Coupled bunch instability cause by electron cloud History since 1995

K. Ohmi, KEK

ECLOUD04

19-23, 2004, Napa, California

History since KEK-PF instability

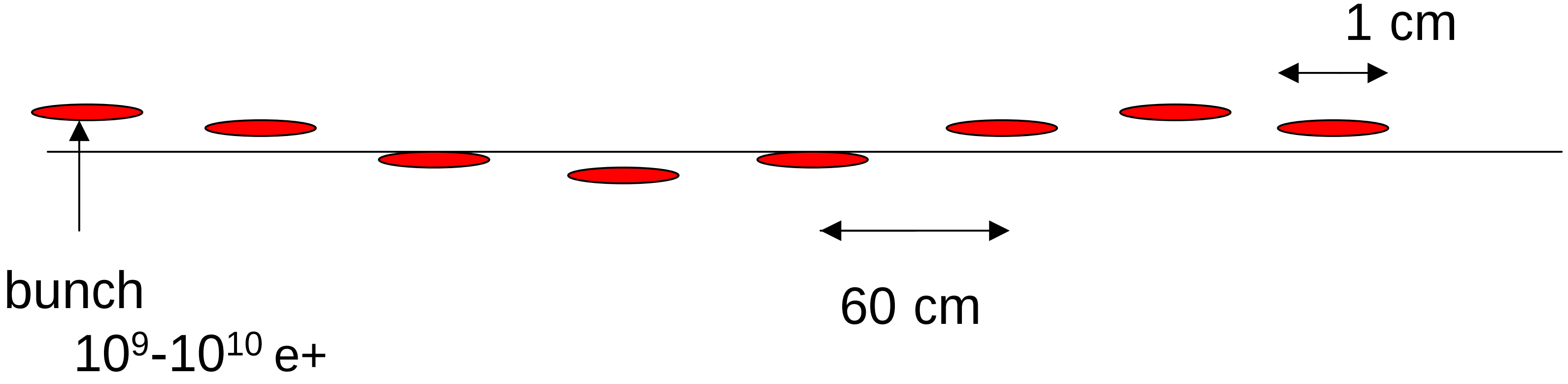
- An operation with positron storage had been planed to avoid ion trapping at KEK-PF. However since the operation had started (1988), a strong coupled bunch instability, which had not observed in electron storage, was observed.
- Interpretation with photoelectron cloud instability (1995).
- Reconfirmation at BEPC.
- Electron cloud measurement at APS.
- Studies toward KEKB and PEP-II.
- LHC, LC…many activities

Parallel history

- Multipacting at PSR.
- SNS, J-PARC,…
- LHC,LC

Coupled bunch instability in KEK-PF

- Coupled bunch instability was observed at positron storage. N_{bunch}=200-300, C=186 m, H=312.
- Very low threshold, I~15-20mA.
- The instability was not observed at electron storage.



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

BPM spectrum for V motion.

Electron 354 mA

Positron 324 mA &   240 mA

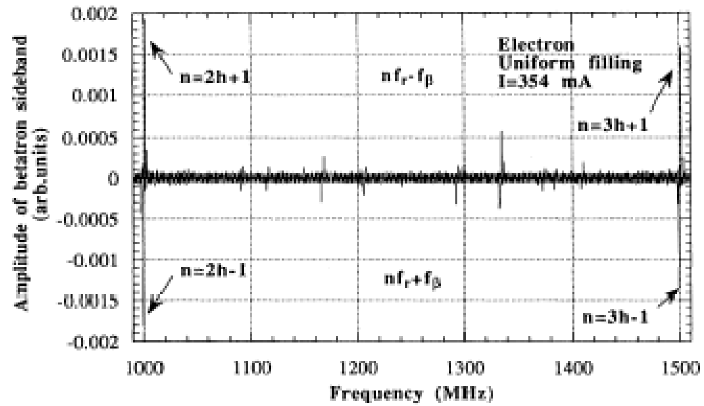


FIG. 1. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling.

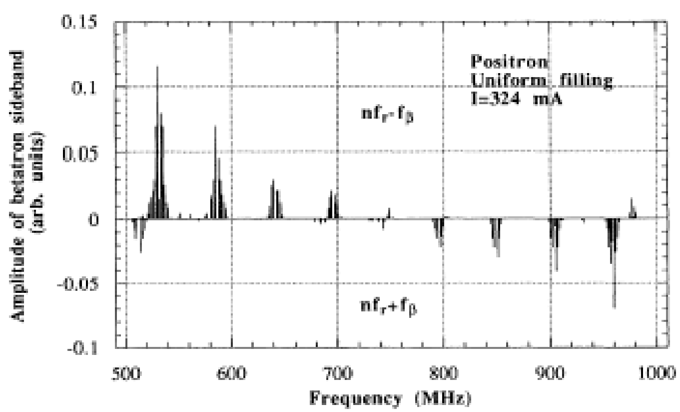


FIG. 2. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling.

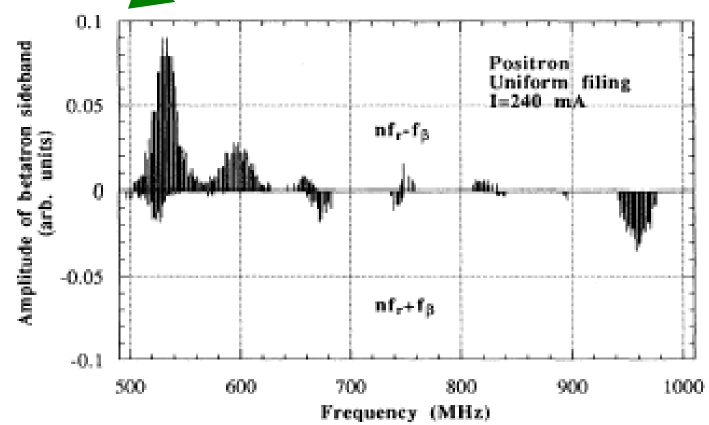


FIG. 3. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling. Only the stored current is different from Fig. 2.

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

Photon factory I=100mA

PRL,75,1526 (1995)

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

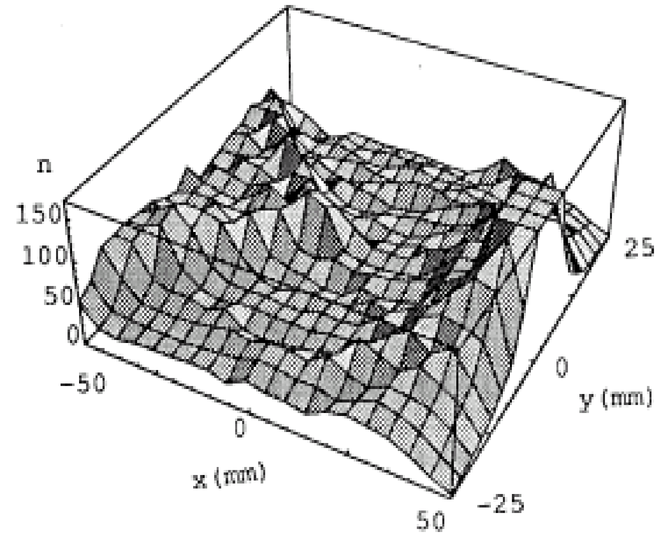


FIG. 2. A stationary distribution of photoelectrons with $\epsilon_0 =$ 5 eV.

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 2×10^6 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.

Equations of the beam-electron system

$$\frac{d^2\mathbf{x}_{p,i}}{ds^2} + K(s)\mathbf{x}_{p,i} = -\frac{2r_e}{\gamma}\sum_{a=1}^{N_e}\mathbf{F}(\mathbf{x}_{p,i} - \mathbf{x}_{e,a})\delta(s - s_e) \qquad (1)$$

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

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

$$\Delta\phi(\mathbf{x}) = \sum_{a=1}^{N_e}\delta^3(\mathbf{x} - \mathbf{x}_{e,a}) \qquad (3)$$

Electron cloud build-up

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

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

$$F \xrightarrow{x,y\approx\infty} \frac{(x,y)}{r^2}$$

$$F \xrightarrow{x,y\approx 0} \frac{1}{\sigma_x+\sigma_y}\left(\frac{x}{\sigma_x},\frac{y}{\sigma_y}\right)$$

- Solve Eq.(2) for $\mathbf{x}_{p,j}=0$.

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 and particle loss

- Ionization ($2x10^{-7}$ Pa)

  $Y_{1,i}=8x10^{-9}e^{-}/(m.p(e^{+}))$

- Particle loss , $4x10^{-8}$/m (PSR)

  $Y_{1,L}=4x10^{-6}e^{-}/(m.p)$

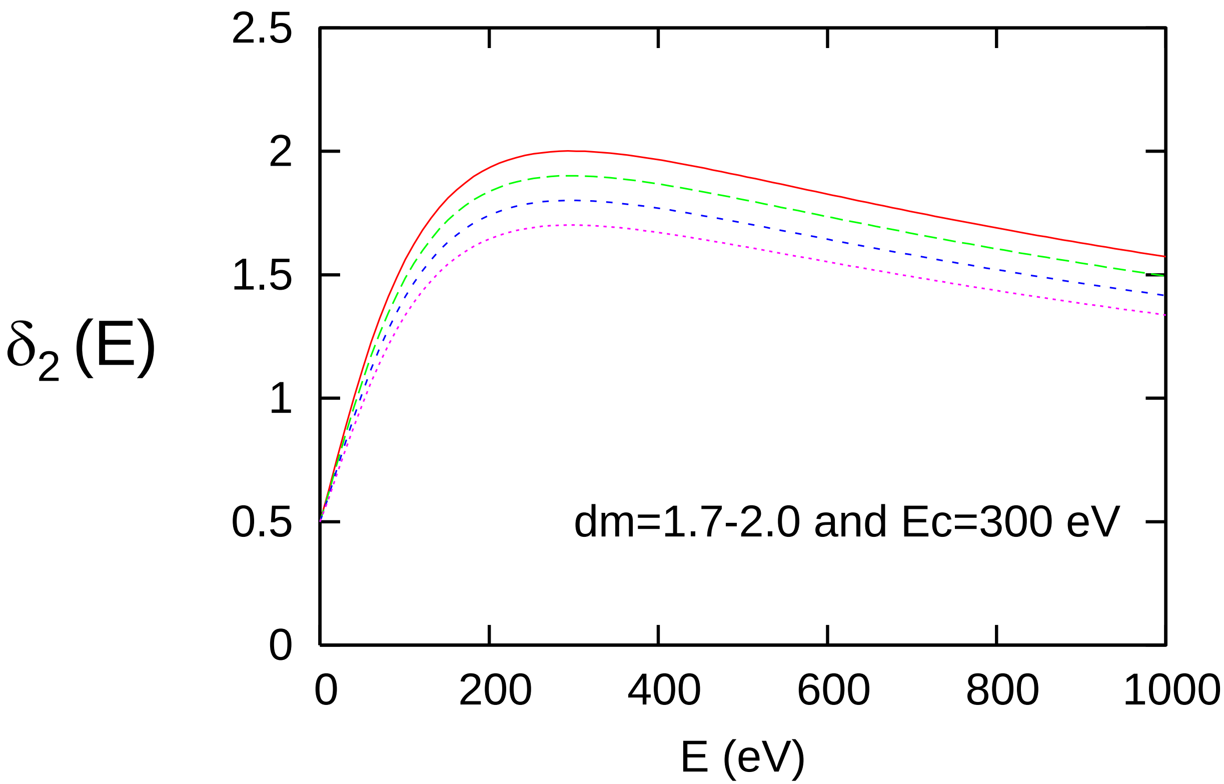
- H- conversion at Foil, 2/rep/L

  $Y_{1,L}=1x10^{-5}e^{-}/(m.p)$

  for example rep=500 and L=300m (JPARC-RCS)

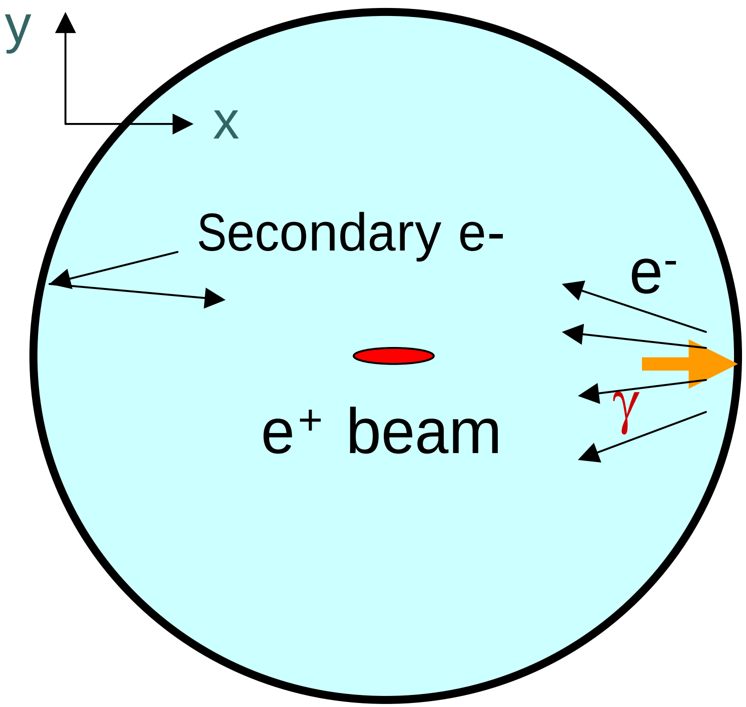
Multipactoring

Number of electrons produced by an incident electron with an energy E.



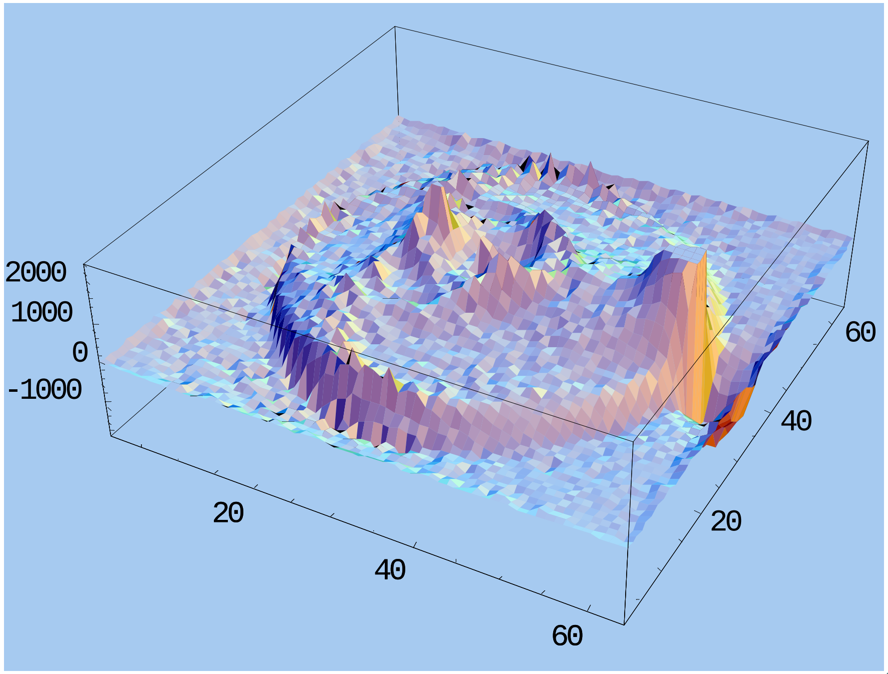
Model and simulation of the electron cloud build-up

Model

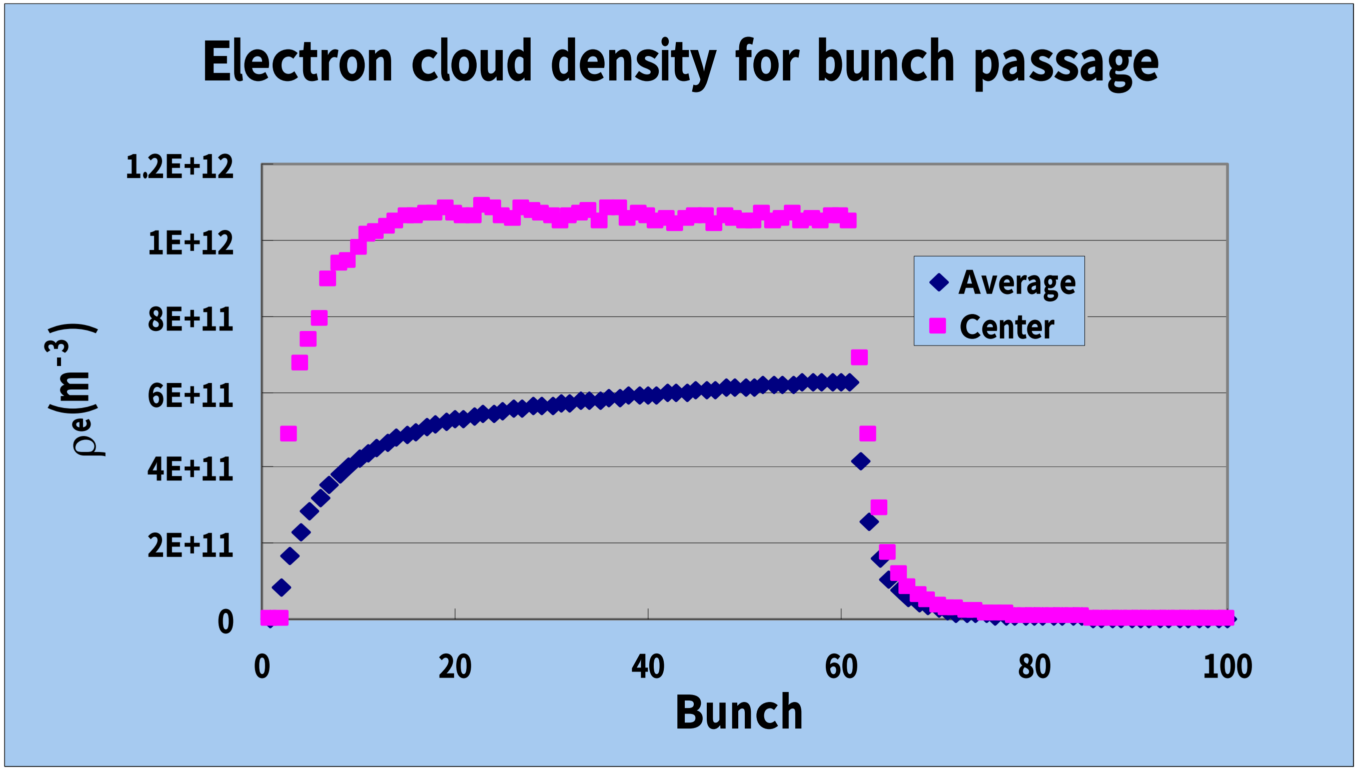


Beam chamber

Electron cloud density

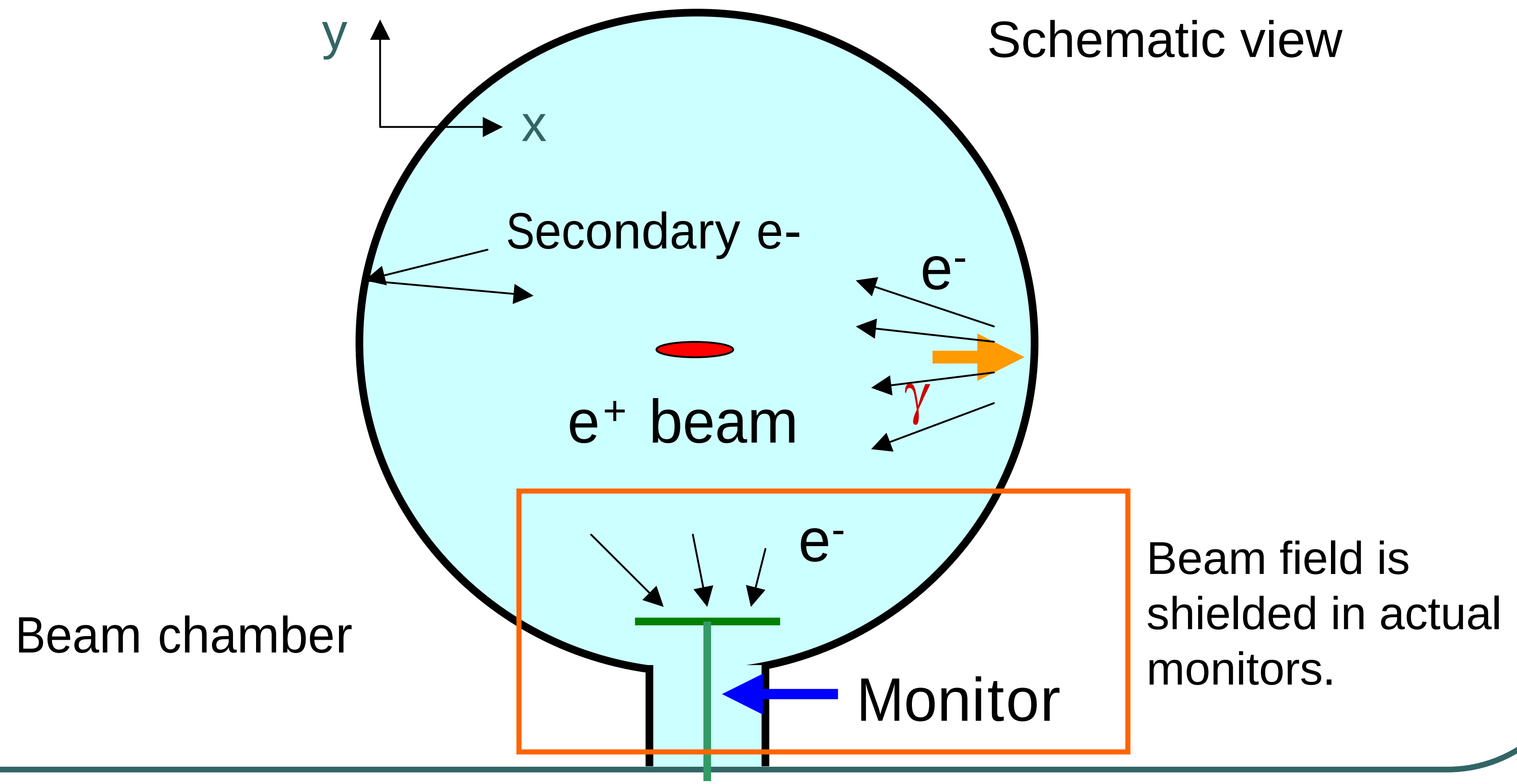


Density of electron cloud

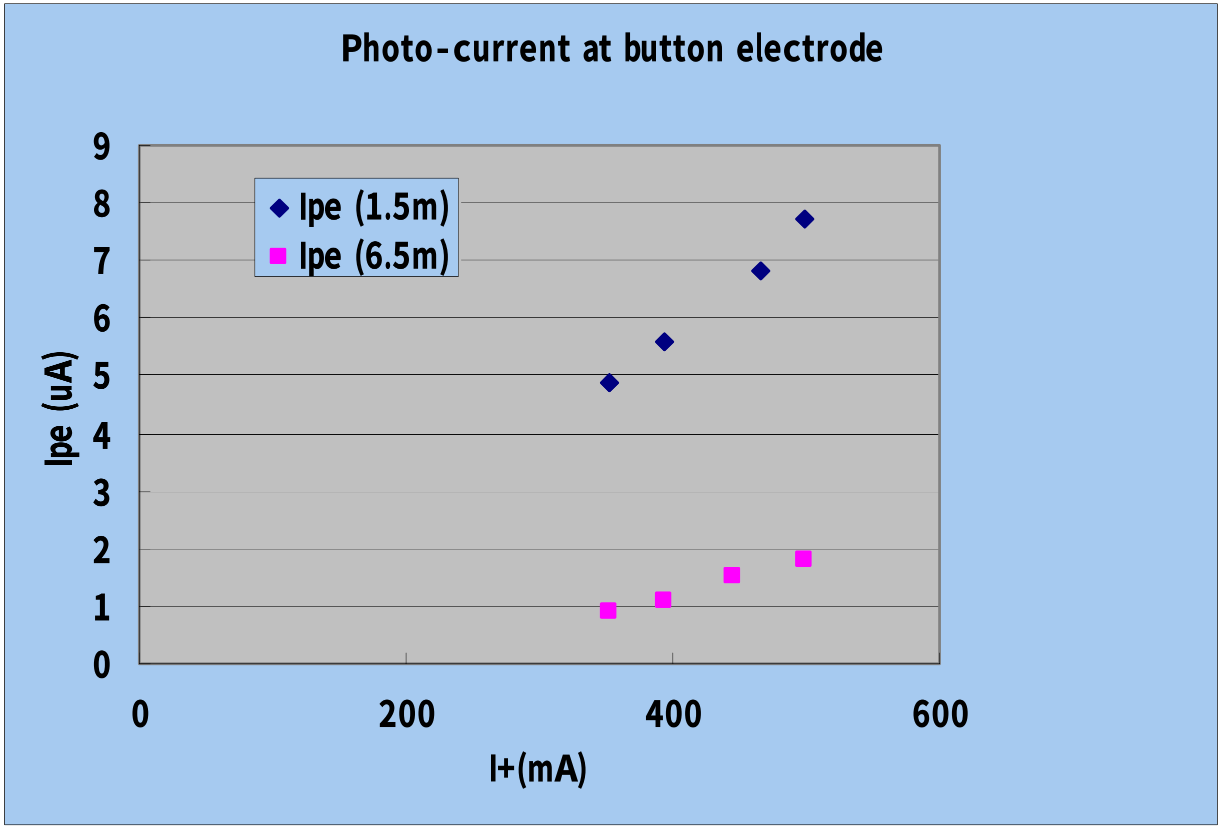


60 bunches pass in every 8ns (KEKB).

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

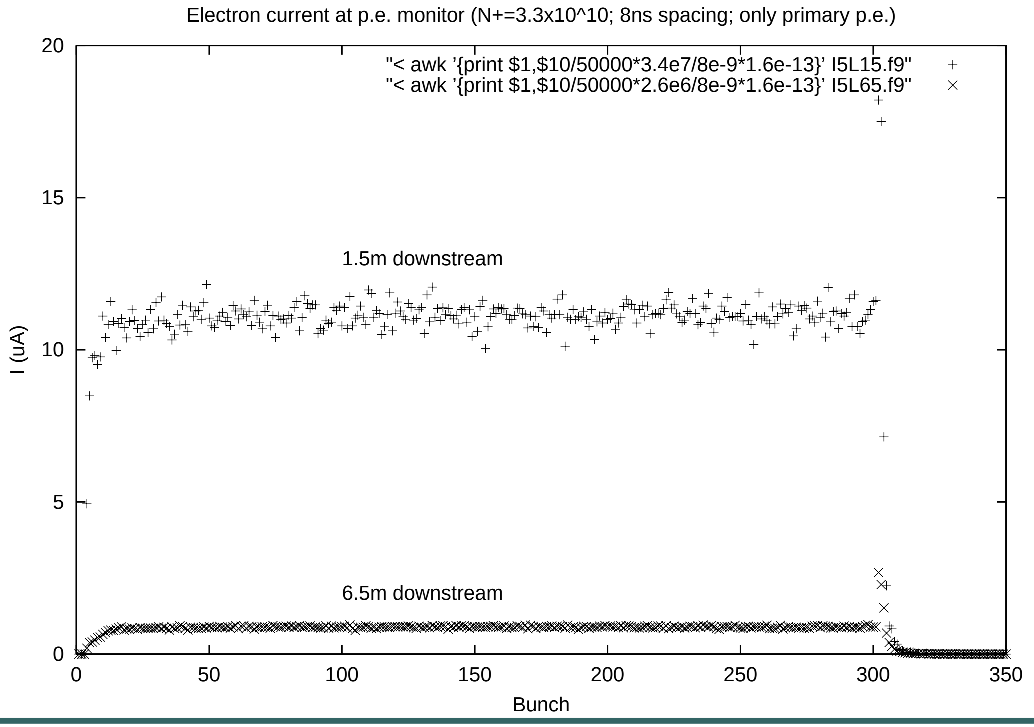


Electron current measured by the monitor

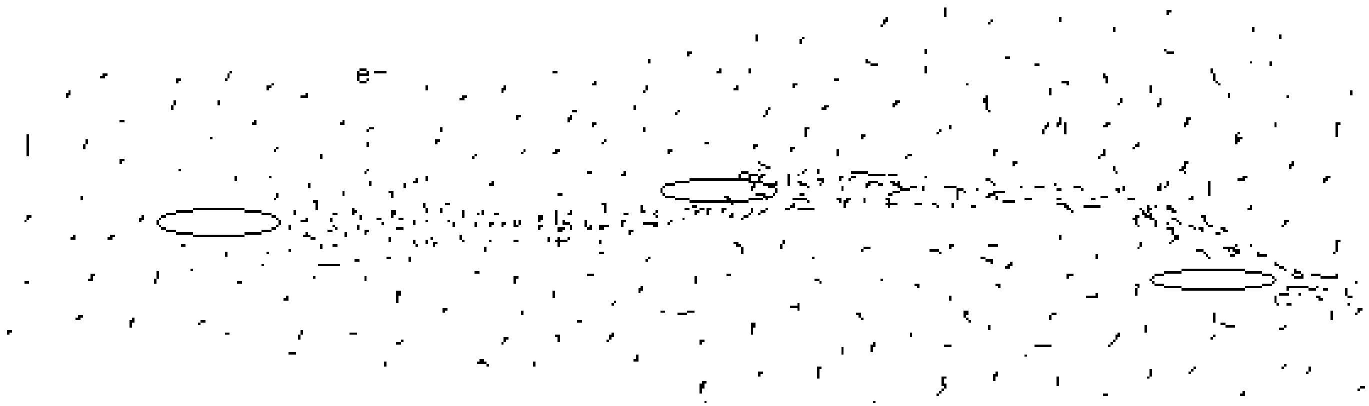


Simulation of the measurement

- Well coincides with experiments.
- We understand production and motion of photoelectrons.



Mechanism of coupled bunch instability caused by electron cloud



- Wake force is induced by photoelectron cloud.
- Beam instability is caused by the wake force,with the result that the beam loss occurs.

Instability evaluation with the wake force

- Motion of bunches is assumed to be expressed as

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

$W(z_n-z_m)$： 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. The force linearly depends on y_m. The coefficient is defined as W.

Estimation of the wake force with 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. The equilibrium distribution is obtained by a series of bunches without displacement.
- 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 for KEK-PF

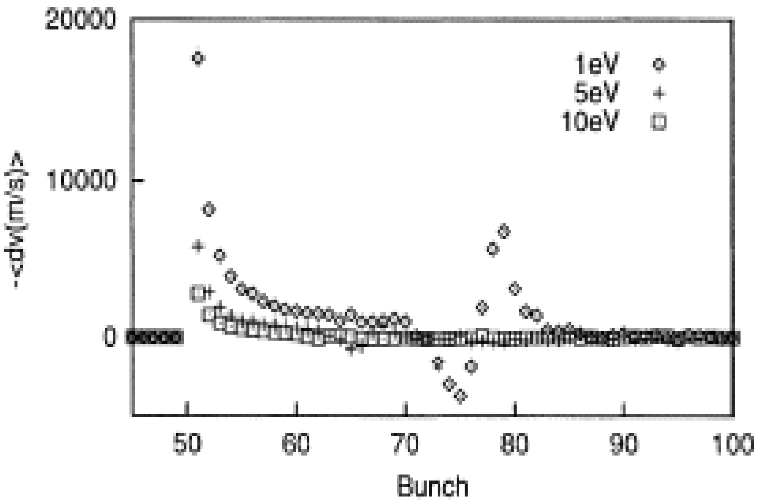


FIG. 3. Wake forces for each initial photoelectron energy. To obtain the wake, 10^6 virtual electrons in every bunch were used.

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

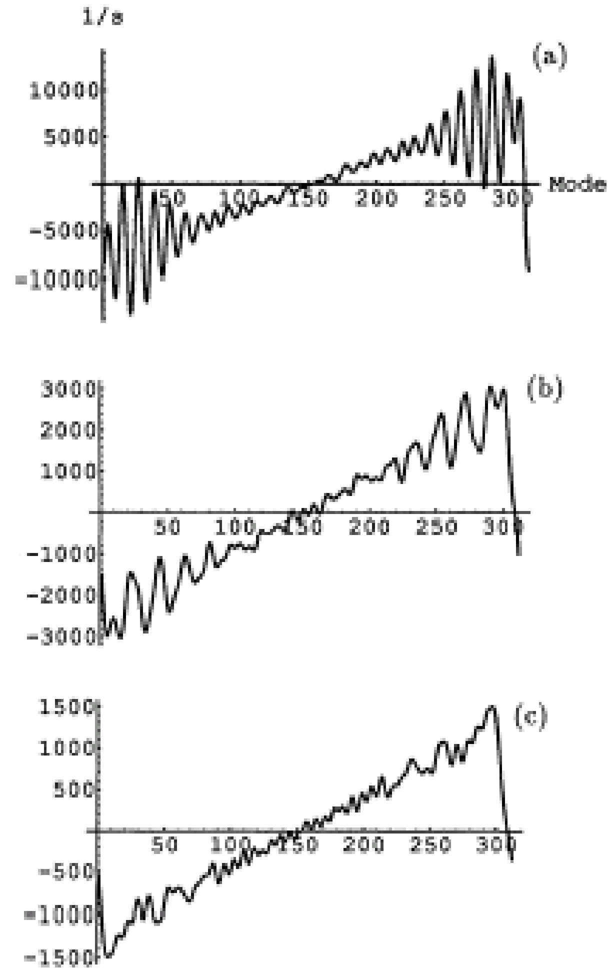
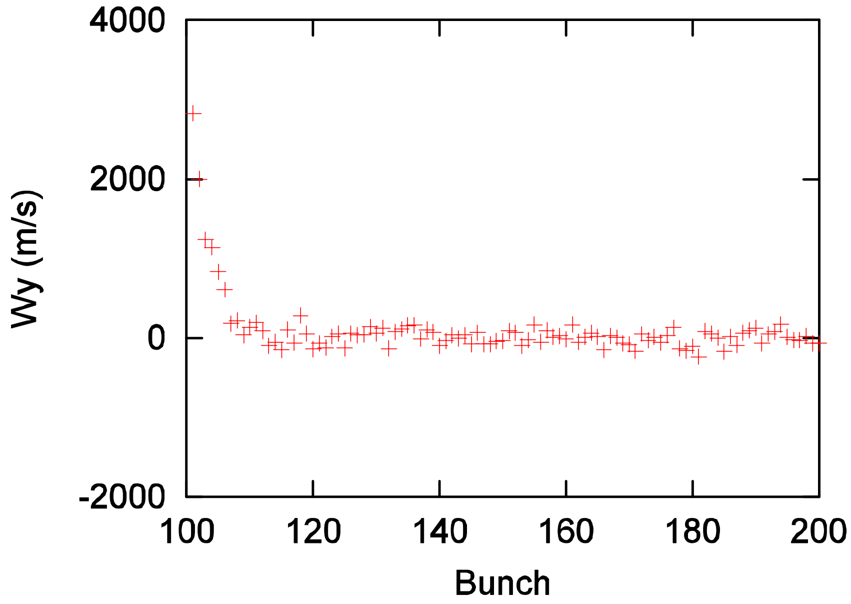


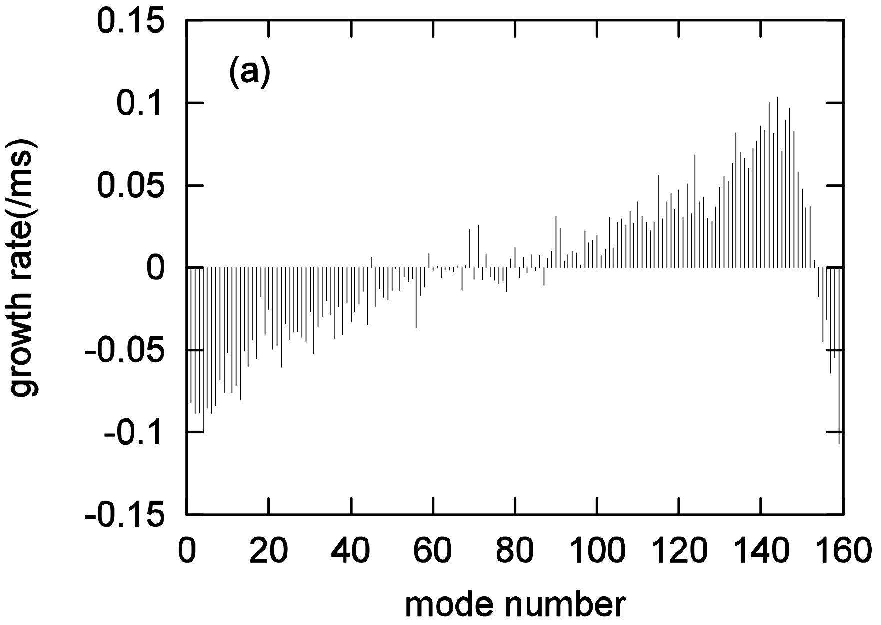
FIG. 4. Growth rates of the coupled-bunch instability. The positive values mean unstable modes. The wakes of 51 to 100 bunches in Fig. 3 were summed with Eq. (8). (a) $\epsilon_0 = 1$ eV. (b) $\epsilon_0 = 5$ eV. (c) $\epsilon_0 = 10$ eV.

IHEP(Beijing)-BEPC

Vertical wake



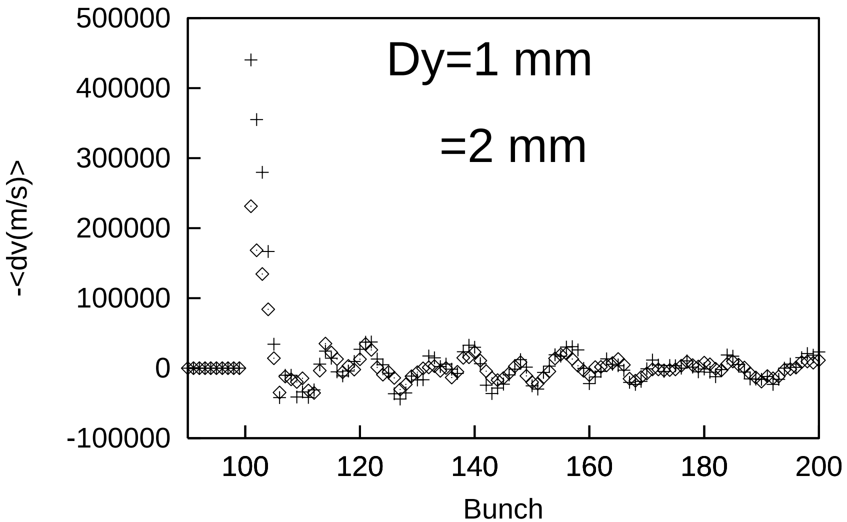
Growth mode

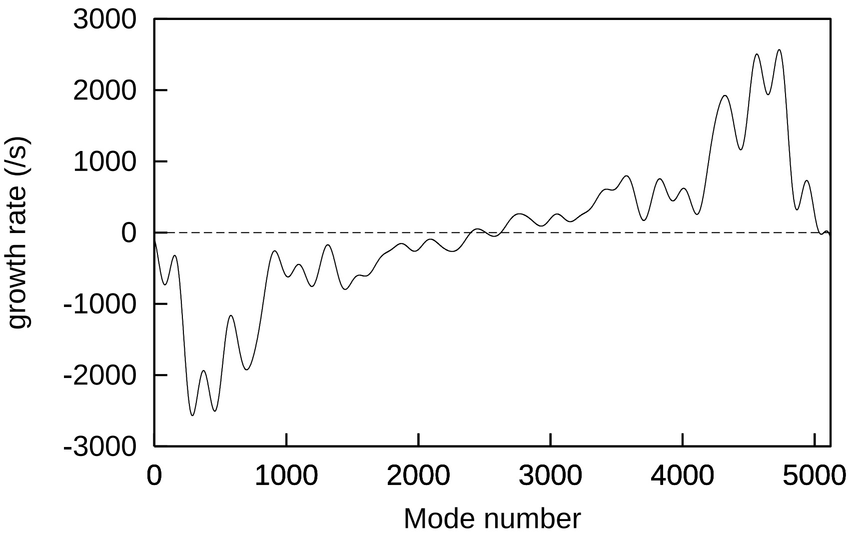


Guo, et al, PRST (2002).

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





KEKB design report (1996 or 7)

Linearity of the wake force

- In above example, the linearity of the wake is no problem for first several bunches.
- When some part of electrons are trapped, the wake force has long tail. Such the long range tail of wake force does not have good linearity for the displacement.
- Solenoid traps electrons and gives wake with a frequency related to the cyclotron frequency. The linearity of this wake is questionable.

Tracking simulation

K.Ohmi, PRE55,7550 (1997)

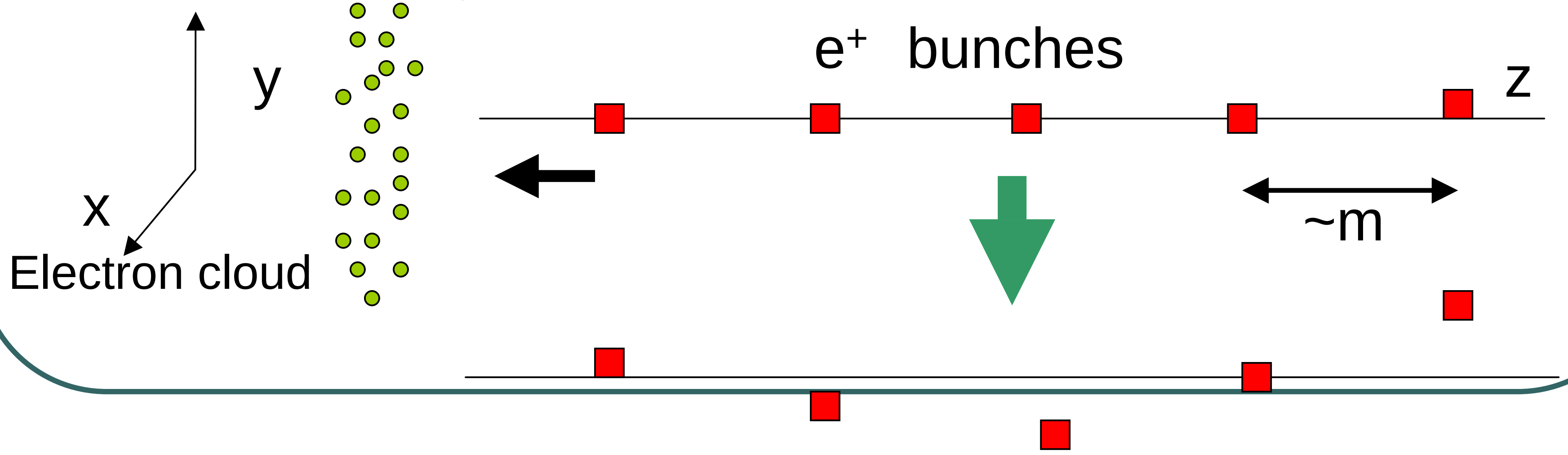
K.Ohmi, PAC97, pp1667.

Solve both equations of beam and electrons simultaneously

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

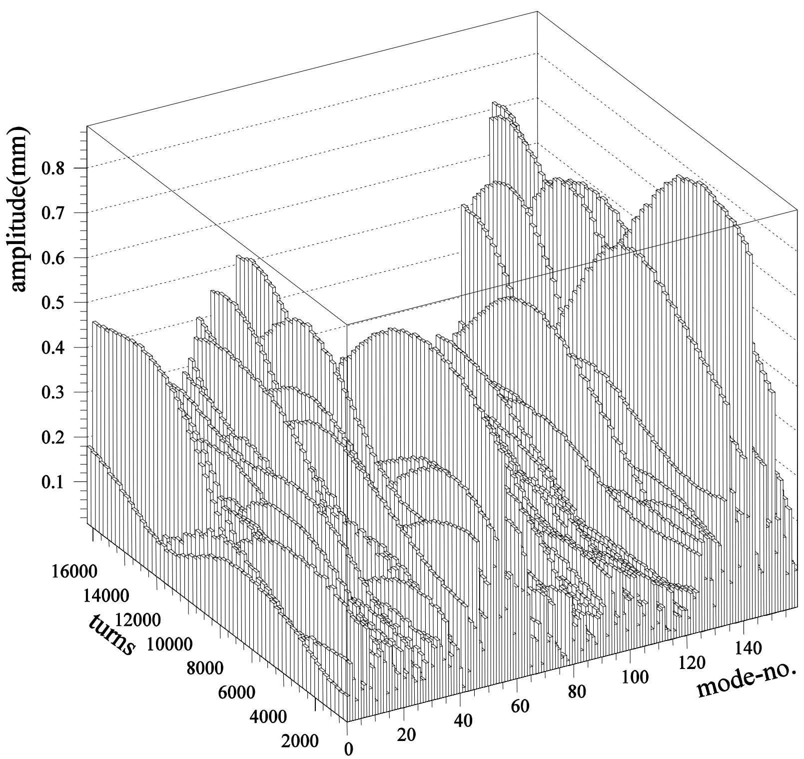
$$\frac{d^2\mathbf{x}_{e,a}}{dt^2} = \frac{e}{m}\frac{d\mathbf{x}_{e,a}}{dt}\times\mathbf{B} - 2N_p r_e c\sum_n\sum_{i=1}^{N_b}\mathbf{F}(\mathbf{x}_{e,a} - \mathbf{x}_{p,i})\delta(t - t_i(s_e + nL))$$

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

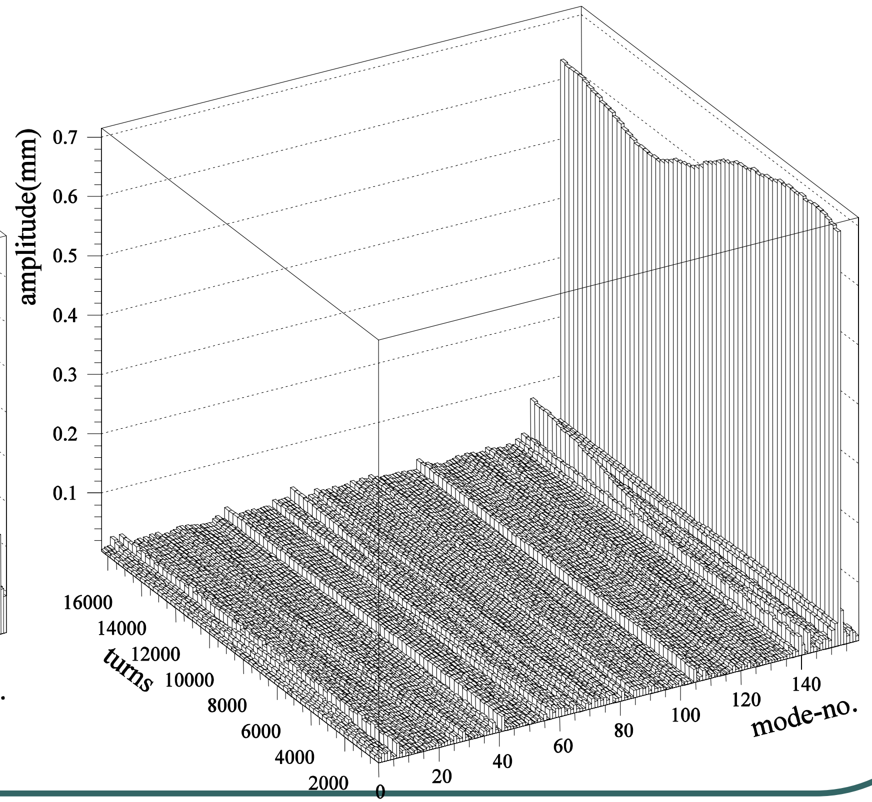


BEPC mode spectra by Single Path Beam Position Monitor (measurement)

Positron



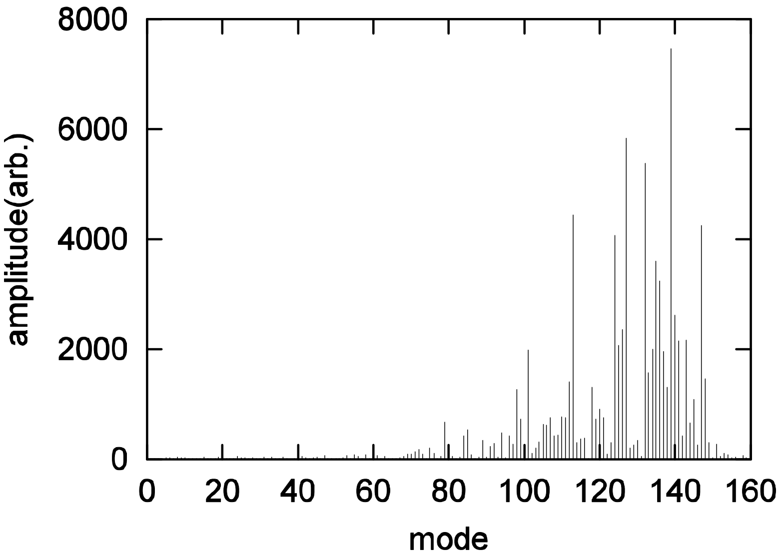
electron



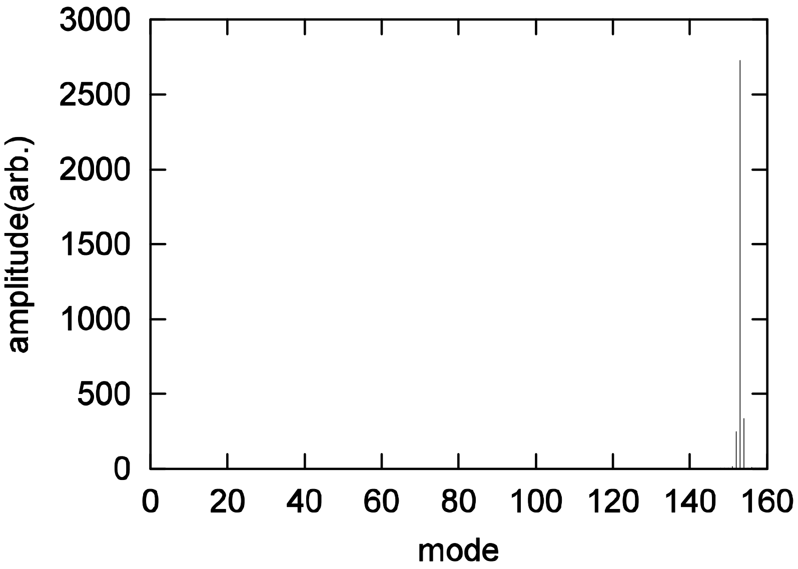
Guo, et al, PRST (2002).

BEPC mode spectra by tracking simulation

Positron



electron

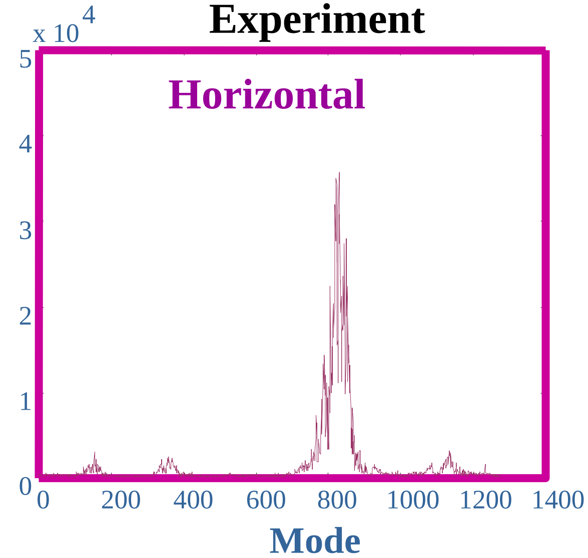


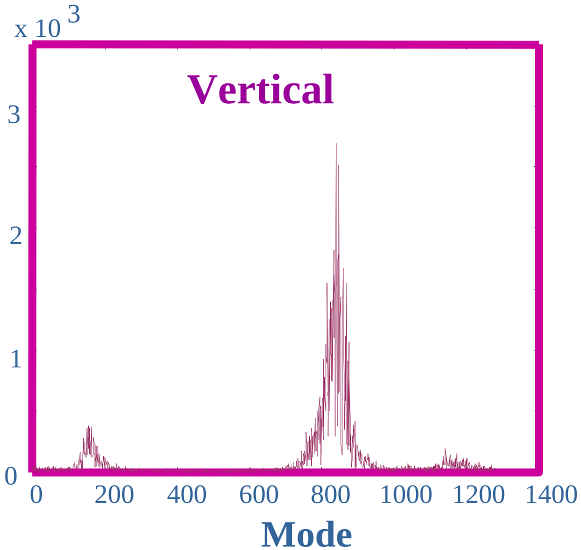
Guo, et al, PRST (2002).

KEKB

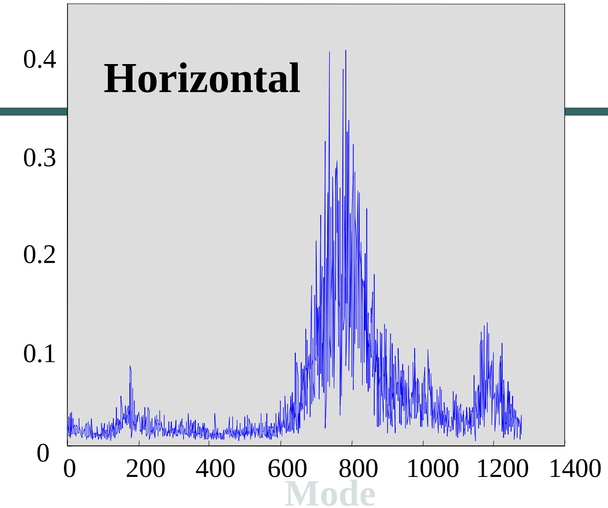
Solenoid-Off

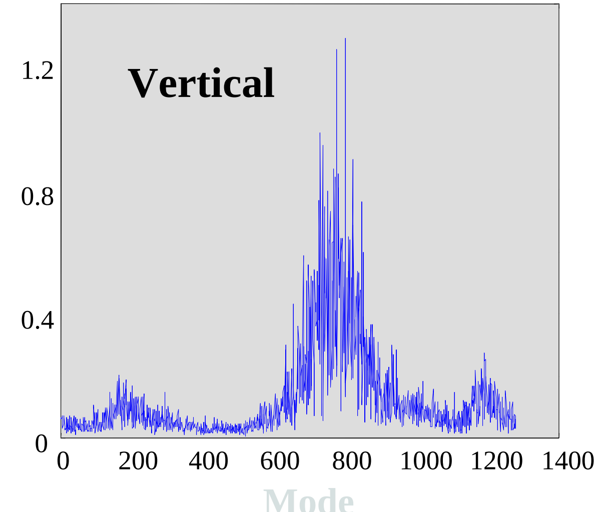
Experiment





Simulation



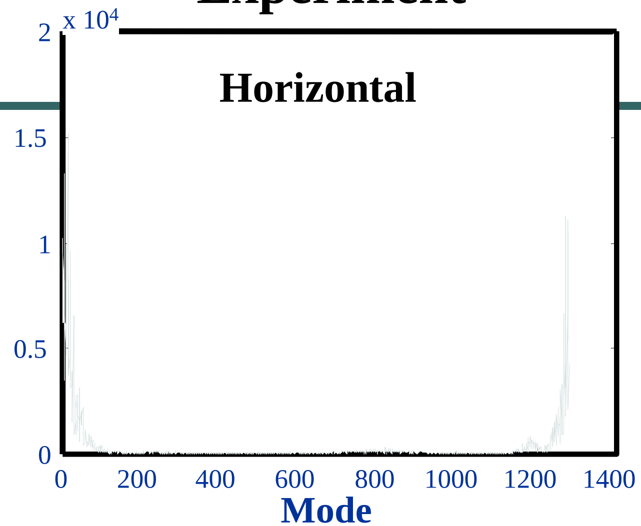


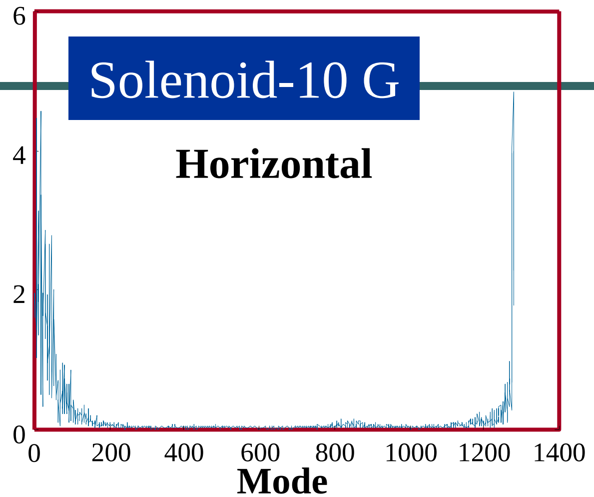
Su Su Win et al,(EC2002)

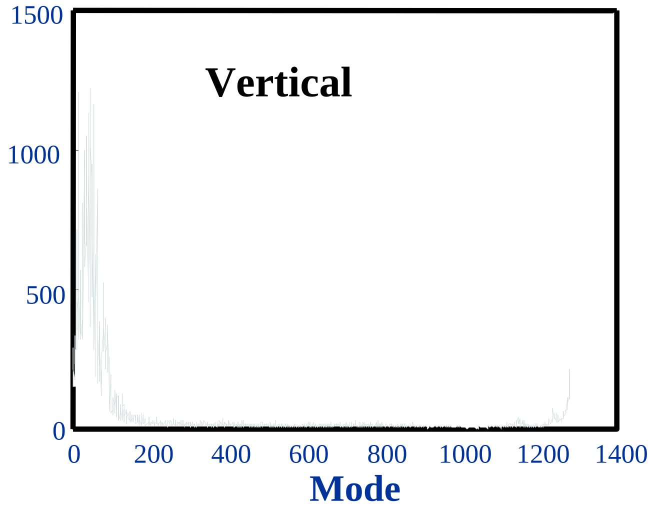
KEKB

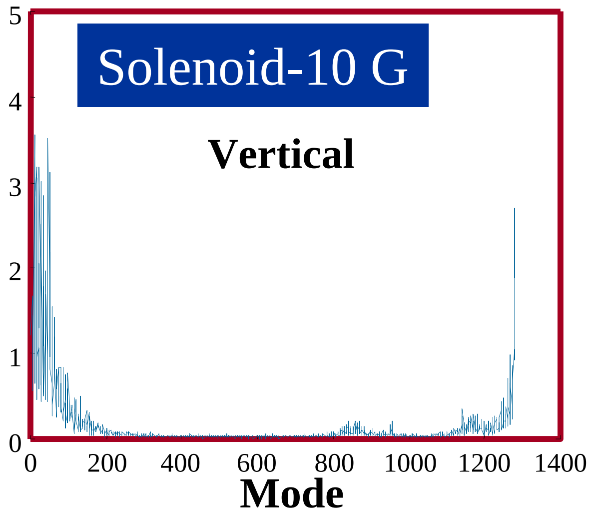
Solenoid-ON

Experiment | **Simulation**









Su Su Win et al., EC2002

Possible wake function

- Drift : Perhaps due to short range wake, otherwise it has freq. ~40MHz.

- Solenoid : The wake has freq. of 7.5 MHz or 120MHz. If 7.5 MHz, the wake has opposite sign for normal wake force. Note f_c~28 MHz (10G). Perhaps the freq. 7.5 MHz corresponds to the drift frequency along the chamber surface.

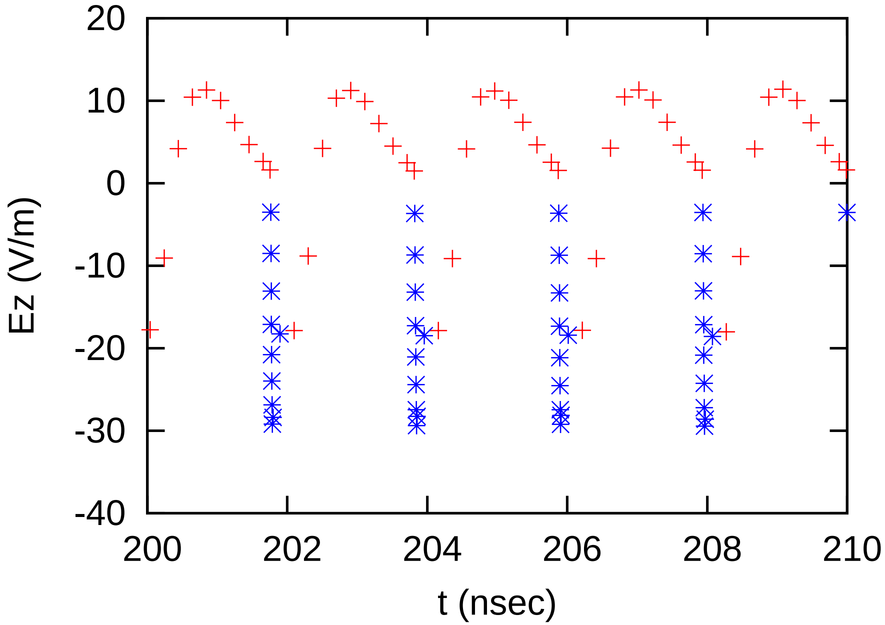
Question to L. Wang (homework)

- Does the wake component with the cyclotron freq. disappear? There is no signal in both of experiment and simulation.
- Does the wake have opposite sign?
- Growth rate tends to be higher for such long range wake. Does the growth rate show a reliable value?

Longitudinal field due to electron cloud (Novokhatski, Rumolo, Zimmermann)

- Super KEKB

$$E_z(r,z) = Z_0 \int_r^a j_r(r',z)\,dr' = Z_0 \left\langle \frac{ev_r}{2\pi r} \right\rangle$$

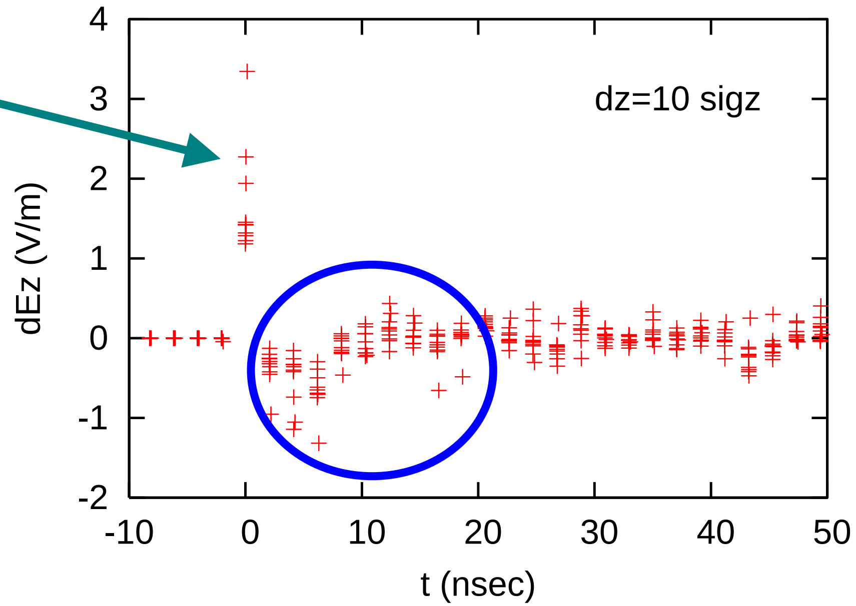


Blue: inside the bunch

Red : outside

Longitudinal wake force

Shifted bunch



Super KEKB

σ_z=3mm, N=1.17E11, L=3016m, η=2E-4, ν_s=0.02

$$W''(z) = \frac{1}{Ne}\frac{dE_s(z)}{dz}L = 5\times 10^{12}\,\mathrm{V/Cm} = 560\,\mathrm{m}^{-2}$$

Longitudinal coupled bunch instability

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

$$\Omega_m - \omega_s = -\frac{N_p r_e \eta c}{2\gamma T_0 \omega_s} \sum_{n=1}^{n_0} W_0''\left(\frac{n}{h} L\right) \left[1 - \exp\left(2\pi i n \frac{m+\nu_s}{h}\right)\right]$$

$$\frac{1}{\tau} = 0.01 \times \sum_{n=1}^{n_0} W''\left(\frac{n}{h} L\right) [m^{-2}] \sin\left(2\pi n \frac{m+\nu_s}{h}\right)$$

$\tau > 10\text{ms}$ in our case (super KEKB).

Summary

- Thanks for many discussions in those days.

  J.Byrd, A.Chao, Y.Chin, Dekansky, H.Fukuma, M.Furman, Z.Guo, K.Harkay, S. Heifets, M.Izawa, M.Kobayashi, Lambertson, K.Oide, Pestrikov, Perevedentsev, J.Rogers, K.Sato, Y.Sato, J.Seeman, G.Stupakov, T.Raubenheimer, Toyomasu, G.Voss, C.Zhang, M.Zisman, F.Zimmermann…….

Sorry if I miss the list.