

CEPC Parameter Optimization and Booster Design

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Many Thanks: K. Oide(KEK), Y. Cai (SLAC), K. Ohmi(KEK)

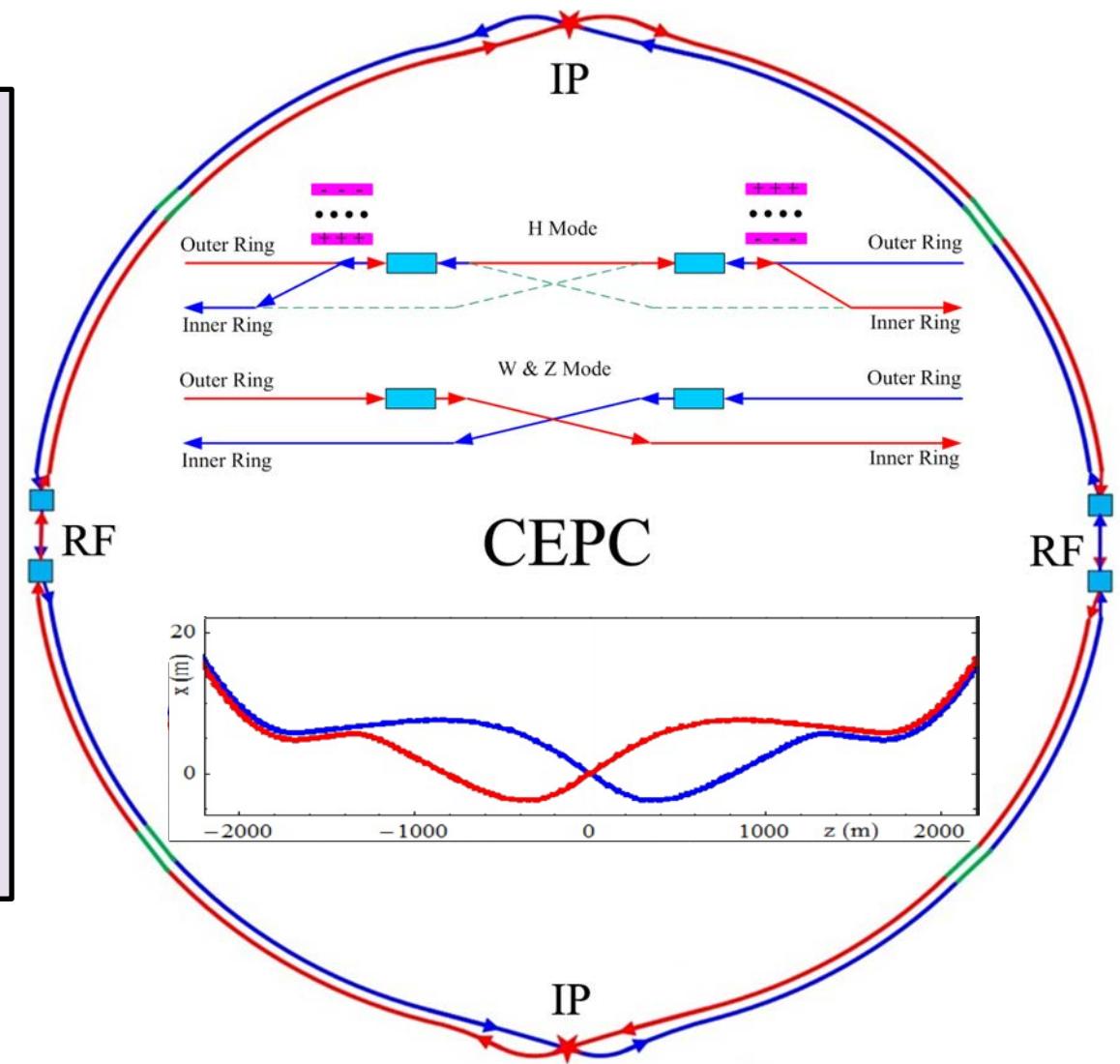
Outline

1. CEPC Parameter Optimization

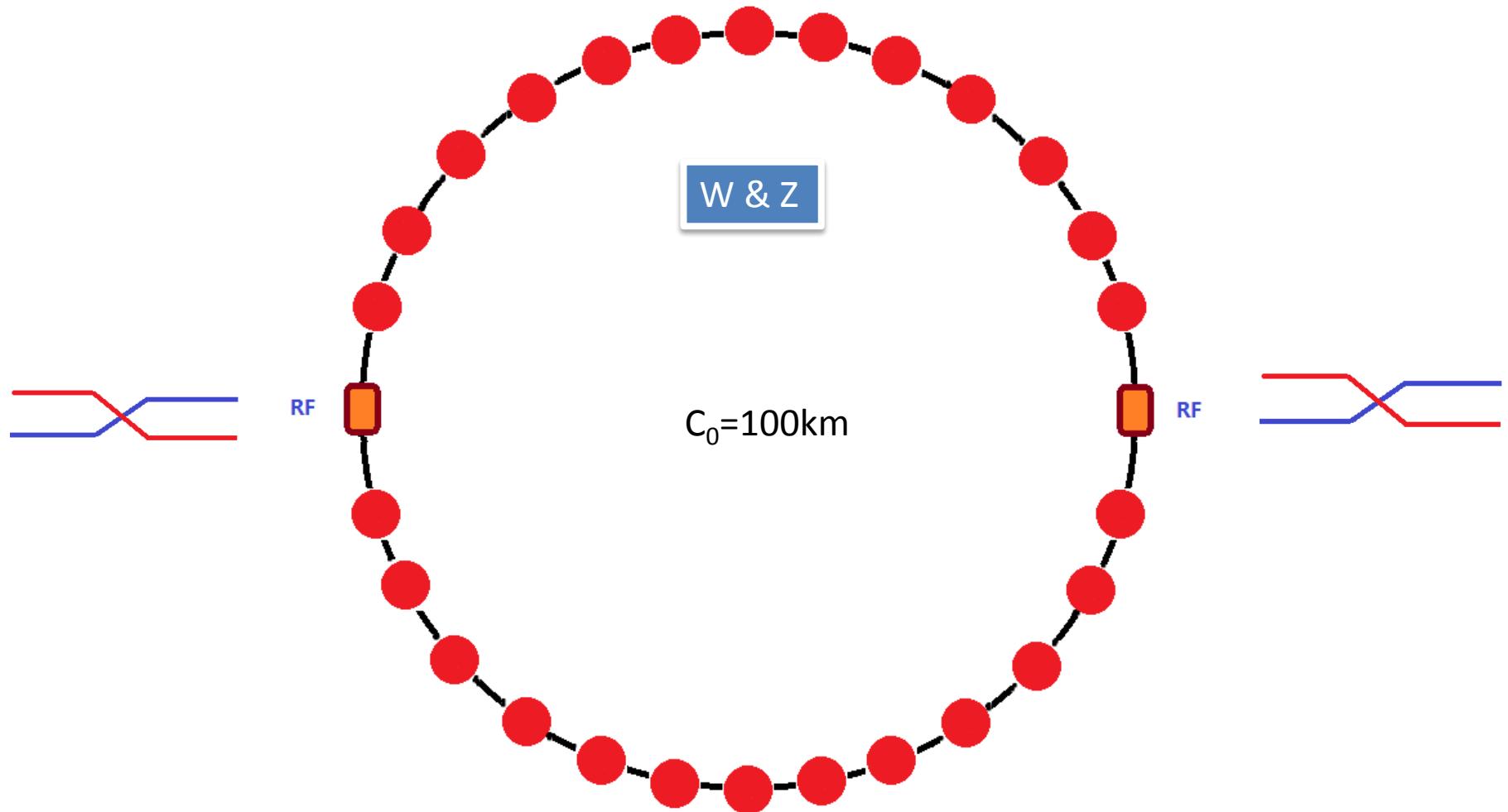
2. CEPC Booster Design

Layout of CEPC double ring

- 100 km
- Double ring
- 2 IPs
- Crab waist collision
- 3 energy modes:
Higgs, W, Z
- Shared RF @ H
- Independent RF @ W & Z

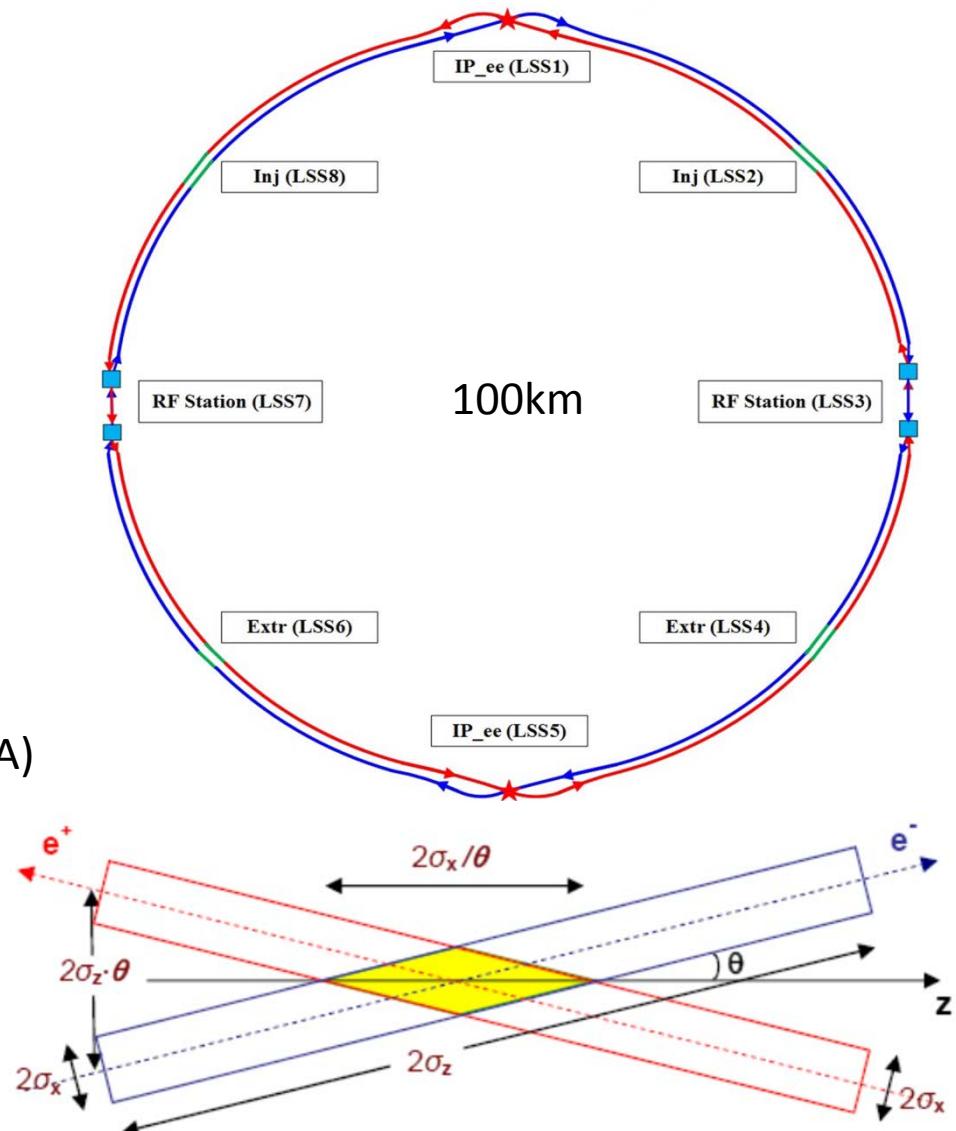


CEPC bunch distribution



Machine input / given parameters

- Energy $E_0 = \mathbf{120\text{GeV}}$
- Circumference $C_0 = \mathbf{100\text{km}}$
- $N_{IP} = \mathbf{2}$
- Beam power $P_0 \leq \mathbf{30\text{MW}}$
- $\beta_y^* = \mathbf{1.5\text{mm}}$
- Emittance coupling factor κ_e
- Bending radius $\rho = \mathbf{10.6\text{km}}$
- Crossing angle $\theta = \mathbf{33\text{mrad}}$
- ξ_y enhancement by crab waist F_l
- Energy acceptance requirement (DA)
- Phase advance per cell (FODO)



Constraint for CEPC parameter choice

➤ SR beam power

SR power for single beam: $\leq \text{30 MW}$

➤ Limit of Beam-beam tune shift*

$$\xi_y = \frac{2845}{2\pi} \sqrt{\frac{U_0}{2\gamma E_0 N_{IP}}} \times F_l \quad F_l: \xi_y \text{ enhancement by crab waist} \\ (F_l=2.0@\text{H}, 2.0@\text{W}, 2.6@\text{Z})$$

➤ Beam lifetime due to beamstrahlung

$$\text{BS life time: } \sim 30 \text{ min} \quad \frac{N_e}{\sigma_x \sigma_z} \leq 0.1 \eta \frac{\alpha}{3\gamma r_e^2}$$

➤ Beamstrahlung energy spread

$$A = \delta_0 / \delta_{BS} \quad (A \geq 5)$$

➤ HOM power per cavity (coaxial coupler)

$$P_{HOM} = k(\sigma_z) e N_e \cdot 2 I_b \leq 2 \text{ kW}$$

*J. Gao, emittance growth and beam lifetime limitations due to beam-beam effects in e+e- storage rings, Nucl. Instr. and methods A533 (2004) p. 270-274.

Parameter Optimization method

- start from the design goals
 - energy, luminosity/IP, number of IPs...
- consider very key beam physics limitations
 - beam-beam effects, Beamstrahlung effect, crab waist enhancement...
- take into account of economical and technical limitations
 - synchrotron radiation power, total AC power, HOM power/cavity, number of bunches due to instabilities...
- Include all the limitations in an analytical way
- An analytical optimized design method developed both for head-on collision and carb-waist collision.

CEPC CDR parameters

	<i>Higgs</i>	<i>W</i>	<i>Z</i>
Number of IPs		2	
Energy (GeV)	120	80	45.5
Circumference (km)		100	
SR loss/turn (GeV)	1.73	0.34	0.036
Half crossing angle (mrad)		16.5	
Piwnski angle	2.58	4.29	16.4
N_e /bunch (10^{10})	15	5.4	4.0
Bunch number (bunch spacing)	242 (0.68us)	3390 (98ns)	8332 (40ns)
Beam current (mA)	17.4	88.0	160
SR power /beam (MW)	30	30	5.73
Bending radius (km)		10.6	
Momentum compaction (10^{-5})		1.11	
β_{IP} x/y (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015
Emittance x/y (nm)	1.21/0.0031	0.54/0.0016	0.17/0.004
Transverse σ_{IP} (um)	20.9/0.068	13.9/0.049	5.9/0.078
ξ_x/ξ_y /IP	0.031/0.109	0.0148/0.076	0.0043/0.04
V_{RF} (GV)	2.17	0.47	0.054
f_{RF} (MHz) (harmonic)		650 (216816)	
Nature bunch length σ_z (mm)	2.72	2.98	3.67
Bunch length σ_z (mm)	3.26	3.62	6.0
HOM power/cavity (kw)	0.54 (2cell)	0.47(2cell)	0.49(2cell)
Energy spread (%)	0.1	0.066	0.038
Energy acceptance requirement (%)	1.52		
Energy acceptance by RF (%)	2.06	1.47	0.76
Photon number due to beamstrahlung	0.29	0.16	0.28
Lifetime due to beamstrahlung (hour)	1.0		
Lifetime (hour)	0.67 (40 min)	2	4
F (hour glass)	0.89	0.94	0.99
L_{max} /IP ($10^{34}\text{cm}^{-2}\text{s}^{-1}$)	2.93	7.31	4.1

luminosity

- Luminosity of H & W limited by the SR power **30 MW**.
 - Luminosity @ H: $2.93 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 242 bunches
 - Luminosity @ W: $7.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 3390 bunches
- Luminosity of Z limited by beam-beam and electron cloud instability.
 - **6.4nC/bunch** → beam-beam
 - Luminosity @ Z: $4.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 8332 bunches
 - The minimum bunch separation for Z due to electron cloud effect is **40 ns**.

Beam-beam tune shift

➤ definition

$$\xi_x = \frac{r_e N_e \beta_x^*}{2\pi\gamma\sigma_x^* \sqrt{1+\Phi^2} (\sigma_x^* \sqrt{1+\Phi^2} + \sigma_y^*)}, \quad \xi_y = \frac{r_e N_e \beta_y^*}{2\pi\gamma\sigma_y^* (\sigma_x^* \sqrt{1+\Phi^2} + \sigma_y^*)}$$

	H	W	Z
$\xi_x/\xi_y/\text{IP}$	0.031/0.109	0.015/0.076	0.0041/0.039

➤ Why not larger ξ_y

- H: ξ_y close to the beam-beam limit
- W: ξ_y is conservative
- Z: $\xi_y \rightarrow$ stable collision without bootstrapping, beam-beam study going on

➤ Why not larger ξ_x

- larger ξ_x introduce coherent beam-beam instability (x-z resonance)

Key parameters

- $\beta_y^* = 1.5\text{mm}$, *luminosity potential by lower β_y^* is small*
 - H: close to minimum coupling (0.256%)
 - Z: vertical emittance limited by coupling due to 3T detector solenoid (2.4%)
- β_x^* choice — Balance between DA and coherent beam-beam instability
 - H & W: 0.36 m
 - Z: 0.2 m (coherent beam-beam instability)
- Solenoid coupling effect: *Vertical emittance growth @ Z most serious!*

$$N_{\text{th}} \propto \frac{\alpha_p \sigma_\delta \sigma_z}{\beta_x^*}$$

	Higgs	W	Z
Vertical emittance due to solenoid[pmrad]	0.14	0.42	3.1
$\mathcal{E}_{y,\text{solenoid}} / \mathcal{E}_x$ (%)	0.01	0.08	1.9
Emittance Coupling Budget (%)	0.26	0.3	2.4

- Bunch length: *Design luminosities include the bunch lengthening effect*
 - H: bunch lengthening ~20%
 - W: bunch lengthening ~ 21%
 - Z: bunch lengthening ~ 60%, energy spread increase ~12%

Beam lifetime

(Beamstrahlung & Radiative Bhabha)

➤ Beamstrahlung

$$\tau_{BS} = \frac{2\pi R}{c} \frac{\sqrt{6\pi} r_e \gamma e^{1.475u}}{0.057 \alpha^2 \eta \sigma_z} * \left(u = \frac{\eta_e E}{E_{cb}} = \frac{\alpha \eta_e \sigma_x \sigma_z}{3\gamma \cdot r_e^2 N_e} \right)$$

- calculation: ~1 hour @ Higgs
- simulation: ~100 min @ Higgs (with real lattice)

➤ Radiative Bhabha

$$\tau_{bb} = \frac{I_b}{e L_0 N_{IP} \sigma_{bb} f_0} / 60 \quad \text{min}$$

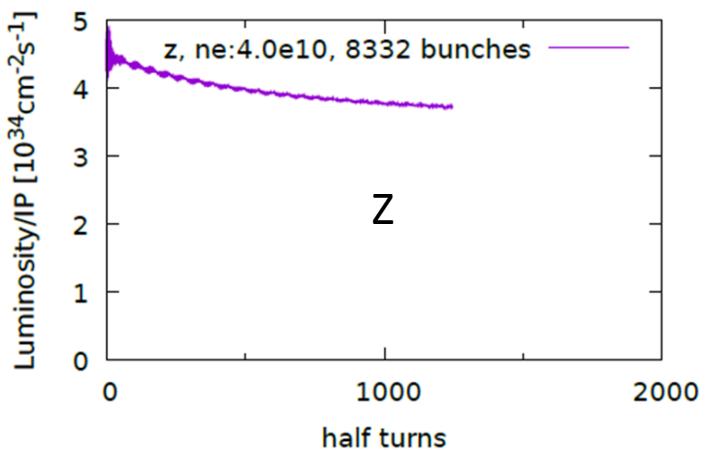
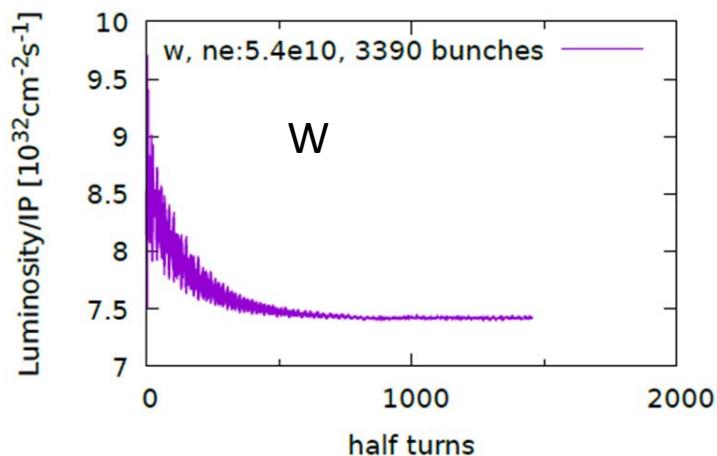
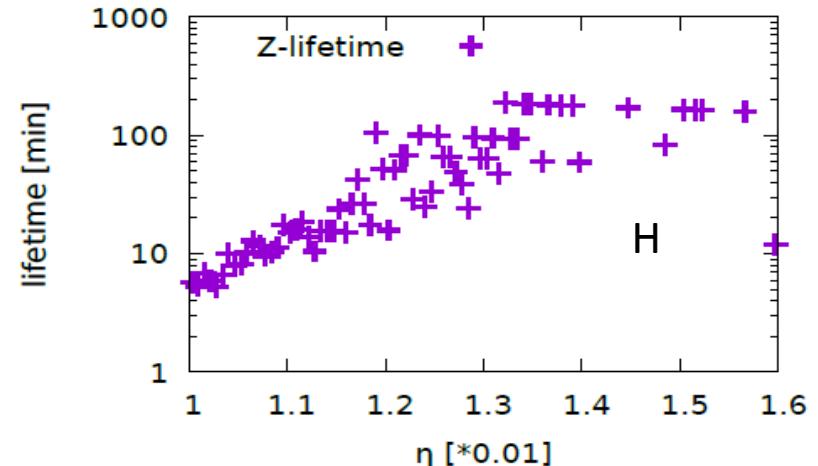
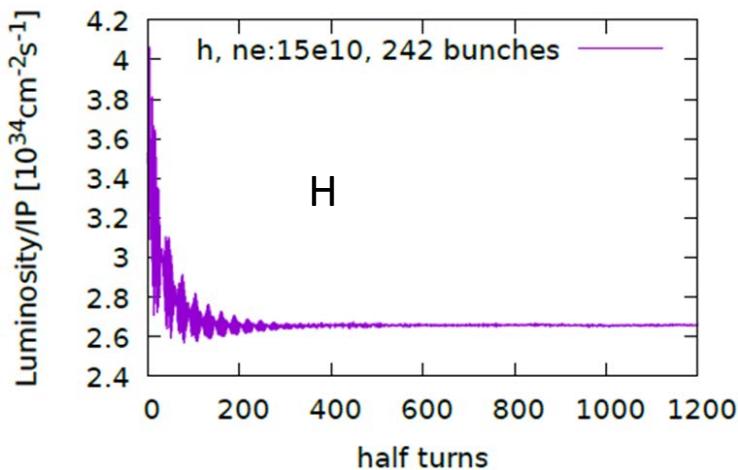
- Higgs: $\sigma_{bb} = 1.6 \times 10^{-25} \text{ cm}^2$, Bhabha lifetime = ~65 min
- W: $\sigma_{bb} = 1.8 \times 10^{-25} \text{ cm}^2$, Bhabha lifetime = ~2 hour
- Z: $\sigma_{bb} = 1.9 \times 10^{-25} \text{ cm}^2$, Bhabha lifetime = ~6 hour

➤ Total lifetime due to beamstrahlung and Bhabha for Higgs at the level: ~ 40 min

*V.I. Telnov, "Issues with current designs for e+e- and gammagamma colliders", PoS Photon2013 (2013) 070.
https://inspirehep.net/record/1298149/files/Photon%202013_070.pdf

Beam-beam simulations

- Beam-beam simulations agree well with the parameter design.

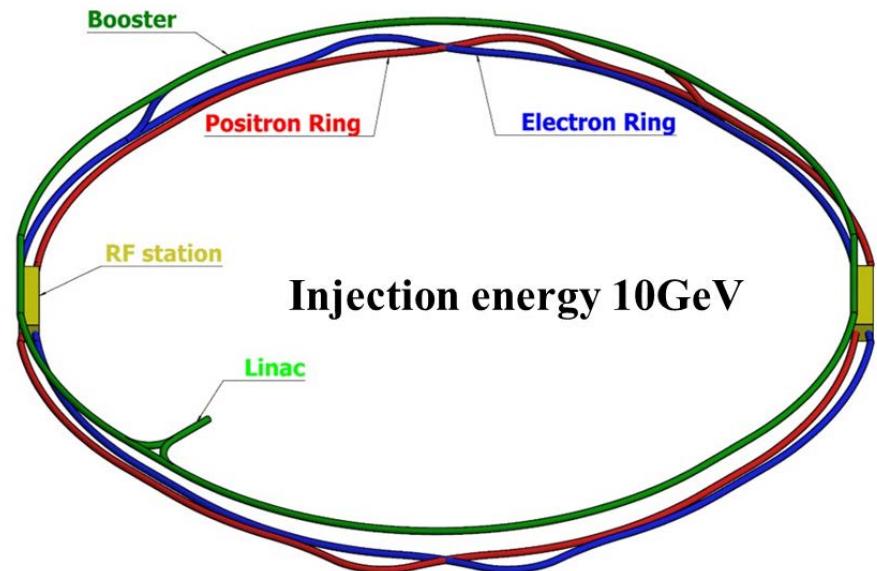
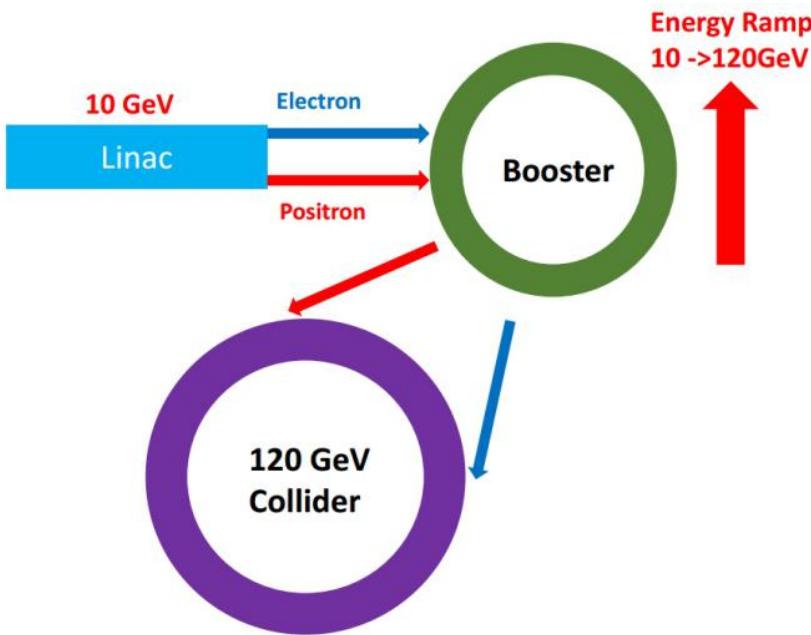


Outline

1. CEPC Parameter Optimization

2. CEPC Booster Design

CEPC injector chain



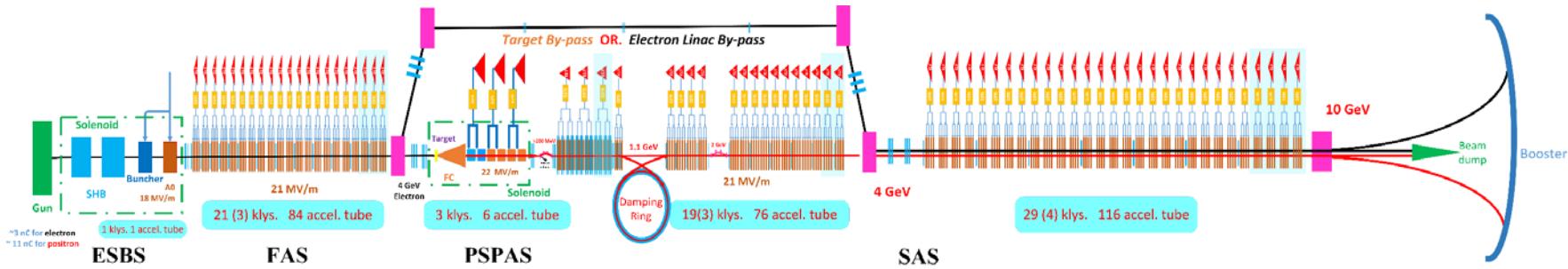
- 10 GeV linac provides electron and positron beams for booster.
- Top up injection for collider ring $\sim 3\%$ current decay
- Booster is in the same tunnel as collider ring, above the collider ring.
- Booster has the same geometry as collider ring except for the two IRs.
- Booster bypasses the collider ring from the outer side at two IPs.

Design requirements for CEPC booster

<i>Parameters</i>	<i>Design goals</i>
Beam current (mA)	<0.8
Emittance in x (nm rad)	<3.6
Dynamic aperture (σ , normalized by linac beam size)	>3
Energy acceptance	>1%
Booster transfer efficiency	>92%
total transfer efficiency (inc. inj. & ext.)	>90% (99%*92%*99%)
Timing	Meet the top-up injection requirements

- Beam current threshold in booster is limited by TMCI ~**0.8mA**.
- The diameter of the inner aperture is selected as **55mm** due to impedance issue.
- Booster transfer efficiency **92%**: 3% beam loss due to quantum lifetime + 5% beam loss during ramping process.

CEPC Linac



Parameter	Symbol	Unit	Baseline	Designed
e ⁻ / e ⁺ beam energy	E_{e^-}/E_{e^+}	GeV	10	10
Repetition rate	f_{rep}	Hz	100	100
e ⁻ / e ⁺ bunch population	N_{e^-}/N_{e^+}		$> 9.4 \times 10^9$	$1.9 \times 10^{10} / 1.9 \times 10^{10}$
		nC	> 1.5	3.0
Energy spread (e ⁻ / e ⁺)	σ_e		$< 2 \times 10^{-3}$	$1.5 \times 10^{-3} / 1.6 \times 10^{-3}$
Emittance (e ⁻ / e ⁺)	ε_r	nm· rad	< 120	5 / 40 ~120
Bunch length (e ⁻ / e ⁺)	σ_l	mm		1 / 1
e ⁻ beam energy on Target		GeV	4	4
e ⁻ bunch charge on Target		nC	10	10

Booster parameters @ injection (10GeV)

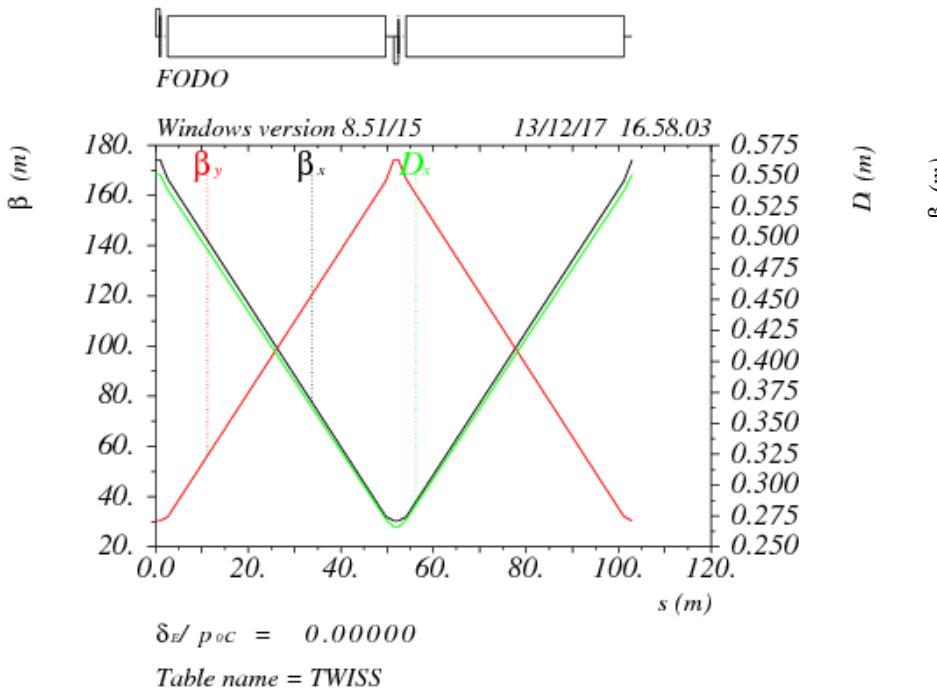
		H	W	Z
Bunch number		242	848	926
Transmission efficiency	%	0.92	0.92	0.92
Bunch charge	nC	0.72	0.2592	0.192
Beam current	mA	0.5227	0.66	0.5334
Natural Energy spread	%		0.0078	
SR loss/turn	keV		73.5	
Momentum compaction factor	10^{-5}		2.44	
Natural Emittance	nm		0.025	
RF voltage	GV		0.0857	
Longitudinal fractional tune			0.12	
RF energy acceptance	%		2.3	
Damping time	s		90.7	
Bunch length from linac	mm		1	
Energy spread from linac	%		0.2	
Emittance from linac	nm		40~120	

Booster parameters @ extraction

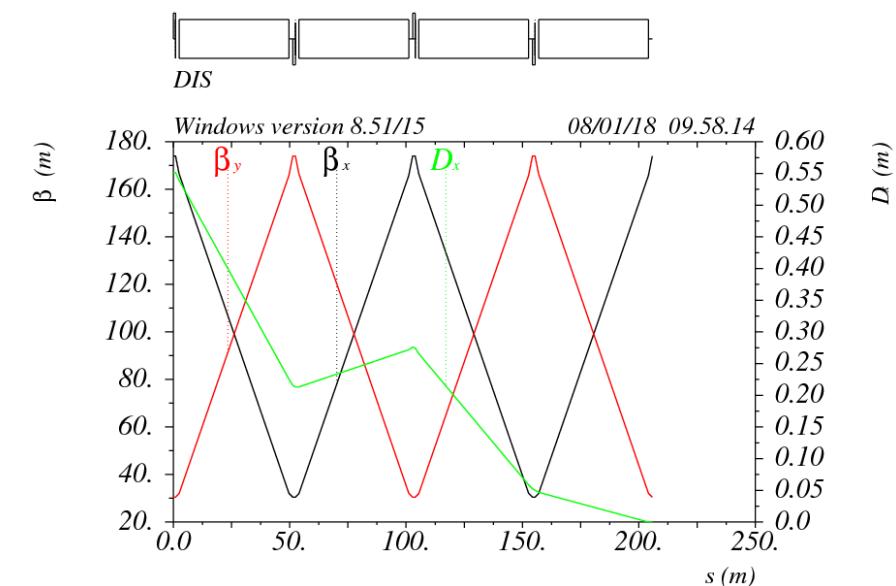
		H	W	Z
Bunch number		242	848	926
Transmission efficiency	%	0.92	0.92	0.92
Bunch charge	nC	0.72	0.2592	0.192
Beam current	mA	0.5227	0.66	0.5334
Ramping time (up+down)	s	10	6.6	3.8
Injection time (e+, e-)	s	25.84	163.12	348.84
Number of Cycles		1	4	9
Natural (extr.) Energy spread	%	0.094	0.062	0.0355
SR loss/turn	GeV	1.5	0.3	0.032
Momentum compaction factor	10^{-5}	2.44	2.44	2.44
Natural (extr.) Emittance	nm	3.58	1.59	0.51
RF voltage	GV	1.84	0.75	0.39
Longitudinal fractional tune		0.12	0.12	0.12
RF energy acceptance	%	0.79	1.6	2.1
Damping time	s	0.052	0.177	0.963
Natural (extr.) Bunch length	mm	3.0	2.0	1.1

Booster optics - ARC

- 90°/ 90° FODO cell
- FODO length: 102.9m
- Noninterleave sextupole scheme
- Dispersion suppressor
 - two standard FODO cell
 - ½ bend strength



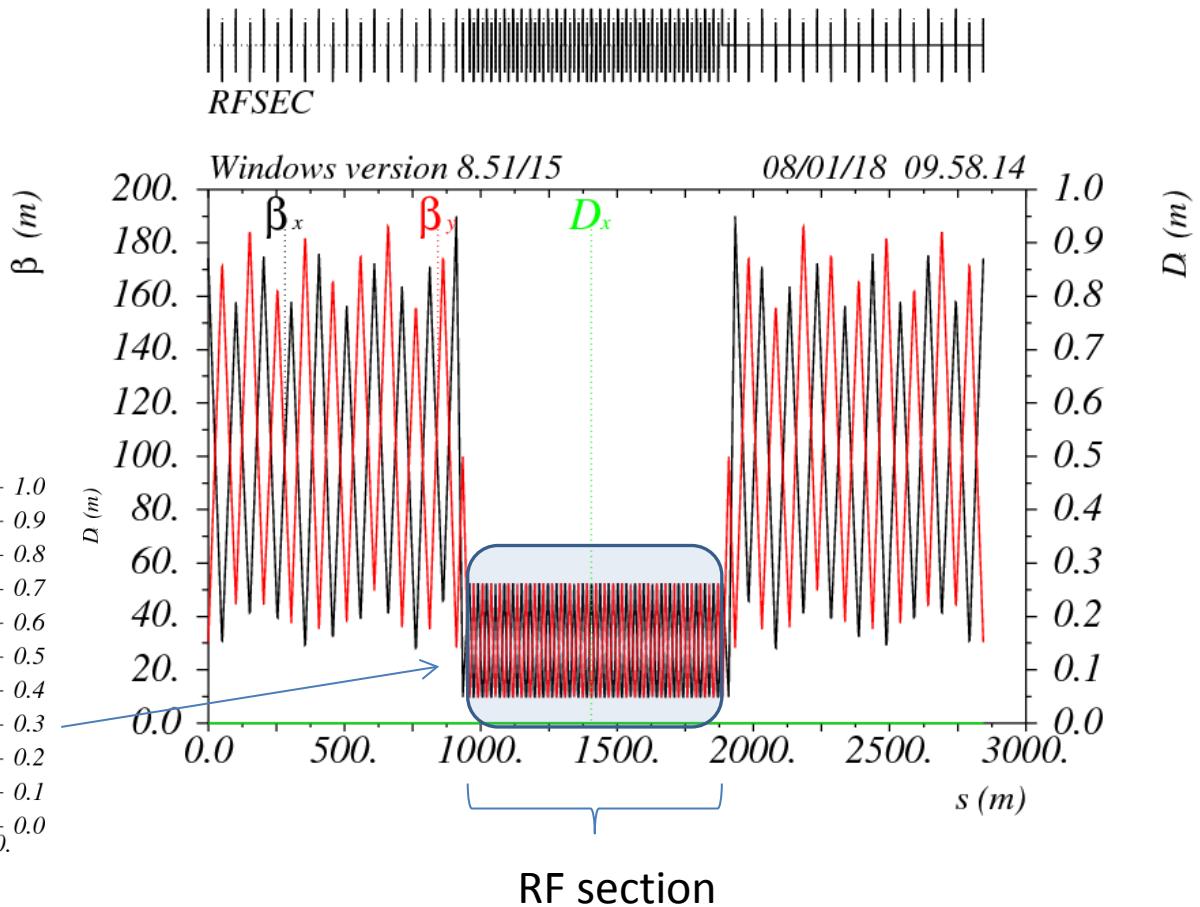
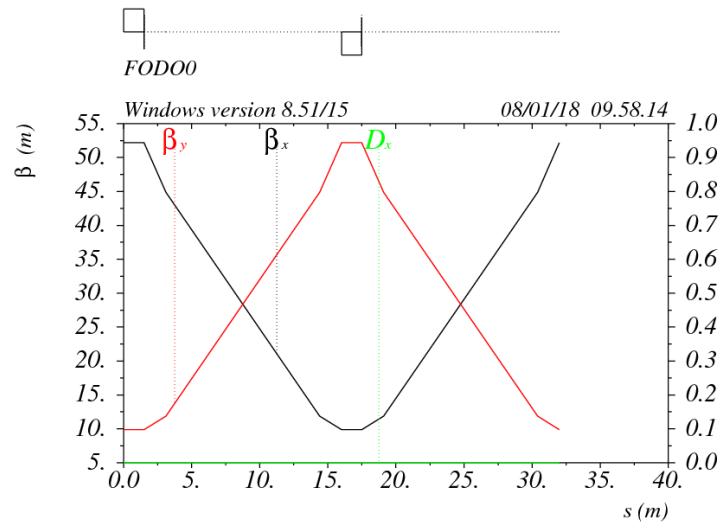
FODO cell



Dispersion suppressor

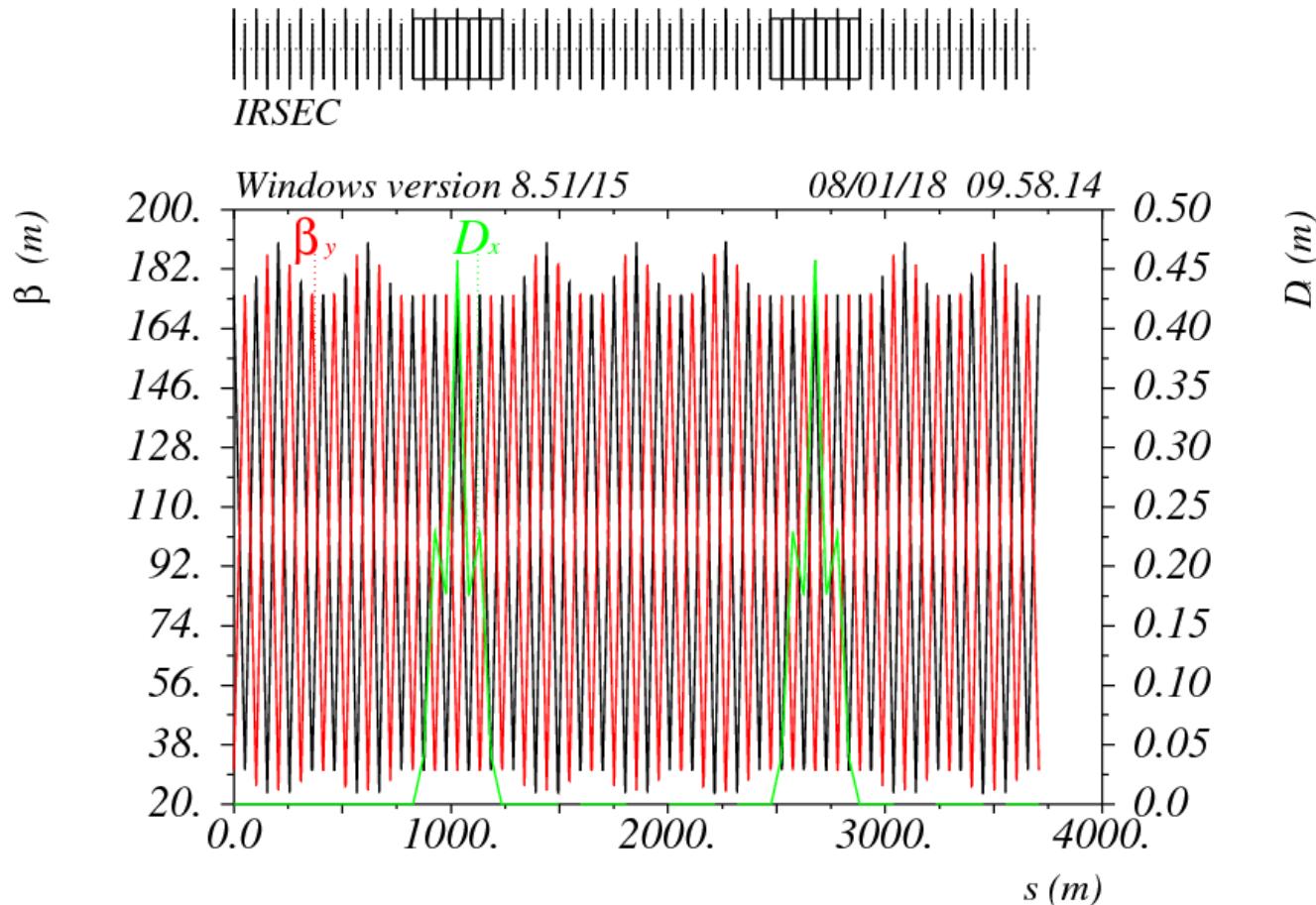
Booster optics - RF

- Booster RF straight section at the same location as collider ring
- Low average beta to reduce the multi-bunch instability by RF cavities
 - 90°/ 90° FODO cell
 - Average beta: 30 m
 - Space between quadrupoles :12m



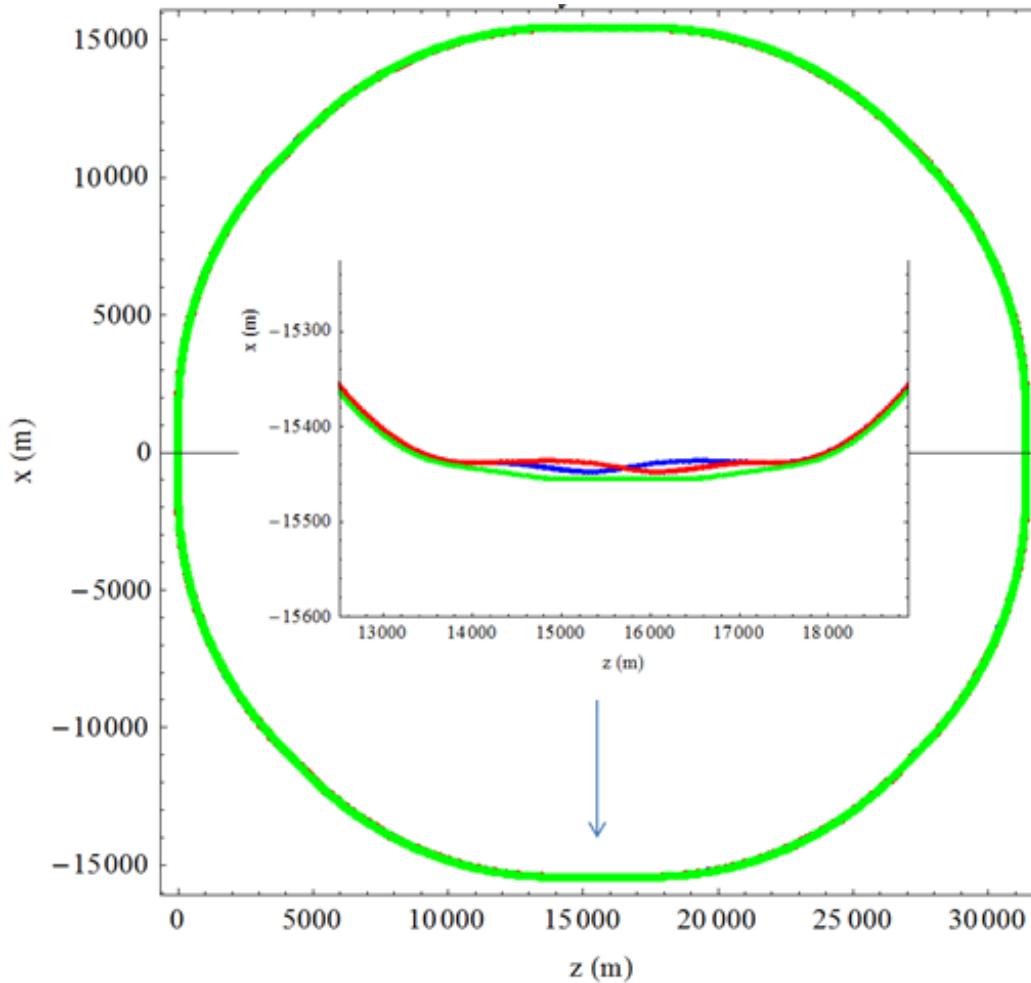
Booster optics – IR bypass

- In CEPC detector region, booster bypasses the collider ring from the outer side.



Booster geometry

- Booster has exactly same geometry as collider ring except for the two IRs.
- Separation between detector center and booster: ~ 20 m
- Minimum separation between booster and collider @ IR: ~ 10 m



Booster error studies

- Gaussian distribution and cut-off at 3σ

Errors Setting

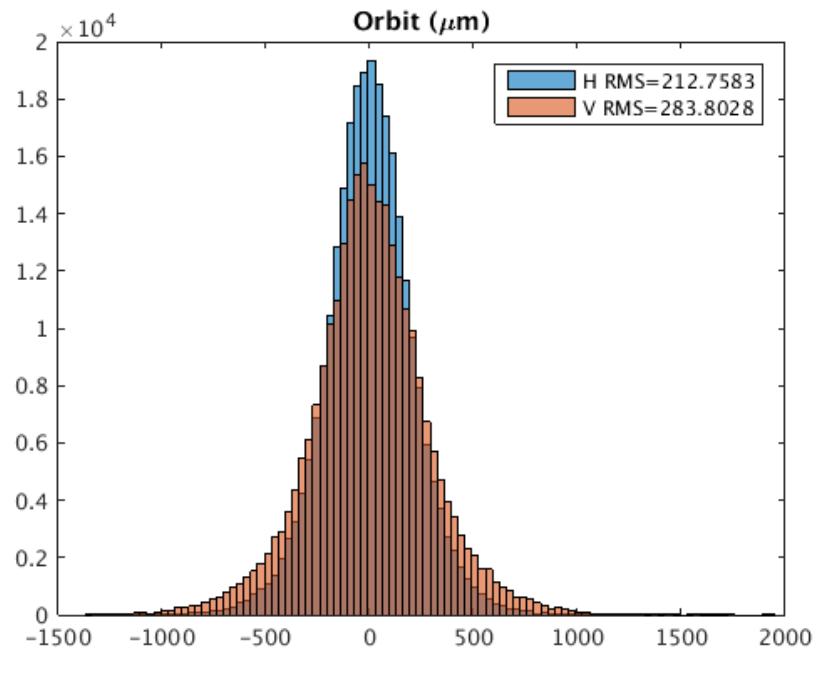
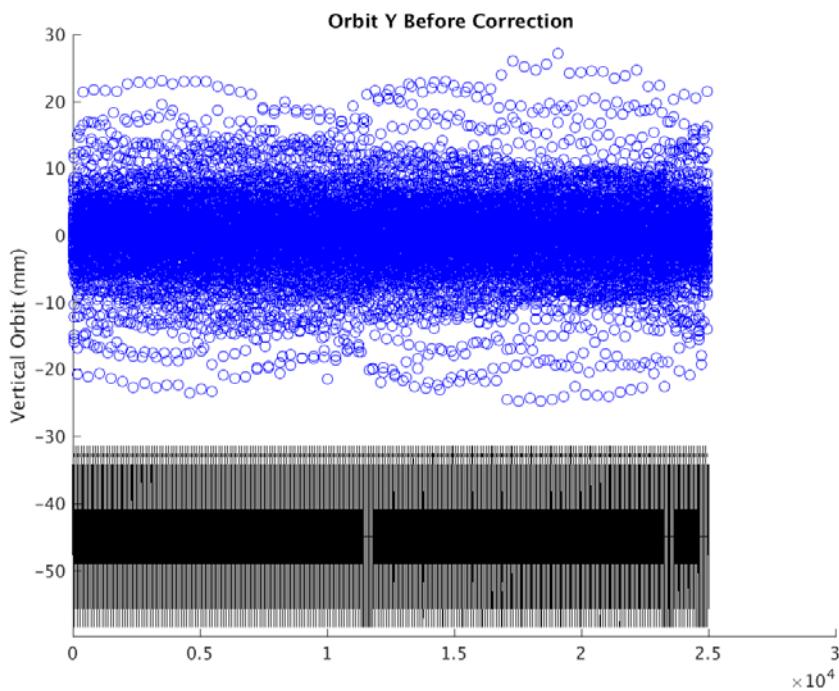
	Dipole	Quadrupole	Sextupole	Corrector
Transverse shift X/Y (μm)	100	100	100	100
Longitudinal shift Z (μm)	150	150	150	150
Tilt about X/Y (mrad)	0.1	0.2	0.2	0.2
Tilt about Z (mrad)	0.05	0.2	0.2	0.2
Nominal field	1e-3	1e-3	1e-3	1e-2

	Accuracy (m)	Tilt (mrad)	Gain	Offset after BBA(mm)
BPM	1e-5	10	5%	1e-3

Booster orbit with errors

- Orbit within the beam stay clear
- “First turn trajectory” is not necessary

Horizontal Corrector: 48 correctors +856 BTs
Vertical Corrector : 904 correctors
BPM : 904*2

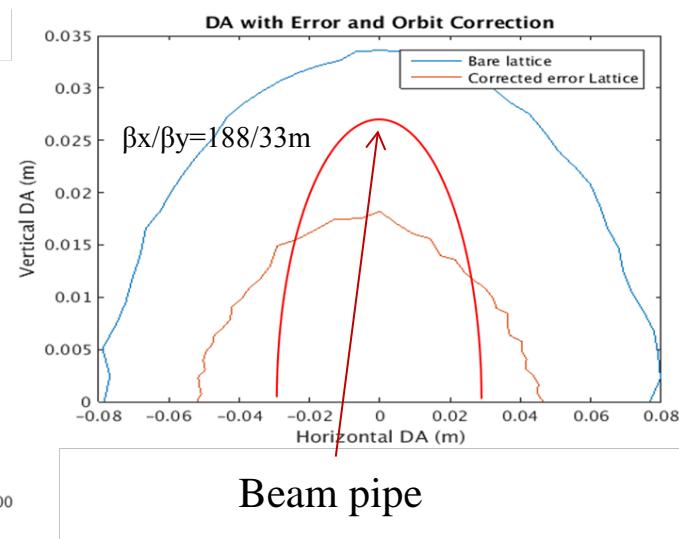
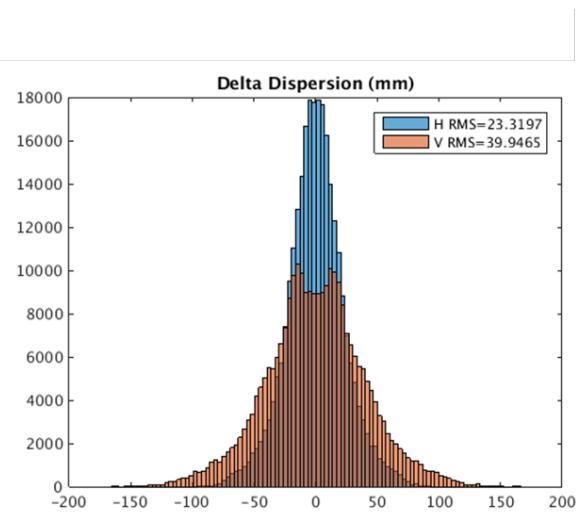
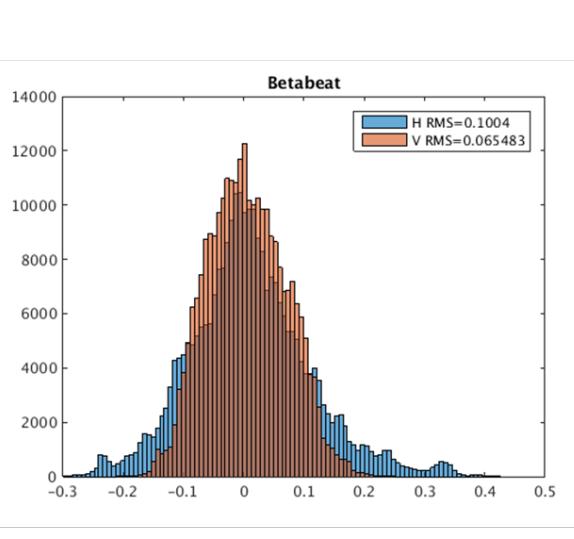


Hor. 0.2mm

Ver. 0.3mm

Booster optics & DA with corrections

- DA is half of the bare lattice, $\pm 50\text{mm} \times \pm 18\text{mm}$, **without optics correction, satisfy requirement**
- Emittance growth is less than 10% for the simulation seeds
- Satisfy the requirement of injection and beam lifetime
- Skew quadrupoles are needed to control the coupling



Hor. 10%

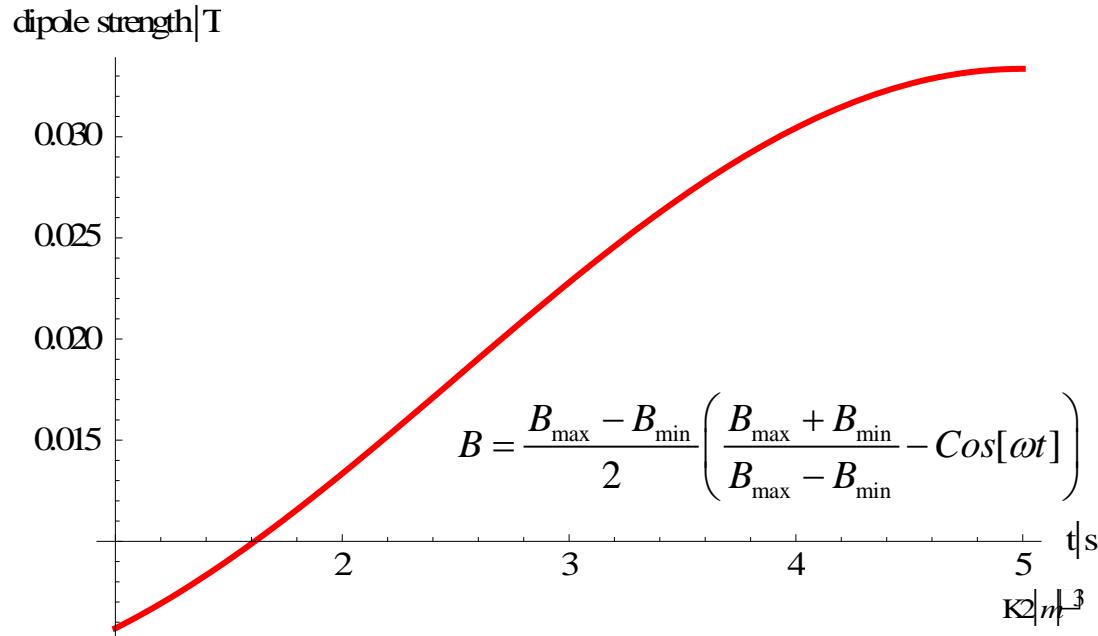
Ver. 6.5%

Hor. 0.023m

Ver. 0.04m

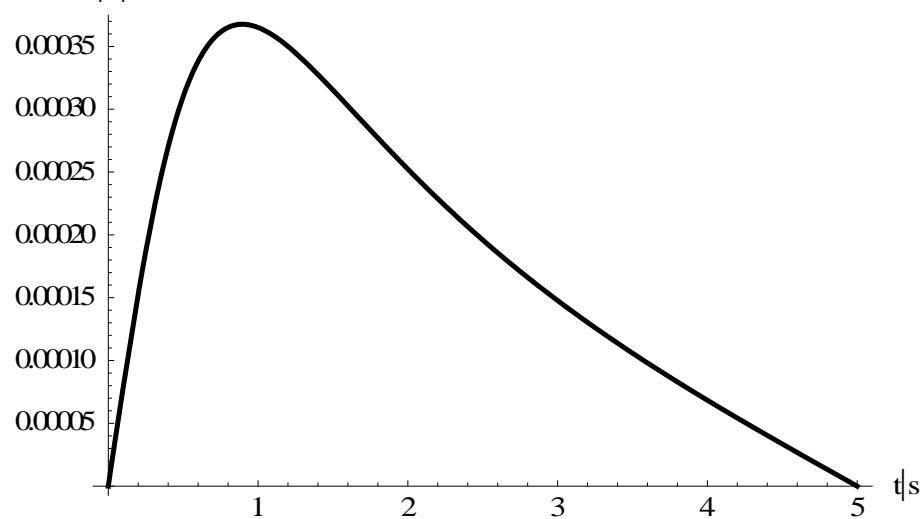
$\varepsilon_{\text{injx}} = 120\text{nm}, A_x = 2(9\sigma_x + 5\text{mm})$
 $\varepsilon_{\text{injy}} = 120\text{nm}, A_y = 2(6\sigma_y + 5\text{mm})$

Eddy current effect

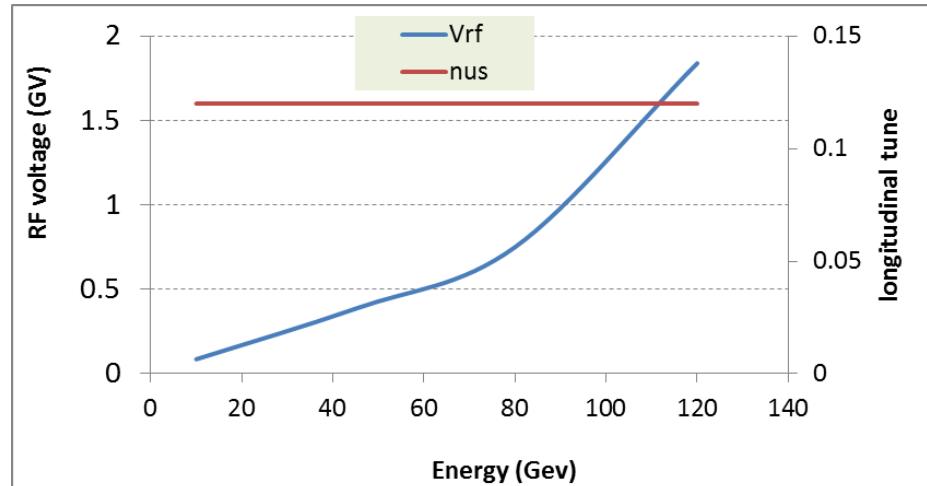
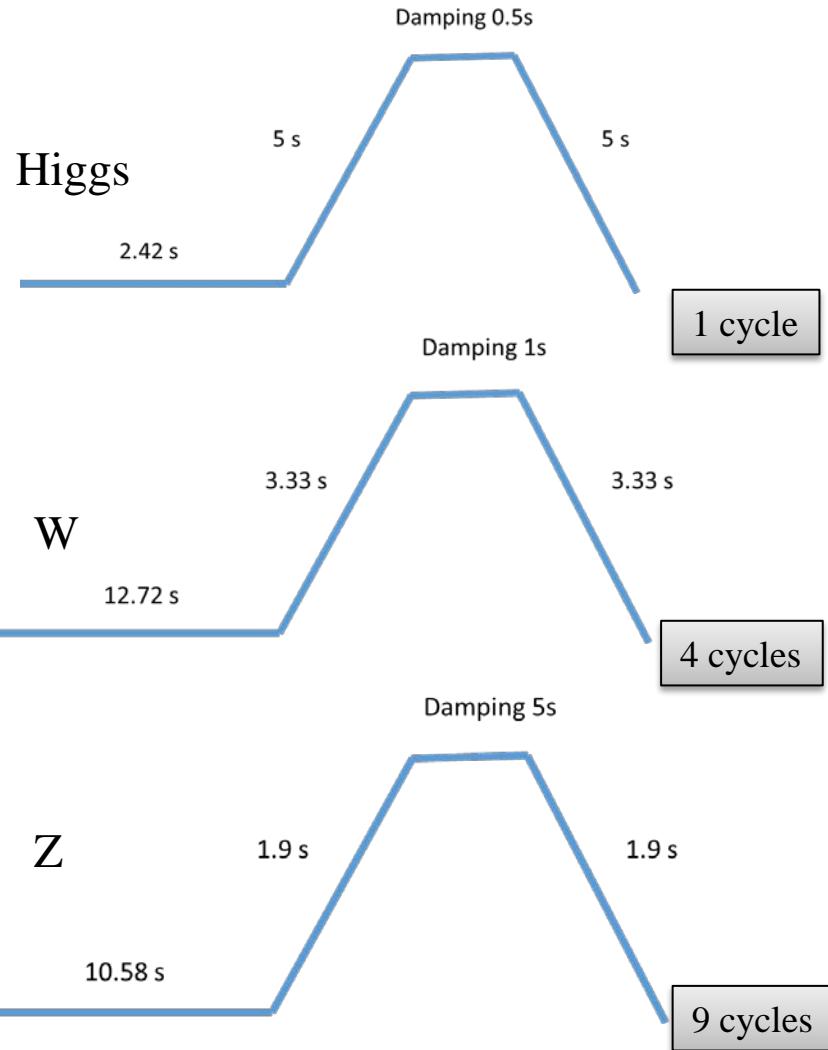


- Chromaticity distortion needs to be corrected during ramping.
- Dynamic chromaticity correction and according DA is under studying.

- During ramping, parasitic sextupole field is induced in dipoles due to eddy current.
- Ramping rate is limited by eddy current effect.
- Dedicated ramping curve to control the maximum K2.



Injection time structure

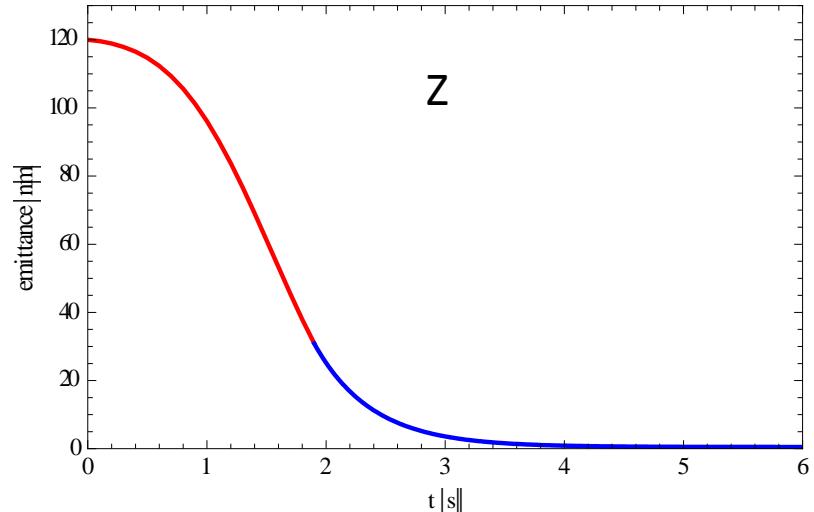
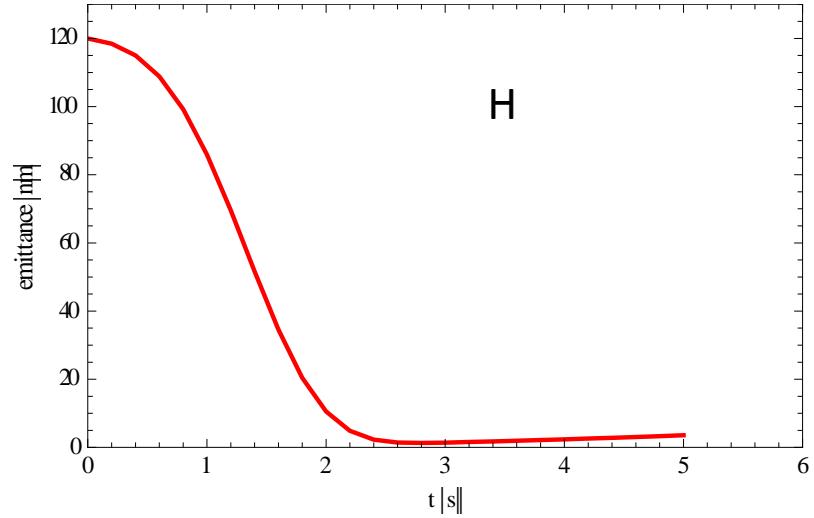
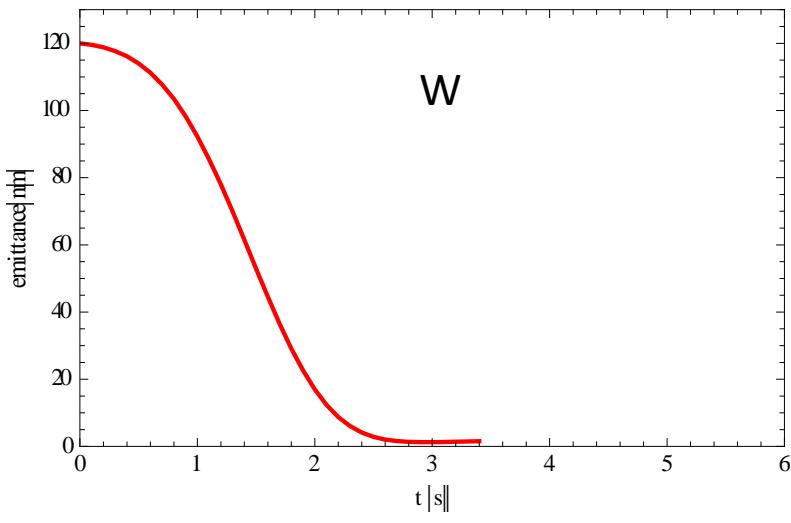


30Gauss @ 10GeV
Eddy current effect

- Transverse quantum lifetime@ 10GeV:
 1.65×10^8 s ($\epsilon_{\text{inj}}=120\text{nm}$)
- Beam loss due to lifetime << **1%**

Emittance evolution

- Beam lifetime is dominated by transverse quantum lifetime at 10 GeV.
- Beam loss due to lifetime determined by the emittance of Linac and the DA.



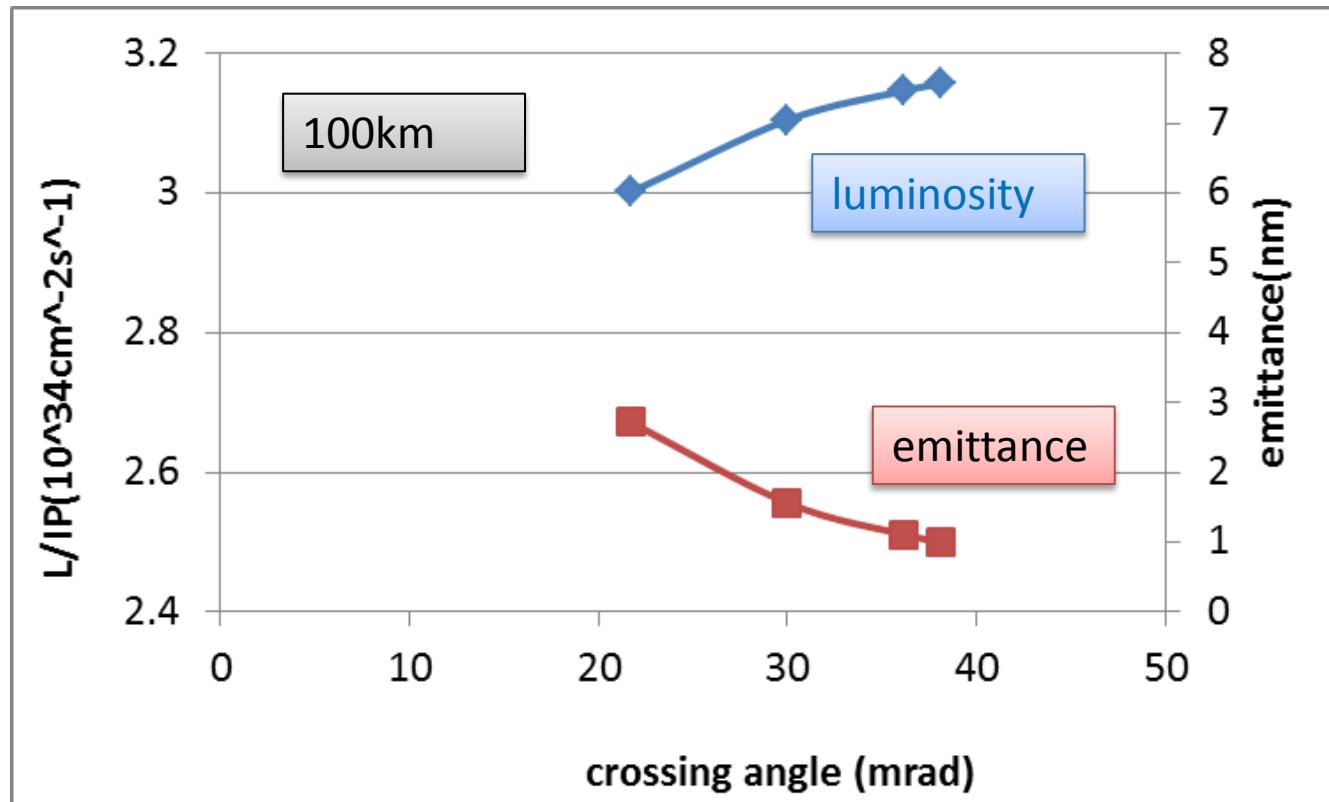
Summary

- A consistent analytical method for CEPC parameter design with carb waist scheme has been created.
- Luminosity of Higgs/W is limited by power budget and luminosity of Z is limited by beam-beam and electron cloud instability. Effort to increase luminosity and reduce machine cost is always under studying.
 - **H: $2.93 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 242 bunches, 30 MW/beam**
 - **W: $7.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 3390 bunches, 30 MW/beam**
 - **Z: $4.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 8332 bunches, 5.7 MW/beam**
- The booster design can meet the injection requirements at three energy modes. The study of dynamic chromaticity correction and dynamic DA is ongoing.
- Low magnetic field in the booster is still a challenge. Studies are underway.

Back up

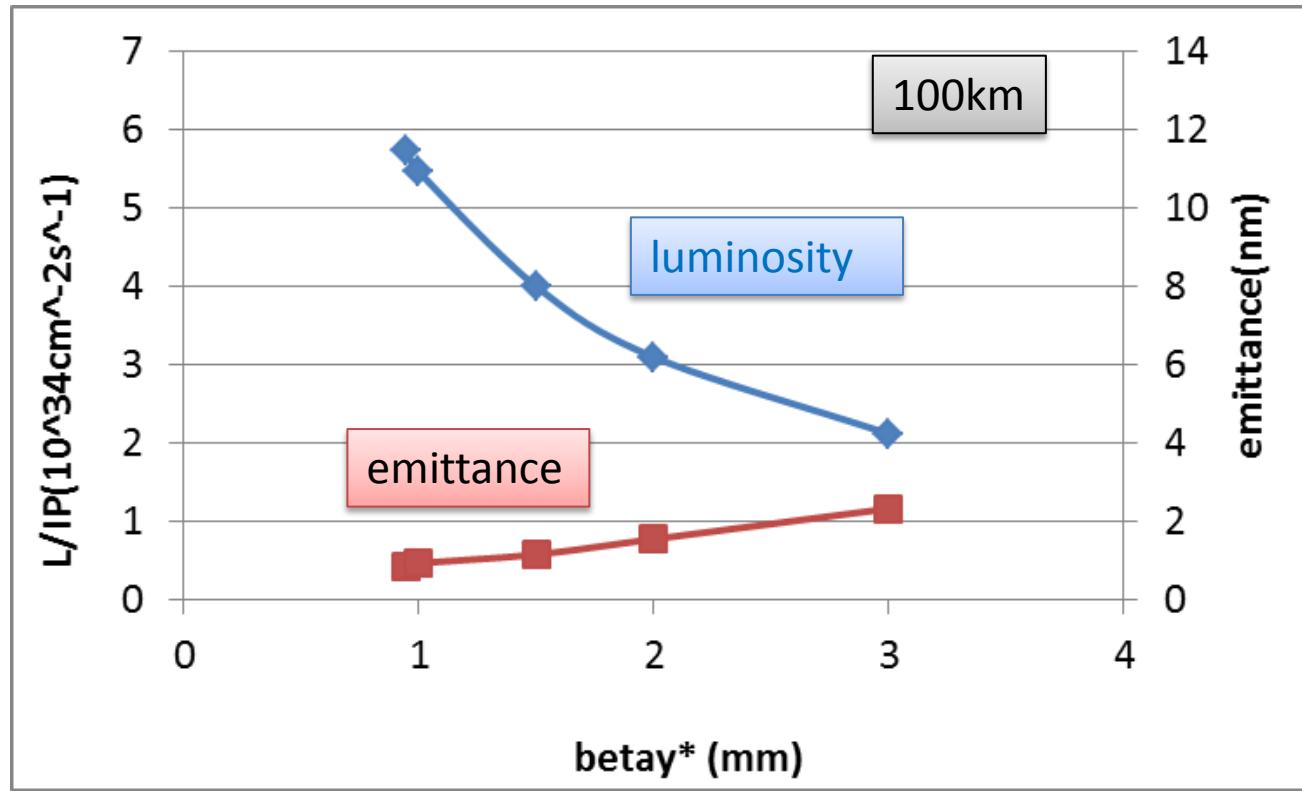
Higgs Luminosity vs. crossing angle

- Keep beamstrahlung life time constant (52min)
- 50MW SR power

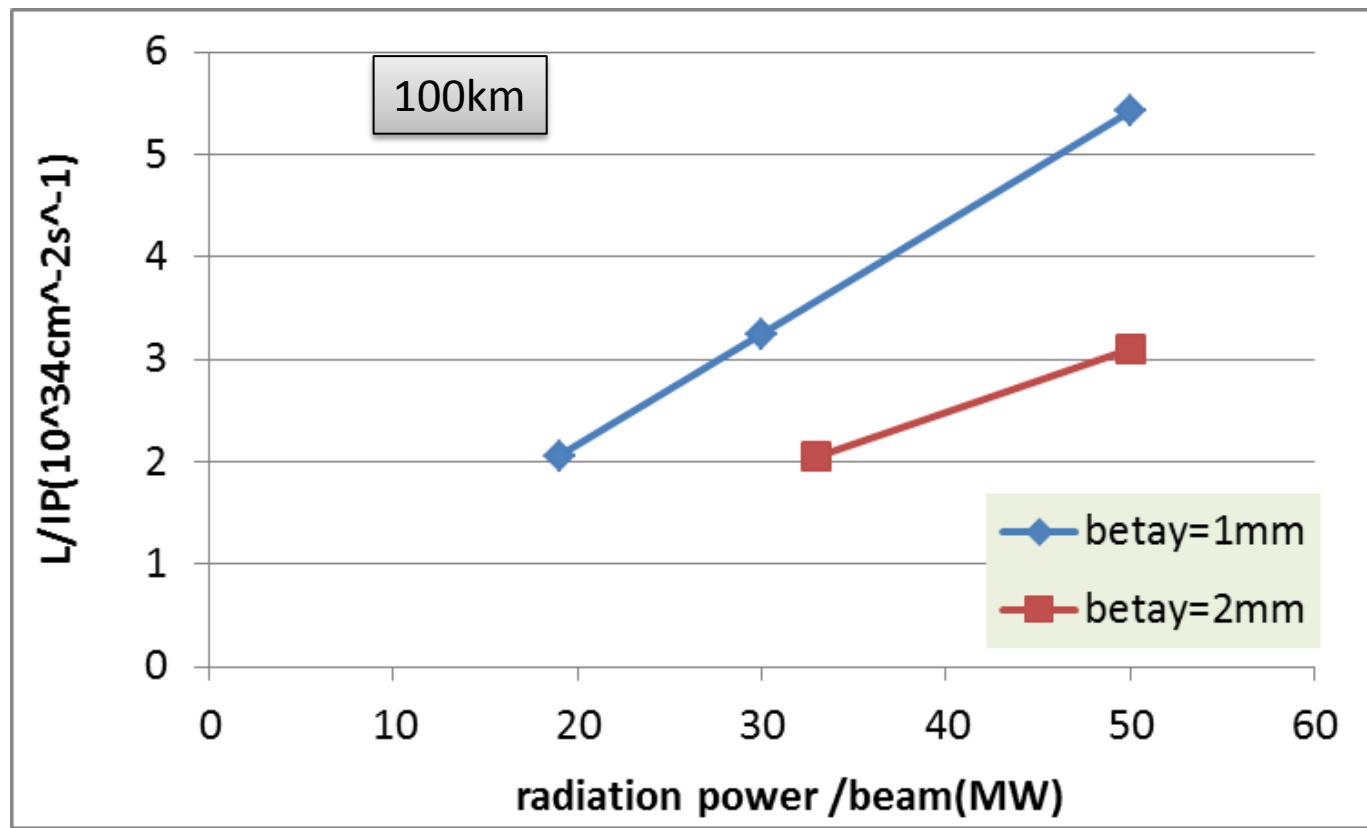


Higgs Luminosity vs. βy^*

- Keep beamstrahlung life time constant (52min)
- 50MW SR power



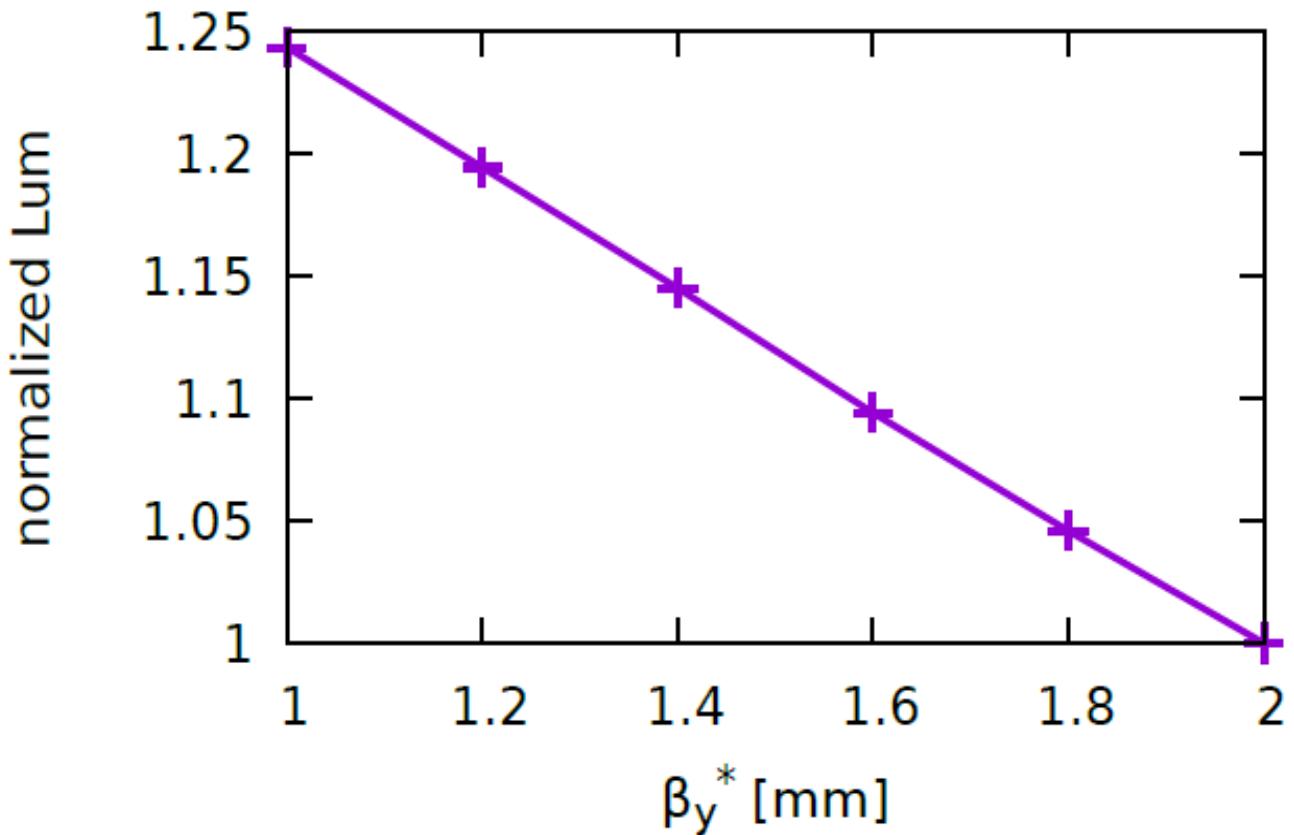
Higgs Luminosity vs. SR power



Higgs: Discussion on Luminosity

- β_y^*

$\sigma_{y,\text{eff}} + \text{Hourglass}$



Higgs: Discussion on Luminosity

- Coupling
 - 3e34: 0.25% coupling

