Beam-Beam Effect & Dynamic Aperture at CEPC

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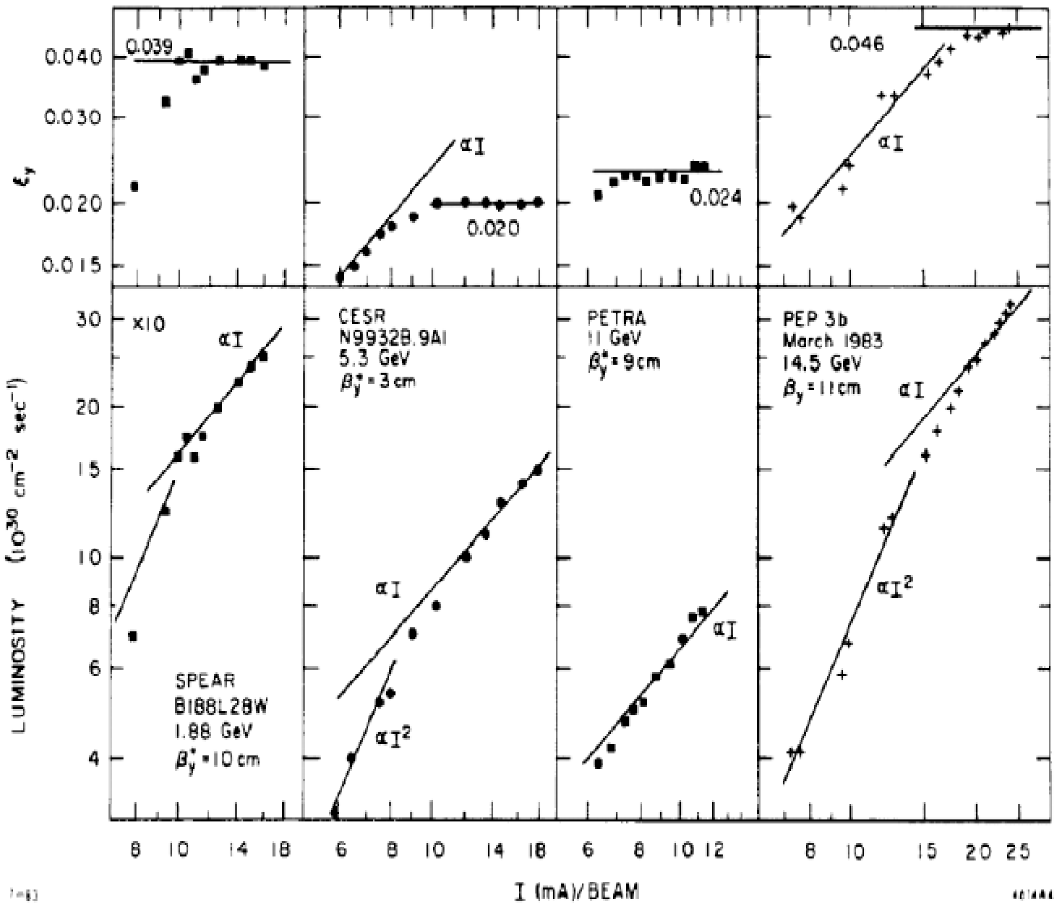
Workshop on the Circular Electron–Positron Collider – EU edition

Acknowledgements: K. Ohmi(KEK), D. Shatilov(BINP), K. Oide(CERN,KEK), D. Zhou(KEK)

Outline

- Introduction
- Beam-Beam Effect at H/W/Z
- DA w/ and w/o Beam-Beam Interaction
- Summary

Beam-beam parameter in early machines



J. Seeman, “Observations of the beam–beam interaction”, 1985

Collider	Energy (GeV)	ξ_v	Nb of IP
VEPP-2M	0.5	0.050	2
DCI	0.8	0.041	2
ADONE	1.5	0.070	6
SPEAR	1.2	0.018	2
	1.9	0.056	2
	2.1	0.055	2
BEPC	1.6	0.035	2
DORIS-2	5.3	0.026	2
VEPP-4	5.0	0.050	1
KEK-AR	5.0	0.030	2
	5.0	0.045	1
CESR	4.7	0.018	2
	5.0	0.022	2
	5.3	0.026	2
	5.5	0.028	2
	5.4	0.020	2
	5.4	0.035	1
PEP	14.5	0.045	6
	14.5	0.065	2
	14.0	0.050	1
PETRA	7.0	0.014	4
	11.0	0.024	4
	17.0	0.040	4
TRISTAN	30.4	0.034	4
LEP	45.6	0.035	4

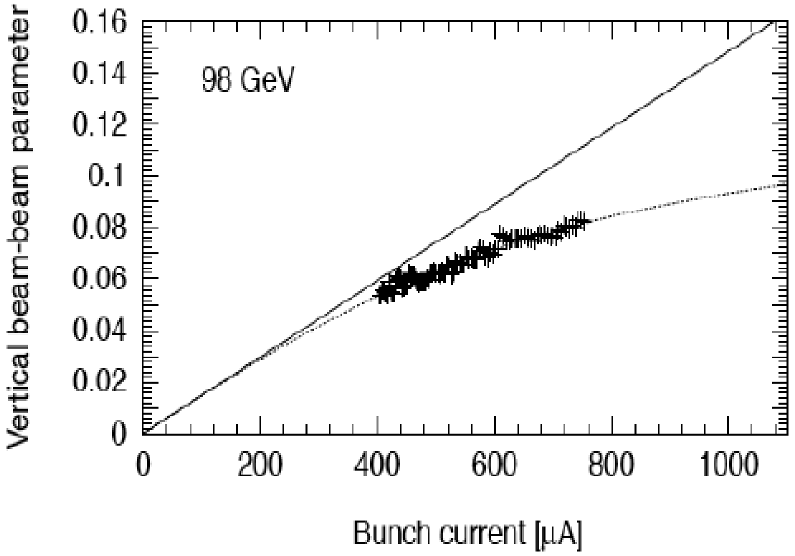
Machine Parameters of the KEKB (June 17 2009)

	LER	HER	
Circumference	3016		m
RF Frequency	508.88		MHz
Horizontal Emittance	18	24	nm
Beam current	1637	1188	mA
Number of bunches	1584 + 1		
Bunch current	1.03	0.750	mA
Bunch spacing	1.84		m
Bunch trains	1		
Total RF volatage Vc	8.0	13.0	MV
Synchrotron tune ν_s	-0.0246	-0.0209	
Betatron tune ν_x / ν_y	45.506/43.561	44.511/41.585	
beta's at IP β_x^* / β_y^*	120/0.59	120/0.59	cm
momentum compaction a	3.31 x 10^{-4}	3.43 x 10^{-4}	
Estimated vertical beam size at IP from luminosity σ_y^*	0.94	0.94	µm
beam-beam parameters ξ_x / ξ_y	0.127/0.129	0.102/0.090	
Beam lifetime	133@1637	200@1188	min.@mA
Luminosity (Belle CsI)	21.08		10^{33}/cm^2/sec
Luminosity records per day / 7days/ 30days	1.479/8.428/30.208		/fb

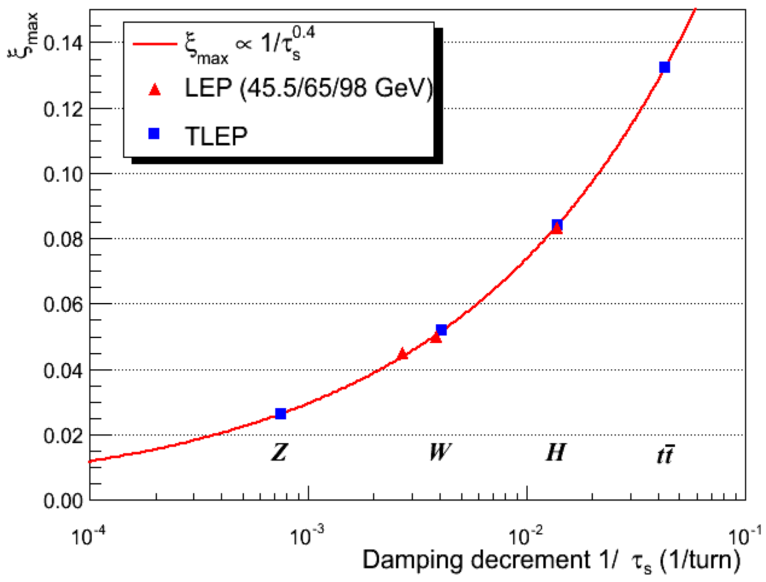
$\xi_y \sim 0.1$

Beam-Beam Parameter at LEP

- Vertical Beam-Beam Parameter measured at LEP



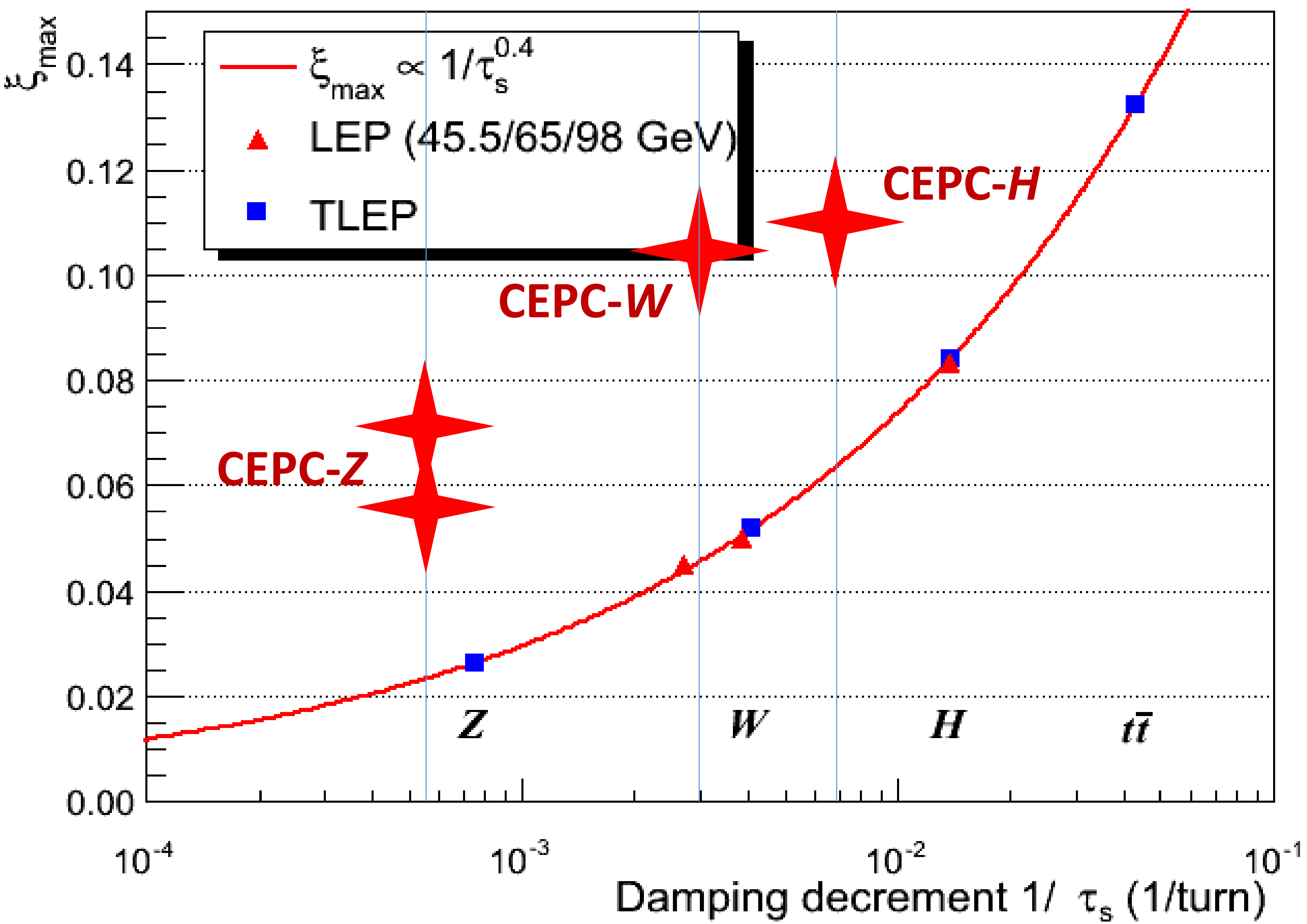
http://tlep.web.cern.ch/content/accelerator-challenges



R. Assmann

CEPC Parameters

	Higgs	*W*	*Z*（*3T*）	*Z*（*2T*）
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	242 (0.68μs)	1524 (0.21μs)	12000 (25ns+10%gap)	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
HOM power/cavity (2 cell) (kw)	0.54	0.75	1.94	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	1.35	0.4	0.23	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.29	0.35	0.55	
Lifetime _simulation (min)	100			
Lifetime (hour)	0.67	1.4	4.0	2.1
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP *L* (10^{34}cm^{-2}s^{-1})	2.93	10.1	16.6	32.1



the damping rate per beam-beam interaction

Crab-Waist Compensation

Collision with large Φ is not a new idea .....

Crab-Waist transformation is !

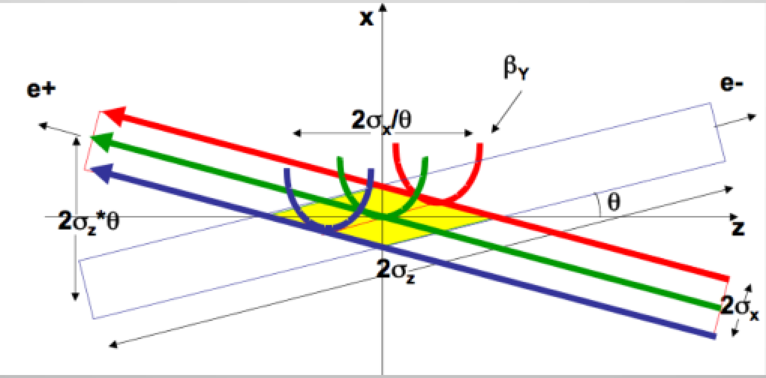
$$y = \frac{xy'}{2\theta}$$

sextupole (anti)sextupole

$$\Delta\nu_x = \pi$$
$$\Delta\nu_y = \frac{\pi}{2}$$

- $L_{\text{geometric}}$ gain
- x-y synchro-betatron and betatron resonance suppression

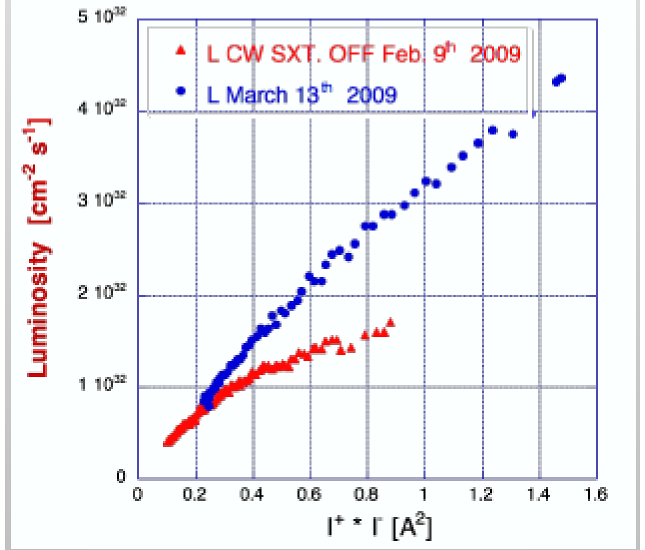
P. Raimondi , 2° *SuperB Workshop, March 2006*
P.Raimondi, D.Shatilov, M.Zobov, physics/0702033
C. Milardi et al., Int.J.Mod.Phys.A24, 2009
M. Zobov et al., Phys. Rev. Lett. 104, 2010



DAΦNE Luminosity and Tune Shift

	KLOE (Spt 2005)	FINUDA (Apr 2007)	SIDDHARTA *CW* (Jun 2009)
Luminosity [10^{32} $cm^{-2}s^{-1}$]	1.53	1.6	**4.53** (5.0)
I(ele) [A]	1.38	1.50	1.52
I(pos) [A]	1.18	1.1	1
n_b	111	106	105
ε_x [mm mrad]	0.34	0.34	0.28
β_x [m]	1.5	2.	0.25
β_y [cm]	1.8	1.9	0.9
ξ	0.0245	0.0291	**0.0443 (0.074)**

Luminosity as a function of colliding currents
CW-Sextupole excitation



C. Milardi

Simulation of Beamstrahlung

K. Ohmi

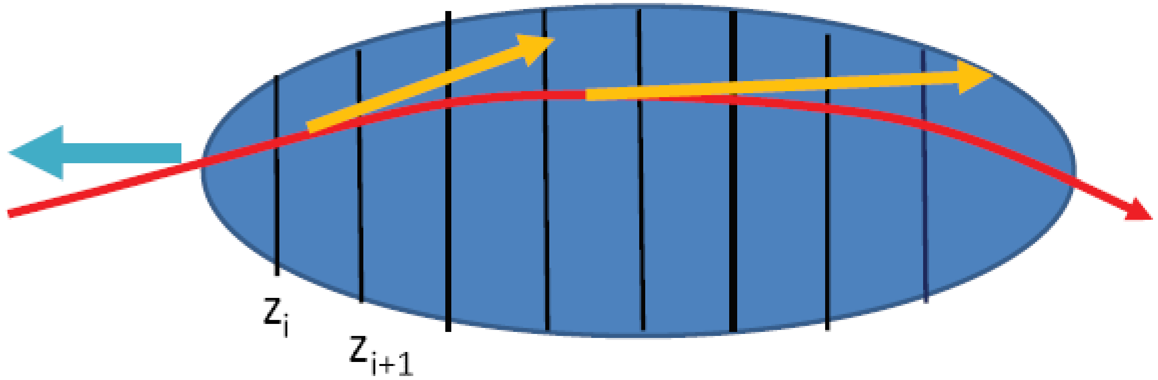
$$\Delta s = (z_i - z_{i+1})/2$$

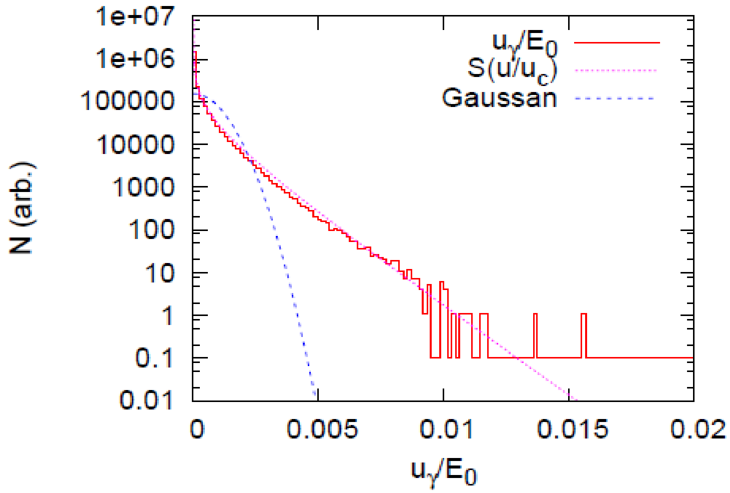
$$\frac{1}{\rho_{xy}} = \frac{\Delta p_{xy}}{\Delta s} \qquad \frac{1}{\rho} = \sqrt{\frac{1}{\rho_x^2} + \frac{1}{\rho_y^2}}$$

$$u_c = \hbar\omega_c = \frac{3\hbar c\gamma^3}{2\rho}$$

$$n_\gamma = \int_0^\infty \frac{dn_\gamma(\omega)}{d\omega} d\omega = \frac{5\sqrt{3}}{6\rho}\Delta s$$

$$\frac{dn_\gamma(\omega)}{d\omega} = \frac{\sqrt{3}\alpha\gamma\Delta s}{2\pi\rho\omega_c} S\left(\frac{\omega}{\omega_c}\right) \qquad S(\xi) = \int_\xi^\infty K_{\frac{5}{3}}(y)dy$$





Beamstrahlung lifetime

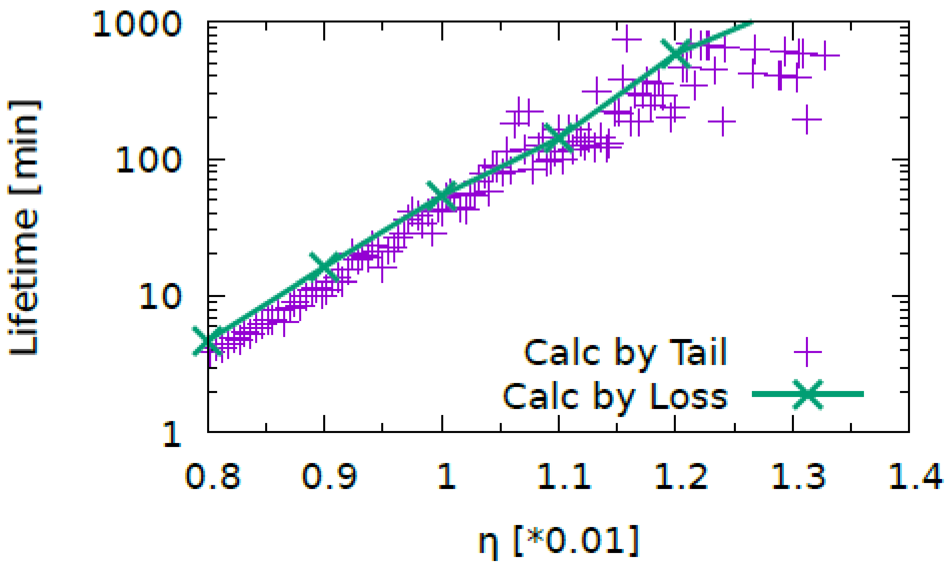
- Analysis [*V. Telnov, Phys. Rev. Letters 110 (2013) 114801*]

$$\tau_{BS} \approx \frac{1}{n_{IP} f_{rev}} \frac{4\sqrt{\pi}}{3} \sqrt{\frac{\delta_{acc}}{\alpha r_e}} \exp\left(\frac{2}{3} \frac{\delta_{acc}\alpha}{r_e \gamma^2} \frac{\gamma \sigma_x \sigma_z}{\sqrt{2} r_e N_b}\right) \frac{\sqrt{2}}{\sqrt{\pi}\sigma_z \gamma^2} \left(\frac{\gamma \sigma_x \sigma_z}{\sqrt{2} r_e N_b}\right)^{3/2}$$

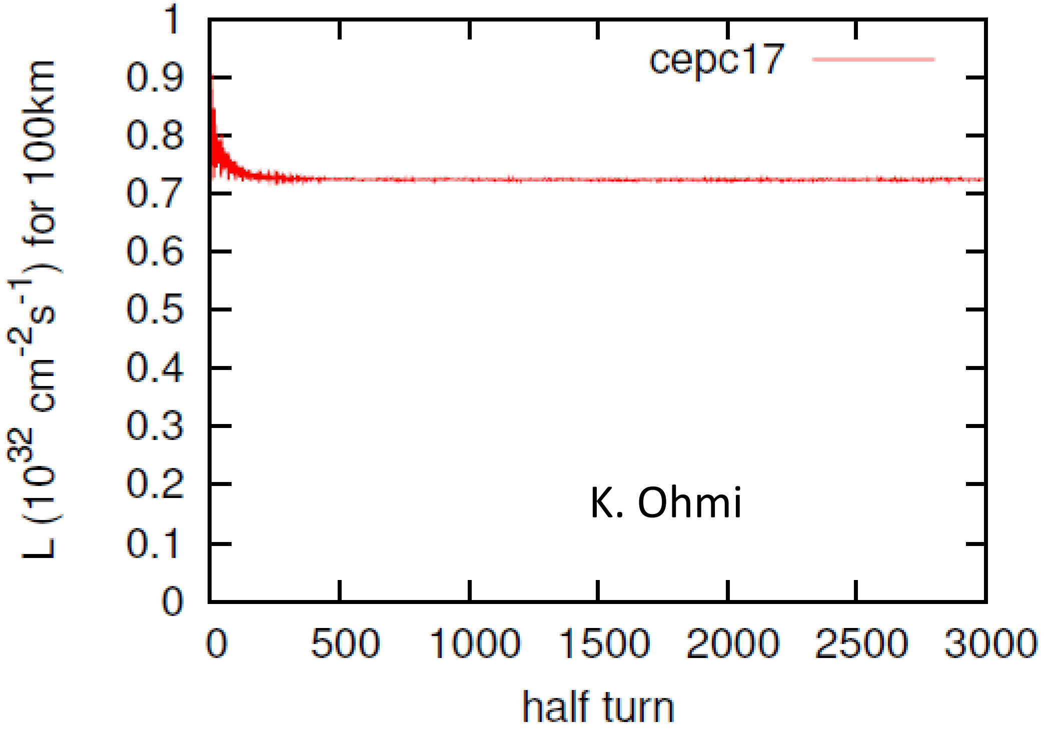
- Calculated by beam distribution K. Ohmi

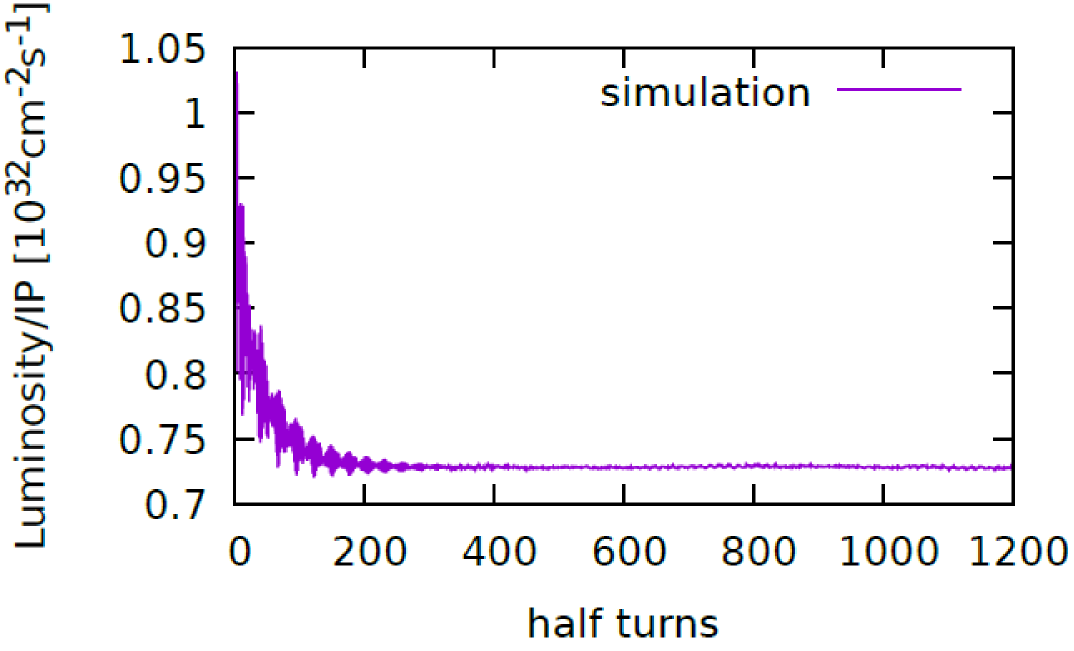
$$\tau_{bs} = \frac{\tau_z}{2Af(A)}$$

- A is the boundary of momentum acceptance in action,
- $f(J)$ is the distribution of action with beam-beam, $\int_0^\infty dJ\, f(J) = 1$
- τ_z is the longitudinal damping time



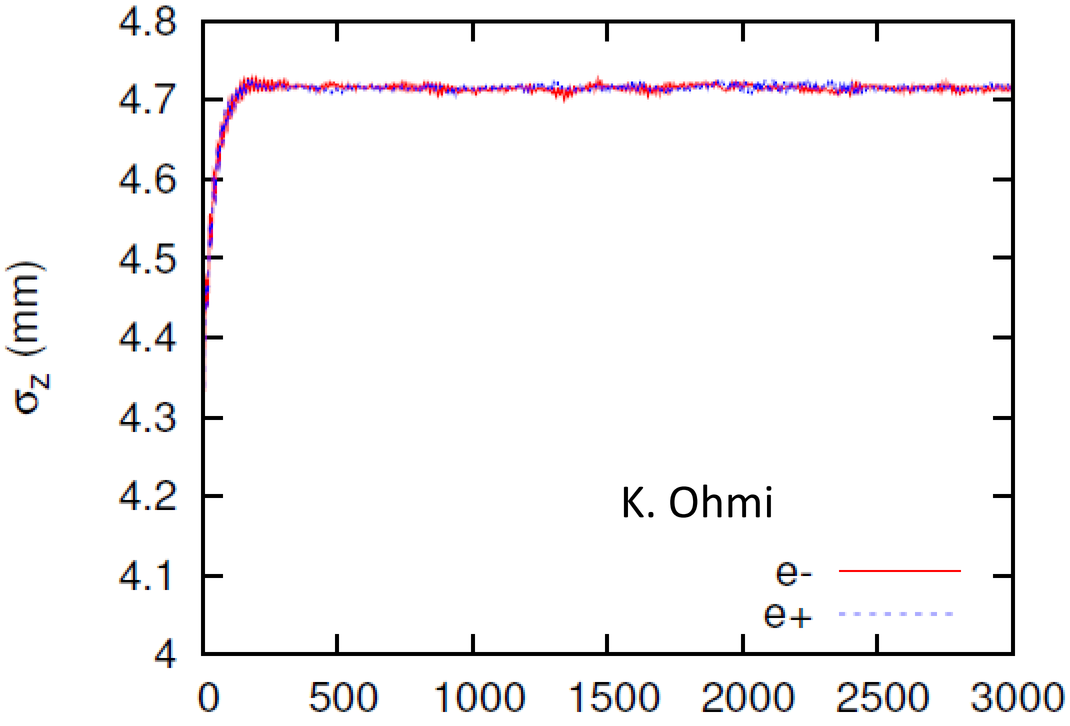
Beam-Beam Code Check (1) - CEPC

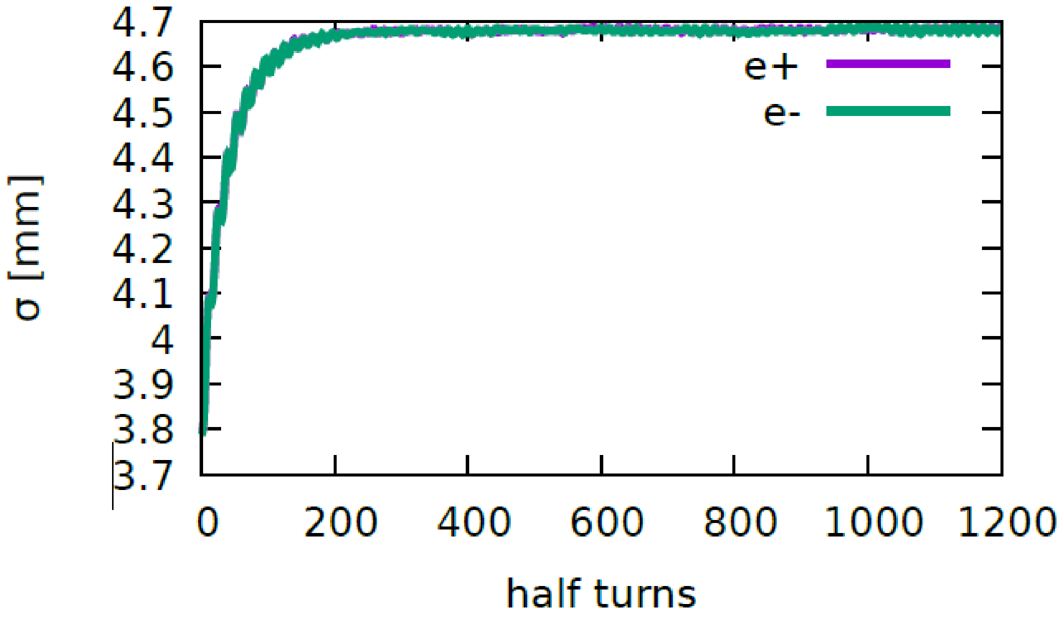




Beam-Beam Code Check (2) - CEPC

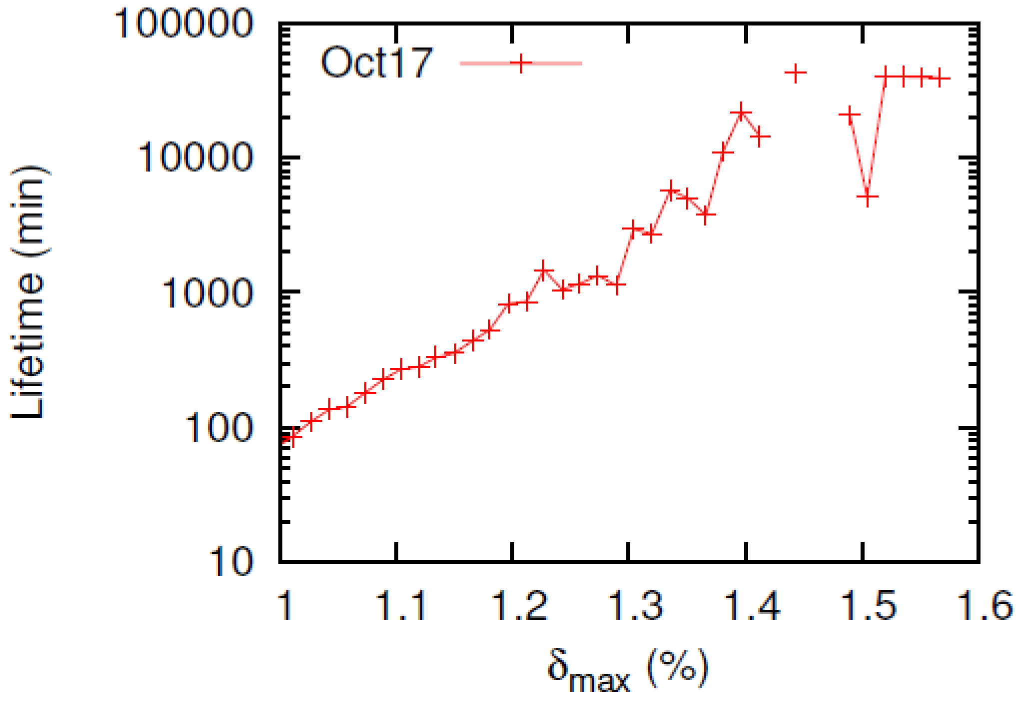
Old Parameters

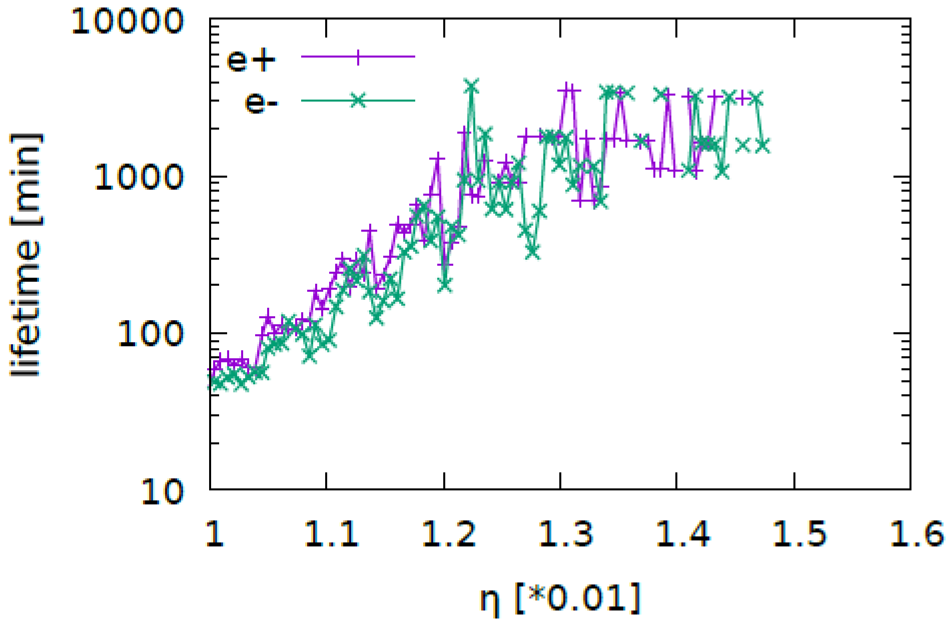




Beam-Beam Code Check (3) – CEPC

Old Parameters





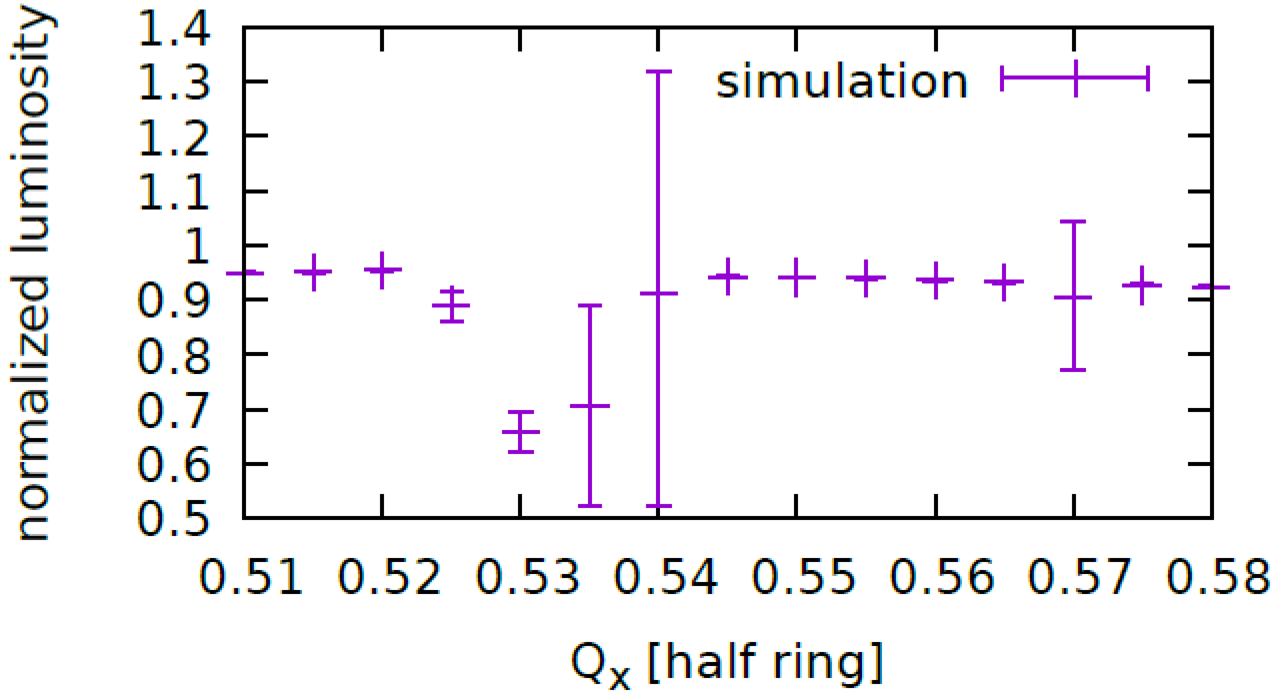
If the machine parameter is reasonable

- Limit of bunch population by beam-beam interaction
  - Beamstrahlung lifetime
  - If X-Z instability is suppressed
  - If Asymmetric Collision is OK
  - If there exist large enough stable working point space
  - If Beam-beam parameter is safe enough

Higgs

Tune Scan

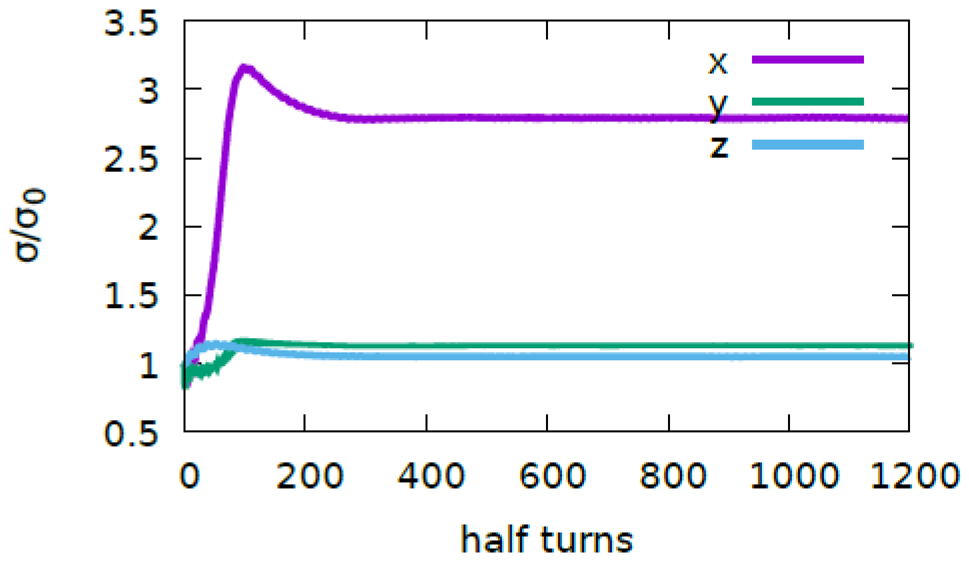
Q_y =0.61, Q_s = 0.035

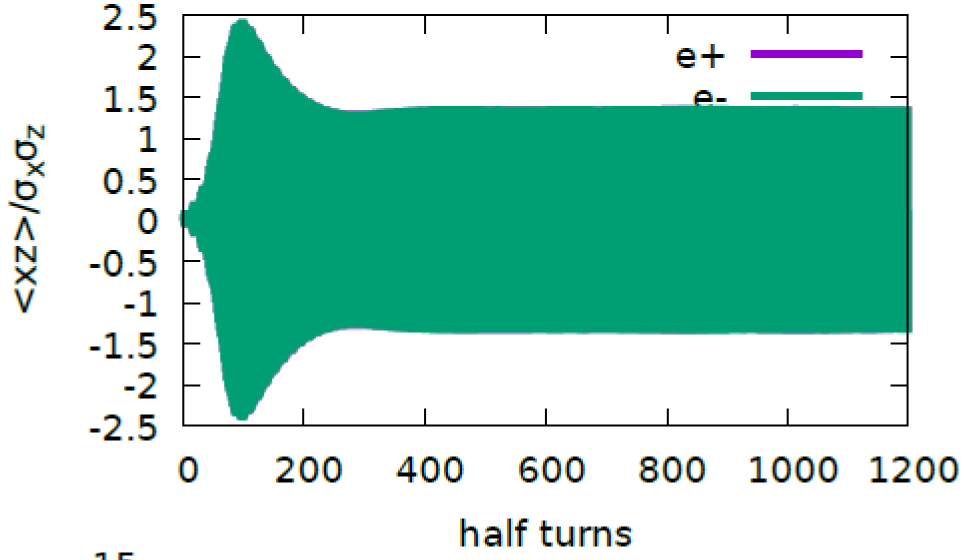


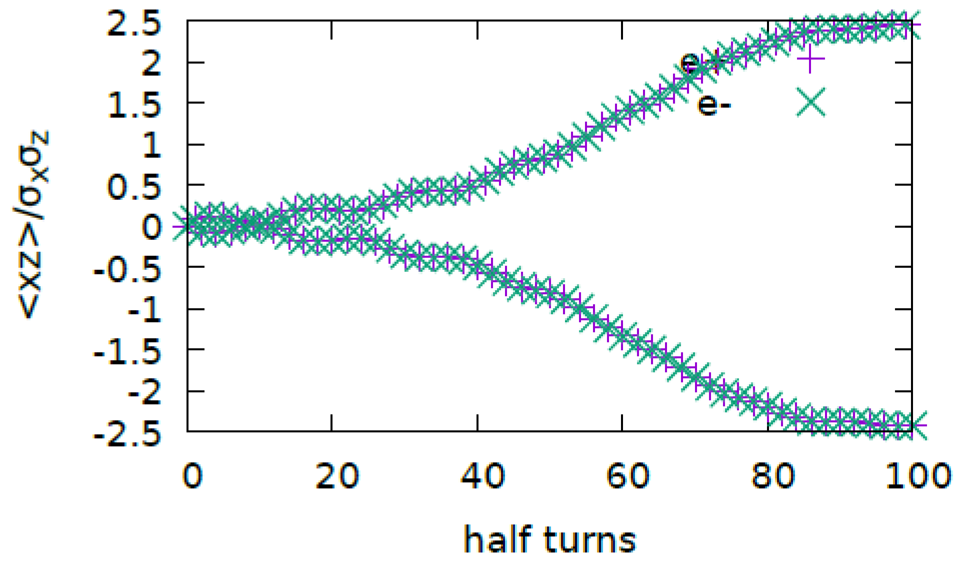
The error bar shows the turn-by-turn luminosity difference.

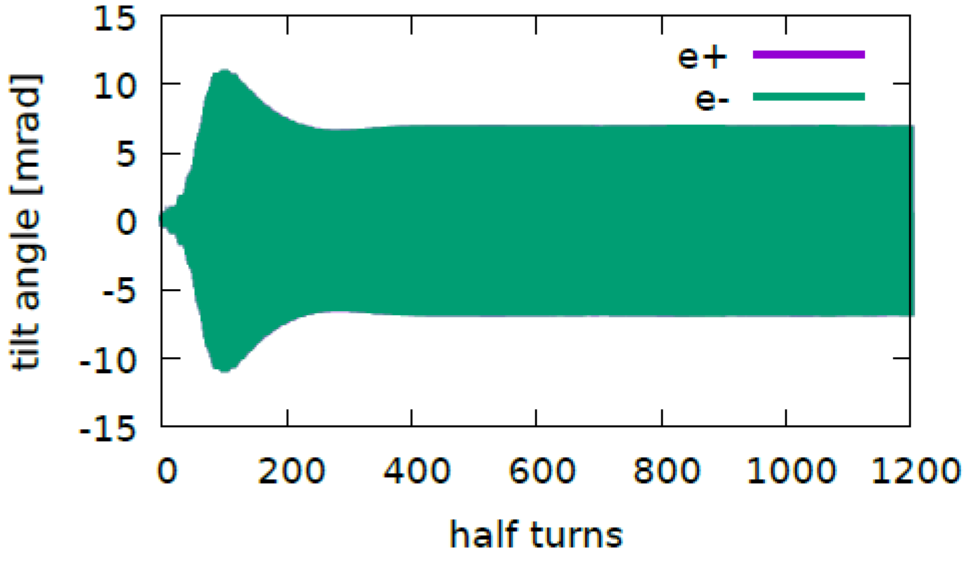
K. Ohmi and etal., DOI:10.1103/PhysRevLett.119.134801

X-Z instability @(0.535,0.61)





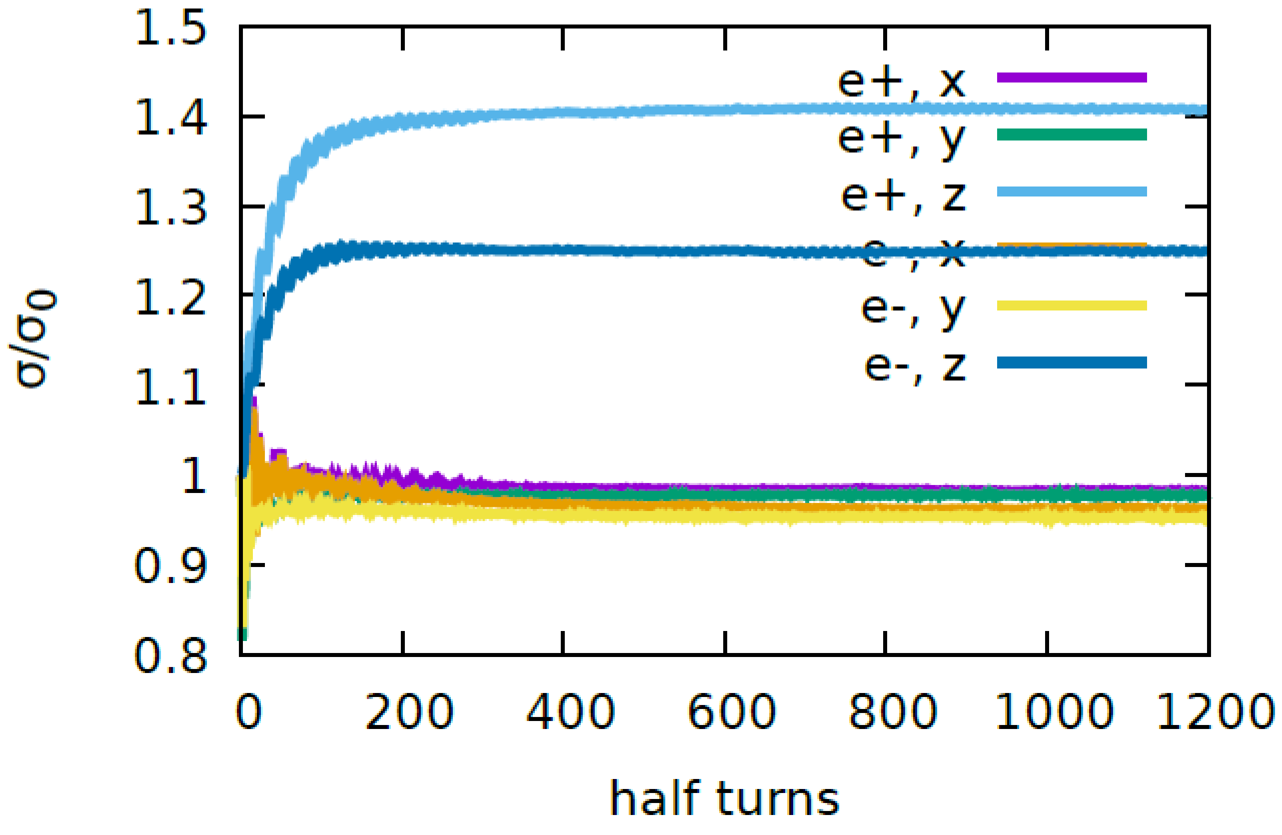




Unequal e+/e- current

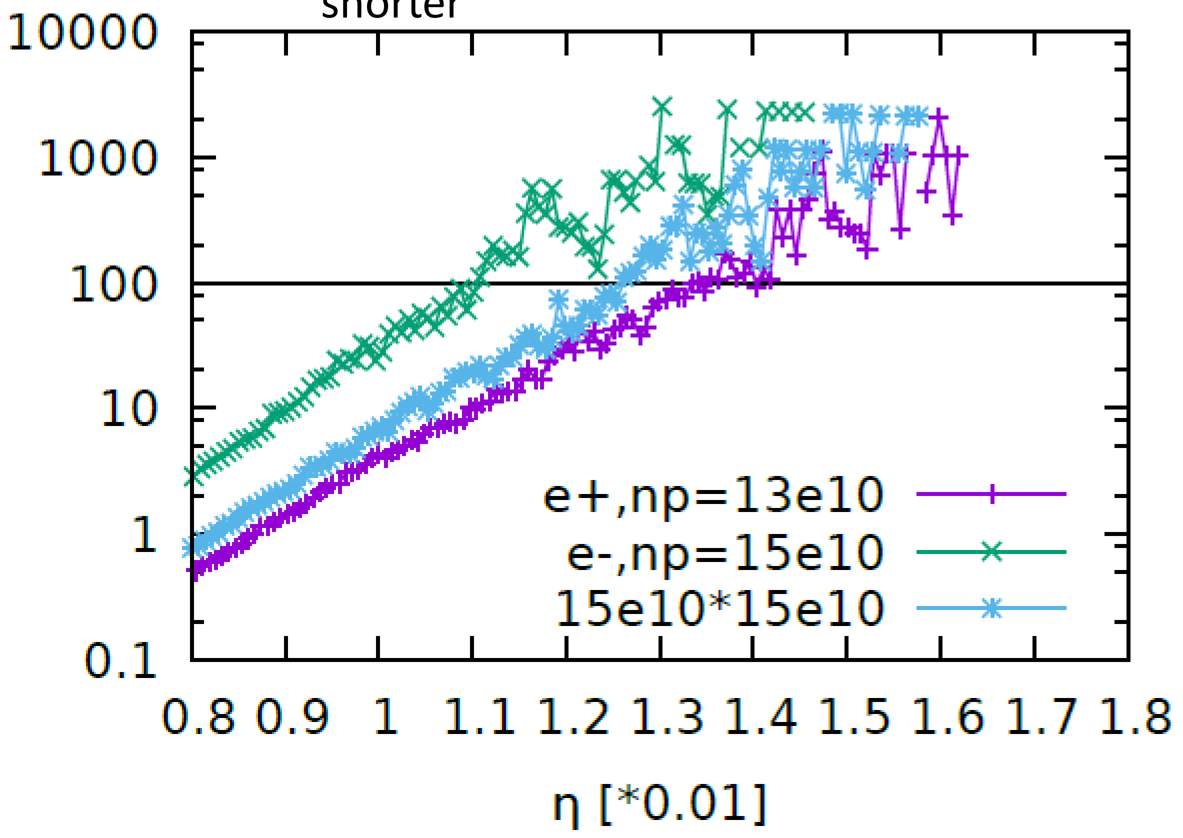
- With 13e10*15e10(13%), the weak beam's lifetime is about half of the symmetric collision (15e10*15e10)
- With 5% difference, the weak beam's lifetime is about 20-30% shorter

RMS Size Evolution



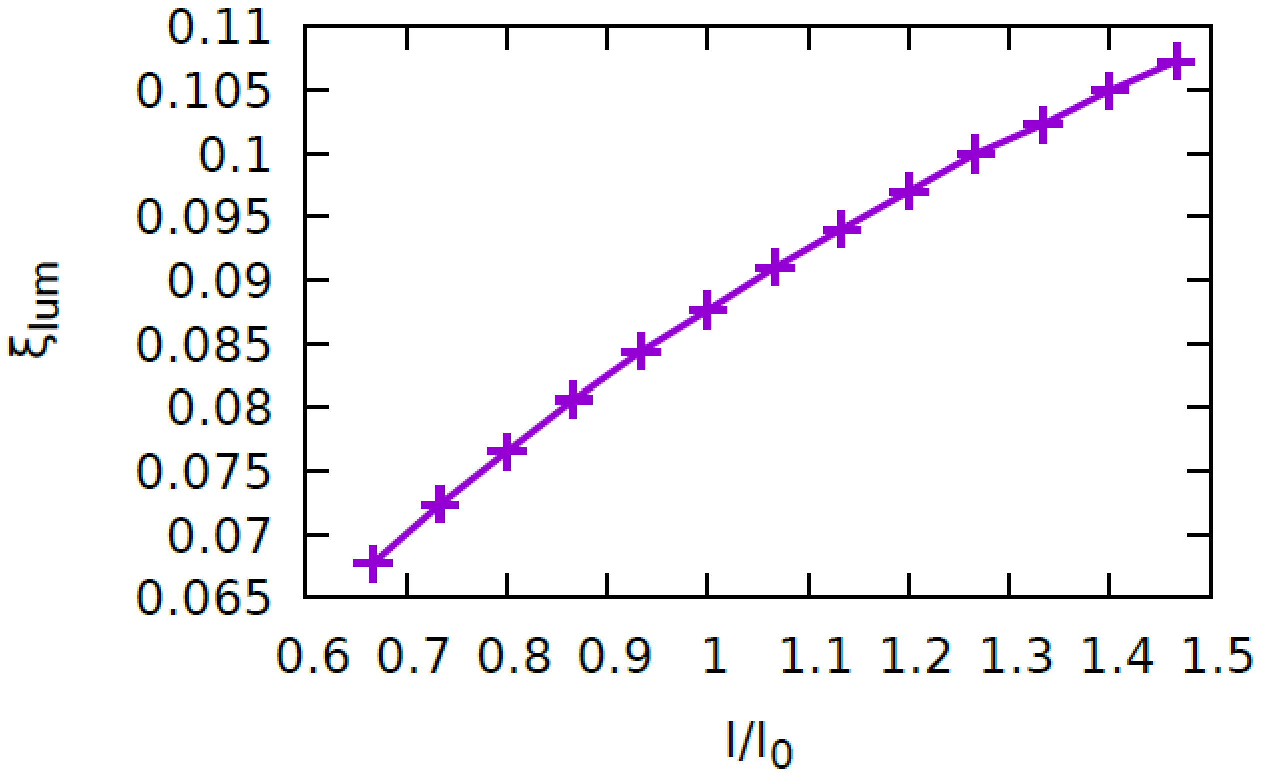
Collision is stable

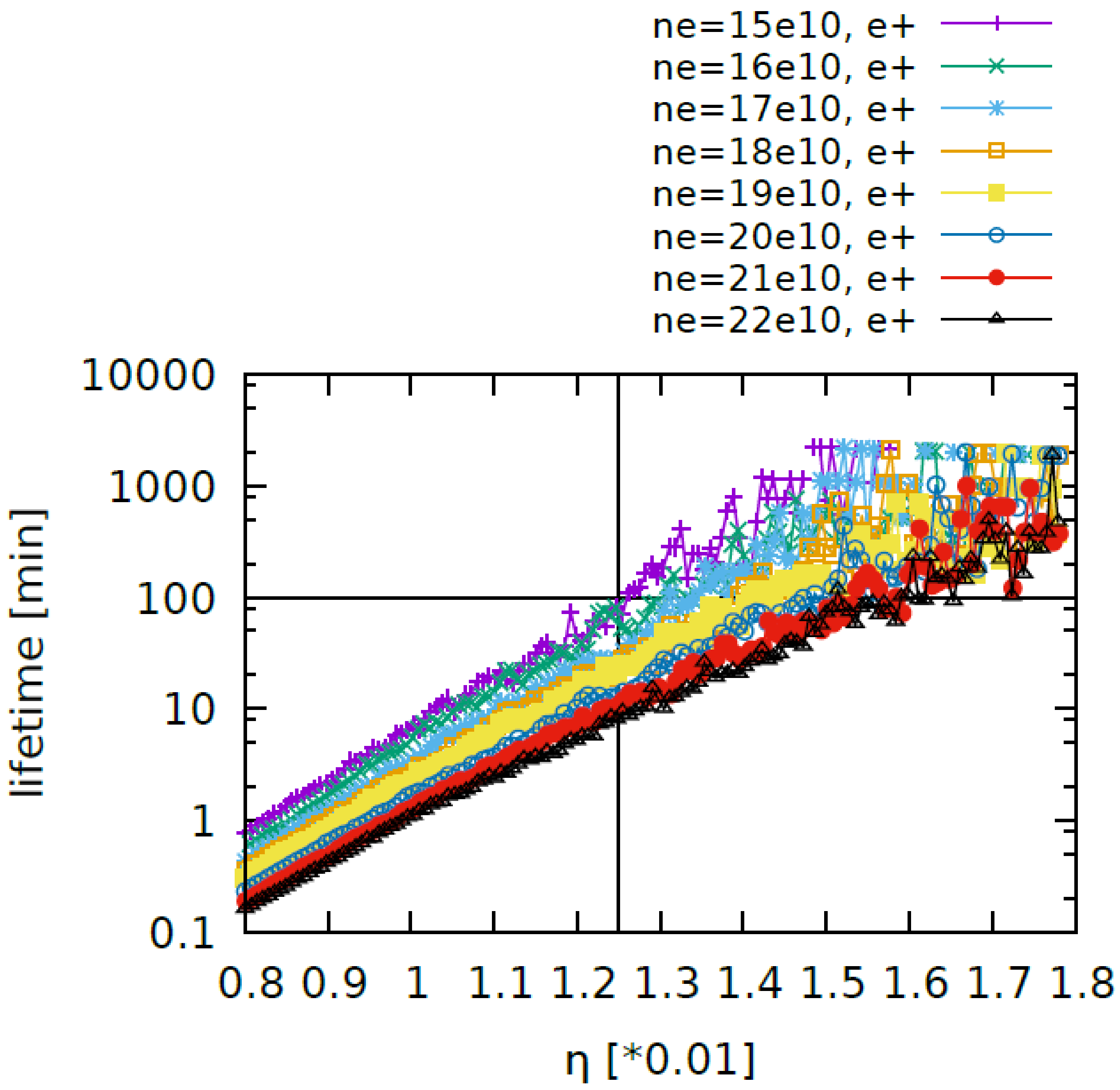
13% difference



Bunch Current Limit

$$\xi_y = \frac{2r_e\beta_y^0}{N\gamma}\frac{L}{f_0}$$



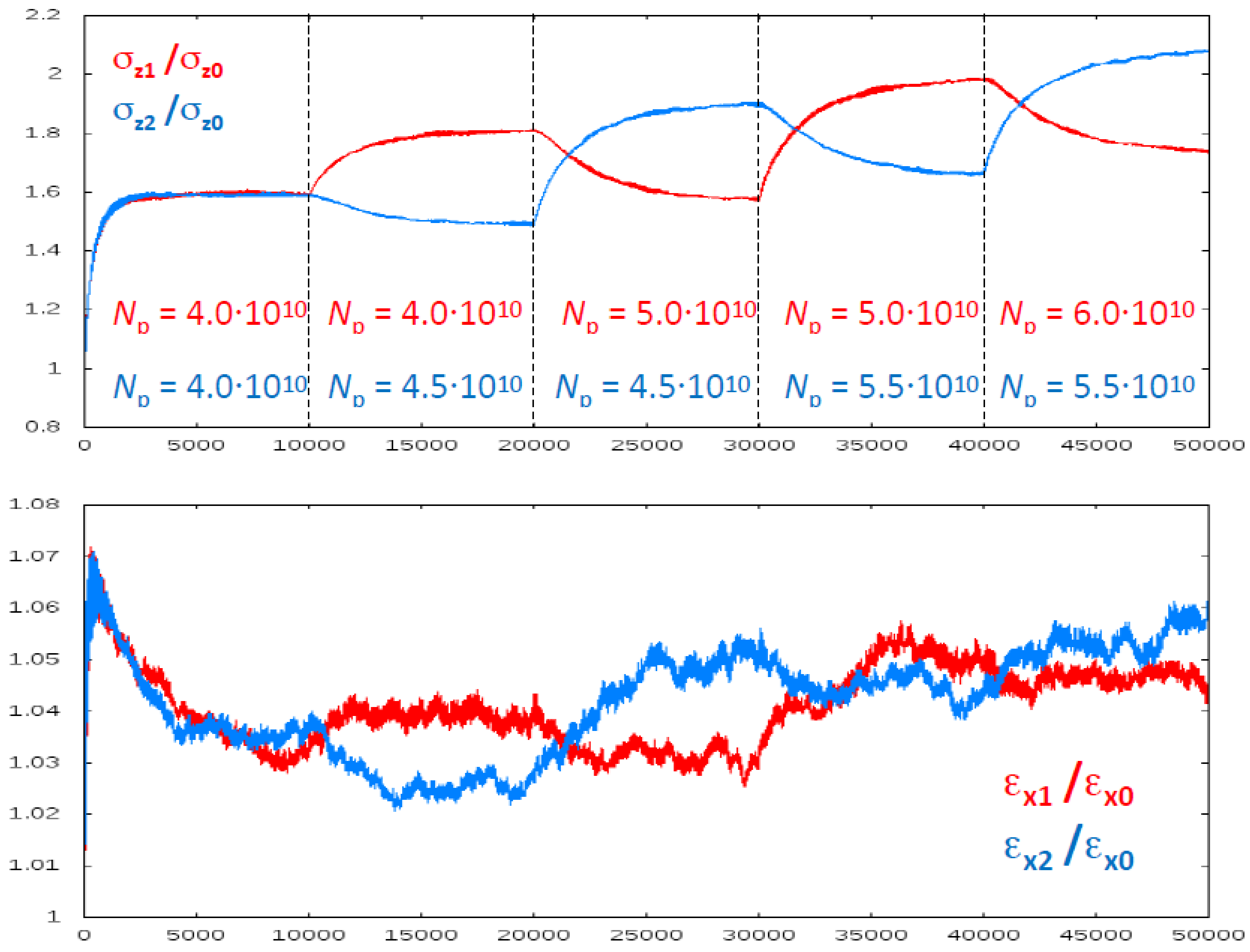


W

Bootstrapping

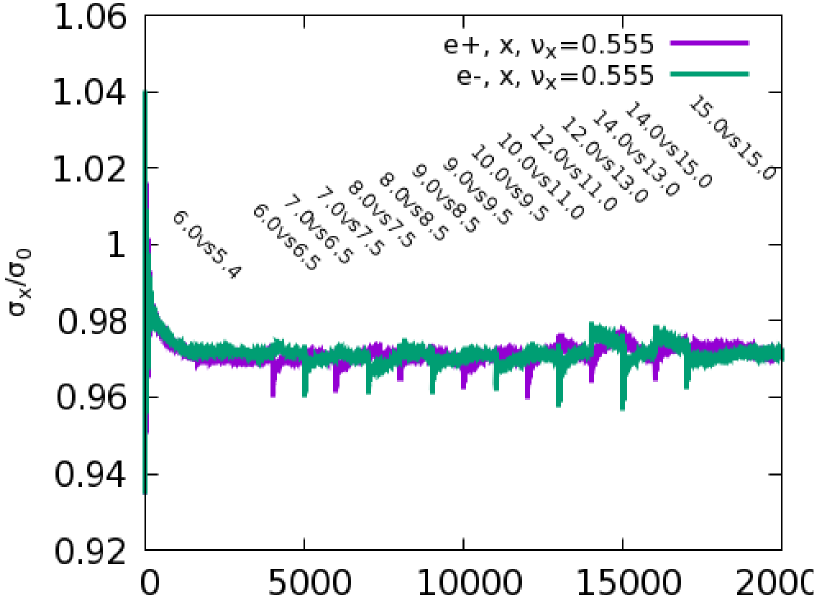
D. Shatilov

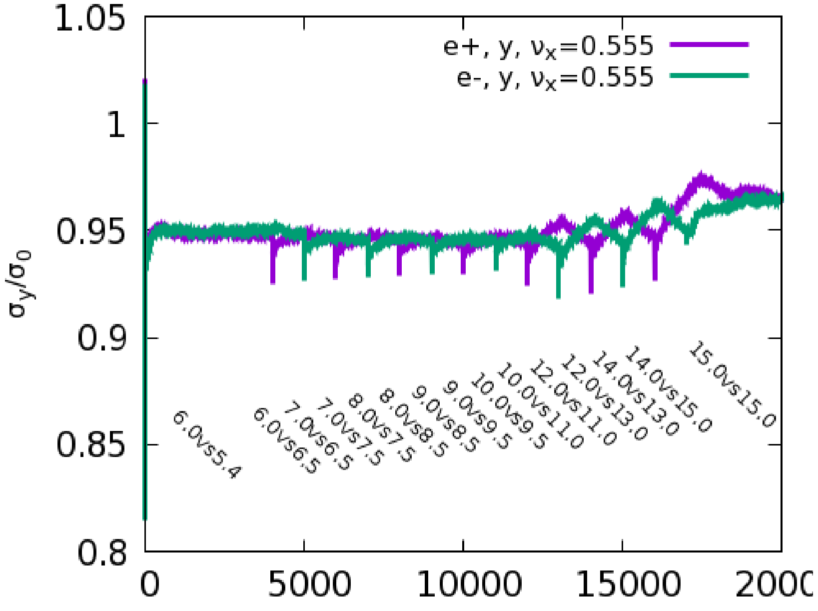
$$\mathrm{Np} \propto \frac{\alpha_p \sigma_\delta \sigma_z}{\beta_x^*}$$ (K. Oide)

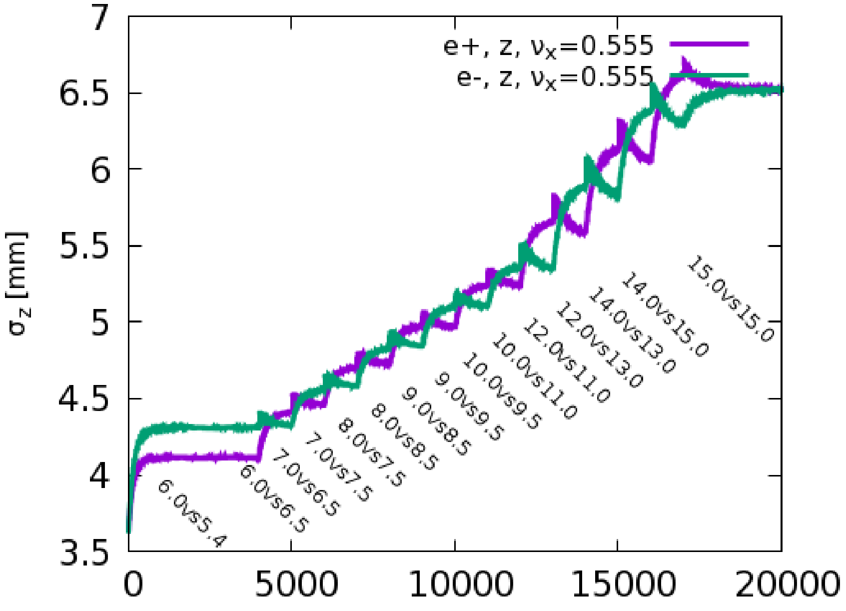


- The maximum bunch charge is determined considering the balance of beamstrahlung, momentum acceptance, and the capability of injector.

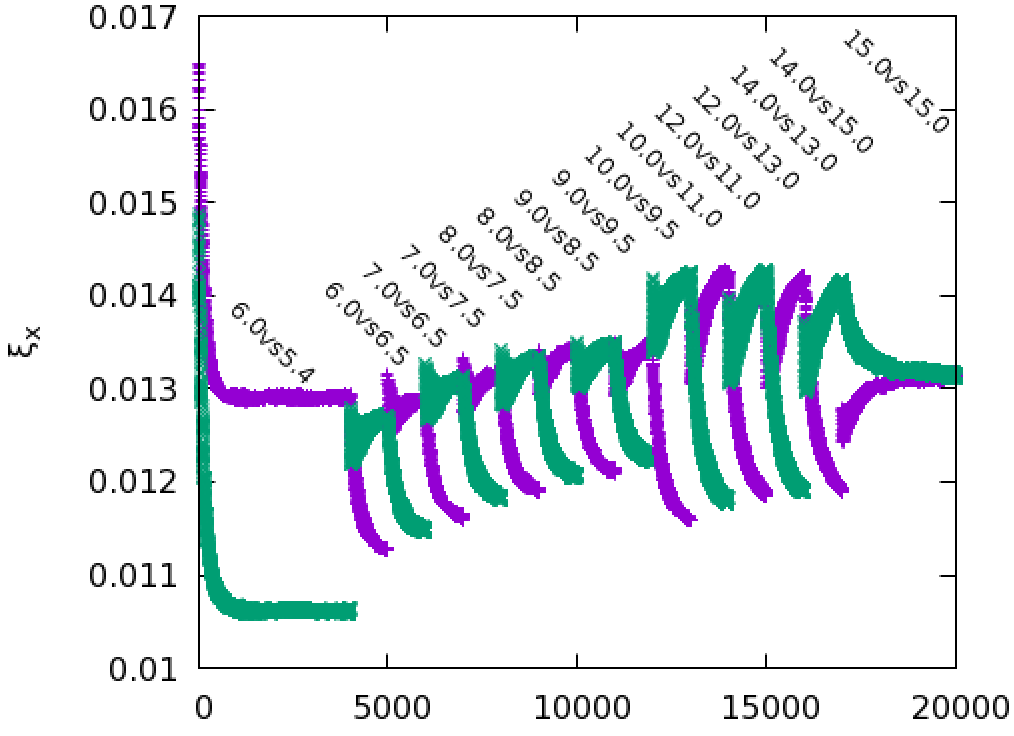
RMS size Evolution during Bootstrapping @ Qx=0.555

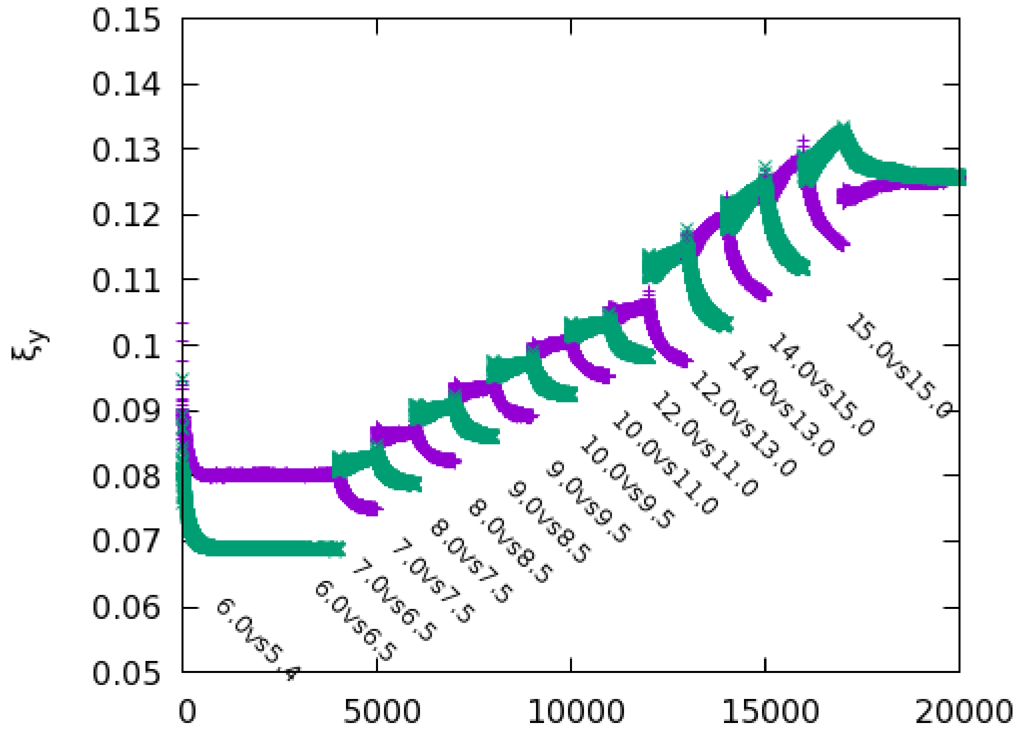






Beam-beam Parameter Evolution During Bootstrapping @ Qx=0.555



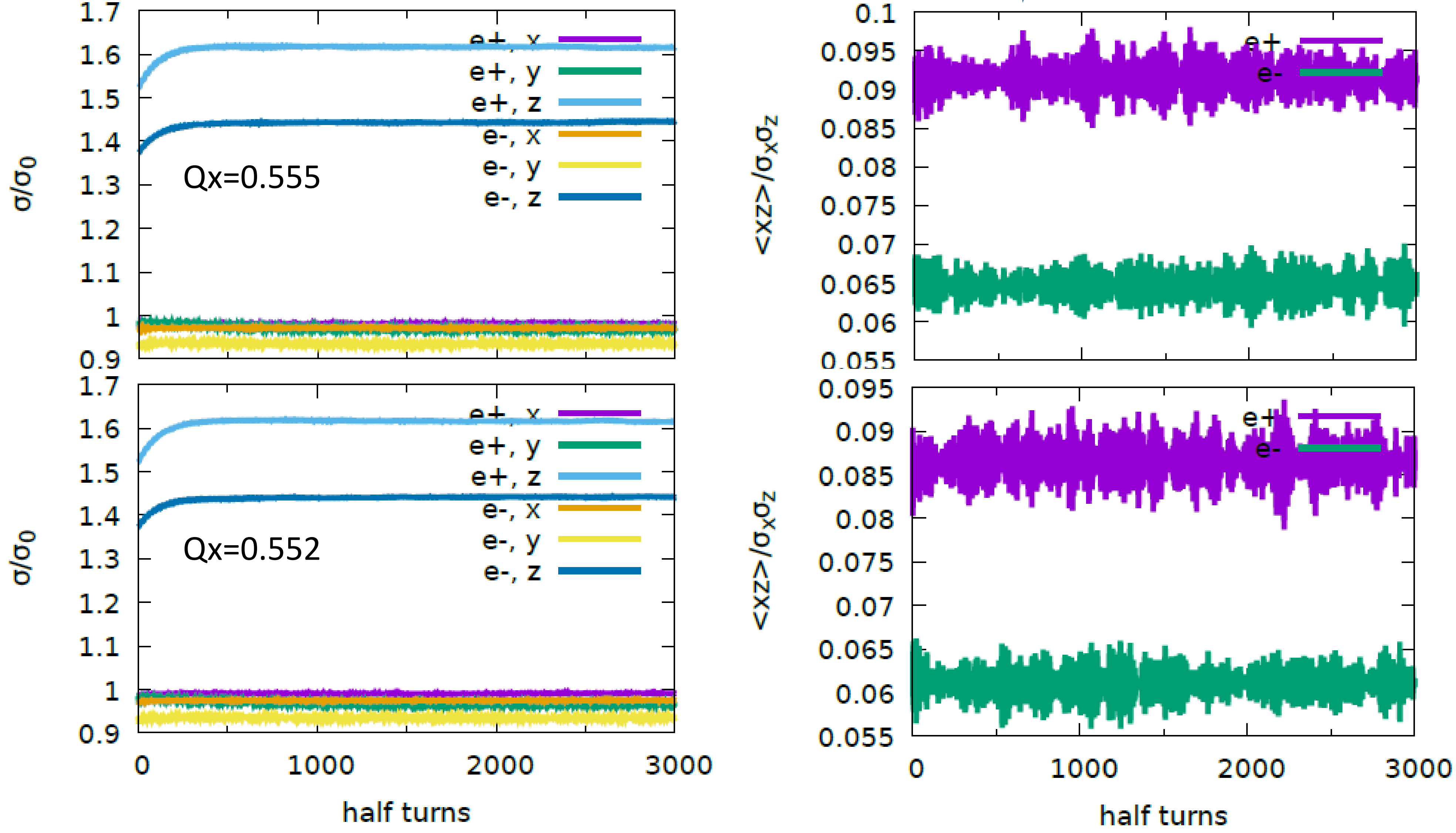


$$\boxed{\xi_x^{\pm} = \frac{N^{\mp} r_e}{\gamma^{\pm}} \frac{\beta_x^{\pm}}{2\pi\sigma_{x,\text{eff}}^{\mp}\left(\sigma_{x,\text{eff}}^{\mp} + \sigma_y^{\mp}\right)}}$$

$$\sigma_{x,\text{eff}} = \sqrt{\sigma_z^2 \tan^2\theta + \sigma_x^2}$$

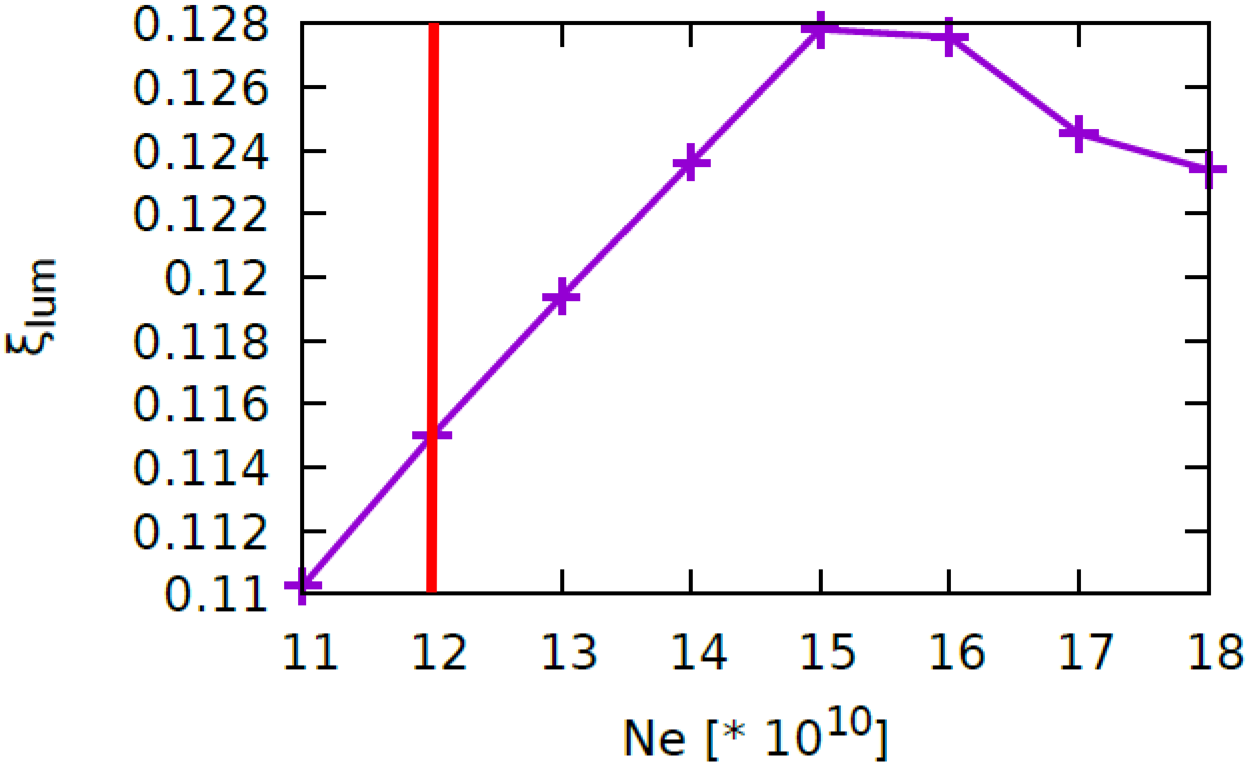
$$\boxed{\xi_y^{\pm} = \frac{N^{\mp} r_e}{\gamma^{\pm}} \frac{\beta_x^{\pm}}{2\pi\sigma_y^{\mp}\left(\sigma_{x,\text{eff}}^{\mp} + \sigma_y^{\mp}\right)}}$$

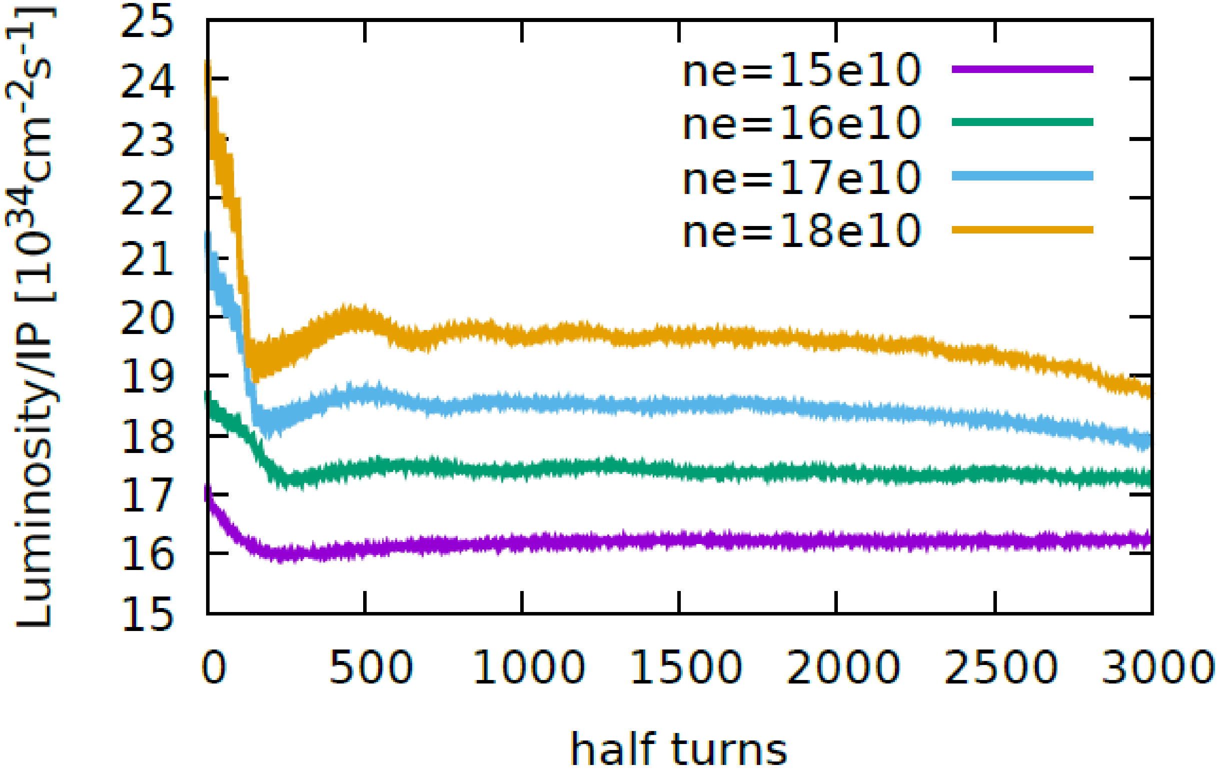
NP = 13.5e10 vs 15e10



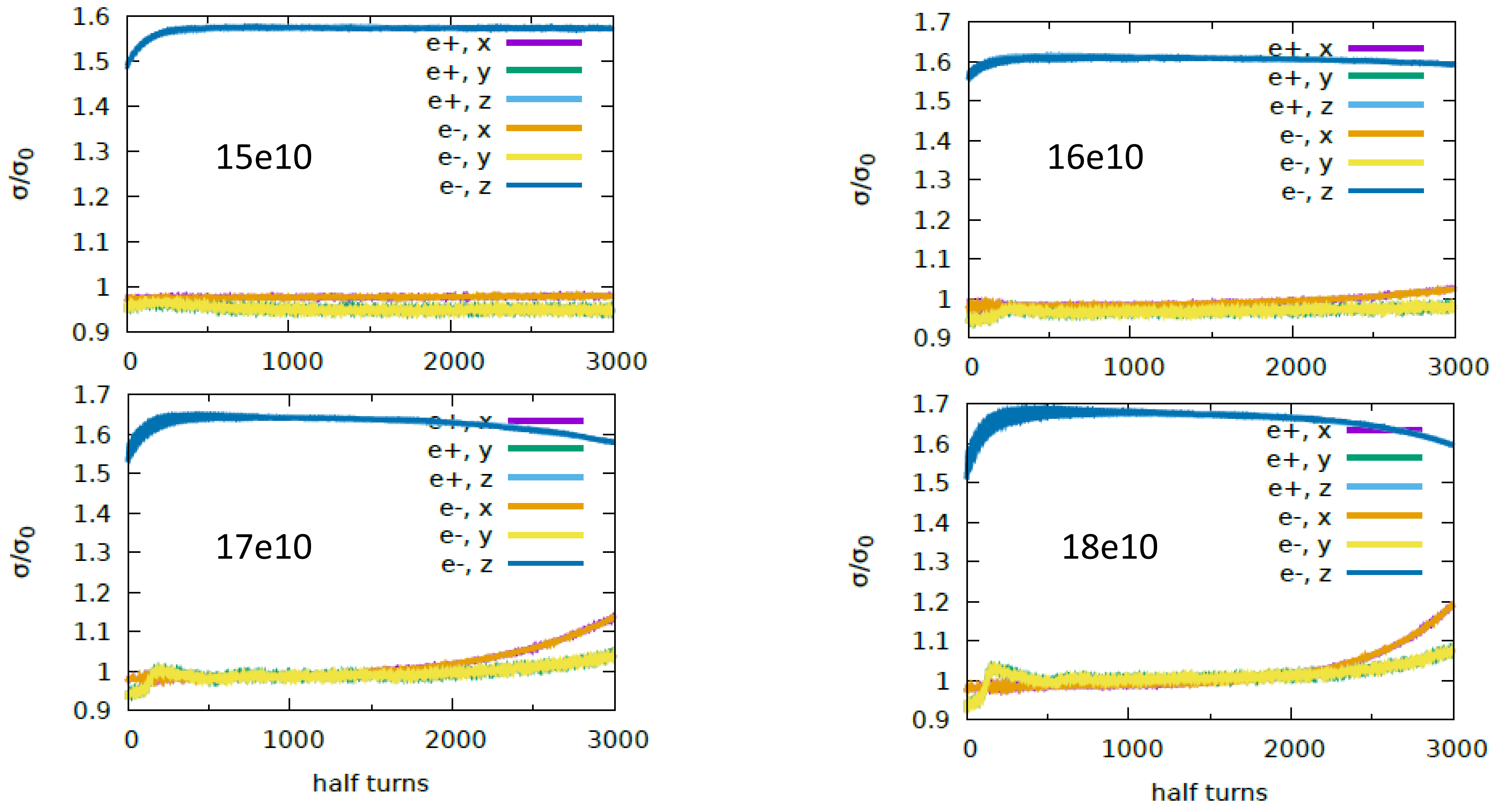
Bunch Current Limit

$$\xi_y = \frac{2r_e\beta_y^0}{N\gamma}\frac{L}{f_0}$$

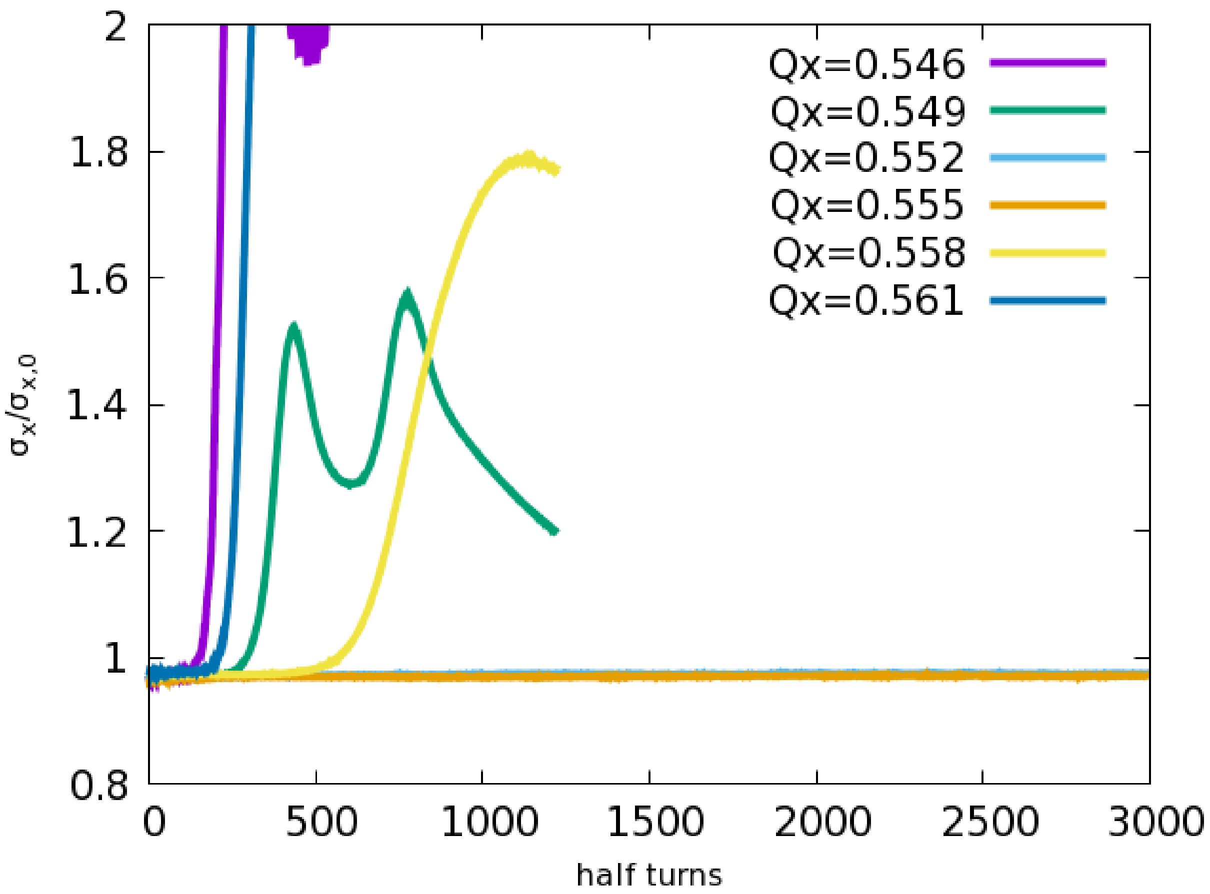




RMS Size Evolution with higher bunch population

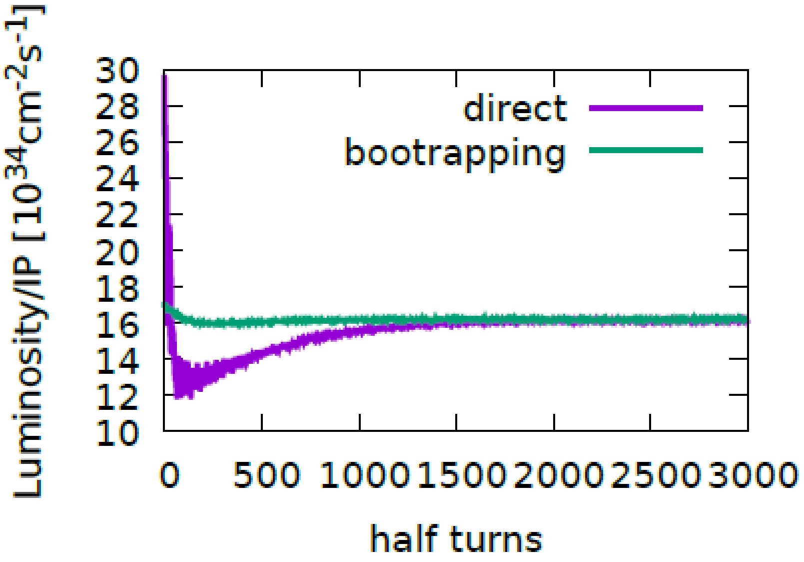


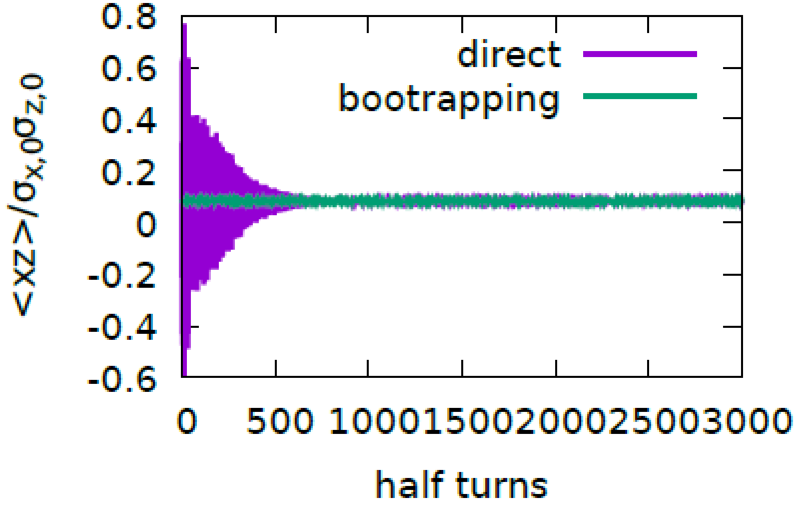
Horizontal Tune with Ne=12×10^{10}

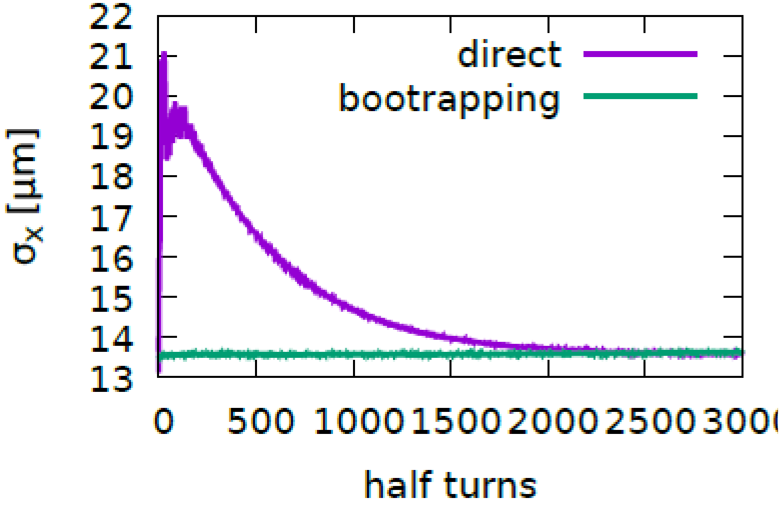


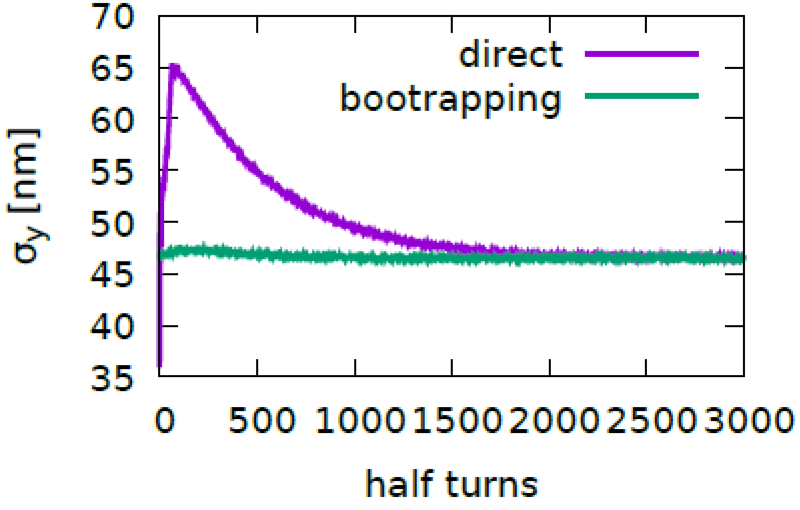
- Collision is stable in the range of [0.552, 0.555]

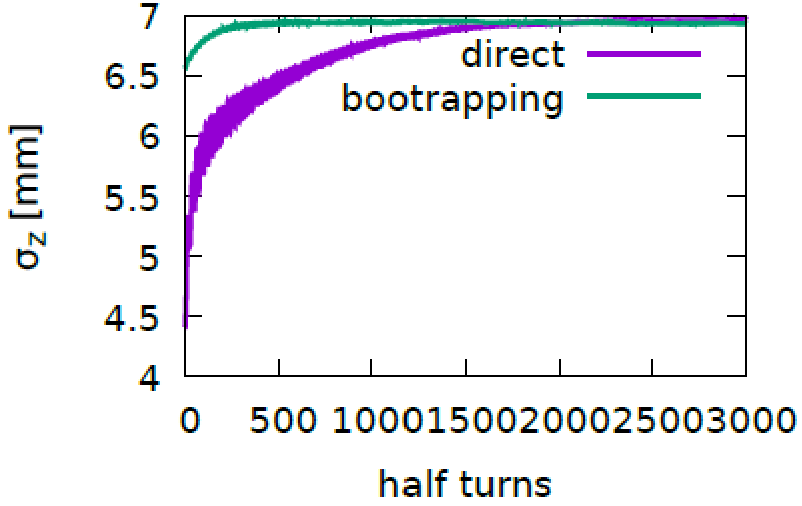
Bootstrapping is necessary? (15e10*15e10)





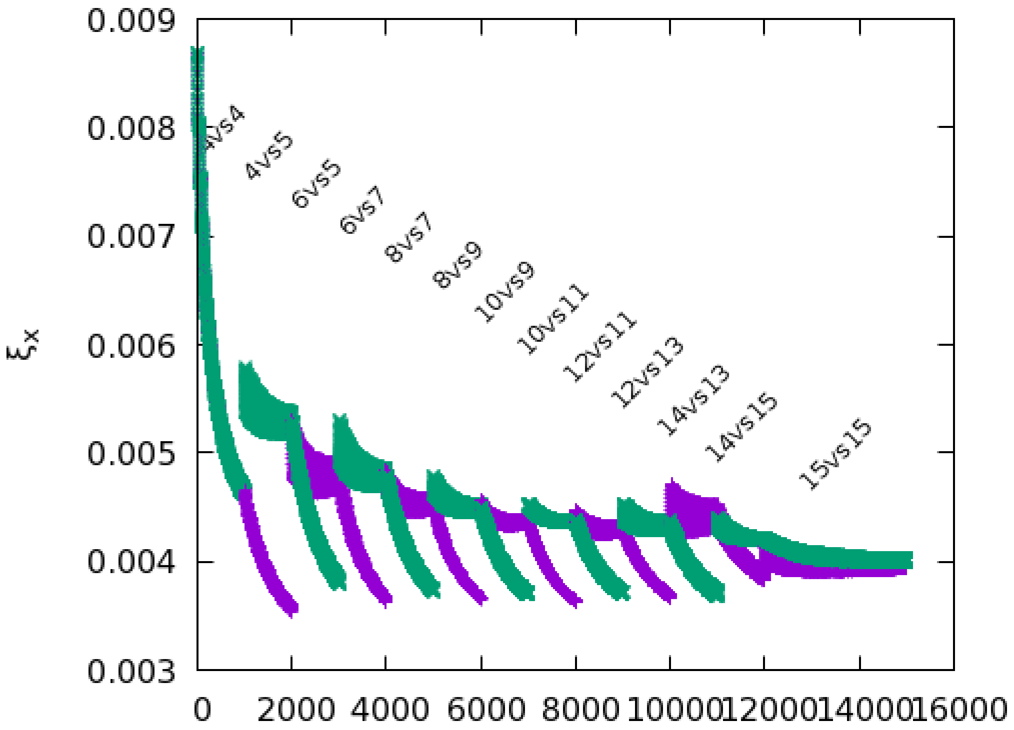


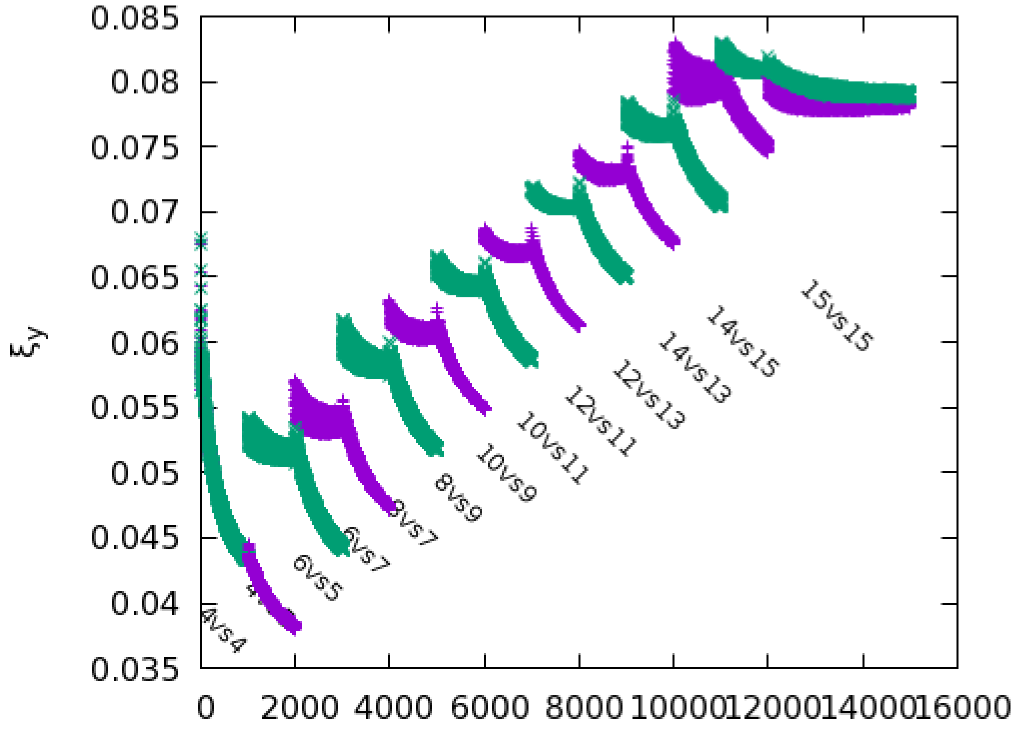




Z

Beam-beam Parameter Evolution During Bootstrapping





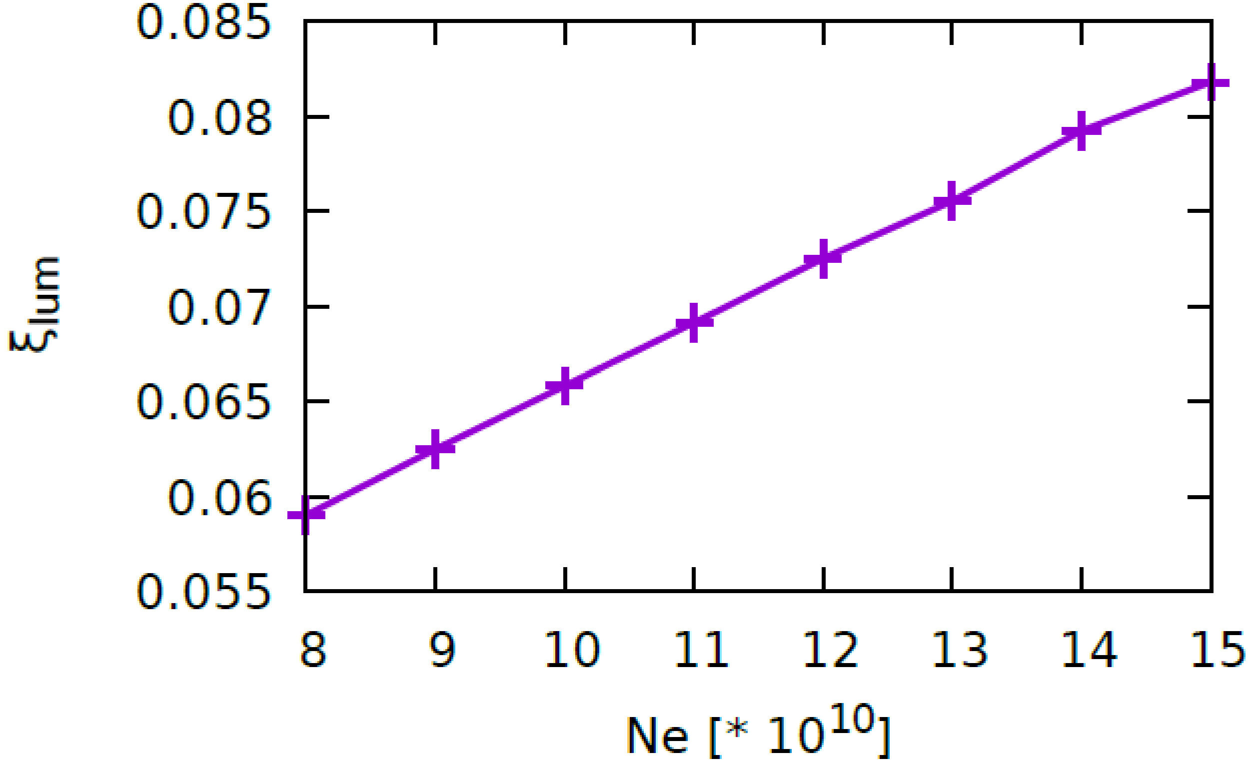
$$\boxed{\xi_x^{\pm} = \frac{N^{\mp} r_e}{\gamma^{\pm}} \frac{\beta_x^{\pm}}{2\pi\sigma_{x,\mathrm{eff}}^{\mp}\left(\sigma_{x,\mathrm{eff}}^{\mp} + \sigma_y^{\mp}\right)}}$$

$$\sigma_{x,\mathrm{eff}} = \sqrt{\sigma_z^2 \tan^2\theta + \sigma_x^2}$$

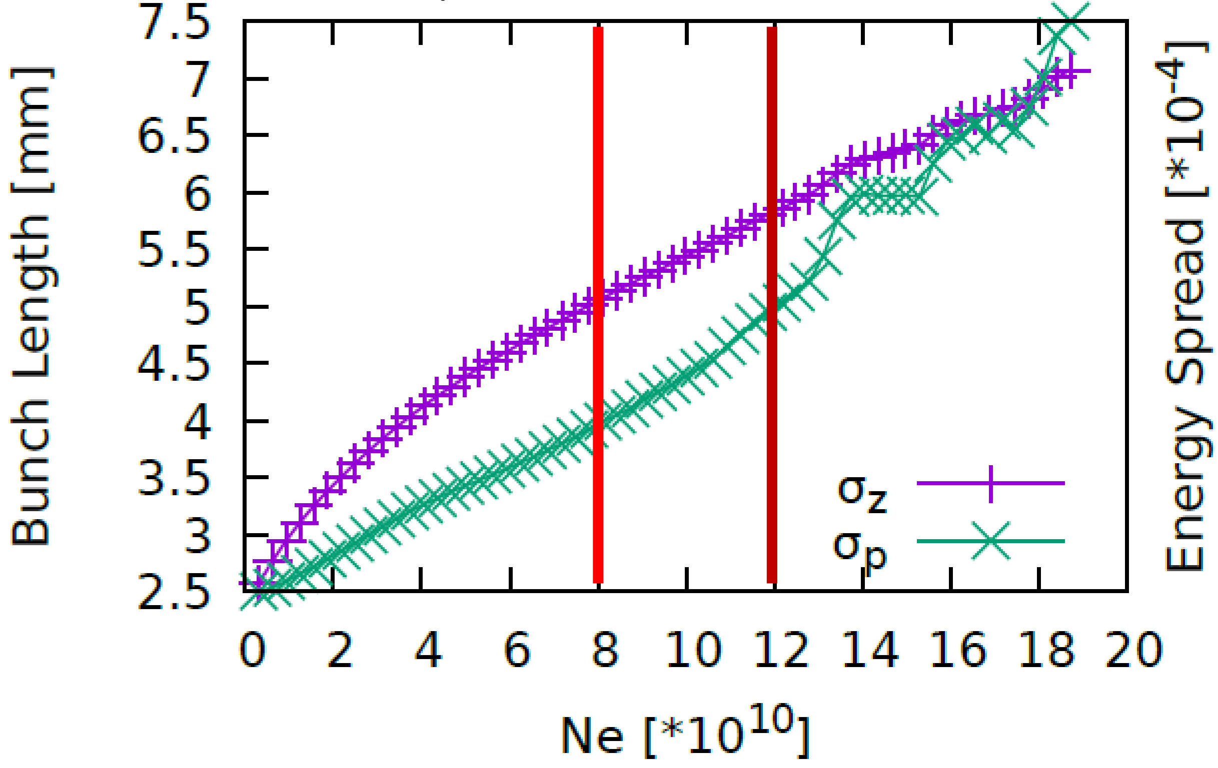
$$\boxed{\xi_y^{\pm} = \frac{N^{\mp} r_e}{\gamma^{\pm}} \frac{\beta_x^{\pm}}{2\pi\sigma_y^{\mp}\left(\sigma_{x,\mathrm{eff}}^{\mp} + \sigma_y^{\mp}\right)}}$$

Bunch Current Limit

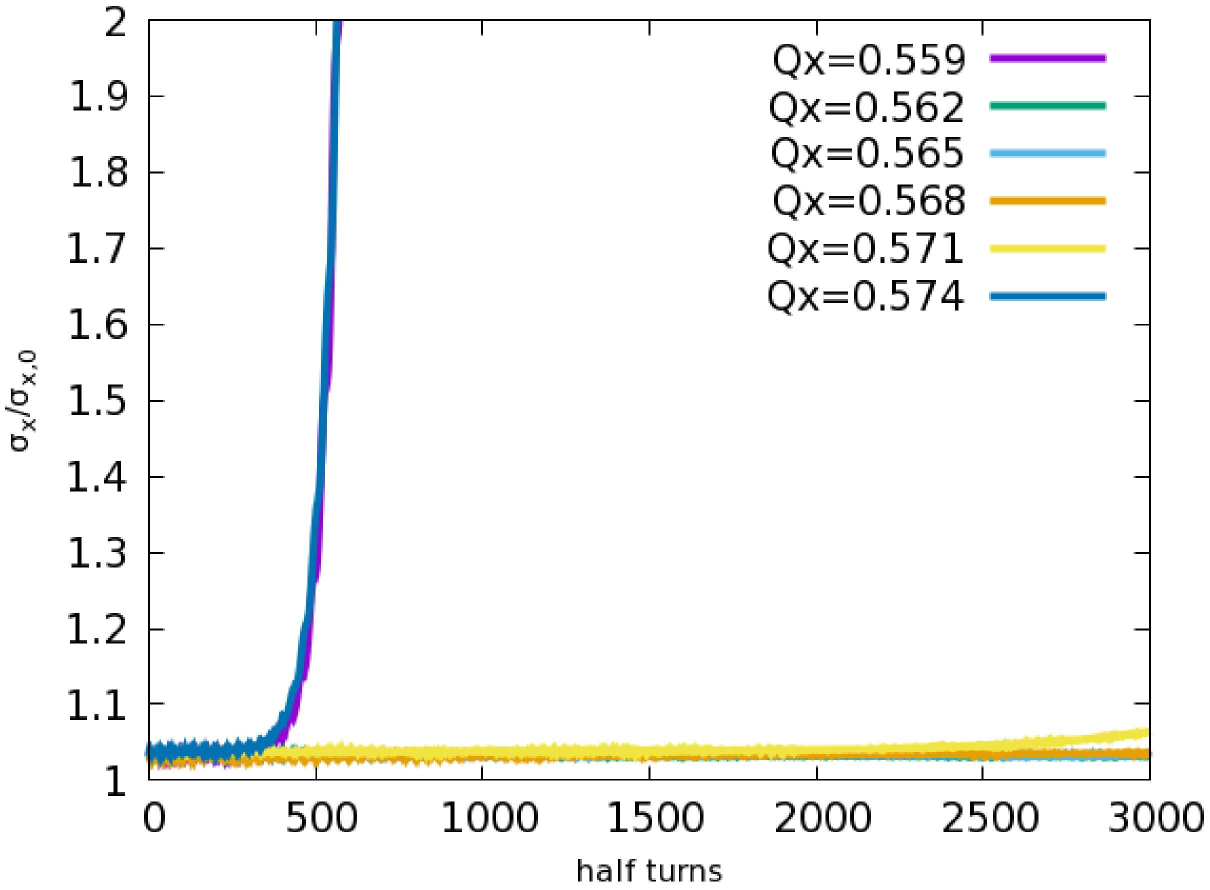
$$\xi_y = \frac{2r_e\beta_y^0}{N\gamma}\frac{L}{f_0}$$



Bunch Lengthening and Energy Spread versus Ne
w/o beam-beam interaction

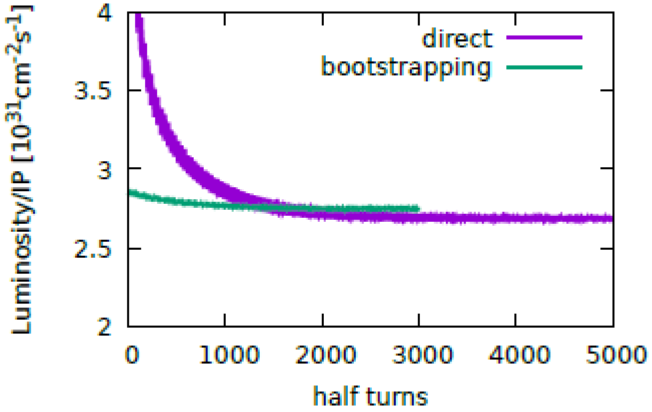


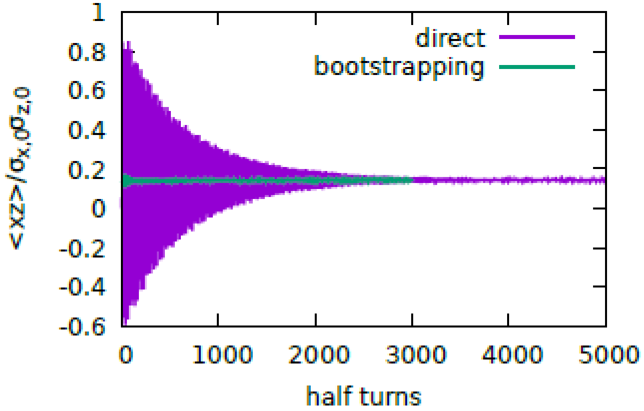
Horizontal Tune with Ne=15×10^{10}

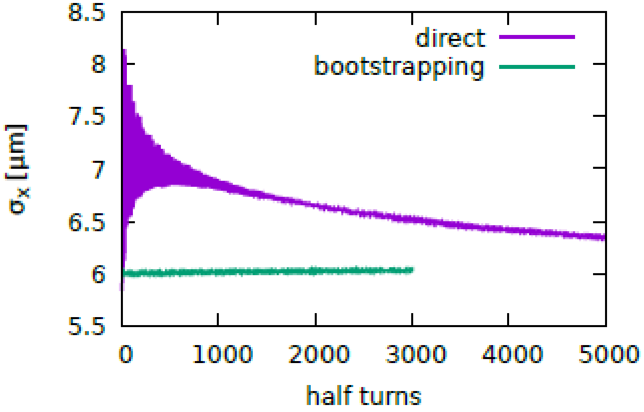


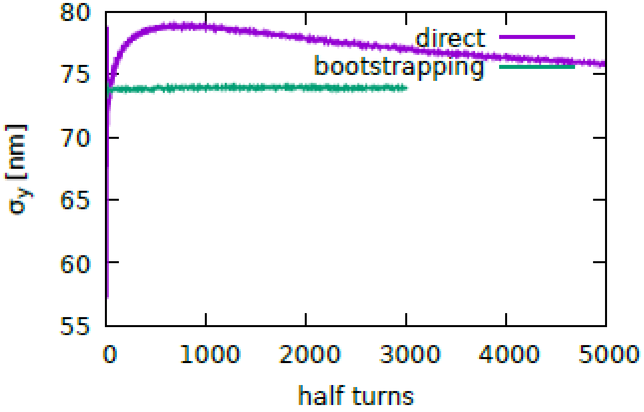
- Collision is stable in the range of [0.562, 0.568]

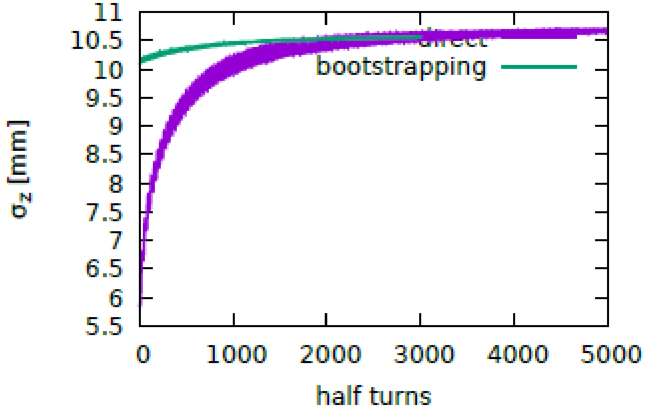
Z: Bootstraping is necessary? (ne=12e10, qx=0.568)





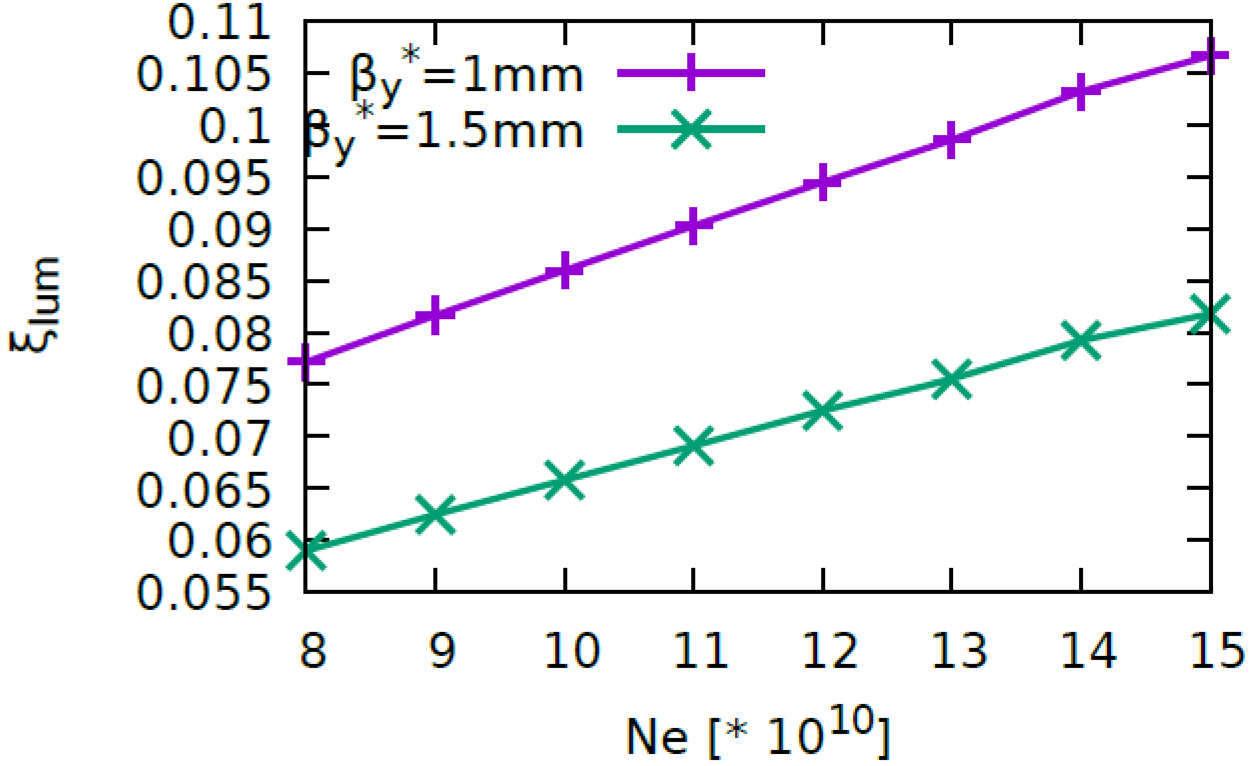






β_y^*=1.5mm->1mm (with Lower Solenoid Strength)

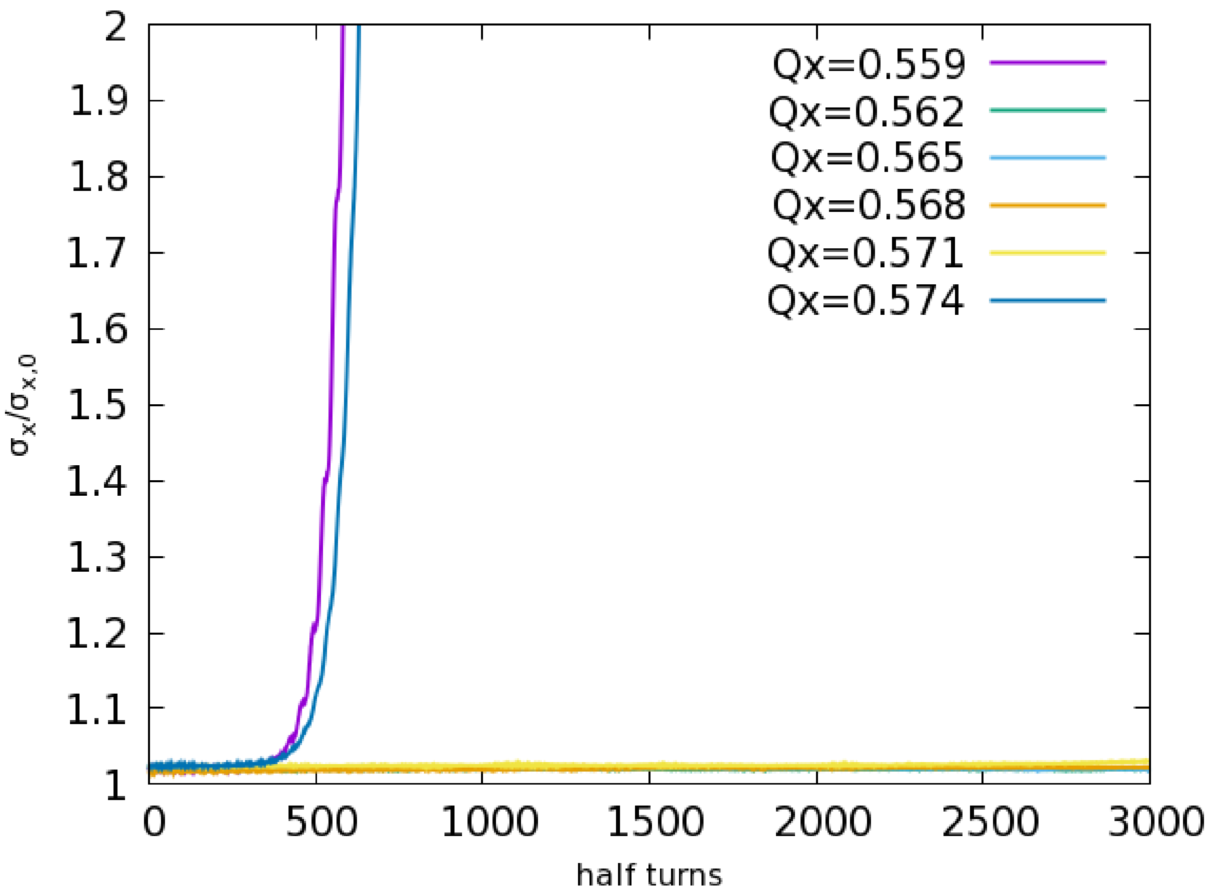
$$\xi_y = \frac{2r_e\beta_y^0}{N\gamma}\frac{L}{f_0}$$



With same beam current,

- smaller β_y^*+weaker solenoid, luminosity increase by a factor of one.
- bunch population increase from 8×10^{10} to 12×10^{10}, luminosity increase about 20%.

β_y^*=1mm, Horizontal Tune with Ne=12×10^{10}

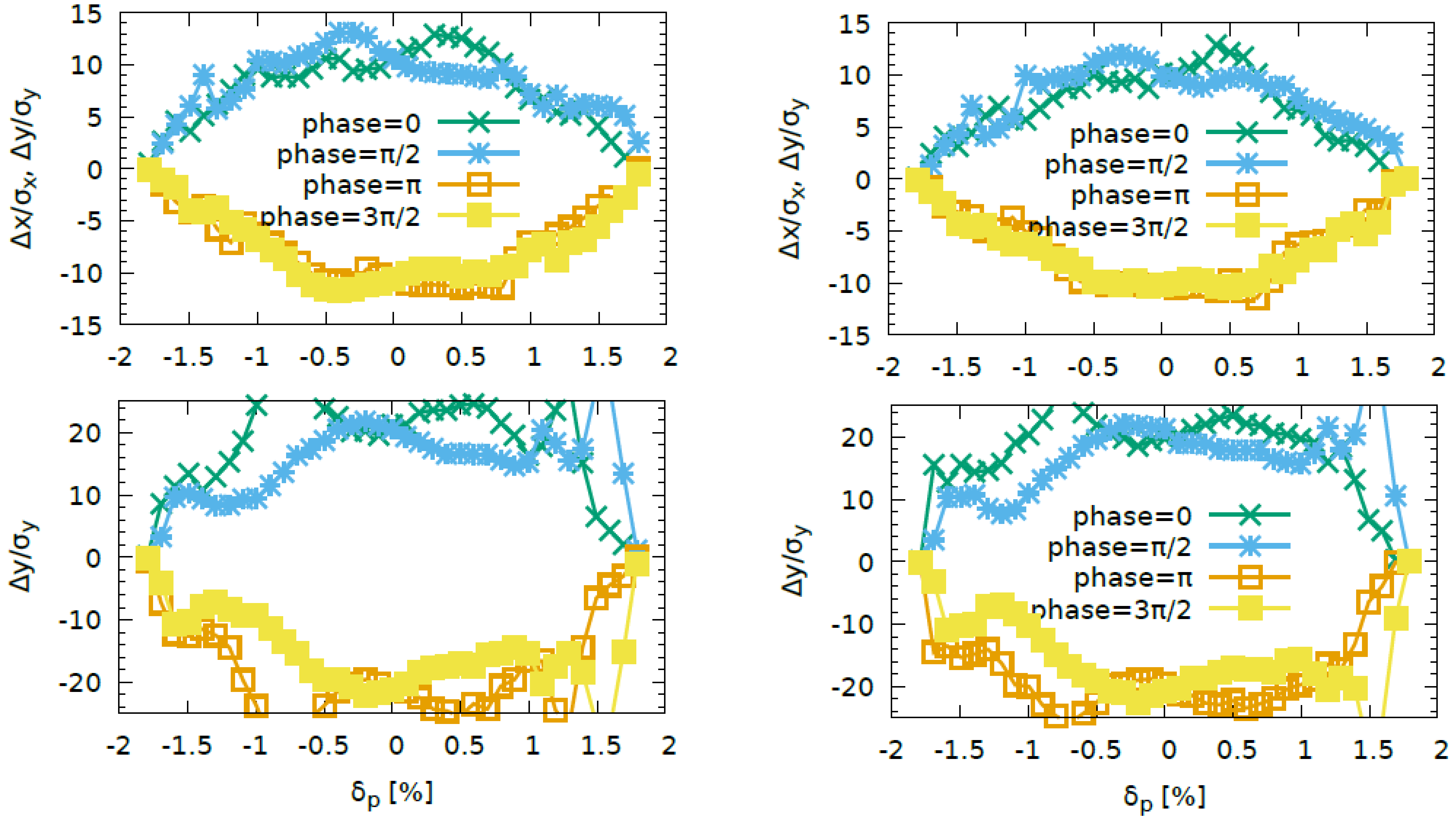


- Collision is stable in the range of [0.562, 0.568]

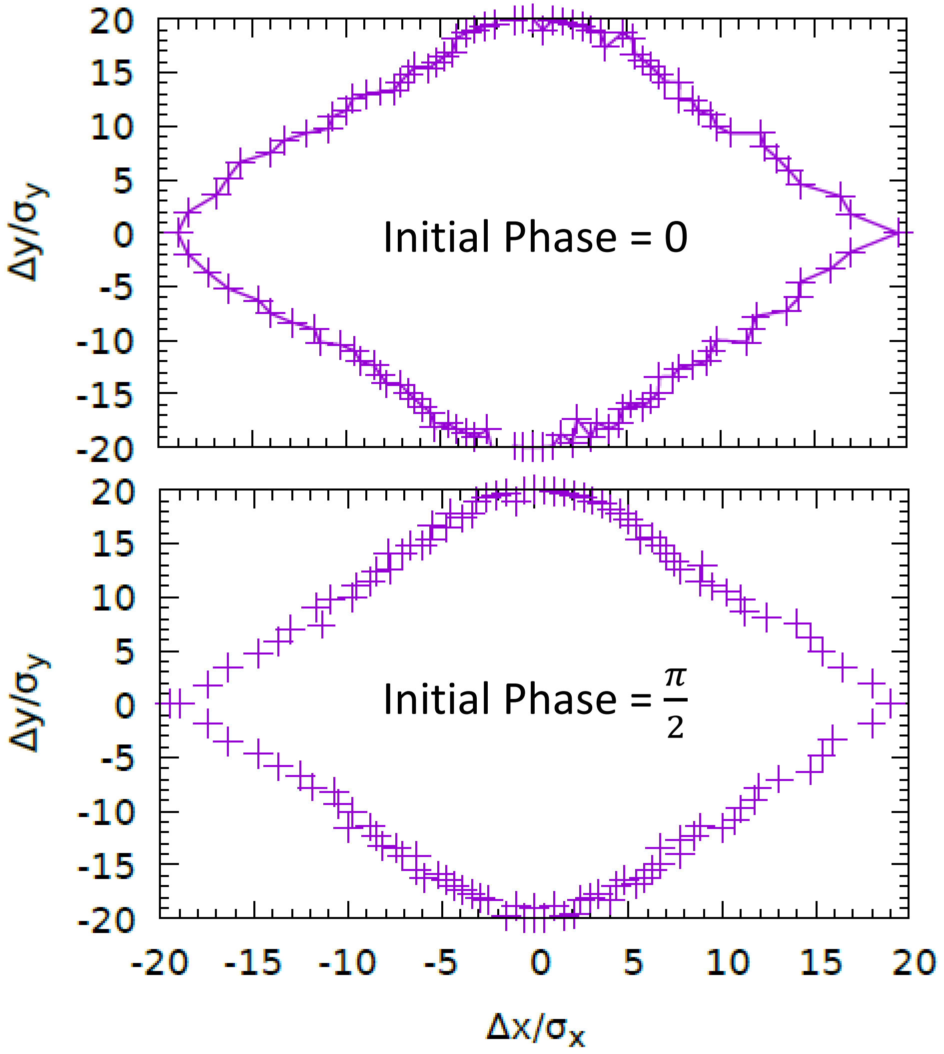
Dynamic Aperture

DA: w/o and w/ beam-beam interaction

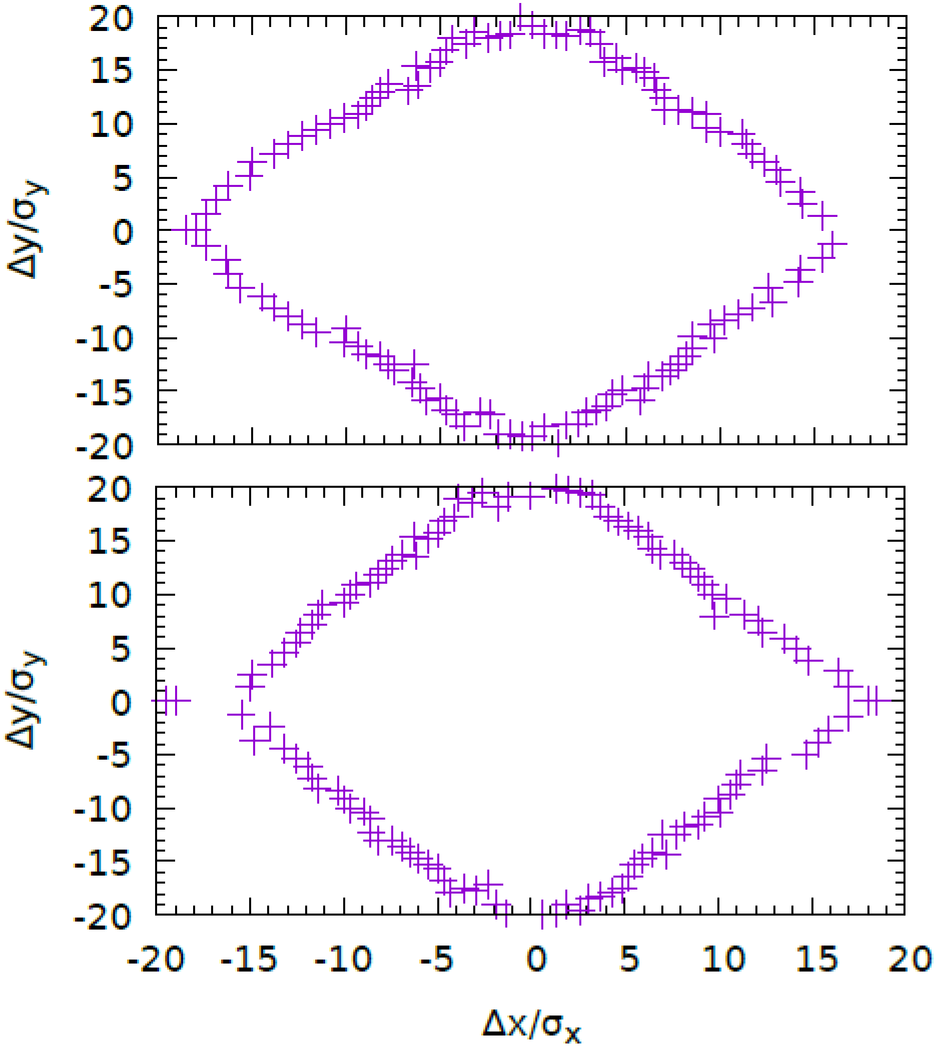
100 samples
90% survival



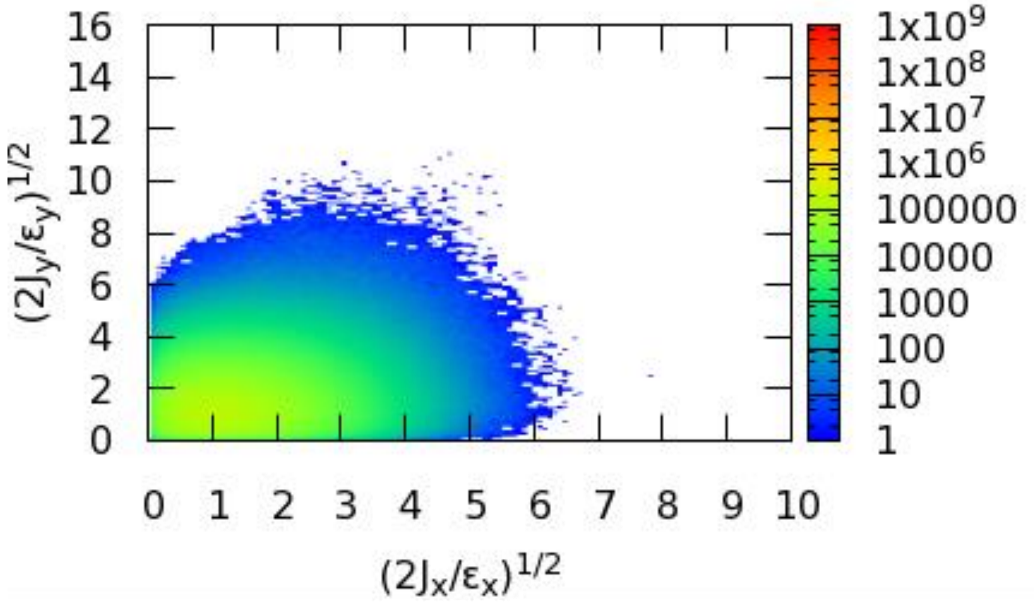
DA: w/o and w/ beam-beam interaction

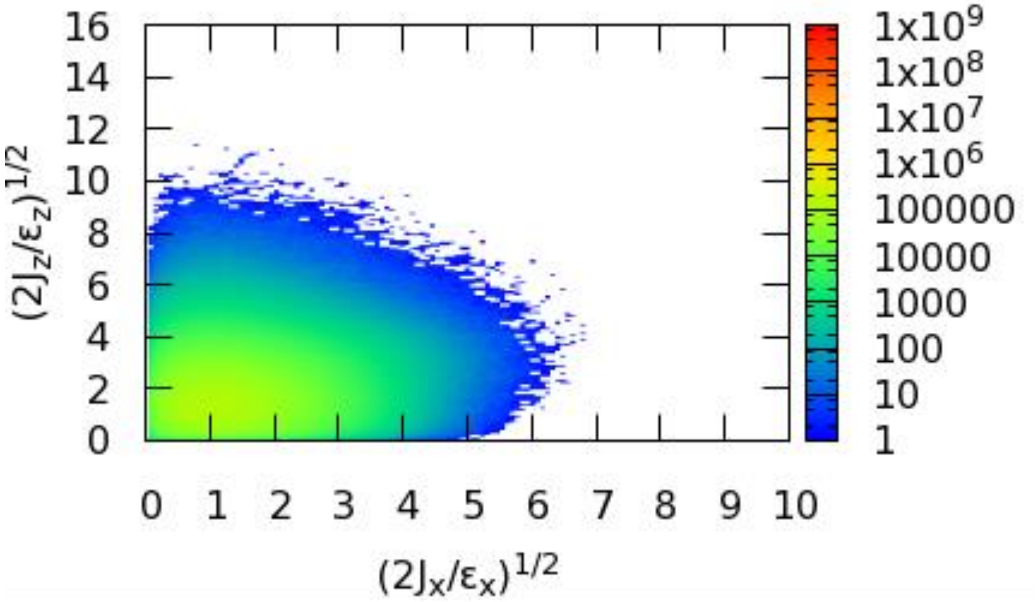


Off - > On

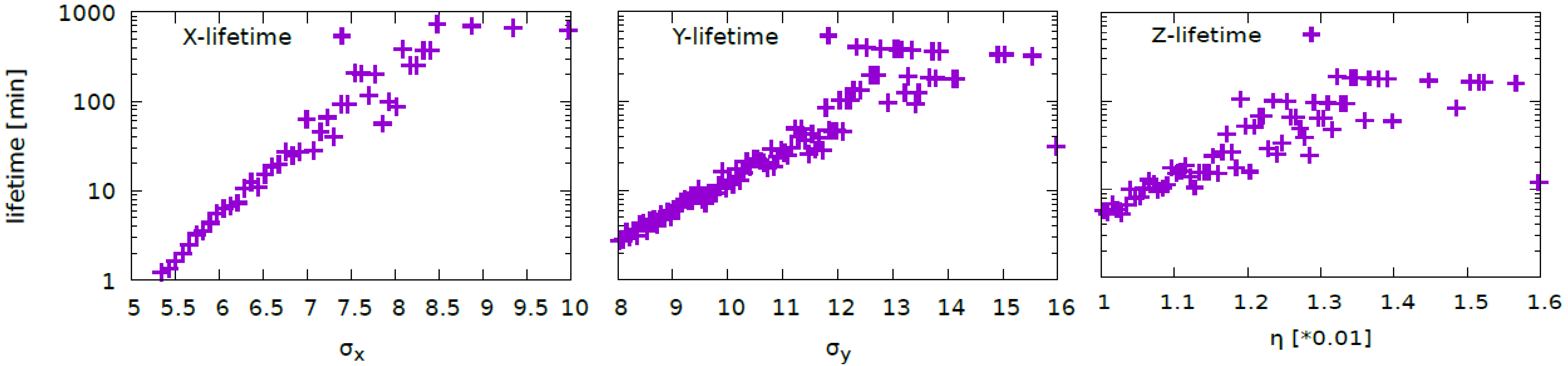


Beam Distribution: by=1.5mm
Lattice + Beamstrahlung + SR Fluctuation





Beam Lifetime: by=1.5mm
Lattice + Beamstrahlung + SR Fluctuation



100min, DA requirement: $7.5\sigma_x$, $12.5\sigma_y$, 0.0135

Achieved DA: ~$15\sigma_x$, ~$15\sigma_y$, ~0.015

Summary

- The present beam-beam parameter is about two times higher than that of LEP experience, which is the benefit of crab-waist.
  - Higgs is mainly limited by beamstrahlung lifetime
  - W nearly reaches the beam-beam limit
  - It seems we could increase bunch population by 50% for Z
- New x-z instability limit the choice of horizontal working point
- The strong-strong simulation shows that bootstrapping may be unnecessary at CEPC as far as beam-beam is concerned
- Initial result shows that the beam-beam interaction does not reduce the DA seriously