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Low Emittance Optics Design for CEPC Booster

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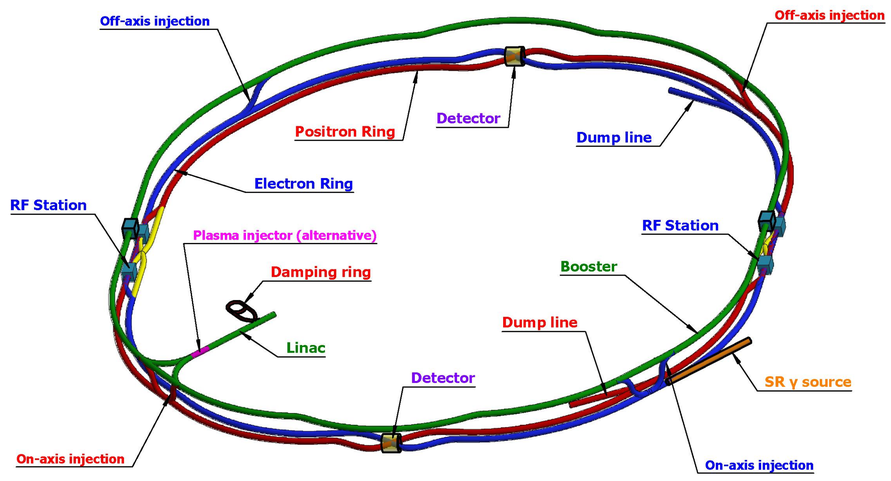
The CEPC booster has been designed to provide electron and positron beams at different energies for the collider. The latest booster design aligns with the TDR's higher luminosity objectives for four energy modes. The booster's optics have transitioned from FODO in the CDR to TME structure, resulting in a significant reduction in emittance to match the lower emittance of the collider in the TDR. Extensive efforts have been invested to address the challenge of error sensitivity for the booster, ensuring that the dynamic aperture with errors meets the requirements across all energy modes. Additionally, a combined magnets scheme (B+S) has been proposed to minimize the magnet construction costs and reduce the operation costs through lower power consumption.

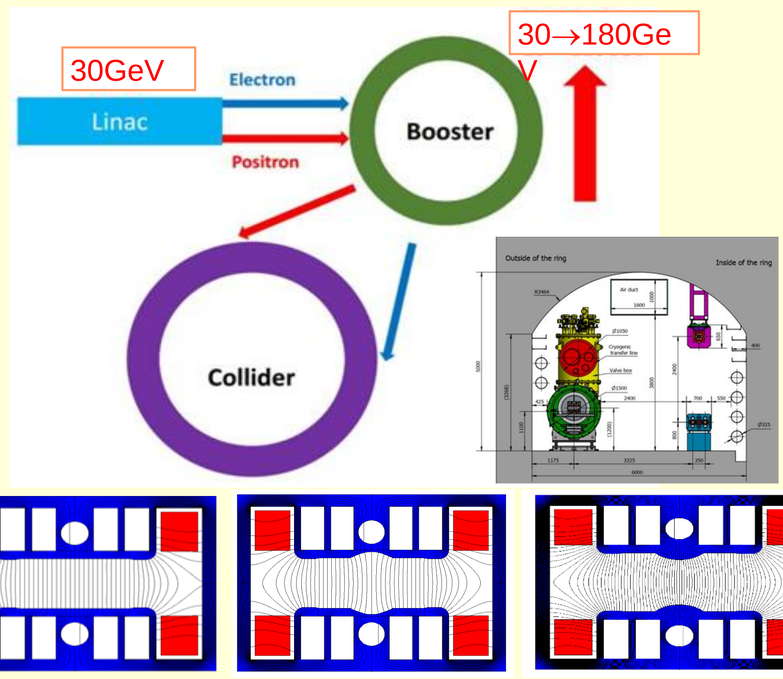
CEPC TDR Parameters（2023）

	Higgs	*W*	*Z (2T)*	*ttbar*
Number of IPs	2			
Circumference (km)	100.0			
Bunch number	268	1297	11934	35
Beta functions β_x^*/β_y^* (m/mm)	0.3/1	0.21/1	0.13/0.9	1.04/2.7
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.87/1.7	0.27/1.4	1.4/4.7
Energy acceptance (%)	1.6	1.0	1.0	2.0
Luminosity per IP ($10^{34}cm^{-2}s^{-1}$)	**5.0**	**16**	**115**	**0.5**

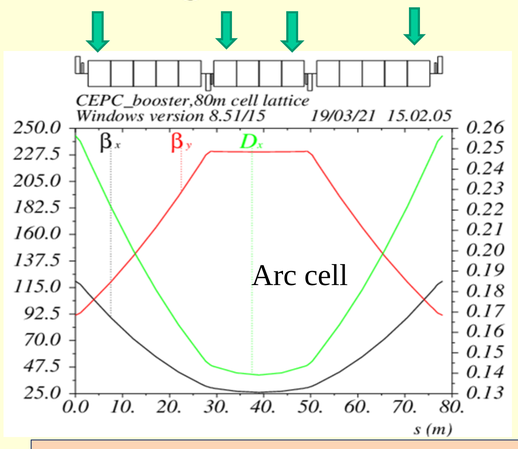
CEPC accelerator complex

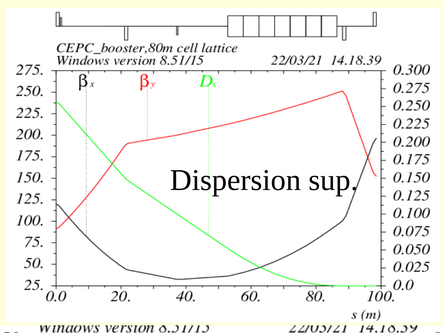


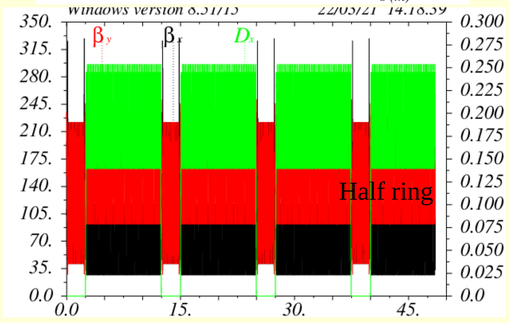
Booster design



- TME like structure (cell length=78m)
- Combined magnets (D+S)
- Interleave sextupole scheme
- Emittance@120GeV=1.26nm







- Lattice design with TME structure, lower emittance than CDR
- Sufficient Dynamic Aperture for all energies with errors

Booster parameters

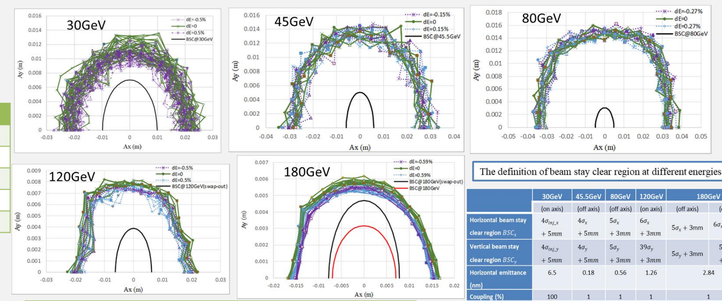
		tt	*H*	*W*	*Z*	
Beam energy	GeV	30				
Bunch number		35	268	1297	3978	5967
Threshold of single bunch current	μA	8.68	6.3	5.8		
Threshold of beam current (limited by coupled bunch instability)	mA	97	106	100	93	96
Bunch charge	nC	1.1	0.78	0.81	0.87	0.9
Single bunch current	μA	3.4	2.3	2.4	2.65	2.69
Beam 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 ν_x/ν_y		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				

		tt	*H*		*W*	*Z*	
		Off axis injection	Off axis injection	On axis injection	Off axis injection	Off axis injection	
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	μA	3.0	2.1	61.2	2.2	2.4	2.42
Threshold of single bunch current	μA	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 ν_x/ν_y		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

Error study

	Dipole	Quadrupole	Sextupole
Transverse shift X/Y (μm)	100	100	-
Longitudinal shift Z (μm)	100	150	-
Tilt about X/Y (mrad)	0.2	0.2	-
Tilt about Z (mrad)	0.1	0.2	-
Nominal field	1e-3	2e-4	3e-4

dipole	quadrupole
B1/B0 ≤ 2×10^{-4}	
B2/B0 ≤ 5×10^{-4}	B2/B1 ≤ 3×10^{-4}
B3/B0 ≤ 2×10^{-5}	B3/B1 ≤ 2×10^{-4}
B4/B0 ≤ 8×10^{-5}	B4/B1 ≤ 1×10^{-4}
B5/B0 ≤ 2×10^{-5}	B5/B1 ≤ 1×10^{-4}
B6/B0 ≤ 8×10^{-5}	B6/B1 ≤ 5×10^{-5}
B7/B0 ≤ 2×10^{-5}	B7/B1 ≤ 5×10^{-5}
B8/B0 ≤ 8×10^{-5}	B8/B1 ≤ 5×10^{-5}
B9/B0 ≤ 2×10^{-5}	B9/B1 ≤ 5×10^{-5}
B10/B0 ≤ 8×10^{-5}	B10/B1 ≤ 5×10^{-5}



	Accuracy (m)	Tilt (mrad)	Gain	Offset w/ BBA(mm)
BPM(10Hz)	1e-7	10	5%	30e-3

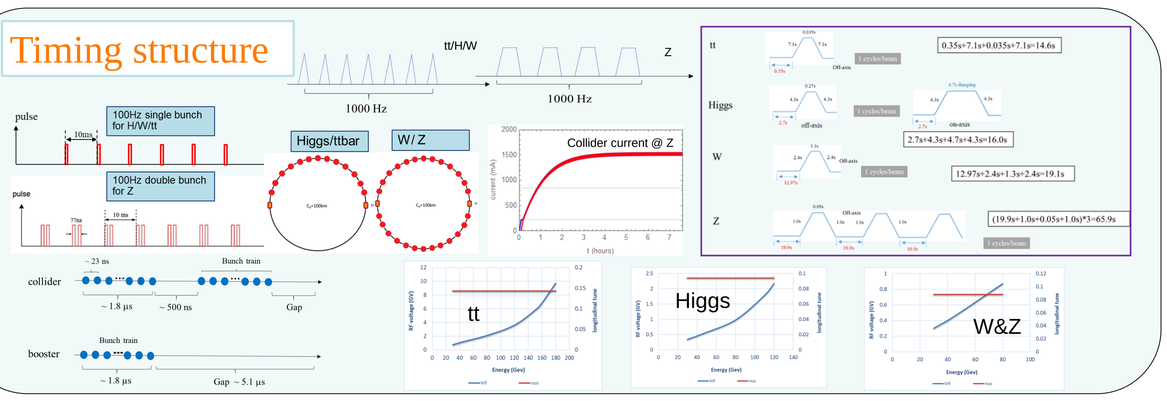
The definition of beam stay clear region at different energies

	30GeV	45.5GeV	80GeV	120GeV	180GeV
	(on axis)	(off axis)	(on axis)	(off axis)	(on axis)	(off axis)	(on axis)
Horizontal beam stay clear region BSC_x	$4\sigma_{x,y}$ + 5mm	$4\sigma_x$ + 5mm	$5\sigma_x$ + 3mm	$6\sigma_x$ + 3mm	$5\sigma_x$ + 3mm	$6\sigma_x$ + 3mm
Vertical beam stay clear region BSC_y	$4\sigma_{x,y}$ + 5mm	$4\sigma_y$ + 5mm	$5\sigma_y$ + 3mm	$39\sigma_y$ + 3mm	$5\sigma_y$ + 3mm	$50\sigma_y$ + 3mm
Horizontal emittance [nm]	6.5	0.18	0.56	1.26	2.84	
Coupling [%]	100	1	1	1	1	
Beam energy spread [%]	0.15	0.037	0.067	0.1	0.147	

Residual errors (rms)	X	Y
Orbit (mm)	0.1300	0.0724
Beta beating (%)	0.57	0.19
Dispersion (mm)	1.82	3.5

- Orbit/dispersion correction + optics correction

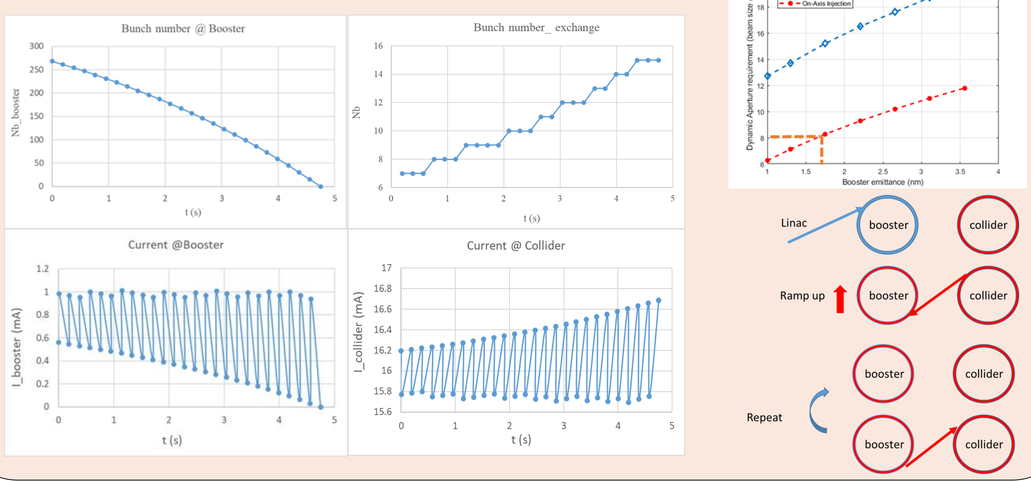
Timing structure



- R&D plan for EDR phase (2024-2027) before construction have been established, with the aim of starting the construction in “15th five-year-plan” (2026-2030) .

On-axis injection from booster to collider

- On-axis injection scheme was developed for CEPC @ Higgs to reduce the DA requirement of the collider ring.



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