Upgrade and Super KEKB

K. Ohmi for superKEKB design group

DAFNE-KEK meeting

11 December, 2008

Machine parameters (preliminary)

		LoI (updated)	Upgrade (LER/HER)	
Emittance	ε_x	24	12/13	nm
	ε_y	0.18	0.060/0.066	nm
Beta at IP	β_x*	200	200	mm
	β_y*	3	3	mm
Beam size at IP*1	σ_x*	50.0	37.5/39.8	μm
	σ_y*	1.0	2.11/2.28	μm
Bunch length	σ_z	3	3	mm
Transverse damping time	τ_x	47	84/47	msec
Betatron/synchrotron tune	$\nu_x/\nu_y/\nu_s$	M+0.506/N+0.545/-0.031*1	M+0.505/N+0.550/-0.025	M,N:integ er
Beam Energy	E_+/E_-	3.5/8.0	3.5/8.0	
Beam current	I_+/I_-	9.4/4.1	9.4/4.1	A
#bunches	N_b	5018	5018	
Crossing angle	$2\phi_x$	30 → 0 (crab crossing)	30 → 0 (crab crossing)	mrad
Beam-beam*2	ξ_x	0.135	0.153	
	ξ_y	0.215	0.296	
Beam-beam reduction*3	$R_{\xi x}$	0.99	0.99	
	$R_{\xi y}$	1.11	1.11	
Luminosity reduction*3	R_L	0.86	0.86	
Luminosity	L	4.0×10^{35}	5.5×10^{35}	$cm^{-2}s^{-1}$

*1 include beam-beam effects *2 calculated from luminosity *3 nominal values

Y. Ohnishi

Comparison of parameters

	KEKB Design (A)	KEKB (achieved)	KEKB upgrade (B)	Gain Factor (B/A)
β_y^* (mm)	10	5.9/6.5 (5.9/5.9)	3	3.3
ξ_y	0.052	0.056 (0.093)	0.296	
$R_{\xi y}$	0.885	0.879(1.15)	1.11	
$\xi_y/R_{\xi y}$	0.059	0.063(0.081)	0.267	4.5
I_{beam} (H/L) (A)	1.1/2.6	1.45/1.8 (0.95/1.62)	4.1/9.4	3.6
R_L	0.845	0.715(0.827)	0.86	1.02
Luminosity (10^{34} cm^{-2} s^{-1})	1	1.71 (1.46)	55	55
σ_z (mm)	4	( ): with crab	3	

Bunch length

- Mechanism
  - Potential-well distortion
  - Micro-wave instability
  - CSR
- KEKB (Measurement)
  - HER
    - ~6.8mm@0.45mA, 13MV
    - σ_z(cal) = 5.2mm@0mA, 13MV
  - LER
    - ~6.5mm@0.95mA, 8MV
    - σ_z(cal) = 4.7mm@0mA, 8MV
- KEKB upgrade (Design)
  - HER
    - 3mm@0.82mA
  - LER

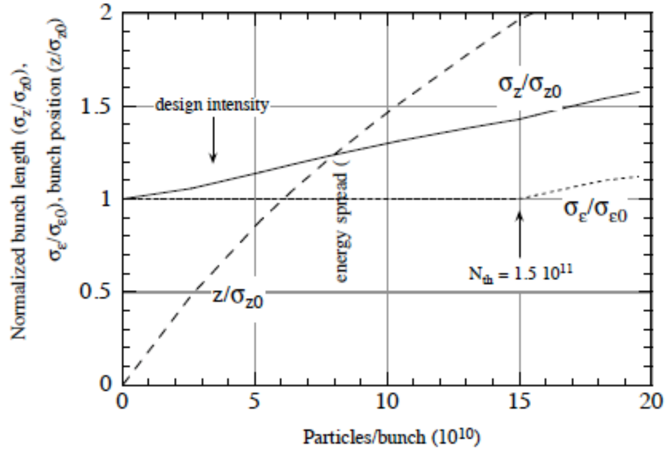

Figure 5.6: Bunch length and energy spread in the LER.

Careful design of vacuum components including chamber radius is still going on.

In the KEKB upgrade, vacuum components should be redesigned and replaced.

MAXWELL'S EQUATIONS

K. OIDE

$$\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial r E_r}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_r}{\partial \phi^2} + \frac{\partial^2 E_r}{\partial y^2} - \frac{1}{c^2}\frac{\partial^2 E_r}{\partial t^2} - \frac{2}{r^2}\frac{\partial E_\phi}{\partial \phi} = \frac{1}{\varepsilon_0}\frac{\partial \rho}{\partial r}$$

$$\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial r E_\phi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_\phi}{\partial \phi^2} + \frac{\partial^2 E_\phi}{\partial y^2} - \frac{1}{c^2}\frac{\partial^2 E_\phi}{\partial t^2} + \frac{2}{r^2}\frac{\partial E_r}{\partial \phi} = \frac{1}{\varepsilon_0}\left(\frac{1}{r}\frac{\partial \rho}{\partial \phi} + \frac{1}{c}\frac{\partial \rho}{\partial t}\right)$$

$$\rho \propto \delta(r-R)\delta(y)\exp\left(ik(R\phi - ct)\right)$$

$$E_{r,\phi} = \overline{E}_{r,\phi}(\phi)\exp\left(ik(R\phi - ct)\right)$$

$$\overline{E}_r = \overline{E}_r + \overline{E}_{r0} \ ,$$

$$\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial r \overline{E}_{r0}}{\partial r} + \frac{\partial^2 \overline{E}_{r0}}{\partial y^2} = \frac{1}{\varepsilon_0}\frac{\partial \rho}{\partial r}$$

★ **IGNORE** $\frac{\partial^2 \overline{E}}{\partial \phi^2}$ **TERMS (AGOH-YOKOYA)**

RESULTS(2): SUPERKEKB ANTECHAMBERS

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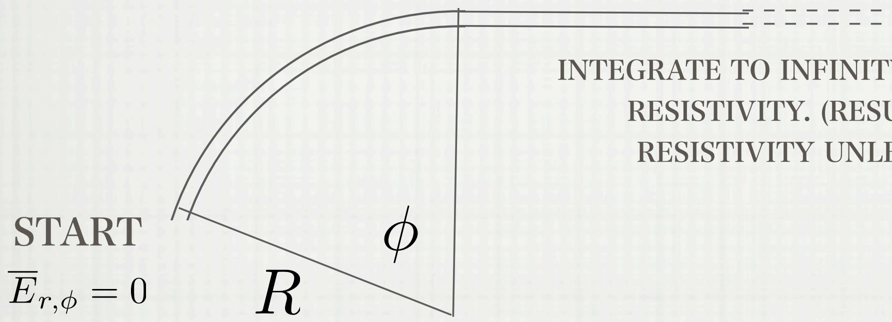
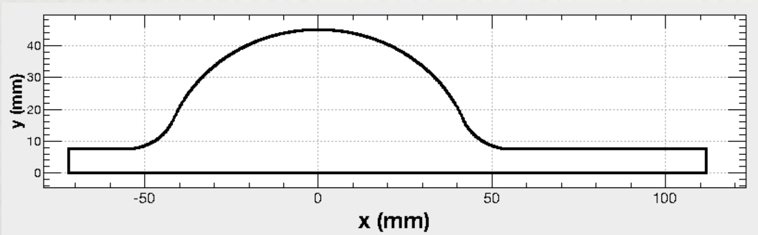
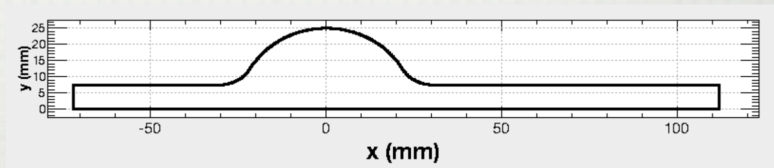


INTEGRATE TO INFINITY, ASSUMING DAMPING BY SURFACE RESISTIVITY. (RESULT DOES NOT DEPEND ON THE RESISTIVITY UNLESS DAMPING IS TOO STRONG.)



$a = 45$ mm

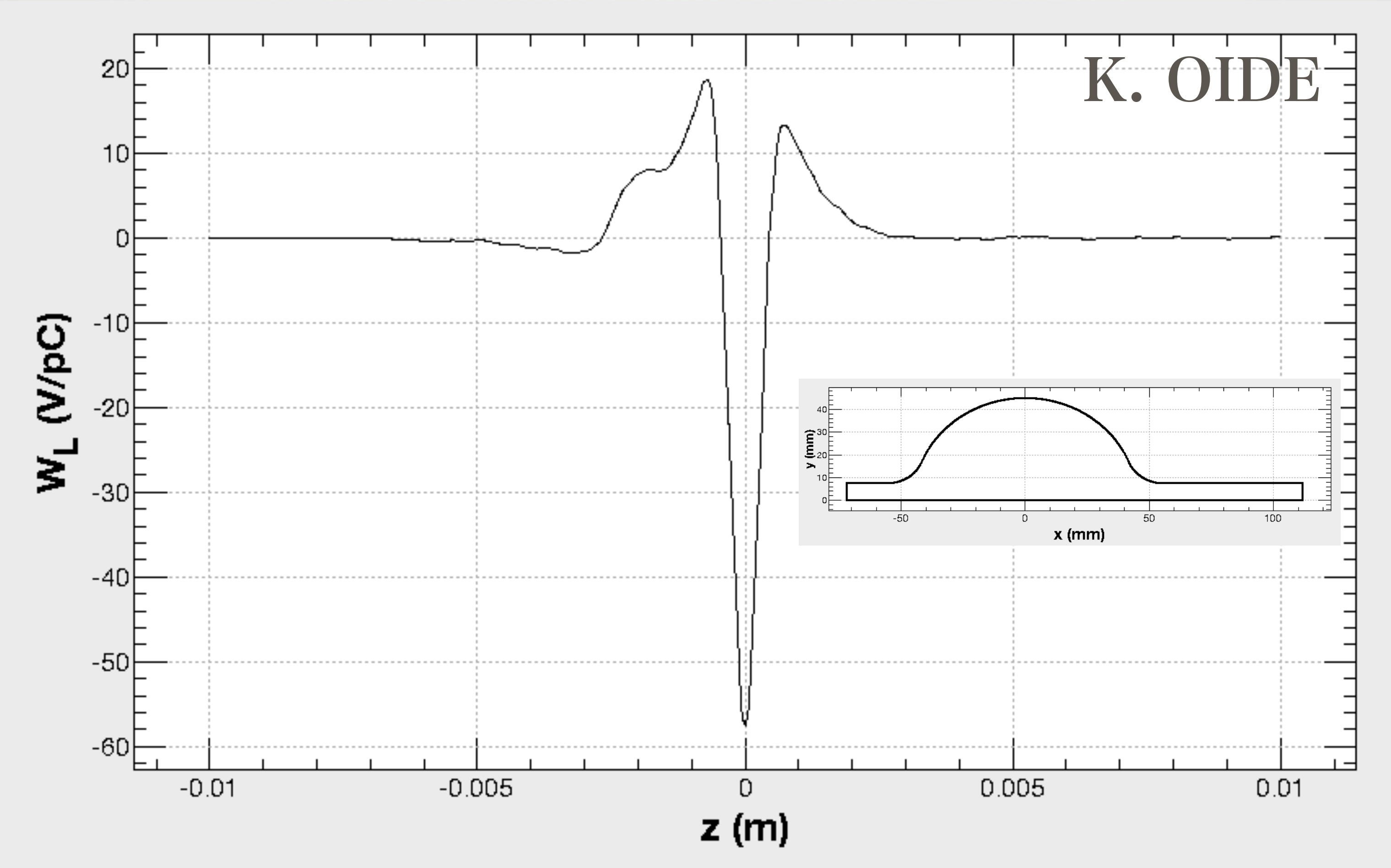


$a = 25$ mm

CROSS SECTIONS BY SUETSUGU

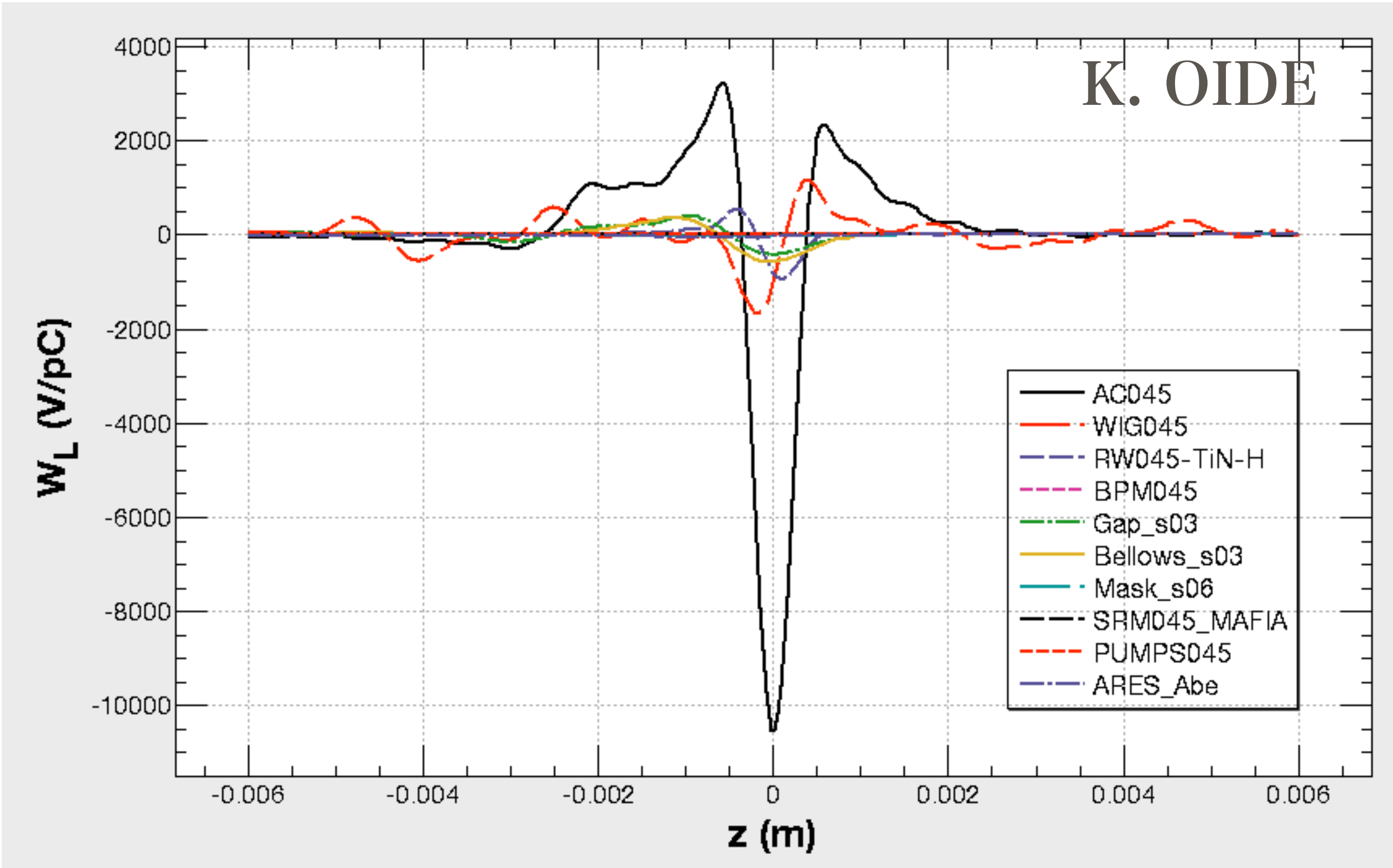
rac = 45 mm, rho = (B2P) m, s = (B2P) + (res), sigz = 0.3 mm,

omax = 3.5/sigz, nomega = 32, varmesh (dlim/4)



2 SEP 2008

45 mm All



23 Sep 2008

All wakes, incl. wigglers

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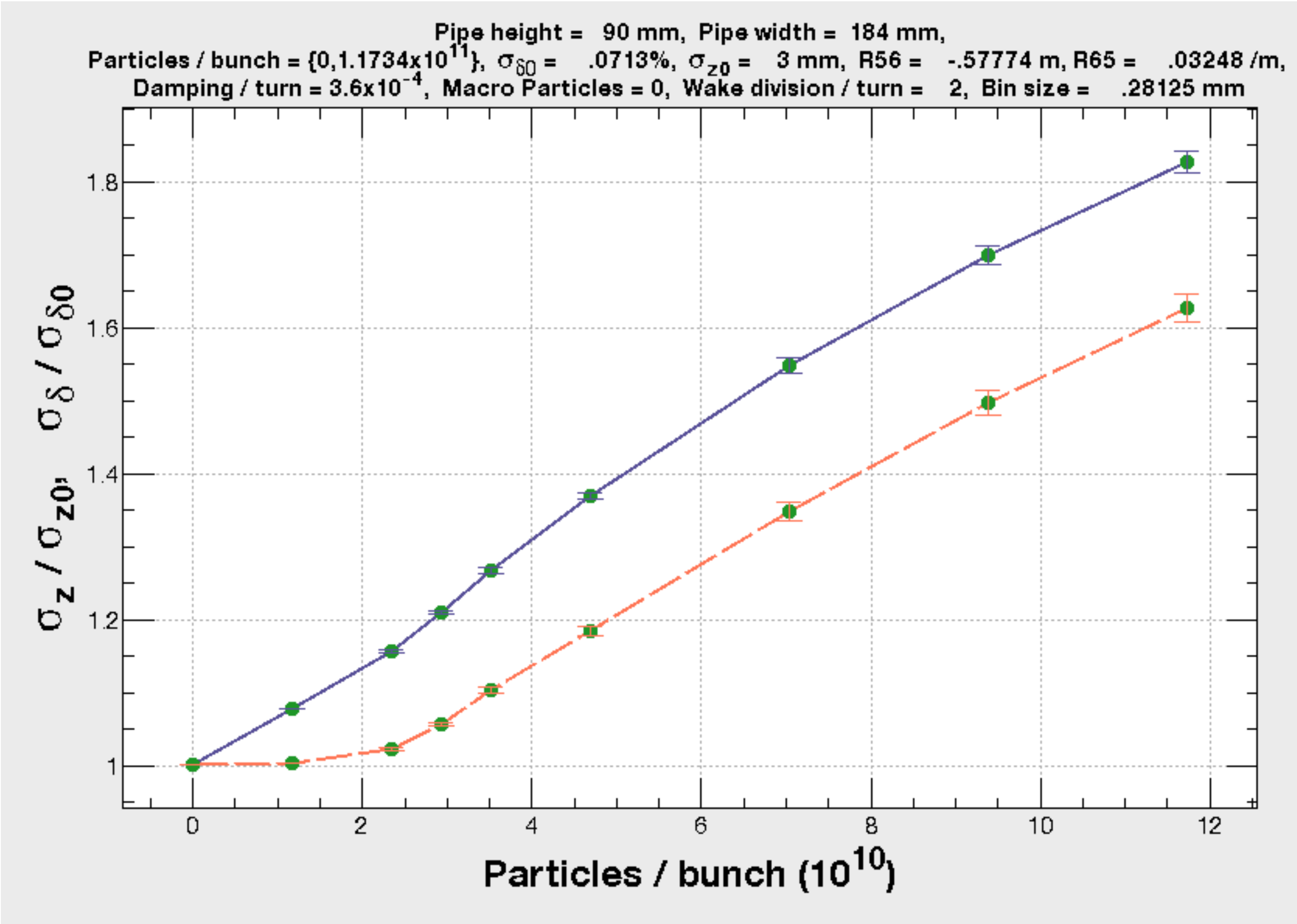
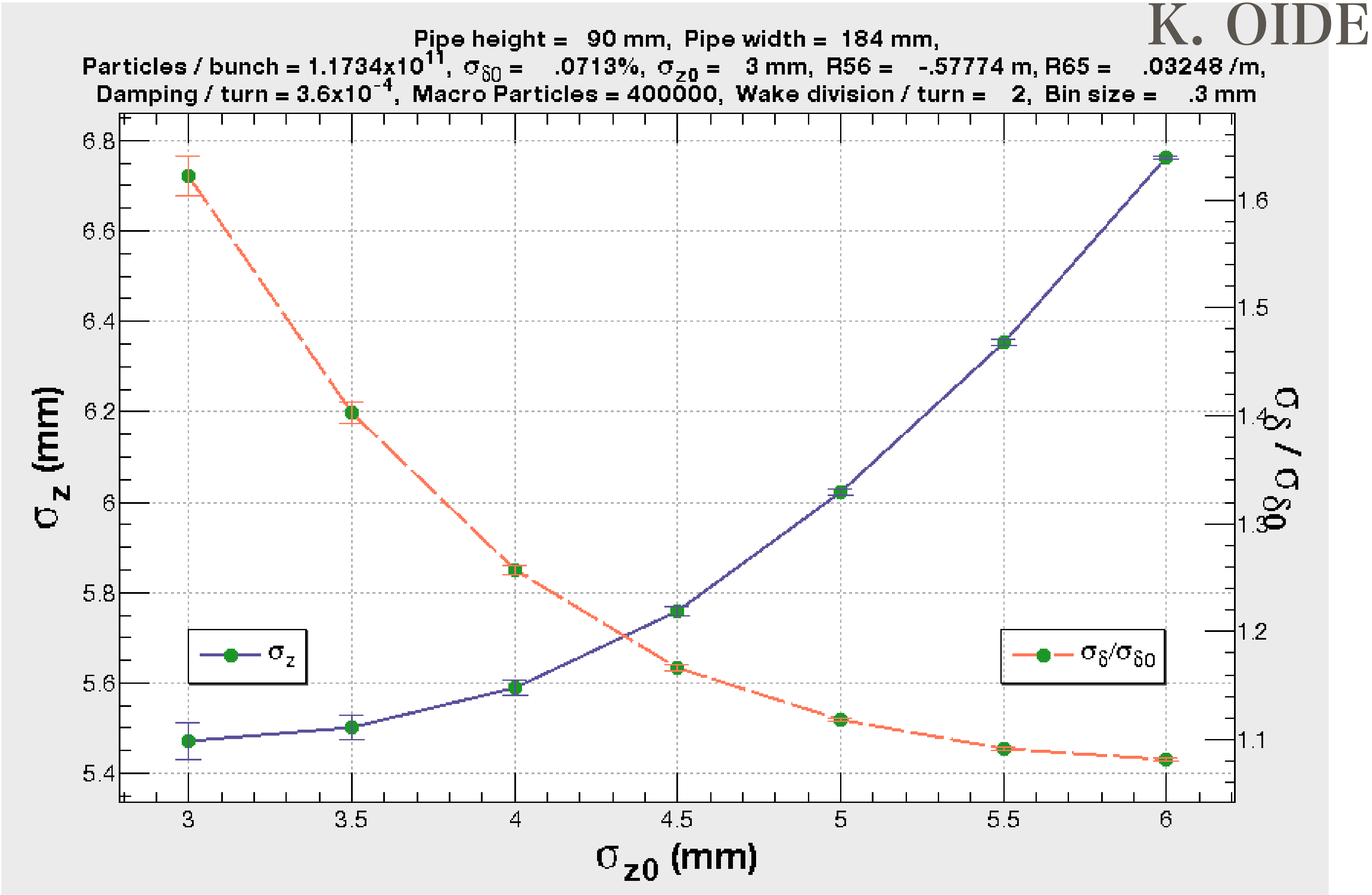


23 Sep 2008

All wakes (45 mm), incl. wigglers



26 Sep 2008

All wakes (45 mm), incl. wigglers

negative alpha

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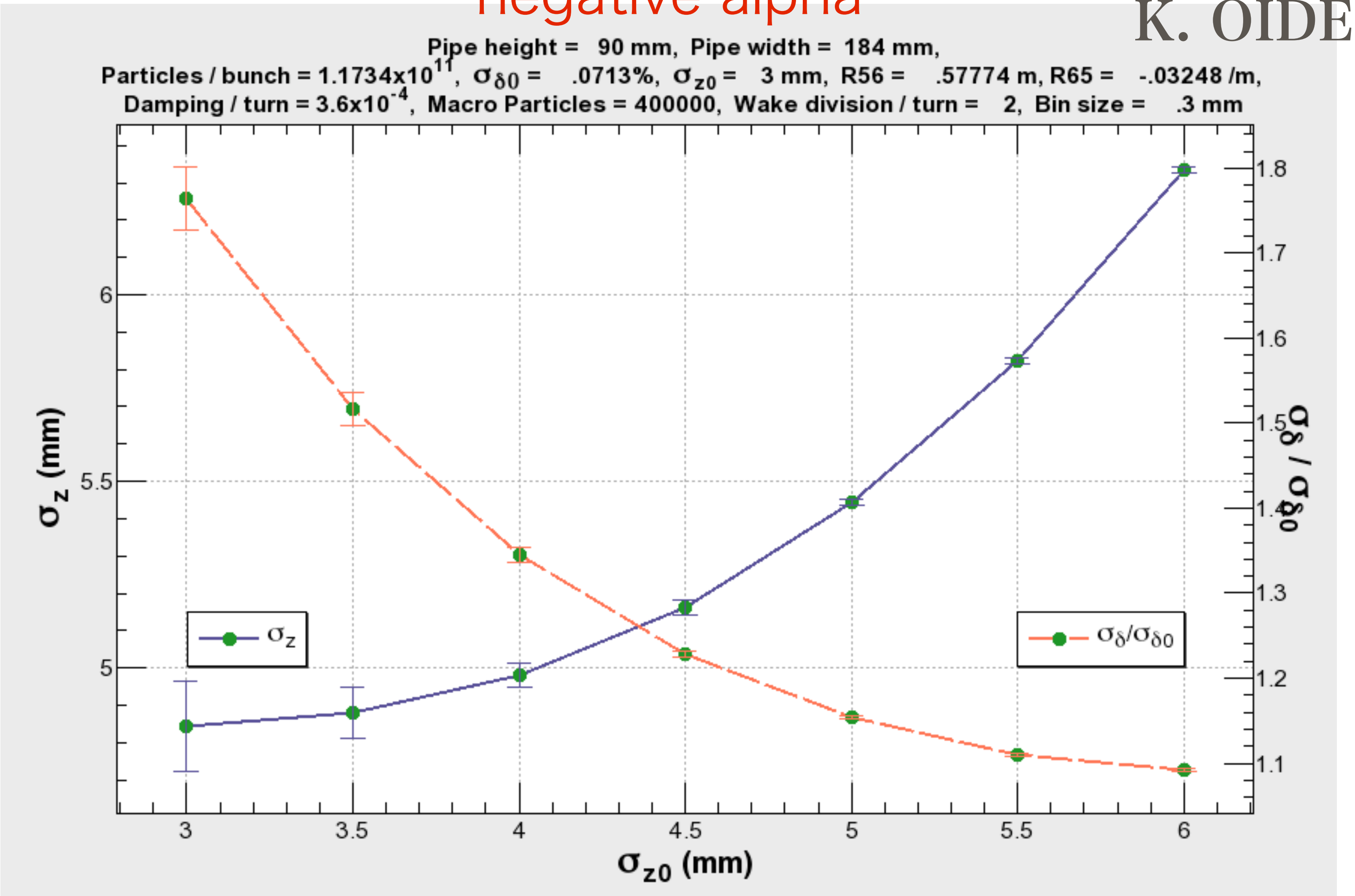

9 Oct 2008

HER

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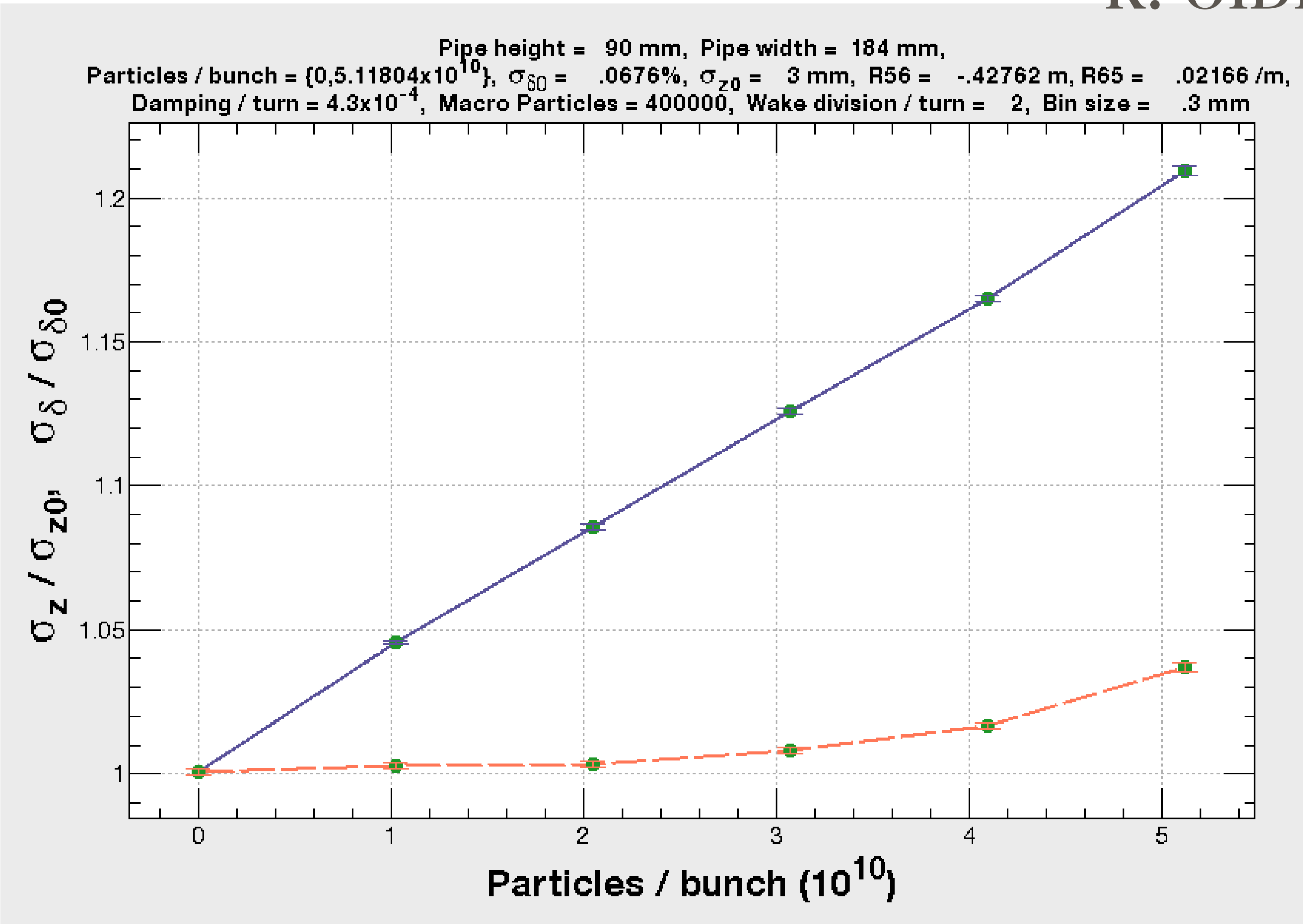
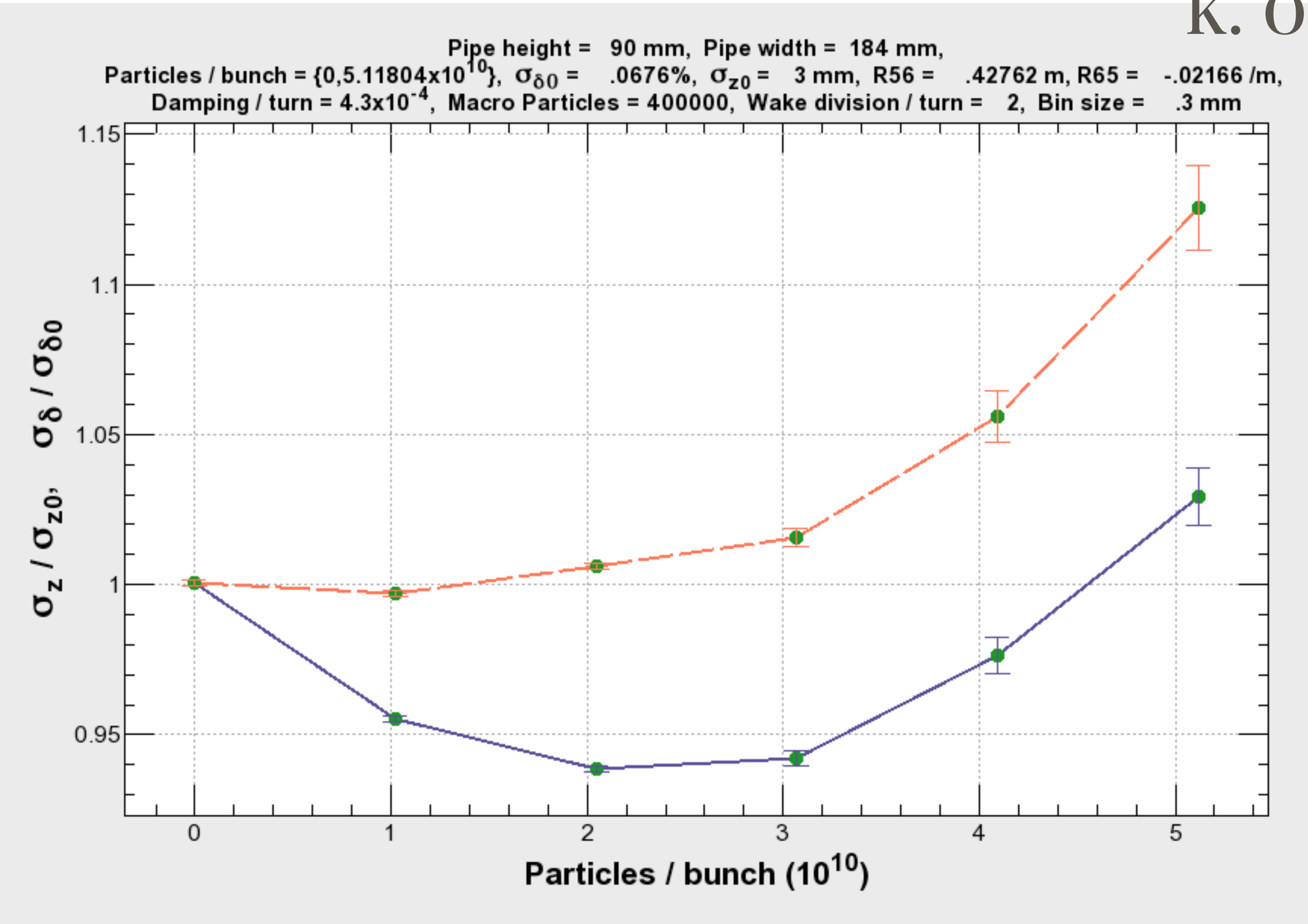


26 Sep 2008

HER negative alpha

K. OIDE



9 Oct 2008

Tentative Design Parameters

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		zero bunch current	design bunch current	
LER	sigz	5	6	mm
	sige	7.1	8.0	10^{-4}
LER neg. alpha	sigz	4.5	5.3	mm
	sige	7.1	8.5	10^{-4}
HER	sigz	3	3.6	mm
	sige	6.8	7.0	10^{-4}
HER neg. alpha	sigz	3	3.1	mm
	sige	6.8	7.7	10^{-4}

Luminosity optimization under the bunch length limit

- Using travel focus only in LER
- Different β, ε for two beams.
- Longer damping time of LER, 8000 (LER) and 4000 turns(HER).
- β_x=0.2m or 0.4m.

Parameters

β_x (m)	0.2	0.4
β_y (mm)	$6_H/3_L$	$6_H/3_L$
ε_x (nm)	12/20	12/20
τ/T_0	4000/8000	4000/8000
σ_z(mm)	3.5/6	3.5/6
L	5×10^{35}	$3\text{-}4 \times 10^{35}$

Physics of extreme high tune spreading nonlinear system

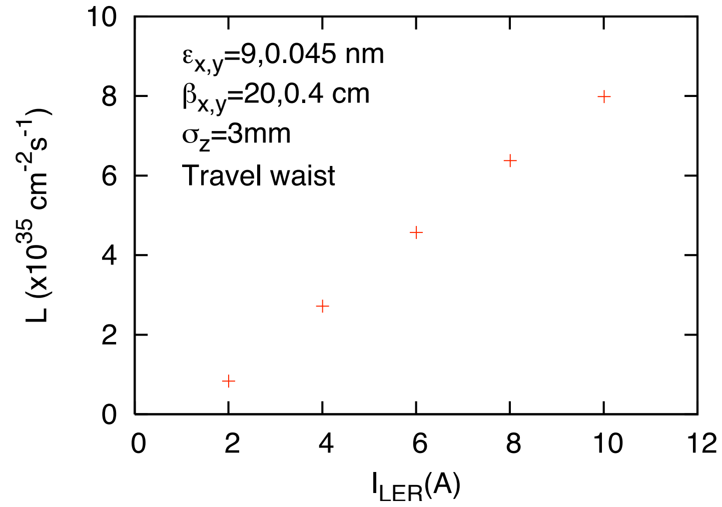
- Suppression of the incoherent emittance growth
- Emittance growth, chaos and degree of freedom of motion. Decreasing the degree of freedom suppresses slow emittance growth
- Equilibrium emittance, Equilibrium between diffusion rates and radiation damping

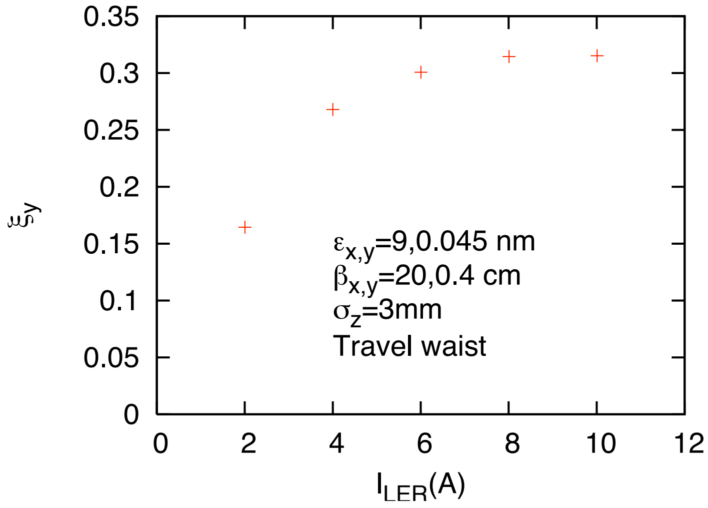
$$\varepsilon_y = (\langle \Delta x^2(\mathrm{radiation})\rangle + \langle \Delta x^2(\mathrm{fundermental})\rangle + \langle \Delta x^2(\mathrm{crossing\ angle})\rangle + \langle \Delta x^2(\mathrm{errors})\rangle)\tau_x/2T_0$$

Extremely high beam-beam tune shift

- Strong-strong

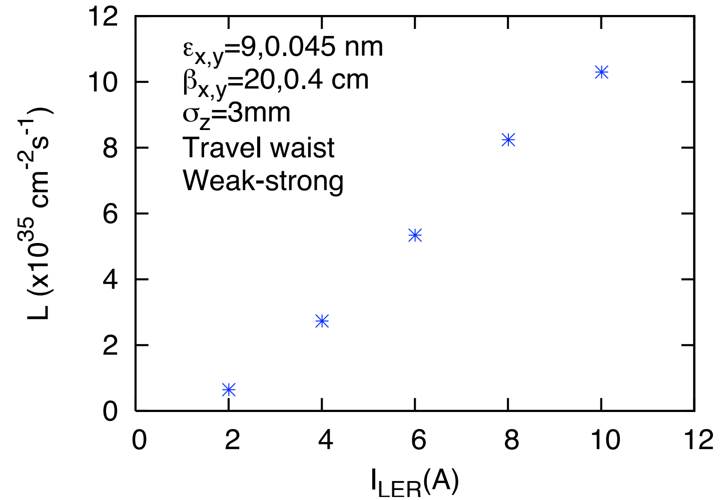
ξ ~0.3

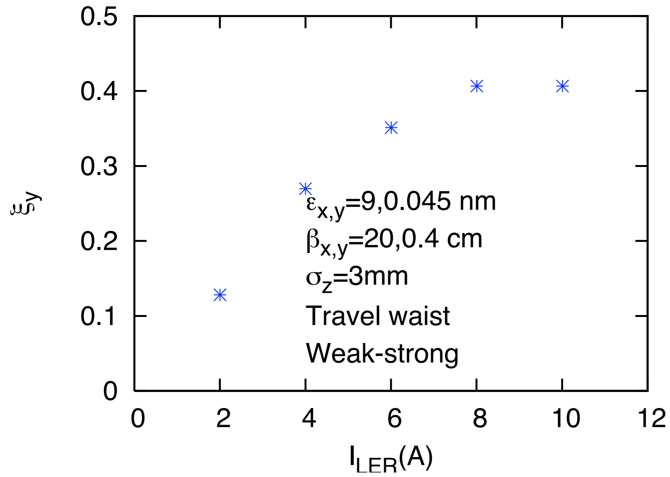




- weak-strong

ξ ~0.4





Waist control-I   traveling focus

$$\mathbf{M}_{IP} = e^{:H_I:}\mathbf{M}_{bb}e^{-:H_I:}$$

$$H_I = \frac{a}{2}p_y^2 z$$

$$\bar{y} = y + \frac{\partial H_I}{\partial p_y} = y + azp_y \qquad \bar{\delta} = \delta - \frac{\partial H_I}{\partial z} = \delta - \frac{a}{2}p_y^2$$

- Linear part for y. z is constant during collision.

$$\begin{pmatrix} \bar{\beta} & -\bar{\alpha} \\ -\bar{\alpha} & \bar{\gamma} \end{pmatrix} = T\begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}T^t = \begin{pmatrix} \beta + \dfrac{a^2z^2}{\beta} & \dfrac{az}{\beta} \\ \dfrac{az}{\beta} & \dfrac{1}{\beta} \end{pmatrix} \qquad \alpha=0$$

$$T = \begin{pmatrix} 1 & az \\ 0 & 1 \end{pmatrix}$$

Waist position for given z

- Variation for s

$$M(s)\begin{pmatrix} \beta + \dfrac{a^2 z^2}{\beta} & \dfrac{az}{\beta} \\ \dfrac{az}{\beta} & \dfrac{1}{\beta} \end{pmatrix} M^t(s) = \begin{pmatrix} \beta + \dfrac{(s+az)^2}{\beta} & \dfrac{s+az}{\beta} \\ \dfrac{s+az}{\beta} & \dfrac{1}{\beta} \end{pmatrix}$$

- Minimum β is shifted s=-az

Crabbing beam in sextupole

- Crabbing beam in sextupole can give the nonlinear component at IP
- Traveling waist is realized at IP.

$$H_I = \frac{a}{2} p_y^2 z$$

- At the sextupole position

$$z^* = \sqrt{\frac{\beta_x(s)}{\beta_x^*}}\theta x(s)$$

$$K_2 = \frac{1}{2}\frac{B''L}{p/e} \approx \frac{1}{\theta}\frac{1}{\beta_y^*\beta_y}\sqrt{\frac{\beta_x^*}{\beta_x}}$$ K_2~30-50

- The same strength as the crab waist sextupole

Travel waist in the weak-strong model

- Reduction of z degree of freedom

$$\boldsymbol{x}(+0) = S\exp\left[- : \int_{-\Delta}^{\Delta} V_0^{-1}(s_i) H_{bb} V_0(s_i) ds_i :\right] \boldsymbol{x}(-0), \qquad s_i(z) = \frac{z - z_i}{2}$$

$$\begin{aligned} V_0(s) &\equiv V_0(s,0) = S\exp\left[- : \int_0^s H_0 ds :\right] \\ &= \prod_{i=\pm} \exp\left[- : \frac{p_{x,i}^2 + p_{y,i}^2}{2} s :\right], \end{aligned}$$

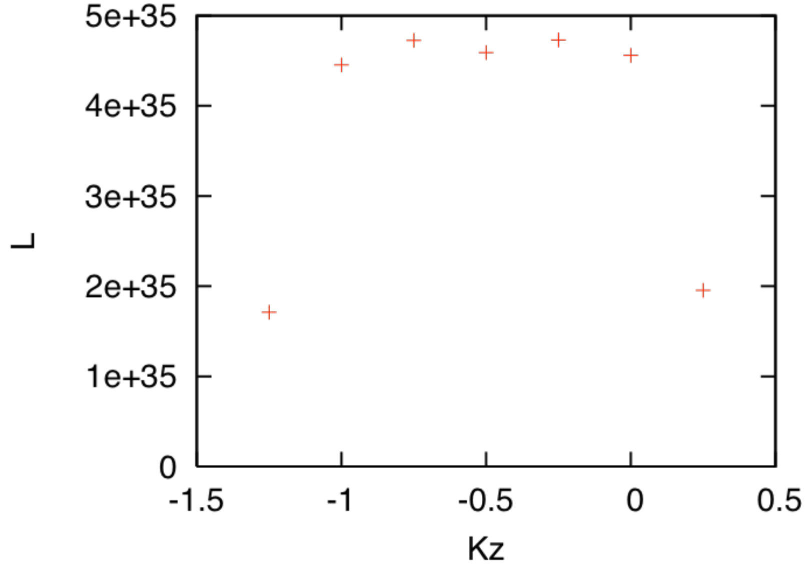
- Travel focus

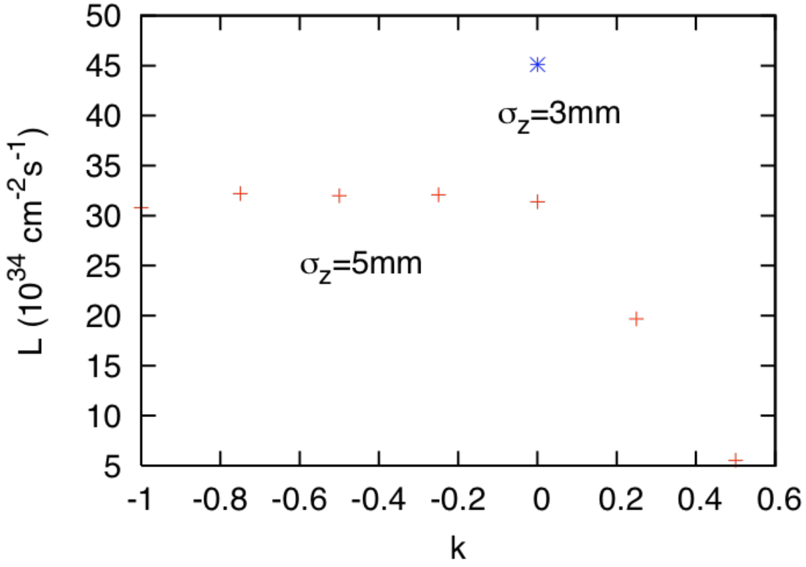
$$\begin{aligned} \boldsymbol{x}(+0) &= e^{-H_I(z)} S\exp\left[- : \int_{-\Delta}^{\Delta} V_0^{-1}(s_i(z)) H_{bb} V_0(s_i(z)) ds_i :\right] e^{H_I(z)} \boldsymbol{x}(-0) \\ &\approx S\exp\left[- : \int_{-\Delta}^{\Delta} V_0^{-1}(z_i/2) H_{bb}(\boldsymbol{x}) V_0(z_i/2) ds_i :\right] \boldsymbol{x}(-0) \end{aligned}$$

- This transformation does not include z.
- This beam-beam system is two degree of freedom (x-y).

Travel focusing results

- $\sigma_{z,HL}$=3mm, β_y=3mm, ε_x=18/24nm
- $\sigma_{z,HL}$=5mm, β_y=3mm, ε_x=18/24nm



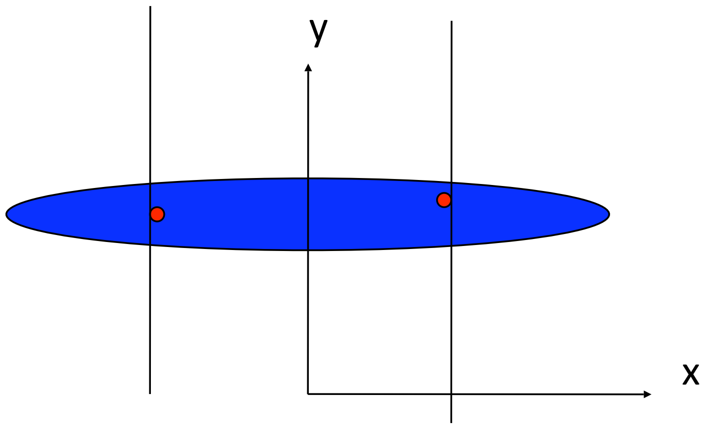


Travel focus does not give extreme high performance for the luminosity, though the integrability of the beam-beam system improves.

The extreme reduction of the vertical diffusion

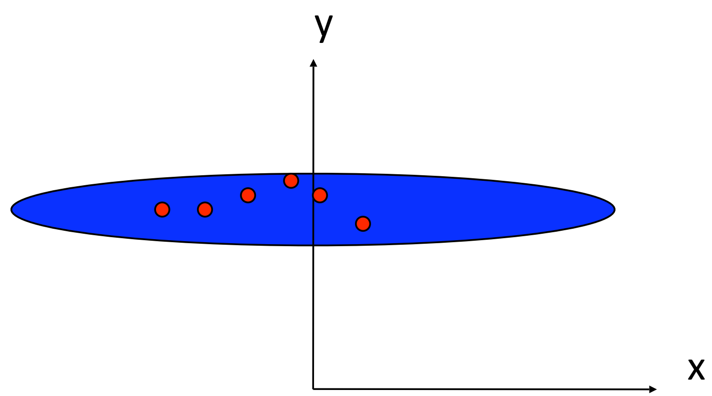
Approach to ν_x=0.5

- Particles collide with fixed charged distribution at x and –x alternately.
- Since $F_y(x,y)=F_y(-x,y)$, motion is on y-p_y phase space.
- The system is reduced to one dimensional motion, with the result that very high beam-beam parameter is realized.



$\nu_x = 0.5 + \alpha$

- Since $\langle p_x^2 \rangle$ diverges at $\nu_x = 0.5$, an accelerator is operated at $\nu_x = 0.5 + \alpha = 0.505$(KEKB).
- X variates slowly.
- The potential and vertical force variate slowly for the variation of X.
- Particles experience y-p_y phase space with changing potential adiabatically. Vertical emittance approximately conserved.



Near the half integer tune in Horizontal

- Transformation

$$x_{n+1} = \left(1 - \frac{\mu_x^2}{2}\right) x_n + \beta_x \mu_x p_{x,n}$$

$$p_{x,n+1} = -\mu_x x_n + \left(1 - \frac{\mu_x^2}{2}\right) p_{x,n} - F_x(x_{n+1}, y_{n+1})$$

$$x(n) = (-1)^n x_n$$

$$\mu_x = 2\pi(\nu_x - 0.5)$$

$$F(-x, y) = -F(x, y)$$

$$F_x(x, y) = F_x(x, 0) + \cancel{\left.\frac{\partial F_x}{\partial y}\right|_{y=0} y + \frac{1}{2} \left.\frac{\partial^2 F_x}{\partial y^2}\right|_{y=0} y^2}$$

$$\left.\frac{\partial F_x}{\partial y}\right|_{y=0} = 0 \qquad \frac{1}{2} \left.\frac{\partial^2 F_x}{\partial y^2}\right|_{y=0} y^2 \approx F_x(x, y) \times \frac{\sigma_y}{\sigma_x}$$

Vertical motion

- Vertical map

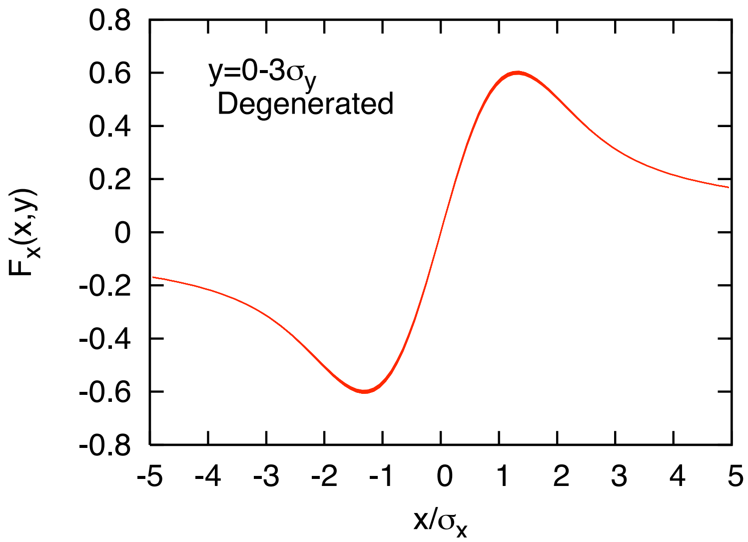
$$y(n+1) = \cos\mu_y y(n) + \beta_y \sin\mu_y p_y(n)$$

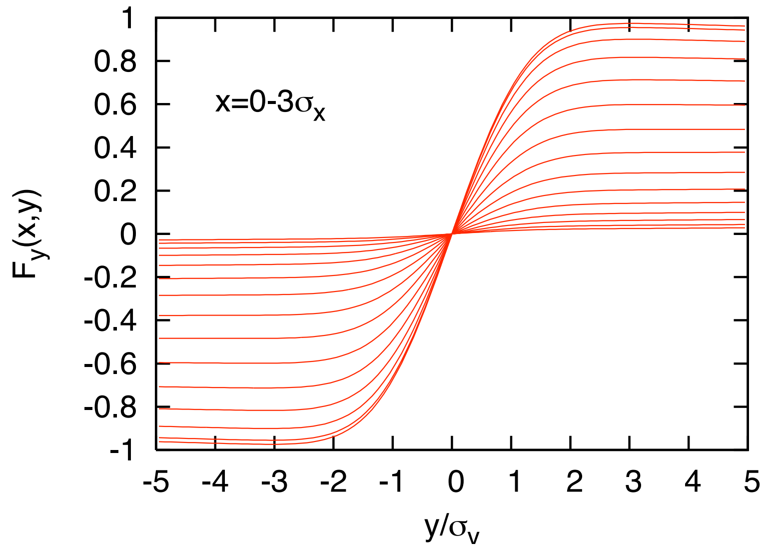
$$p_y(n+1) = -\frac{1}{\beta_y}\sin\mu_y y(n) + \cos\mu_y p_y(n) - F_y(x(n+1), y(n+1))$$

$$F_y(\bar{x} + x_r, y) = F_y(\bar{x}, y) + \frac{1}{2}\left.\frac{\partial^2 F_y}{\partial x^2}\right|_{x=\bar{x}} \langle x_r^2 \rangle + ...$$

- F_y fluctuates due to
- If horizontal motion is chaotic, stochasticity of the vertical motion increases, with the result that emittance growth is enhanced.

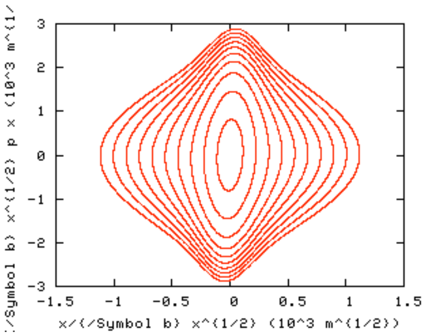
- Beam-beam force for a flat beam, σ_x/σ_y=100.

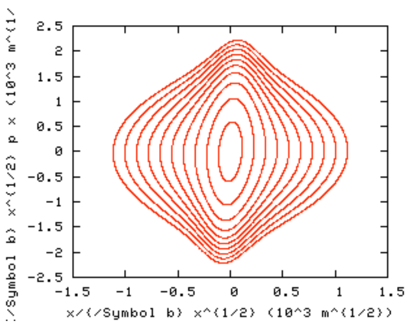


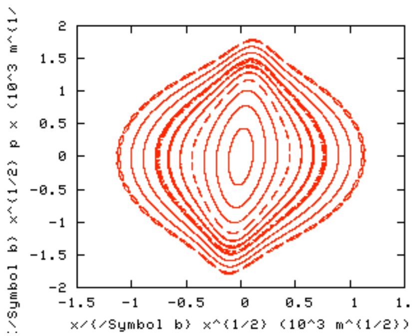


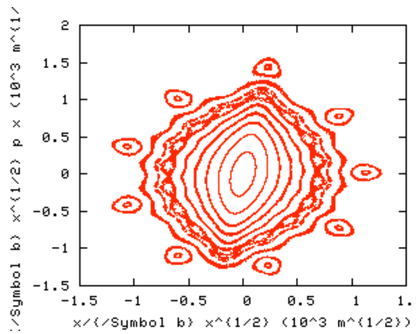
Horizontal motion

- y=0 μm
- 0.505 0.510 0.520 0.550

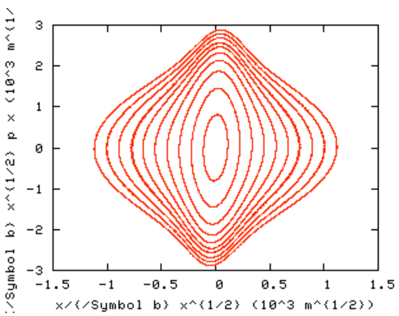


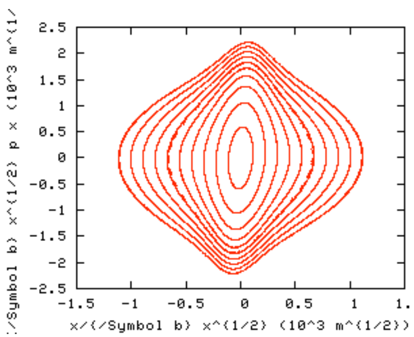


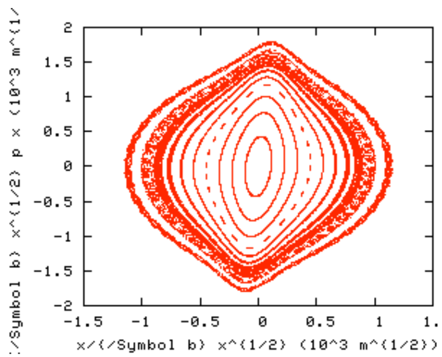


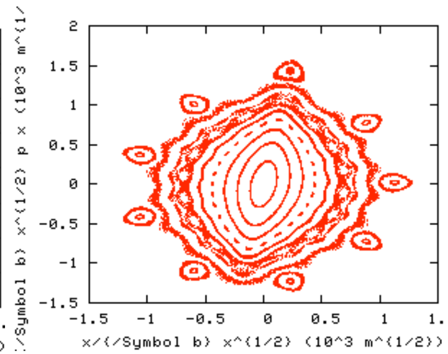


- y=2 μm







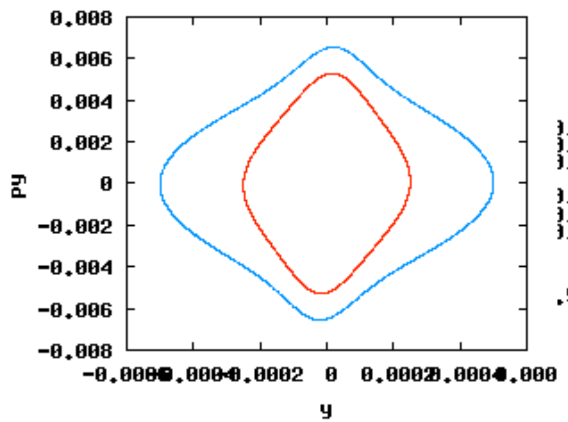


- The figures are roughly independent of y.

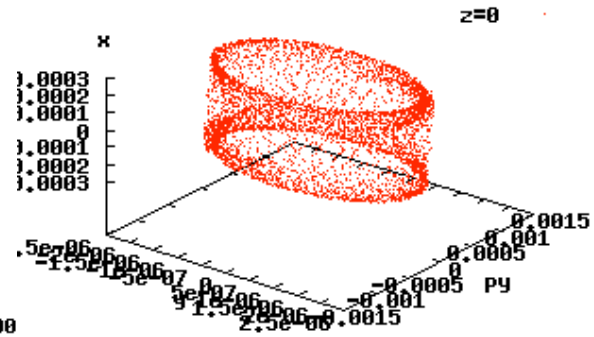
ν_x=0.505

- X motion is clearly solved at ν_x=0.505.
- Y motion is bound on surface. No emittance growth.

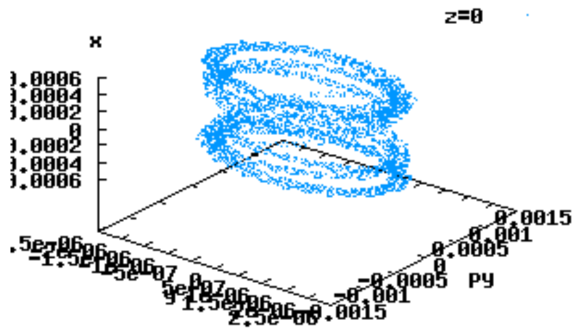
x-p_x



y-p_y-x



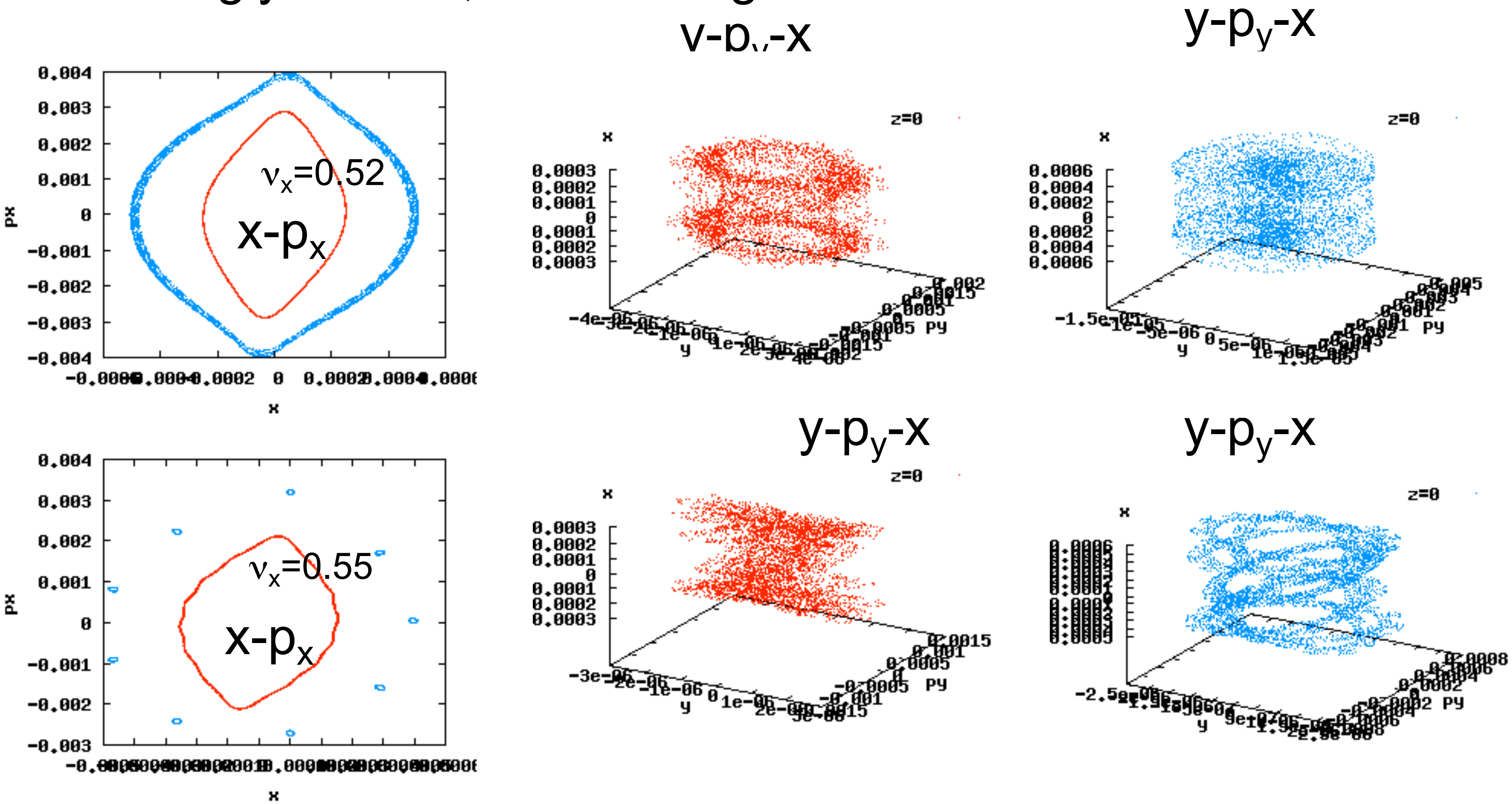
y-p_y-x



Horizontal tune near the half integer is better for luminosity.

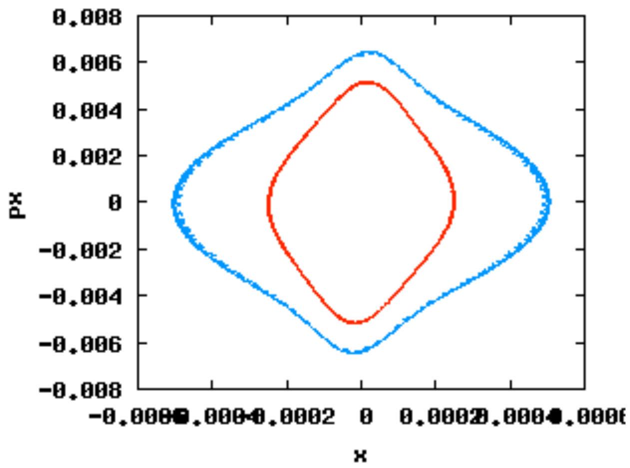
ν_x=0.55 and 0.6

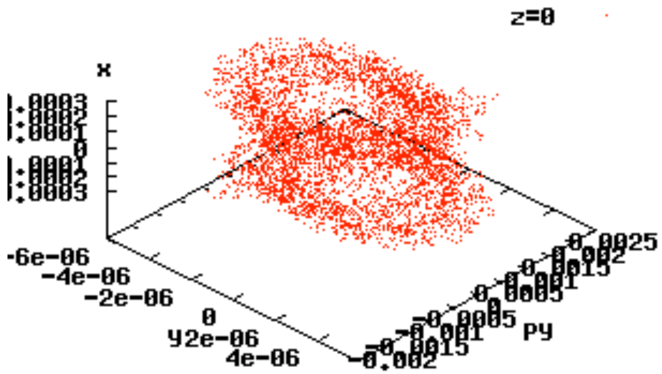
- When ν_x=0.55, 0.6, x motion is chaotic. y motion is strongly chaotic, emittance growth.

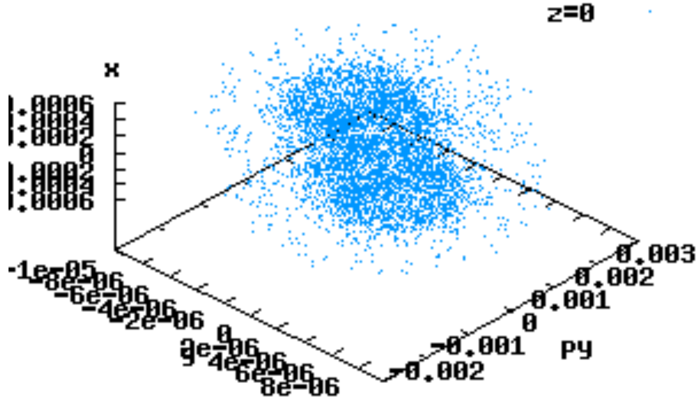


x-y coupling, ν_x=0.505

- R1=3.17e-3, R2=-0.22e-3, R3=0.059, R4=0.025 (1 unit of KEKB knob scan)





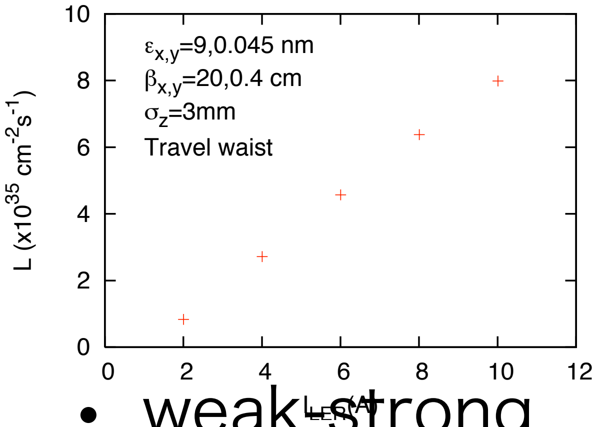


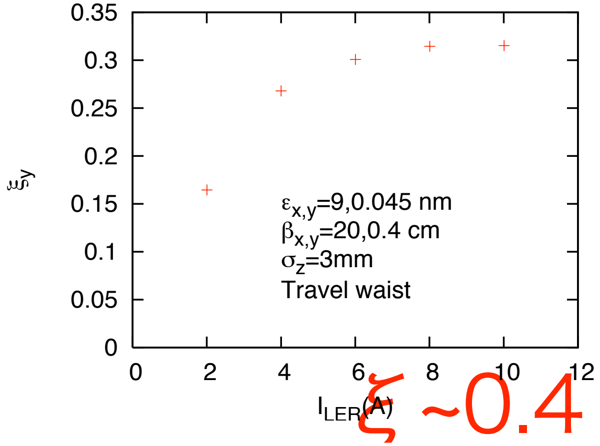
Extremely high beam-beam tune shift

Achieved by the reduction of the degree of freedom

- Strong-strong

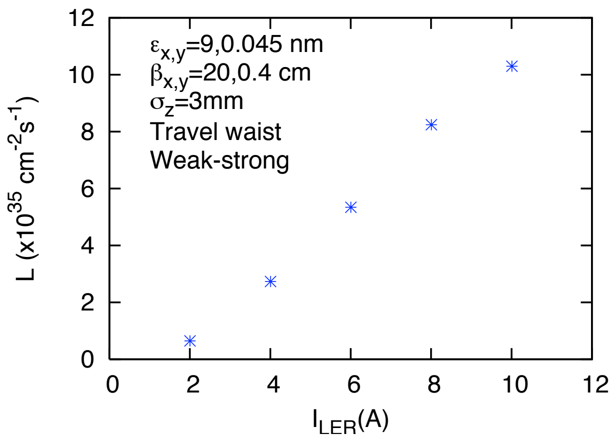
ξ ~0.3

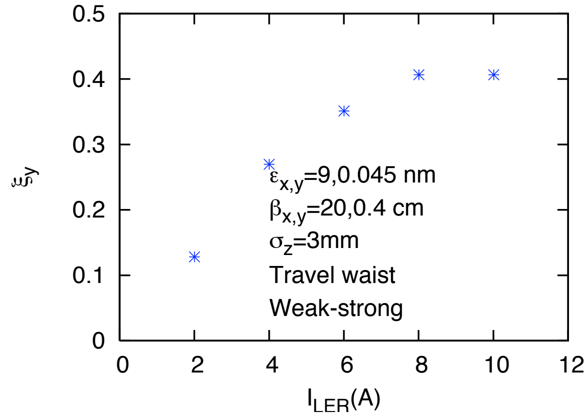




- weak-strong

ξ ~0.4



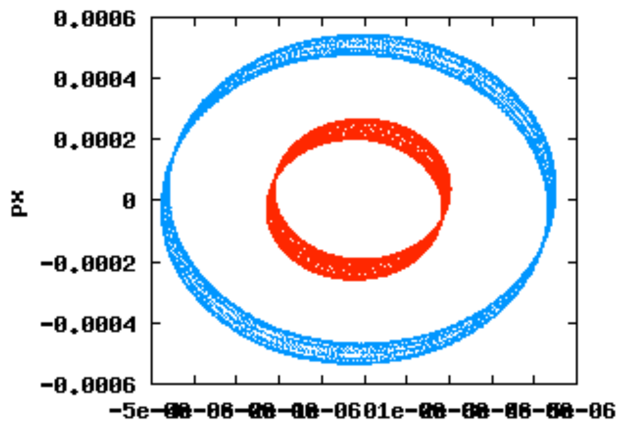


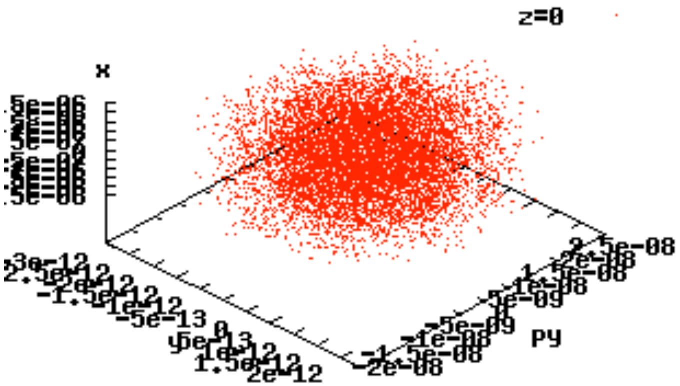
SuperBunch-crab waist option

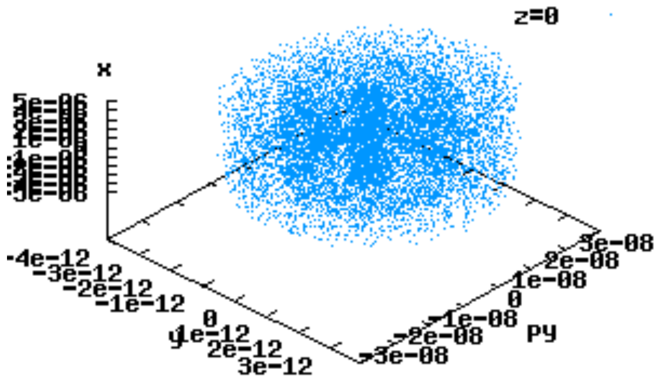
- We have some difficulties to go the scheme with keeping the present luminosity.
- To increase the luminosity step by step, β_x at IP should be reduced, with keeping ε_x.
- Low β_x had been tried a long ago. In present KEKB, β_x<0.5m seems to be difficult to inject the beam, though dynamic β may affect.
- Operation far from 0.5 was also difficult for the present current.
- However we should try low β_x at another tune operating point far from 0.5 again.

Phase space trajectory for crab waist scheme, z=0

- x-p_x motion is near integrable for z=0.
- y-p_y-x (z=0) is not integrable.







parameters of several cases

	Super KEKB	Normal ε	LER low-ε	L/H low-ε	KEKB test
εx (nm)	$12_H/20_L$	10/10	1/10	1/1	18/18
εy(nm)	0.06/0.1	0.1	0.01/0.04	0.01/0.01	0.18/0.18
βx (mm)	200	10/10	10/10	10	50
βy (mm)	6/3	0.6/0.6	0.8/0.2	0.2	3
σz (mm)	3.5/6	6	6	6	6
φσz/σx	0.0	9	28/9	28	2.2
ne	5.25×10^{10}	2.2×10^{10}	2.2×10^{10}	2.2×10^{10}	1.75×10^{10}
np	$12.\times10^{10}$	3.3×10^{10}	3.3×10^{10}	3.3×10^{10}	4×10^{10}
φ/2 (mrad)	0	15	15	15	11
ξn,x	0.397	0.0017	0.0018	0.0018	0.0108
ξn,y	0.3	0.047/0.031	0.035/0.11	0.09	0.069
Lum (W.S.)	5×10^{35}	1×10^{35}	2×10^{35}	5×10^{35}	4×10^{34}
Lum (S.S.)	5×10^{35}				

Summary

- CSR limits the bunch lengths. They are expected 3.5mm and 6mm for HER and LER, respectively.
- IR design and dynamic aperture study gave the limit of β_x=0.2-0.4m at IP. Dynamic beta is one of cause of the limit.
- Beam-beam performance under the conditions is $L=5\times10^{35}cm^{-2}s^{-1}$ for β_x=0.2m. It degrade 20-30% for β_x=0.4m.
- To steer the superbunch-crab waist scheme with keeping or improving the present performance, β_x should be lower than 5cm at least.

Cost estimation

	Old estimation Full Spec SuperKEKB	Construction (for 3 years)	Upgrade after operation restart
Vacuum	116.86	139.36	0
RF	115.873	16.45	84.25
Infrastructure	84.3	3	75.2 + α
Injector	58	10	53.7
Magnet	16.7008	31.9	0
Crab	17	5	10
Beam monitor	17.4684	17.7	4.5
Damping Ring (other than RF, monitor)	16.8	0	21.26
Control	9.4	2	7.4
IR	8	14.7	0
Beam transport	2.5	2.5	0
Sum	462.9022	242.61	256.31