Beam Dynamics Studies in SuperKEKB

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SuperB workshop at INFN-Frascati
March 19-24, 2012

Parameters

	2011 Feb. HER no wiggler	2012 Feb. HER 60% wigglers
Energy (GeV) (LER/HER)	4.0/7.00729	4.0/7.00729
β_y^* (mm)	0.27/0.30	0.27/0.30
β_x^* (mm)	32/25	32/25
ε_x (nm)	3.2/5.3	3.2/4.6
$\varepsilon_y/\varepsilon_x$ (%)	0.27/0.24	0.27/0.28
σ_y(nm)	48/62	48/62
ξ_y	0.0897/0.0807	0.0881/0.0801
σ_z (mm)	6/5	6/5
I_{beam} (A)	3.6/2.6	3.6/2.6
$N_{bunches}$	2500	2500
Luminosity (10^{34} cm^{-2} s^{-1})	80	80

HER ε_x with 60% wigglers is used as the nominal value.
Lower HER ε_x can relax some other parameters ($\beta_{x/y}^*$, $\varepsilon_y/\varepsilon_x$, etc.).
At present, larger $\varepsilon_y/\varepsilon_x$ in HER is adopted.

Contents

- Strong-strong beam-beam simulation, synchro-beta resonances
- Tolerance of IP parameter
- Electron cloud & Ion
- TMCI and beam tilt due to mask impedance
- Injection, life time, background, dynamic aperture
-

Progress of Strong-strong simulation

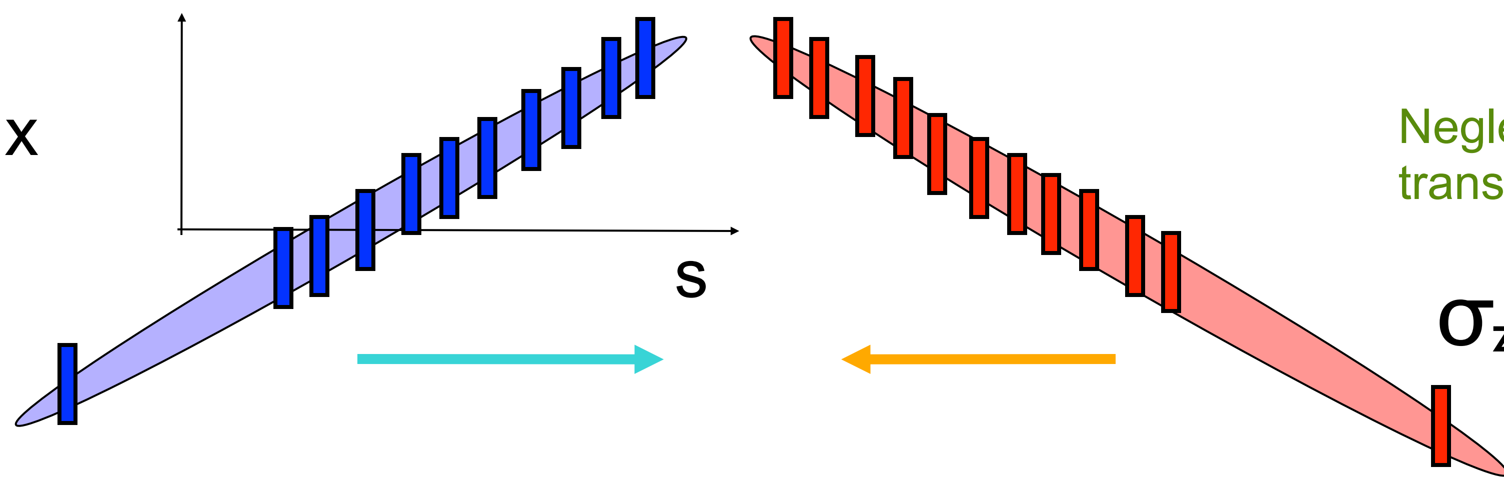
- Gaussian approximation
- Particle In Cell-Gauss composite
- Fully Particle In Cell

Bunch slicing

- Integral along collision, bunch slicing
- nslice=(5~10)x$\sigma_z\theta/\sigma_x$= (5~10)x25

$\sigma_z\theta/\sigma_x$=1 for KEKB

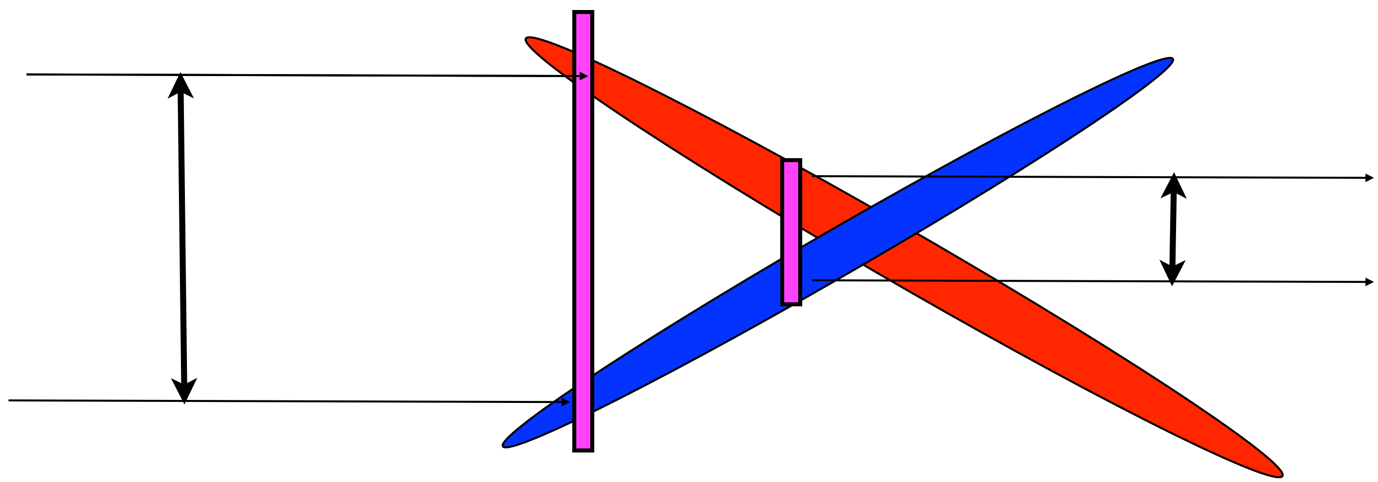
- Should be smooth function for z.



Neglect parallel translation to x

$\sigma_{z+}>\sigma_{z-}$

Gaussian and PIC combined method (done 2010)



$Dx > 5\sigma_x$

Gaussian approximation

$Dx < 5\sigma_x$

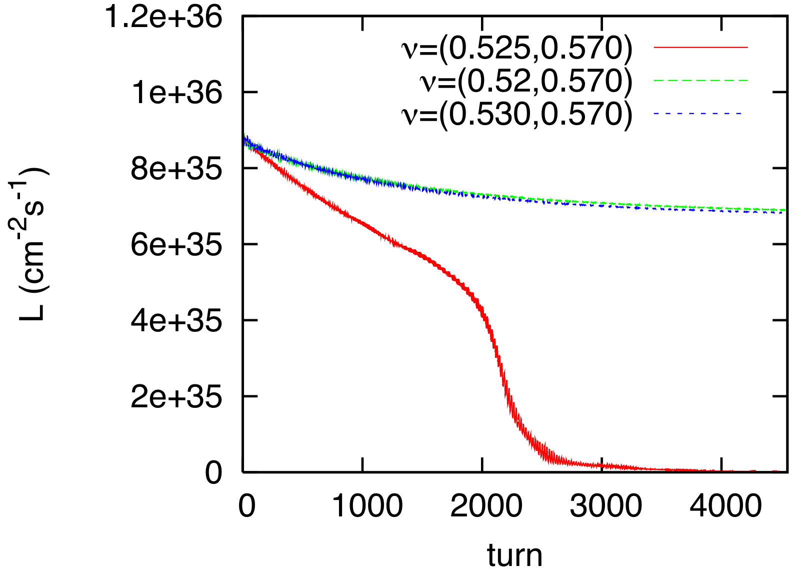
Partcle In Cell

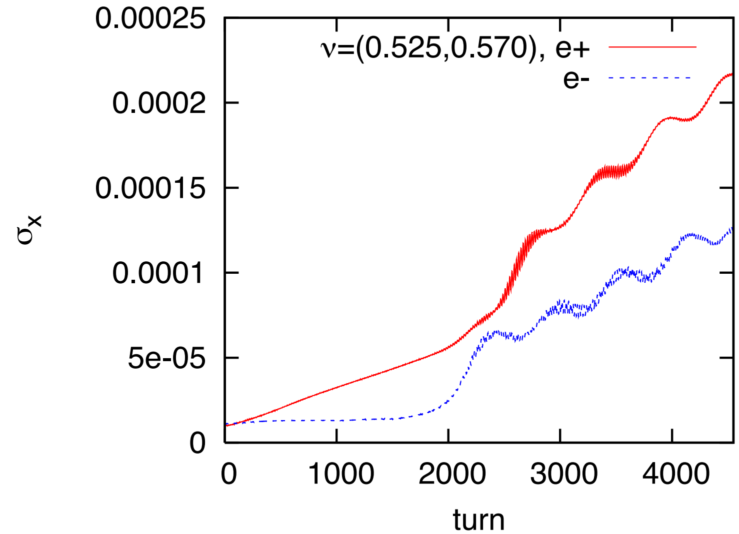
Potential solve

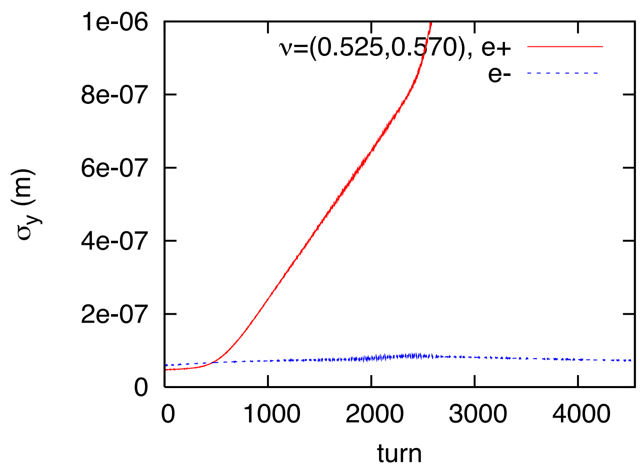
- 5000 PIC sub collision and 35000 gaussian collision

Strong-strong beam-beam simulation

- Coherent instability should be studied by strong-strong model

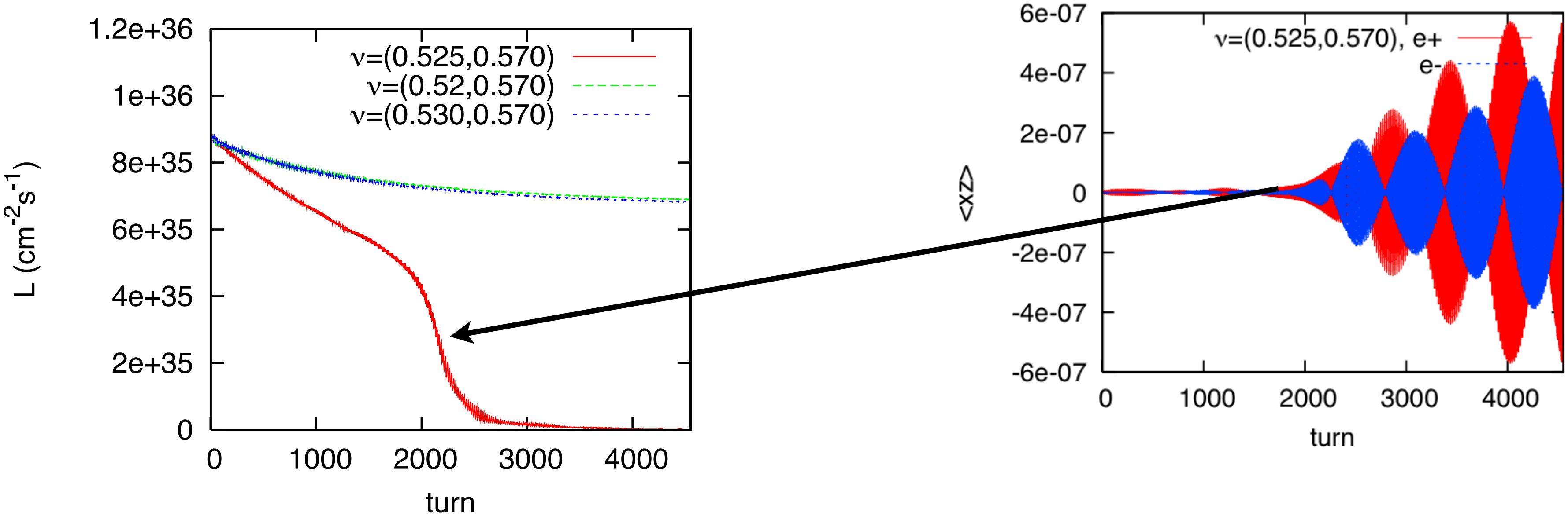


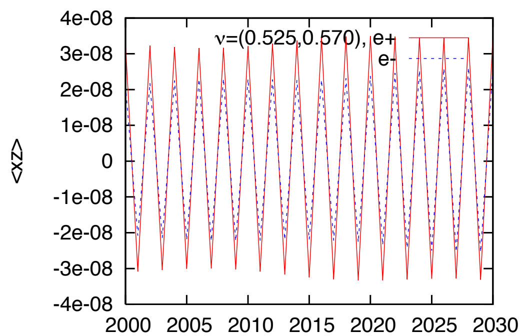




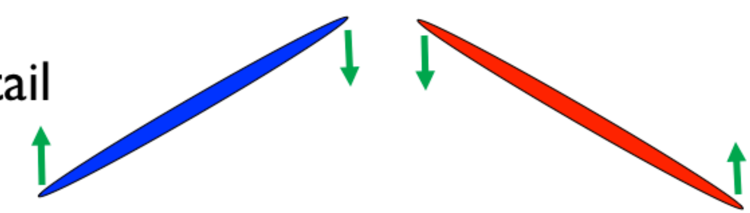
Gaussian and PIC combined method

Example: study of synchro-beta effect





- $2\nu_x - 2\nu_s = \text{int}$
- Coherent head-tail mode



Particle in Cell

- Potential solve for arbitrary beam distribution in transverse plane
- KEKB   50(~7x7) subcollision/collision
- SuperKEKB   40,000(~200x200) subcollision/collision

Shifted Green function

$$\phi(\mathbf{r}) = -\frac{1}{2\pi\varepsilon_0}\int d\mathbf{r}'\,G(\mathbf{r}-\mathbf{r}'-\mathbf{r}_0)\,\rho(\mathbf{r}'+\mathbf{r}_0)$$

J. Qiang

- Potential where apart from a distance

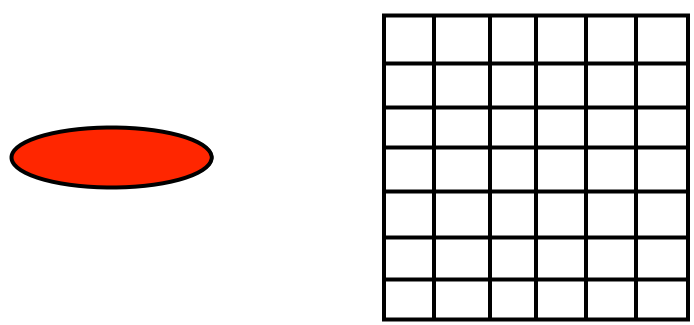
$$f(x_{i+}-x_0,y_{i+}-y_0)-f(x_{i+}-x_0,y_{i-}-y_0)-f(x_{i-}-x_0,y_{i+}-y_0)+f(x_{i-}-x_0,y_{i-}-y_0)$$

$$f(x_{i+}-2\Delta x-x_0,y_{i+}-y_0)-f(x_{i+}-2\Delta x-x_0,y_{i-}-y_0)-f(x_0-2\Delta x+x_{i-},y_{i+}-y_0)+f(x_{i-}-2\Delta x-x_0,y_{i-}-y_0)$$

$$f(x_0+x_{i+},y_0-2\Delta y+y_{i+})-f(x_0+x_{i+},y_0-2\Delta y+y_{i-})-f(x_0+x_{i-},y_0-2\Delta y+y_{i+})+f(x_0+x_{i-},y_0-2\Delta y+y_{i-})$$

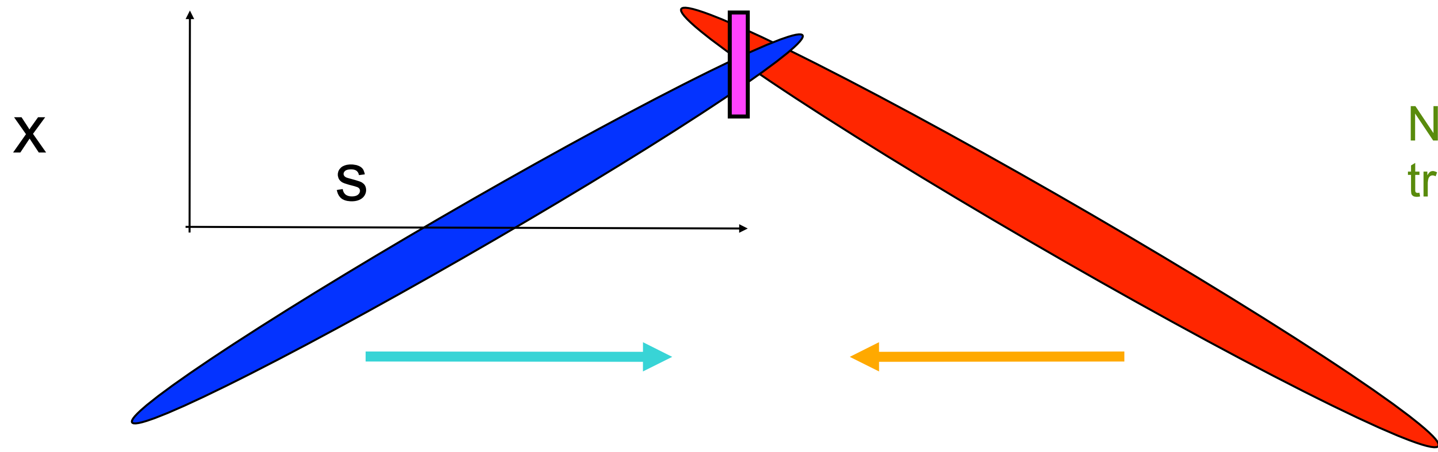
$$f(x_0-2\Delta x+x_{i+},y_0-2\Delta y+y_{i+})-f(x_0-2\Delta x+x_{i+},y_0-2\Delta y+y_{i-})-f(x_0-2\Delta x+x_{i-},y_0-2\Delta y+y_{i+})+f(x_0-2\Delta x+x_{i-},y_0-2\Delta y+y_{i-})$$

$$f(x,y)=\int dxdyG(\mathbf{r}) = -3xy + x^2\tan^{-1}(y/x) + y^2\tan^{-1}(y/x) + xy\log(x^2+y^2)$$



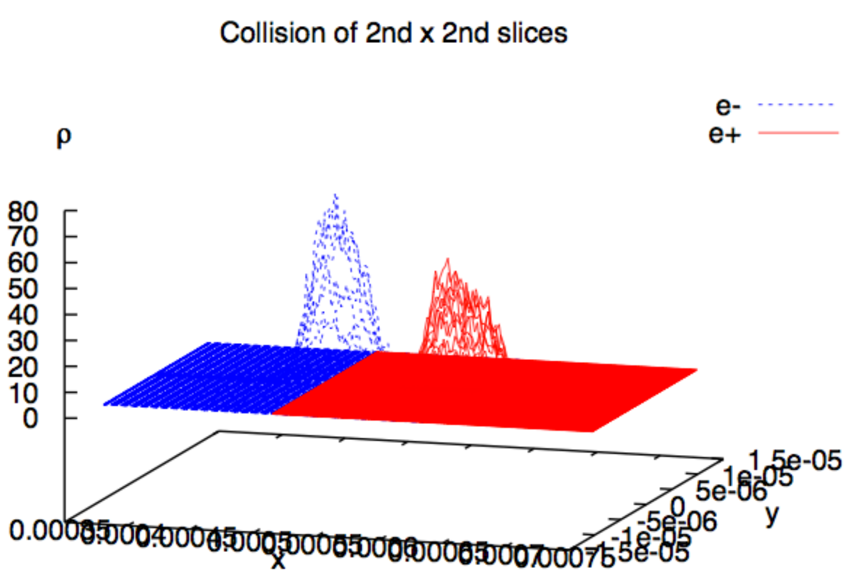
Φ_{ij} is given on the grid space far from colliding beam.

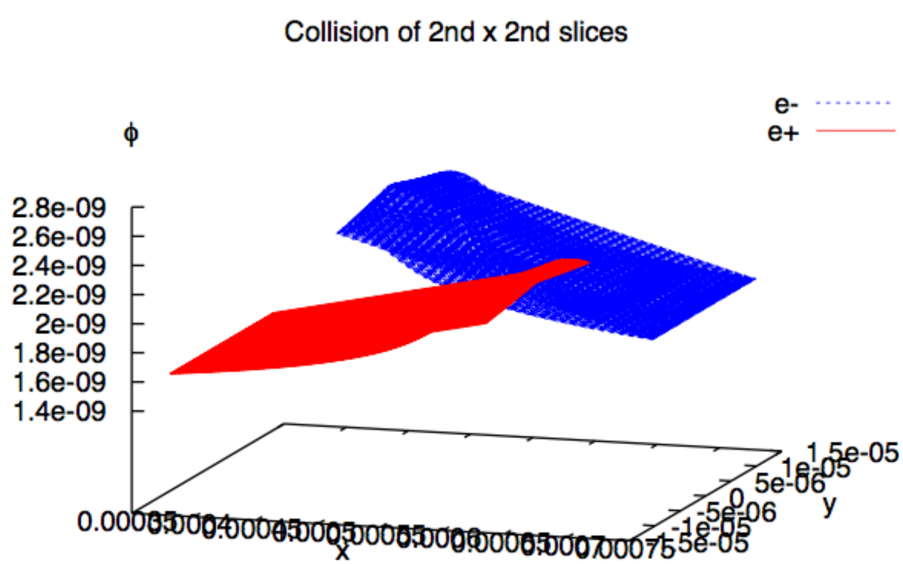
Beam distribution and potential



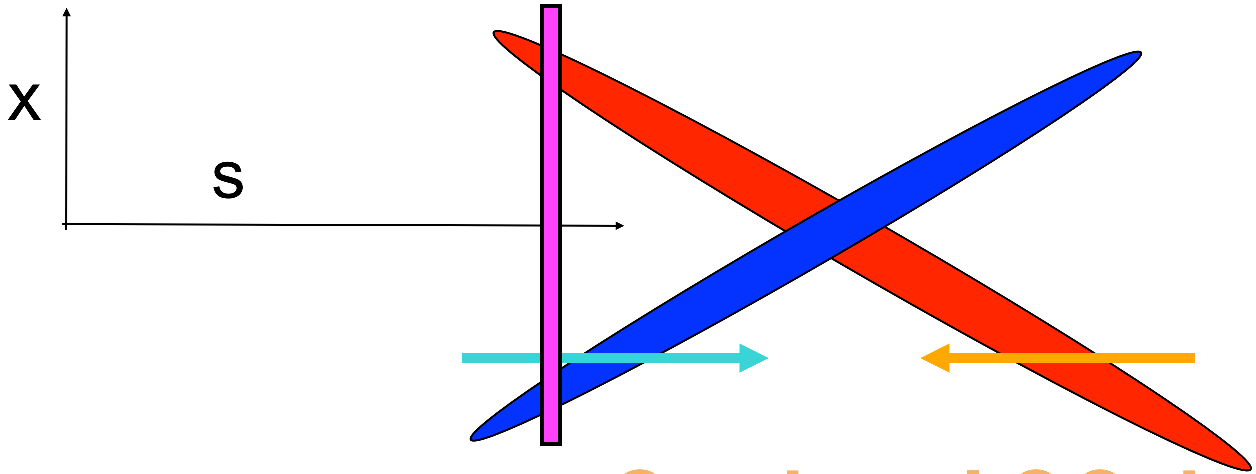
Neglect parallel translation to x

$\sigma_{z+} > \sigma_{z-}$



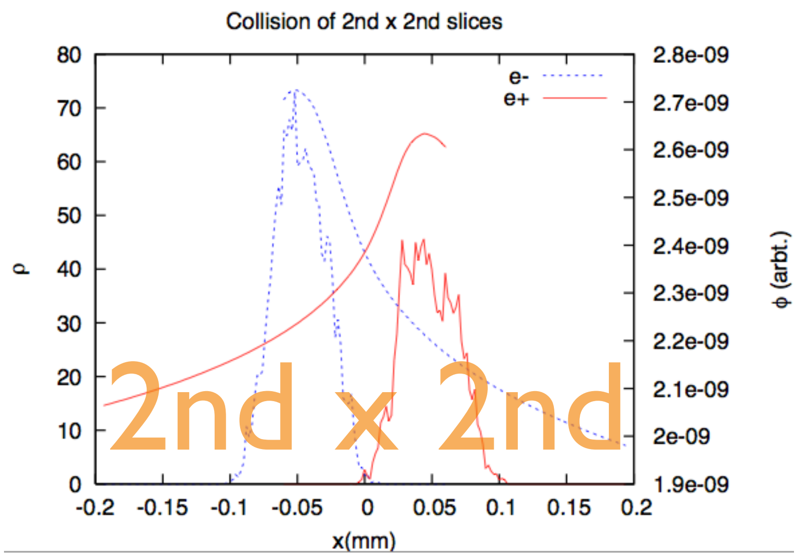


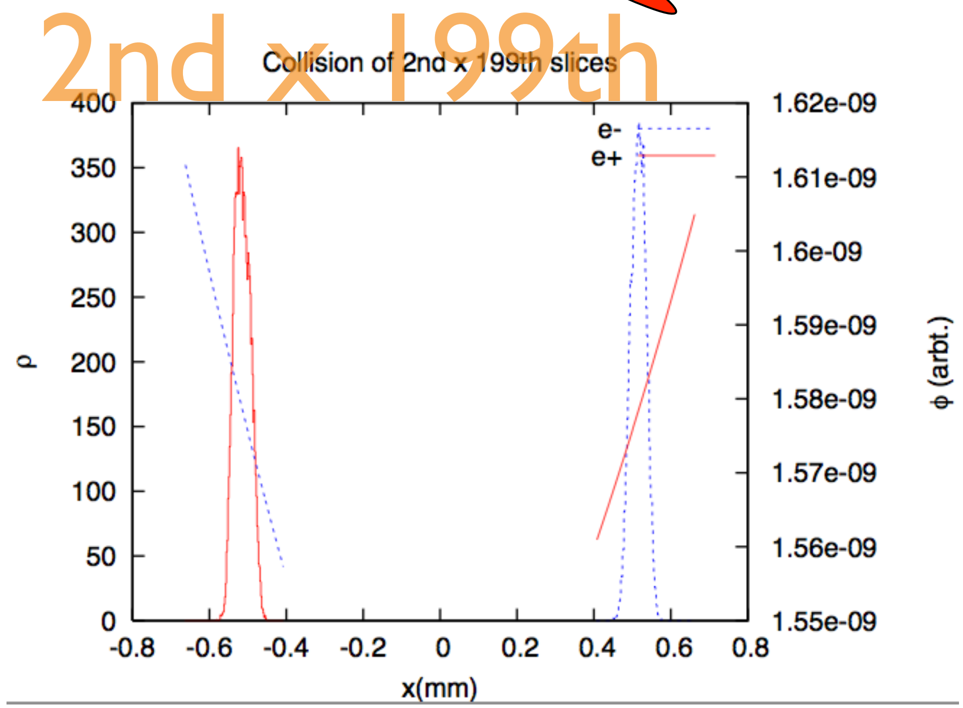
Beam distribution and potential



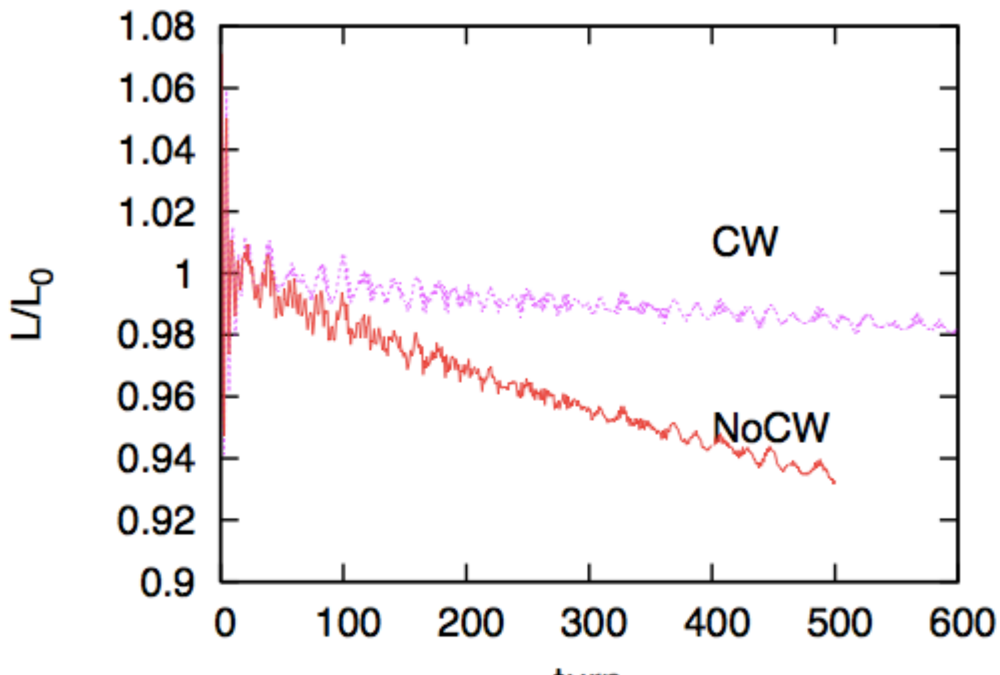
Neglect parallel translation to x

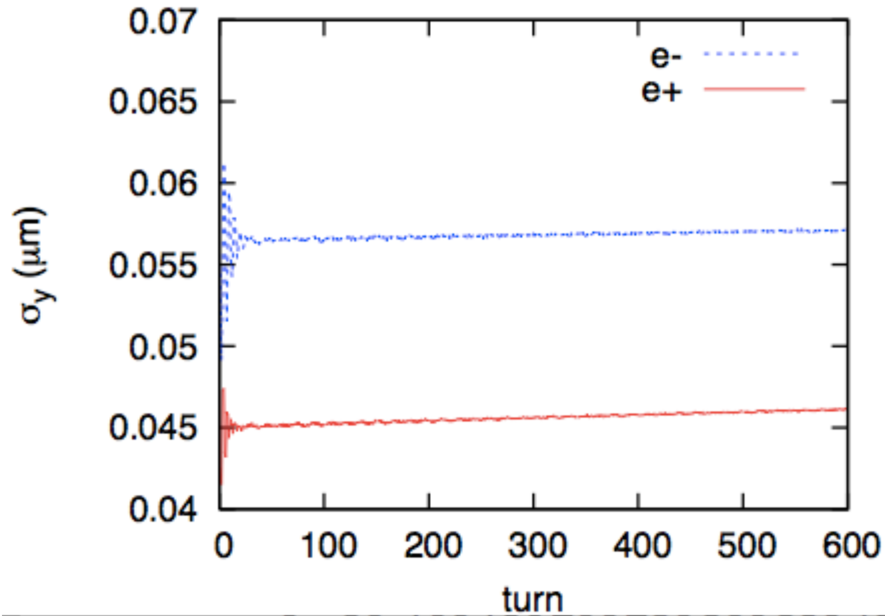
$\sigma_{z+} > \sigma_{z-}$

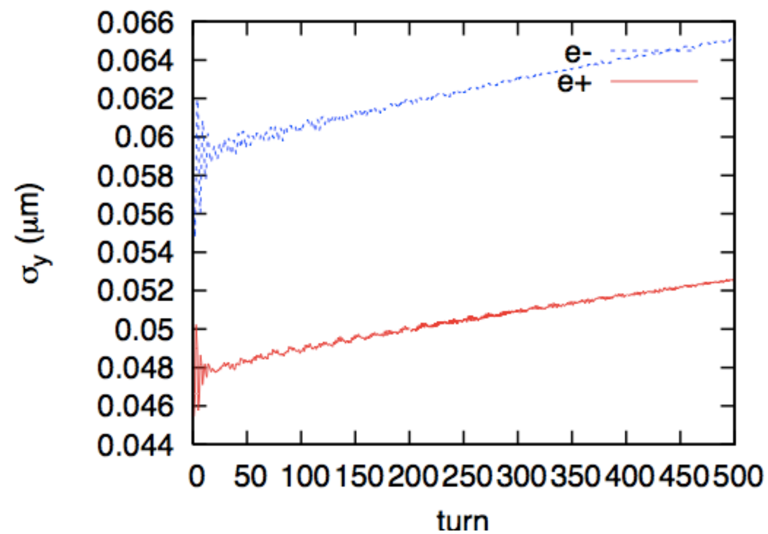




Tentative result



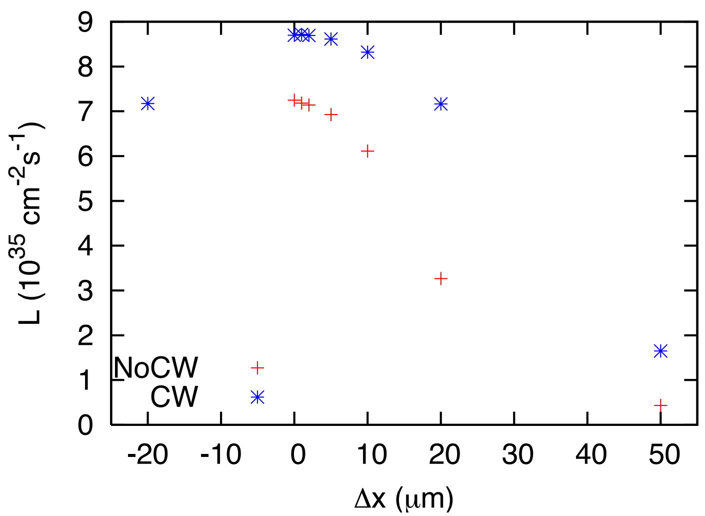


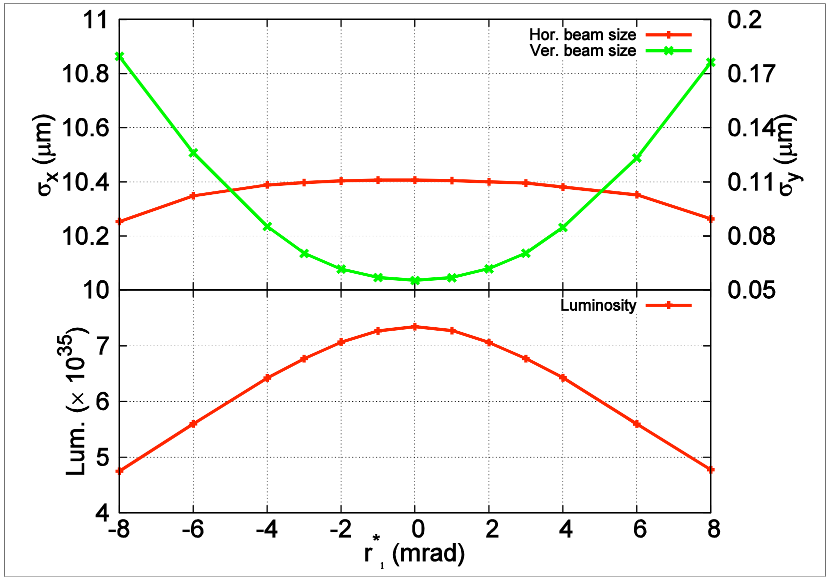


- Equilibrium luminosity is not obtained in fully PIC simulation yet.
- Degradation of the luminosity is weak for CW.

Tolerance of IR parameters beam-beam

- Weak-strong simulation is used for the parameter scan, because the strong-strong requires very long CPU time.
- Examples, x-offset and r_l*.





Summary – tolerance for parameters with 20% luminosity degradation

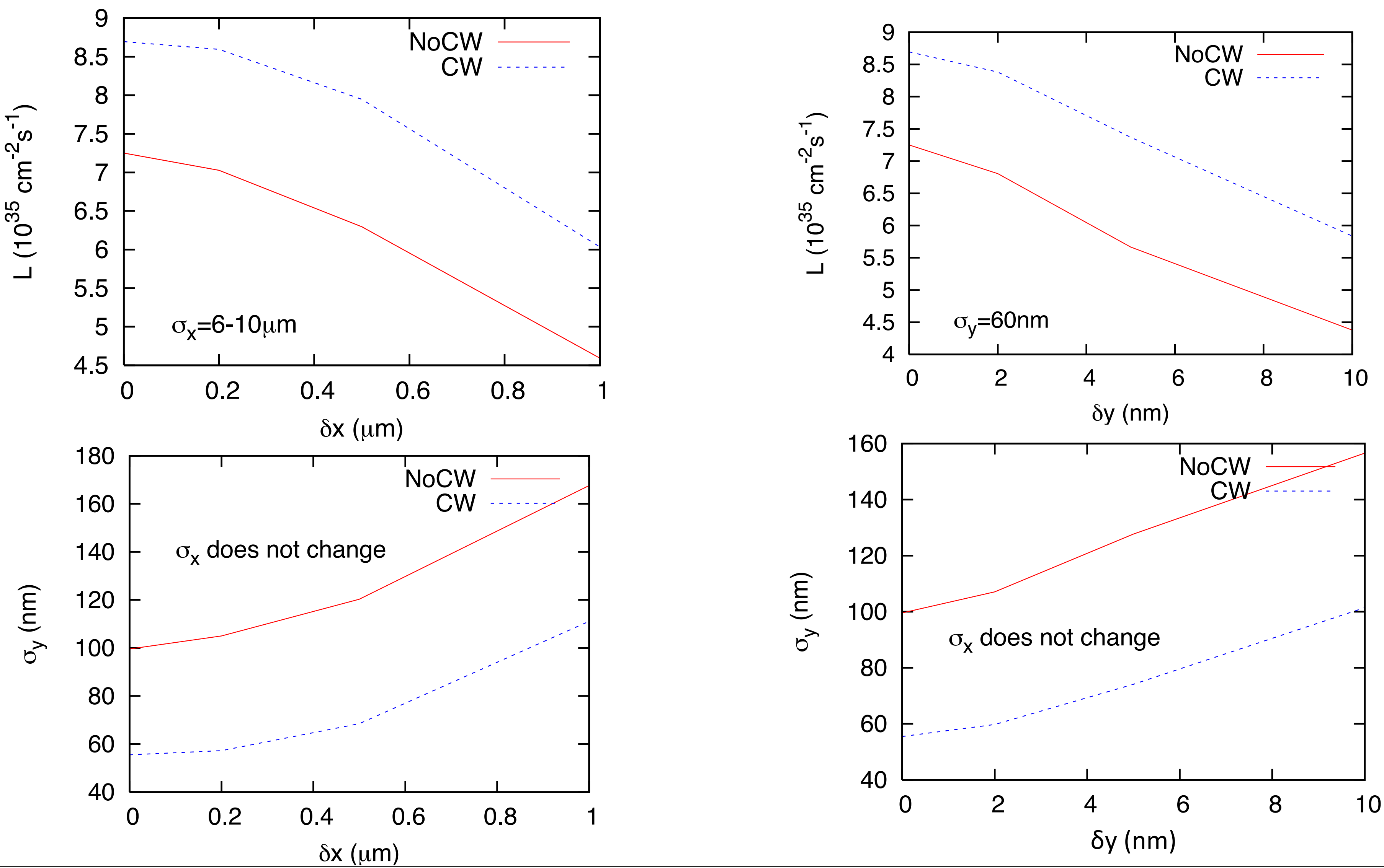
Parameter	w/ crab waist	w/o crab waist
r_1^* (mrad)	±5.3	±3.5
r_2^* (mm)	±0.18	±0.13
r_3^* (m^{-1})	±44	±15
r_4^* (rad)	±1.4	±0.4
$\partial r_1^* / \partial \delta$ (rad)	±2.4	±2.1
$\partial r_2^* / \partial \delta$ (m)	±0.086	±0.074
$\partial r_3^* / \partial \delta$ (m^{-1})	$\pm 1.0 \times 10^4$	±8400
$\partial r_4^* / \partial \delta$ (rad)	±400	±290
η_y^* (μm)	±62	±31
$\eta_y'^*$	±0.73	±0.23
Δx (μm) collision offset	10	10
Δs (μm) waist error	100	100
Δy,Δy'(μm,μrad) collision offset	0.02 (100)	
δx (μm) turn by turn noise	0.5	0.5
δy (nm)	4	4

The degradation is roughly quadratic

σx=6-10μm σy=60 nm

Beam noise

- Turn by turn noise without correlation in turns.



Ion instability

- Turn-by-turn noise due to ion instability.
- Coupled bunch instability with very high growth rate.
- Feedback system suppresses the instability.
- Residual dipole motion as a turn by turn noise may degrade the beam-beam performance.
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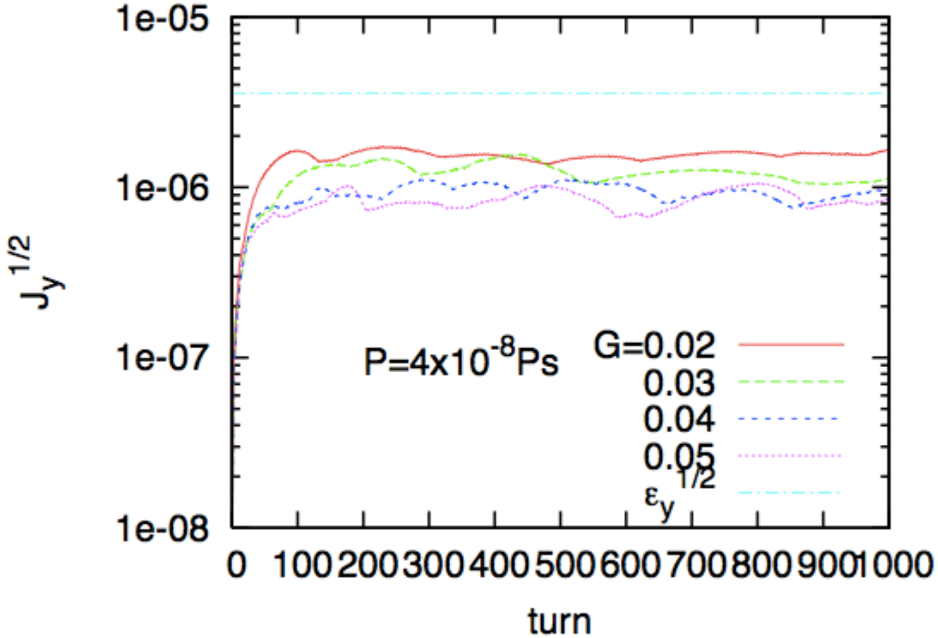
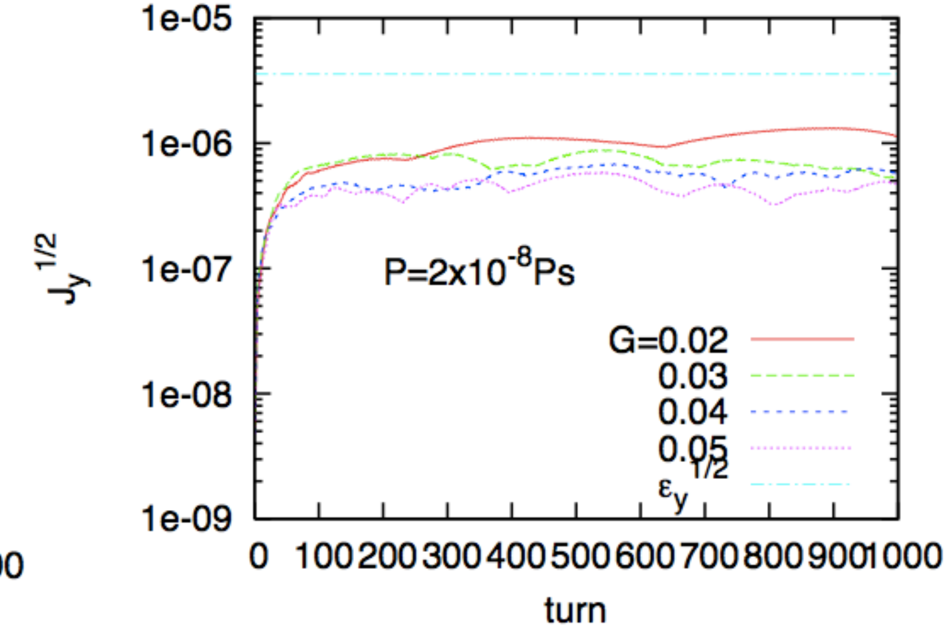
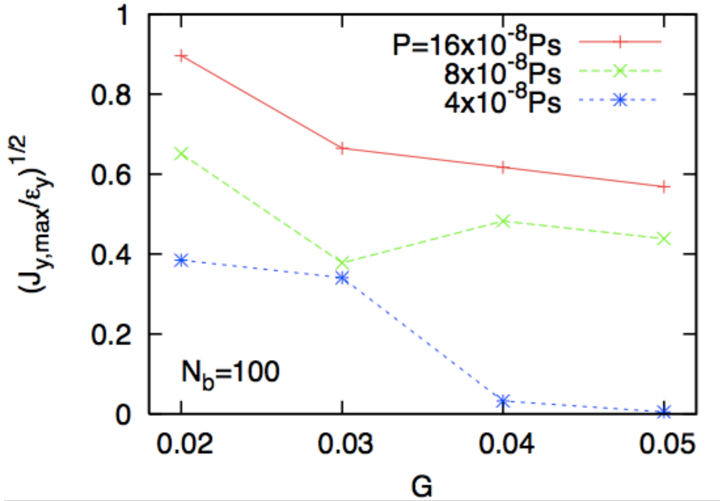
Instability growth with bunch-by-bunch feed back

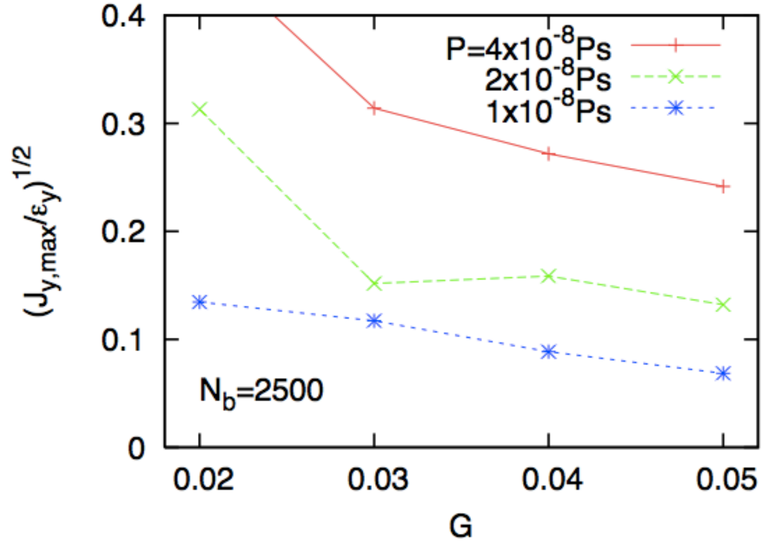


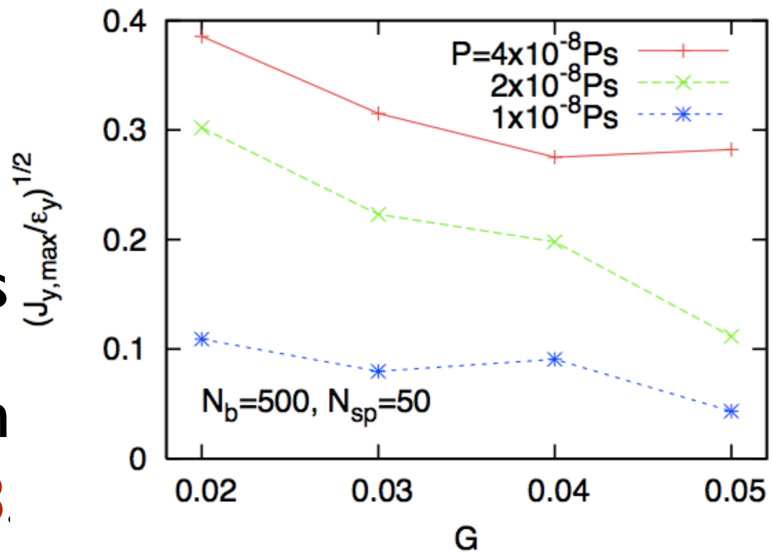


- Examples of ion instability growth
- Bunch train length of Nb=2500 with spacing=4ns.

Residual vertical amplitude







- The dipole oscillation has correlation time of 1/G turns
- The tolerance is relaxed with $G^{1/2}$. $(J/\varepsilon)^{1/2}$= 4/60/ $G^{1/2}$ ~0.38. Not very serious

Electron cloud instability

- $\omega_e \sigma_z / c$ is very high in low emittance rings.

- Single bunch instability
- Coupled bunch instability

Threshold of the strong head-tail instability (Balance of growth and Landau damping)

- Stability condition for $\omega_e\sigma_z/c>1$

$$\omega_e=\sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}$$

$$U=\frac{\sqrt{3}\lambda_p r_0\beta}{\nu_s \quad \gamma \quad \omega_e\sigma_z/c}\frac{|Z_\perp(\omega_e)|}{Z_0}=\frac{\sqrt{3}\lambda_p r_0\beta}{\nu_s \quad \gamma \quad \omega_e\sigma_z/c}\frac{KQ}{4\pi}\frac{\lambda_e}{\lambda_p}\frac{L}{\sigma_y(\sigma_x+\sigma_y)}=1$$

- Since $\rho_e=\lambda_e/2\pi\sigma_x\sigma_y$,

$$\rho_{e,th}=\frac{2\gamma\nu_s\,\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L}$$

Origin of Landau damping is momentum compaction

$$\nu_s\sigma_z=\alpha\sigma_\delta L$$

- $Q=\min(Q_{nl}, \omega_e\sigma_z/c)$
- $Q_{nl}=10$ in this presentation, depending on the nonlinear interaction.
- K characterizes cloud size effect and pinching.

Parameters

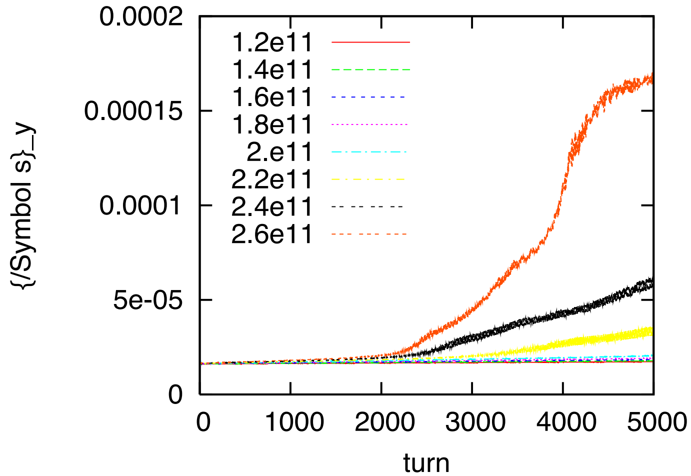
Table 1: Basic parameters of the positron rings

Lattice		KEKB	Cesr-TA	PETRA-III	SuperKEKB	Super B
Circumference	L (m)	3,016	768	2304	3016	1260
Energy	E (GeV)	3.5	2-5	6	4.0	6.7
Bunch population	$N_+(10^{10})$	8	2	0.5	9	5
Beam current	I_+ (A)	1.7	-	0.1	3.6	1.9
Emittance	ε_x(nm)	18	2.3	1	3.2	2
	ε_y(nm)	0.18	0.023	0.01	0.01	0.005
Momentum compaction	$\alpha(10^{-4})$	3.4	68	12.2	3.5	
Bunch length	σ_z(mm)	6	6.8	12	6	5
RMS energy spread	$\sigma_E/E(10^{-3})$	0.73	0.8		0.8	0.64
Synchrotron tune	ν_s	0.025	0.067	0.049	0.0256	0.0126
Damping time	τ_x(ms)	40	56.4	16	43	26

Table 2: Threshold of the B factories positron rings and others

		KEKB (no sol.)	KEKB (50 G sol.)	Cesr-TA	PETRA-III	SuperKEKB	SuperB
Bunch population	$N_+(10^{10})$	3	8	2		8	5
Beam current	I_+ (A)	0.5	1.7	-	0.1	3.6	1.9
Bunch spacing	ℓ_{sp}(ns)	8	7	4-14	8	4	4
Electron frequency	$\omega_e/2\pi$(GHz)	28	40	43	35	150	175
Phase angle	$\omega_e\sigma_z/c$	3.6	5.9	11.0	8.8	18.8	18.3
Threshold	ρ_e (10^{12} m^{-3})	0.63	0.38	1.7	1.2	0.27	0.54

SuperKEKB



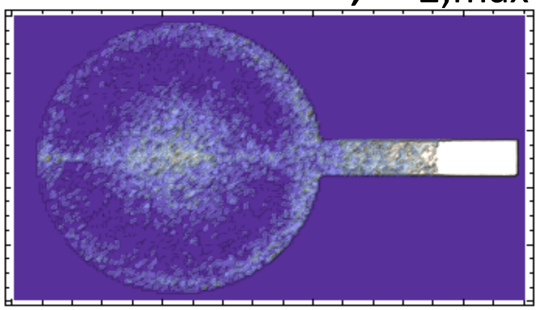
Y. Susaki, K. Ohmi, IPAC10

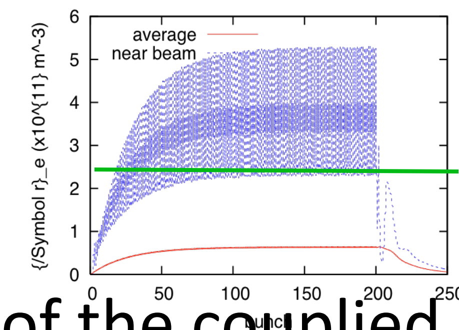
- Simulation ρ_{th}=2.1x10^{11} m^{-3}.(ν_s=0.012)
- Analytic ρ_{th}=2.7x10^{11} m^{-3}.
- Target ρ_e~1x10^{11} m^{-3}
- Take care of high β section. Effects are enhanced.

$$\oint \rho_e \beta_y ds/L = 10^{11} \times 10 \text{ m}^{-2}$$

Estimation of cloud density and coupled bunch instability

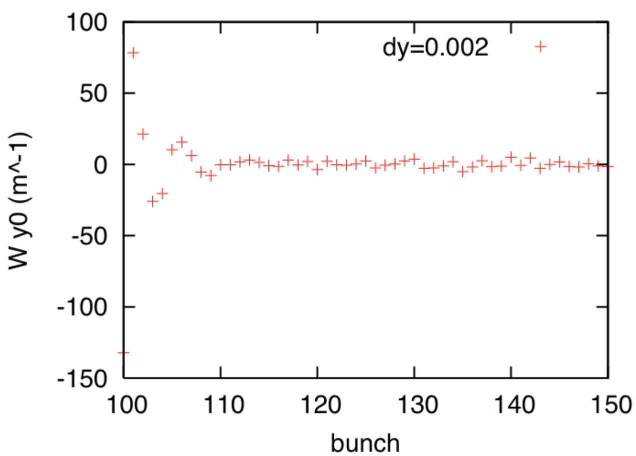
- Ante-chamber, $\delta_{2,max}$=1.2 without special structure like groove

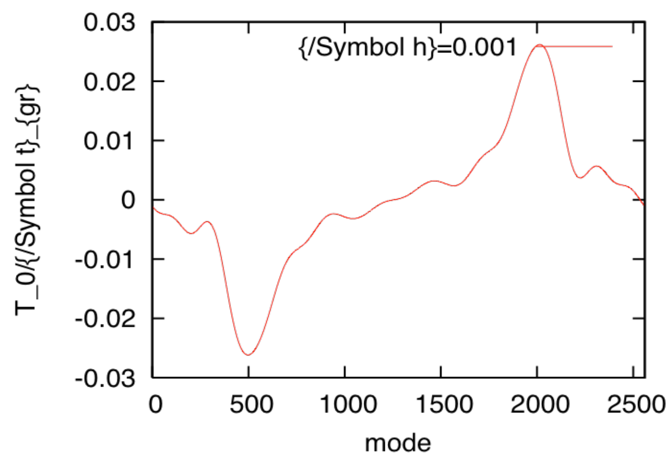




ρ_e=2.2x10^{11} m^{-3}

- Wake field and growth rate of the coupled bunch instability.



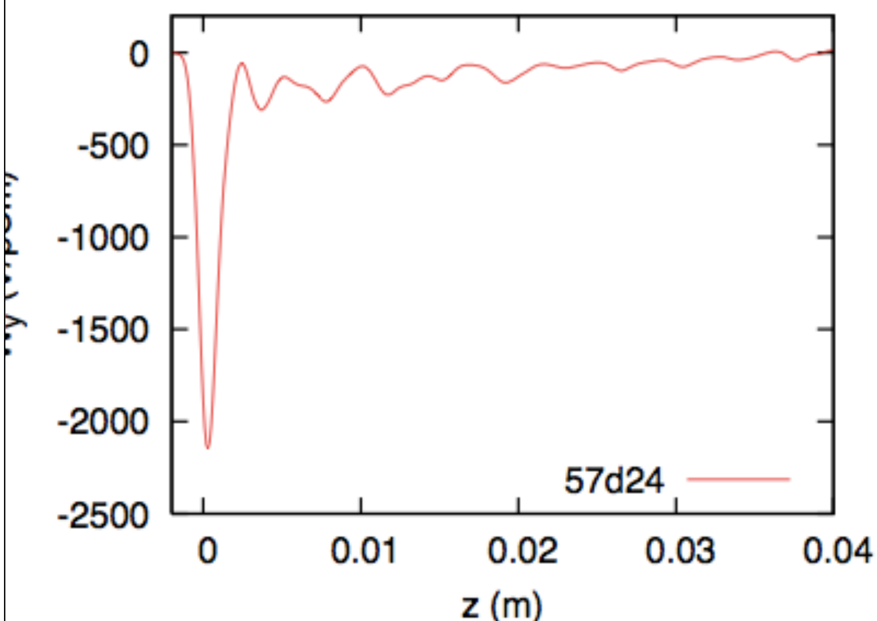


Growth time is 40 turns. It should be suppressed at ρ_e=1x10^{11} m^{-3}.

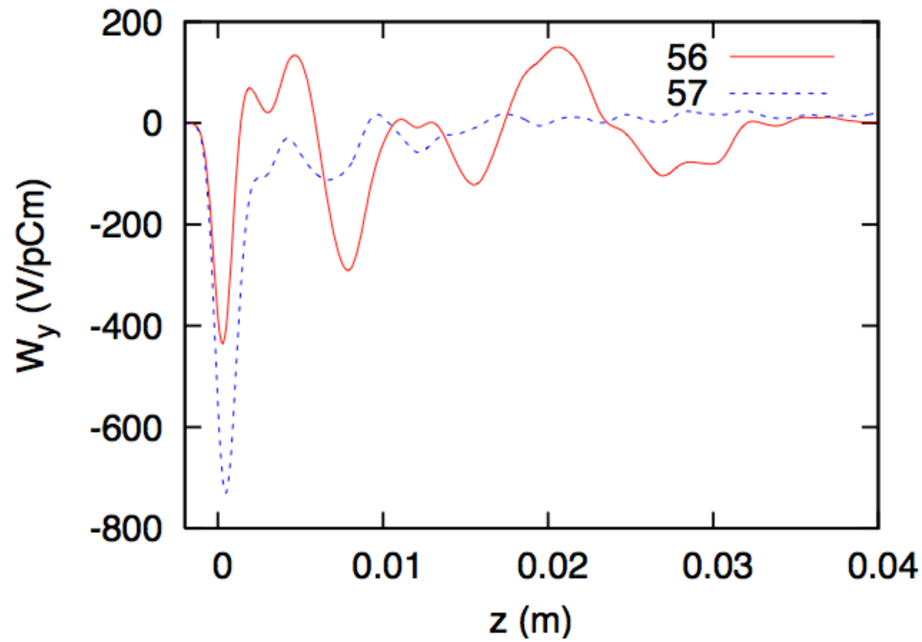
- Suetsugu-san estimates the density based on measurements and is designing the chamber to achieve density.

Impedance designed in 2011

d=2.4mm mask for LER



d=5mm mask for HER

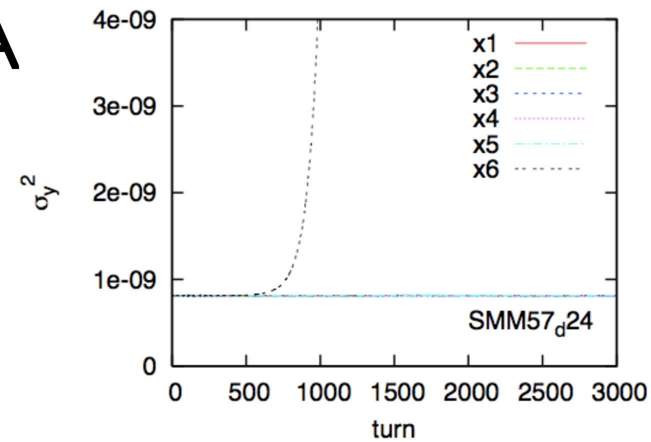


2 types numbered 56 & 57

TMCI (σ_z=6mm)

- LER : d=2.42 mm gap collimator at β_y=94m.

  I_{th}=1.44mAx5~6=7.2~8.6mA



- HER : two d=5 mm gap collimators at β_y=508m.

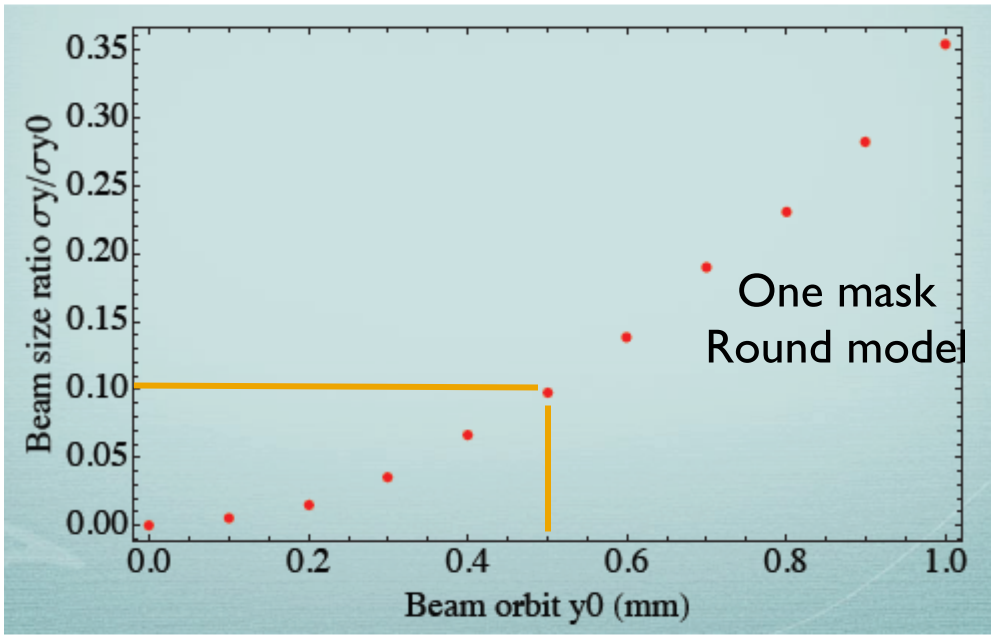
  I_{th}=1.04mAx2~3=2~3mA 1.04x1~1.5=1~1.5mA

- Consistent design for QCS aperture and TMCI is on going.

Beam tilt due to the impedance

$$\Delta y(z) = \sqrt{\beta_y \beta_y^*} \Delta y'(z) = \sqrt{\beta^*} \sum_i \sqrt{\beta_y(i)} y_0(i) \frac{1}{eE} \int_0^\infty \rho(z' + z) W_{y1}(z') dz'$$

D. Zhou & A. Chao



- Round model impedance: 1/10 of instability threshold.
- For the case of the impedance corresponding the instability threshold, tolerance of the orbit shift is 0.5 mm for 10% beam size increase.

Space charge tune shift in LER

Mikhail pointed out

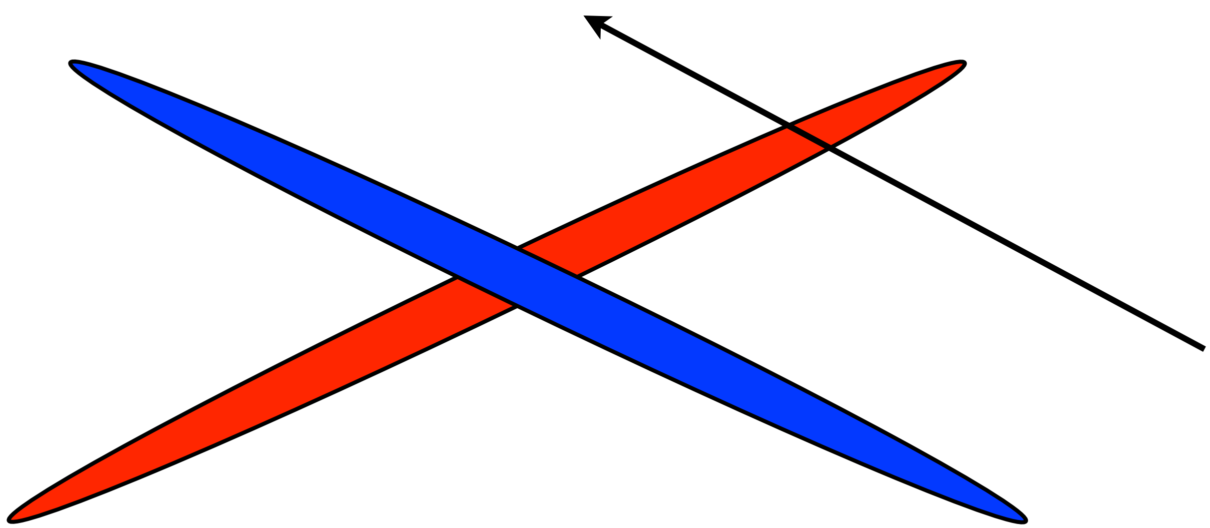
$$\Delta\nu_x = \frac{\lambda_p r_e \beta_x L}{2\pi\gamma_p^3 \sigma_x(\sigma_x + \sigma_y)} \approx -0.0056$$

$$\Delta\nu_y = \frac{\lambda_p r_e \beta_y L}{2\pi\gamma_p^3 \sigma_y(\sigma_x + \sigma_y)} \approx -0.11$$

- This tune shift is not very large compare than recent proton machines.
- Manageable perhaps?

Injection and life time

- beam-beam & simple revolution matrix
- beam-beam interaction, Nslice=300

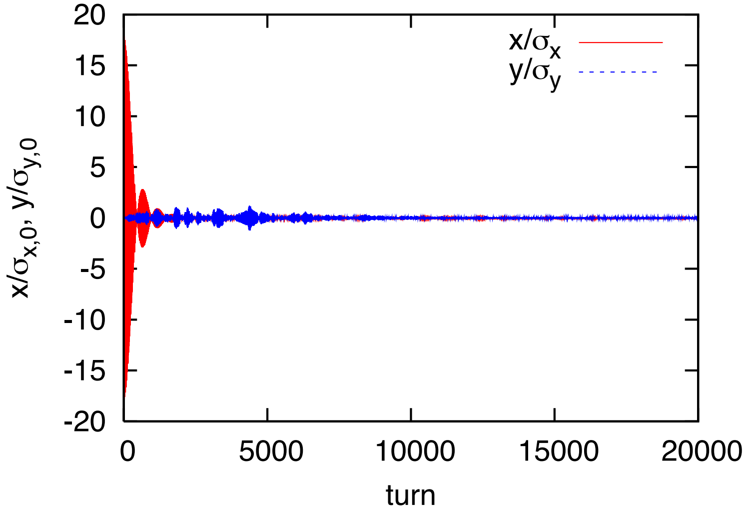


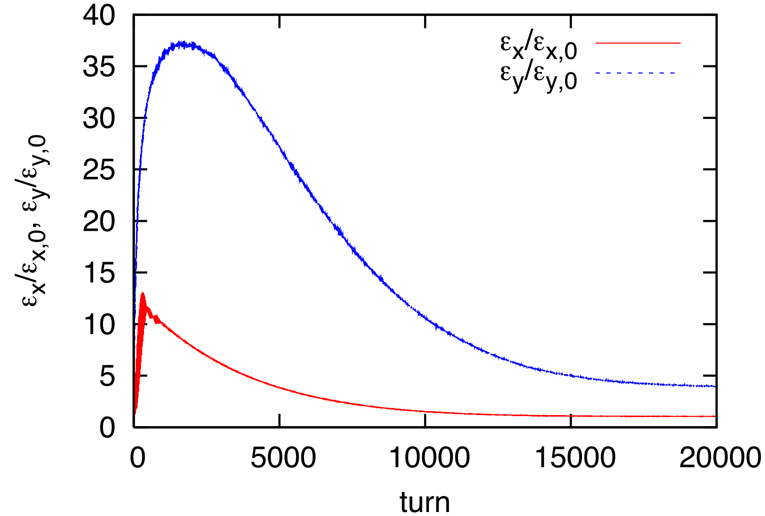
σ_x=6μm
x_0=180μm
$\sigma_z\Phi$=250μm
$dz=x_0/\Phi$=4mm
β_y/β_{y0}=180

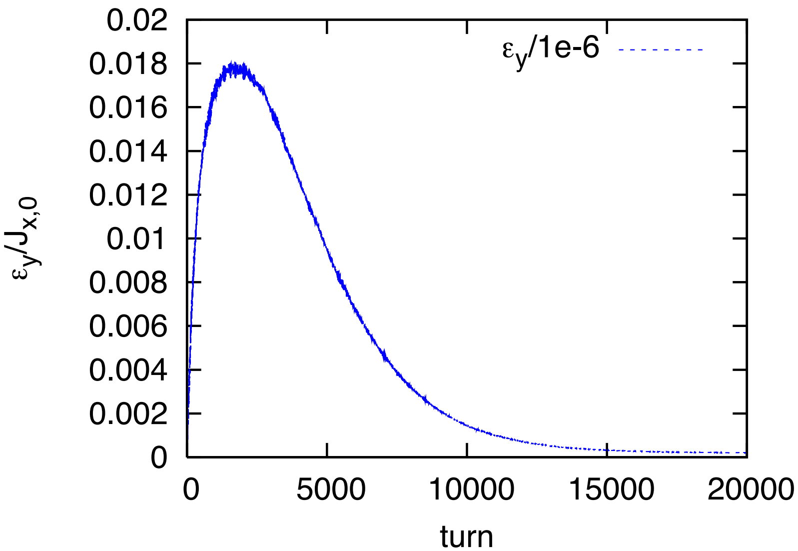
Crab waist β_y/β_{y0}=1

SAD simulation including lattice is also done.

No CW

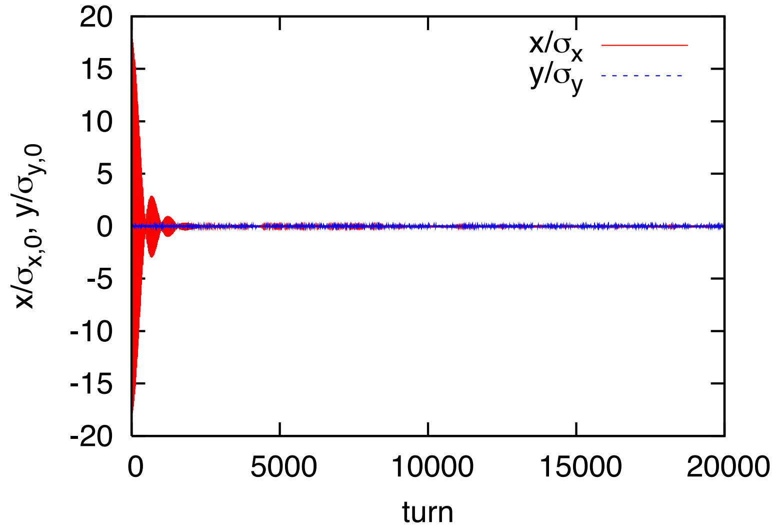


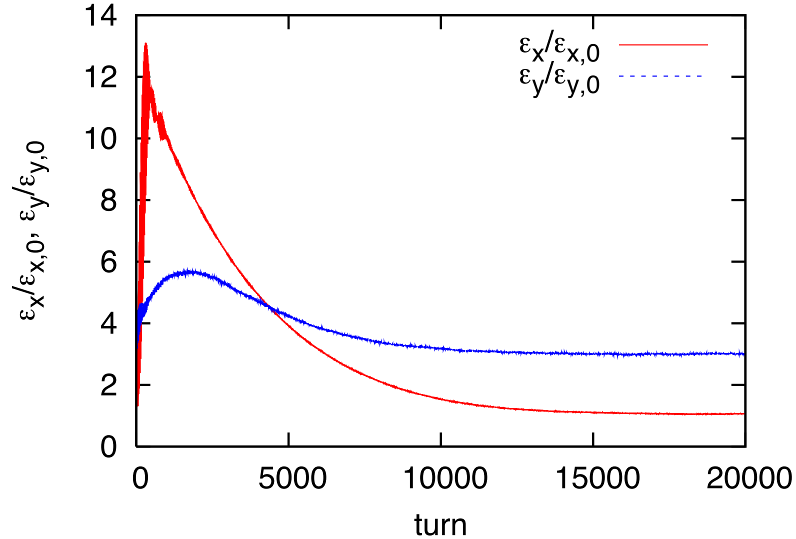


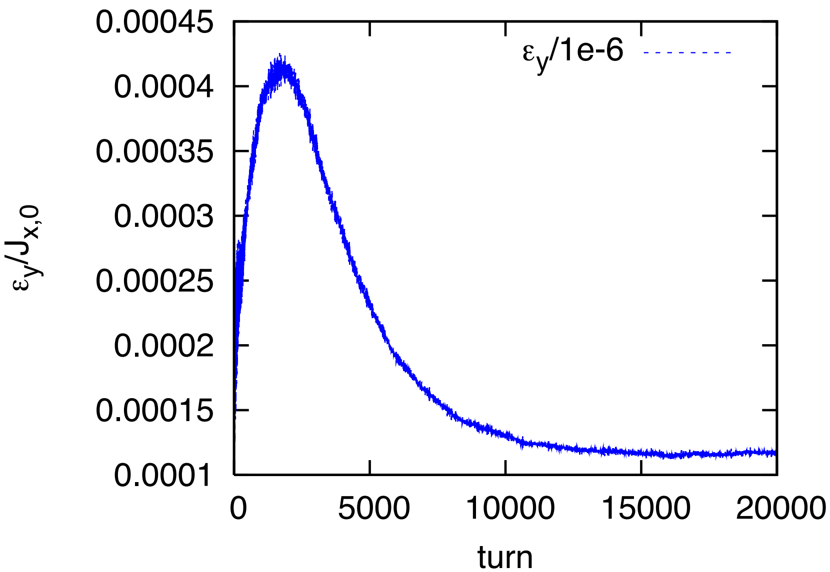


- ε_yは入射振幅の4%以下
- アパーチャにあまり影響してない?

CW

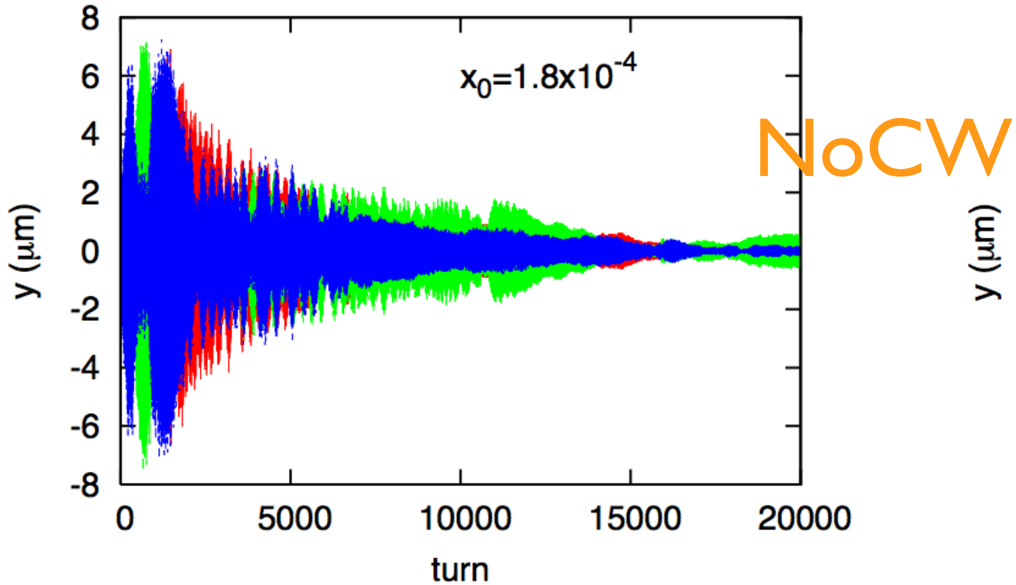


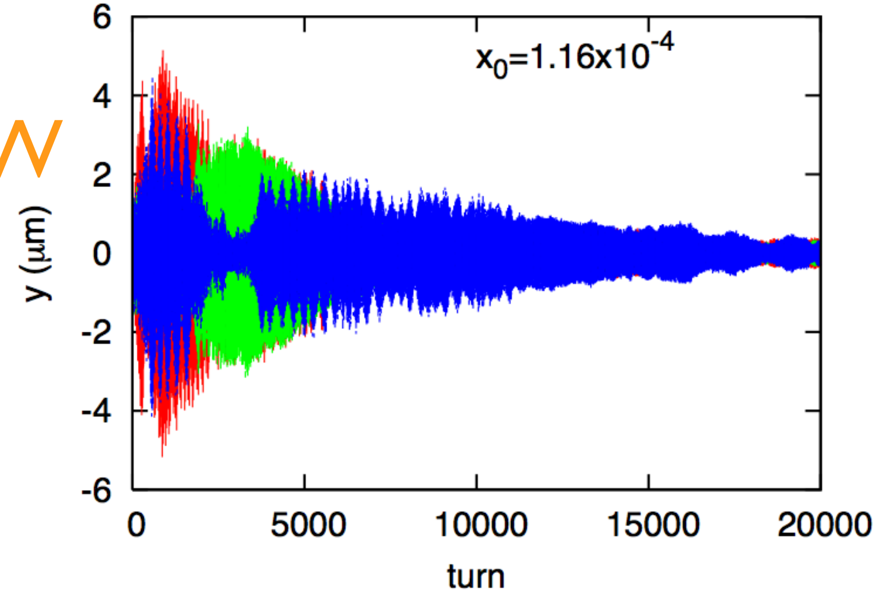


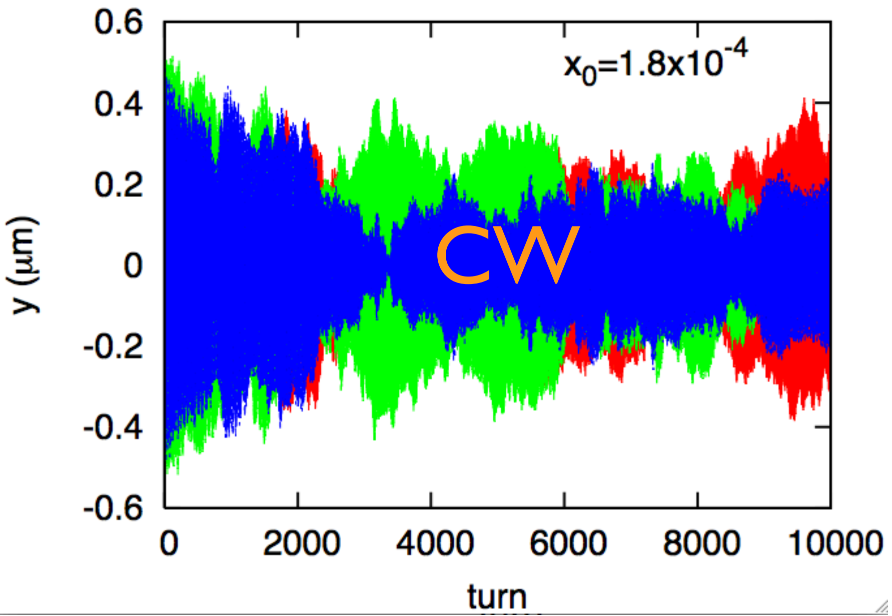


- $\varepsilon_y = 0.04\% J_{x0}$

Motion of three sampled particles

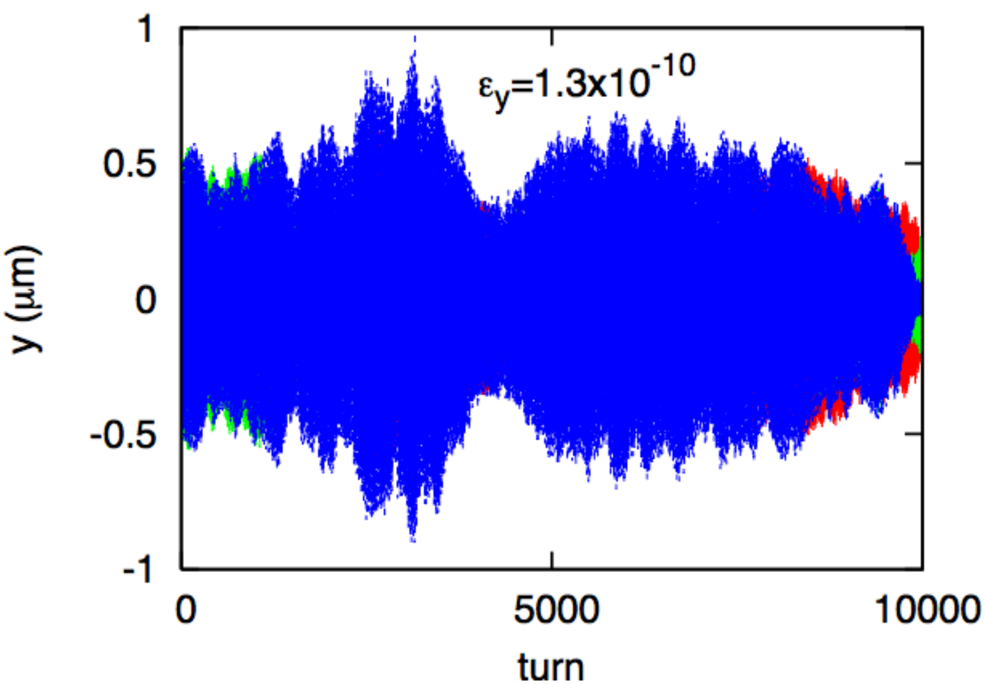


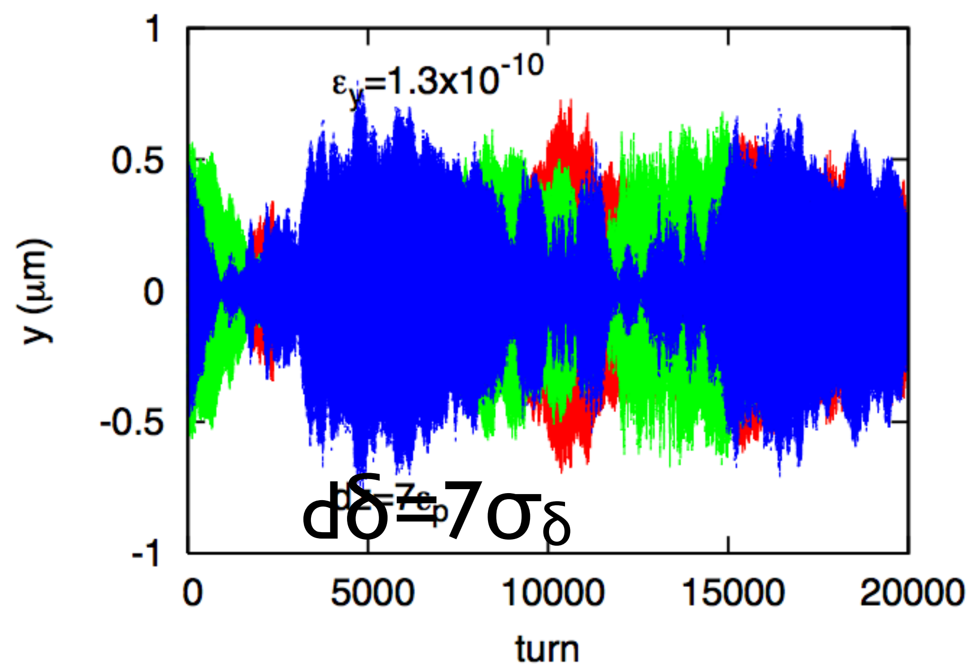




- Large vertical amplitude is induced for NoCW.
- Samll for Crab waist $\varepsilon y=1.3\mathrm{x}10^{-10}$, $\sigma y=0.2\mu m$

Synchrotron injection



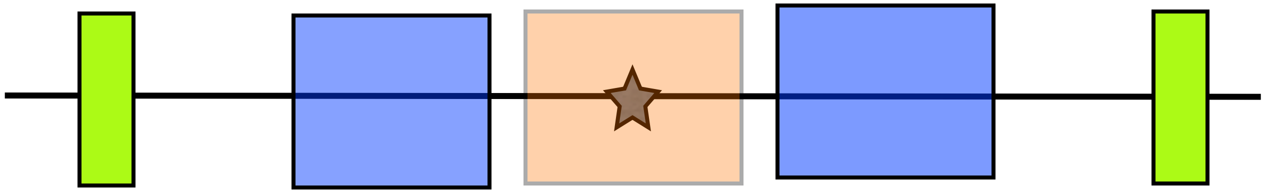


- z oscillation does not induce vertical motion.
- Synchrotron injection is proposed especially in HER (smaller dynamic aperture than LER)

Touschek life time

- Horizontal amplitude is induced by dispersion at Touschek events.
- Vertical emittance increases for large horizontal amplitude without CW.
- Beam-beam make worse Touschek life time.
- This effect is being studied.

Crab waist and IR nonlinearity



$$\mathcal{M}_{IR} = e^{-axy^2} e^{-H_{Q's}} e^{-H_{Sol}} e^{-H_{BB}} e^{-H_{Sol}} e^{-H_{Q's}} e^{-axy^2}$$

$$\not\parallel$$

$$e^{-H_{Q's}} e^{-H_{Sol}} e^{-xp_y^2/2\phi} e^{-H_{BB}} e^{-xp_y^2/2\phi} e^{-H_{Sol}} e^{-H_{Q's}}$$

- Strong dynamic aperture degradation is seen by crab sextupole installation (H. Koiso).
- We do not know how to handle the nonlinear terms of Q's and Solenoid located at very high β.
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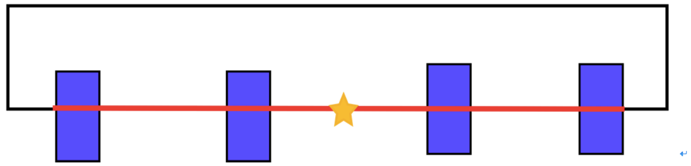
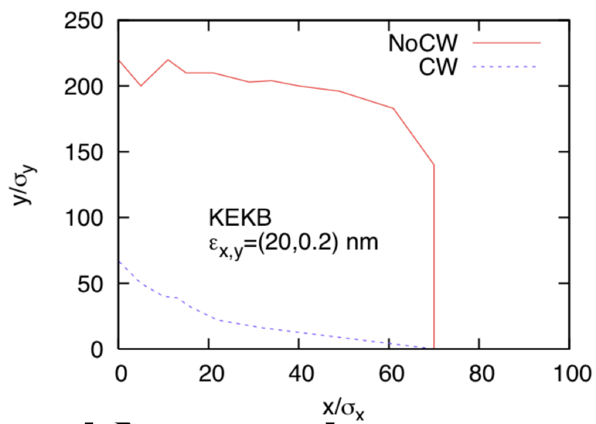
Study with a simple model

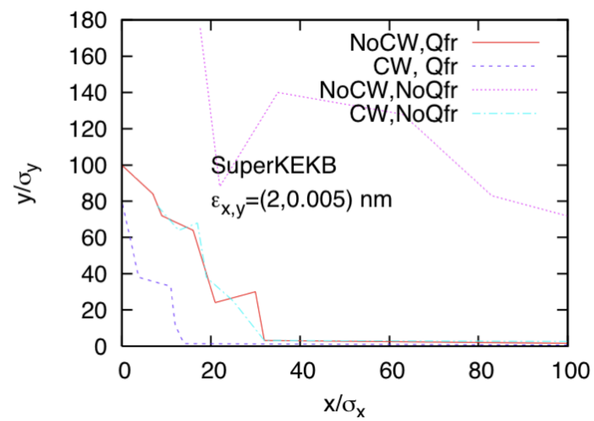
K.Ohmi & H.Koiso, IPAC10



$$\mathcal{M}_{IR} = e^{-H_{QF}} e^{-H_{L1}} e^{-H_{QD}} e^{-H_{L0}} e^{-H_{L0}} e^{-H_{QD}} e^{-H_{L1}} e^{-H_{QF}}$$

$$\mathcal{M}_{rev} = \mathcal{M}_{IR} \mathcal{M}_{arc}$$





- Dynamic aperture is degraded by installation of crab waist sextupoles.

Crab waist or not

- Crab waist scheme well matches the large Piwinski angle collision for injection and Touschek event if dynamic aperture is sufficient.
- It seems to be hard to use the crab waist scheme in very low beta interaction point for the dynamic aperture issue.
- Do we have a local chromaticity and nonlinearity compensation technique? This is very interesting subject.

Summary

- Beam dynamics studies have been continued as is listed in SuperKEKB.

- Dynamic aperture study is most important.
- Especially, "crab waist or not" is interesting subject for beam-beam interaction, aperture, injection, life time...

- This can be one of collaboration subjects between SuperB and SuperKEKB.

Others

- Background studies are being performed by H. Nakayama, Y. Ohnishi et al.
- Damping ring micro-bunch instability is studied by H. Ikeda and D. Zhou.
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