# Electron cloud instability in low emittance rings

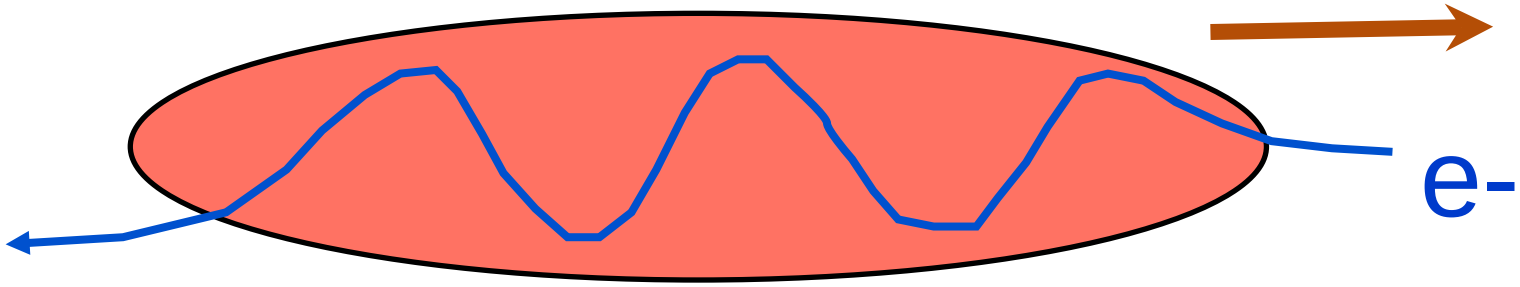
H. Jin (Postech), K. Ohmi (KEK)
ECLOUD'10@Cornell
Oct. 8-12, 2010

# Introduction

- Fast head-tail instability in CesrTA and SuperKEKB.
- Multibunch instability

# Coherent strong head-tail instability

- Coherent motion between inner bunch and electron cloud.
- Electrons oscillate electric force inner bunch along z, $\omega_e = \sqrt{\dfrac{\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}}$
- The instability is characterized by $\omega_e \sigma_z / c$, number of electron oscillation along the bunch.



# Threshold of the strong head-tail instability (Balance of growth and Landau damping)

- Stability condition for $\omega_e \sigma_z/c>1$

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

$$U=\frac{\sqrt{3}\lambda_p r_0 \beta}{\nu_s \quad \gamma \quad \omega_e\sigma_z/c}\frac{\left|Z_\perp(\omega_e)\right|}{Z_0}=\frac{\sqrt{3}\lambda_p r_0 \beta}{\nu_s \quad \gamma \quad \omega_e\sigma_z/c}\frac{KQ}{4\pi}\frac{\lambda_e}{\lambda_p}\frac{L}{\sigma_y(\sigma_x+\sigma_y)}=1$$

- Since $\rho_e=\lambda_e/2\pi\sigma_x\sigma_y$,

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

Origin of Landau damping is momentum compaction

$$\nu_s\sigma_z=\alpha\sigma_\delta L$$

- Q=min($Q_{nl}$, $\omega_e \sigma_z/c$)
- $Q_{nl}$=5-10?, depending on the nonlinear interaction.
- K characterizes cloud size effect and pinching.
- $\omega_e \sigma_z/c$~12-20 for damping rings.
- We use K=$\omega_e \sigma_z/c$ and $Q_{nl}$=7 for analytical estimation.

# Parameters

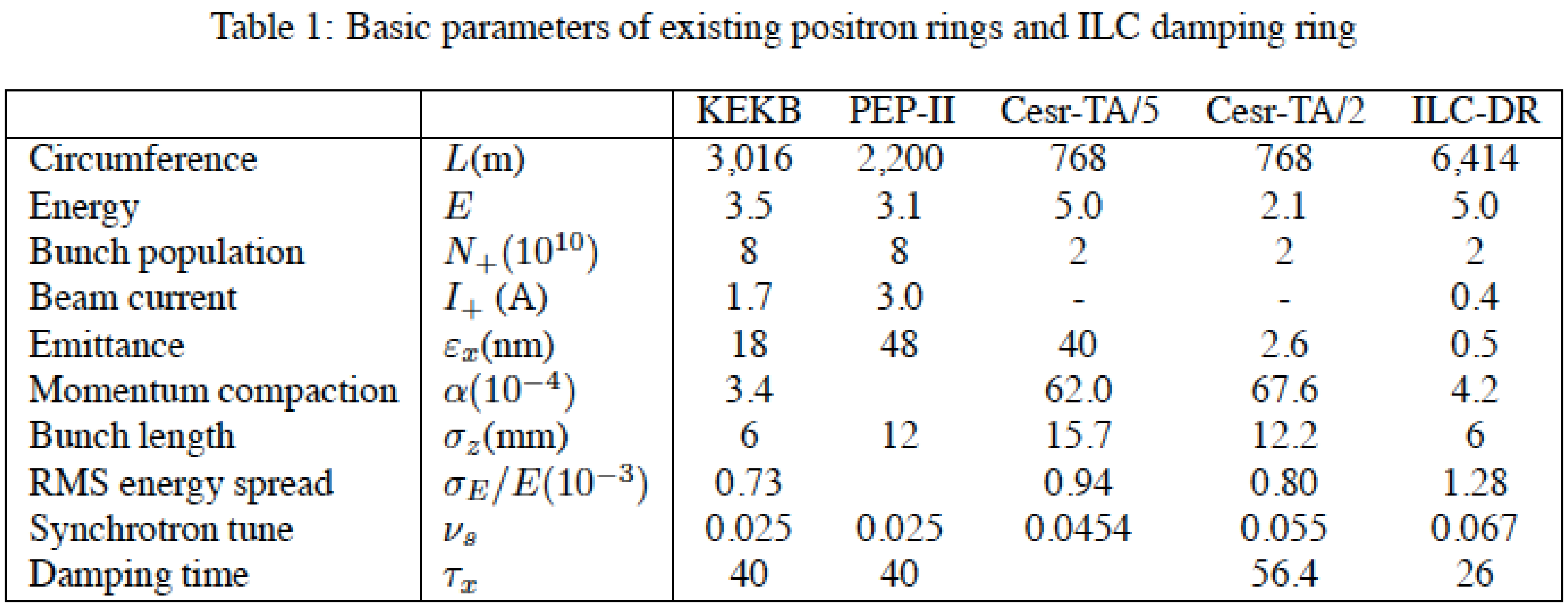


Table 1: Basic parameters of existing positron rings and ILC damping ring

| | | KEKB | PEP-II | Cesr-TA/5 | Cesr-TA/2 | ILC-DR | SuperKEKB |
|---|---|---|---|---|---|---|---|
| Circumference | $L$(m) | 3,016 | 2,200 | 768 | 768 | 6,414 | 3016 |
| Energy | $E$ | 3.5 | 3.1 | 5.0 | 2.1 | 5.0 | 4.0 |
| Bunch population | $N_+(10^{10})$ | 8 | 8 | 2 | 2 | 2 | 9 |
| Beam current | $I_+$ (A) | 1.7 | 3.0 | - | - | 0.4 | 3.6 |
| Emittance | $\varepsilon_x$(nm) | 18 | 48 | 40 | 2.6 | 0.5 | 2 |
| Momentum compaction | $\alpha(10^{-4})$ | 3.4 | | 62.0 | 67.6 | 4.2 | 3.5 |
| Bunch length | $\sigma_z$(mm) | 6 | 12 | 15.7 | 12.2 | 6 | 6 |
| RMS energy spread | $\sigma_E/E(10^{-3})$ | 0.73 | | 0.94 | 0.80 | 1.28 | 0.8 |
| Synchrotron tune | $\nu_s$ | 0.025 | 0.025 | 0.0454 | 0.055 | 0.067 | 0.0256 |
| Damping time | $\tau_x$ | 40 | 40 | | 56.4 | 26 | 43 |

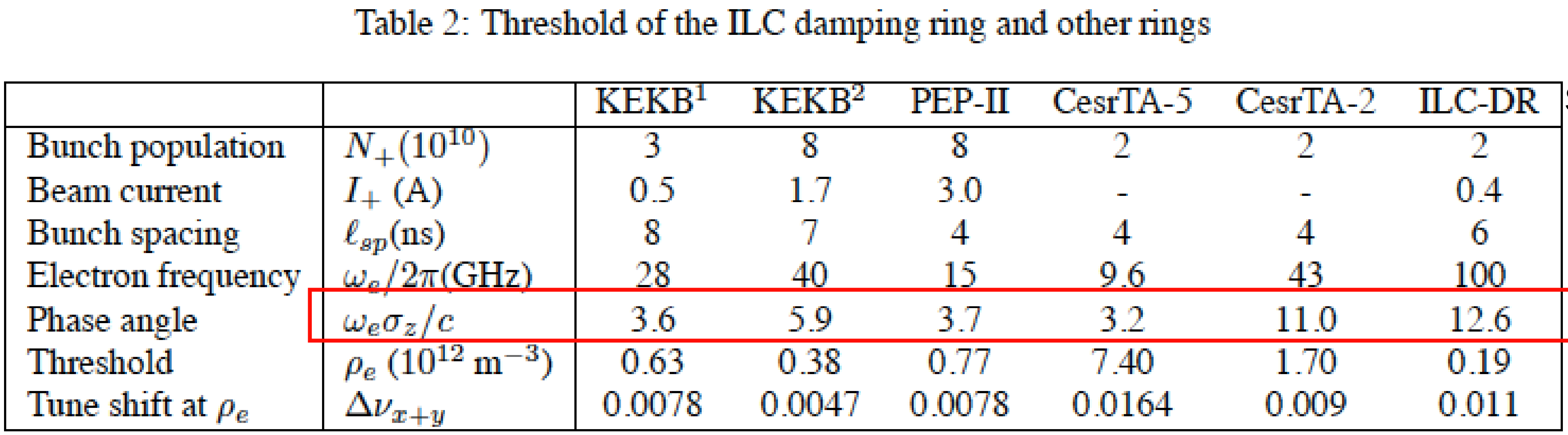


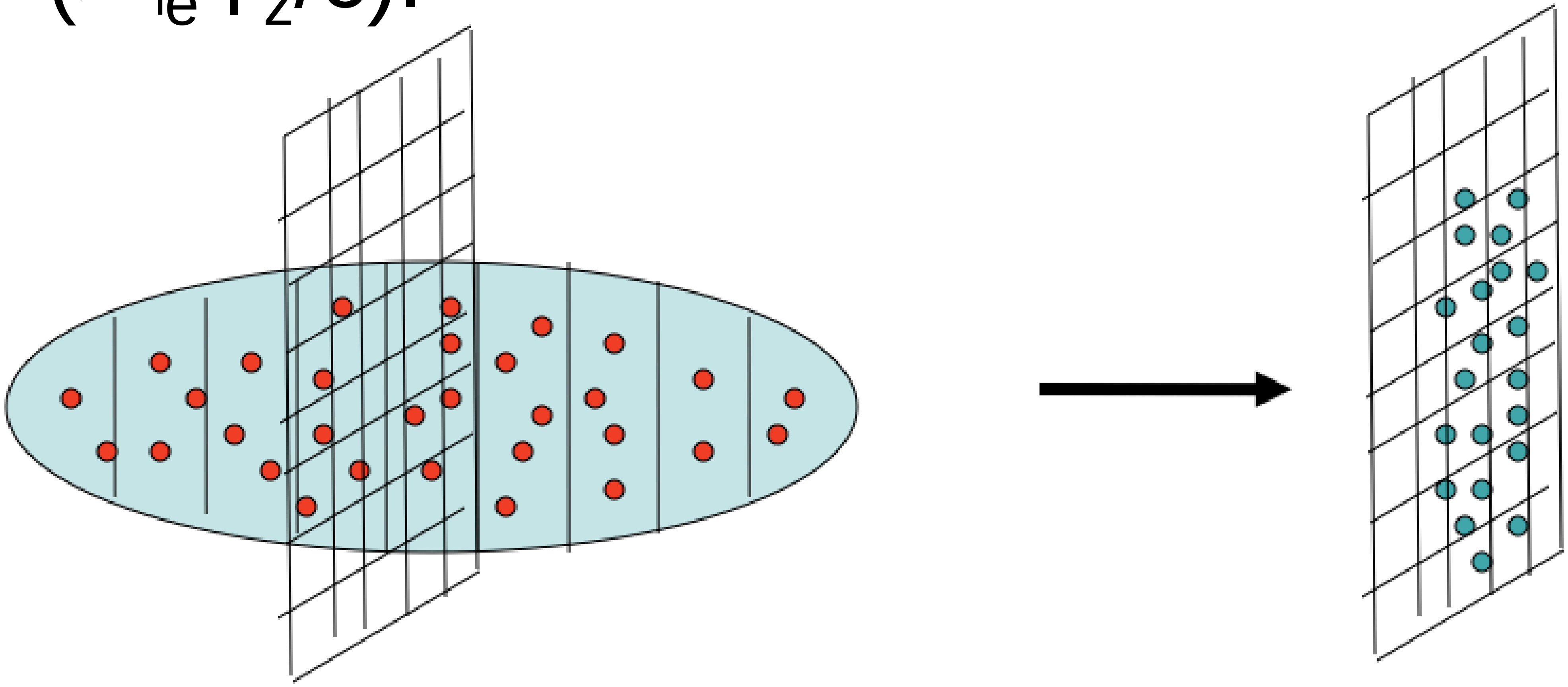
Table 2: Threshold of the ILC damping ring and other rings

| | | KEKB[1] | KEKB[2] | PEP-II | CesrTA-5 | CesrTA-2 | ILC-DR | SuperKEKB |
|---|---|---|---|---|---|---|---|---|
| Bunch population | $N_+(10^{10})$ | 3 | 8 | 8 | 2 | 2 | 2 | 9 |
| Beam current | $I_+$ (A) | 0.5 | 1.7 | 3.0 | - | - | 0.4 | 3.6 |
| Bunch spacing | $\ell_{sp}$(ns) | 8 | 7 | 4 | 4 | 4 | 6 | 4 |
| Electron frequency | $\omega_e/2\pi$(GHz) | 28 | 40 | 15 | 9.6 | 43 | 100 | 189 |
| Phase angle | $\omega_e\sigma_z/c$ | 3.6 | 5.9 | 3.7 | 3.2 | 11.0 | 12.6 | 23.8 |
| Threshold | $\rho_e$ ($10^{12}$ m$^{-3}$) | 0.63 | 0.38 | 0.77 | 7.40 | 1.70 | 0.19 | 0.27 |
| Tune shift at $\rho_e$ | $\Delta\nu_{x+y}$ | 0.0078 | 0.0047 | 0.0078 | 0.0164 | 0.009 | 0.011 | 0.003 |

High $\omega_e\sigma_z/c$ characterizes low emittance ring.

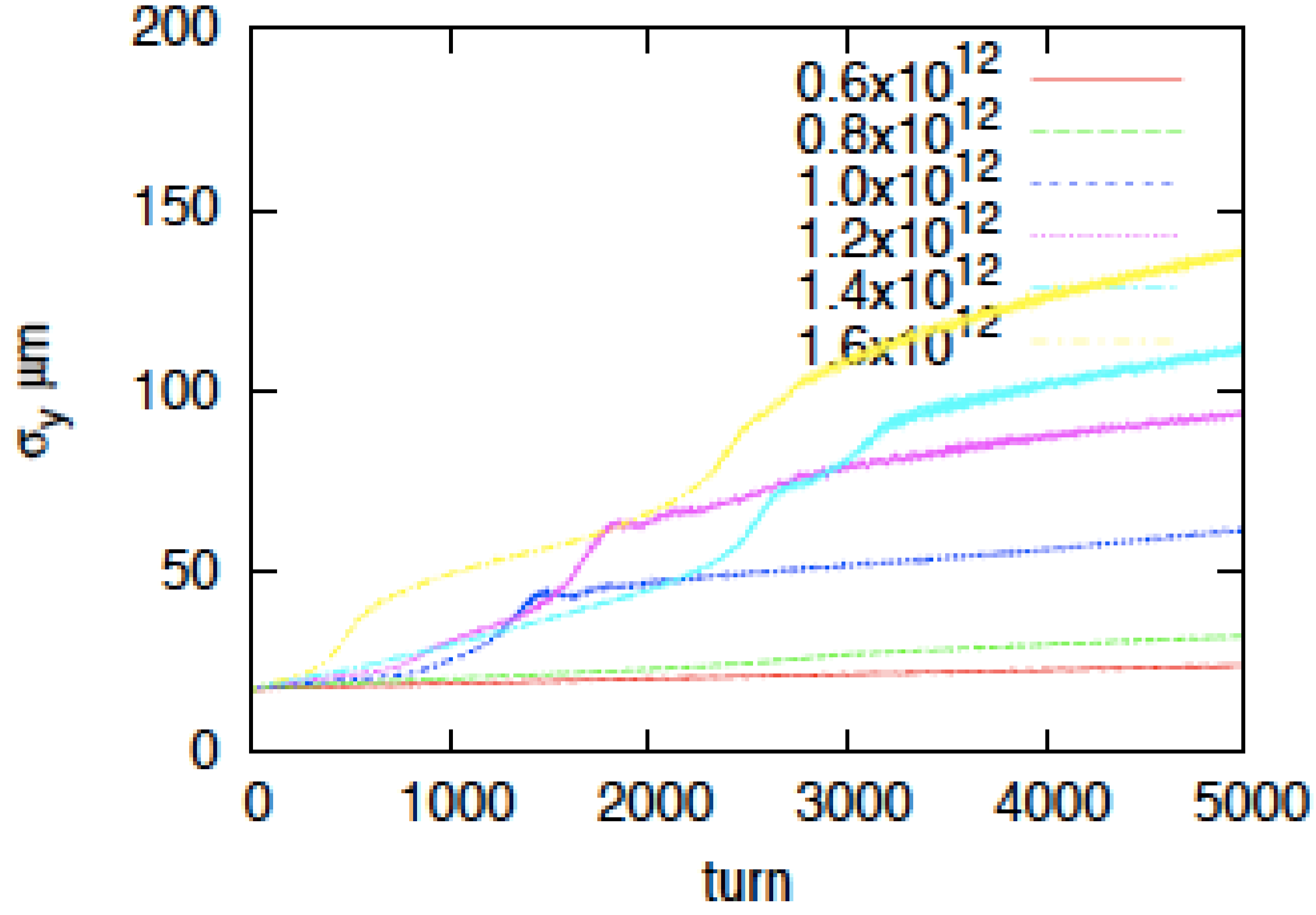
# Particle in Cell simulation (PEHTS)

- Electron clouds are located several or many s position in a ring.
- Potential solver based on 2D FFT.
- Beam is sliced into 30-100 pieces (>⌉$_e$ ⌠$_z$/c).



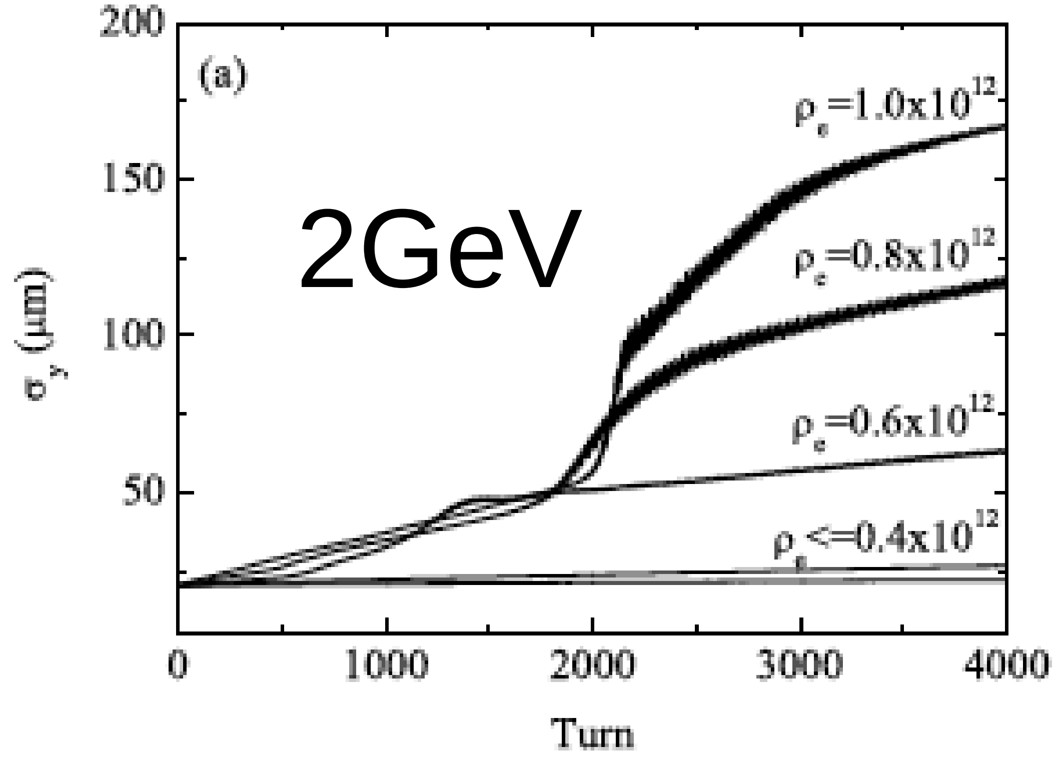
# Simulation for CestTA

# I=1.3mA, N=$2\times10^{10}$



- Simulation $\rho_{th}=1\times10^{12}$ m$^{-3}$.
- Analytic $\rho_{th}=1.7\times10^{12}$ m$^{-3}$.

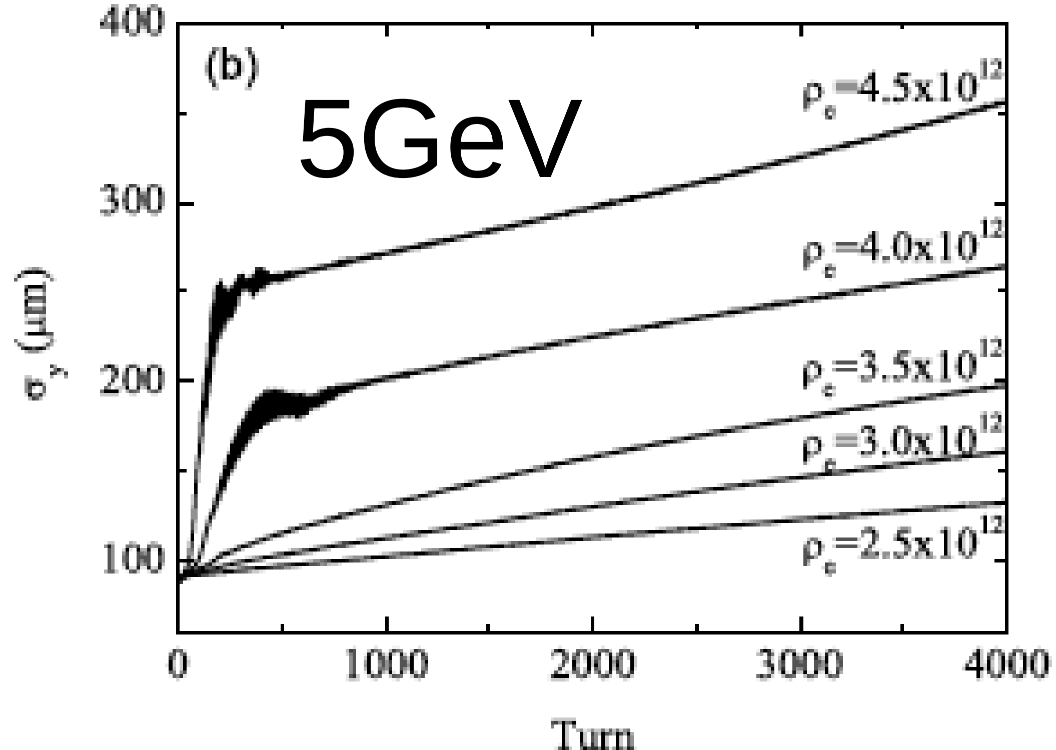
# CesrTA 2 and 5 GeV



2GeV

$\rho_{th}=0.8 \times 10^{12}$ cm$^{-3}$

- High(2GeV) and low(5GeV) $\omega_e \sigma_z / c$.

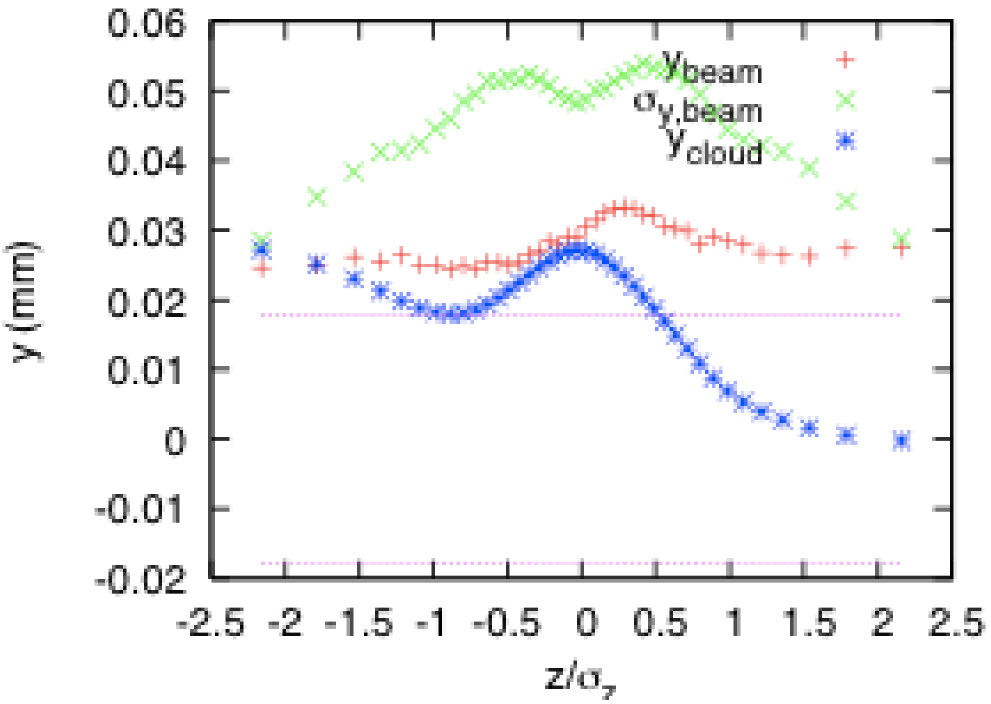


5GeV

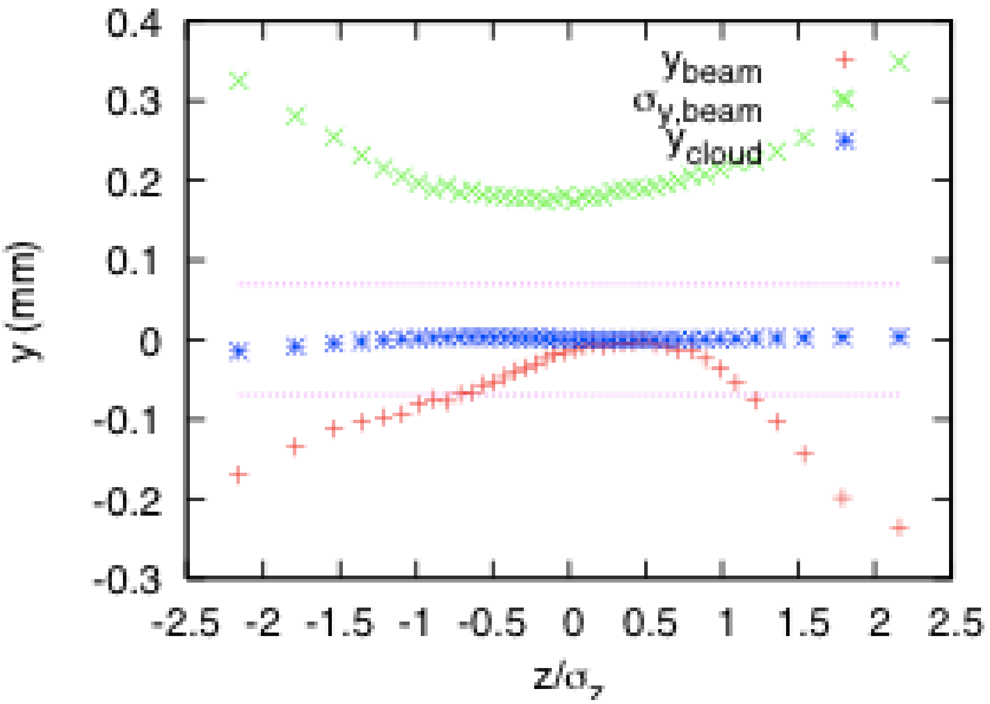
$\rho_{th}=4 \times 10^{12}$ cm$^{-3}$

# Coherent motion in the simulation

- 2 GeV



5 GeV

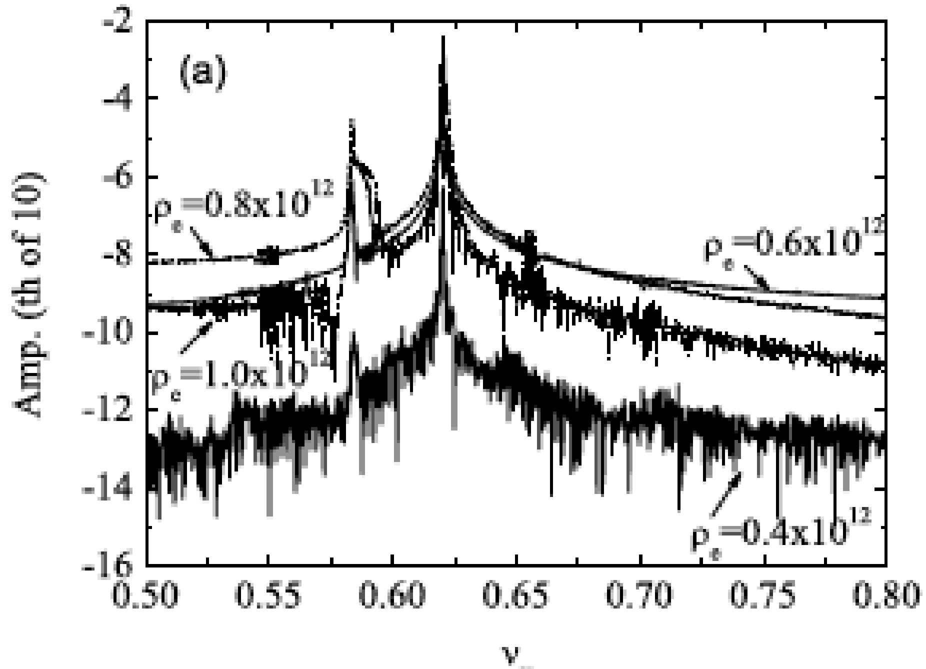


- High(2GeV) and low(5GeV) $\omega_e\sigma_z/c$.

# Simulated Unstable spectra

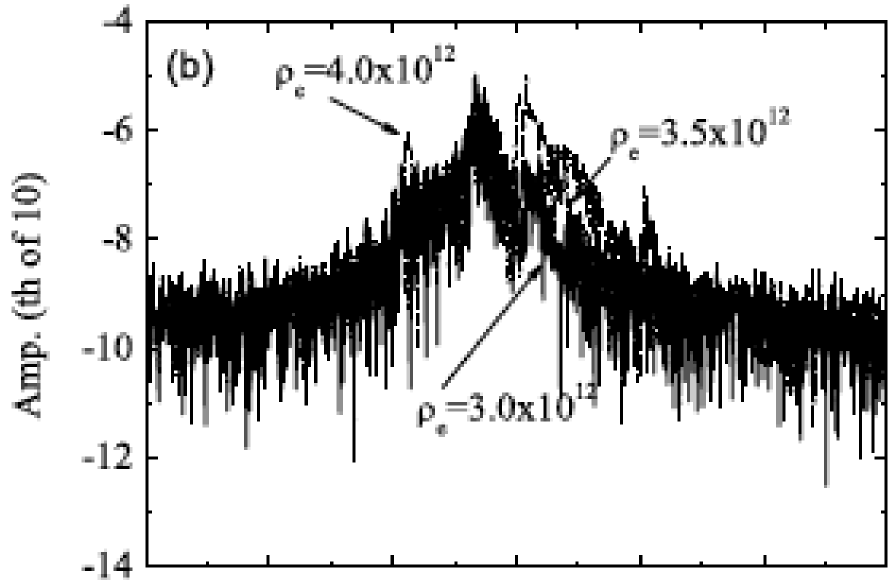
- Lower sideband is dominant for high $\omega_e\sigma_z/c$ (low emittance).

2 GeV

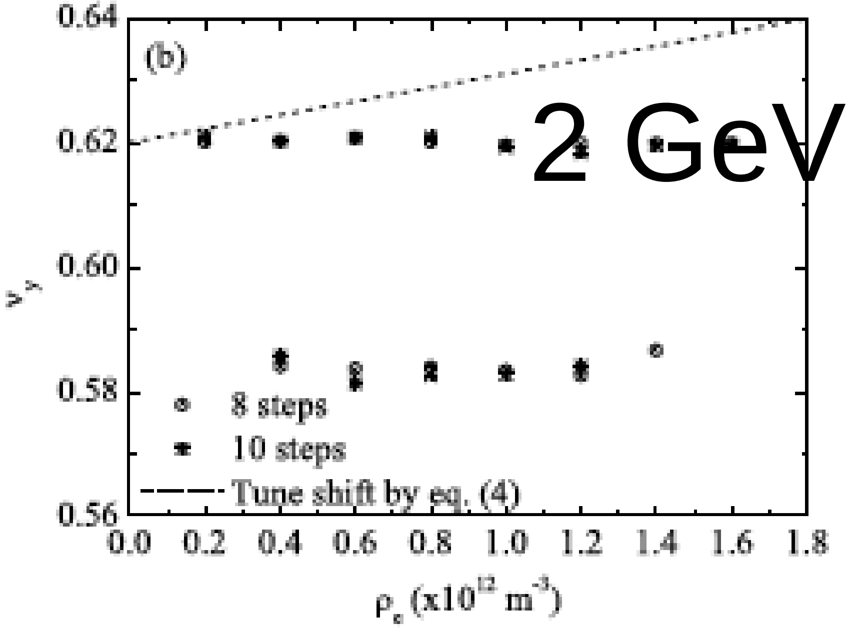


- Upper sideband is dominant for 5GeV

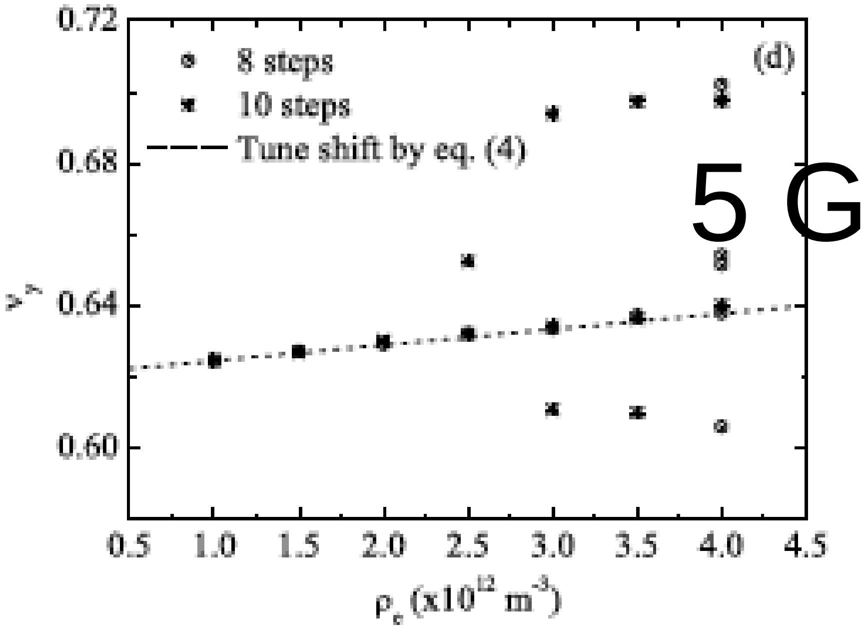
5 GeV



# Simulated beam spectra



2 GeV



5 GeV

- Lower sideband is seen for high $\omega_e\sigma_z/c$, 2GeV.
- Upper sideband is seen for low $\omega_e\sigma_z/c$, 5 GeV.

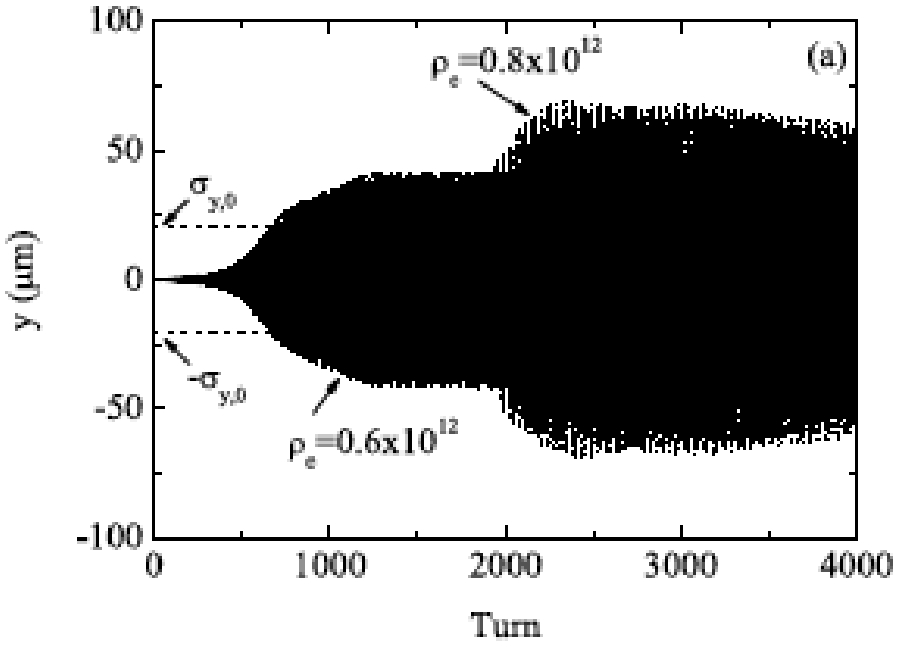
# Bunch by bunch feed back

- Model, feedback with one turn delay

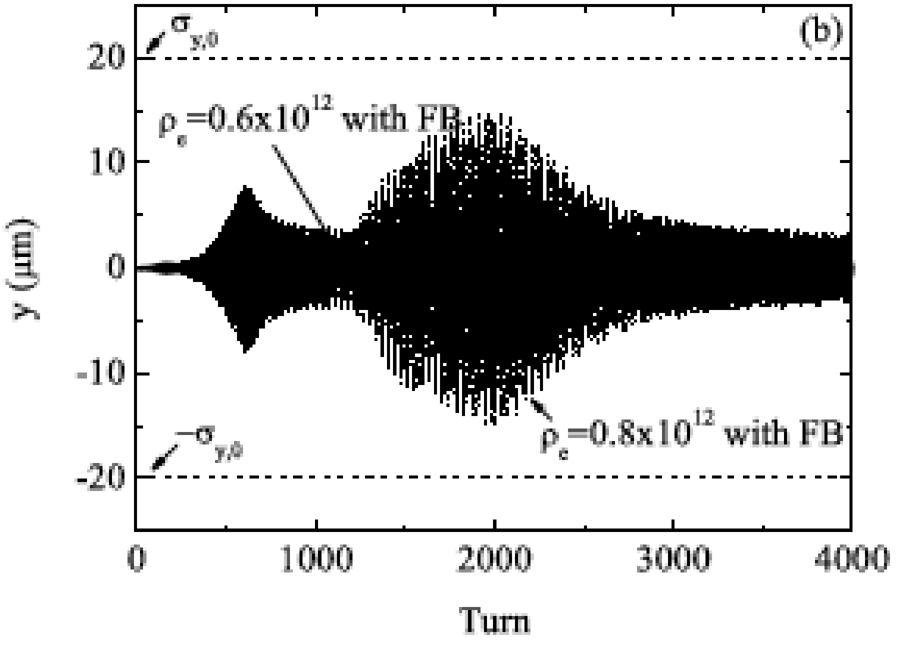
$$\begin{pmatrix} y \\ y' \end{pmatrix}_{n,+} = \begin{pmatrix} y \\ y' \end{pmatrix}_{n,-} - \alpha M \begin{pmatrix} \langle y \rangle \\ \langle y' \rangle \end{pmatrix}_{n-1,+}$$

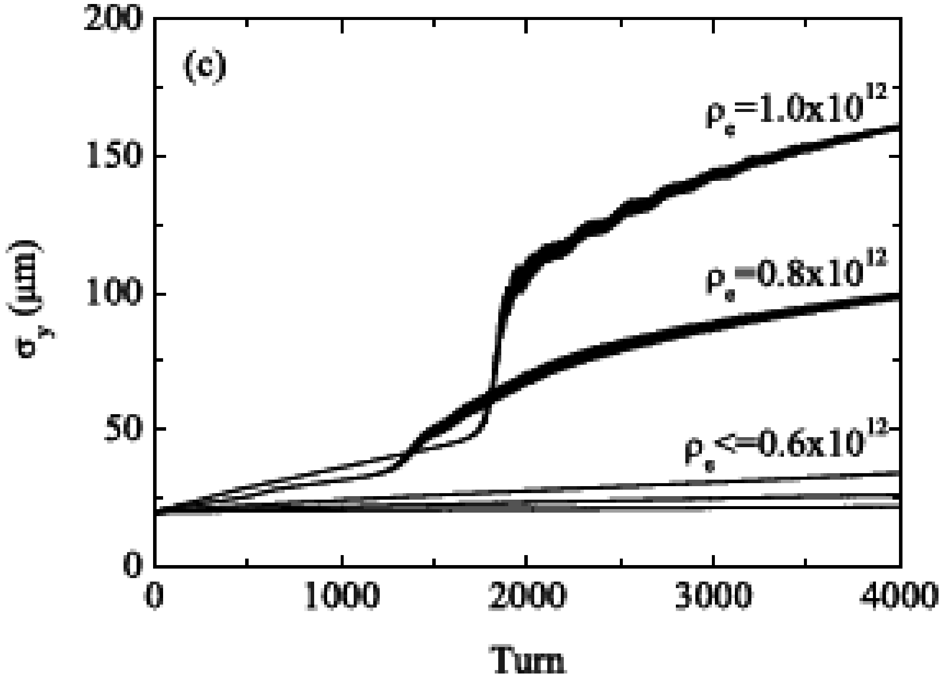
- M: revolution matrix
- α: feedback damping rate
- n: n-th turn
- ±: after or before feedback kick
- <>: average over beam particles

# FB suppresses the instability a little(2GeV)

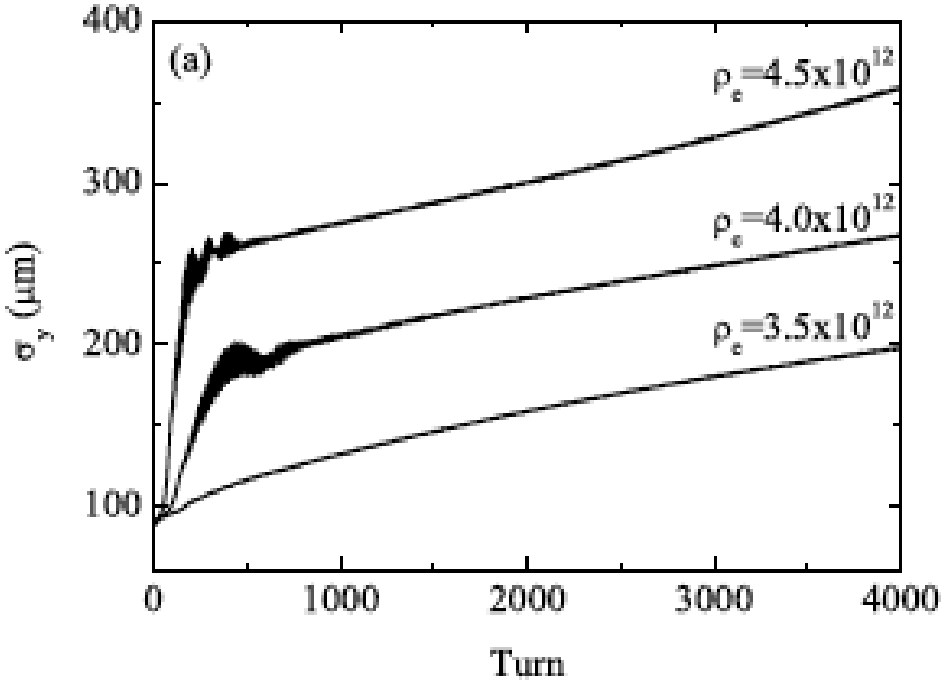


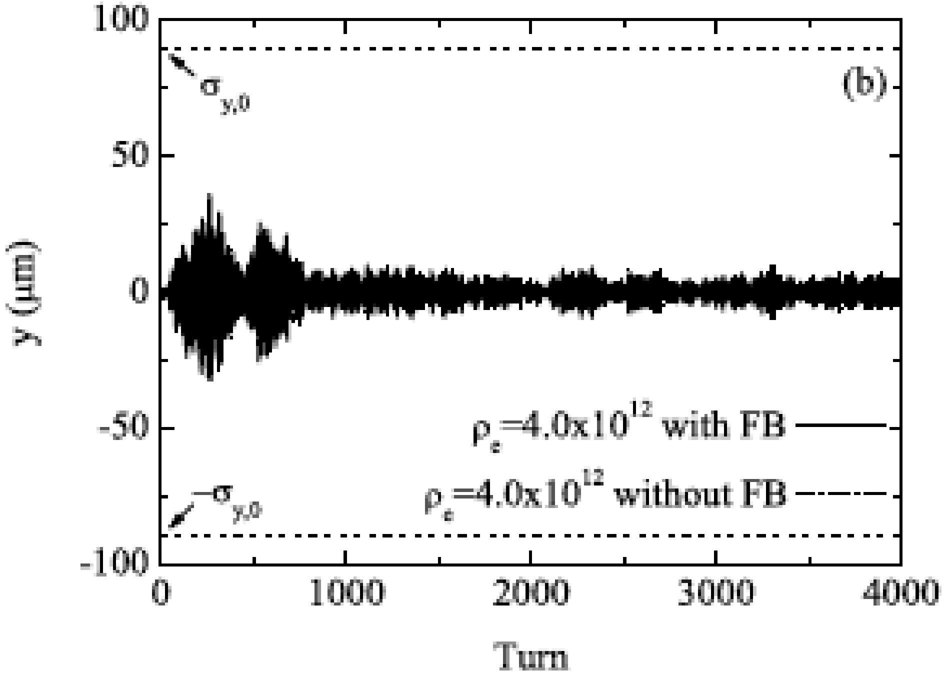
- High $\omega_e\sigma_z$/c, 2GeV.
- Dipole motion is suppressed a little, threshold increase a little.





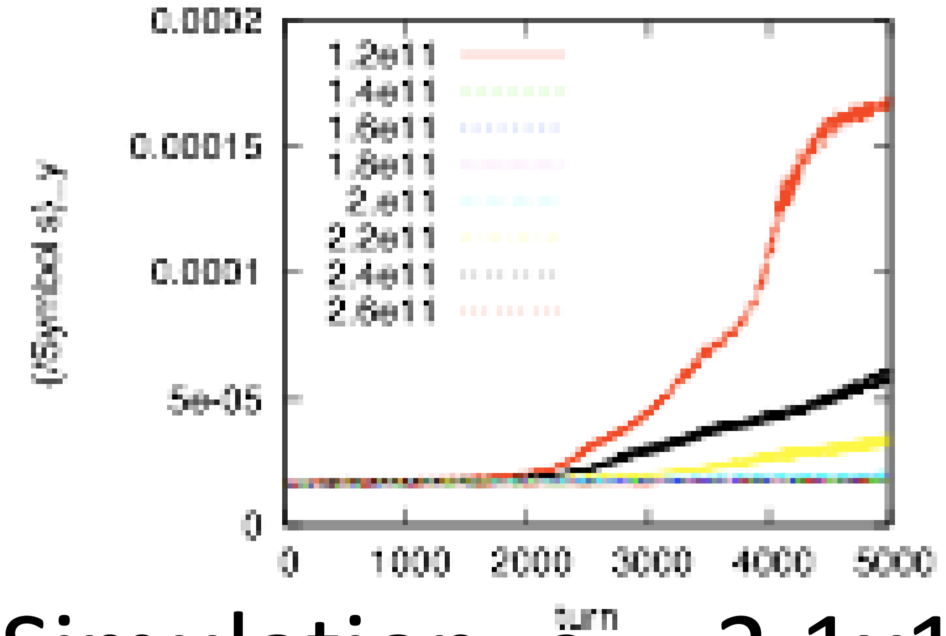
# No effect for FB (5GeV)





- Low $\omega_e\sigma_z/c$, 5GeV.
- Dipole motion is suppressed but head-tail motion remains.

# SuperKEKB



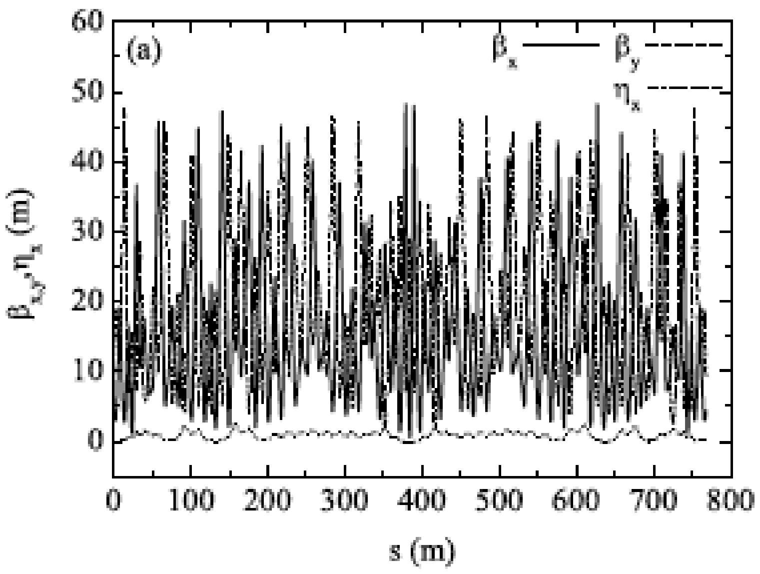
Y. Susaki, K. Ohmi, IPAC10

This simulation is for old parameter νs=0.12. Present νs=0.26. The threshold should be twice higher.

- Simulation $\rho_{th}=2.1\text{x}10^{11}$ m$^{-3}$.
- Analytic $\rho_{th}=1.1\text{x}10^{11}$ m$^{-3}$.
- Target $\rho_e<1\text{x}10^{11}$ m$^{-3}$
- Update parameters (both for CesrTA and SuperKEKB).
- Take care of high β section. Effects are enhanced.

# Incoherent effect in CesrTA

- Emittance growth due to nonlinear interaction with electron cloud



- Nonlinearity of beam-cloud interaction
- Integrated the nonlinear terms with multiplying β function and cos (sin) of phase difference

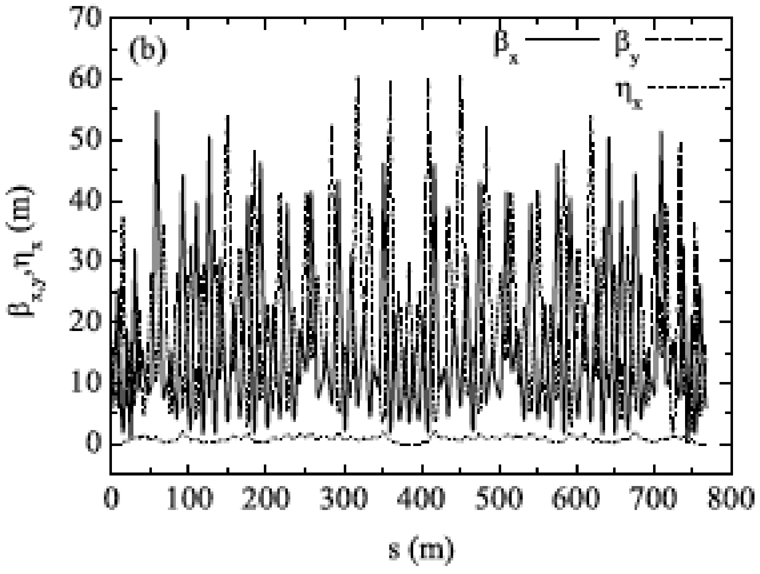
$$M = e^{-:\phi_1:}\, e^{-:F_{12}:}\, e^{-:\phi_2:}\, e^{-:F_{23}:}\, e^{-:\phi_3:}\, e^{-:F_{34}:}\, e^{-:\phi_4:}\, e^{-:F_{45}:}\, e^{-:\phi_5:} \ldots e^{-:F_{n1}:}$$

$$\approx e^{-:F_{11}:} \exp\left( -:\sum_{i=1}^{n} \phi_i (e^{-:F_{1i}:}\mathbf{x}) : \right)$$

F: (non)linear lattice transformation

ϕ: cloud interaction

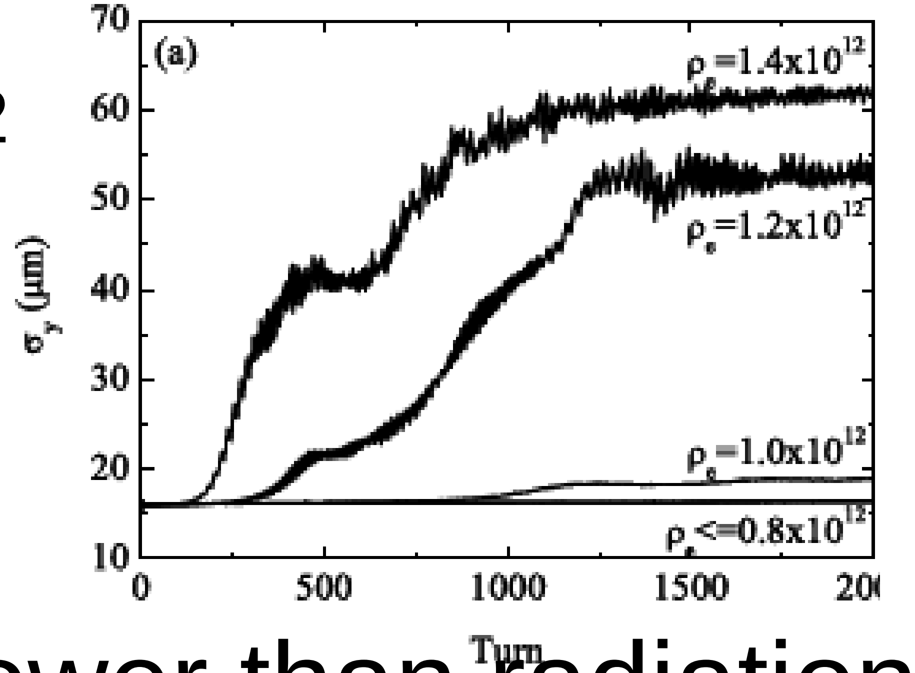
$$kx^m \Rightarrow k\beta_i^{m/2} J^{m/2} \cos(m\Delta\psi_{1i})$$

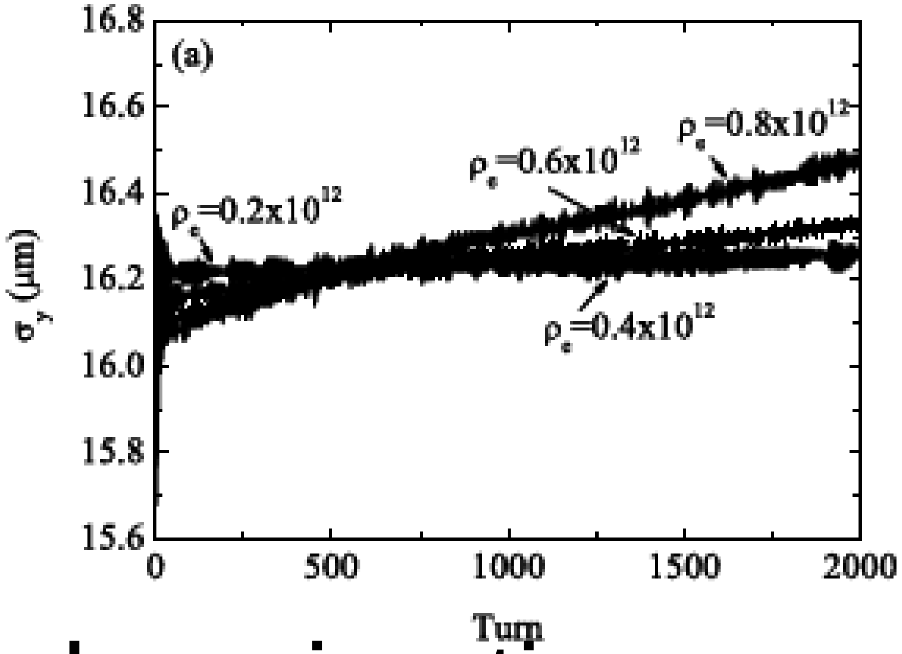


# Slow growth lower than the threshold

2GeV

$\rho_{th}$=1.2x$10^{12}$

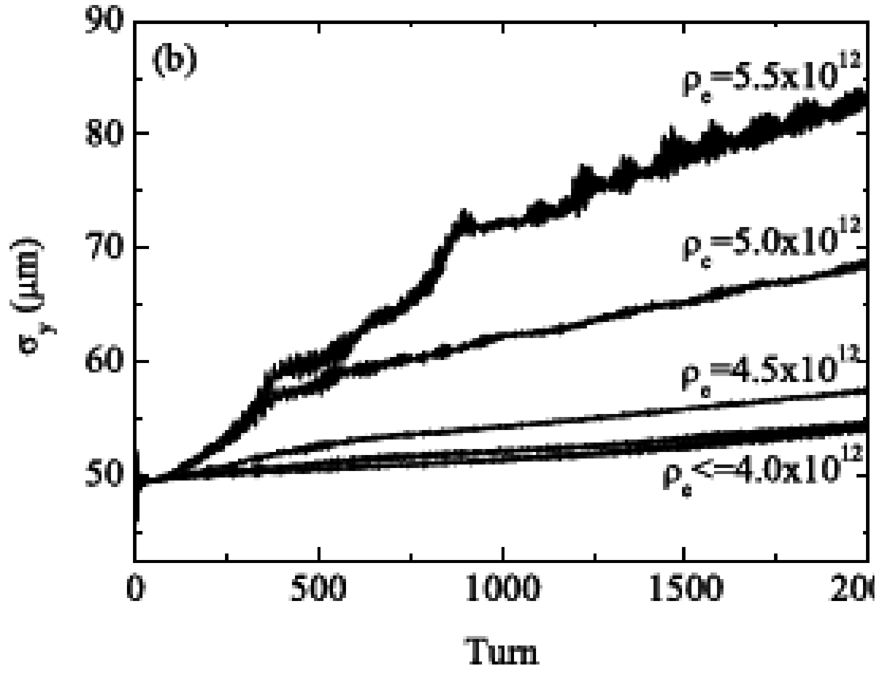


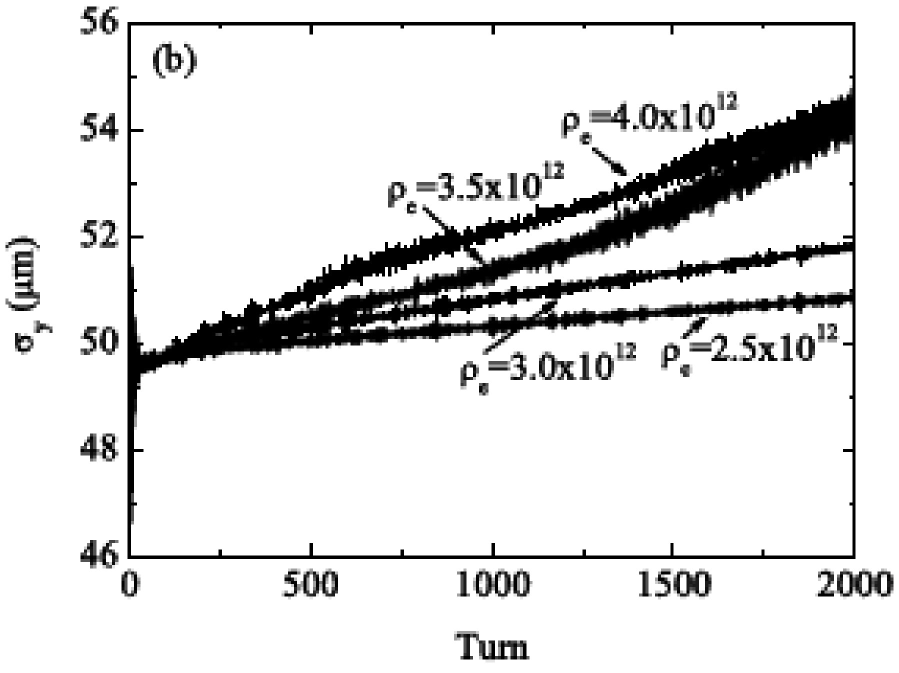


Slower than radiation damping time

5GeV

$\rho_{th}$=5x$10^{12}$





# Study of multibunch instability

- Self consistent solution of the cloud build-up and bunch motion.
- Wake field calculation
- Self consistent simulation
- Multi-bunch instability induces a fast beam loss, though fast head-tail instability does not.

# Tracking simulation

K.Ohmi, PRE55,7550 (1997)

K.Ohmi, PAC97, pp1667.

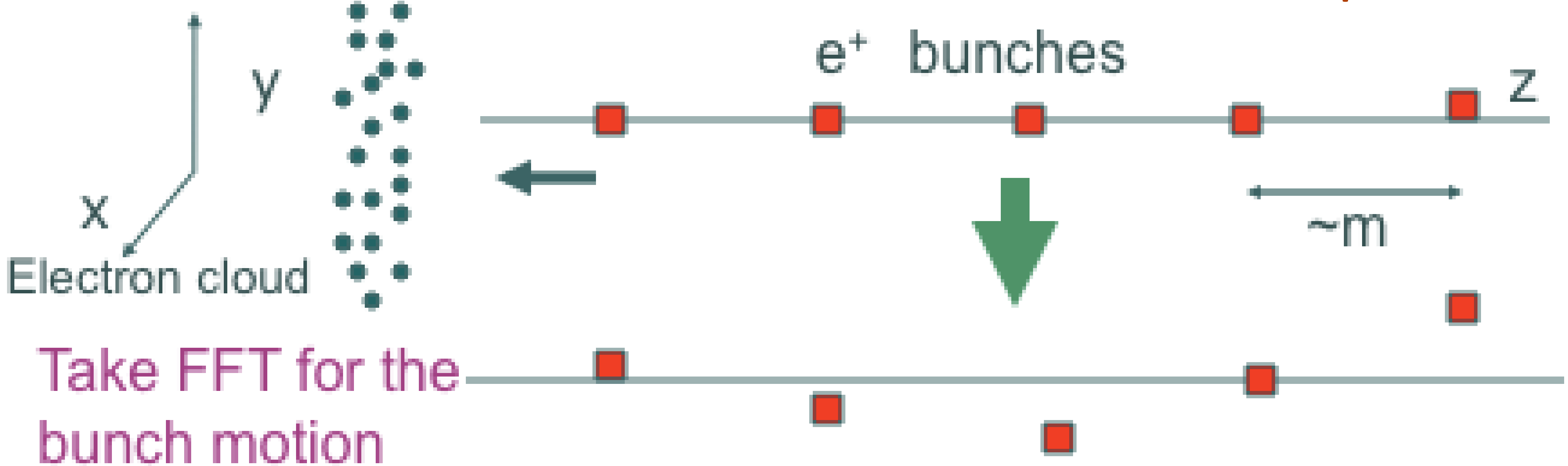
Solve both equations of beam and electrons simultaneously

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

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

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

Self consistent build-up code, PEI

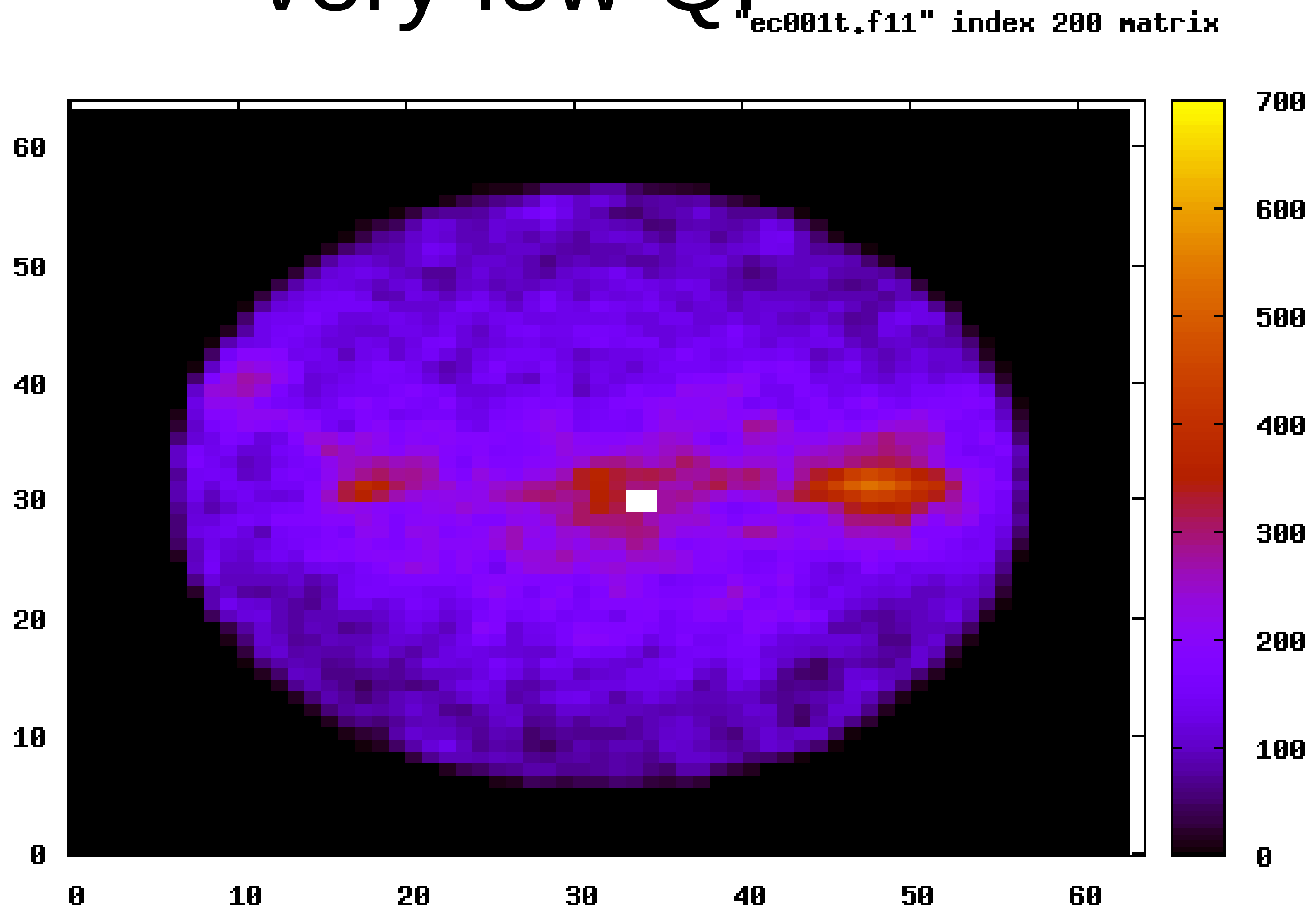


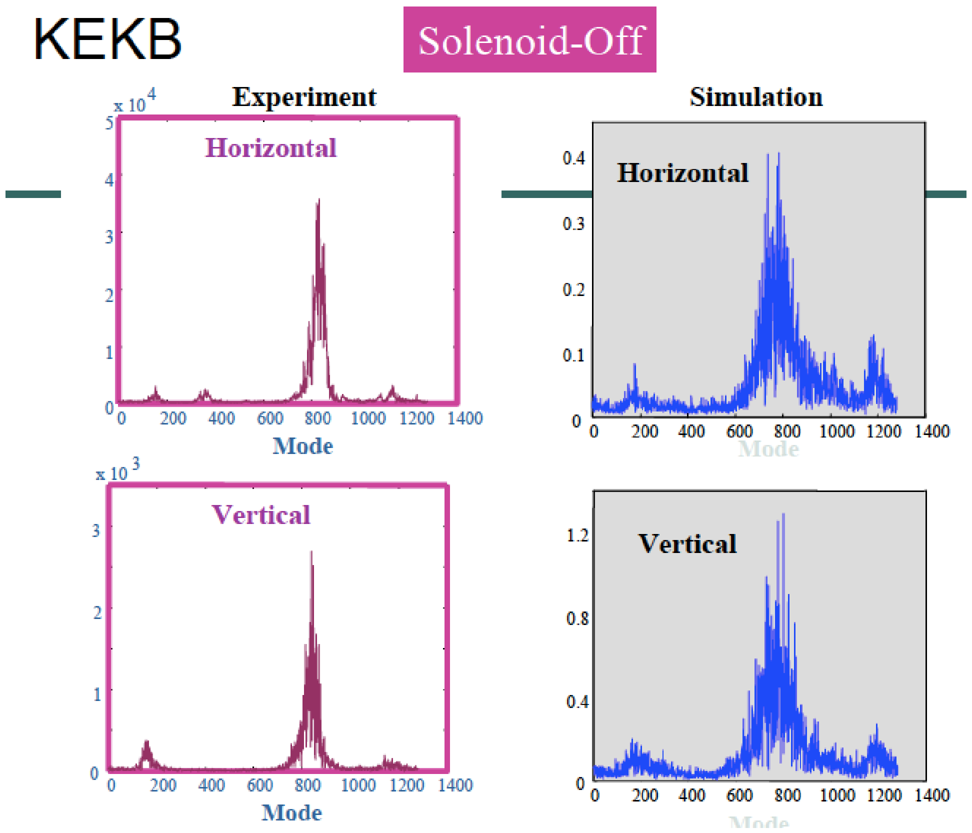
Take FFT for the bunch motion

# Multi-bunch instability

## Beam dancing with electron cloud

- Drift space
- Electrons move one way
- Bunch by bunch correlation is short, very low Q,

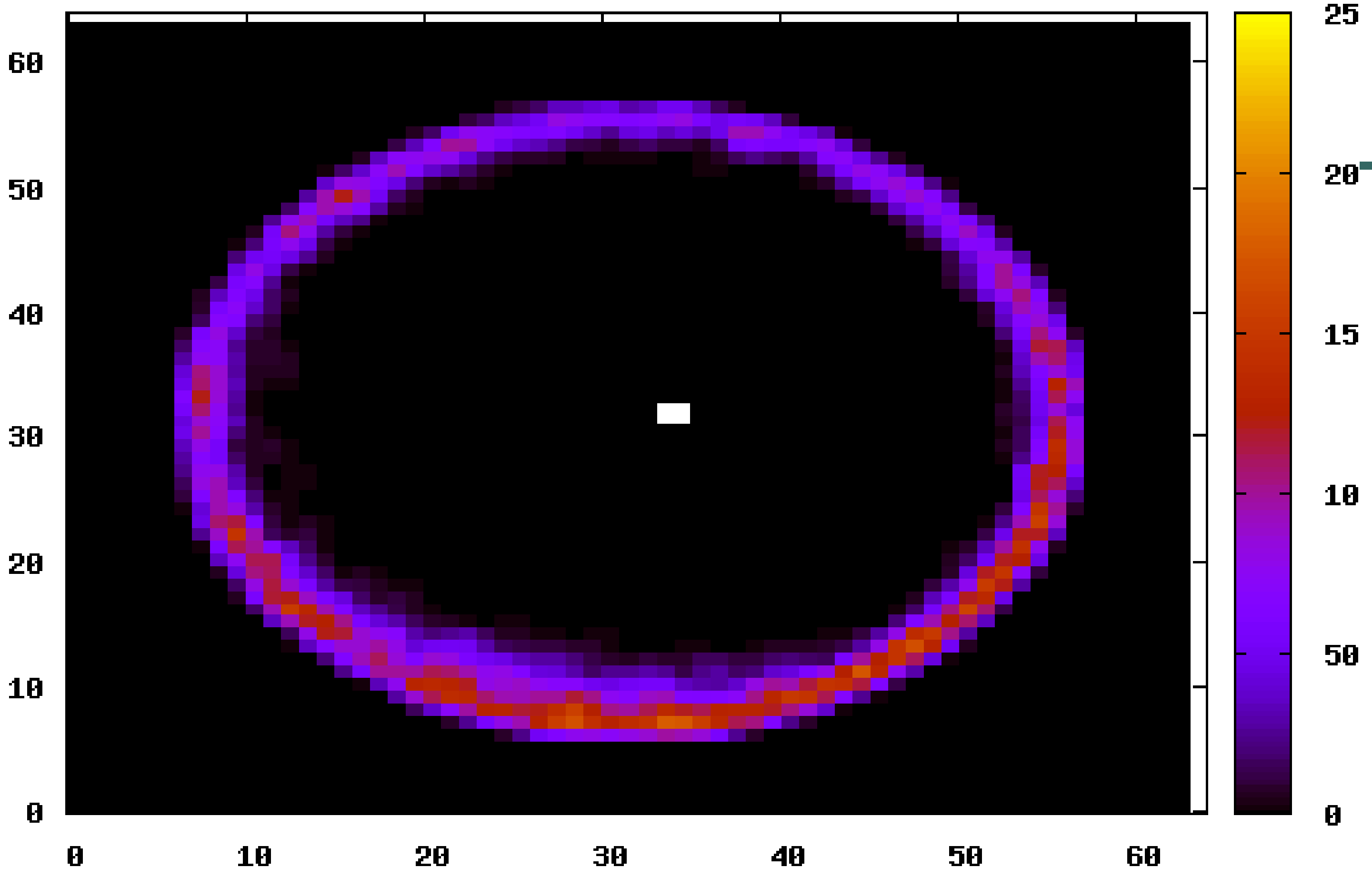


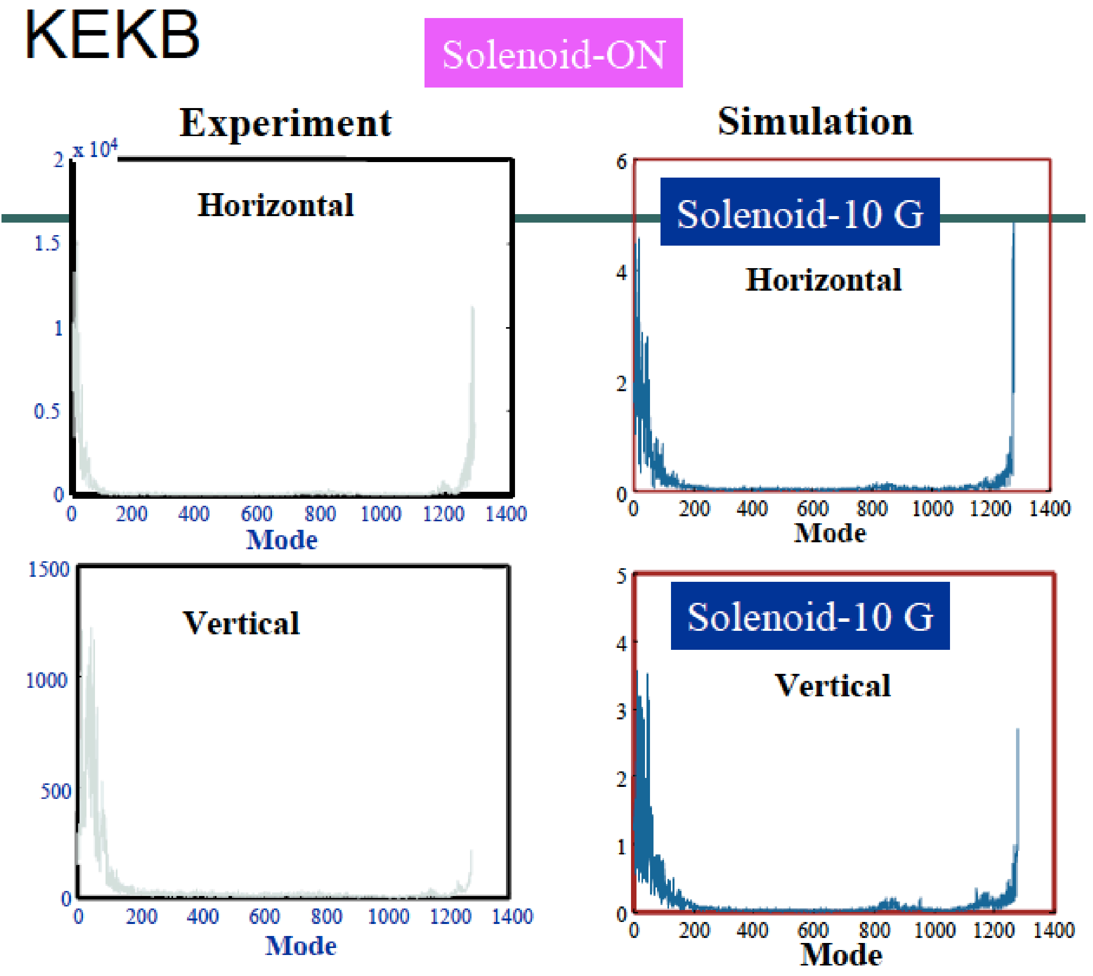


# Multi-bunch instability

## Beam dancing with electron cloud

- In solenoid magnets
- Electrons move along the chamber surface.
- Long life time electron, high Q wake.



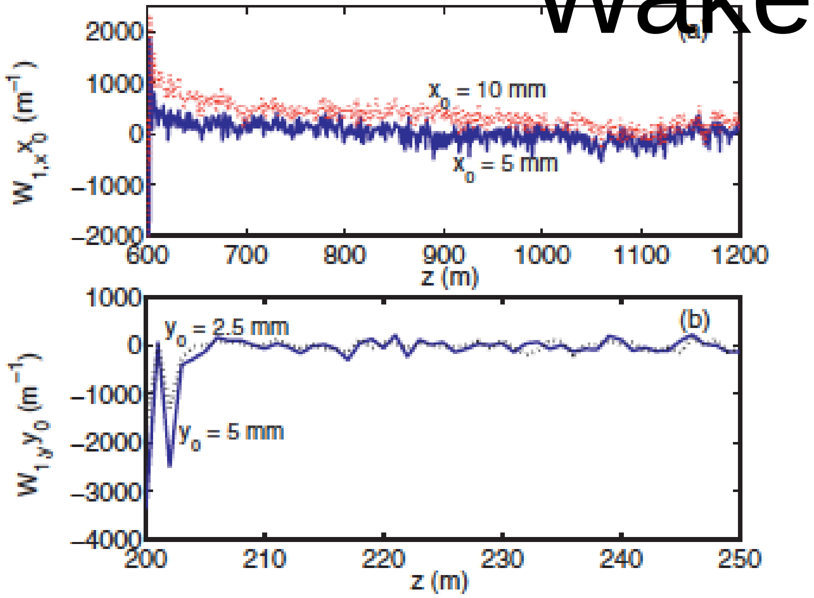


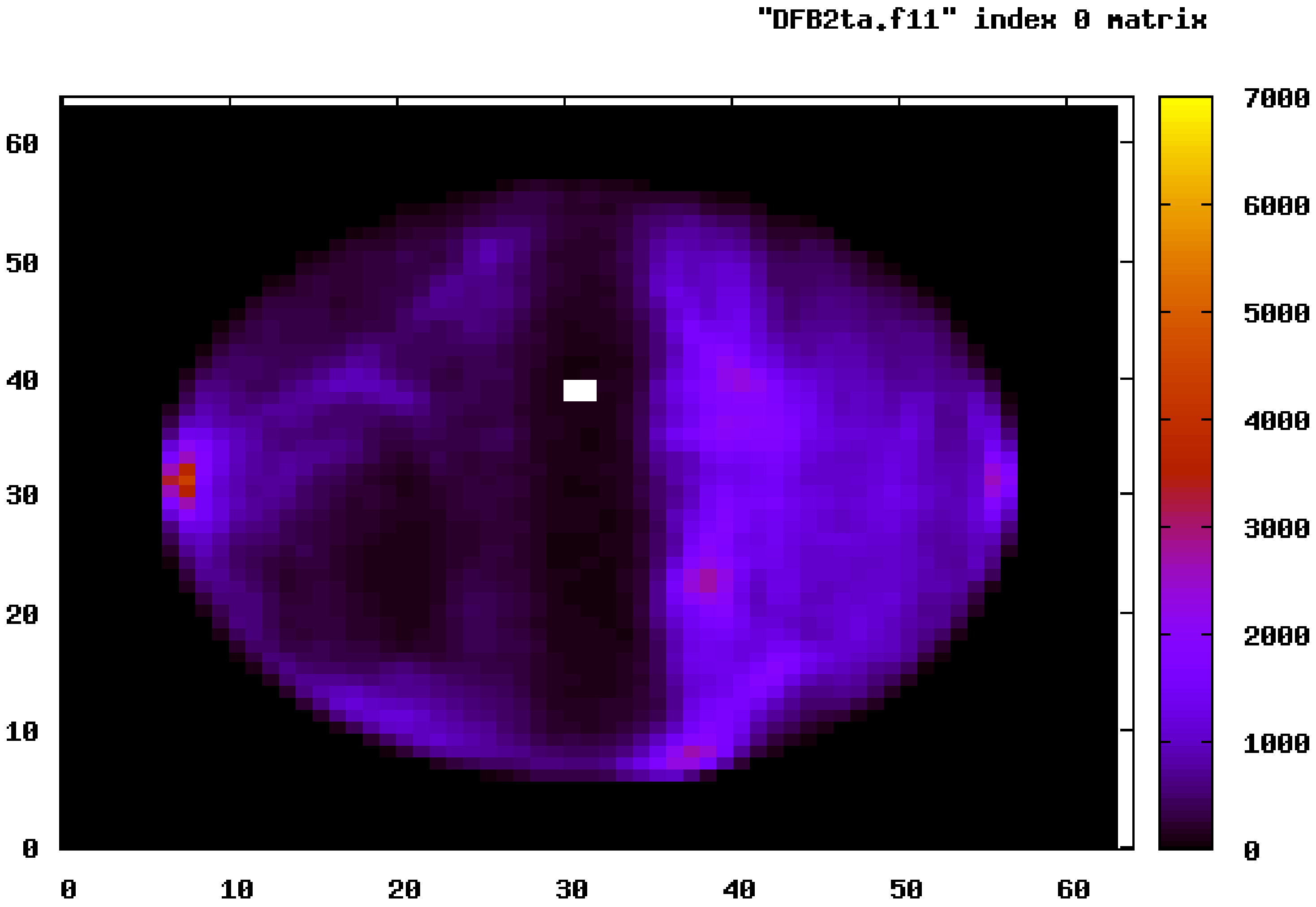
# Multi-bunch instability

Beam dancing with electron cloud

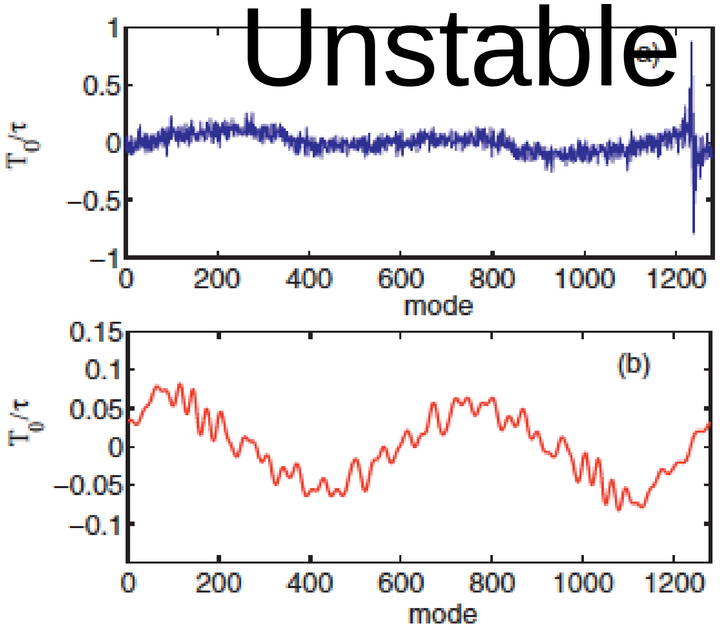
- Electron cloud in bending magnet
- Does beam dance with electron cloud pillar?

Wake

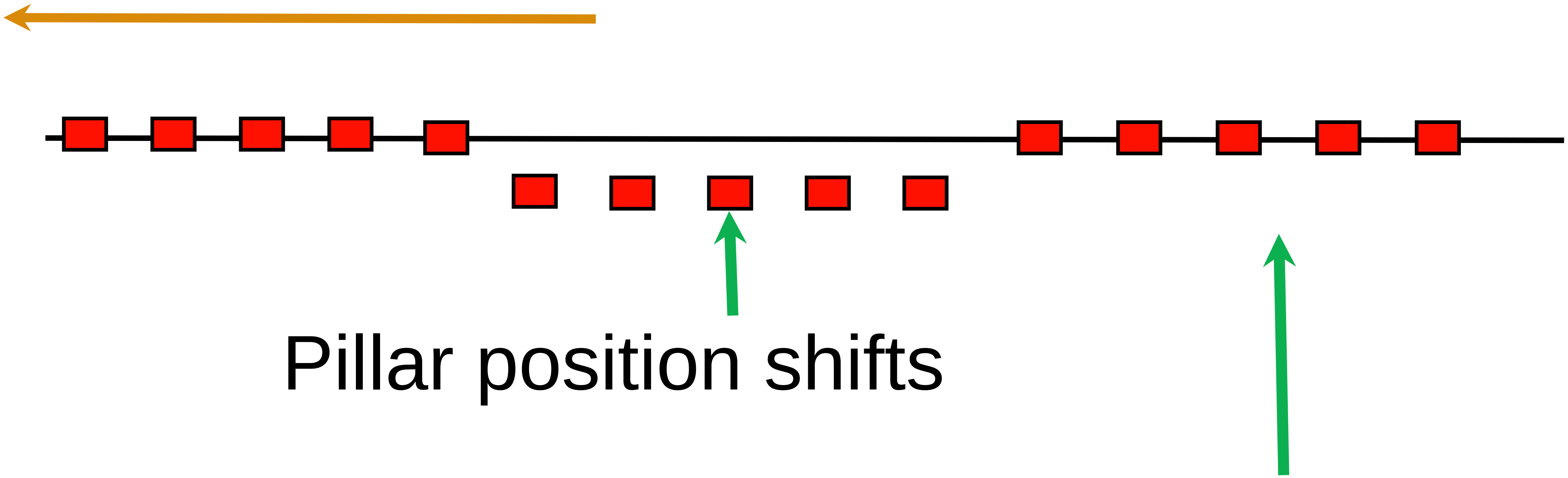




Unstable mode



# Correlation time of the pillar (stripe)



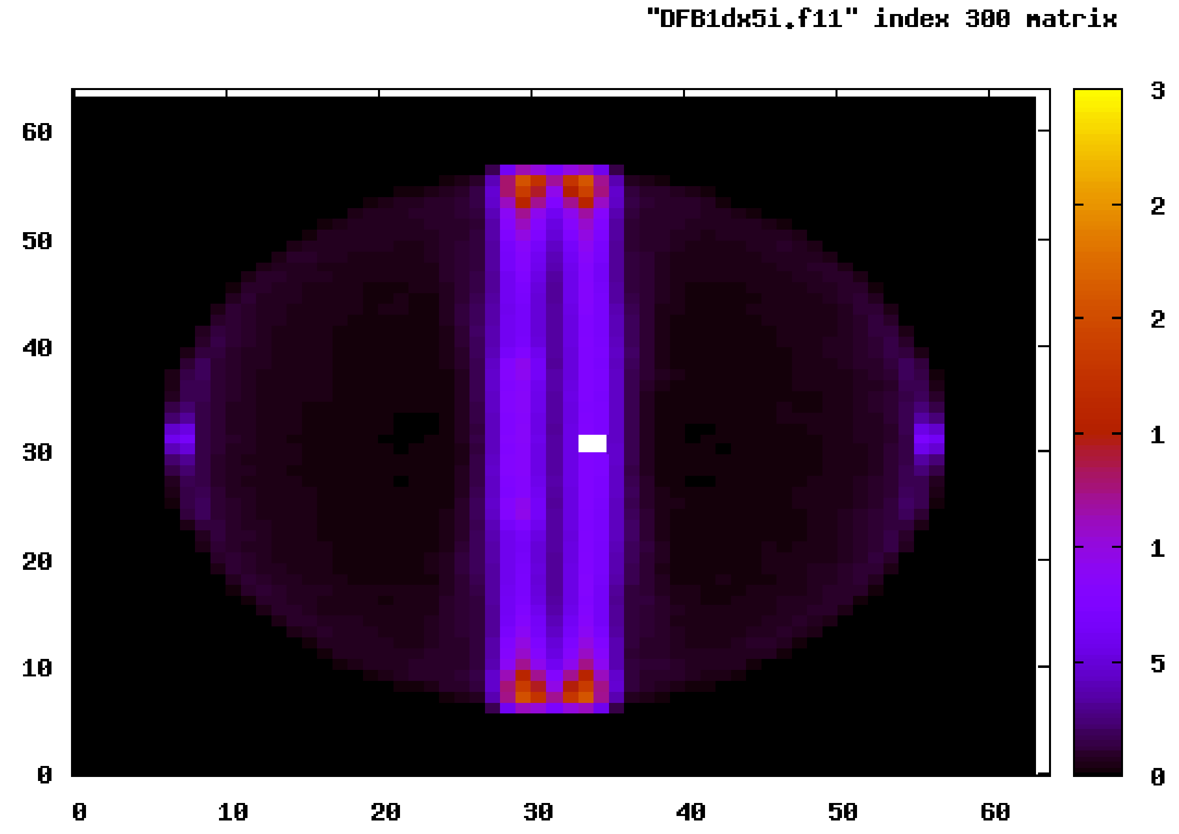
Pillar position shifts

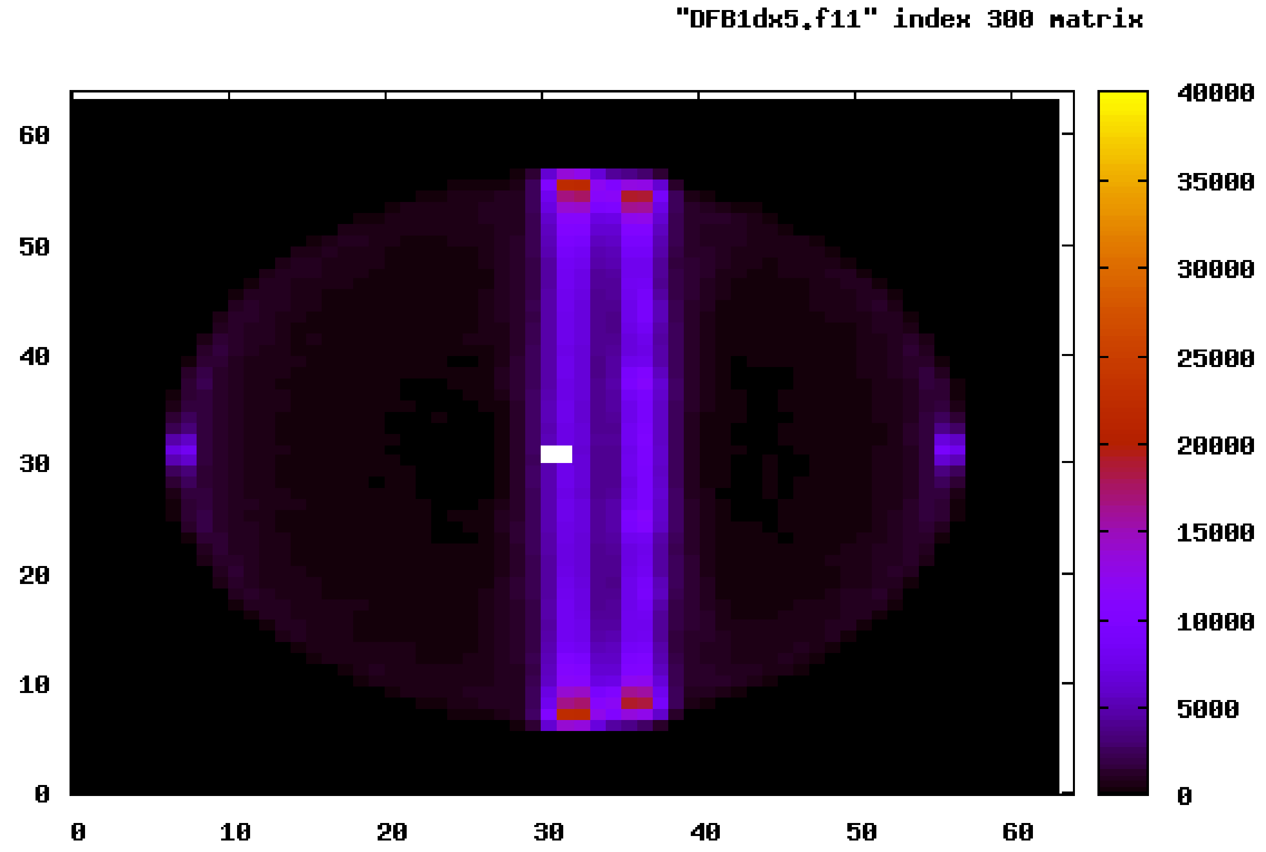
Receive wake force from the shifted pillar

- Bunch length ~1cm, bunch spacing ~1m

# Characteristic time of pillar formation

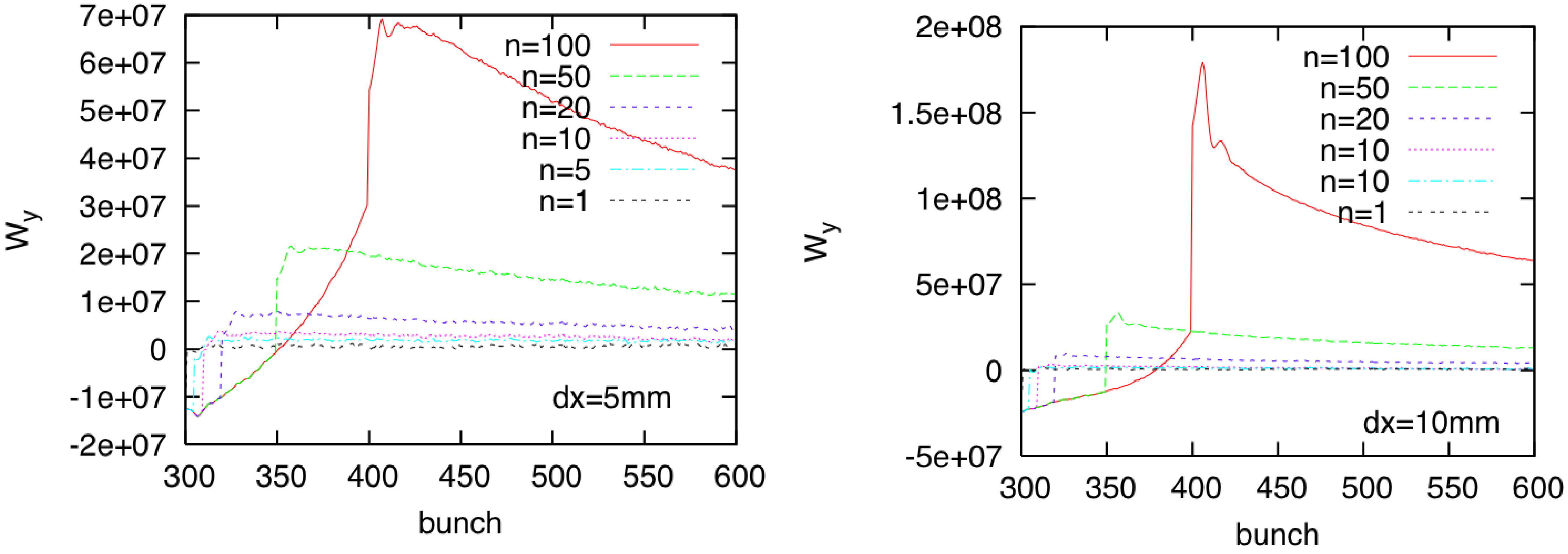
- DAFNE parameter,  ~200ns
- Formed pillar and then shift beam position
- Pillar position shifts to beam position in ~200ns.





# Wake force for the pillar formation

- Bunch by bunch correlation of slowest mode, m=-1, will be induced.



DAFNE type of multi-bunch instability

# Summary

- Characteristics of the fast head tail instability is determined by $\omega_e\sigma_z/c$.
- Appearance of upper or lower sideband, and feedback response depend on $\omega_e\sigma_z/c$.
- The threshold (2GeV) is $\rho_{th}=1\text{x}10^{12}$ cm$^{-3}$ for simulation and $1.7\text{x}10^{12}$ cm$^{-3}$ for analytic.
- The threshold (5GeV) is $\rho_{th}=5\text{x}10^{12}$ cm$^{-3}$ for simulation and $7\text{x}10^{12}$ cm$^{-3}$ for analytic.
- Incoherent emittance growth is week in positron machines.
- Movies for coupled bunch instability. Slowest mode is induced by electrons in bending magnets.