CEPC parameter choice and partial double ring design

Dou Wang, Jie Gao, Feng Su, Yuan Zhang, Jiyuan Zhai, Yiwei Wang, Bai Sha, Huiping Geng, Tianjian Bian, Na Wang, Xiaohao Cui, Weiren Chou, Chuang Zhang, Qing Qin

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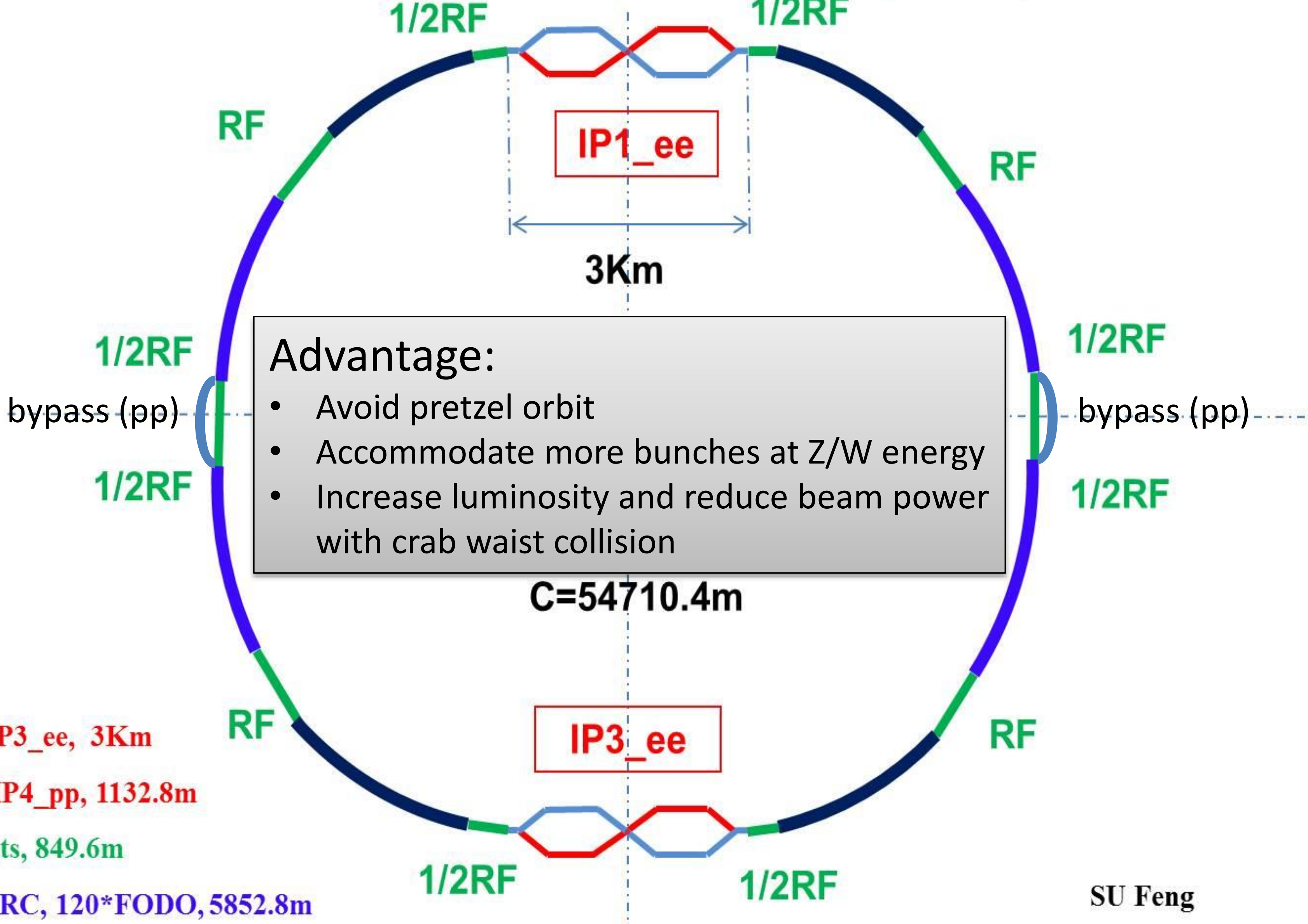
CEPC Partial Double Ring Layout



Advantage:

- Avoid pretzel orbit
- Accommodate more bunches at Z/W energy
- Increase luminosity and reduce beam power with crab waist collision

IP1_ee/IP3_ee, 3Km

IP2_pp/IP4_pp, 1132.8m

4Straights, 849.6m

4Long ARC, 120*FODO, 5852.8m

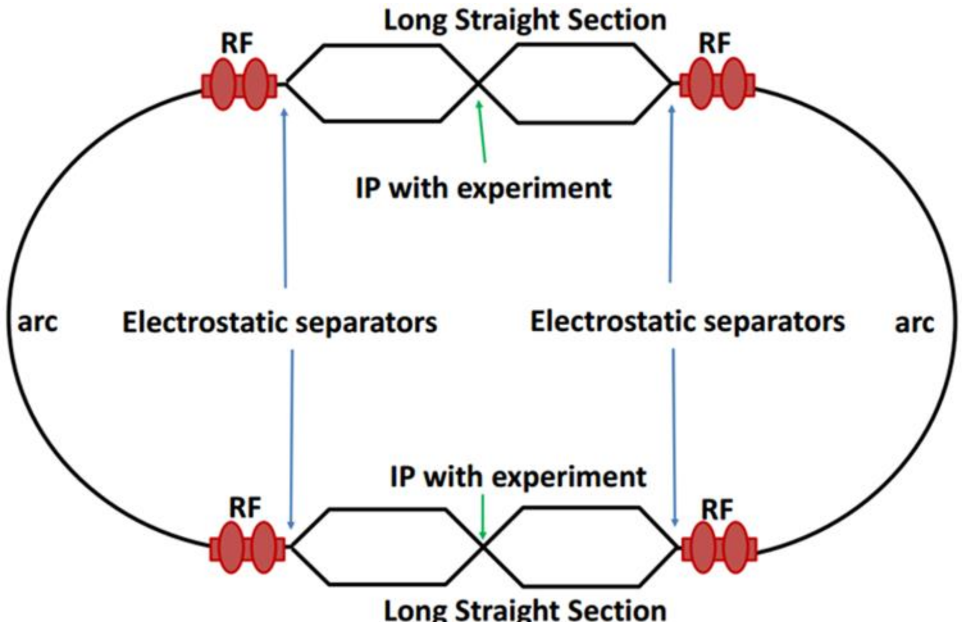
4Short ARC, 100*FODO, 4908.8m

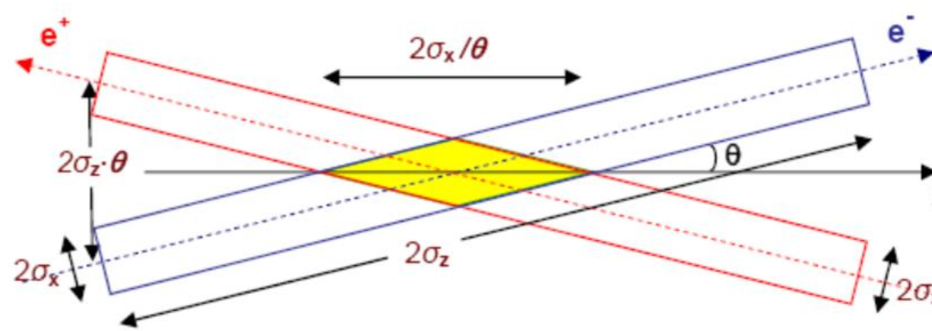
SU Feng

2015.10.12

Machine constraints / given parameters

- Energy E_0
- Circumference C_0
- N_{IP}
- Beam power P_0
- β_y*
- Emittance coupling factor κ_ε
- Bending radius ρ
- Piwinski angle Φ
- ξy enhancement by crab waist F_l~1.5 (2.6)
- Energy acceptance (DA)
- Phase advance per cell (FODO)





Constraints for parameter choice

- Limit of Beam-beam tune shift

$$\xi_y = \frac{2845}{2\pi}\sqrt{\frac{U_0}{2\gamma E_0 N_{IP}}} \times F_l \,*$$

F_l: ξy enhancement by crab waist

- Beam lifetime due to beamstrahlung

BS life time: 30 min

$$\frac{N_e}{\sigma_x \sigma_z} \le 0.1\eta \frac{\alpha}{3\gamma r_e^2}$$

V.I. Telnov

- Beamstrahlung energy spread

A=δ_0/δ_{BS} (A≥3)

- HOM power per cavity

$$P_{HOM} = k(\sigma_z) e N_e \cdot 2I_b \le 1kw$$

*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 choice – step 1

$$U_0 = 88.5 \times 10^3 \frac{E_0^4(GeV)}{\rho(m)}$$

$$I_b = \frac{eP_0}{U_0}$$

$$\delta_0 = \gamma \sqrt{\frac{C_q}{J_\varepsilon \rho}}$$

Beam-beam limit:

$$\xi_y = \frac{2845}{2\pi} \sqrt{\frac{U_0}{2\gamma E_0 N_{IP}}} \times F_l *$$

F_l: ξy enhancement by crab waist, ~ 1.5.

Parameter choice – step 2

$$L_0[cm^{-2}s^{-1}] = 2.17\times10^{34}\left(1+r\right)\xi_y \frac{eE_0(GeV)N_bN_e}{T_0(s)\beta_y^*(cm)}$$

$$\xi_y = \frac{2845}{2\pi}\sqrt{\frac{U_0}{2\gamma E_0 N_{IP}}}\times F_l$$

$$\Rightarrow \quad L_0\left[cm^{-2}s^{-1}\right] = 0.7\times10^{34}\left(1+r\right)\frac{F_l}{\beta_y\left[cm\right]}\sqrt{\frac{E_0\left[GeV\right]I_b\left[mA\right]P_0\left[MW\right]}{\gamma N_{IP}}}$$

Parameter choice – step 3

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

ξy: $\frac{N_e}{\sigma_x\sigma_y\sqrt{1+\Phi^2}} = \frac{2\pi\gamma}{r_e\beta_y}\xi_y$

$\Rightarrow \frac{N_e^2}{\sigma_x^2\sigma_y\sigma_z} = \frac{0.2\pi\eta\alpha\xi_y\sqrt{1+\Phi^2}}{3r_e^3\beta_y}$

$$\delta_{BS} = \frac{\delta_0}{A} \qquad (A \ge 3) \Rightarrow \frac{N_e^2}{\sigma_x\sigma_y\sigma_z} = \frac{3\delta_0}{2.6r_e^3\gamma rA}$$

$$\sigma_x = \frac{5.77\delta_0\beta_y}{\pi\eta\alpha\xi_y\sqrt{1+\Phi^2}\gamma rA} \rightarrow$$

$$\sigma_y = r\sigma_x, \qquad \varepsilon_y = \frac{\sigma_y^2}{\beta_y}$$

$$\varepsilon_x = \frac{\varepsilon_y}{\kappa_\varepsilon}, \qquad \beta_x^* = \frac{\sigma_x^2}{\varepsilon_x}$$

$$\varepsilon_x = \frac{C_q\gamma^2\varphi^3\left(1-\frac{3}{4}\sin^2\left(\frac{\mu}{2}\right)+\frac{1}{60}\sin^4\left(\frac{\mu}{2}\right)\right)}{8J_x\sin^3\left(\frac{\mu}{2}\right)\cos\left(\frac{\mu}{2}\right)} \rightarrow \varphi$$

μ-- phase advance/cell,
φ-- bending angle/cell.

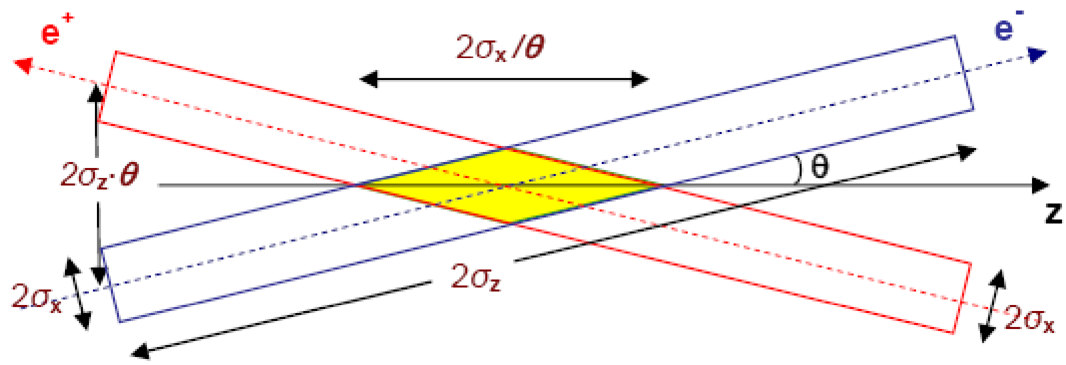
Estimate : $\alpha_p = (\frac{\varphi}{2})^2(\frac{1}{sin^2\frac{\mu}{2}} - \frac{1}{12})$

Parameter choice – step 4

$$N_e = \frac{2\pi\gamma\xi_y\sqrt{1+\Phi^2}}{r_e\beta_y}\sigma_x\sigma_y \longrightarrow N_b = \frac{I_b T_0}{eN_e}$$

$$\left.\begin{aligned} \sigma_z &= \frac{3\gamma r_e^2 N_e}{0.1\eta\alpha\sigma_x} \\ \Phi &= \frac{\sigma_z}{\sigma_x} tg\theta_h \end{aligned}\right\} \quad \theta_h = Arctg\left(\frac{0.1\eta\alpha\sigma_x^2\Phi}{3\gamma r_e^2 N_e}\right)$$

Parameter choice – step 5



Effective bunch length: overlap area of colliding bunches

$$\sigma_{zeff} = \frac{\sigma_x}{\sin\theta_h}$$

Hour glass effect: $$F_h = \frac{\beta_y}{\sqrt{\pi}\sigma_{zeff}} \exp\left(\frac{\beta_y^2}{2\sigma_{zeff}^2}\right) K_0\left(\frac{\beta_y^2}{2\sigma_{zeff}^2}\right)$$

→ $$L = L_0 F_h$$

Parameter choice – step 6

$$U_0 = eV_{rf} \sin\phi_s$$

$$\sigma_{z0} = \sigma_z \times \frac{A}{1+A} = \sqrt{-\frac{2\pi E_0 \alpha_p}{f_{rf} T_0 e V_{rf} \cos\phi_s}} \bar{R} \delta_0$$

$\Rightarrow$ $V_{rf},\ \phi_s$

Energy acceptance from RF:

$$\eta_{RF} = \sqrt{\frac{2U_0}{\pi \alpha_p f_{rf} T_0 E_0} \left(\sqrt{q^2 - 1} - \arccos\left(\frac{1}{q}\right) \right)} \qquad \left(q = \frac{eV_{rf}}{U_0} \right)$$

Parameter choice – step 7

- Beam lifetime due to radiative Bhabha scattering

$$\tau_{bhabha} = \frac{I_b}{eLN_{IP}\sigma_{ee} f_0} \qquad \left(\sigma_{ee} = 1.52\times10^{-25} cm^2\right)$$

- Beam lifetime due to Beamstrahlung

$$\tau_{BS} = \frac{2\pi R}{c}\frac{\sqrt{6\pi} r_e \gamma e^{1.475u}}{0.057\alpha^2\eta\sigma_z} *$$

- HOM power per cavity

$$P_{HOM} = k(\sigma_z)eN_e \cdot 2I_b \le 1kw$$

HOM loss factor: $$k(\sigma_z) = \frac{1.8}{\sqrt{\sigma_z / 0.00265}} \quad V/pC$$

*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

parameter for CEPC partial double ring

（wangdou20160325）

	Pre-CDR	***H-high lumi.***	***H-low power***	***W***	***Z***
Number of IPs	2	2	2	2	2
Energy (GeV)	120	120	120	80	45.5
Circumference (km)	54	54	54	54	54
SR loss/turn (GeV)	3.1	2.96	2.96	0.59	0.062
Half crossing angle (mrad)	0	15	15	15	15
Piwinski angle	0	2.5	2.6	5	7.6
N_e/bunch (10^{11})	3.79	2.85	2.67	0.74	0.46
Bunch number	50	67	44	400	1100
Beam current (mA)	16.6	16.9	10.5	26.2	45.4
SR power /beam (MW)	51.7	50	31.2	15.6	2.8
Bending radius (km)	6.1	6.2	6.2	6.1	6.1
Momentum compaction (10^{-5})	3.4	2.5	2.2	2.4	3.5
β_{IP} x/y (m)	0.8/0.0012	0.25/0.00136	0.268 /0.00124	0.1/0.001	0.1/0.001
Emittance x/y (nm)	6.12/0.018	2.45/0.0074	2.06 /0.0062	1.02/0.003	0.62/0.0028
Transverse σ_{IP} (um)	69.97/0.15	24.8/0.1	23.5/0.088	10.1/0.056	7.9/0.053
ξ_x/IP	0.118	0.03	0.032	0.008	0.006
ξ_y/IP	0.083	0.11	0.11	0.074	0.073
V_{RF} (GV)	6.87	**3.62**	**3.53**	**0.81**	**0.12**
f_{RF} (MHz)	650	650	650	650	650
Nature σ_z (mm)	2.14	**3.1**	**3.0**	**3.25**	**3.9**
Total σ_z (mm)	2.65	4.1	4.0	3.35	4.0
HOM power/cavity (kw)	3.6	2.2	1.3	0.99	0.99
Energy spread (%)	0.13	0.13	0.13	0.09	0.05
Energy acceptance (%)	2	2	2		
Energy acceptance by RF (%)	6	**2.2**	**2.1**	**1.7**	**1.1**
n_γ	0.23	0.47	0.47	0.3	0.24
Life time due to beamstrahlung_cal (minute)	47	36	32		
F (hour glass)	0.68	0.82	0.81	0.92	0.95
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.04	2.96	2.01	3.09	3.09

CEPC single ring parameter-54km

	H		***Z***	
	Pre-CDR	***Low-HOM***		
Number of IPs	2	2	2	
Energy (GeV)	120	120	45.5	
Circumference (km)	54	54	54	
SR loss/turn (GeV)	3.1	3.1	0.062	
N_e/bunch (10^{11})	3.79	1.0	0.13	
Bunch number	50	187	4800	100
Beam current (mA)	16.6	16.6	55.5	1.1
SR power /beam (MW)	51.7	50	3.45	0.072
Bending radius (km)	6.1	6.1	6.1	
Momentum compaction (10^{-5})	3.4	3.4	3.4	
β_{IP} x/y (m)	0.8/0.0012	0.06/0.001	0.4/0.0012	
Emittance x/y (nm)	6.12/0.018	6.13/0.018	0.9/0.018	
Transverse σ_{IP} (um)	69.97/0.15	19.2/0.13	18.9/0.15	
ξ_x/IP	0.118	0.031	0.072	
ξ_y/IP	0.083	0.074	0.028	
V_{RF} (GV)	6.87	6.87	0.68	
f_{RF} (MHz)	650	650	650	
Nature σ_z (mm)	2.14	2.13	1.5	
Total σ_z (mm)	2.65	2.4	1.5	
HOM power/cavity (kw)	3.6	1.0	0.55	0.01
Energy spread (%)	0.13	0.13	0.05	
Energy acceptance (%)	2	1.5		
Energy acceptance by RF (%)	6	6.1	4.5	
n_γ	0.23	0.21	0.028	
Life time due to beamstrahlung_cal (minute)	47	46		
F (hour glass)	0.68	0.66	0.82	
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.04	2.1	1.04	0.022

parameter for CEPC PDR-88km

（wangdou20160329）

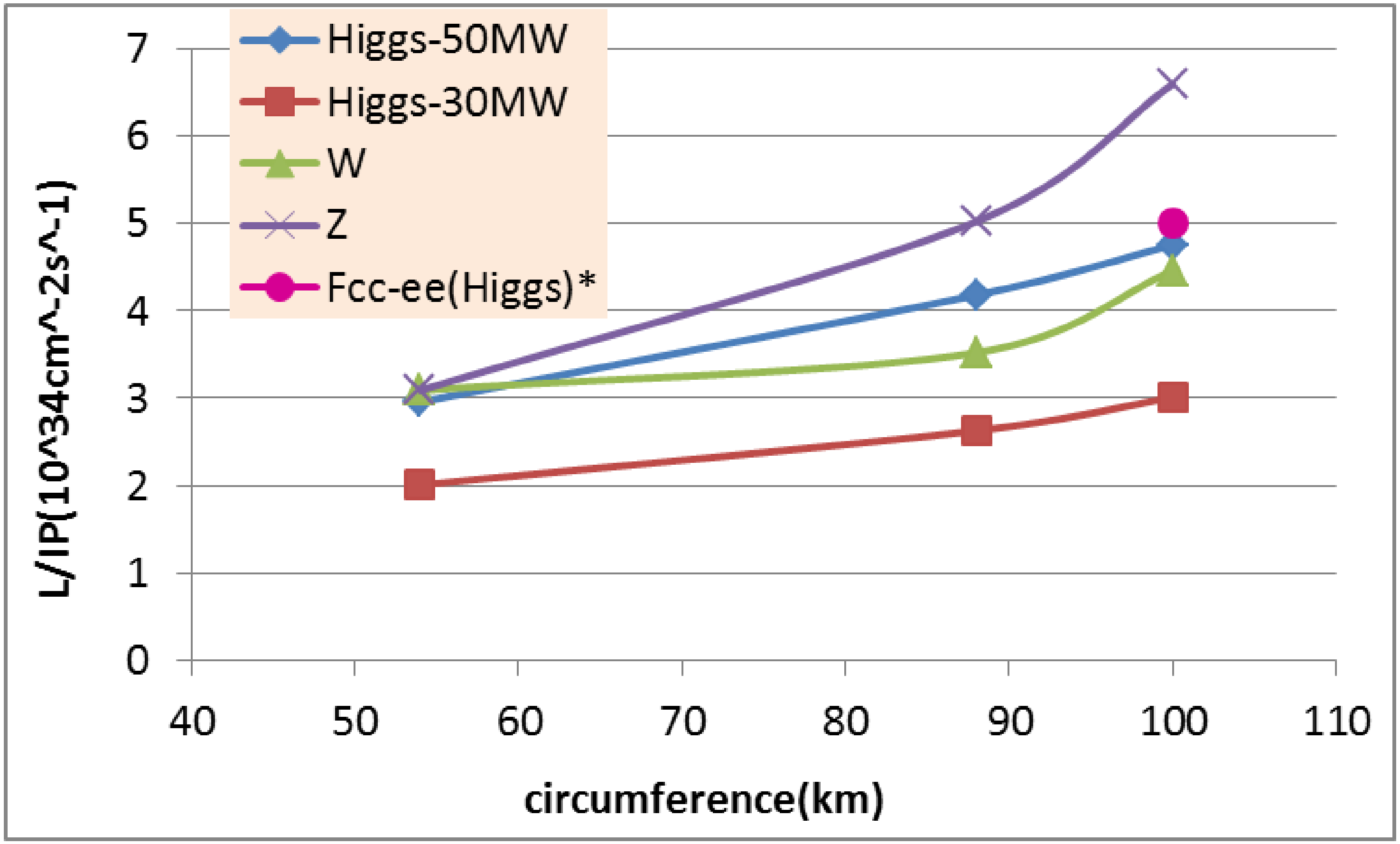
	H-high lumi.	*H-low power*	*W*	*Z*
Number of IPs	2	2	2	2
Energy (GeV)	120	120	80	45.5
Circumference (km)	88	88	88	88
SR loss/turn (GeV)	2.0	2.0	0.4	0.04
Half crossing angle (mrad)	15	15	15	15
Piwinski angle	2.0	2.6	6.3	12.1
N_e/bunch (10^{11})	1.75	1.53	0.565	0.24
Bunch number	257	176	1150	6600
Beam current (mA)	24.5	14.7	35.5	86.5
SR power /beam (MW)	50	30	14.3	3.6
Bending radius (km)	9.0	9.0	9.0	9.0
Momentum compaction (10^{-5})	1.9	1.5	1.9	1.9
β_{IP} x/y (m)	0.36/0.0011	0.36/0.0011	0.1/0.001	0.1/0.001
Emittance x/y (nm)	1.63/0.005	1.15 /0.0035	0.76/0.0023	0.24/0.0011
Transverse σ_{IP} (um)	24.4/0.074	20.5/0.062	8.7/0.048	4.9/0.033
ξ_x/IP	0.04	0.033	0.0053	0.0033
ξ_y/IP	0.091	0.091	0.061	0.06
V_{RF} (GV)	**3.1**	**2.57**	**0.57**	**0.074**
f_{RF} (MHz)	650	650	650	650
Nature σ_z (mm)	**2.7**	**2.94**	**3.55**	**3.93**
Total σ_z (mm)	3.25	3.53	3.65	4.0
HOM power/cavity (kw)	2.2	1.1	0.99	0.97
Energy spread (%)	0.1	0.1	0.07	0.04
Energy acceptance (%)	1.5	1.4		
Energy acceptance by RF (%)	**3**	**2.1**	**1.4**	**0.9**
n_γ	0.29	0.31	0.27	0.2
Life time due to beamstrahlung_cal (minute)	32	40		
F (hour glass)	0.78	0.82	0.94	0.97
L_{max}/IP (10^{34}cm^{-2}s^{-1})	4.18	2.63	3.52	5.02

parameter for CEPC PDR-100km

（wangdou20160329）

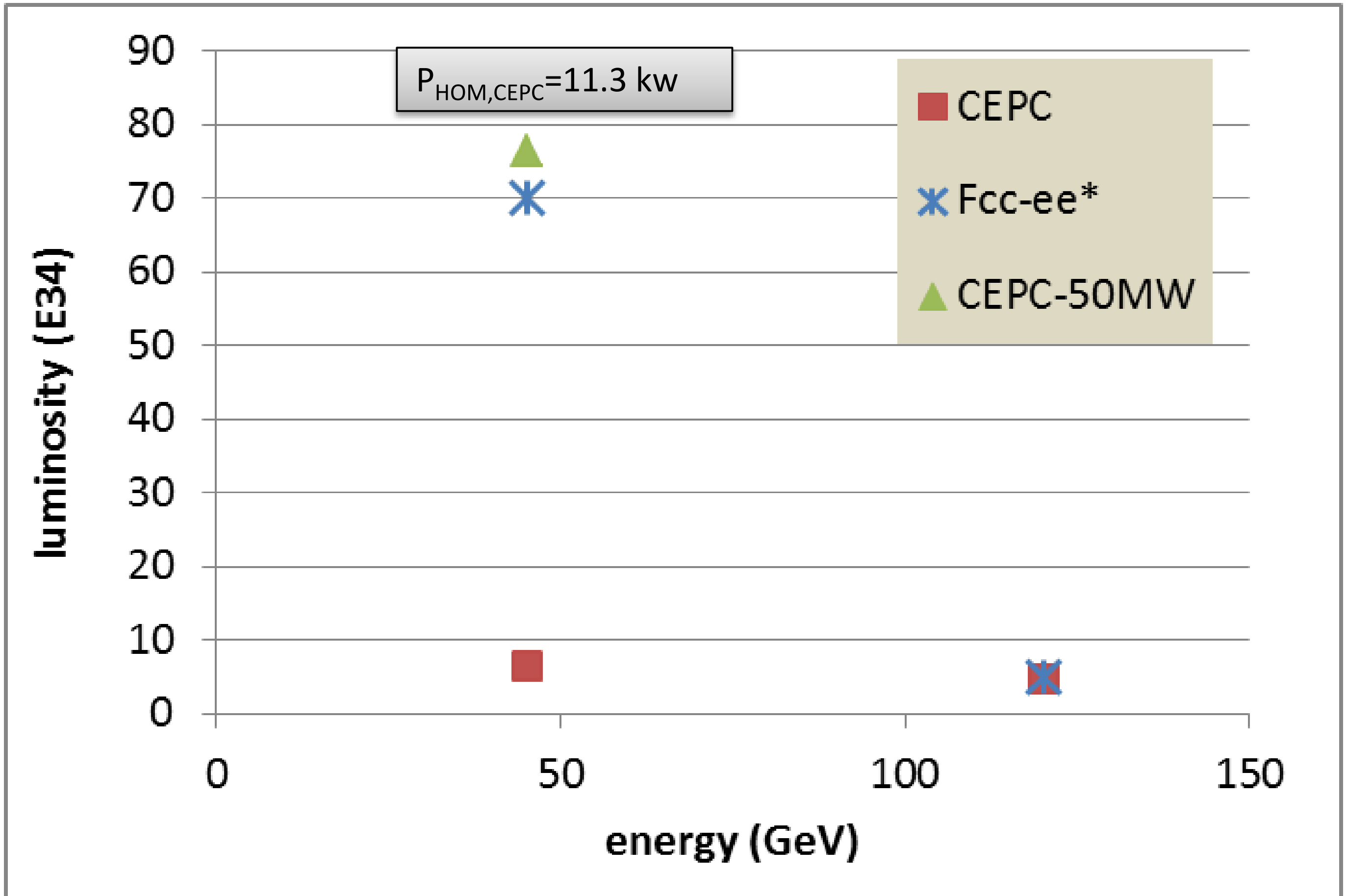
	H-high lumi.	***H-low power***	***W***	***Z***	
Number of IPs	2	2	2	2	
Energy (GeV)	120	120	80	45.5	
Circumference (km)	100	100	100	100	
SR loss/turn (GeV)	1.7	1.7	0.33	0.034	
Half crossing angle (mrad)	15	15	15	15	
Piwinski angle	2.0	2.83	8.65	15.8	
N_e/bunch (10^{11})	1.43	1.22	0.42	0.165	
Bunch number	436	307	2400	15800	182260
Beam current (mA)	30	18	48.7	125.3	1449.7
SR power /beam (MW)	50	30	16.0	4.3	50
Bending radius (km)	11	11	11	11	
Momentum compaction (10^{-5})	1.8	1.4	1.4	1.3	
β_{IP} x/y (m)	0.297/0.0011	0.3/0.0011	0.1/0.001	0.1/0.001	
Emittance x/y (nm)	1.63/0.0049	1.03/0.003	0.46/0.0014	0.14/0.00065	
Transverse σ_{IP} (um)	22/0.074	17.6/0.59	6.8/0.037	3.8/0.026	
ξ_x/IP	0.033	0.025	0.003	0.002	
ξ_y/IP	0.083	0.083	0.055	0.054	
V_{RF} (GV)	**3.1**	**2.25**	**0.41**	**0.053**	
f_{RF} (MHz)	650	650	650	650	
Nature σ_z (mm)	**2.45**	**2.77**	**3.8**	**3.94**	
Total σ_z (mm)	2.94	3.33	3.9	4.0	
HOM power/cavity (kw)	2.3	1.1	0.98	0.97	11.3
Energy spread (%)	0.1	0.1	0.065	0.037	
Energy acceptance (%)	1.46	1.4			
Energy acceptance by RF (%)	**3.5**	**2.2**	**0.9**	**0.7**	
n_γ	0.27	0.28	0.26	0.18	
Life time due to beamstrahlung_cal (minute)	40	49			
F (hour glass)	0.8	0.85	0.96	0.985	
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	4.75	3.01	4.46	6.59	76.4

CEPC PDR Luminosity vs circumference



* Fabiola Gianotti, Future Circular ColliderDesign Study, ICFA meeting, J-PARC, 25-2-2016.

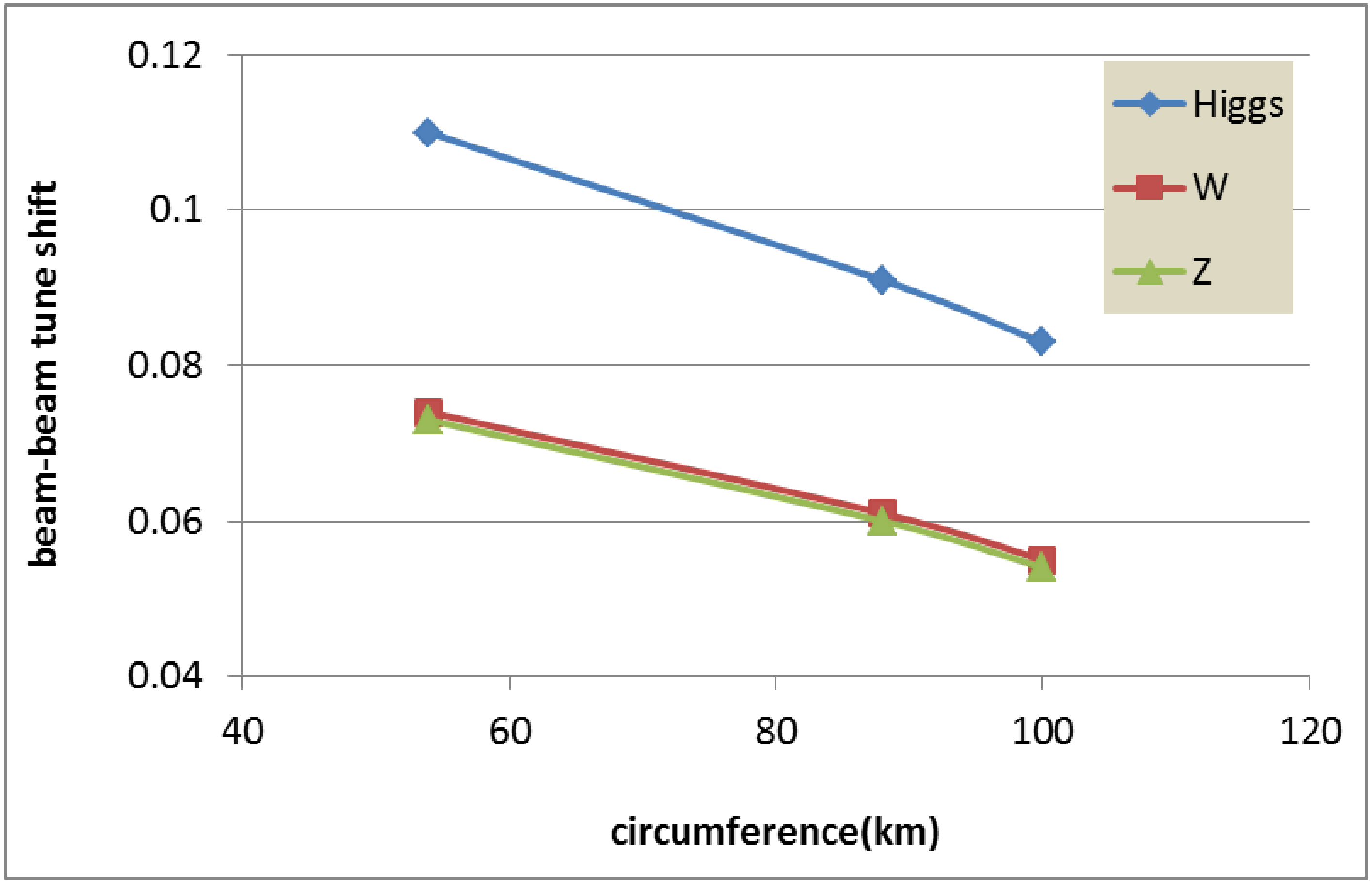
100km CEPC PDR vs Fcc-ee



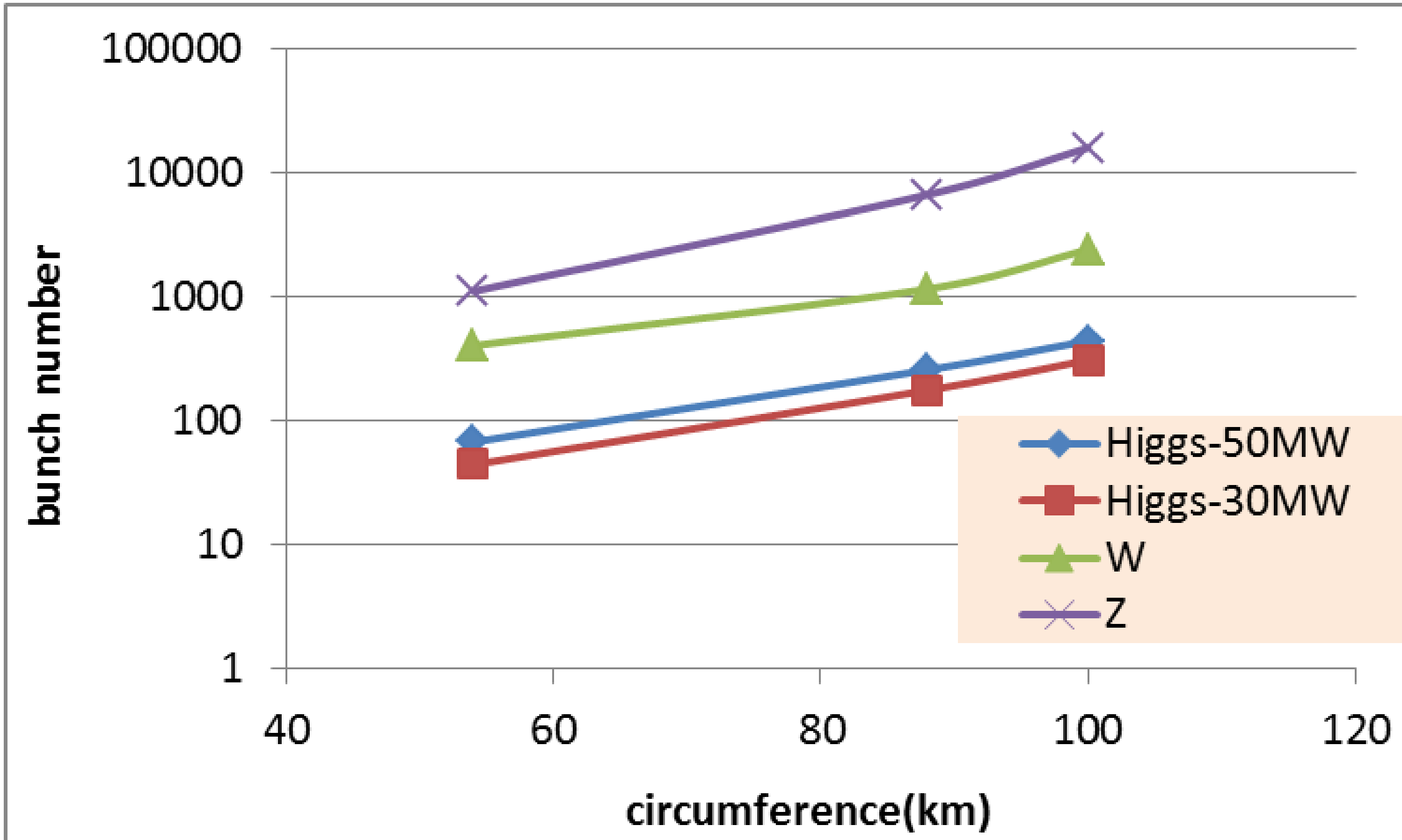
- The large difference of Z is due to the constraint for RF HOM power.

* Fabiola Gianotti, Future Circular ColliderDesign Study, ICFA meeting, J-PARC, 25-2-2016.

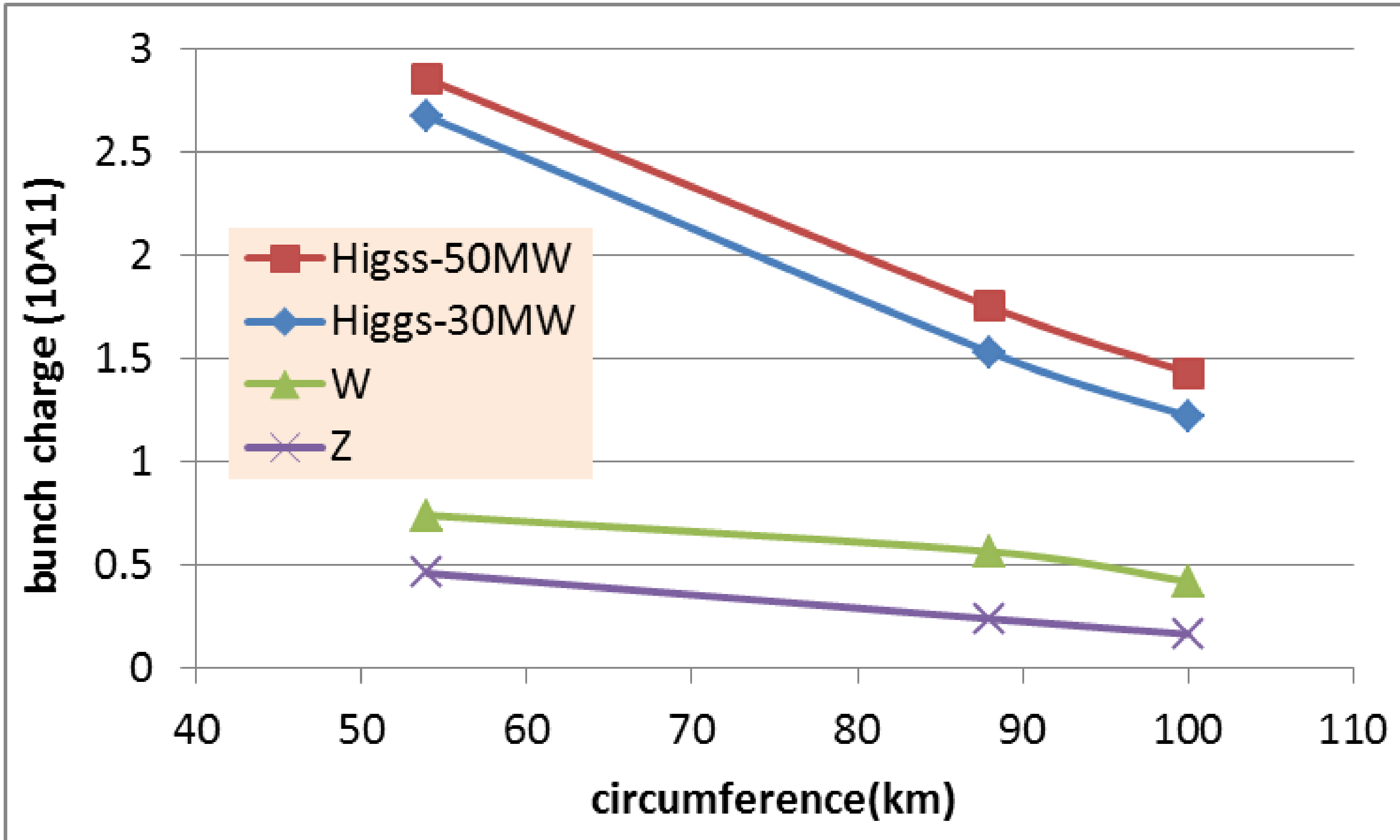
CEPC PDR ξ_y vs circumference (Higgs)



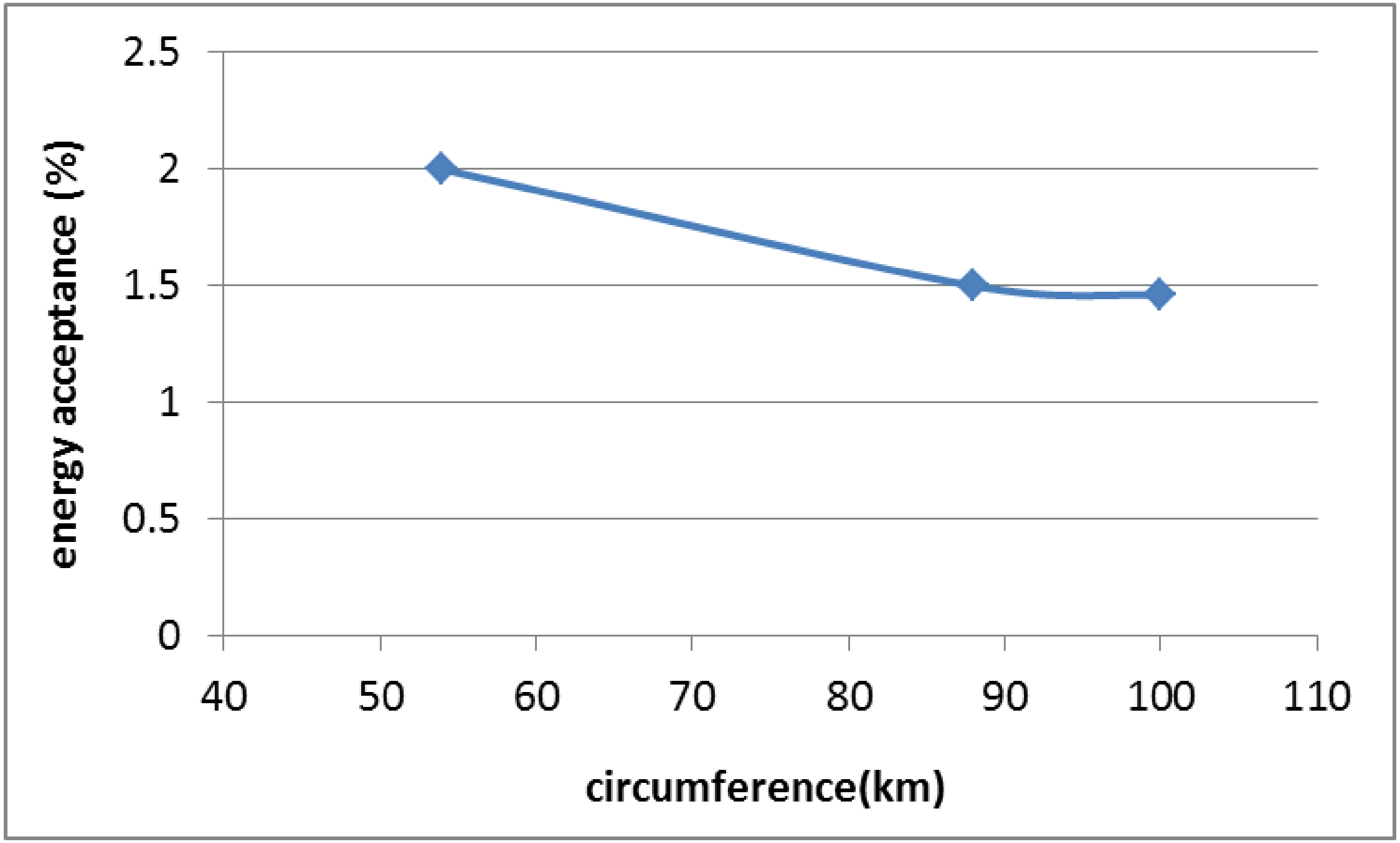
CEPC PDR bunch number vs circumference



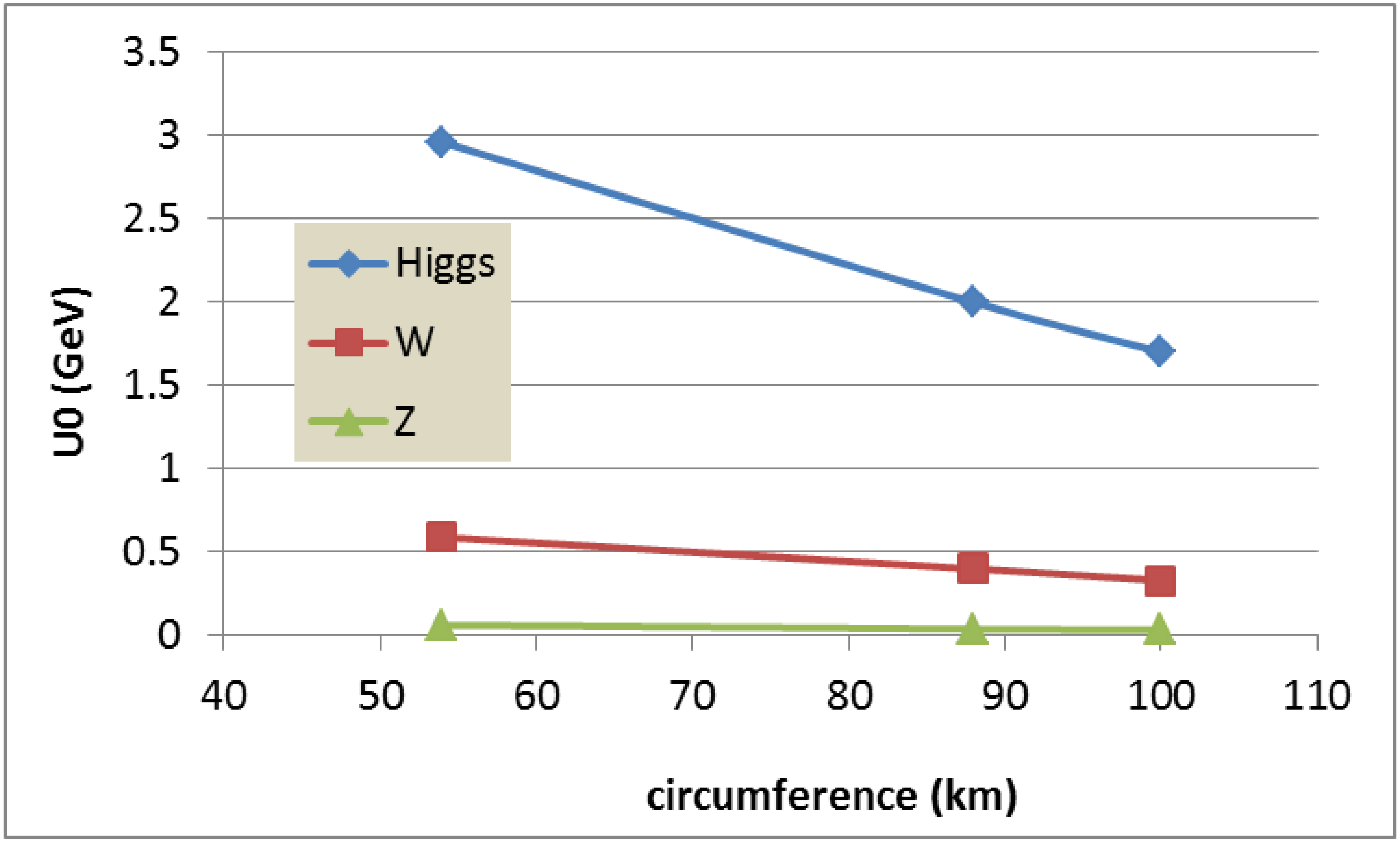
CEPC PDR bunch charge vs circumference



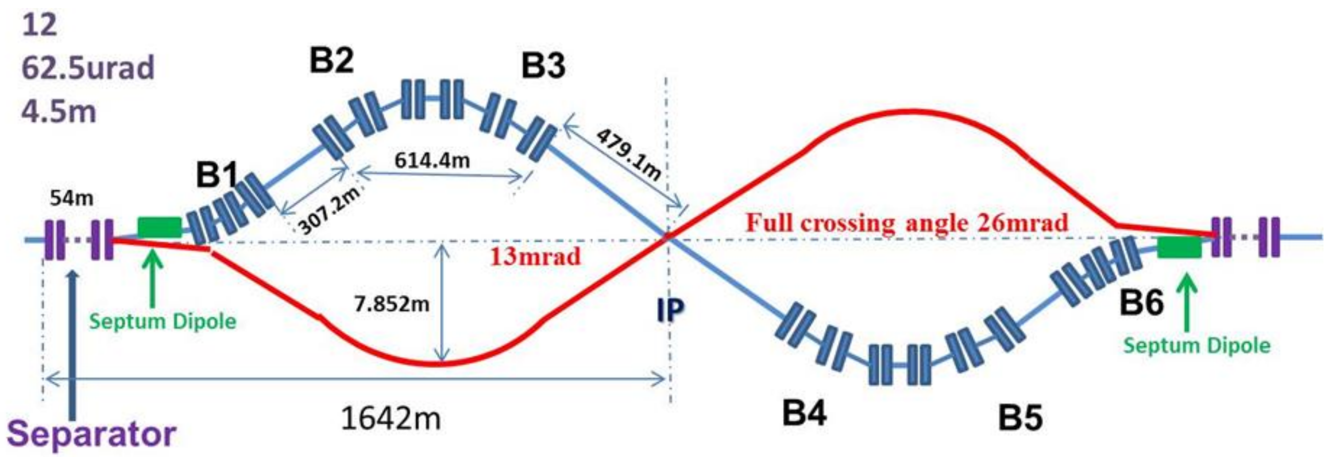
CEPC PDR energy acceptance vs circumference (Higgs)

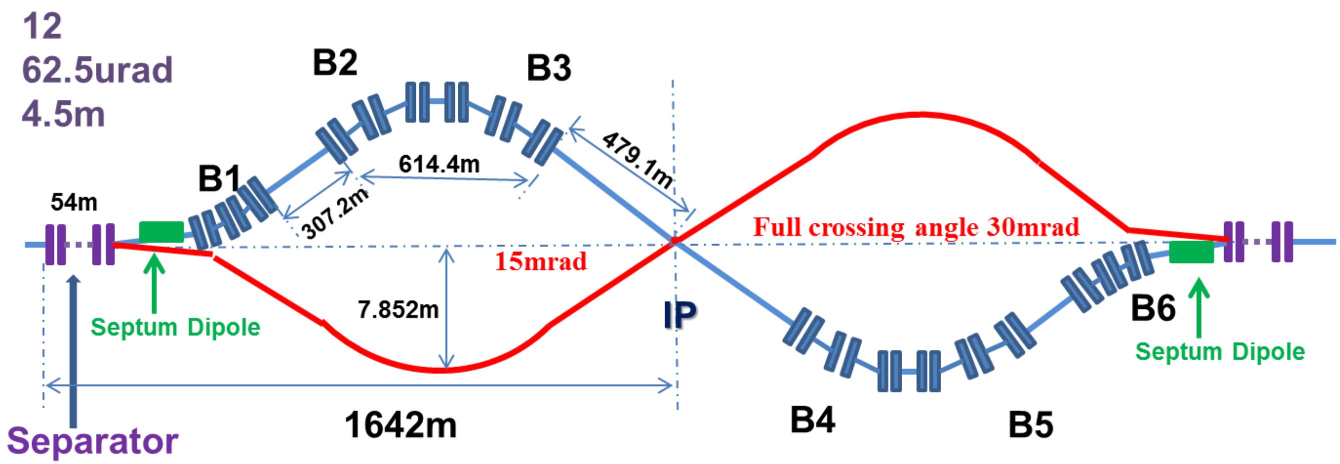


CEPC PDR SR loss vs circumference



CEPC Partial Double Ring Lattice





For CEPC 120GeV beam:

- **Max. deflection per separator is 66μrad.**

Using Septum Dipole after separator to acquire 15 mrad

Version 1.0

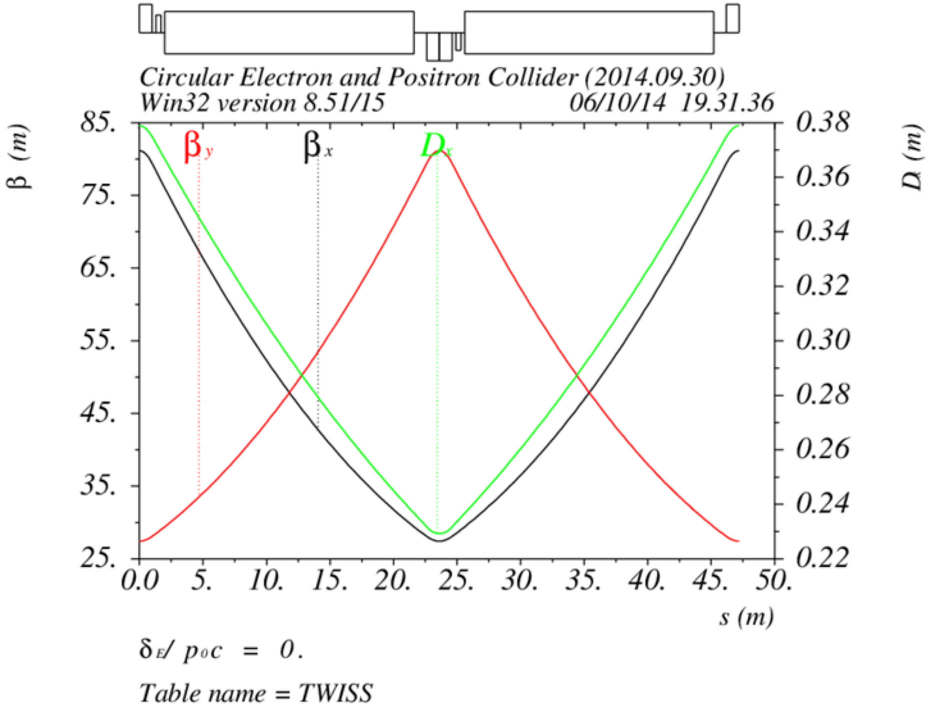
sufeng

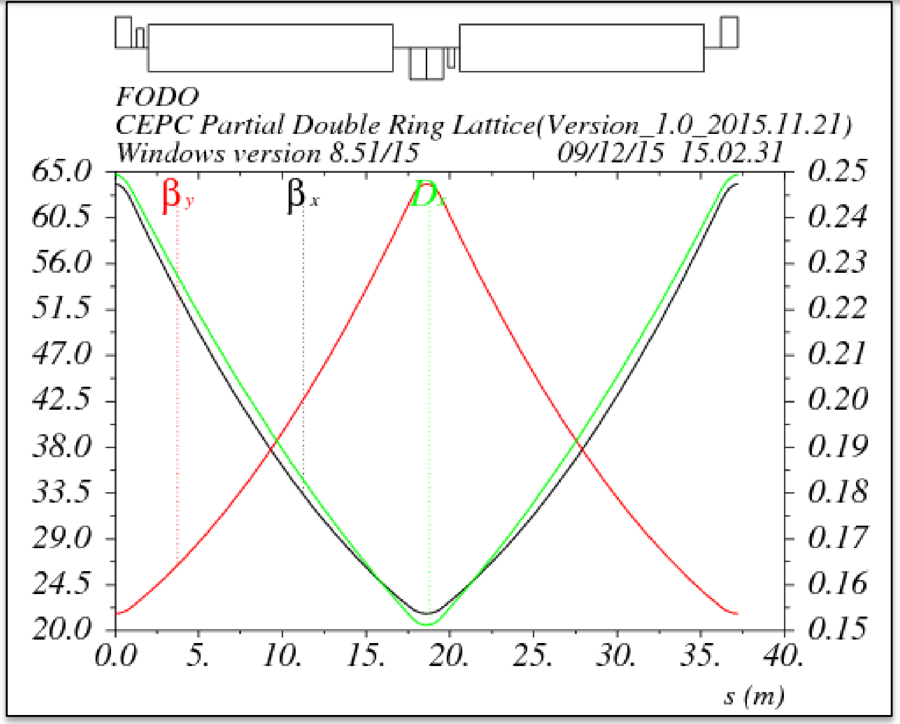
2015.12.20

Arc redesign-lower emittance

- Length of FODO cell: 47.2m
- Phase advance of FODO cells: 60/60 degrees
- Emittance: 7.9nm, αp=5.38E-5
- Bunch length: 2.3mm

- Length of FODO cell: 37.5m
- Phase advance of FODO cells: 60/60 degrees
- Emittance: 4.3nm , αp=2.25E-5
- Bunch length: 3.3mm





Low emittance arc – 90°/60°

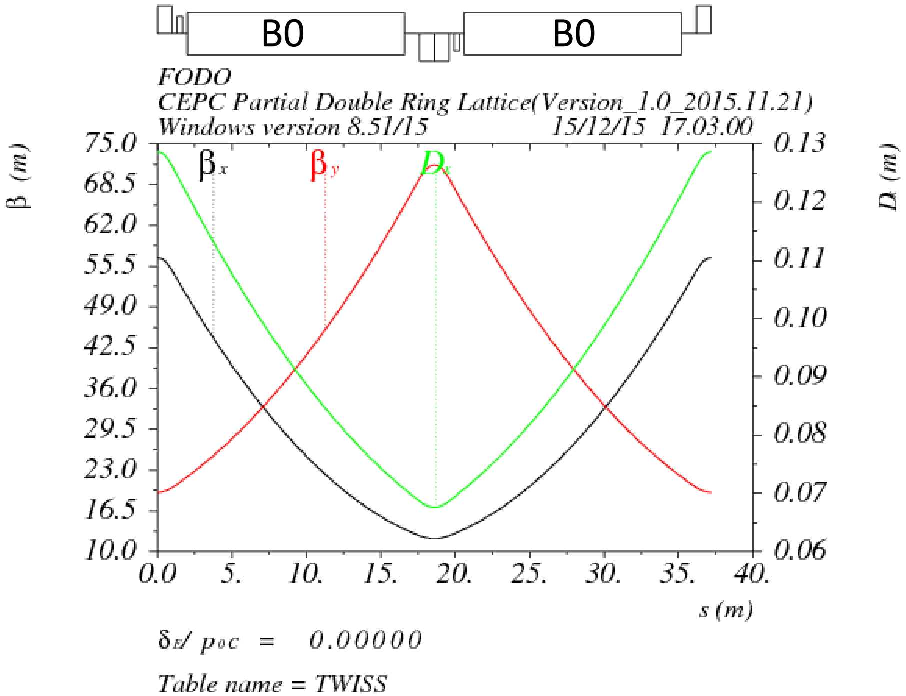
- Length of FODO cell: 37.5m
- Phase advance of FODO cells: 90/60 degrees
- Emittance: 2.3nm, αp=1.07E-5
- Bunch length: 3.1mm

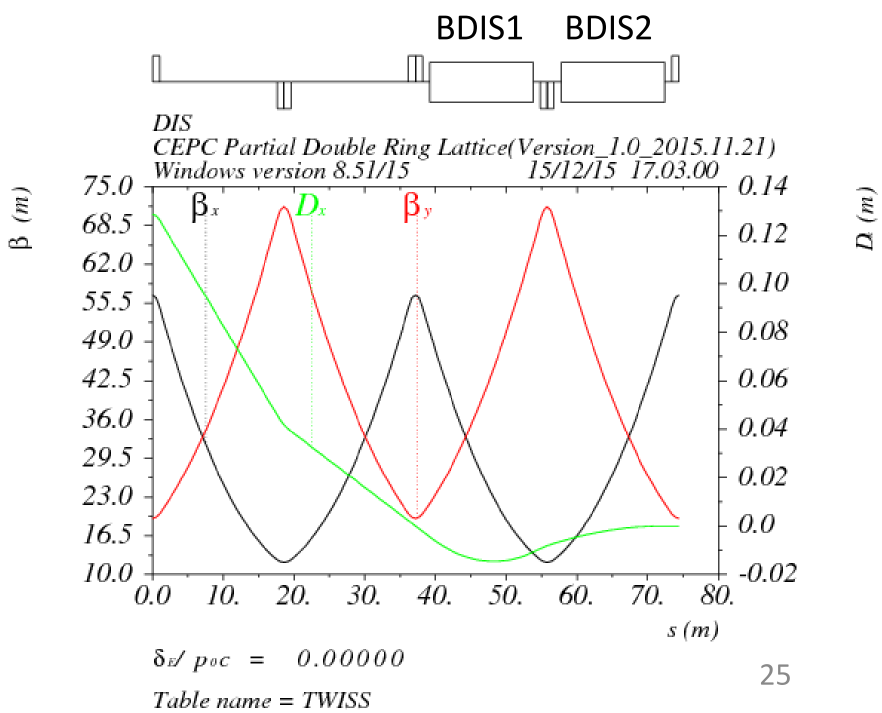
- Dispersion supressor:

Angle(BDIS1)=3.583724E-3

Angle(BDIS2)=-8.598108E-4

Angle(B0)=2.723923E-3





Low emittance arc – 90°/90°

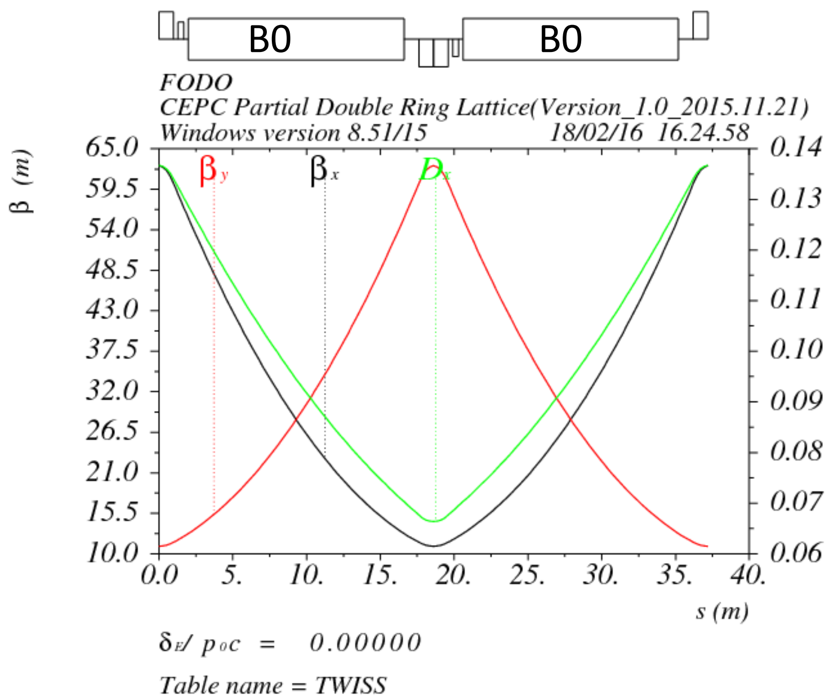
- Length of FODO cell: 37.5m
- Phase advance of FODO cells: 90/90 degrees
- Emittance: 2.3nm, αp=1.02E-5
- Bunch length: 3.1mm

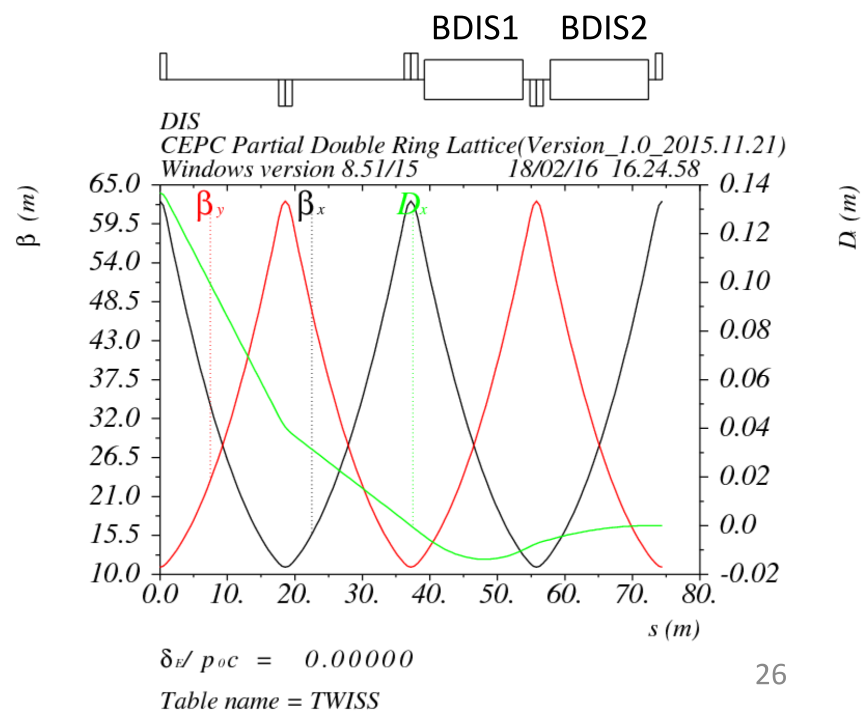
- Dispersion supressor:

  Angle(BDIS1)=3.50284406482E-3

  Angle(BDIS2)=-7.78931580723E-4

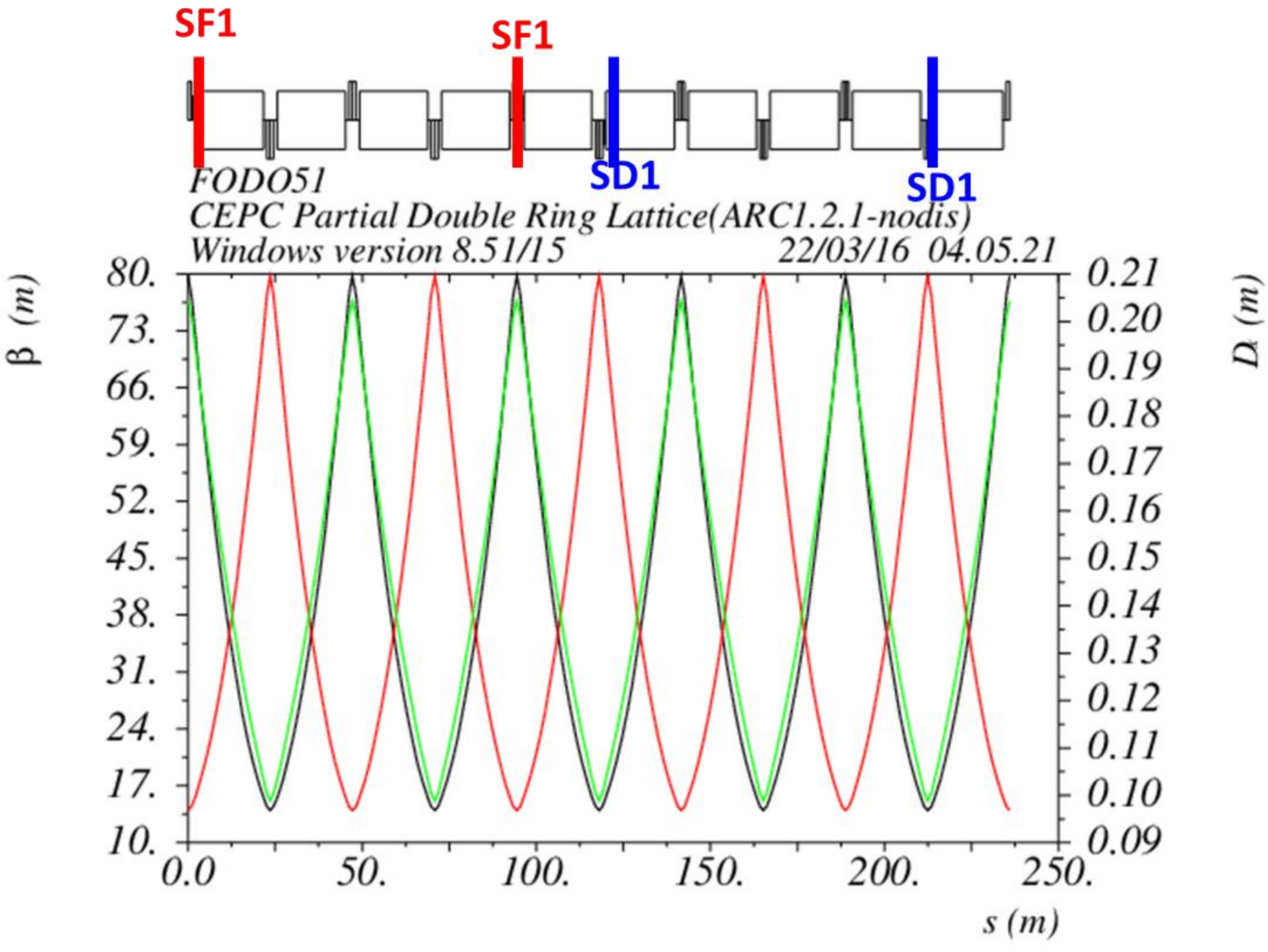
  Angle(B0)=2.723923E-3





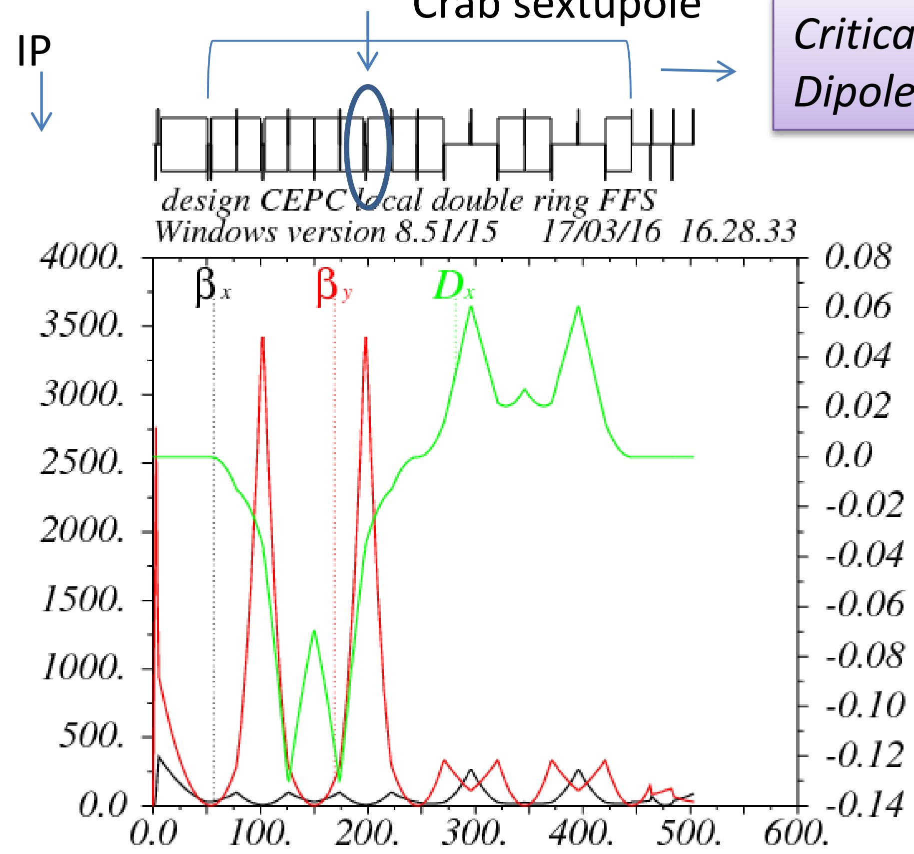
Non-interleave sextupoles in arc

(90°/90° FODO)



Partial double ring FFS design with crab sextupoles

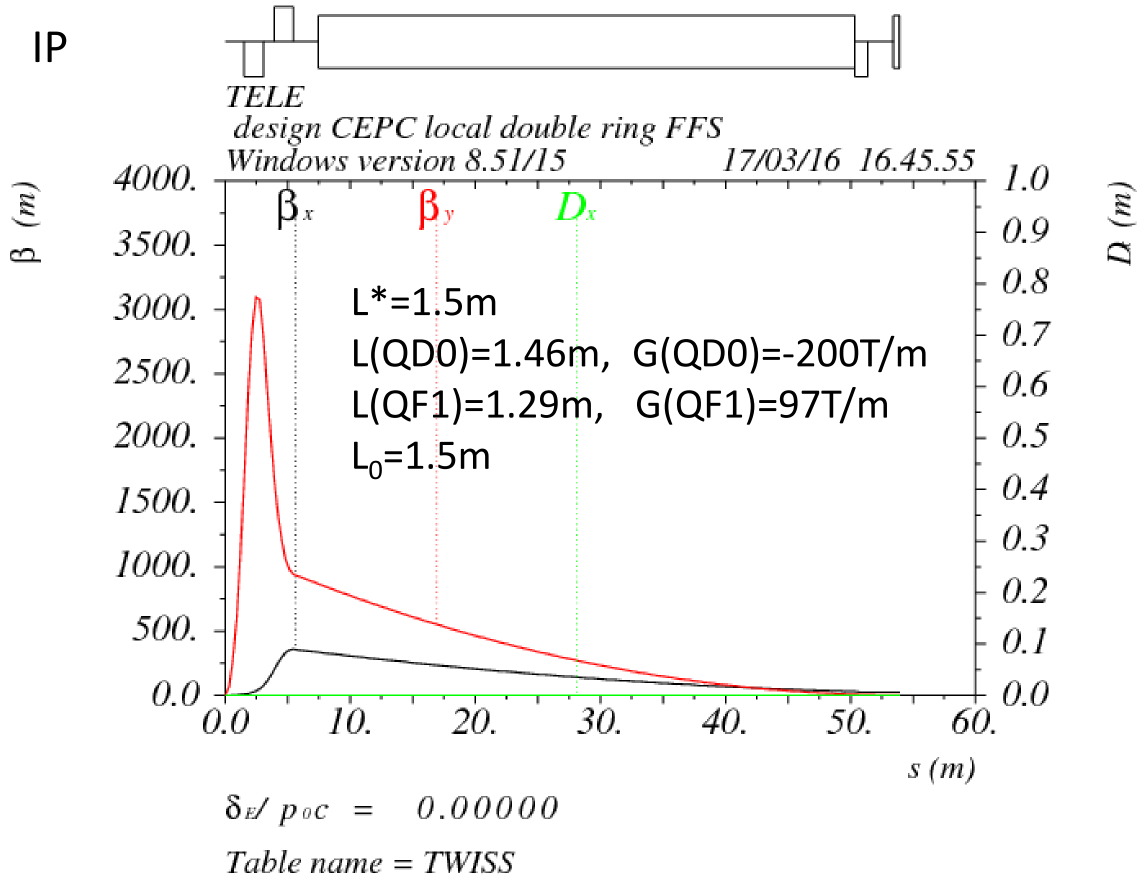
Betax=0.25m
Betay=0.00136m
K2hs=26.8 m^{-3}
K2vs=32.2 m^{-3}



Critical energy: Ec=190 keV
Dipole strength: B=0.019 T

➢ The second FFS sextupoles of the CCS-Y section work as the crab sextupoles.

Final doublet



Crab sextupole strength

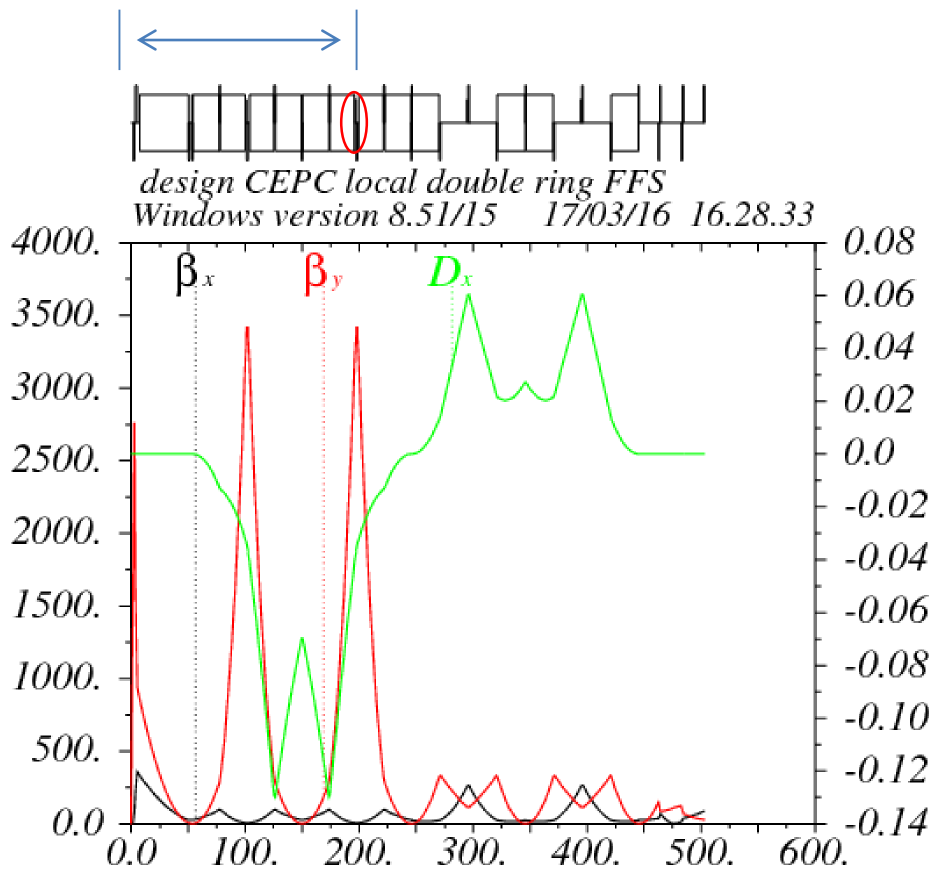
➢ The crab sextupole should be placed on both sides of the IP in phase with the IP in the horizontal plane and at π/2 in the vertical one.

$$KL = \frac{1}{2\theta}\frac{1}{\beta_y^*\beta_y}\sqrt{\frac{\beta_x^*}{\beta_x}} = 1.27m^{-2}$$

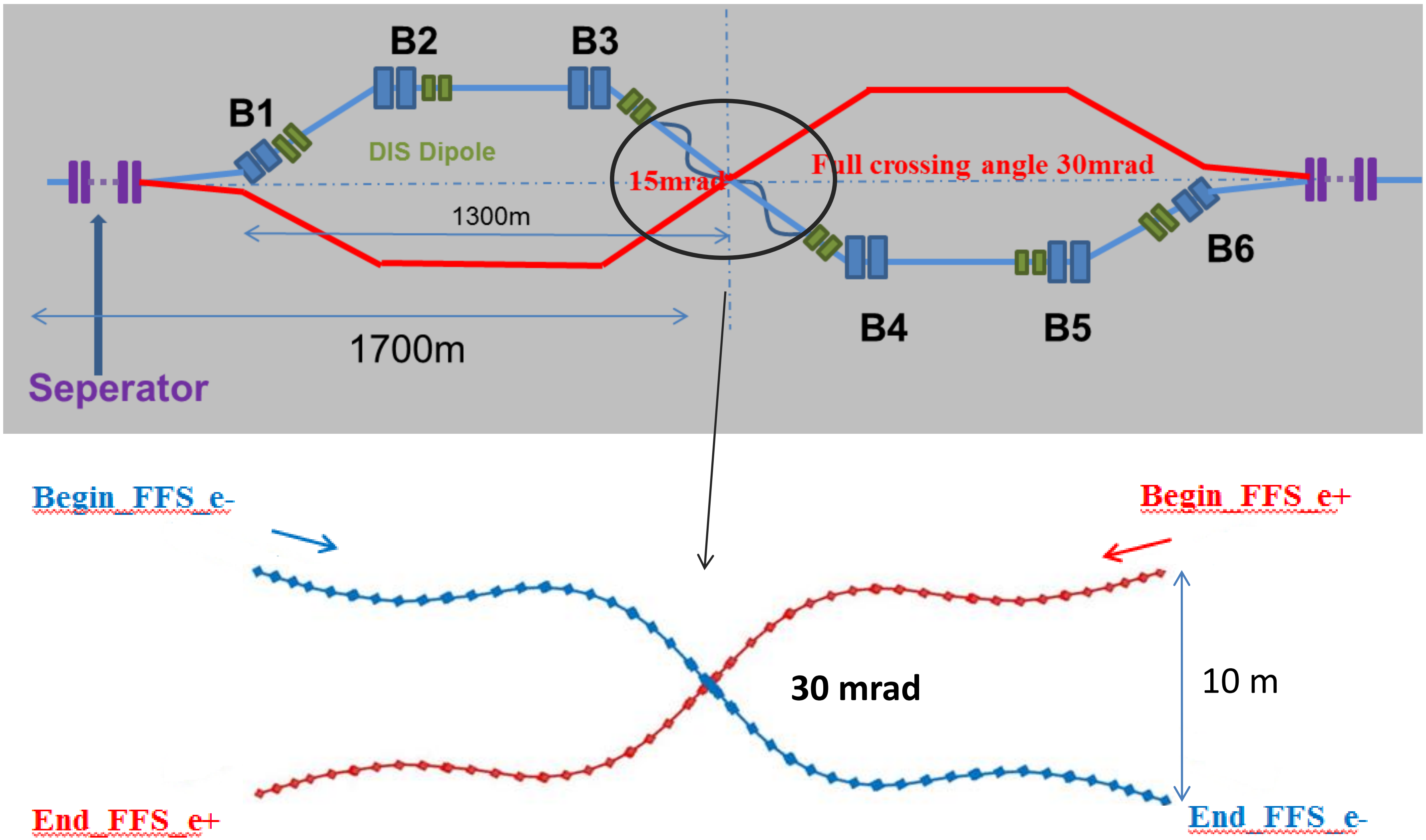
$$K_2 = 4.2m^{-3}$$

13% strength of main sextupoles

$\Delta\varphi_x=2\pi$, $\Delta\varphi_y=2.5\pi$



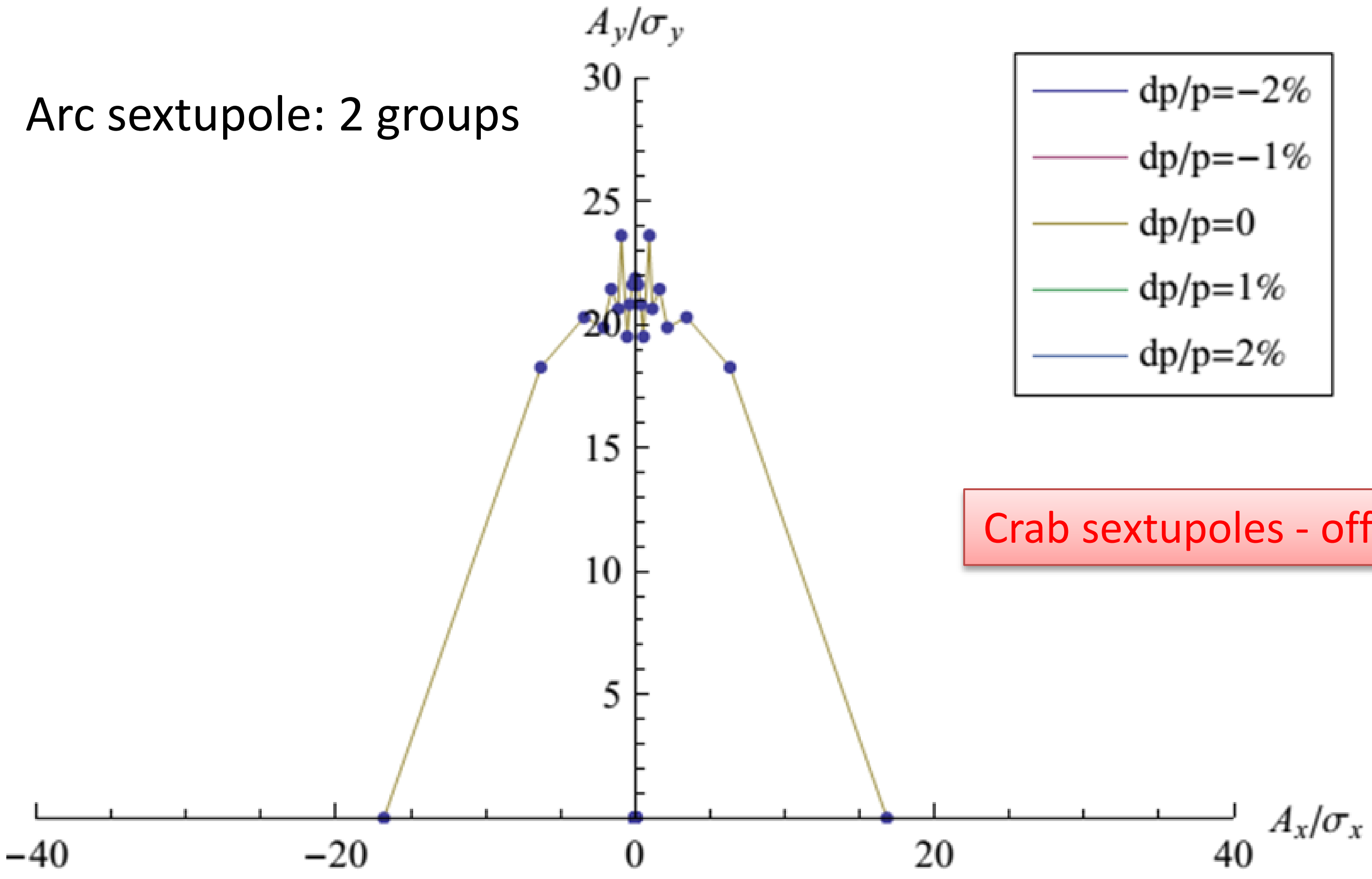
Combine with partial double ring lattice



DA of the whole ring
(arc+PDR+bypass+FFS)

Su Feng 2016.03.30

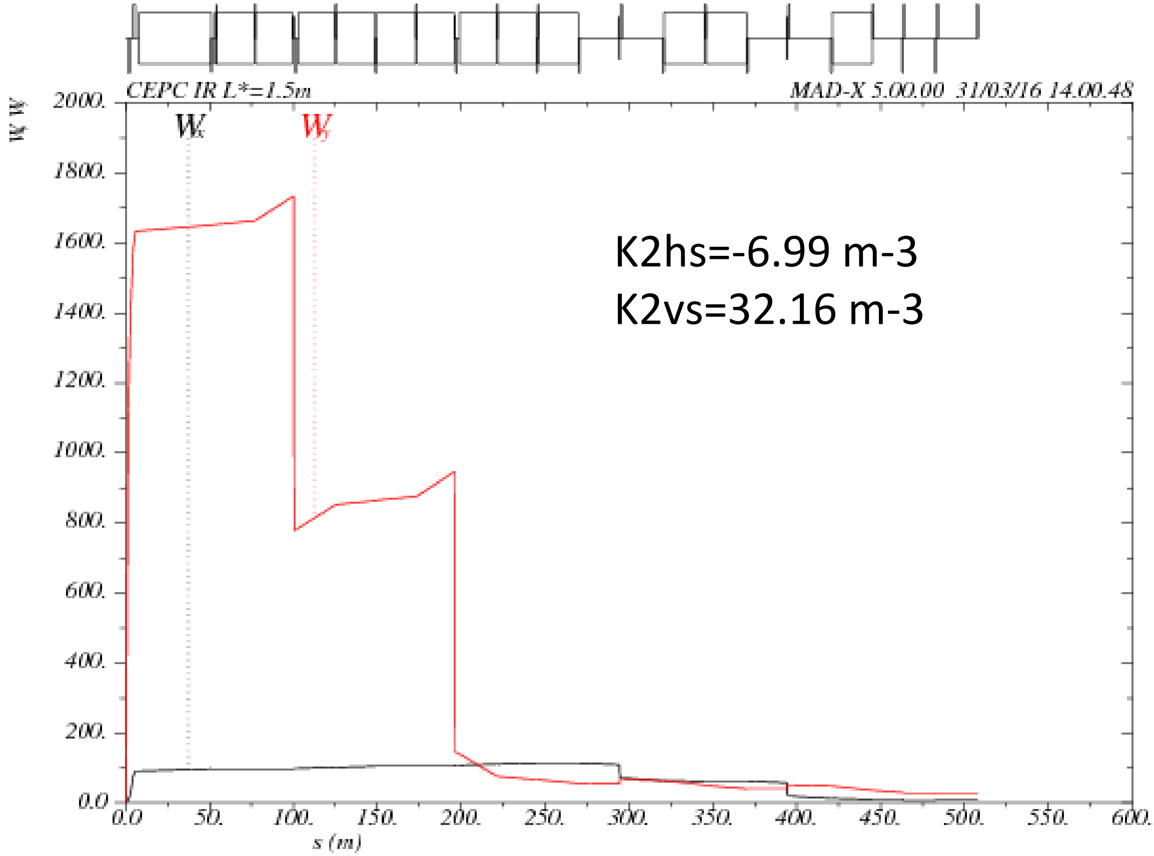
Arc sextupole: 2 groups



Crab sextupoles - off

Chromaticity correction in FFS

- Fine tuning the phase of main sextupoles.
- Weak sextupoles are -10% of main sextupoles to correct the sextupoles' length effect*

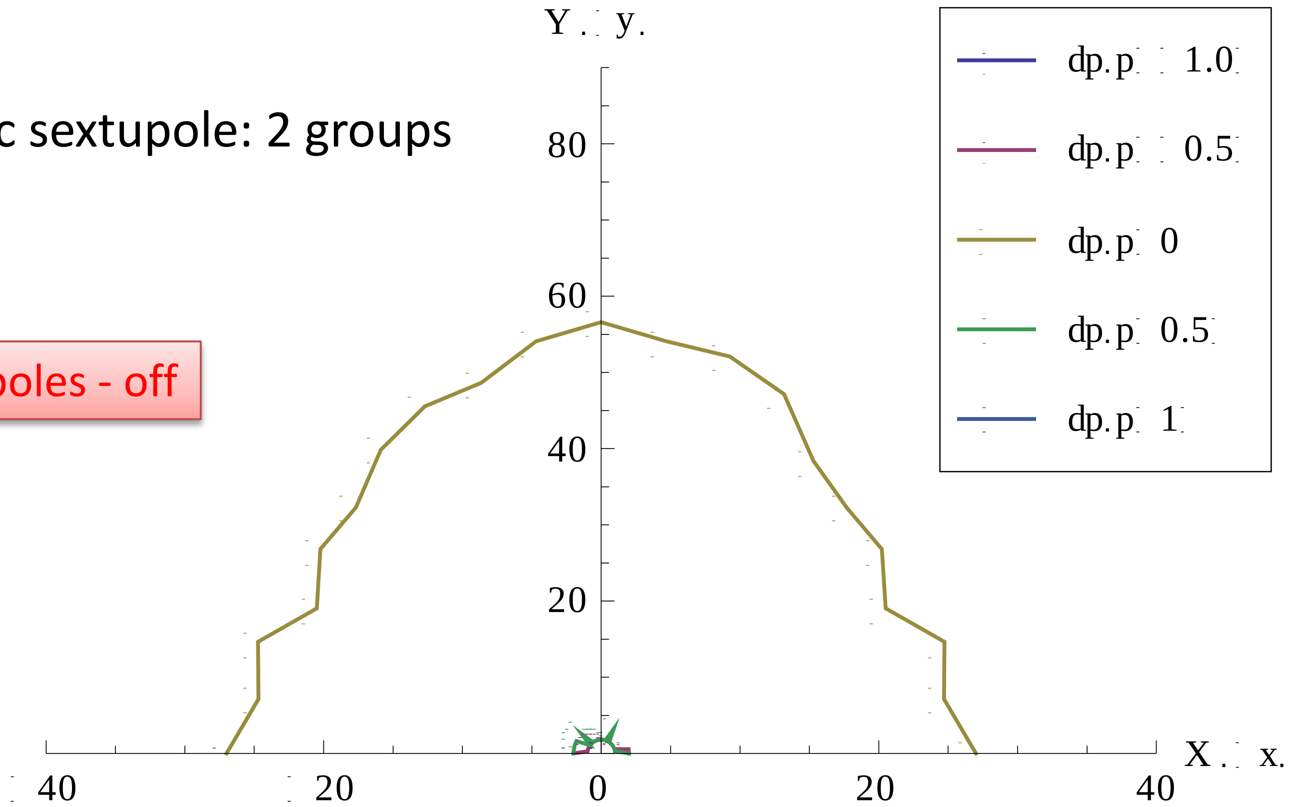


*A. Bogomyagkov, S. Glukhov, E. Levichev and P. Piminov, "effect of the sextupole finite length on dynamic aperture in the collider final focus", [arXiv:0909.4872v1] [physics.acc-ph]

DA after chromaticity correction

Arc sextupole: 2 groups

Crab sextupoles - off



- DA (on-momentum): $27\sigma_x \times 57\sigma_y$
- DA (±0.5%): $2\sigma_x \times 2\sigma_y$

summary

- A consistent calculation method for CEPC parameter choice with carb waist scheme has been created. Larger ring has the potential to reach higher luminosity.
- Based on partial double ring scheme, we can get higher luminosity (+50%) keeping Pre-CDR beam power or to reduce the beam power (30 MW) keeping same luminosity.
- For "H-high lumi" mode, the HOM power per cavity can not be reduced under 1kw. The minimum value is about 2 kw.
- Based on partial double ring scheme, we get a set of Z parameter with $3.1*10^{34}cm^{-2}s^{-1}$ luminosity using 1100 bunches.
- CEPC single ring scheme is neither easy to reduce cavity HOM power for Higgs nor to accommodate more bunches for Z.
- FFS with crab sextupoles and lower emittance arc has been designed. On-momentum DA of whole ring is good enough and the optimization of DA bandwidth is ongoing.

THANKS !