Discovery and mitigation of the Electron cloud at KEK

K. Ohmi KEK

Accelerator Physics and Technology Seminars

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Contents

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 2^{nd} generation light source operated by both of positron and electron beams. E=2.5 GeV L=186 m, Frf=500MHz.
- Instability was observed at multi-bunch operation of positron beam. N_{bunch}=200-300 for h=312.
- Very low threshold. I~15-20mA.
- 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

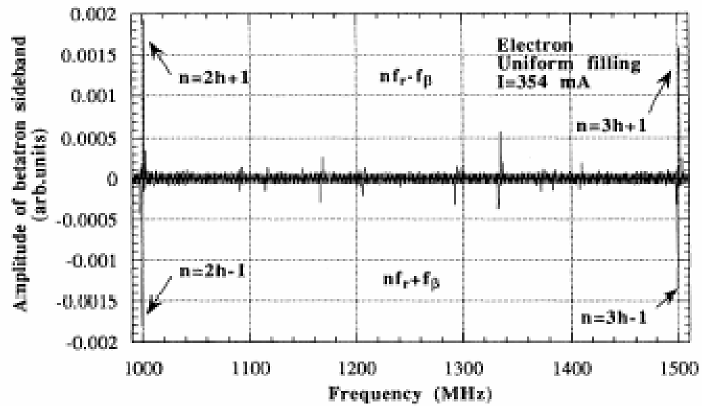


FIG. 1. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling.

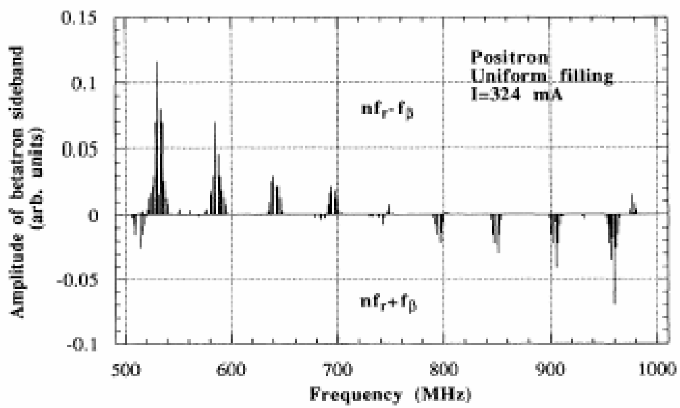


FIG. 2. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling.

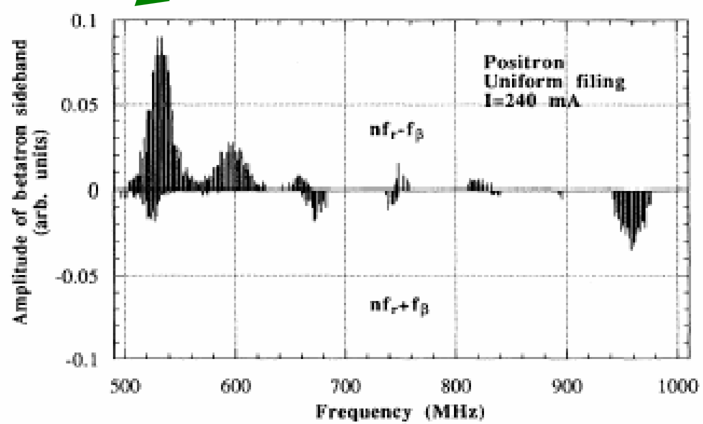


FIG. 3. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling. Only the stored current is different from Fig. 2.

Interpretation of instability due to photo-electron cloud

- Positron beam emits synchrotron radiation.
- Electrons are produced at the chamber wall by photoemission. Production efficiency ~ $0.1e^-/\gamma$.
- 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

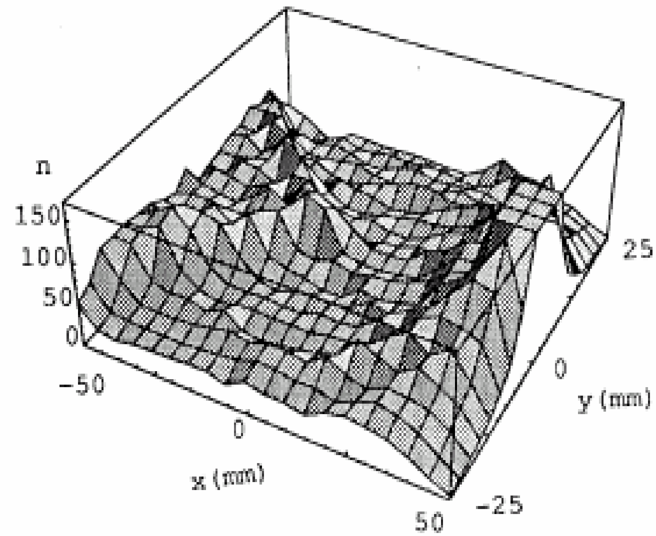


FIG. 2. A stationary distribution of photoelectrons with $\epsilon_0 = 5$ eV.

Photon factory I=100mA

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 2×10^6 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.

PRL,75,1526 (1995)

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

Wake force and unstable mode for KEK-PF

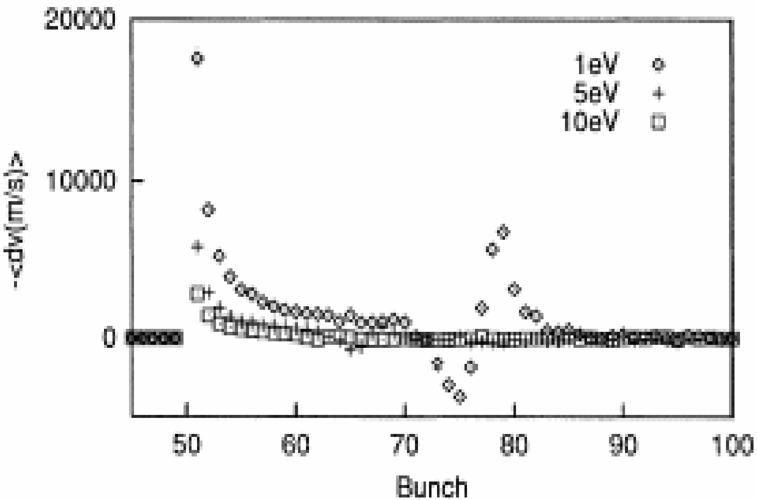


FIG. 3. Wake forces for each initial photoelectron energy. To obtain the wake, 10^6 virtual electrons in every bunch were used.

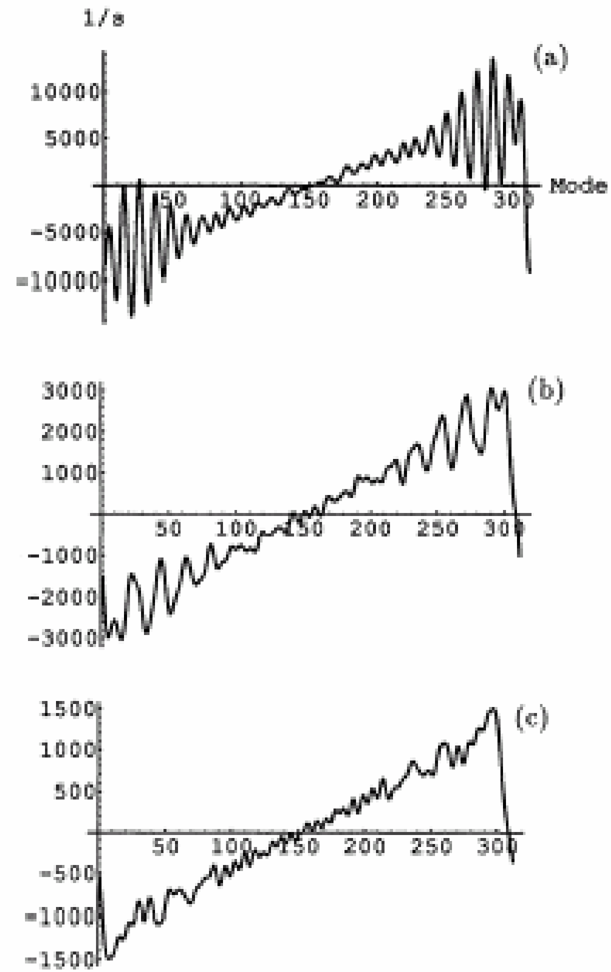


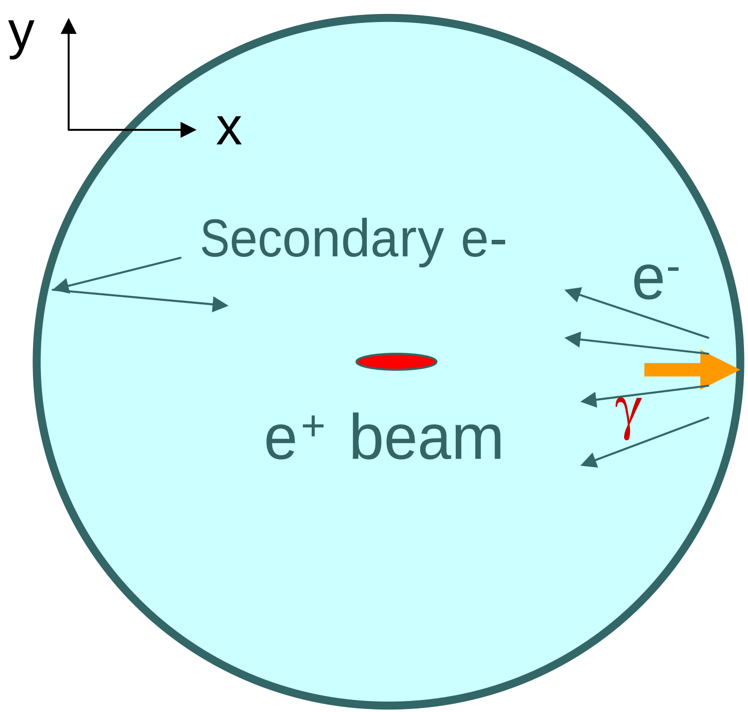
FIG. 4. Growth rates of the coupled-bunch instability. The positive values mean unstable modes. The wakes of 51 to 100 bunches in Fig. 3 were summed with Eq. (8). (a) $\epsilon_0 = 1$ eV. (b) $\epsilon_0 = 5$ eV. (c) $\epsilon_0 = 10$ eV.

Very fast growth of the coupled bunch instability was explained.

K.Ohmi, PRL,75,1526 (1995)

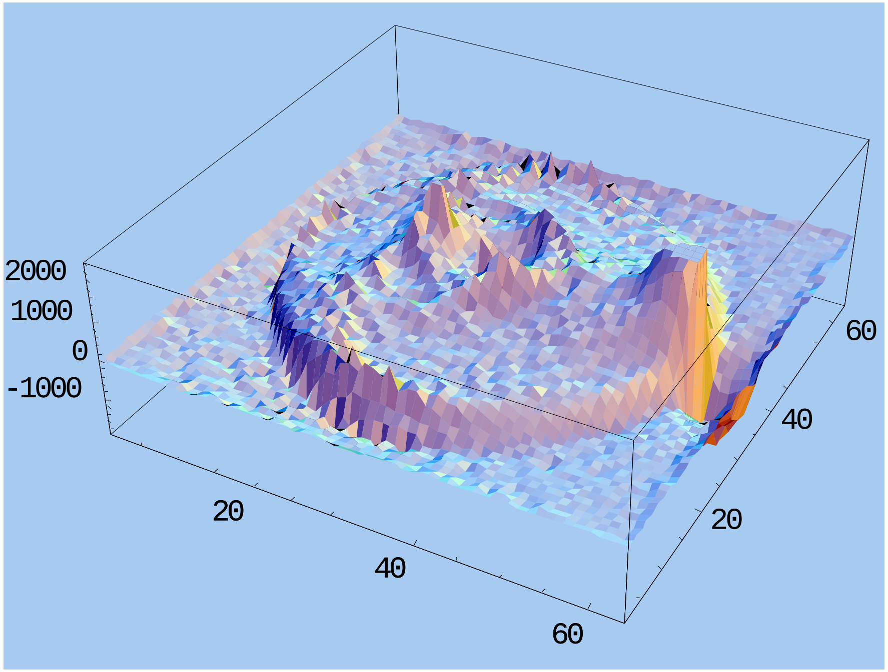
Model and formation of electron cloud by computer simulation

Model



Beam chamber

Electron cloud density



Number of produced electrons

Number of photon emitted by a positron par unit meter.

$$Y_\gamma = \frac{5\pi}{\sqrt{3}} \frac{\alpha\gamma}{L}$$

α : fine structure const=1/137

- KEKB-LER γ=6850 → $Y\gamma$=0.15/m
- KEK-PF =4892 → $Y\gamma$=1.7/m

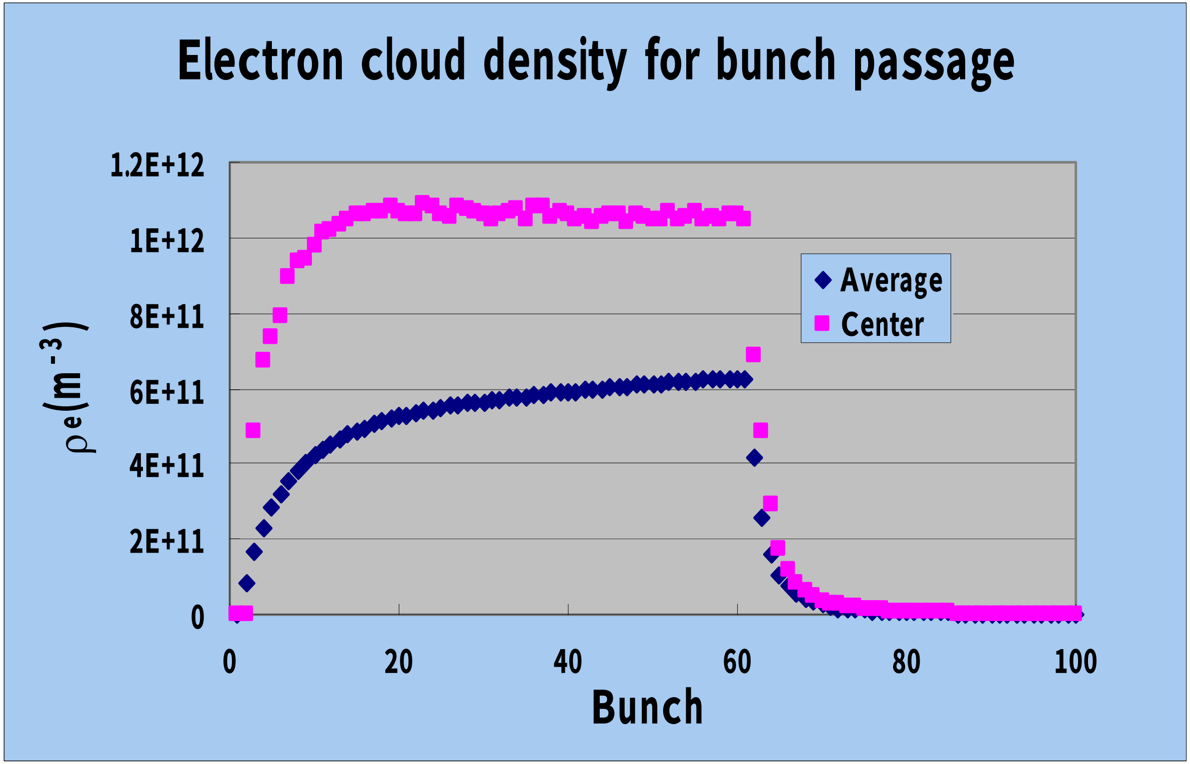
- Bunch population

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

  $N_p=5\text{x}10^{9}$ (KEK-PF 400mA)
- Quantum efficiency ($\eta=n_{p.e.}/n_\gamma$) 0.1
- Energy distribution 10±5 eV

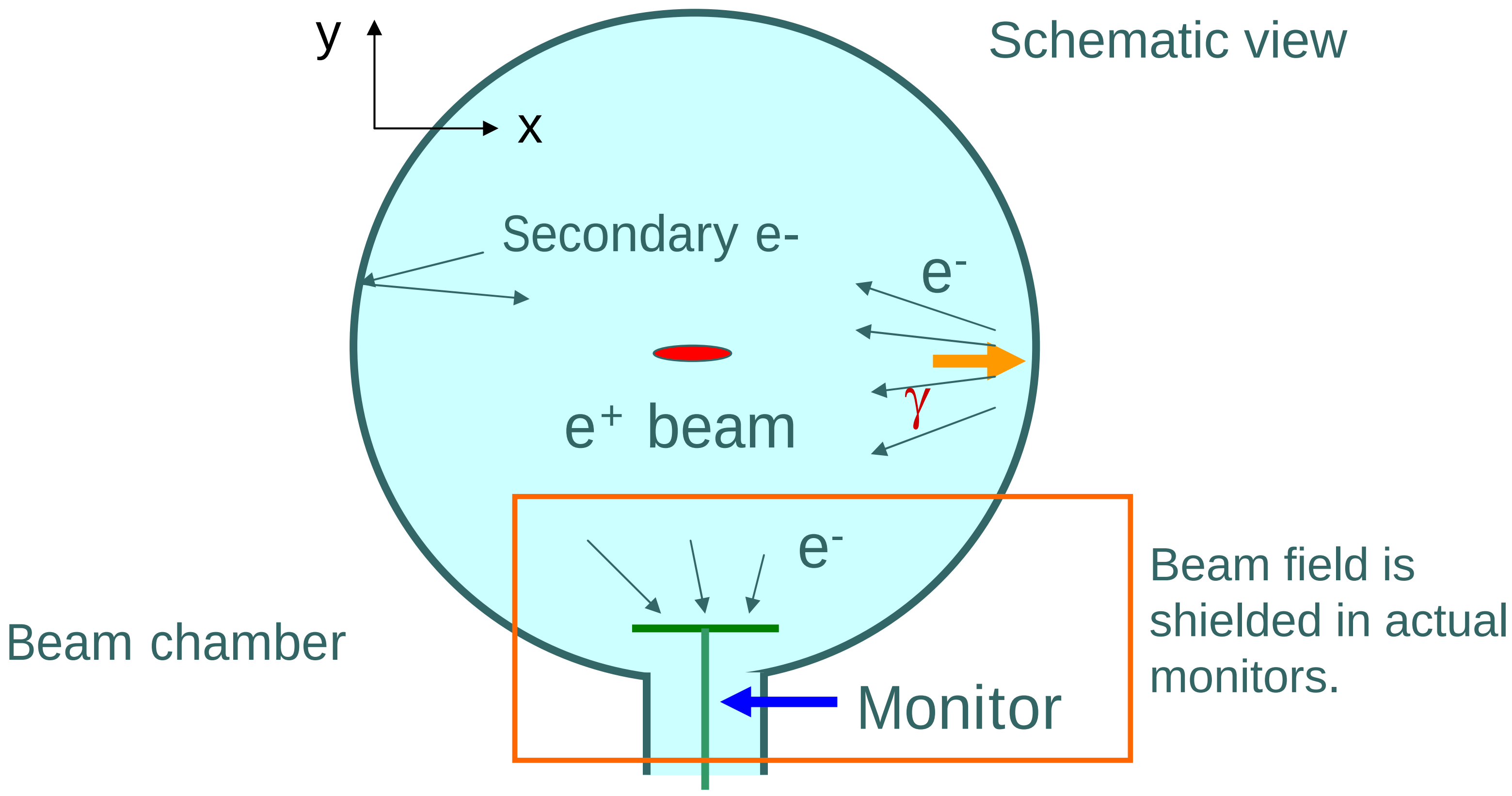
- KEKB-LER $Y_{p.e.}$=0.015 $e^-/m.e^+$
- KEK-PF $Y_{p.e.}$=0.17 $e^-/m.e^+$,
- ionization 10^{-8} $e^-/m.e^+$, proton loss(PSR) $4\text{x}10^{-6}$ $e^-/m.p$

Electron cloud density given by simulation



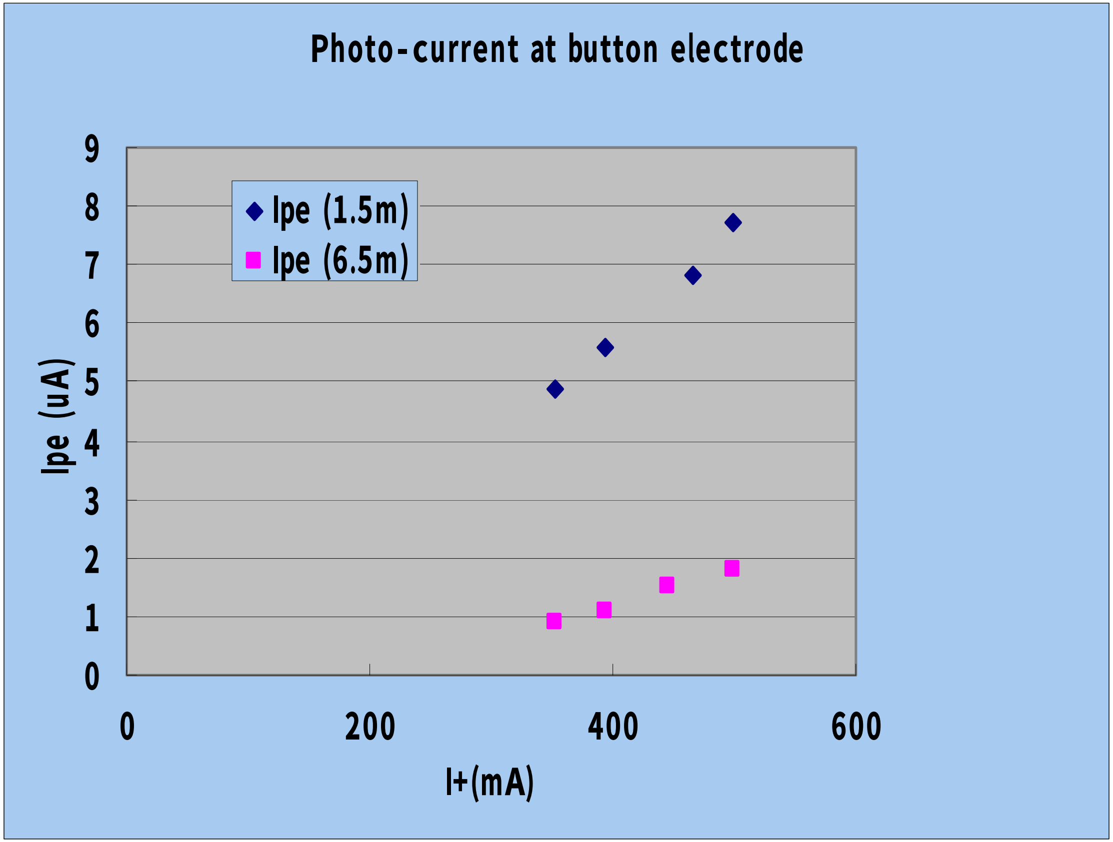
60 bunches pass in every 8ns (KEKB).

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



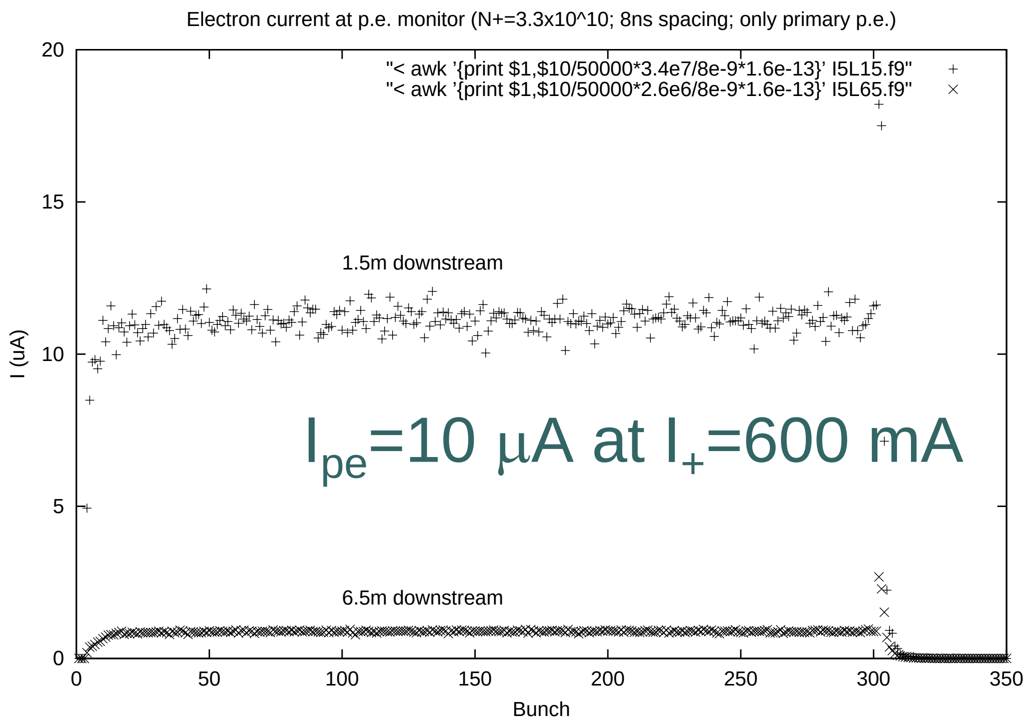
Experimental results

I_{pe}=10 μA at I_+=600 mA



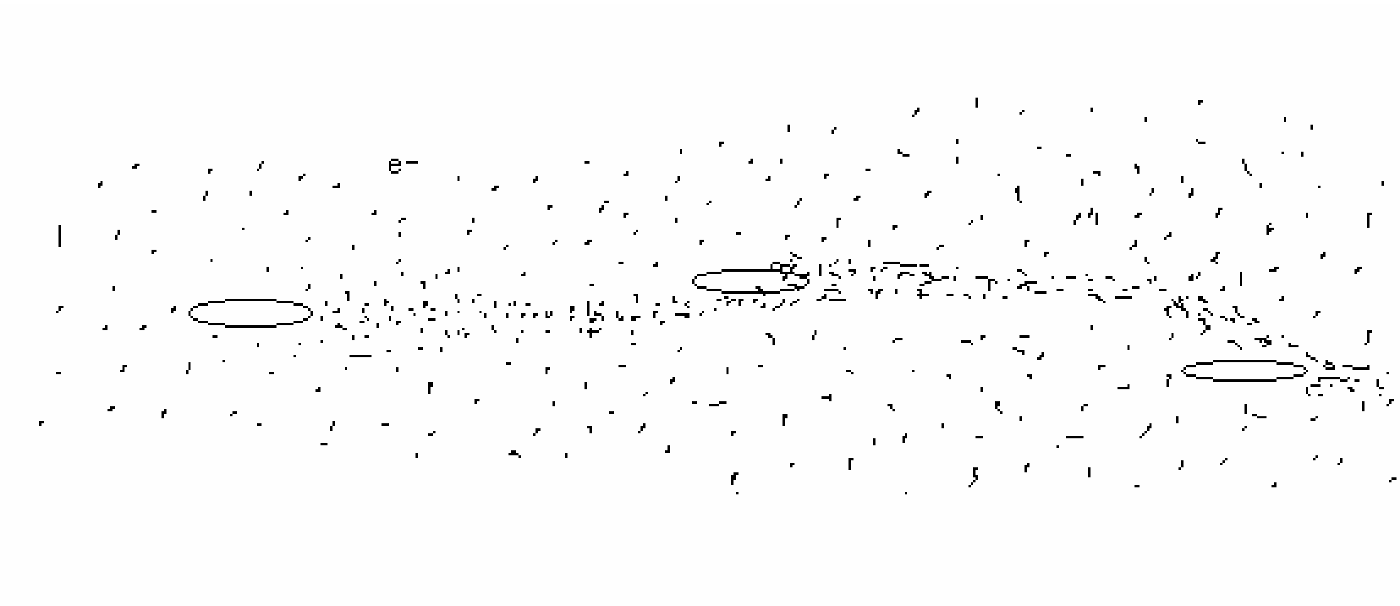
Simulation of the measurement

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



I_{pe}=10 μA at I_{+}=600 mA

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



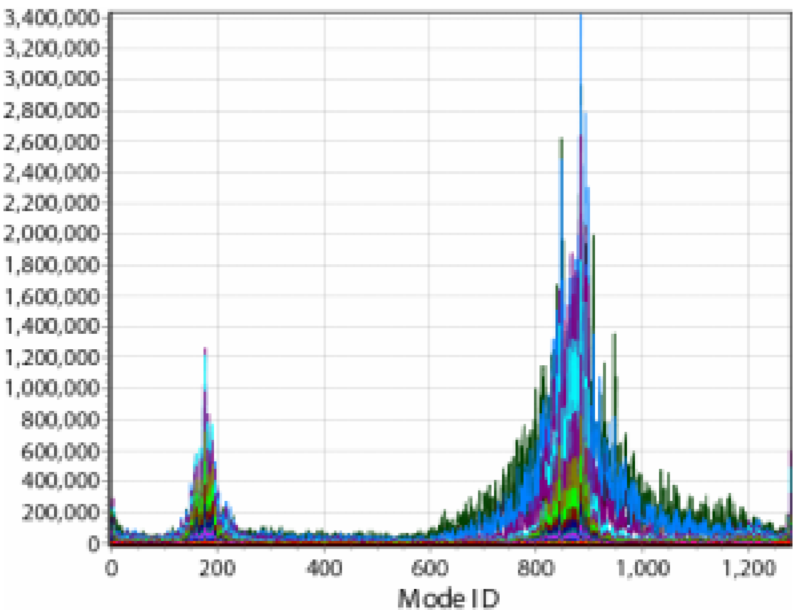
- Wake field is induced by the electron cloud
- Coupled bunch instability due to the wake field causes beam loss.

Measurement of the coupled bunch instability in KEKB

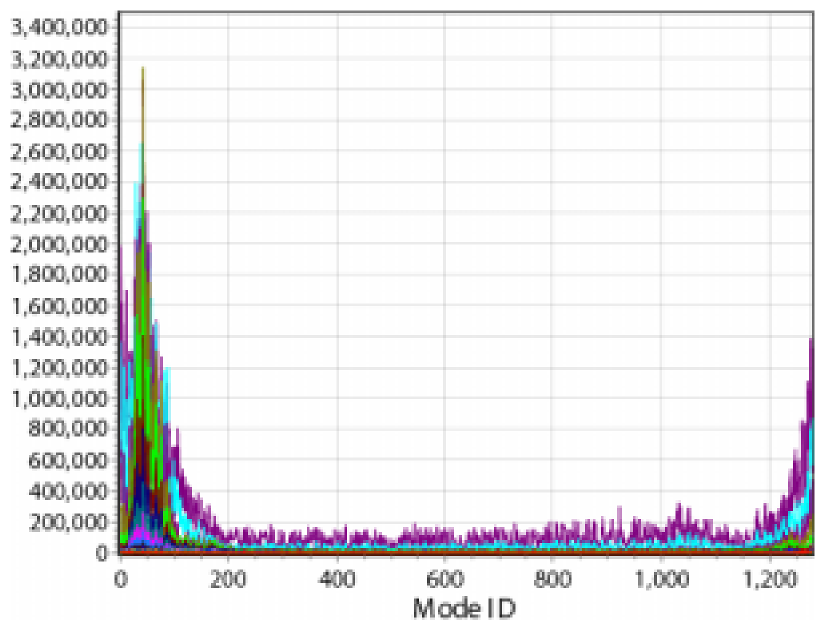
- Fast amplitude growth which causes beam loss has been observed.
- The mode spectrum of the instability depends on excitation of solenoid magnets.

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

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

$W(z_n\text{-}z_m)$： 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. 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.

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

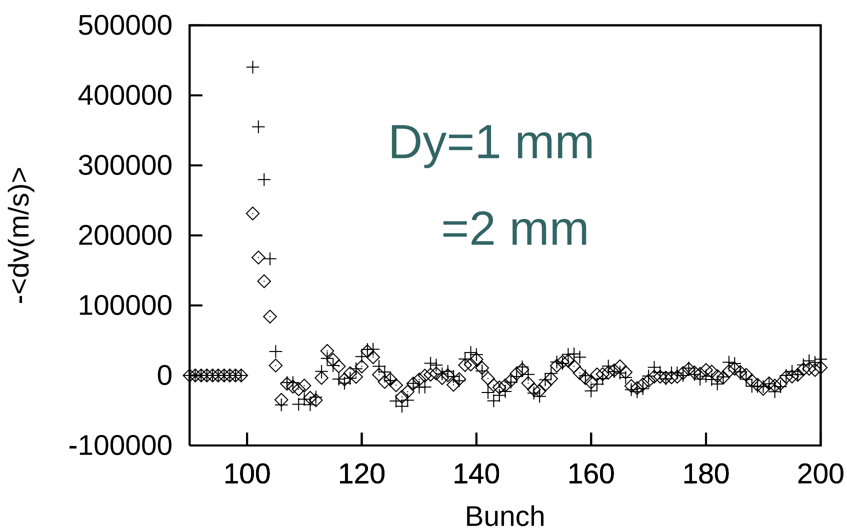
$$\Omega_m - \omega_\beta = \frac{N_p r_e c}{2\gamma T_0 \omega_\beta} \sum_{n=1}^{n_0} W\left(\frac{n}{h} L\right) \exp\left(2\pi i n \frac{m+\nu_y}{h}\right)$$

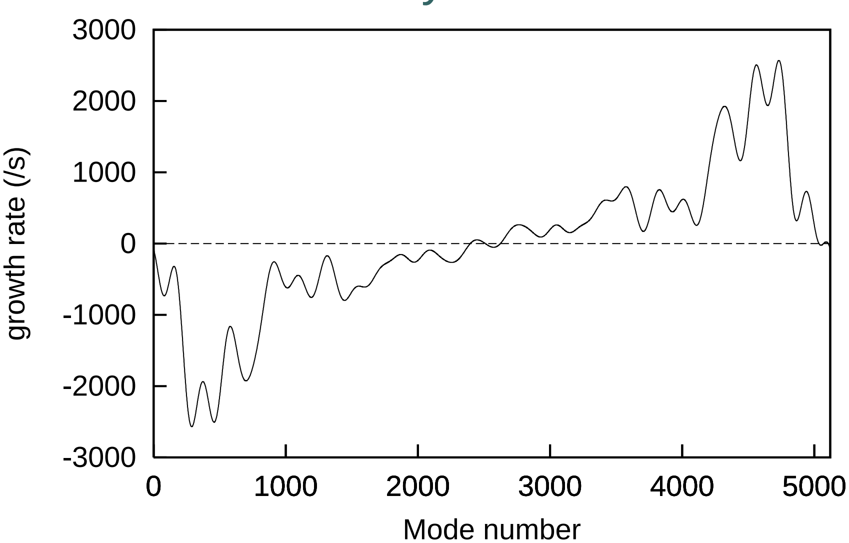
Imaginary part of Ω：growth rate of the instability

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.





KEKB design report (1996 or 7)

Tracking simulation

K.Ohmi, PRE55,7550 (1997)

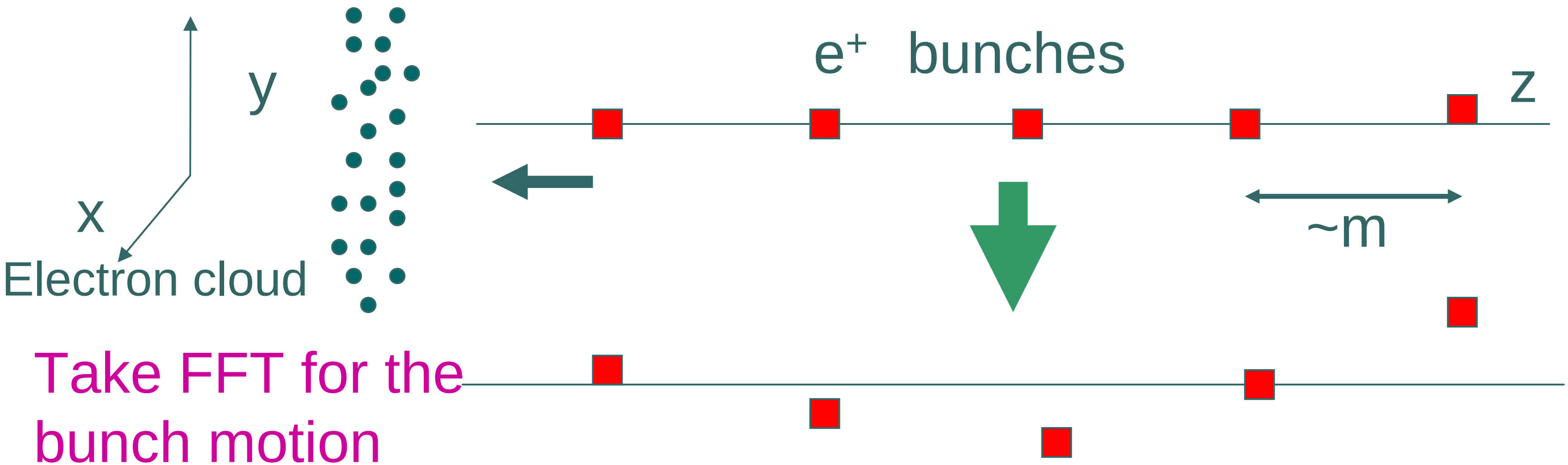
K.Ohmi, PAC97, pp1667.

Solve both equations of beam and electrons simultaneously

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

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

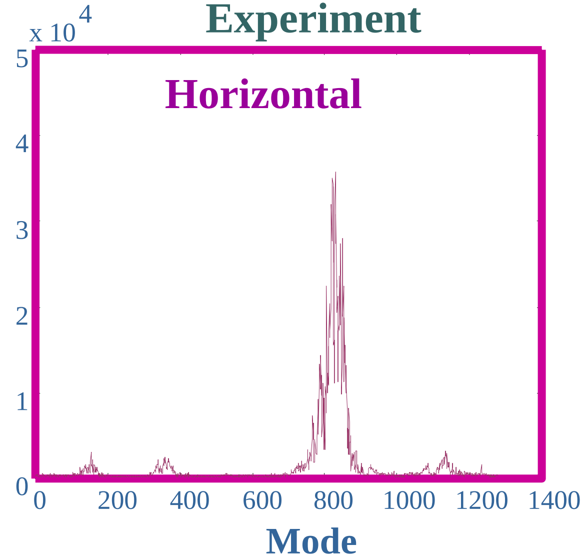
$$-r_e c^2\frac{\partial\phi(\mathbf{x}_{e,a})}{\partial\mathbf{x}_{e,a}} \qquad (2)$$

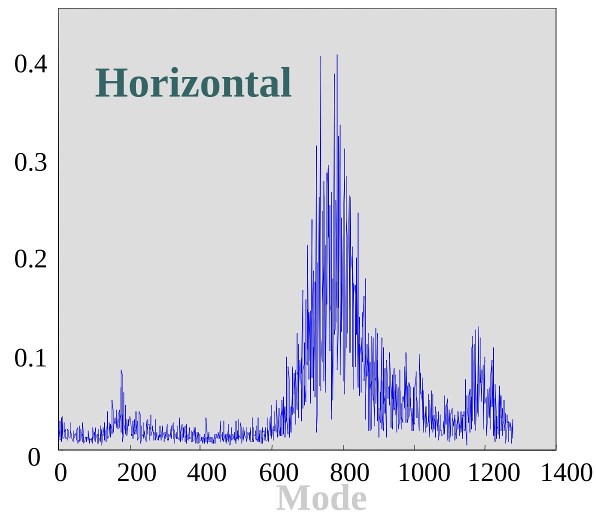


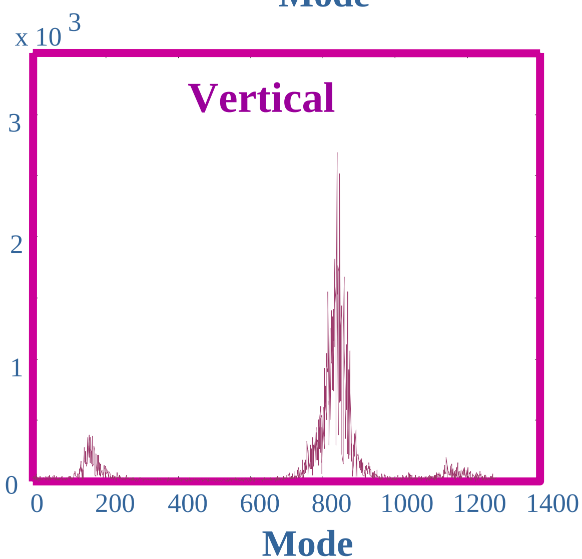
Take FFT for the bunch motion

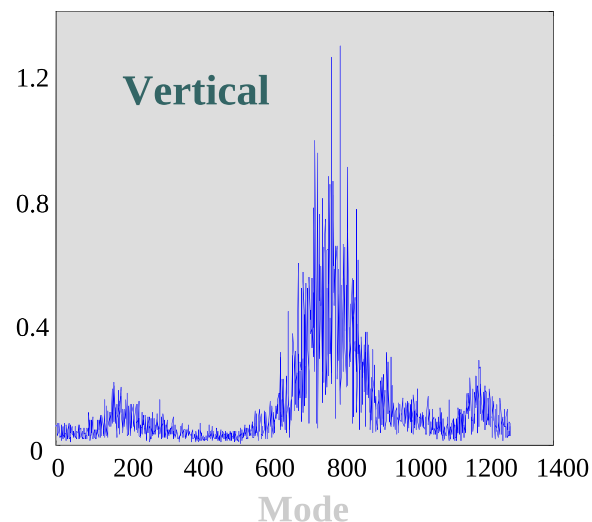
CBI mode spectra in KEKB **Solenoid-Off**

Experiment | **Simulation**









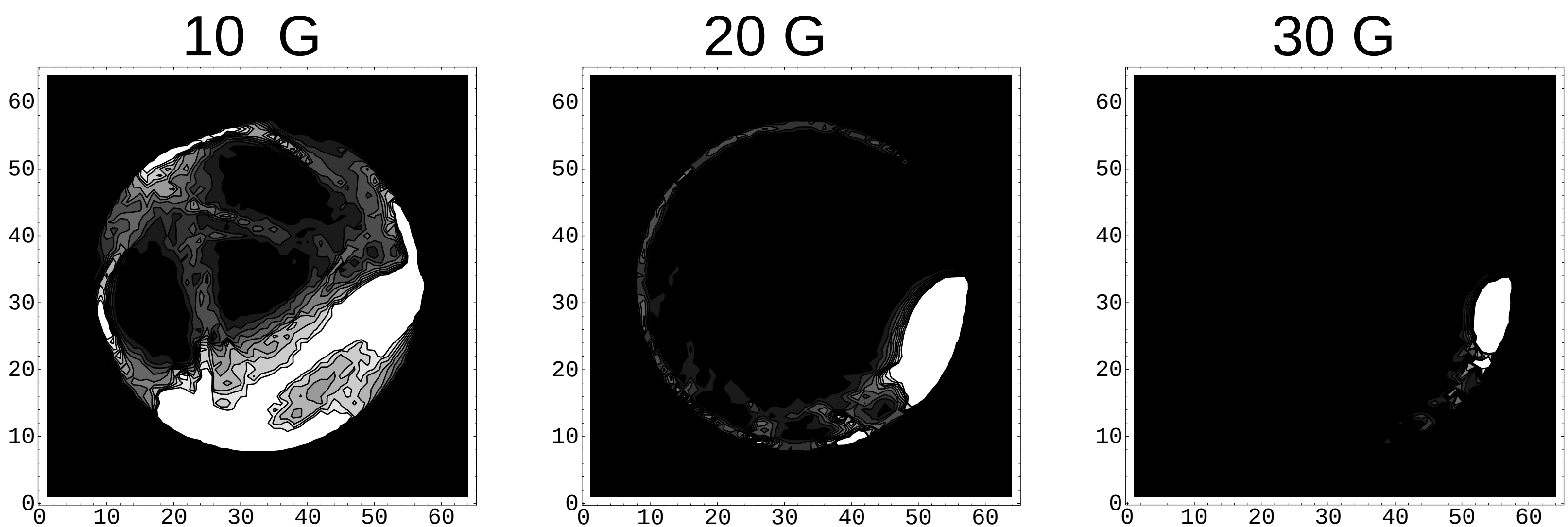
Bunches are filled every 4 bucket.

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

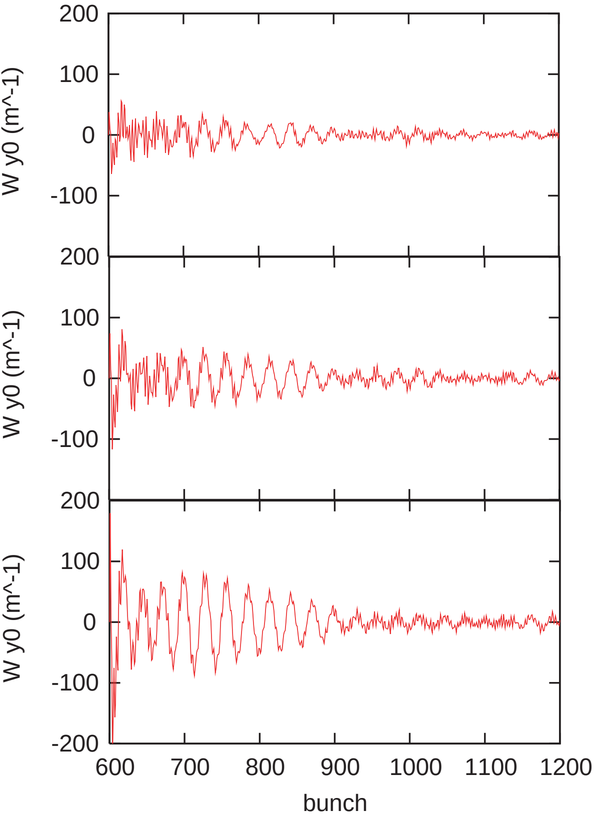
- Cloud distribution (K. Ohmi, APAC98)



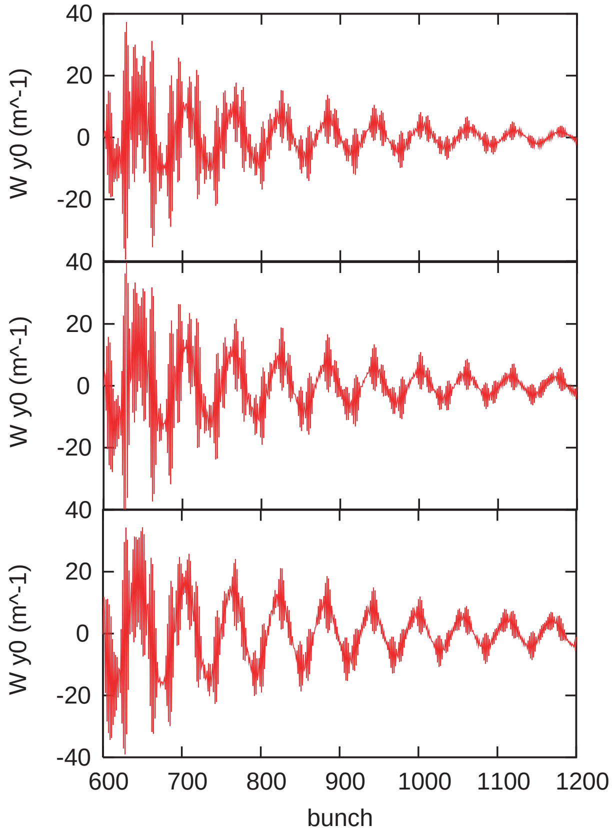
Wake force in weak solenoid field

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

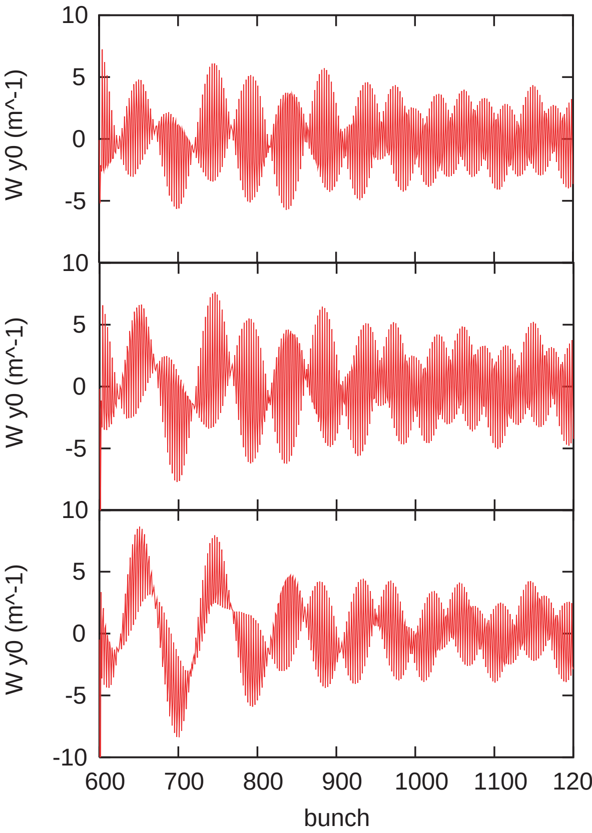
Δy=1(top), 2(middle), 5(bottom) mm



Bz=10G



20 G

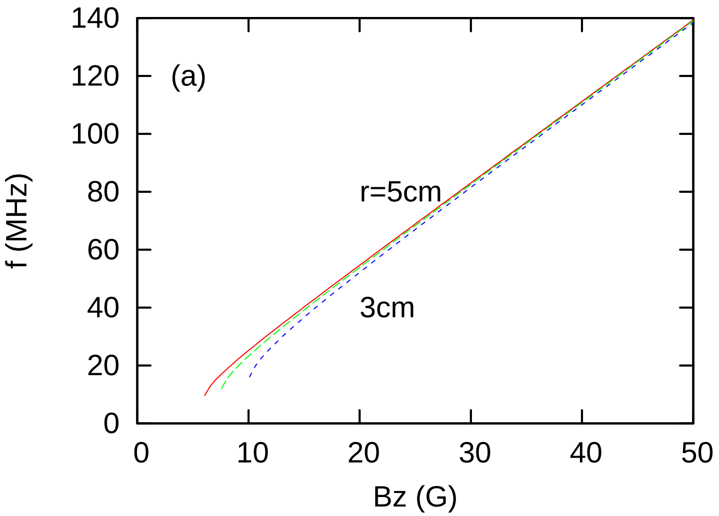


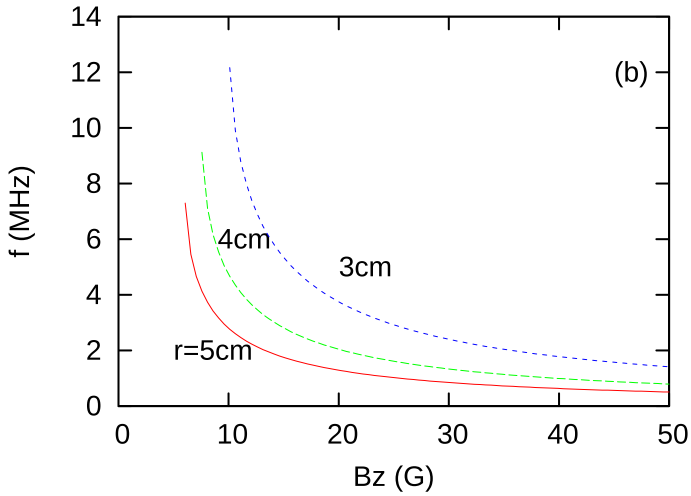
30 G

Electron motion in solenoid magnet

- Two frequency components

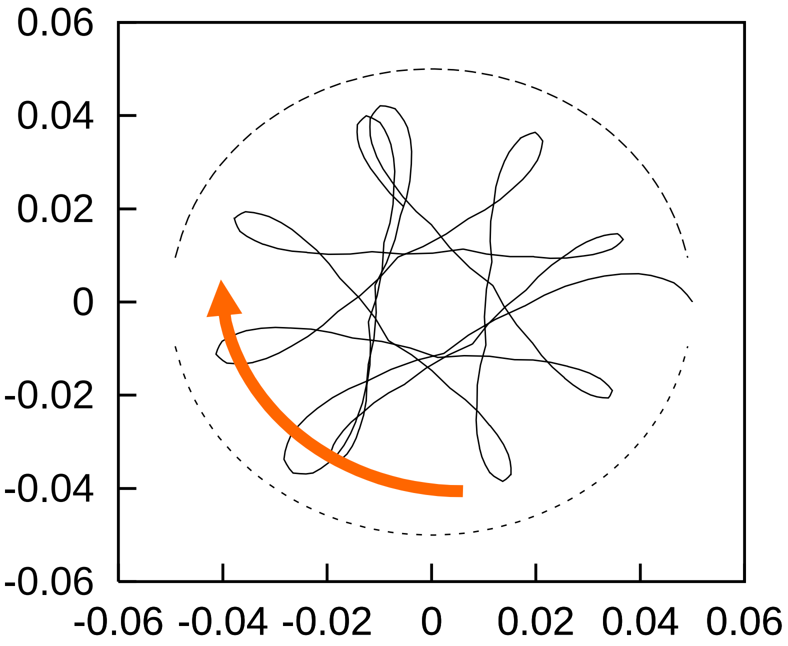
$$\omega_{\pm} = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\lambda_p r_e c^2}{\bar{r}^2}} \quad \text{where} \quad \omega_c = \frac{eB}{m_e}$$





$\sim\omega_c$ $\ll \omega_c$

- Example of trapped electron trajectory for Bz=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.

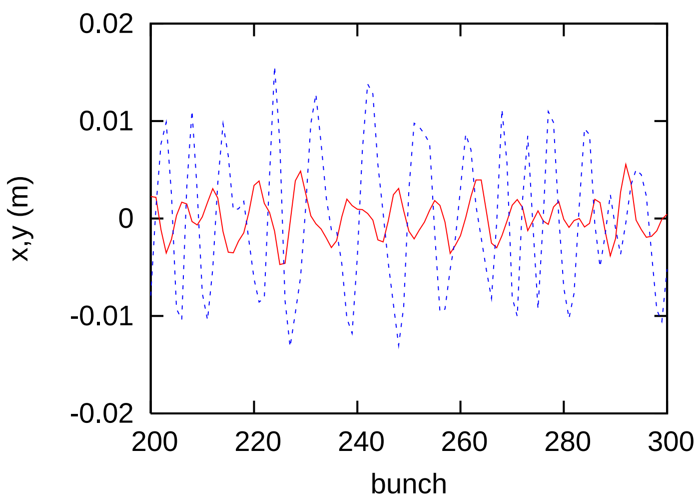
$$\omega = (H - m)\omega_0 - \omega_\beta$$

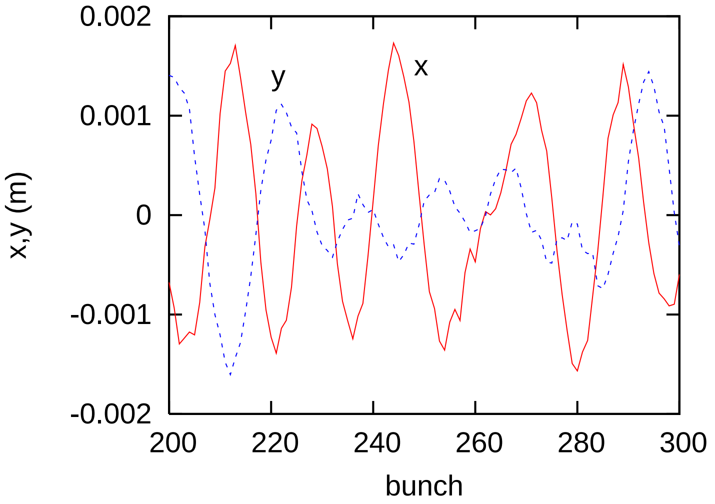
$$\omega = m\omega_0 + \omega_\beta$$

Tracking simulation for CBI due to electron cloud in solenoid magnet

- 0 G, 50-th turn

10 G, 100-th turn

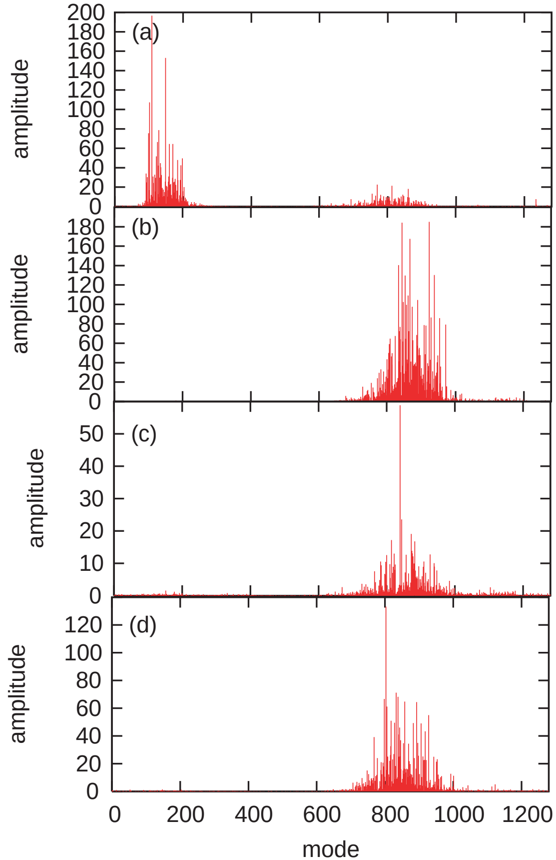




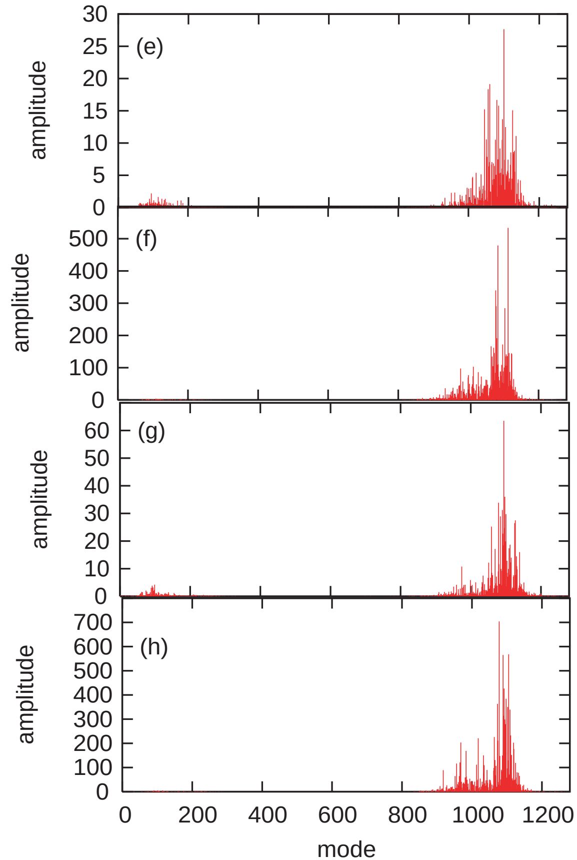
Slow mode

Mode spectra for drift space

Illum. and uniform

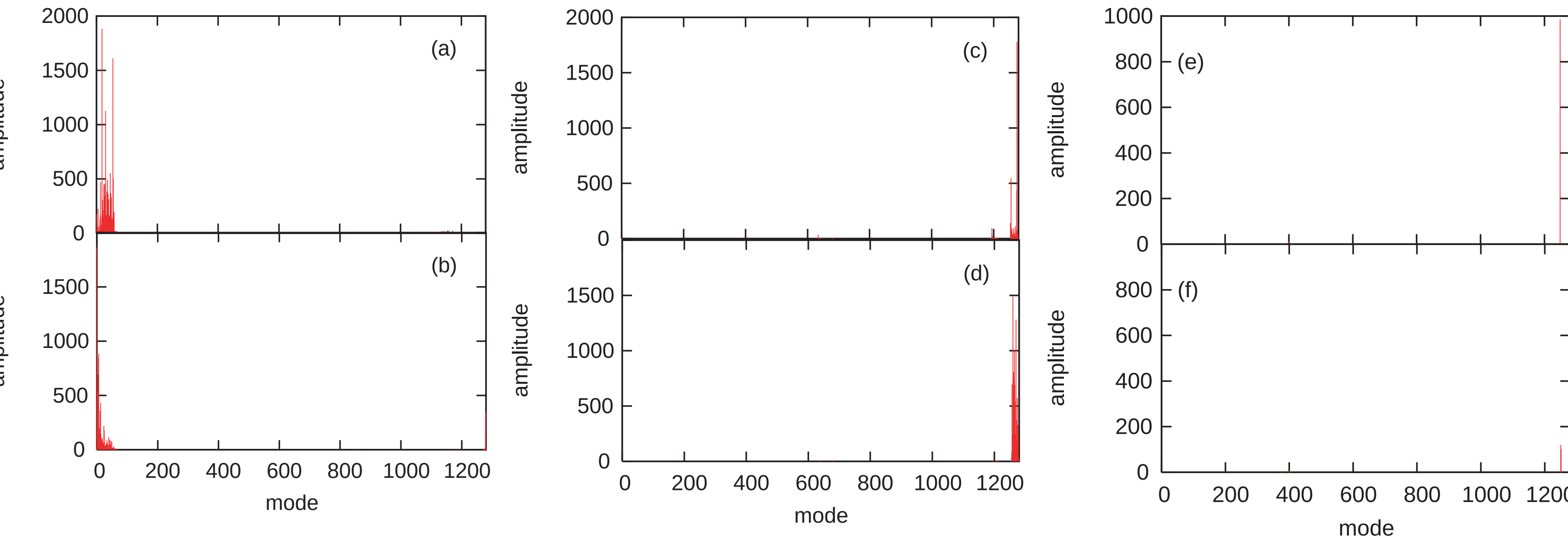


High secondary



Mode spectra in solenoid magnet

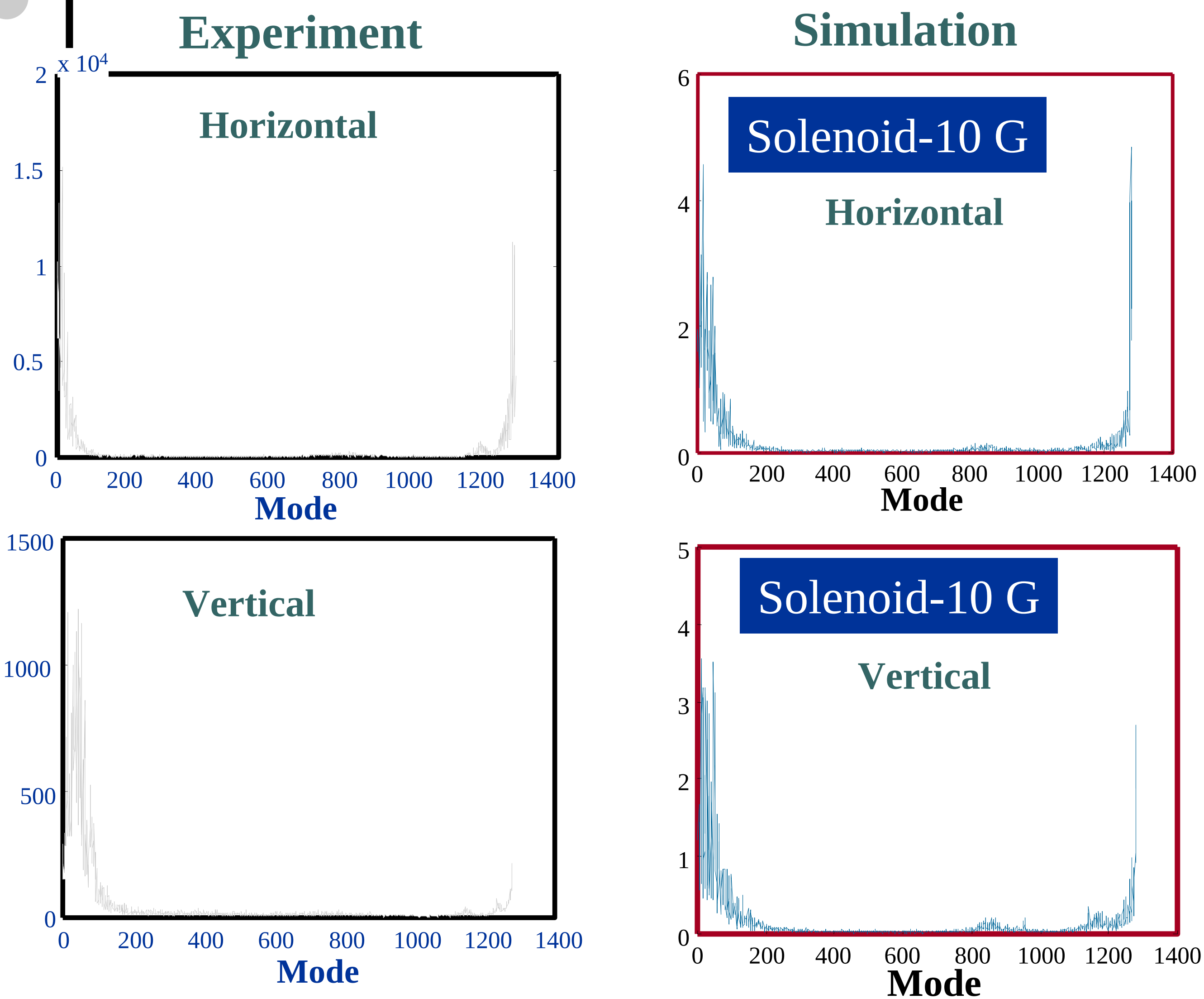
10 G 20 G 30 G



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

KEKB

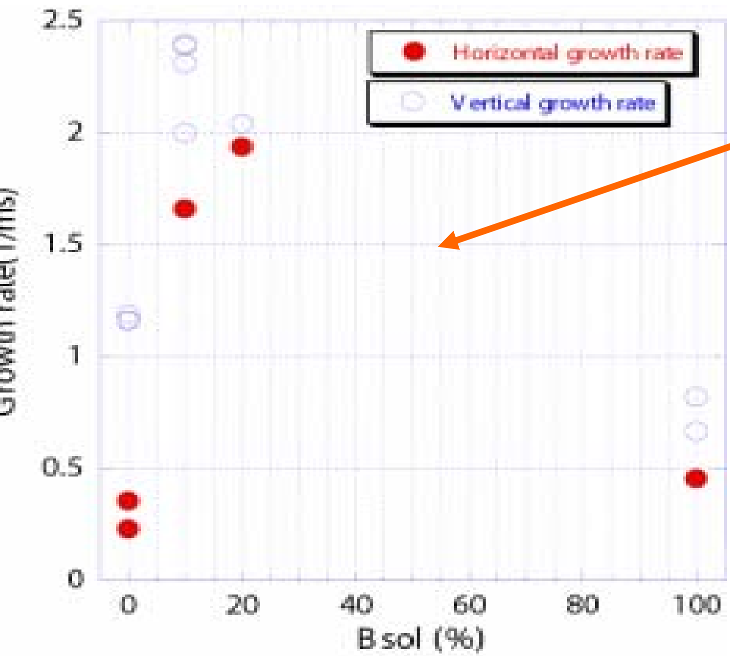
Solenoid-ON

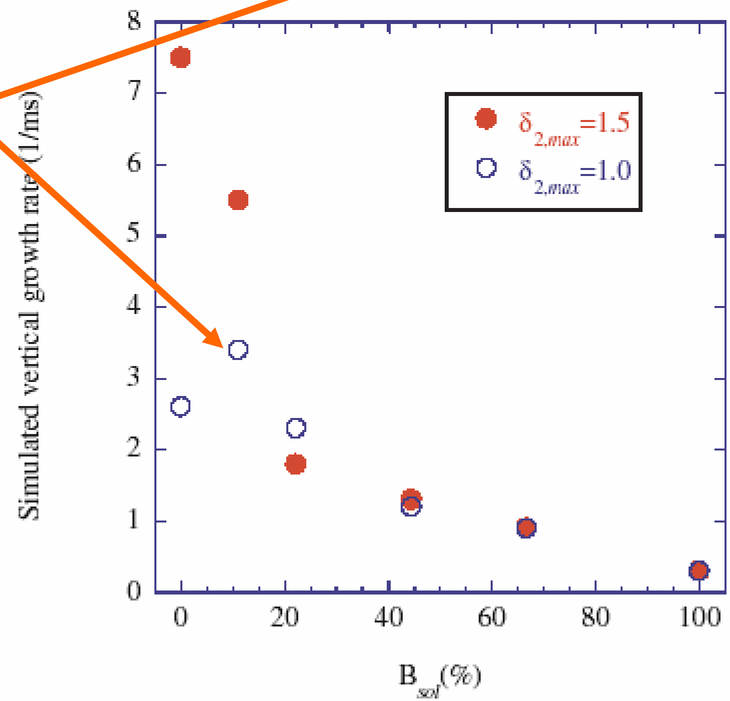


Su Su Win et al., EC2002

Growth rate for solenoid strength

- 600 mA 100%~50 G
- Simulation with δ_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.

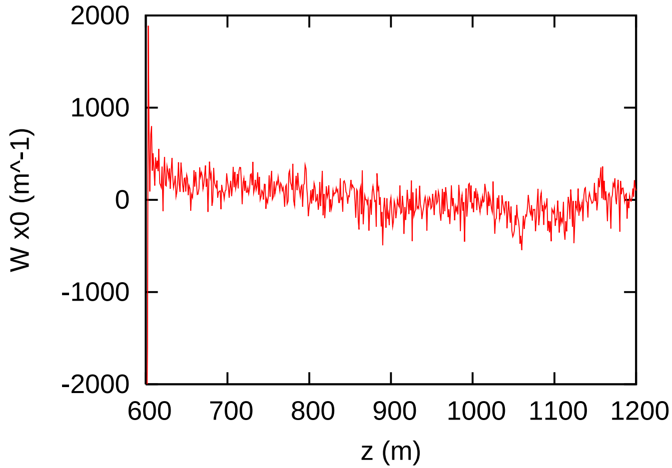
Electron cloud in Bending magnet

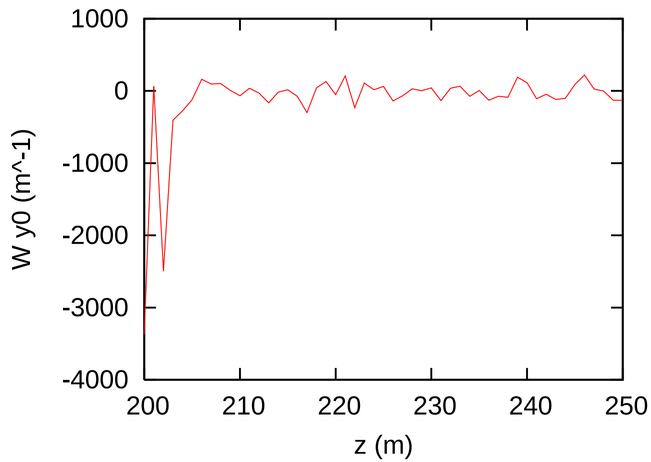
- Strong magnetic field By.
- Electrons move along y direction.

- If electrons are produced illuminated position only, they little affect the beam.
- Here electrons are assumed to be produced uniformly at the chamber.

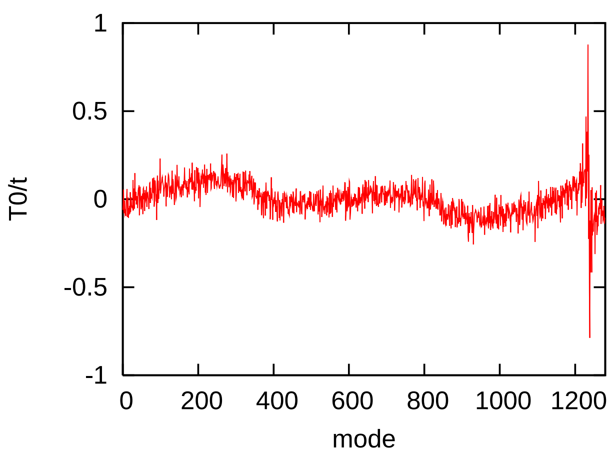
Wake force and growth mode due to electron cloud in bending magnet

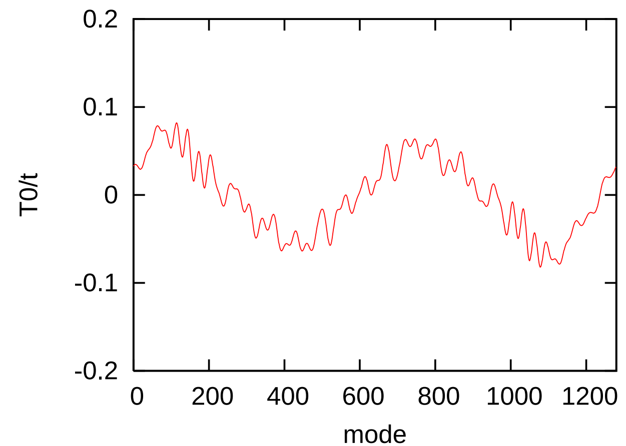
Horizontal Vertical





wake

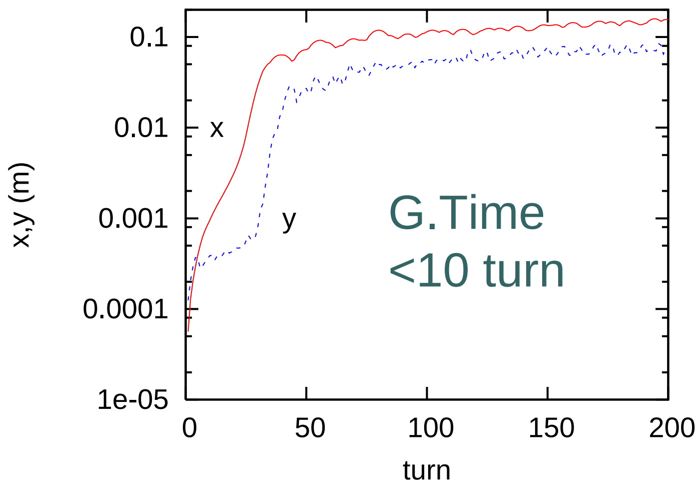


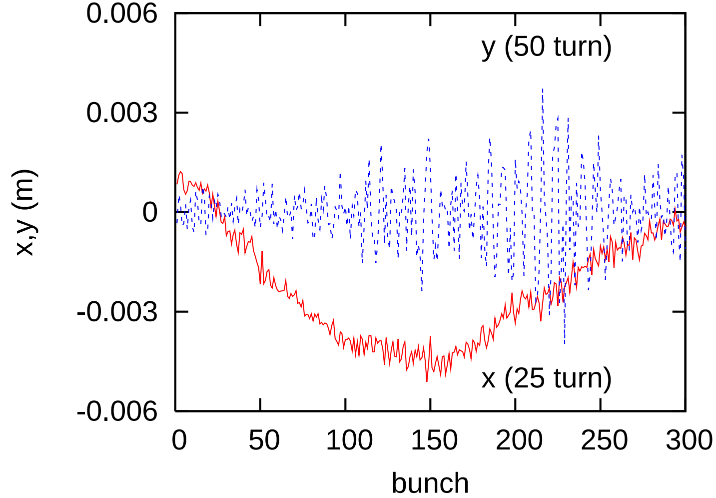


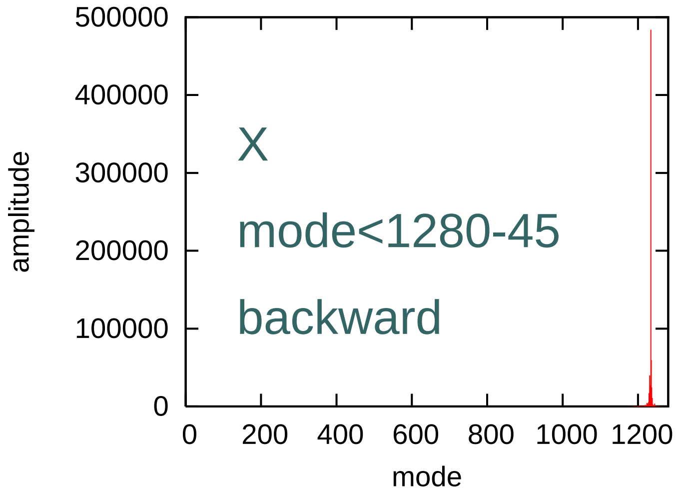
Mode

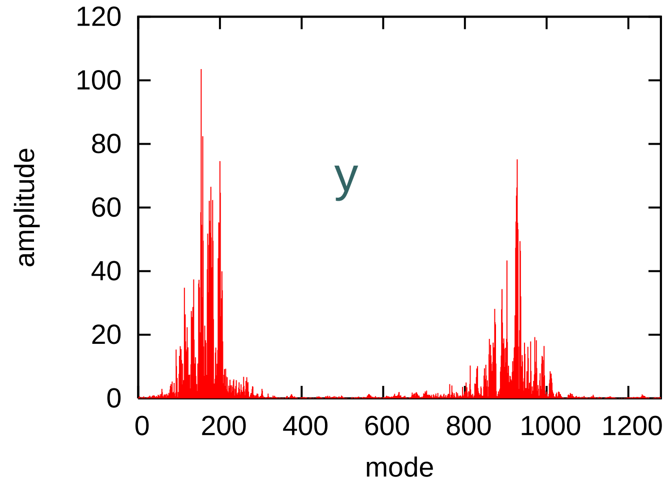
Tracking for CBI in bending magnet

- Growth and mode spectra









We do not observe CBI signal characterized by bending magnet

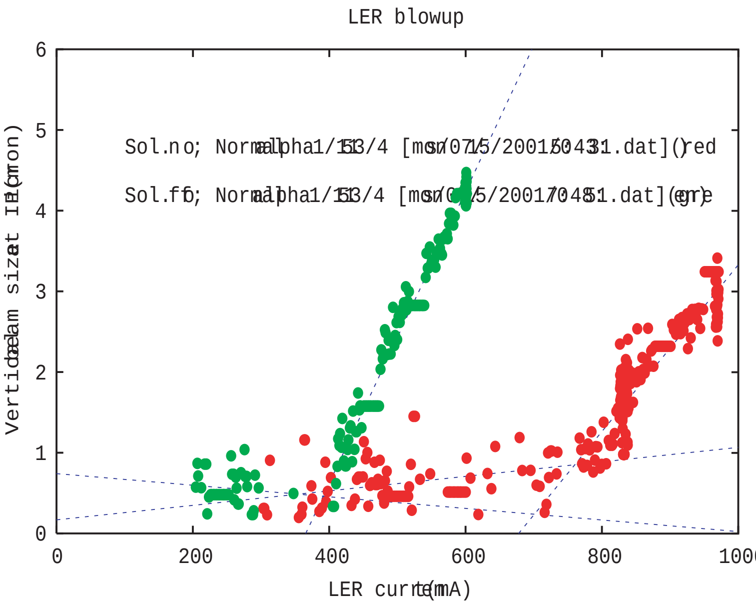
Single bunch instability
Vertical Beam size blow up of positron beam at commissioning of KEKB

- 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.

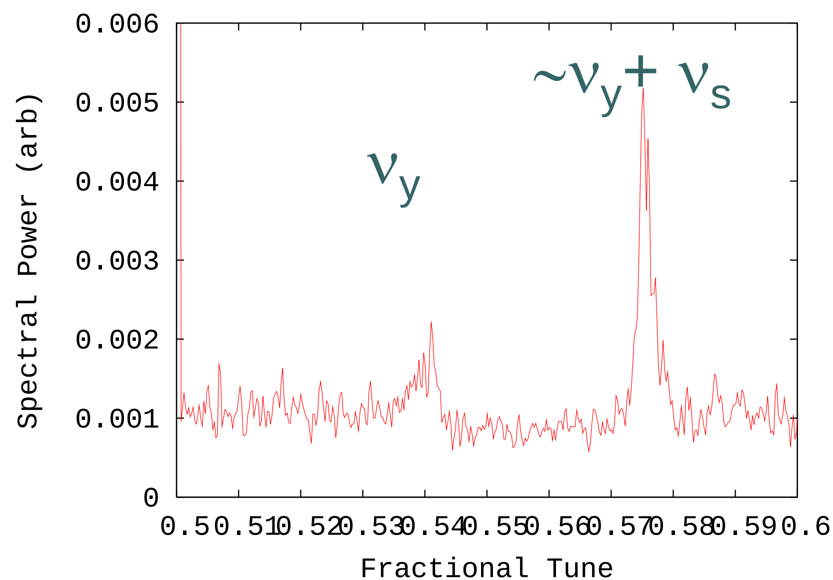
- Synchro-beta sideband induced by electron cloud head-tail instability was observed.

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.

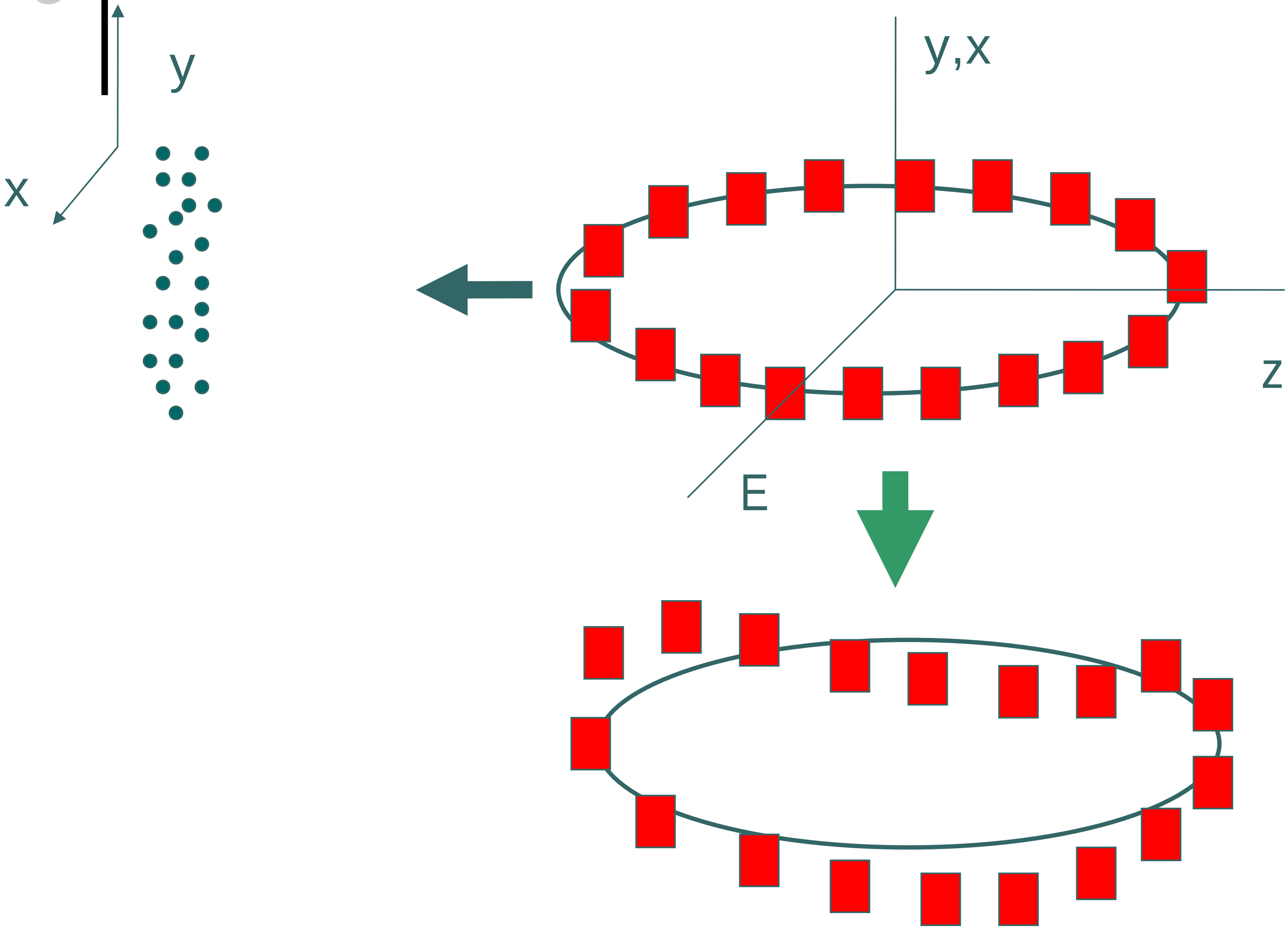
$$\frac{d^2\mathbf{x}_{+,a}}{ds^2} + K(s)\mathbf{x}_{+,a} = \frac{2r_e}{\gamma}\sum_{j=1}^{N_i}\mathbf{F}_G(\mathbf{x}_{+,a} - \mathbf{x}_{e,j}; \sigma(s))\delta(s - s_j)$$

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

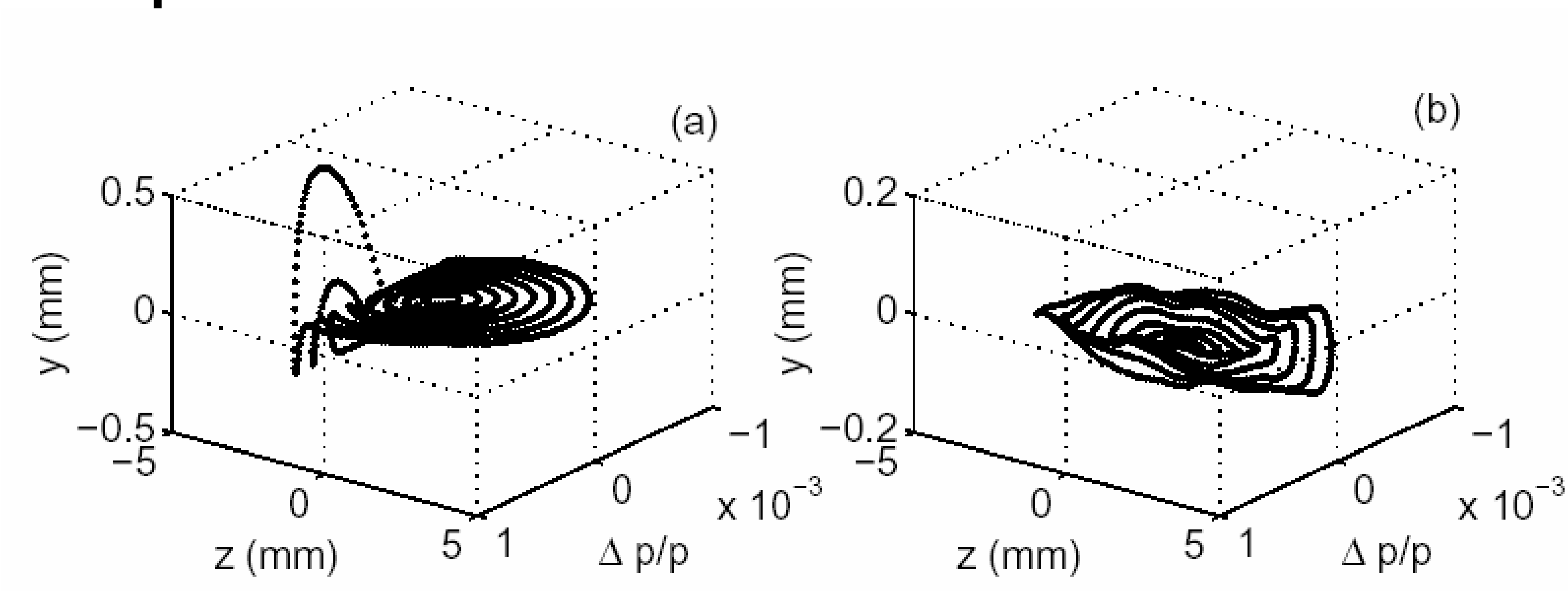
$$F \xrightarrow{x,y\approx\infty} \frac{(y+ix)}{r^2} \qquad F \xrightarrow{x,y\approx 0} \frac{1}{\sigma_x + \sigma_y}\left(\frac{y}{\sigma_y} + i\frac{x}{\sigma_x}\right)$$

Electron cloud

Positron bunch



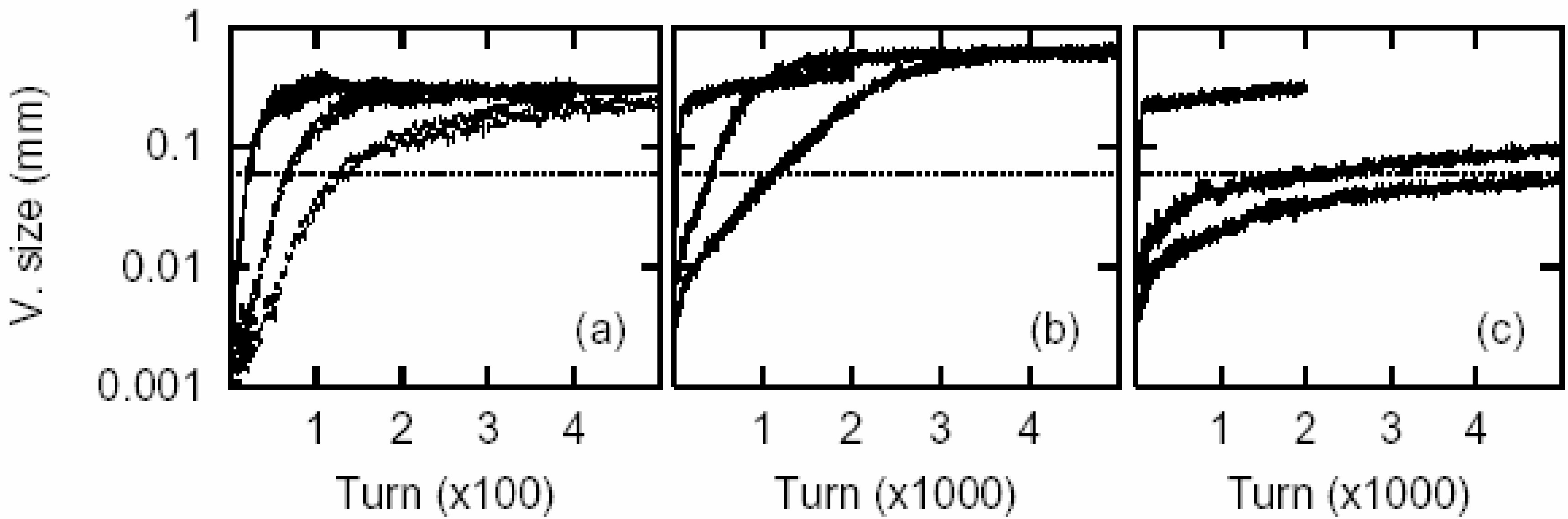
Bunch head-tail motion w/wo synchrotron motion.



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.

K. Ohmi, F. Zimmermann, PRL85, 3821 (2000).

Head-tail and strong head-tail instability



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

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

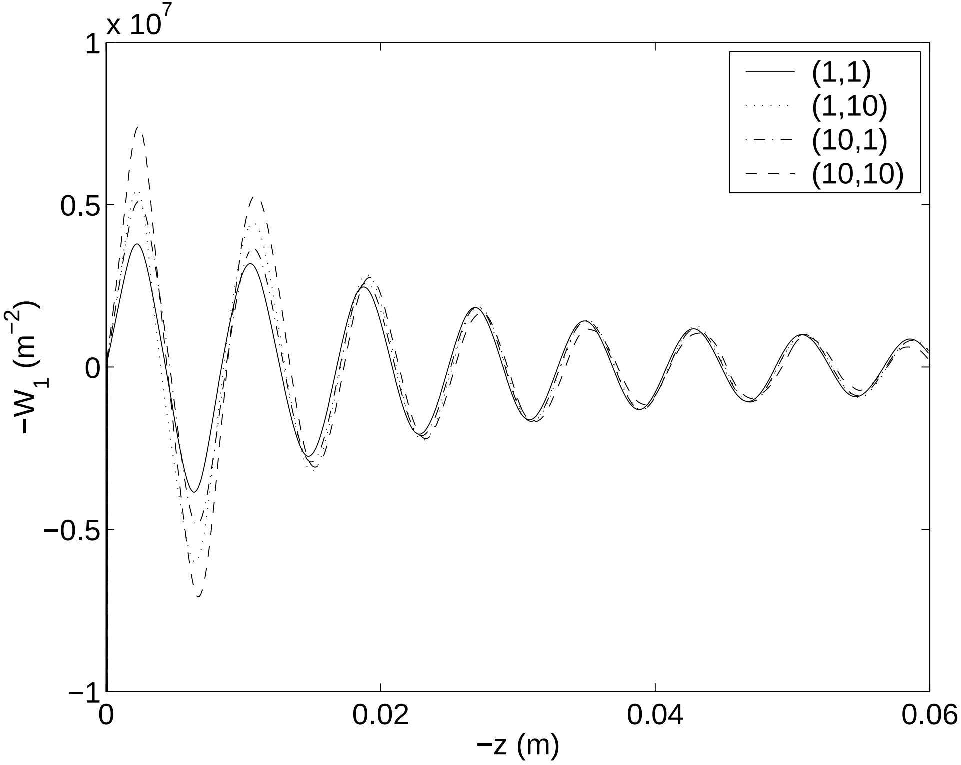
Wake field approach

- 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.

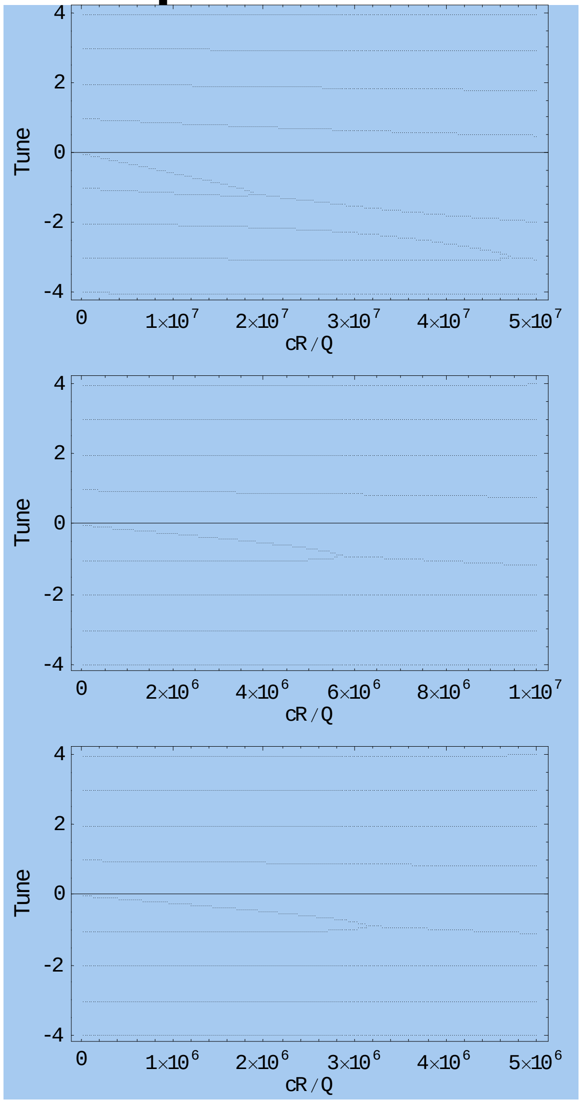
Vertical wake field given by the numerical r



- (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 : $\rho_e = 1\text{-}2\times10^{12}\,\mathrm{m}^{-3}$

- Coasting beam model

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

$Q = \min(Q_{nl},\ \omega_e\sigma_z/c)$

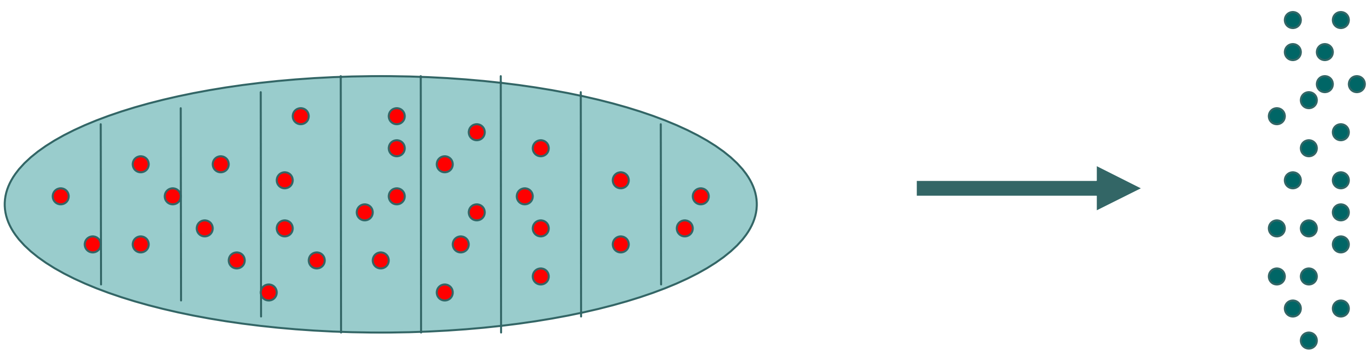
$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}$$

  Threshold : $\rho_e = 5\times10^{11}\,\mathrm{m}^{-3}$

- Coasting beam model is better coincident with simulation.

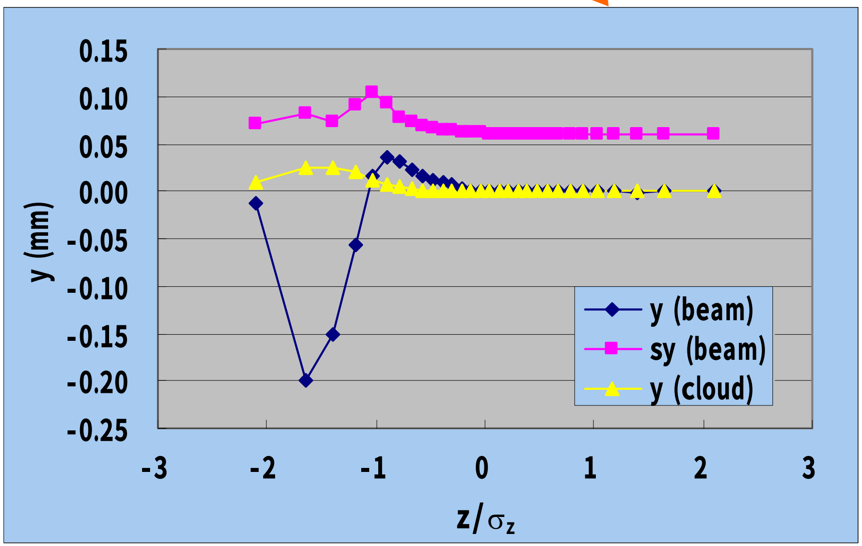
Simulation with Particle In Cell method

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

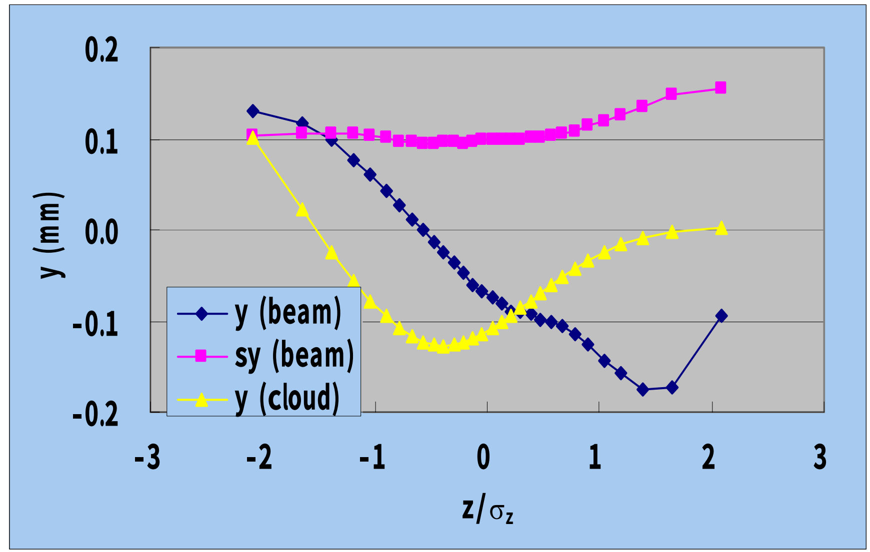


PIC simulation

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



BBU



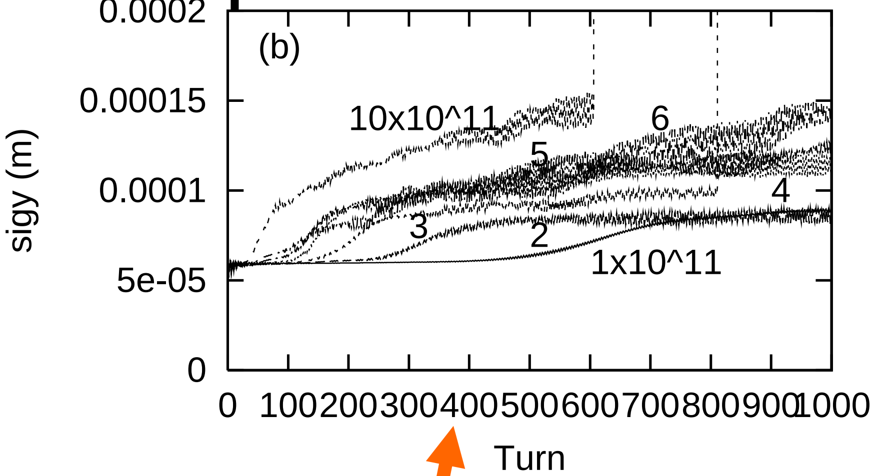
Head-tail motion

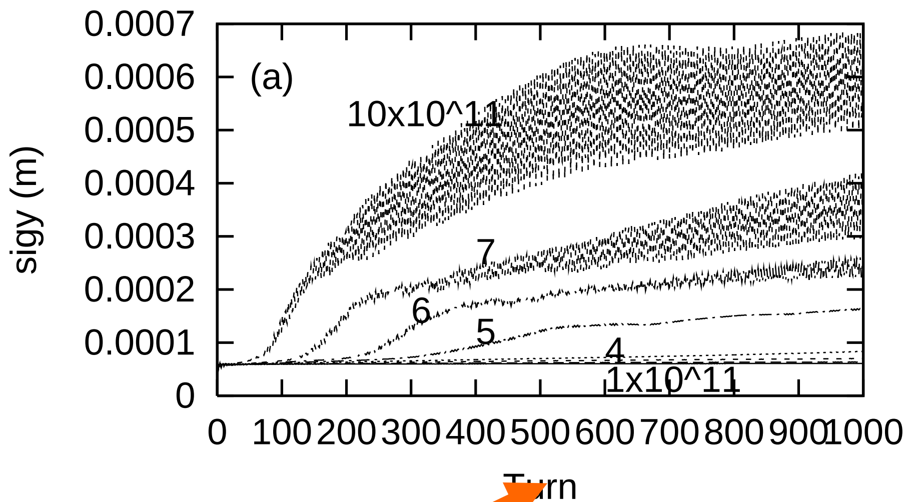
Pink: size along bunch length

yellow: <y> of cloud

Dark blue: <y> of bunch

Threshold behavior





- ν_s=0 no threshold, ν_s>0 clear threshold.
- $\rho_{e,th}=5\mathrm{x}10^{11}\mathrm{m}^{-3}$
- The cloud density is consistent with that prediceted 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).

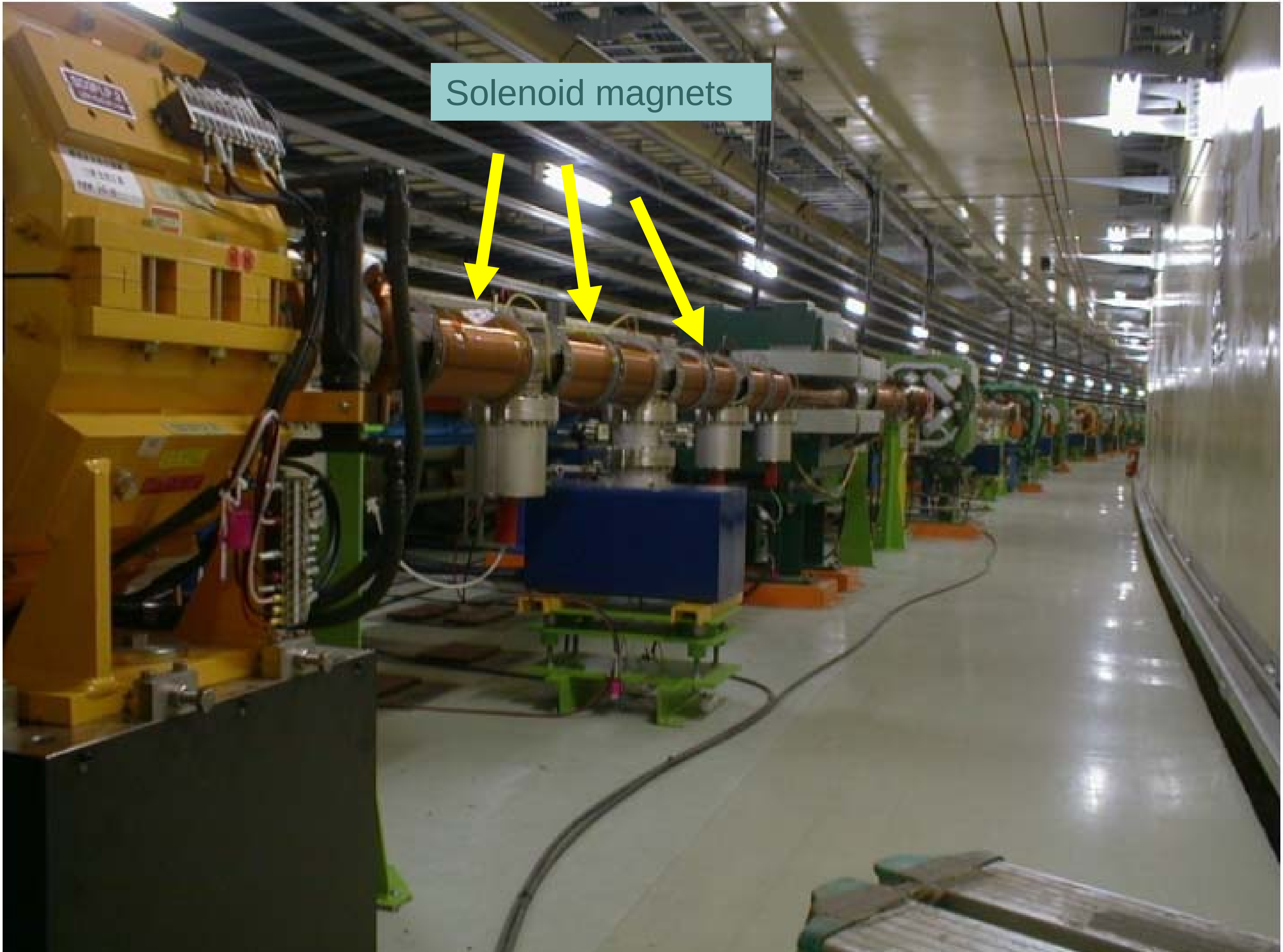
(2) Solenoids are wound additionally in the arc section of 500m (Jan. 2001).

(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 ¼ of quadrupole magnets (2005)


Solenoid magnets

Machine studies for solenoid effect on Luminosity (9 May, 01)

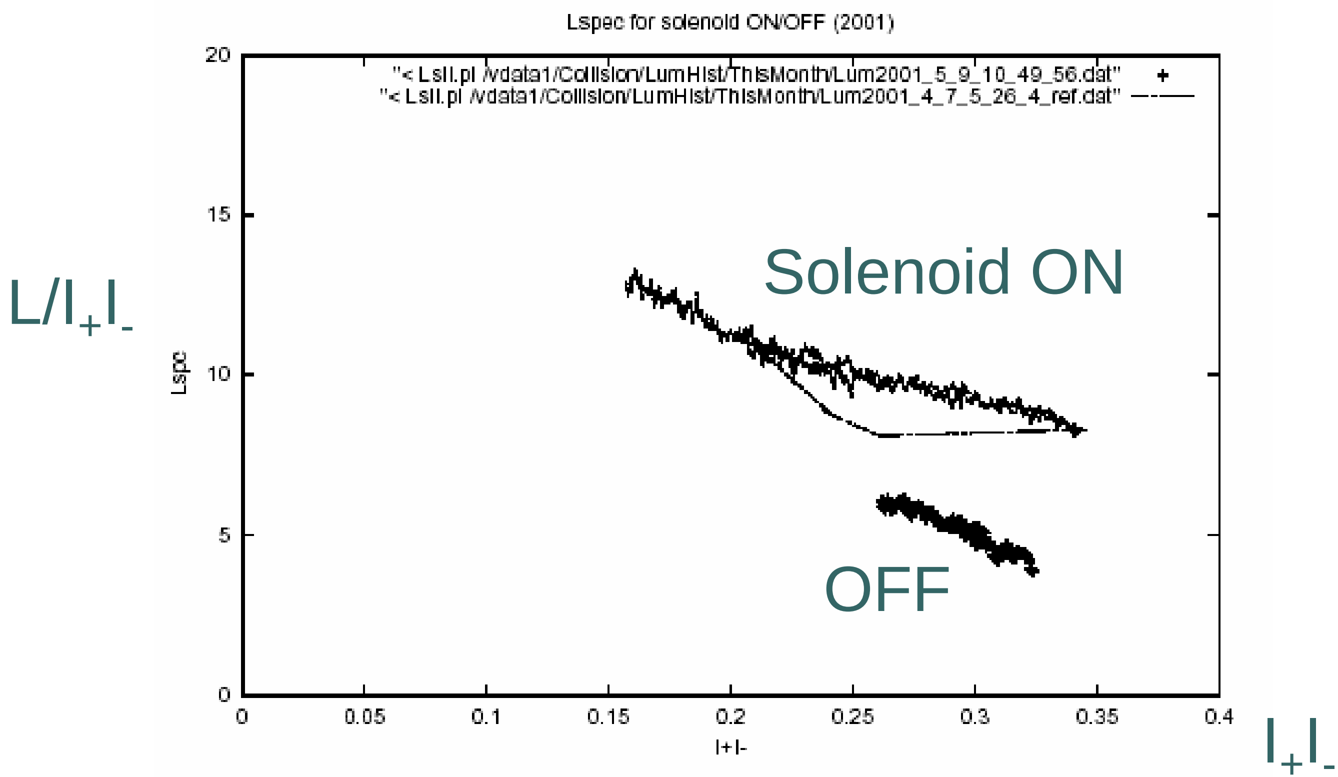
- We use specific luminosity of 24 bucket spacing as a reference.
- Comparison of luminosity between solenoid ON/OFF (28 Dec, 2000 and 9 May, 2001).
- Effect of additional solenoid (500m).

Luminosity in the end of 2000 and the beginning of 2001.

Solenoids ON/OFF

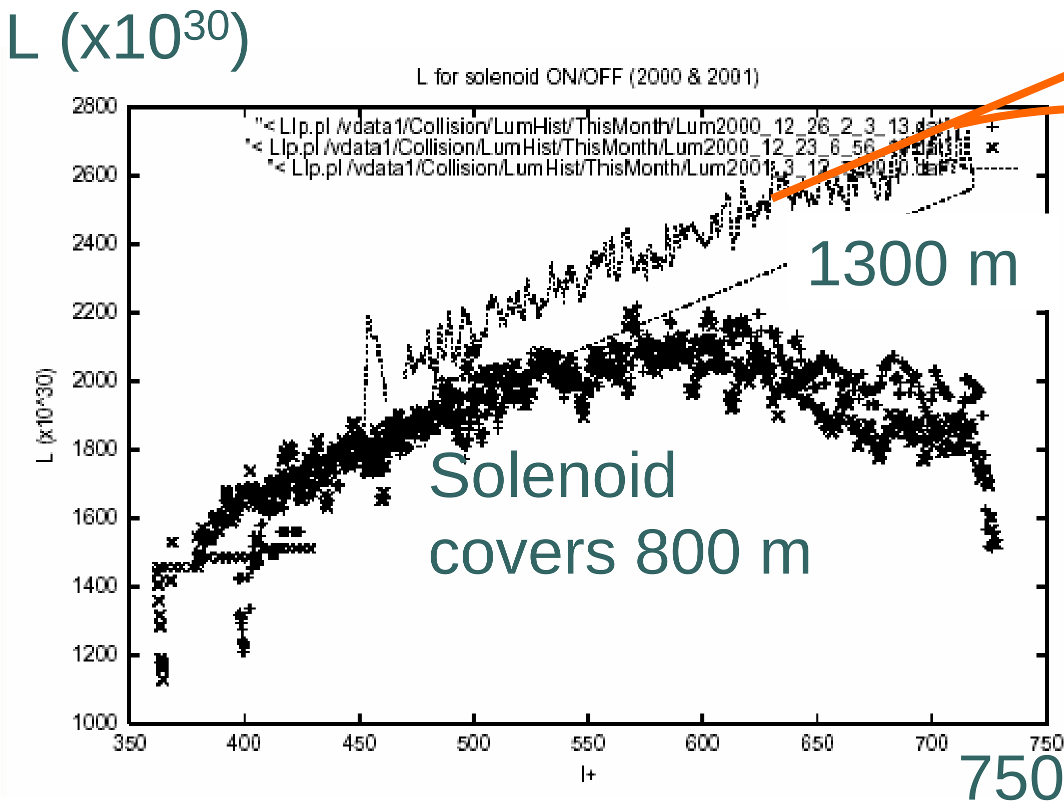
- When solenoids turn off, stored current is limited to a lower value than usual operation due to beam loss (coupled bunch instability)
- Luminosity is quite low (~half).

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



Effect of additional solenoid
Typical luminosity behavior at Dec. 2000 and March. 2001

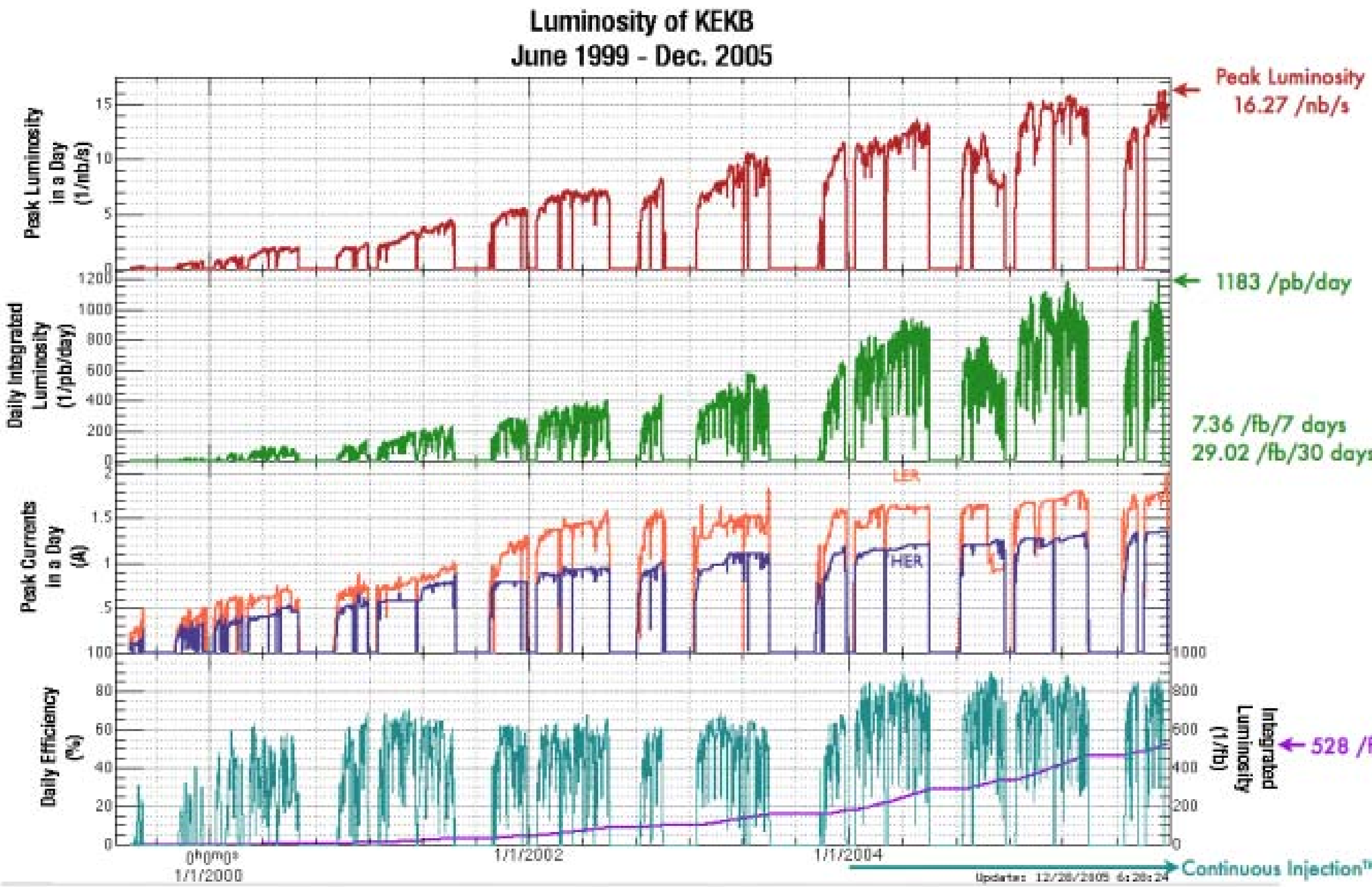
Longer and longe



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

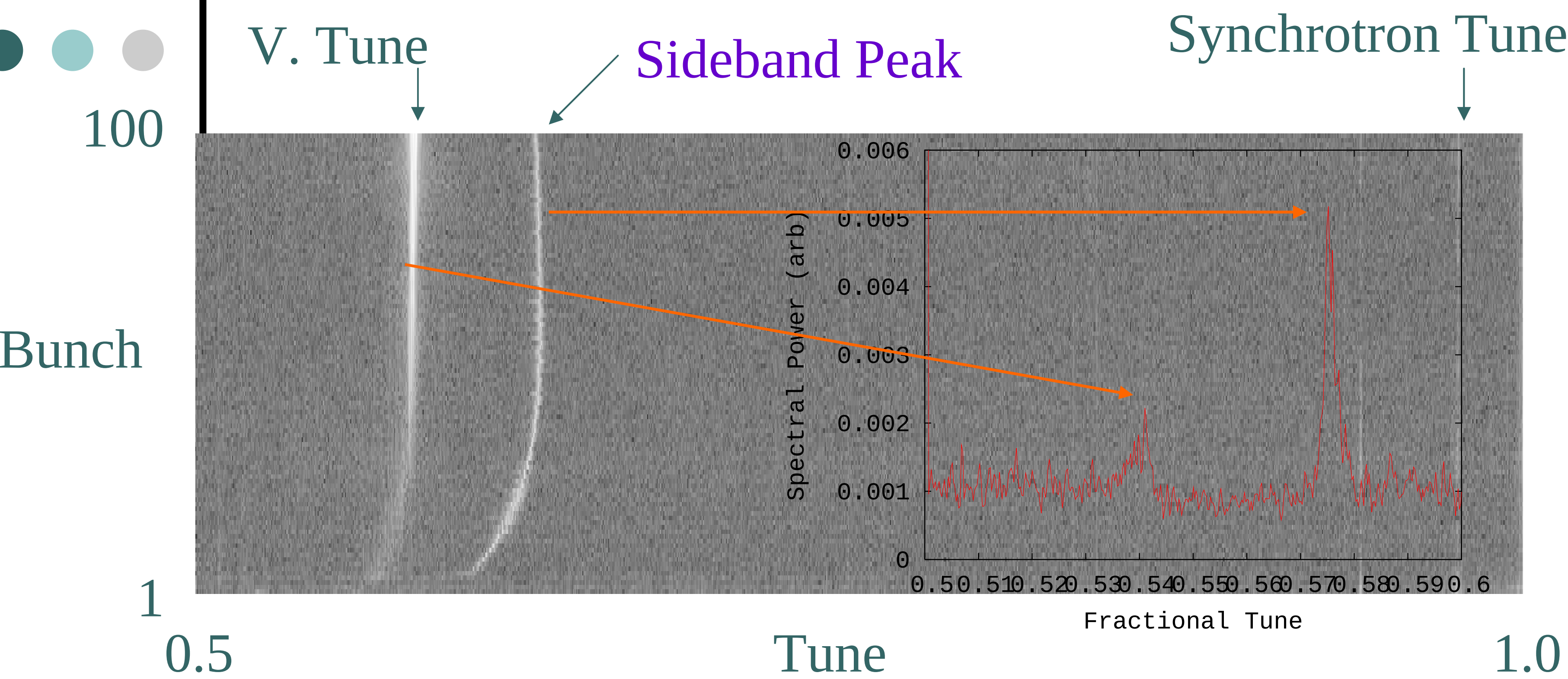


Measurement of synchro-beta sideband - evidence for head-tail instability

- 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 $\sim\nu_y+\nu_s$, while simulation gives $\sim\nu_y-\nu_s$, 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 μm ->283 μm at 400 mA

Vertical feedback gain lowered

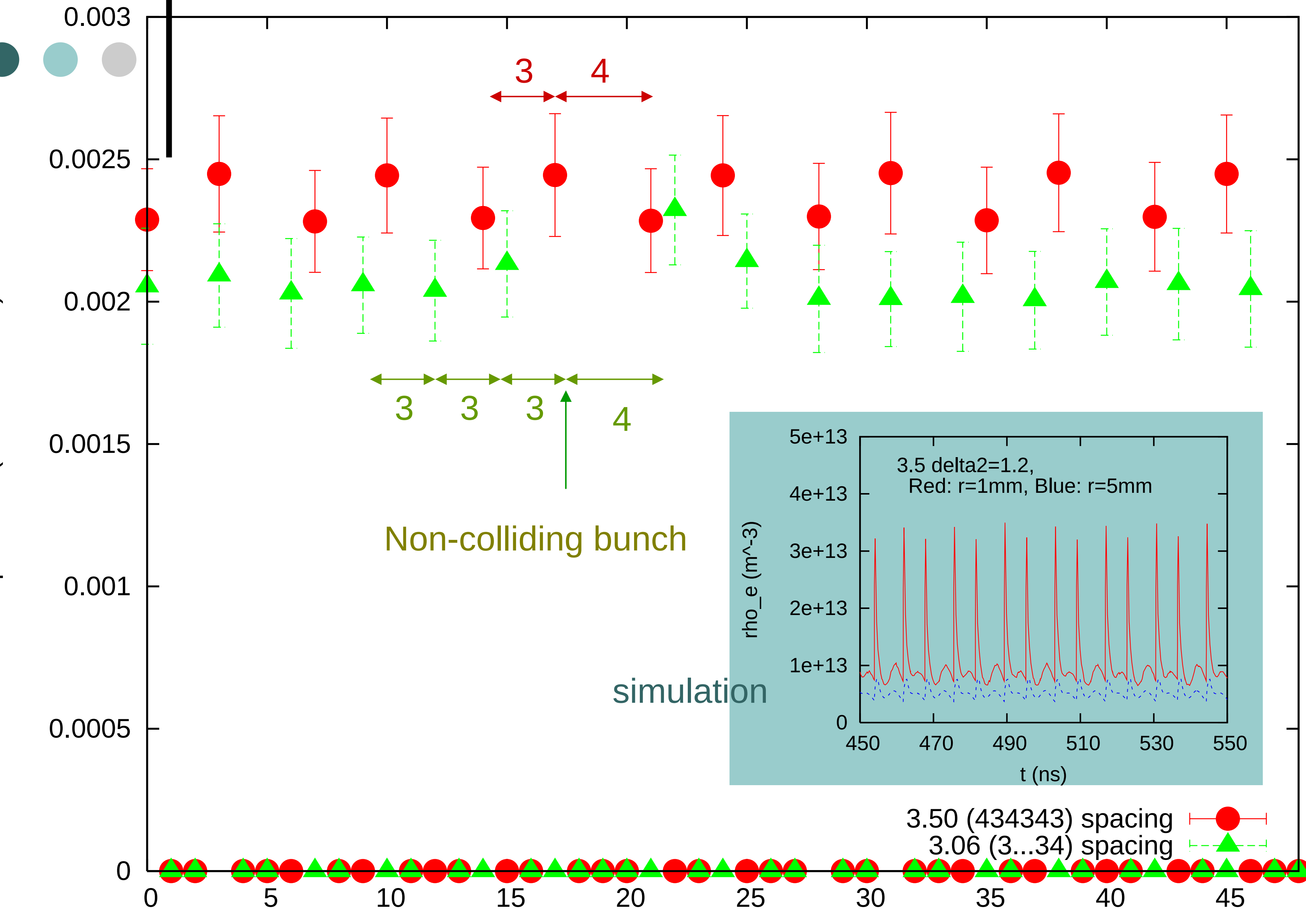
- This brings out the vertical tune without external excitation

J. Flanagan et al., PRL94, 054801 (2005)

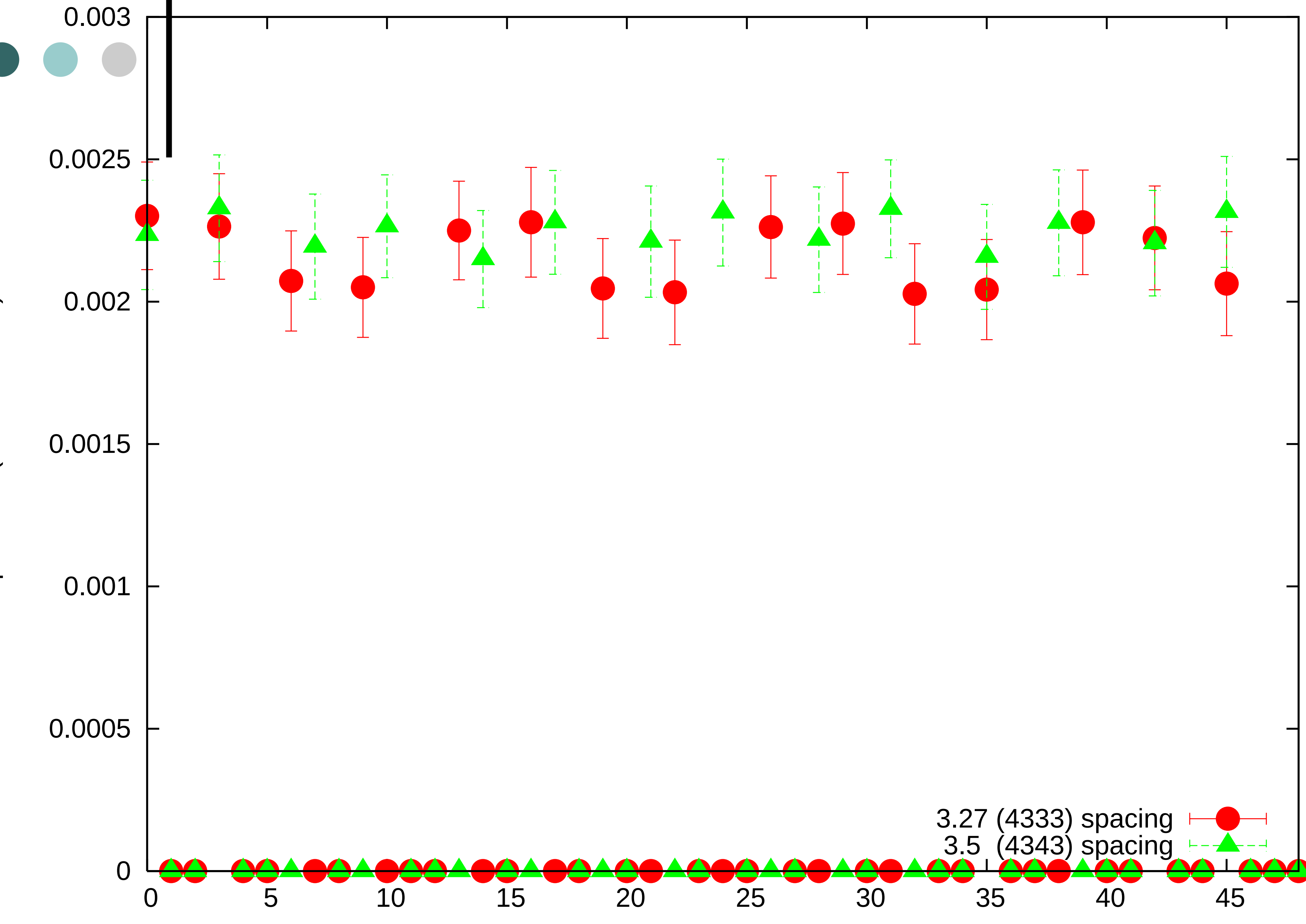
Filling pattern and specific luminosity using bunch by bunch luminosity monitor

- 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.

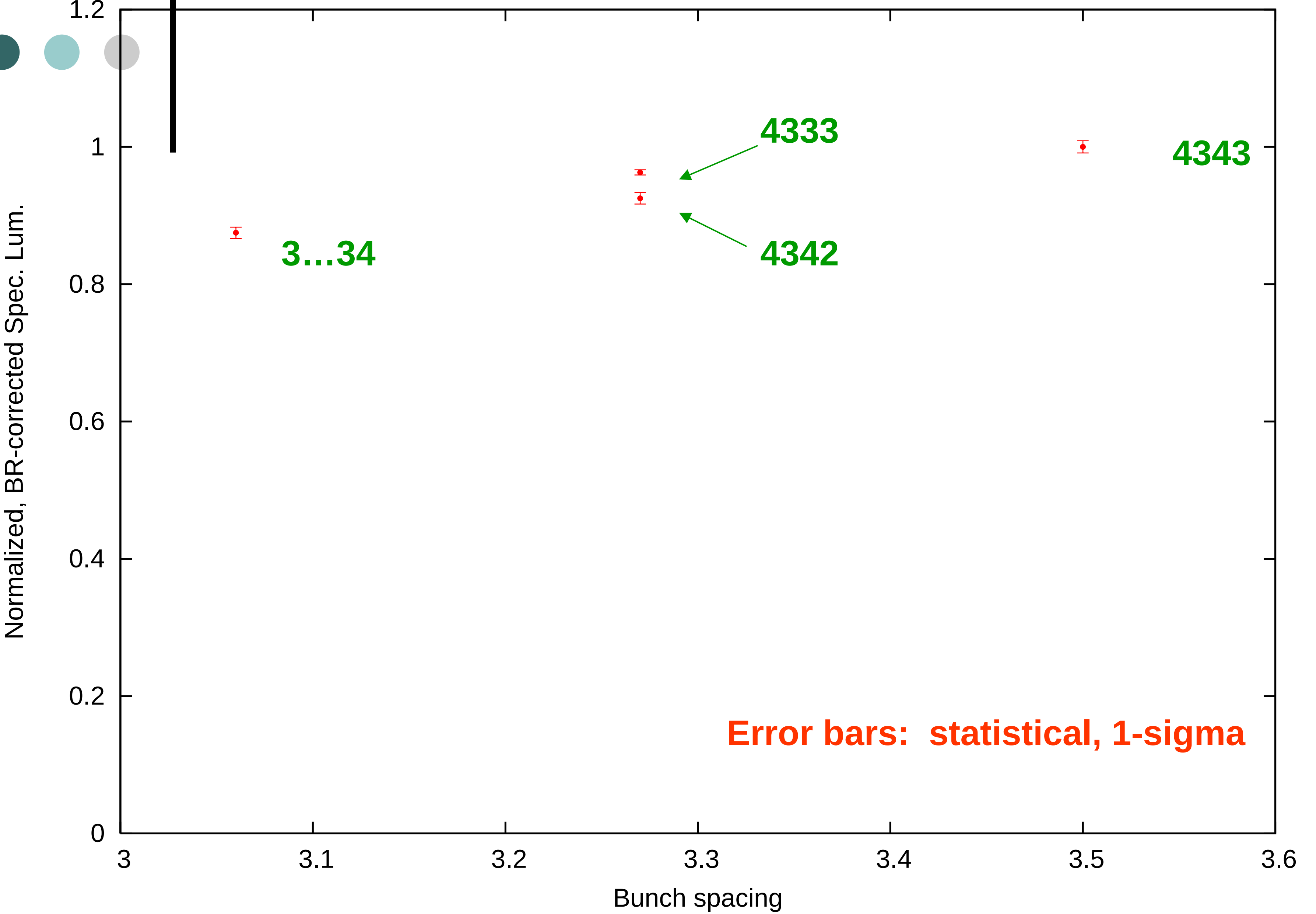
Specific Luminosity (49-folded)



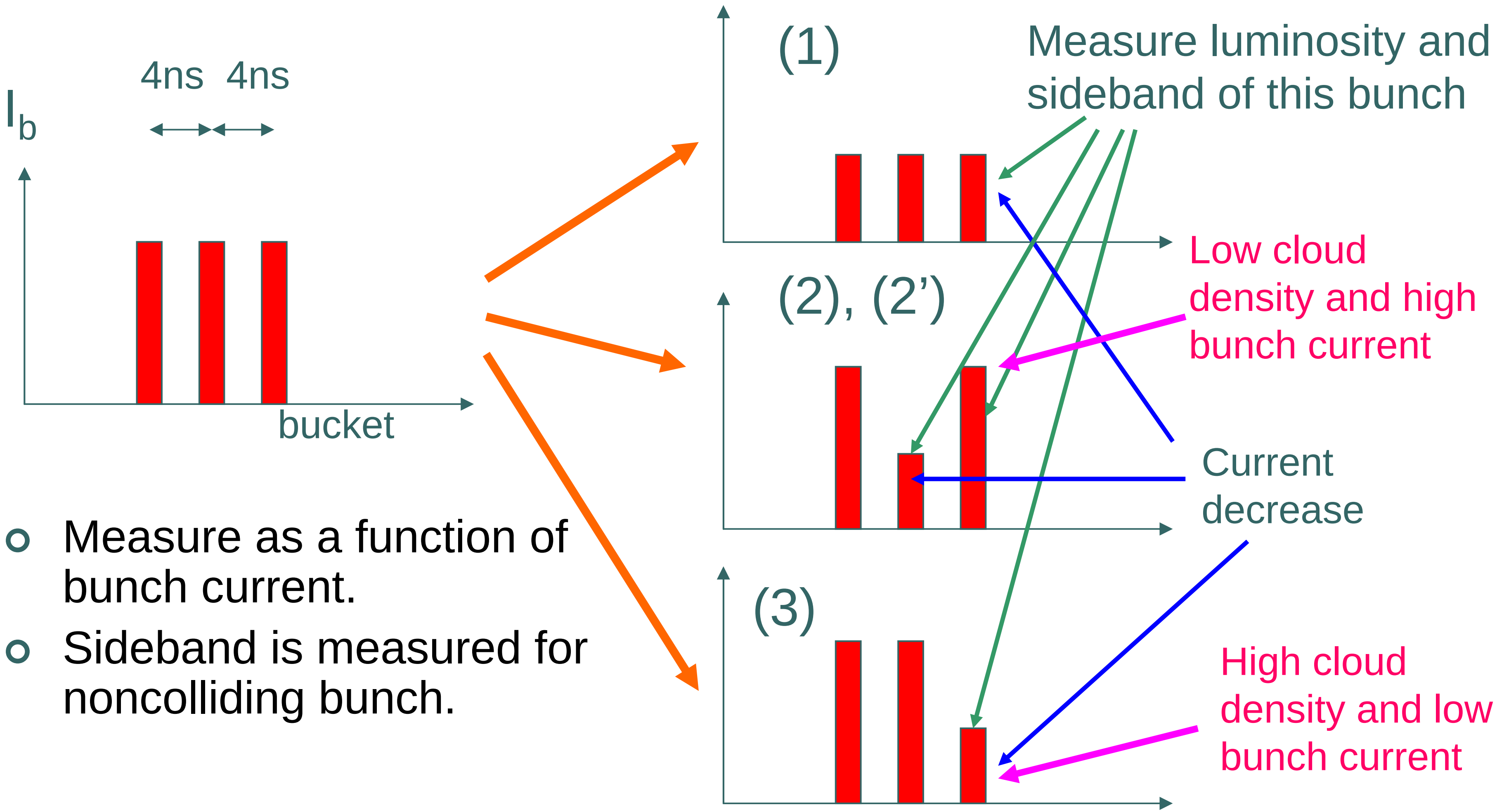
Specific Luminosity (49-folded)



Bunch Spacing vs Spec. Lum.



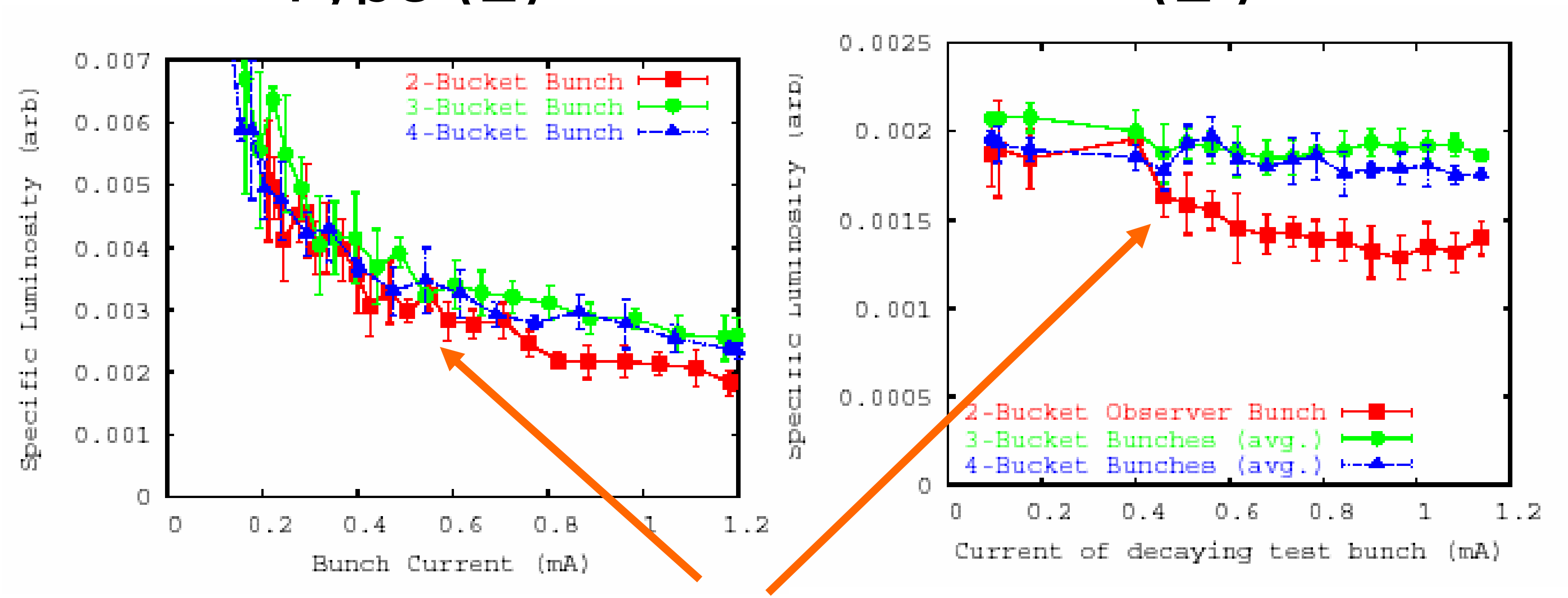
Luminosity-bunch current-sideband experiment



- Measure as a function of bunch current.
- Sideband is measured for noncolliding bunch.

Luminosity degradation coincided with sideband appearance basically.

Type (2) (2’)



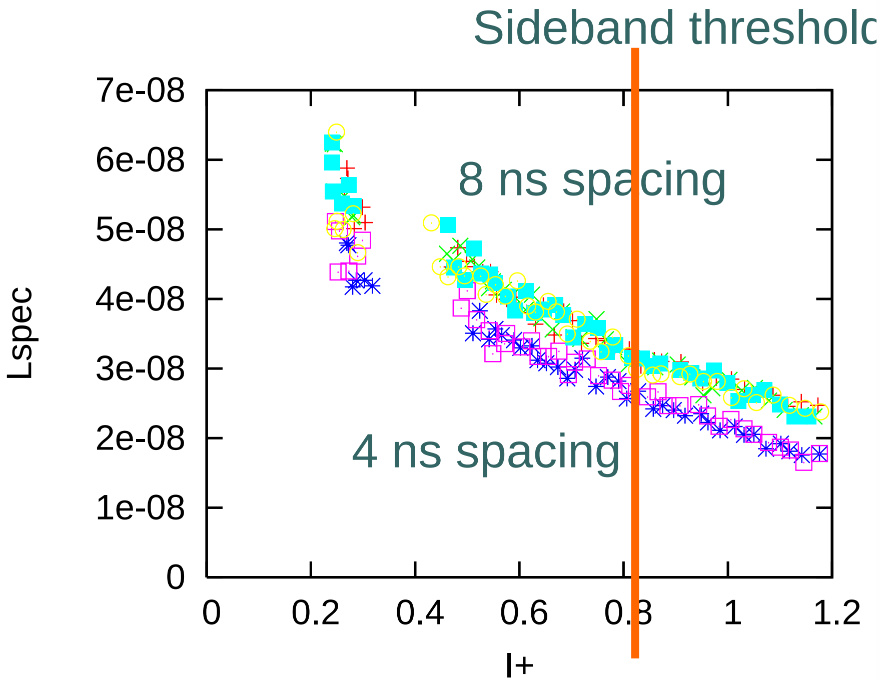
Sideband disapears these current values

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

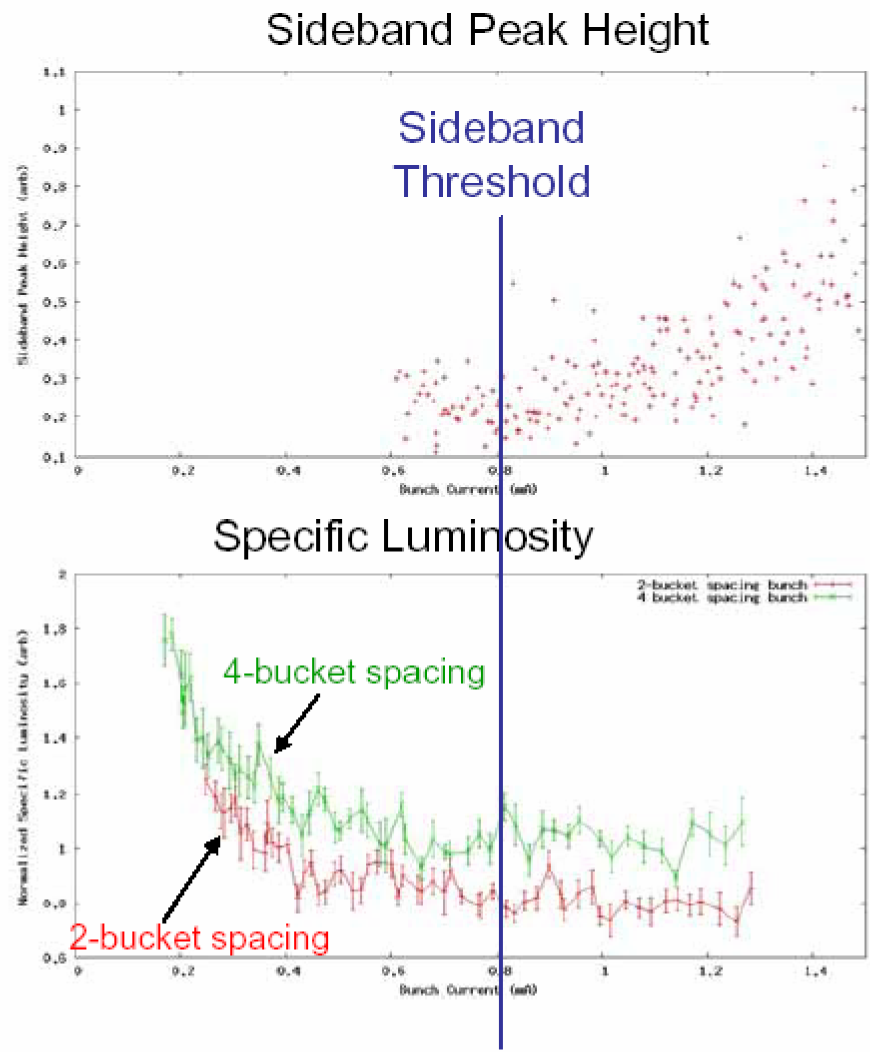
These data may be indication of an incoherent effect of electron cloud, or coupled effect with beam-beam.

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

- Type (1)



Type (3)



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 synchro-betatron 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 1.625×10^{34} $cm^{-2}s^{-1}$.
- 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.

Measurements at KEKB

- Vertical Beam size blow up of positron beam at commissioning of KEKB.
- Head-tail instability model is proposed.
- Winding solenoid and luminosity upgrade.
- Measurement of synchro-betatron sideband which is an evidence of electron cloud induced head-tail instability.
- Measurement coupled bunch instability which reflects electron motion in solenoid magnets.
- Measurement of correlation between the luminosity and the sideband.
- Measurement of electron cloud induced incoherent effect