Electron cloud effects in KEKB and ILC

K. Ohmi KEK

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Thanks for the hospitality and GuoXing, Rainer and Eckhard.

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
- Electron cloud instability in ILC damping ring
- Works at DESY with A. Markovik and R. Wanzenberg.

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.

- Had similar instability been observed at DORIS? Multi mode instability (197~ or 198~?)

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

BPM spectrum for V motion.

Electron 354 mA

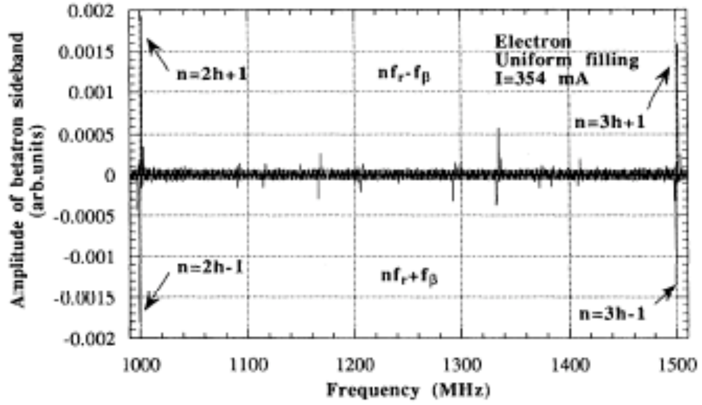


FIG. 1. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling.

Positron 324 mA & 240 mA

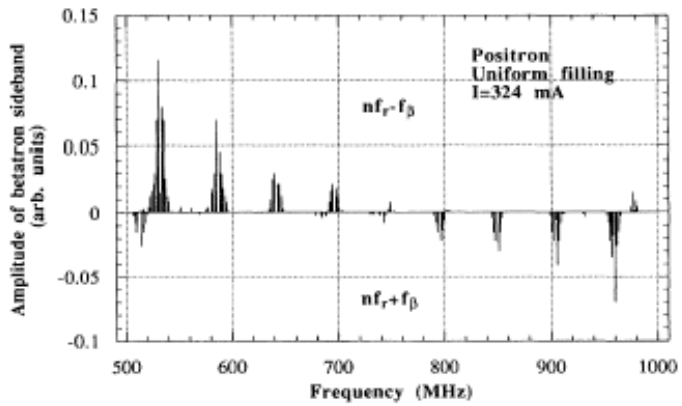


FIG. 2. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling.

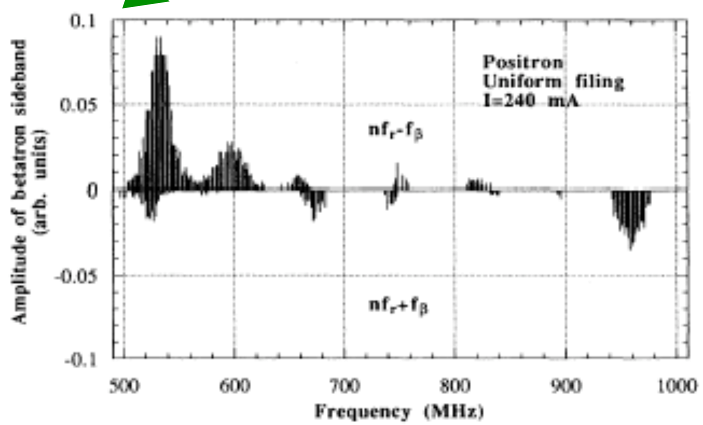


FIG. 3. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling. Only the stored current is different from Fig. 2.

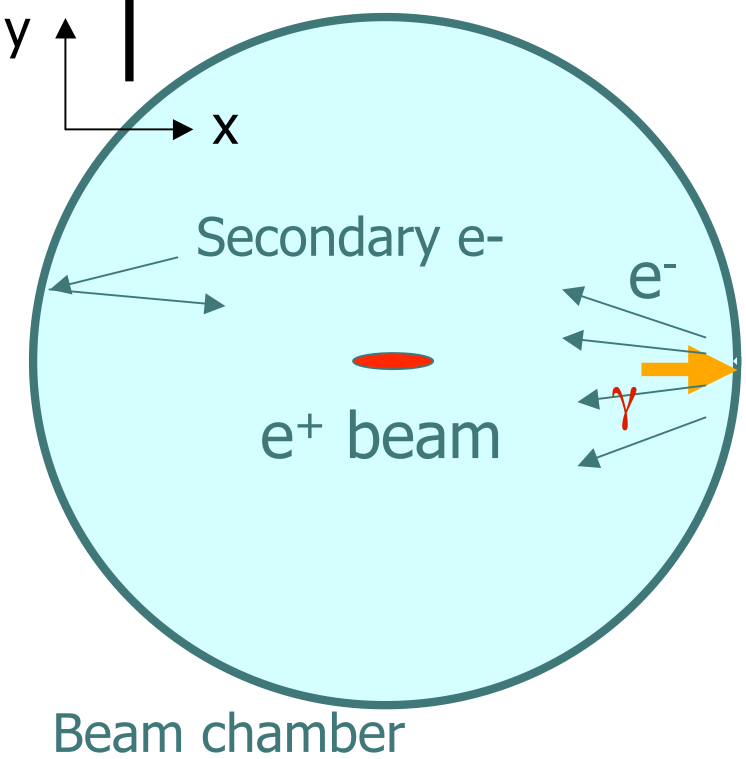
Interpretation of instability due to photo-electron cloud

- 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

Model



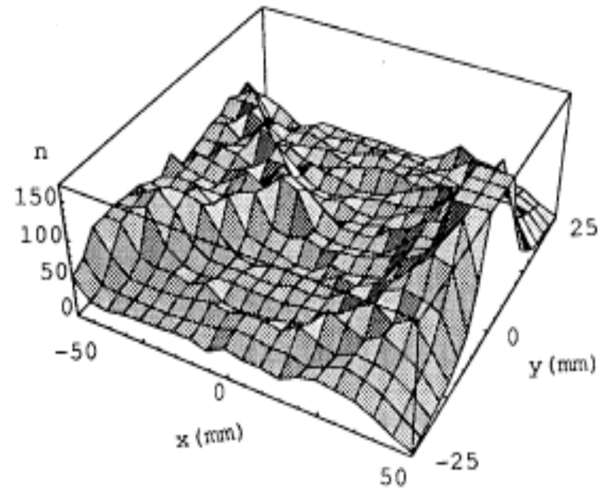


FIG. 2. A stationary distribution of photoelectrons with $\epsilon_0 = 5$ eV.

PRL,75,1526 (1995)

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

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 $2 \times 10^6\ \mathrm{cm}^{-3}$. 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.

Number of produced electrons

Number of photon emitted by a positron par unit meter.

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

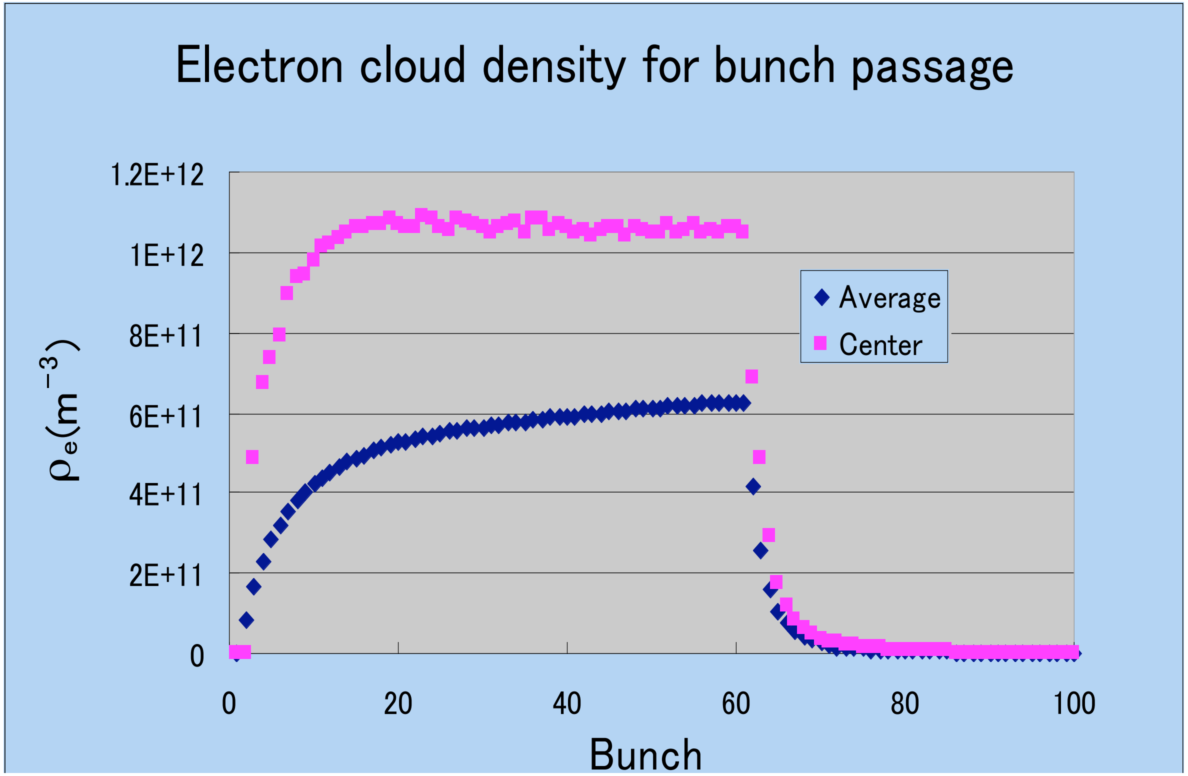
α : fine structure const=1/137

- KEKB-LER γ=6850 → Yγ=0.15/m
- KEK-PF =4892 → Yγ=1.7/m

- Bunch population
  N_p=3.3x10^{10} (KEKB-LER design 2.6A)
  N_p=5x10^9 (KEK-PF 400mA)
- Quantum efficiency (η=$n_{p.e.}/n_\gamma$) 0.1
- Energy distribution 10±5 eV

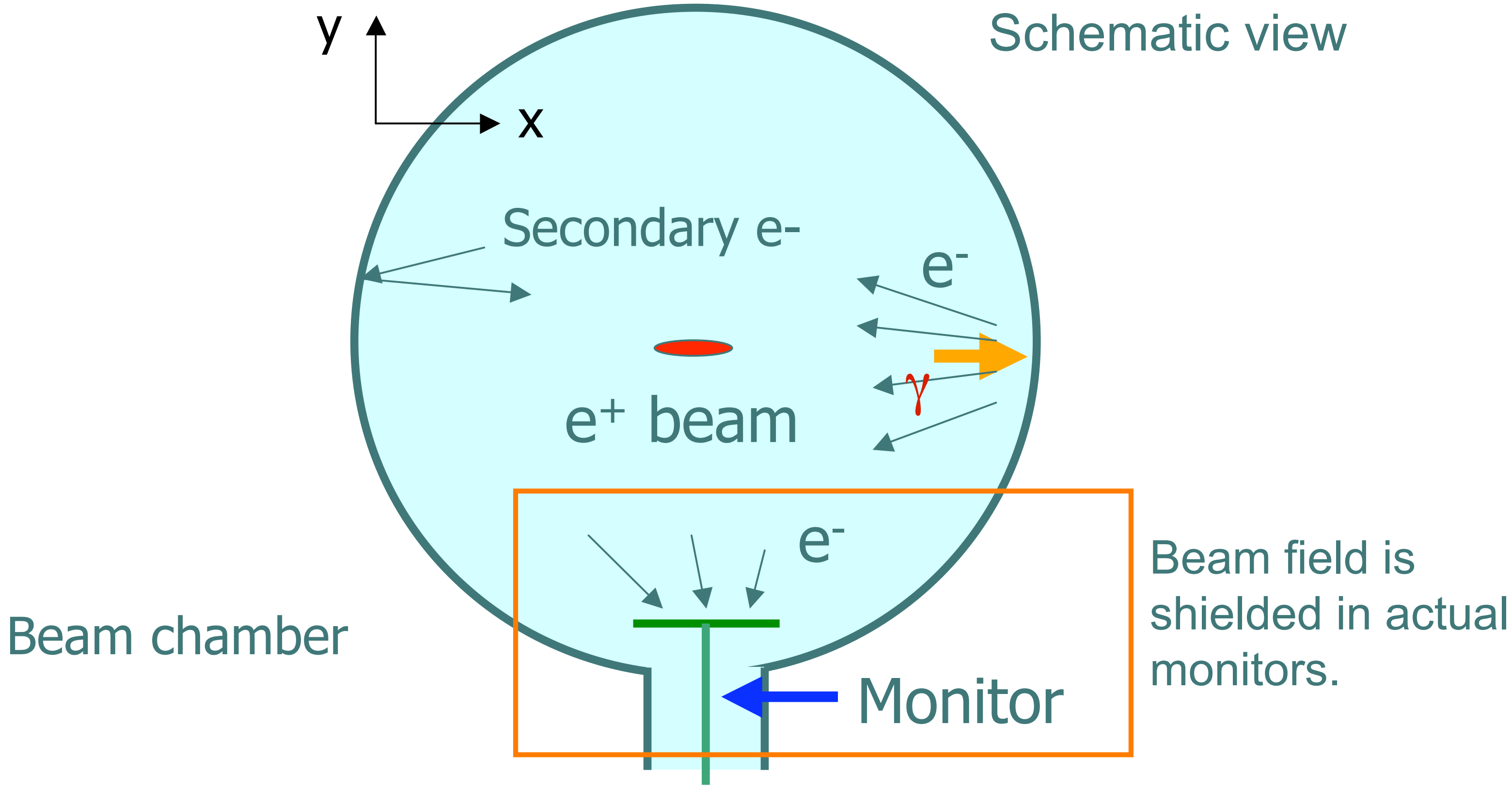
- KEKB-LER $Y_{p.e.}$=0.015 e^-/m.e^+
- KEK-PF $Y_{p.e}$=0.17 e^-/m.e^+ ,
- ionization 10^{-8} e^-/m.e^+ , proton loss(PSR) 4x10^{-6} e^-/m.p

Electron cloud density given by simulation



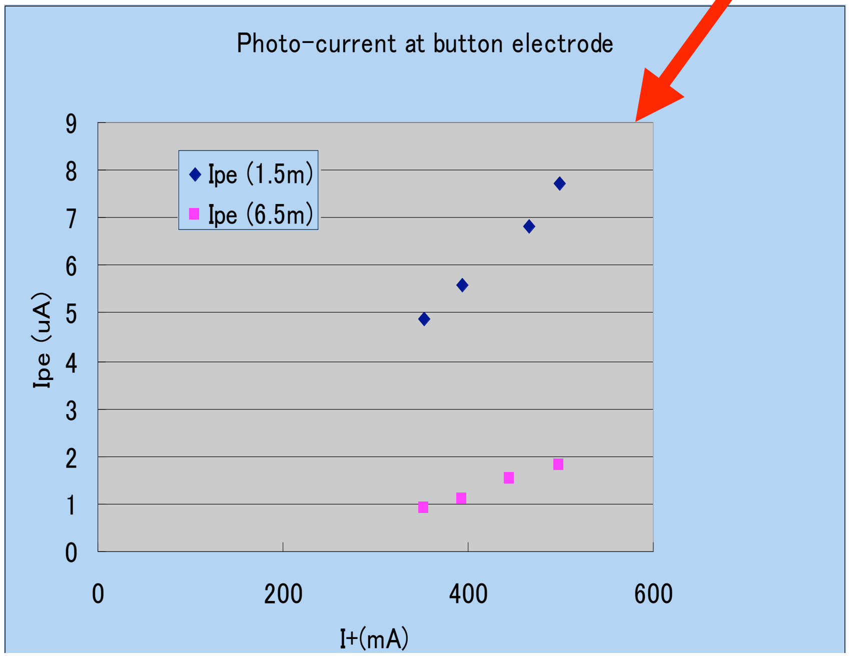
60 bunches pass in every 8ns (KEKB).

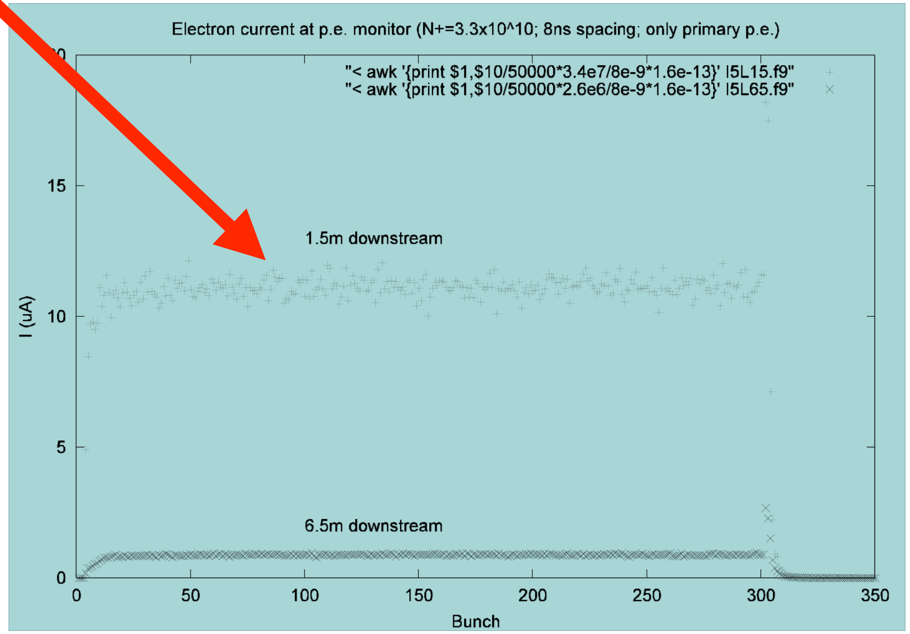
Measurement of electron cloud (Y. Suetsugu, K. Kanazawa et.al.)



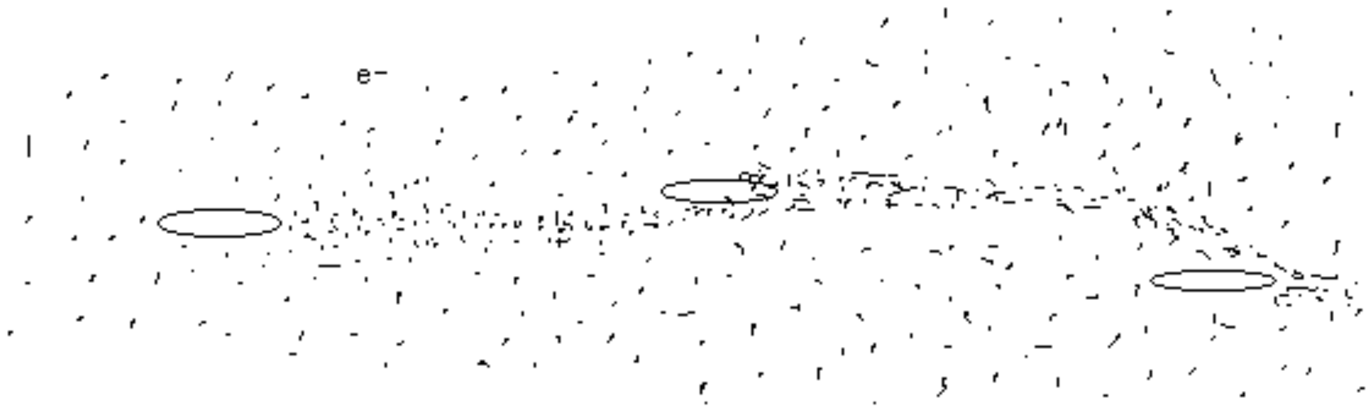
Experiment and simulation results

I_{pe}=10 μA at I_+=600 mA at
1.5 m down stream of Bend.





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.

Wake force and unstable mode for KEK-PF

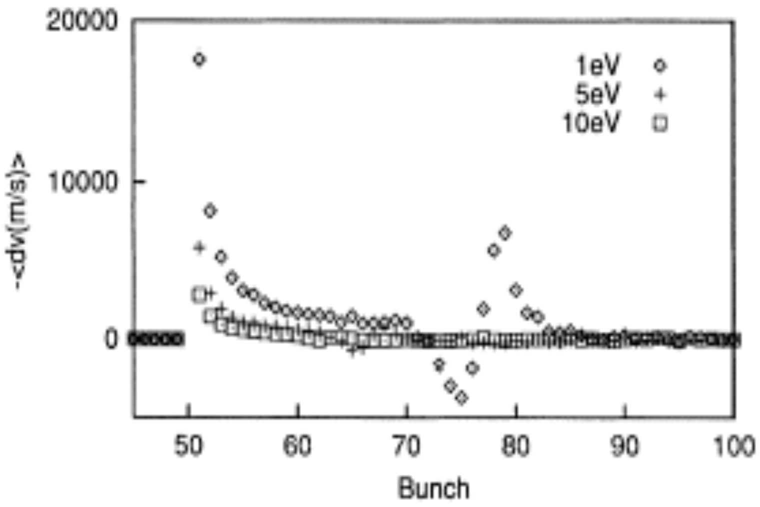


FIG. 3. Wake forces for each initial photoelectron energy. To obtain the wake, 10^6 virtual electrons in every bunch were used.

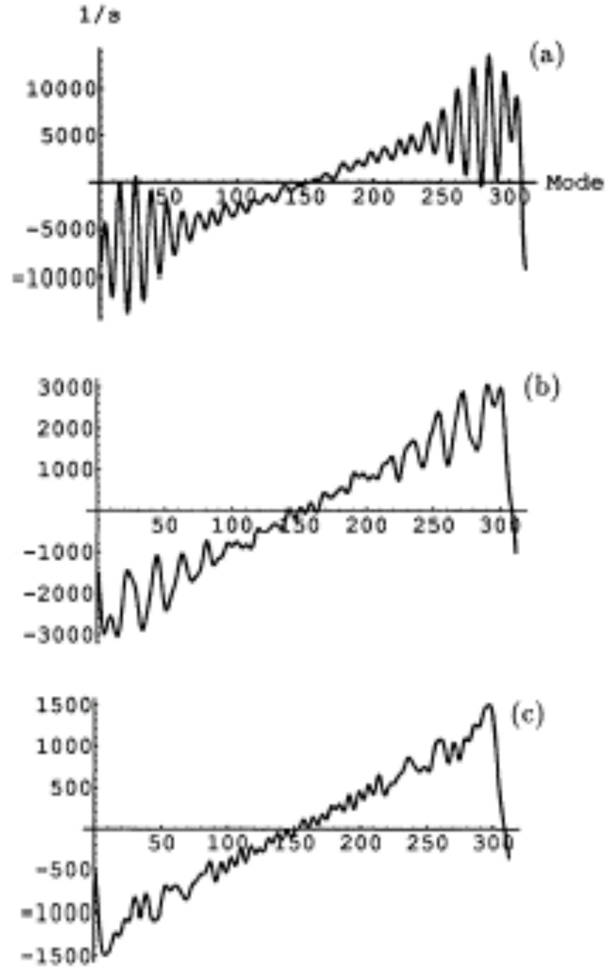


FIG. 4. Growth rates of the coupled-bunch instability. The positive values mean unstable modes. The wakes of 51 to 100 bunches in Fig. 3 were summed with Eq. (8). (a) $\epsilon_0 = 1$ eV. (b) $\epsilon_0 = 5$ eV. (c) $\epsilon_0 = 10$ eV.

Very fast growth of the coupled bunch instability was explained.

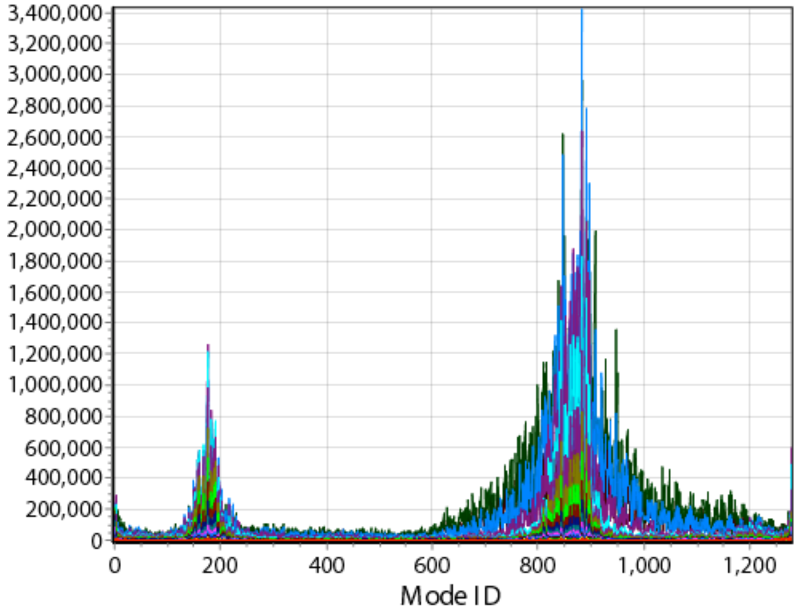
K.Ohmi, PRL,75,1526 (1995)

Measurement of the coupled bunch instability in KEKB

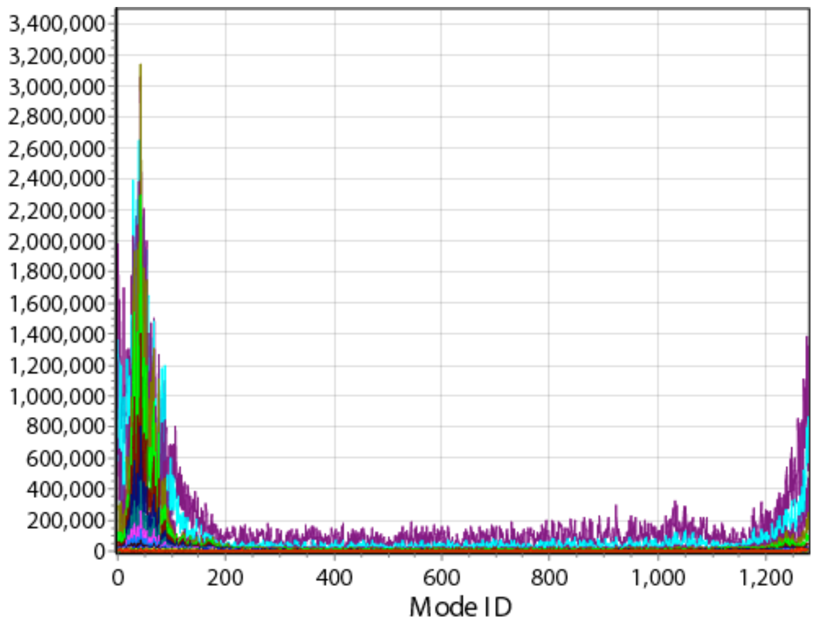
- Fast amplitude growth which causes beam loss has been observed.
- The mode spectrum of the instability depends on excitation of solenoid magnets.

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

Solenoid off



on (measurement)



Tracking simulation

K.Ohmi, PRE55,7550 (1997)

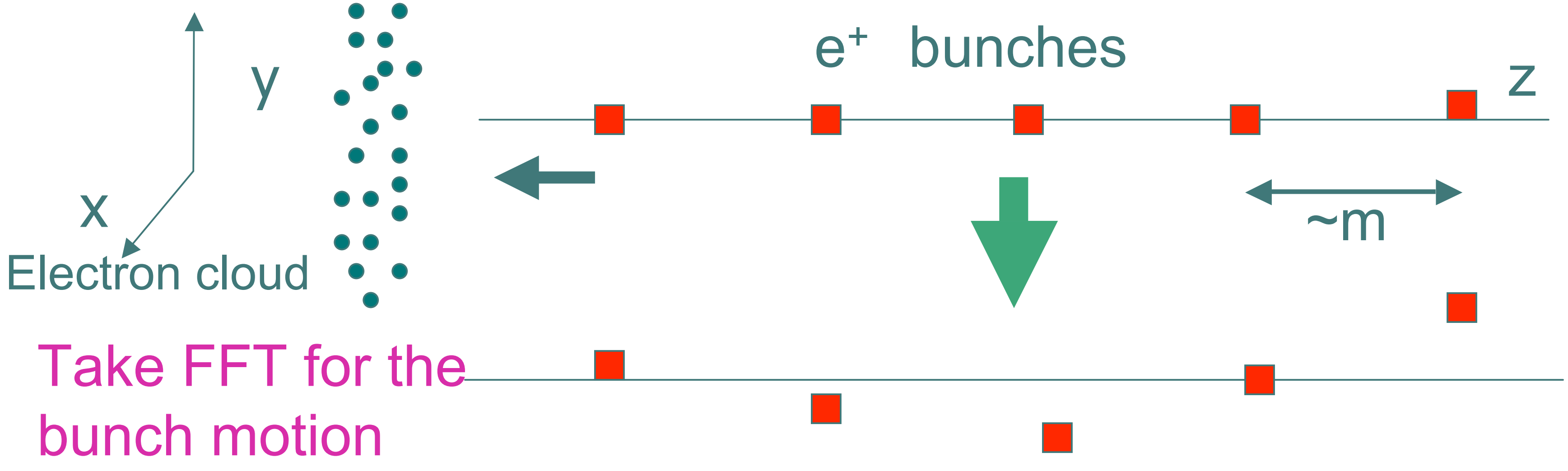
K.Ohmi, PAC97, pp1667.

Solve both equations of beam and electrons simultaneously

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

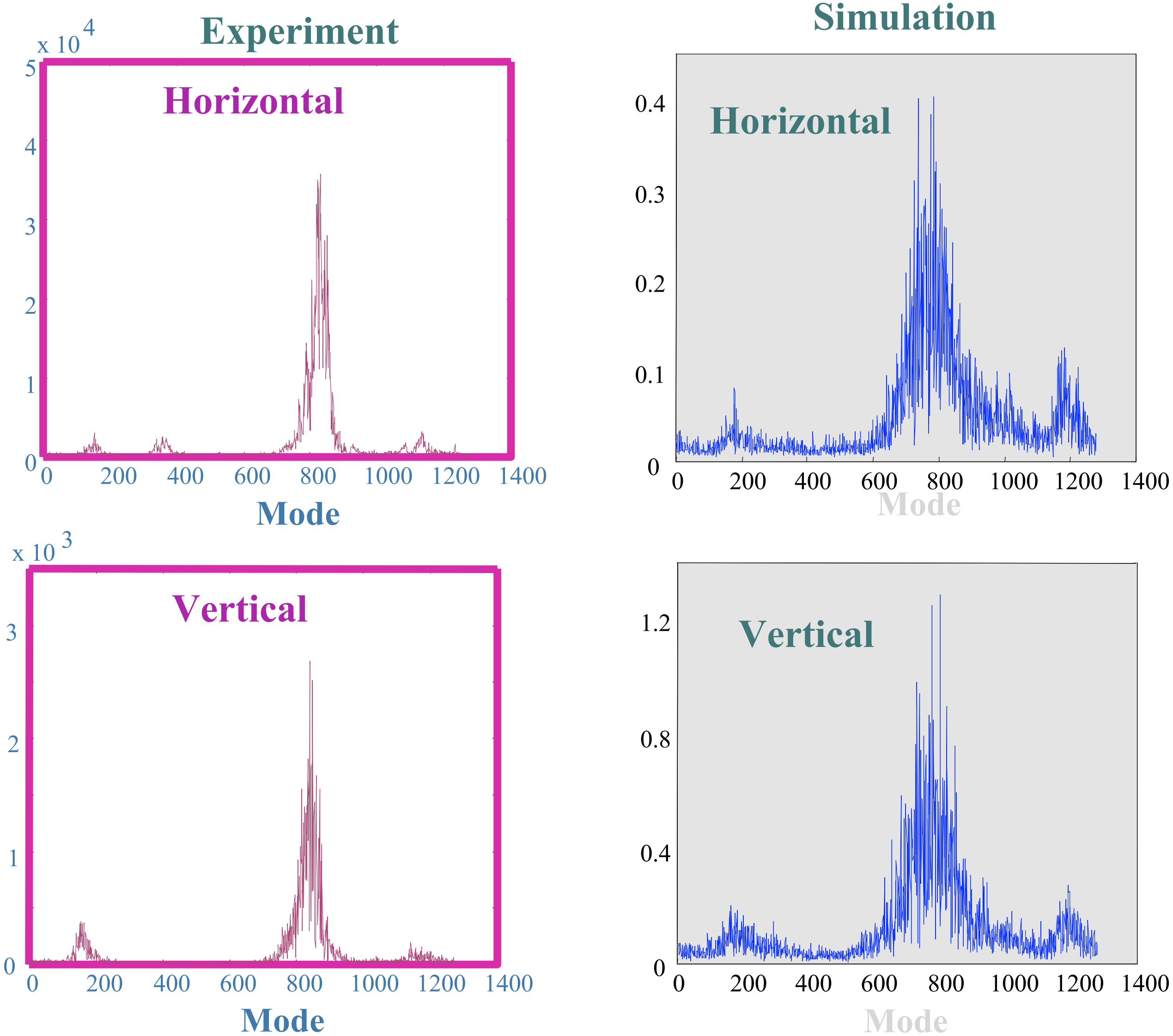
$$\frac{d^2\mathbf{x}_{e,a}}{dt^2} = \frac{e}{m}\frac{d\mathbf{x}_{e,a}}{dt}\times\mathbf{B} - 2N_p r_e c\sum_n\sum_{i=1}^{N_b}\mathbf{F}(\mathbf{x}_{e,a} - \mathbf{x}_{p,i})\delta(t - t_i(s_e + nL))$$

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



Take FFT for the bunch motion

CBI mode spectra in KEKB Solenoid-Off



Bunches are filled every 4 bucket.

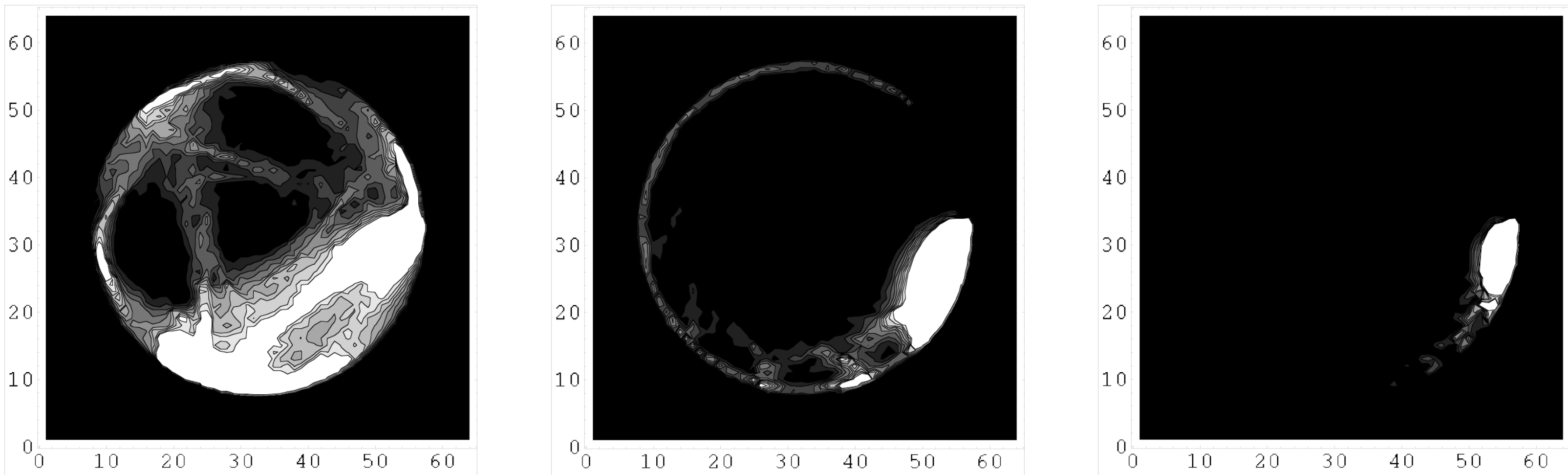
Su Su Win et al,(EC2002)

Effect of Solenoid magnet

- Solenoid magnets suppress the electron cloud effect partially.
- We can observe electron cloud effect characterized by solenoid magnet.

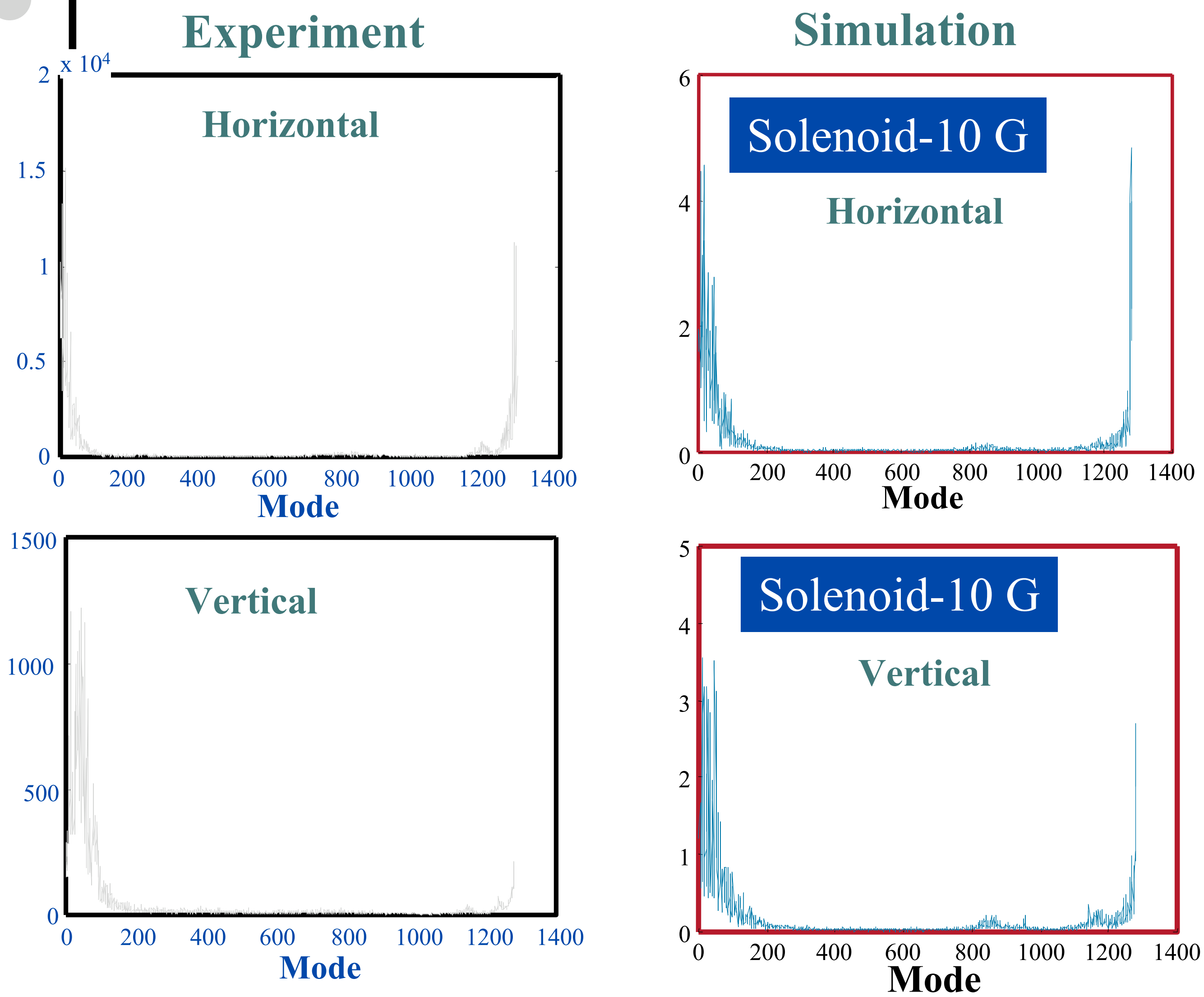
- Cloud distribution (K. Ohmi, APAC98)

10 G 20 G 30 G



KEKB

Solenoid-ON



Su Su Win et al., EC2002

Single bunch instability

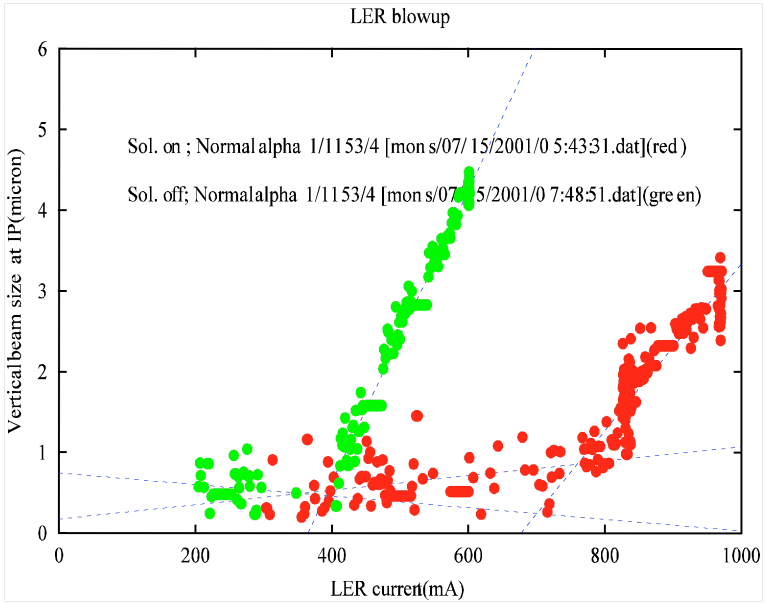
Vertical Beam size blow up of positron beam at commissioning of KEKB

- A beam-size blow-up has been observed above a threshold current. The threshold is given for 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.

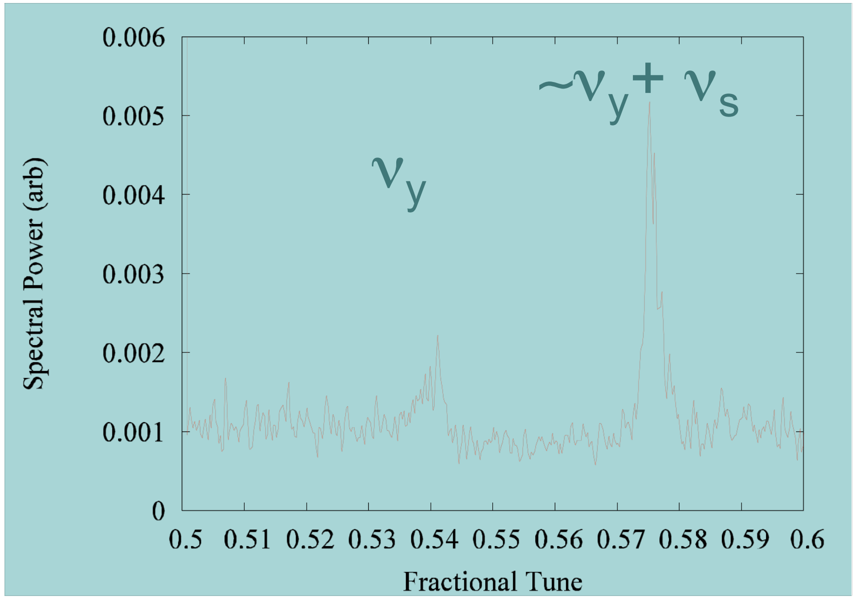
- Synchro-beta sideband induced by electron cloud head-tail instability was observed.

Measurements of the single bunch instability

- Beam size blow-up
- Synchro-beta sideband



Fukuma et al.



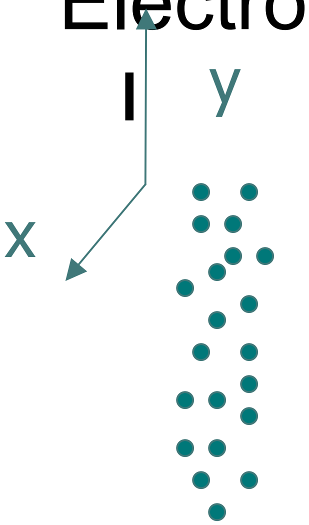
J. Flanagan et al.

Head-tail instability model

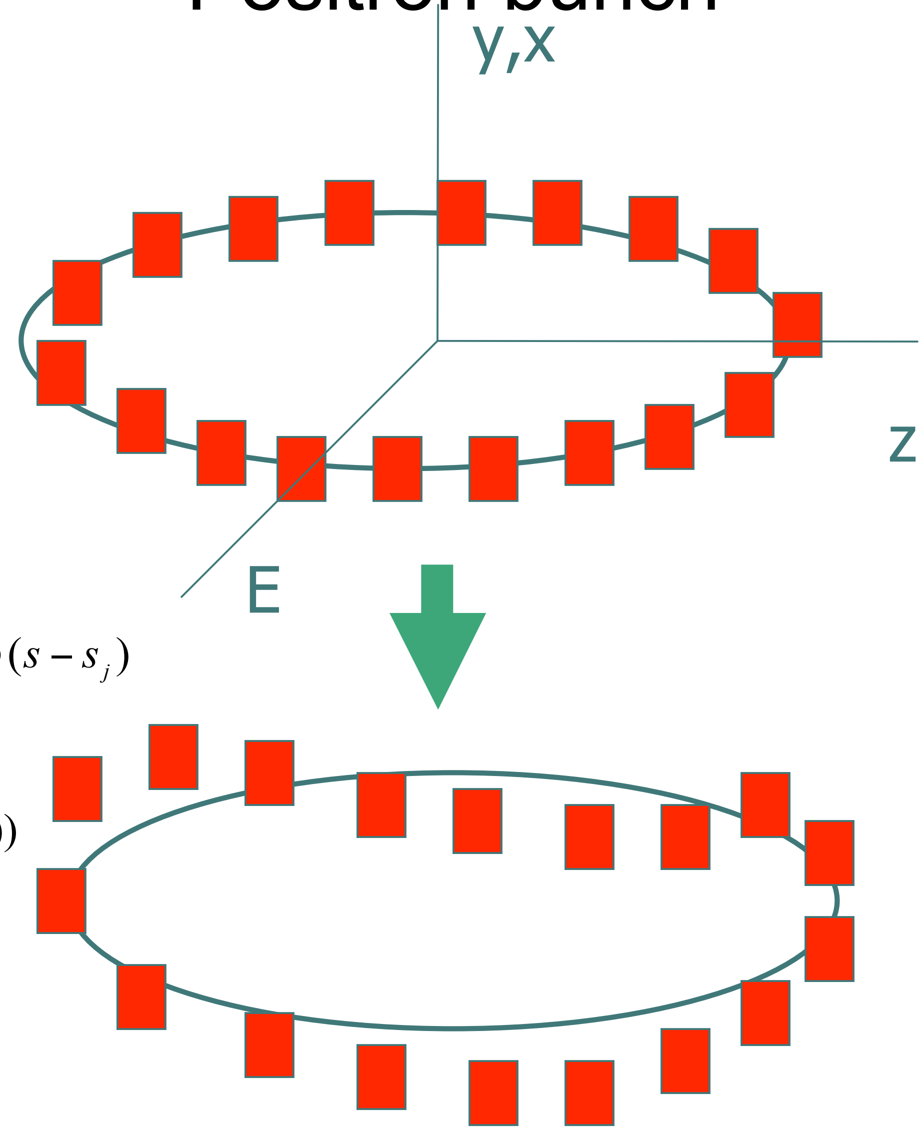
- Simulation using Gaussian model, the same method as the study for CBI.
- Wake field approach, the same as CBI.
- PIC simulation (like beam-beam strong-strong)

Simulation using Gaussian micro-bunch model

Electron cloud



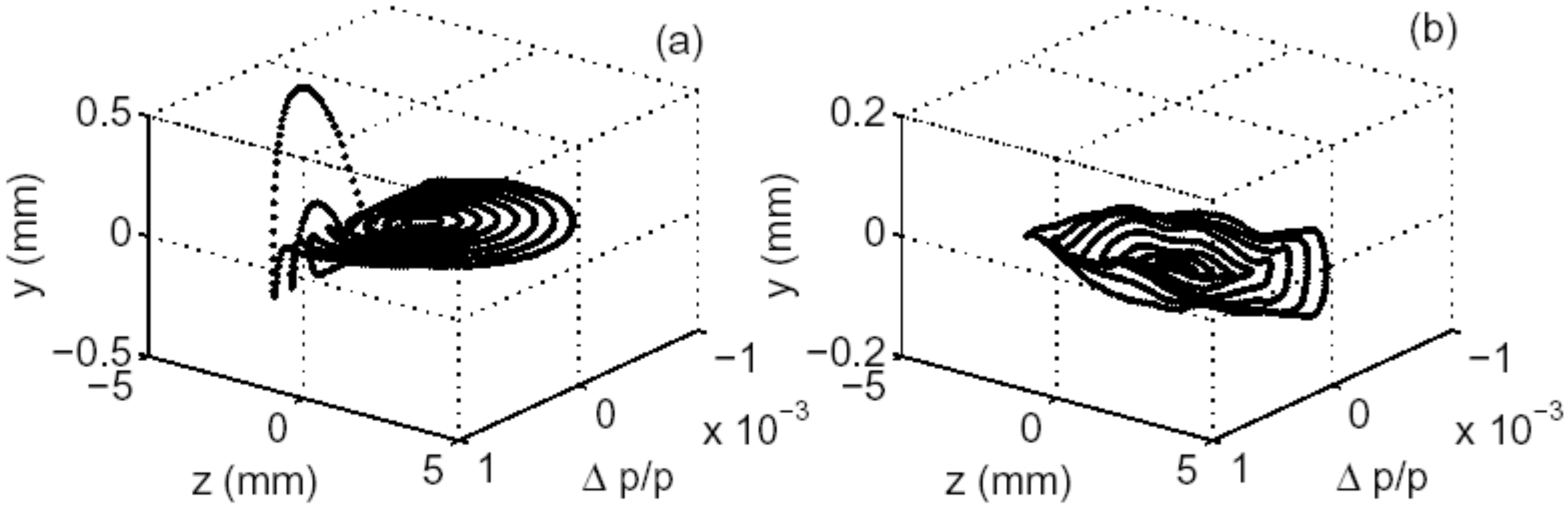
Positron bunch



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

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

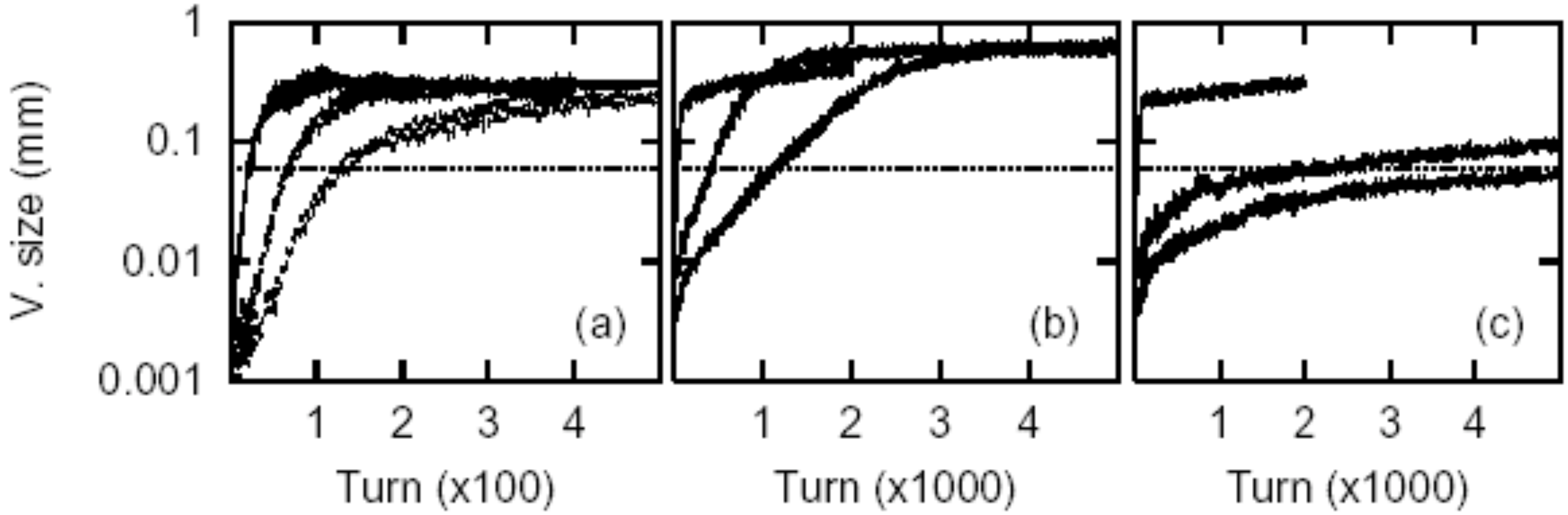
Bunch head-tail motion w/wo synchrotron motion.



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



ρ_e=2x10^{11} , 4x10^{11}, 10x10^{11} m^{-3}

- Unstable for Positive chromaticity --- head-tail
- Unstable for ρ_e= 10x10^{11} m^{-3} irrelevant to chromaticity --- strong head-tail

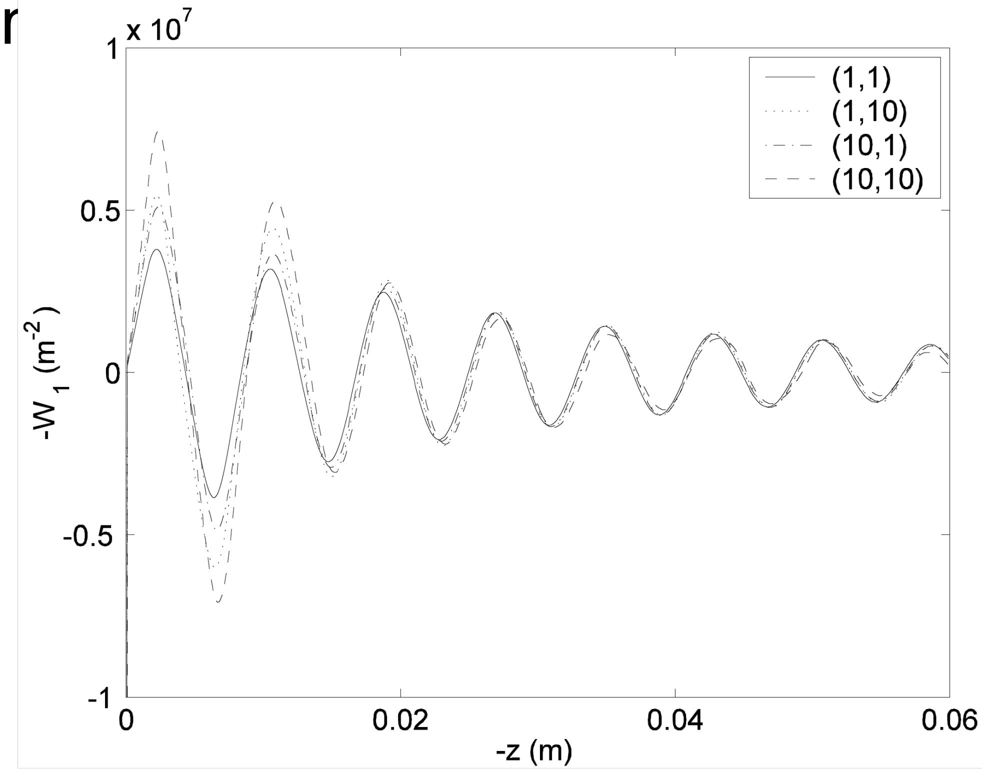
Wake field approach

- 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.

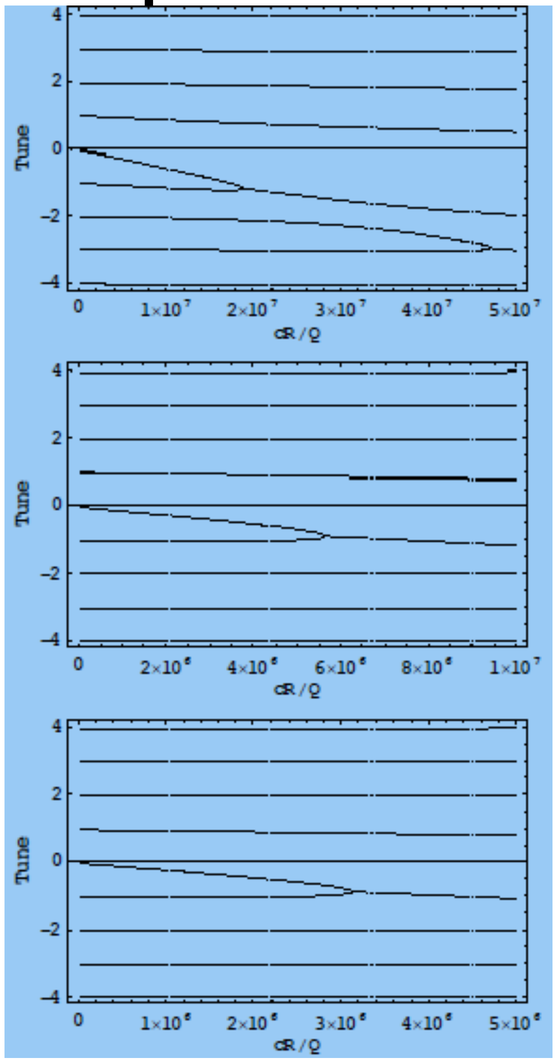
Vertical wake field given by the numerical r



- (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 : ρ_e=1-2x$10^{12}$$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)

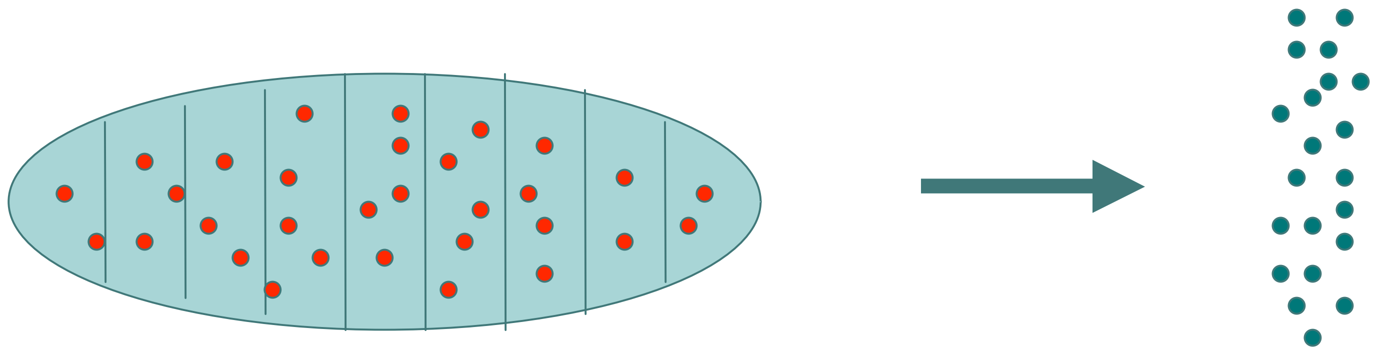
$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}$$

Threshold : ρ_e=5x$10^{11}$$m^{-3}$

- Coasting beam model is better coincident with simulation.

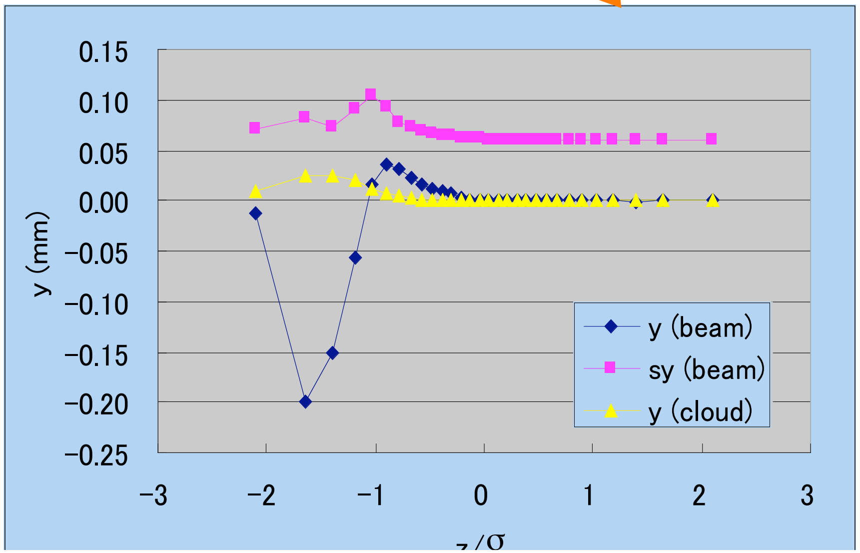
Simulation with Particle In Cell method

- 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.

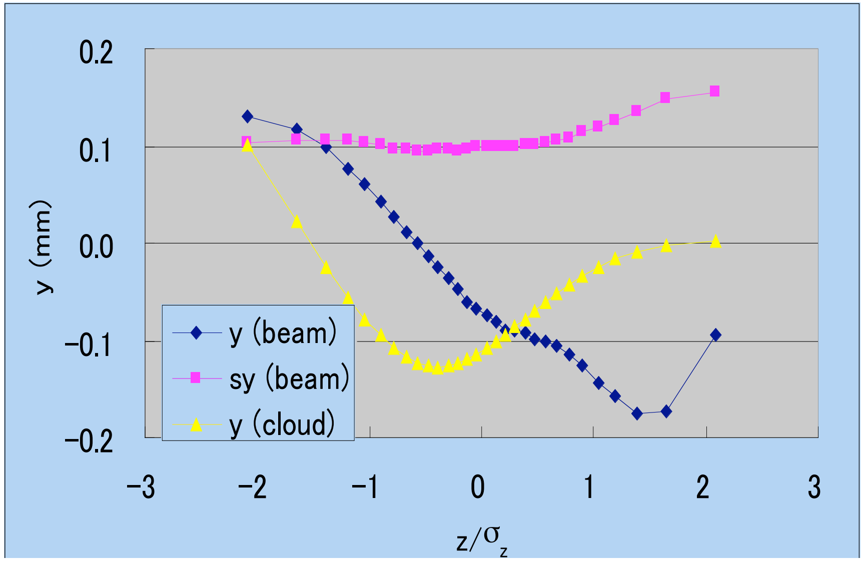


PIC simulation

Snap shot of beam and cloud shape for ν_s=0 and ν_s>0



BBU



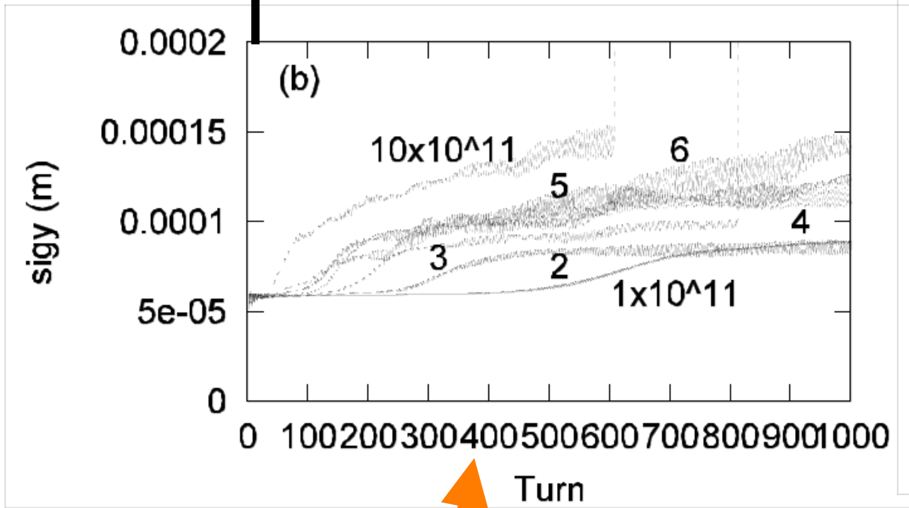
Head-tail motion

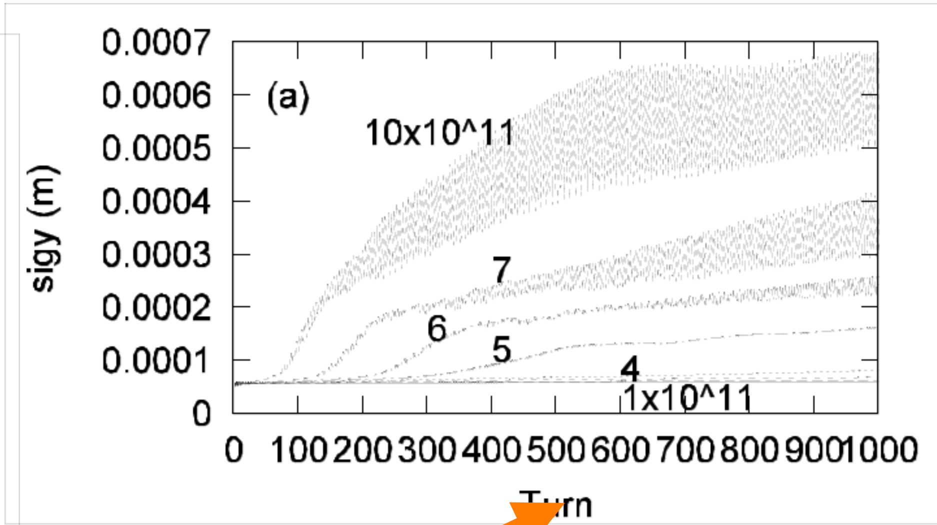
Pink: size along bunch length

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 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).

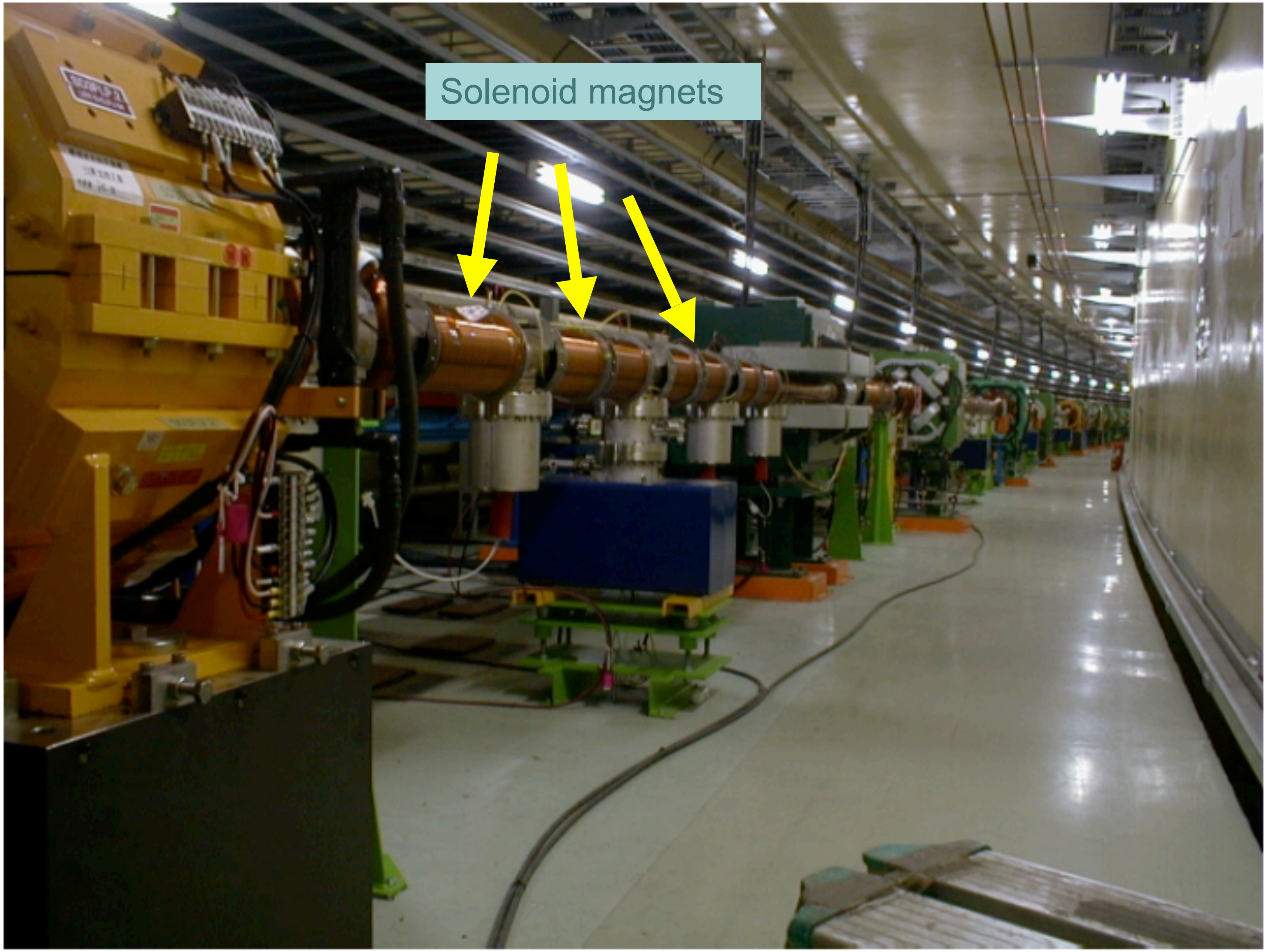
(2) Solenoids are wound additionally in the arc section of 500m (Jan. 2001).

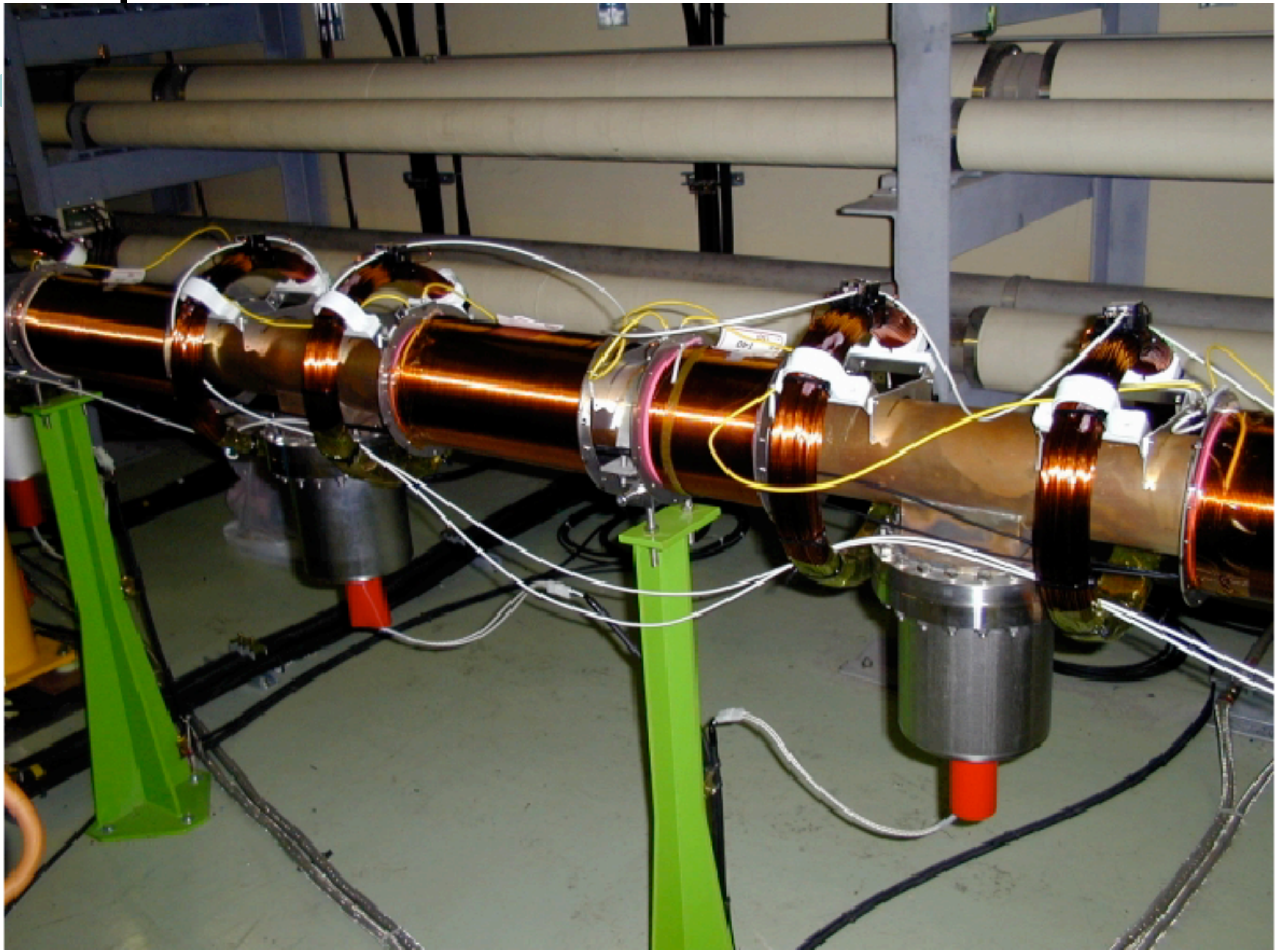
(3) Solenoids are wound in the straight section of *100m (Apr. 2001).

(4) Add solenoids even in short free space (August 2001).

(5) 95 % of drift space is covered (~2005).

(6) Solenoid in ¼ of quadrupole magnets (2005)

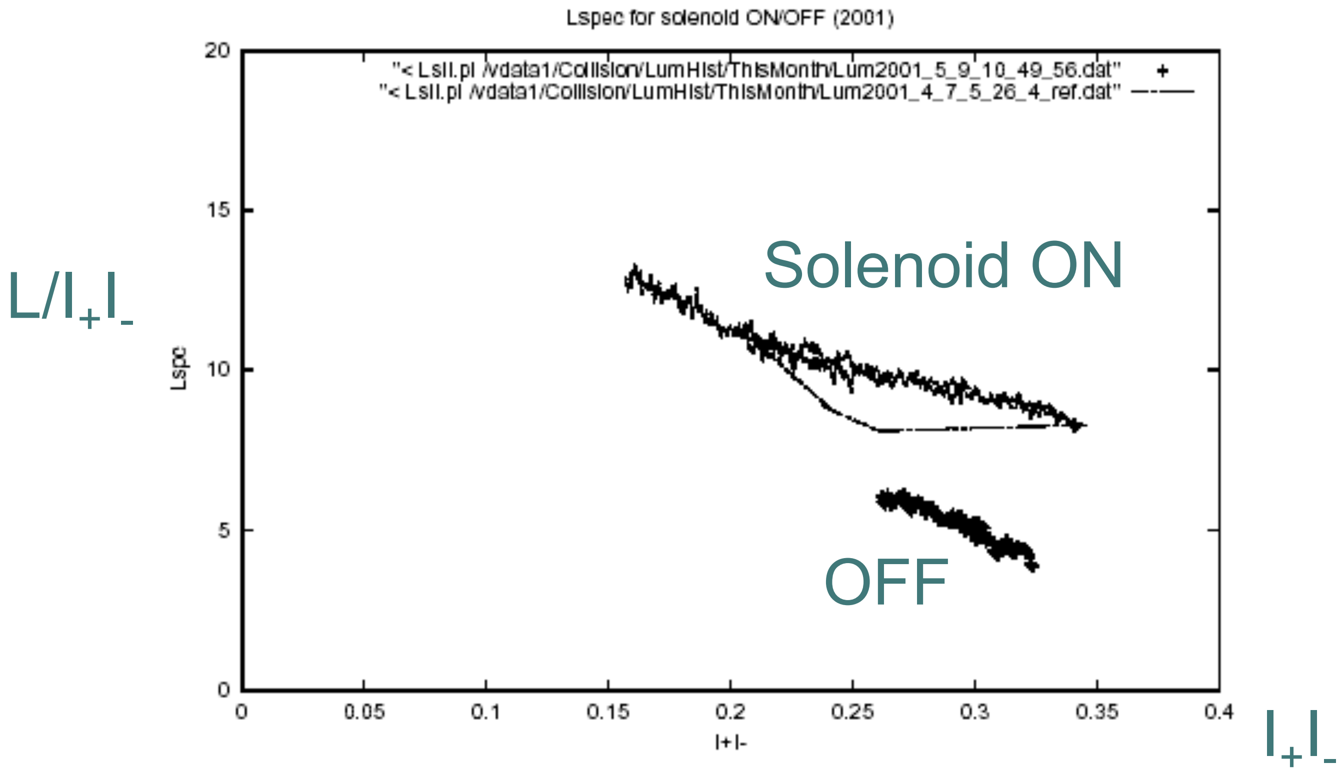

Solenoid magnets



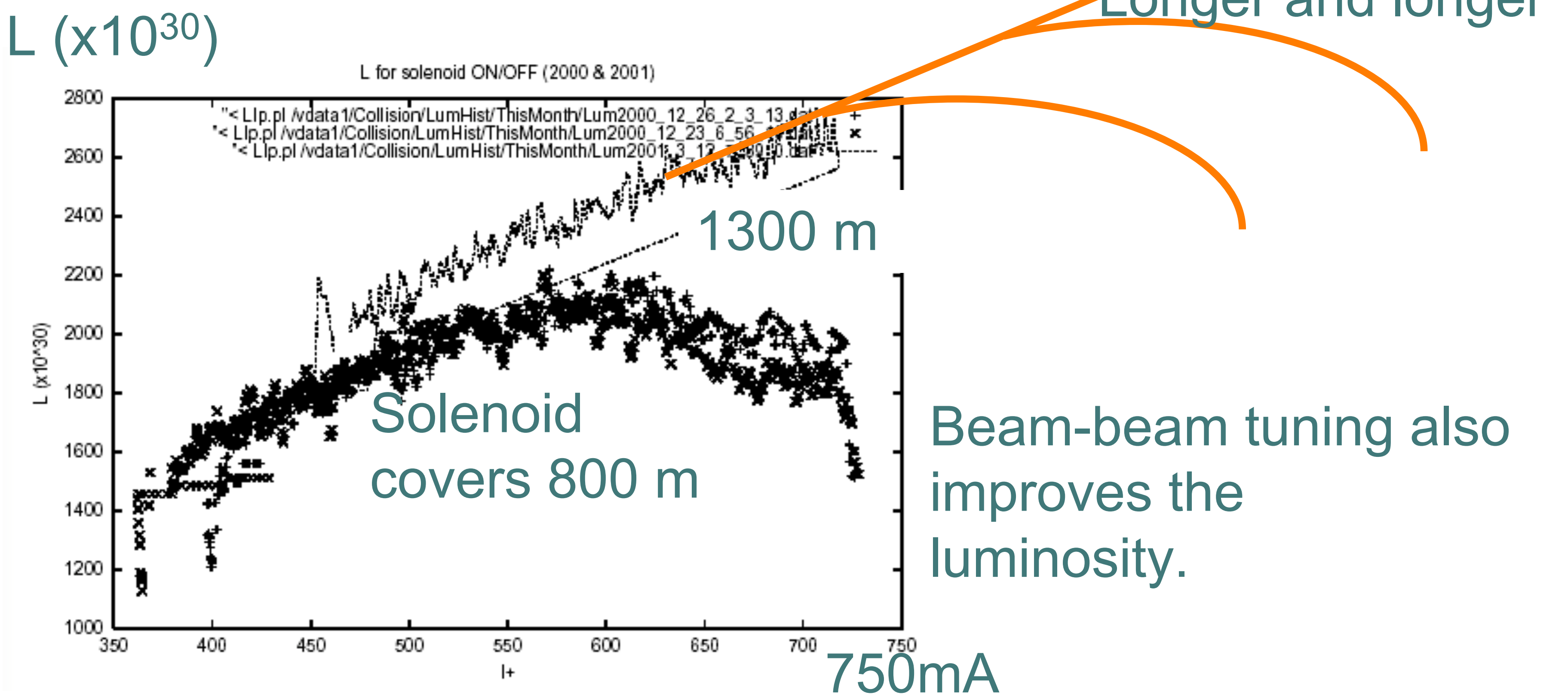
Luminosity for Solenoids ON/OFF

- 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)



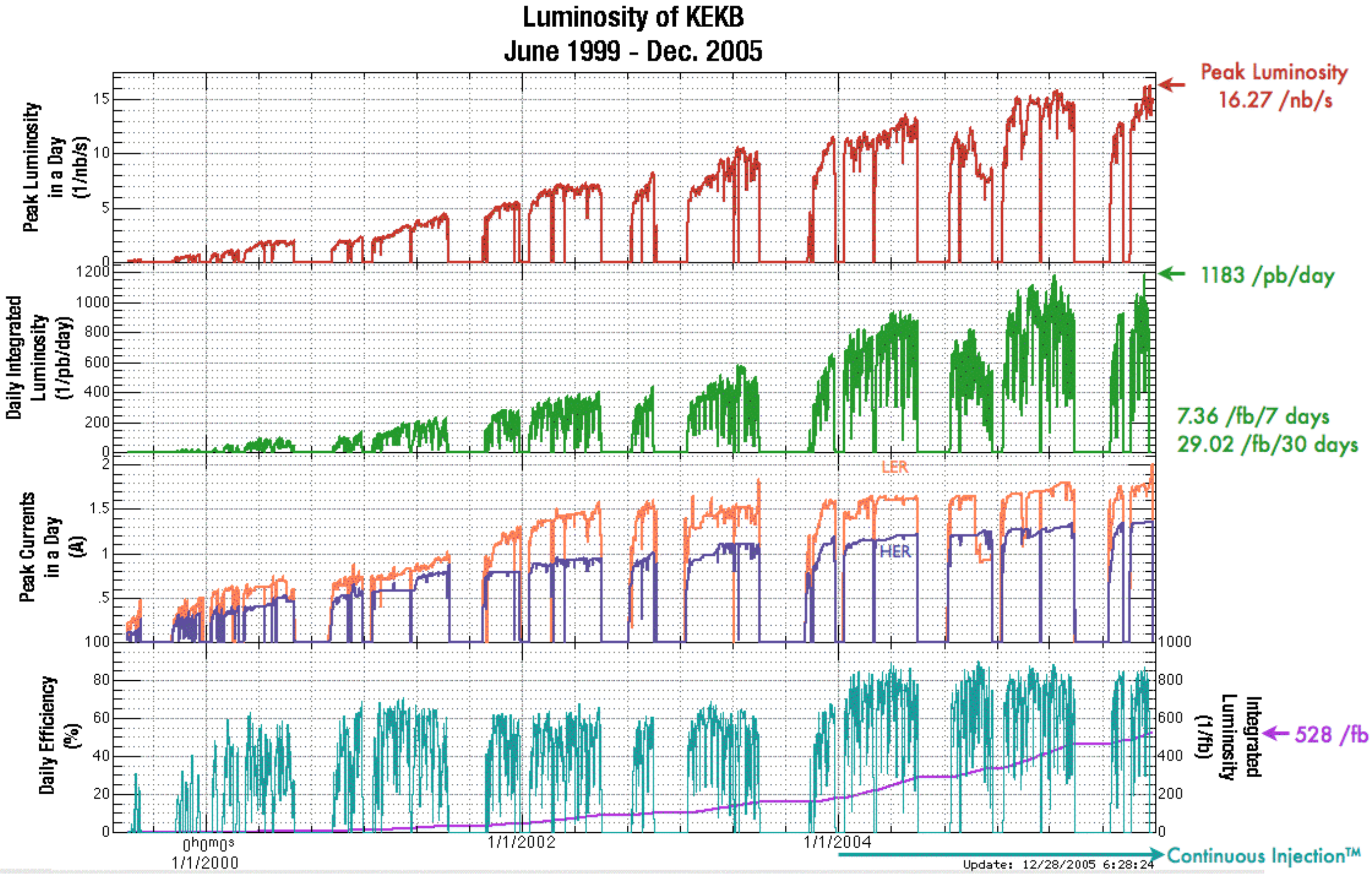
Effect of additional solenoid Typical luminosity behavior at Dec. 2000 and March. 2001



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

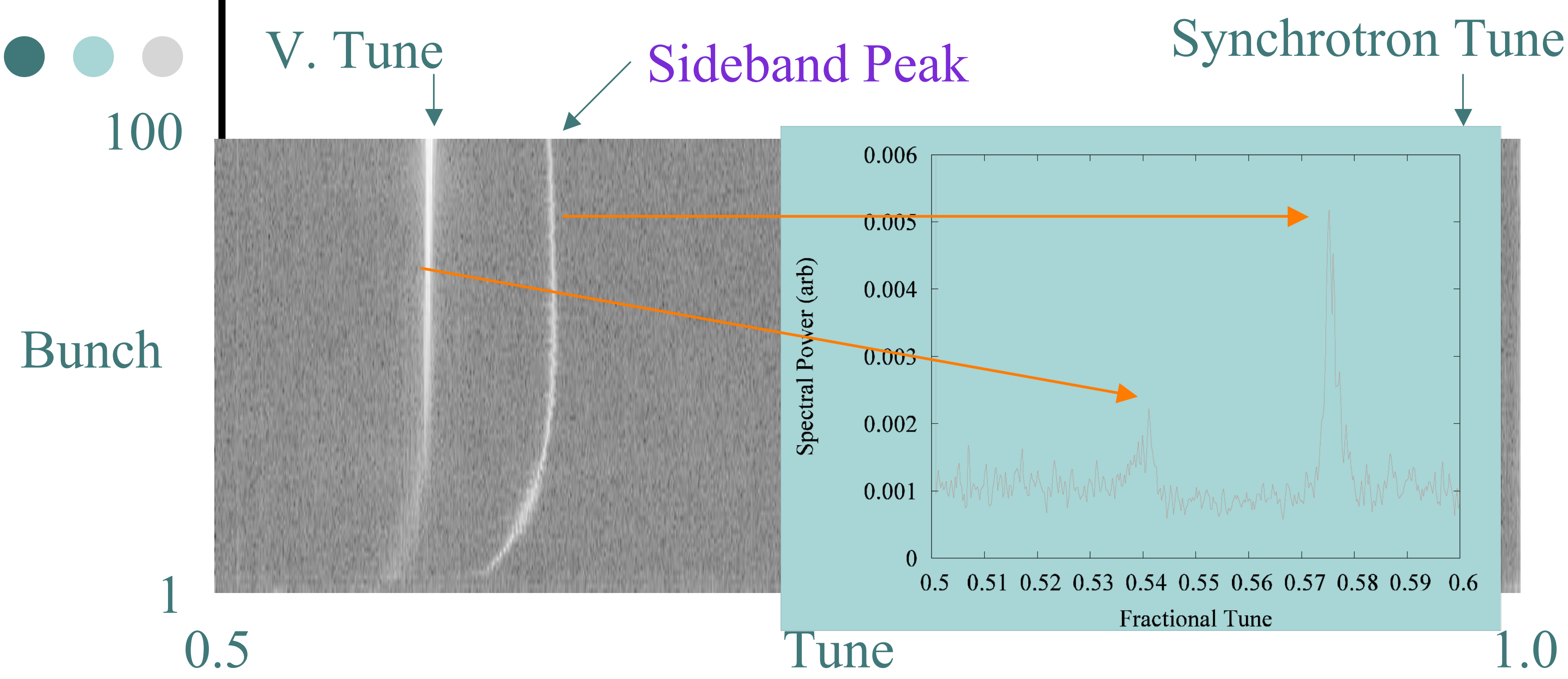


Measurement of synchro-beta sideband - evidence for head-tail instability

- 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 excitationBunch Spacing vs Spec. Lum.Luminosity-bunch current-sideband experiment
- Measure as a function of bunch current.
- Sideband is measured for noncolliding bunch.

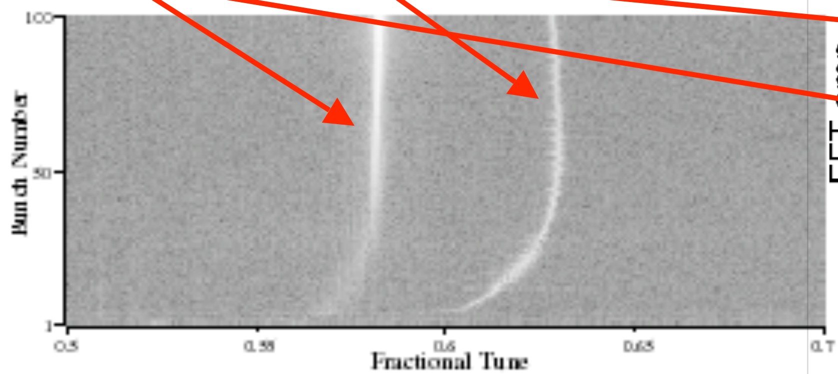
J. Flanagan et al., PRL94, 054801 (2005)

Electron cloud induced head-tail instability

- E. Benedetto, K. Ohmi, J. Flanagan
- Measurement at KEKB

Simulation (PEHTS) HEADTAIL gives similar results

Betatron sideband Tail of train



Head of train

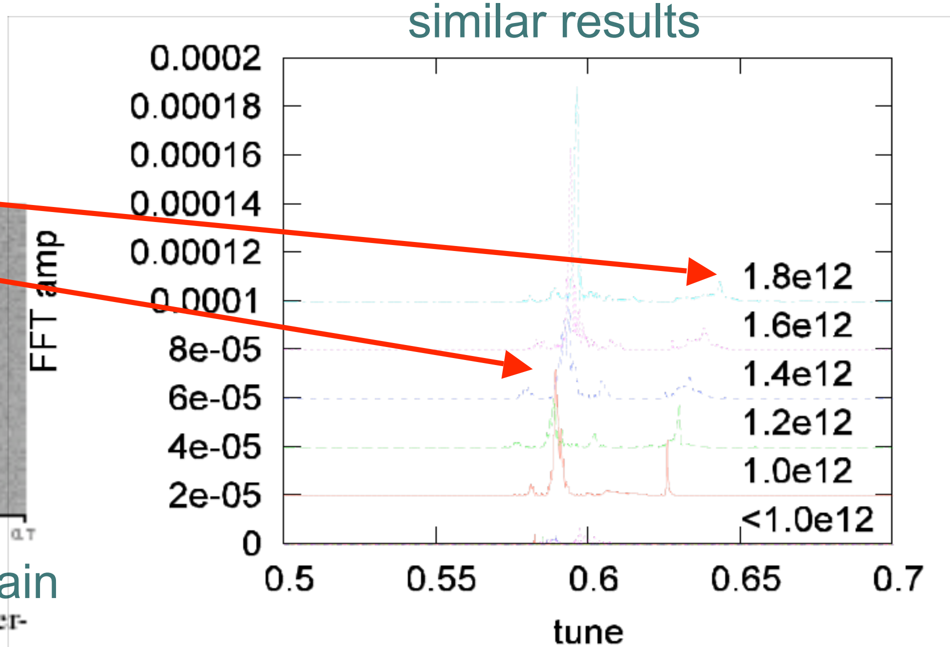
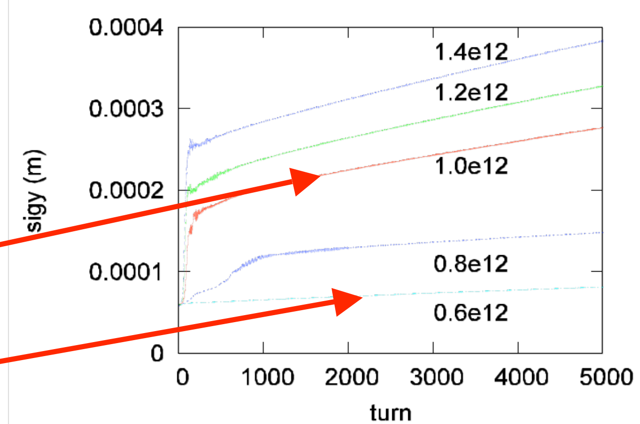


FIG. 1. Two-dimensional plot of vertical bunch spectrum versus bunch number. The horizontal axis is the fractional tune, from 0.5 on the left edge to 0.7 on the right edge. The vertical axis is the bunch number in the train, from 1 on the bottom edge to 100 on the top edge. The bunches in the train are spaced 4-rf buckets (about 8 ns) apart. The bright, curved line on the left is the vertical betatron tune, made visible by reducing the bunch-by-bunch feedback gain by 6 dB from the level usually used for stable operation. The line on the right is the sideband.



Head-tail regime

Incoherent regime

Feedback does not suppress the sideband

- Bunch by bunch feedback suppress only betatron

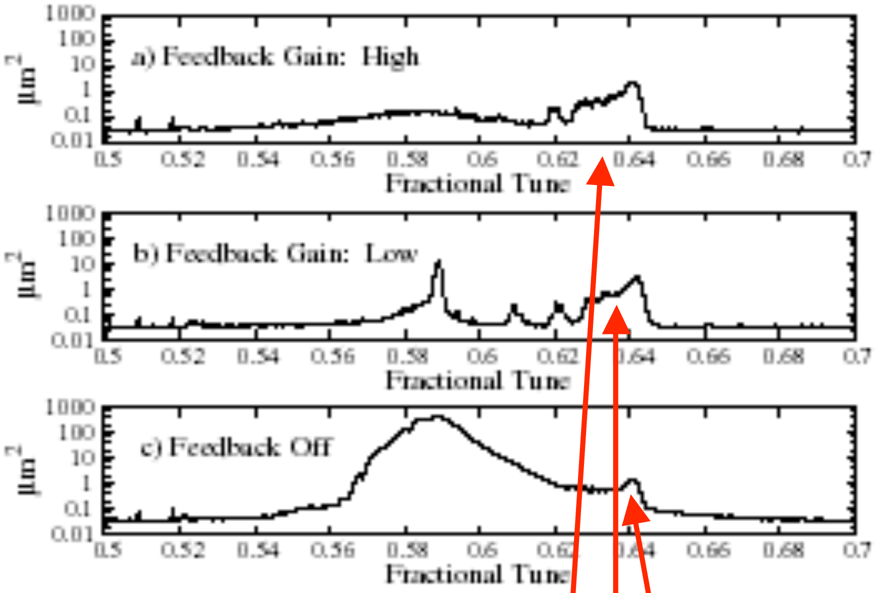
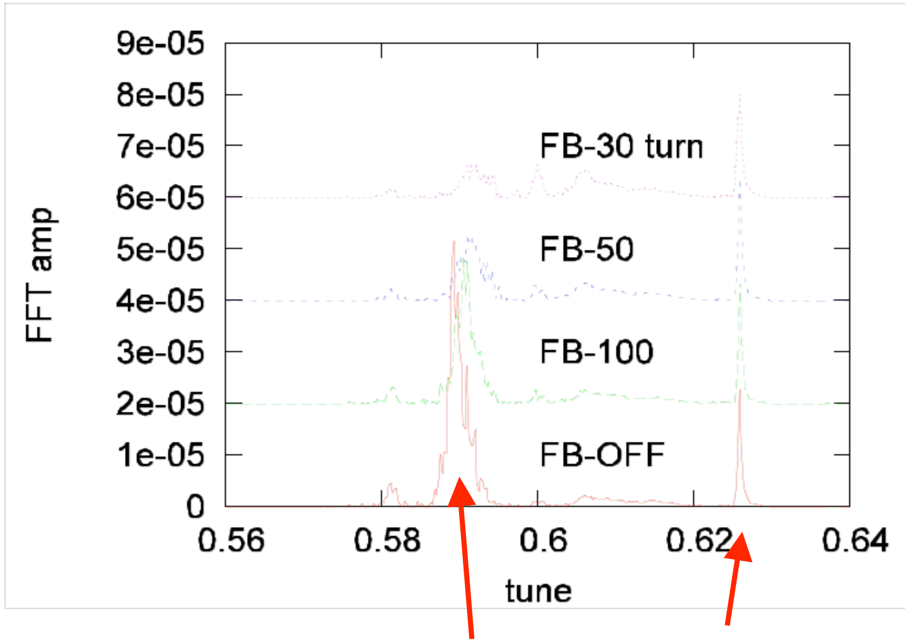


FIG. 2. Averaged spectra of all bunches with the feedback gain (a) high, (b) low, and (c) set to zero. The vertical betatron peak is visible at 0.588, and the sideband peak can be seen around 0.64.

Sideband signal is Integrated over the train

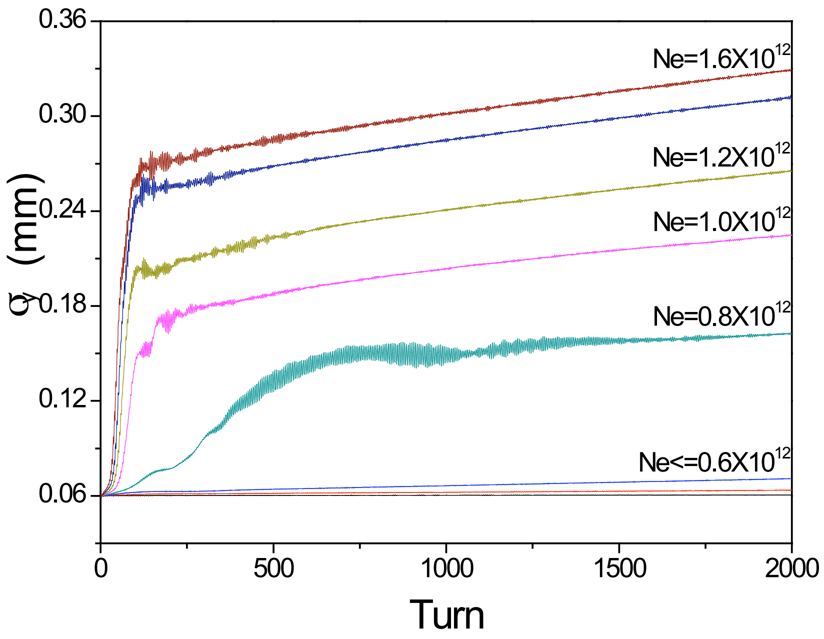


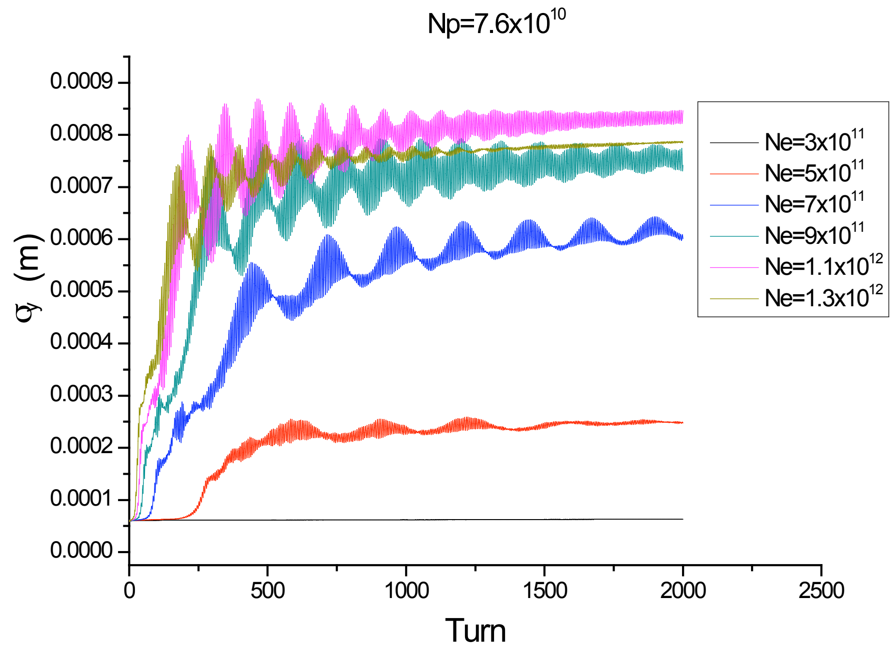
Simulation (PEHTS)

ILC damping ring: from experiences in KEKB

- Without solenoid, the strong head-tail instability occurs at 1000 bunch and 500 mA.
- Simulations (PEHTS) gives threshold density 0.8×10^{12} cm^{-3} at the beam parameters.
- With solenoid, the strong head-tail instability occurs at 1300 bunch and 1700 mA. Simulations gives threshold density 0.4×10^{12} cm^{-3} at the beam parameters.

N_+=3.3x10^{10}, 7.6x10^{10}

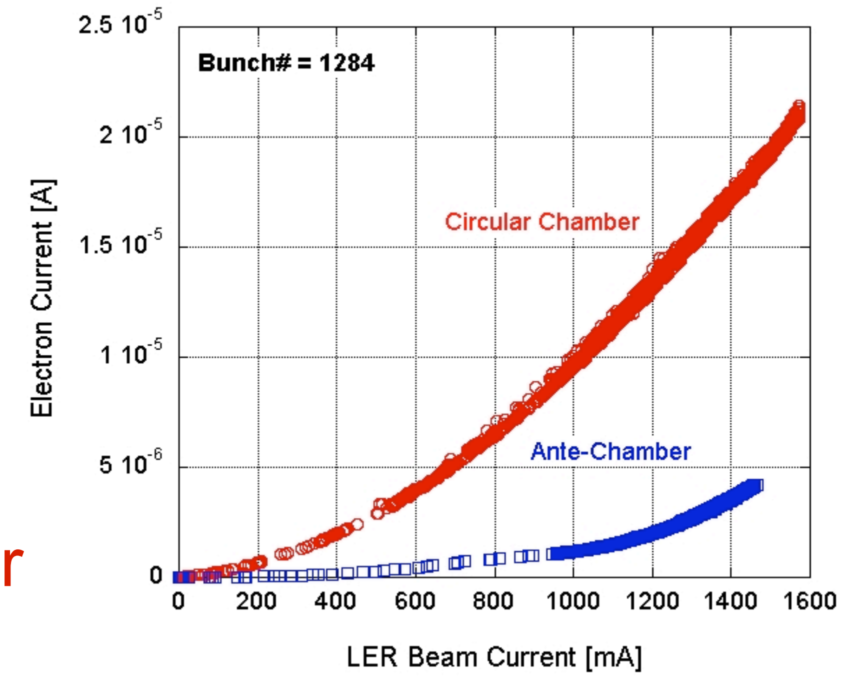




By H. Jin

Cloud density - current relation

- Electron current
- Cloud density is current times electron travel time.
- High current means a short travel time.
- The cloud density may approximately be linear for current in circular chamber.
- Solenoid reduces cloud density 1/6.
- Antechamber reduces cloud density 1/10 at <1A.



Measurement by Y.Suetsugu et al.

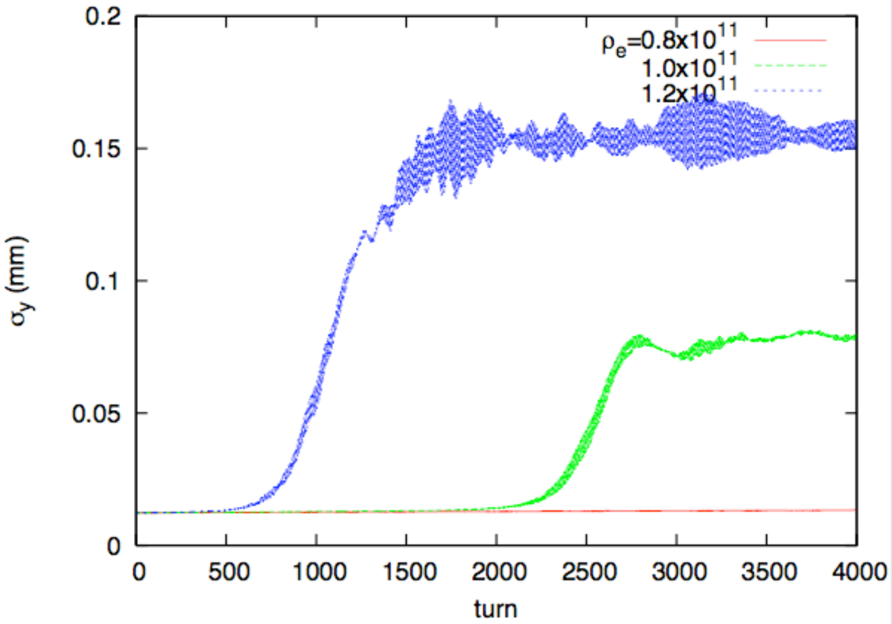
Low emittance operation in KEKB for ILC

	Nor ε	Nor ε	Low ε–I	Low ε–II
E (GeV)	3.5	3.5	2.3	5.0
N_+ (10^{10})	3.3	7.6	2.0	2.0
N_b	1000	1338	1250	2500
I (mA)	500	1700	400	800
ε_x (nm)	18	18	1.5	1.0
σ_z (mm)	6	7	9	9
ν_s	0.024	0.024	0.011	0.011
$\omega_e \sigma_z/c$	3.1	5.1	12.5	12.5
$\rho_{e,th}$(m^{-3})	$8x10^{11}$	$4x10^{11}$	$1x10^{11}$	$2.2x10^{11}$
ρ_e(m^{-3})	$8x10^{11}$	$4x10^{11}$	$0.6x10^{11}$	$2.7x10^{11}$

- ω_e: electron frequency in a bunch
- $\rho_{e,th}$: threshold density,
- ρ_e: estimated or predicted electron density for cylindrical chamber

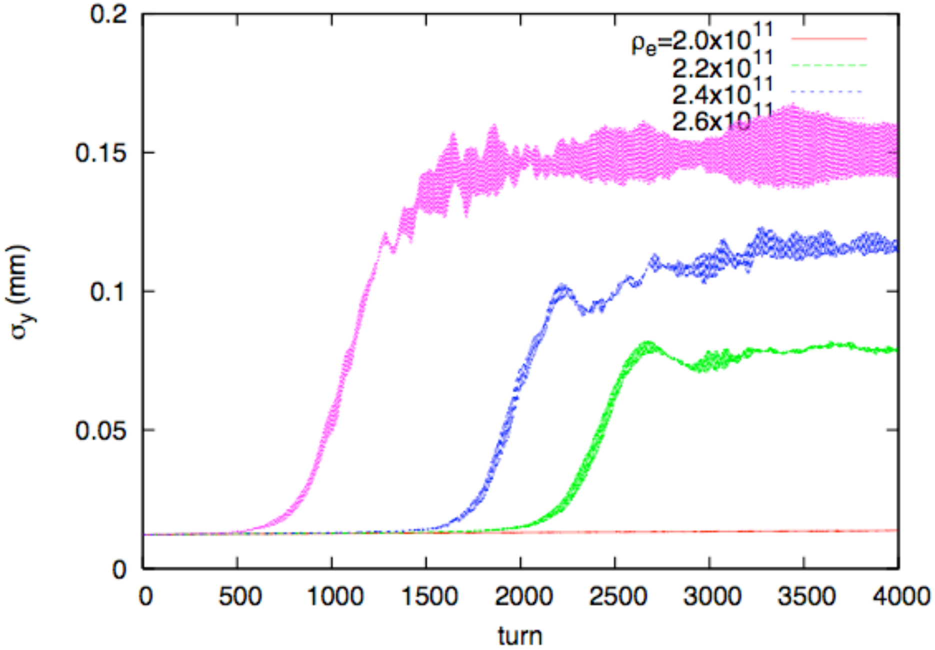
Threshold cloud density given by PEHTS at the Low emittance

2.3 GeV,



$\rho_{e,th}$=1.0x10^{11} cm^{-3}

5 GeV



$\rho_{e,th}$=2.2x10^{11} cm^{-3}

Cloud density and threshold at the low emittance operation

- Cloud density is not considered to depend on emittance strongly.
- Electron density is proportional to energy for the case of photoelectron dominant, and is also proportional to beam current.
- Current is 400mA which is 1/4.25 of the present KEKB.
- The cloud density at low $\varepsilon - I$ can be below the threshold.

- These should be studied experimentally at KEKB.

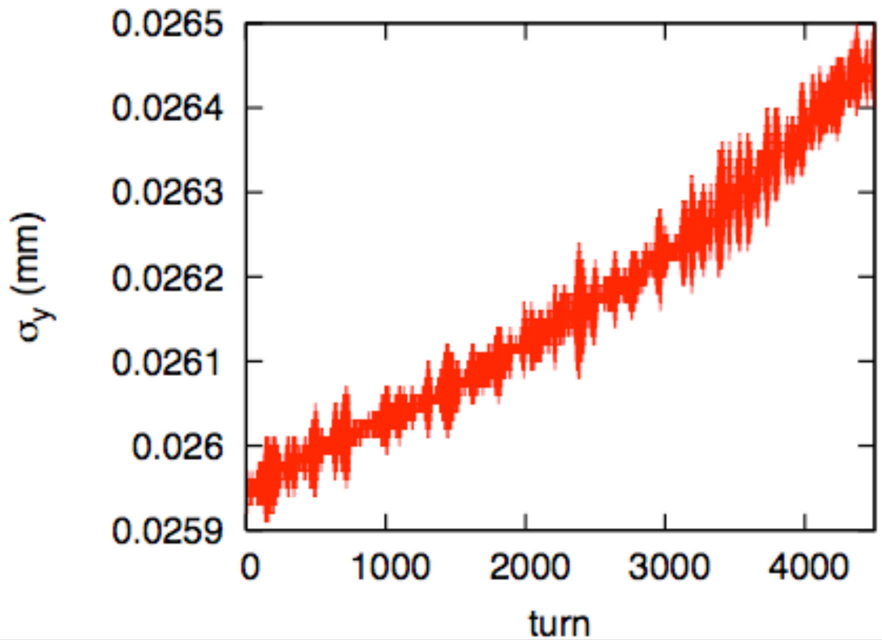
For actual Damping ring

- Higher energy gives high cloud density, but the threshold increases due to the larger γ factor.
- The scaling of $\rho_{e,th}/\nu_s$ was perfect for coherent instability in simulations and theory:i.e., a higher ν_s is higher threshold.
- Ante-chamber can suppress electrons further.
- The actual damping ring with 3000 m circumference, low ε–II, may be within the range depending on the study progress.

- The electron cloud instability does not seem to be very serious.

Incoherent emittance growth

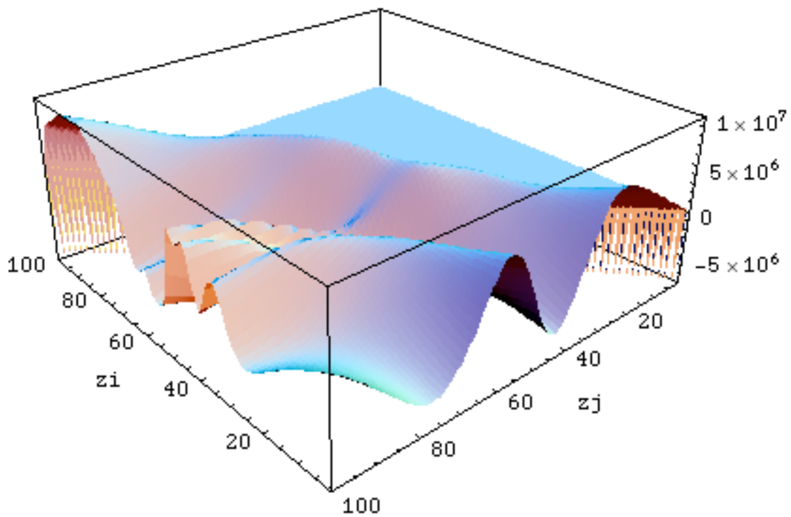
- Blow the coherent threshold.
- The growth is very slow compare than radiation damping rate.



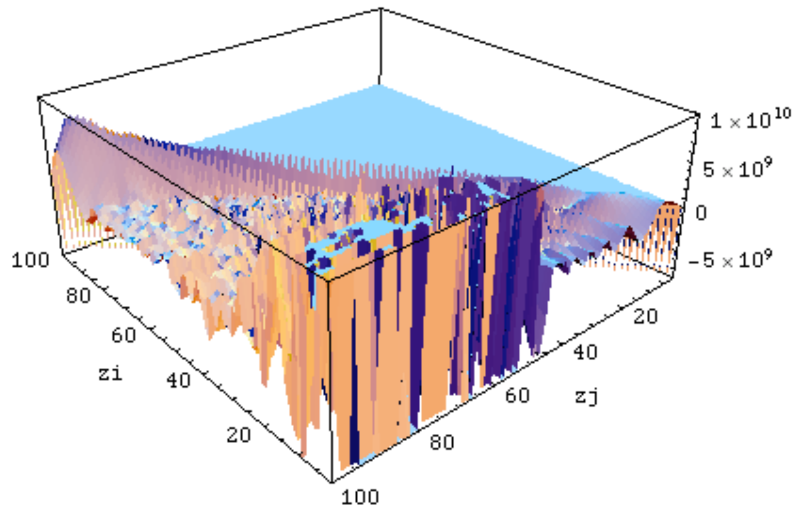
Model with normal cells and matching section of OCS

Two values wake field, $W(z_1,z_2)$ preliminary

- Z_1 and z_2 are perturbation and action position. Ordinary wake is $W(z_1-z_2)$.



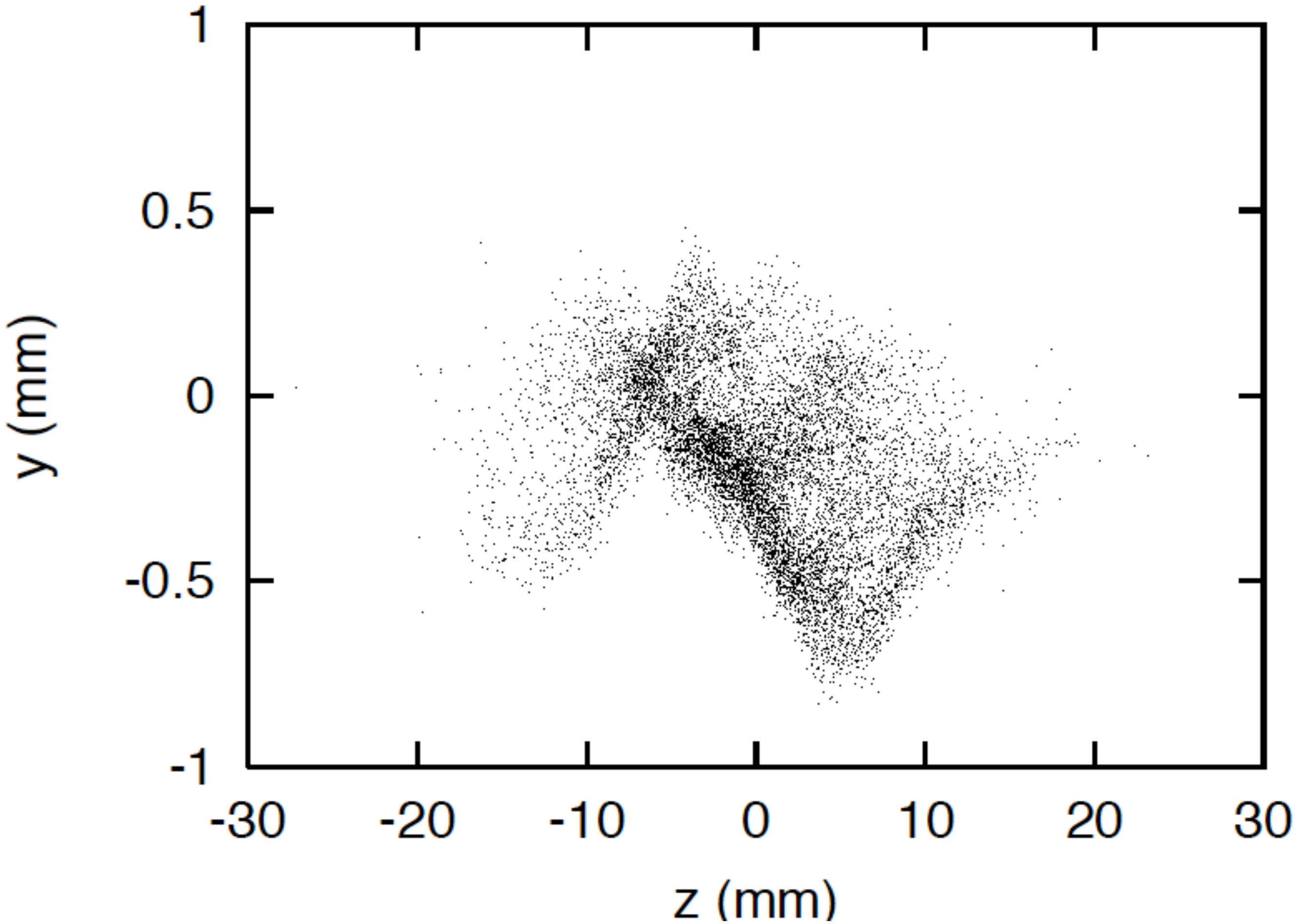
KEKB



ILC-DR

$$\Delta p(z) = \frac{Nr_e}{\gamma} \int W(z,z')\rho_y(z')dz'$$

Particle tracking using the wake (preliminary)



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.
- 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. Simulations also gave the sideband spectrum.
- The peak luminosity of KEKB is achieved 1.72×10^{34} $cm^{-2}s^{-1}$ by winding the solenoid magnets.
- The electron cloud instability does not seem to be very serious in ILC damping ring.
- Does the two values wake field model explain the sideband and other effects of electron clouds?