Theory and simulation of Electron cloud instability

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Electron cloud instabilities

- Coupled bunch instability in positron storage rings
- Single bunch instability in positron storage rings

  short bunch (~cm), short bunch spacing (~1m)
- Single bunch instability in proton rings

  long bunch (~100m)

  short bunch (~10cm), short bunch spacing (~10m)

Electron cloud build-up

Primary electron production

- Positron ring (e^+ 3.5GeV)

  Photoelectron $Y_{1,\gamma}=1.5\times10^{-2}e^-/(m.e^+)$

- Proton ring

  Ionization (1nTorr) $Y_{1,i}=5.3\times10^{-9}e^-/(m.p)$

  Proton loss machine dependent

  $Y_{1,L}=4.4\times10^{-6}e^-/(m.p)$ (PSR, M.Furman)

  H- injection, ….

Secondary electron production

- Material $Y_{2,peak}=1$ (Cu) ~ 2.1 (Al, SUS)

Elastic reflection $Y_2(E\sim0)$

Motion of electrons interacting with the beam Coulomb force

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

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

ϕ : space charge force between electrons

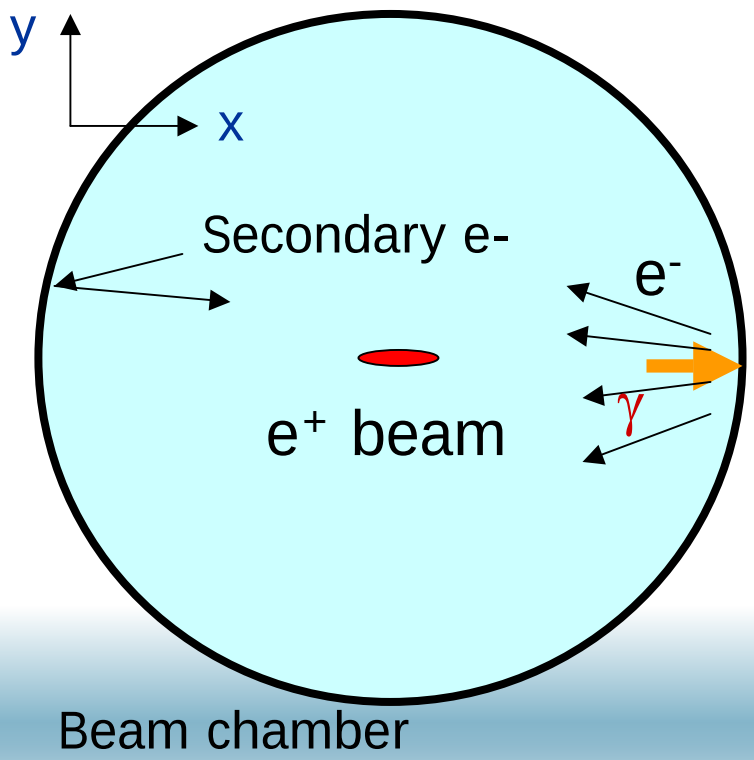
Initial conditions

Electrons are created at the chamber surface (photo-emisson, proton loss) or beam position (ionization).

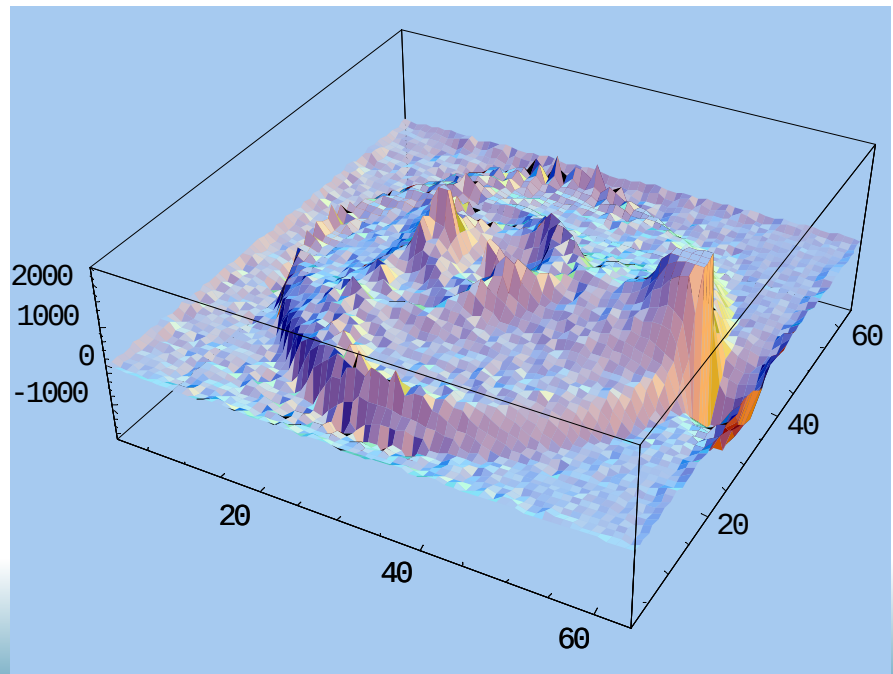
Initial energy ~eV.

Model and formation of electron cloud by computer simulation

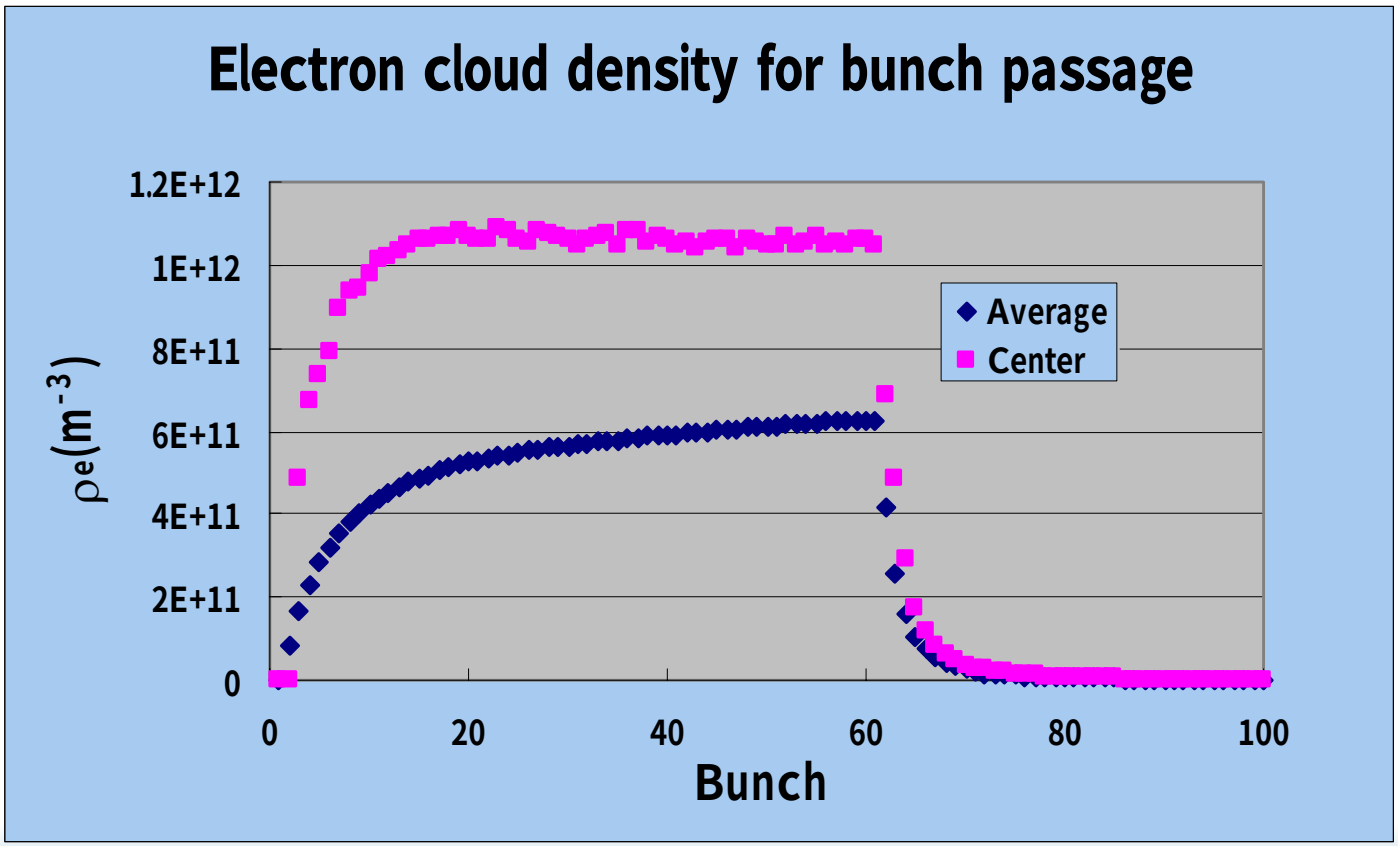
Model



Electron cloud density



Electron cloud density



60 bunches pass in every 8ns (KEKB).

Coupled-bunch instability caused by the electron cloud

- Instability has been observed at multi-bunch operation of positron beam.

  KEK-PF, BEPC, KEKB

- Very low threshold. I~15-20mA (PF,BEPC).
- It was not observed at electron beam operation.

Interpretation of the instability

- Wake field, which is induced by the electron cloud, causes coupled bunch instability. (Medium range wake force ~1m)

Wake field calculation

We represent interactions between positron bunch and electron cloud using wake field as is done for impedance problems.

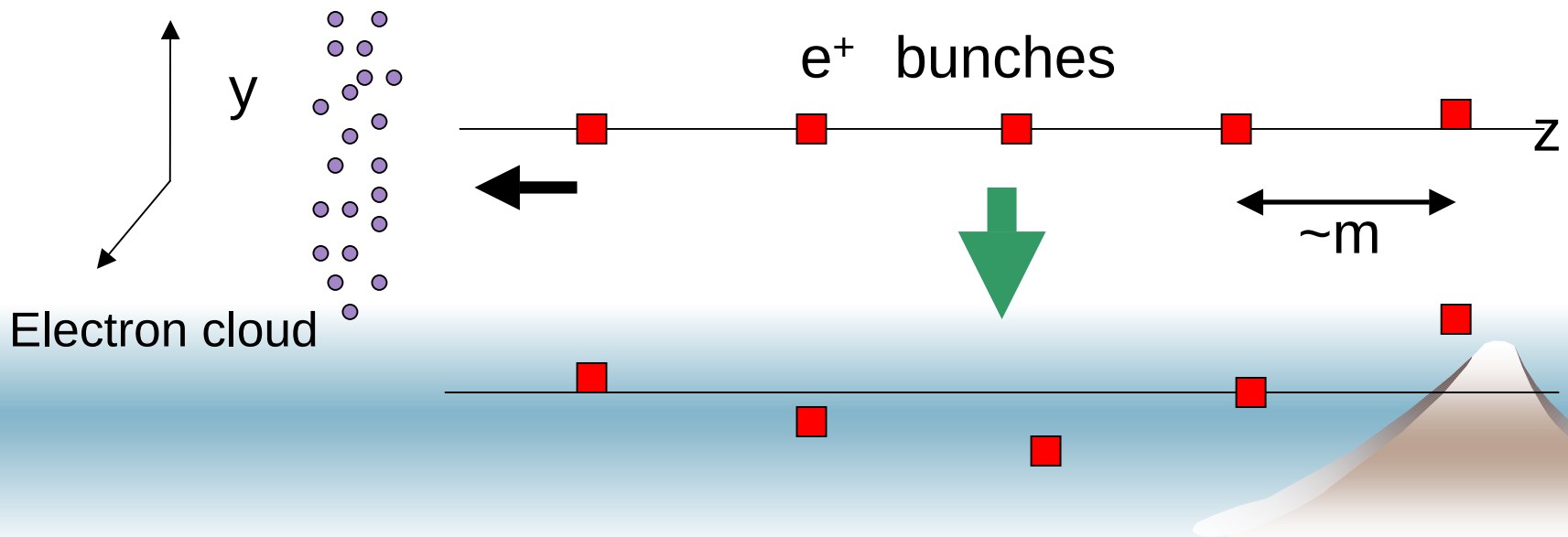
- Calculate equilibrium electron cloud distribution
- A bunch with slightly displacement passes though the cloud.
- The electron cloud disturbed by the bunch.
- Calculate kicks of succeeding bunches which feel from disturbed cloud.

Tracking simulation

Solve both equations of beam and electrons simultaneously

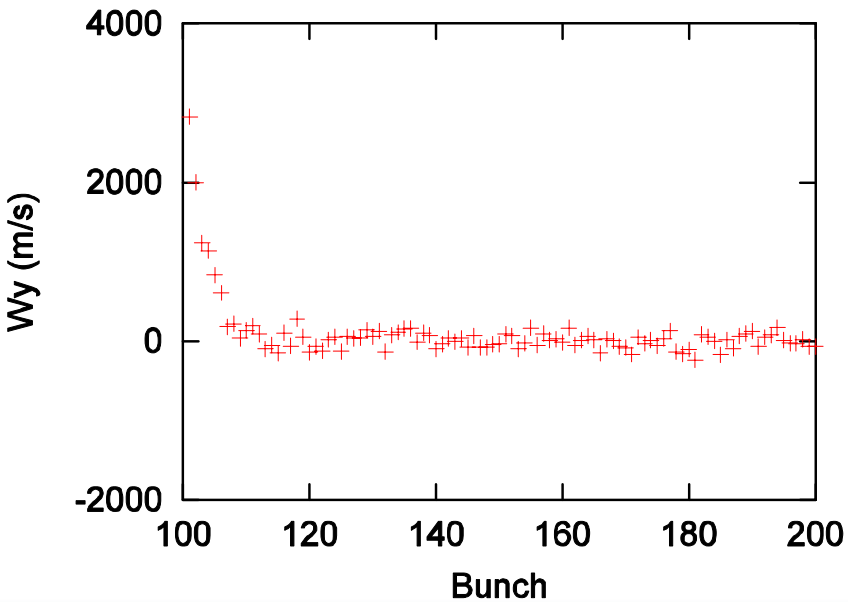
$$\frac{d^2\mathbf{x}_{+,a}}{ds^2} + K(s)\mathbf{x}_{+,a} = \frac{2r_e}{\gamma}\sum_{j=1}^{N_i}\mathbf{F}_G(\mathbf{x}_{+,a} - \mathbf{x}_{e,j};\sigma(s))\delta(s - s_j)$$

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

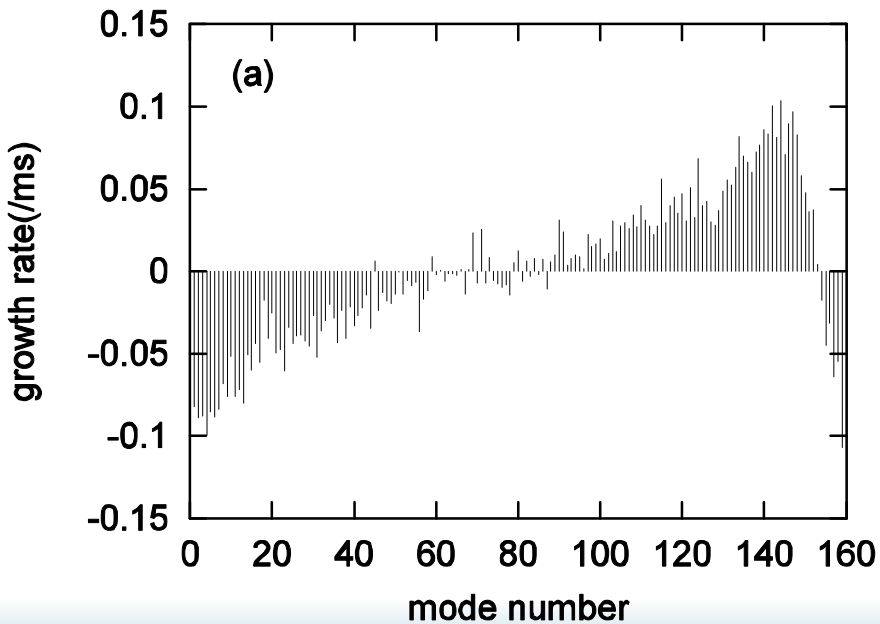


IHEP(Beijing)-BEPC

Vertical wake



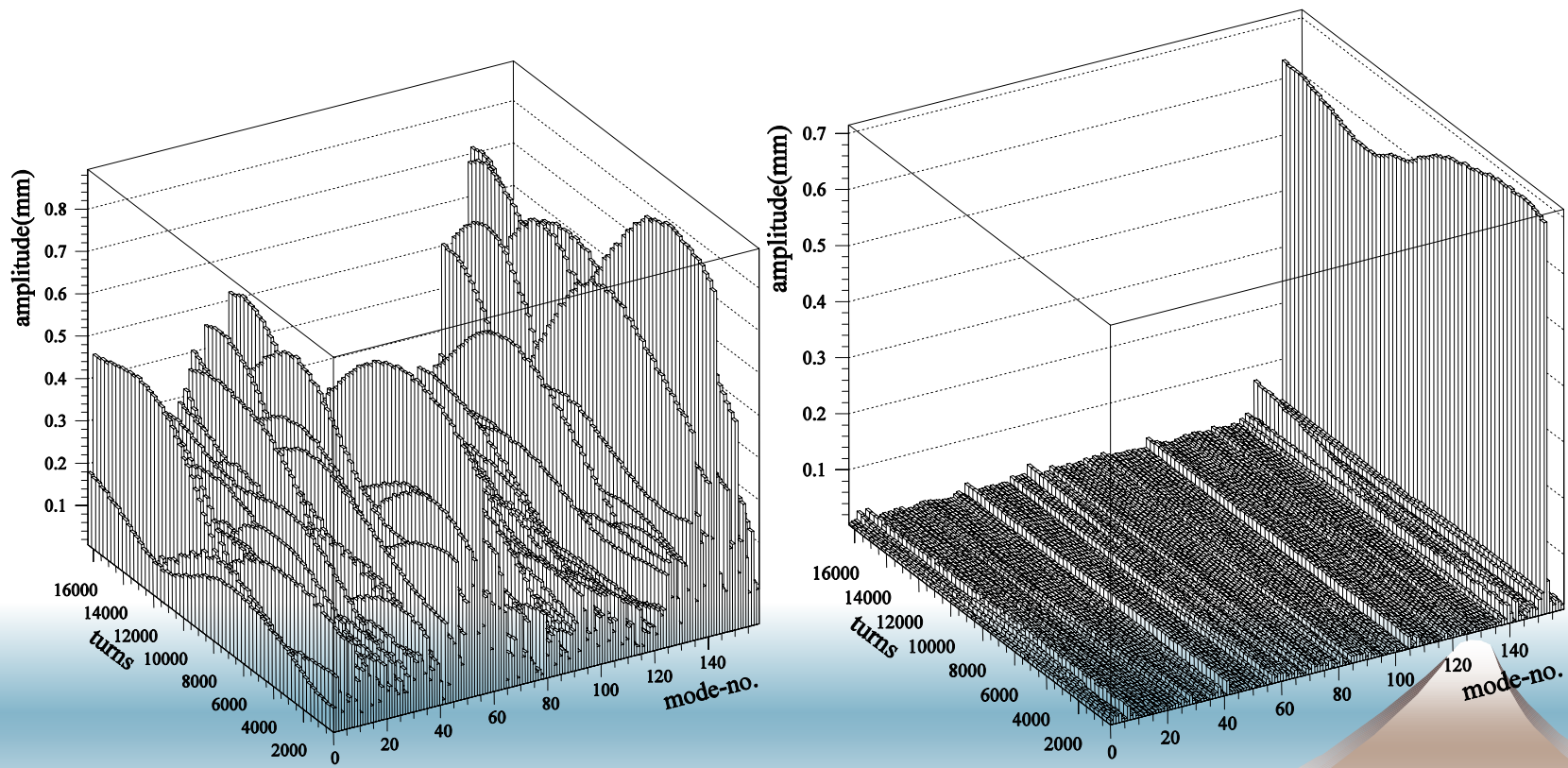
Growth mode



BEPC mode spectra by Single Path Beam Position Monitor

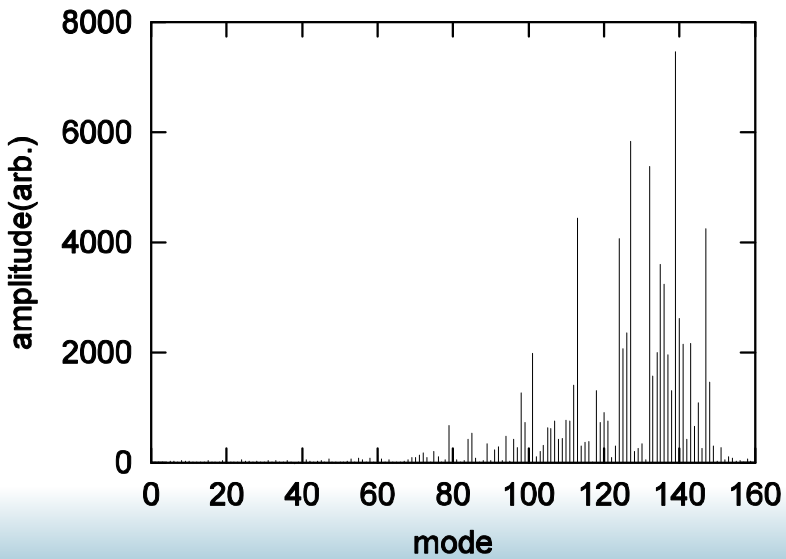
Positron

electron

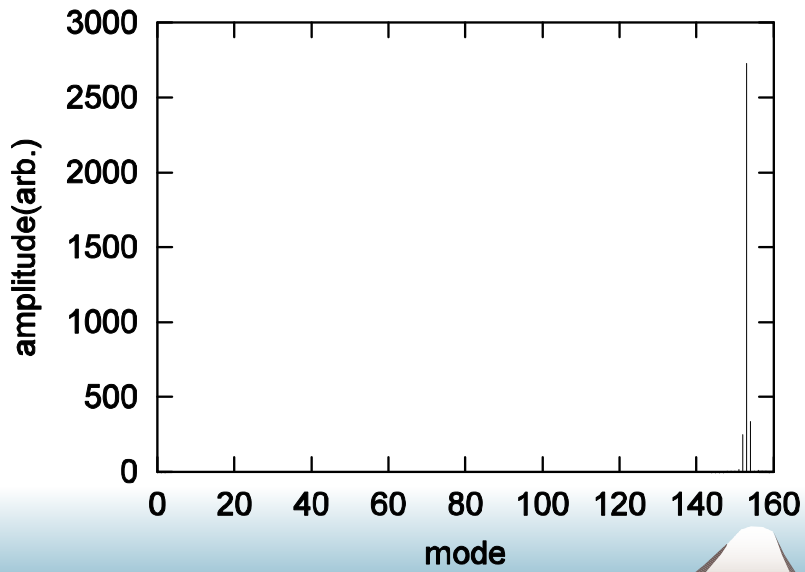


BEPC mode spectra by tracking simulation

Positron



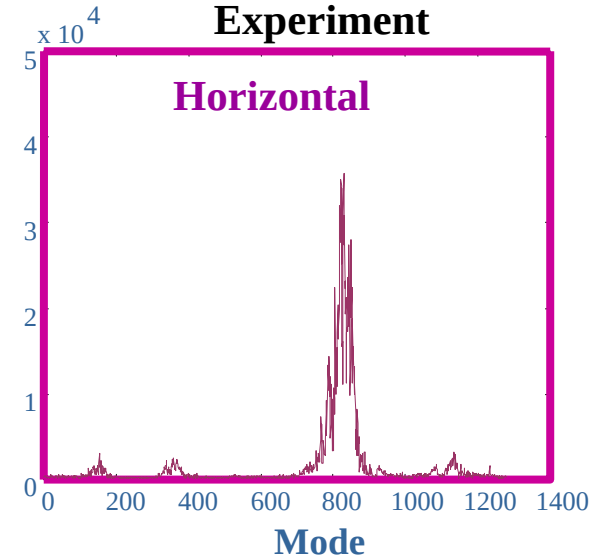
electron

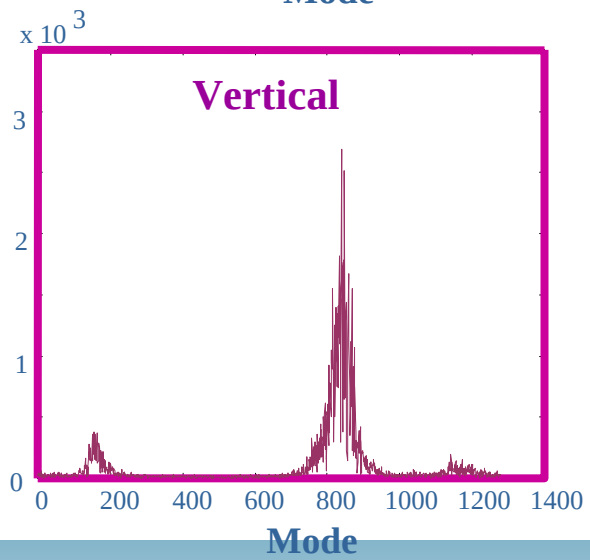


KEKB

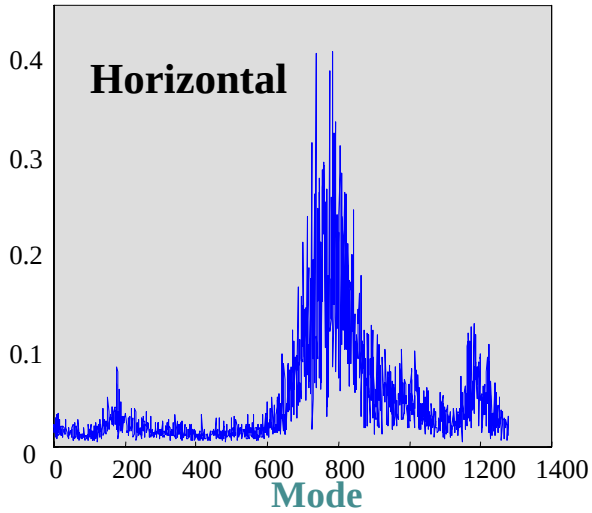
Solenoid-Off

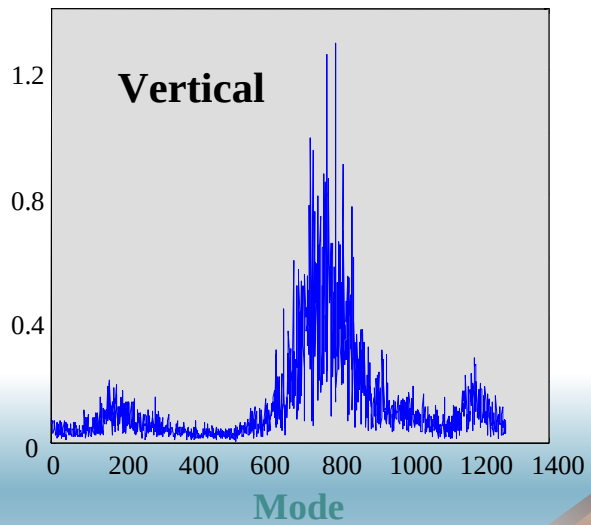
Experiment





Simulation



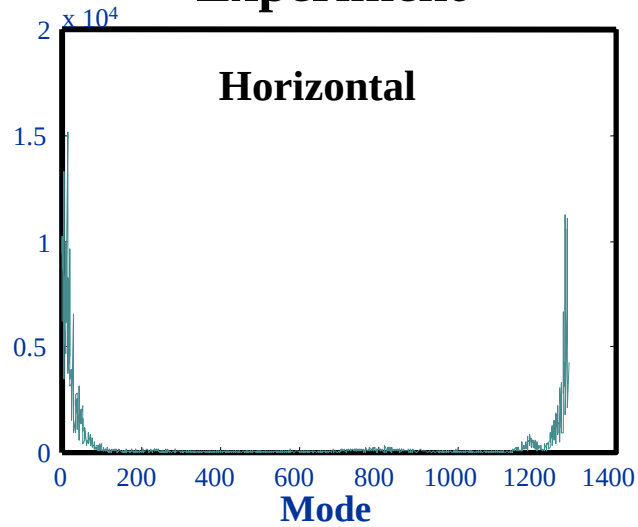


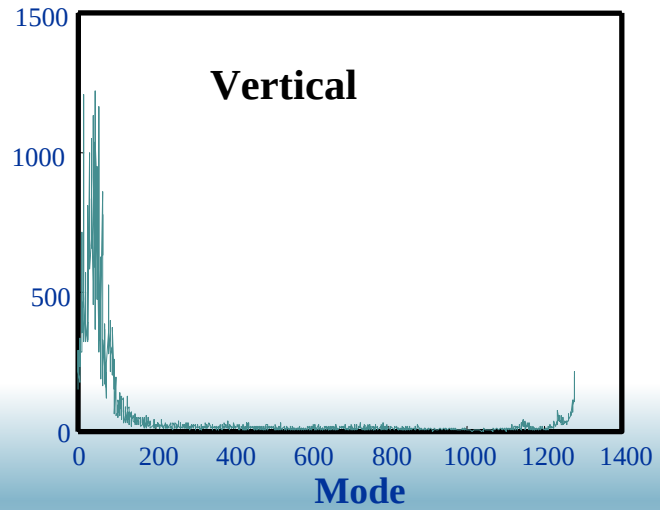
By Su Su Win

KEKB

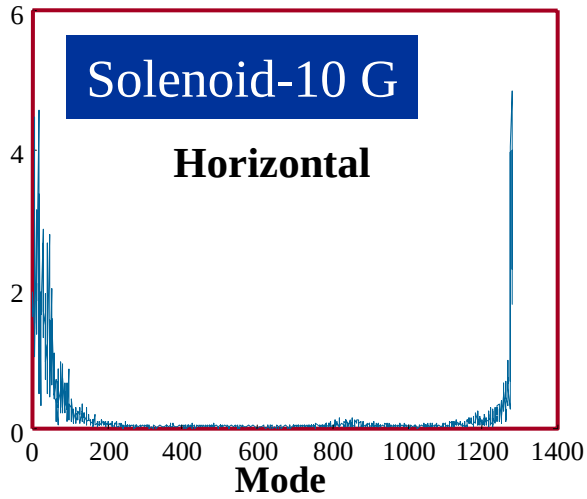
Solenoid-ON

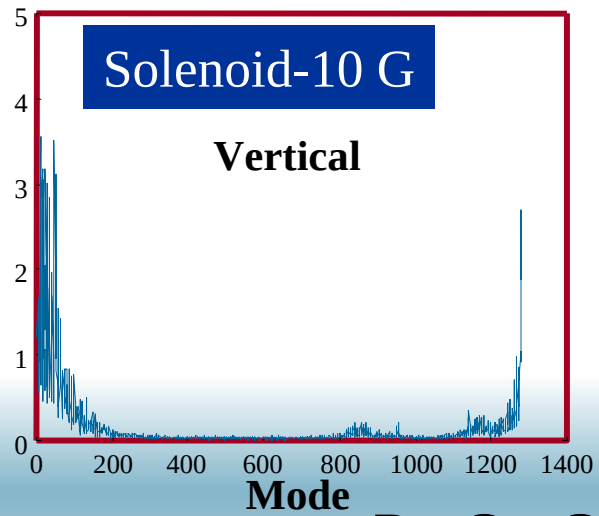
Experiment





Simulation





By Su Su Win

Single bunch (head-tail) instability caused by the electron cloud

- Beam-size blow-up and luminosity degrade observed at KEKB ad PEPII.
- The blow-up was observed in multi-bunch operation, but was perhaps single bunch effect.
- Observed only in positron rings.

Study of the instability

- Simulation using Gaussian model
- Wake field approach (short range ~cm)
- PIC simulation (like beam-beam strong-strong)

Equation of motion for Gaussian model

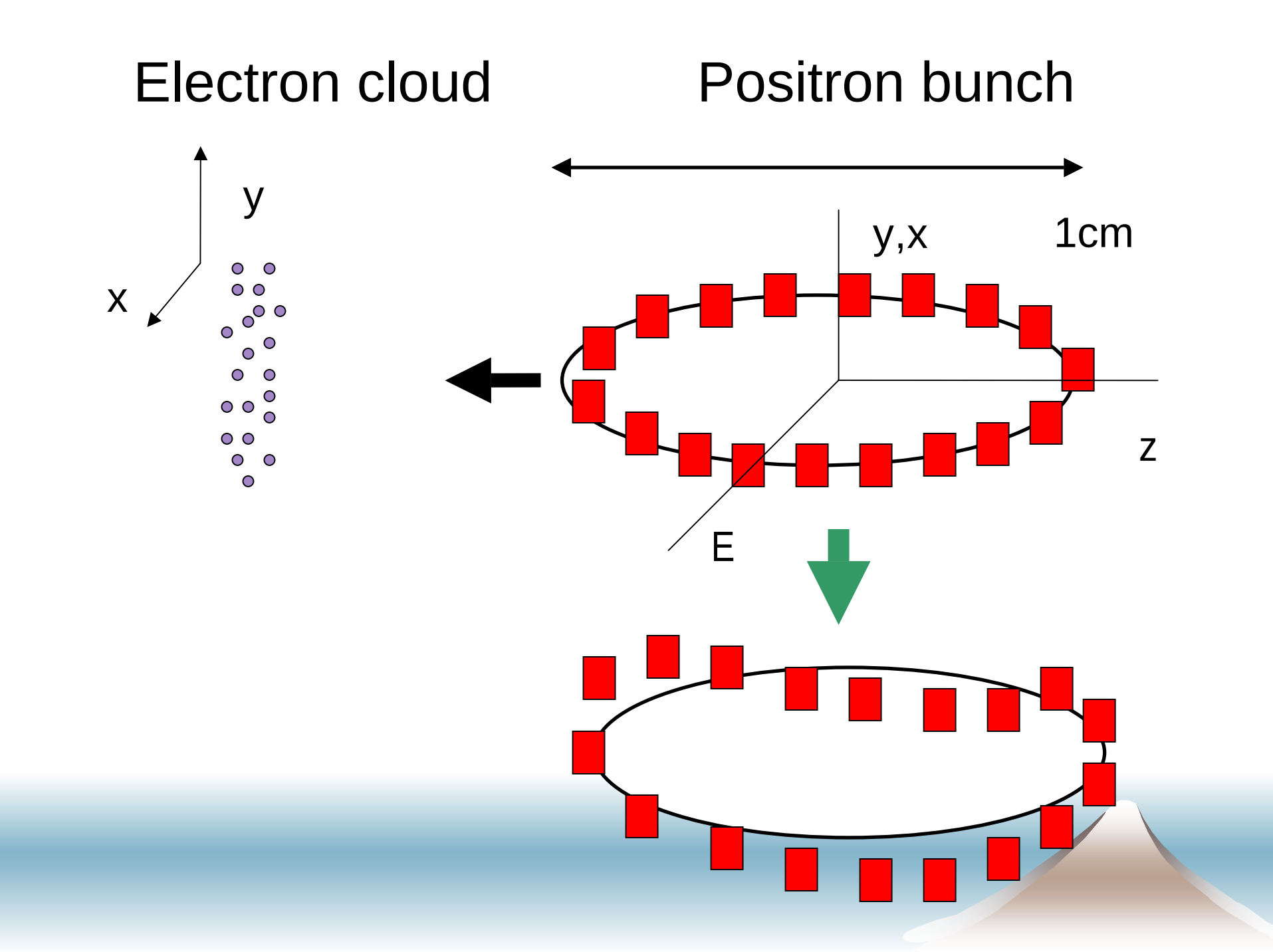
- Macro-particles with fixed transverse Gaussian size (distributed in the longitudinal phase space).
- Macro-electrons in transverse plane.

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

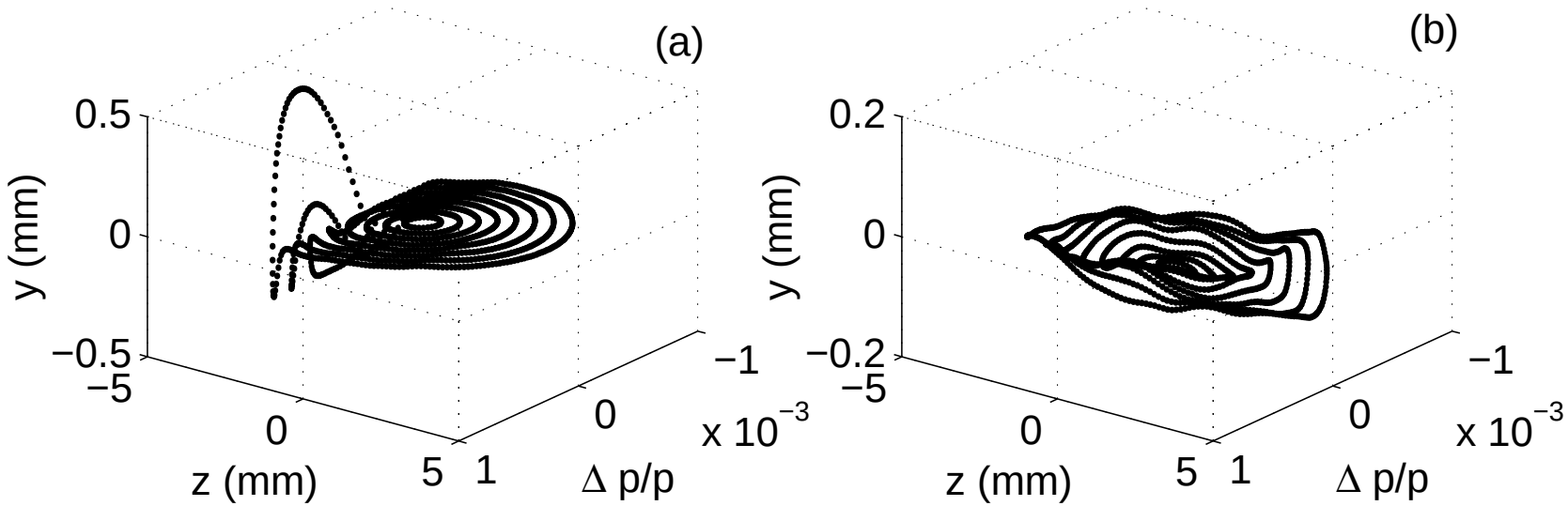
$$\frac{d^2\mathbf{x}_{e,j}}{dt^2} = 2N_+ r_e c^2 \mathbf{F}_G(\mathbf{x}_{e,j} - \mathbf{x}_{+,a};\sigma(s))\delta(t - t(s_{+,a}))$$

The same equation as CBI except of the time scale (s~1cm).

CBI (s~1m)


Electron cloud
Positron bunch
y
x
y,x
1cm
z
E

- 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.

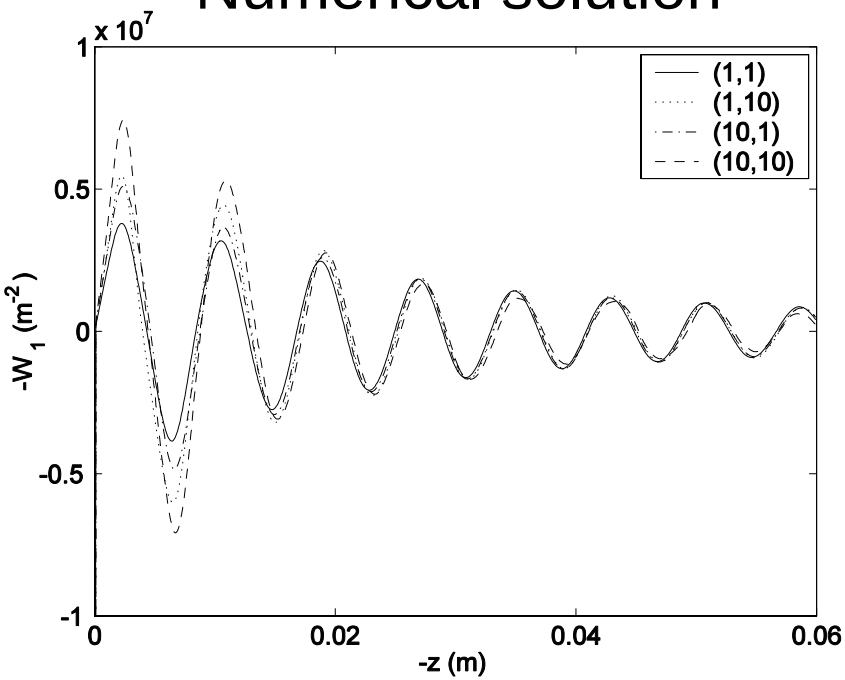
Wake field given by the numerical method

Electron cloud with a size ($n\sigma_x$,$m\sigma_y$) is initially set at beam position. The wake field caused by the cloud is calculated.

Analytical solution

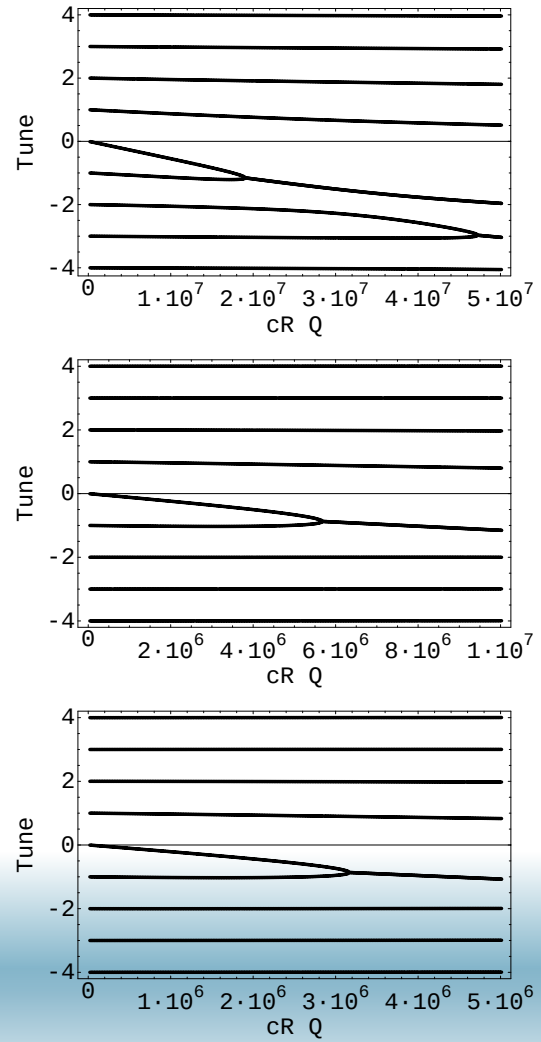
$$W = K\frac{\lambda_e}{\lambda_p}\frac{L}{(\sigma_x+\sigma_y)\sigma_y}\frac{\omega_e}{c}\sin\left(\frac{\omega_e}{c}z\right)$$

Numerical solution



- (1,1) is consistent with the analytical calculation.
- (10,10) is twice larger than (1,1).

Threshold of strong head-tail instability



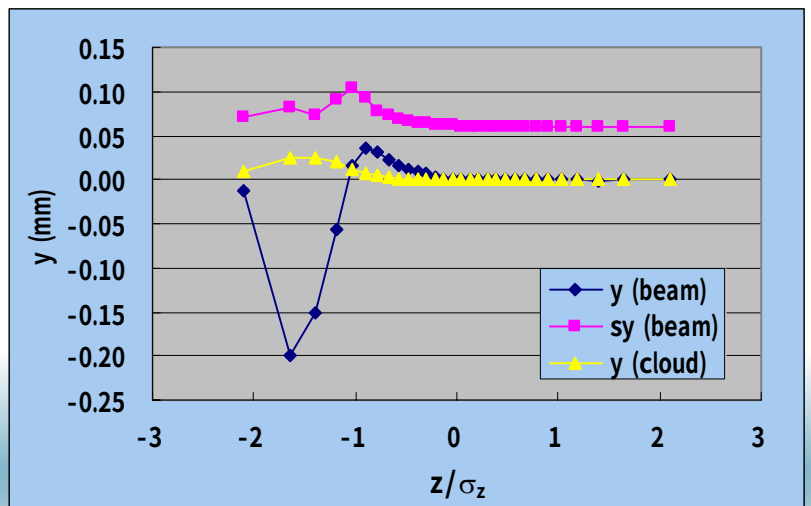
- Threshold : ρ_e=1-2x$10^{12}$$m^{-3}$
- Consistent with the simulation.

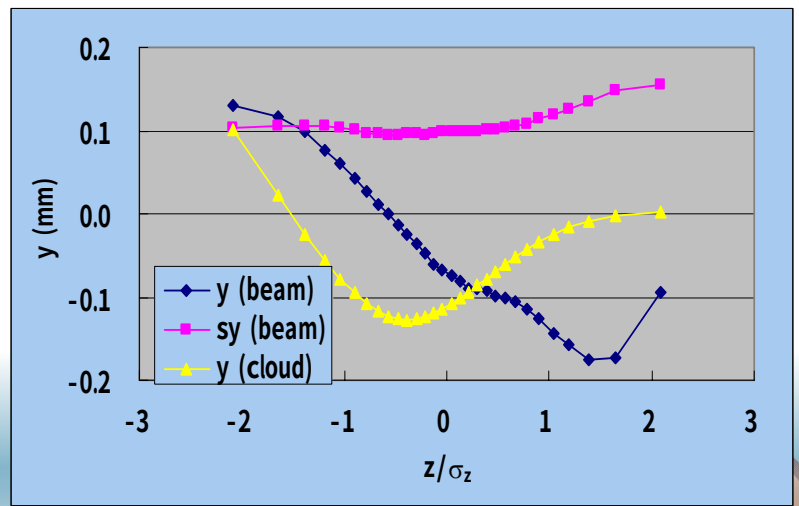
PIC simulation

•Transverse mesh. 2D electric field calculation for electrons and positron bunch.

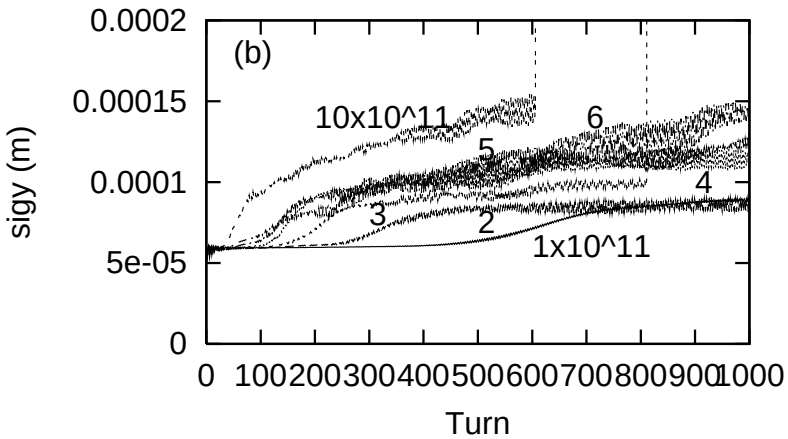
•A bunch was sliced into 20-30 in the longitudinal direction.

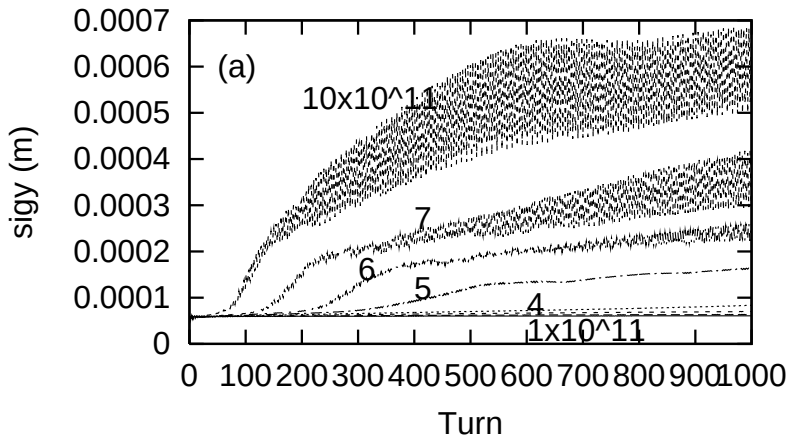
Snap shot of beam shape for $\nu_s=0$ and $\nu_s>0$





Threshold behavior





- ν_s=0 no threshold, ν_s>0 clear threshold.
- $\rho_{e,th}=5x10^{11}m^{-3}$

Electron cloud instability in proton rings

- We study single bunch instability for a long proton bunch.

Wake field approach

- A proton bunch interacts with electron cloud with the same transverse size (σ_x,σ_y).

Tracking simulation

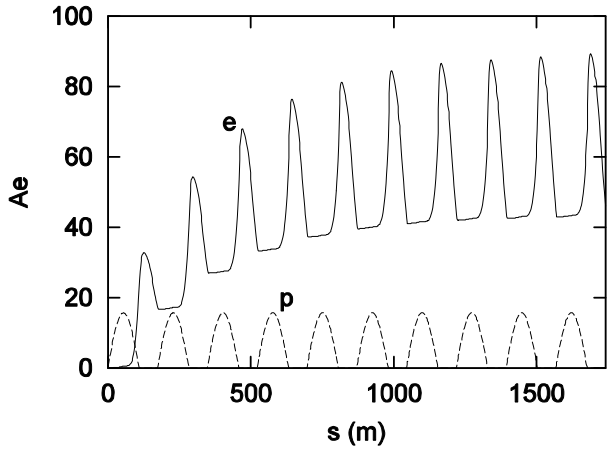
- Rigid Gaussian (x-y) macro-protons and soft electron cloud

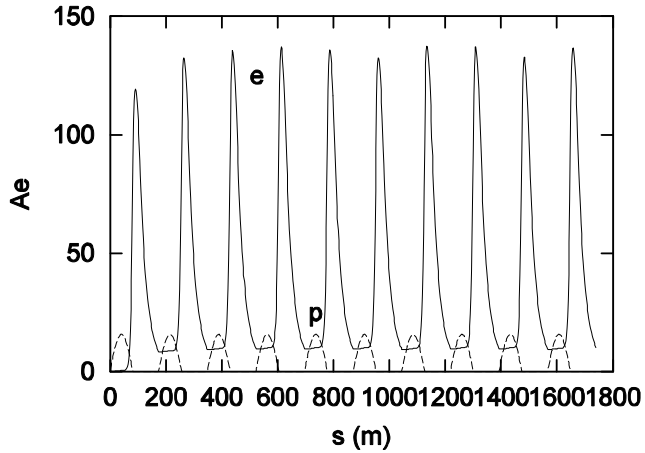
Electron cloud build-up in proton ring

JKJ 3GeV

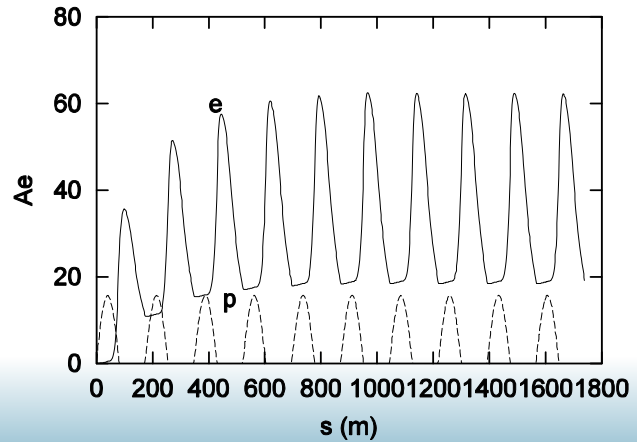
50GeV

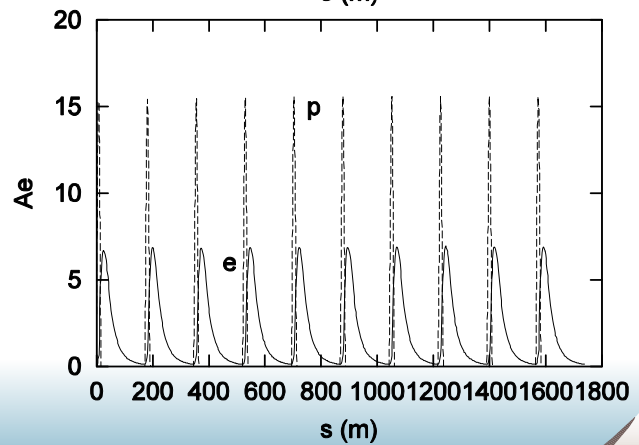
Inj.





Ext.

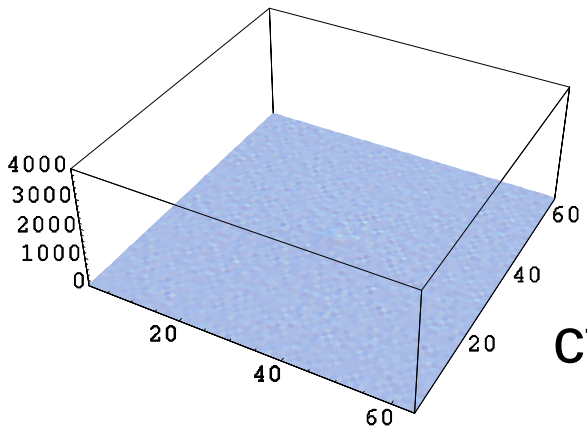




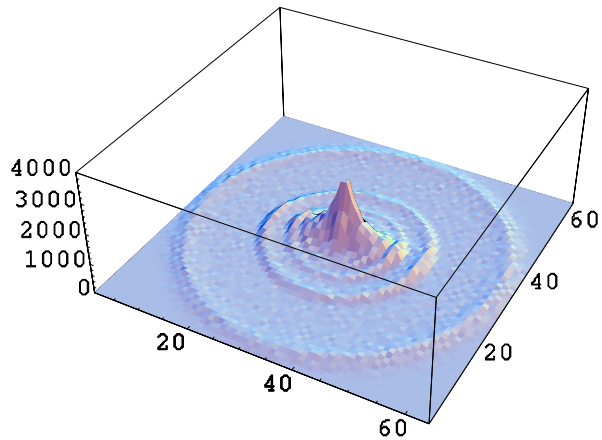
Ae: Amplification of initial electrons

Electron distribution during bunch passage

- Electrons are gathered at the beam position immediately at starting interaction
- Electrons disappear after the interaction

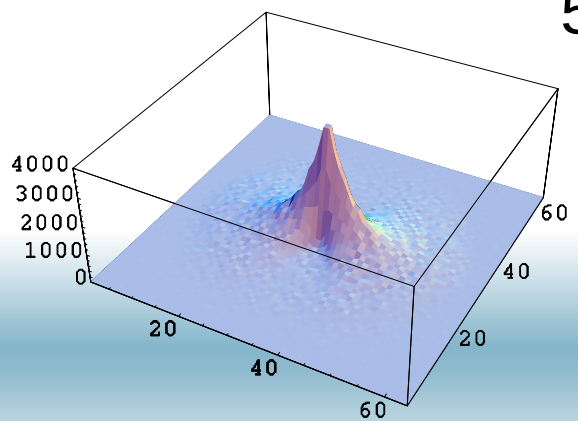


ct=0m

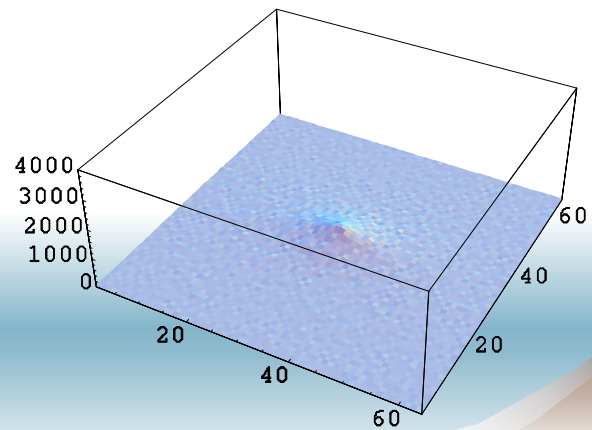


20m

50m



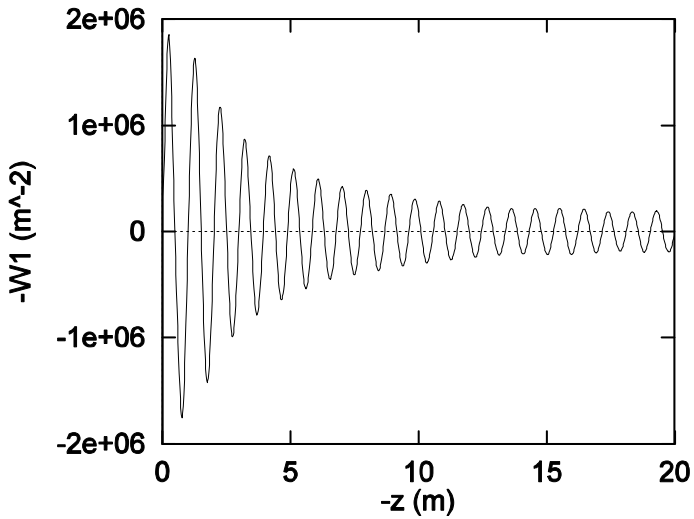
100m



Wake field

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

Q factor becomes finite due to non-linearity and beta modulation.



Resonator parameter

simulation (analytic)

- cR/Q=1.9x10^6 m^{-2} (1.1x10^6 m^{-2})
- ω_e =1.9x10^9 s^{-1} (1.2x10^9 s^{-1})
- Q=13

Instability threshold

$\omega_e \sigma_z / c >> 1$ Coasting beam model

$$U \equiv \frac{\sqrt{3}\lambda_p r_0 \beta}{\eta \sigma_e \gamma} \frac{\omega_0}{\omega_e} \frac{\left|Z_\perp(\omega_e)\right|}{Z_0}$$

$$= \frac{\sqrt{3}\lambda_p r_0 \beta}{\nu_s \gamma \omega_e \sigma_z / c} \frac{\left|Z_\perp(\omega_e)\right|}{Z_0} = 1$$

	RCS	MR
U_L	0.08	0.11
U_H	0.16	1.5

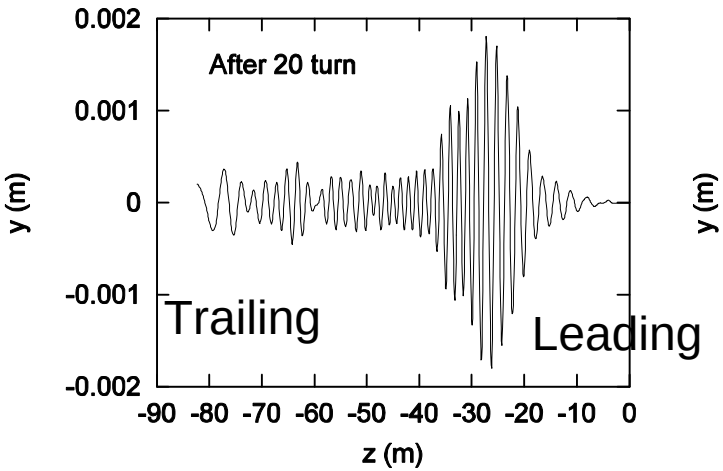
@inj

Estimated by bottom Ae

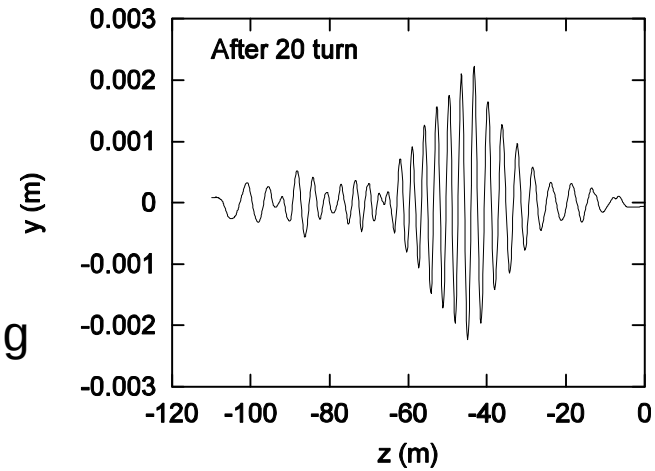
by top Ae

Tracking simulation

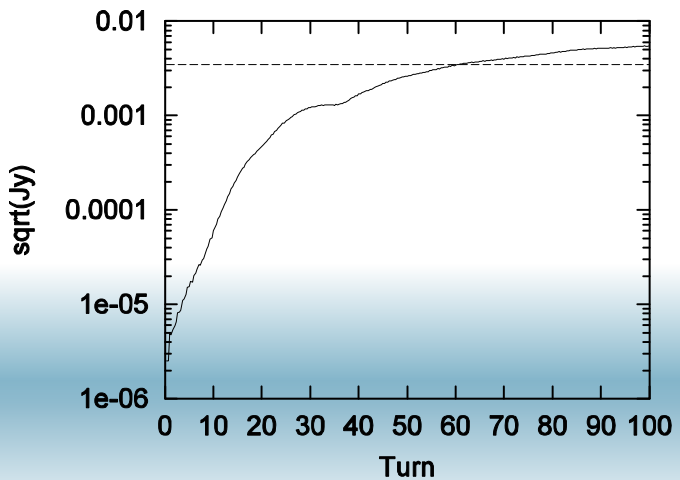
3GeV RCS inj.

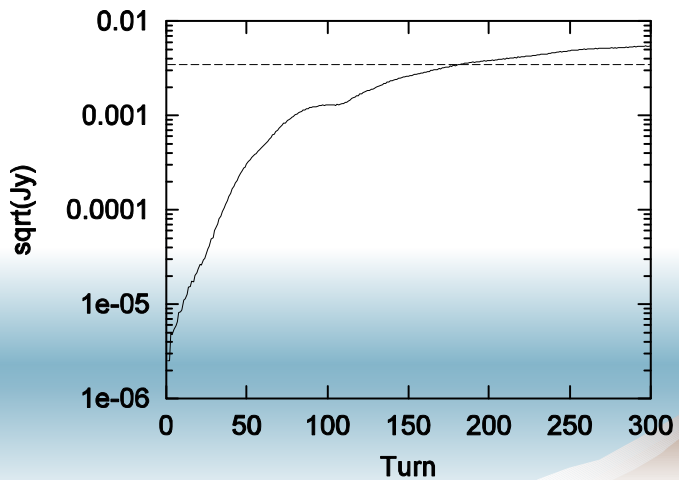


50GeV MR inj.



Transverse bunch profile





Growth

Taking into account of Landau damping

- λ_e/λ_p=0.08 and 0.11 for 3 and 50 GeV, respectively.
- τ_g/T_0=10~20turns for 3 and 50GeV inj.

$$U = \frac{\sqrt{3}}{\Delta\omega\tau_g} = \frac{\sqrt{3}\,T_0/\tau_g}{2\pi\nu_s\,\omega_e\sigma_z/c}$$

U=0.15~0.08 and 0.23~0.12 for 3 and 50GeV.

Consistent with the analytical estimation.

Summary

- Electron cloud build-up

  Photoelectron ： well understood, since Y_1 is well-known and is dominant.

  Proton machine ：Y_1,Y_2 are ambiguous.
- Coupled bunch instabilities, which were observed at KEK-PF, BEPC and KEKB, were consistent with the simulations.
- Single-bunch instability , which was observed at KEKB, was consistent with the simulations for threshold behavior and effect of solenoid.
- Instability for proton rings should be studied more, especially for Y_1,Y_2.