Electron cloud effects, coupled bunch instability

K. Ohmi (KEK)

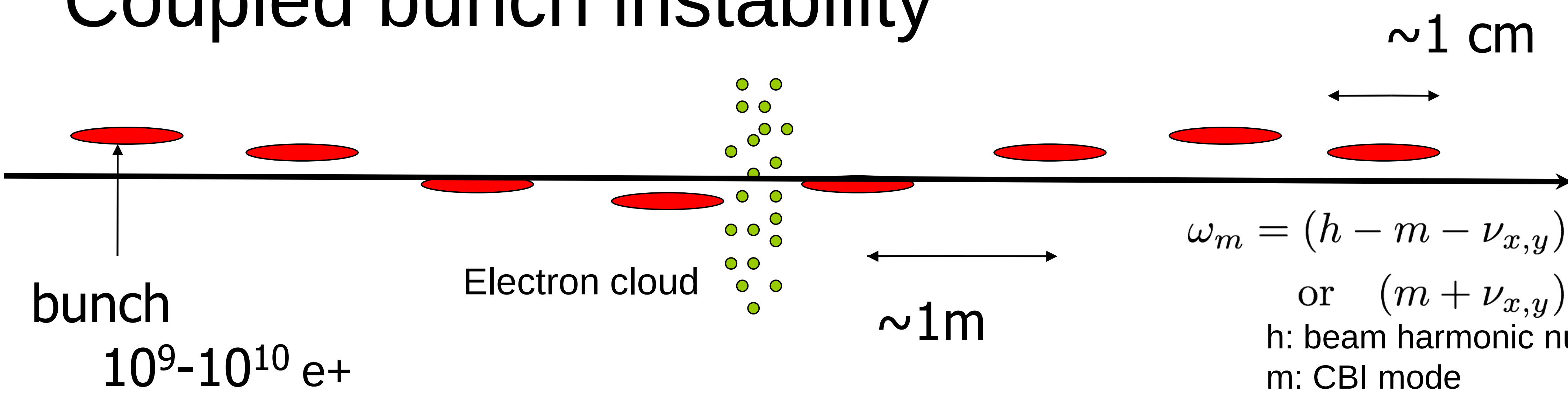
17 Dec, 2015

Fermilab

Thanks to: Y. Alexahin and S. Antipov

Observation of electron cloud effects

- Coupled bunch instability



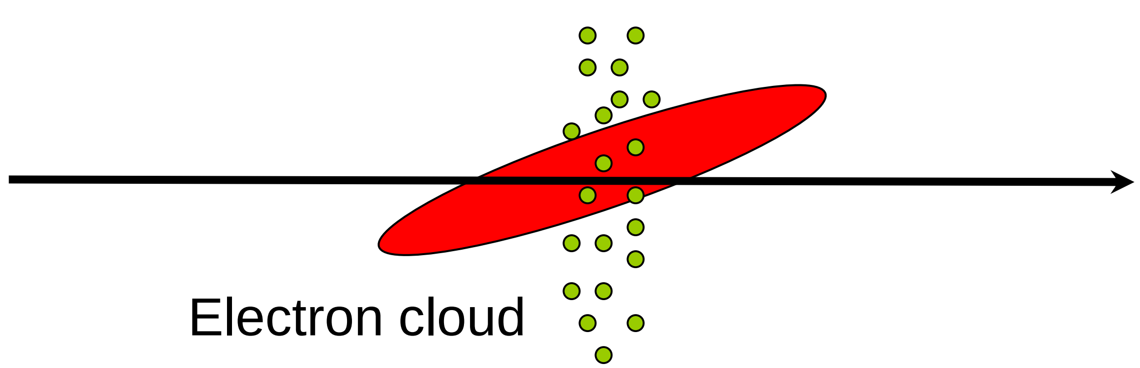
$$\omega_m = (h - m - \nu_{x,y})\omega_0$$

$$\text{or} \quad (m + \nu_{x,y})\omega_0$$

h: beam harmonic number
m: CBI mode

Coherent motion of bunch train and electron cloud

- Single bunch fast head-tail instability



$$\omega_m = \omega_\beta \pm a\omega_s$$

Coherent motion of a bunch and local electrons

Multi-bunch instability observed at KEK-PF

- KEK-PF is a 2nd generation light source operated by both of positron and electron beams. E=2.5 GeV L=186 m, Frf=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.

Measurements of electron cloud instability

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

PF: 2nd generation light source operated by both of positron and electron beams. E=2.5 GeV L=186 m

BPM spectrum for V motion.

Electron 354 mA

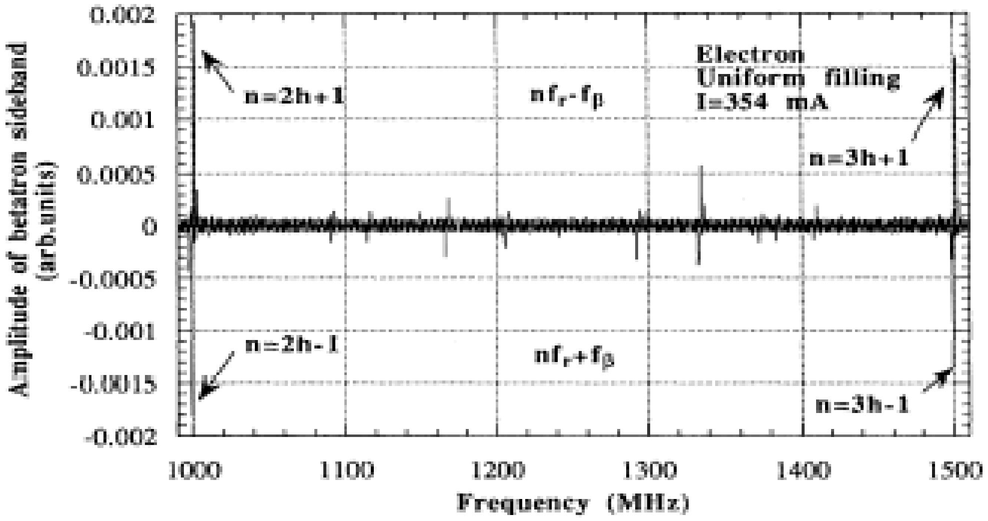


FIG. 1. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling.

Positron 324 mA & 240 mA

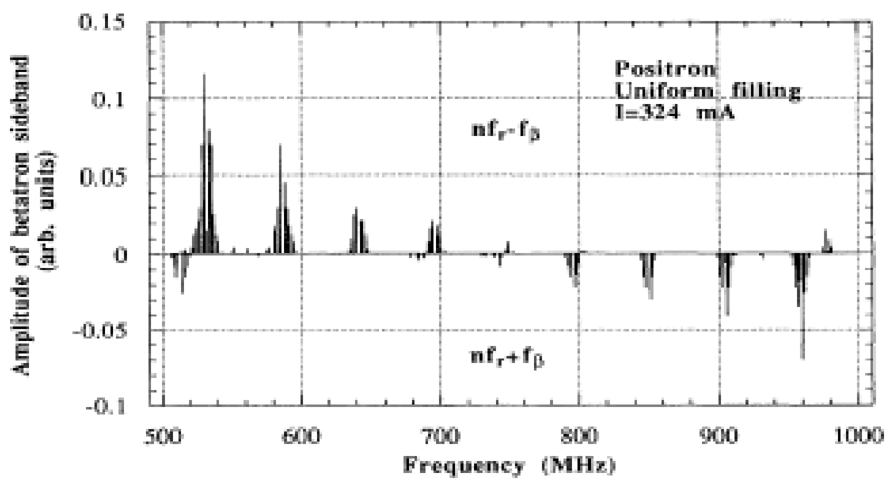


FIG. 2. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling.

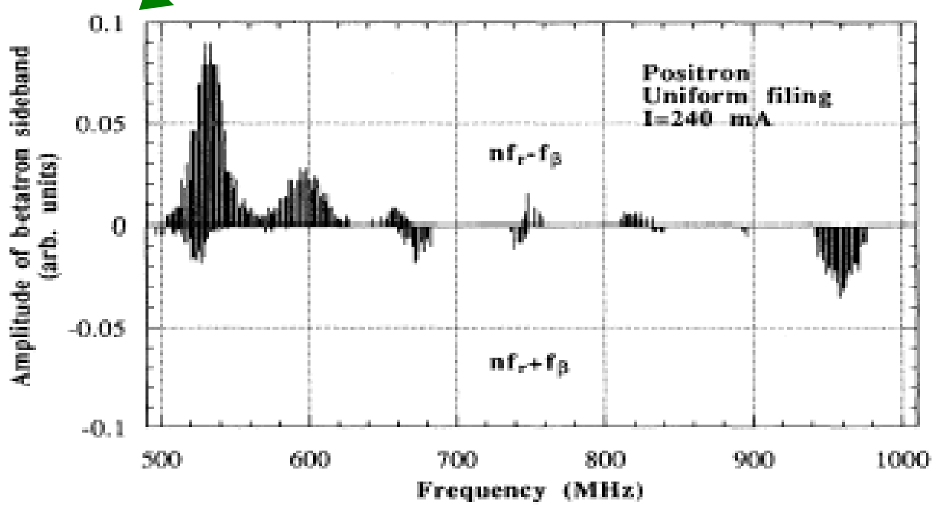
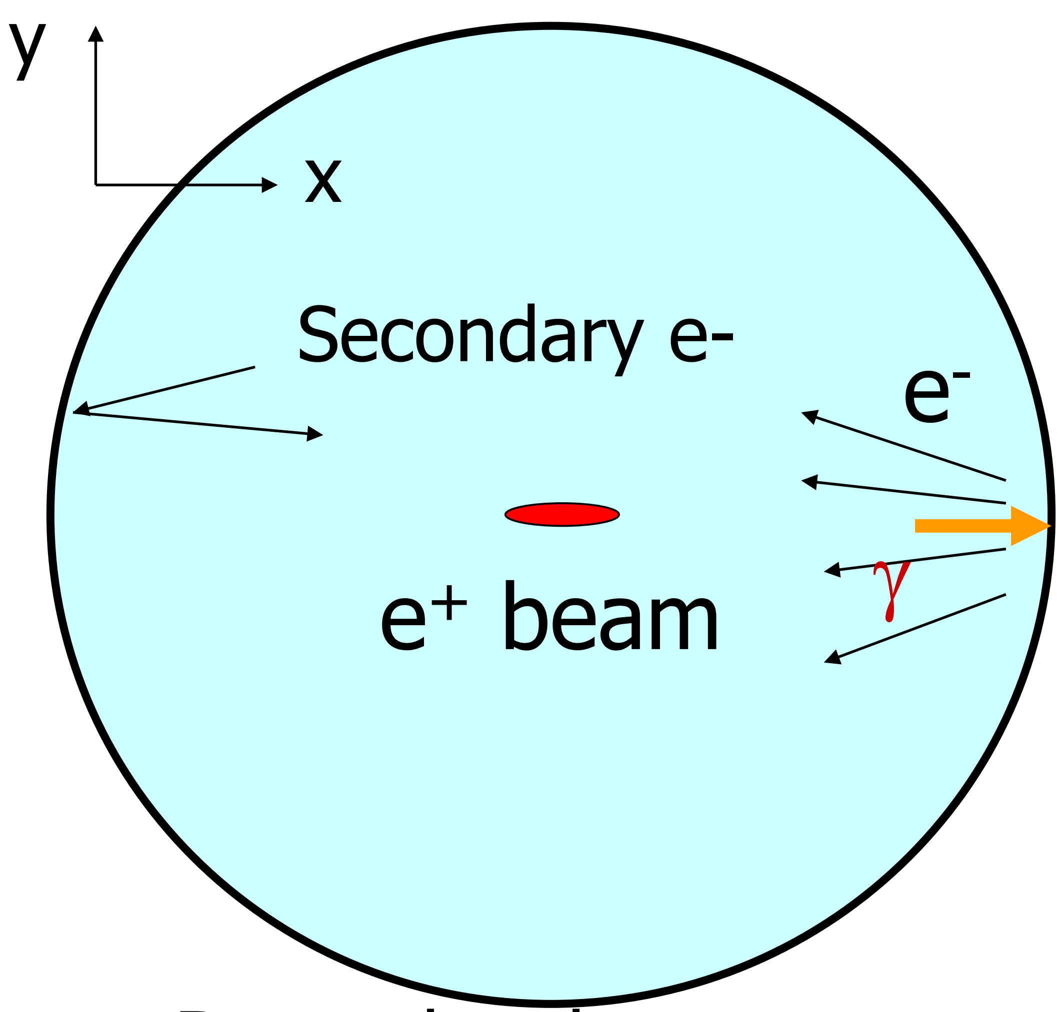


FIG. 3. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling. Only the stored current is different from Fig. 2.

Different spectra are observed for e+ or e- storage. Mode spectra depend on beam current.

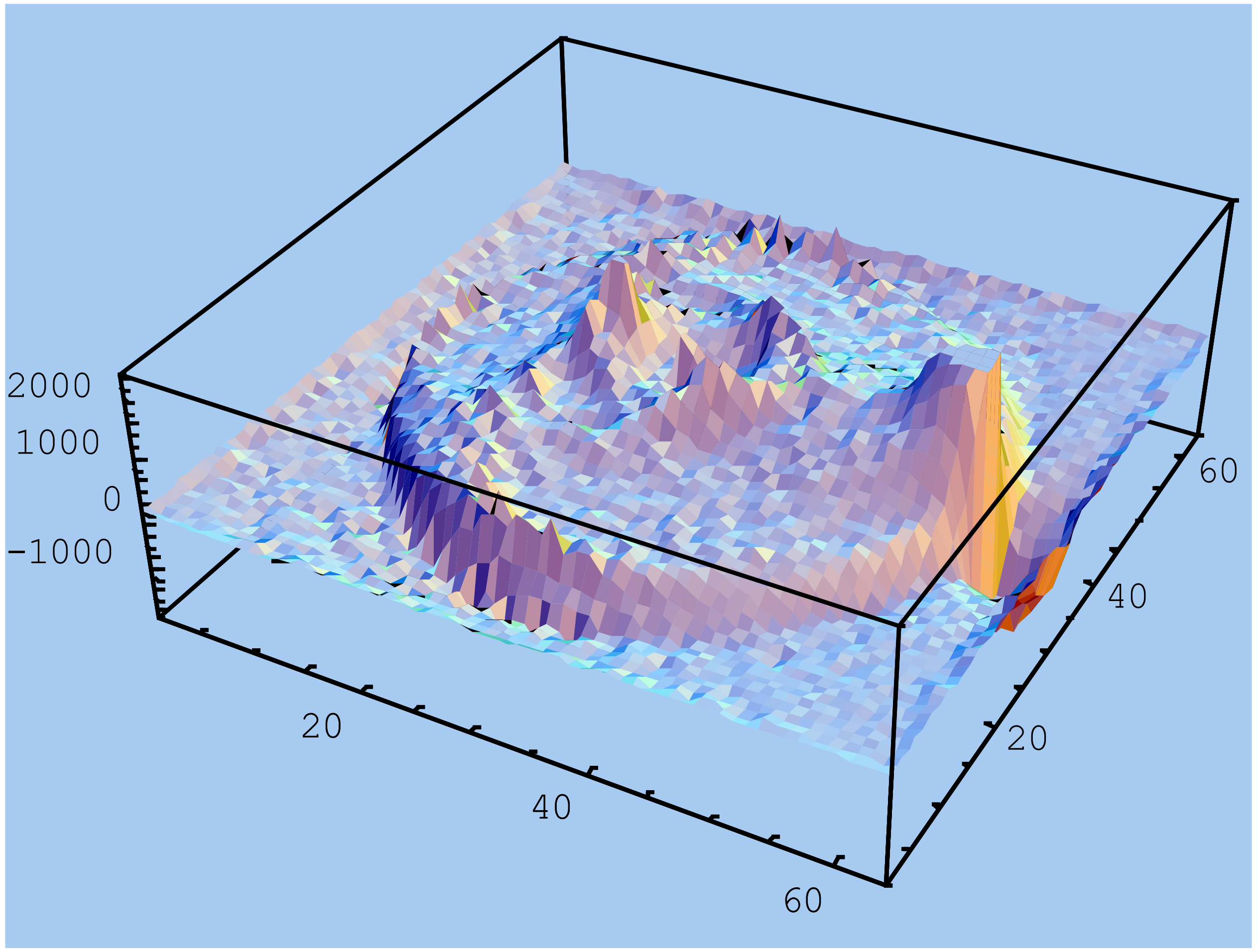
Model and formation of electron cloud by computer simulation

Model



Beam chamber

Electron cloud density



Instability evaluation with the wake force

- Motion of bunches is assumed to be expressed as

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

$W(z_n$-$z_m)$： 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.

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. Δy_m
- The electron cloud is disturbed by the displaced bunch.
- Estimate the force which following bunches experience due to the cloud disturbance. $\Delta p_{y,n}$, n<m

$$\Delta p_{y,n} = \frac{N r_e}{\gamma} W_{nm} \Delta y_m$$

- Check the linearity and superposition of the wake force.

Estimation of instability

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

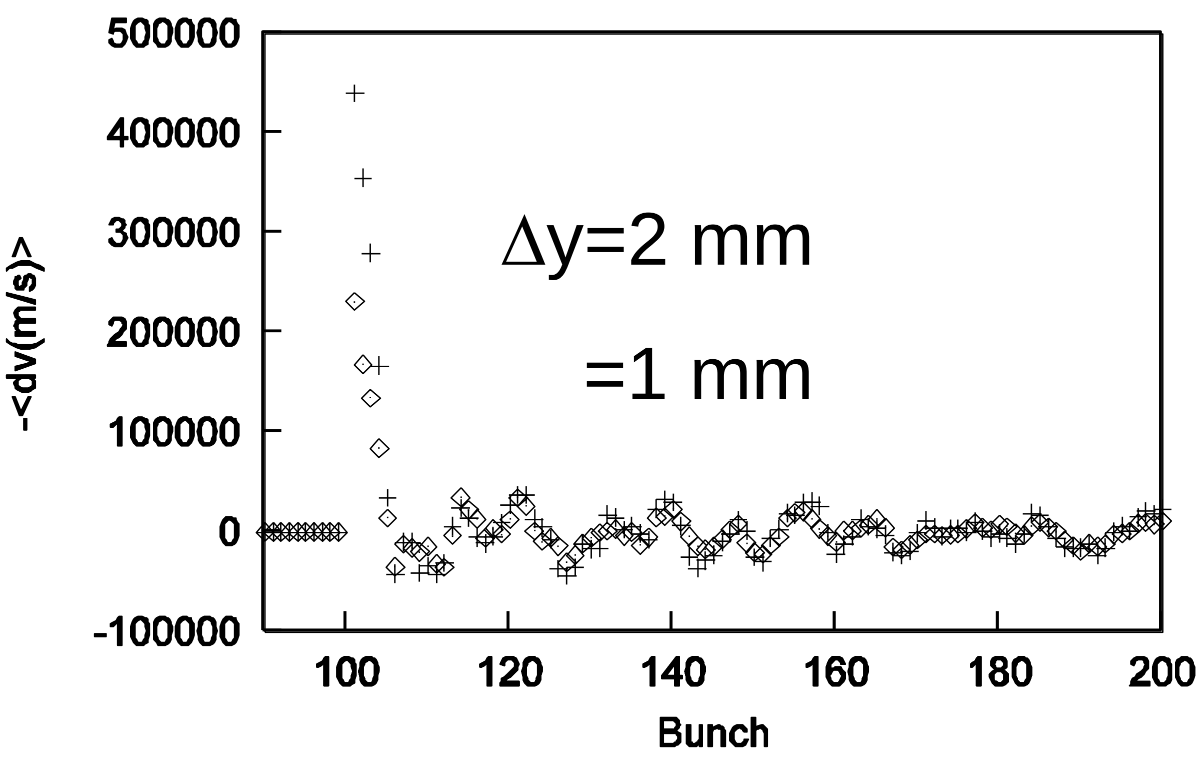
$$y_n^{(m)} \propto \exp\left(2\pi i n \frac{m}{h}\right) \exp\left(-i\Omega^{(m)} \frac{s}{c}\right)$$

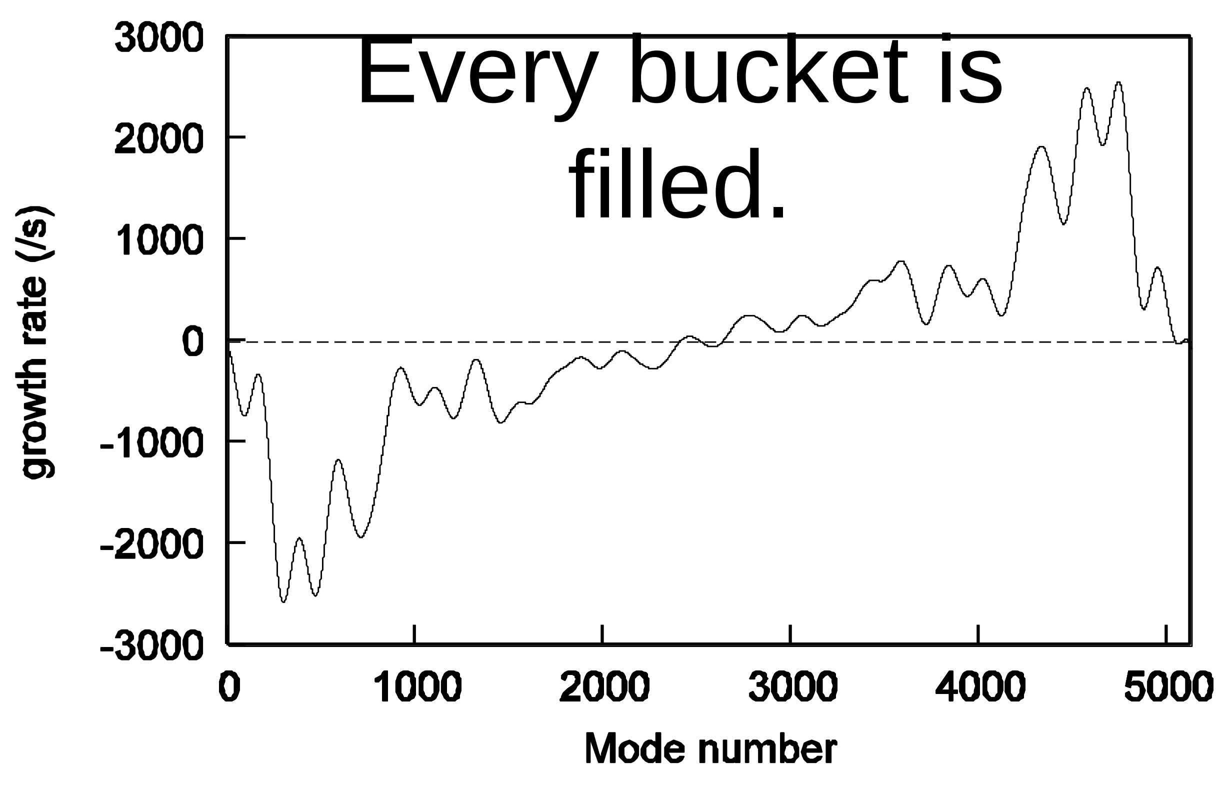
$$\Omega_m - \omega_\beta = \frac{N_p r_e c}{2\gamma T_0 \omega_\beta} \sum_{n=1}^{n_0} W\left(\frac{n}{h} L\right) \exp\left(2\pi i n \frac{m+\nu_y}{h}\right)$$

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





KEKB design report (1996)

Simulation of coupled bunch instability

K.Ohmi, PRE55,7550 (1997)

K.Ohmi, PAC97, pp1667.

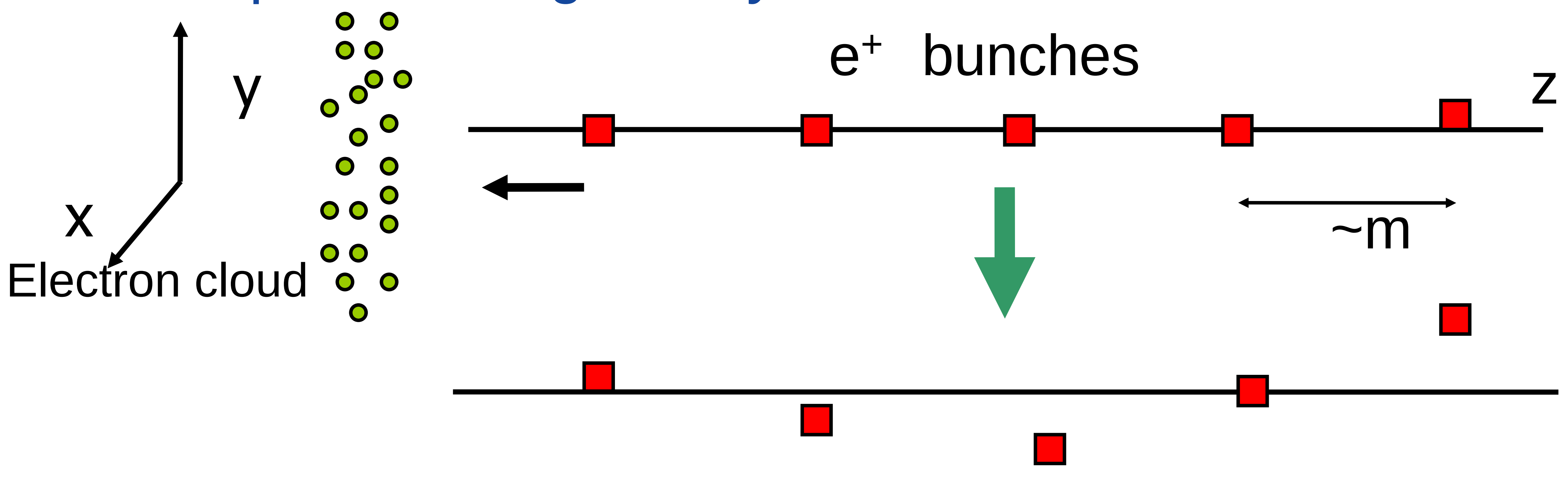
Solve both equations of beam and electrons simultaneously

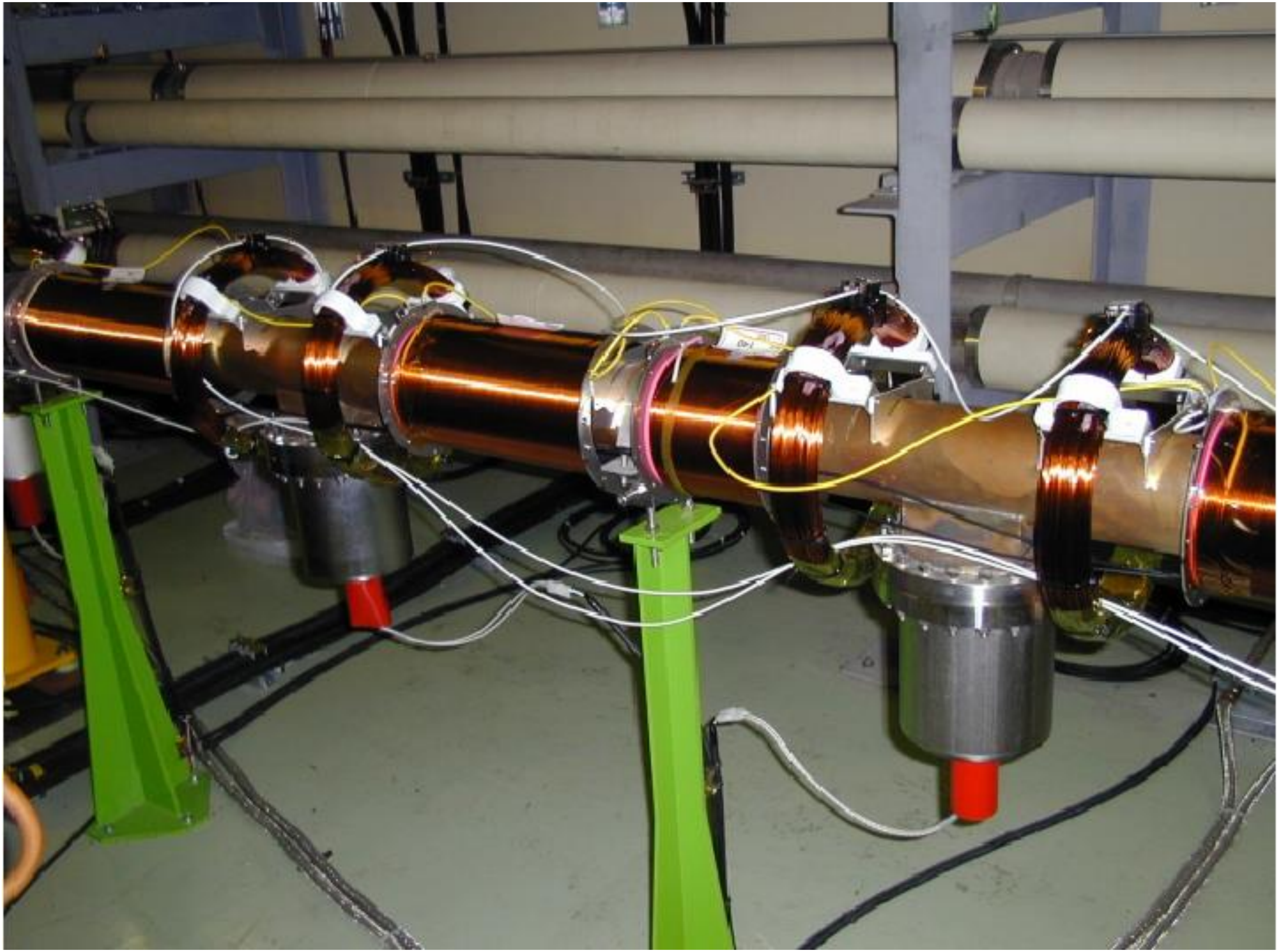
$$\frac{d^2\boldsymbol{x}_p}{ds^2} + K(s)\boldsymbol{x}_p = \frac{2N_e r_e}{\gamma}\sum_{e=1}^{N_e}\boldsymbol{F}_G(\boldsymbol{x}_p - \boldsymbol{x}_e)\delta_P(s - s_e)$$

$$\frac{d^2\boldsymbol{x}_e}{dt^2} = \frac{e}{m_e}\frac{d\boldsymbol{x}_e}{dt} \times \boldsymbol{B} - 2N_p r_e c\sum_{p=1}^{N_p}\boldsymbol{F}_G(\boldsymbol{x}_e - \boldsymbol{x}_p)\delta_P(t - t_p(s_e)) - r_e c^2\frac{\partial\phi(\boldsymbol{x}_e)}{\partial\boldsymbol{x}_e}$$

$$\triangle\phi(\boldsymbol{x}) = \sum_{e=1}^{N_e}\delta(\boldsymbol{x} - \boldsymbol{x}_e)$$

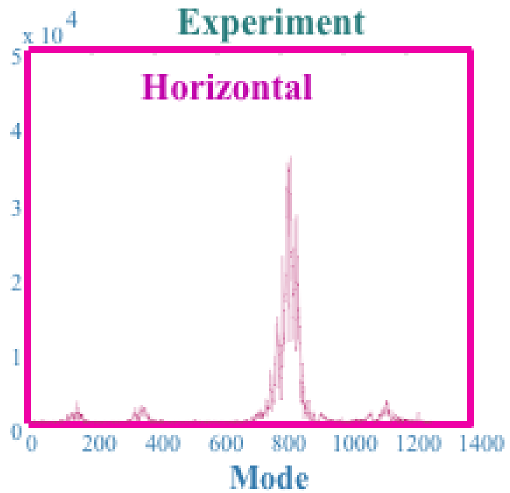
Mode spectrum is given by FFT of bunch motion

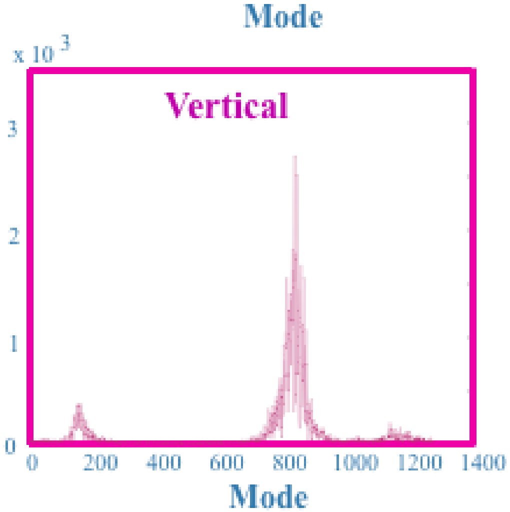




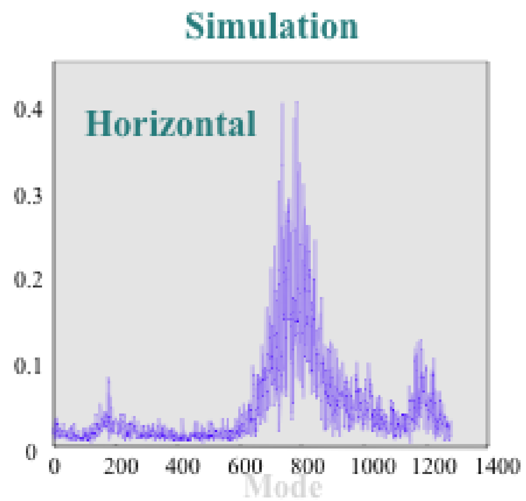
Measurement in KEKB

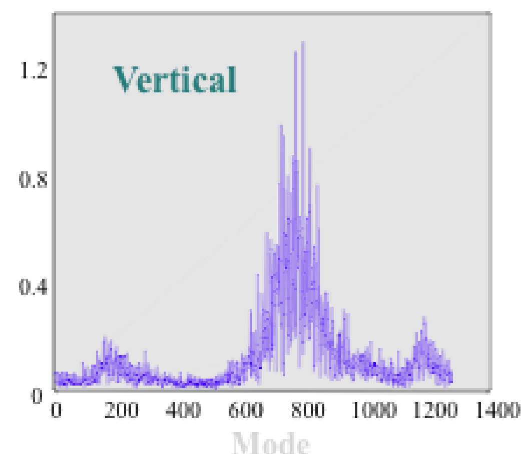
- CBI mode spectra in KEKB Solenoid-Off





Bunches are filled every 4 bucket.





Su Su Win et al,(EC200

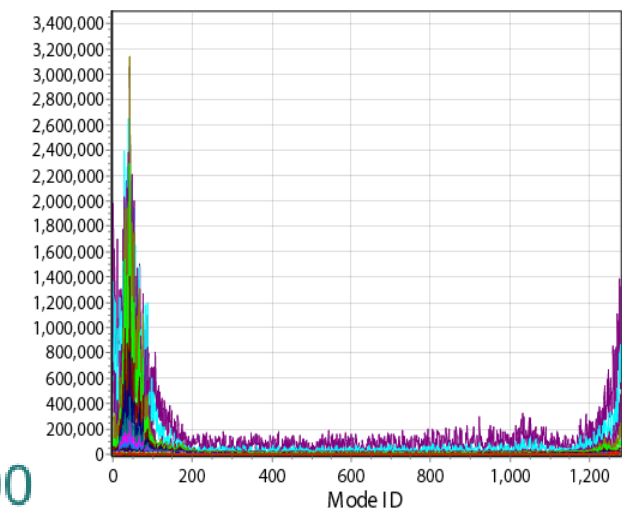
Solenoid ON

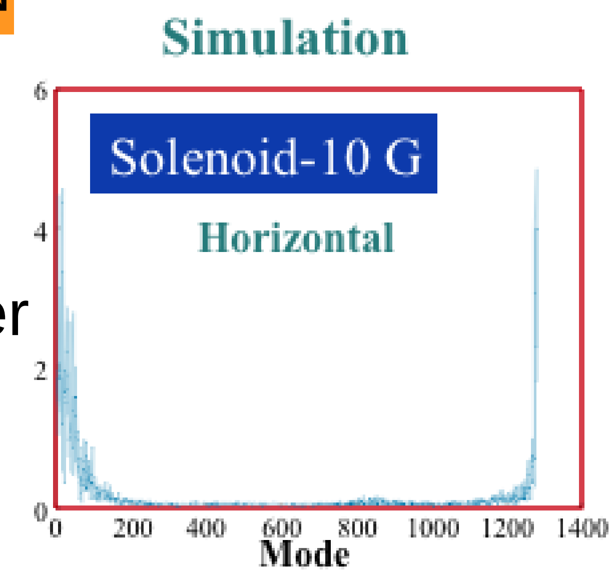
$$\omega_m = (h - m - \nu_{x,y})\omega_0$$

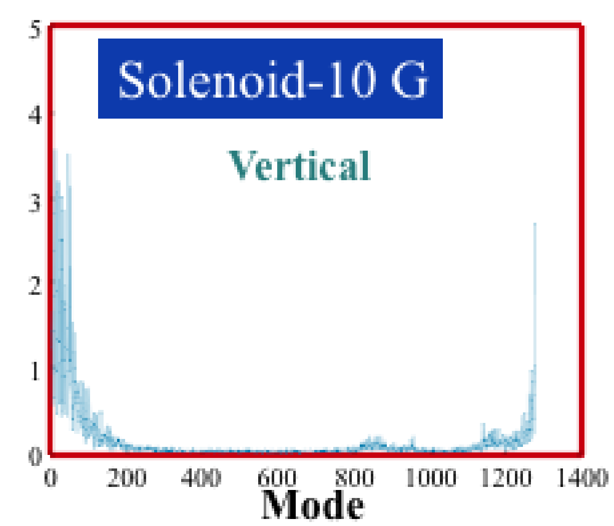
$$\text{or} \quad (m + \nu_{x,y})\omega_0$$

h: beam harmonic number
m: CBI mode

measurement





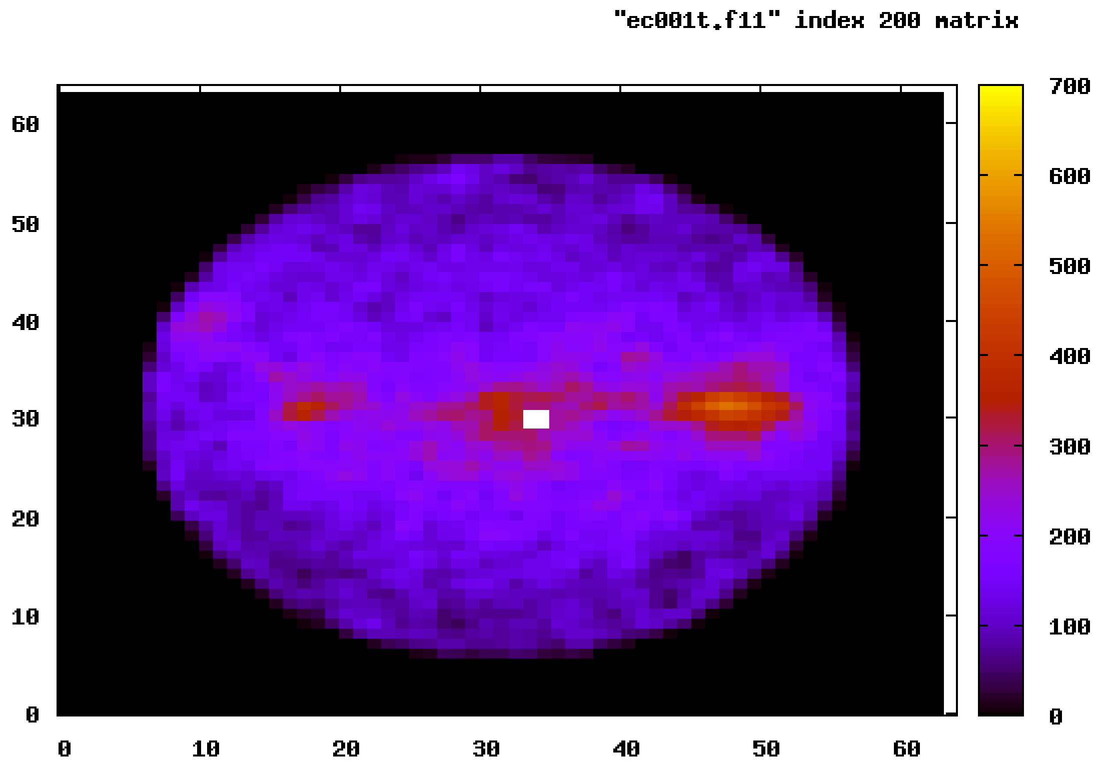


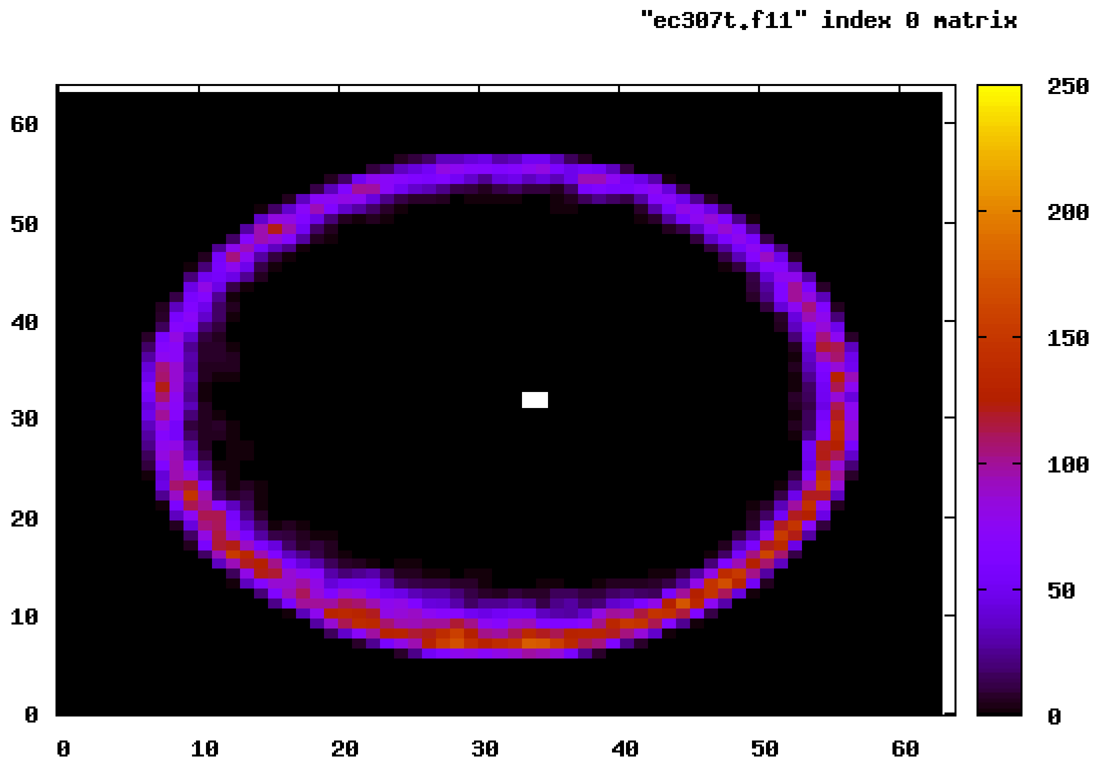
Solenoid is installed to protects electron cloud near the beam. The mode of the coupled bunch instability depends on the solenoid ON/OFF.

Electron distribution and Coupled bunch motion

- Drift Solenoid

White point: beam position passing through the chamber

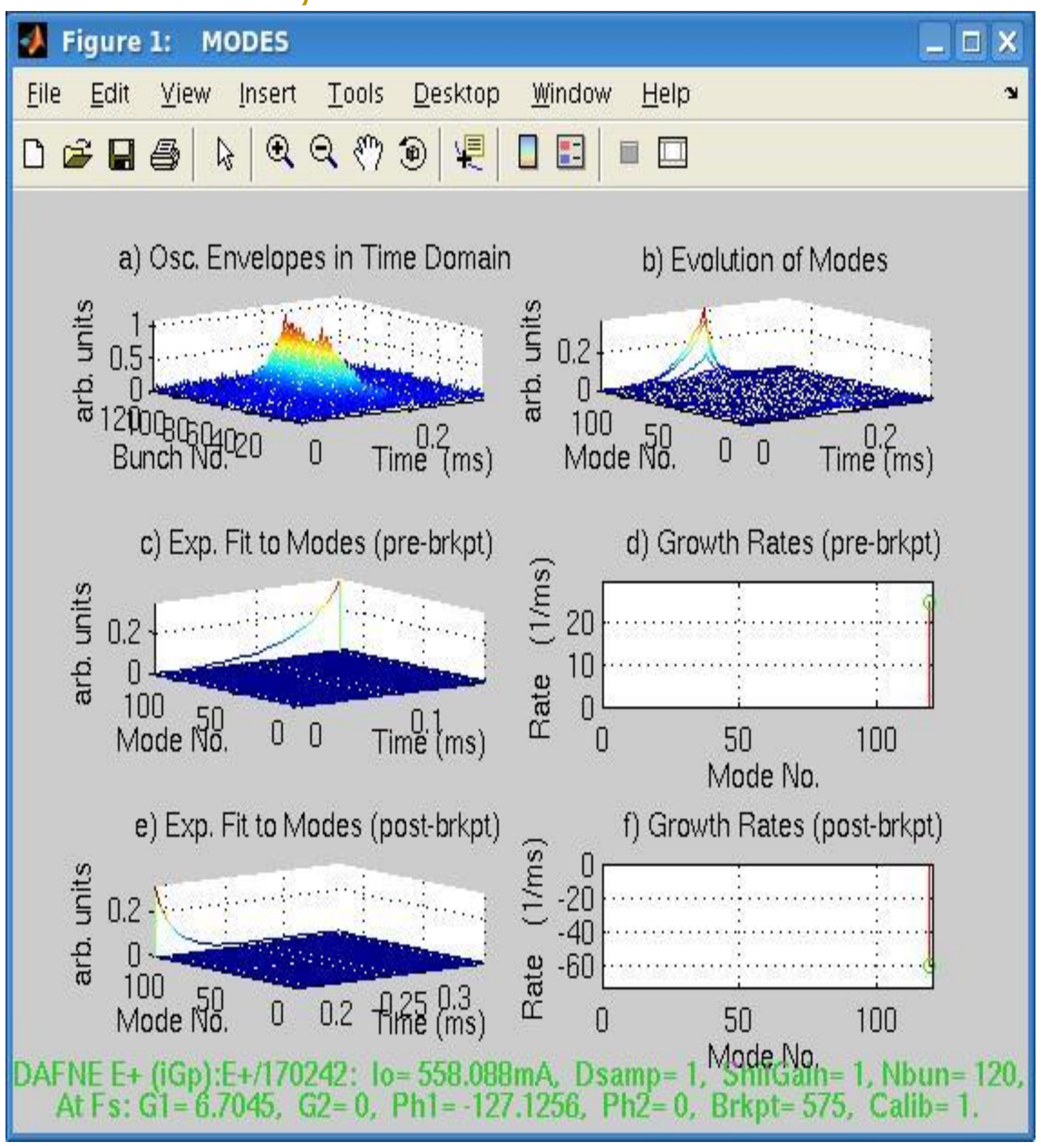




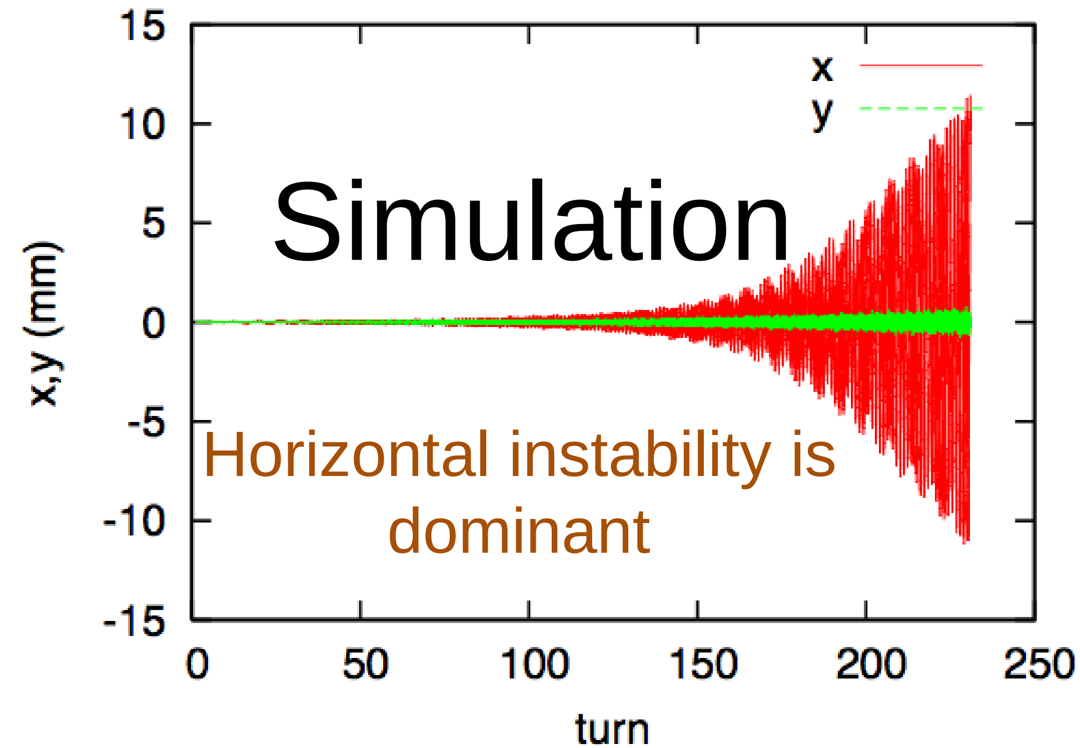
Coupled bunch instability due to electron cloud in strong bending field

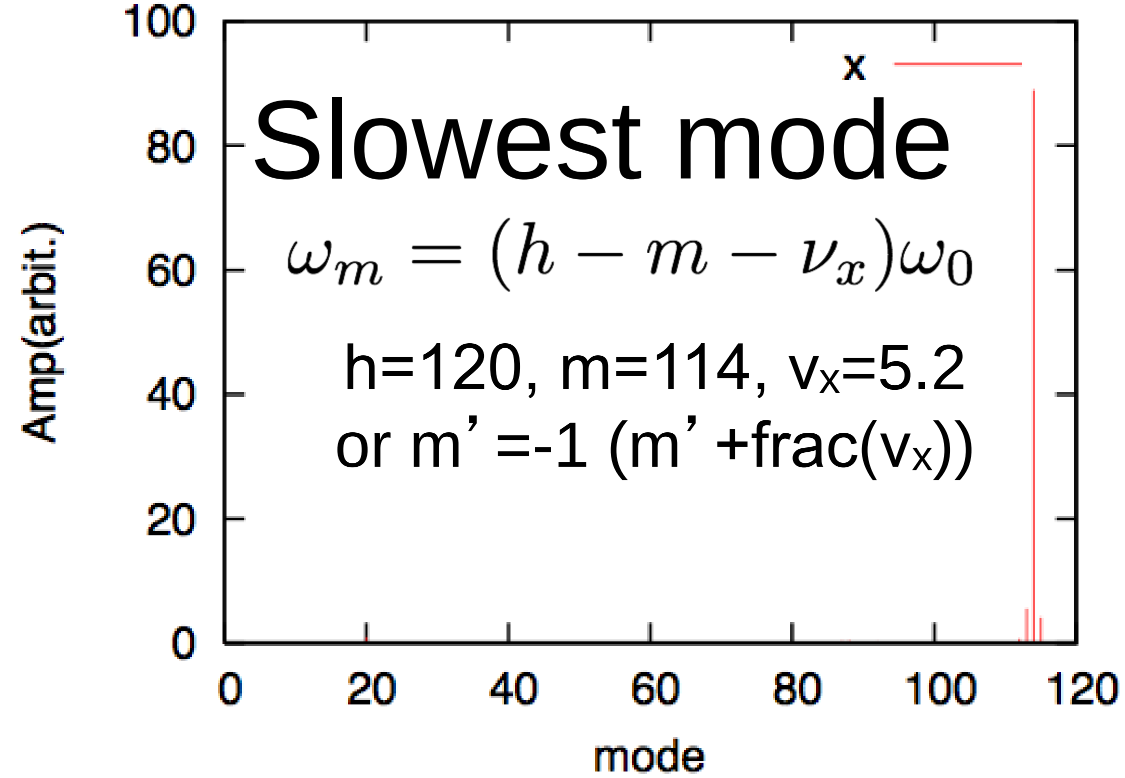
Measurement in DAFNE

M. Zobov, ECLOUD12



Horizontal coupled bunch instability

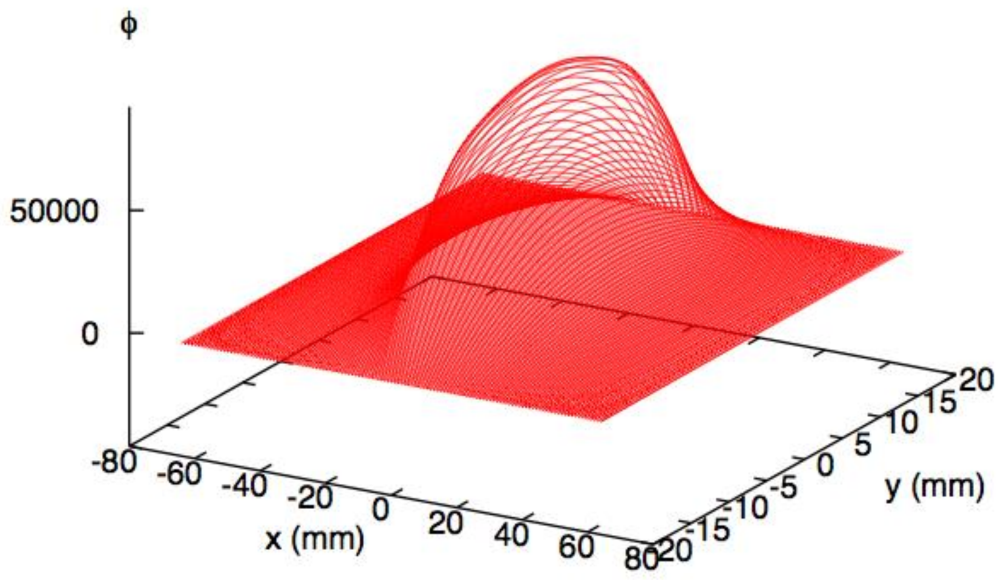


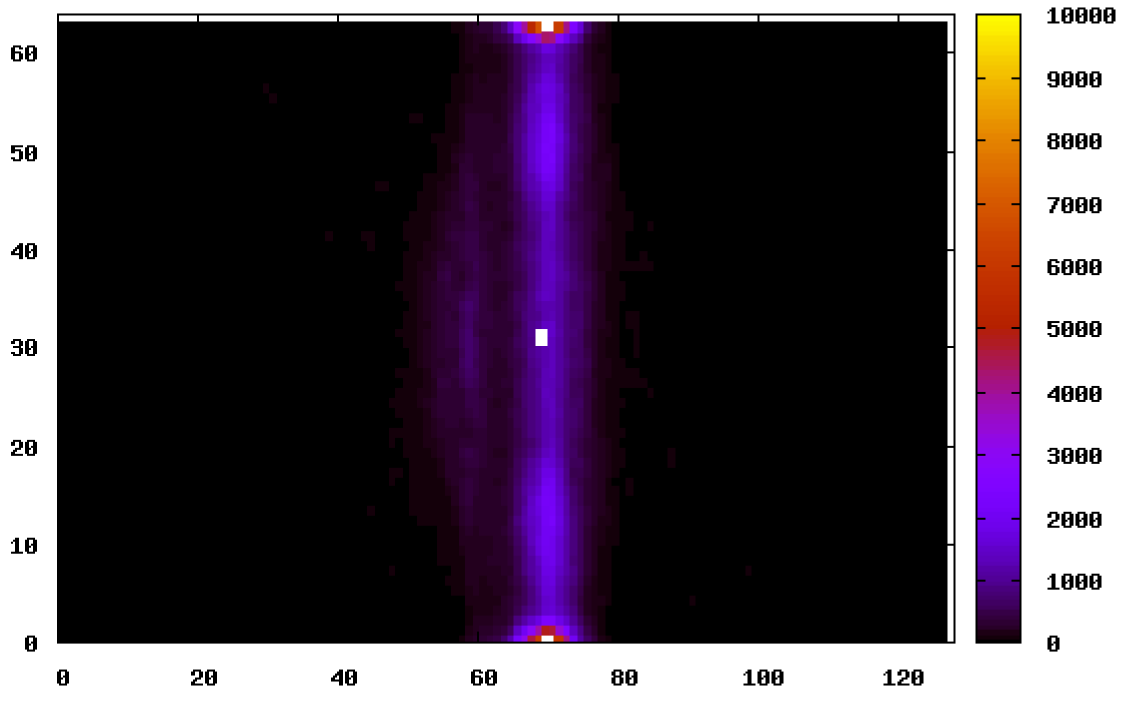


Coherent motion of beam and electron stripe

- Electron stripe is formed in bending magnet.
- The beam and stripe move coherently, then horizontal coupled bunch instability is induced.

Electron potential





Fermilab Recycler Ring

Parameters

$L=3300\text{m}$, $h=588$, $N_{bunch}=500$, $N_{p/bunch}=5\text{x}10^{10}$

$\varepsilon_{x,rms}=5.5\text{x}10^{-8}$ m, $<\beta>=40$ m

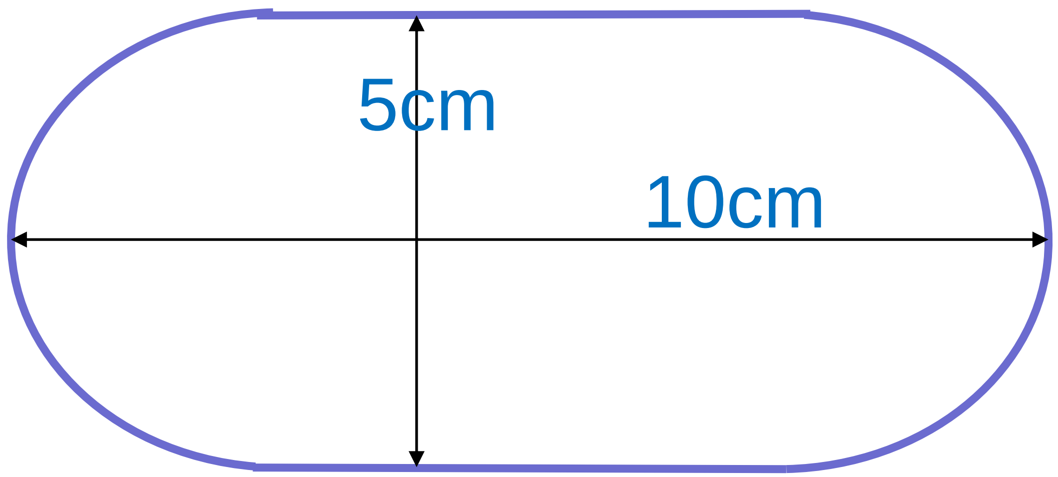
$\sigma_{z,rms}=0.3\text{m}$, $\sigma_{\delta,rms}=0.03\%$

$L_{bsep}=5.6\text{m}$ (1.87ns), $\lambda_p=8.9\text{x}10^9\ \text{m}^{-1}$(line density).

$\omega_e/2\pi=344$ MHz, $\omega_e\sigma_z/c=2.2$

Chamber geometry

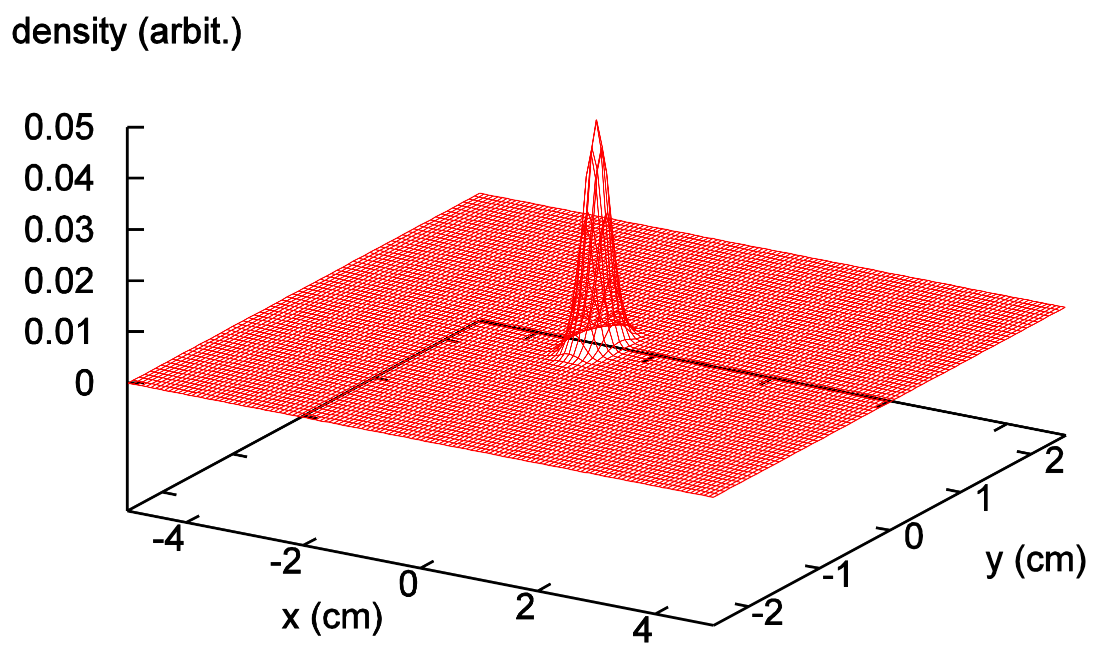
- Elliptic cross section 10cmx5cm
- Potential solver using Band Matrix Solver.
- $\sigma_{xy,rms}$=1.5mm, no very small for the chamber
- Beam potential is evaluated by Potential solver.
  (not by Bassetti-Erskine formula and its mirror)

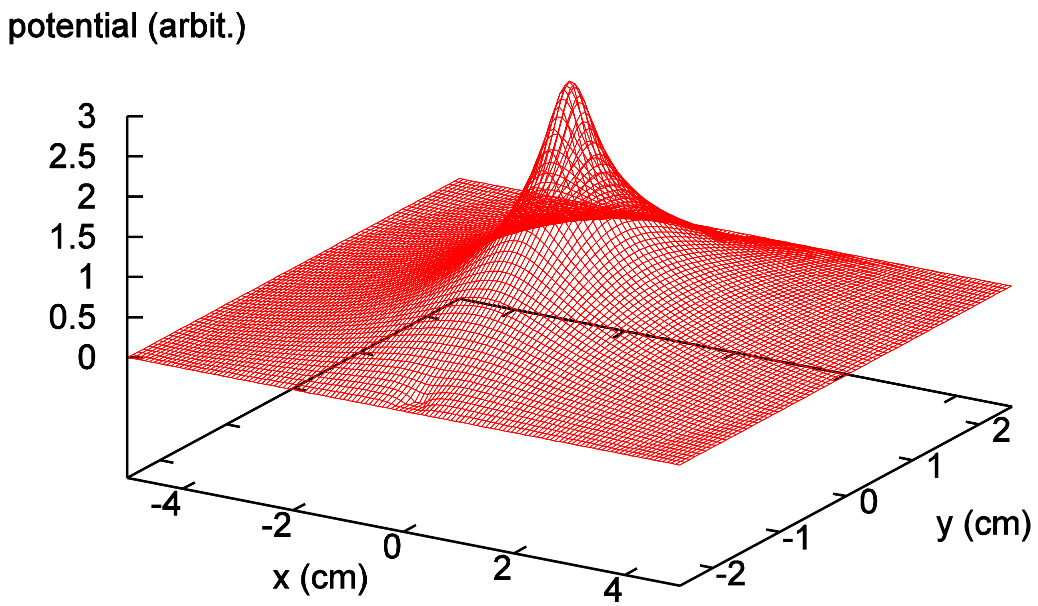


model: race track
10cmx5cm

Beam potential

beam charge density and potential in meshed space

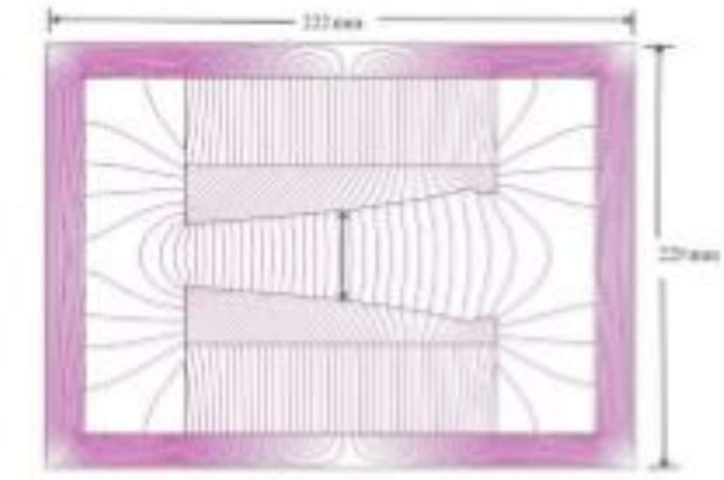




$\sigma_{xy,rms}$=1.5mm

Combined bend

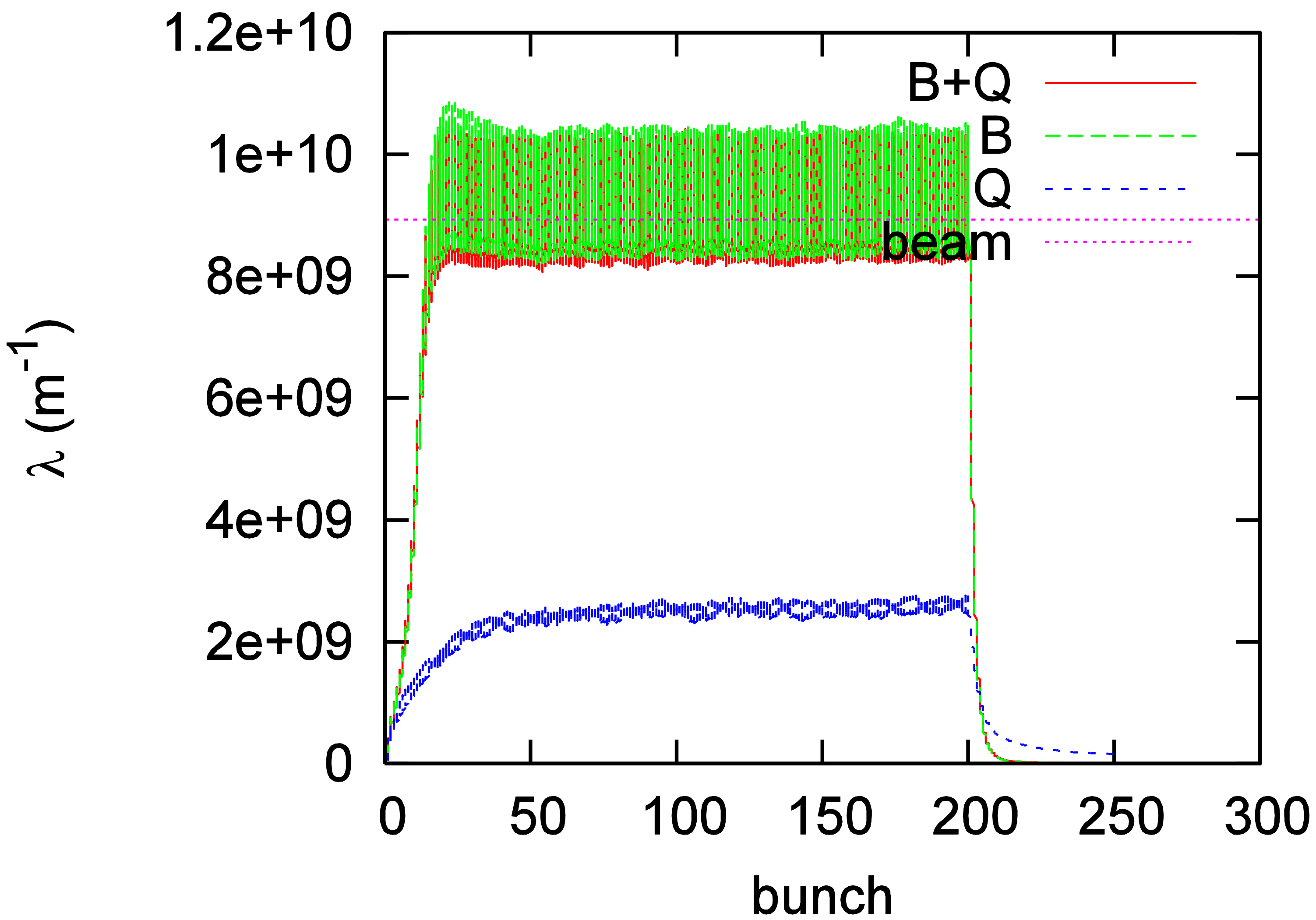
Magnet	Central Field, kG	Bdl, kG-m	Quadrupole, kG/m
RGF	1.3752	6.182	3.355
RGD	1.3752	6.183	-3.238
SGF	1.330	4.121	6.682
SGD	1.330	4.121	-6.824



- Electron motion in combined bend.
- Integrate cyclotron motion using local magnetic field.
- Runge-Kutta integration is slow for high field, high cyclotron freq.

Electron cloud buildup and damp

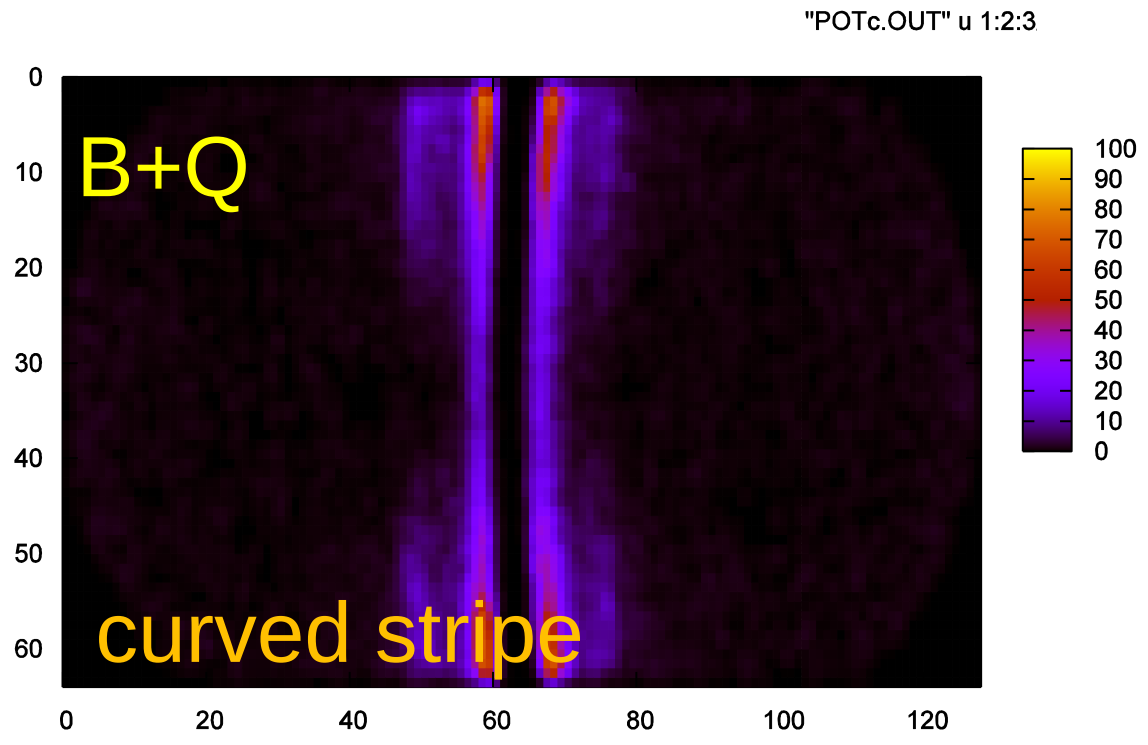
- 200 bunch and 50 empty bucket
- Initial e^-: 3.3×10^8/m.bunch, uniform
- Y_{2max}=1.8 at 300 eV, Reflection at 0eV =50%

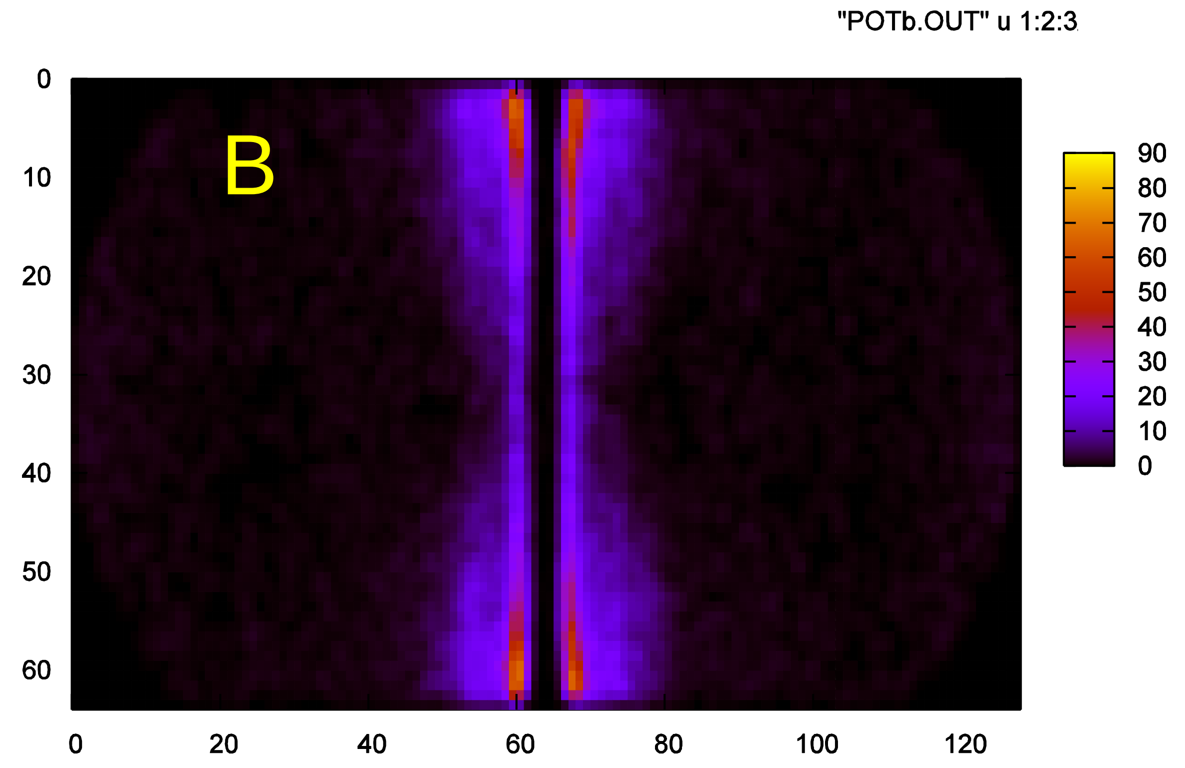


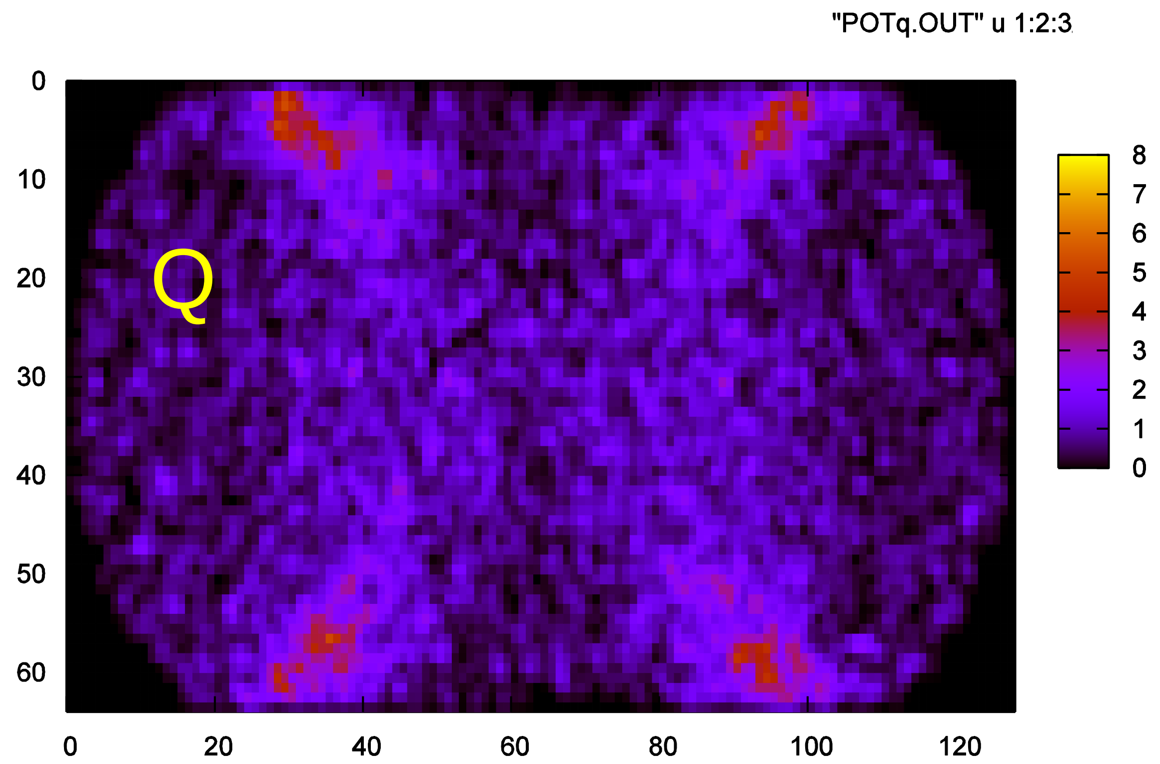
No big difference between “B” and “B+Q”

B=1375 G
Q=3355 G/m

Electron distribution







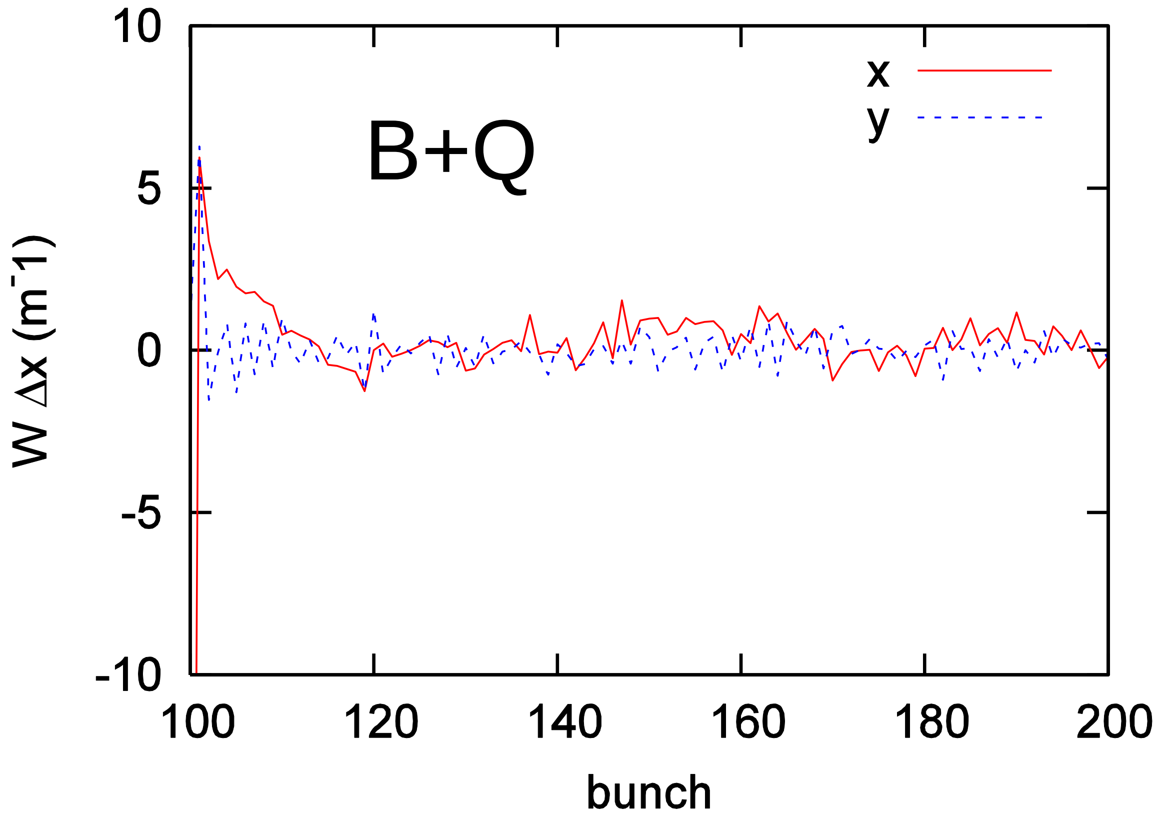
Wake force for the electron cloud

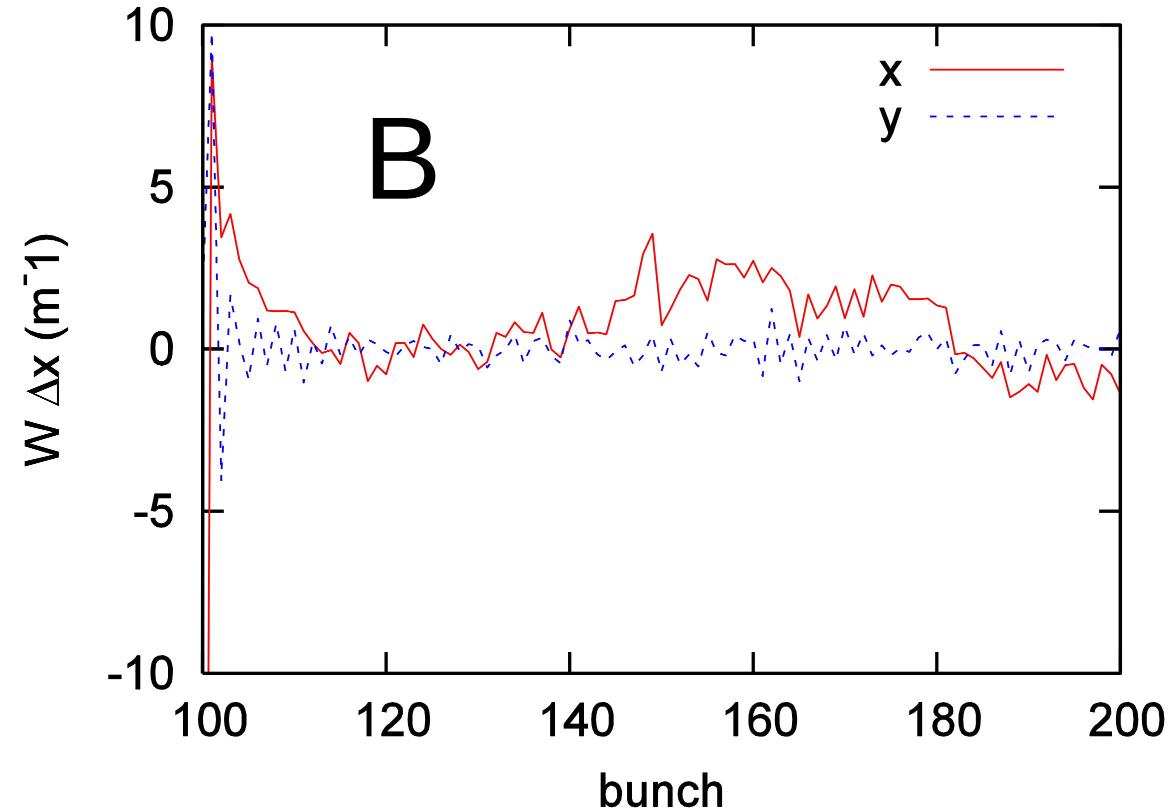
- Electron density is saturate after 20-30 bunches passage.
- A bunch (100-th) shifts 1cm, then calculate kick of bunches (>100-th) from cloud.
- The code gives total velocity change of macro-electrons, $\Delta v_{xy,tot}(ixL_{bsep})$, i>100.
- Beam is kicked by the velocity change per circumference taking into account real/macro ratio. (rne*L/ne in the code)

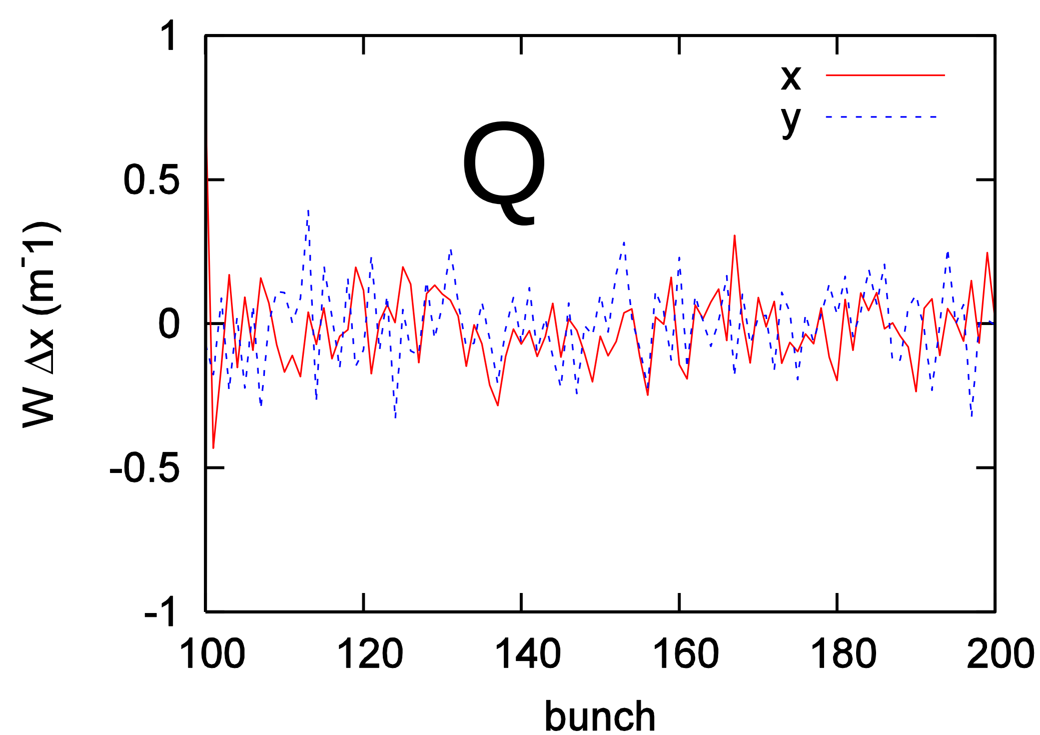
$$\Delta p_{xy,n+i} = \frac{m_e}{M_p}\frac{\Delta v_{xy,tot}}{N_p \gamma c} = \frac{N_p r_p}{\gamma} W_{xy}(iL_{bsep})\Delta y_n$$

$$W_{xy}(iL_{bsep})\Delta y_n = \frac{m_e}{M_p}\frac{\Delta v_{xy,tot}(iL_{bsep})}{N_p^2 r_p c}$$

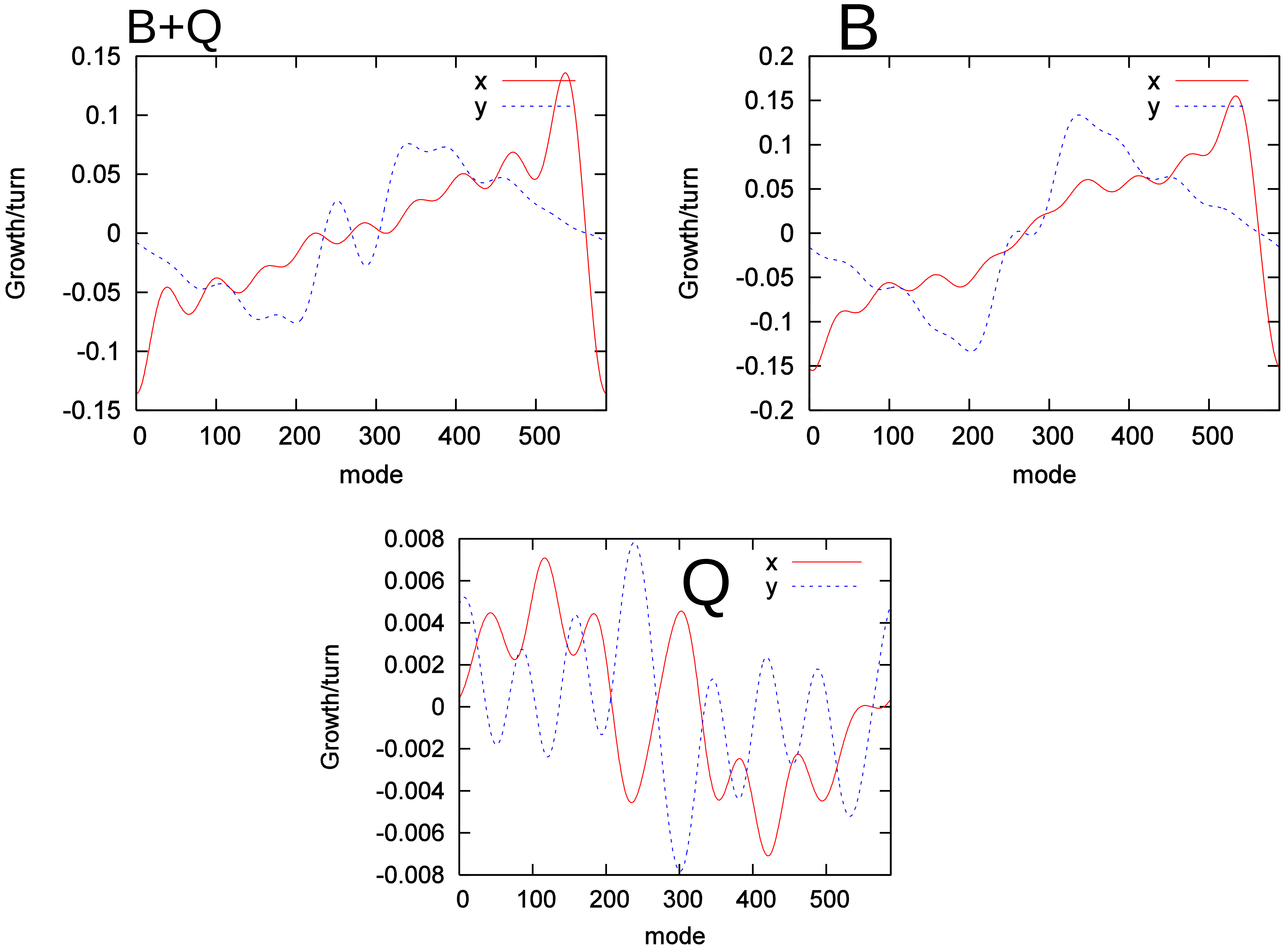
Wake force in each magnet







Growth rate of coupled bunch instability



Summary

- Code development for Recycler was been performed.
- Combined bend is implemented. Chamber geometry is now racetrack model.
- Electron density and distribution are obtained.
- Wake force in each magnet and growth rate are obtained.
- For neutralized electron, the growth time is 10 turns for bend/combined bend.
- Detailed study can be started.

Thank you for your attention

Memo injection of RR

- h=84x7=588
- 81bunch/batch
- 3 empty bucket at the tail of batch
- inject 81bunchx6batch=486
- Slip stacking 2+6, 4+6, 6+6
- PIP-I 4.3x10^{12}/batch PIP-II 6.3x10^{12}/batch
- β_x=44(F)-13(D) m, β_y=14(F)-45(D) m
- η_x=1-1.5 m. γ_t=20.26.