Preliminary simulation of Beam-beam effect at CEPC

Y. Zhang(IHEP), D. Zhou(KEK),
D. Shatilov(BINP), K. Ohmi(KEK),
Y. Guo(IHEP)

International Workshop on Future High Energy Circular Colliders (Beijing), 16-17 Dec. 2013

Thanks to H.P. Geng and D. Wang

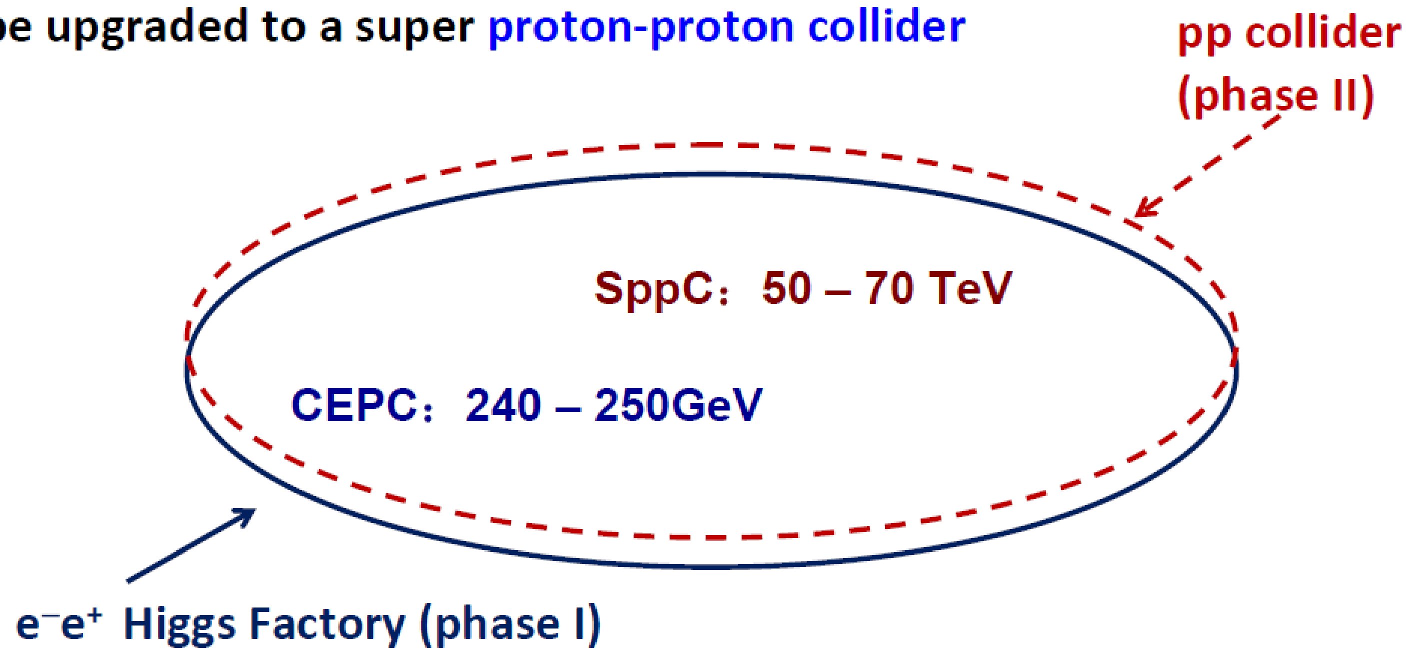
Outline

- Introduction of CEPC
- Simulation result w/o beamstrahlung
- Simulation result & Discussion
- Summary

1. Overview of CEPC

CEPC is

- an Circular Electron Positron Collider
- proposed to carry out high precision study on Higgs bosons
- to be upgraded to a super proton-proton collider



CEPC basic parameter:

- Beam energy ~120 GeV.
- Synchrotron radiation power ~50 MW.
- 50/70 km in circumference.

SppC basic parameter:

- Beam energy ~50-70 TeV.
- 50/70 km in circumference.
- Needs B_{max} ~20T.

The circumference of CEPC is determined by that of the SppC, which is determined by the final energy of proton beam and the achievable dipole field strength.

H.P. Geng and etal. “CEPC Accelerator Study”, 6th TLEP Workshop, Oct, 2013

Main beam parameters for CEPC at 50km

Parameter	Unit	Value	Parameter	Unit	Value
Energy	GeV	120	Circumference	km	50
Number of IP		1	SR loss	(GeV/turn)	2.96
N_e/bunch	1E11	3.52	N_b/beam		50
Beam current	mA	16.9	SR power/beam	MW	50
Partition Je		2	Long. damp. time	ms	6.7
Dipole field	Tesla	0.065	Bending radius	km	6.2
Dipole length	m	9.978	Bending angle	mrad	1.609
Emittance (x/y)	nm	6.69/0.033	β_{IP} (x/y)	mm	200/1
Trans. size (x/y)	μm	36.6/0.18	Mom. compaction	1E-4	0.4
$\xi_{x,y}$ /IP		0.1/0.1	Bunch length	mm	3
RF voltage V_{rf}	GV	4.2	RF frequency f_{rf}	GHz	0.7
Long. tune ν_s		0.13	Harmonic number		116747
Hourglass factor		0.6	n_γ		0.42
Energy spread SR		0.0013	Energy spread BS		0.00014
Energy acceptance	%	2.7	Lifetime BS	hr	1.6
L_0 /IP (10^{34})	$cm^{-2}s^{-1}$	2.65	L_{limit} /IP (10^{34})	$cm^{-2}s^{-1}$	1.26

D. Wang and etal. "CEPC Machine Optimization and Final Focus Design", 6th TLEP Workshop, Oct, 2013

Lower power design of CEPC

	Baseline	***Low power design***		
Number of IPs	1	1	1	1
Energy (GeV)	120	120	120	120
Circumference (km)	50	50	50	50
SR loss/turn (GeV)	2.96	2.96	2.96	2.96
N_e/bunch (10^{12})	0.79	0.38	0.33	0.28
Bunch number	22	23	21	19
Beam current (mA)	16.9	8.45	6.76	5.07
SR power /beam (MW)	50	25	20	15
B_0 (T)	0.065	0.065	0.065	0.065
Bending radius (km)	6.2	6.2	6.2	6.2
Momentum compaction (10^{-4})	0.38	0.38	0.38	0.38
β_{IP} x/y (m)	0.2/0.001	0.071/0.00048	0.056/0.00042	0.041/0.00035
Emittance x/y (nm)	14.6/0.073	9.5/0.035	9.1/0.031	8.9/0.026
Transverse σ_{IP} (um)	54/0.27	25.9/0.13	22.7/0.11	19.2/0.096
ξ_x/IP	0.103	0.076	0.069	0.06
ξ_y/IP	0.103	0.103	0.103	0.103
V_{RF} (GV)	6	6	6	6
f_{RF} (MHz)	704	704	704	704
σ_z (mm)	2.2	2.2	2.2	2.2
Energy spread (%)	0.13	0.13	0.13	0.13
Energy acceptance (%)	5	5	5	5
γ_{BS} (10^{-4})	13.8	13.8	13.8	13.8
n_γ	0.6	0.6	0.6	0.6
δ_{BS} (10^{-4})	4.3	4.3	4.3	4.3
Life time due to beamstrahlung (minute)	30	30	30	30
F (hour glass)	0.68	0.48	0.45	0.41
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	3.1	2.31	1.97	1.58
AC power for RF source/two beam (MW)	286	143	114	86

Simulation tools

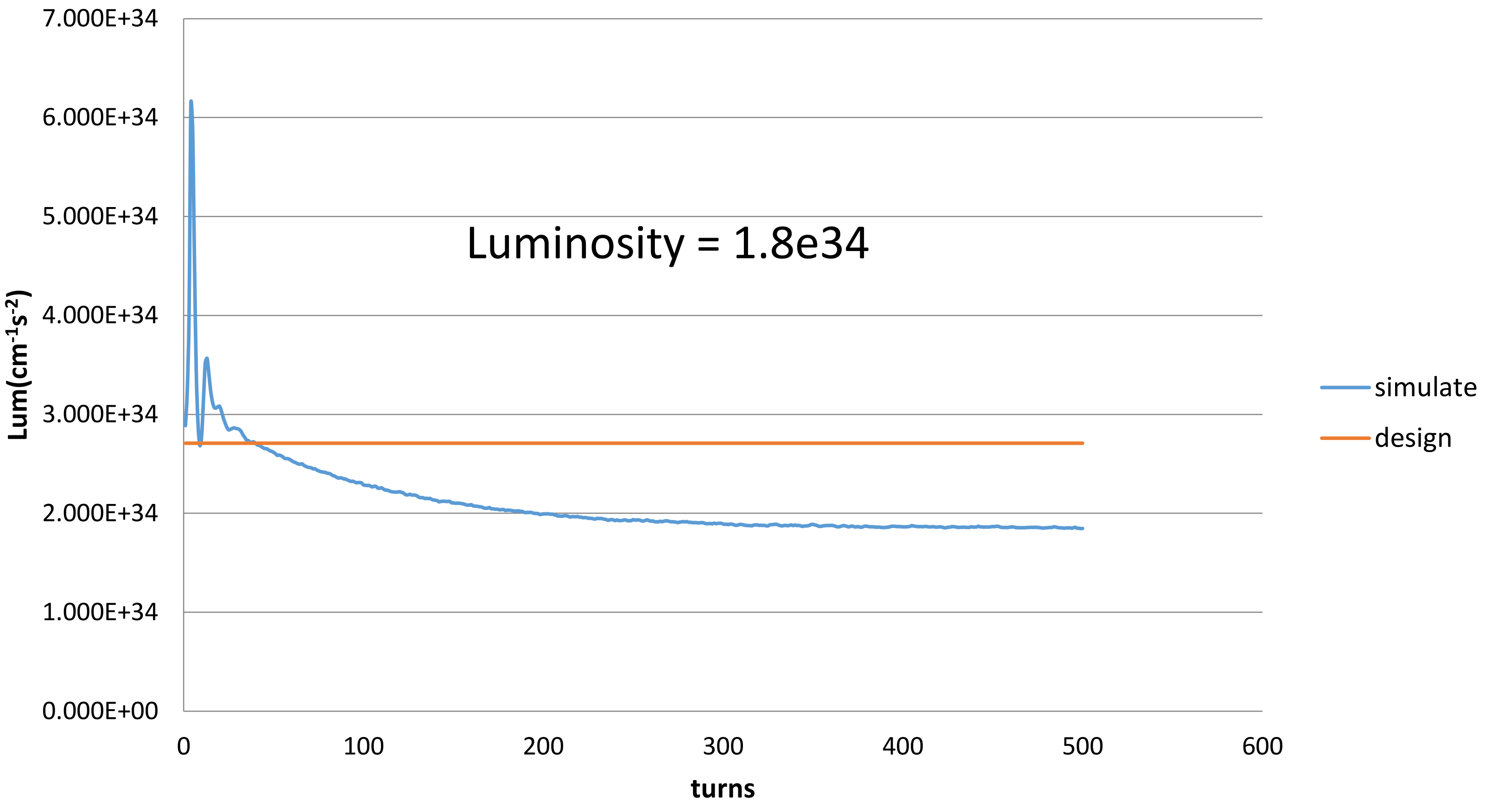
- LIFETRAC by D. Shatilov
- BBWS and BBSS by K. Ohmi
- Beamstrahlung is included in all codes

  Ref:

* A.Bogomyagkov, E.Levichev, D. Shatilov, arXiv 1311.1580v1, 2013

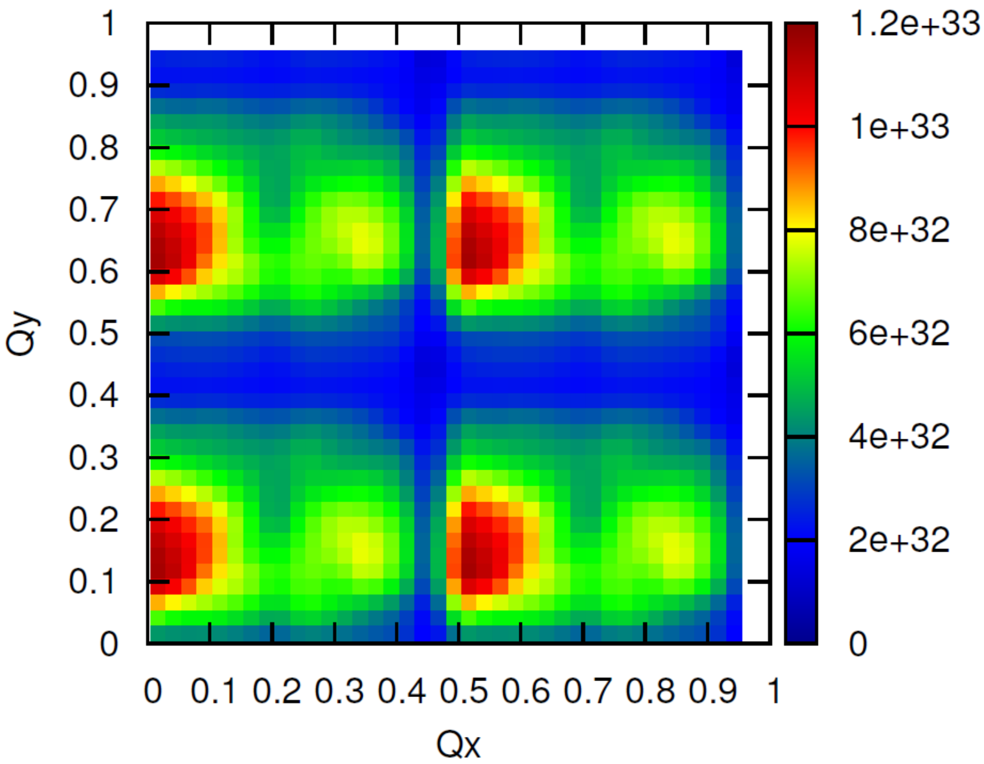
* K. Ohmi, "Beam-beam simulations including Beamstrahlung in TLEP", TLEP workshop at Fermilab, 25-26 July, 2013

Emitx=6.69nm, bx/by=200/1mm w/o bs

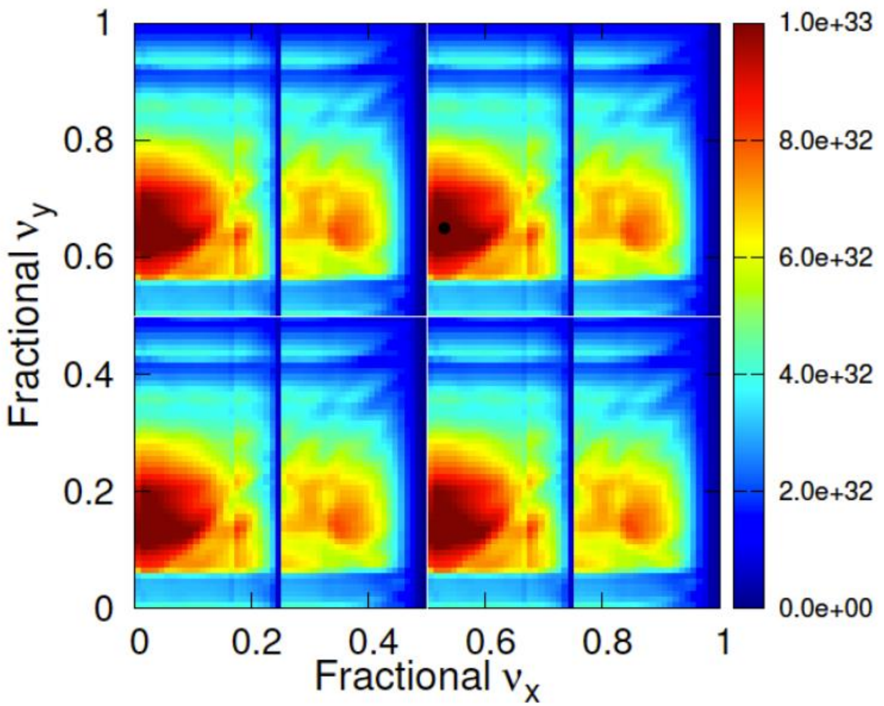


Luminosity: Tune Scan w/o bs
EmitX=14.6nm, Sigmaz = 3mm, nus =0.13

- LIFETRAC



- BBWS



Lifetime[s]: Tune Scan w/o bs
EmitX=14.6nm, SigmaZ = 3mm, nus =0.13

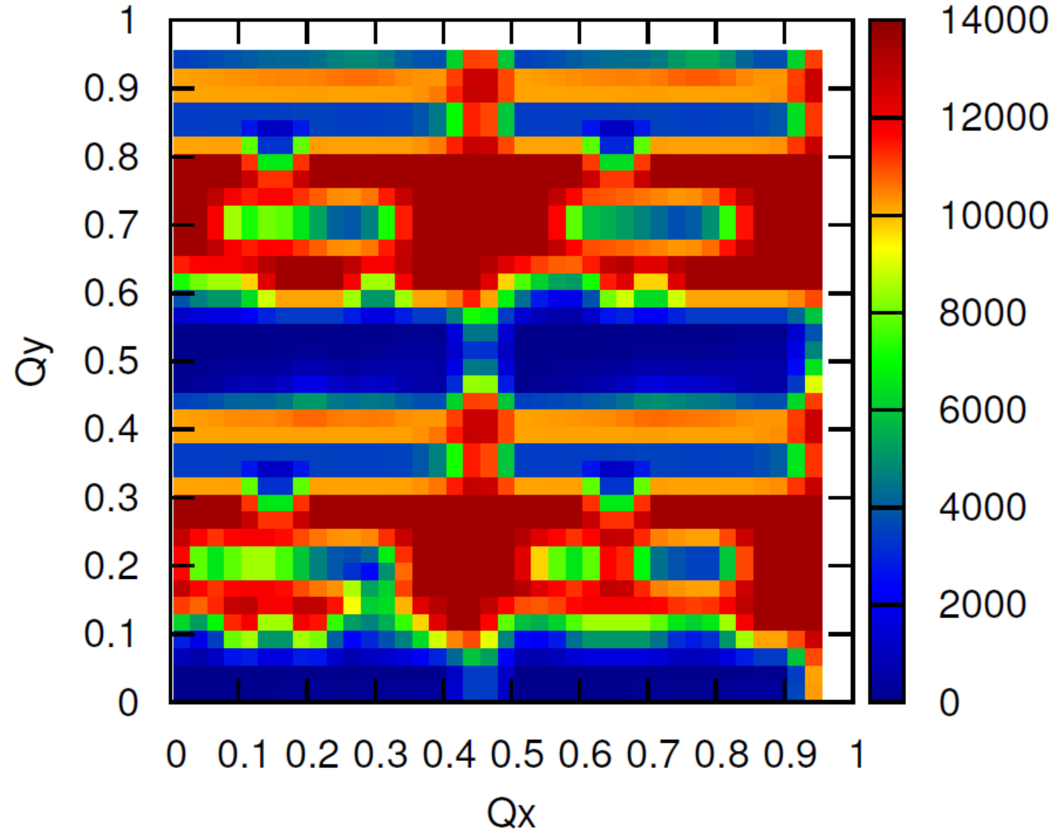
Aperture:

$20\sigma_x$

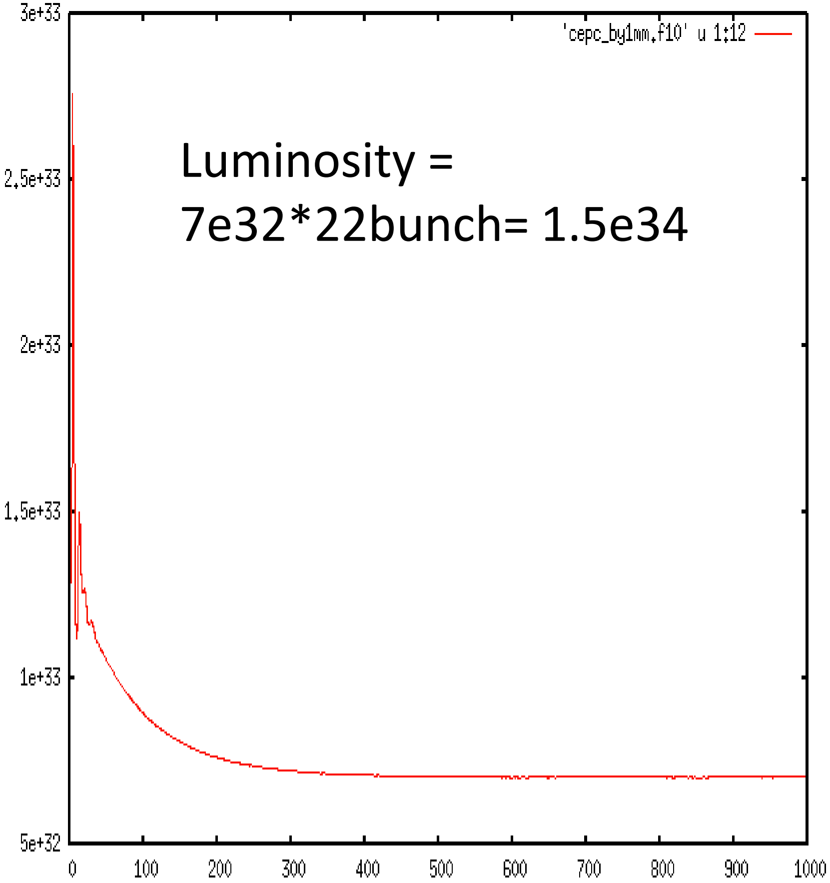
$40\sigma_y$

0.02

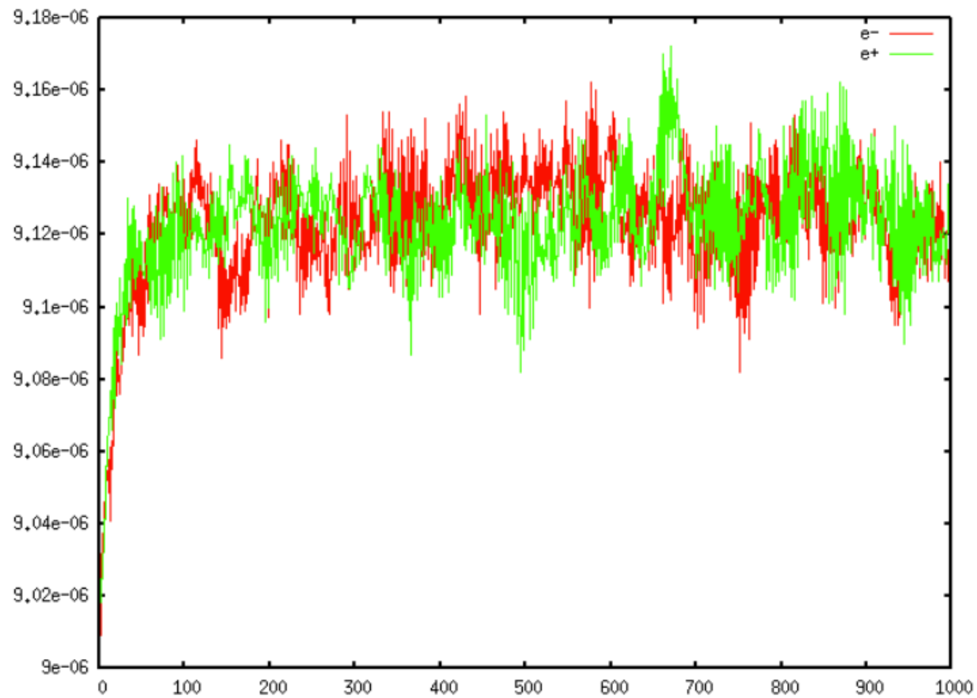
with Lifetrac



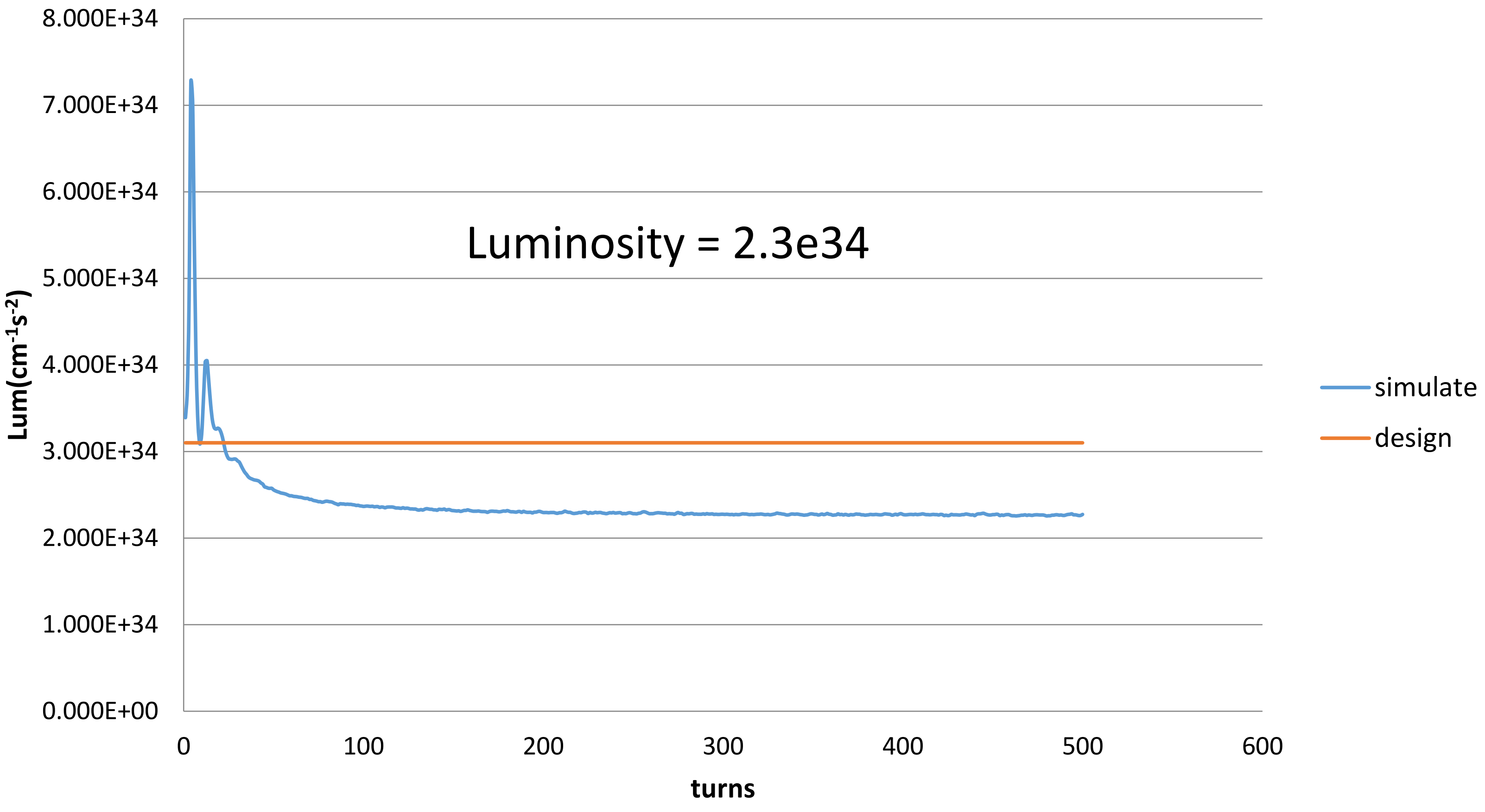
14.6nm , sigmaz=3mm, nus=0.13, @(0.52,0.58) w/o bs



beam size <zz>

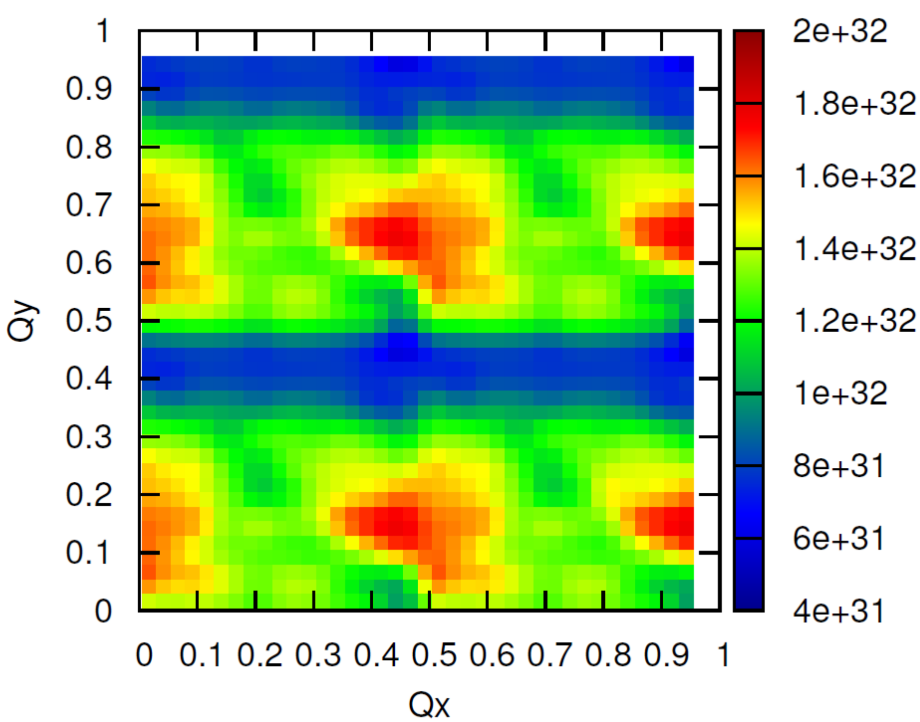


14.6nm , sigmaz=2.2mm, nus=0.175, @(0.52,0.58) w/o beamstrahlung

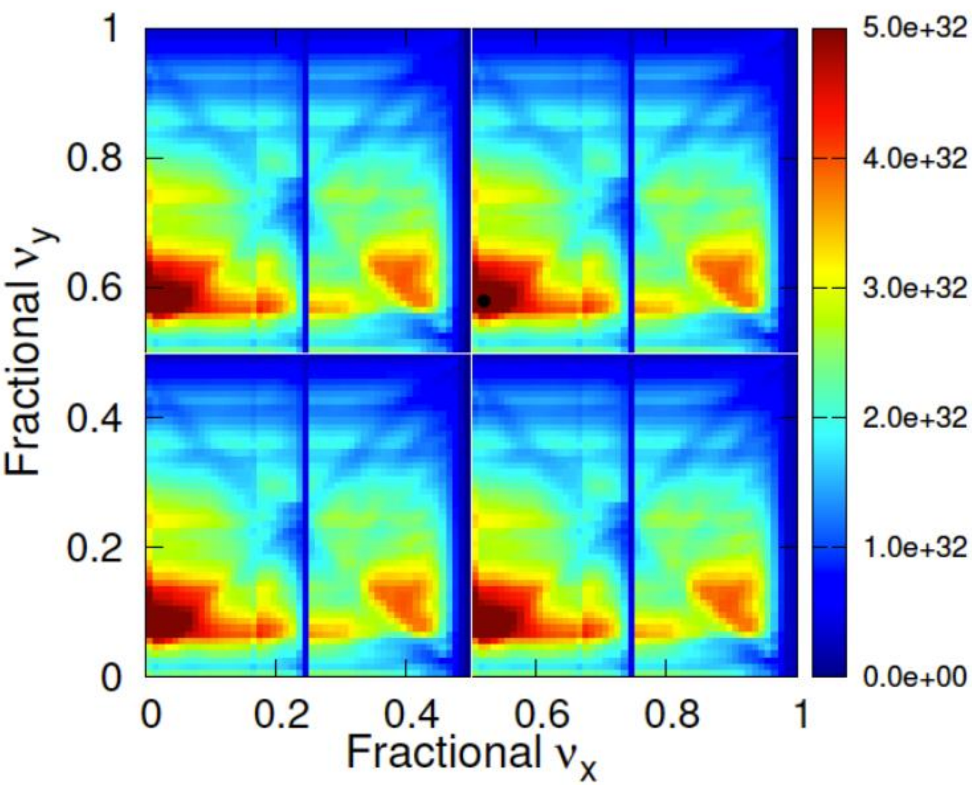


Luminosity: Tune Scan w/ beamstrahlung

LIFETRAC

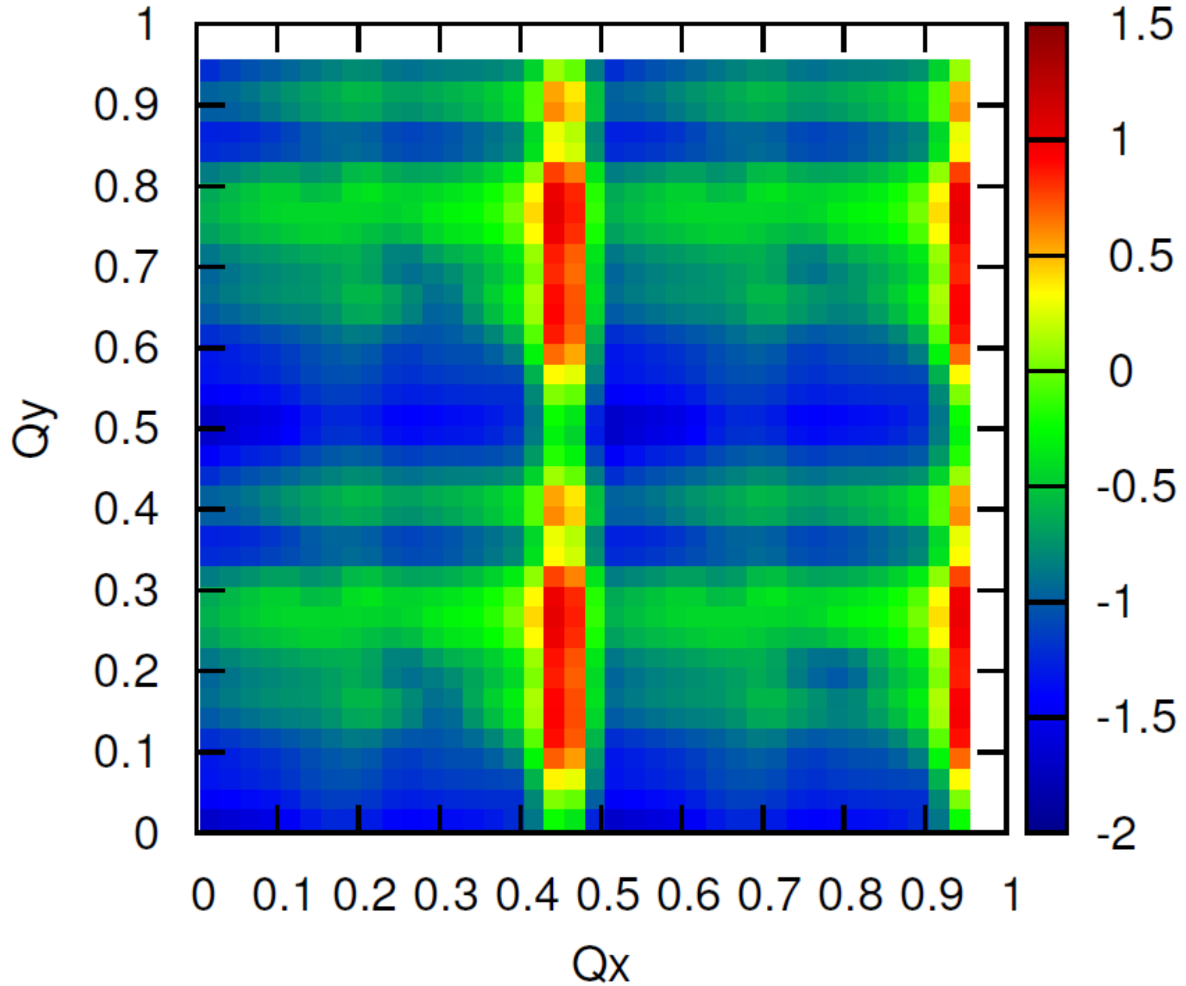


BBWS

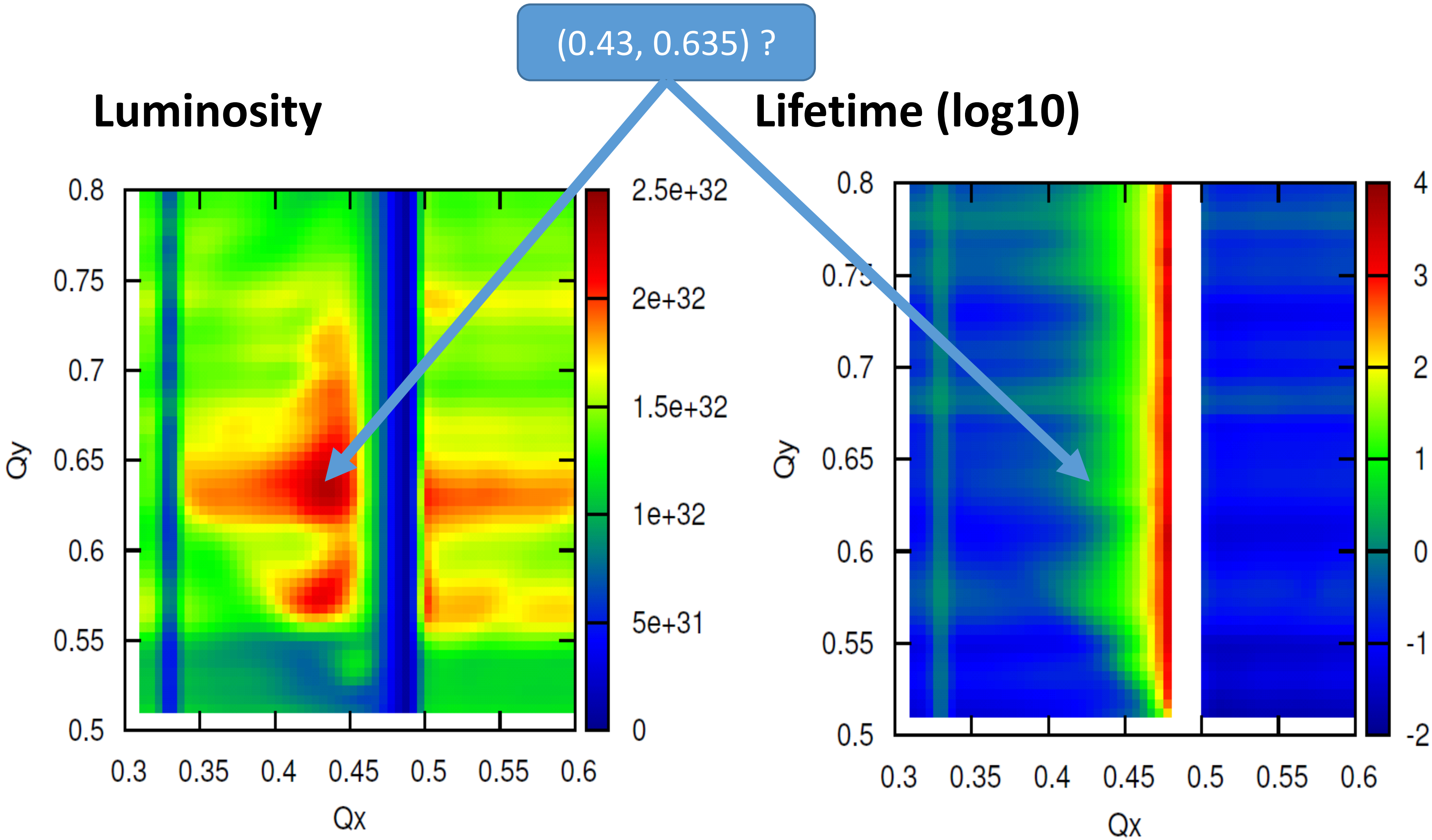


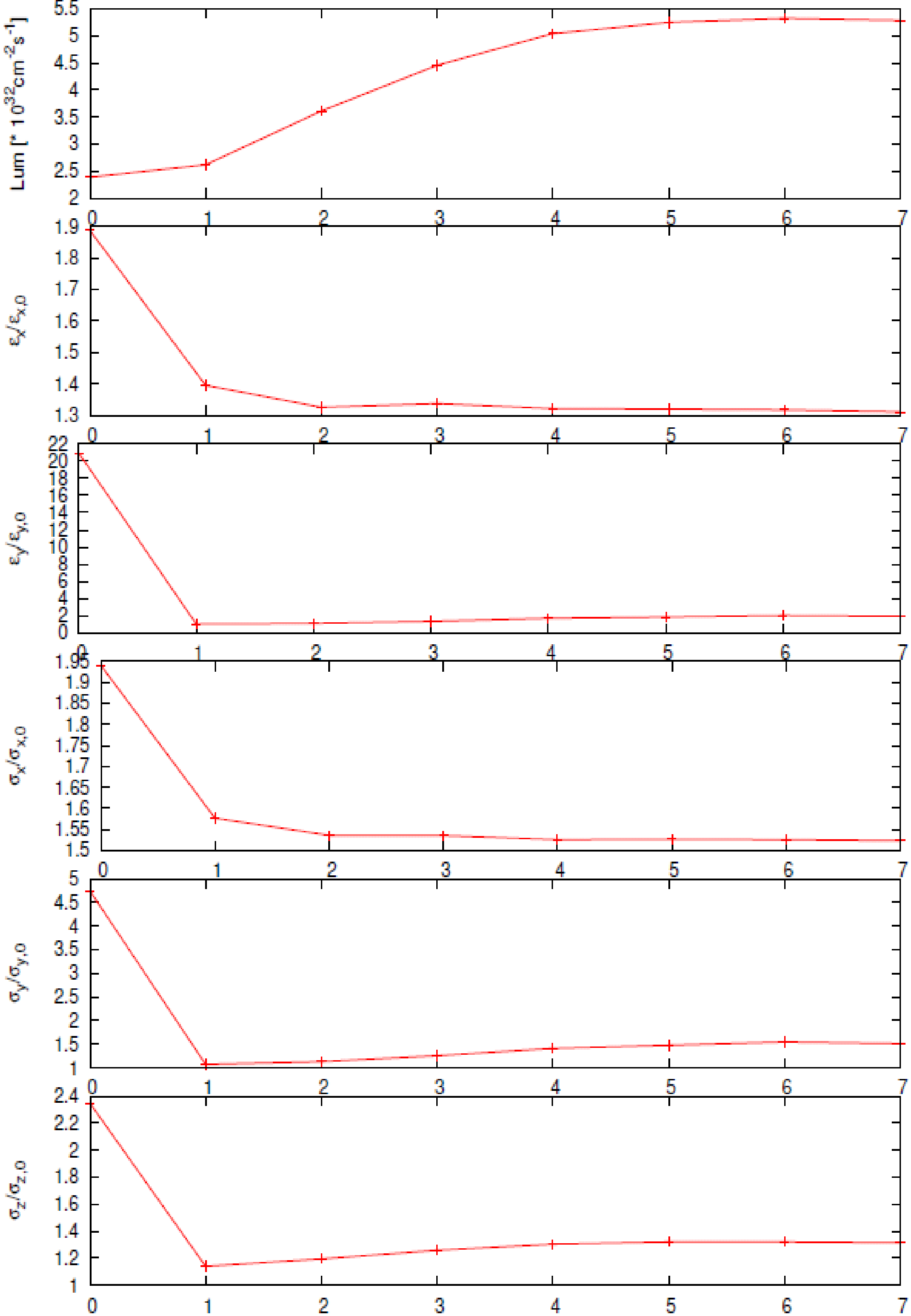
Lifetime[log10]: Tune Scan w/ beamstrahlung

LIFETRAC



lifetrac

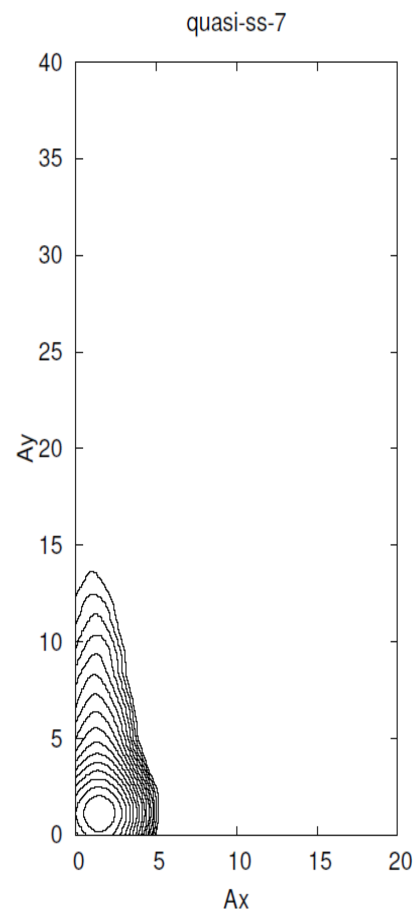

(0.43, 0.635) ?
Luminosity
Lifetime (log10)
Qy
Qx
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.3 0.35 0.4 0.45 0.5 0.55 0.6
2.5e+32
2e+32
1.5e+32
1e+32
5e+31
0
4
3
2
1
0
-1
-2



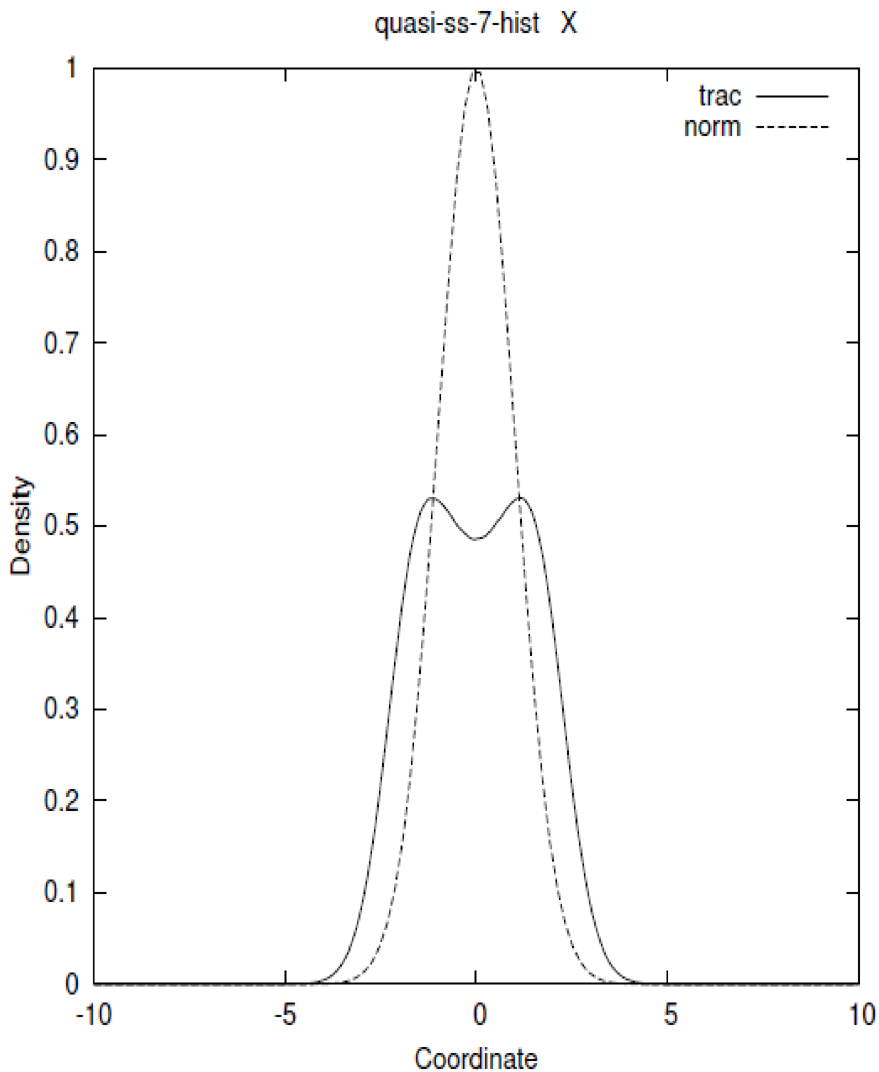
Quasi-Strong-Strong Simulation with LIFETRAC @(0.43,0.635),

Lum=5.2e32*22=1.1e34

Lifetime > 10,000 sec ?!



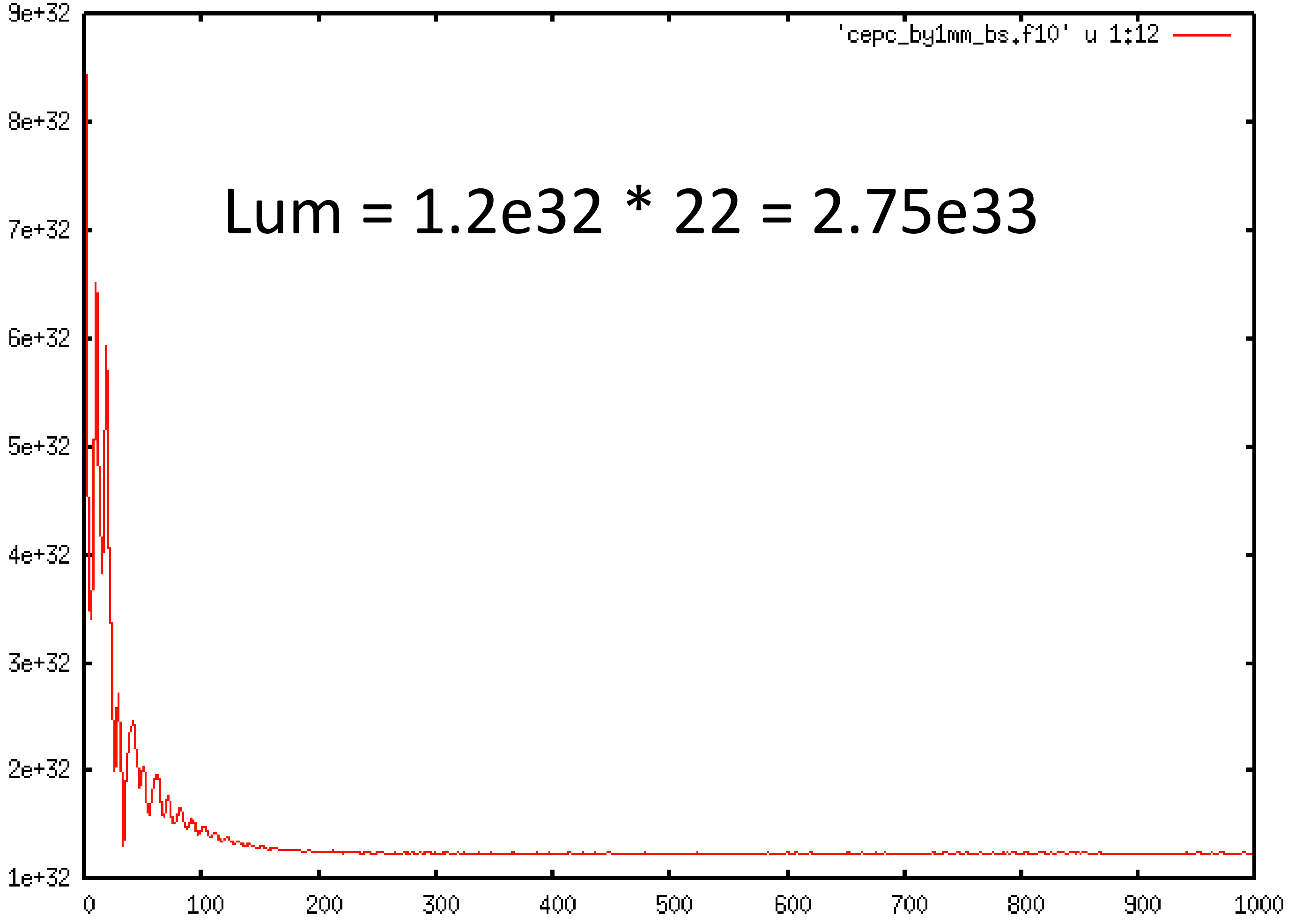
Quasi-Strong-Strong Simulation with LIFETRAC @(0.43,0.635)



Horizontal distribution is different from Gaussian distribution?!

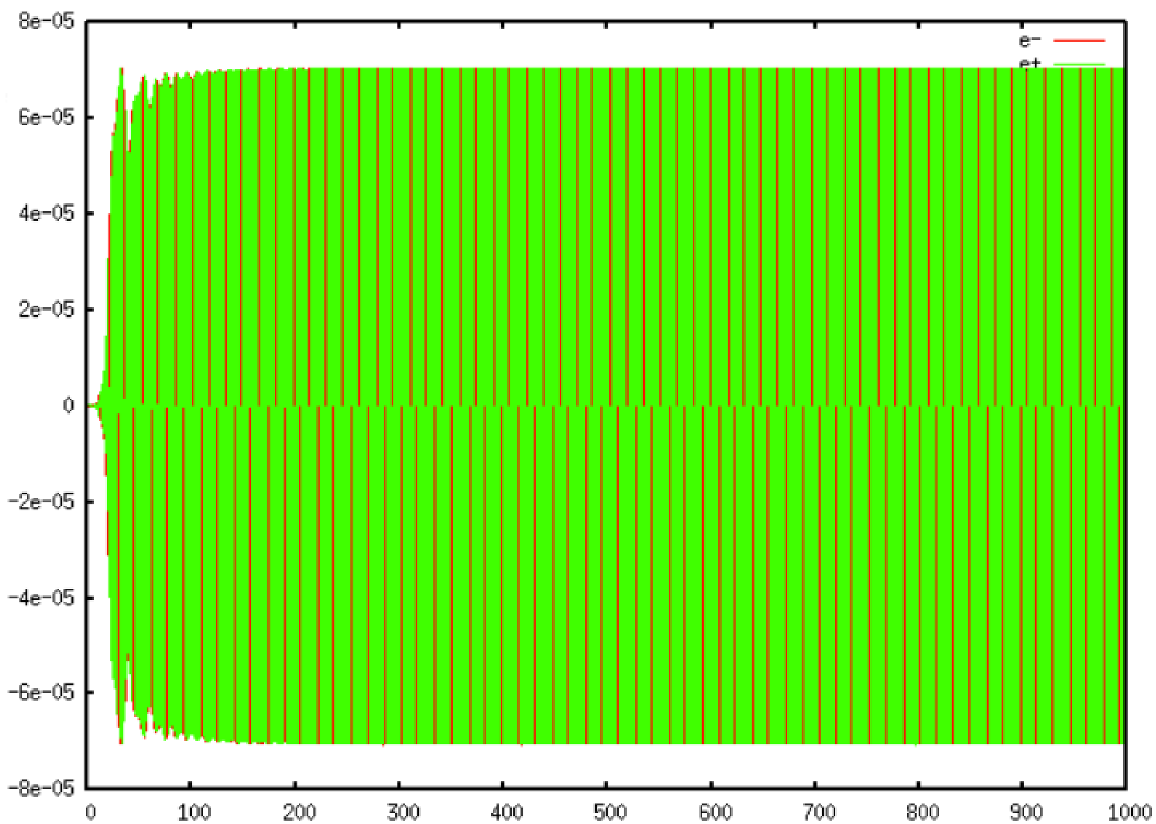
Not self consistent!

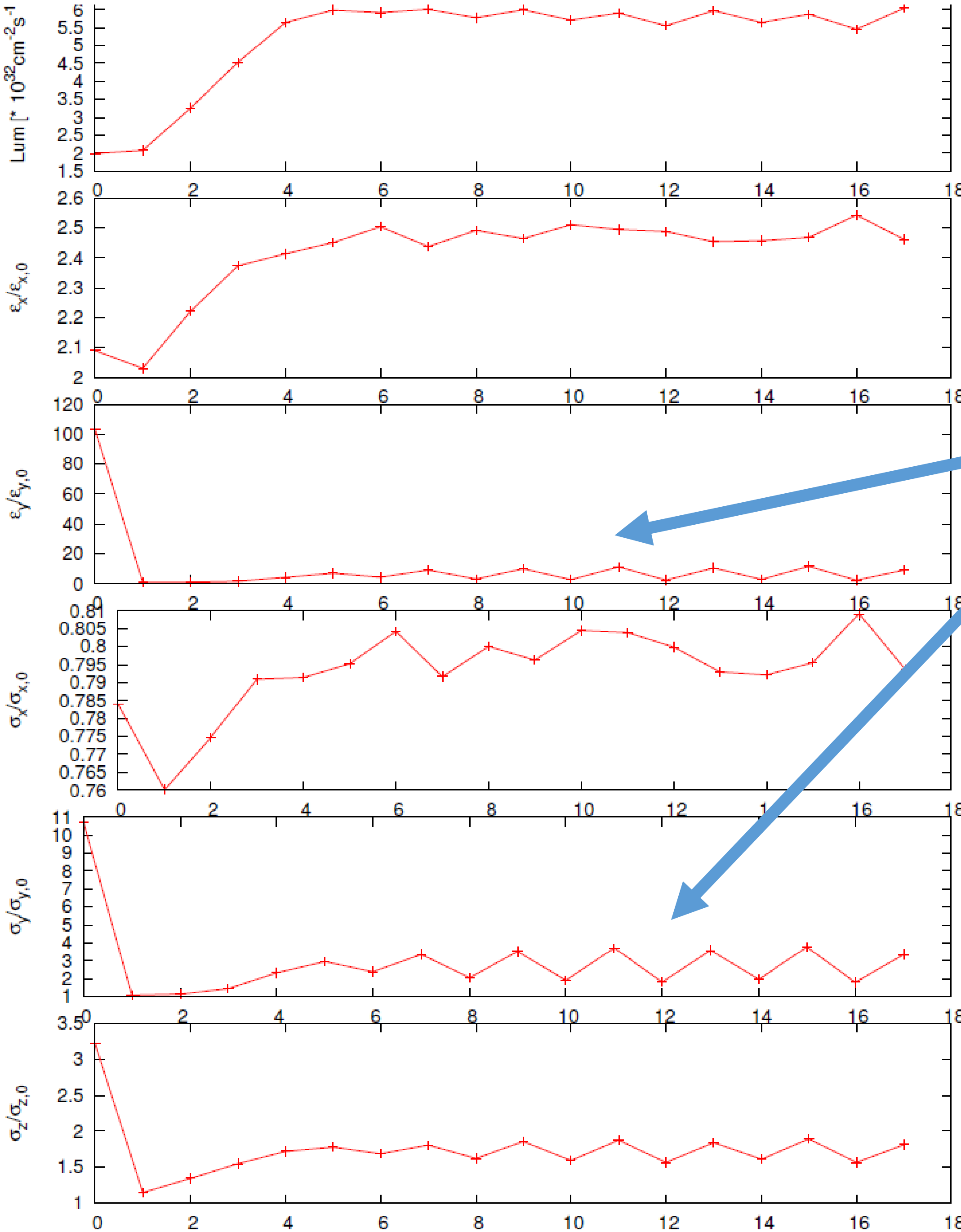
Strong-Strong Simulation with BBSS @ (0.43,0.635)



Strong-Strong Simulation with BBSS @ (0.43,0.635)

beam center <x>





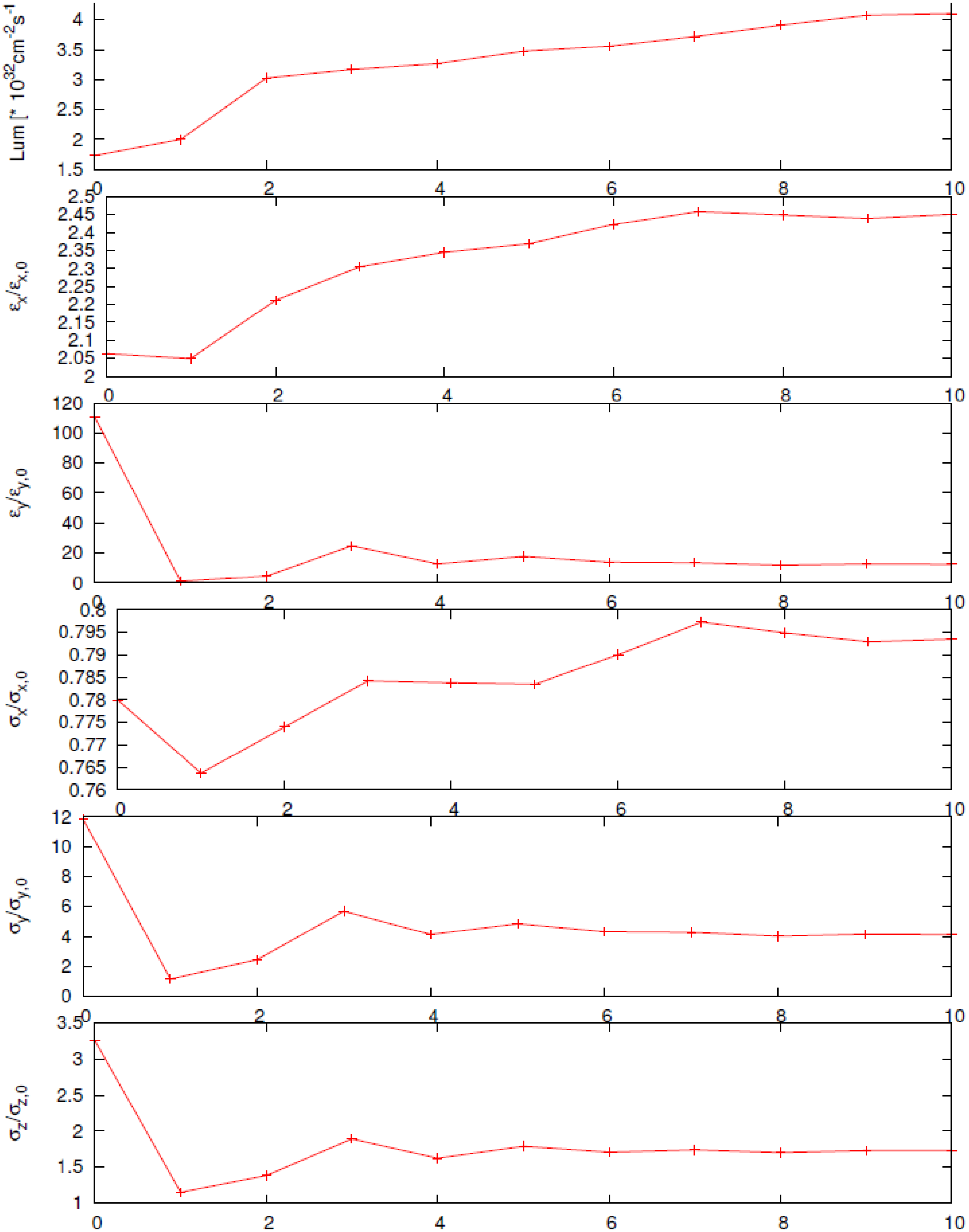
Quasi-Strong-Strong Simulation with LIFETRAC @(0.51,0.63),

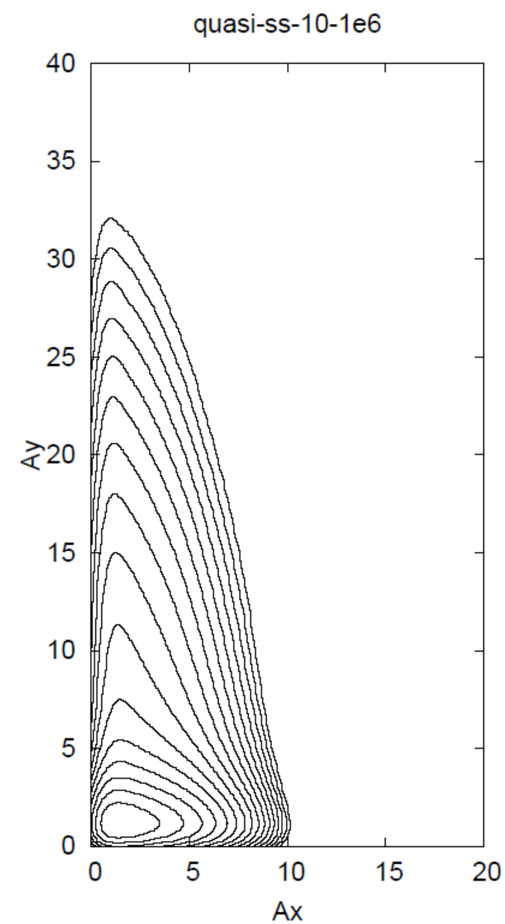
Iteration does not convergent!
No stable solution!

Quasi-Strong-Strong Simulation with LIFETRAC @(0.51,0.575),

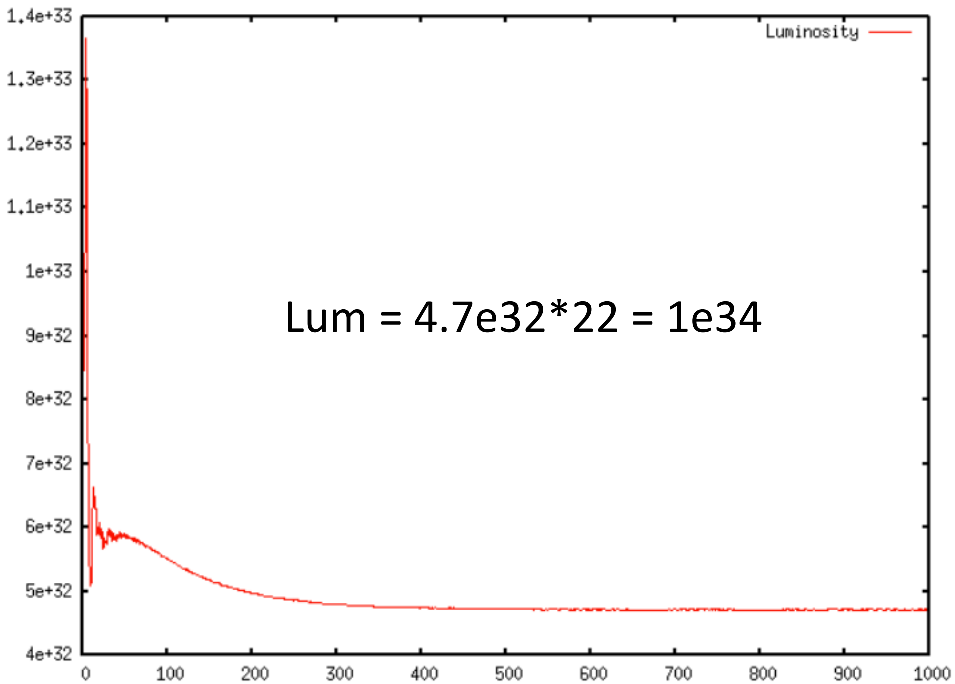
Lum=4.1e32*22=0.9e34

Lifetime = 25s

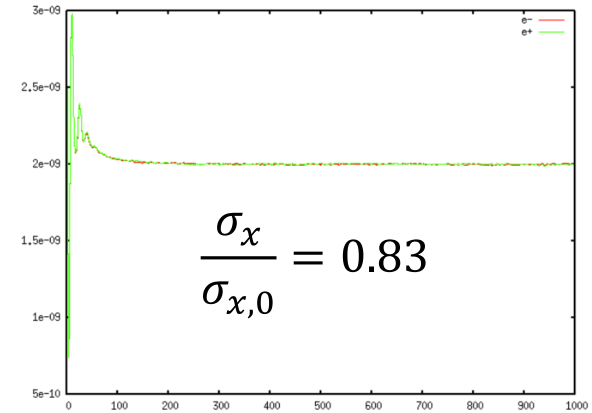




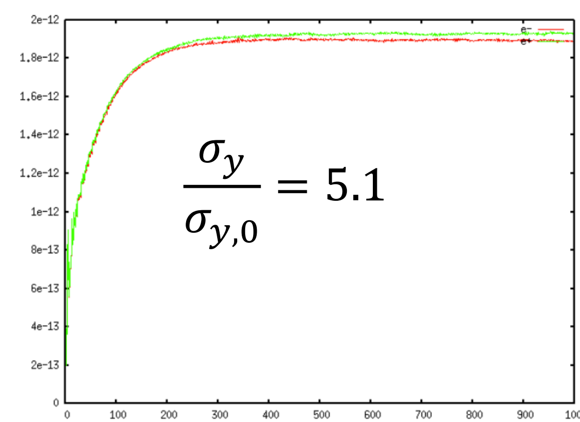
Strong-Strong@(0.52,0.58)



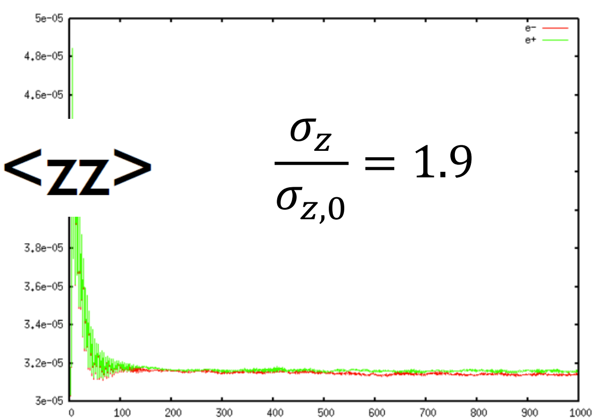
beam size <xx>

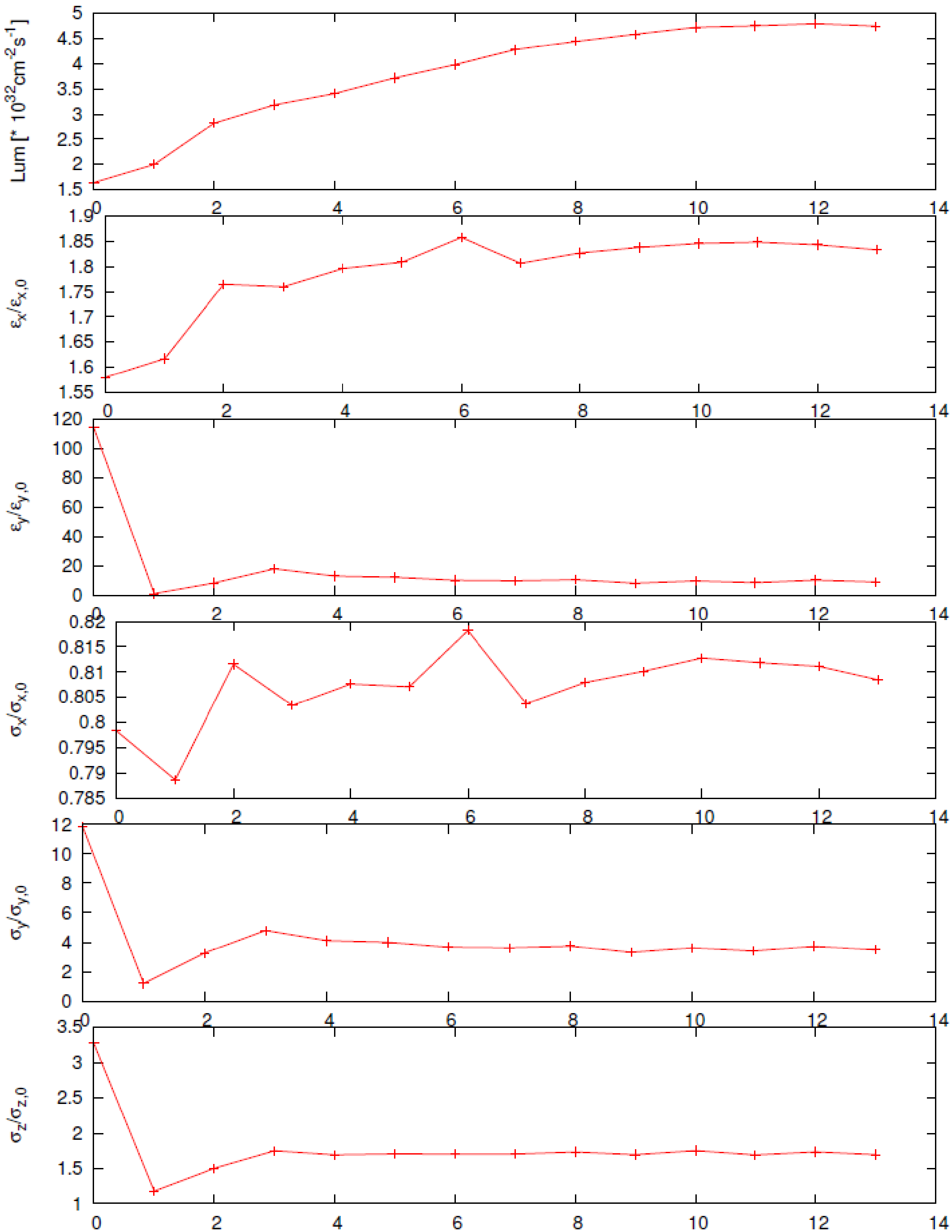


beam size <yy>



beam size <zz>





Quasi-Strong-Strong Simulation with LIFETRAC @(0.52,0.58),

Lum = 4.7e32*22=1e34, coincides well with strong-strong simulation result!

$\frac{\sigma_x}{\sigma_{x,0}} = 0.8$ concides well with strong-strong simulation result!

$\frac{\sigma_y}{\sigma_{y,0}} = 3.6$ vs 5.1 by BBSS

$\frac{\sigma_z}{\sigma_{z,0}} = 1.7$ vs 1.9 by BBSS

The Quasi-Strong-Strong Simulation seems work well!

beam-beam tune shift

- nominal: 0.1

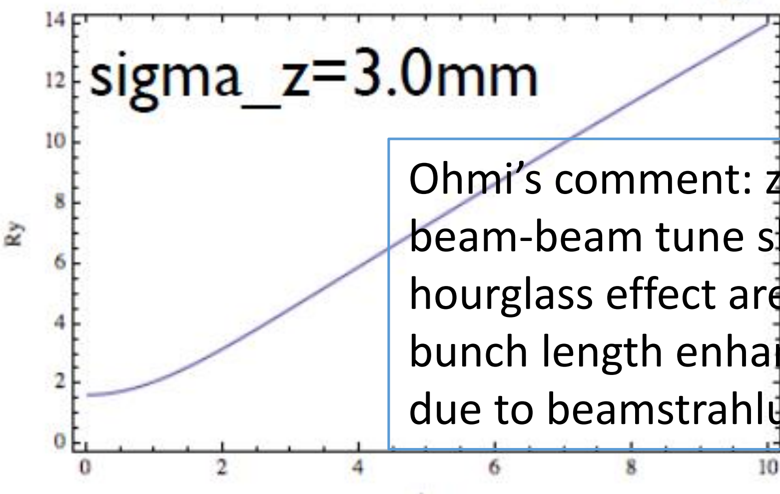
Ref. M. Furman, LBL-30833, ESG-137

$$R_{y+}(z) \equiv \xi_{y+}(z)/\xi_{0y+} = \int_{-\infty}^{\infty} \frac{dt}{\sqrt{\pi}} \frac{(1+t^2/t_1^2)\exp(-(t-t_0)^2)}{\sqrt{1+t^2/t_2^2}\left(v\sqrt{1+t^2/t_2^2}+h\sqrt{1+t^2/t_3^2}\right)} \tag{4}$$

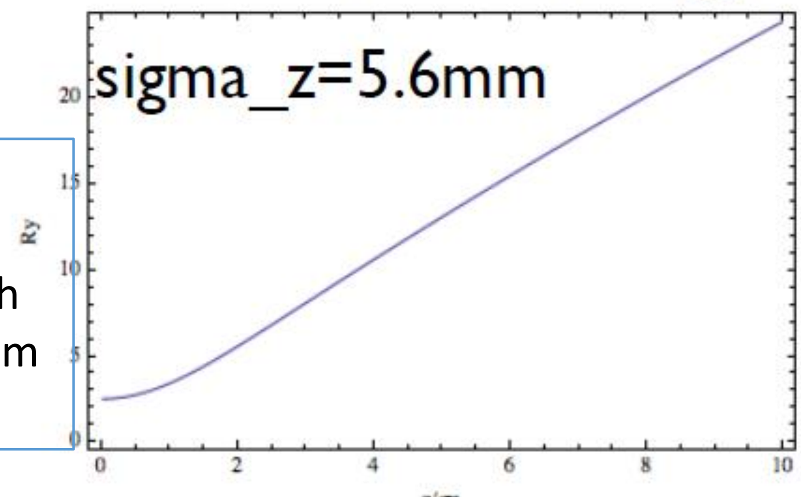
where $h = \sigma^*_{x-}/(\sigma^*_{x-}+\sigma^*_{y-})$, $v = \sigma^*_{y-}/(\sigma^*_{x-}+\sigma^*_{y-})$, $t_0 = z/\sqrt{2}\sigma_{s-}$, $t_1 = \sqrt{2}\beta^*_{y+}/\sigma_{s-}$, $t_2 = \sqrt{2}\beta^*_{y-}/\sigma_{s-}$ and $t_3 = \sqrt{2}\beta^*_{x-}/\sigma_{s-}$. The nominal (zero-bunch-length) vertical beam-beam parameter ξ_{0y+} of the central positron is

$$\xi_{0y+} = \frac{r_0 N_- \beta^*_{y+}}{2\pi\gamma_+\sigma^*_{y-}(\sigma^*_{x-}+\sigma^*_{y-})} \tag{5}$$

w/o beamstrahlung



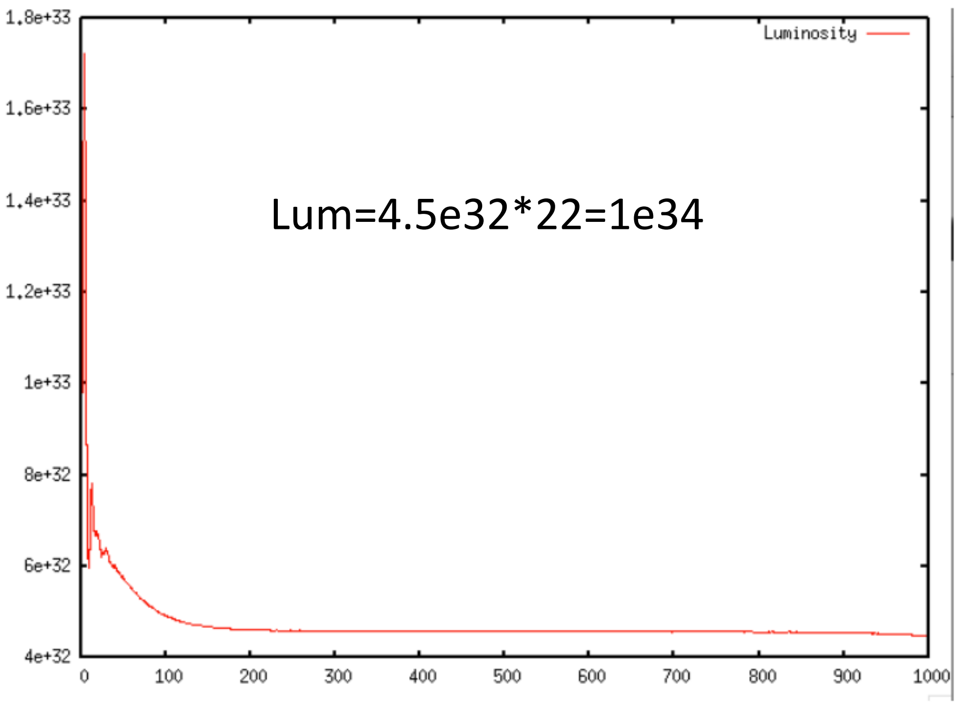
w/ beamstrahlung

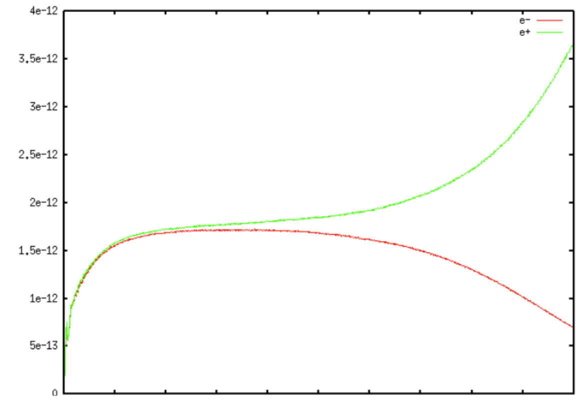


Ohmi's comment: z-dependent beam-beam tune shift due to hourglass effect are too large with bunch length enhanced to ~5.6mm due to beamstrahlung

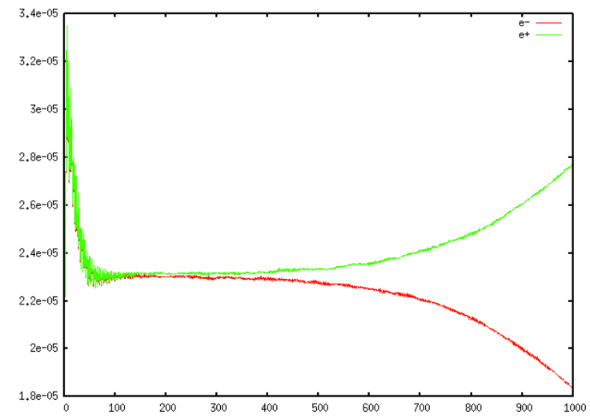
With higher RF voltage, bunch length: 2.2mm, nus: 0.13->0.179

beam size <yy>



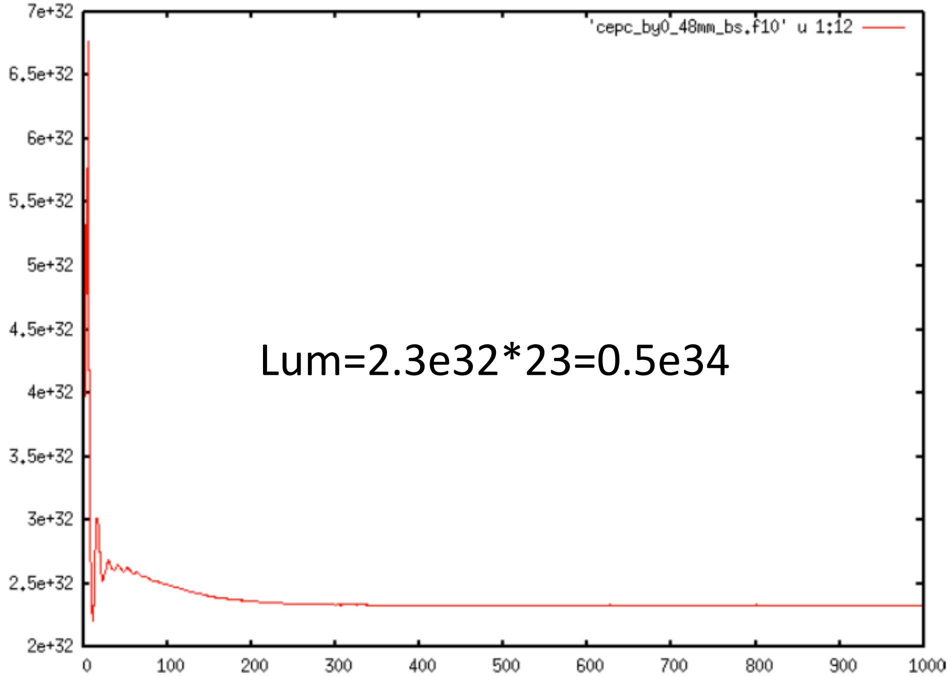


beam size <zz>

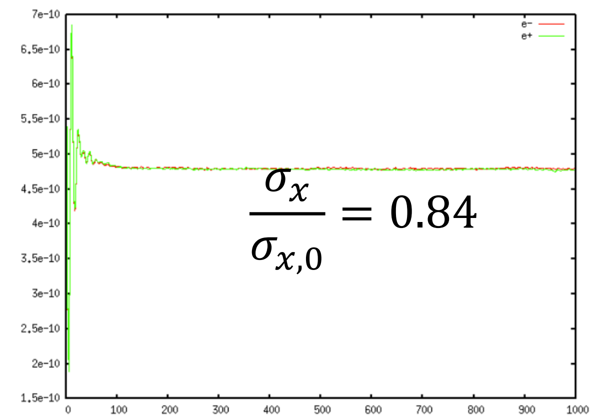


Simulation with BBSS

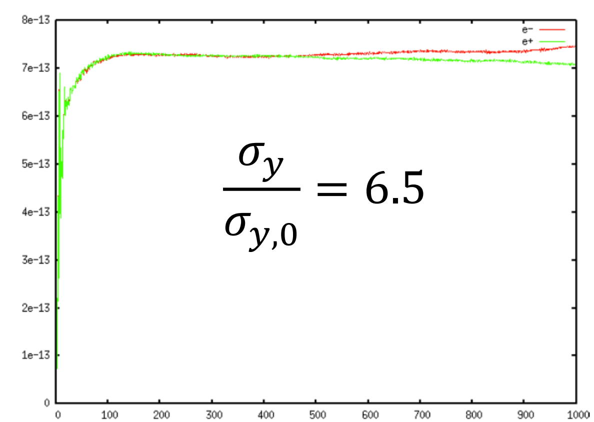
Bunch Length 2.2mm, bx/by=71/0.48mm



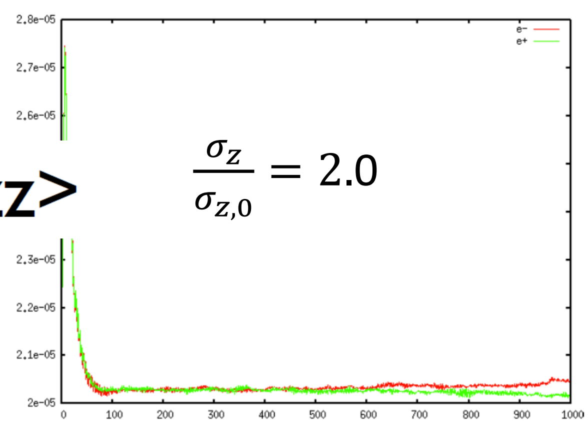
beam size <xx>

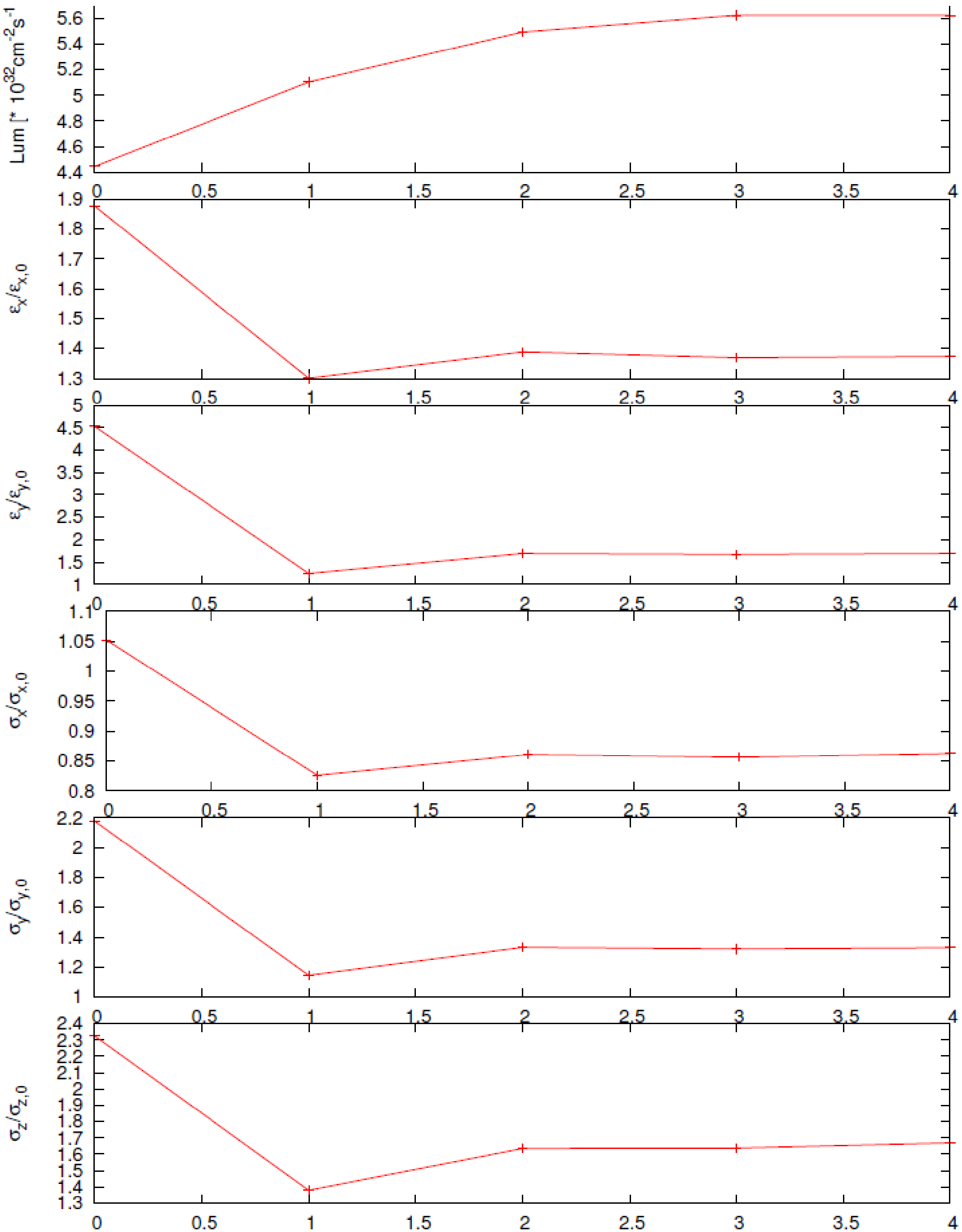


beam size <yy>



beam size <zz>





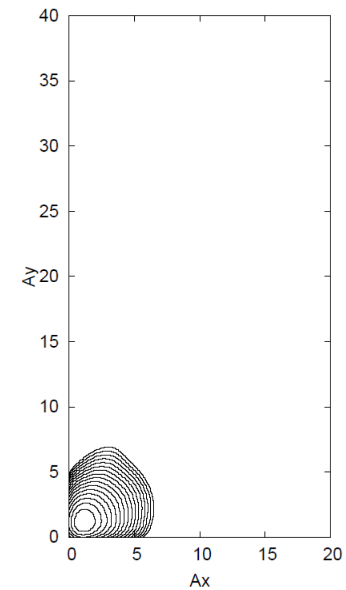
Quasi-Strong-Strong Simulation with LIFETRAC @(0.51, 0.63) with full crossing angle 40mrad in horizontal direction.

Lum = 1.2e34

Piwinski Angle:
1.1 before collision
2.1 after collision

Vertical blowup disappear!

Lifetime: 600 s !



Analytical Analysis of Beamstrahlung

The radiation integrals [7] are modified according to

$$\Delta I_2 = \left(\frac{L}{\rho_x^2} + \frac{L}{\rho_y^2}\right) N_{ip}\,, \tag{14}$$

$$\Delta I_3 = \frac{L}{\rho^3} N_{ip}\,, \tag{15}$$

$$\frac{1}{\rho_x} \approx \frac{1}{\rho_y} \approx \frac{N_p r_e}{\gamma \sigma_s \sigma_x}\,. \tag{9}$$

$$L = \sqrt{\frac{\pi}{2}} \frac{\sigma_s}{\sqrt{1+\phi^2}} \quad \left(L_{Telnov} = \frac{\sigma_s}{2}\right)\,, \tag{12}$$

$$\frac{1}{\rho} = \sqrt{\frac{1}{\rho_x^2} + \frac{1}{\rho_y^2}} \approx \frac{N_p r_e}{\gamma \sigma_x \sigma_s} \sqrt{2} \quad \left(\frac{1}{\rho_{Telnov}} \approx \frac{N_p r_e}{\gamma \sigma_x \sigma_s} 2\right)\,. \tag{13}$$

A.Bogomyagkov, E.Levichev, D. Shatilov, arXiv:1311.1580 [physics.acc-ph]

Analysis of Beamstrahlung in CEPC

$$I_2 = \oint \frac{1}{\rho^2} ds$$

$$I_3 = \oint \frac{1}{|\rho^3|} ds$$

$$\sigma_{\delta,new}^2 \propto \frac{I_3 + \Delta I_3}{I_2 + \Delta I_2}$$

For $\rho_B = 6.2$ km, I_2 =1.01e-3, I_3 = 1.63e-7
For 3mm bunch length, emitx=14.6nm, bx/by=0.2/0.001m,

$\rho = 17$m!

ΔI_2=1.31e-5, ΔI_3 = 7.43e-7

The main contribution comes from the ΔI_3!

According to the analysis estimation, $\sigma_{\delta,new} = 2.3\ \sigma_{\delta,0}$
According to the weak-strong simulation, $\sigma_{\delta,new} = 3.4\ \sigma_{\delta,0}$
According to the strong-strong simulation, $\sigma_{\delta,new} = 1.9\ \sigma_{\delta,0}$

Modification of CEPC parameters

- β_x: 0.2m -> 0.4m
- ϵ_y/ϵ_x: 0.5% -> 0.25%

According to the analysis estimation, ΔI_3 could be reduced by a factor of $2^{\frac{3}{2}}$ (~ 2.8) , which means $\sigma_{\delta,new}$ would be reduced by a factor 1.4 in our case.

The weak-strong simulation shows that the $\sigma_{\delta,new}$ is reduced by a factor 1.5!

The two method coincides very good!

Modification of CEPC parameters (2)

However the collision is a strong-strong model instead of weak-strong.

The quasi-strong-strong shows that $\sigma_{\delta,new}$ is reduced only by a factor 1.16.

Lifetime: 7s!

The luminosity is also reduced 10%.

Modification of CEPC parameters (3)

- With full crossing angle 40mrad in horizontal direction

  Luminosity could achieve 1.5e34

  Beamstrahlung lifetime could achieve 3000s!

- Crossing angle could help us!

CEPC 50km scenario

- Circumference C =50 km
- Ring filling factor $\kappa = 0.78$ (C=50km)

$\Rightarrow$ $\rho = 6.2\text{km}$

- SR power of beam = 50 MW

$$P[\mathrm{GW}] = C_\gamma \frac{E[\mathrm{GeV}]^4}{\rho[\mathrm{m}]} I[\mathrm{A}]$$

$$C_\gamma = 88.5 \times 10^{-6} \frac{\mathrm{m}}{\mathrm{GeV}^3}$$

$\Rightarrow$ $I = k_b I_b = 16.9\mathrm{mA}$

CEPC luminosity

$$L[\mathrm{cm}^{-2}\mathrm{s}^{-1}] = 2.17\times 10^{34}(1+r)\xi_y \frac{E[\mathrm{GeV}]I[\mathrm{A}]}{\beta_y[\mathrm{cm}]}$$

- **Empirically choose**

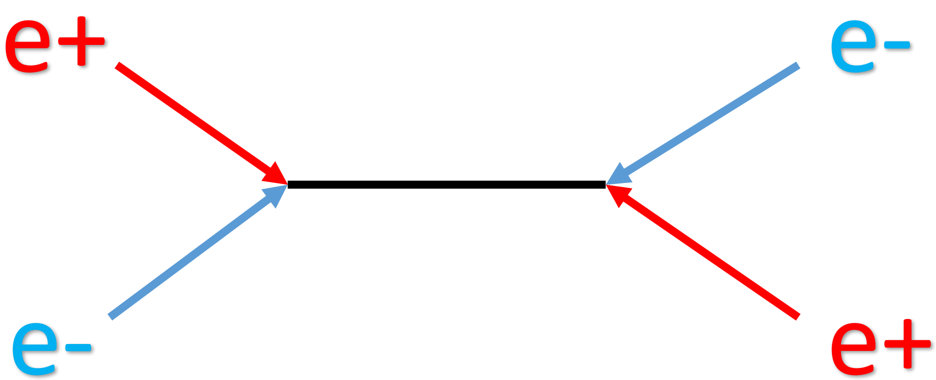
$$\xi_y = 0.1,\ \ \beta_y = 1\mathrm{mm}$$

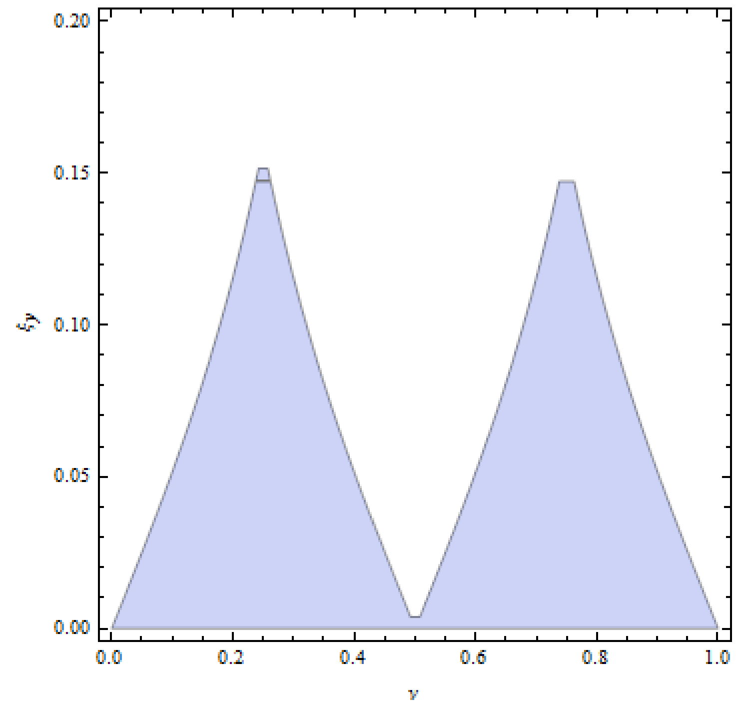
$$\Rightarrow \quad L = 4.42\times 10^{34}[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$$

(Hour glass effect excluded)

Compensation of Beam-Beam Effect including Beamstrahlung

- Unsuccessful collision: four beams with two ring





Is it possible that the fast SR damping in Higgs factory could help us suppress the coherent instability?

$$\left\{\left\{\lambda \to \mathrm{Cos}[\mu 0] - 2\pi\xi\,\mathrm{Sin}[\mu 0] - \frac{\sqrt{-1 + 4\pi^2\xi^2 + \mathrm{Cos}[2\mu 0] - 4\pi^2\xi^2\,\mathrm{Cos}[2\mu 0] - 4\pi\xi\,\mathrm{Sin}[2\mu 0]}}{\sqrt{2}}\right\},\right.$$

$$\left\{\lambda \to \mathrm{Cos}[\mu 0] - 2\pi\xi\,\mathrm{Sin}[\mu 0] + \frac{\sqrt{-1 + 4\pi^2\xi^2 + \mathrm{Cos}[2\mu 0] - 4\pi^2\xi^2\,\mathrm{Cos}[2\mu 0] - 4\pi\xi\,\mathrm{Sin}[2\mu 0]}}{\sqrt{2}}\right\},$$

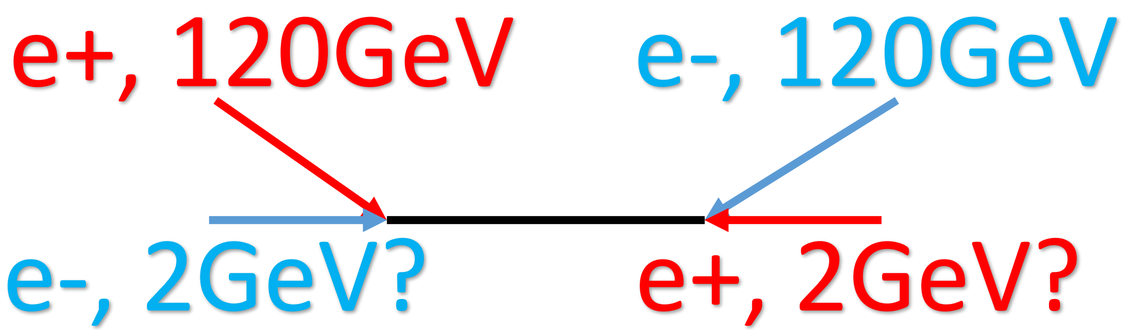
$$\left\{\lambda \to \mathrm{Cos}[\mu 0] + 2\pi\xi\,\mathrm{Sin}[\mu 0] - \frac{\sqrt{-1 + 4\pi^2\xi^2 + \mathrm{Cos}[2\mu 0] - 4\pi^2\xi^2\,\mathrm{Cos}[2\mu 0] + 4\pi\xi\,\mathrm{Sin}[2\mu 0]}}{\sqrt{2}}\right\},$$

$$\left.\left\{\lambda \to \mathrm{Cos}[\mu 0] + 2\pi\xi\,\mathrm{Sin}[\mu 0] + \frac{\sqrt{-1 + 4\pi^2\xi^2 + \mathrm{Cos}[2\mu 0] - 4\pi^2\xi^2\,\mathrm{Cos}[2\mu 0] + 4\pi\xi\,\mathrm{Sin}[2\mu 0]}}{\sqrt{2}}\right\}\right\}$$

Is it possible some decoherence could help suppress the coherent instability below the threshold of dipole mode?

- More work need to do

Is it possible: one ring + two linac?



- The energy of the linac beam need not to be so high
- Could the physics people accept the collision?
- Could the accelerator people implement such a collision scheme?

Summary

- The pure weak-strong simulation does not work well
- Quasi-strong-strong could help us and save time. But the result should be checked by the strong-strong simulation
- The head-on collision scheme could only achieve 1e34 by simulation and lifetime is very bad
- We need to optimize machine parameters
- It seems the crossing angle could help us suppress hourglass effect, even though the bunch lengthening is unavoidable.
- We could achieve 1.5e34 with full crossing angle 40mrad and much better lifetime (need check by strong-strong simulation)

Thank you for your attention!