Institute of High Energy Physics
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THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

100km CEPC parameters and lattice design

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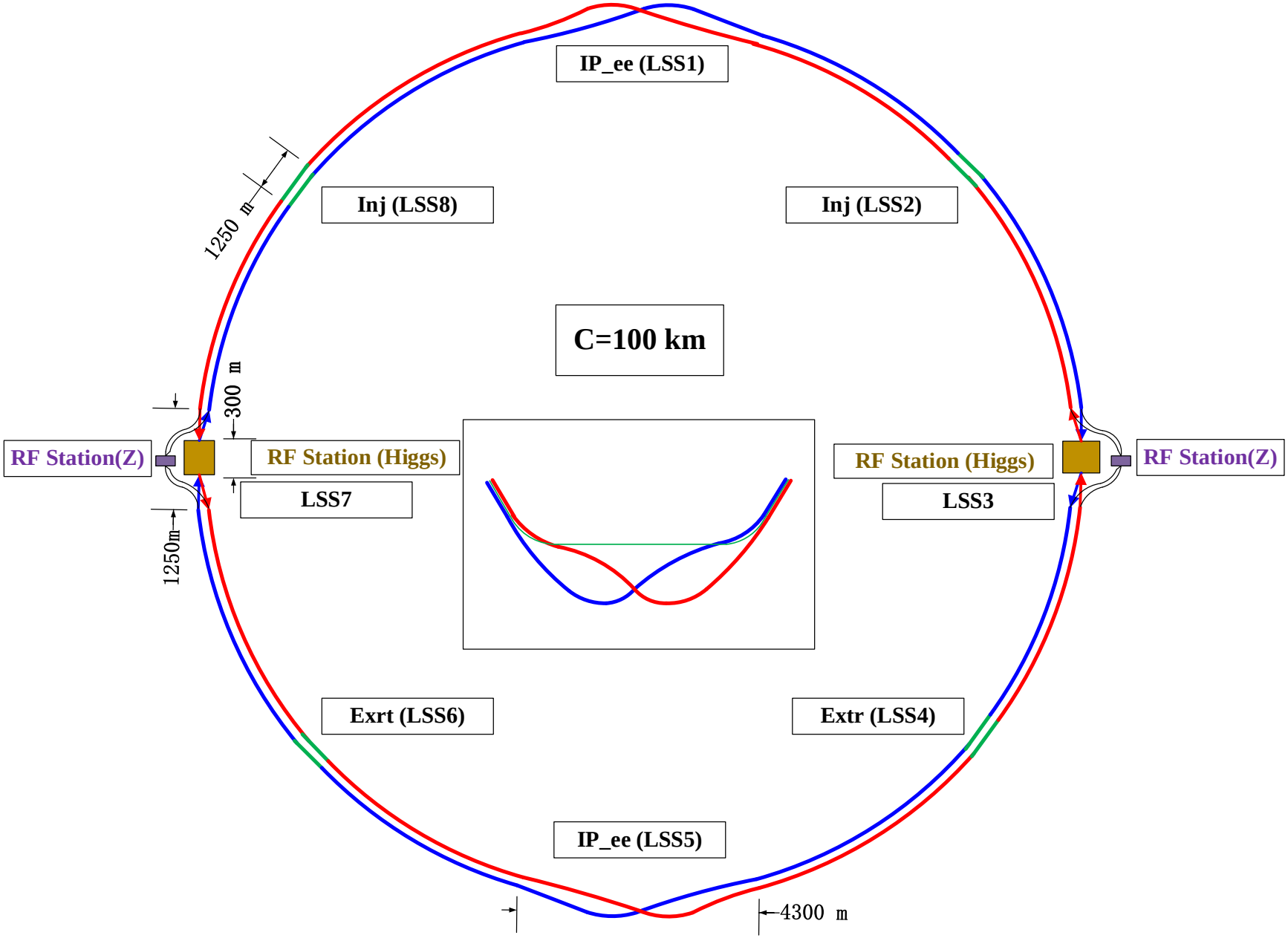
IAS Program on High Energy Physics, Jan 23-26, 2017 . IAS, Hong Kong.

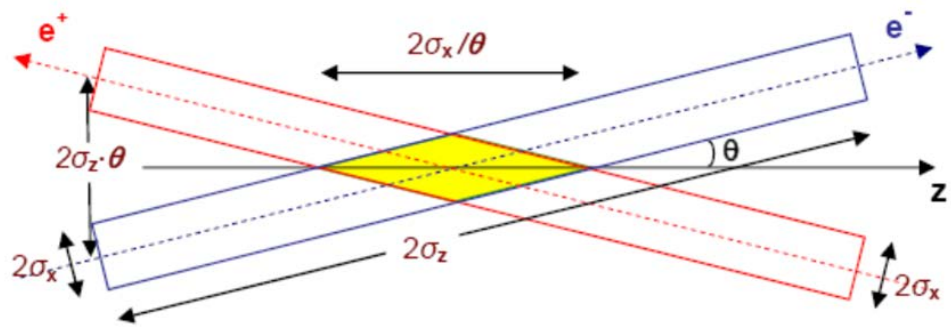
Layout of CEPC Double Ring

(Dec. 15, 2016, Su Feng)



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 requirement (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 (coaxial coupler)

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

*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.

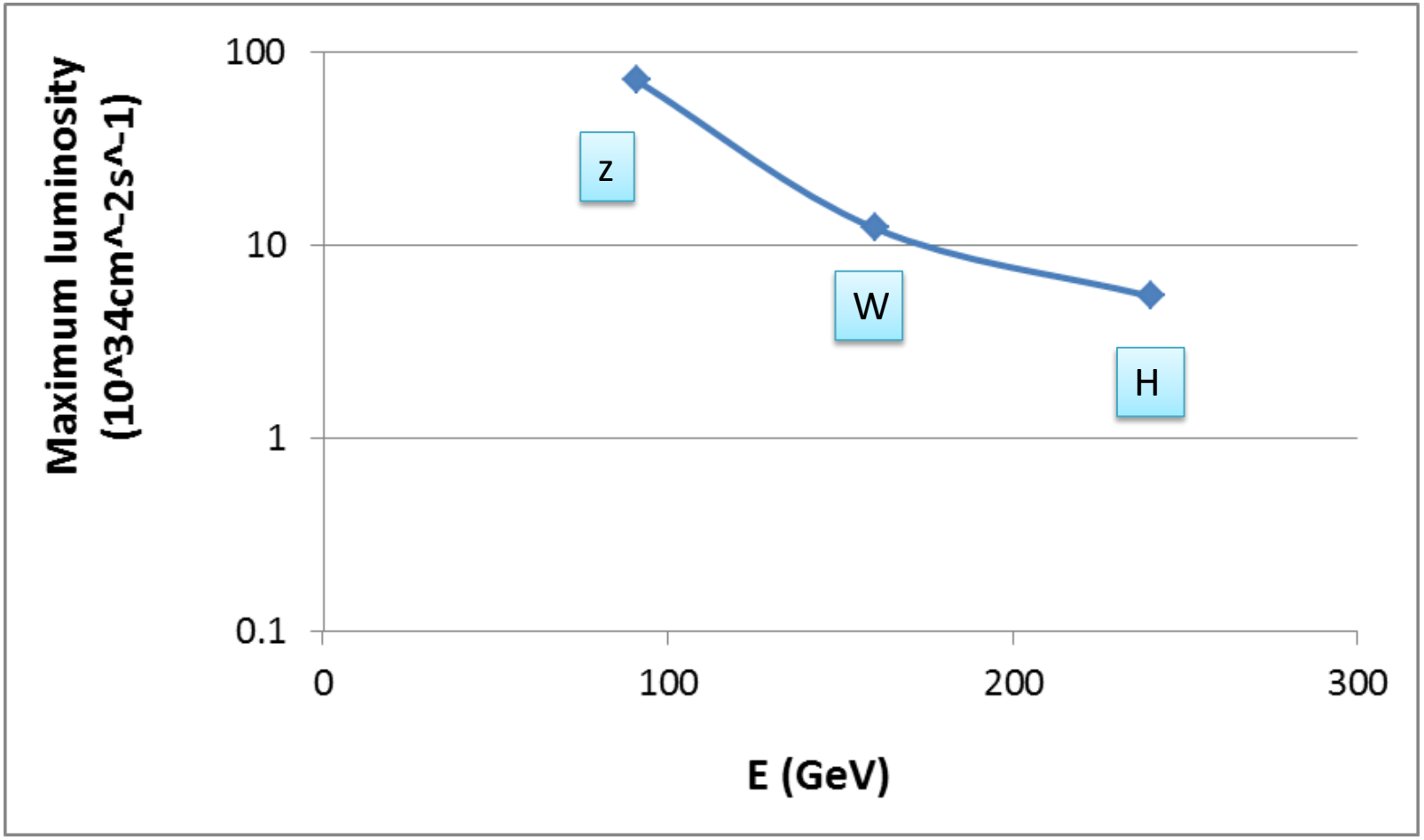
parameters for CEPC double ring

（wangdou20161219-100km_1mmβy）

	Pre-CDR	H-high lumi.	H-low power		W	Z	
Number of IPs	2	2	2	2	2	2	2
Energy (GeV)	120	120	120	120	80	45.5	45.5
Circumference (km)	54	100	100	100	100	100	100
SR loss/turn (GeV)	3.1	1.67	1.67	1.67	0.33	0.034	0.034
Half crossing angle (mrad)	0	15	15	15	15	15	15
Piwinski angle	0	2.5	2.5	2.5	3.57	5.69	5.69
N_e/bunch (10^{11})	3.79	1.12	1.12	1.12	1.05	0.46	0.46
Bunch number	50	555	333	211	1000	16666	65716
Beam current (mA)	16.6	29.97	17.98	11.4	50.6	367.7	1449.7
SR power /beam (MW)	51.7	**50**	**30**	**19**	16.7	12.7	50
Bending radius (km)	6.1	11	11	11	11	11	11
Momentum compaction (10^{-5})	3.4	0.96	0.96	0.96	3.1	3.3	3.3
β_{IP} x/y (m)	0.8/0.0012	0.3/0.001	0.3/0.001	0.3 /0.001	0.1 /0.001	0.12/0.001	0.12/0.001
Emittance x/y (nm)	6.12/0.018	1.01/0.0031	1.01/0.0031	1.01/0.0031	2.68/0.008	0.93/0.0049	0.93/0.0049
Transverse σ_{IP} (um)	69.97/0.15	17.4/0.055	17.4/0.055	17.4/0.055	16.4/0.09	10.5/0.07	10.5/0.07
ξ_x/ξ_y/IP	0.118/0.083	0.029/0.083	0.029/0.083	0.029/0.083	0.0082/0.055	0.0075/0.054	0.0075/0.054
RF Phase (degree)	153.0	123.3	123.3	123.3	149	160.8	160.8
V_{RF} (GV)	6.87	**2.0**	**2.0**	**2.0**	**0.63**	**0.11**	**0.11**
f_{RF} (MHz) (harmonic)	650	650	650	650	650 (217800)	650 (217800)	
Nature σ_z (mm)	2.14	**2.72**	**2.72**	**2.72**	**3.8**	**3.93**	**3.93**
Total σ_z (mm)	2.65	2.9	2.9	2.9	3.9	4.0	4.0
HOM power/cavity (kw)	3.6 (5cell)	0.75(2cell)	0.45(2cell)	0.28(2cell)	1.0 (2cell)	1.6(1cell)	6.25(1cell)
Energy spread (%)	0.13	0.098	0.098	0.098	0.065	0.037	0.037
Energy acceptance (%)	2	1.5	1.5	1.5			
Energy acceptance by RF (%)	6	1.8	1.8	1.8	1.5	1.1	1.1
n_γ	0.23	0.26	0.26	0.26	0.26	0.18	0.18
Life time due to beamstrahlung_cal (minute)	47	52	52	52			
F (hour glass)	0.68	0.83	0.83	0.83	0.84	0.91	0.91
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.04	5.42	3.25	2.06	4.08	18.0	70.97

100km CEPC luminosity potential

(50MW/beam)



parameters for CEPC double ring

（wangdou20161202-100km_2mmβy）

	Pre-CDR	***H-high lumi.***	***H-low power***
Number of IPs	2	2	2
Energy (GeV)	120	120	120
Circumference (km)	54	100	100
SR loss/turn (GeV)	3.1	1.67	1.67
Half crossing angle (mrad)	0	15	15
Piwinski angle	0	2.9	2.9
N_e/bunch (10^{11})	3.79	0.97	0.97
Bunch number	50	644	425
Beam current (mA)	16.6	29.97	19.8
SR power /beam (MW)	51.7	**50**	**33**
Bending radius (km)	6.1	11	11
Momentum compaction (10^{-5})	3.4	1.3	1.3
β_{IP} x/y (m)	0.8/0.0012	0.144 /0.002	0.144 /0.002
Emittance x/y (nm)	6.12/0.018	1.56/0.0047	1.56/0.0047
Transverse σ_{IP} (um)	69.97/0.15	15/0.097	15/0.097
ξ_x/ξ_y/IP	0.118/0.083	0.0126/0.083	0.0126/0.083
RF Phase (degree)	153.0	131.2	131.2
V_{RF} (GV)	6.87	**2.22**	**2.22**
f_{RF} (MHz) (harmonic)	650	650 (217800)	650 (217800)
Nature σ_z (mm)	2.14	**2.72**	**2.72**
Total σ_z (mm)	2.65	2.9	2.9
HOM power/cavity (kw)	3.6 (5cell)	0.64 (2cell)	0.42 (2cell)
Energy spread (%)	0.13	~~0.098~~	~~0.098~~
Energy acceptance (%)	2	1.5	1.5
Energy acceptance by RF (%)	6	2.2	2.2
n_γ	0.23	0.26	0.26
Life time due to beamstrahlung_cal (minute)	47	52	52
F (hour glass)	0.68	0.95	0.95
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.04	3.1	2.05

Parameter for single ring-100km

（wangdou20161122）

	Pre-CDR	***New-100km***	
Number of IPs	2	2	2
Energy (GeV)	120	120	120
Circumference (km)	54	100	100
SR loss/turn (GeV)	3.1	1.67	1.67
N_e/bunch (10^{11})	3.79	1.79	1.79
Bunch number	50	350	100
Beam current (mA)	16.6	30.0	8.6
SR power /beam (MW)	51.7	50	14.3
Bending radius (km)	6.1	11	11
Momentum compaction (10^{-5})	3.4	3.15	3.15
β_{IP} x/y (m)	0.8/0.0012	0.4/0.0012	0.4/0.0012
Emittance x/y (nm)	6.12/0.018	6.18/0.019	6.18/0.019
Transverse σ_{IP} (um)	69.97/0.15	49.5/0.15	49.5/0.15
ξ_x/IP	0.118	0.055	0.055
ξ_y/IP	0.083	0.055	0.055
V_{RF} (GV)	6.87	4.88	4.88
f_{RF} (MHz)	650	650	650
Nature σ_z (mm)	2.14	2.41	2.41
Total σ_z (mm)	2.65	2.47	2.47
HOM power/cavity (kw)	**3.6**	**3.2**	**0.92**
Energy spread (%)	0.13	0.098	0.098
Energy acceptance (%)	2	0.94	0.94
Energy acceptance by RF (%)	6	4.5	4.5
n_γ	0.23	0.15	0.15
Life time due to beamstrahlung_cal (minute)	47	54	54
F (hour glass)	0.68	0.7	0.7
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.04	2.5	0.72

Strong-strong simulation – 100km

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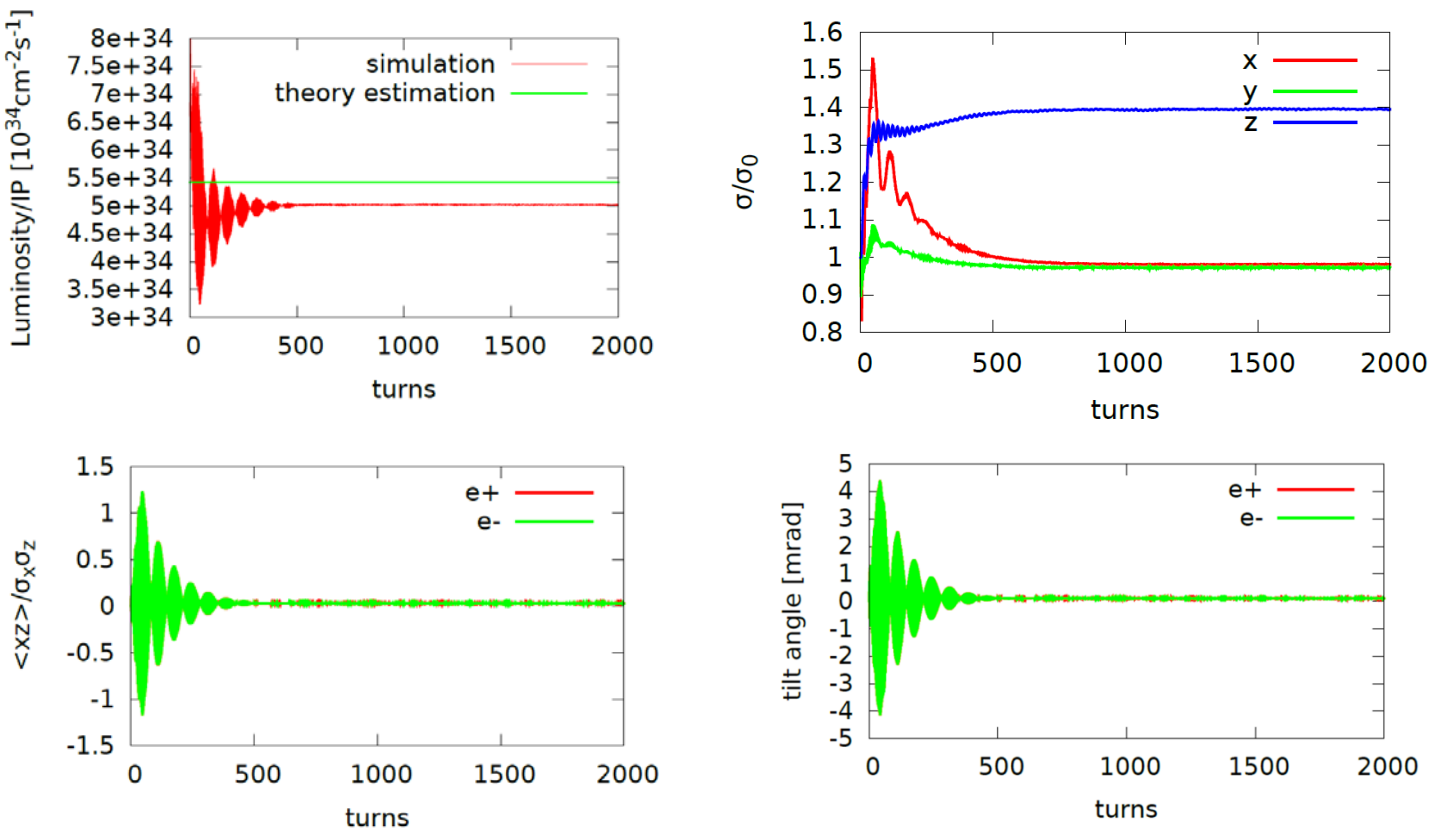
- wangdou20161219-100km_1mmβy with full crab waist, Higgs
- Working point: (0.54, 0.61) with ν_s = 0.0272
- Lifetime: 400min
- In Phase <xz> oscillation in the first few hundred collisions



Strong-strong simulation-100km

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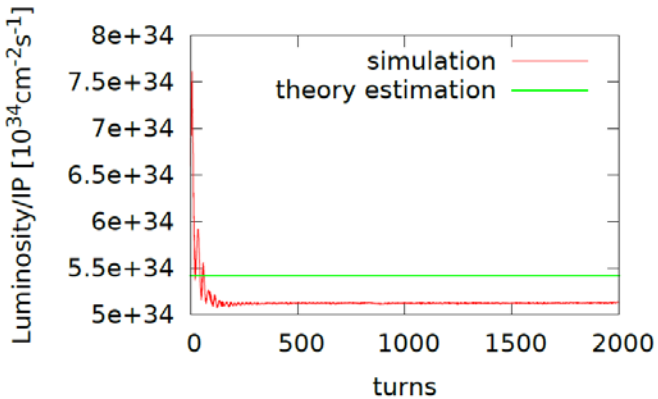
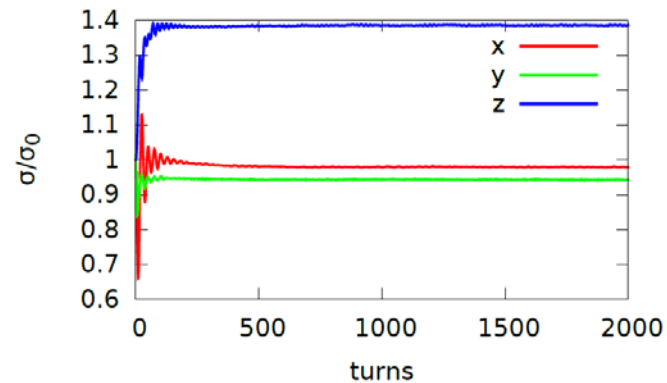
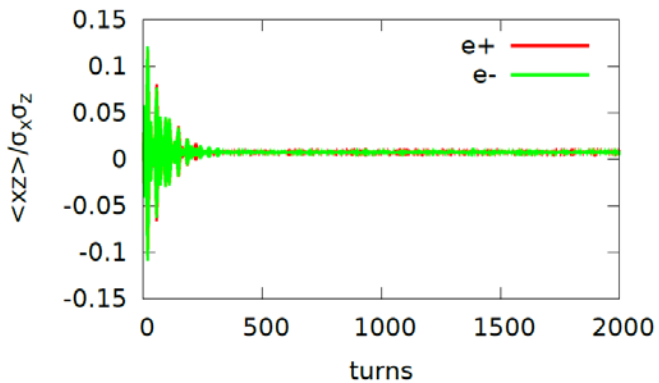
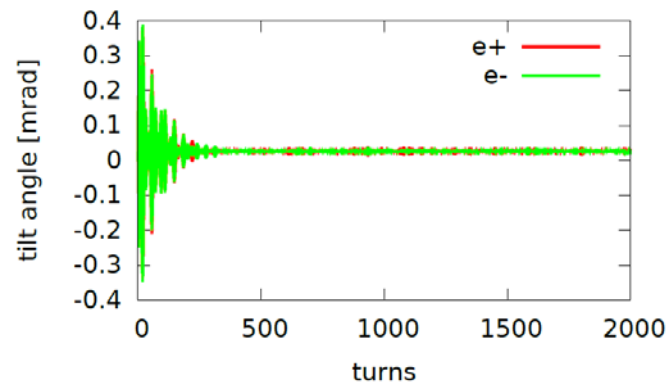
- wangdou20161219-100km_1mmβy with full crab waist, Higgs
- (0.51,0.55) with ν_s =0.0272 could help suppress the <xz> oscillation









Strong-strong simulation-100km

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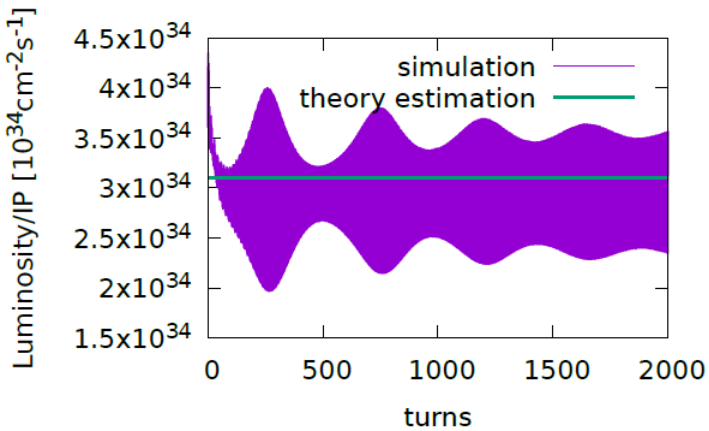
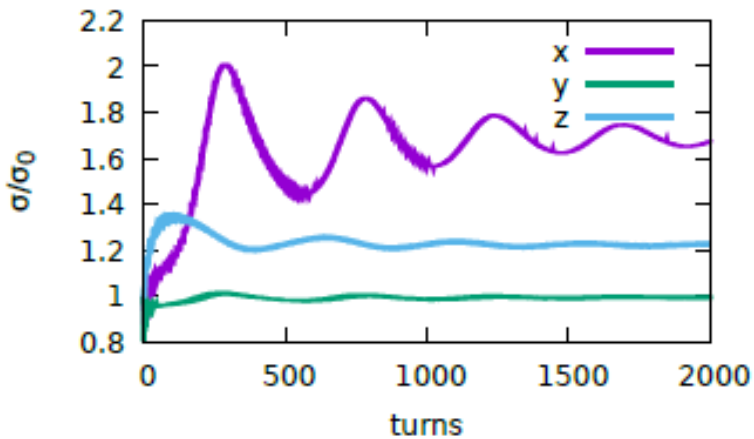
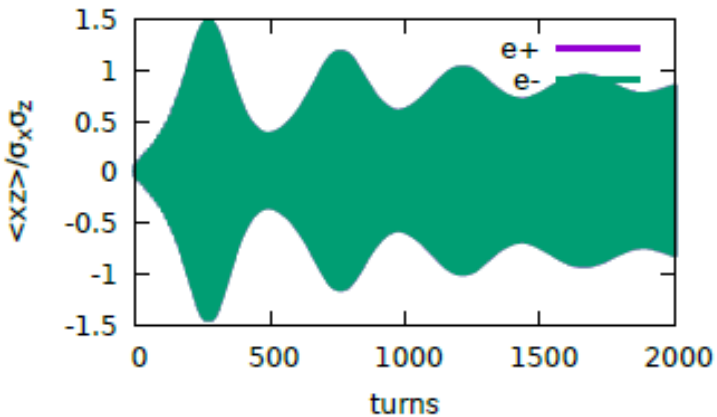
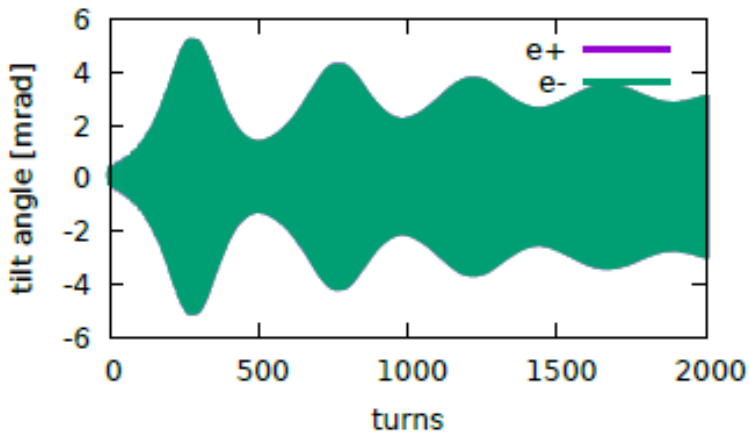
- 161202-100km-2mm-higgs-highlum with full crab waist
- Working point: (0.54,0.61, 0.037)
- Strong <xz> oscillation !









Strong-strong simulation-100km

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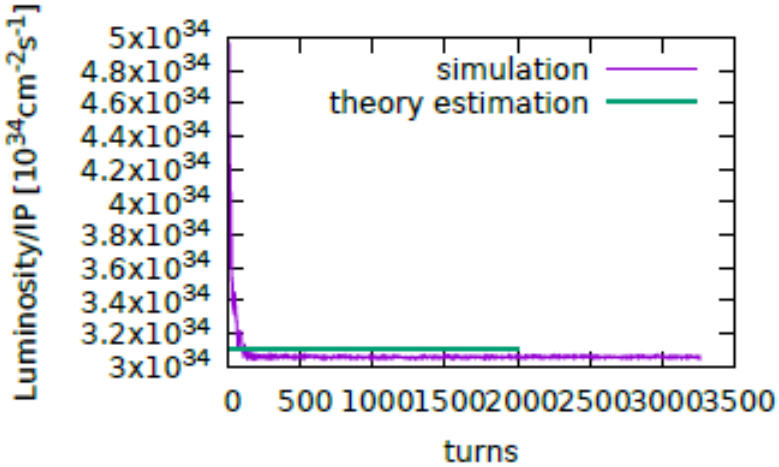
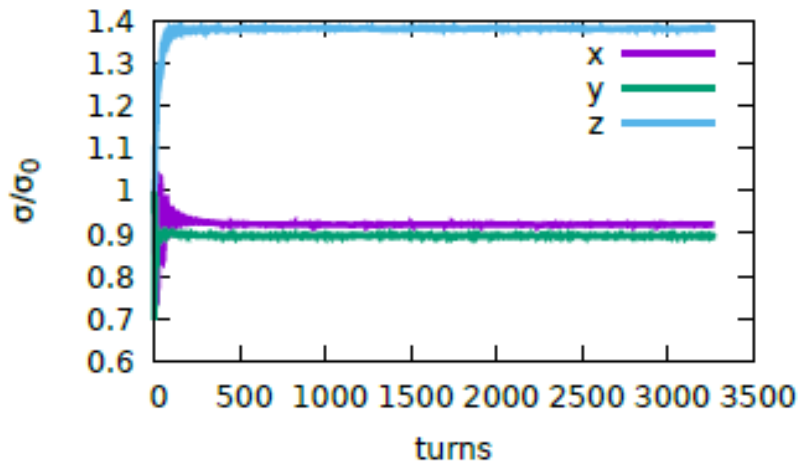
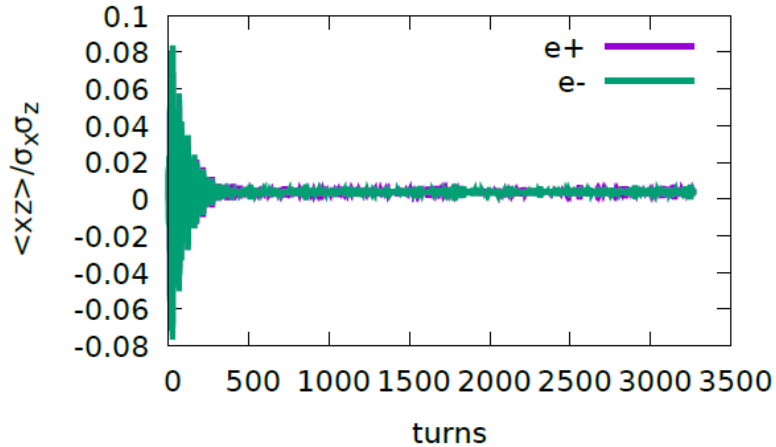
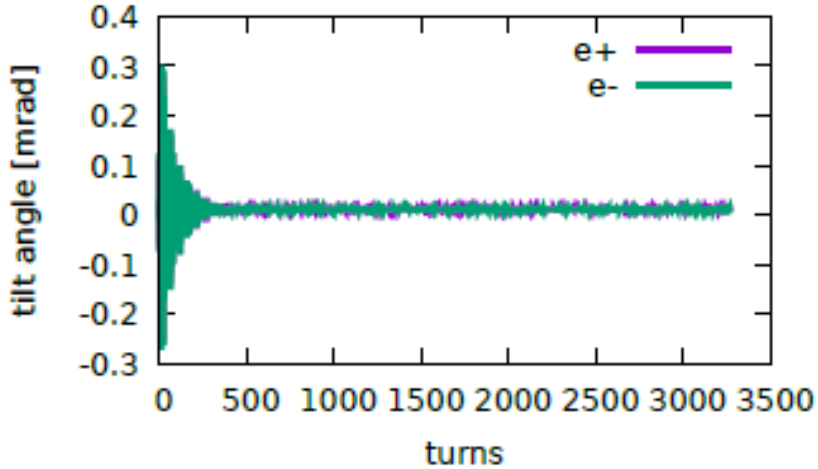
- 161202-100km-2mm-higgs-highlum with full crab waist
- Working point: (0.51,0.55,0.037)





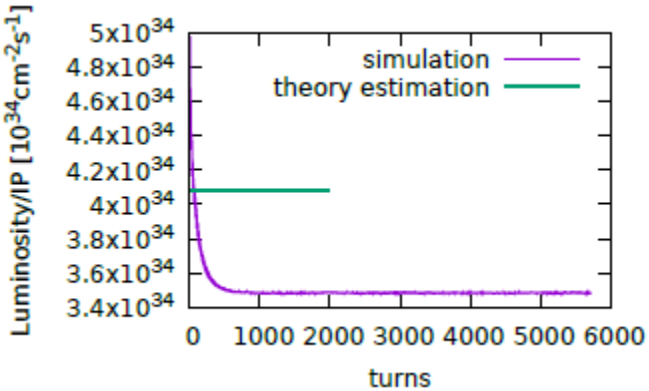


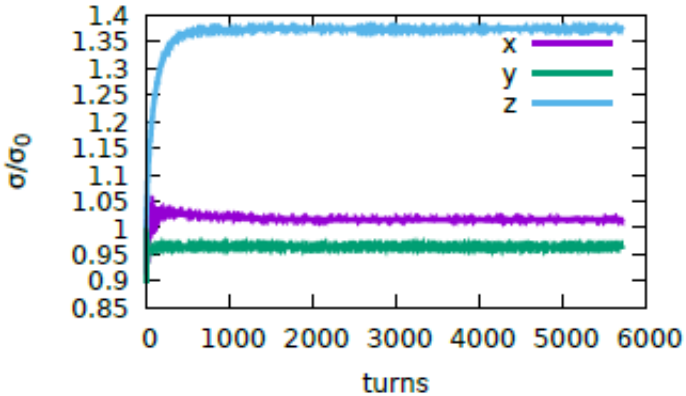


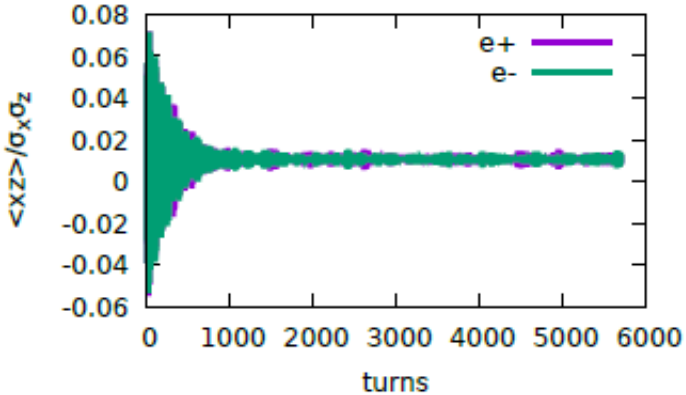
Strong-strong simulation-100km

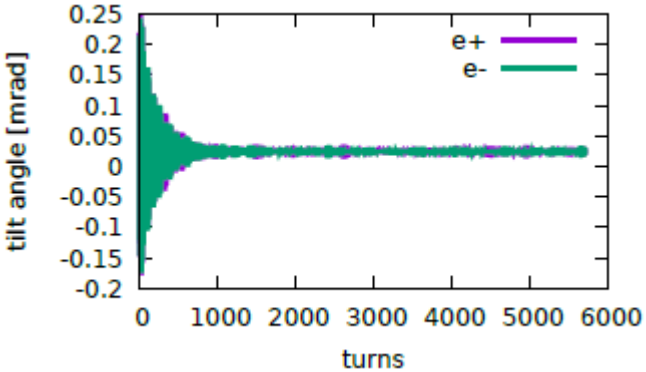
zhangy@ihep.ac.cn

- 100km_1mmβy_W
- Working point: (0.535, 0.61, 0.0425)

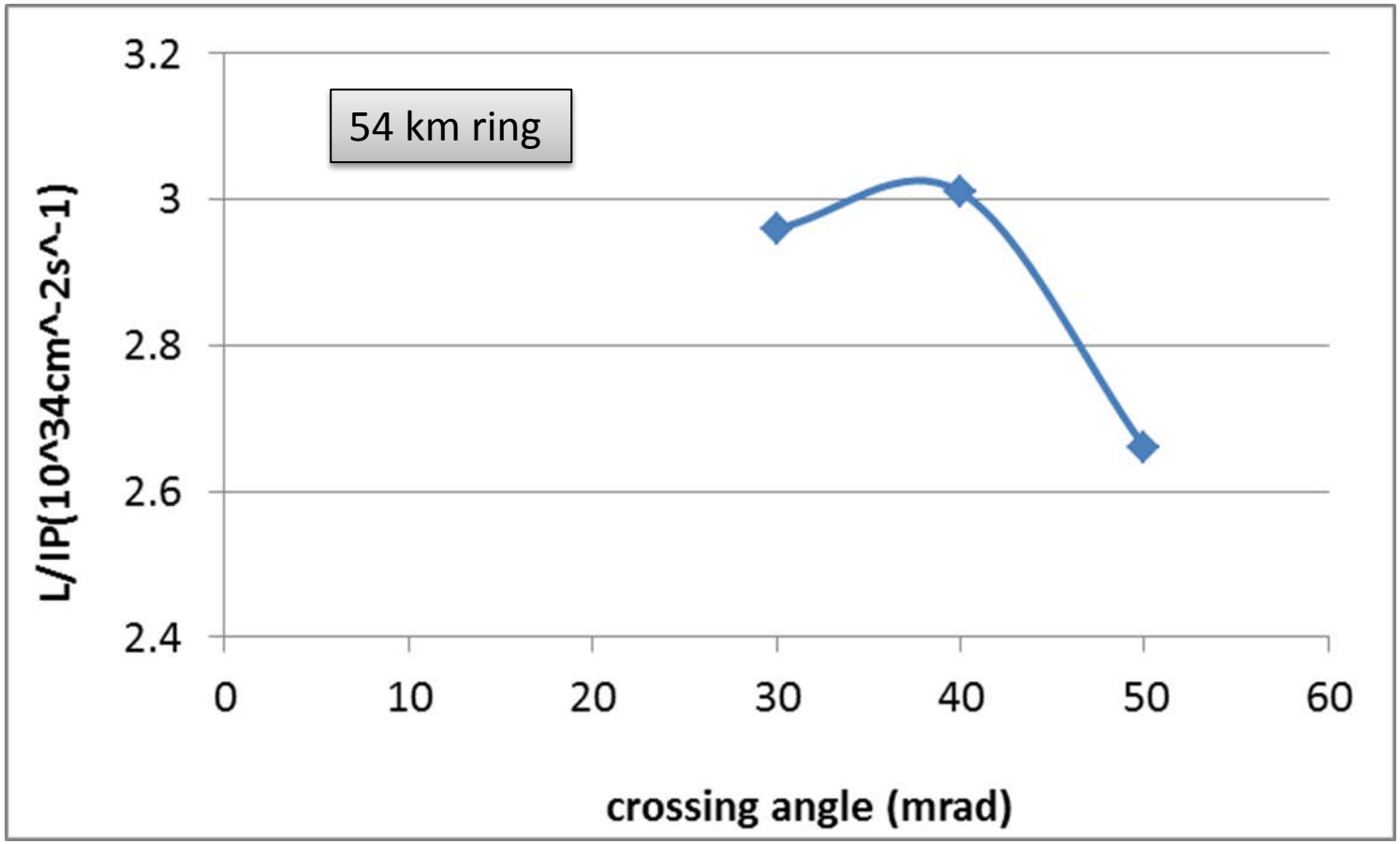




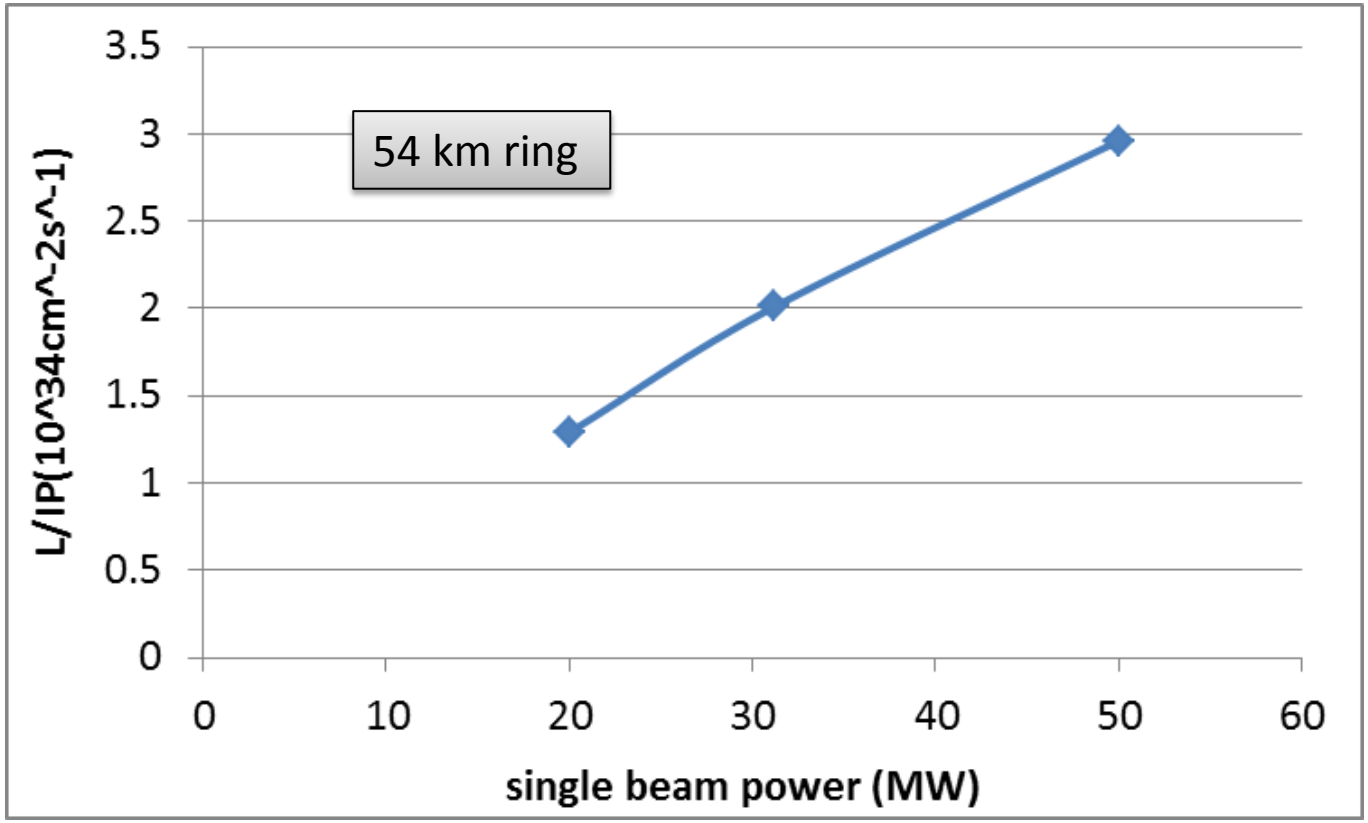




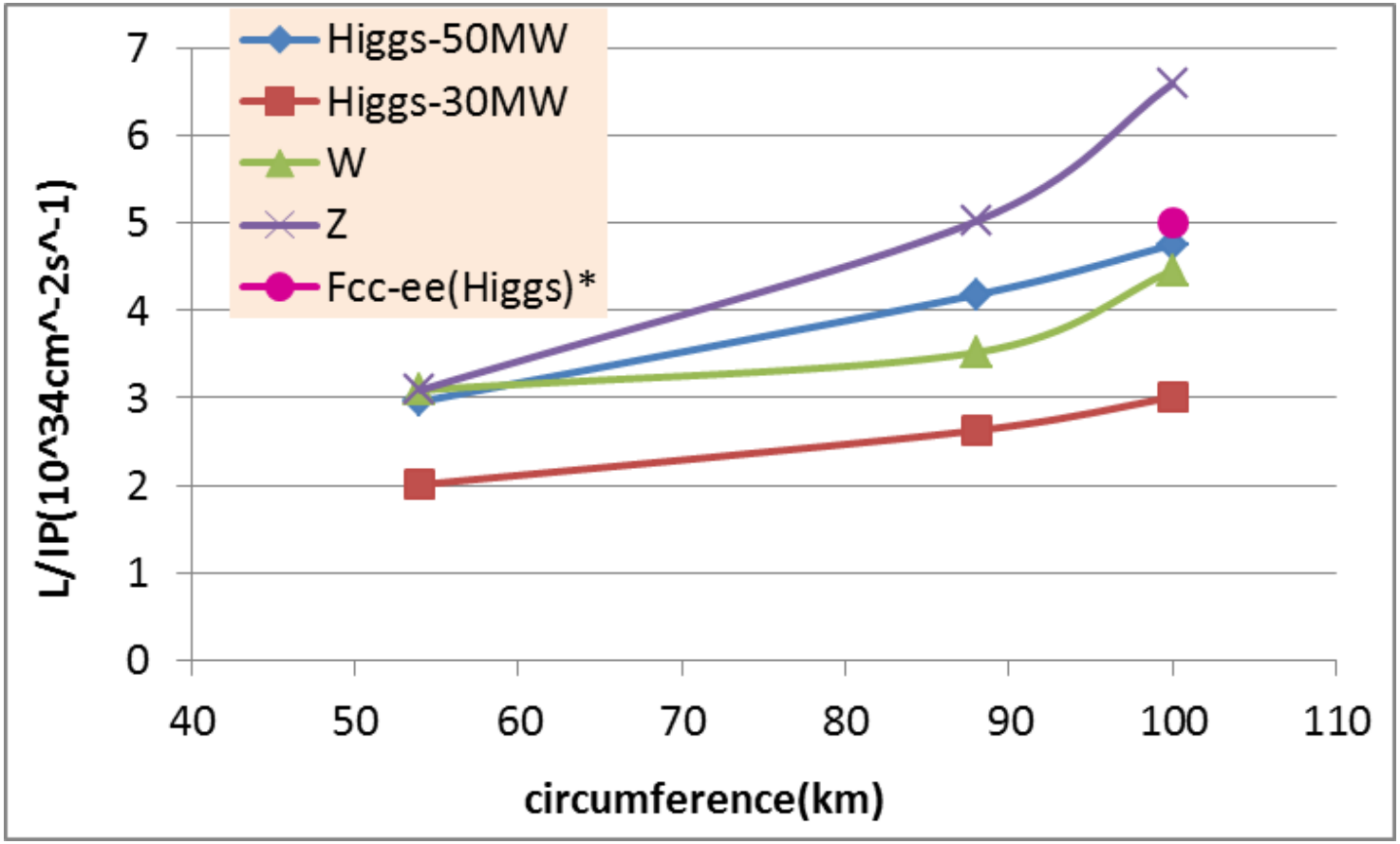
CEPC Higgs luminosity vs. crossing angle



CEPC Higgs Luminosity vs beam power

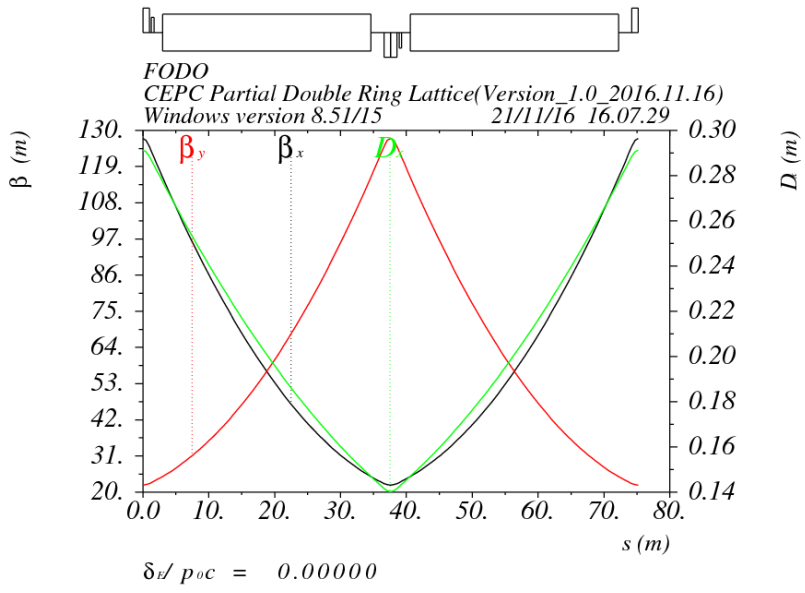


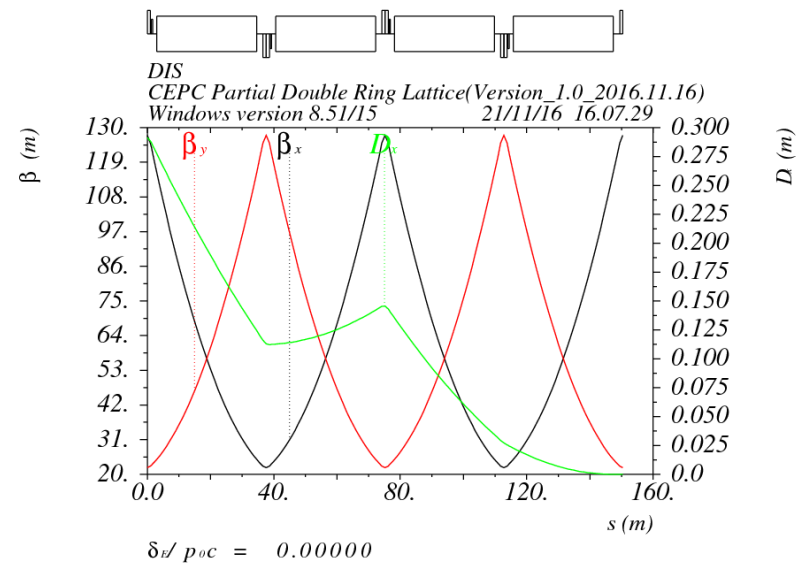
CEPC Luminosity vs circumference

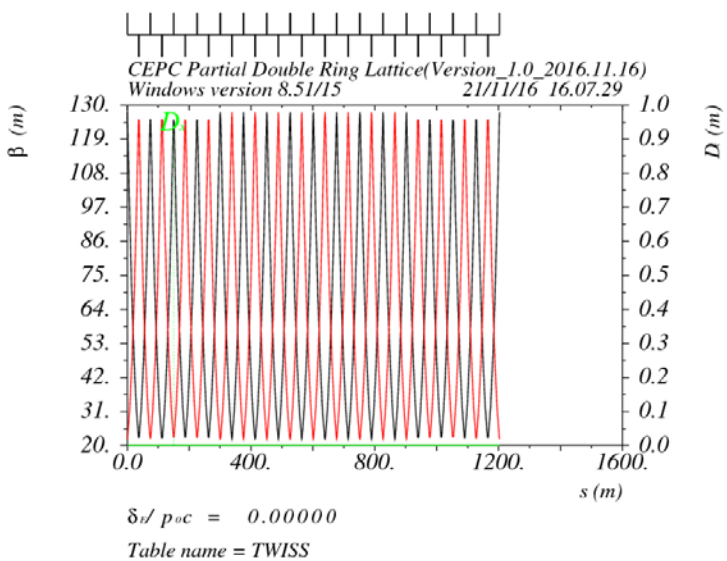


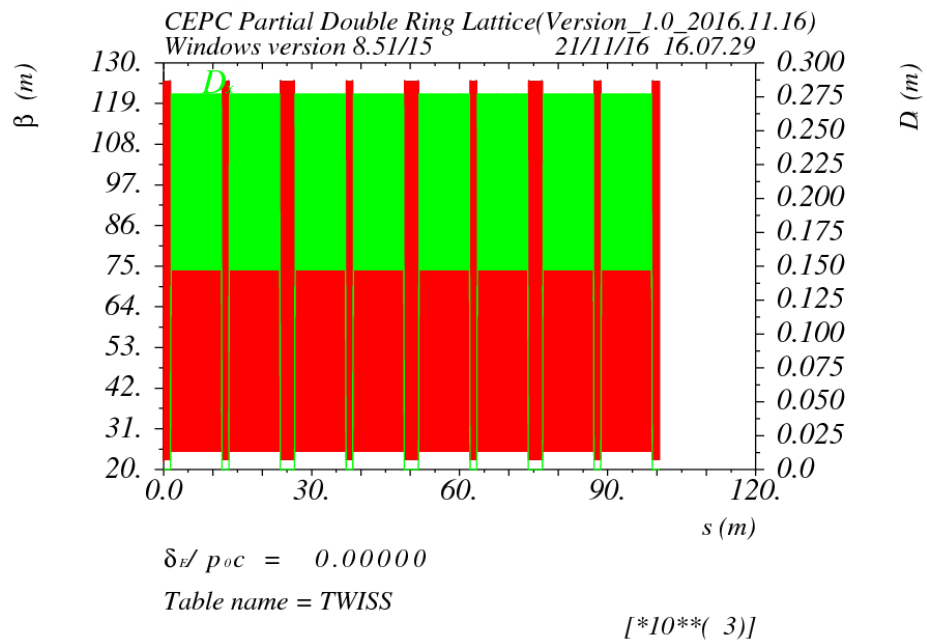
* Fabiola Gianotti, Future Circular ColliderDesign Study, ICFA meeting, J-PARC, 25-2-2016.

Arc design for 100km CEPC







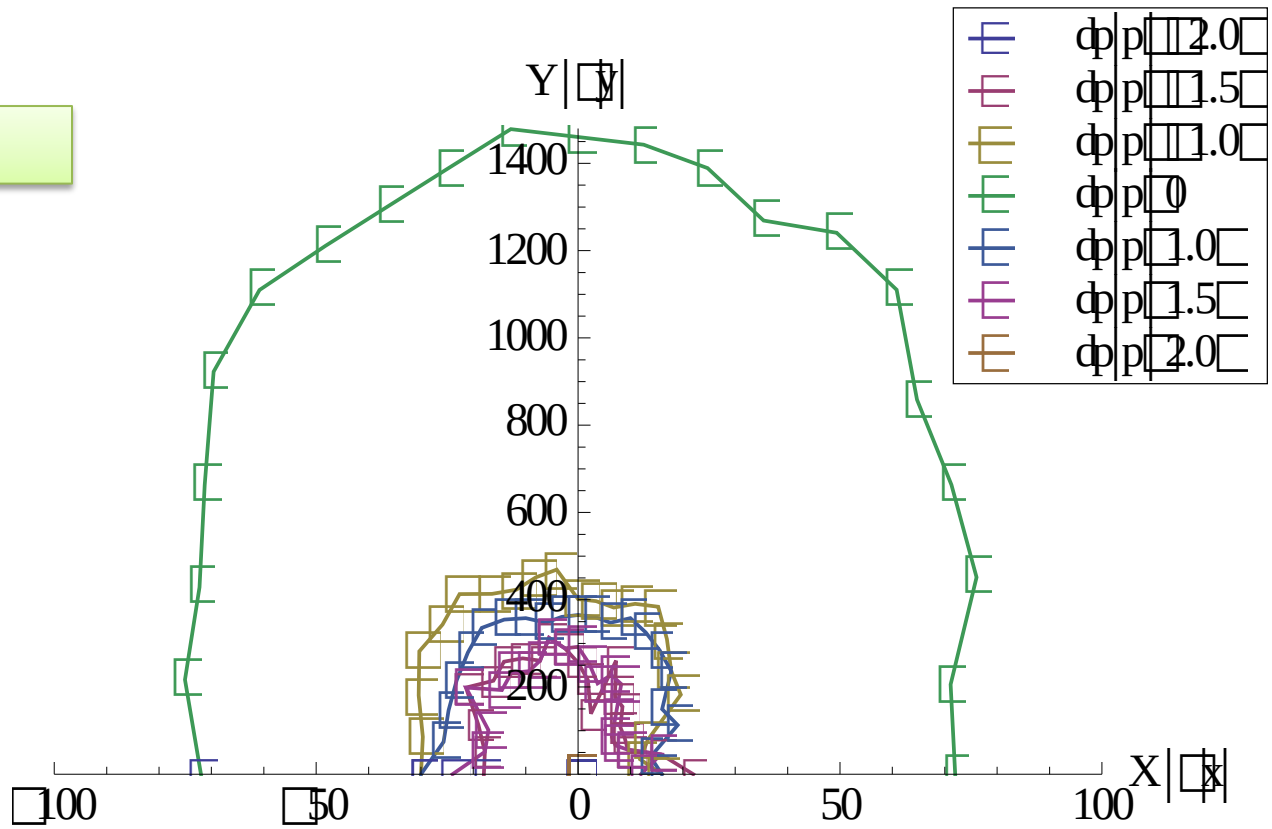


Arc DA (2 fam)

2 families sextupole in arc

No damping

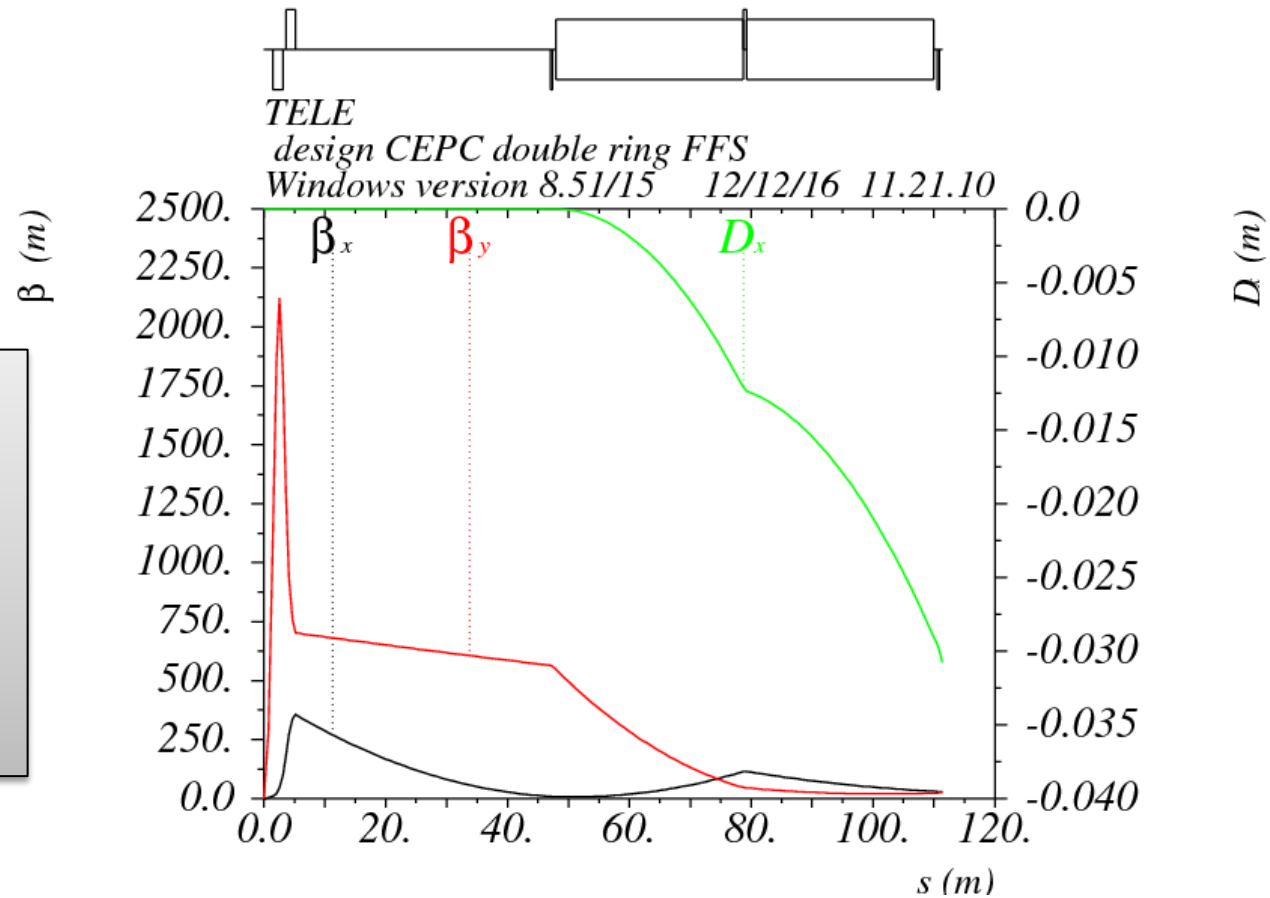
Tracking 240 turns



Final doublet + triplet

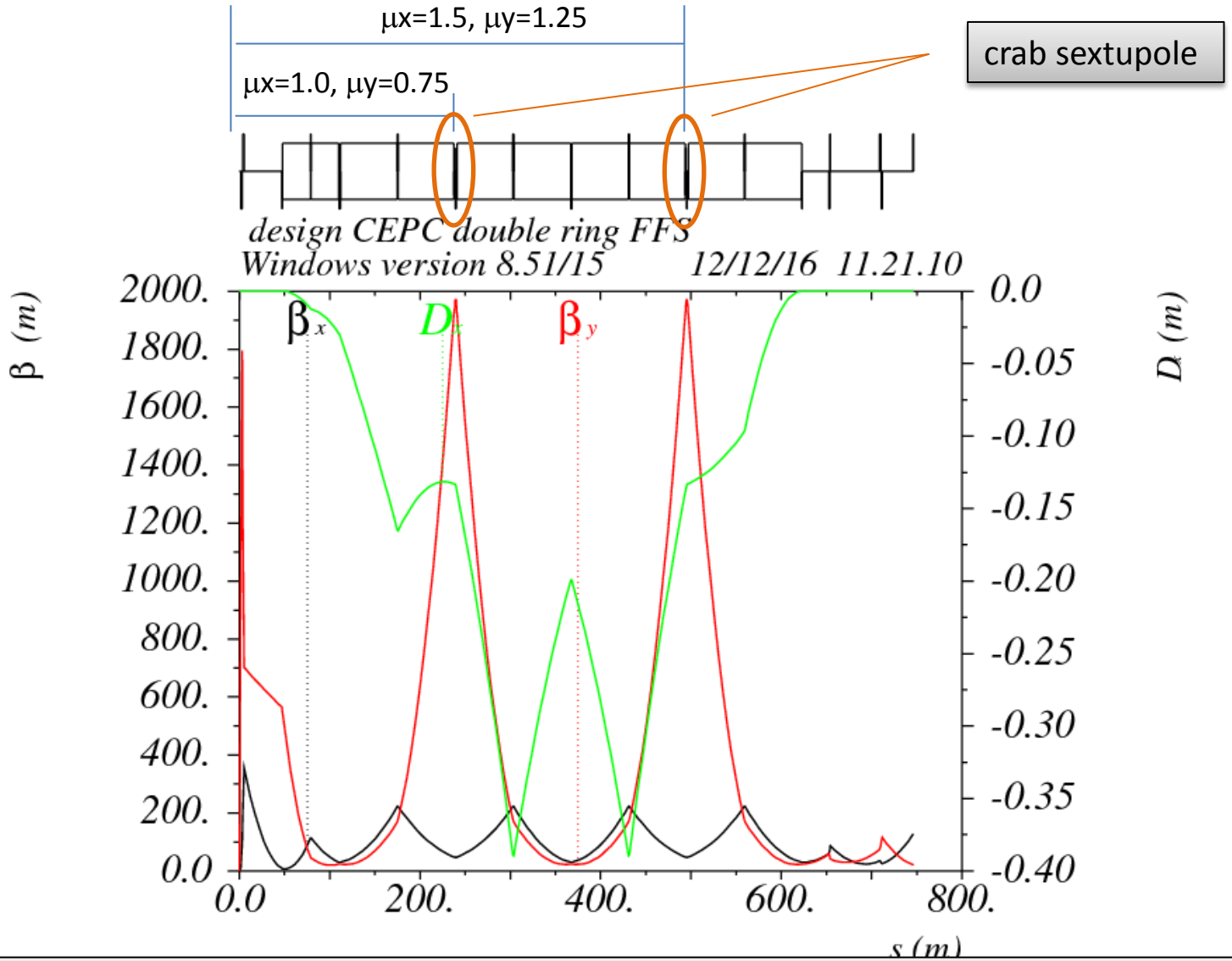
Betax=0.22m
Betay=0.002m

μx=0.75, μy=0.5



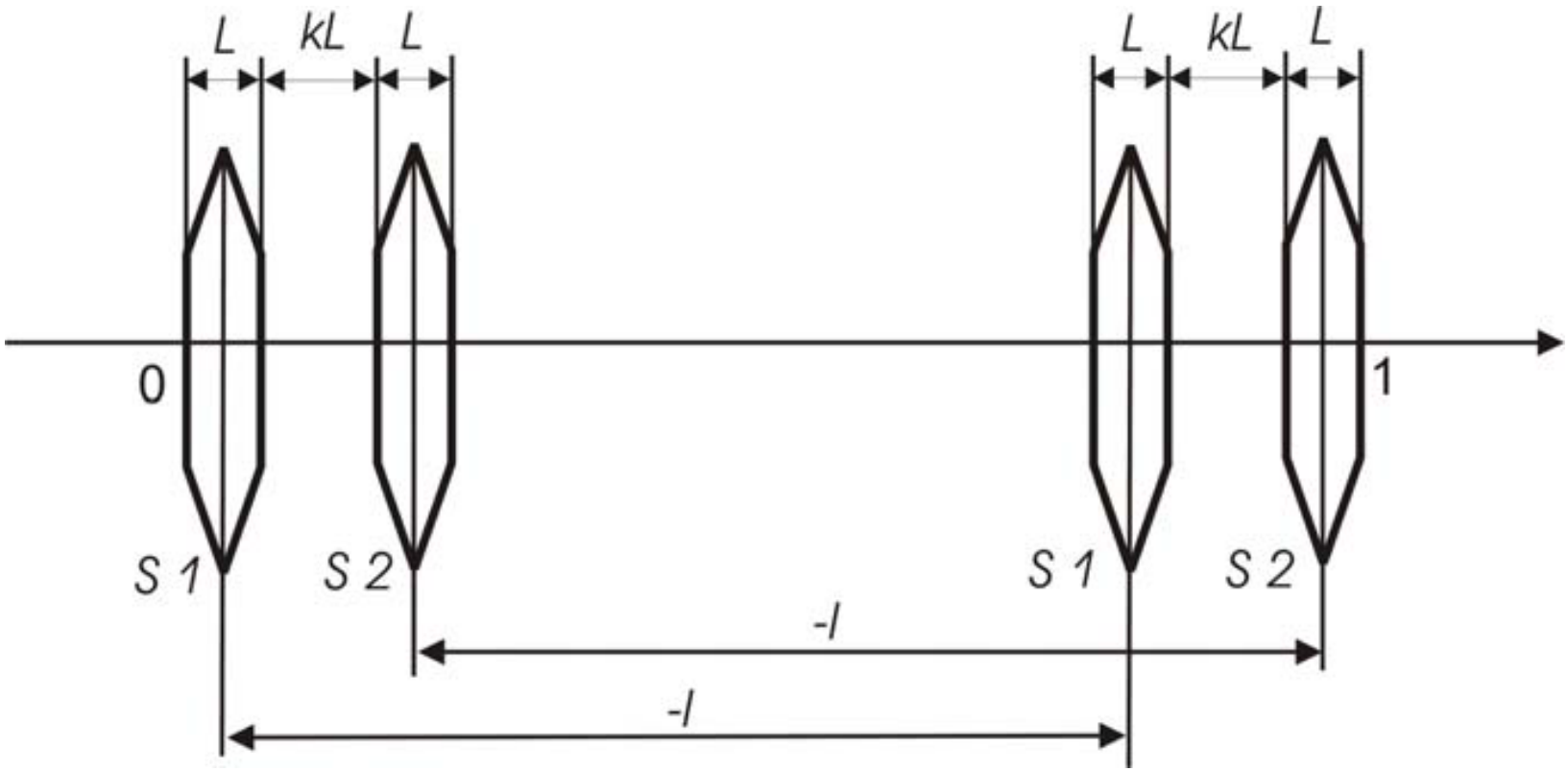
L*=1.5
L(QD0)=1.64m
L(QF1)=1.54m
k(QD0)=-200T/m
k(QF1)=113T/m
L_0=0.5m

FFS optics



- Both FFS sextupoles of the CCS-Y section can work as the crab sextupoles.

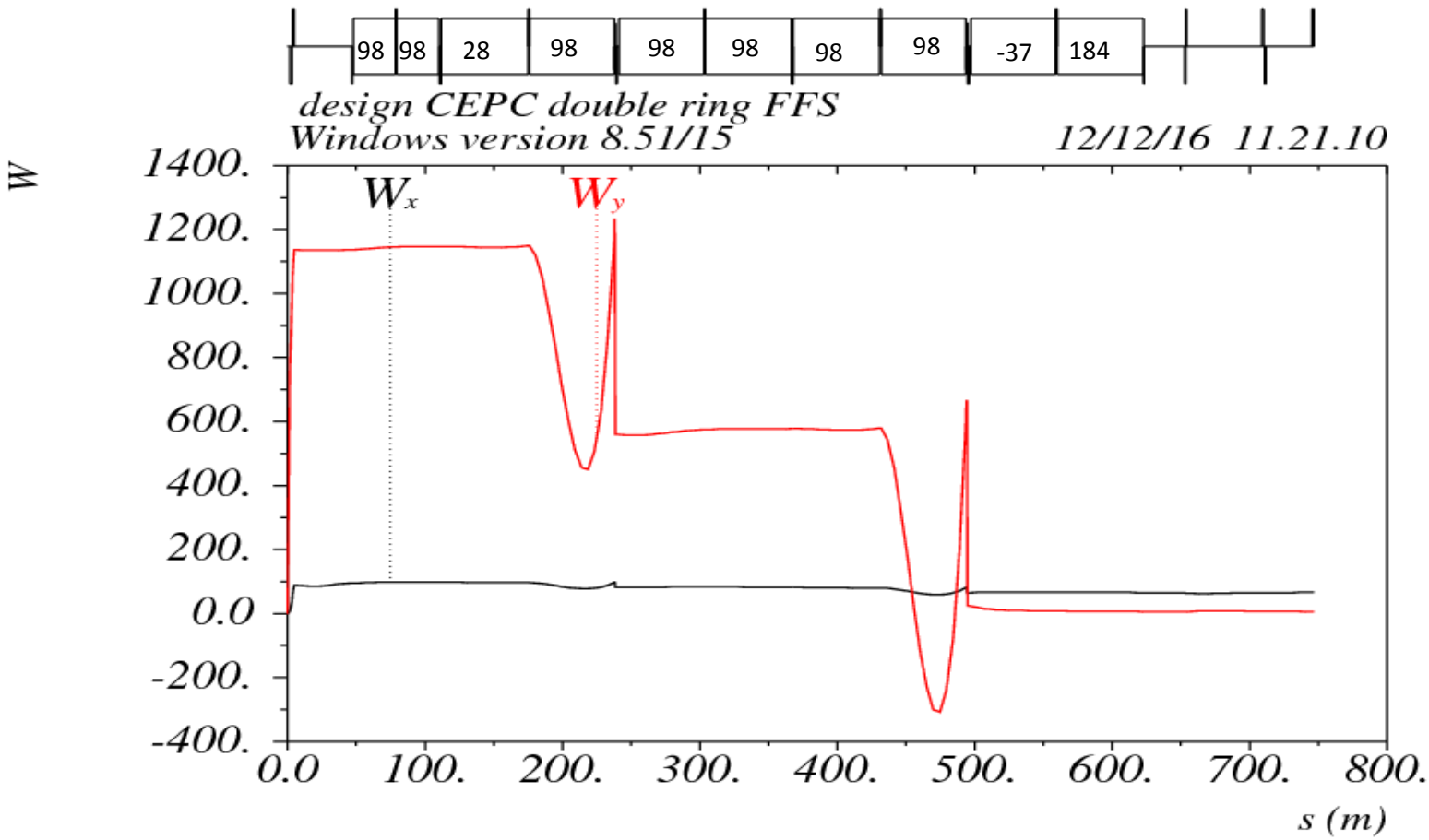
Correction of the sextupole length effect



- S1: main sextupole pair
- S2: correcting sextupole pair ~ –0.1*k_2(S1)

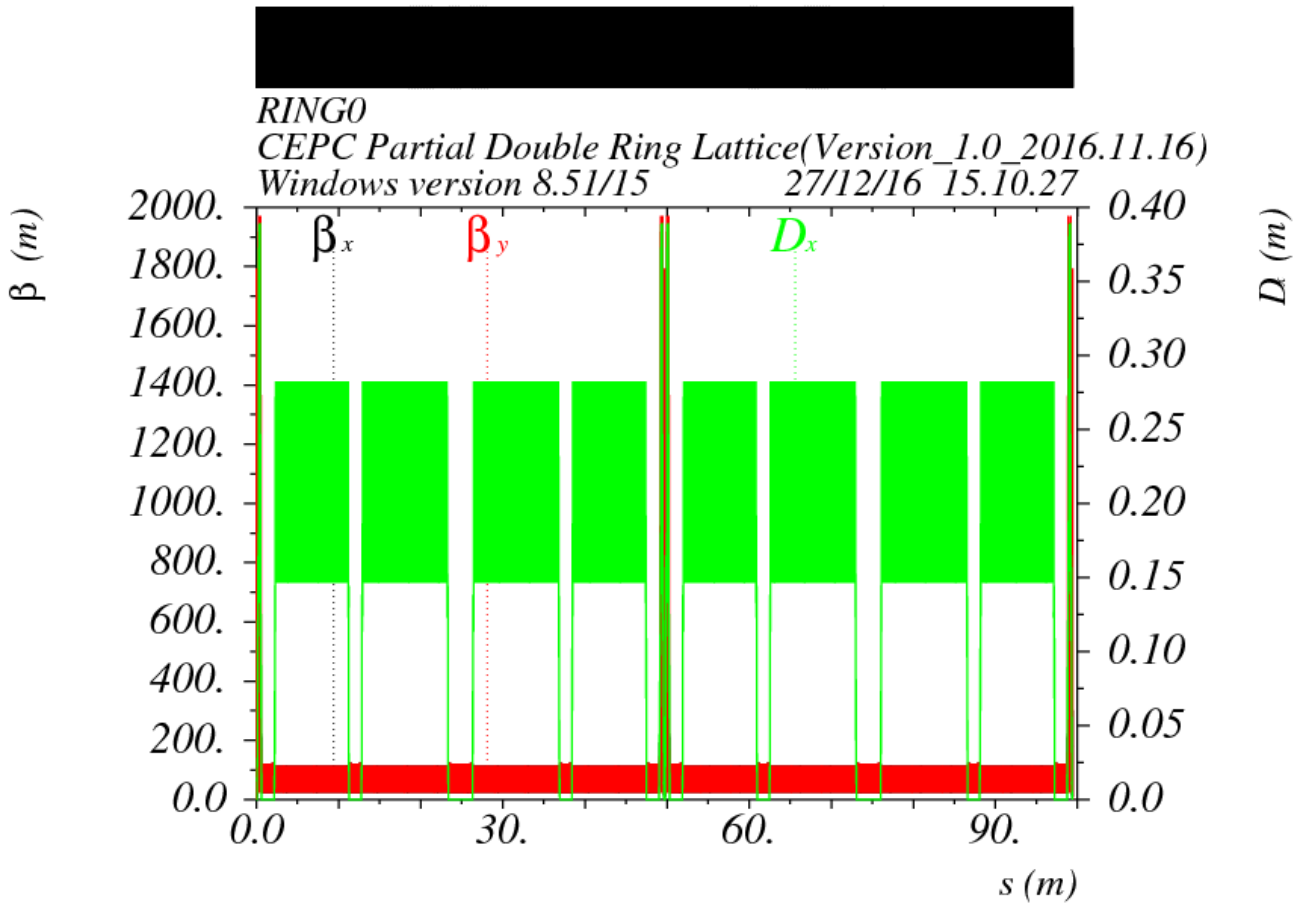
*A.Bogomyagkov, S.Glykhov, E.Levichev, P.Piminov

W function of FFS



- **Critical energy** Ec < 100 keV within 560m, Ec < 200 keV within 630m.
- **Horizontal chromaticity leak** Wx=70

Arc + FFS


RING0
CEPC Partial Double Ring Lattice(Version_1.0_2016.11.16)
Windows version 8.51/15 27/12/16 15.10.27
β (m)
D (m)
s (m)
βx
βy
Dx
2000.
1800.
1600.
1400.
1200.
1000.
800.
600.
400.
200.
0.0
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.0
0.0
30.
60.
90.

Arc + FFS (2 fam)

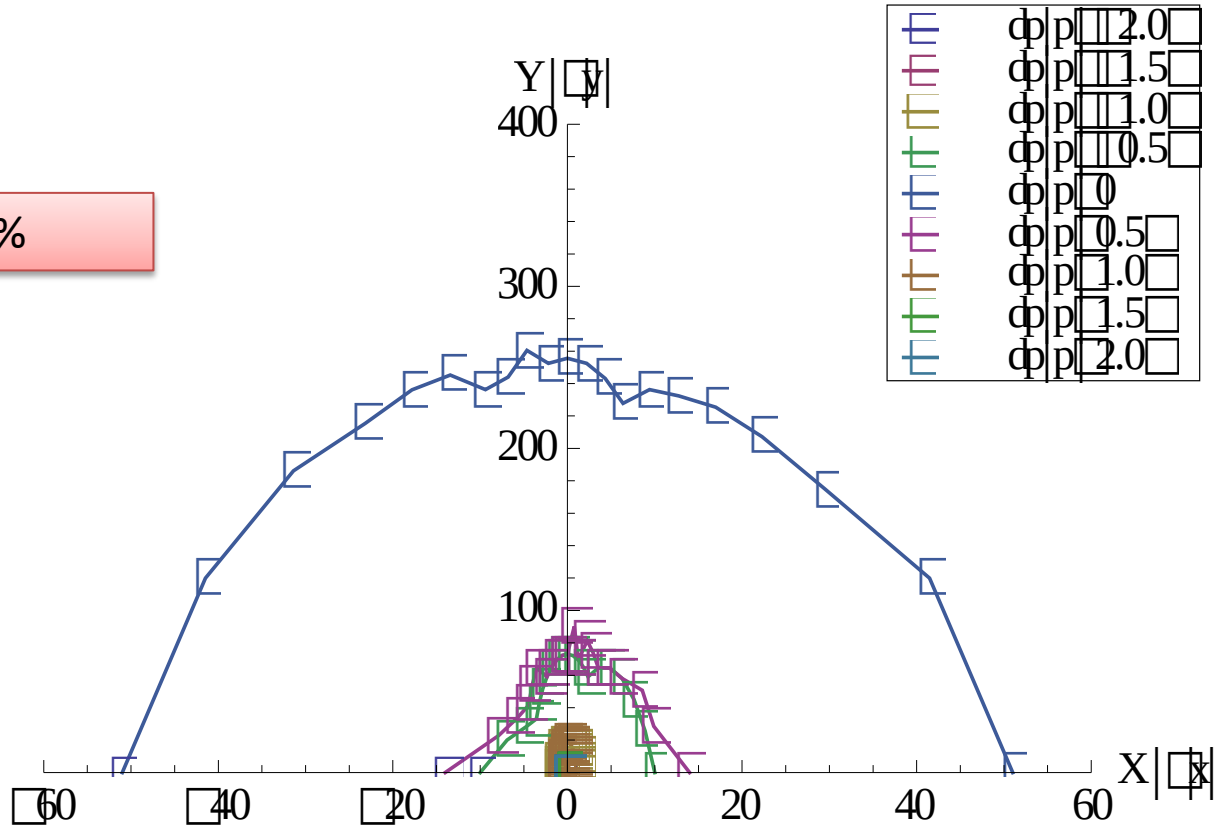
2 families sextupole in arc

No damping

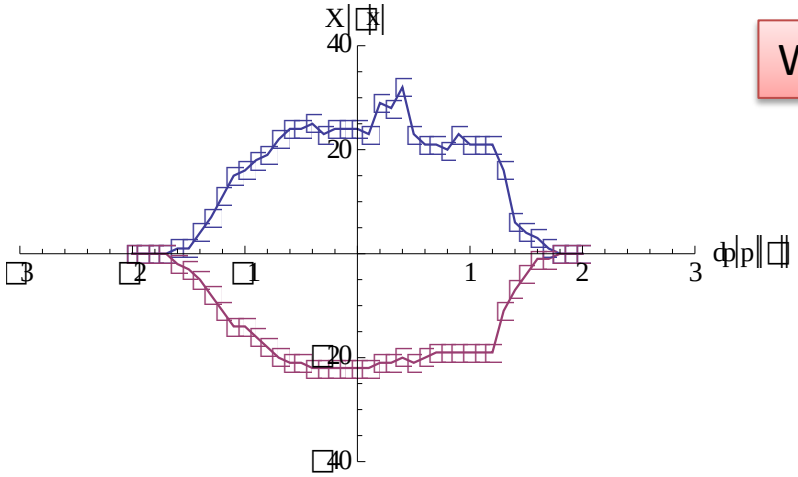
Tracking 200 turns

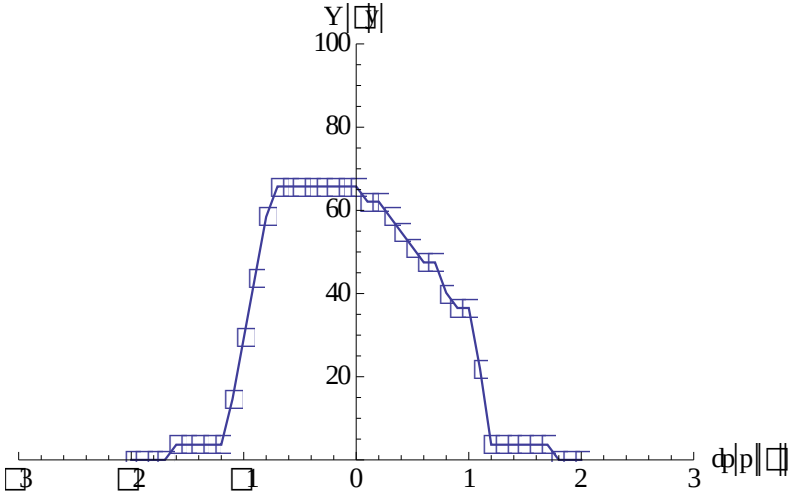
Energy acceptance： 0.5%

DA: 50σ_x×260 σ_y



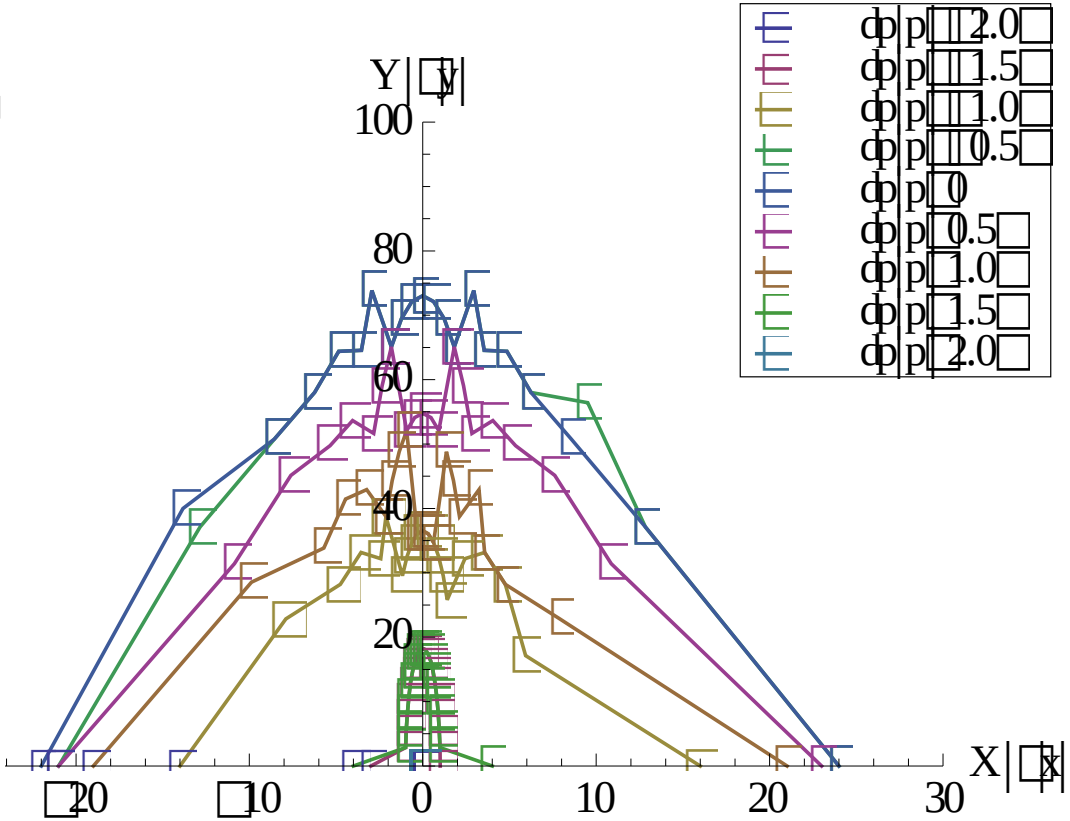
Arc + FFS (104 fam)



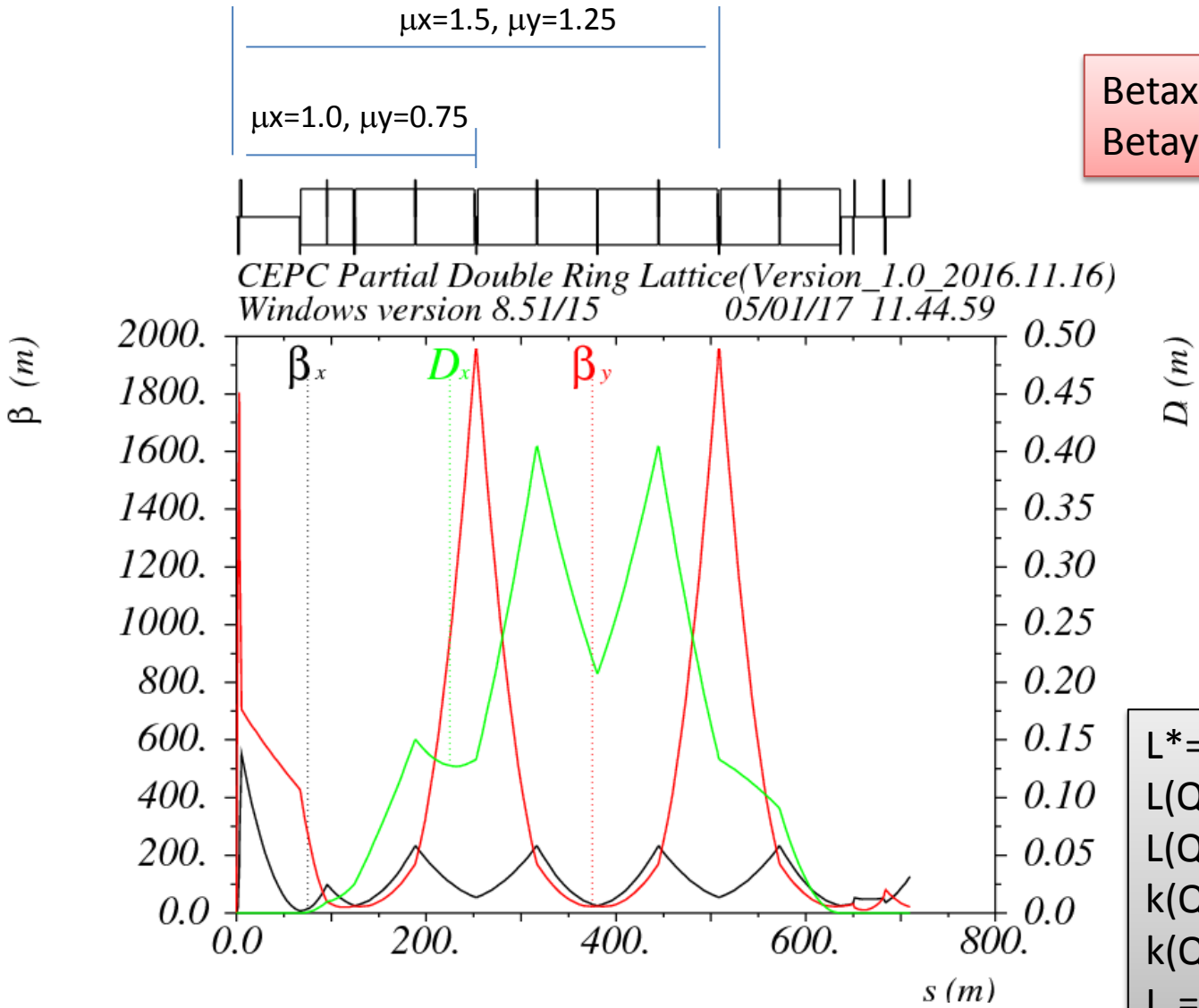


With damping

Tracking 200 turns



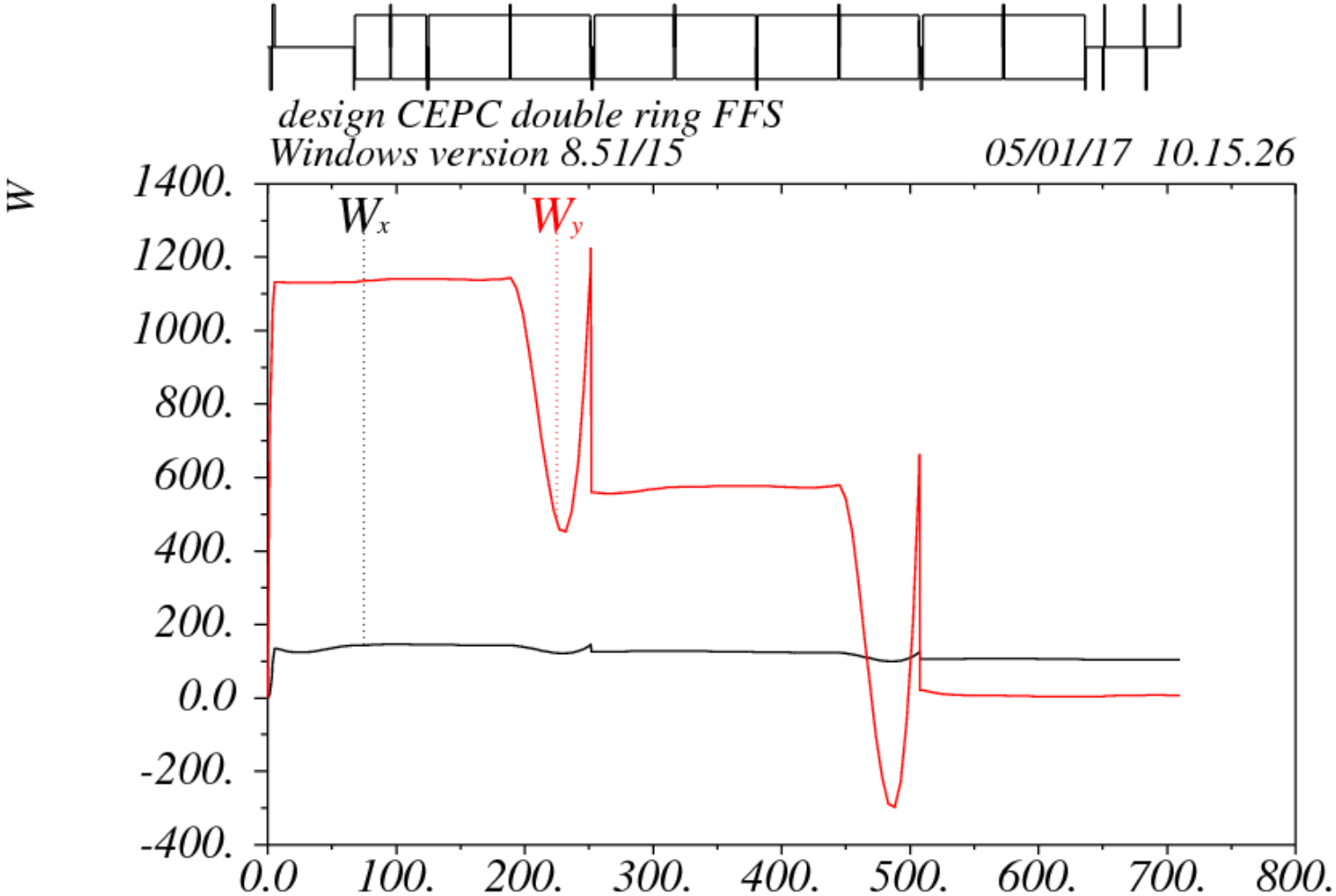
FFS optics-smaller betax*



Betax=0.144m
Betay=0.002m

L*=1.5
L(QD0)=1.63m
L(QF1)=1.59m
k(QD0)=-200T/m
k(QF1)=106T/m
L_0=0.5m

Chromaticity of FFS

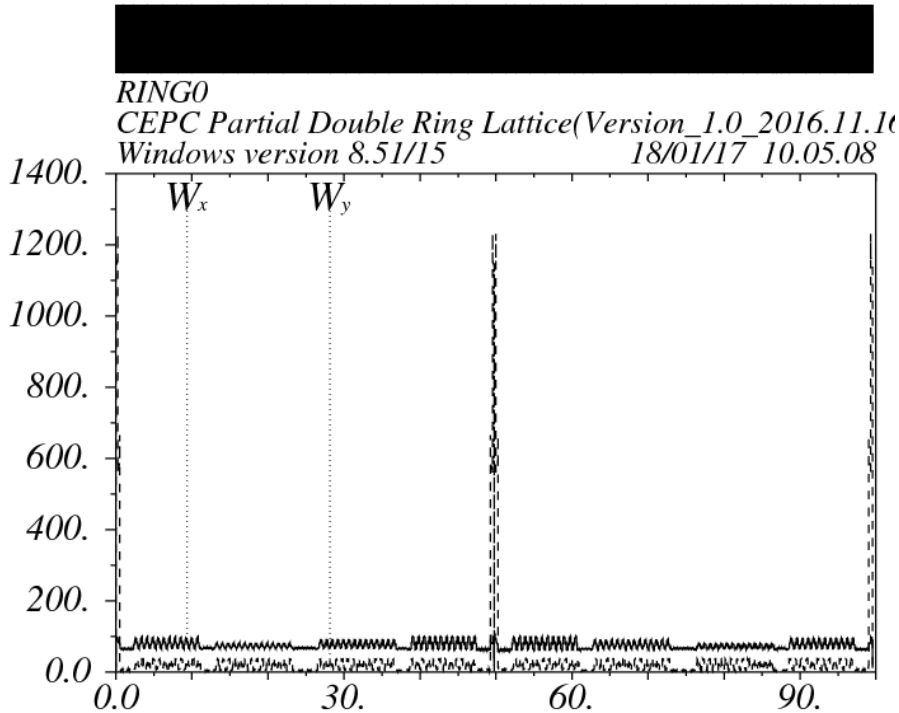


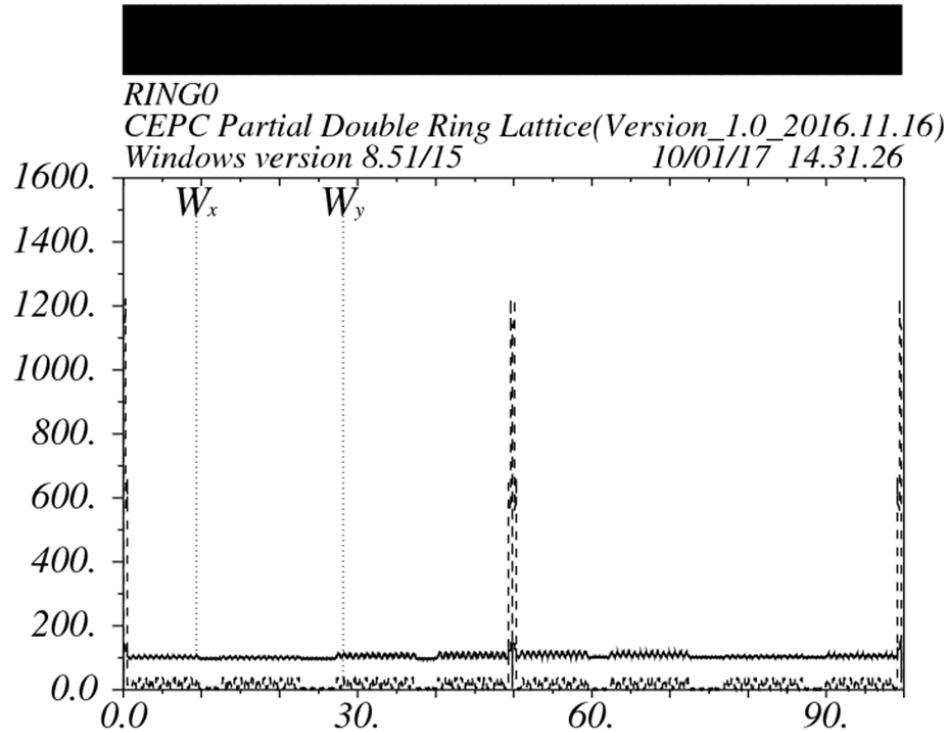
- **Critical energy** Ec < 100 keV within 560m, Ec < 200 keV within 630m.
- **Horizontal chromaticity leak** Wx=110

W function of whole ring

Betax=0.22m
Betay=0.002m

Betax=0.144m
Betay=0.002m



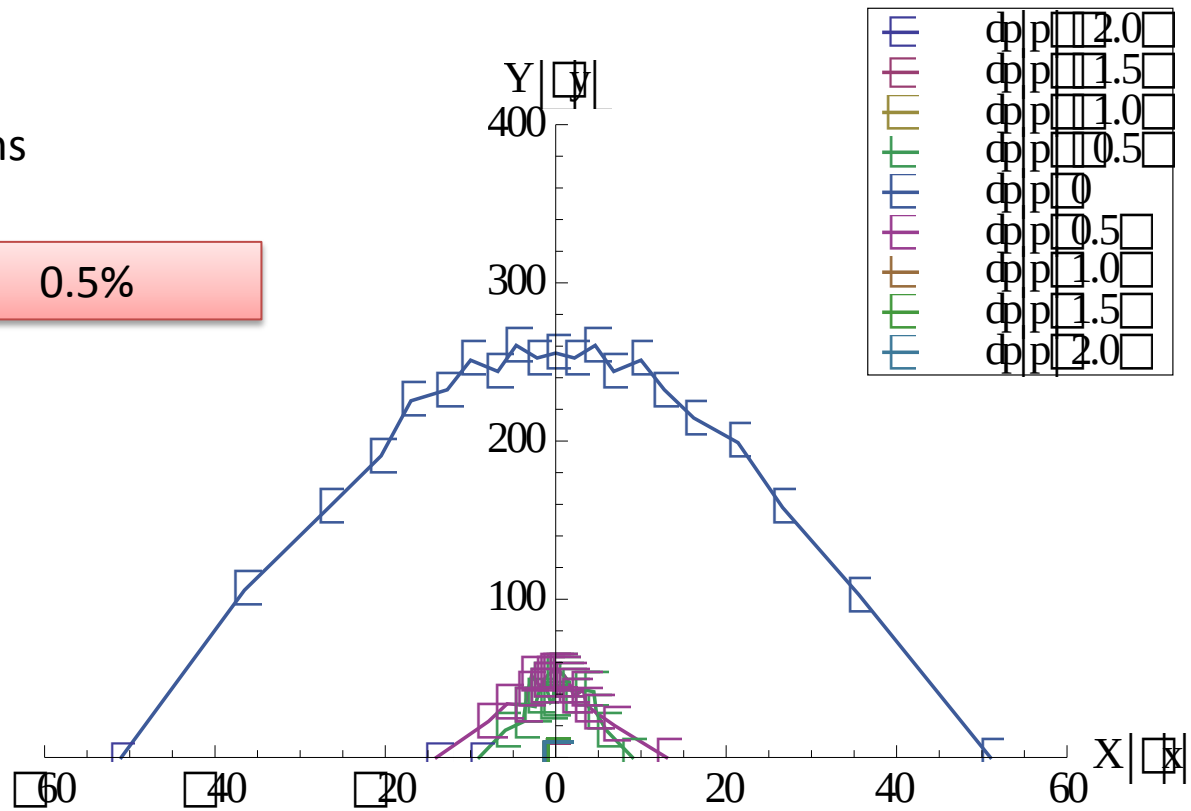


Arc + FFS (2 fam)

No damping

Tracking 200 turns

Energy acceptance： 0.5%

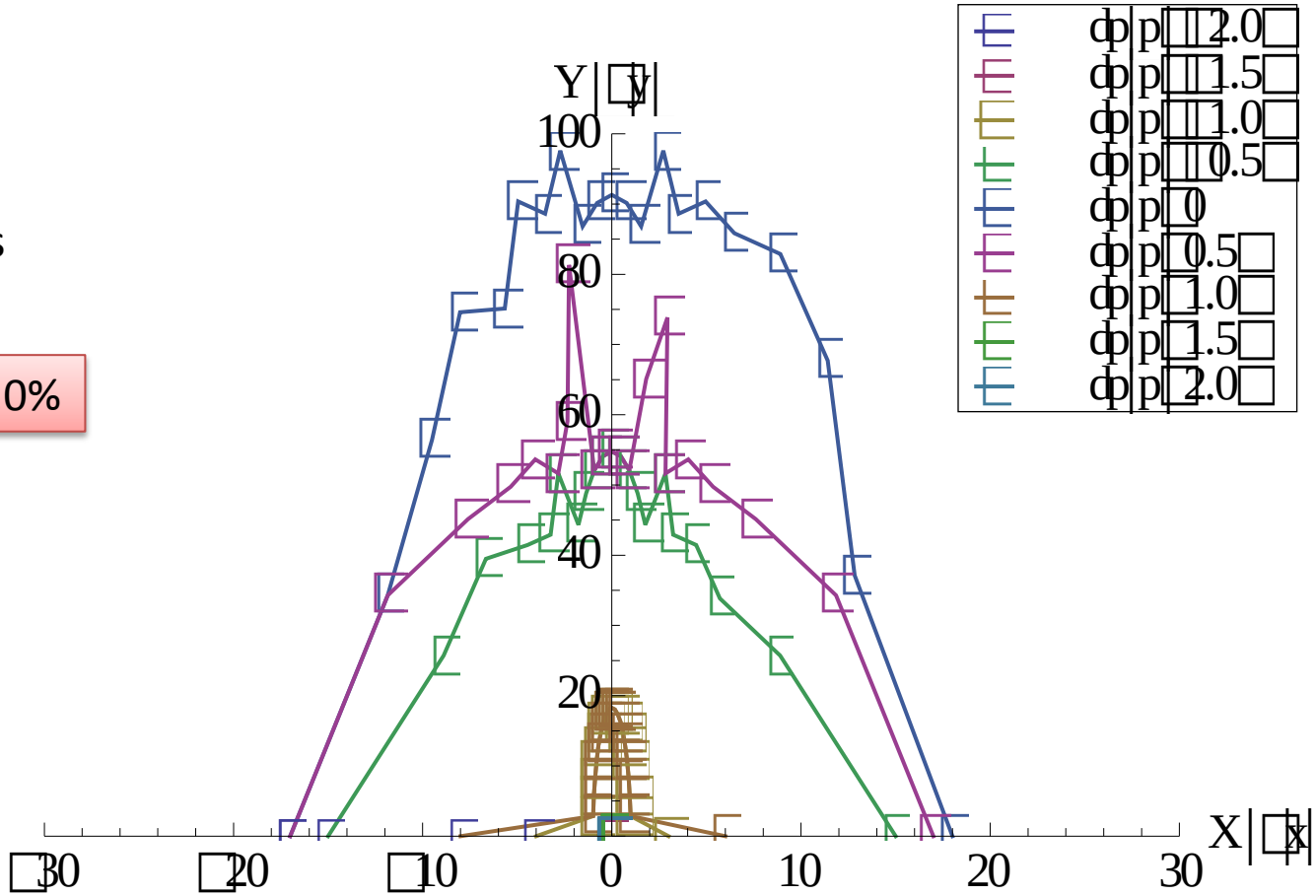


Arc + FFS (104 fam)

With damping

Tracking 200 turns

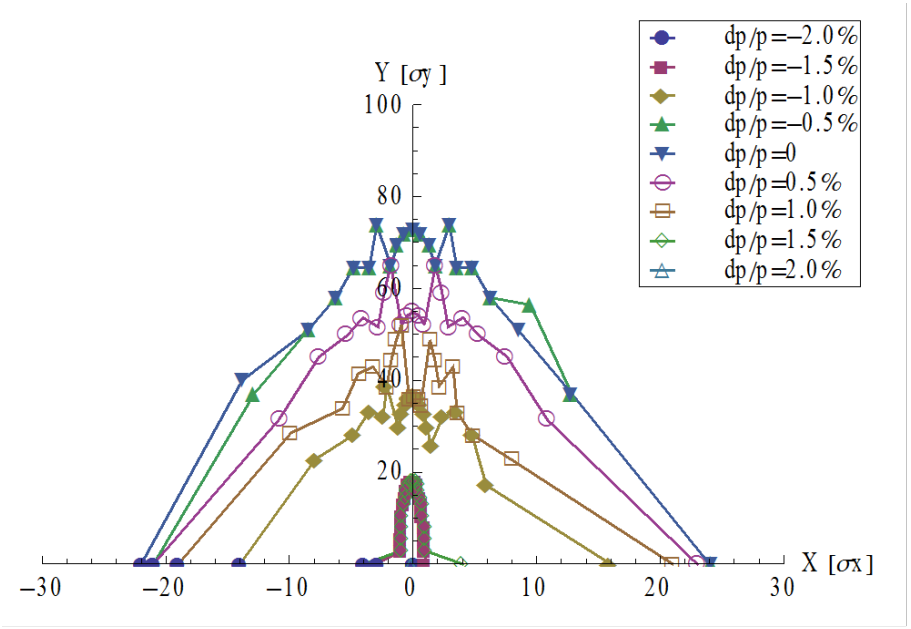
Energy acceptance： 1.0%



Arc + FFS (104 fam)

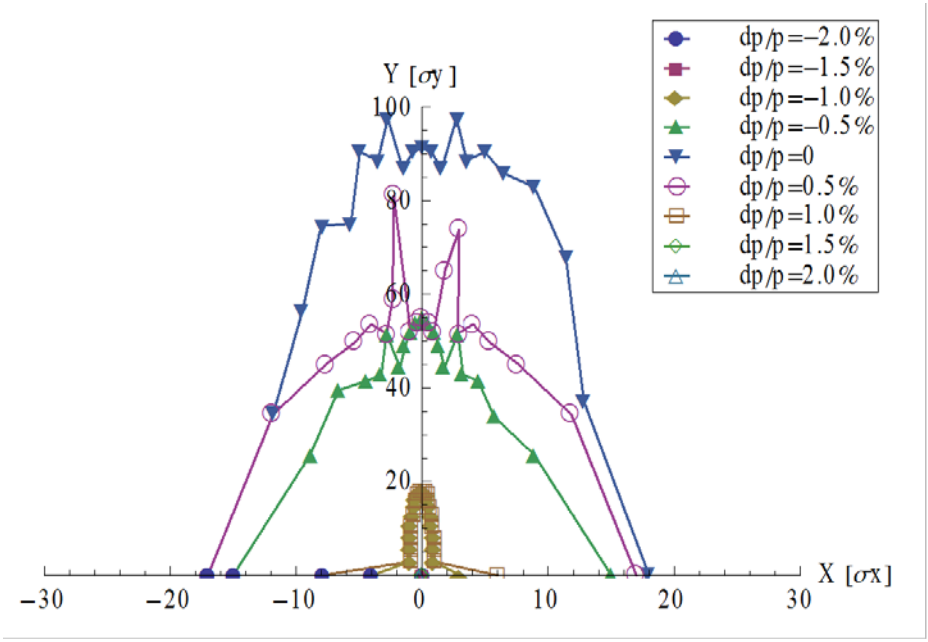
- With damping, crab sextupoles: close
- Tracking 200 turns

Betax=0.22m
Betay=0.002m



Energy acceptance: 1.5%

Betax=0.144m
Betay=0.002m



Energy acceptance: 1.0%

Nonlinearity sources

$$H = \frac{1}{2}\left(p_x^2 + p_y^2\right) + \frac{1}{2}k_1(s)\left(x^2 - y^2\right)$$

$$\boxed{+\frac{1}{8}\left(p_x^2 + p_y^2\right)^2}$$

$$-\frac{1}{48}k_1''(s)\left(x^4 + 6x^2y^2 - y^4\right) - \frac{1}{2}k_1'(s)x^2yp_y$$

$$+\frac{1}{24}k_3(s)\left(x^4 - 6x^2y^2 + y^4\right)$$

- *The undisturbed linear part,*
- *The kinematic part,*
- *The influence of the fringe field,*
- *The octupole component.*

Amplitude dependent non-linear tune shift:

$$\nu_{x,y} = \frac{1}{2\pi}\oint \frac{\partial}{\partial J_{x,y}}\left\langle H(s)\right\rangle_{\phi_y,\phi_x} ds$$

So,

$$\Delta\nu_x = C_{xx}J_x + C_{xy}J_y,$$
$$\Delta\nu_y = C_{xy}J_x + C_{yy}J_y,$$

$$\left(C = C^k + C^e + C^o\right)$$

Kinematic effects

- Hamiltonian includes the high-order terms of Px and Py.
- nonlinear kinematic effect originated from the large angles of particles in the interaction region is responsible for the large tune-shift which in turn limits the dynamic aperture.

$$C_{xx}^{k} = \frac{3}{16\pi}\oint \gamma_{x}^{2}(s)\,ds, \qquad C_{yy}^{k} = \frac{3}{16\pi}\oint \gamma_{y}^{2}(s)\,ds,$$

$$C_{xy}^{k} = \frac{1}{8\pi}\oint \gamma_{x}(s)\gamma_{y}(s)\,ds,$$

Then,

$$C_{xx}^{k} = \frac{3}{16\pi}\frac{L}{\beta_{x}^{*2}}, \qquad C_{xy}^{k} = \frac{1}{8\pi}\frac{L}{\beta_{x}^{*}\beta_{y}^{*}}, \qquad C_{yy}^{k} = \frac{3}{16\pi}\frac{L}{\beta_{y}^{*2}}.$$

$$L = 2L^{*}$$

A.Bogomyagkov, S.Glykhov, E.Levichev, P.Piminov

Quadrupole fringe fields

$$C_{xx}^{e} = -\frac{1}{32\pi}\oint k_1''(s)\beta_x^2(s)\,ds, \qquad C_{yy}^{e} = \frac{1}{32\pi}\oint k_1''(s)\beta_y^2(s)\,ds,$$

$$C_{xy}^{e} = -\frac{1}{16\pi}\oint \beta_x(s)\left(k_1''(s)\beta_y(s) - 4k_1'(s)\alpha_y(s)\right)ds.$$

With a simple model of two matched parabolas for fringe field

$$C_{xx}^{e} \approx \frac{1}{8\pi}k_{10}^{2}\beta_{x0}^{2}L\left(1-\frac{1}{4}k_{10}L^{2}\right),$$

$$C_{xy}^{e} \approx \frac{1}{4\pi}k_{10}^{2}\beta_{x0}\beta_{y0}L,$$

$$C_{xx}^{e} \approx \frac{1}{8\pi}k_{10}^{2}\beta_{y0}^{2}L\left(1+\frac{1}{4}k_{10}L^{2}\right).$$

A.Bogomyagkov, S.Glykhov, E.Levichev, P.Piminov

Chromatic sextupoles

Vertical chromatic sextupole pair separated by –I transformer gives the following coordinate transformation in the first order*)

Pair of sextupoles

$$y = y_0$$
$$p_y = -p_{y0} - \frac{(K_2 L_s)^2 L_s}{6}\left(y_0^3 + x_0^2 y_0\right)$$

Octupole

$$y = y_0$$
$$p_y = p_{y0} - \frac{K_3 L}{6}\left(y_0^3 - 3x_0^2 y_0\right)$$

By analogy to the octupole and using the expression for the FF chromaticity we found for the vertical detuning (2 pairs)

$$C_{yy}^{sp} = \frac{1}{16\pi}\left(K_2 L_s\right)^2 L_s \beta_y^2 \approx \frac{1}{4\pi}\frac{L_s}{\eta_s^2}\left(\frac{L^*}{\beta^*}\right)^2 = \frac{1}{4\pi}\frac{L_s}{\eta_s^2}\xi^{*2}$$

*) A.Bogomyagkov, S.Glykhov, E.Levichev, P.Piminov http://arxiv.org/abs/0909.4872

CEPC amplitude-tune dependence

βx=0.22 βy=0.002	C_{xx} (m^{-1})	C_{xy} (m^{-1})	C_{yy} (m^{-1})
Kinematic effects	3.7	271	44762
Fringe field (QD0+QF1)	2.0+1.4	5788+2444	21.3+4.0

βx=0.144 βy=0.002	C_{xx} (m^{-1})	C_{xy} (m^{-1})	C_{yy} (m^{-1})
Kinematic effects	8.6	414	44762
Fringe field (QD0+QF1)	3.0+2.0	8558+3450	21.3+3.7

* Nonlinear effect of sextupole pairs can be corrected by the attached weak sextupole pairs.

summary

- A consistent calculation method for CEPC parameter choice with carb waist scheme has been created. Crosscheck luminosity with beam-beam simulations
- Based on double ring scheme with 100 km circumference, we can get higher Higgs luminosity (+170%) keeping Pre-CDR beam power or to reduce the beam power (19 MW) keeping same luminosity. Luminosity for Z: ~$10^{35}cm^{-2}s^{-1}$
- Requirement for energy acceptance reduced to 1.5% enlarging the ring.
- The horizontal βx^* affects the difficulty of the FFS design.
- has got 1.5% energy acceptance without crab sextupoles. Further studies of DA are going on.

THANKS !

Back up

parameter for CEPC partial double ring

（wangdou20160325-54km）

	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	8.5/7.6
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	0.005/0.006
ξ_y/IP	0.083	0.11	0.11	0.074	0.084/0.073
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	0.27/0.24
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	3.61/3.09

parameter for CEPC partial double ring

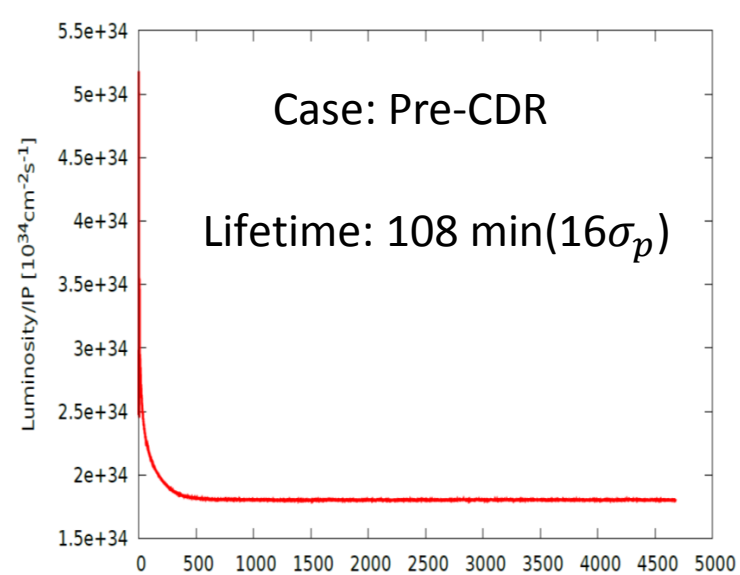
（wangdou20161109-61km）

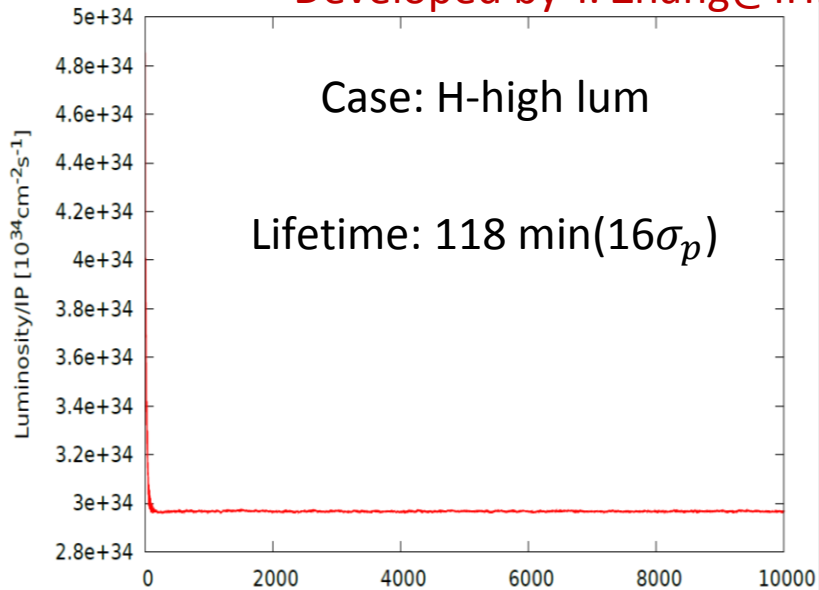
	Pre-CDR	*H-high lumi.*	*H-low power*	*W*	*Z*	*Z-5cell*
Number of IPs	2	2	2	2	2	2
Energy (GeV)	120	120	120	80	45.5	45.5
Circumference (km)	54	61	61	61	61	61
SR loss/turn (GeV)	3.1	2.96	2.96	0.58	0.061	0.061
Half crossing angle (mrad)	0	15	15	15	15	15
Piwinski angle	0	1.88	1.84	4.11	5.86	5.87
N_e/bunch (10^{11})	3.79	2.0	1.98	0.85	0.6	0.6
Bunch number	50	107	70	400	1100	700
Beam current (mA)	16.6	16.9	11.0	26.8	52.0	33.1
SR power /beam (MW)	51.7	50	32.5	15.7	3.2	2.0
Bending radius (km)	6.1	6.2	6.2	6.2	6.2	6.2
Momentum compaction (10^{-5})	3.4	1.48	1.48	1.48	3.1	3.1
β_{IP} x/y (m)	0.8/0.0012	0.272/0.0013	0.275 /0.0013	0.16/0.001	0.12/0.001	0.12/0.001
Emittance x/y (nm)	6.12/0.018	2.05/0.0062	2.05 /0.0062	0.93/0.003	0.87/0.0046	0.87/0.0046
Transverse σ_{IP} (um)	69.97/0.15	23.7/0.09	23.7/0.09	12.2/0.056	10.2/0.068	10.2/0.068
ξ_x/IP	0.118	0.041	0.042	0.0145	0.0098	0.0098
ξ_y/IP	0.083	0.11	0.11	0.084	0.073	0.073
V_{RF} (GV)	6.87	**3.48**	**3.51**	**0.7**	**0.12**	**0.12**
f_{RF} (MHz)	650	650	650	650	650	650
Nature σ_z (mm)	2.14	**2.7**	**2.7**	**3.23**	**3.9**	**3.9**
Total σ_z (mm)	2.65	2.95	2.9	3.35	4.0	4.0
HOM power/cavity (kw)	3.6	0.74	0.48	0.47	0.59	0.93
Energy spread (%)	0.13	0.13	0.13	0.087	0.05	0.05
Energy acceptance (%)	2	2	2			
Energy acceptance by RF (%)	6	**2.3**	**2.4**	**1.3**	**1.1**	**1.1**
n_γ	0.23	0.35	0.34	0.28	0.24	0.24
Life time due to beamstrahlung_cal (minute)	47	37	37			
F (hour glass)	0.68	0.82	0.82	0.89	0.92	0.92
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.04	3.1	2.01	3.5	3.44	2.24

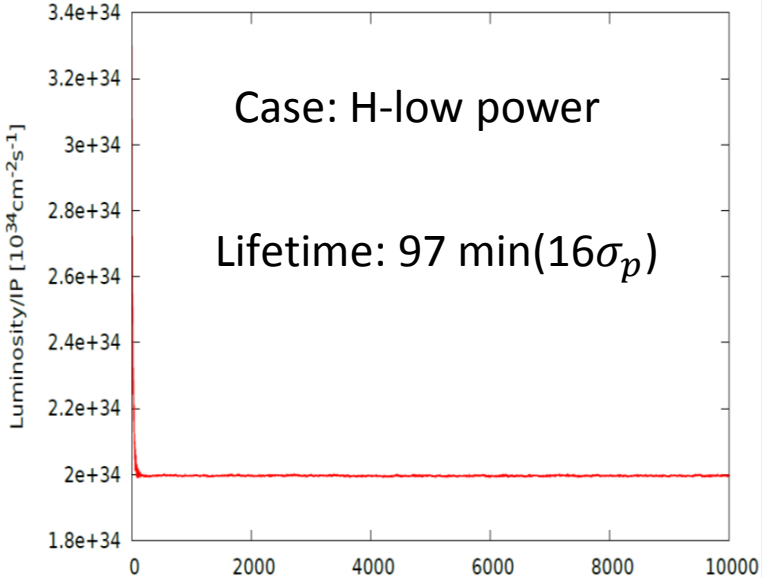
Beam-beam simulation-54km

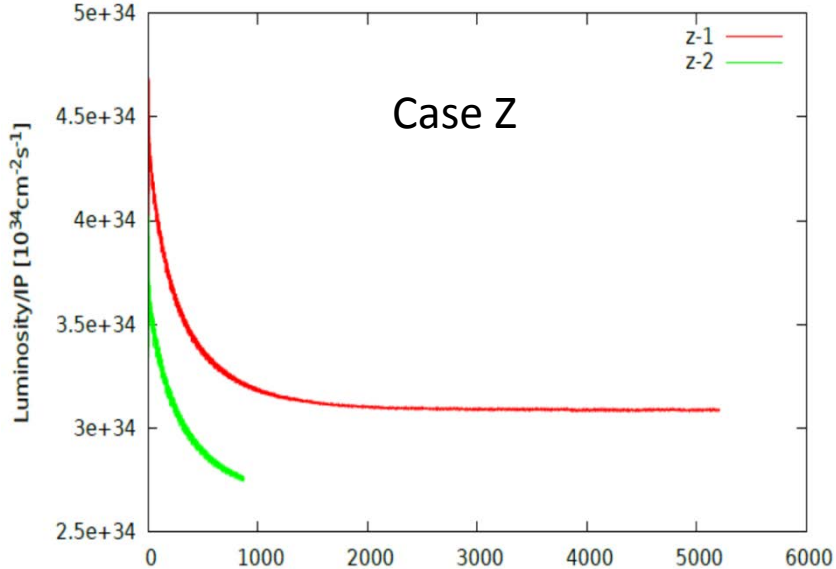
IBB: Strong-Strong Beam-Beam Code with Beamstrahlung effect

Developed by Y. Zhang@IHEP









Beam-beam simulation-61km

IBB: Strong-Strong Beam-Beam Code with Beamstrahlung effect

Developed by Y. Zhang@IHEP