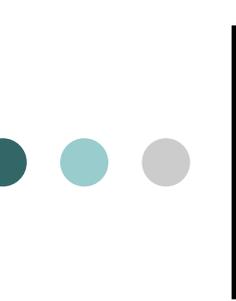


Discovery and mitigation of the Electron cloud at KEK

K. Ohmi KEK

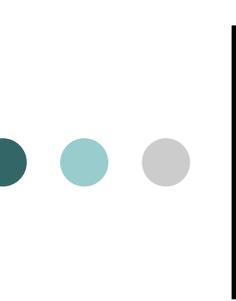
Accelerator Physics and Technology Seminars

2, March, 2006, FNAL



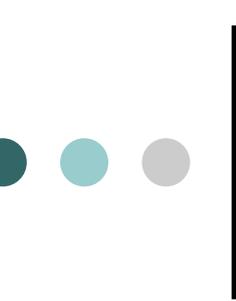
Contents

- History, electron cloud effect in KEK-PF
- Electron cloud build-up
- Coupled bunch instability caused by electron cloud
- Single bunch instability caused by electron cloud



History

- Coupled-bunch instability observed at KEK-PF.
- Interpretation of the instability using photo-electron cloud model.
- The instability was observed at BEPC (China).
- Study of electron cloud effect for design of KEKB.
- Studies for PSR, LHC, SPS, SNS, JPARC, ILC ...many machines.



Multi-bunch instability observed at KEK-PF

- KEK-PF is a 2nd generation light source operated by both of positron and electron beams. $E=2.5$ GeV $L=186$ m, $Frf=500$ MHz.
- Instability was observed at multi-bunch operation of positron beam. $N_{\text{bunch}}=200-300$ for $h=312$.
- Very low threshold. $I\sim 15-20$ mA.
- The instability was not observed at electron beam operation.

Izawa et.al., Phys. Rev. Lett. 74, 5044 (1995).

BPM spectrum for V motion.

Electron 354 mA

Positron 324 mA & 240 mA

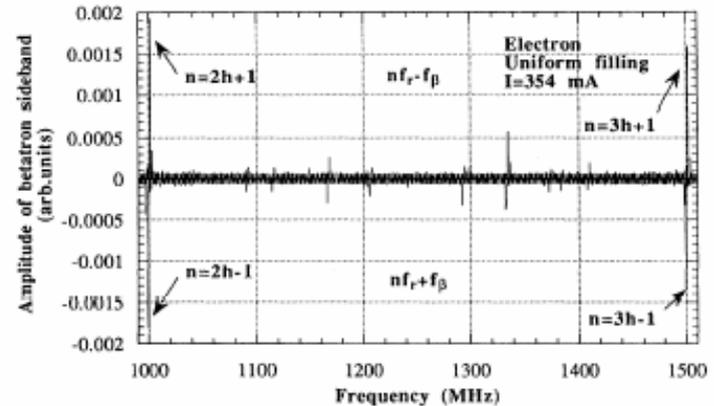


FIG. 1. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling.

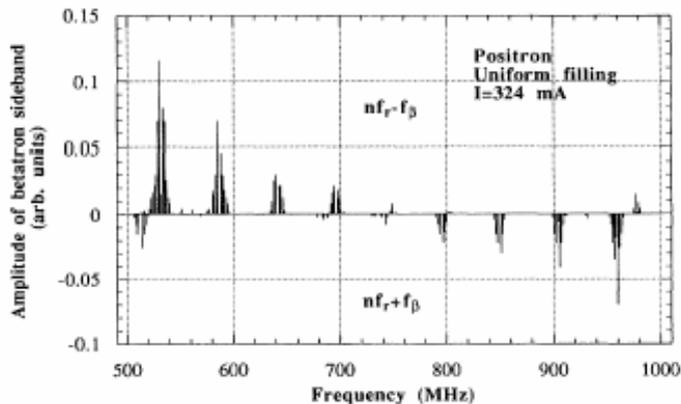


FIG. 2. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling.

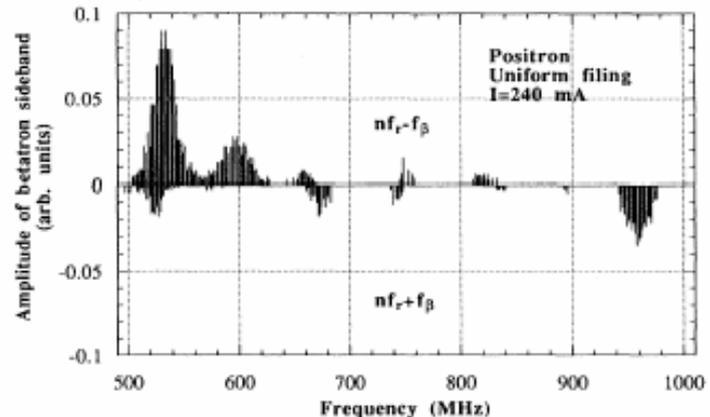
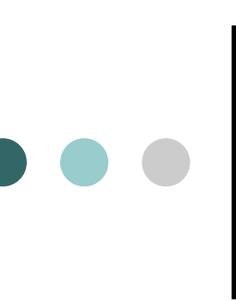


FIG. 3. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling. Only the stored current is different from Fig. 2.



Interpretation of instability due to photo-electron cloud

- Positron beam emits synchrotron radiation.
- Electrons are produced at the chamber wall by photoemission. Production efficiency $\sim 0.1 e^-/\gamma$.
- Electrons are attracted and interacts with the positron beam, then absorbed at the chamber wall after several 10 ns. Secondary electrons are emitted according the circumferences.
- Electrons are supplied continuously for multi-bunch operation with a narrow spacing, therefore electron cloud are formed.
- A wake force is induced by the electron cloud, with the result that coupled bunch instability is caused.

K. Ohmi, Phys. Rev. Lett., 75, 1526 (1995).

First figure for electron cloud build-up

Photon factory I=100mA

PRL,75,1526 (1995)

Recipes for electron cloud
build-up are written in this
paper.

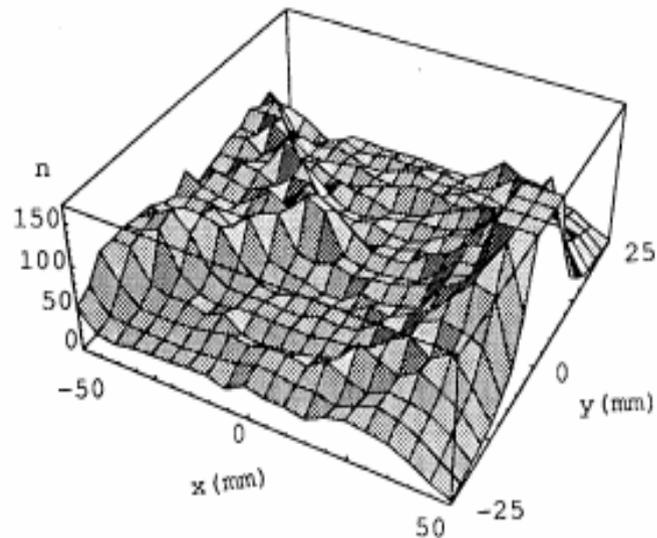


FIG. 2. A stationary distribution of photoelectrons with $\epsilon_0 = 5$ eV.

direction, the practical density is given by multiplying 2×10^4 by the value from Fig. 2 in cm^3 . Typically, if we use 100, as in the figure, the density is $2 \times 10^6 \text{ cm}^{-3}$. We consider the space-charge effect of the electron distribution. The electric field due to the peak distribution, which is a few hundreds in the figures, can be estimated to be ~ 100 V/m. The field from the beam is ~ 600 V/m at a distance of 1 cm from the beam center. Thus, when the electron motion is near the beam, the field of the beam is dominant.

Wake force and unstable mode for KEK-PF

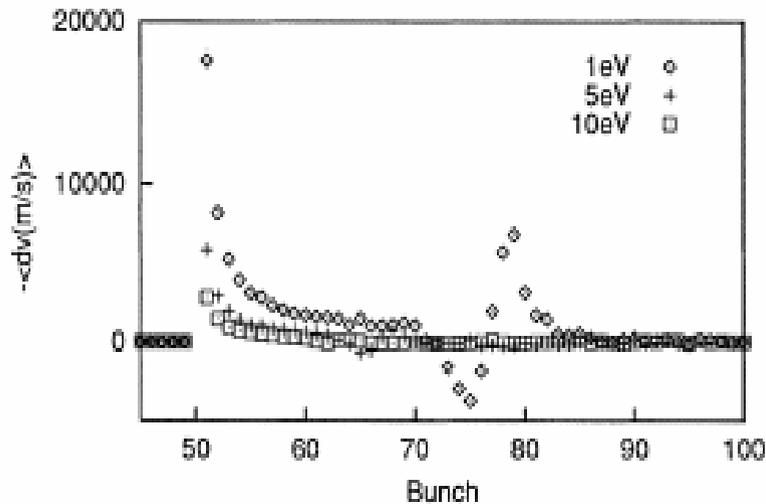


FIG. 3. Wake forces for each initial photoelectron energy. To obtain the wake, 10^6 virtual electrons in every bunch were used.

Very fast growth of the coupled bunch instability was explained. K. Ohmi, PRL, 75, 1526 (1995)

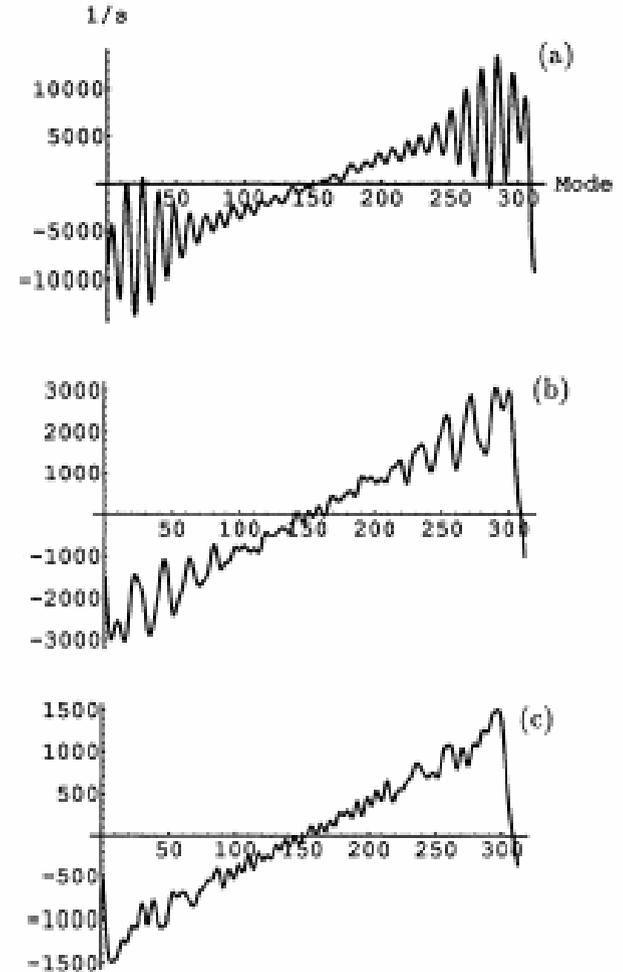
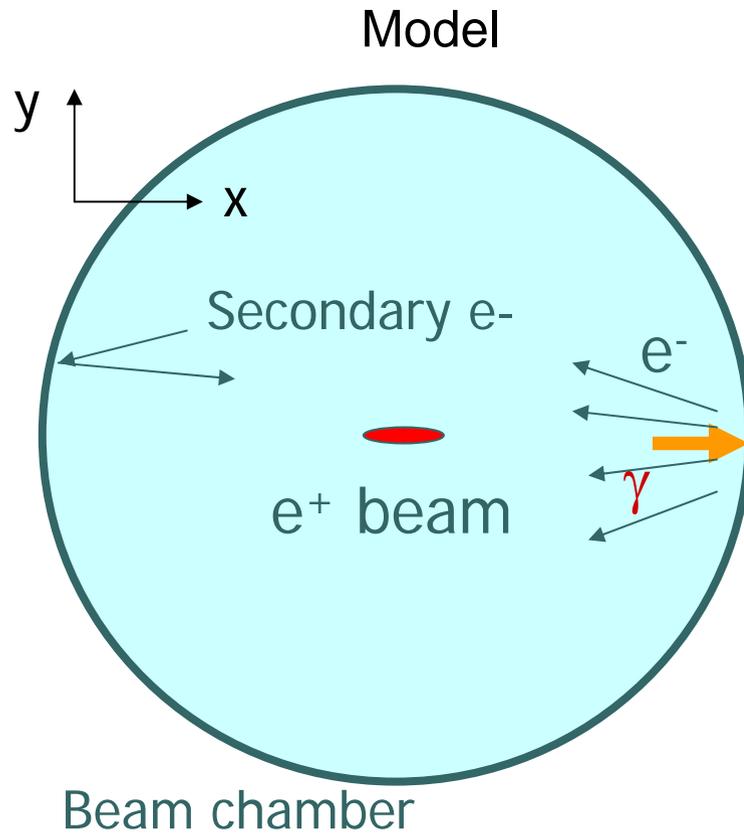
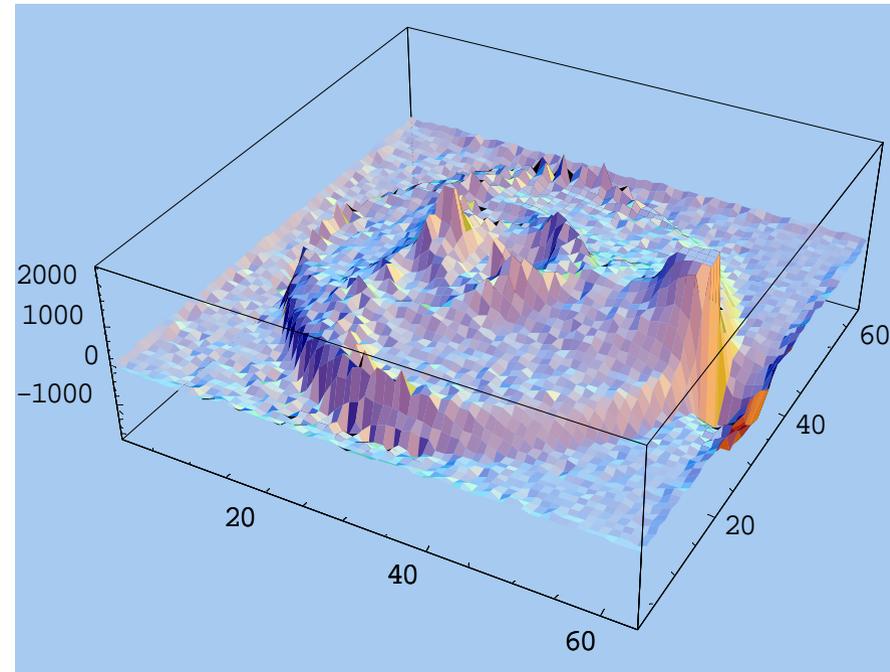


FIG. 4. Growth rates of the coupled-bunch instability. The positive values mean unstable modes. The wakes of 51 to 100 bunches in Fig. 3 were summed with Eq. (8). (a) $\epsilon_0 = 1 \text{ eV}$. (b) $\epsilon_0 = 5 \text{ eV}$. (c) $\epsilon_0 = 10 \text{ eV}$.

Model and formation of electron cloud by computer simulation



Electron cloud density



Number of produced electrons

Number of photon emitted by a positron per unit meter.

$$Y_{\gamma} = \frac{5\pi}{\sqrt{3}} \frac{\alpha\gamma}{L} \quad \alpha : \text{fine structure const}=1/137$$

◆ KEKB-LER $\gamma=6850 \rightarrow Y_{\gamma}=0.15/\text{m}$

◆ KEK-PF $=4892 \rightarrow Y_{\gamma}=1.7/\text{m}$

○ Bunch population

$N_p=3.3 \times 10^{10}$ (KEKB-LER design 2.6A)

$N_p=5 \times 10^9$ (KEK-PF 400mA)

○ Quantum efficiency ($\eta=n_{\text{p.e.}}/n_{\gamma}$) 0.1

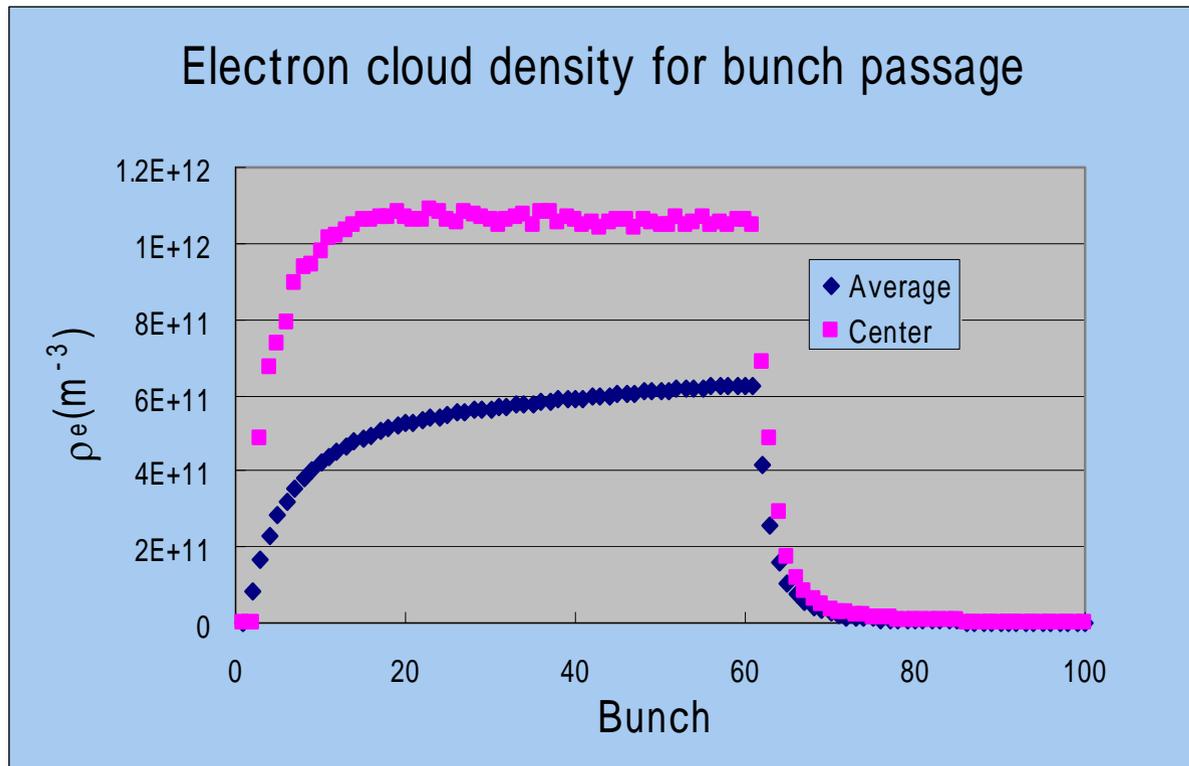
○ Energy distribution $10 \pm 5 \text{ eV}$

○ KEKB-LER $Y_{\text{p.e.}}=0.015 \text{ e}^-/\text{m.e}^+$

○ KEK-PF $Y_{\text{p.e.}}=0.17 \text{ e}^-/\text{m.e}^+$,

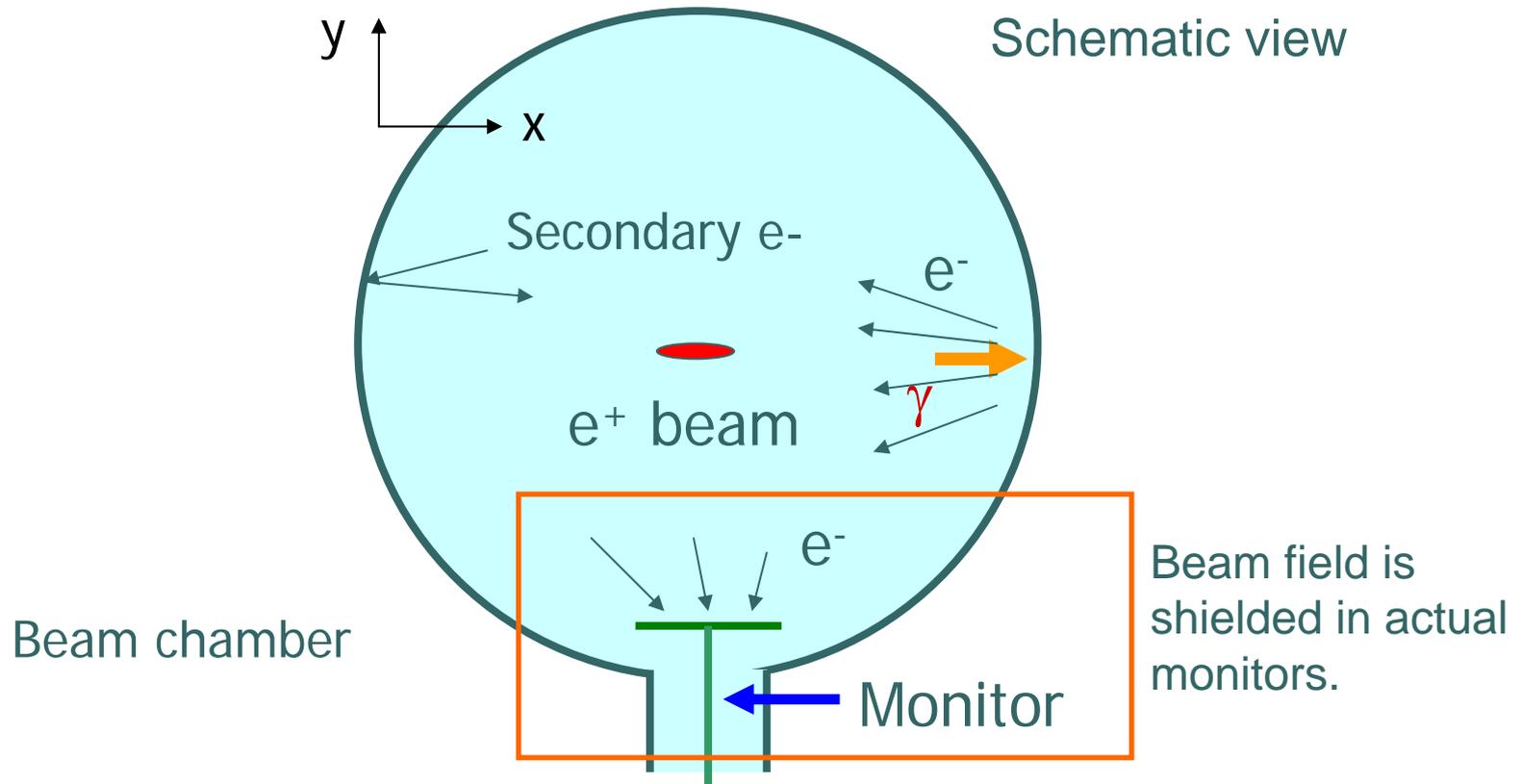
○ ionization $10^{-8} \text{ e}^-/\text{m.e}^+$, proton loss(PSR) $4 \times 10^{-6} \text{ e}^-/\text{m.p}$

Electron cloud density given by simulation



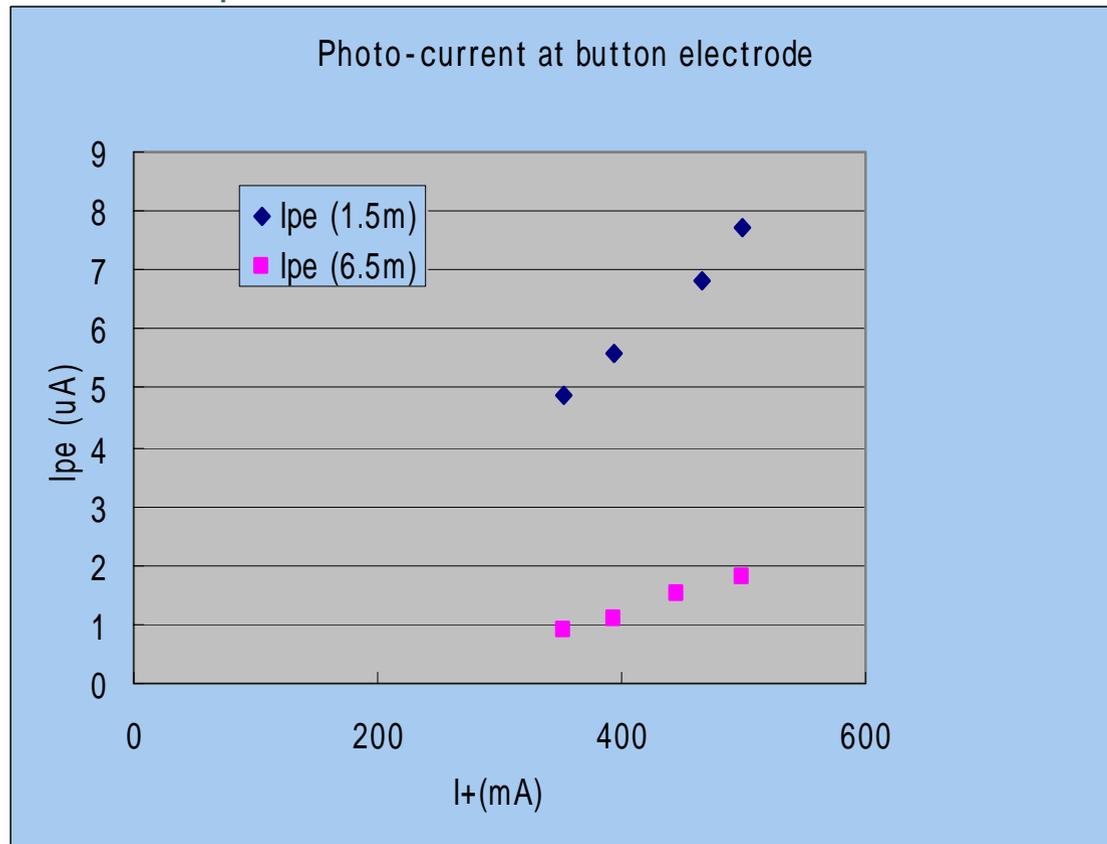
60 bunches pass in every 8ns (KEKB).

Measurement of electron cloud (K. Harkay et.al. K. Kanazawa et.al.)



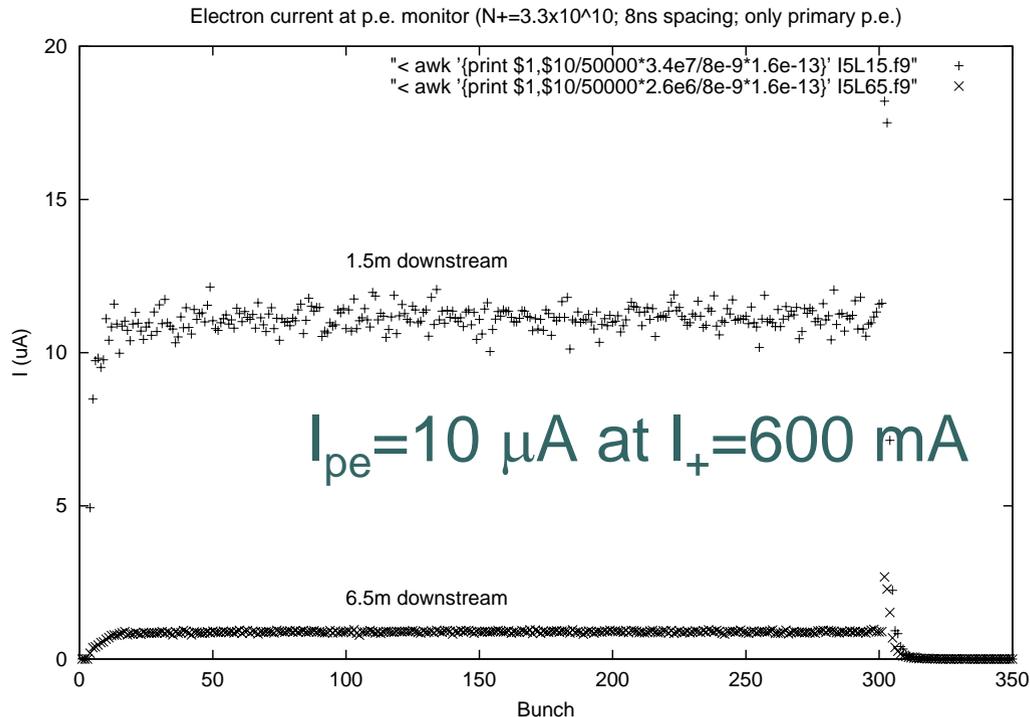
Experimental results

$I_{pe} = 10 \mu\text{A}$ at $I_+ = 600 \text{ mA}$

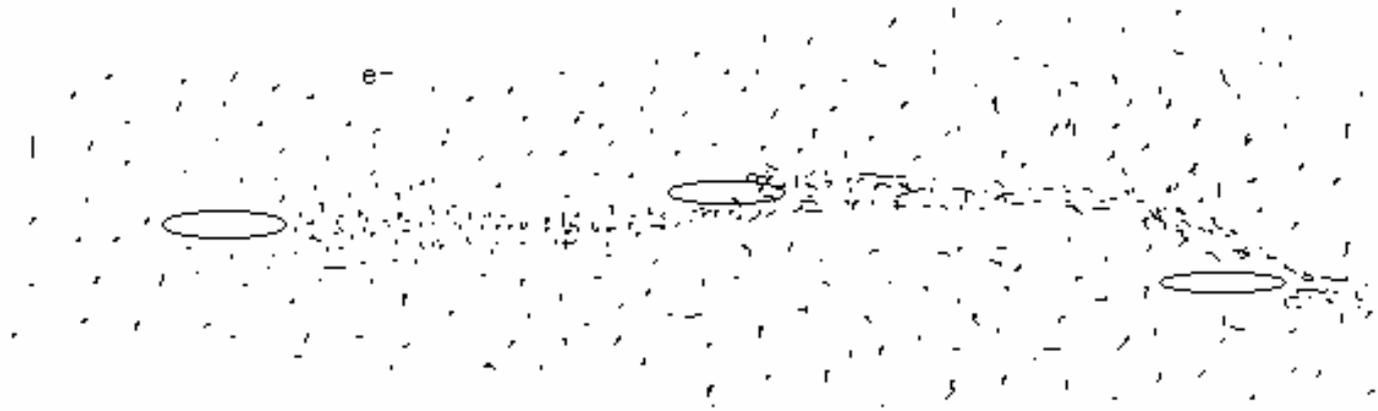


Simulation of the measurement

- Well coincides with experiments.
- The quantum efficiency 0.1 is consistent with the experiment.
- We understand the production and motion of photoelectrons.



Coupled-bunch instability (CBI) caused by the electron cloud



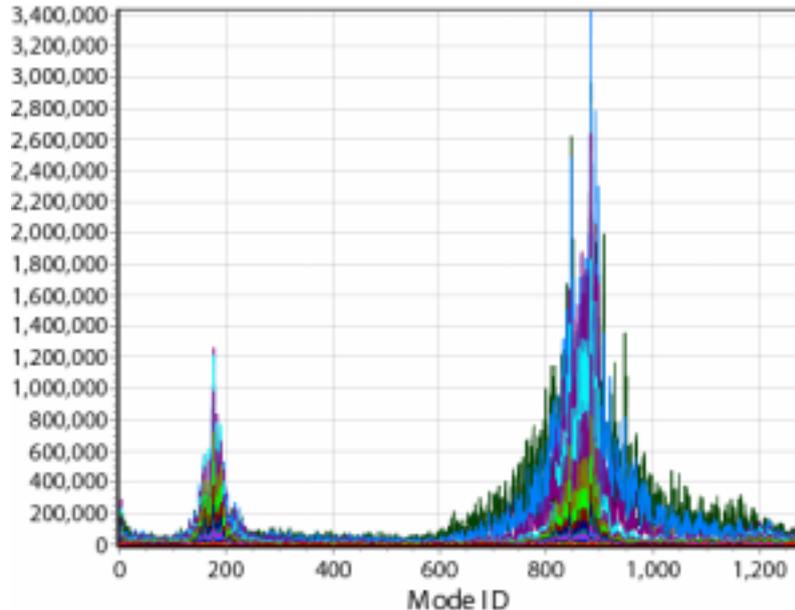
- **Wake field** is induced by the electron cloud
- Coupled bunch instability due to the wake field causes beam loss.

Measurement of the coupled bunch instability in KEKB

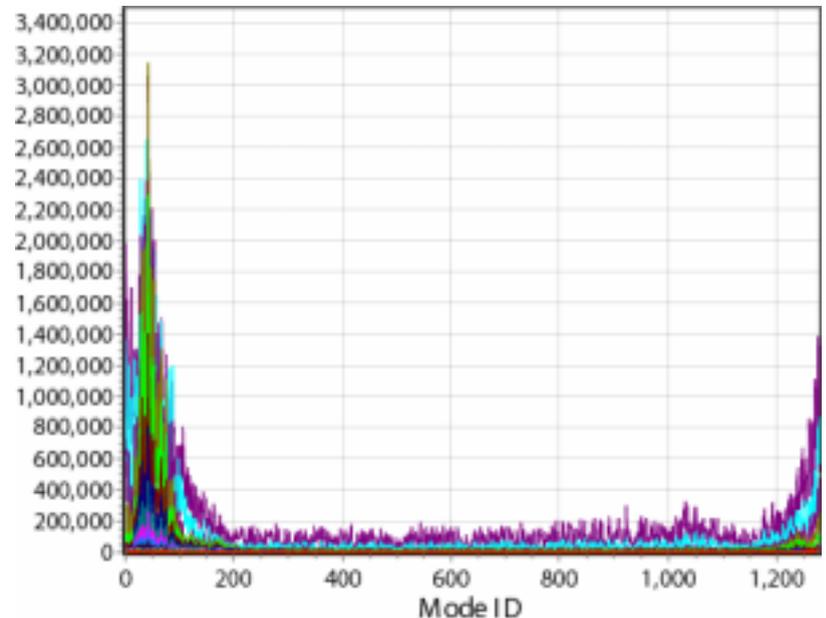
- Fast amplitude growth which causes beam loss has been observed.
- The mode spectrum of the instability depends on excitation of solenoid magnets.

M. Tobiyama et al., PRST-AB (2005)

Solenoid off



on (measurement)

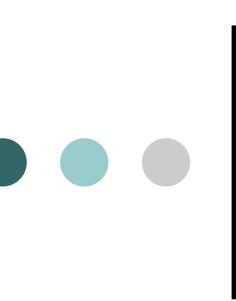


Instability evaluation with the wake force

- Motion of bunches is assumed to be expressed as

$$\frac{d^2 y_n}{ds^2} + \left(\frac{\omega_\beta}{c} \right)^2 y_n = \frac{Nr_e}{\gamma} \sum_{i=n+1}^{\infty} W(z_n - z_m) y_m$$

$W(z_n - z_m)$: The force, which n-th bunch experiences, is induced by a displacement of m-th bunch with y_m ahead of $z_n - z_m$ for n-th bunch. If the force linearly depends on y_m , the coefficient is defined as W .



Estimation of the wake force with a numerical method

- Calculate equilibrium electron cloud distribution.
- A bunch with a displacement X or Y direction makes passage in the electron cloud.
- The electron cloud is disturbed by the displaced bunch.
- Estimate the force which following bunches experience due to the cloud disturbance.
- Check the linearity and superposition of the wake force.

Estimation of unstable mode

- The equation of beam motion can be solved. Coupled oscillation represented by mode number m .

$$y_n^{(m)} \propto \exp\left(2\pi i n \frac{m}{h}\right) \exp\left(-i\Omega^{(m)} \frac{s}{c}\right)$$

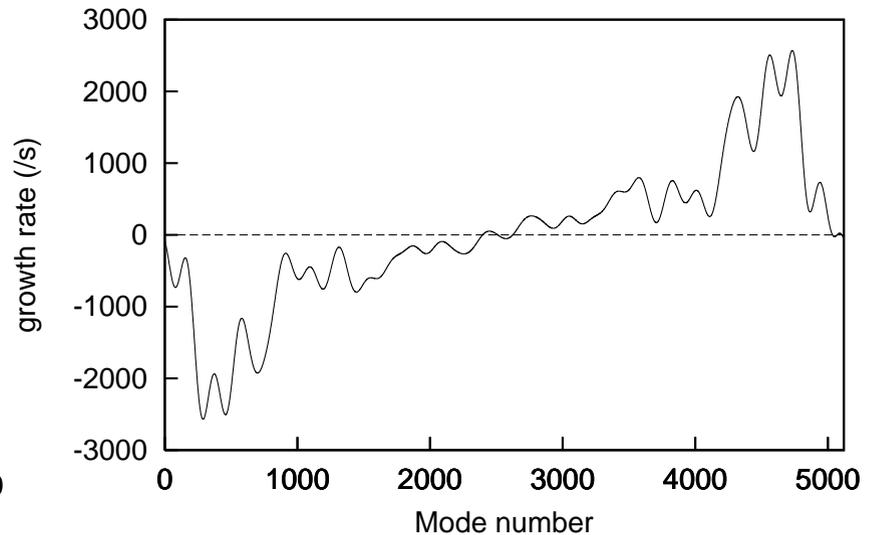
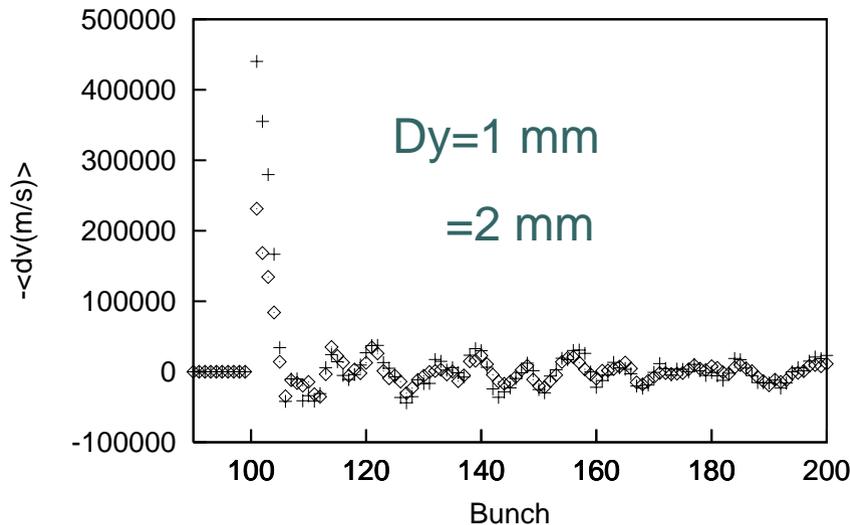
$$\Omega_m - \omega_\beta = \frac{N_p r_e c}{2\gamma T_0 \omega_\beta} \sum_{n=1}^{n_0} W\left(\frac{n}{h} L\right) \exp\left(2\pi i n \frac{m + v_y}{h}\right)$$

Imaginary part of Ω : growth rate of the instability

Wake force and unstable mode caused by electron cloud for KEKB

- Very rapid growth time (~ 10 turn for KEKB at 2.6 A, 5000 bunch)
- Broad mode spectrum
- Defocusing wake, kicked the same direction for a displacement of perturbed bunch

Every bucket is filled.



Tracking simulation

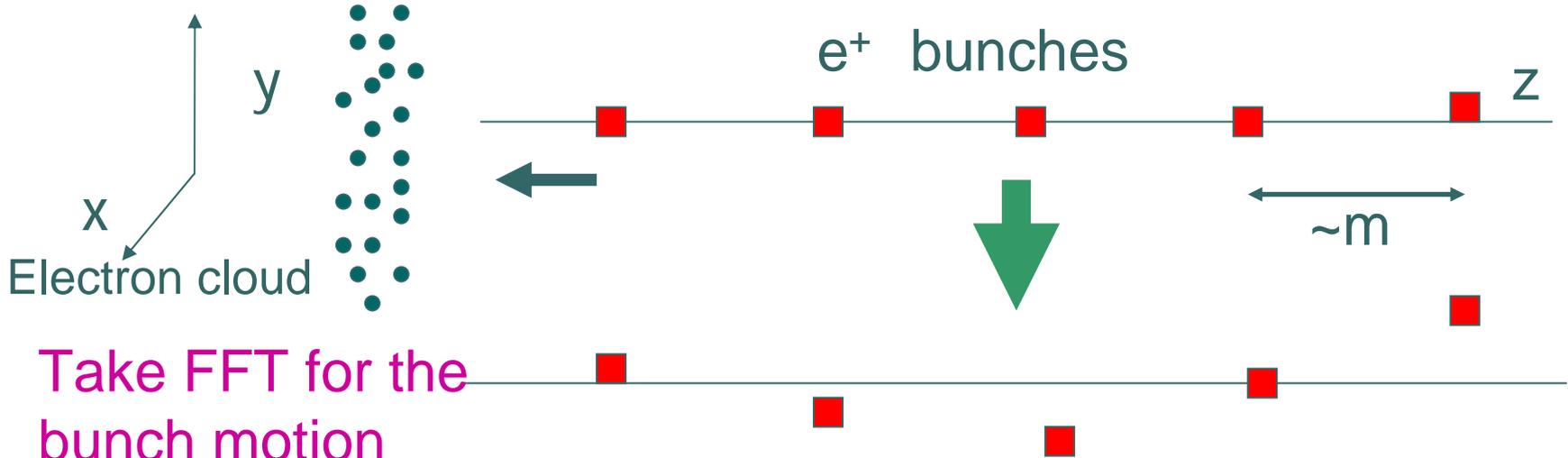
K.Ohmi, PRE55,7550
(1997)

K.Ohmi, PAC97, pp1667.

Solve both equations of beam and electrons simultaneously

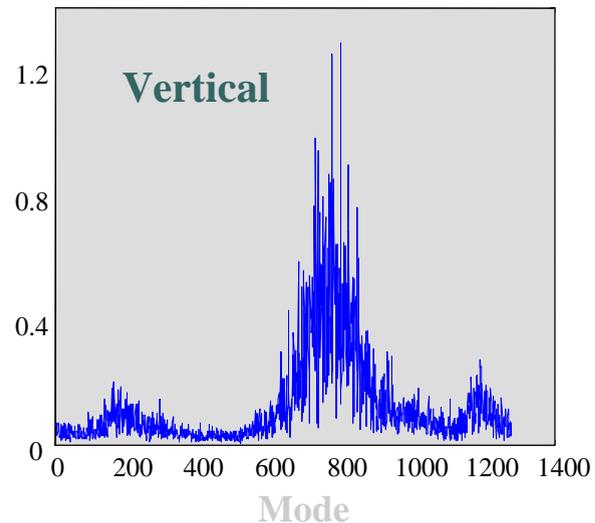
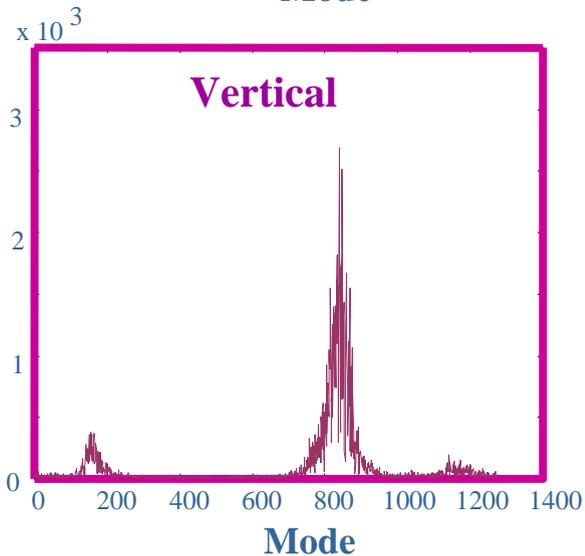
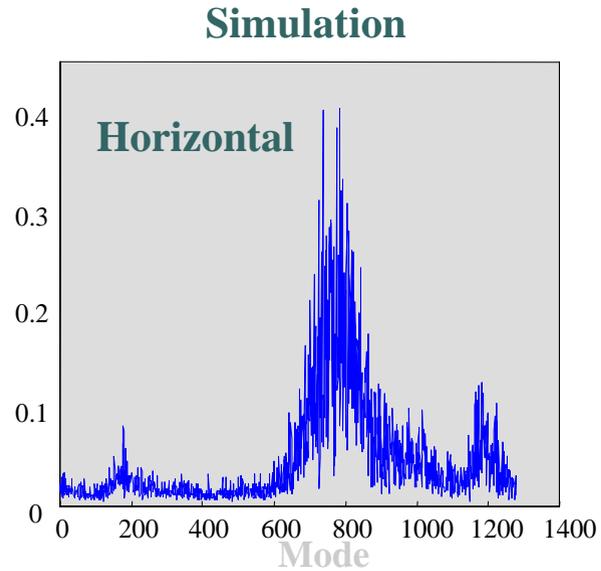
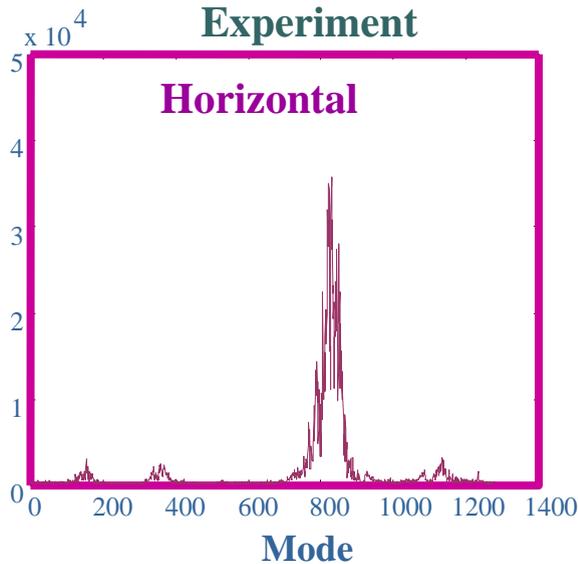
$$\frac{d^2 \mathbf{x}_{+,a}}{ds^2} + K(s) \mathbf{x}_{+,a} = \frac{2r_e}{\gamma} \sum_{j=1}^{N_i} \mathbf{F}_G(\mathbf{x}_{+,a} - \mathbf{x}_{e,j}; \sigma(s)) \delta(s - s_j)$$

$$\frac{d^2 \mathbf{x}_{e,a}}{dt^2} = \frac{e}{m} \frac{d\mathbf{x}_{e,a}}{dt} \times \mathbf{B} - 2N_p r_e c \sum_n \sum_{i=1}^{N_b} \mathbf{F}(\mathbf{x}_{e,a} - \mathbf{x}_{p,i}) \delta(t - t_i(s_e + nL)) - r_e c^2 \frac{\partial \phi(\mathbf{x}_{e,a})}{\partial \mathbf{x}_{e,a}} \quad (2)$$



CBI mode spectra in KEKB

Solenoid-Off



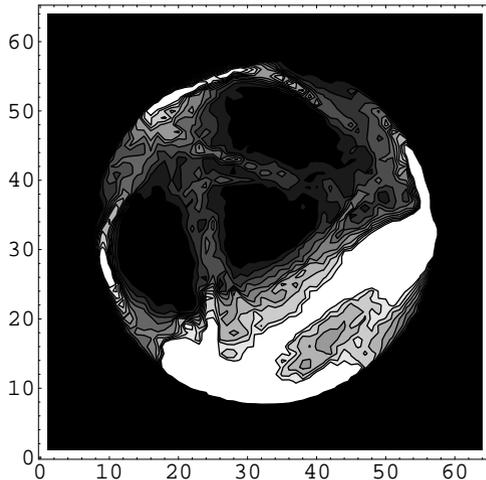
Bunches are filled every 4 bucket.

Su Su Win et al, (EC2002)

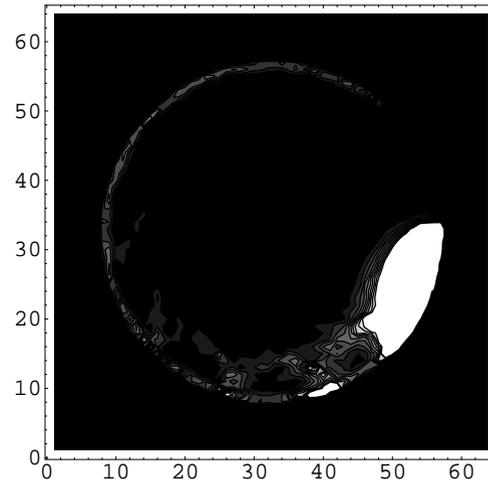
Effect of Solenoid magnet

- Solenoid magnets suppress the electron cloud effect partially.
- We can observe electron cloud effect characterized by solenoid magnet.
- Cloud distribution (K. Ohmi, APAC98)

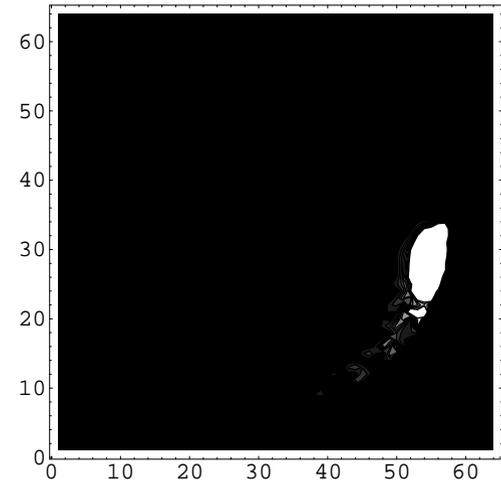
10 G



20 G



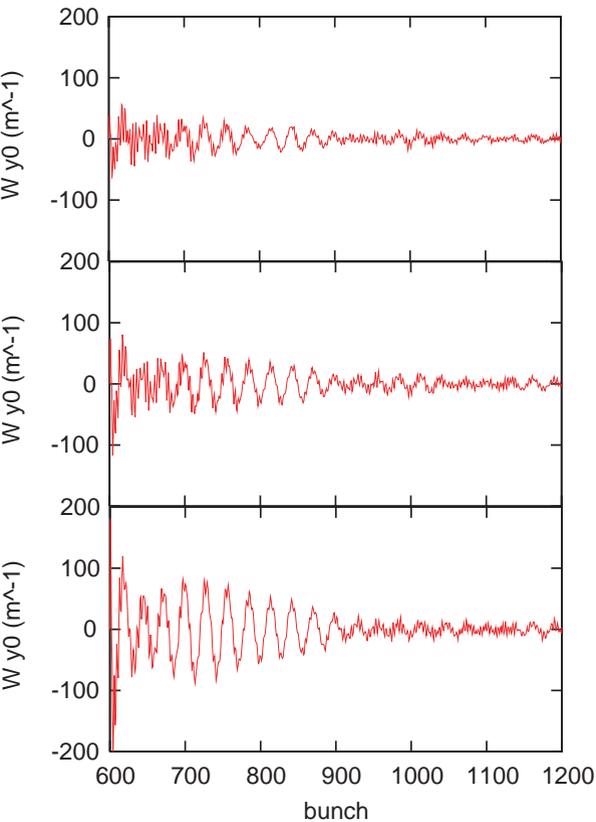
30 G



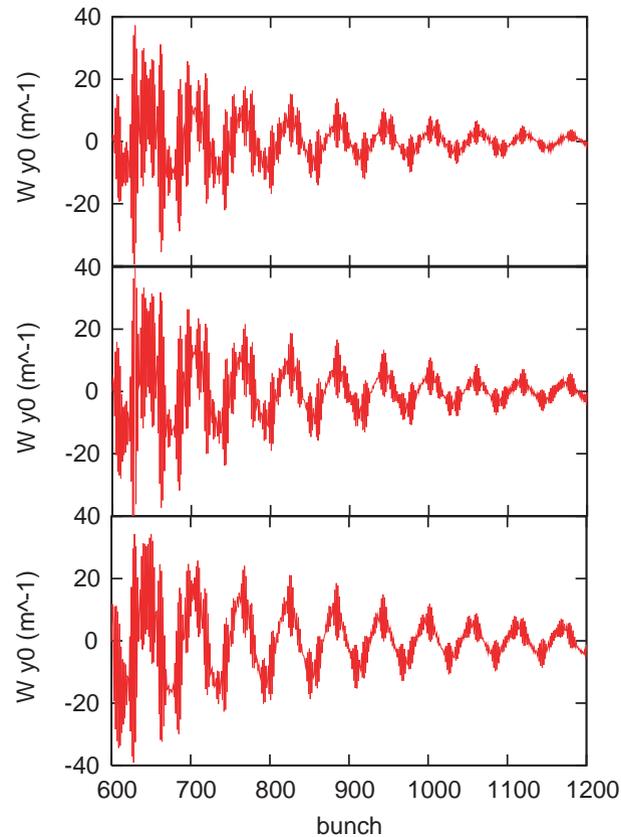
Wake force in weak solenoid field

S. Win et al, PRST-AB (2005)

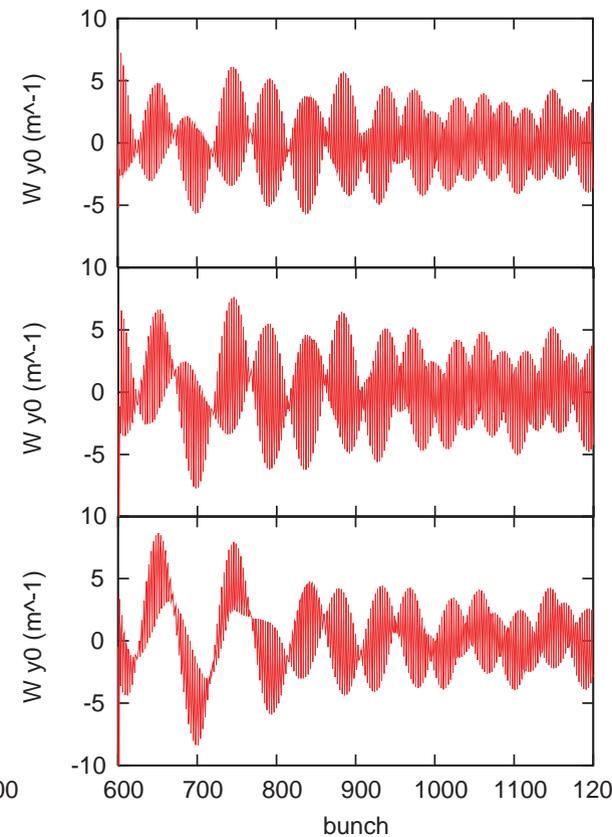
$\Delta y=1$ (top), 2 (middle), 5 (bottom) mm



Bz=10G



20 G



30 G

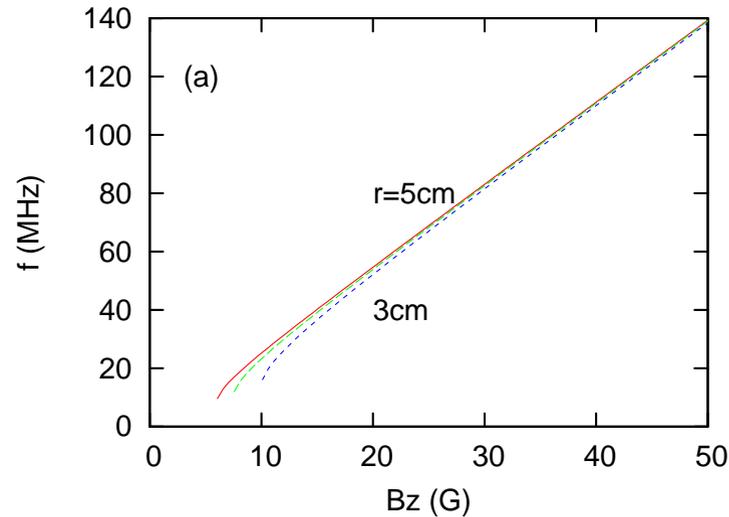
Electron motion in solenoid magnet

- Two frequency components

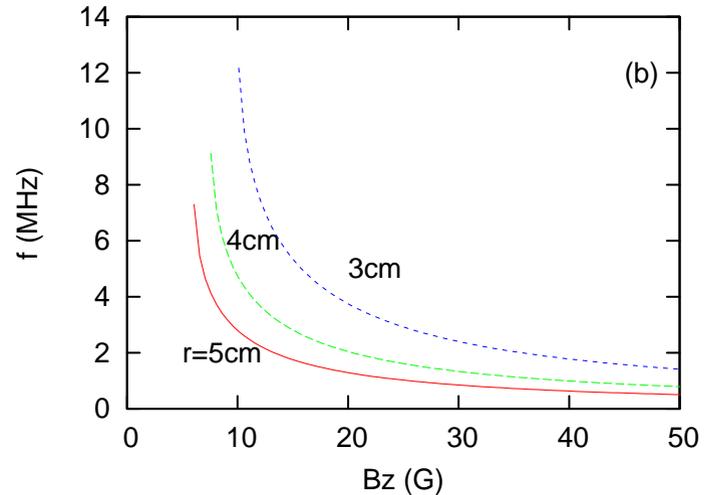
$$\omega_{\pm} = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\lambda_p r_e c^2}{r^2}}$$

where

$$\omega_c = \frac{eB}{m_e}$$

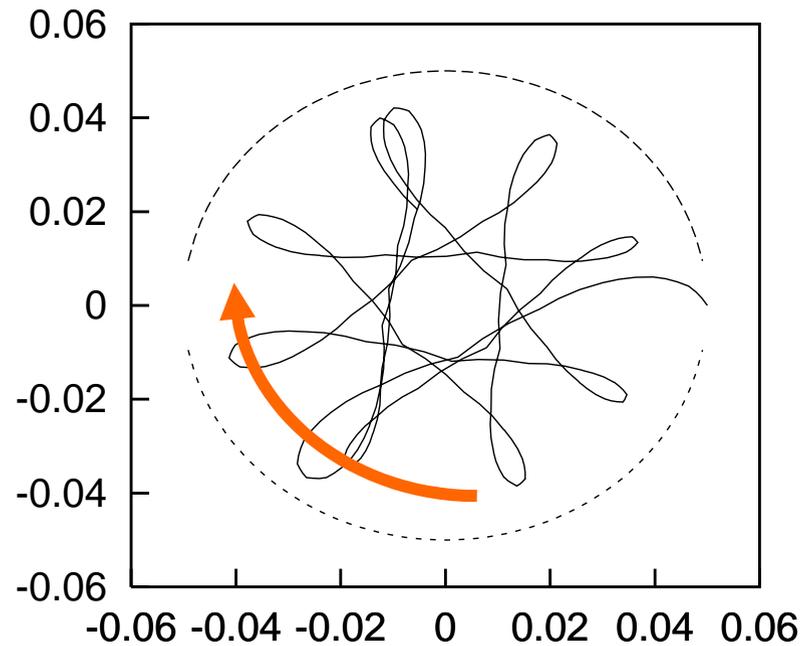


$\sim \omega_c$



$\ll \omega_c$

- Example of trapped electron trajectory for $B_z=10$ G



Characteristics of the wake force in solenoid magnet

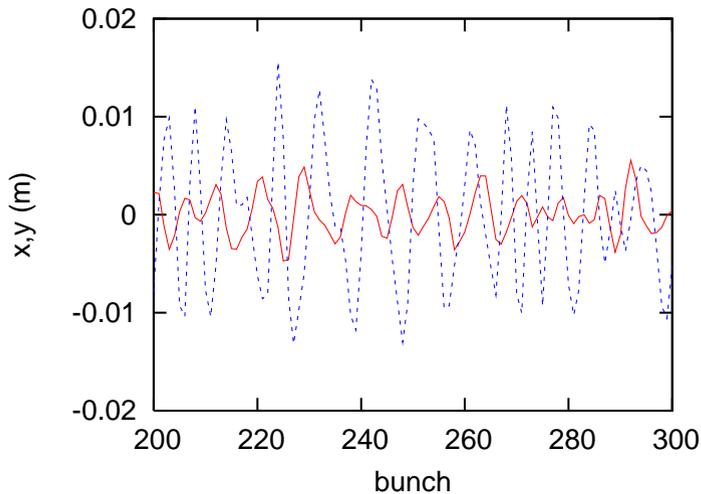
- **Focusing wake**. Following bunches are kicked opposite direction for a displacement of a bunch.
- Ordinary wake is **defocusing**.
- **Forward traveling modes** will be induced.

$$\omega = (H - m)\omega_0 - \omega_\beta$$

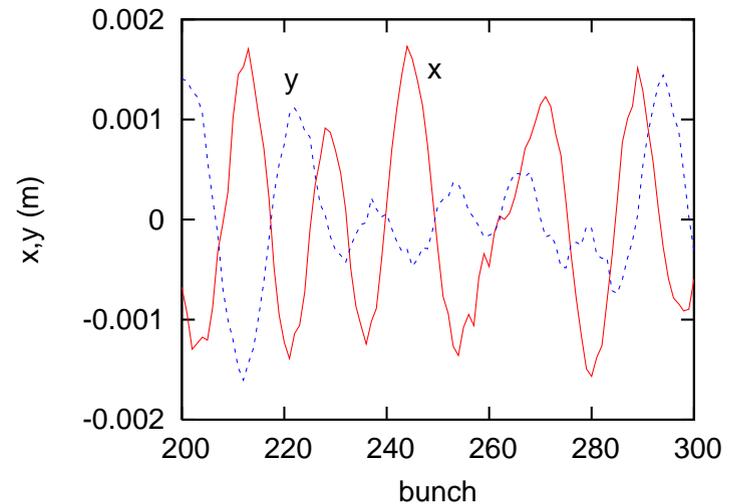
$$\omega = m\omega_0 + \omega_\beta$$

Tracking simulation for CBI due to electron cloud in solenoid magnet

○ 0 G, 50-th turn



○ 10 G, 100-th turn

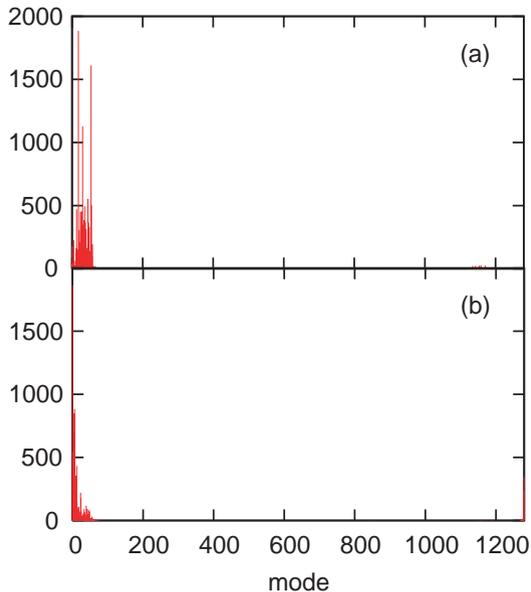


We observe only slow mode.

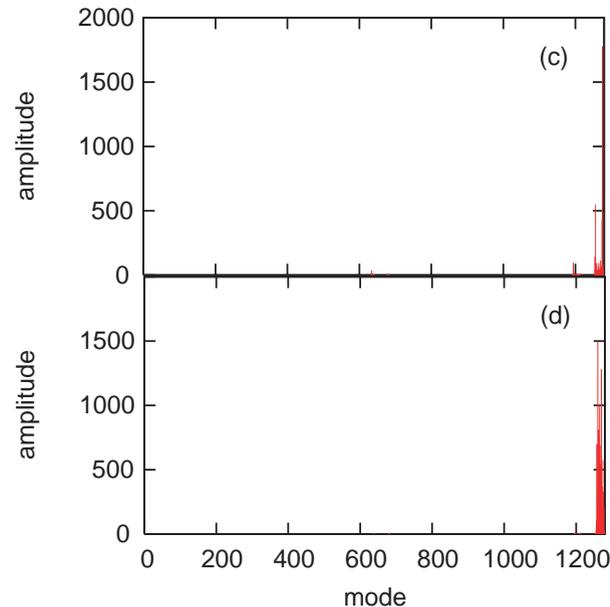
Mode spectra in solenoid magnet

We observe only slower mode, but not observe mode correspond to cyclotron frequency.

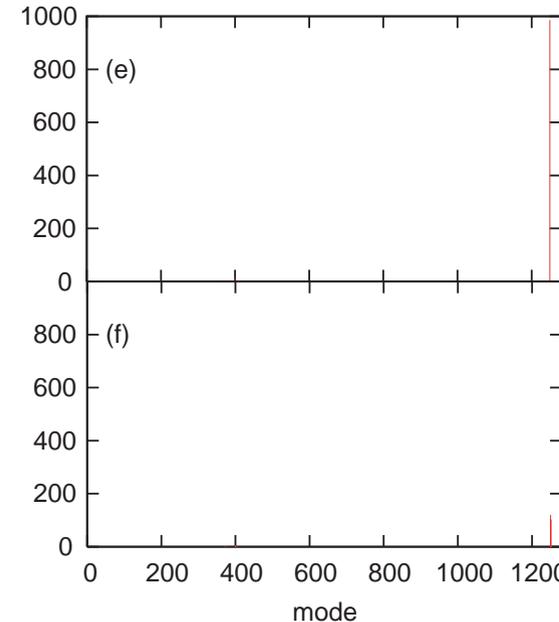
10 G



20 G



30 G



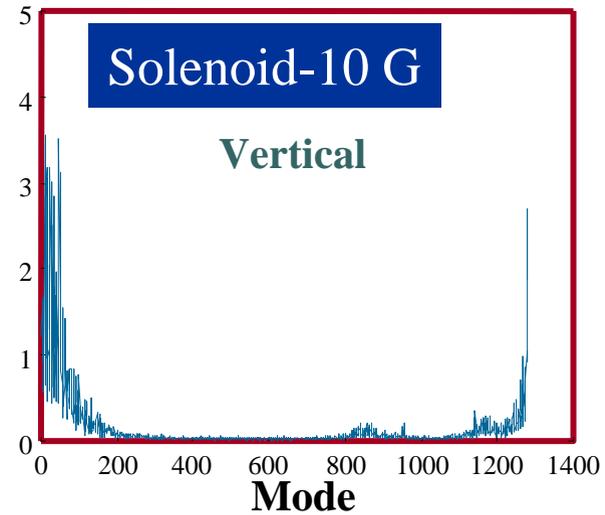
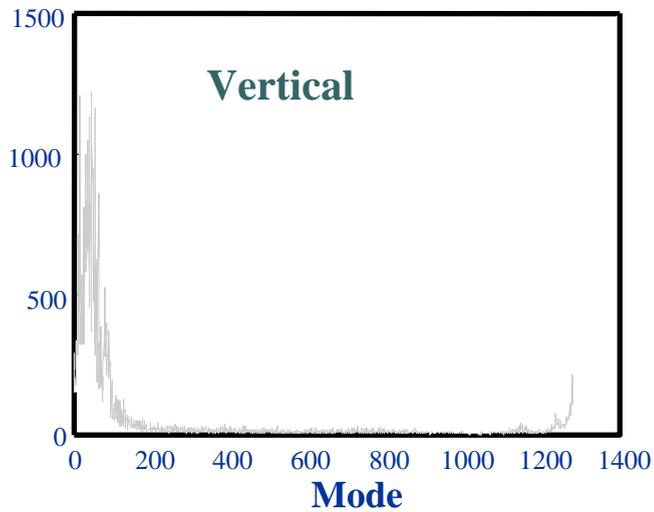
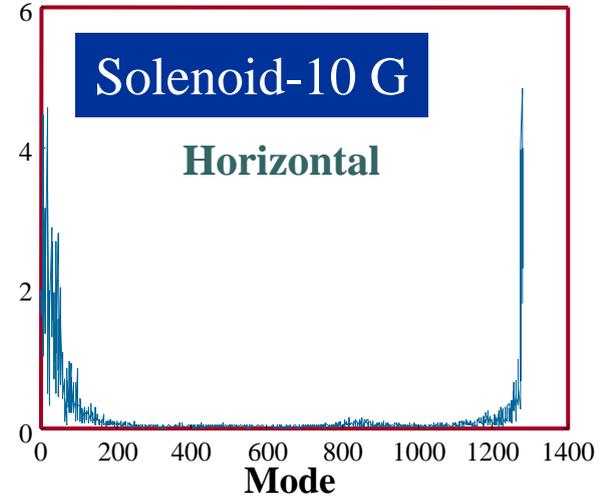
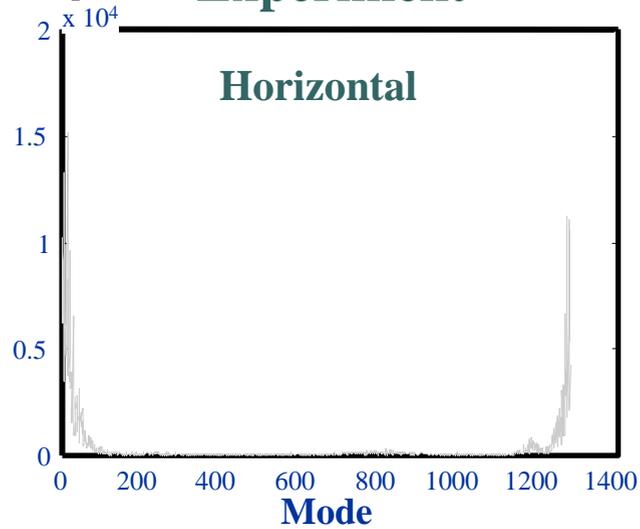
All are forward traveling mode $m > 1280 - 45$ or $m < 1280/2$.

KEKB

Solenoid-ON

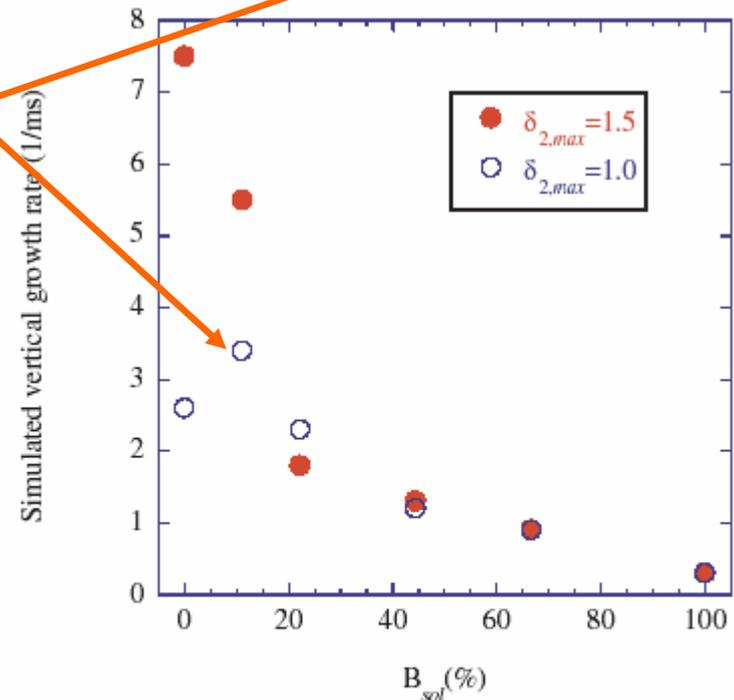
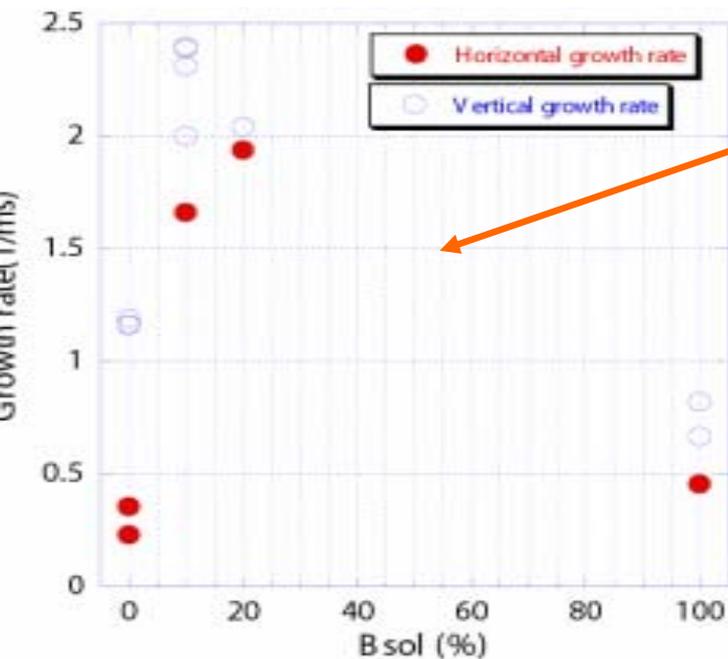
Experiment

Simulation



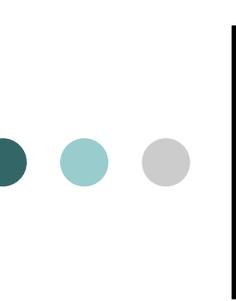
Growth rate for solenoid strength

- 600 mA 100%~50 G
- Simulation with $\delta_2=1.0$ is consistent with the experiment.



M. Tobiyama et al, PRST-AB (2005)

FIG. 17. (Color) Simulated vertical growth rate for the case of $\delta_{2,max} = 1.5$ (solid circle) and $\delta_{2,max} = 1.0$ (open circle), where $\delta_{2,max}$ is the secondary yield of the photoelectron.



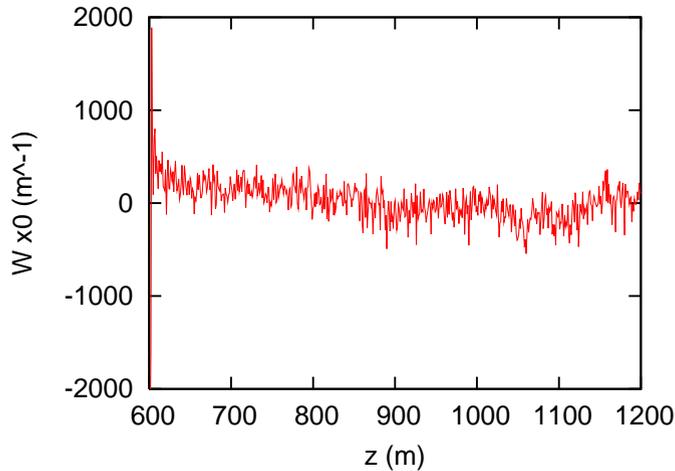
Electron cloud in Bending magnet

- Strong magnetic field B_y .
- Electrons move along y direction.
- If electrons are produced illuminated position only, they little affect the beam.
- Here electrons are assumed to be produced uniformly at the chamber.

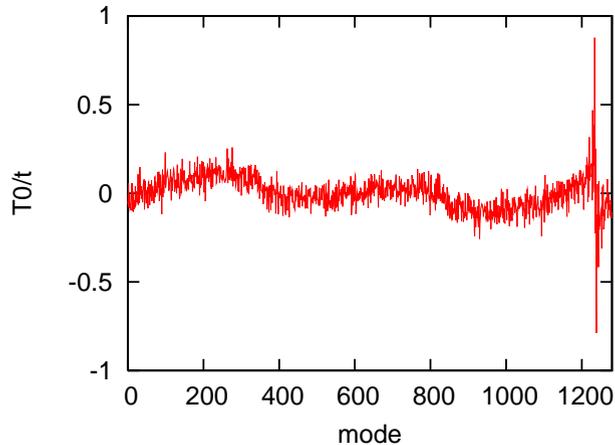
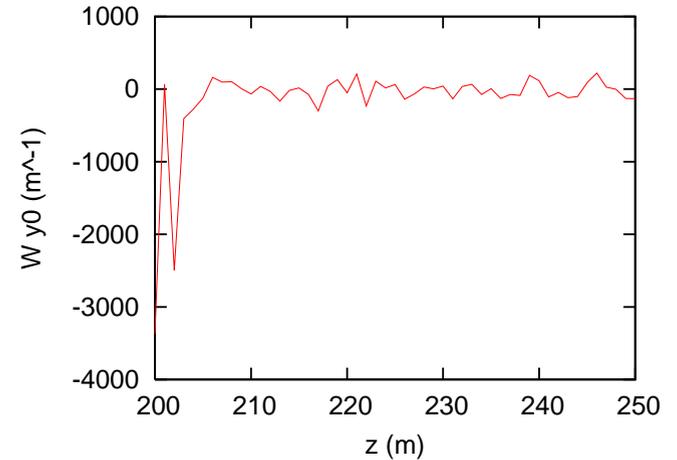
Wake force and growth mode due to electron cloud in bending magnet

Horizontal

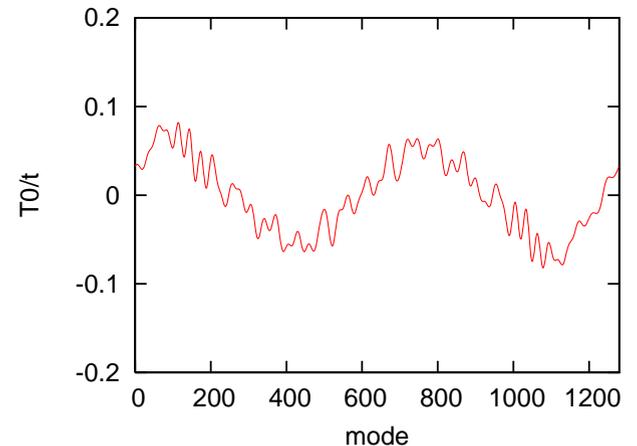
Vertical



wake

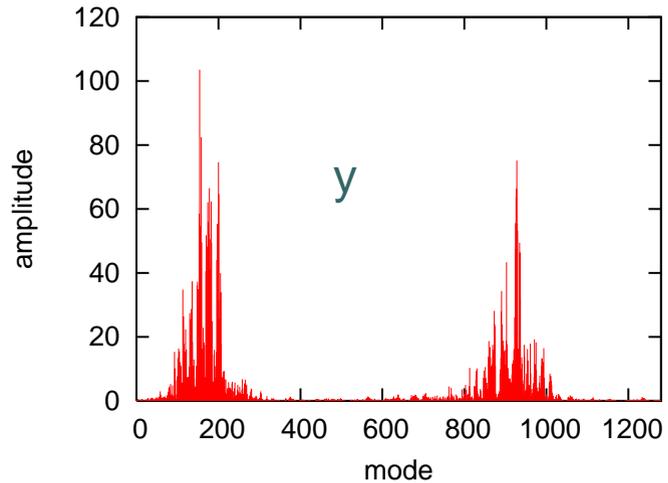
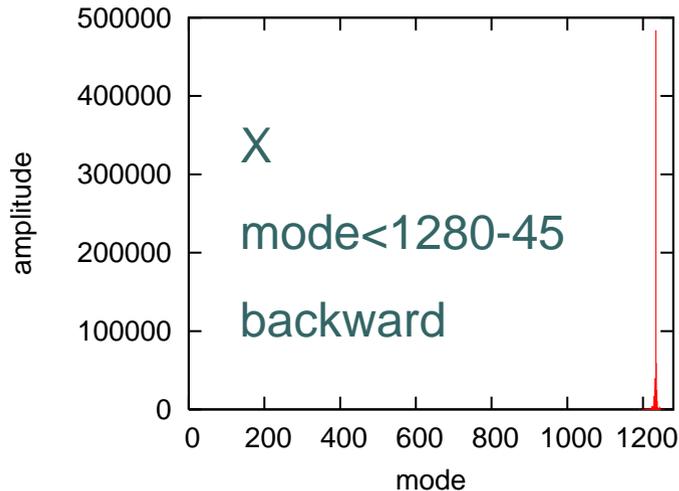
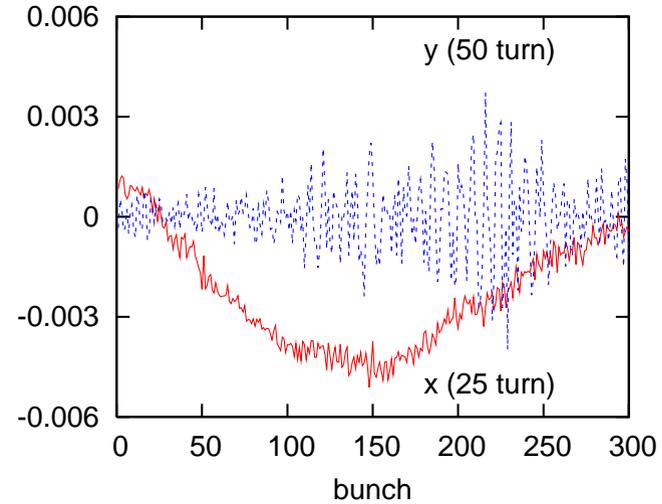
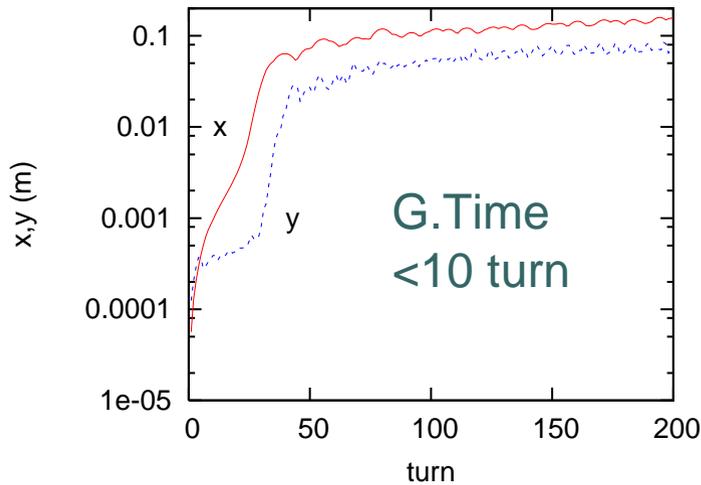


Mode



Tracking for CBI in bending magnet

○ Growth and mode spectra



We do not observe CBI signal characterized by bending magnet

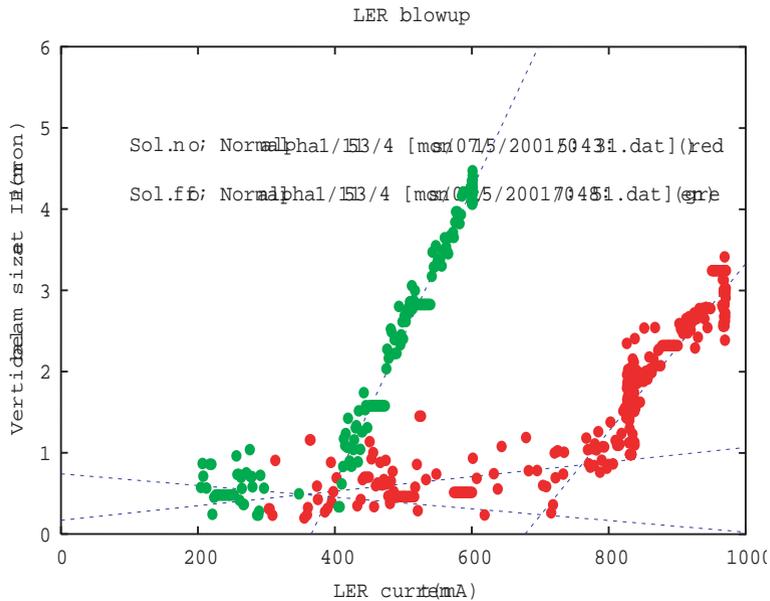
Single bunch instability

Vertical Beam size blow up of positron beam at commissioning of KEKB

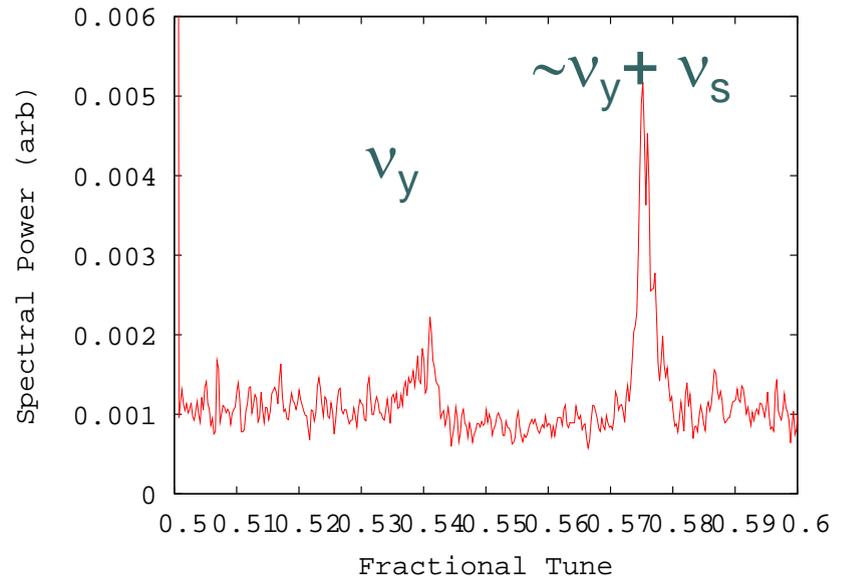
- We observed the beam-size blow-up at a threshold current. The threshold was determined by total current.
- The blow-up was observed in multi-bunch operation, but was perhaps single bunch effect. Beam size was measured by putting a bunch with an arbitrary current in a bunch train.
- Luminosity is limited by the beam size blow-up.
- Synchro-beta sideband induced by electron cloud head-tail instability was observed.

Measurements of the single bunch instability

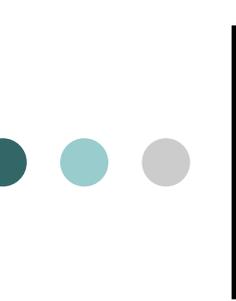
- Beam size blow-up
- Synchro-beta sideband



Fukuma et al.



J. Flanagan et al.



Head-tail instability model

- Simulation using Gaussian model
- Wake field approach
- PIC simulation (like beam-beam strong-strong)

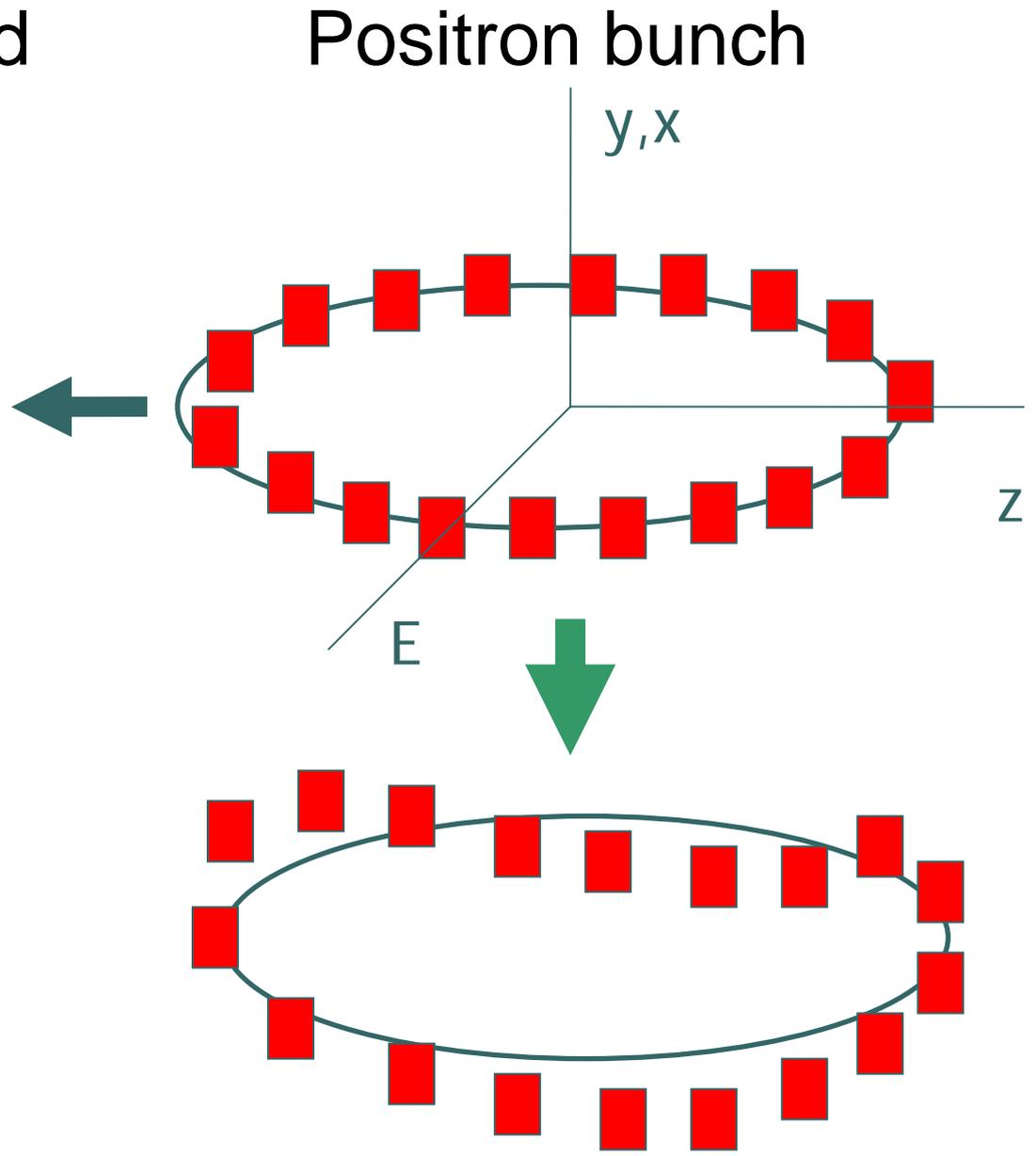
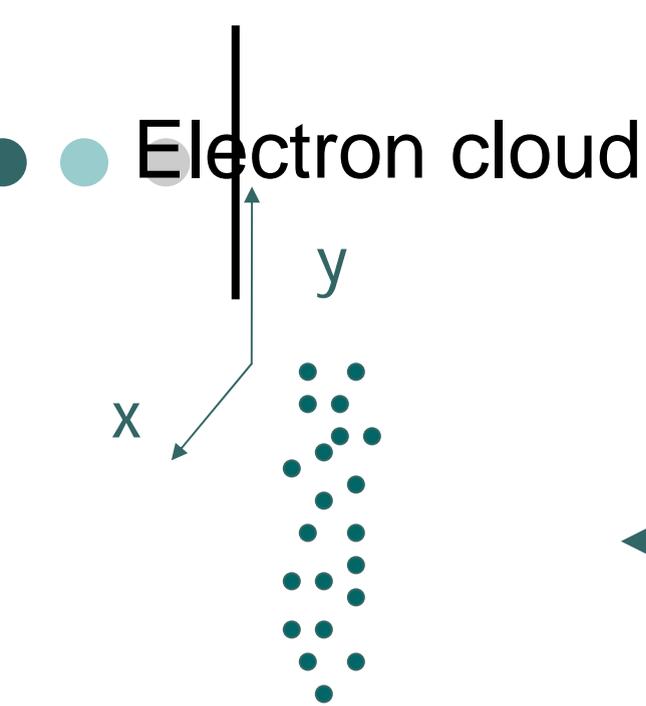
Equation of motion for Gaussian model

- Macro-particles with fixed transverse Gaussian size (distributed in the longitudinal phase space).
- Macro-electrons in transverse plane.

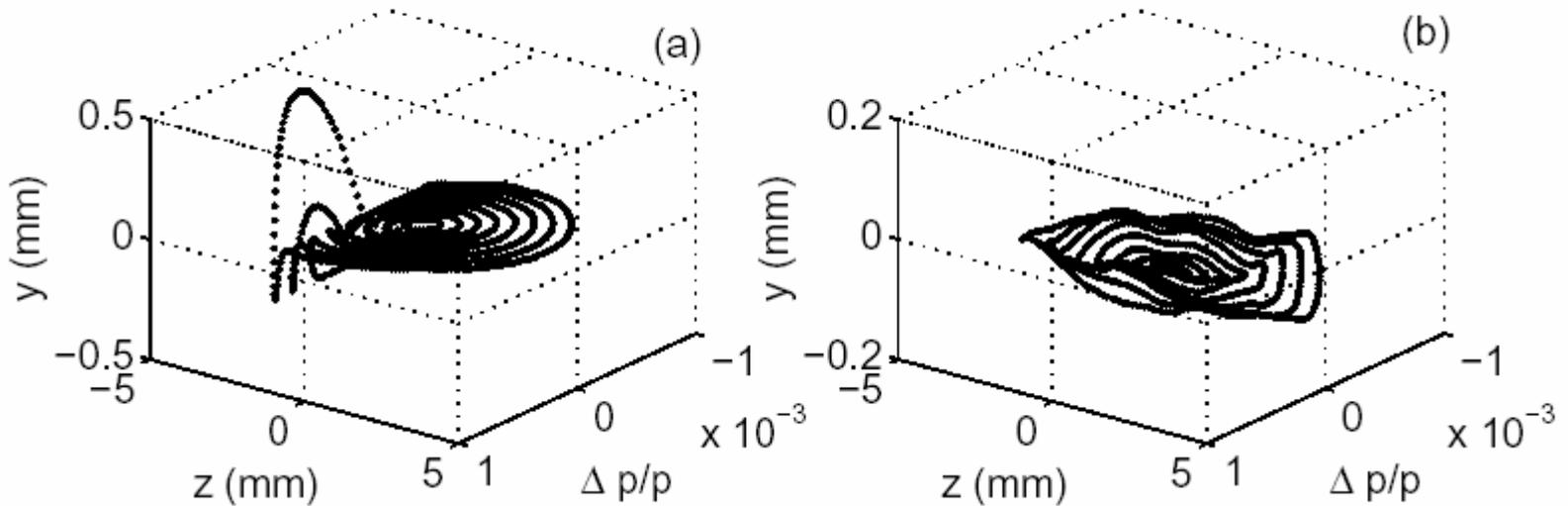
$$\frac{d^2 \mathbf{x}_{+,a}}{ds^2} + K(s) \mathbf{x}_{+,a} = \frac{2r_e}{\gamma} \sum_{j=1}^{N_i} \mathbf{F}_G(\mathbf{x}_{+,a} - \mathbf{x}_{e,j}; \sigma(s)) \delta(s - s_j)$$

$$\frac{d^2 \mathbf{x}_{e,j}}{dt^2} = 2N_+ r_e c^2 \mathbf{F}_G(\mathbf{x}_{e,j} - \mathbf{x}_{+,a}; \sigma(s)) \delta(t - t(s_{+,a}))$$

$$F \xrightarrow{x, y \approx \infty} \frac{(y + ix)}{r^2} \qquad F \xrightarrow{x, y \approx 0} \frac{1}{\sigma_x + \sigma_y} \left(\frac{y}{\sigma_y} + i \frac{x}{\sigma_x} \right)$$

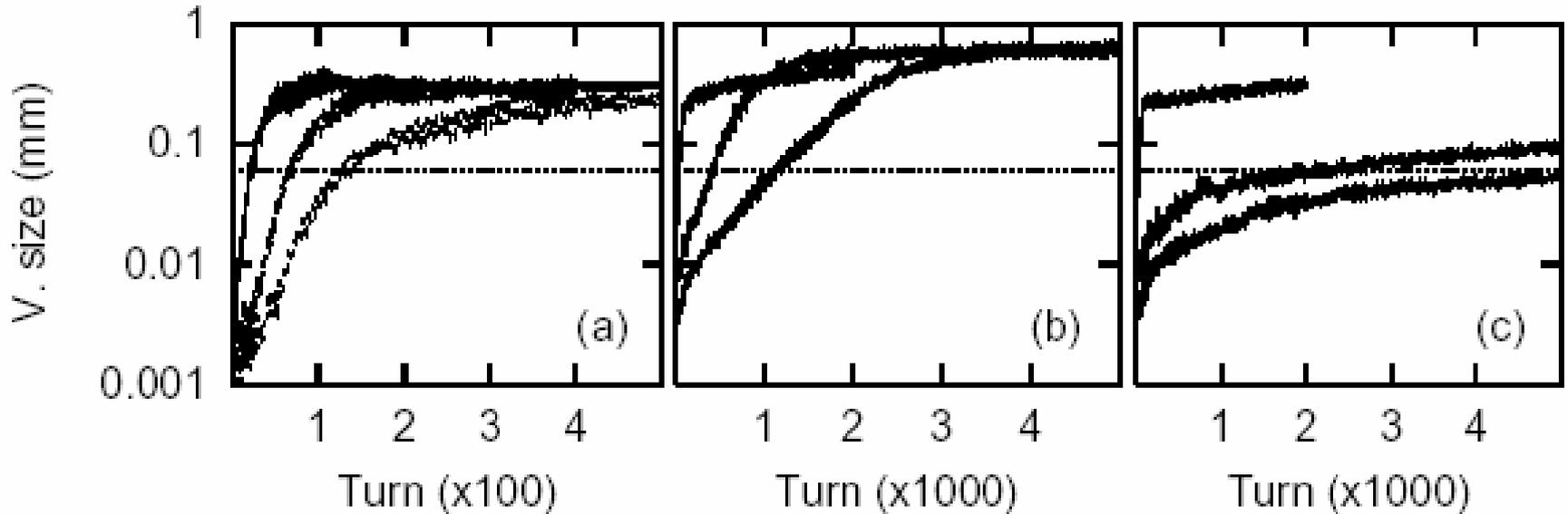


- Bunch head-tail motion w/wo synchrotron motion.



Vertical amplitude of the macro-particles in the longitudinal phase space are plotted. Multi-airbag model (z - δ) is used to visualize in these figures.

Head-tail and strong head-tail instability



$$\rho_e = 2 \times 10^{11}, 4 \times 10^{11}, 10 \times 10^{11} \text{ m}^{-3}$$

- Unstable for Positive chromaticity --- head-tail
- Unstable for $\rho_e = 10 \times 10^{11} \text{ m}^{-3}$ irrelevant to chromaticity --
- strong head-tail

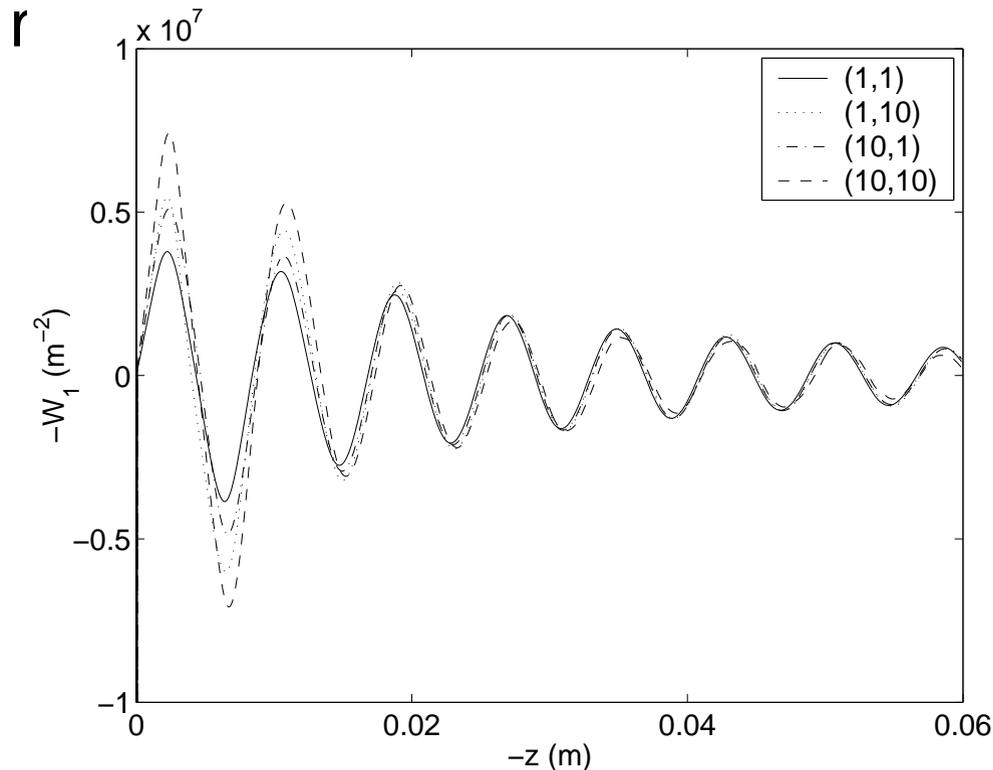
Wake field approach

- Linearized model.
- Numerical calculation including nonlinearity. (Similar way to the calculation of the multi-bunch wake field)

$$W = K \frac{\lambda_e}{\lambda_p} \frac{L}{(\sigma_x + \sigma_y)\sigma_y} \frac{\omega_e}{c} \sin\left(\frac{\omega_e}{c} z\right)$$

K=1 for Linearized model. K~2-3 for the numerical calculation.

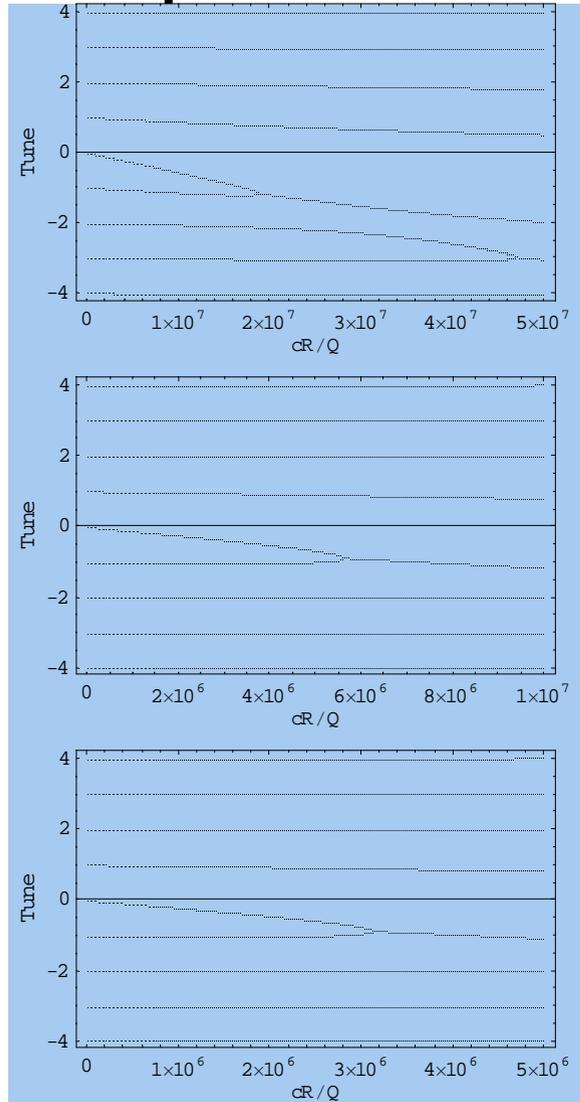
Vertical wake field given by the numerical



- (1,1) is consistent with the analytical calculation.
- (10,10) is twice larger than (1,1).
- Instability threshold is calculated by the wake force.

K. Ohmi, F. Zimmermann, E. Perevedentsev, PRE65,016502 (2001)

Threshold of strong head-tail instability



- Mode coupling theory
Threshold : $\rho_e = 1-2 \times 10^{12} \text{m}^{-3}$

- Coasting beam model

$$\rho_{e,th} = \frac{2\gamma v_s \omega_e \sigma_z / c}{\sqrt{3} K Q r_0 \beta L} \quad Q = \min(Q_{nl}, \omega_e \sigma_z / c)$$

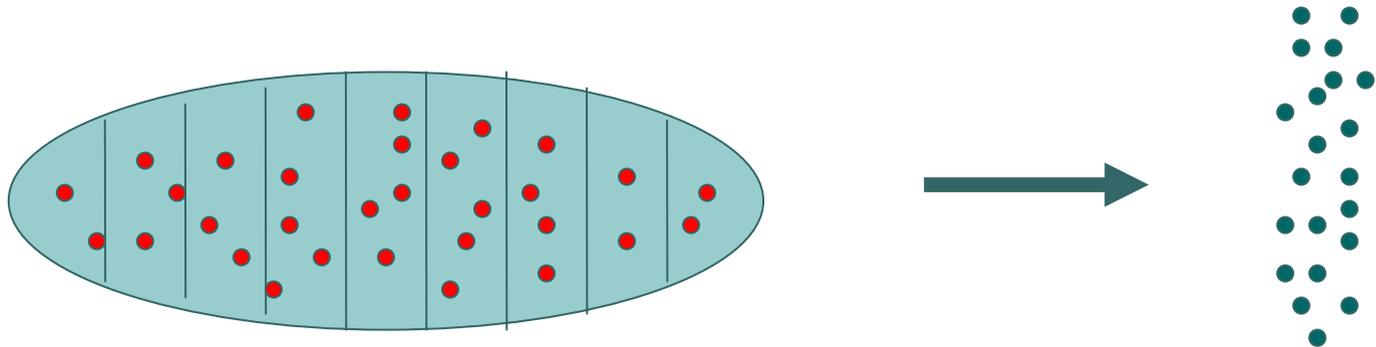
$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y (\sigma_x + \sigma_y)}}$$

Threshold : $\rho_e = 5 \times 10^{11} \text{m}^{-3}$

- Coasting beam model is better coincident with simulation.

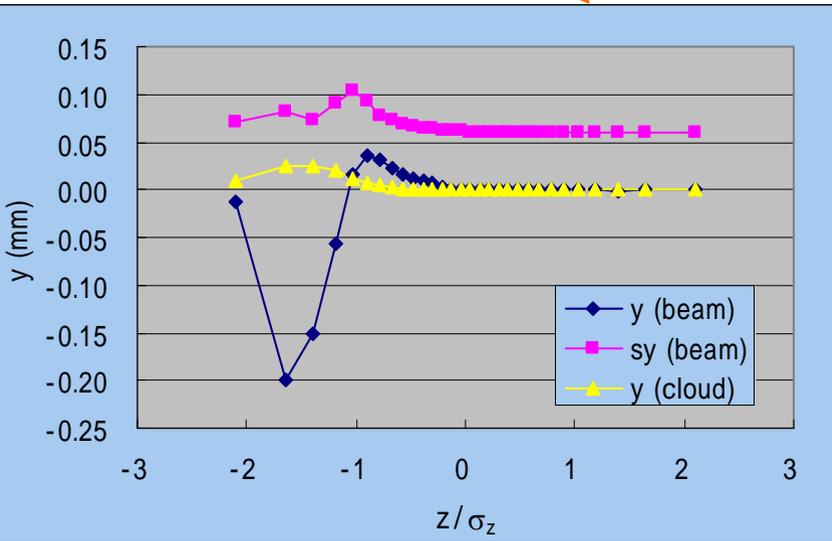
Simulation with Particle In Cell method

- Electron clouds are put at several positions in a ring.
- Beam-cloud interaction is calculated by solving 2 dimensional Poisson equation on the transverse plane.
- A bunch is sliced into 20-30 pieces along the length.

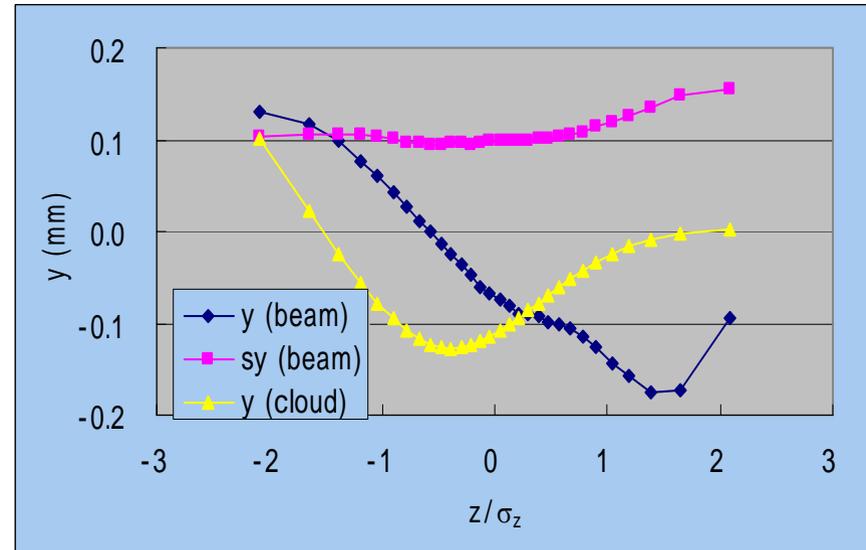


PIC simulation

Snap shot of beam and cloud shape for $v_s=0$ and $v_s>0$



BBU



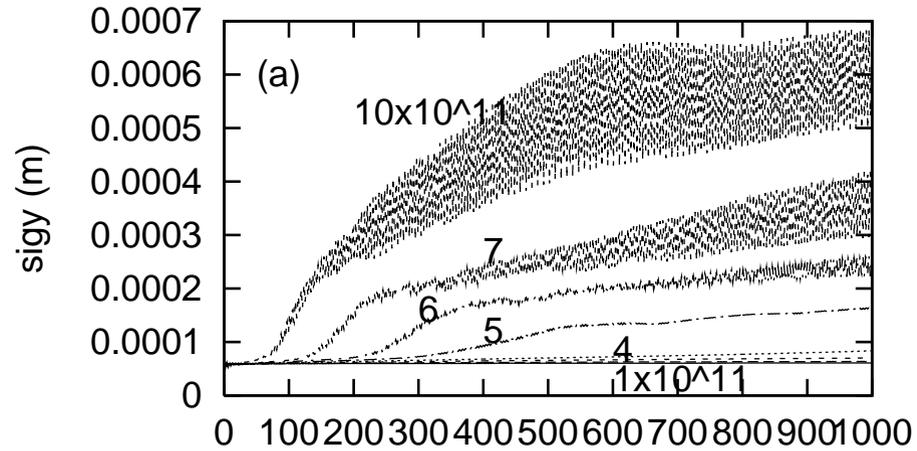
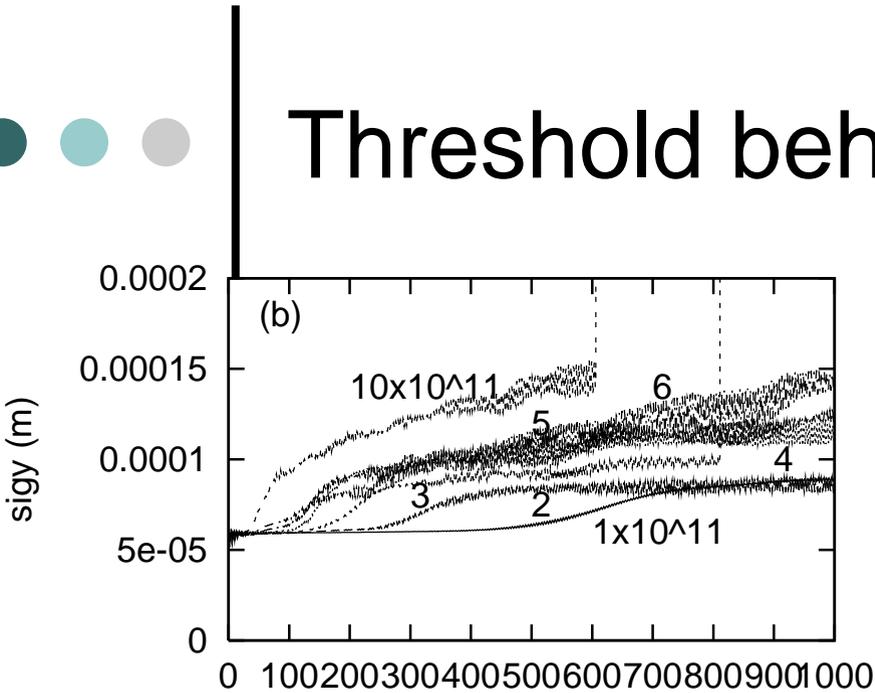
Head-tail motion

Pink: size along bunch length

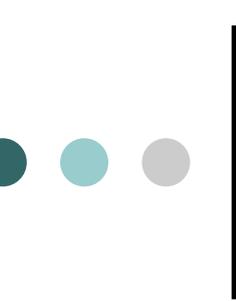
yellow: $\langle y \rangle$ of cloud

Dark blue: $\langle y \rangle$ of bunch

Threshold behavior



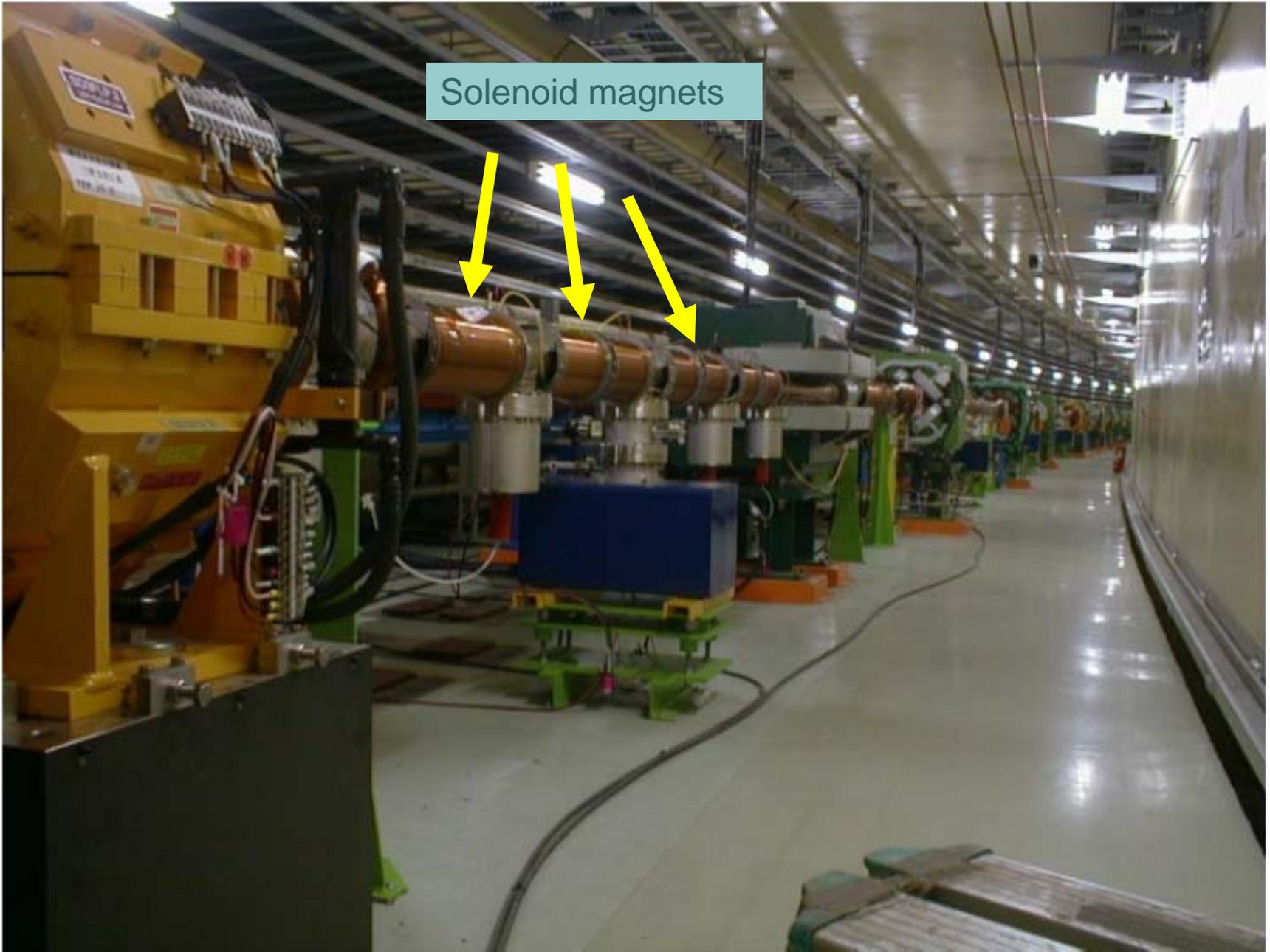
- $v_s = 0$ no threshold, $v_s > 0$ clear threshold.
- $\rho_{e,th} = 5 \times 10^{11} \text{ m}^{-3}$
- The cloud density is consistent with that predicted by the measurement of electron current.
- This beam size blow-up can be understood as strong head-tail instability caused by electron cloud.

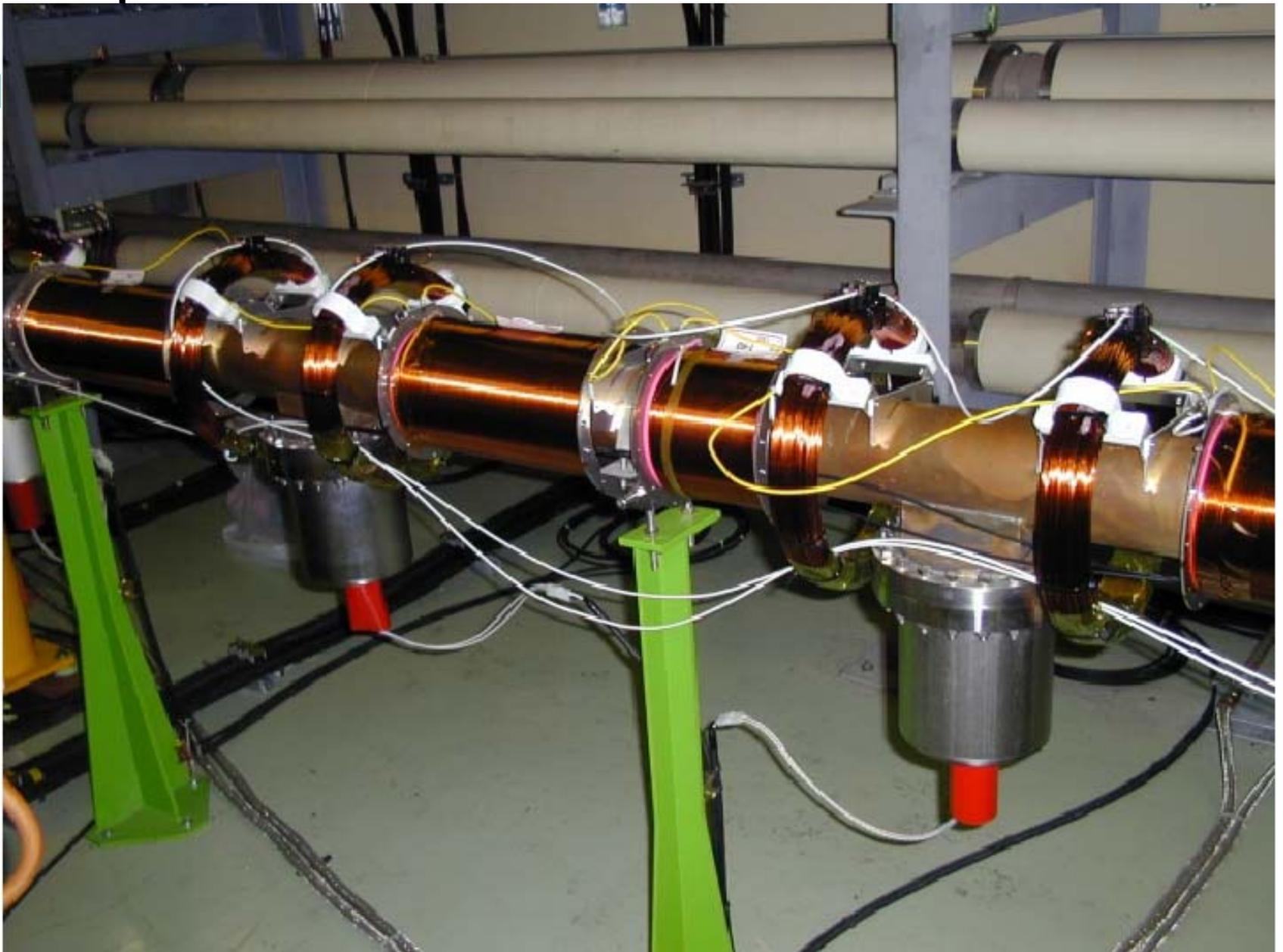


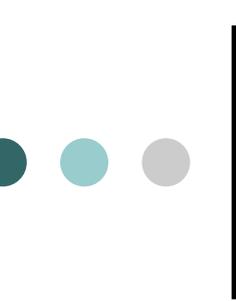
Solenoid winding in KEKB ring

- (0) C-yoke permanent magnets are attached in the arc section of ~800m
- (1) Solenoids are wound in the arc section of 800m (Sep. 2000).
- (2) Solenoids are wound additionally in the arc section of 500m (Jan. 2001).
- (3) Solenoids are wound in the straight section of *100m (Apr. 2001).
- (4) Add solenoids even in short free space (August 2001).
- (5) 95 % of drift space is covered (~2005).
- (6) Solenoid in $\frac{1}{4}$ of quadrupole magnets (2005)

Solenoid magnets







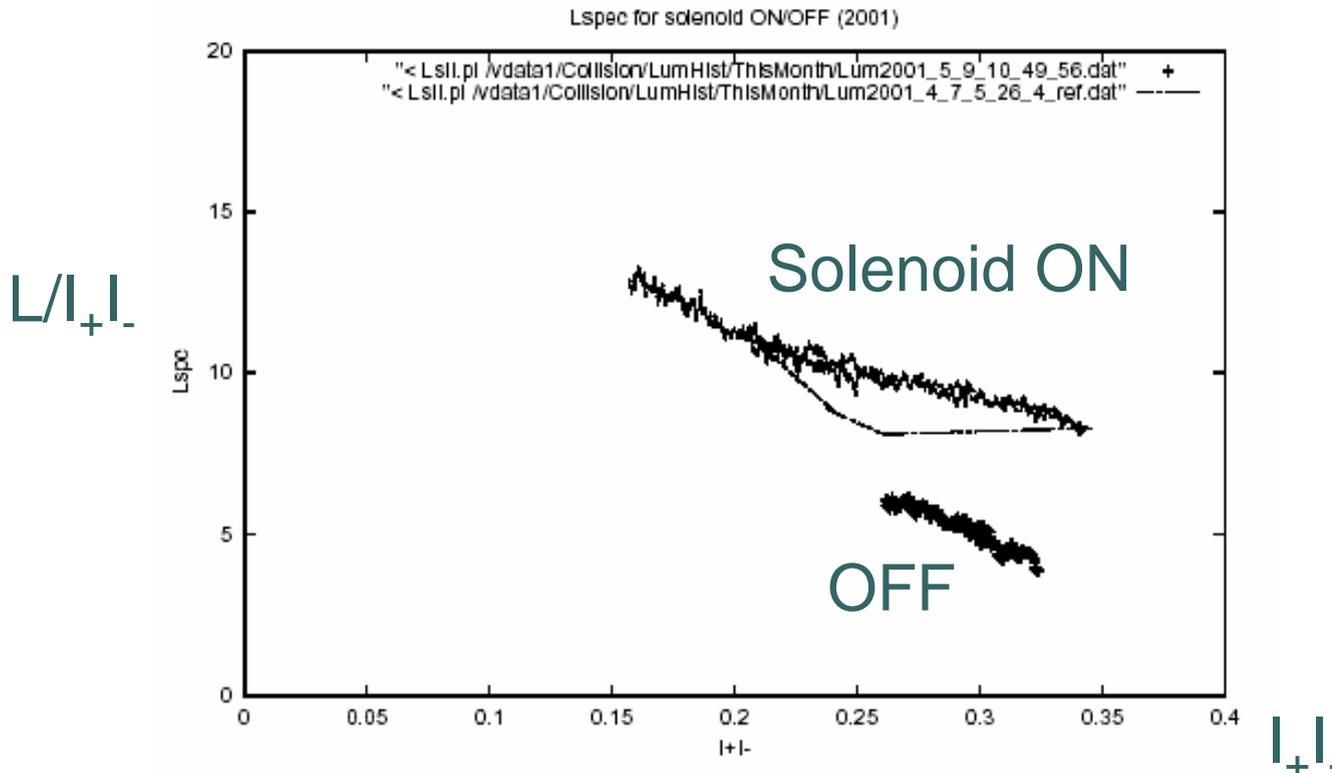
Machine studies for solenoid effect on Luminosity

- We use specific luminosity of 24 bucket spacing as a reference.
- Comparison of luminosity between solenoid ON/OFF
- Effect of additional solenoid (500m).
Luminosity in the end of 2000 and the beginning of 2001.

Solenoids ON/OFF

- When solenoids turn off, stored current is limited to a lower value than usual operation due to beam loss (coupled bunch instability)
- Luminosity is quite low (~half).

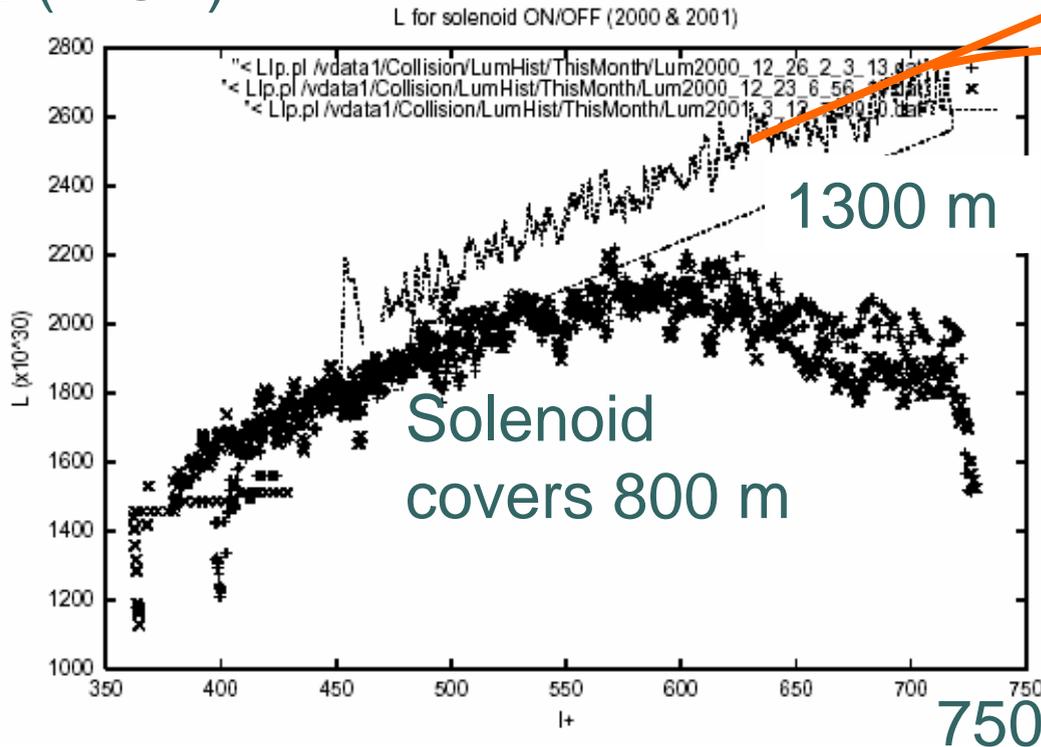
Specific Luminosity for Solenoid ON/OFF (measurement at May.2001)



Effect of additional solenoid

Typical luminosity behavior at Dec. 2000 and March. 2001

L ($\times 10^{30}$)

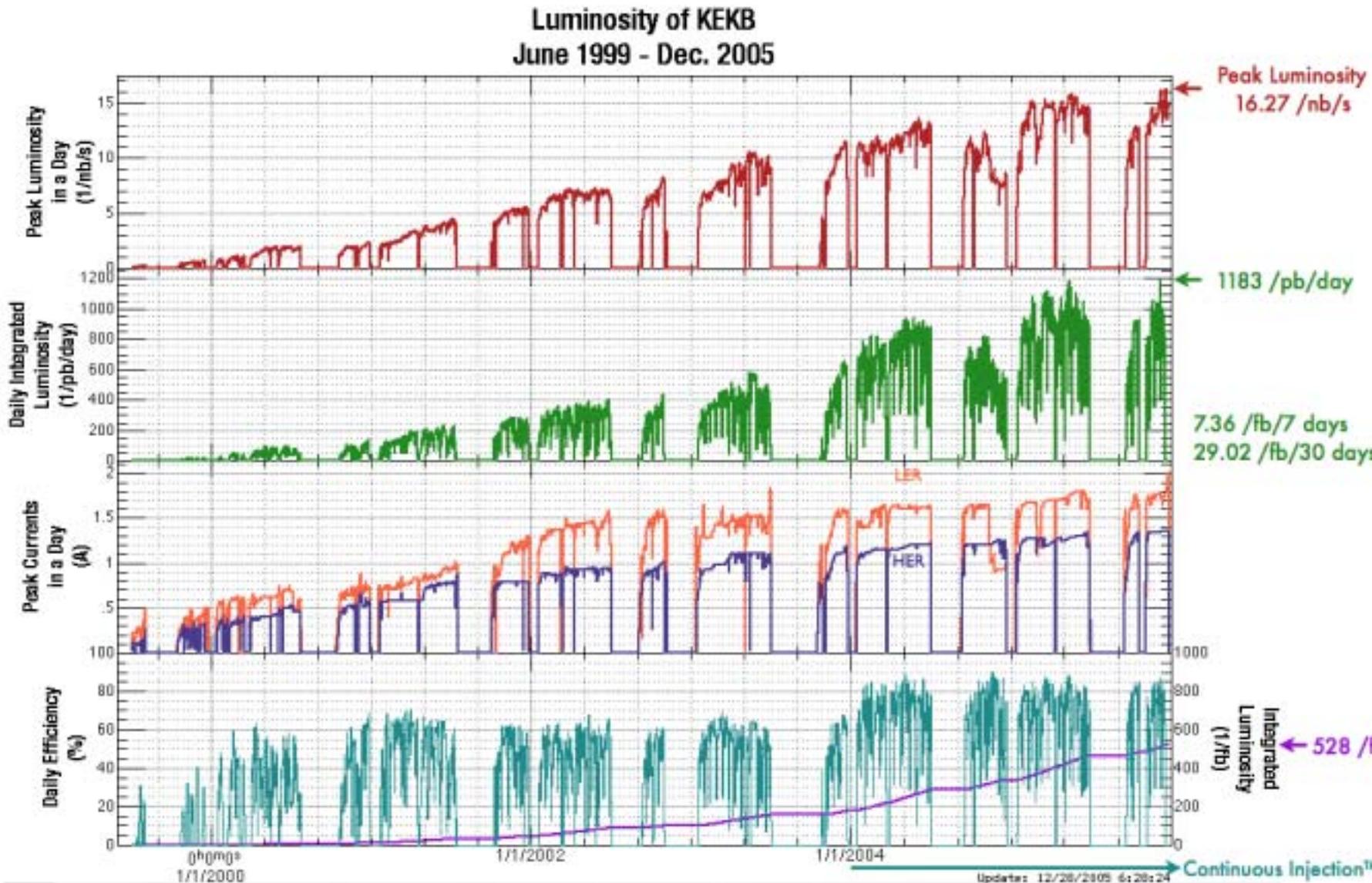


Longer and longer

Beam-beam tuning also improves the luminosity.

- Adding solenoid, positron current with peak luminosity increases.
- Now peak luminosity is given at around 1600-1800 mA.

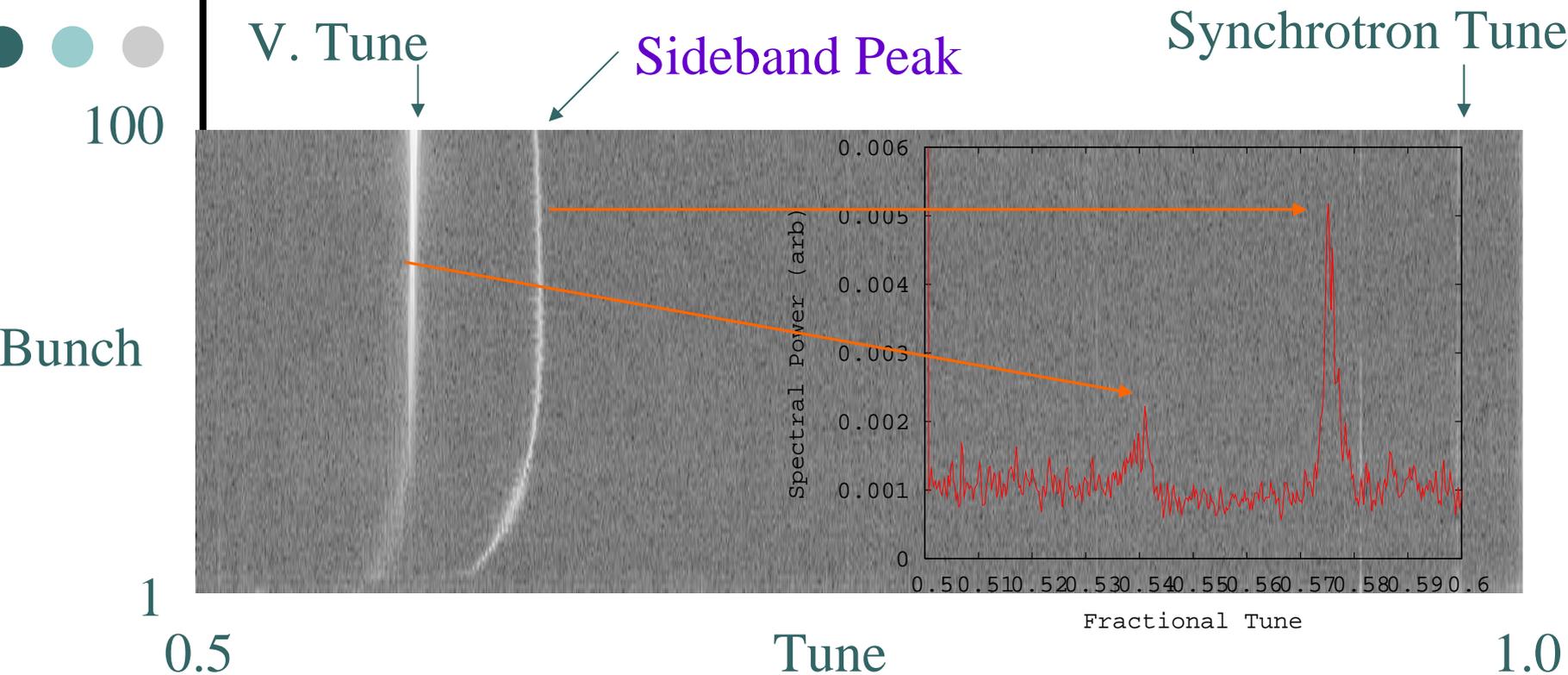
Luminosity history of KEKB



Measurement of synchro-beta sideband - evidence for head-tail instability

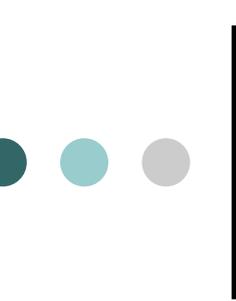
- If the beam size blow-up is due to head-tail instability, a synchro-betatron sideband should be observed above the instability threshold.
- The sideband spectra was observed with a bunch oscillation recorder.
- The threshold was consistent with simulations.
- The sideband appear near $\sim v_y + v_s$, while simulation gives $\sim v_y - v_s$, like ordinary strong head-tail instability.

Fourier power spectrum of BPM data



LER single beam, 4 trains, 100 bunches per train, 4 rf bucket spacing
Solenoids off: beam size increased from $60\ \mu\text{m}$ \rightarrow $283\ \mu\text{m}$ at 400 mA
Vertical feedback gain lowered

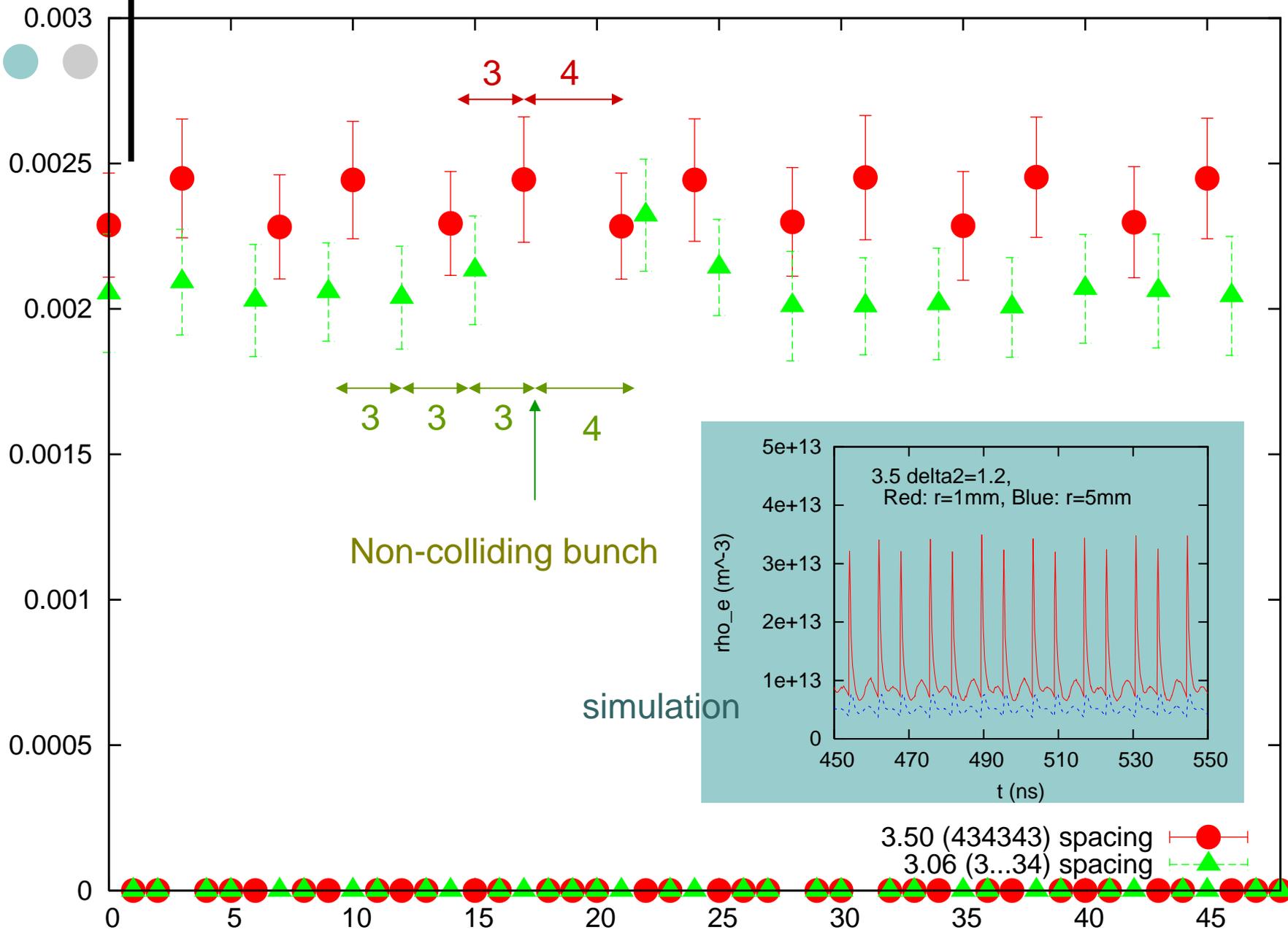
- This brings out the vertical tune without external excitation



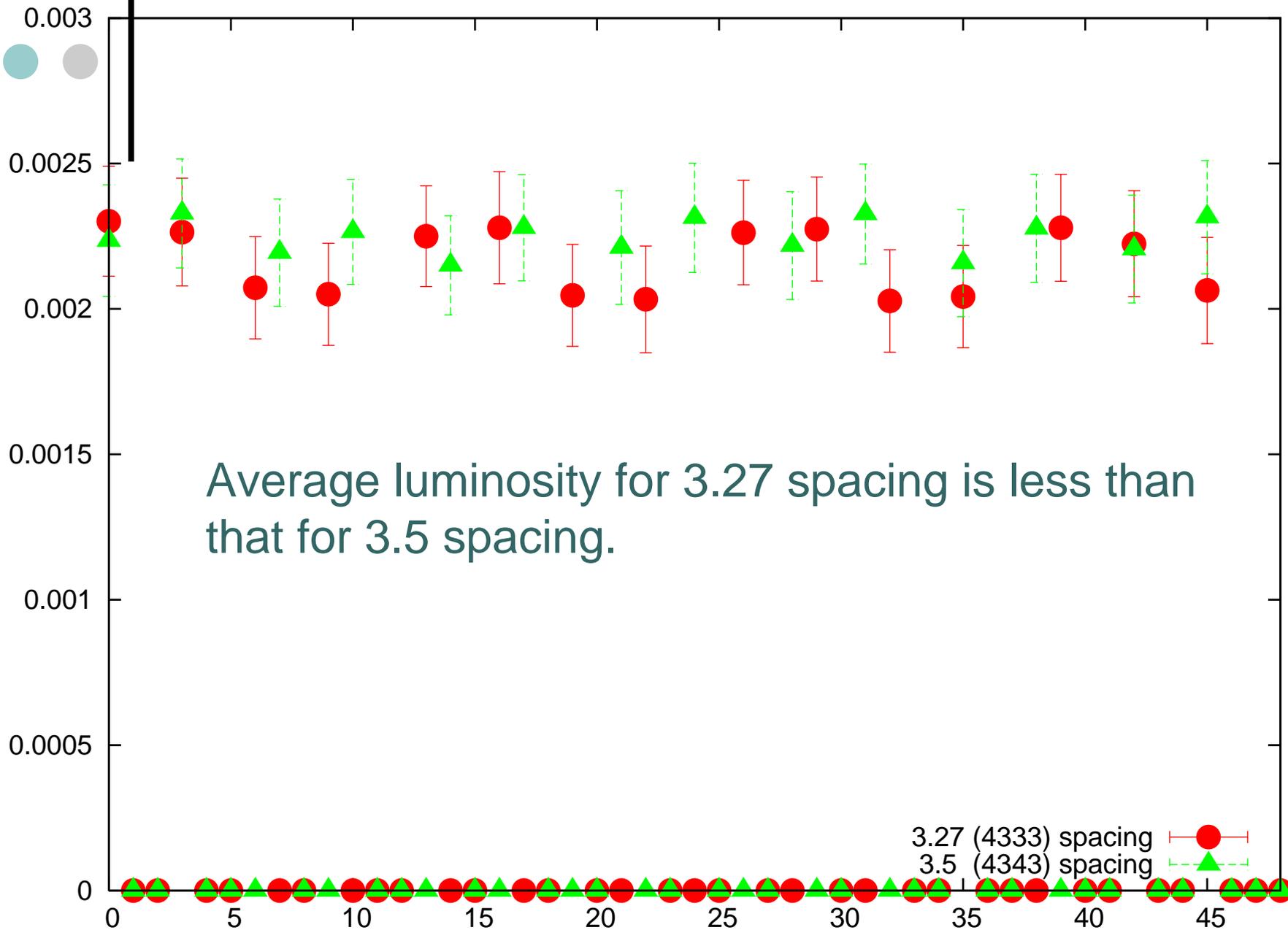
Filling pattern and specific luminosity using bunch by bunch luminosity monitor

- Various filling patterns are examined to get higher luminosity.
- To keep colliding condition, only a small part of train (300/5120 bucket) is filled with various pattern. The beam study was done parallel with physics run.

Specific Luminosity (49-folded)

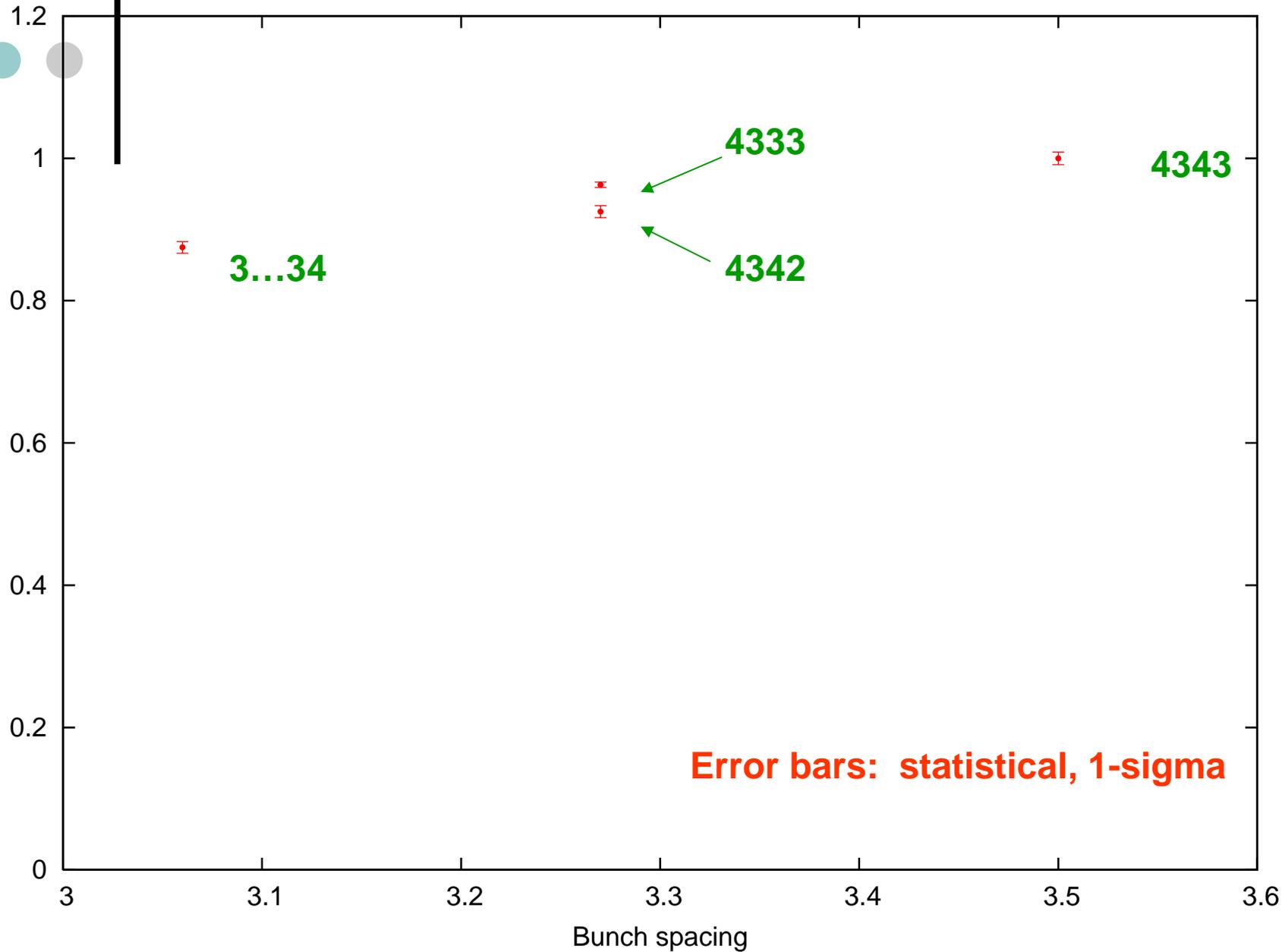


Specific Luminosity (49-folded)



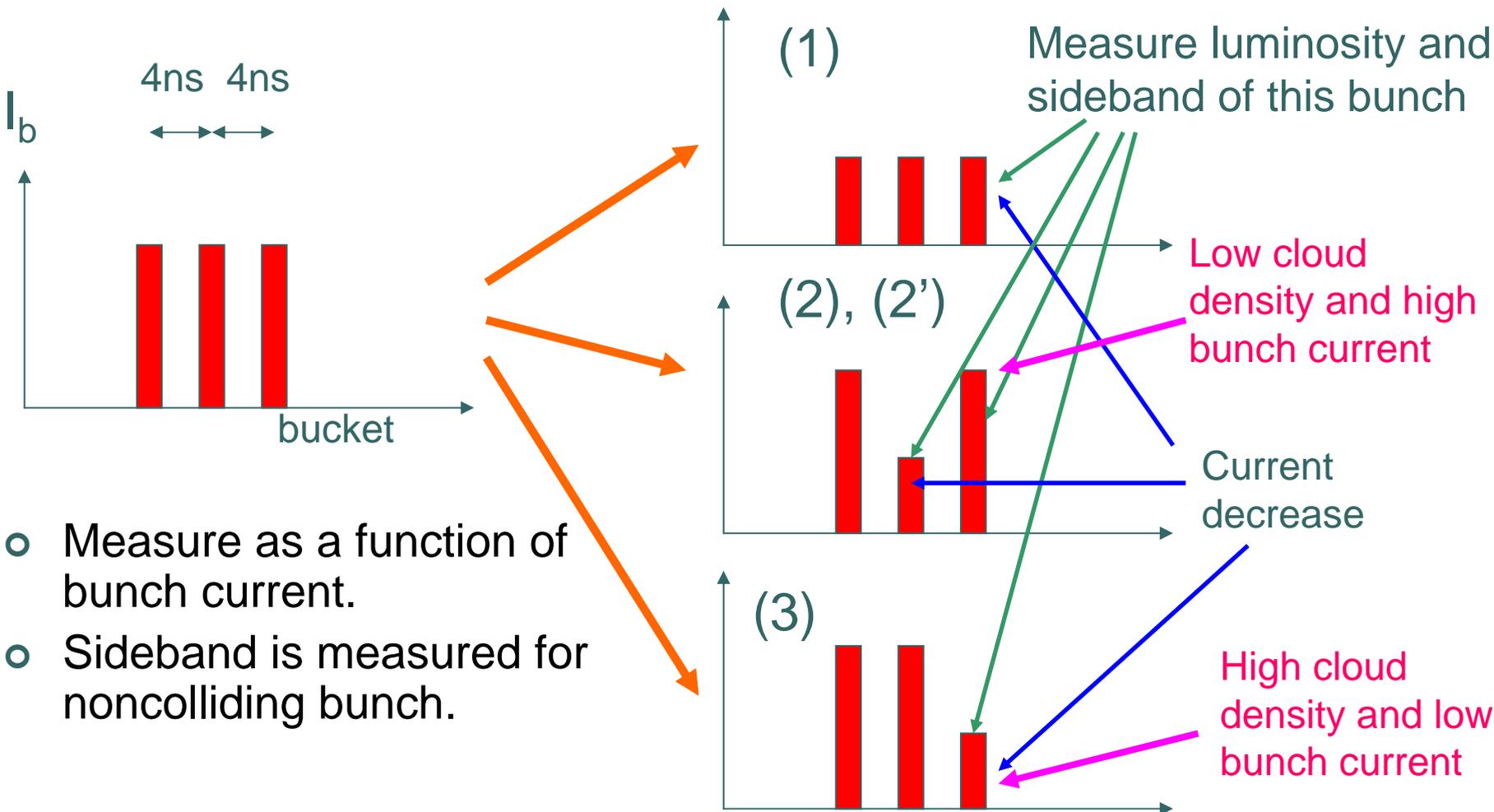
Bunch Spacing vs Spec. Lum.

Normalized, BR-corrected Spec. Lum.



Error bars: statistical, 1-sigma

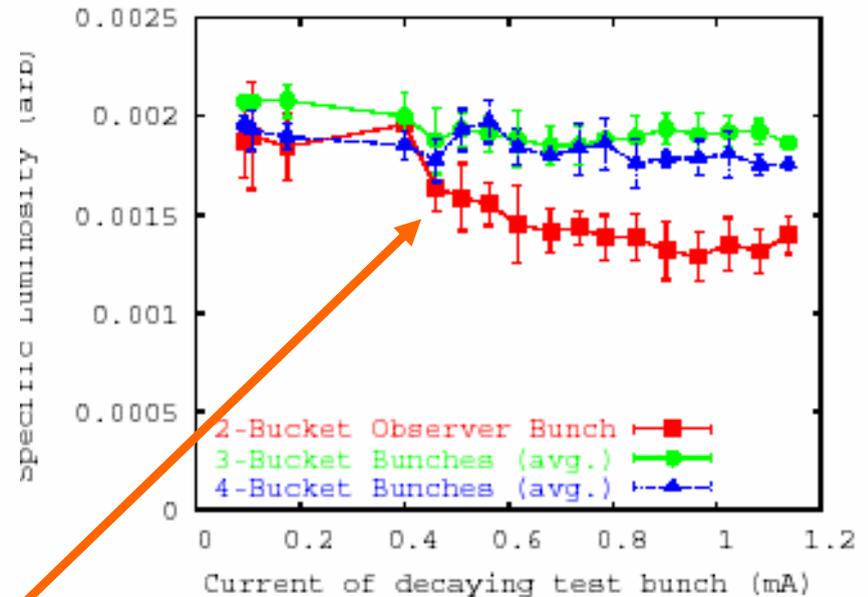
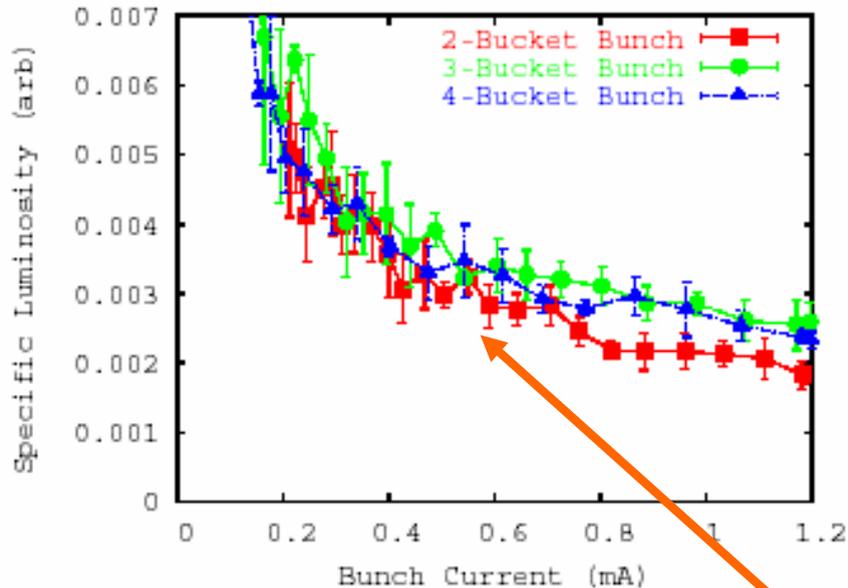
Luminosity-bunch current-sideband experiment



Luminosity degradation coincided with sideband appearance basically.

Type (2)

(2')



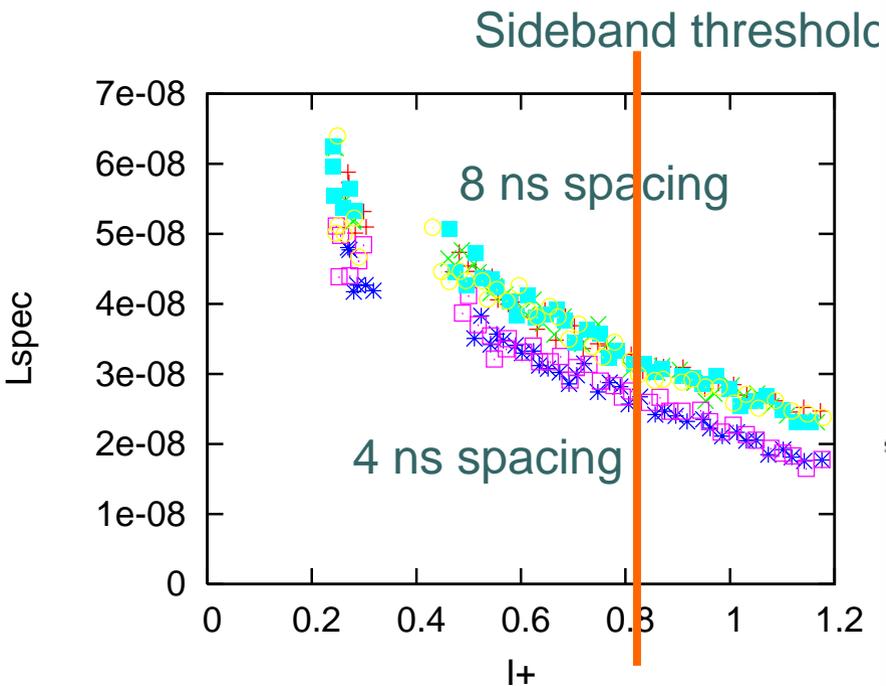
Sideband disappears these current values

Specific luminosity for 4ns spacing is lower below threshold than that for 8 ns depending on measurement method, i.e., high cloud density (2).

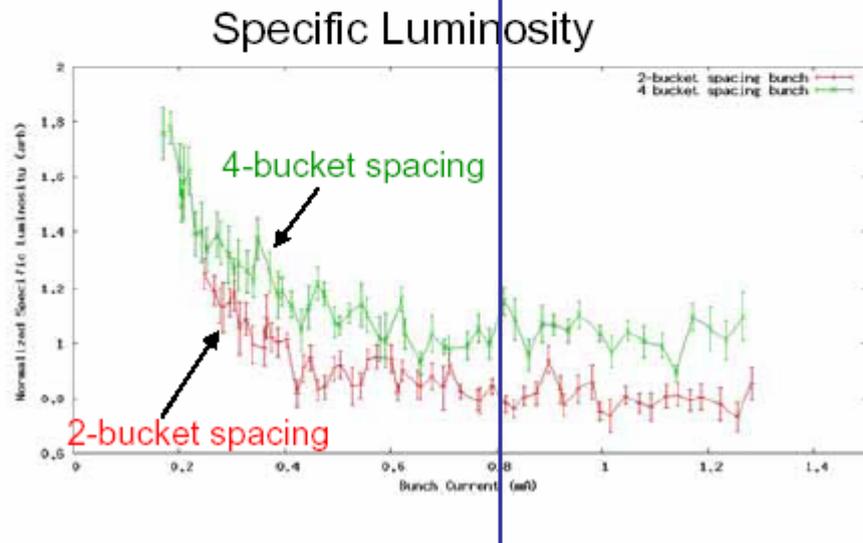
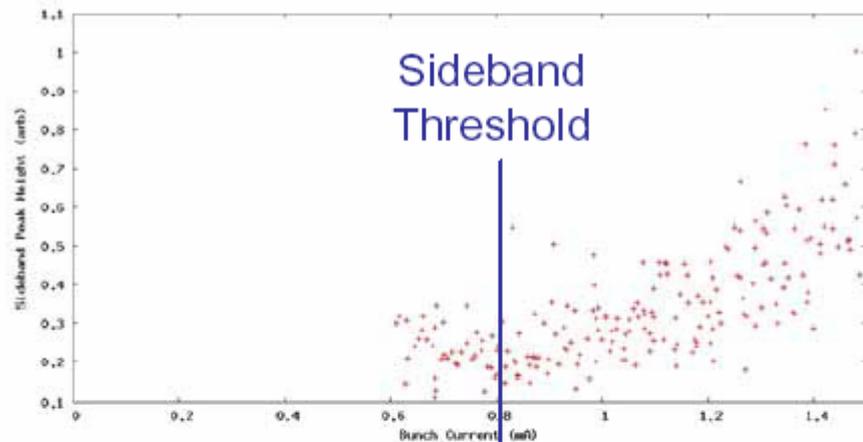
These data may be indication of an incoherent effect of electron cloud, or coupled effect with beam-beam.

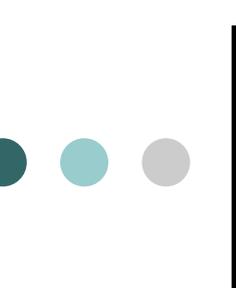
Luminosity degradation is seen below the threshold for type (1) and (3) measurement

○ Type (1)



Type (3)
Sideband Peak Height





Summary

- Electron cloud effect has been studied during KEKB commissioning.
- Coupled bunch instability (CBI), which was due to electron cloud, was observed at KEK-PF, BEPC and KEKB.
- Simulations can explain mode spectra and growth rate for solenoid ON/OFF.
- We observe CBI mode characterized by solenoid magnets clearly., i.e., electrons in solenoid is dominant more than those in bending magnet in KEKB, as long as we observe CBI.
- Beam-size blow-up in multi-bunch operation had been observed had degraded their luminosity.

- 
- The size blow-up is caused by strong head-tail instability due to electron cloud. Coherent synchrotron sideband signal has been observed above a threshold which changes for solenoid ON/OFF.
 - Solenoid magnets wound around whole ring recovered the luminosity degradation.
 - The peak luminosity of KEKB is $1.625 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.
 - Detailed measurements has been continued the bunch by luminosity monitor and sideband measurement.
 - The luminosity degradation coincided with sideband appearance basically, but another incoherent effect (coupled to beam-beam?) is observed.