Beam-beam effect and degree of freedom

K. Ohmi

KEK

Contents

- Incoherent emittance growth and diffusion in Gaussian model
- Effect of crossing angle
- Mysterious of the beam-beam limit, Non-Gaussian distribution.
- Feedback noise
- Coherent motion and tune difference

Incoherent effects

- Weak-strong model is available, if we know a self consistent distribution of beams.
- Emittance growth due to nonlinear force interacting with a fixed charged distribution,

1. Gaussian, simple but not almighty,
2. Non-Gaussian, determined by strong-strong simulation, discussed later.

$$\varepsilon = \varepsilon_0 (1 + D_C t) \qquad \sigma^2 = \sigma_0^2 (1 + D_C t)$$

Synchrotron radiation, excitation and damping

- Damping, τ: damping time

$$\varepsilon = \varepsilon_0 (1 - 2t/\tau) \qquad \sigma^2 = \sigma_0^2 (1 - 2t/\tau)$$

- Equilibrium emittance is determined by the balance of radiation excitation and diffusion. The equilibrium emittance is ε_0 for $D_\gamma=2/\tau$
- KEKB $D_\gamma=5\text{x}10^{-4}$ /turn DAFNE $D_\gamma=1.8\text{x}10^{-5}$ /turn
- Correlation between the diffusions due to radiation and nonlinearity.

Non-correlation

$$\frac{\varepsilon(t=\infty)}{\varepsilon_0} = \frac{(D_\gamma + D_C)}{D_\gamma}$$

Correlation

$$\frac{\varepsilon(t=\infty)}{\varepsilon_0} = \frac{D_\gamma + D_C + D_{C\gamma}}{D_\gamma}$$

Symplectic diffusion due to the beam-beam interaction

- Calculate diffusion rate for symplectic system.
- Use Gaussian model.

$$U(x,y;\sigma_x(z),\sigma_y(z)) = -\frac{N(z)r_e}{\gamma}\int_0^\infty \frac{\exp\left(-\frac{x^2}{2\sigma_x^2+u}-\frac{y^2}{2\sigma_y^2+u}\right)}{\sqrt{2\sigma_x^2+u}\sqrt{2\sigma_y^2+u}}du$$

$$\mathbf{x}(s+0) = S\exp\left[-:\int_{-\Delta}^{\Delta} V_0^{-1}(s)U(s)V_0(s)ds:\right]\mathbf{x}(s-0)$$

$$V_0(s) = S\exp\left[-:\int_0^s \frac{p_x^2+p_y^2}{2}ds:\right] \qquad \mathbf{x} = (x,p_x,y,p_y,z,\delta)^t$$

- Synchro-beta mapping, by Danilov et al, and Hirata et al.
- Strong beam is sliced into some pieces with z_i. s is now function of z_i and z.

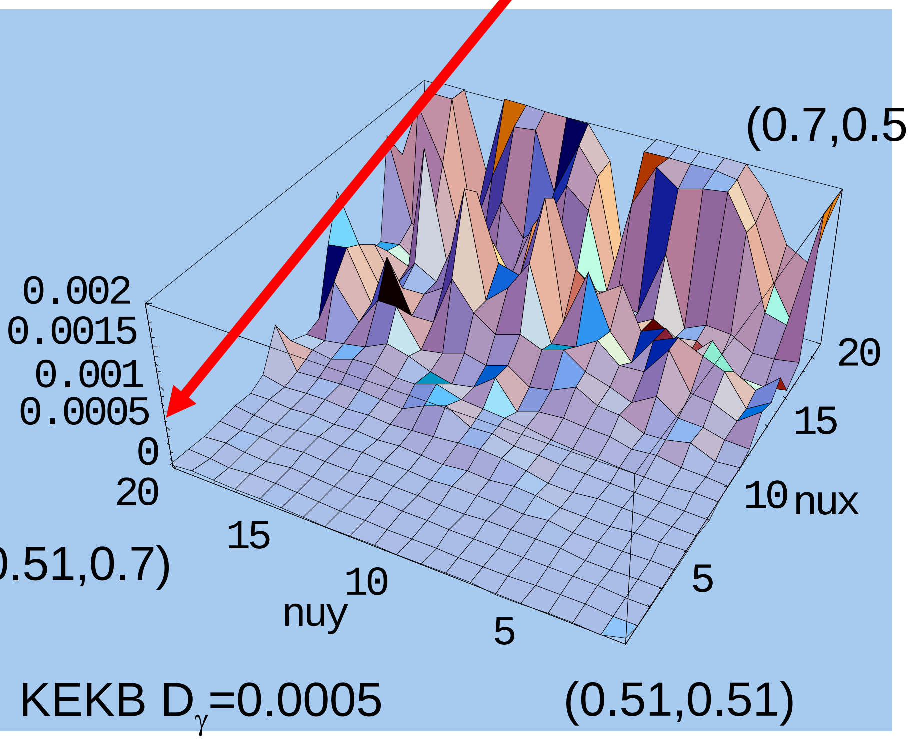
Diffusion rate in tune space

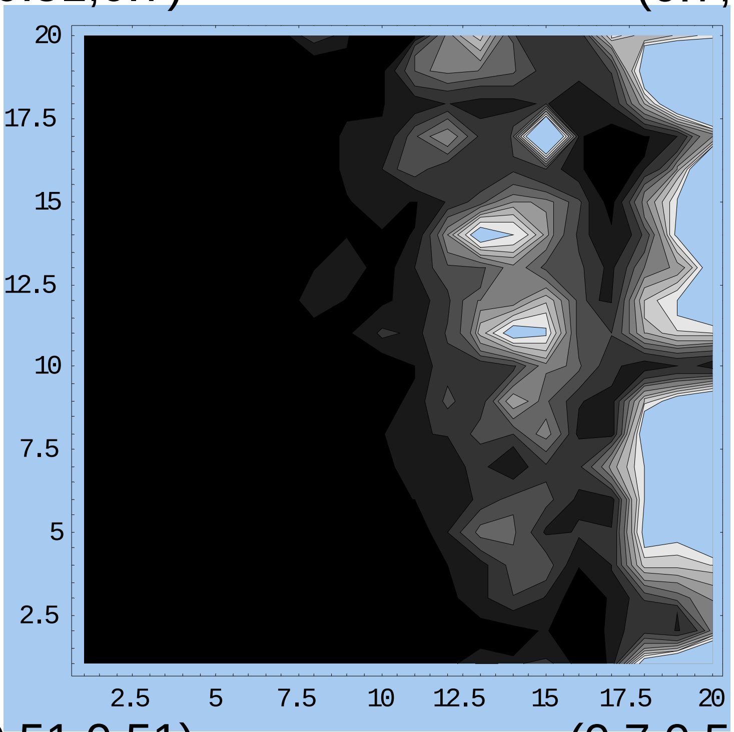
- We investigate emittance growth, diffusion, due to symplectic nonlinear force.
- These calculation is done for KEKB. Higher statistics is needed for DAFNE, because small diffusion rate should be concerned.

  KEKB D_γ=5x10^{-4} /turn   DAFNE D_γ=1.8x10^{-5} /turn
- Increment of second order moment $\langle y^2 \rangle$ is evaluated. Luminosity decrement is somewhat easier than the diffusion of the second moment.

Two dimensional model

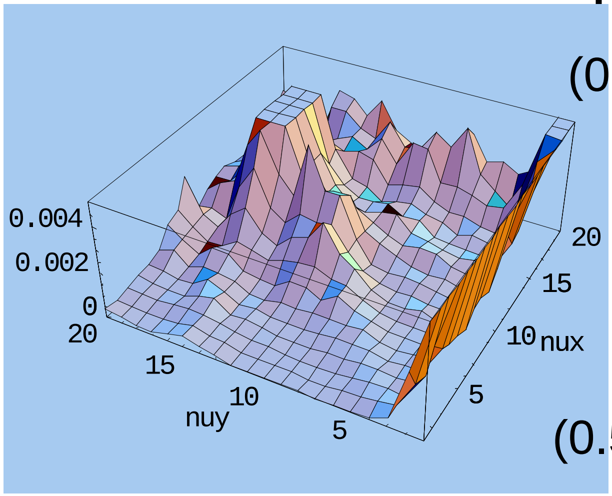
- Vertical diffusion for ξ=0.136
- $D_C \ll D_\gamma$ for wide region (painted by black).
- No emittance growth, if no interference. Actually, simulation including radiation shows no luminosity degradation nor emittance growth in the region.
- Note KEKB $D_\gamma=5\times10^{-4}$ /turn   DAFNE $D_\gamma=1.8\times10^{-5}$ /turn





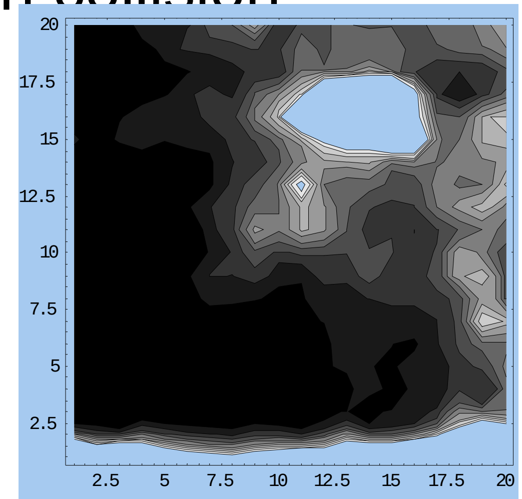
3-D simulation including bunch length ($\sigma_z \sim \beta_y$)

Head-on collision



(0.7,0.51)

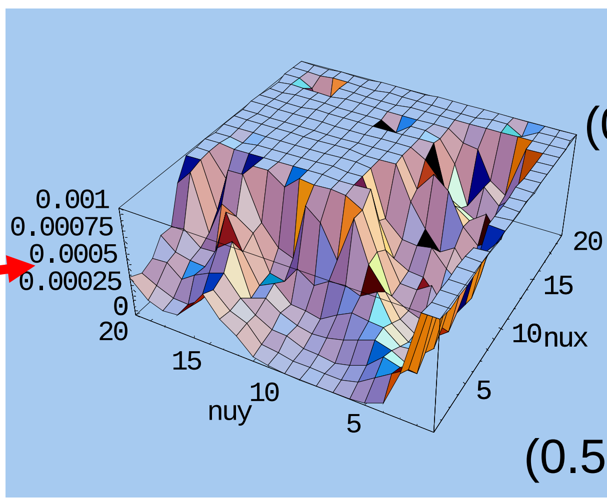
(0.51,0.51)



- Good region shrunk drastically.
- Synchrobeta effect near $\nu y \sim 0.5$.
- $\nu x \sim 0.5$ region remains safe.

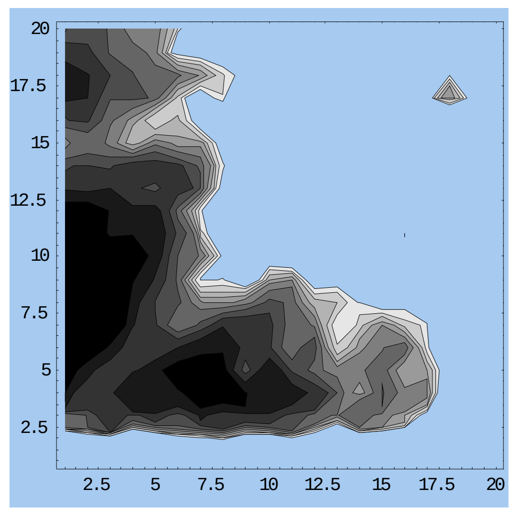
- Global structure of the diffusion rate.
- Fine structure near $\nu_x = 0.5$

Contour plot

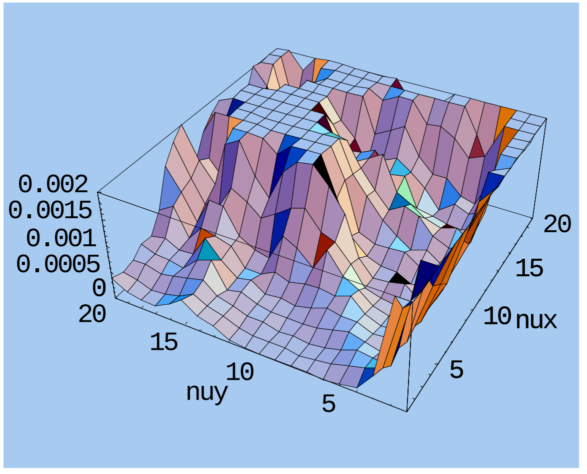


(0.7,0.51)

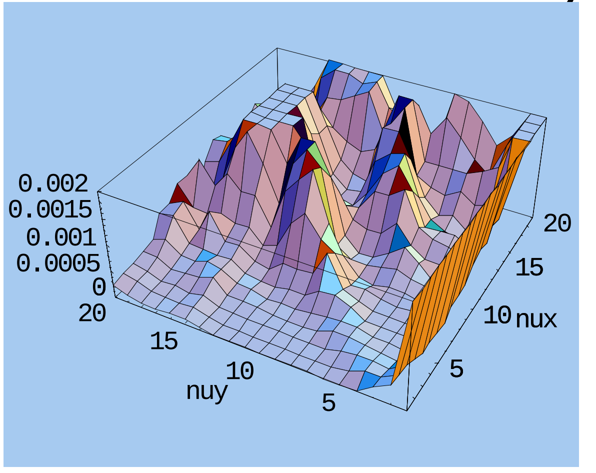
(0.51,0.51)



Bunch length dependence ($\sigma_z \sim \beta_y/2$)

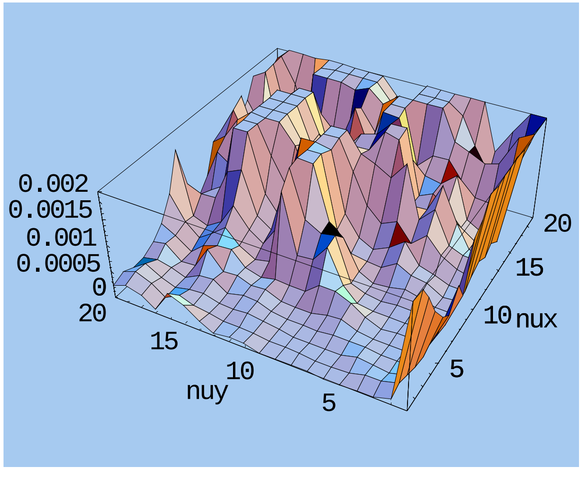


$\sigma_z \sim \beta_y$

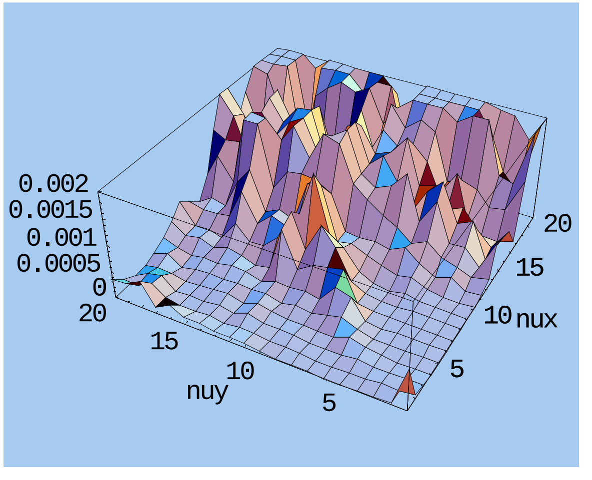


$\sigma_z \sim \beta_y/2$

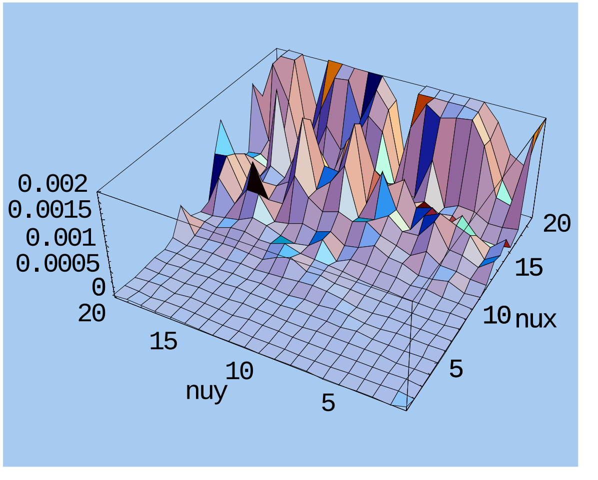
$\sigma_z \sim \beta_y/4$



$\sigma_z \sim \beta_y/10$



2 dim.

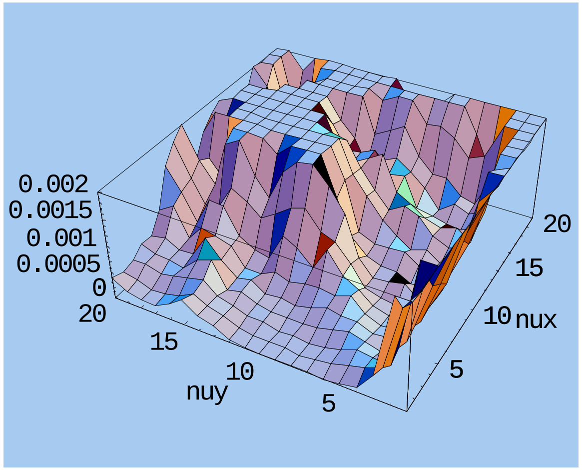


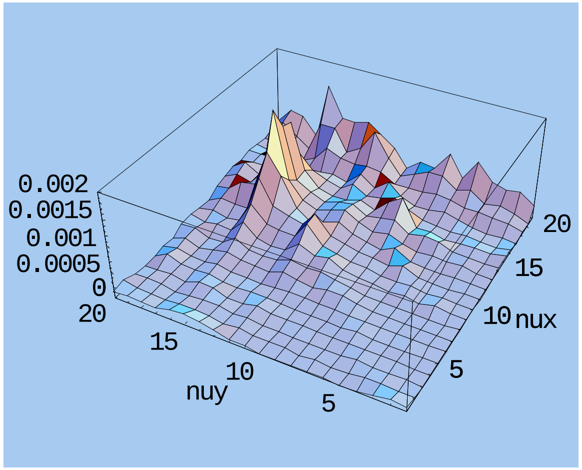
Shorter bunch is better.

Synchrotron tune

- Slow synchrotron tune is better

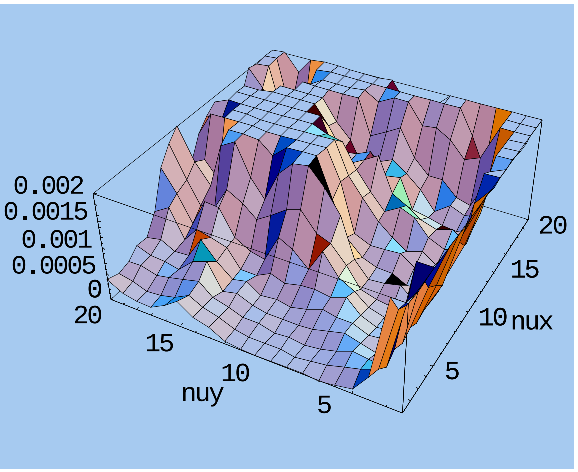
ν_s=0.024 ν_s=0.004



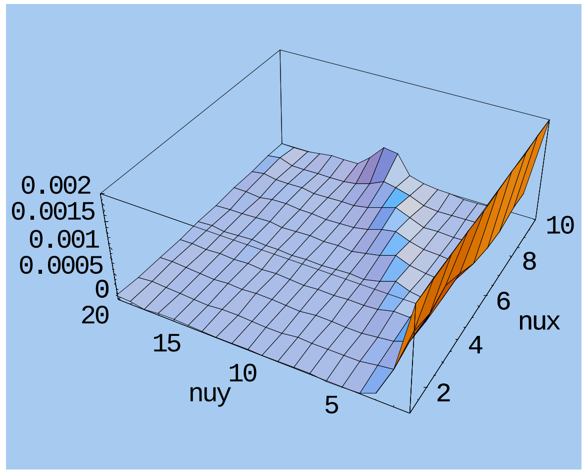


Current - ξ parameter

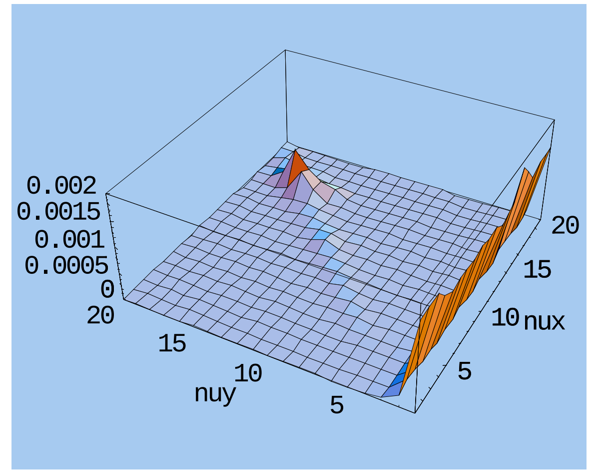
ξ=0.136



0.07



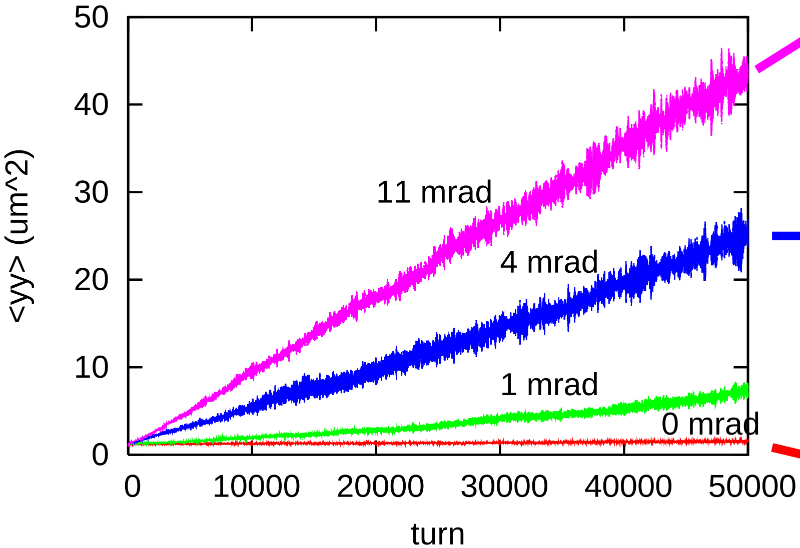
0.035

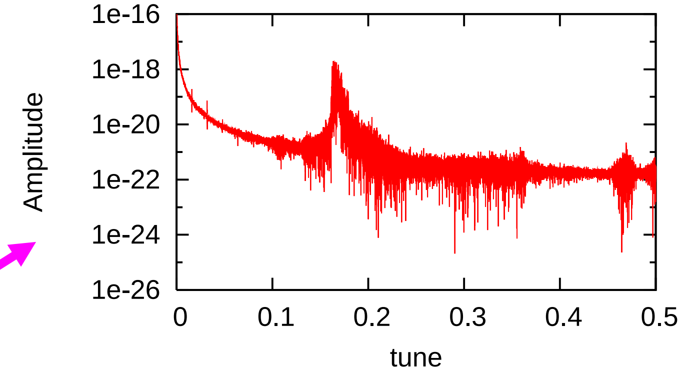


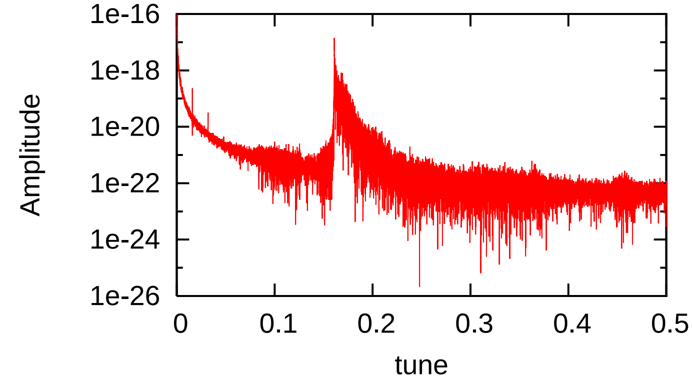
The diffusion rate strongly depend on the beam-beam parameter

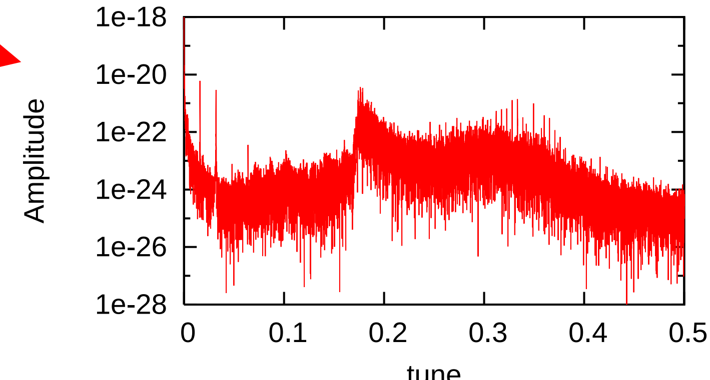
- Note KEKB D_γ=5x10^{-4} /turn DAFNE D_γ=1.8x10^{-5} /turn

Diffusion due to crossing angle and frequency spectra of <y^2>





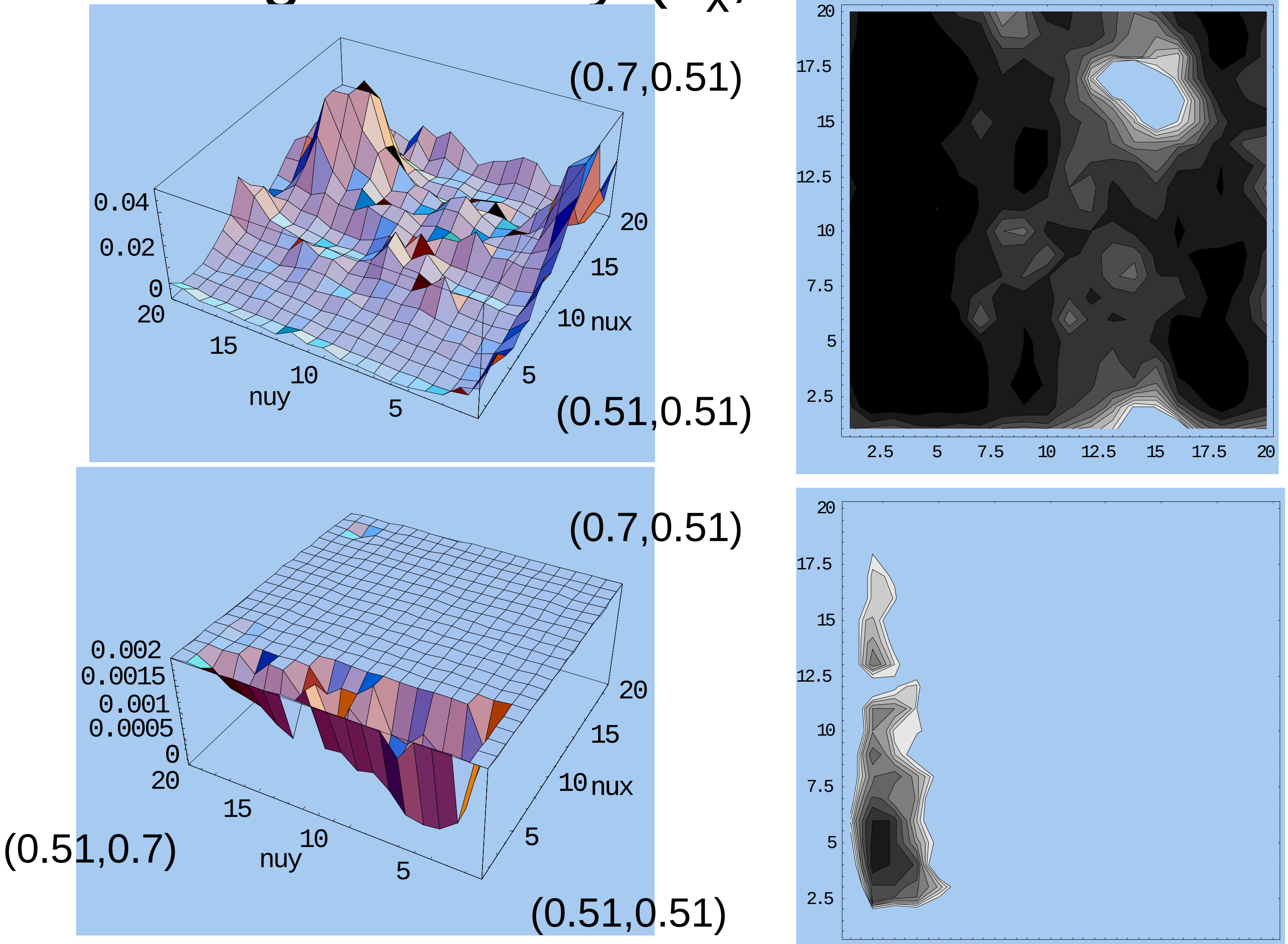




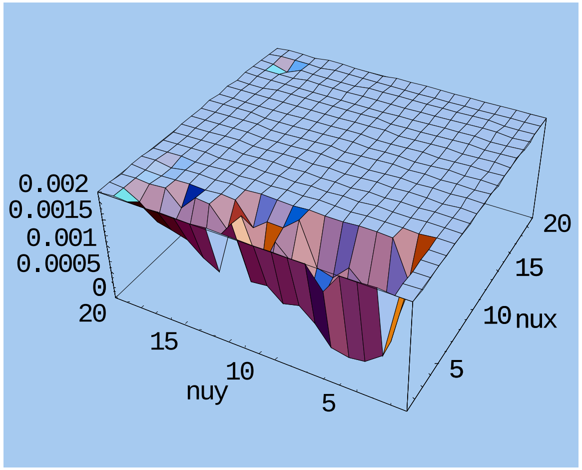
Only $2\nu_y$ signal was observed.

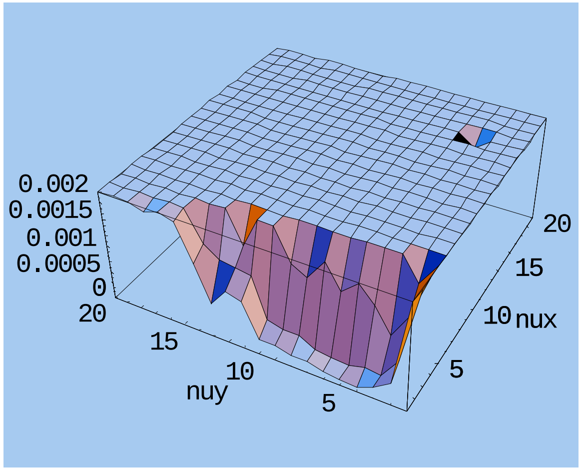
Crossing angle ($\phi\sigma_z/\sigma_x \sim 1$, $\sigma_z \sim \beta_y$)

- Good region is only $(\nu_x, \nu_y) \sim (0.51, 0.55)$.



Bunch length dependence for finite crossing angle (11 mrad)



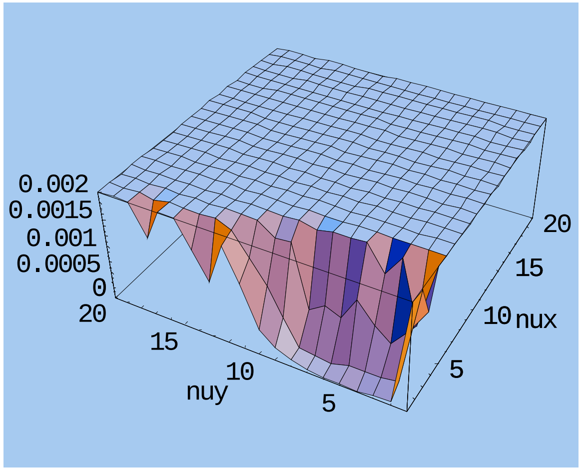


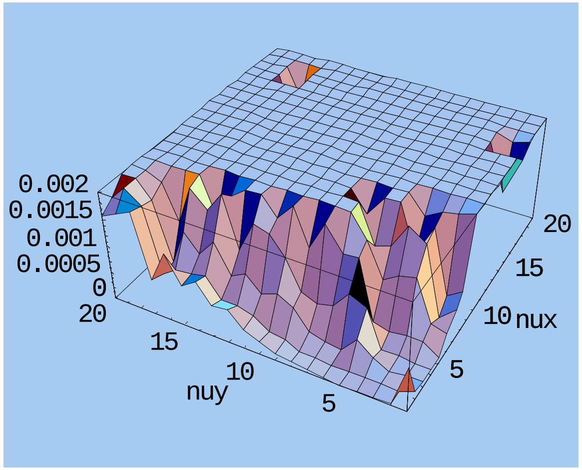
$\sigma_z \sim \beta_y$

$\sigma_z \sim \beta_y/2$

$\sigma_z \sim \beta_y/4$

$\sigma_z \sim \beta_y/10$

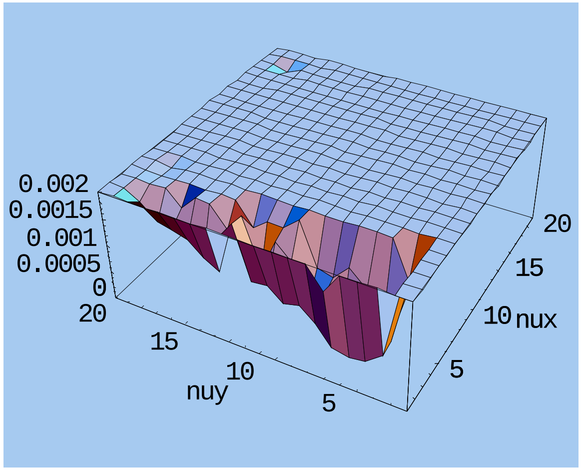


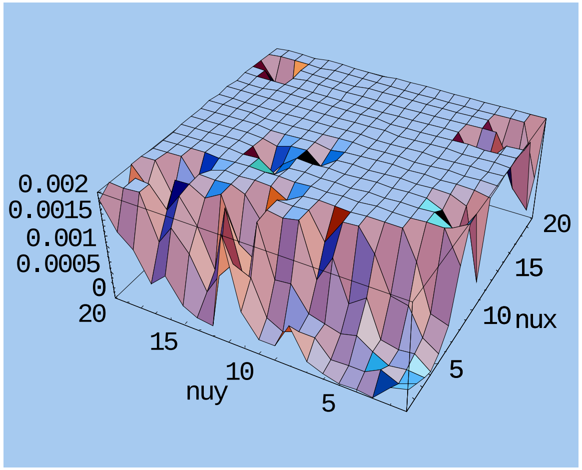


Even in very short bunch, the effect is not negligible.

Synchrotron tune dependence for crossing angle 11mrad

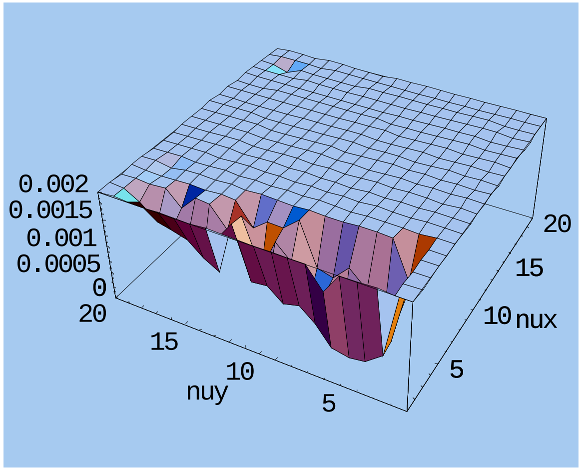
- ν_s=0.024 ν_s=0.004

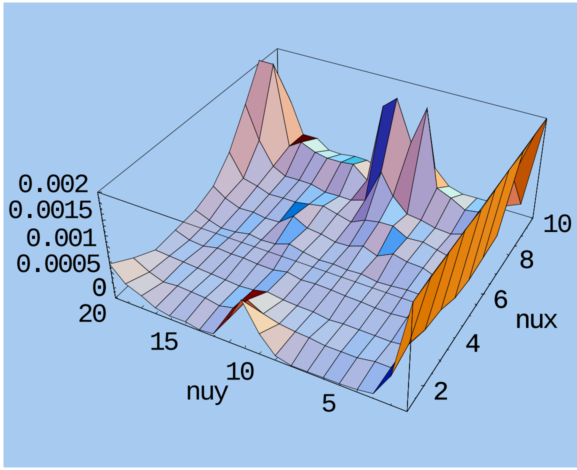


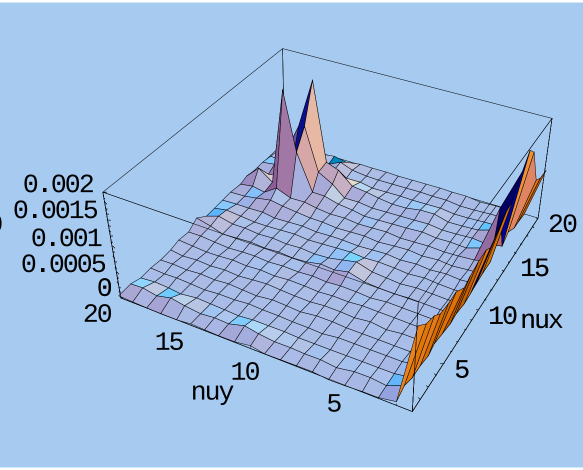


Current dependence for crossing angle, 11 mrad

ξ=0.136 0.07 0.035

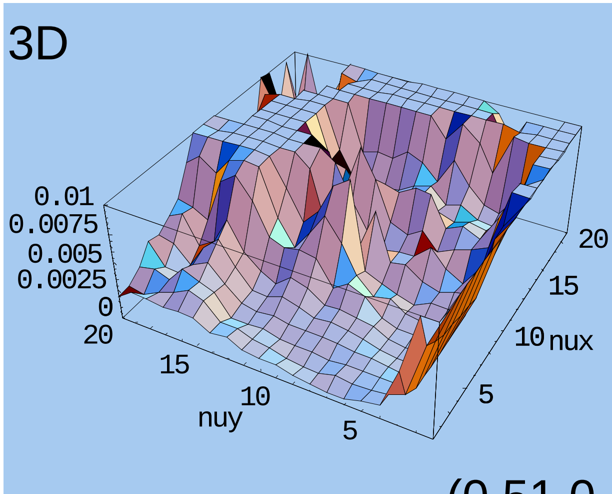




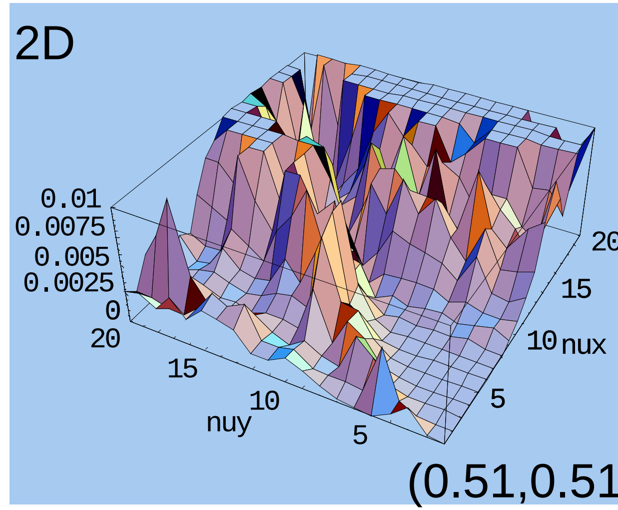


The diffusion rate strongly depend on the beam-beam parameter.

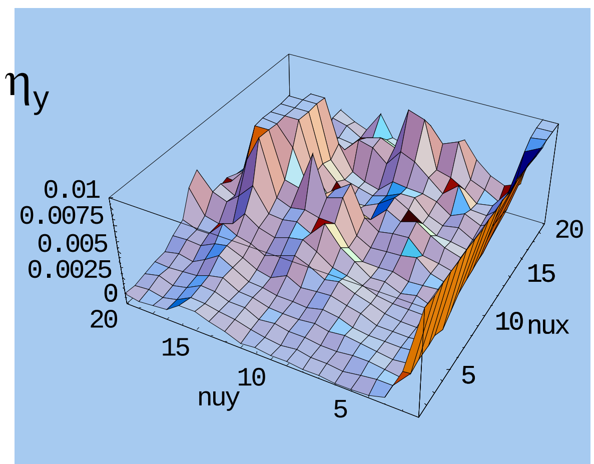
X-y coupling and dispersion at the collision point



(0.51,0.51)



(0.51,0.51)



(0.51,0.51)

- X-Y coupling in 3D and 2D model. Very different behavior.
- Vertical dispersion, η_y=1mm.
- They have strong effects.
- Note KEKB $D_\gamma=5\times10^{-4}$ /turn DAFNE $D_\gamma=1.8\times10^{-5}$ /turn

Fearless hypothesis in incoherent emittance growth

$$\lim_{\nu_x \to 0.5+} D_{C,y} = 0$$

if zero-crossing angle and no error. Discuss again later.

- Dynamic beta, and emittance

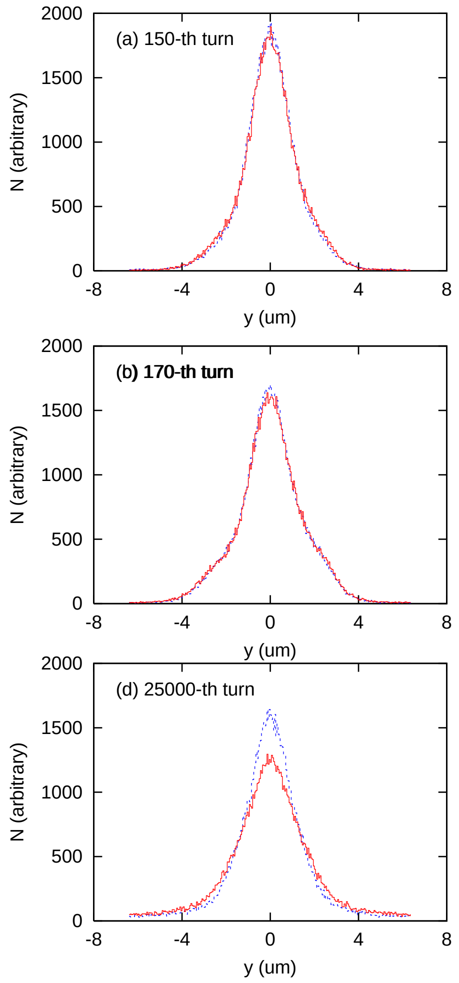
$$\lim_{\nu_x \to 0.5+} \left\langle x^2 \right\rangle < \sigma_{x,0}^2 \qquad \lim_{\nu_x \to 0.5+} \left\langle p_x^2 \right\rangle = \infty$$

- Choice of optimum ν_x

Mysterious of the beam-beam limit -Non-Gaussian distribution-

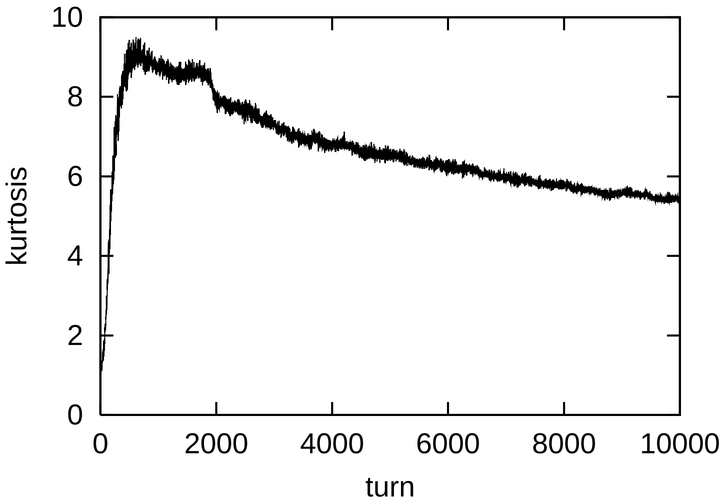
- Beam-beam limit near operating point (0.51,0.55-0.58) is very high (~0.3) in Gaussian model.
- Strong-strong simulation gives a beam-beam limit ~0.1-0.15.
- Charge distribution of the both beam distorted from Gaussian, higher Kurtosis.
- The beam-beam limit is reproduced by **2-D** model and/or weak-strong model, if the strong beam as fixed charge distribution has the self-consistent distorted distribution given by strong-strong simulation.
- Radiation excitation is essential for the emittance growth which cause the beam-beam limit.

Beam-beam limit seen in the strong-strong simulation

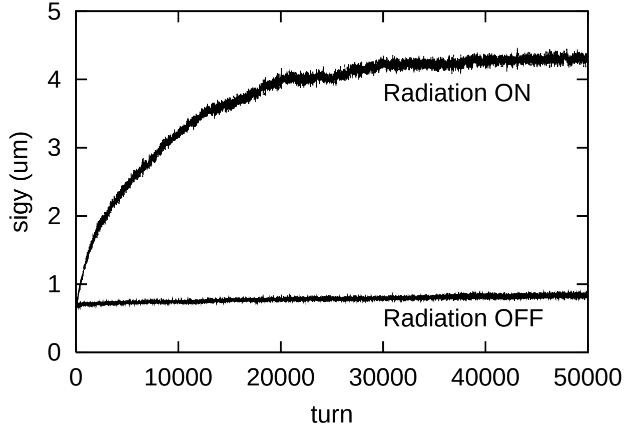


- Beam-beam limit is caused by a change of beam charge distribution.

Kurtosis $=\langle x^4\rangle/3\langle x^2\rangle^2$

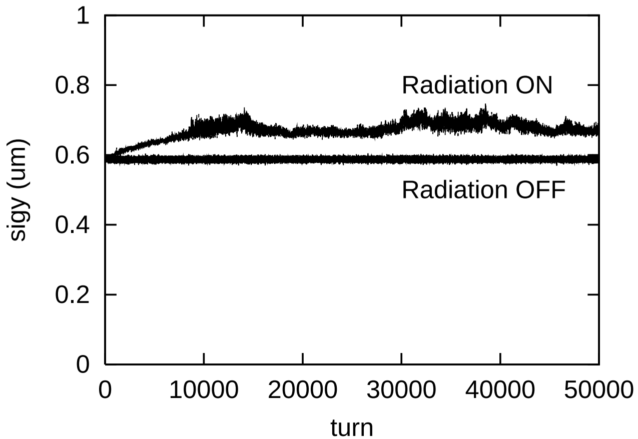


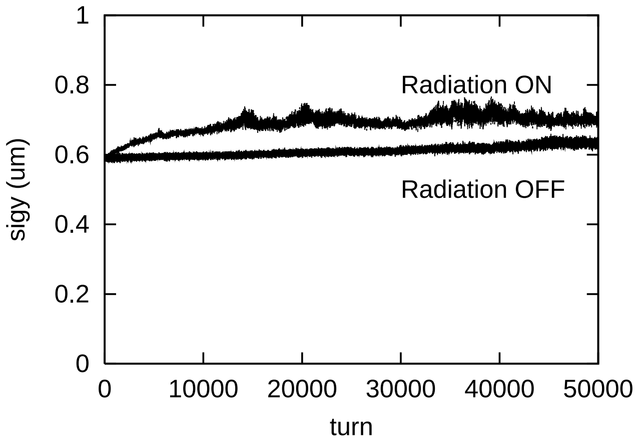
Diffusion seen in the vertical beam size



Strong beam：distorted beam

- Weak-strong simulation using distorted and Gaussian distributions.
- Emittance growth is induced by radiation excitation for the distorted strong beam.
- In the Gaussian strong beam, no strong emittance growth.

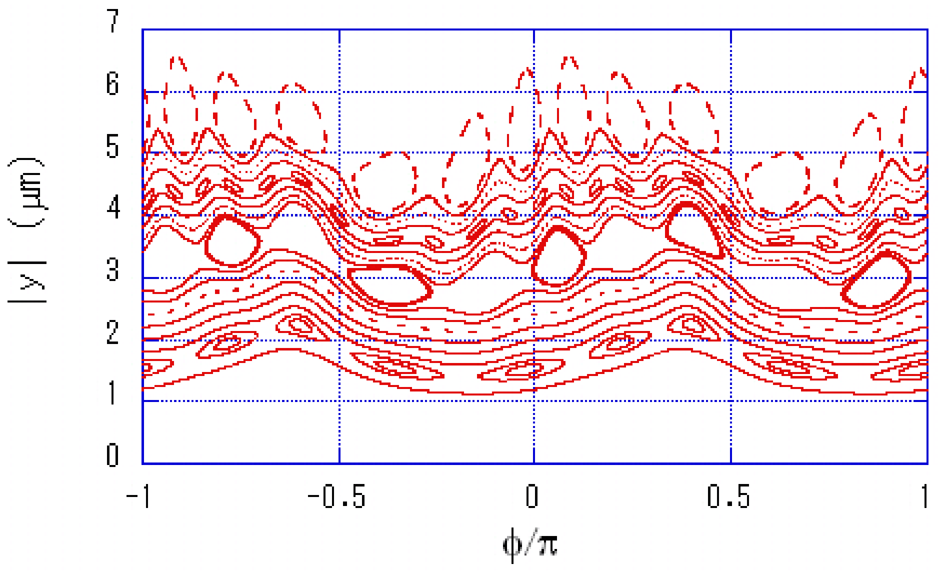




Strong beam：Gaussian   Solver: Error function & PIC

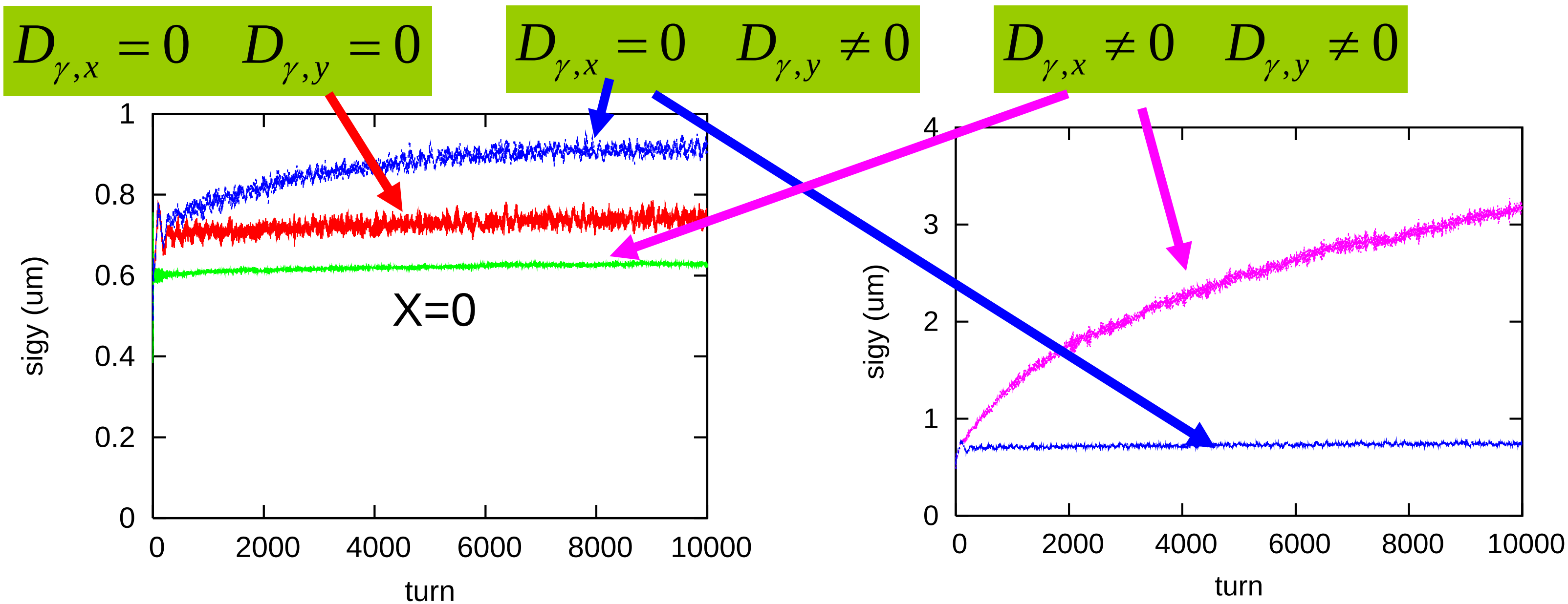
Why such big difference appears?

- Poincare plot for particles with x=0 interacting with the distorted strong beam.
- This figure shows an interesting feature, but it is not essential for the strong diffusion actually.



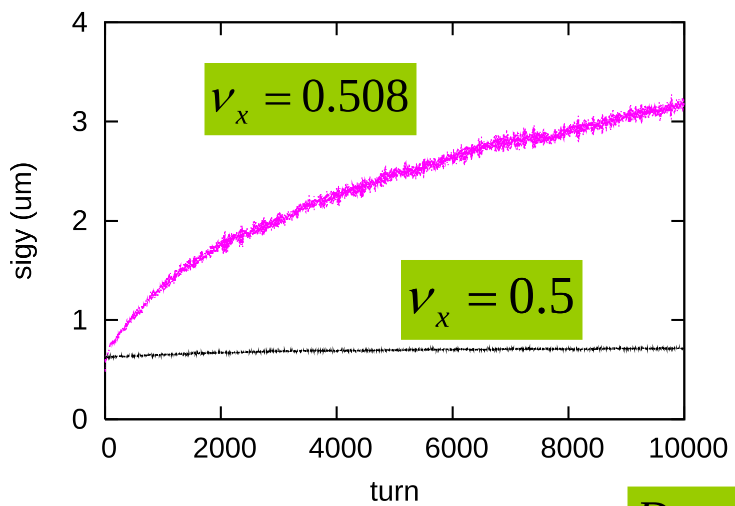
What is the diffusion source?

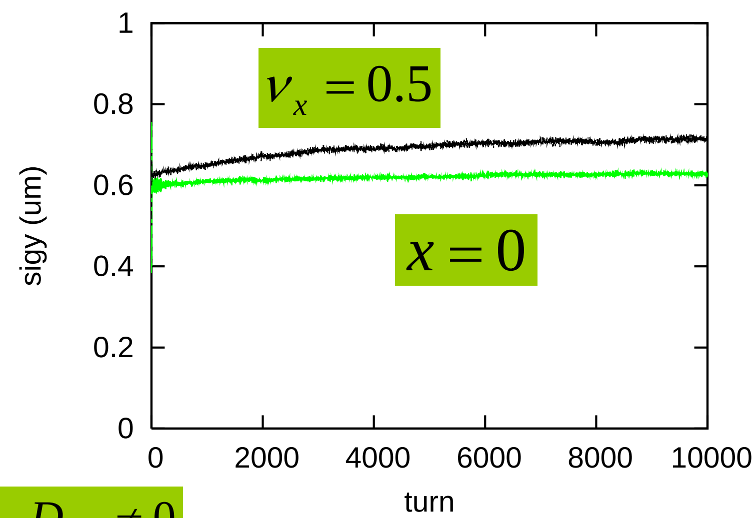
- Particles with x=0 obeys 1 dimensional dynamics. Motion may be chaotic, but KAM surface limits the diffusion in time dependent 1 dimensional system.
- Investigate an effect of the radiation excitation, $D_{\gamma,x}$, $D_{\gamma,y}$, individually.
- $D_{\gamma,x}$ is essential for the emittance growth.
- Perhaps coupling term like $y^n x^m$ contribute the vertical diffusion via $y^n \langle \Delta x^m \rangle$.



$\nu_x \to 0.5$

- For ν_x=0.5, particles experience the same y potential every turns, because the potential is symmetric for x, that is, it is 1 degree of freedom system, therefore no emittance growth.
- Needless to say, <x'^{2}> increases as the side effect.



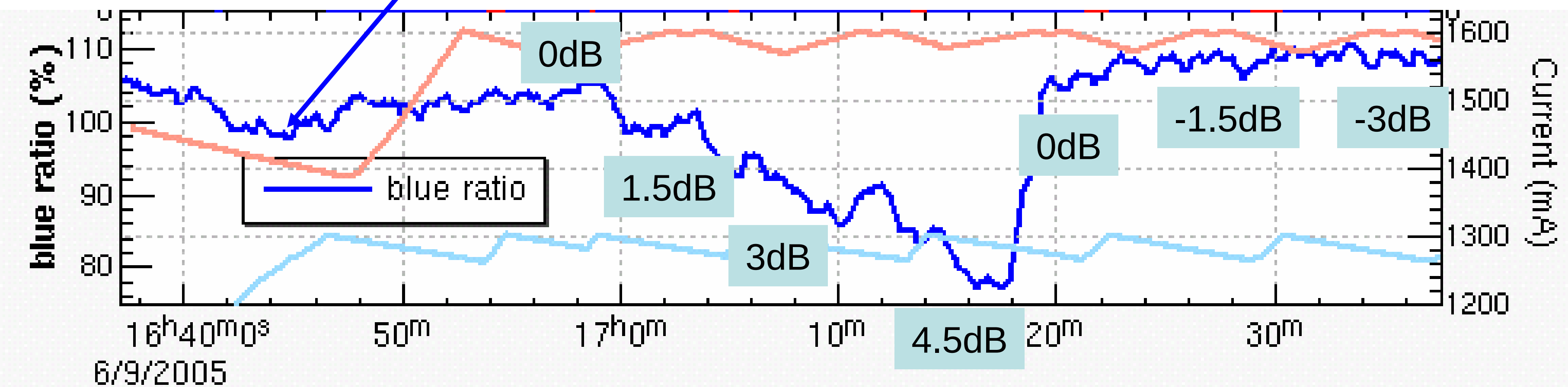


$D_{\gamma,x} \neq 0 \quad D_{\gamma,y} \neq 0$

Luminosity degradation due to noise in KEKB -Feedback noise and beam-beam effect-

- In 2005 spring operation, luminosity boosted up 1.35×10^{34} to 1.58×10^{34} $cm^{-2}s^{-1}$.
- It is due to that the gain of the transverse bunch-by-bunch feedback system was optimized (weakened but kept a sufficient strength to suppress the coupled bunch instability).

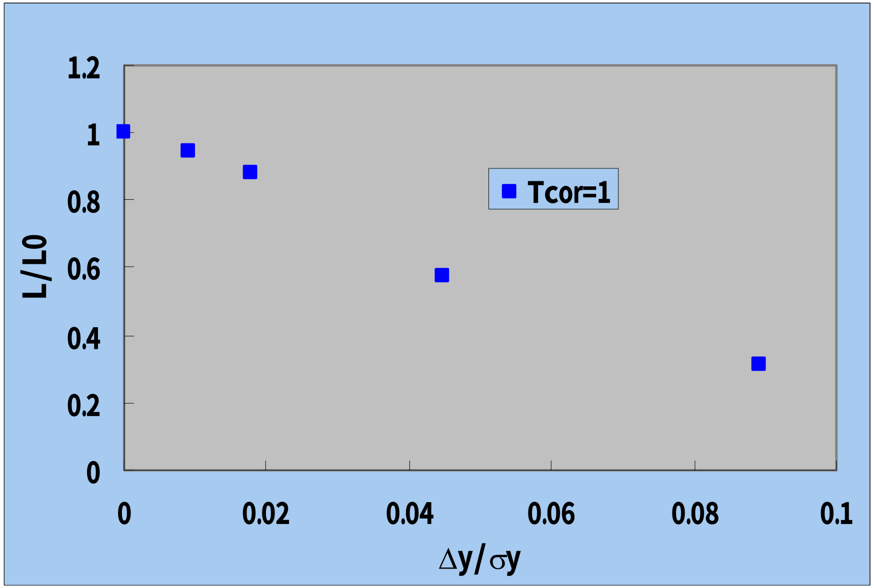
Specific luminosity (by Funakoshi)

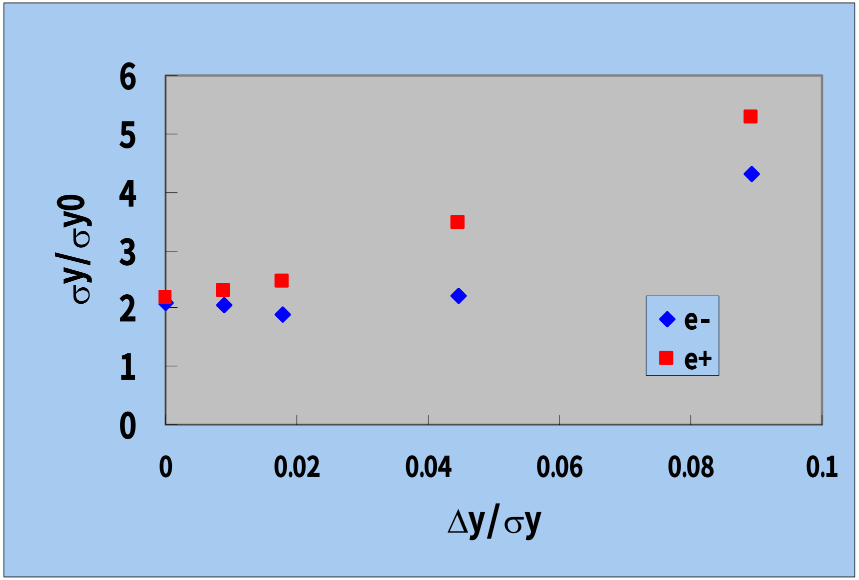


External diffusion: Vertical offset noise (simulation)

- Since the beam-beam system is chaotic, such noise enhances the diffusion of the system.
- Luminosity degradation for the noise without correlation between turns.

$$\left\langle \Delta y(t)\Delta y(t')\right\rangle = \Delta y^2 \delta(t-t')$$

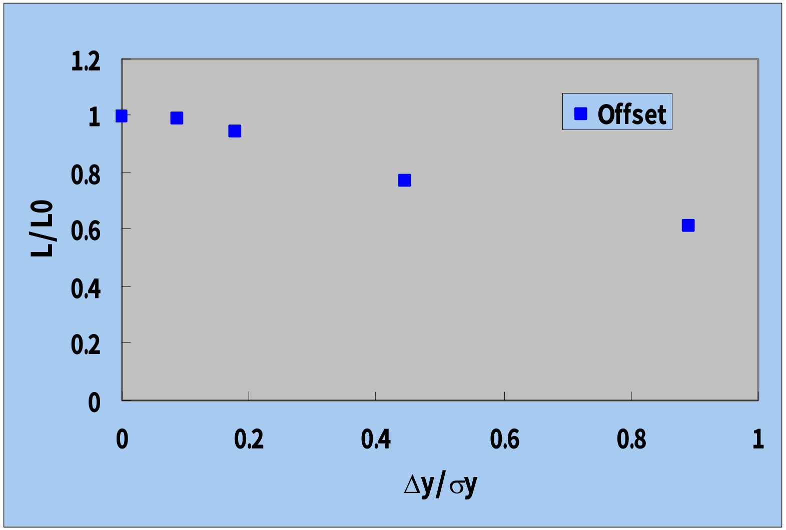


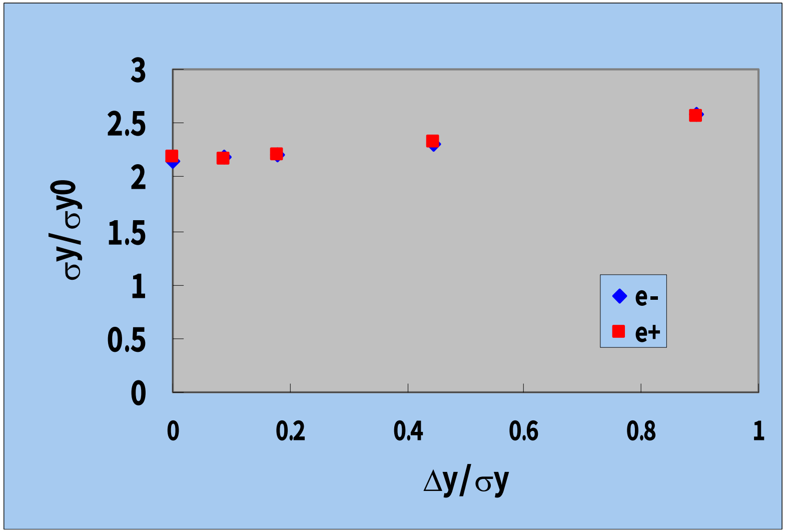


Orbit offset (static) (simulation)

- Static vertical offset. Tolerance is easier than the fast noise.
- For slower variation than radiation damping time, emittance can be an adiabatic invariant.

$$\langle \Delta y(t)\Delta y(t')\rangle = \Delta y^2 \exp(-t/\tau)/2\tau$$





1/20 compare than that for fast noise

Estimation of feedback noise (Hiramatsu, K.O. & Tobiyama)

- Twp-tap filter and vector composition with two position monitors
- Phase space position at kicker, vector composition with two position monitor

$$\begin{pmatrix} X \\ P \end{pmatrix}_K = N \begin{pmatrix} X_1 \\ X_2 \end{pmatrix} \qquad N = \frac{1}{\sin\psi_{21}} \begin{pmatrix} \sin\psi_{2K} & \sin\psi_{K1} \\ -\cos\psi_{2K} & \cos\psi_{K1} \end{pmatrix}$$

- Offset noise due to kicker error (δE) and monitor error(δP(δX_1,δX_2)))

$$\left\langle X^2 \right\rangle = \frac{3\left\langle \delta E^2 \right\rangle + (3K_1^2 + 3K_2^2 + 2K_1K_2\cos\mu)\left\langle \delta P^2 \right\rangle}{-6K_1\cos\mu - 2K_2\cos 2\mu}$$

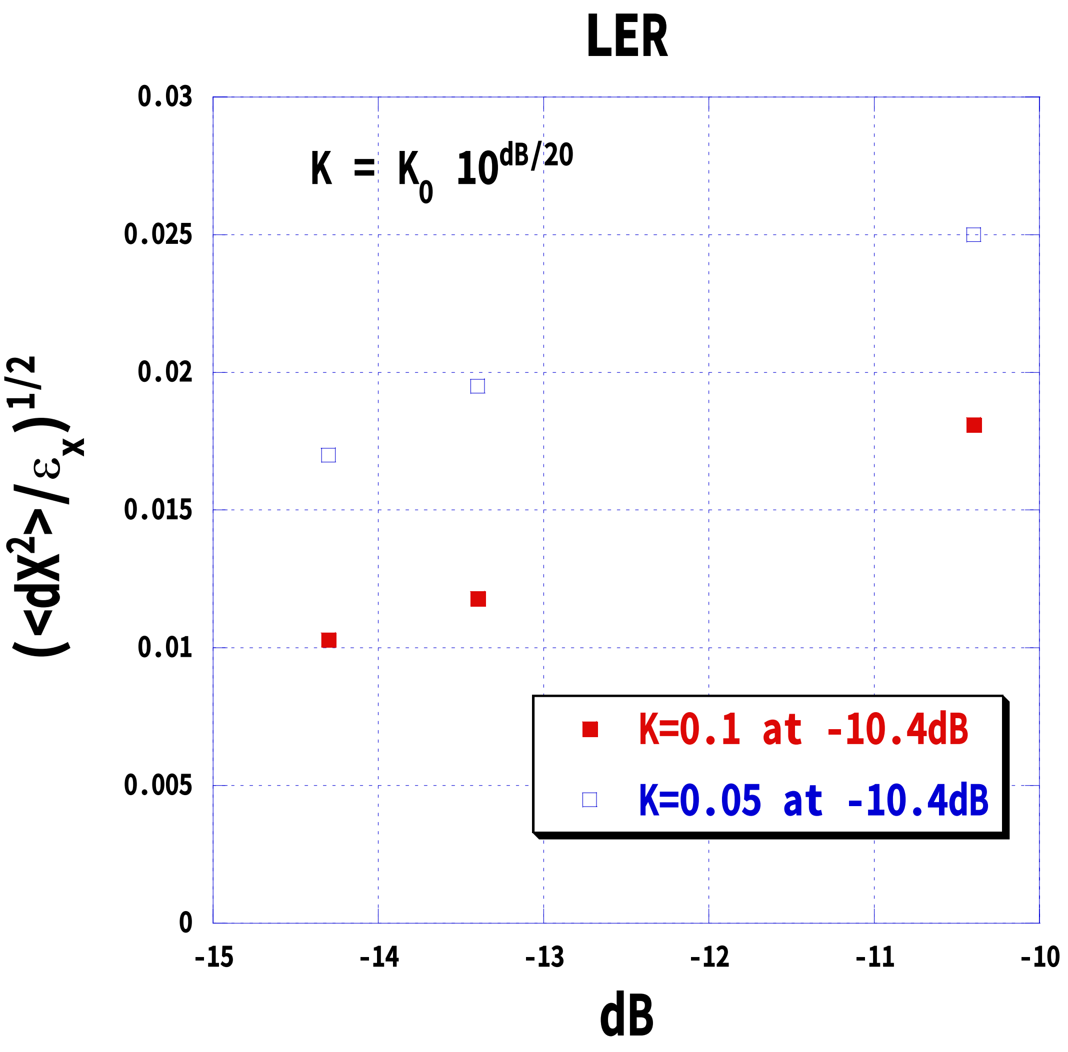
Kicker noise measurement (LER)

- (7/14/05) Kicker output depending on feedback gain.

Feedback Gain set	Out Vp-p	OutVrms	kick(Vrms)	$\delta E (x10^{-7})$
-13.4dB(3.77 oper.)	107mV	16.3mV	100V	0.62
-14.3dB(final value)	87.3mV	13.3mV	83V	0.51
-10.4dB(Bad lum.)	196.9mV	30mV	188V	1.16
FB switch OFF	4.2mV	0.6mV	4.1V	0.025

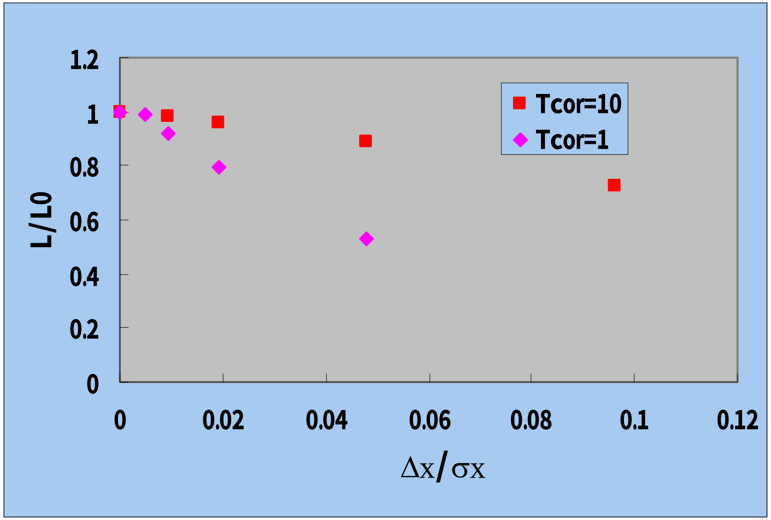
$\delta E = \beta^{1/2}\, \delta k / E_0$ $E_0 = 3.5$ GeV

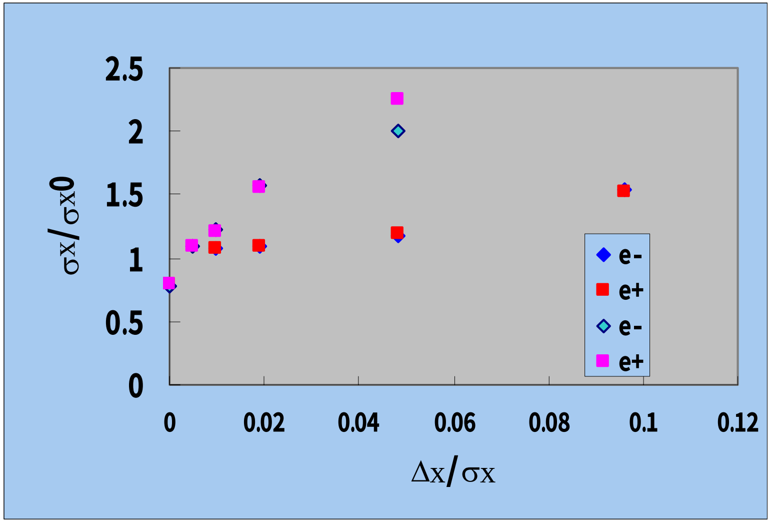
Speculated beam noise for the kicker noise



Effect on the beam-beam performance of the phase jitter of cavity and crab RF's in KEKB

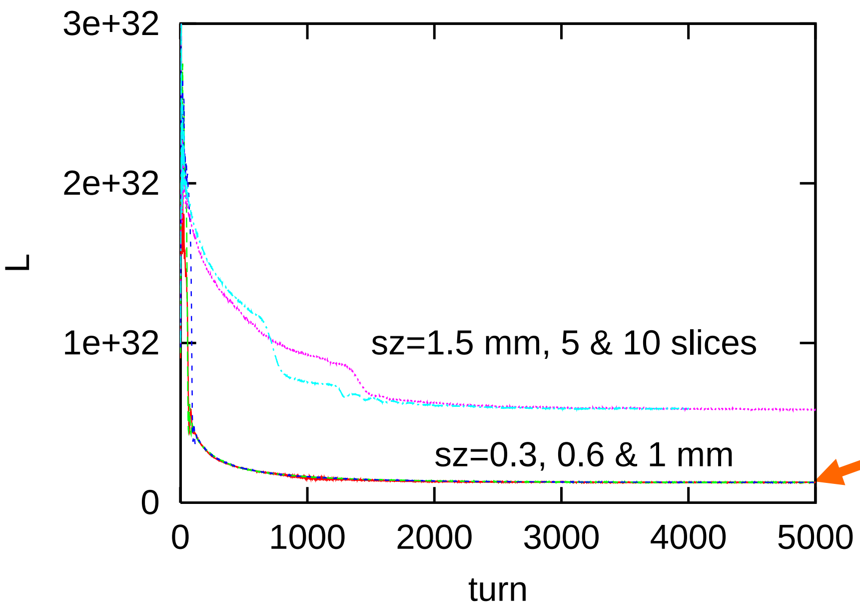
- Luminosity and beam size as functions of δx.
- Correlation time of the jitter, 1 or 10 turns, is important for the degradation.
- Since Q=200,000 and H=5120, the correlation time will be larger than 10 turns.
- Tolerance is 0.05 degree.

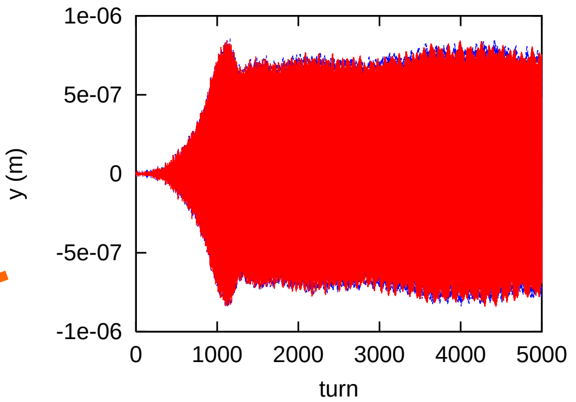




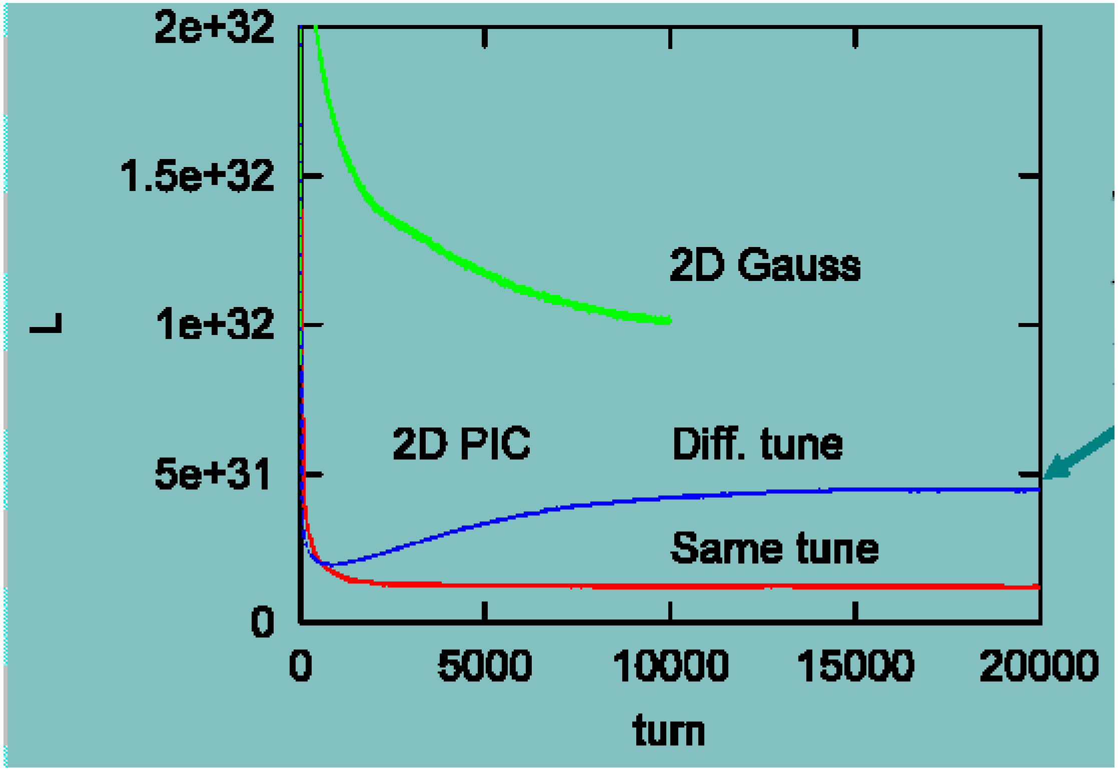
Coherent motion

- Operating point, (0.52,0.58).
- For short bunch $\sigma_z << \beta_y$, vertical coherent motion arise. No coherent motion in horizontal in this operating point.
- The growth rate is not very large.





Tune difference to moderate the coherent motion



Summary

- Sympletic diffusion has been studied using weak-strong Gaussian model. Longitudinal degree of freedom and crossing angle affect the diffusion strongly.
- Golden operation point, $\nu_x \rightarrow 0.5$. For head-on collision, the system is regarded as 1 degree of freedom approximately, therefore no emittance growth.
- Diffusion seen in Non-Gaussian interaction couple to radiation excitation determines final beam-beam limit. $\nu_x \rightarrow 0.5$ is a nice charm again.
- External diffusions, feedback noise, crab cavity noise and others, limit the beam-beam performance.