Experiences for crab cavity operation at KEKB

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CARE-HHH Mini-workshop
-LHC Crab Cavity Validation-
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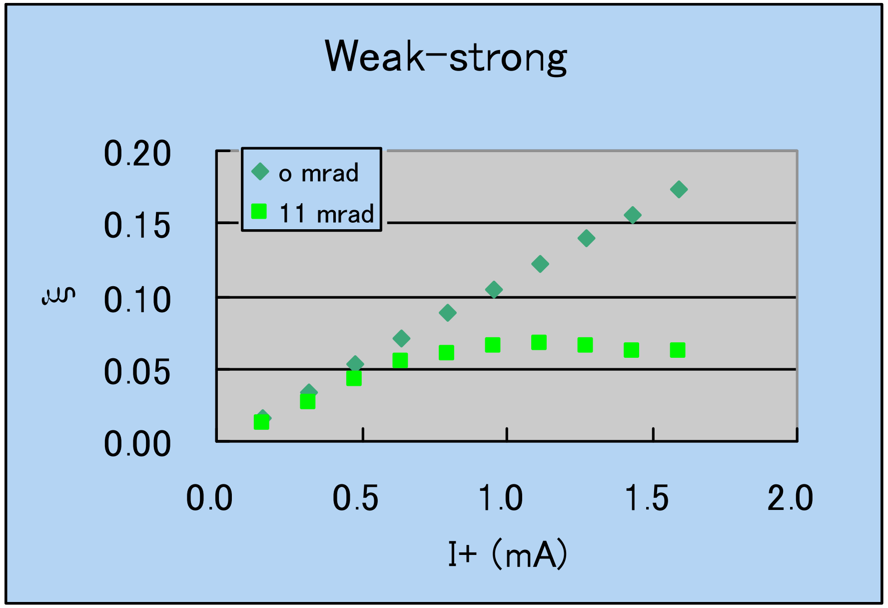
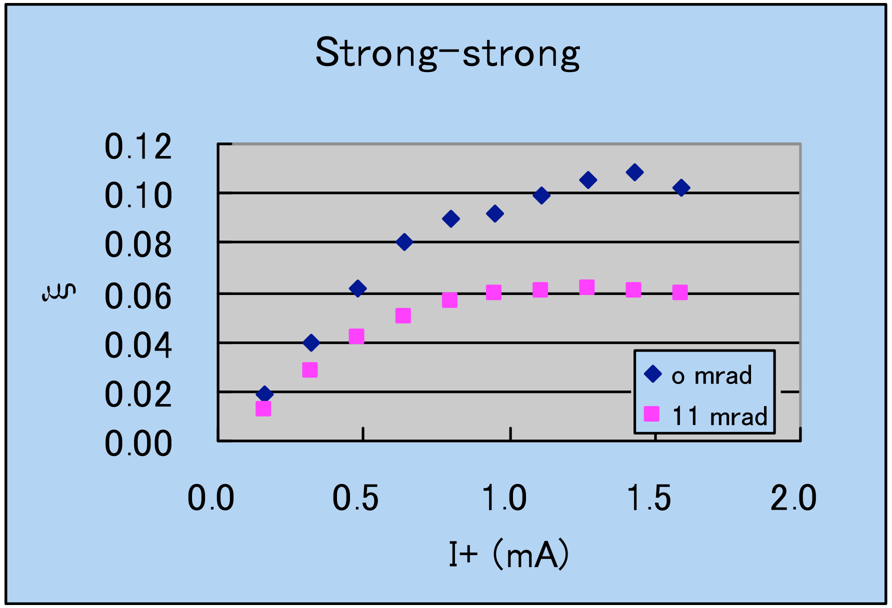
- Why crab crossing is tried in KEKB.
- Simulation of voltage scan. Vertical crossing.
- Wake force effects for tilt beam in single crab scheme.
- Simulation of knob scan to optimize luminosity performance.
- Life time issue. Beam-beam halo estimation with weak-strong simulation.
- Emittance growth due to wake force with offset orbit and crabbing.
- Beam-beam and lattice nonlinearities.
- Fast noise.

Gain for the crab crossing

The beam-beam parameter ξ>0.1 can be achieved by the crab crossing.

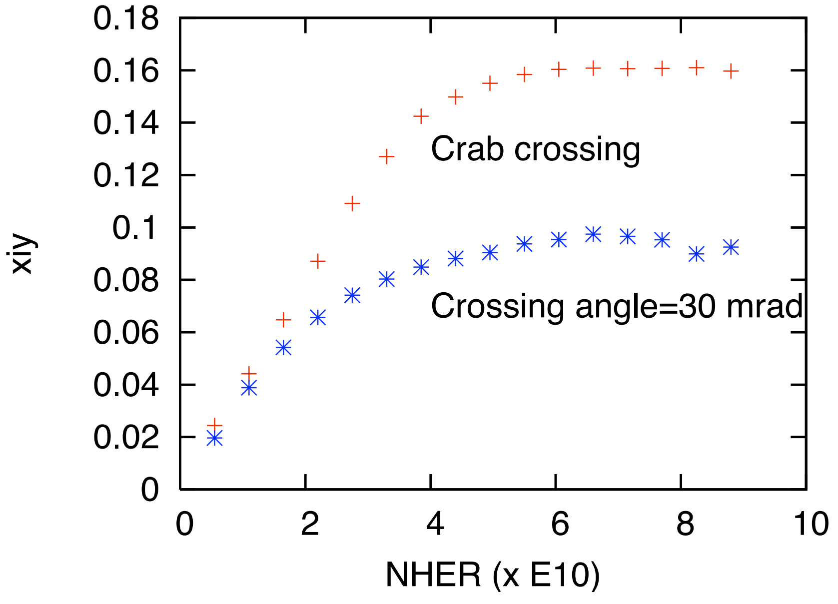


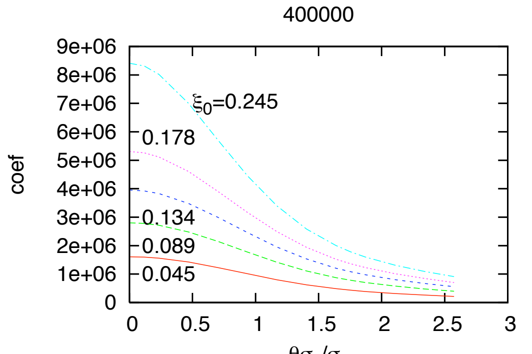


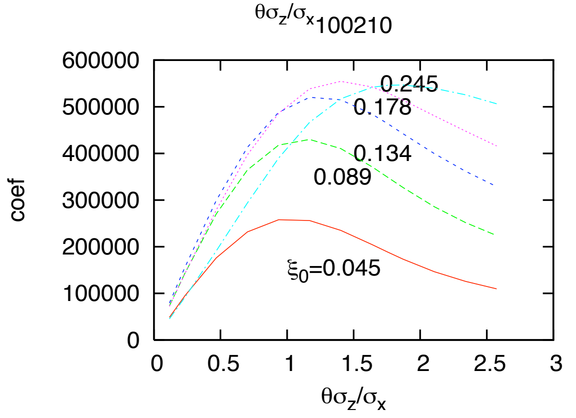
** The beam-beam limit in finite crossing is determined by a weak-strong effect in this parameter.

Beam-beam Interaction and crossing angle

- Beam-beam interaction as a transformation of dynamical variable.
- x^4 , y^4 term decrease but another coupling term increases for crossing angle. A kind of symmetry breaking degrade luminosity performance.

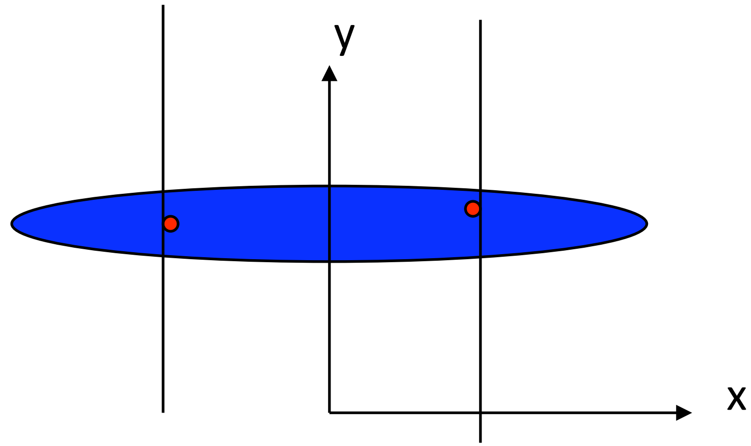






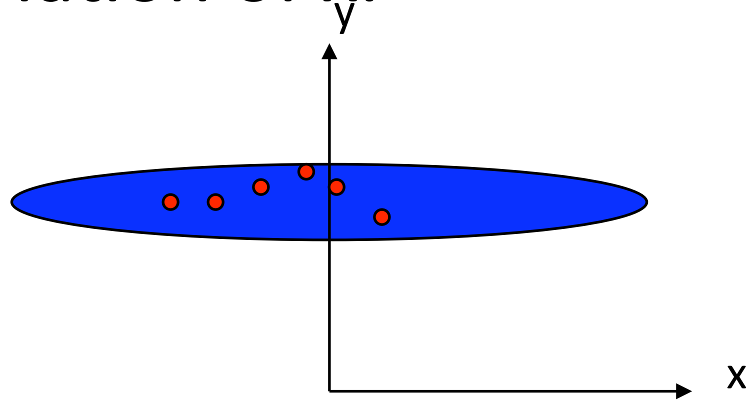
Horizontal tune half integer ν_x=0.5

- Particles interact with fixed beam at x and –x mutually. The phase space structure in y-p_y at x is the same as that at -x, because of symmetry of the fixed beam.
- System is one dimension, beam-beam tune shift is 0.5
- KEKB realizes a high luminosity with this technique.



$\nu_x = 0.5 + \alpha$

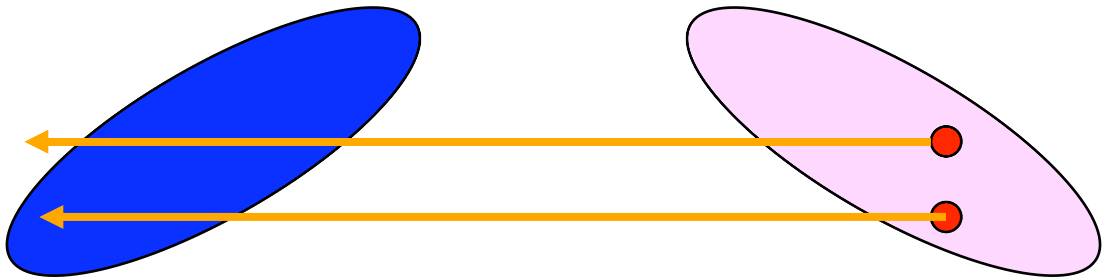
- Since $\langle p_x^2 \rangle$ diverges at $\nu_x=0.5$, ν_x must be slightly higher than 0.5.
- X of particle slowly changes.
- Y force is dependent of x. U(x,y)
- Particle slowly moves across various y-p_y phase space for the variation of x.



Crossing angle

- Crab crossing: symmetric for x→-x

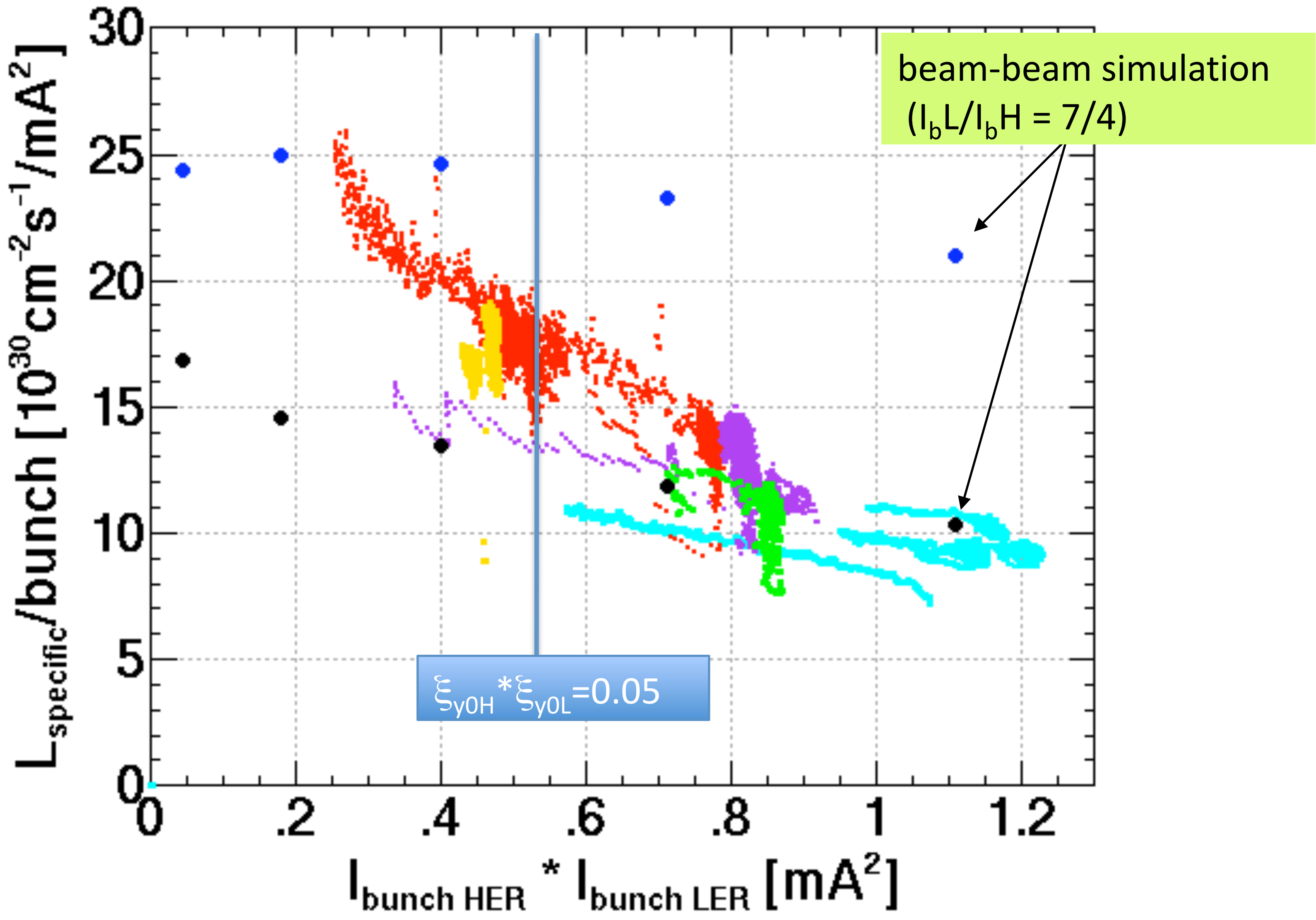
- Crossing collision: no symmetry for x→-x



Beam-beam tune shift is not achieved 0.3 for crossing collision even at ν_x=0.5

- Complex function form for crossing collision.

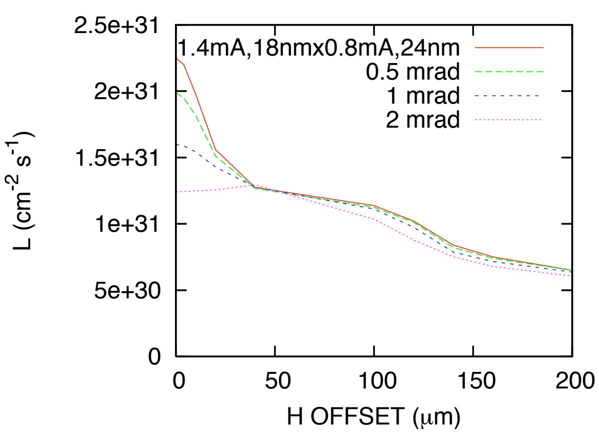
Measured luminosity in KEKB



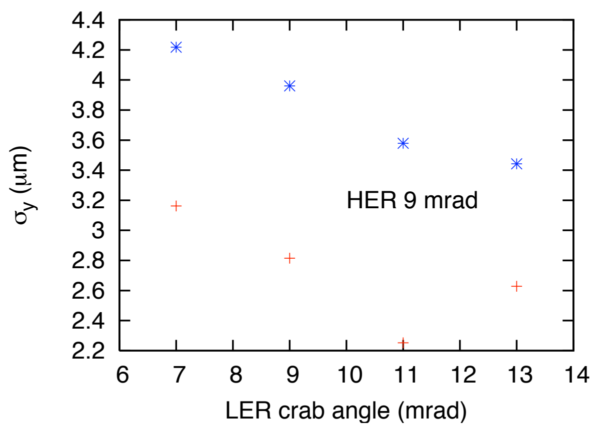
Establish crab collision

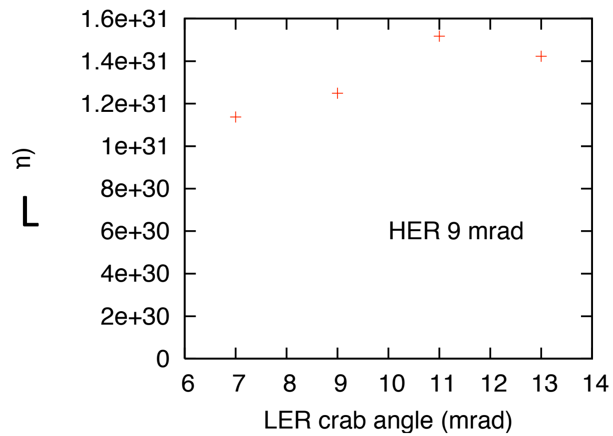
- Voltage scan, luminosity, streak camera,
- Crab cavity phase scan. Orbit distortion for the phase shift depends on the crab voltage. Balance of two crab voltage is checked by the orbit distortions of both rings.
- Various kinds of simulations for the scans were executed.

H Offset scan



LER crab Voltage scan

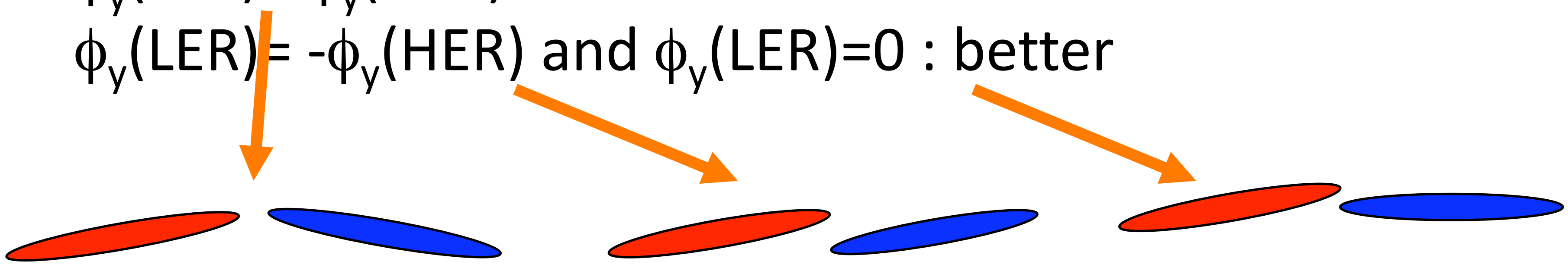


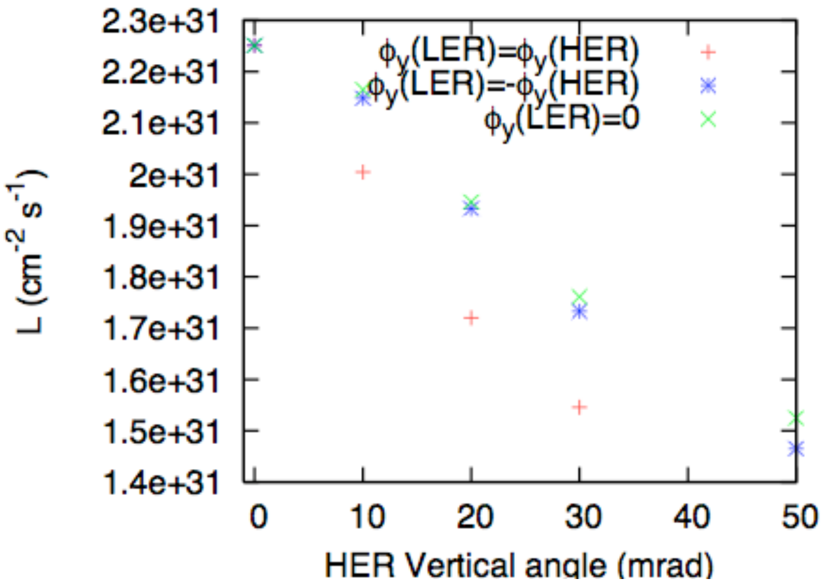


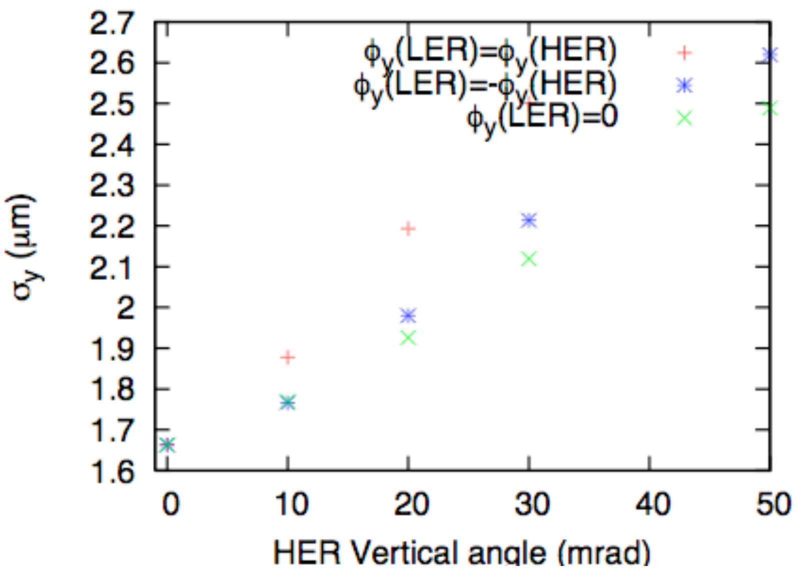
Vertical angle

ϕ_y(LER)= ϕ_y(HER): worst

ϕ_y(LER)= -ϕ_y(HER) and ϕ_y(LER)=0 : better







Effects of the tilt beam in the ring

Effects of the transverse wake force

- Measured by Ieiri.

$$\left(\frac{d\nu_x}{dI}\right)_{I=0} = -\frac{r_e W_0}{8e\gamma\omega_0}\beta$$

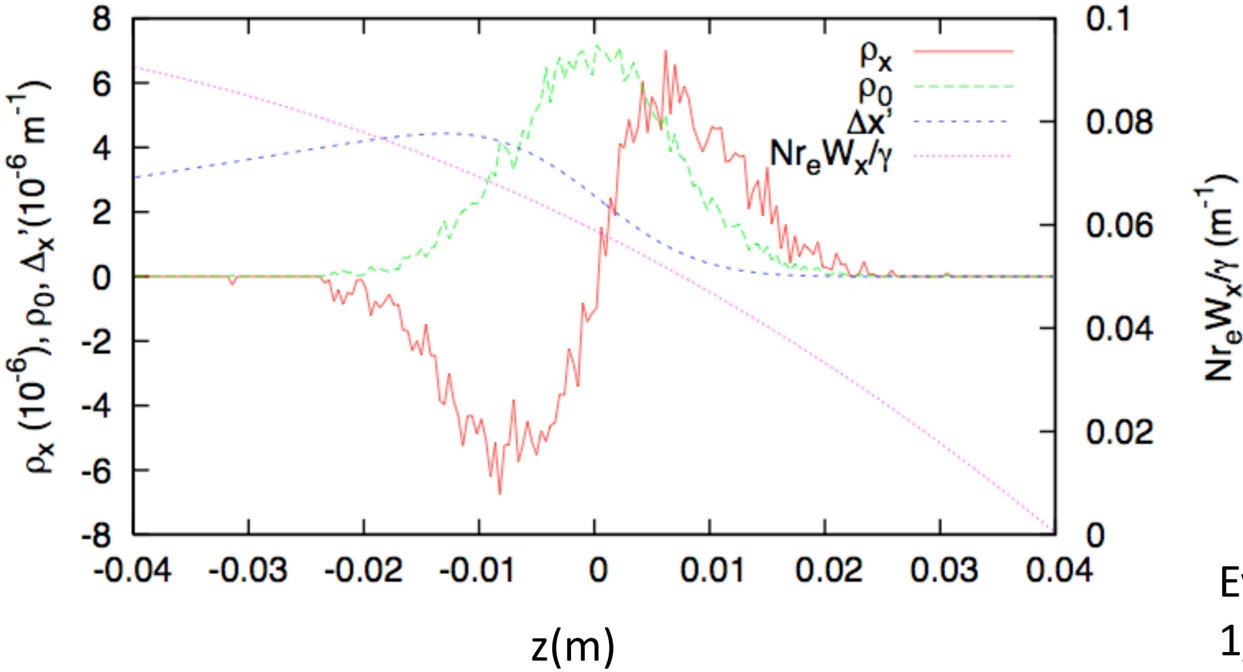
$$W_0 = \left(\frac{d\nu_x}{dI}\right)_{I=0} \frac{8e\gamma\omega_0}{r_e\beta}$$

$$= 1.7 \times 10^6 \mathrm{m}^{-2}$$

$$\left(\frac{d\nu_x}{dI}\right)_{I=0} = 4A^{-1}$$

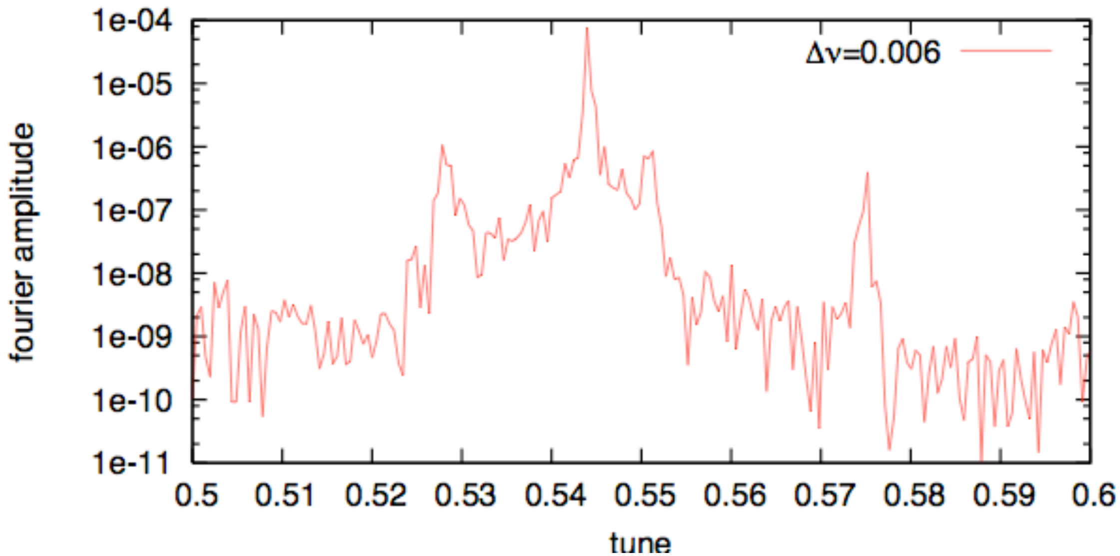
$$\Delta x_2' = \frac{N r_e W_0}{\gamma}\sigma_x = 7.5 \times 10^{-6}$$

$$\Delta x_{crab}' = \frac{eV'}{E}\sigma_z = \frac{eV_0}{E}\frac{\omega_{rf}\sigma_z}{c} = 1.25 \times 10^{-4}$$



*wake z=0~-0.08

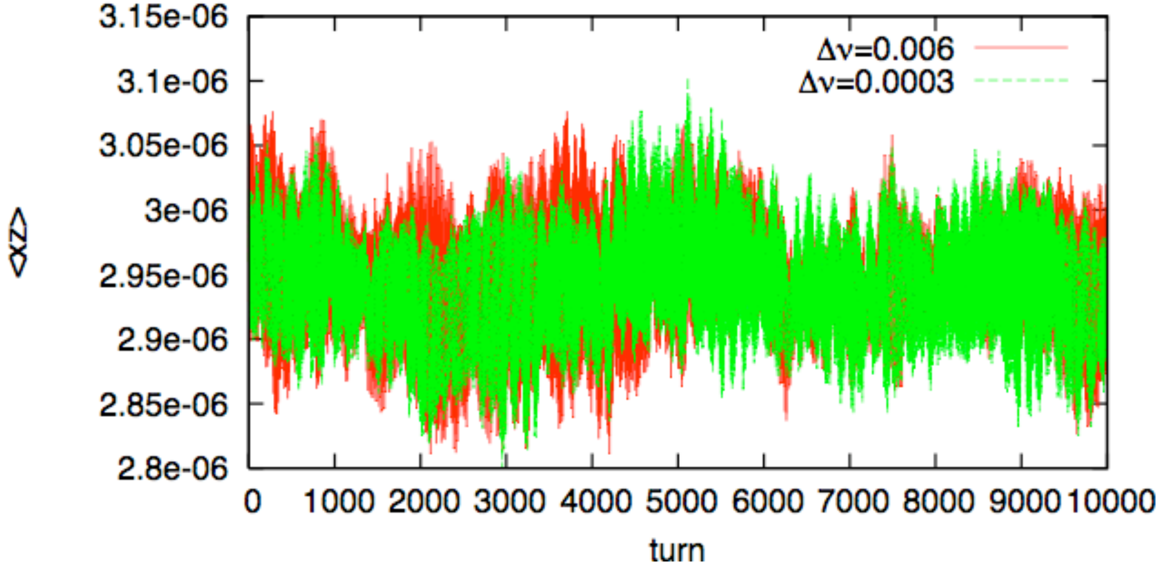
Even $\Delta\nu$=0.006, the kick is 1/30 of crab kick



ν_x=0.55

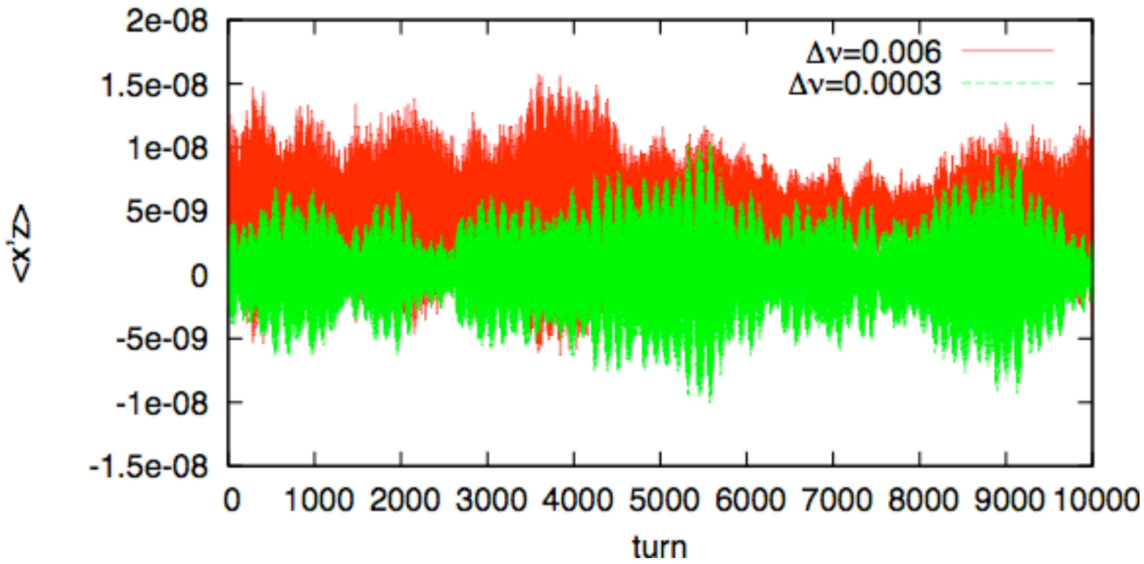
Spectrum by simulation with this condition

$$\Delta x'_{crab} = \frac{eV'}{E}\sigma_z = \frac{eV_0}{E}\frac{\omega_{rf}\sigma_z}{c} = 1.25\times 10^{-4}$$



Change of equilibrium distribution

- <xz> does not change.
- <x'z> change a little $\sigma_{x'}\sigma_z/30$.



The wake effect of x-z tilt beam is weak.

Strong head-tail instability arise before some effect is seen.

Local Optics error at IP

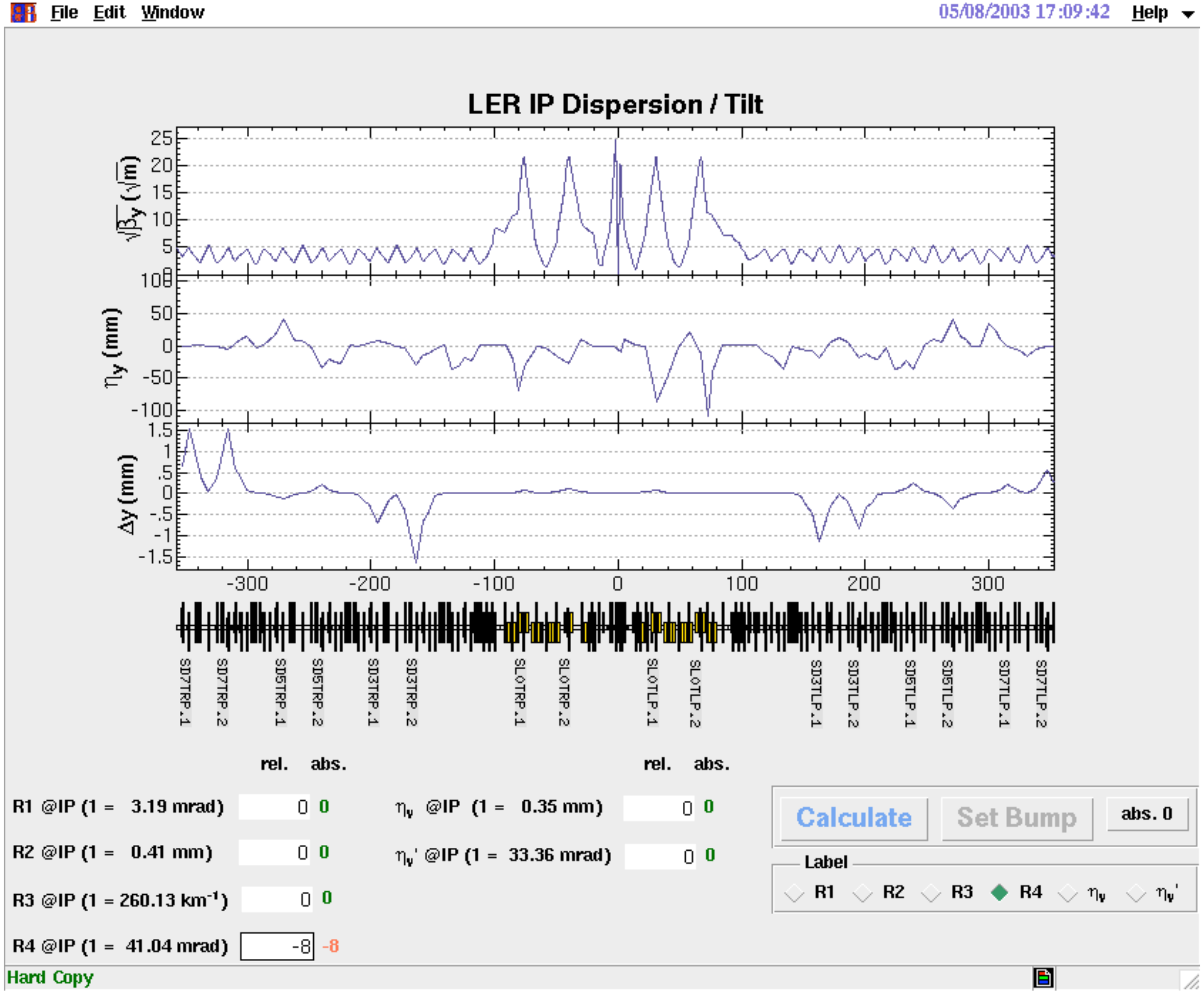
- Local coupling and dispersion at IP affect the beam-beam performance.
- This tuning has been performed since KEK started
- The local optics parameter affect the beam-beam performance dynamically rather than geometrically.

One turn map $$M = \exp(- : \phi :) M_0$$

God decides the effect of ϕ. Beam-beam performance can be controlled by M_0: i.e., optics parameters at IP

- Beam size blow up is suppressed by the local correction of the optics parameters.

- Optics parameters are controlled by local bumps



KEKB

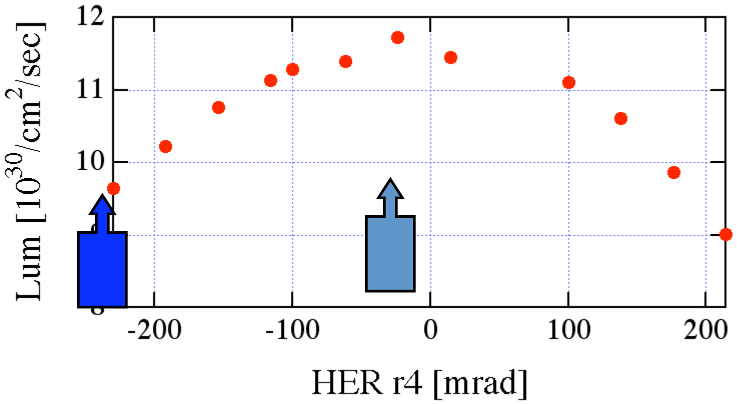
Simulation of knob scan

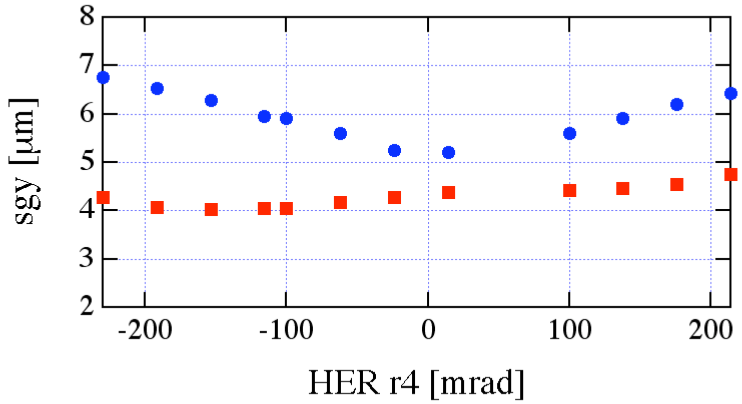
M. Tawada

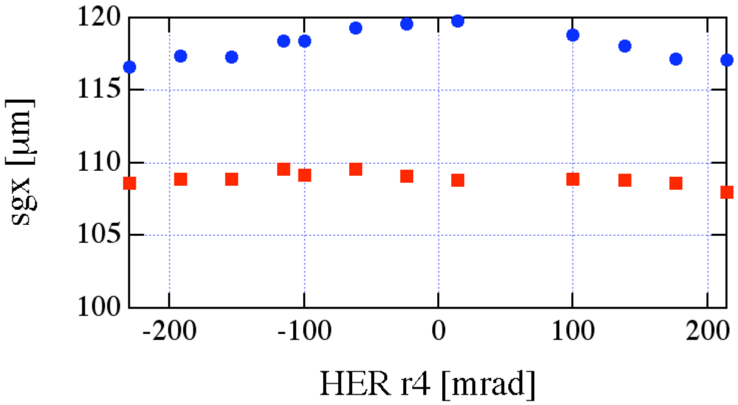
- Current 0.8/1.4 mA/bunch (HER/LER)
- ε_x = 24/18 nm (HER/LER) 1% coupling
- $\beta_{x/y}$ = 80/0.7 cm (both)
- $\nu_{x/y/z}$ = 0.511/0.580/0.025

- R1-4, η_y, η'_y of HER and LER (12 parameters) are scanned everyday in KEKB. The scan process was simulated using strong-strong simulation.
- Down hill simplex method for the 12 parameters is also used to optimize the luminosity.

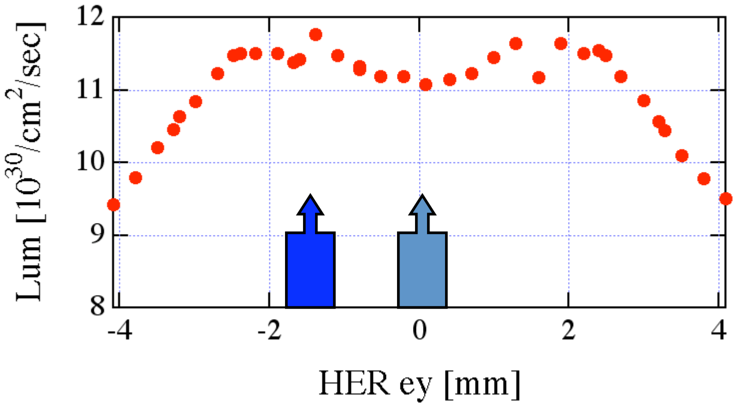
HER r4, example I

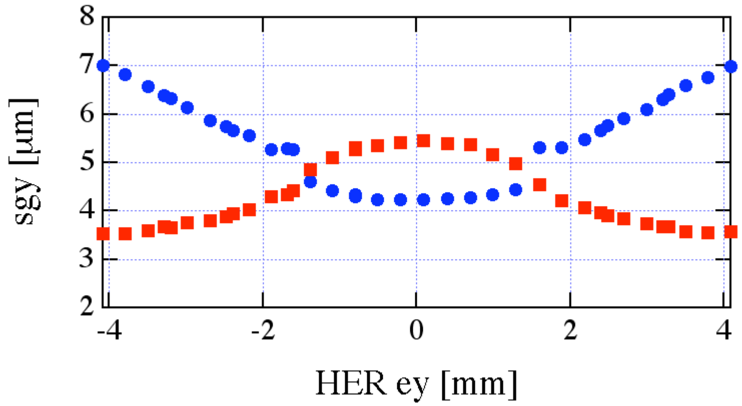


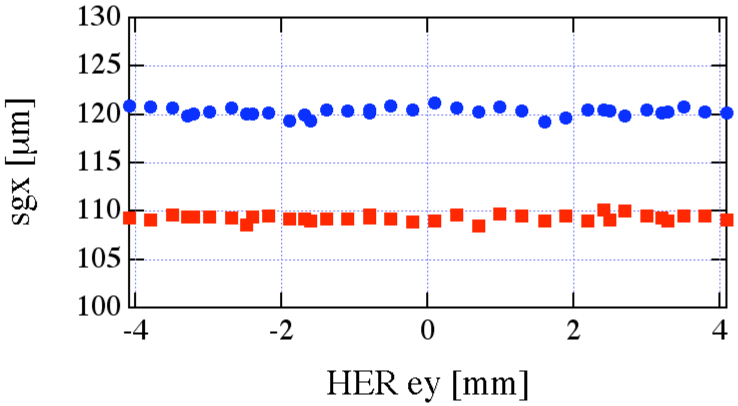




HER ey, example 2







Summary for knob scan simulation

- R1 and R4 mean rotation of real and momentum space, respectively.
- R1(L)=R4(L)=R1(H)=R4(H) (others=0) means simple rotation of both beam should result no luminosity degradation.
- R1-R4 was not resolved and dispersion was mislead due to error each other in 1st cycle.
- The dispersion error was corrected, and R1-R4 tend to coincide for both ring at 2nd cycle.
- Regular scan does not seem to have problem.
- Simplex method also gave high luminosity in this example.

- Another example with a large initial errors did not give high luminosity, ¾ of the previous.

Beam-beam life time issue

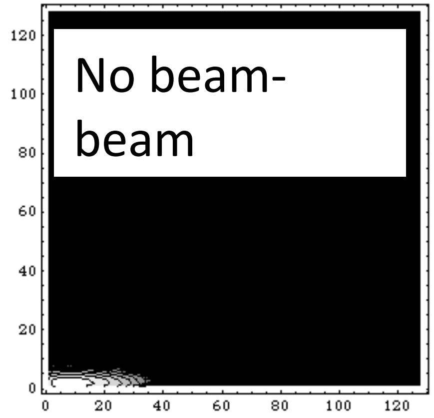
Halo simulation using Gaussian weak-strong model

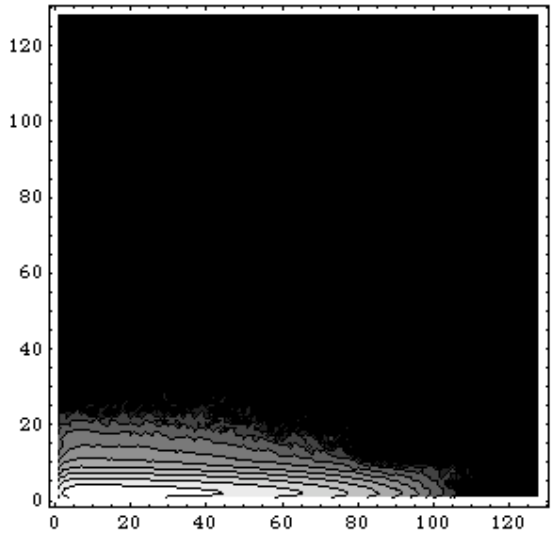
- People supposes that beam life time becomes short due to beam-beam halo.
- Long term simulation with a small number of particles.
- 10 particles and 10^7 turns for linear arc model.
- 10 particles and 10^6 turns for SAD model.
- Aperture H ~30 σ_x, V ~75σ_y (Ax~12 μm Ay~1 μm).

Simple arc transformation using matrix trans.

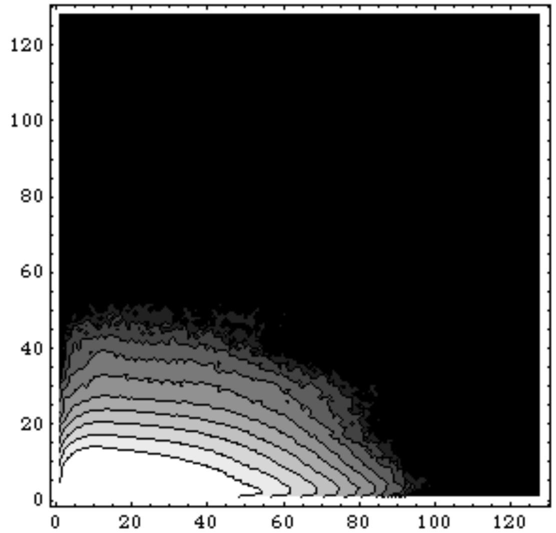
H-axis 0-12.8σ_x (0.1σ_x/unit) V-axis 0-64σ_y (0.5σ_y/unit)

Contour plot with log scale

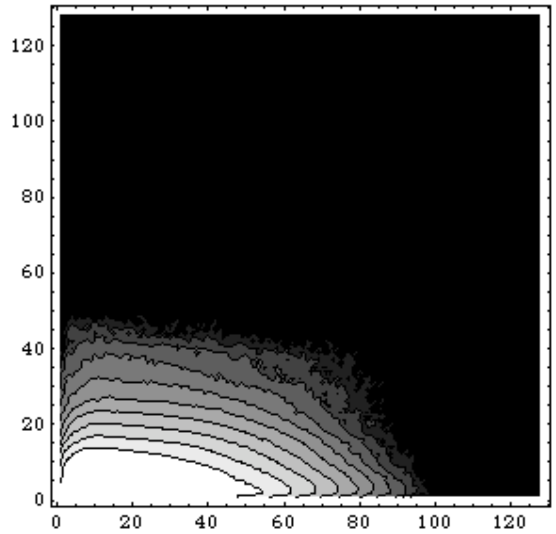




0 μm



+100 μm



-100 μm

Symmetric for Horizontal offset

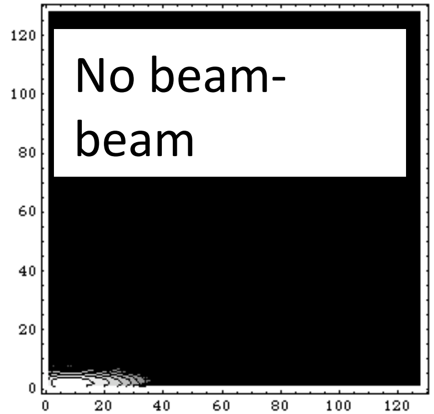
The hor. and ver. halo do not matter.

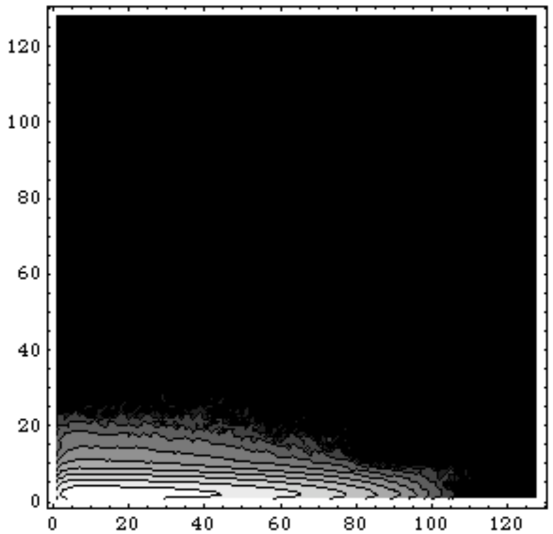
Beam-beam life time

Simple arc transformation
using matrix trans.

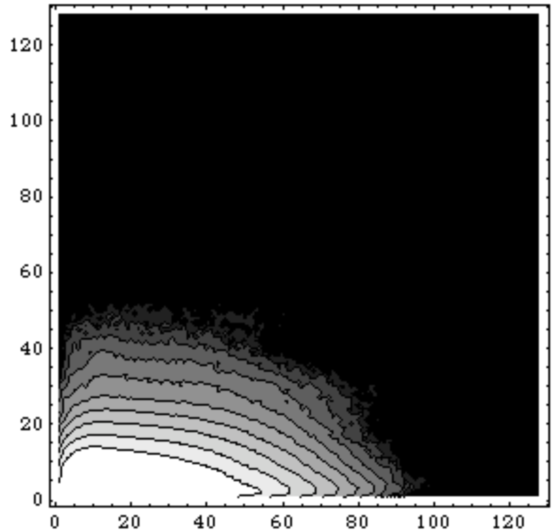
H-axis 0-12.8σ_x (0.1σ_x/unit) V-axis 0-64σ_y (0.5σ_y/unit)

Contour plot with log scale

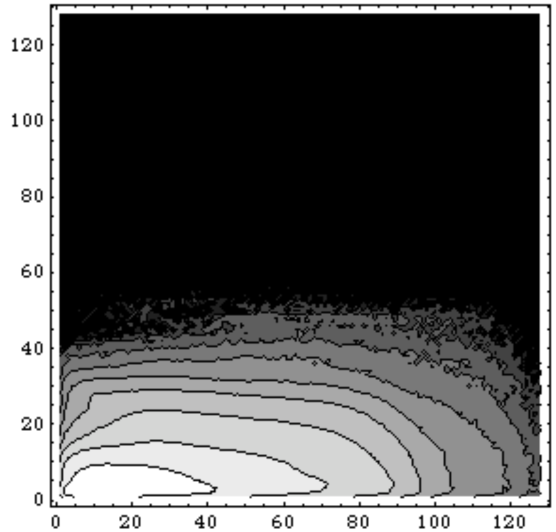




0 μm



+100 μm



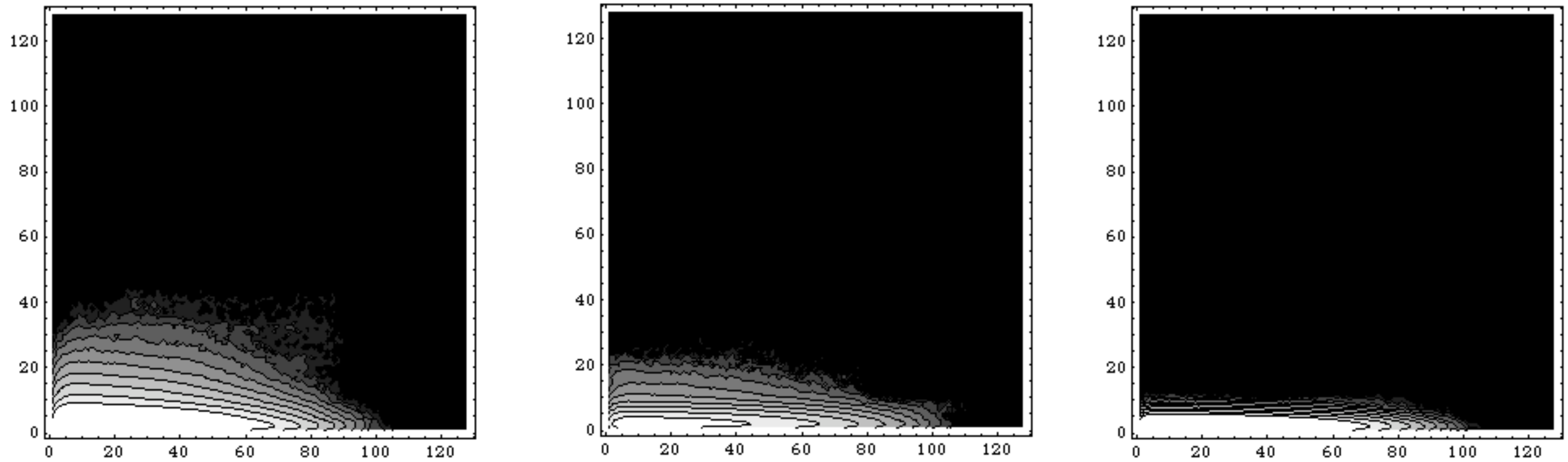
θ=11 mrad

- The hor. and ver. halo do not matter for the operation.
- Vertical halo is formed by horizontal offset of collision.
- Halo is bigger in finite crossing angle collision compare than crab crossing.

iSize, beam size control of colliding beam using vertical dispersion(N. Iida) , should work to suppress the vertical halo

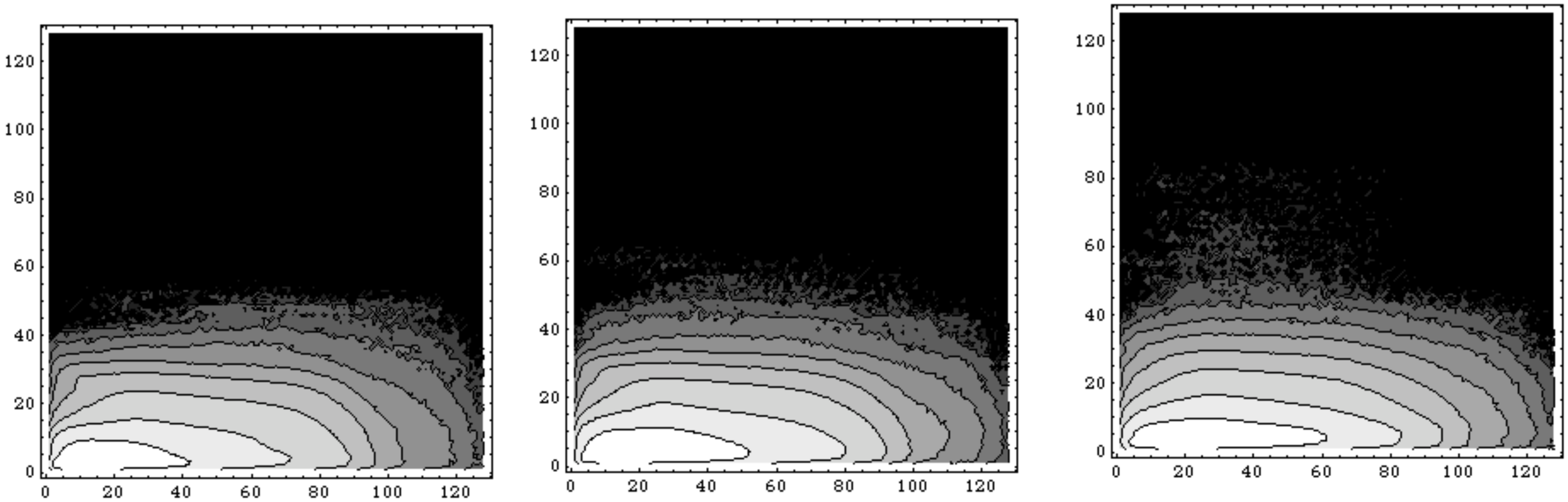
Experiments showed iSize did not work for life time improvement.

ε_y 0.6×10^{-10} 1.8×10^{-10} 5.4×10^{-10}



H-axis 0-12.8σ_x (0.1σ_x/unit) V-axis 0-64σ_y (0.5σ_y/unit)

Crossing collision with 11 mrad



Hoffset 0 μm 50 μm 100 μm

No asymmetry appeared for H offset

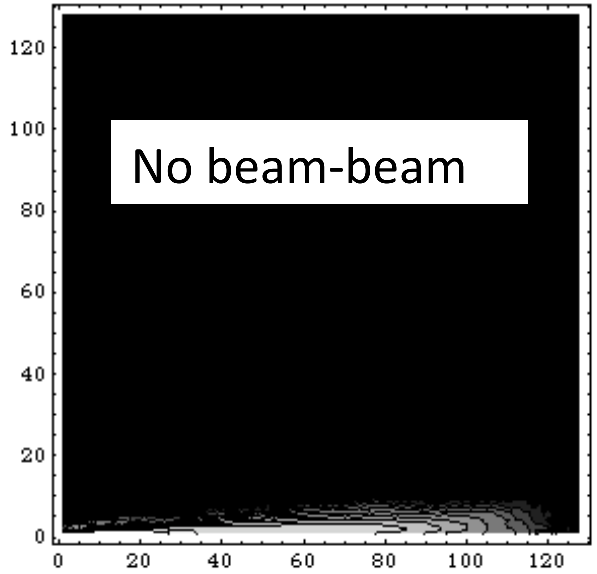
H-axis 0-12.8σ_x (0.1σ_x/unit) V-axis 0-64σ_y (0.5σ_y/unit)

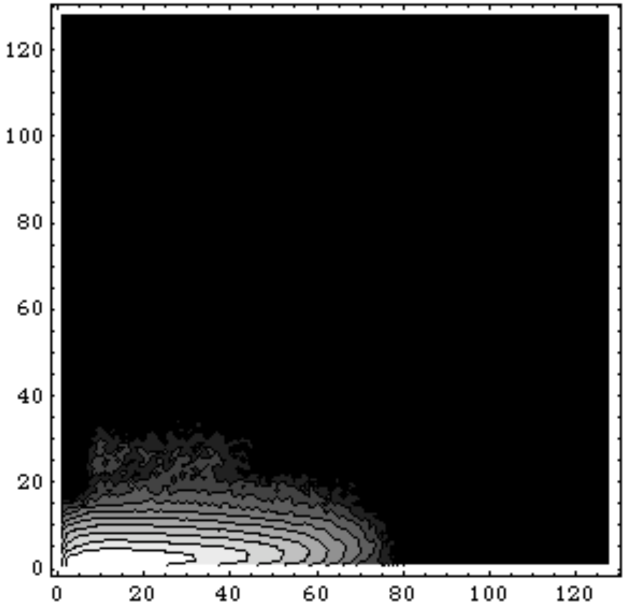
SAD tracking

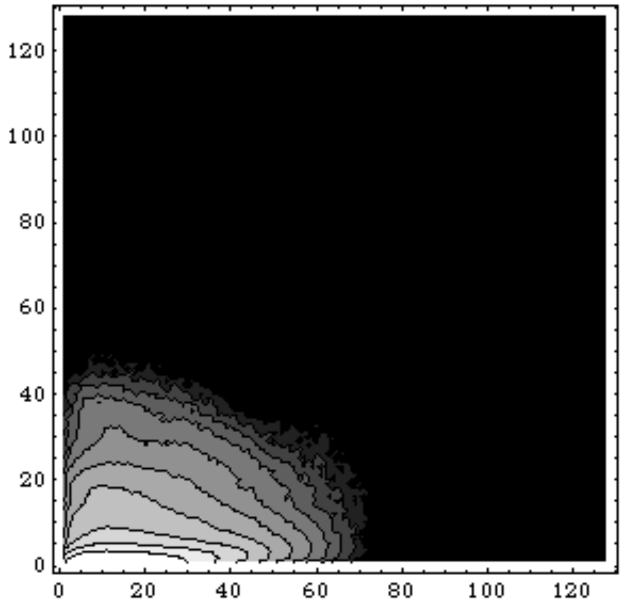
- Simple model did not explain experiments, short life time, its asymmetry for H offset, iSize did not help us.
- Lattice nonlinearity may affect KEKB performance more than our guess.
- Beam-beam code based on weak-strong model installed in SAD (1994) is revived.

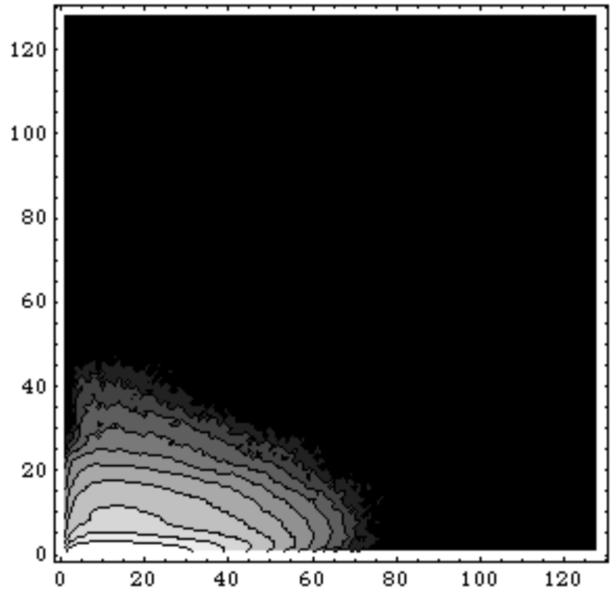
HER

H-axis 0-12.8σ_x (0.1σ_x/unit) V-axis 0-64σ_y (0.5σ_y/unit)







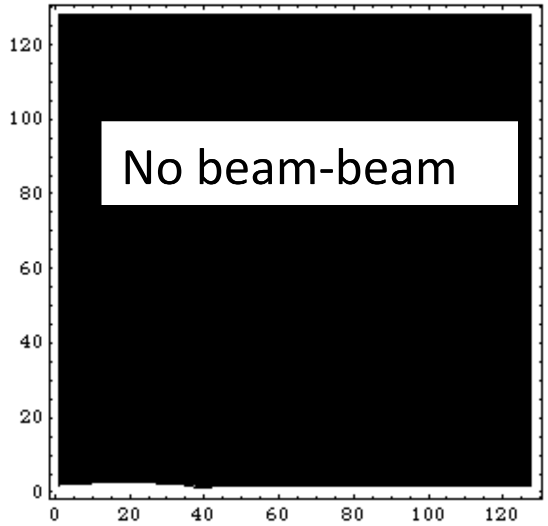


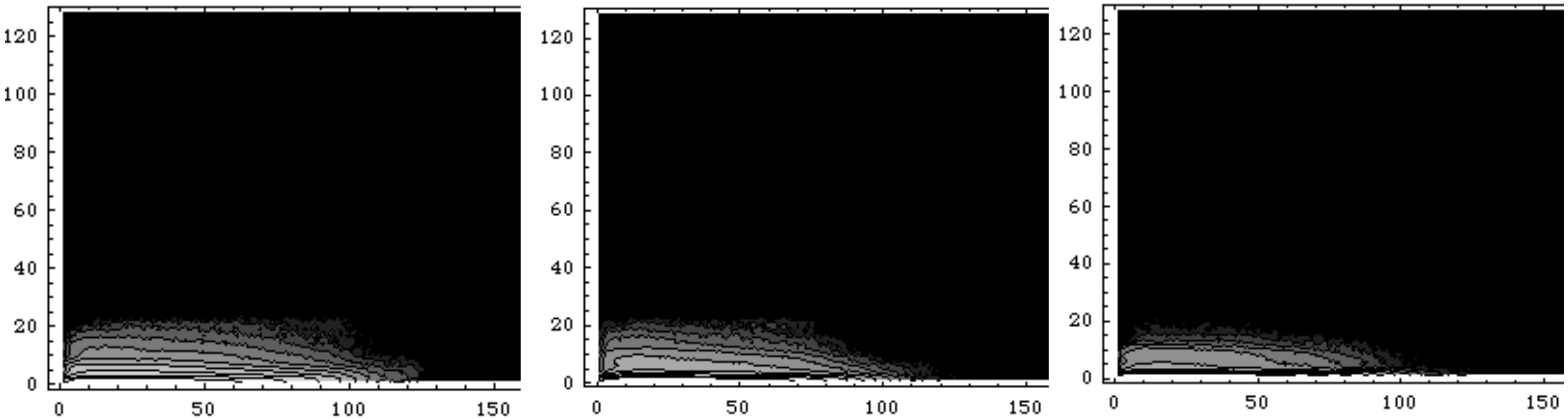
0 μm +100 μm -100 μm

No remarkable asymmetry. No beam-beam case was worst.

LER

H-axis $0.1\sigma_x$/unit V-axis $0.5\sigma_y$/unit



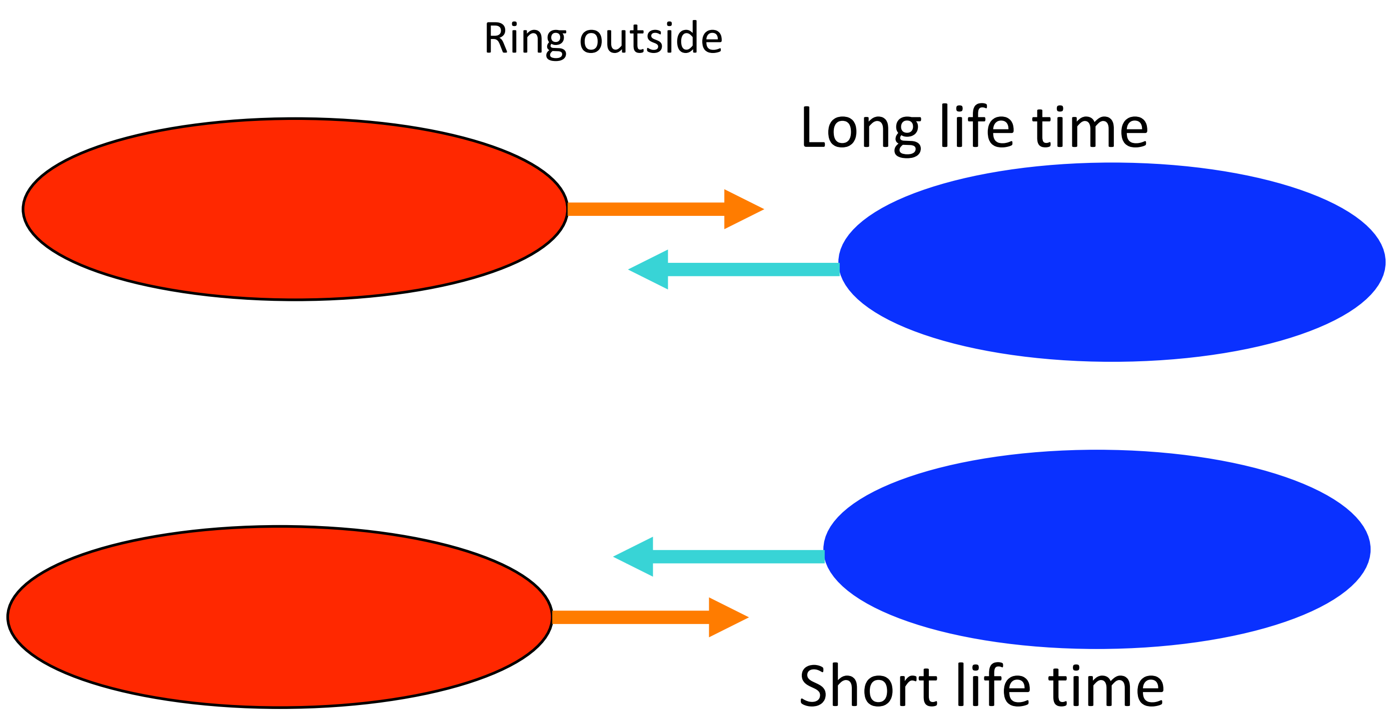


0 μm +100 μm -100 μm

- Asymmetry is seen in vertical tail.
- No beam-beam is no problem

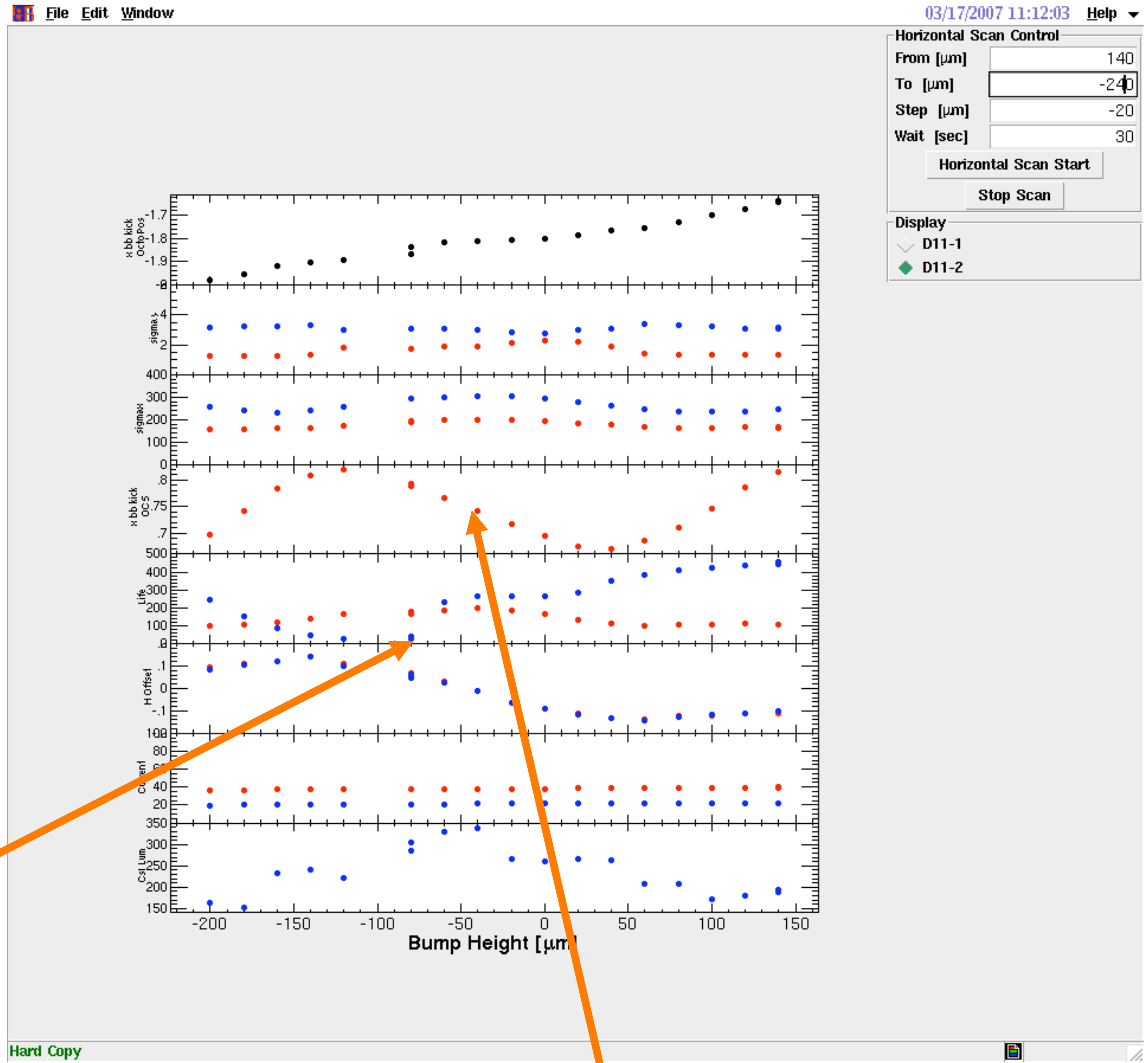
Most serious issue for the crab operation

- Asymmetry for the horizontal offset
- Beam life time is very short in a region of a horizontal offset.
- We still have just like “Egure” effect even in head-on collision.
- This asymmetry can not be reproduced by the simulation.



Horizontal offset scan

- The beam current seems to be limited by the short life time of the region.
- The region is enlarged for high current.



HER life

LER life decrases depending on the condition

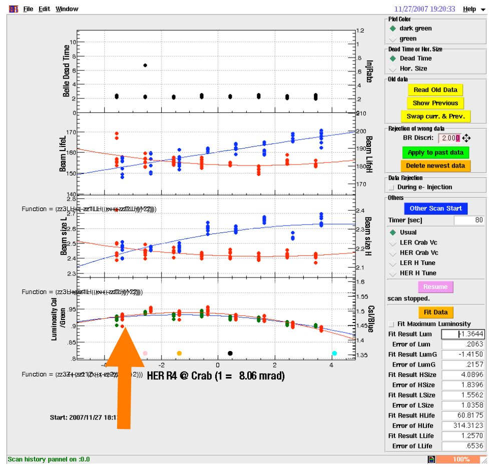
Collision center given by the beam-beam kick

iSize scan ~ V emittance scan

HER/LER V size vs. life

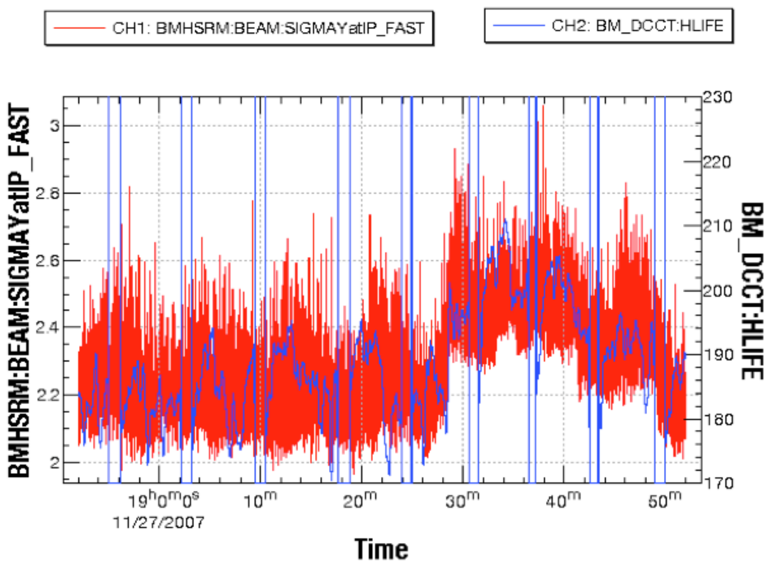
HER iSize bump 0.4 -> 0 mm

Short life time at small size for iSize scan. LER, which respond HER, also have the same feature.

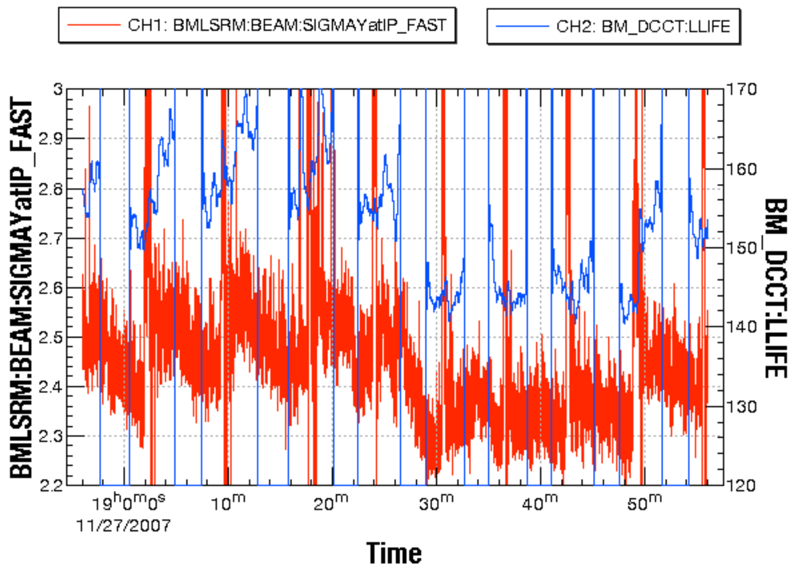


Short life time at small size for R4crab scan.

HER



LER



Summary of life time issue

- Simulation for halo formation is performed with a weak-strong simulation based on Gaussian model.
- The halo did not seem to affect the beam Life time.
- Life time asymmetry was not seen.
- Simulation gives that halo and beam size have positive correlation, but experiment did not show.
- Intrabeam effect? (Oide, Ohnishi)
- Physical aperture limit may be serious by dynamic beta and emittance due to beam-beam. (Funakoshi)

Beam-beam interaction and Lattice nonlinearity

- Beam-beam interaction

$$H_{BB}(J,\psi) = f_{BB}(J) + \sum_m g_{BB,m}(J)\exp(im\psi)$$

Simulation use H_{BB} exactly.

- Lattice nonlinearity

$$H_L(J,\psi) = f_L(J) + \sum_m g_{L,m}(J)\exp(im\psi)$$

- How to model H_L.

1. SAD model. It does not seem errors are modeled in SAD correctly.
2. Measurement based model. Tune scan of beam size without collision.

Effects of Lattice nonlinearity on beam-beam

- Lattice nonlinearity may affect luminosity performance.
- Several signs in which nonlinearity affects luminosity.

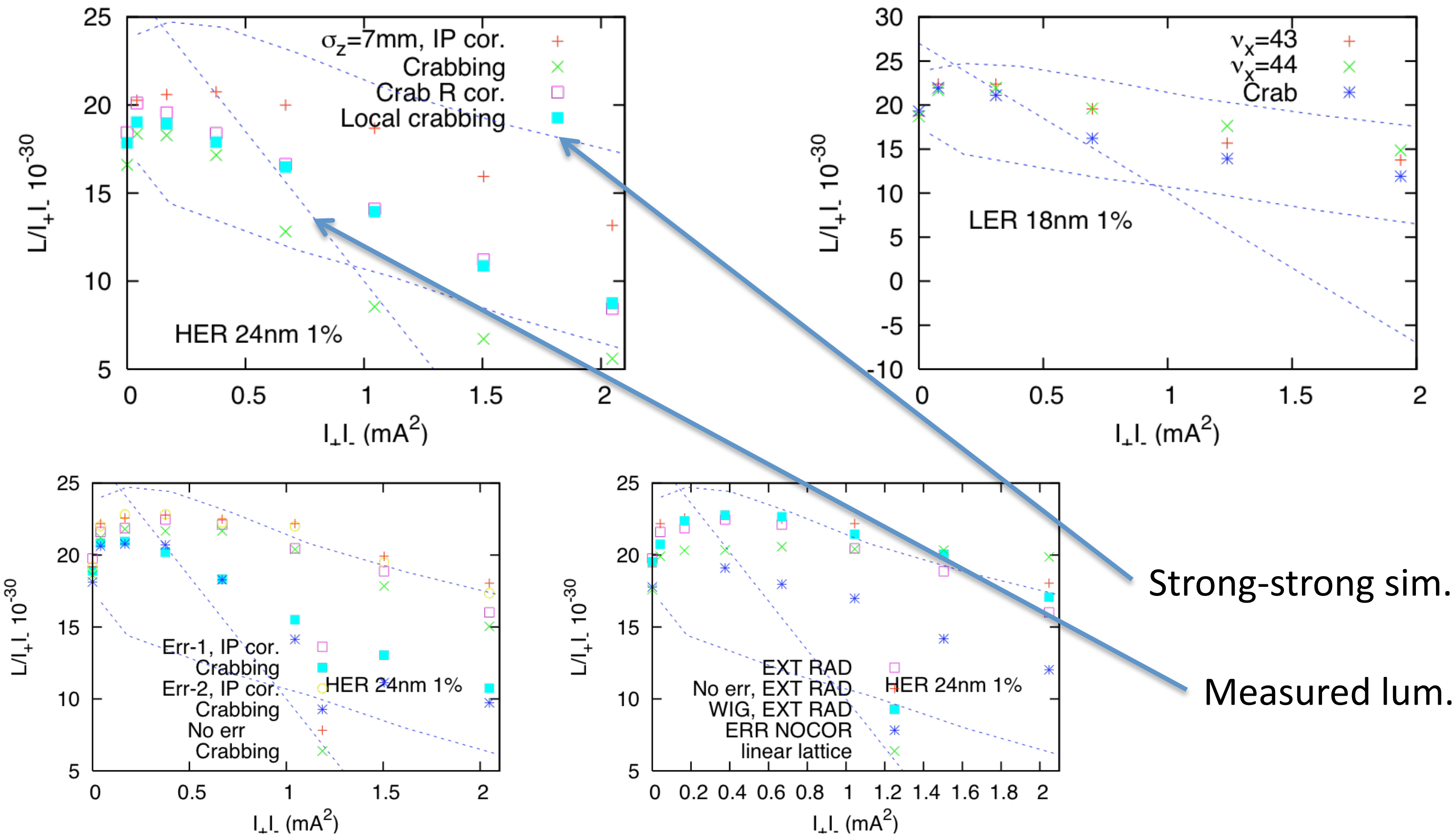
1. Existence of Golden orbit
2. Luminosity performance depended on something run by run, even though IP parameters were tuned hardly.
3. Integer part of tune affected the luminosity performance.
4. Beta distortion in wiggler section made worse the luminosity.

SAD weak-strong simulation

- Errors (sextupole position error) are generated
- Induced linear coupling and dispersion at IP are corrected.
- Difference between HEAD ON and Crab crossing was seen. Crabbing beam experiences lattice nonlinearity? Difficulty of SAD tracking, normal mode given by linear optics differs from tracking a little....More study.

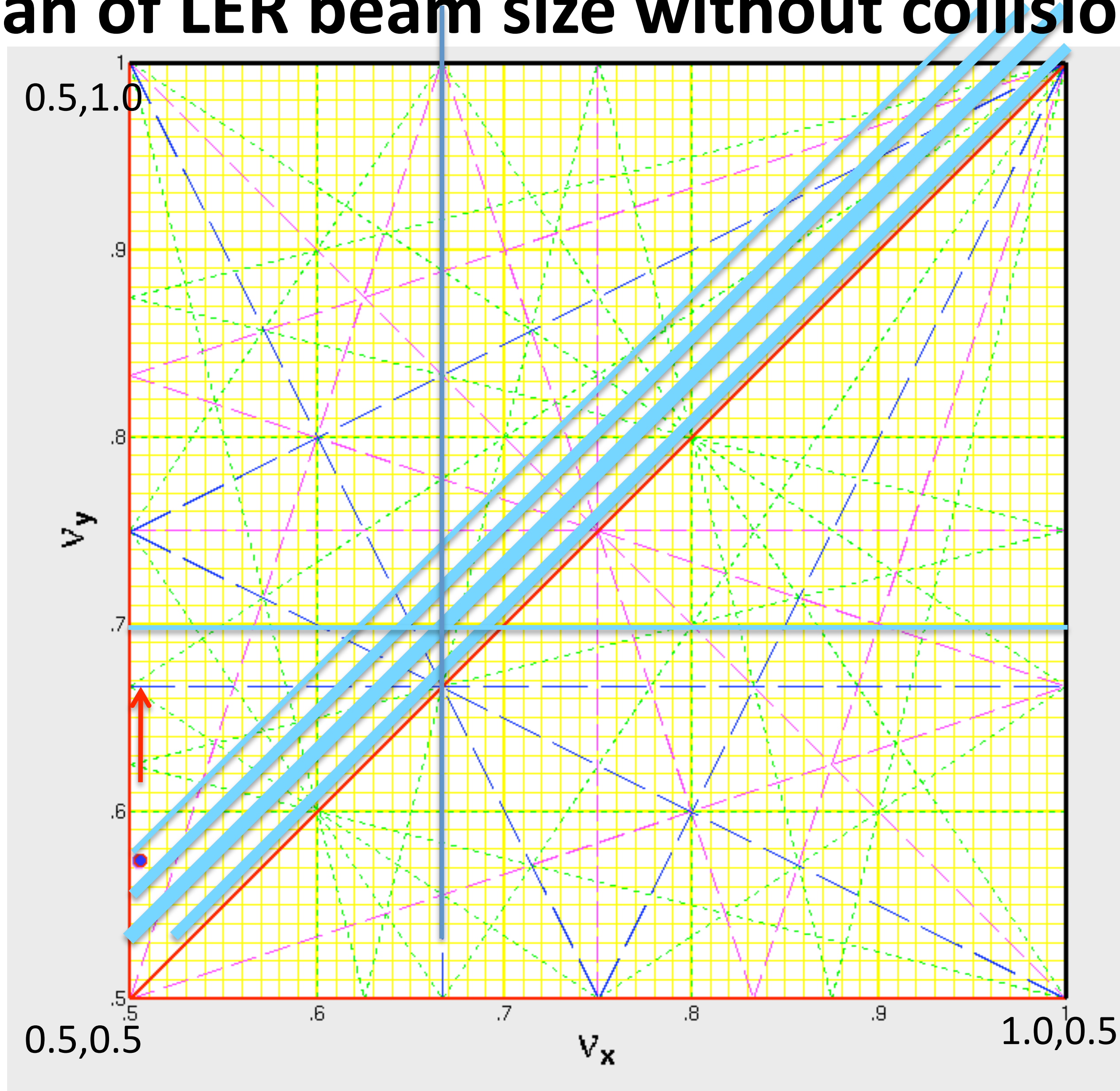
SAD simulation

- LER weak HER weak

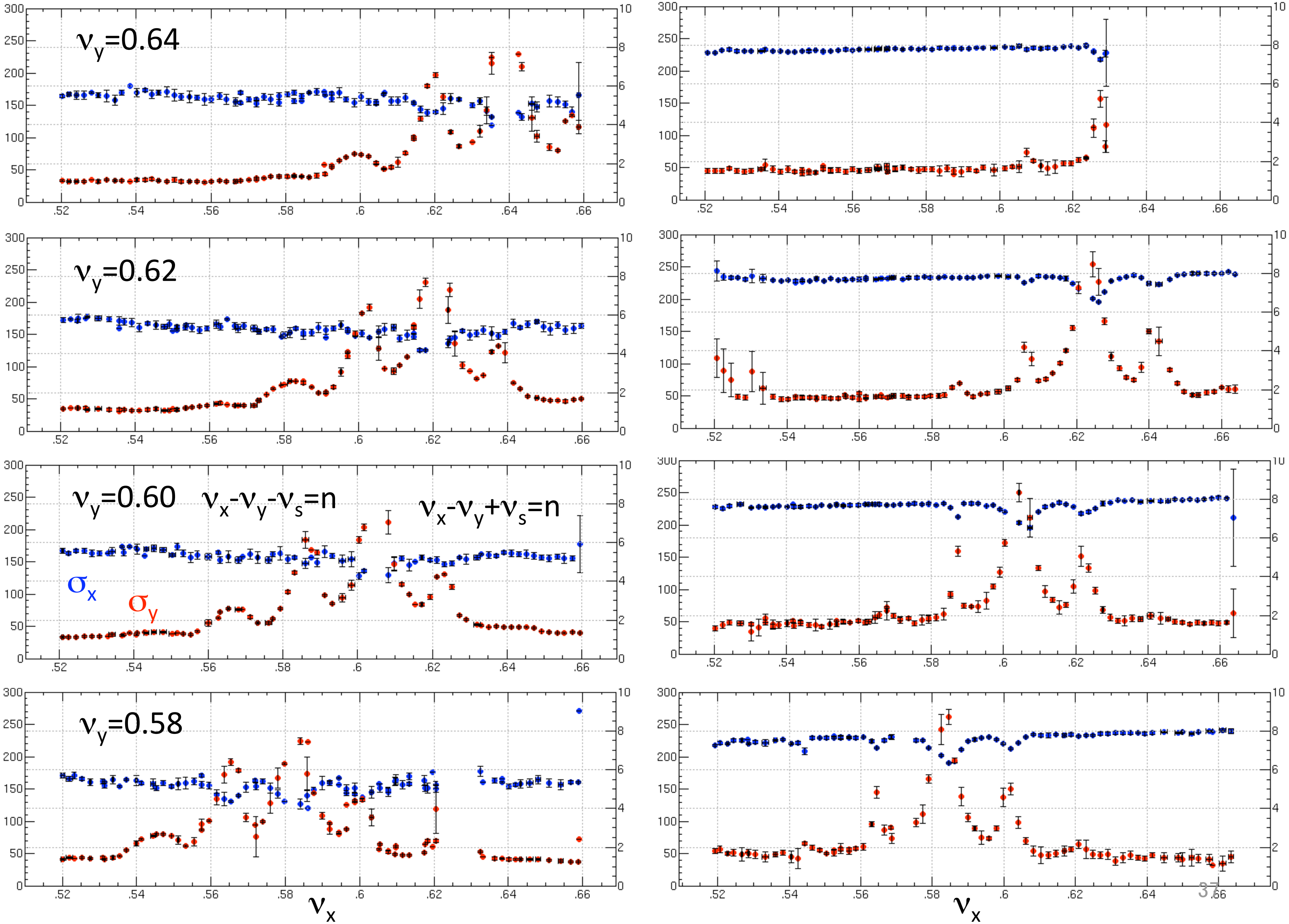


Measurement of lattice nonlinearity (A. Temnykh)

Tune scan of LER beam size without collision



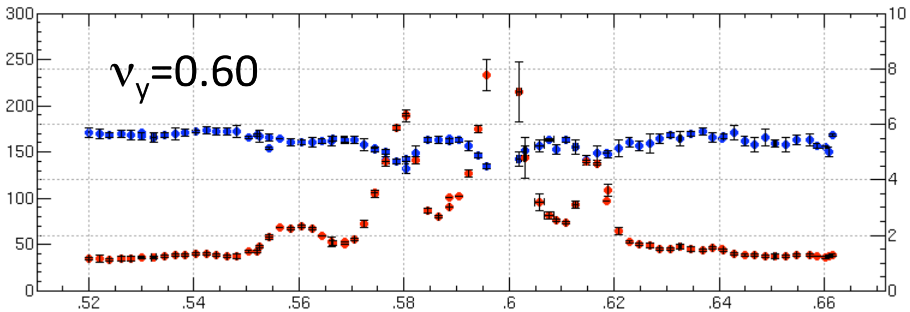
LER ν_s=-0.0240 Y. Ohnishi, K. Ohmi HER ν_s=-0.0209

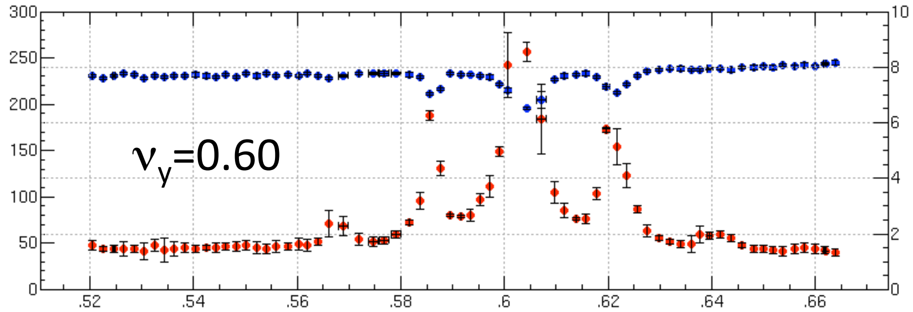


LER

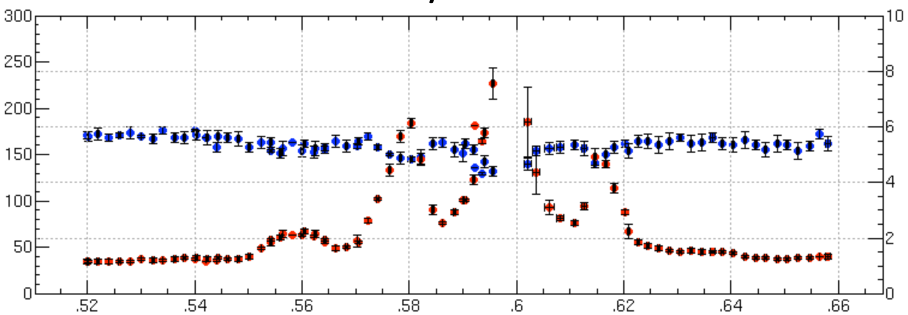
HER

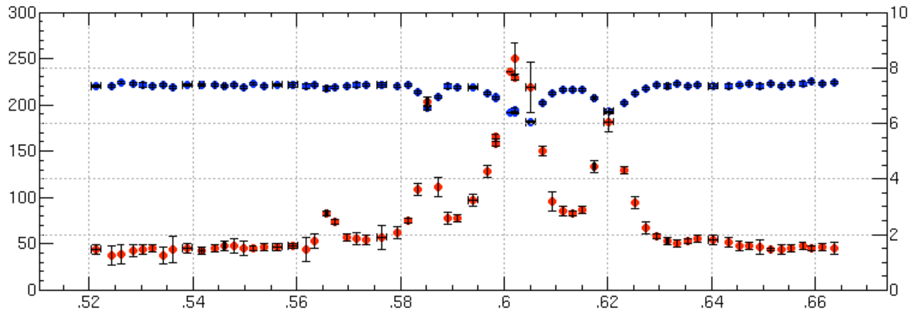
Knob = 0 / CRAB ON



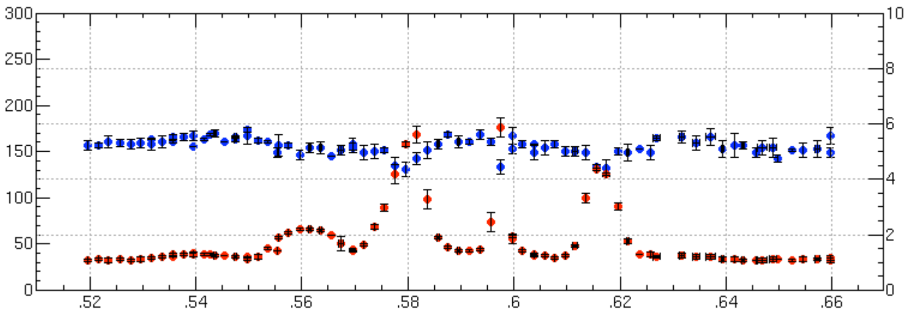


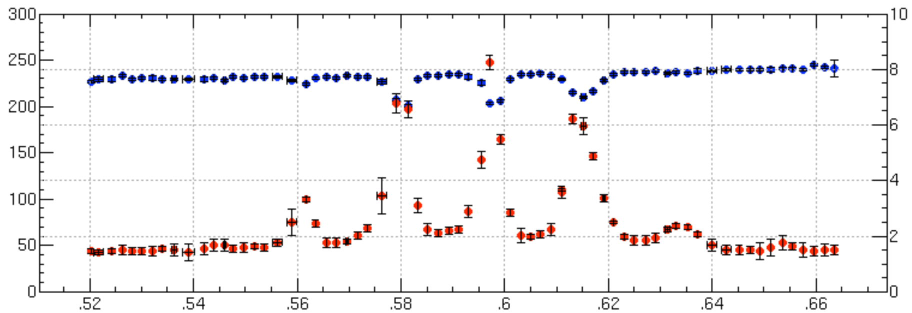
Knob = 0 / CRAB OFF





After optics correction Knob = 0 / CRAB ON





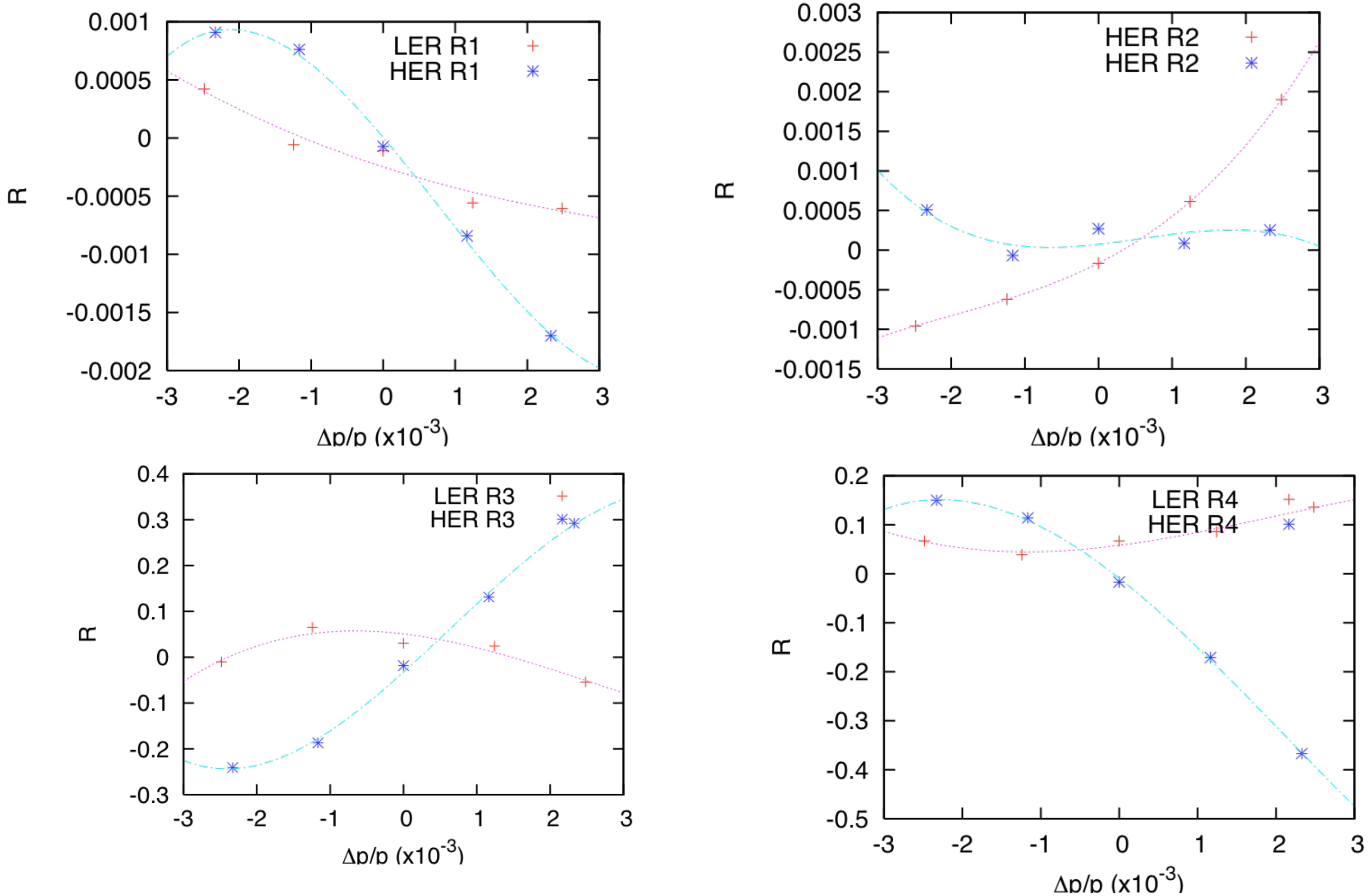
ν_x

ν_x

Coupling chromaticity can cause the resonance lines
Measurement of off momentum R

Y. Seimiya, K. Ohmi, H. Koiso, K. Oide

$$R_i(\delta) = R_{i0} + R_{i1}\delta + R_{i2}\delta^2 + R_{i3}\delta^3$$



R chromaticity of LER

- R_{10}=-0.0002486, R_{11}=-0.1998, R_{12}=21.64, R_{13}=-0.007131
- R_{20}=-0.0001642, R_{21}=0.4696, R_{22}=103.1, R_{23}=0.1062
- R_{30}=0.05080, R_{31}=-19.06, R_{32}=-12881 R_{33}=10.26
- R_{40}=0.05796, R_{41}=20.71, R_{42}=6807., R_{43}=-6.861

R chromaticity of HER

- R_{10}=5.586e-06, R_{11}=-0.7320, R_{12}=-71.60, R_{13}=0.1849
- R_{20}=7.242e-05, R_{21}= 0.1058, R_{22}=50.58, R_{23}=-0.1720
- R_{30}=-0.03256, R_{31}=143.9, R_{32}=10266., R_{33}=-31.63
- R_{40}=-0.009200 R_{41}=-126.1, R_{42}=-18058., R_{43}=16.28

Reconstruct Hamiltonian from the R measurement

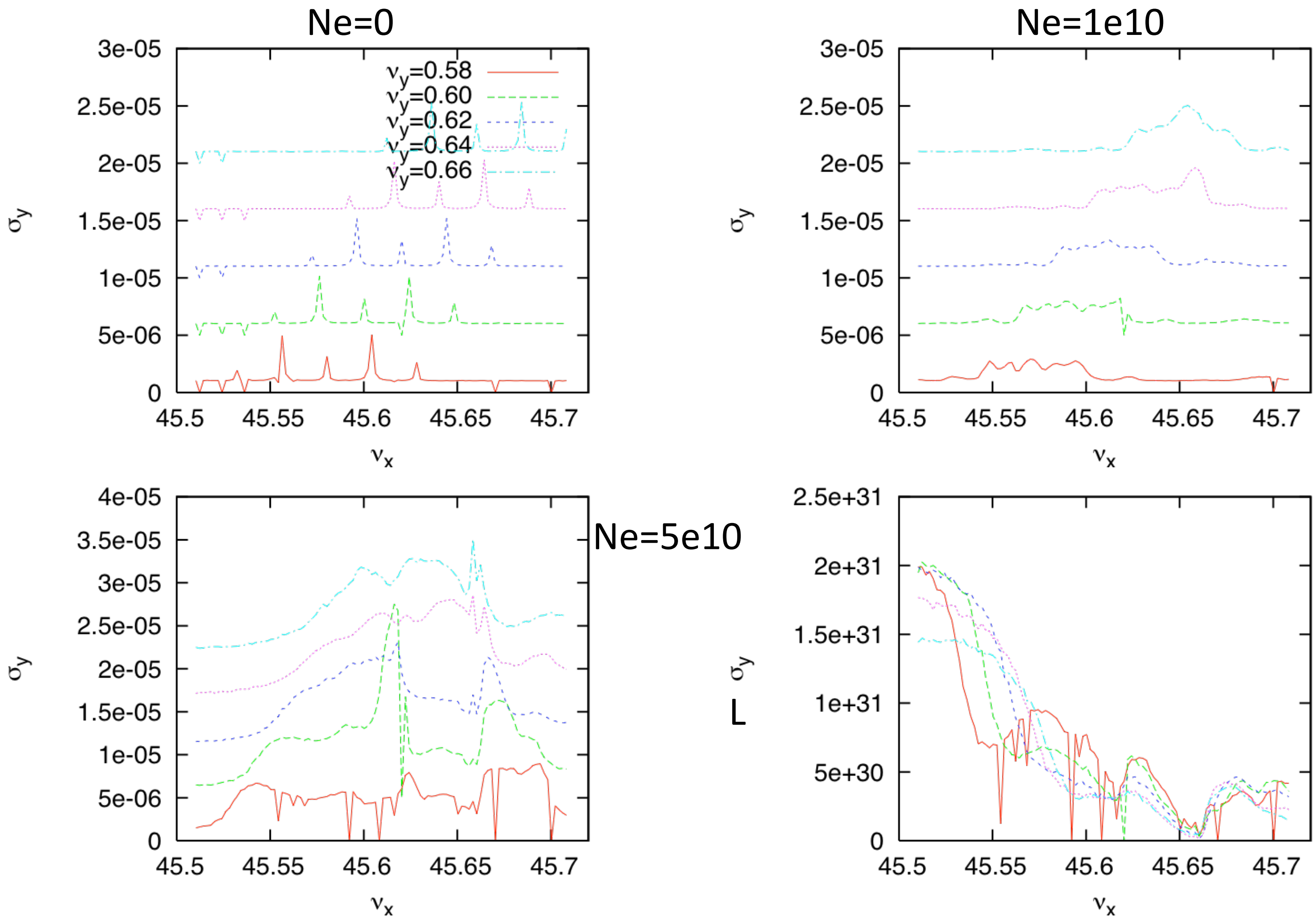
Y. Seimiya, K. Ohmi

- Nonlinear chromaticities (off momentum tune) were also measured.
- 10 chromaticities in each order of δ are given.
- The chromaticities correspond to the coefficient of Hamiltonian.

$$H_I = \sum_{n=1}\Big(a_n x^2 + b_n x p_x + c_n p_x^2 + d_n xy + e_n x p_y + f_n p_x y + g_n p_x p_y + u_n y^2 + v_n y p_y + w_n p_y^2\Big)\delta^n$$

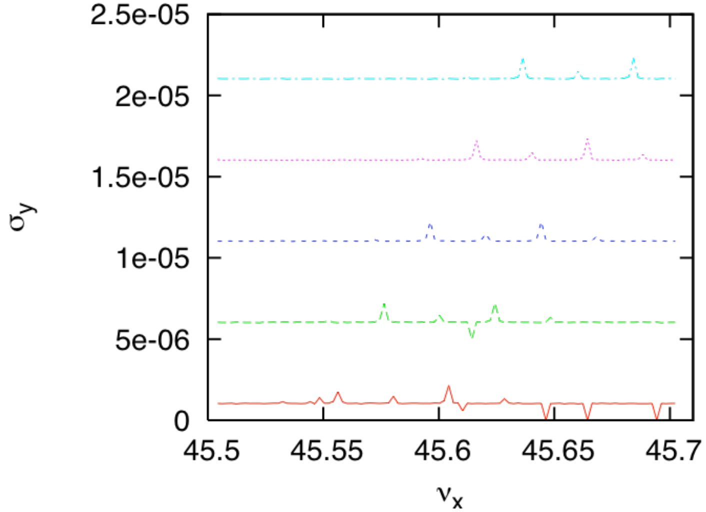
Beam-beam simulation with the chromatic Hamiltonian

Measurement data at Feb 26, 2008   Bad condition

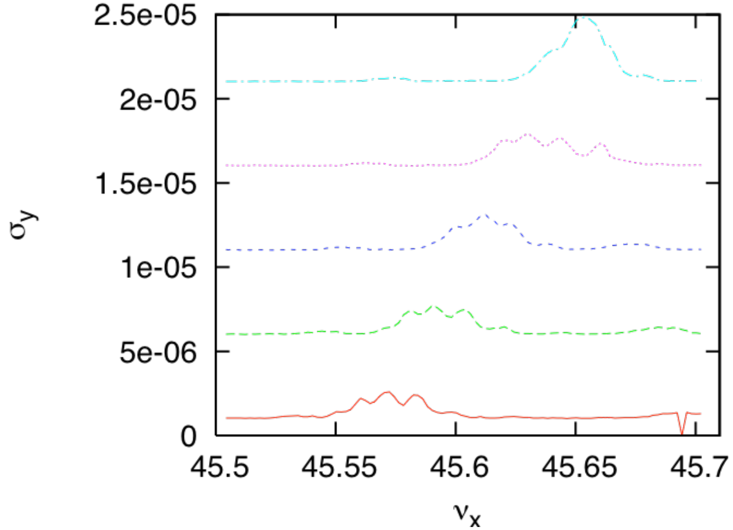


Measurement data at Dec. 12, 2005
Good condition without crab

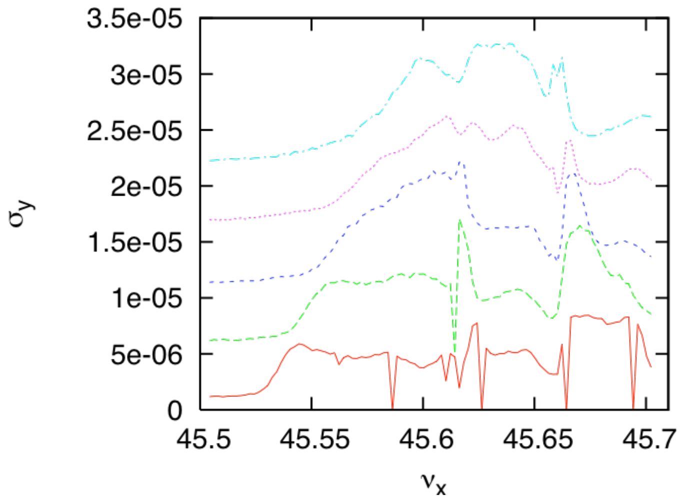
Ne=0

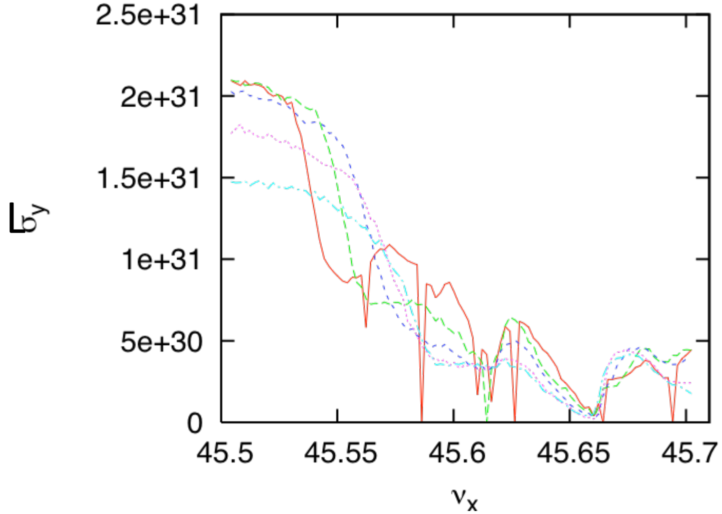


Ne=1e10



Ne=5e10





Linear R chromaticity correction with Skew sextupoles

$$X = \frac{x}{\sqrt{\beta_x^*}} \qquad P_X = \frac{\alpha_x^* x + \beta_x^* p_x}{\sqrt{\beta_x^*}} \qquad k_x = \frac{\beta_x \beta_y^{1/2} K_2}{6} \qquad k_y = \frac{\beta_y^{3/2} K_2}{6}$$

$$J_X = \frac{X^2 + P_X^2}{2} = \frac{\gamma x^2 + 2\alpha_x x p_x + \beta_x p_x^2}{2}$$

$$\exp(-:F_3:)\exp(-:\mu J:) = \exp(-:\phi J:)\exp(-:k_x X^2 Y + k_y Y^3:)\exp(-:(\mu - \phi)J:)$$

$$= \exp(-:\phi J:)\exp(-:k_x X^2 Y + k_y Y^3:)\exp(+:\phi J:)\exp(-:\mu J:)$$

$$= \exp(-:k_x(X\cos\phi_x + P_X \sin\phi_x)^2(Y\cos\phi_y + P_Y \sin\phi_y) + k_y(Y\cos\phi + P_Y\sin\phi)^3 + :)\exp(-:\mu J:)$$

$$H_I \approx \oint \left[\left\{ k_x X\cos\phi_x + P_X \sin\phi_x + \frac{\eta_x}{\sqrt{\beta_x^*}}\delta \right\}^2 (Y\cos\phi_y + P_Y\sin\phi_y) + k_y(Y\cos\phi + P_Y\sin\phi)^3 \right] ds$$

$$\phi = \phi^* - \phi(s)$$

$$H_I \approx \oint \left[\left\{ k_x X \cos\phi_x + P_X \sin\phi_x + \frac{\eta_x}{\sqrt{\beta_x^*}} \delta \right\}^2 (Y\cos\phi_y + P_Y \sin\phi_y) + k_y (Y\cos\phi + P_Y \sin\phi)^3 \right] ds$$

$$X = \frac{x}{\sqrt{\beta_x^*}} \qquad P_X = \frac{\alpha_x^* x + \beta_x^* p_x}{\sqrt{\beta_x^*}} \qquad k_x = \frac{\beta_x \beta_y^{1/2} K_2}{6}$$

$$H_I \approx \oint \frac{\beta_x \sqrt{\beta_y} K_2}{3} \left[\left(\frac{\cos\phi_x + \alpha_x^* \sin\phi_x}{\sqrt{\beta_x^*}} x + \sqrt{\beta_x^*} \sin\phi_x p_x \right) \left(\frac{\cos\phi_y + \alpha_y^* \sin\phi_y}{\sqrt{\beta_y^*}} y + \sqrt{\beta_y^*} \sin\phi_y p_y \right) \frac{\eta_x}{\sqrt{\beta_x^*}} \delta \right] ds$$

$$d_1 = \oint \frac{K_2}{3} \frac{\beta_x \sqrt{\beta_y}}{\beta_x^* \sqrt{\beta_y^*}} \left(\cos\phi_x + \alpha_x^* \sin\phi_x \right) \left(\cos\phi_y + \alpha_y^* \sin\phi_y \right) \eta_x ds = 21.72$$

$$e_1 = \oint \frac{K_2}{3} \frac{\beta_x \sqrt{\beta_y \beta_y^*}}{\beta_x^*} \left(\cos\phi_x + \alpha_x^* \sin\phi_x \right) \sin\phi_y \eta_x ds = 0.0540$$

$$f_1 = \oint \frac{K_2}{3} \frac{\beta_x \sqrt{\beta_y}}{\sqrt{\beta_y^*}} \sin\phi_x \left(\cos\phi_y + \alpha_y^* \sin\phi_y \right) \eta_x ds = -35.89$$

$$g_1 = \oint \frac{\beta_x \sqrt{\beta_y \beta_y^*} K_2}{3} \sin\phi_x \sin\phi_y \eta_x ds = -0.14$$

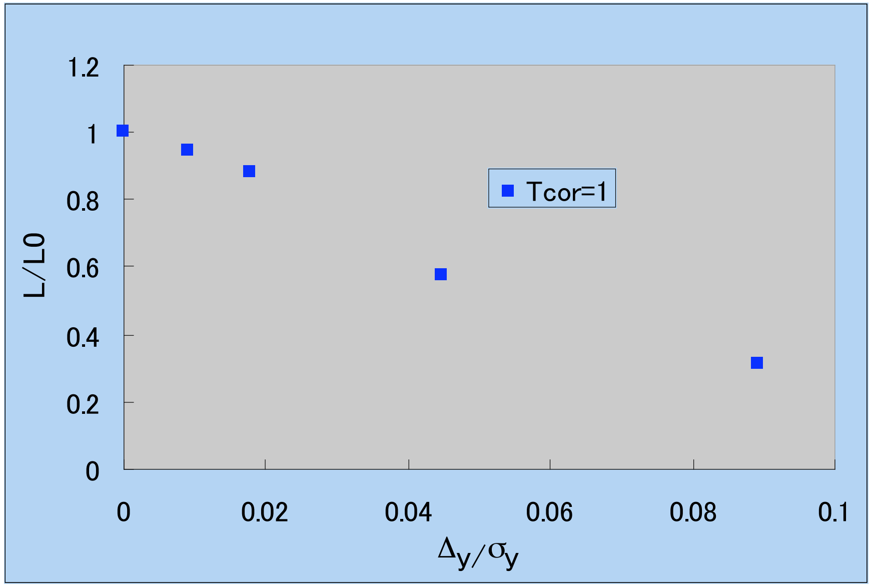
External fluctuation

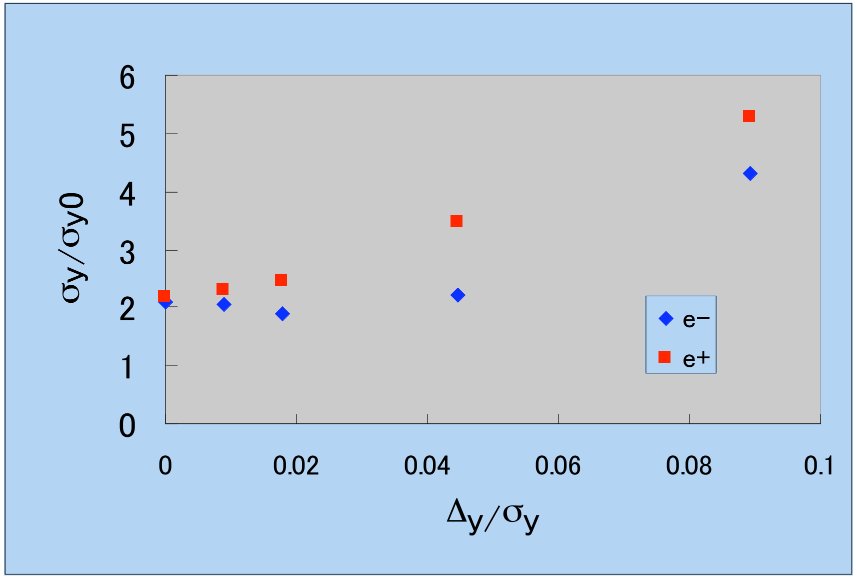
- Noise with High frequency component is important.
- Noise comparable with the radiation excitation can affect luminosity in e+e- colliders.
- From the view of the weak-strong model, beam particle does not distinguish incoherent (radiation) or coherent (feedback) fluctuation: i.e. each particle diffuse due to the fluctuation.
- Radiation excitation $\Delta y^2=2\sigma_y^2/\tau$, where $\tau=4000$ turn for KEKB. Therefore $\Delta y/\sigma_y=0.022$.
- Dipole noise 2 % causes 20 % loss of luminosity.
- The degradation depends on the beam-beam parameter. High beam-beam parameter is more serious, $\sim\xi^2$.

External diffusion: Vertical offset noise (Hawaii05)

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

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

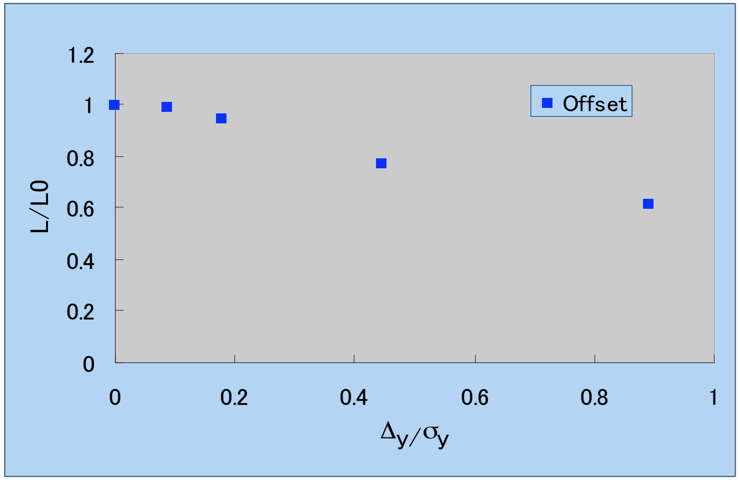


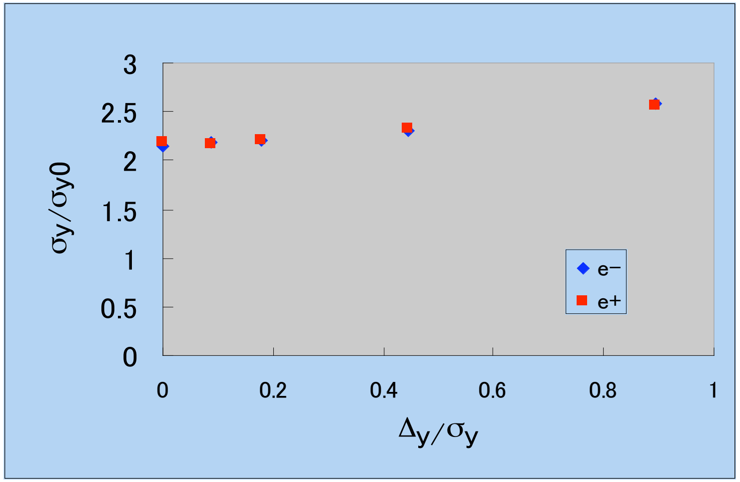


Orbit offset (static) (Hawaii05)

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

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



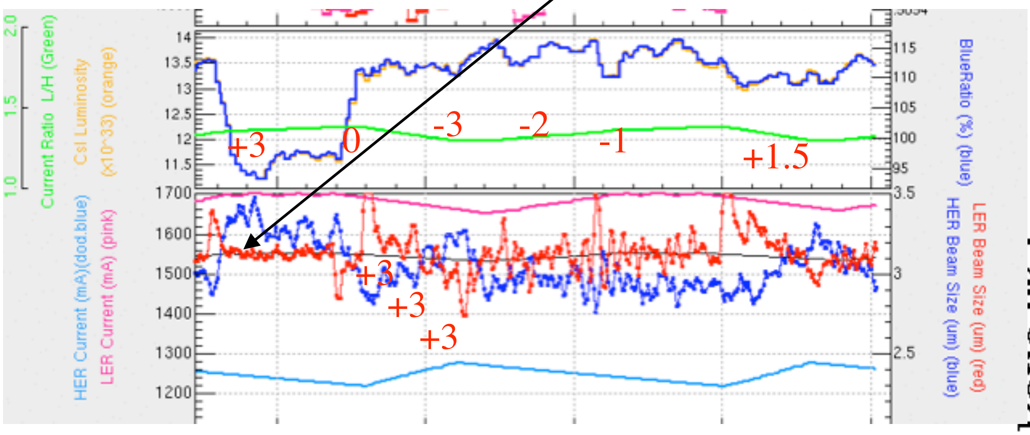


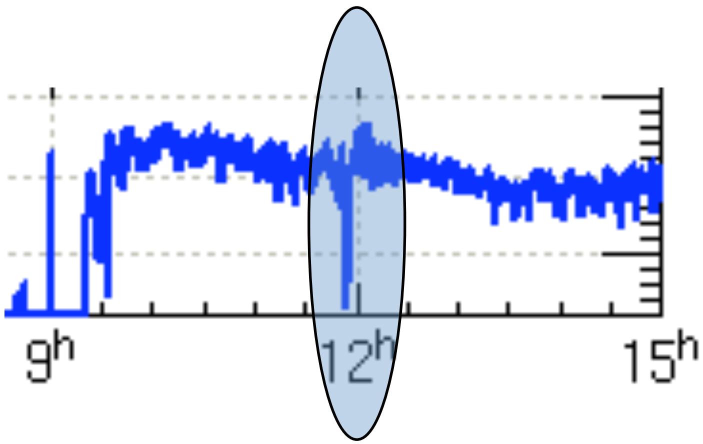
1/20 compare than that for fast noise

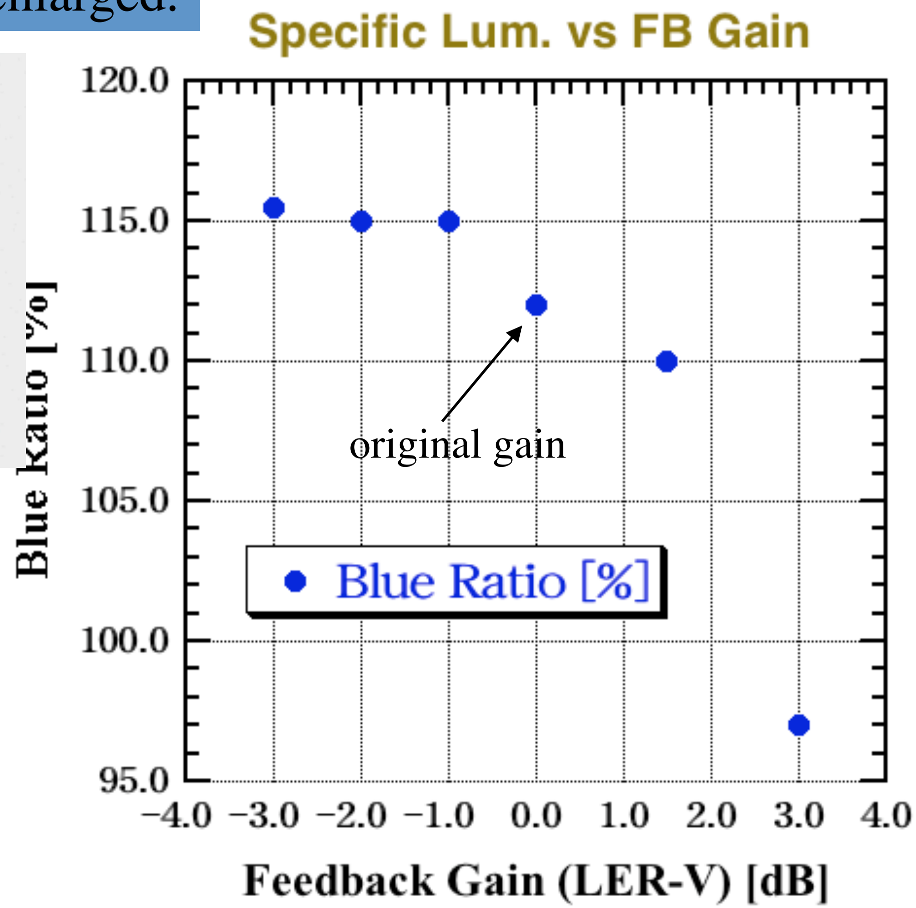
Specific Luminosity vs FB Gain

KEKB

HER vertical size enlarged.



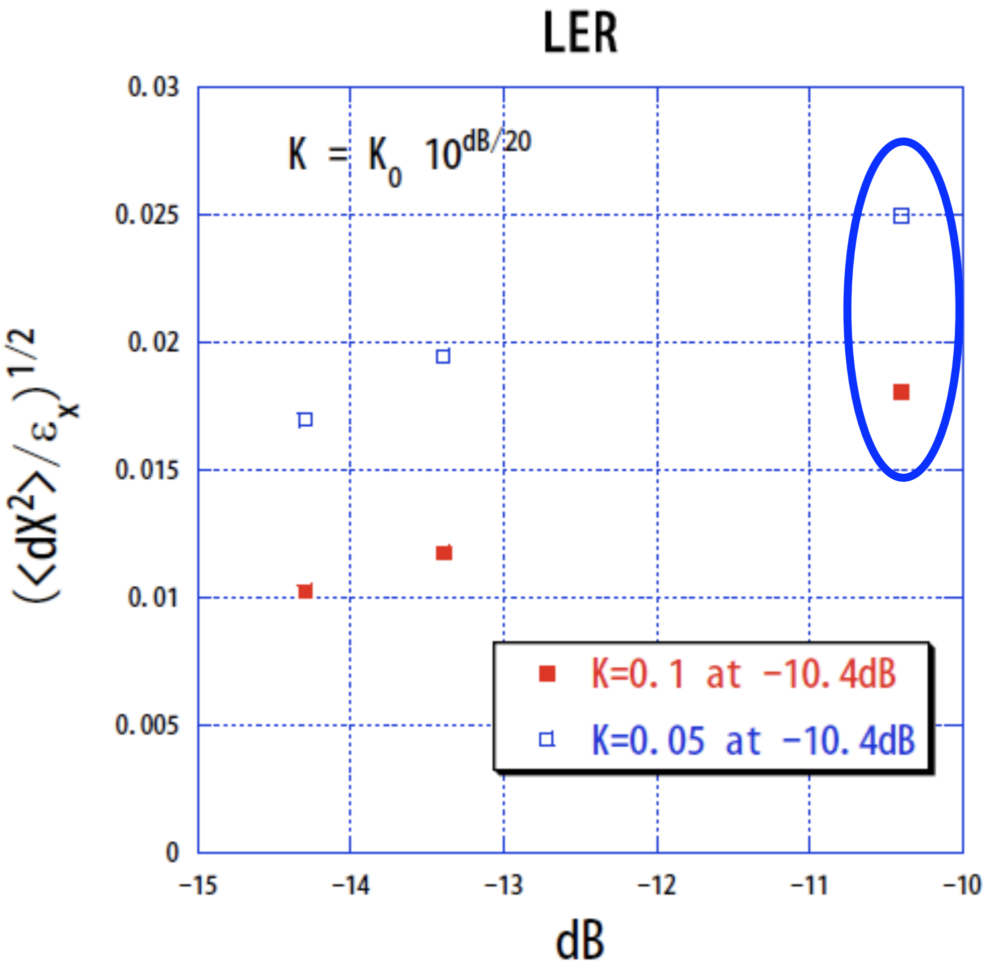




FB gain of the LER vertical affects the specific luminosity.
The other gains (LER H, HER H/V) bring no effects.

Speculated beam noise for the kicker noise

KEKB



This noise level should affect the luminosity.

The luminosity degradation can be explained by the feedback noise.

Summary for present KEKB

- Simulations have not given to explain the bad luminosity performance at KEKB yet.
- Linear optics error can be still considered as a major cause of the luminosity degradation.
- It is not clear whether the luminosity and life time issues are caused by an origin or independent two origins. Physical aperture and dynamic beam-beam may be cause.
- Lattice nonlinearity was estimated. Chromatic synchro-beta resonances and weak 3rd order resonance ($3\nu_y$=n) were seen. The chromaticity was estimated by off-momentum optics measurements.
- Simulation with the chromaticity did not give remarkable luminosity degradation.

LHC simulations

- Simulation for LHC was performed during this stay. Snaked beam, crab waist, LPA… are discussed in 28 Aug.