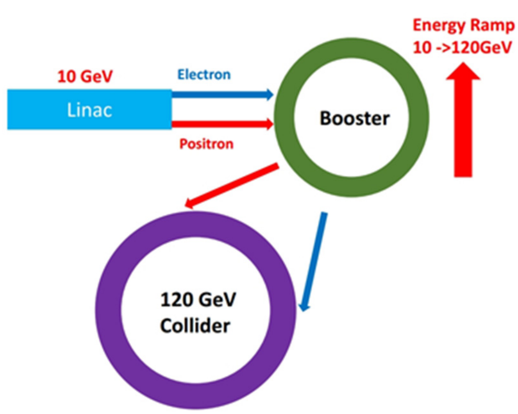

Figure 1: Overall layout of the CEPC injection chain.

BOOSTER PARAMETERS

Booster Design Requirements

The beam quality requirements in the booster are determined by the collider ring and the total beam current in the booster is limited by the RF power which is 1.0mA for Higgs, 4.0 mA for W and 10mA for Z. The energy acceptance of booster should be larger than 1% at four energy modes and the booster emittance at 120GeV should be lower than 3.6 nm in order to fulfill the requirement of injection to collider ring. The coupling of booster should be controlled under 0.5% which is defined by the requirement of Higgs on-axis injection scheme [1]. We assume 3% current decay for top up injection and the total efficiency of CEPC injection chain is 90%. With the limit for total beam current and the assumption of current decay in collider ring, the top up injection for Higgs mode and W mode needs only one cycle, and needs two cycles for Z mode. The top up injection time structures for the three energy modes are shown in Fig. 2. Furthermore, the dynamic aperture should be large enough for both injection and extraction to guarantee the required transfer efficiency which will be discussed in the last chapter.

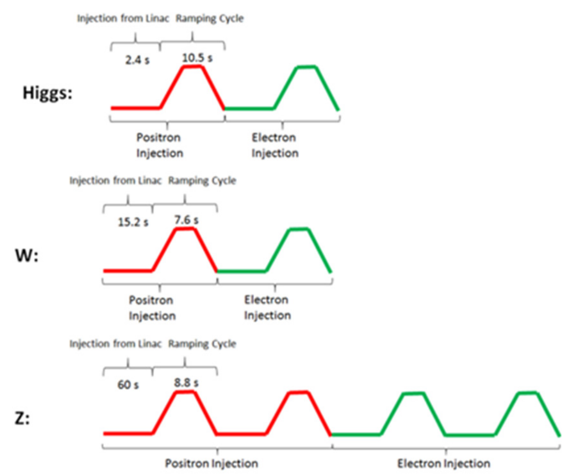

Figure 2: Top up injection time structure for Higgs, W and Z modes.

Beam Parameters at Different Energy

The main booster parameters at injection and extraction energies are listed in Table 1 and Table 2. The beam is injected from linac to booster by on-axis scheme and then injected from booster to collider at three different energies by off-axis scheme. Also the on axis injection from booster to collider for Higgs has been designed in case the dynamic aperture of collider ring at Higgs energy is not good enough for the off-axis injection.

After energy ramping, the booster emittance for Higgs and W approaches the value small enough to inject into the collider. The beam emittance for Z mode after energy ramping still cannot fulfil the collider injection requirement and further damping (5s) is needed before extraction from the booster. The emittance evolution in the booster for three energy modes is show in Fig. 3.

The top up injection time is 25.8 seconds for Higgs off-axis mode, 35.4 seconds for Higgs on-axis mode, 45.8

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seconds for W and 4.6 minutes for Z. When the collider is injected from zero current, the beam lifetime is much longer than the top up injection. At that time, the beam lifetime in collider is dominated by the Touschek effect which is about 695 hours for Higgs, 75 hours for W and about 33 hours for Z. The full injection time from 0 current for both beams is 10 minutes for Higgs, 15 minutes for W and 2.2 hours for Z (bootstrapping start from half of the design current).

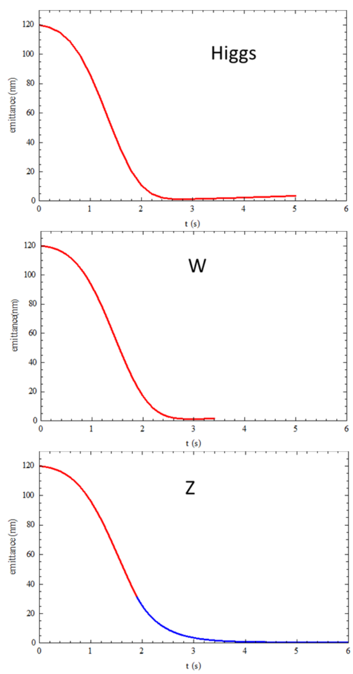

Figure 3: Emittance evolution in the booster from injection to extraction (top: Higgs, middle: W, bottom: Z).

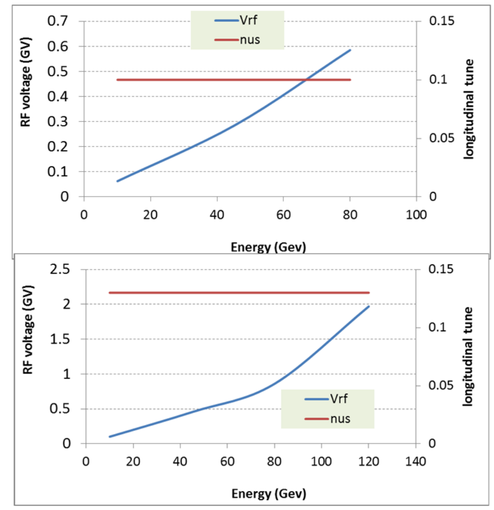

Figure 4: Booster RF ramping curve (top: Z & W, bottom: Higgs).

The RF voltage and longitudinal tune of the booster during ramping for the three energy modes are shown in Fig. 4. The longitudinal tune is constant (0.1) during ramping for Z and W. The longitudinal tune is 0.13 for Higgs to get larger energy acceptance for the on axis injection scheme. The beam lifetime is long enough during the ramping process which is 4.0×10^9 hours at 10 GeV, dominated by the transverse quantum lifetime, and is 7.8×10^{17} hours at 120 GeV, dominated by the longitudinal quantum lifetime.

Table 1: Main Parameters for the Booster at Injection Energy

		H	*W*	*Z*
Beam energy	GeV		10	
Bunch number		242	1524	6000
Threshold of single bunch current	μA		25.7	
Threshold of beam current (limited by coupled bunch instability)	mA		100	
Bunch charge	nC	0.78	0.63	0.45
Single bunch current	μA	2.3	1.8	1.3
Beam current	mA	0.57	2.86	7.51
Energy spread	%		0.0078	
Synchrotron radiation loss/turn	keV		73.5	
Momentum compaction factor	10^{-5}		2.44	
Emittance	nm		0.025	
Natural chromaticity	H/V		-336/-333	
RF voltage	MV		62.7	
Betatron tune $\nu_x/\nu_y/\nu_s$			263.2/261.2/0.1	
RF energy acceptance	%		1.9	
Damping time	s		90.7	
Bunch length of linac beam	mm		~1.0	
Energy spread of linac beam	%		0.2	
Emittance of linac beam	nm		<120	

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Table 2: Main Parameters for the Booster at Extraction Energy

		H		*W*	*Z*
		Off axis injection	On axis injection	Off axis injection	Off axis injection
Beam energy	GeV	120		80	45.5
Bunch number		242	235+7	1524	6000
Maximum bunch charge	nC	0.72	24.0	0.58	0.41
Maximum single bunch current	μA	2.1	70	1.7	1.2
Threshold of single bunch current	μA	300			
Threshold of beam current (limited by RF power)	mA	1.0		4.0	10.0
Beam current	mA	0.52	1.0	2.63	6.91
Injection duration for top-up (Both beams)	s	25.8	35.4	45.8	275.2
Injection interval for top-up	s	47.0		153.0	504.0
Current decay during injection interval		3%			
Energy spread	%	0.094		0.062	0.036
Synchrotron radiation loss/turn	GeV	1.52		0.3	0.032
Momentum compaction factor	10^{-5}	2.44			
Emittance	nm	3.57		1.59	0.51
Natural chromaticity	H/V	-336/-333			
Betatron tune ν_x/ν_y		263.2/261.2			
RF voltage	GV	1.97		0.585	0.287
Longitudinal tune		0.13		0.10	0.10
RF energy acceptance	%	1.0		1.2	1.8
Damping time	ms	52		177	963
Natural bunch length	mm	2.8		2.4	1.3
Injection duration from empty ring	h	0.17		0.25	2.2

BOOSTER OPTICS

The design goal for the booster optics is to make sure the geometry is the same as the collider and satisfy the requirements of beam dynamics. The total number of magnets and sextupole families is minimized taking into account capital and operating costs. The maximum cell length and hence the maximum emittance in the booster is limited by the collider injection requirements.

Survey Design

Figure 5 shows the geometry of booster compared with the collider and Fig. 6 shows the cross section of the tunnel. Both CEPC collider and booster are located inside the same tunnel, and booster is on the top of collider. The horizontal position of the booster has been designed in the center of collider two beams. The horizontal position error of booster was controlled under ±0.17m. To do it, the precision of element length and bending angle has to be controlled carefully.

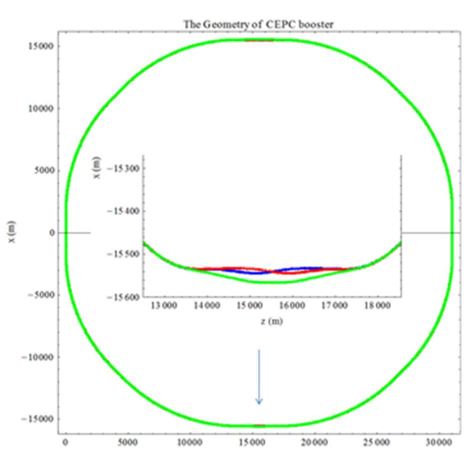

Figure 5: Booster vs. collider layouts.

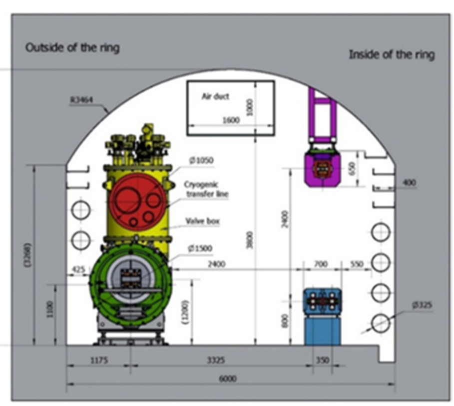

Figure 6: The cross section of CEPC tunnel.

Arc Region

Standard FODO cells have been chosen for the booster lattice [2]. The length of two FODO cells in the booster corresponds to three FODO cells in the collider. The phase advance of each cell is 90/90 degrees in the horizontal and vertical planes. The length of each bend is 46.4 m including ten short dipole magnets. The length of each

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quadrupole is 1.0 m, while the distance between each quadrupole and the adjacent bending magnet is 1.6 m. Thus the total length of each FODO structure is 101 m. 97 FODO structures make up an octant. At the two ends of each octant, there are dispersion suppressors and straight sections. We need to adjust bend strength in the dispersion suppressors in order to match the geometry of collider ring. Figure 7 shows the twiss functions of the FODO cell and Fig. 8 shows twiss functions of the dispersion suppressor.

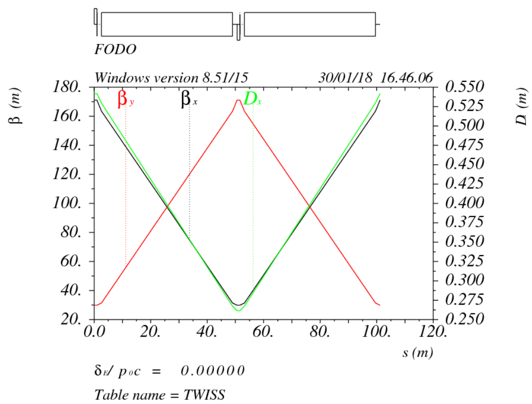

Figure 7: The Twiss functions of the FODO cell.

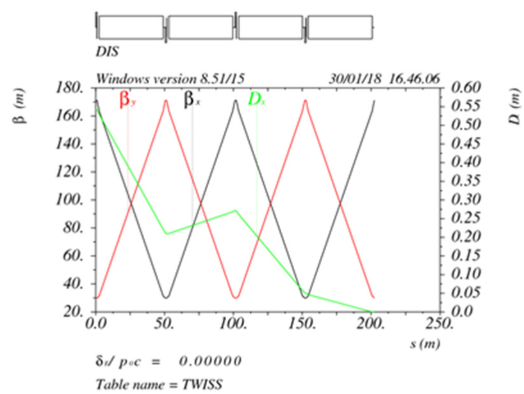

Figure 8: The Twiss functions of the dispersion suppressor.

Injection Region

The length of the straight sections for injection/extraction is exactly the same as in the collider. Figure 9 shows the lattice functions in the injection/extraction region. The phase advance in the injection straight section is tunable for adjusting the working point of the entire ring and also optimizing the off-momentum DA.

RF Region

In the RF section, dedicated optics with a lower beta function is designed to reduce the multi-bunch instability due to the RF cavities. Two matching sections whose phase advances are tunable at the two ends of the RF straight section transfer the beta function from the standard arc to the low beta section. Figure 10 shows the lattice functions in the RF region. The length of the low beta section is 1.6 km and the total length of the RF straight section is 3.4 km which is exactly same as the collider ring.

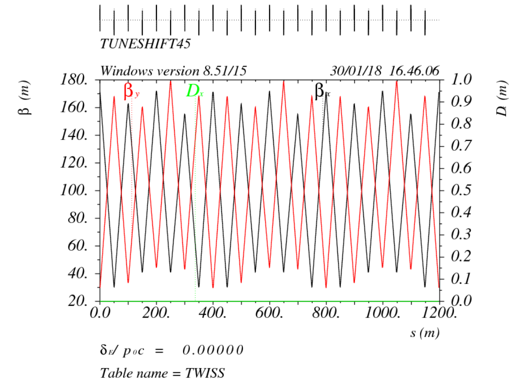

Figure 9: The Twiss functions of injection straight section.

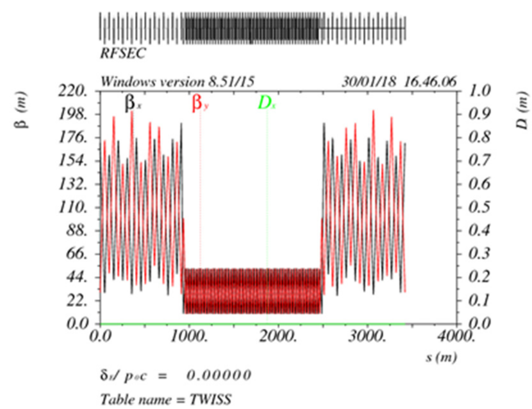

Figure 10: The Twiss functions of RF straight section.

IR Region

The geometry of booster is same as collider ring except for the IR. In the IR region, the booster is bypassed from the outer side to avoid a conflict with the CEPC detectors. The separation between the detector center and booster is 25 m considering the requirements of civil engineering and the radiation protection. Figure 11 shows the lattice functions in the IR.

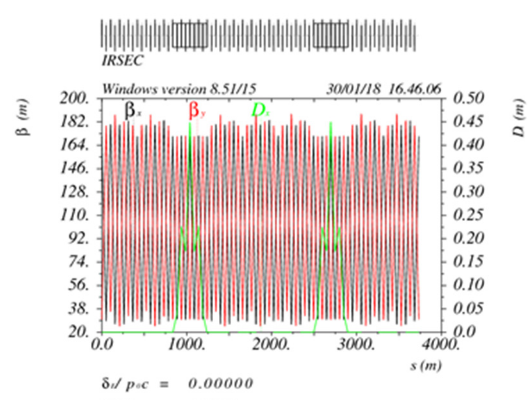

Figure 11: The Twiss functions of IR bypass.

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Sawtooth Effect

With only two RF stations, the maximum sawtooth orbit is 1.7 mm at 120GeV. The off-centre orbits in sextupoles result in extra quadrupole fields and hence result in ~2% distortion of optics. The maximum dispersion distortion is about 50 mm and the emittance growth is about 0.3%. The orbit and optics of booster with sawtooth effect at 120GeV is shown in Fig. 12. No DA reduction due to sawtooth effect is seen in booster. So magnets energy tapering is unnecessary in booster.

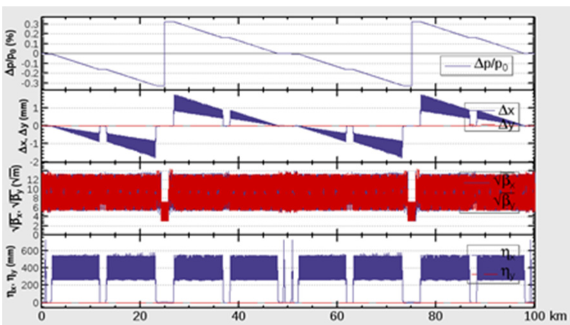

Figure 12: Booster orbit and optics with sawtooth effect at 120GeV.

Off-momentum DA Optimization

The phase of the injection/extraction straight section between two octants is optimized automatically by downhill method [3]. The DA result at 120GeV after optimization without errors is shown in Fig. 13. The design goal is to reach 1% energy acceptance at 120GeV including all kinds of errors which is the requirement of re-injection process for the on-axis injection scheme.

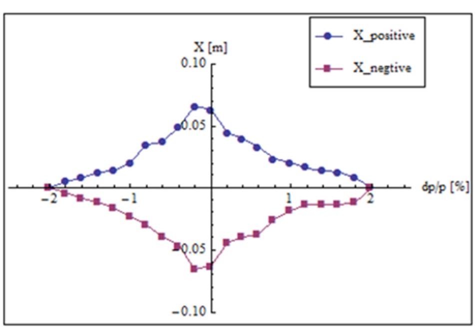

Figure 13: Off-momentum DA at 120 GeV (without errors) after optimization with phase tuning in injection/extraction section.

PERFORMANCE WITH ERRORS

Error Analysis

Table 3 lists the details of the error settings. Gaussian distribution for the errors is used and is cut off at 3σ. With these errors, the closed orbits are smaller than the beam pipe whose diameter is 55mm so first turn trajectory correction is unnecessary. Four horizontal/vertical correctors and 8 BPMs are inserted every 2π phase advance, so totally 1054 horizontal correctors and 1054 vertical correctors are used to correct orbit distortions. Figure 14 shows the closed orbit after correction. The maximum orbit is smaller than 1mm after orbit correction.

11000 locations in the ring and 10 random seeds are chosen to generate distributions for orbit, dispersion and beta-beat. After COD correction, the rms orbit is 80 μm; the rms dispersion is 14 mm and the rms betabeat is 3.5%. Without coupling correction, the relative vertical emittance by coupling is less than 10%. Then 512 Sextupoles are used to correct the coupling and residual coupling after correction is controlled under 0.5% which is shown in Fig. 15.

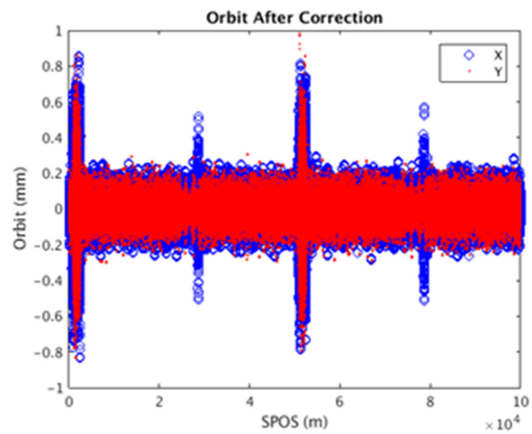

Figure 14: Closed orbit after correction.

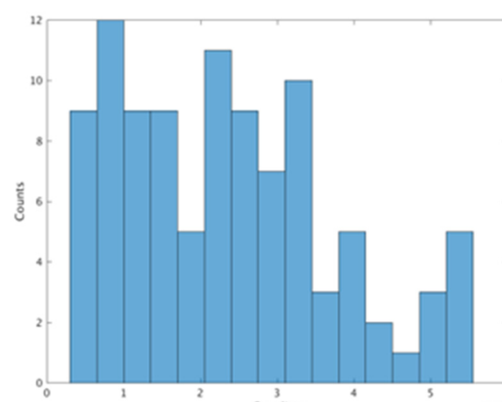

Figure 15: Coupling distribution after coupling correction (100 random seeds).

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Table 3: Error Analysis Settings

Parameters	*Dipole*	*Quadrupole*	*Sextupole*	*Parameters*	*BPM (10Hz)*
Transverse shift x/y (μm)	50	70	70	Accuracy (m)	1×10^{-7}
Longitudinal shift z (μm)	100	150	100	Tilt (mrad)	10
Tilt about x/y (mrad)	0.2	0.2	0.2	Gain	5%
Tilt about z (mrad)	0.1	0.2	0.2	Offset after BBA(mm)	30×10^{-3}
Nominal field	3×10^{-4}	2×10^{-4}	3×10^{-4}		

Dynamic Aperture

A non-interleave scheme and two sextupole families are adopted for linear chromaticity correction. Both the phase advances between sextupole pairs and the ones between octants are optimized carefully in order to achieve larger dynamic aperture. The thick black line in Fig. 16 shows the dynamic aperture of bare lattice; the purple line is the DA with errors and orbit corrections; the red line is the DA with errors; the thin black line in the upper plot is the beam stay clear region at 10GeV and the blue line in the lower plot is the DA with orbit corrections, radiative damping and sawtooth effect at 120GeV.

With errors and orbit corrections, the dynamic aperture of the booster is nearly two thirds of that for the bare lattice as shown in Fig. 16. At 10GeV, the DA with errors should be larger than the beam stay clear region. At 120GeV, the radiative damping effect and sawtooth effect is also considered except for the error effect, and the according DA result including damping and sawtooth is shown as the blue line in the lower plot of Fig. 16. The DA requirement and the real DA results which have been realized are listed in Table 4. Where the DA requirement at 10GeV is determined by the beam stay clear region and is determined by the re-injection process from the collider in the on-axis injection scheme at 120GeV.

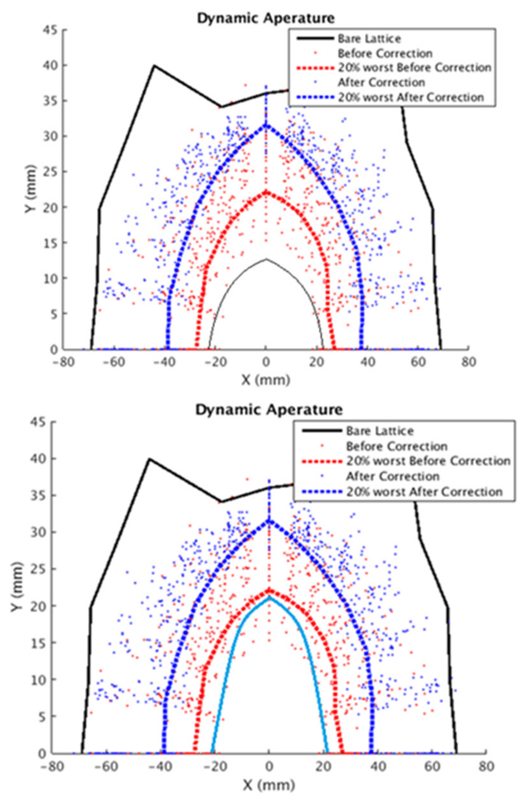

Figure 16: Dynamic aperture of booster (top: 10GeV, bottom: 120GeV).

Table 4: Summary of Booster DA Results

	DA requirement		*DA results*	
	H	V	H	V
10GeV ($\varepsilon_x = \varepsilon_y$ =120nm)	$4\sigma_x$ +5mm	$4\sigma_y$ +5mm	$7.7\sigma_x$ +5mm	$14.3\sigma_y$ +5mm
120GeV (ε_x=3.57nm, $\varepsilon_y = \varepsilon_x$*0.005)	$6\sigma_x$ +3mm	$49\sigma_y$ +3mm	$21.8\sigma_x$ +3mm	$779\sigma_y$ +3mm

SUMMARY

The design status of CEPC 100km booster has been introduced and so far it can meet the injection requirements at three energy modes. Both parameters and optics design was explained in detail. The design goal for the optics is to make sure the geometry of booster can match the one of collider and satisfy the requirements of beam dynamics. A lot of efforts for geometry design and nonlinearity optimization with special sextupoles arrangement have been done. Error studies were also included. The DA results shown the errors in the booster are tolerable.

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