Electron cloud effects, codes & simulations at KEK

K. Ohmi (KEK)

ECLOUD12, 5-8 June, 2012
La Biodola, Isola d'Elba

Short history at the starting of CE

- Very strong coupled bunch instability had been observed in KEK-PF positron operation since 1988. PF people doubted feasibility of KEKB-LER, very high current positron storage ring. I (K.Ohmi) belonged to KEK-PF.
- The positron instability had to be solved to complete KEKB design. Izawa, Sato and Toyomasu had performed many experiments and studied a model to solve it. They consider electron trapping by beam under the condition of electron-ion plasma. They showed that a short range wake gave observed mode spectra.
- K.O. had studied possible model to explain it. Photoelectron supplied continuously from the chamber wall can induce strong coupled bunch instability.
- In Feb 1995, a competition was held at KEK which model was feasible. People agreed photoelectron model.
- The transparency copy was sent to SLAC-PEP-II the next day of the competition.
- Masanori Kobayashi, who was leader of Vacuum group, had discussed with me that the vacuum chamber must be filled by photoelectrons.

- Many many discussions started at KEKB machine advisory committee and workshops every year since 1995.

- Thanks for many discussions in the early days.

  J.Byrd, A.Chao, Y.Chin, N.Dikansky, H.Fukuma, M.Furman, J.Gareyte, Z.Guo, K.Harkay, S. Heifets, K. Hirata, M.Izawa, M.Kobayashi, G.Lambertson, K.Oide, D. Pestrikov, E. Perevedentsev, F. Ruggiero, J.Rogers, S.Sakanaka, K. Satoh, Y.Sato, J.Seeman, G.Stupakov, T.Raubenheimer, Toyomasu, G.Voss, K.Yokoya, C.Zhang, M.Zisman, F.Zimmermann, B.Zotter …….

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PEI code 1995-

The same purpose codes: POSINST, ECLOUD, CLOUDLAND...

- First code for studying electron cloud effects.
- Electron cloud build-up and coupled bunch instability.
- Motivation: Very fast coupled bunch instability observed at positron operation in KEK-Photon Factory.
- Simulations in KEKB, BEPC and DAFNE.

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

Positron 324 mA & 240 mA

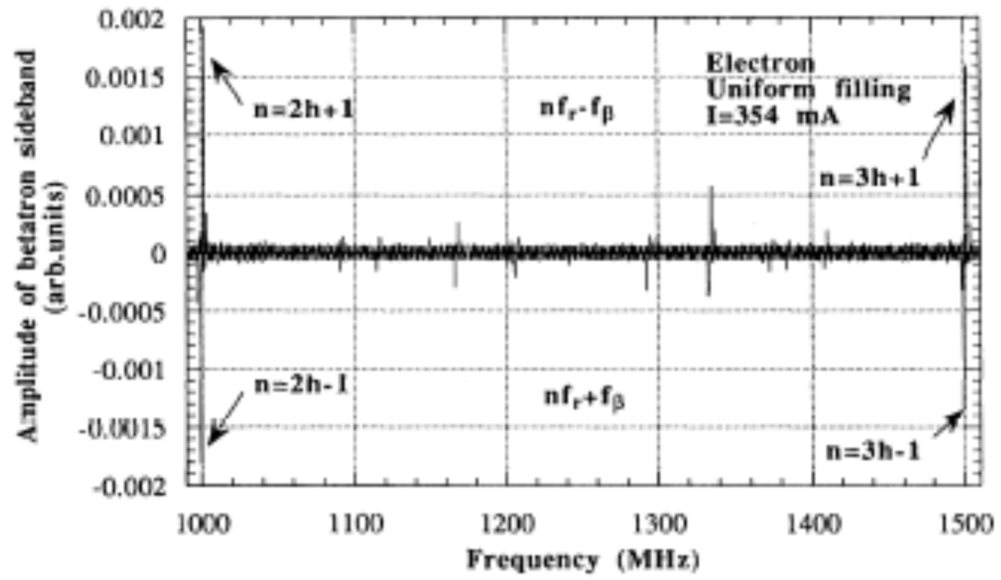
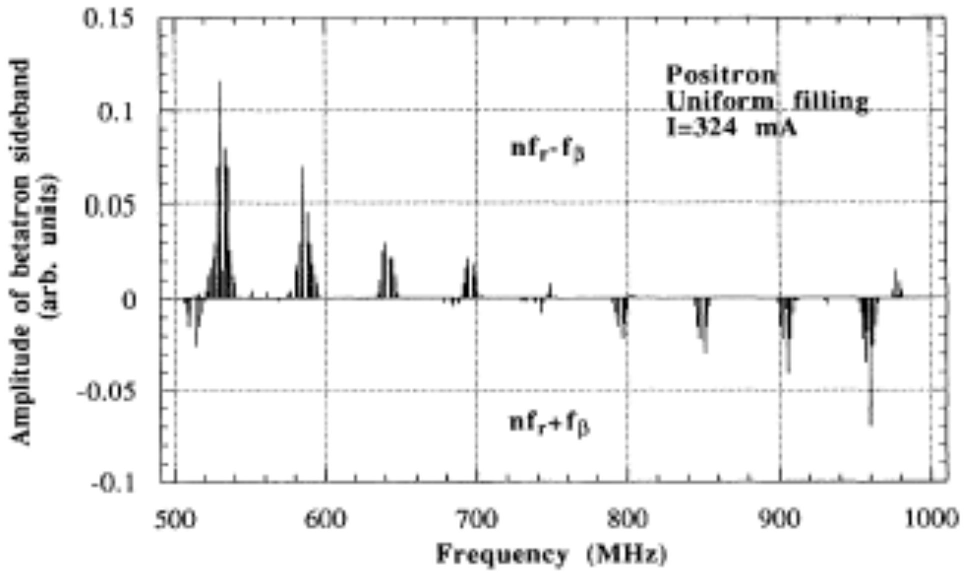


FIG. 1. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling.



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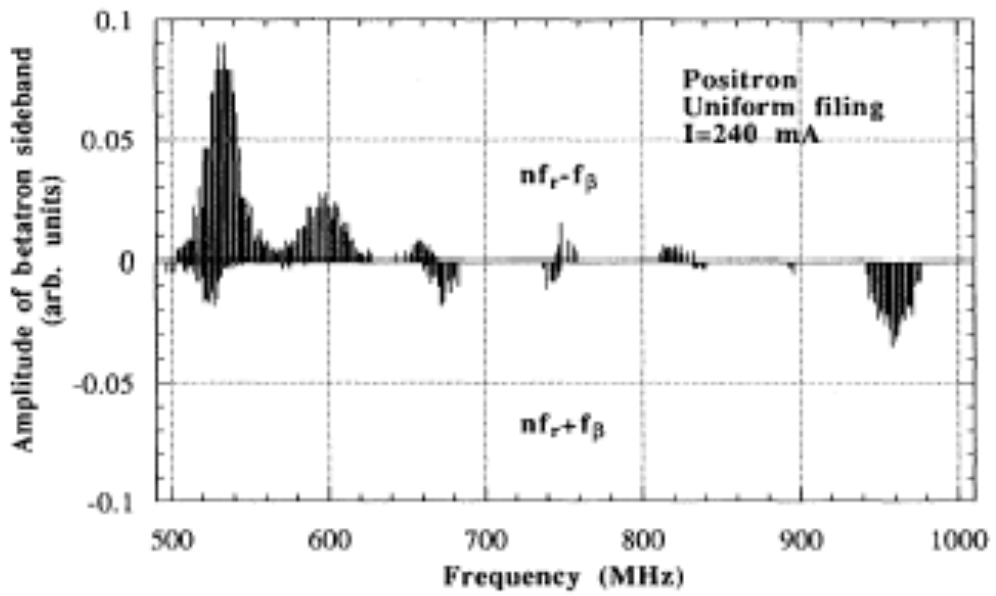
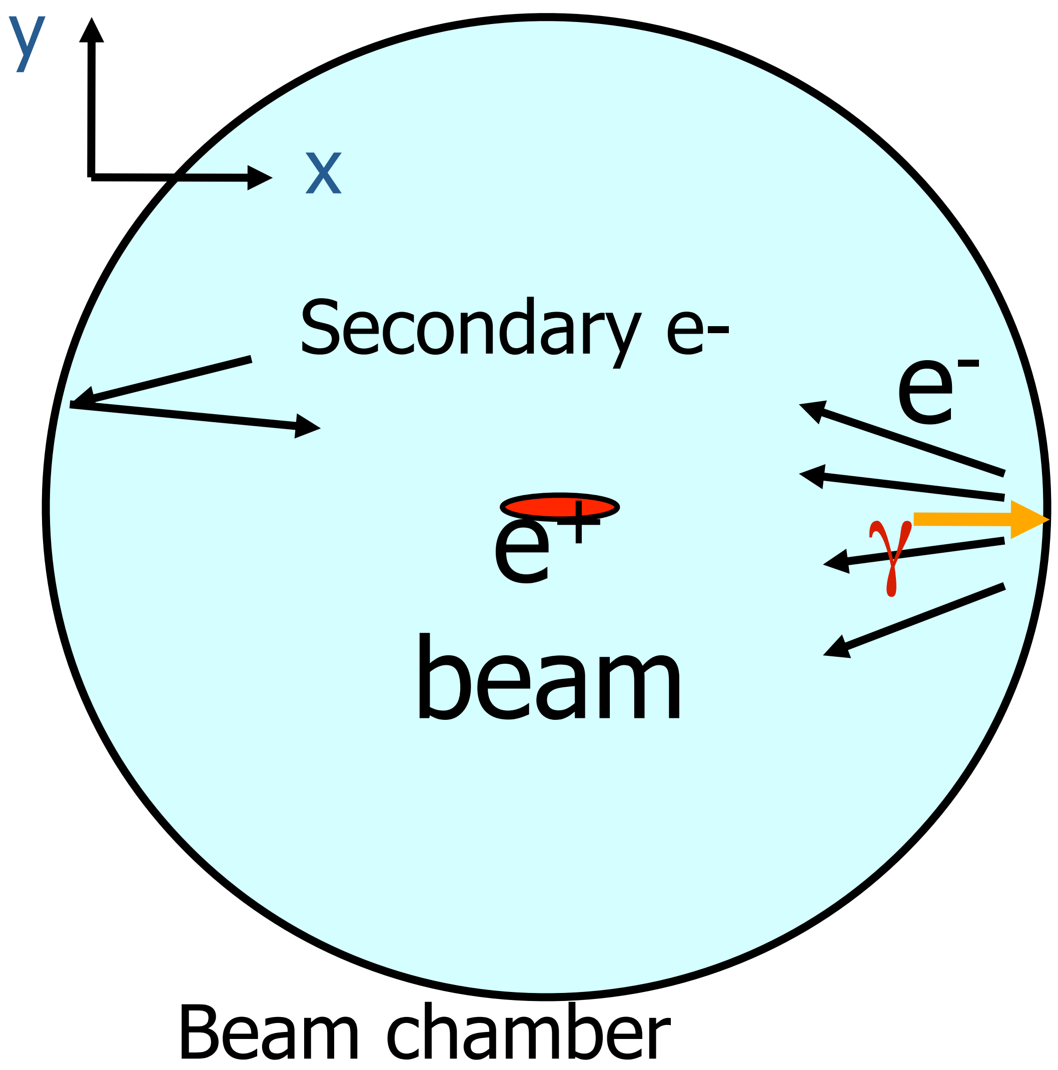


FIG. 3. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling. Only the stored current is different from Fig. 2.

First figure for electron cloud build-up

Model



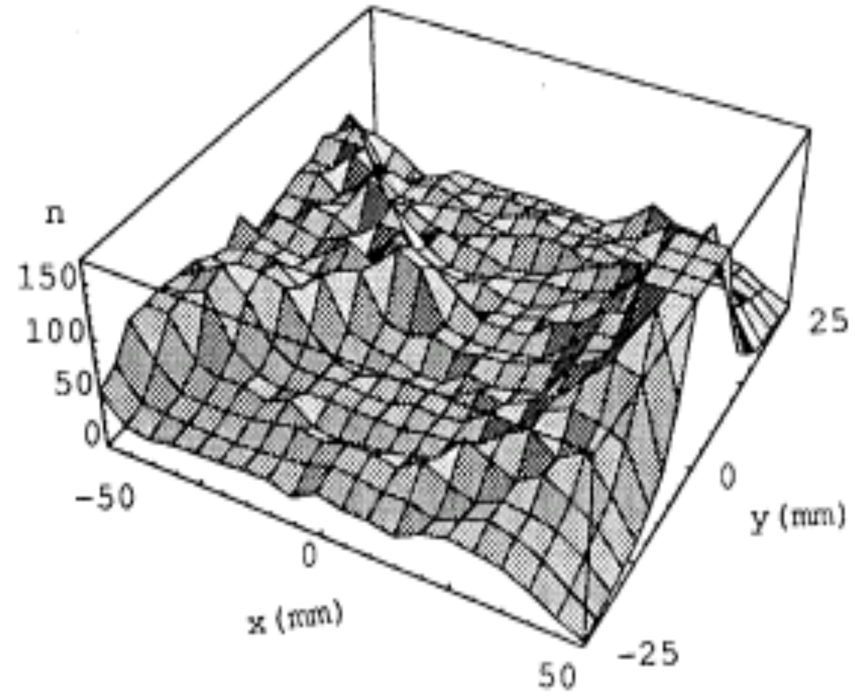


FIG. 2. A stationary distribution of photoelectrons with $\epsilon_0 =$ 5 eV.

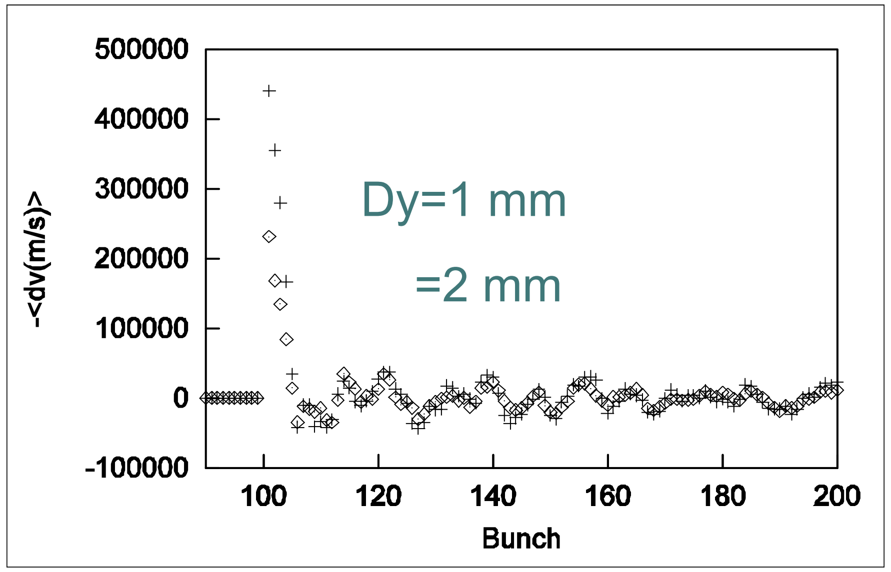
K.Ohmi, PRL,75,1526 (1995)

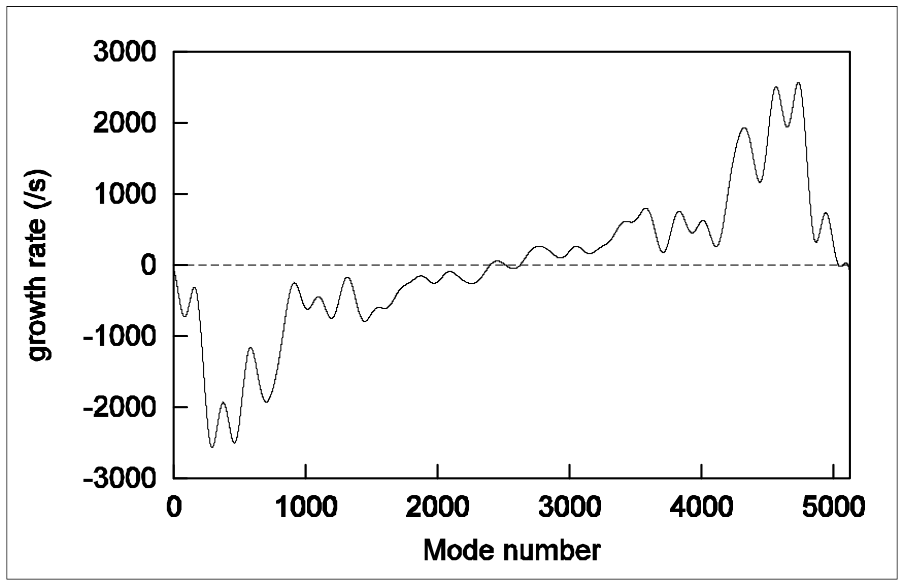
Recipes for electron cloud build-up are written in this paper.

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.

Wake field due to electron cloud

- Calculate equilibrium electron cloud distribution in the buildup code.
- A bunch with a displacement X or Y direction makes passage in the electron cloud.
- The electron cloud is disturbed by the displaced bunch.
- Estimate the force which following bunches experience due to the cloud disturbance.
- Check the linearity and superposition of the wake force.



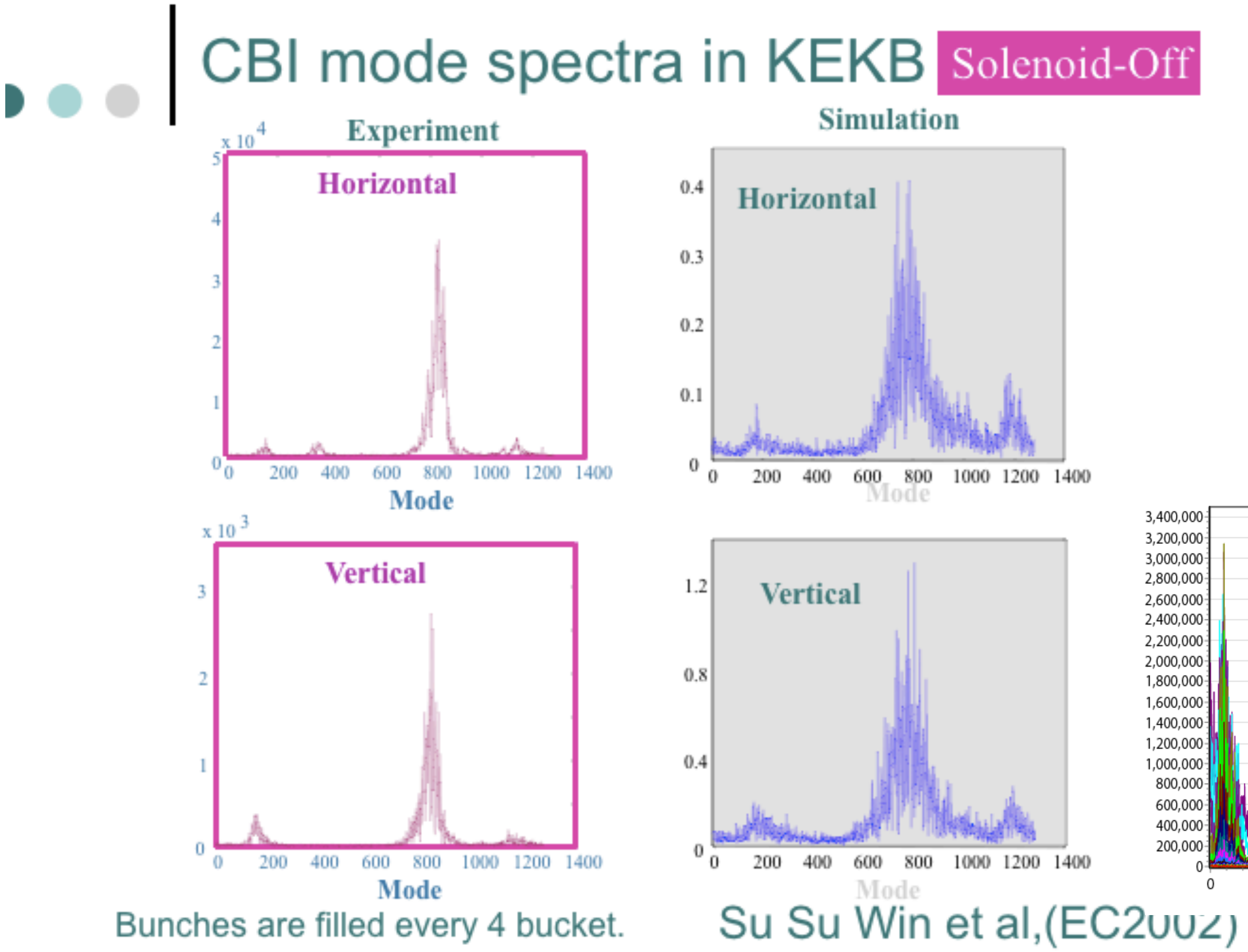


KEKB design report (1996 or 7)

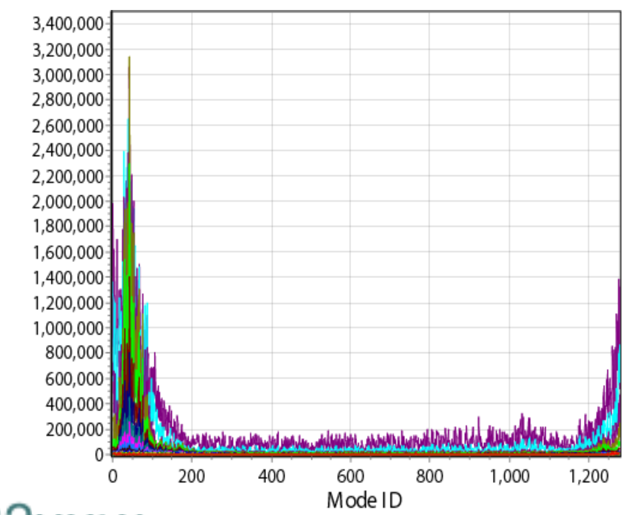
Tracking simulation using rigid bunch (weak-strong) model

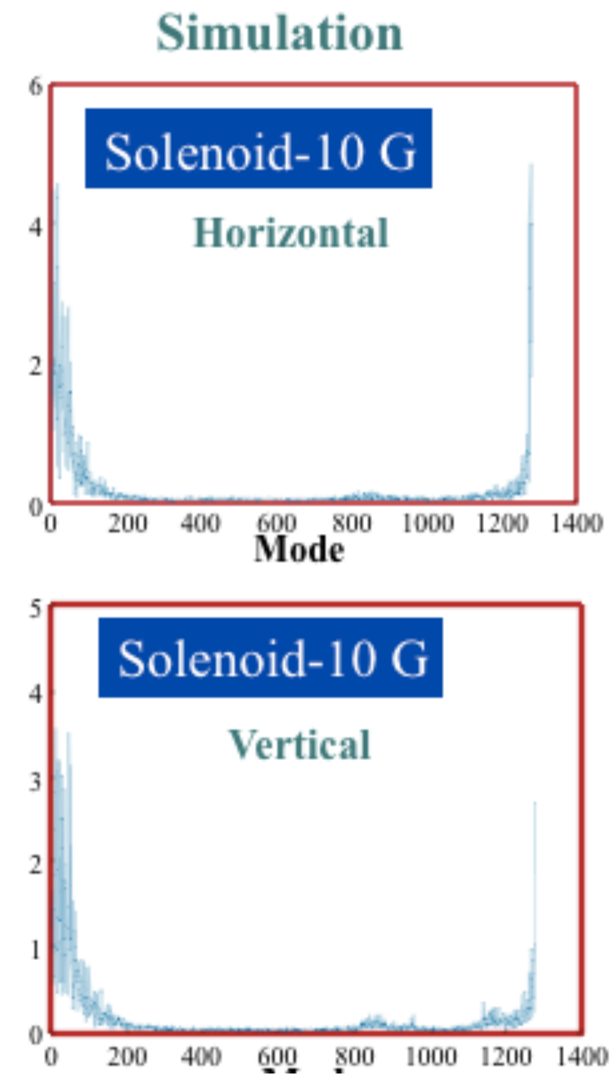
$$\frac{d^2\boldsymbol{x}_p}{ds^2} + K(s)\boldsymbol{x}_p = \frac{2N_e r_e}{\gamma}\sum_{e=1}^{N_e}\boldsymbol{F}_G(\boldsymbol{x}_p - \boldsymbol{x}_e)\delta_P(s - s_e)$$

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



Solenoid ON



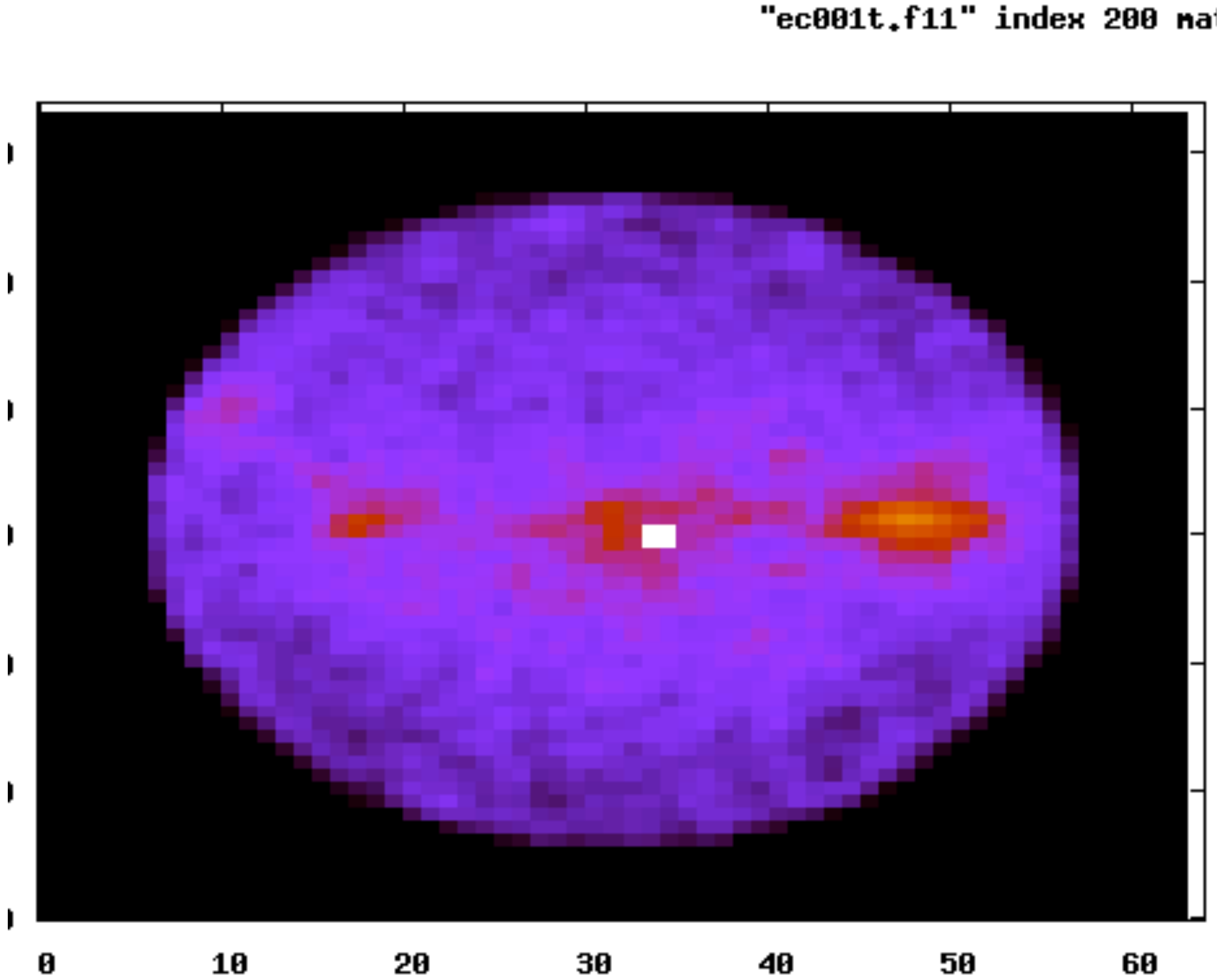


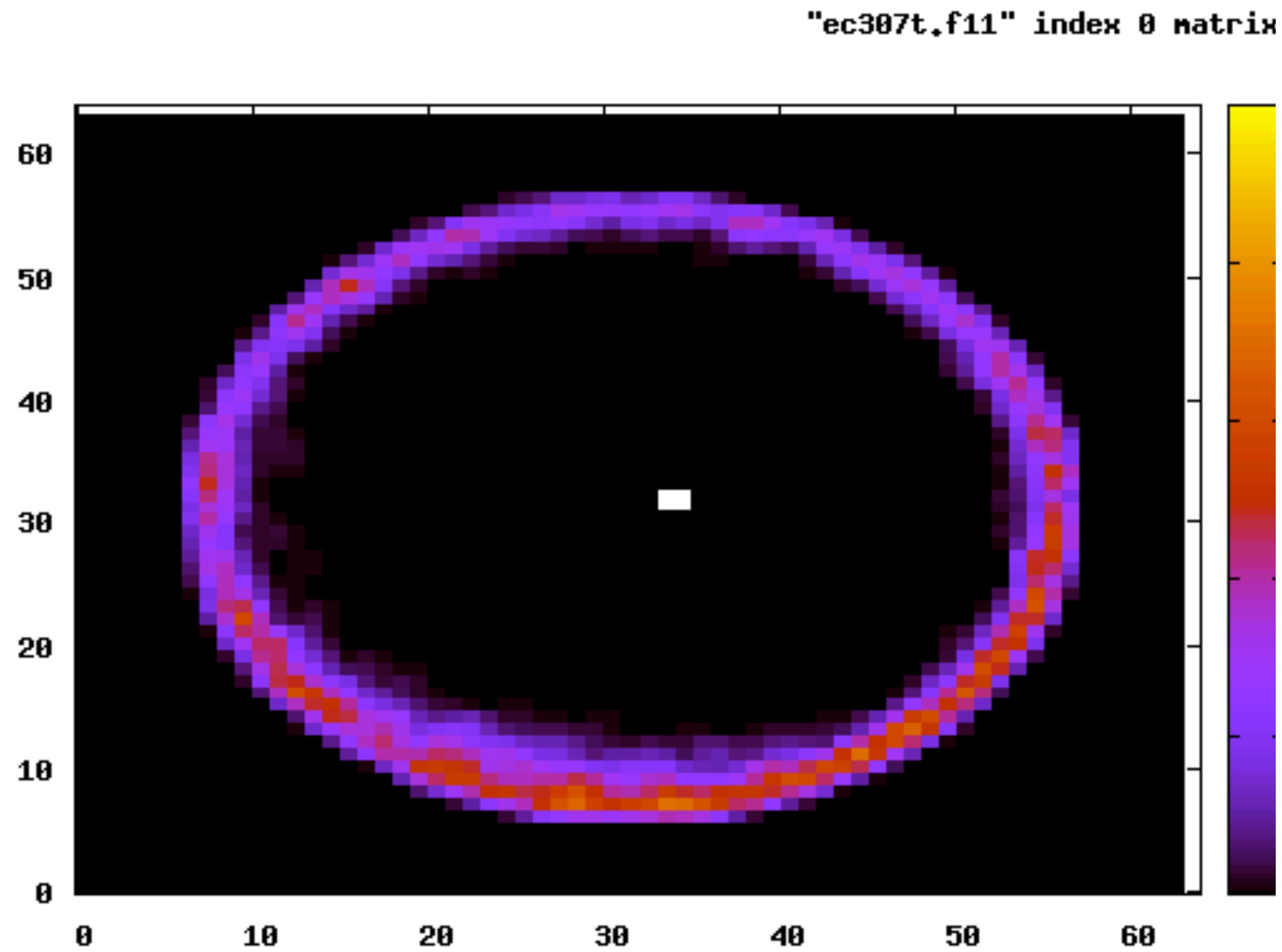
Electron distribution and Coupled bunch motion

Drift

Solenoid

White point: beam position passing through the chamber

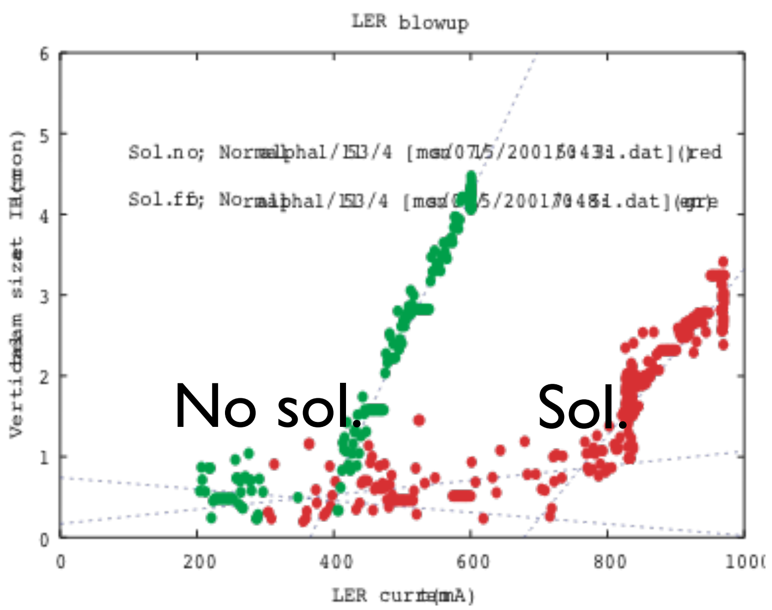




PEHT & PEHTS

The same purpose code: HEADTAIL, C-MAD, WARP...

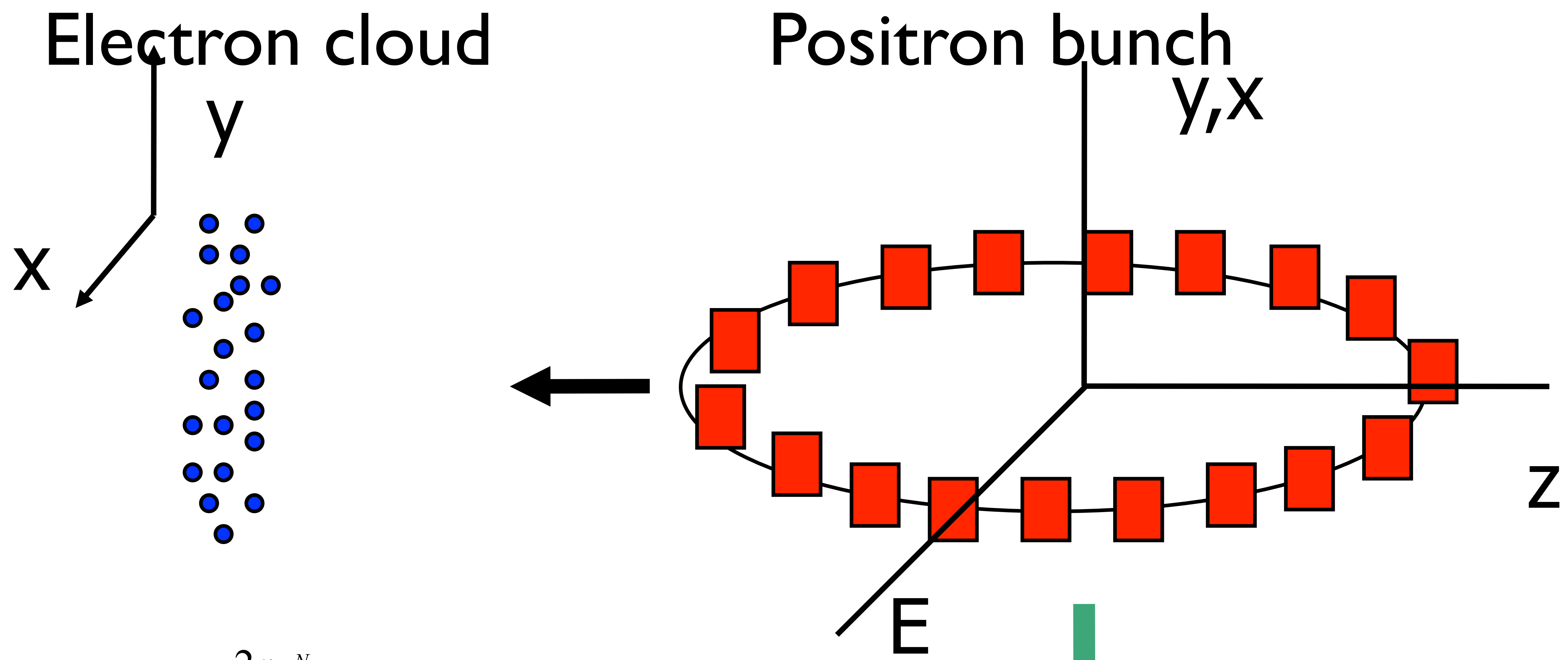
- Simulation of Fast head-tail instability caused by electron cloud
- Incoherent emittance growth using PEHTS
- Purpose: to explain beam size blow up observed in KEKB.



Fukuma et al. measurement at 2001

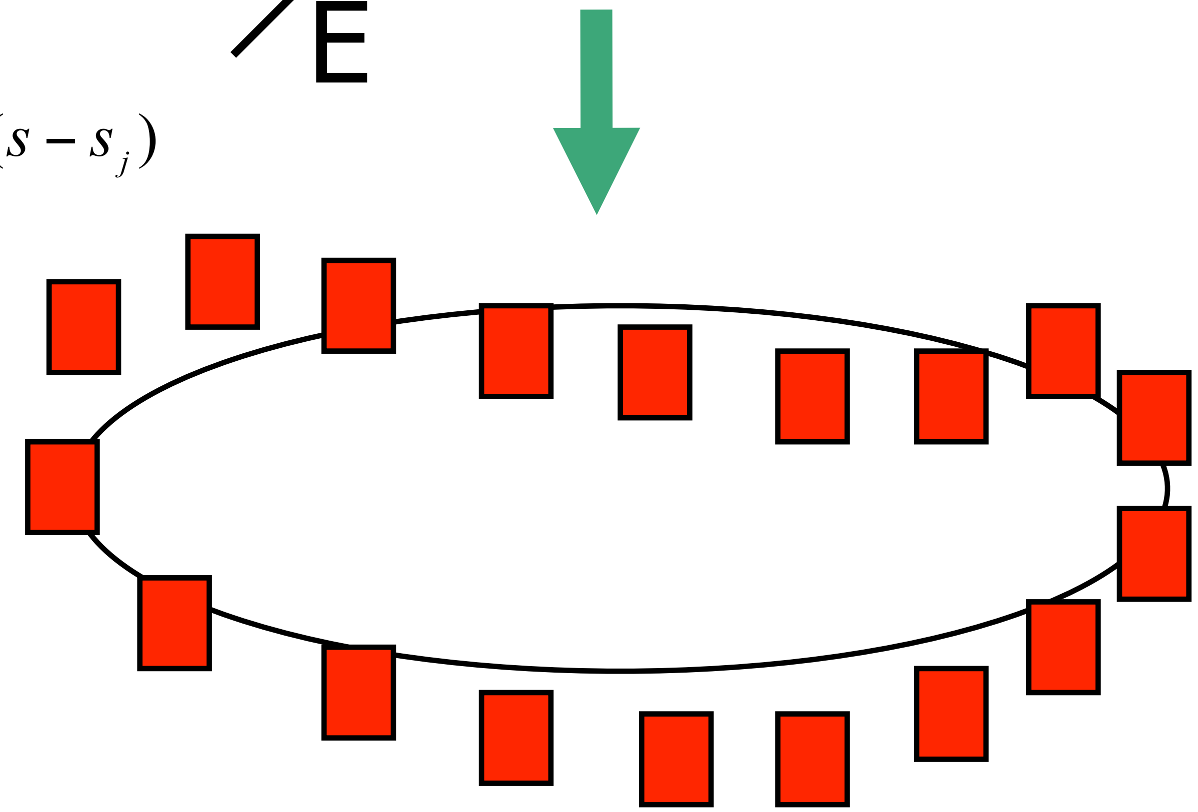
PEHT modeling

Simulation using Gaussian micro-bunch model



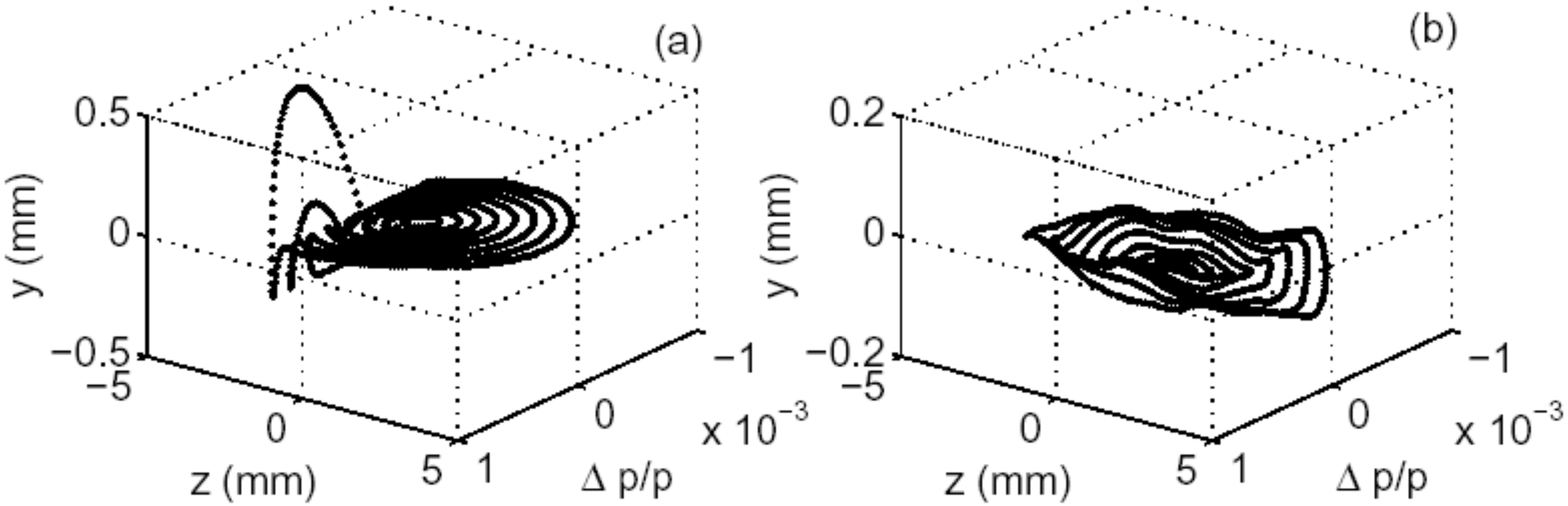
$$\frac{d^2\mathbf{x}_{+,a}}{ds^2}+K(s)\mathbf{x}_{+,a}=\frac{2r_e}{\gamma}\sum_{j=1}^{N_i}\mathbf{F}_G(\mathbf{x}_{+,a}-\mathbf{x}_{e,j};\sigma(s))\delta(s-s_j)$$

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



PEHT results

- Bunch head-tail motion w/wo synchrotron motion.

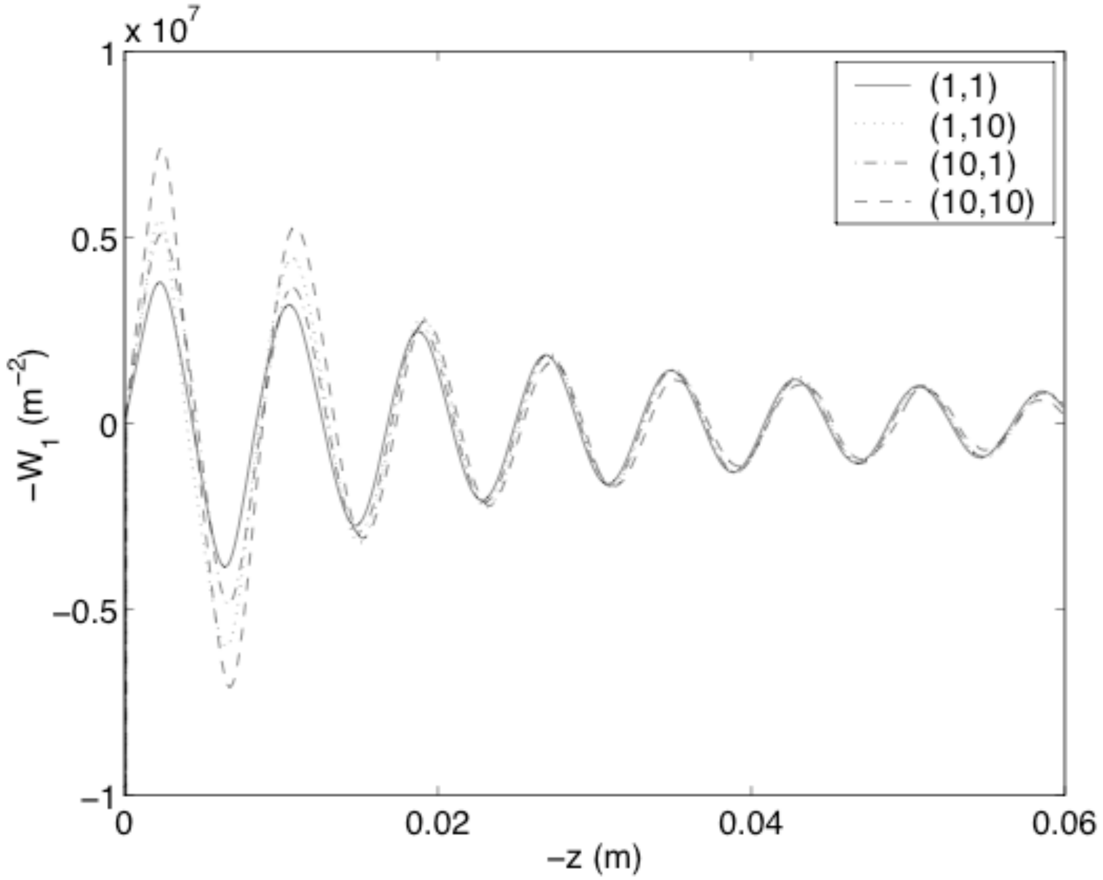


Vertical amplitude of the macro-particles in the longitudinal phase space are plotted. Multi-airbag model (z-δ) is used to visualize in these figures.

K. Ohmi, F. Zimmermann, PRL85, 3821 (2000).

Short range wake field due to electron cloud

Vertical wake field given by the numerical method



$$W(z) \approx \frac{\lambda_e}{\lambda_p} \frac{L}{(\sigma_x + \sigma_y)\sigma_y} \frac{\omega_e}{c} e^{\alpha z/c} \sin\left(\frac{\omega_e}{c} z\right)$$

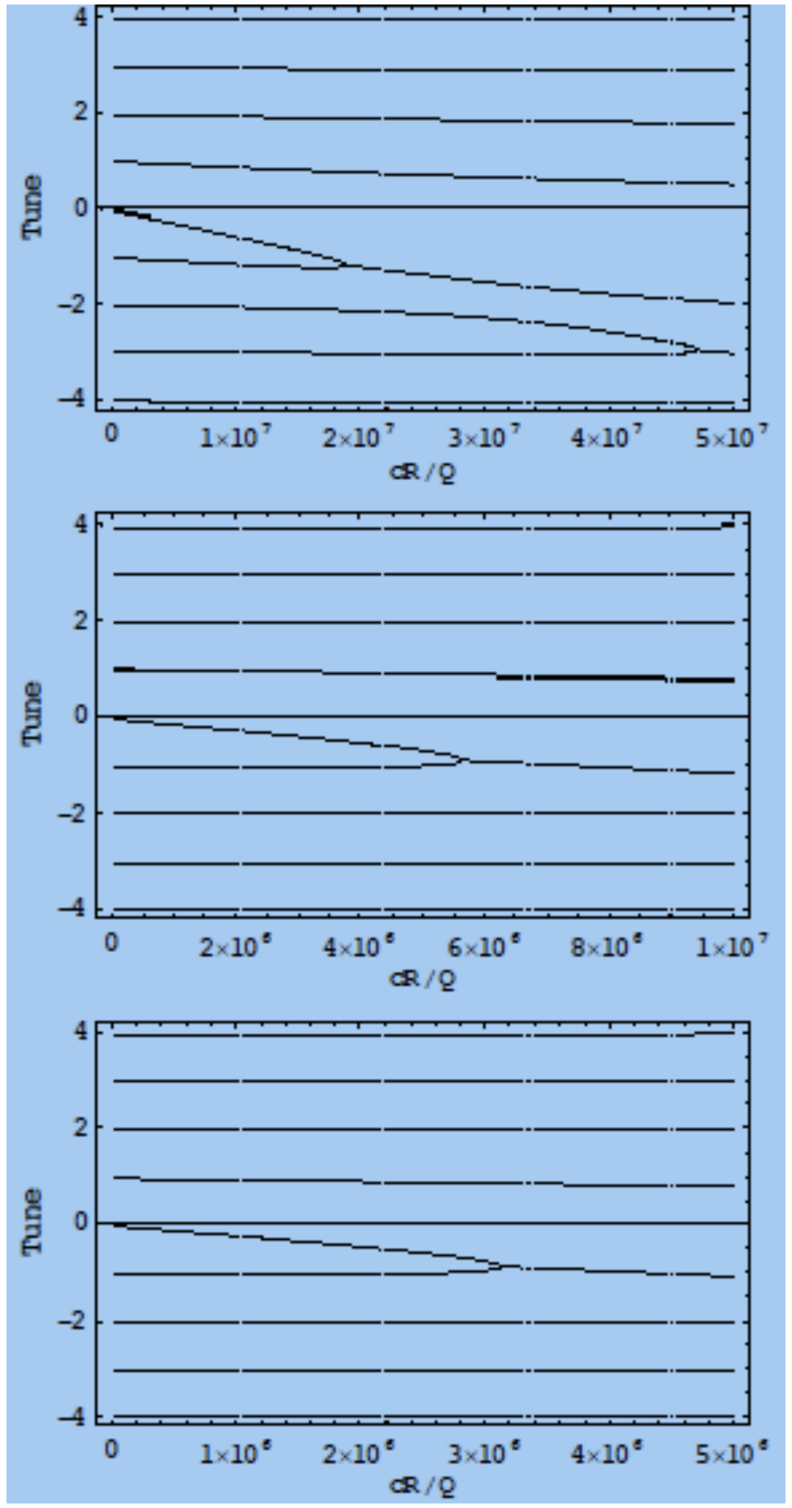
Q=5~10

The same method as the coupled bunch wake

- (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=1-2x10^{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=5x10^{11}m^{-3}

Static tune shift due to ρ_e is not added.

- Coasting beam model is better coincident with simulation.

- This model is insufficient to explain measured sideband spectra.

PEHTS modeling

S: strong-strong model

$$\frac{d^2\boldsymbol{x}_p}{ds^2} + K(s)\boldsymbol{x}_p = \frac{r_e}{\gamma}\frac{\partial\phi_e(\boldsymbol{x}_p)}{\partial\boldsymbol{x}_p}\delta_P(s - s_e)$$

$$\frac{d^2\boldsymbol{x}_e}{dt^2} = \frac{e}{m_e}\frac{d\boldsymbol{x}_e}{dt} \times \boldsymbol{B} - r_e c^2\frac{\partial\phi_p(\boldsymbol{x}_e)}{\partial\boldsymbol{x}_e}\delta_P(t - t_p(s_e)) - r_e c^2\frac{\partial\phi_e(\boldsymbol{x}_e)}{\partial\boldsymbol{x}_e}$$

$$\triangle_\perp\phi_e(\boldsymbol{x}) = \sum_{e=1}^{N_e}\delta(\boldsymbol{x} - \boldsymbol{x}_e) \qquad \triangle_\perp\phi_p(\boldsymbol{x}) = \sum_{p=1}^{N_p}\delta(\boldsymbol{x} - \boldsymbol{x}_p)$$

- 2D-PIC based code
- Time like variable s is used for beam motion, while t is used for electron motion.
- z(t) motion for beam can be treated by $\frac{r_e}{\gamma}\frac{\partial\phi_e(\boldsymbol{x}_p)}{\partial z_p}$, where z=s-ct.

Why 2D modeling

- Why not complete 3D modeling? 3D modeling using t is not fruitful for simulations of instabilities in circular rings; head-tail instability and incoherent emittance growth.

- In head-tail or two stream instability, essential point is transverse coherent motion between beam and electron cloud. Electron phase is chosen by beam phase. Electron s position can be localized and the beam motion is integrated with the step of s. This is common idea of accelerator physics.

- To avoid unphysical emittance growth, tune shift of each interactions should be less than <<1. While structure resonance has to be taken into account correctly. Beta function and phase at the interaction is important.

- $v_{z,e} << c$

KEKB: measurement and simulation of fast head-tail instability

Beam size blow up observed, and simultaneously synchro-beta sideband observed.

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

Betatron sideband

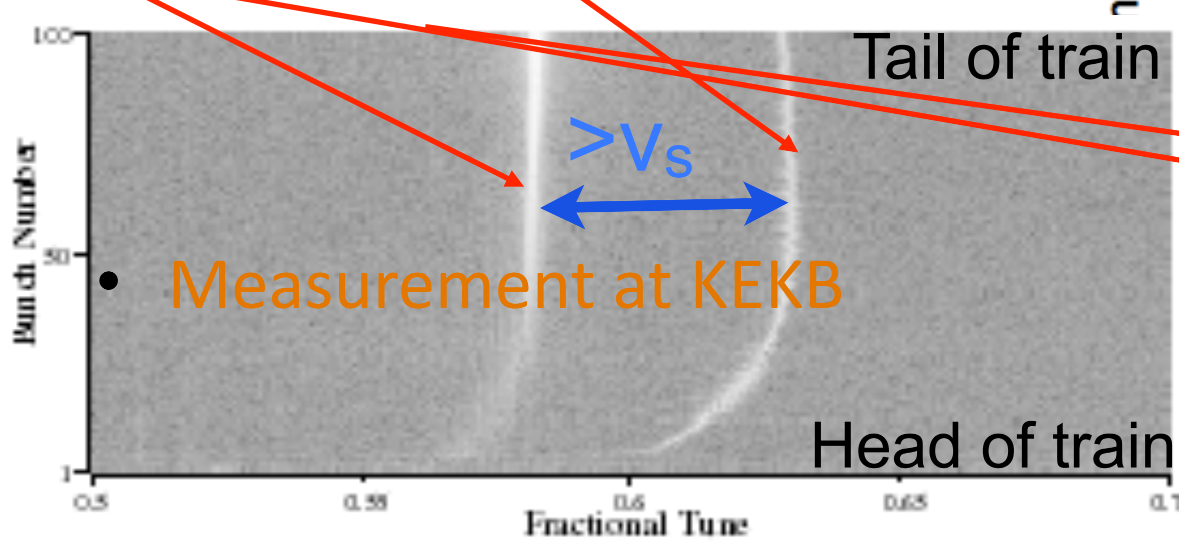
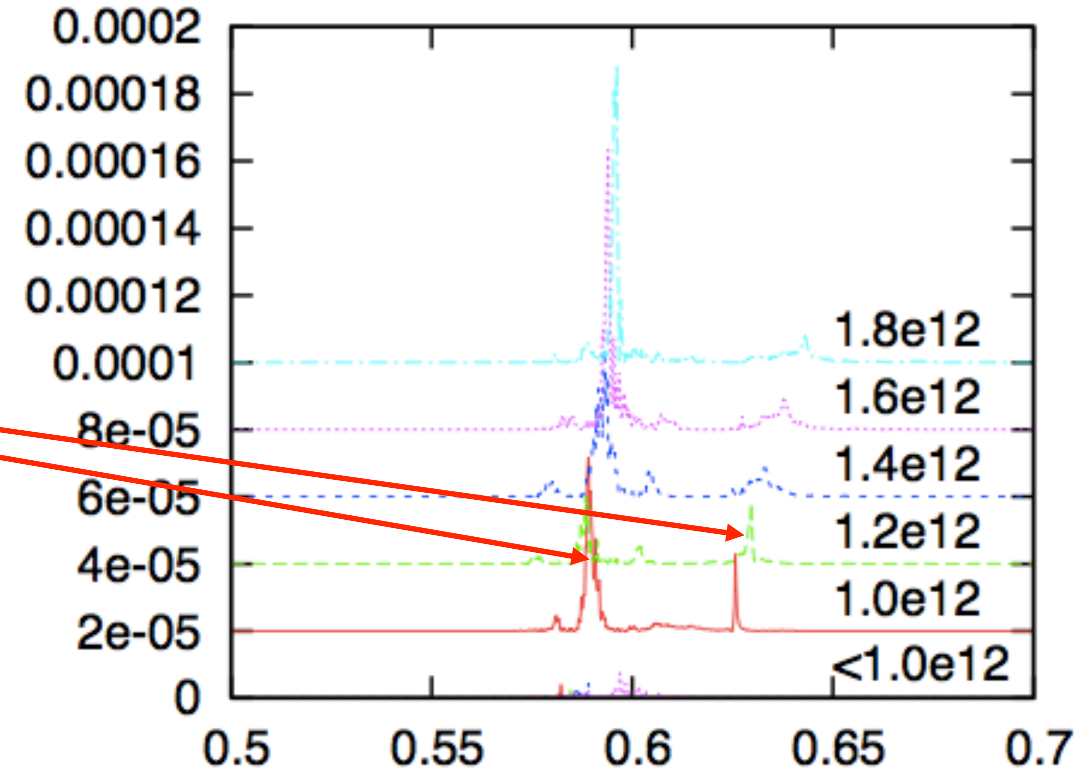
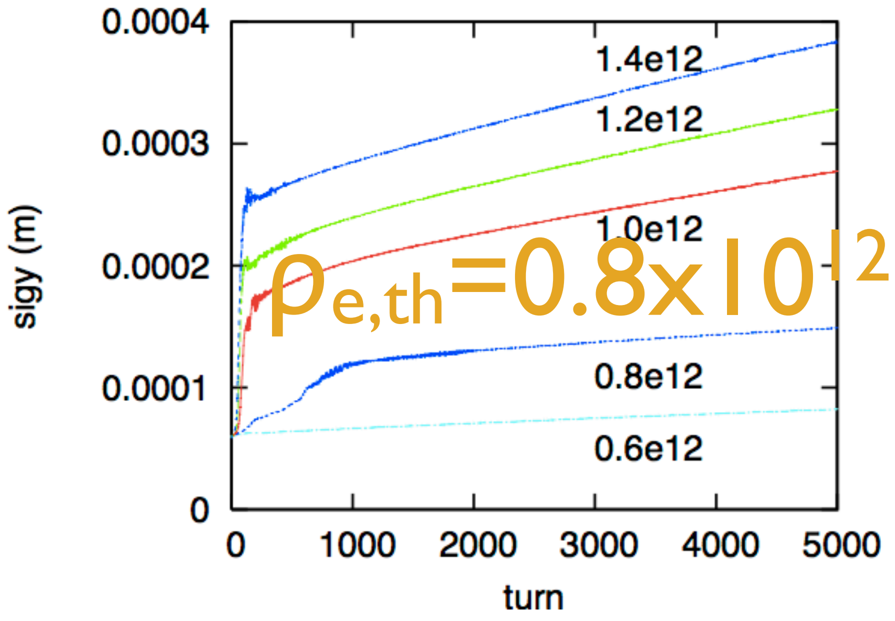


FIG. 1. Two-dimensional plot of vertical bunch spectrum versus bunch number. The horizontal axis is the fractional tune, from 0.5 on the left edge to 0.7 on the right edge. The vertical axis is the bunch number in the train, from 1 on the bottom edge to 100 on the top edge. The bunches in the train are 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.

Simulation (PEHTS)

HEADTAIL gave similar results (E. Beneditto showed large cloud gave the sideband signal)

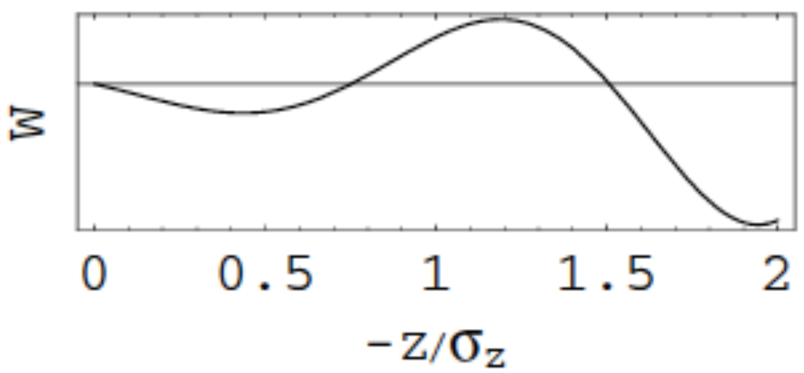




$\rho_{e,th}=0.8\times10^{12}\mathrm{m}^{-3}$

Possible explanation for the sideband

Electron pinching may enlarge the wake field strength.



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

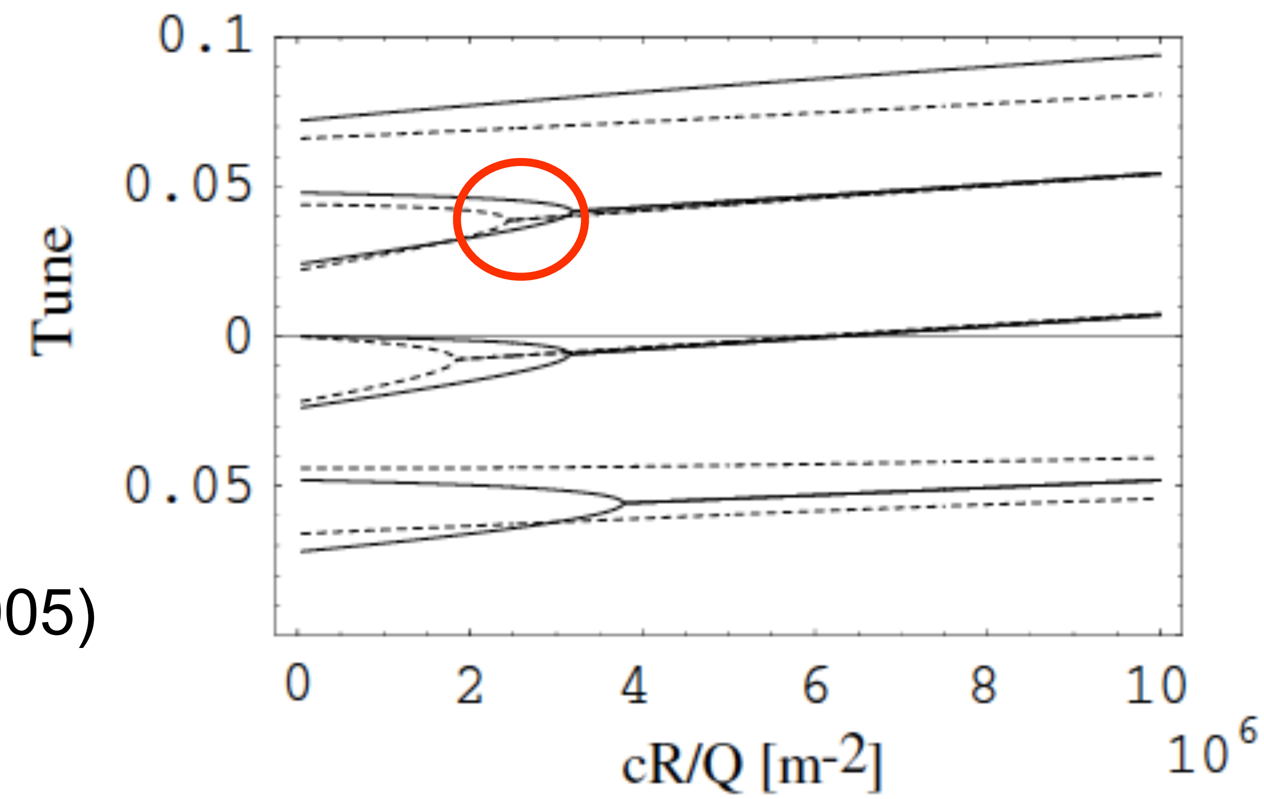


FIG. 6. Example mode spectrum for model focusing wake at $\nu_s = 0.022$ (dashed lines) and $\nu_s = 0.024$ (solid lines).

Mode coupling between m=1 and 2

Static tune shift due to ρ_e is added.

Feedback does not suppress the sideband

- Bunch by bunch feedback suppress only betatron amplitude.

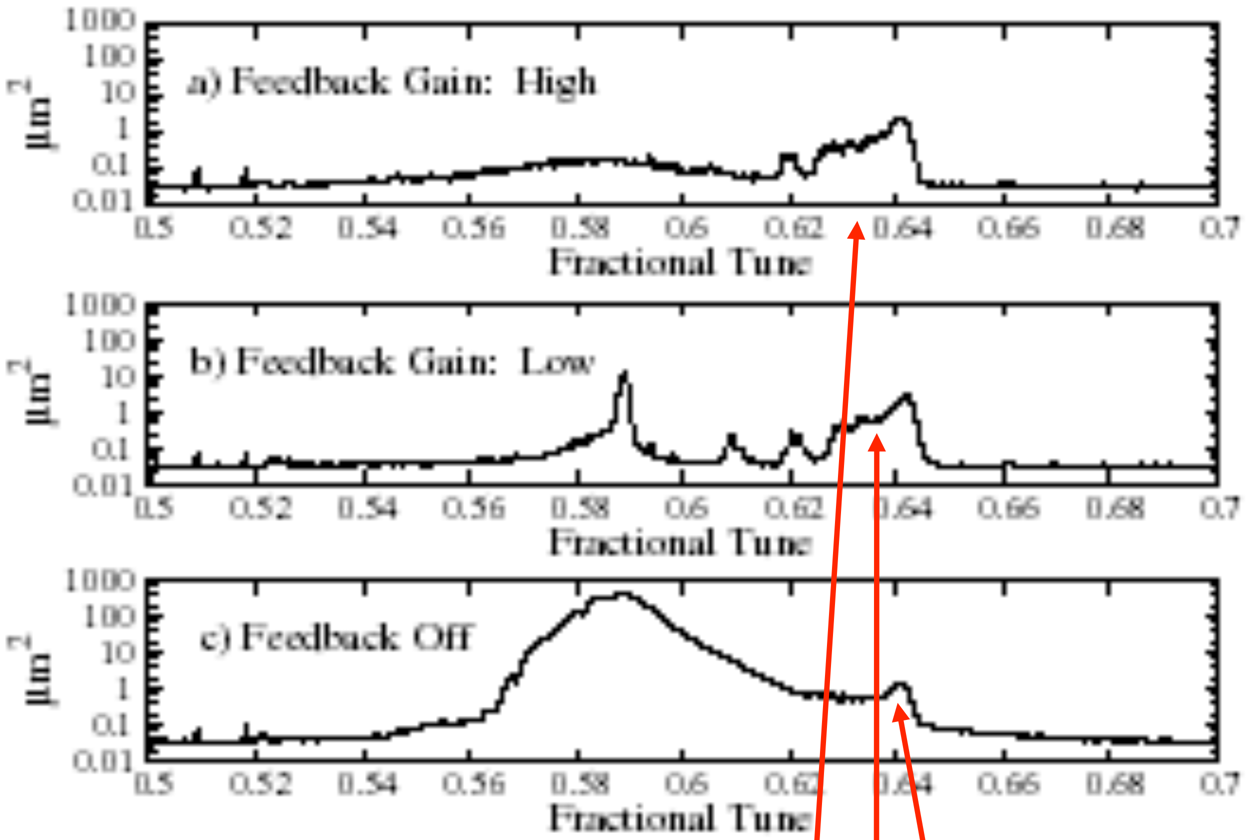
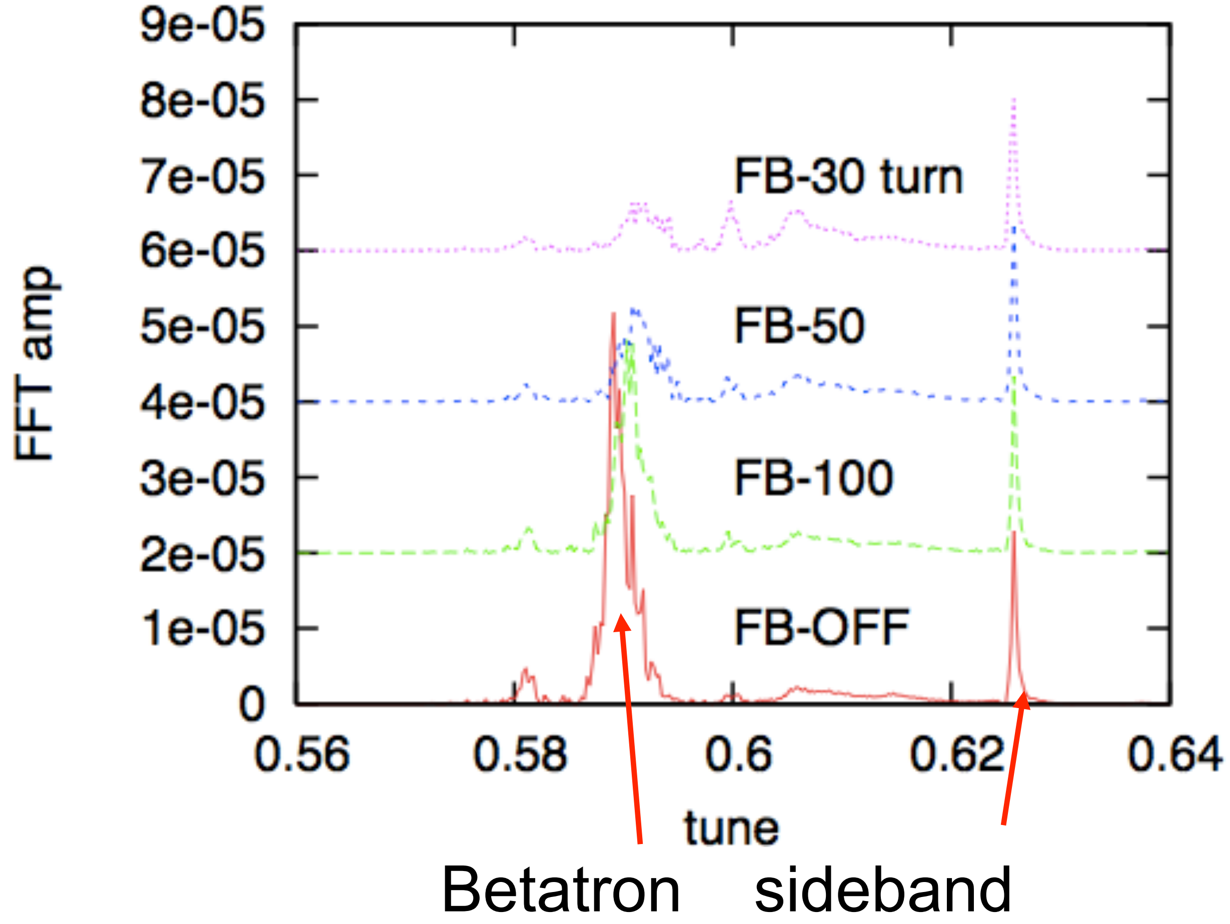


FIG. 2. Averaged spectra of all bunches with the feedback gain (a) high, (b) low, and (c) set to zero. The vertical betatron peak is visible at 0.588, and the sideband peak can be seen around 0.64.

Sideband signal is Integrated over the train



Simulation (PEHTS)

Proton ring

- Electrons induced by ionization, proton loss and their secondary cause a two stream instability.
- Electrons oscillate in proton beam potential.

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

- Long bunch 10m, $\omega_e \sigma_z / c > R/\sigma_r$. All electrons in the chamber are gathered near the beam. Line electron density $\lambda_e (m^{-1})$ characterizes the instability.

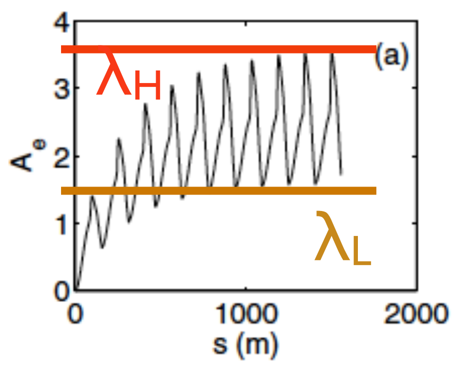
R: chamber radius, σr:beam size

- Short bunch $\omega_e \sigma_z / c \sim 10$ or less $< R/\sigma_r$. The volume density $\rho_e (m^{-3})$ characterizes the instability.

Ecloud instability in Proton rings

TABLE I. Basic parameters of the proton rings.

Variable	Symbol	J-PARC 3 GeV Inj.	J-PARC 3 GeV Ext.	J-PARC 50 GeV Inj.	J-PARC 50 GeV Ext.	PSR	ISIS	SNS	AGS
Circumference	L (m)	348.3	348.3	1567.5	1567.5	90	163	248	800
Relativistic factor	γ	1.4	4.2	4.2	54	1.85	1.07	2.02	3.0
Bunch population	$N_p(\times 10^{13})$	4.15	4.15	4.15	4.15	3	1.25	20.5	1.2
Number of bunches	n_b	2	2	8	8	1	2	1	6
Harmonic number	H	2	2	9	9	1	2	1	6
rms beam sizes	σ_r (cm)	1.9	1.2	1.1	0.5	1.0	3.8	2.8	0.7
Bunch length	ℓ_p (m)	110	82	82	16	65	60	200	68
rms energy spread	$\sigma_{\delta E/E}$ (%)	0.6	0.7	0.7	0.25	0.4	0.5	0.5	0.28
Slippage factor	η	−0.48	−0.047	−0.058	−0.0013	−0.187	−0.83	−0.204	−0.146
Synchrotron tune	ν_s	0.0058	0.0005	0.0026	0.0001	0.0003	0.0036	0.0004	0.0017
Beam pipe radius	R (cm)	12.5	12.5	6.5	6.5	5	8	10	5



K. Ohmi, T. Toyama, C. Ohmori, PRST-AB 5, 114402 (2002).

TABLE III. Wake field and stability for electron cloud instability.

Variable	J-PARC 3 GeV Inj.	J-PARC 3 GeV Ext.	J-PARC 50 GeV Inj.	J-PARC 50 GeV Ext.	PSR	ISIS	SNS	AGS
$Z(\omega_e)_{1,L}/Q$ (MΩ/m)	0.29	0.24	0.68	0.019	0.46	0.0051	0.09	0.024
$Z(\omega_e)_{1,H}/Q$ (MΩ/m)	0.61	0.83	9.7	0.96	0.90	0.0085	0.19	0.37
$\omega_e \ell_p / c$	133	182	199	276	166	27	272	153
U_L $=Gr/D_L$	0.07	0.23	0.11	0.02	1.6	0.007	0.30	0.004
U_H	0.15	0.78	1.6	1.2	3.2	0.012	0.61	0.06

Measurement at J-PARC MR

T. Toyama & M. Uota

- Electron signal had been detected when the intensity is increased ~150kW to 200kW.
- Electron signal was observed for a few in 8 bunches. The signal was seen during several 10 turns, and repeated in the synchrotron period.
- Electron signal and vacuum degradation was synchronized.
- Electrons (vacuum degradation) were seen in the whole ring.
- Sign of beam loss was observed, but not identified clearly yet.
- The signal disappeared after a few days operation of 200kW.

Run42
Shot12147x
2012. 4.13

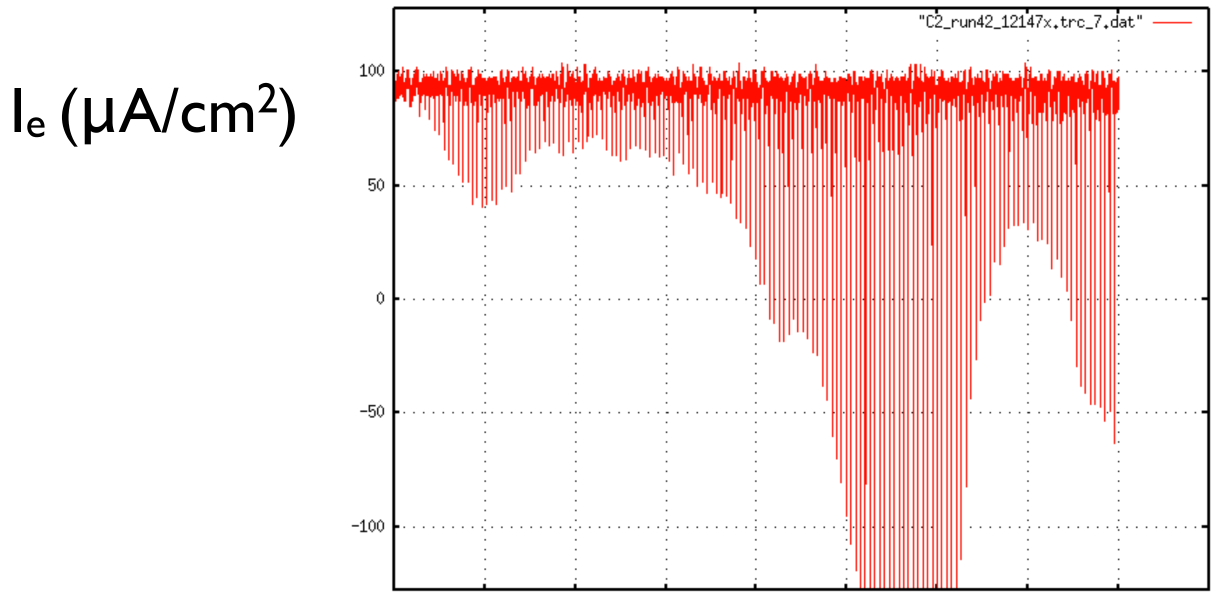
ν user operation
$N_B \sim 10^{14}$ ppp (Np=1.25×10^{13}/bunch)

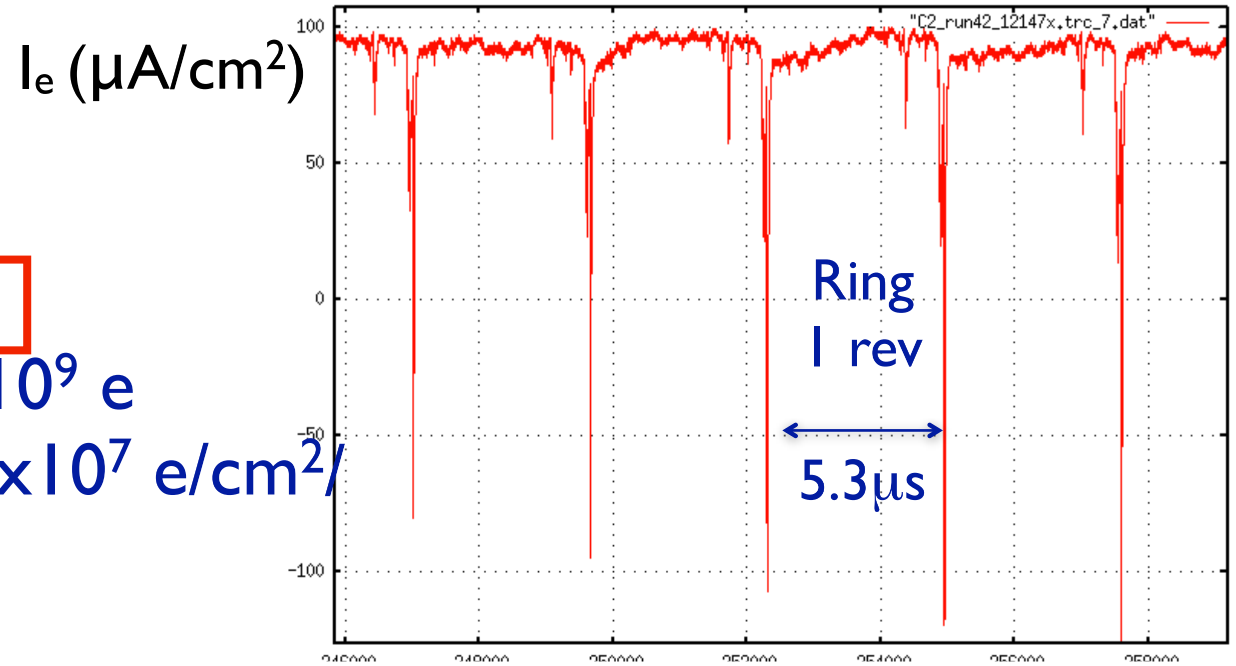
8 buneches
P∼187-189 kW

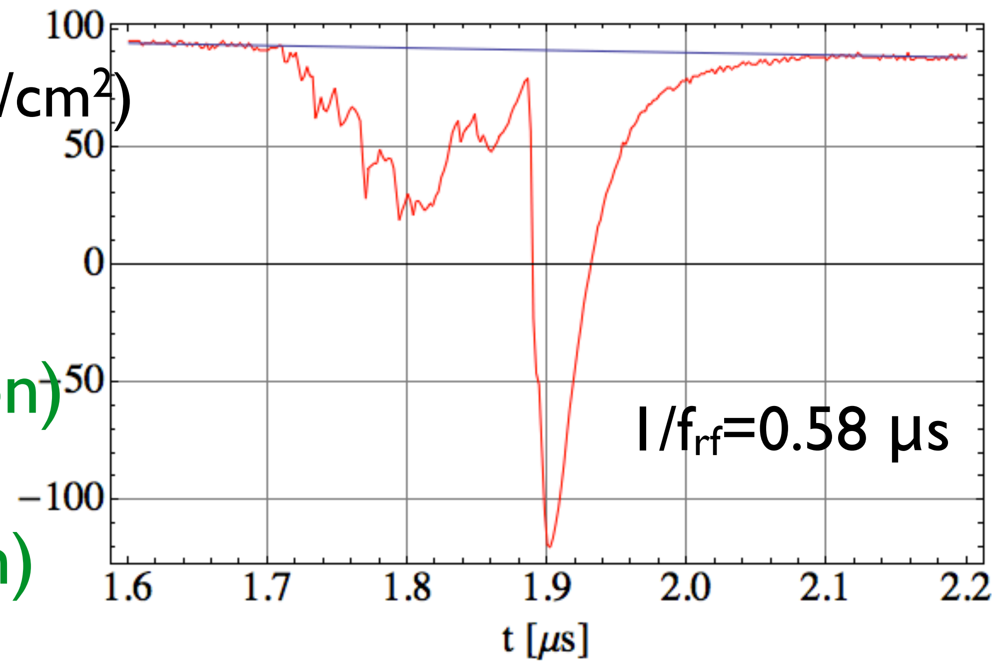
Peak current at the monitor = 2.6 mA
$\boxed{\text{Peak current density} = I_{peak}=200\ \mu\text{A/cm}^2}$
Electron absorption at the monitor = 1.3×10^9 e
Electron absorption rate = $\int_0^{L/h} I_e ds/c$ = 9.7×10^7 e/cm²/passage

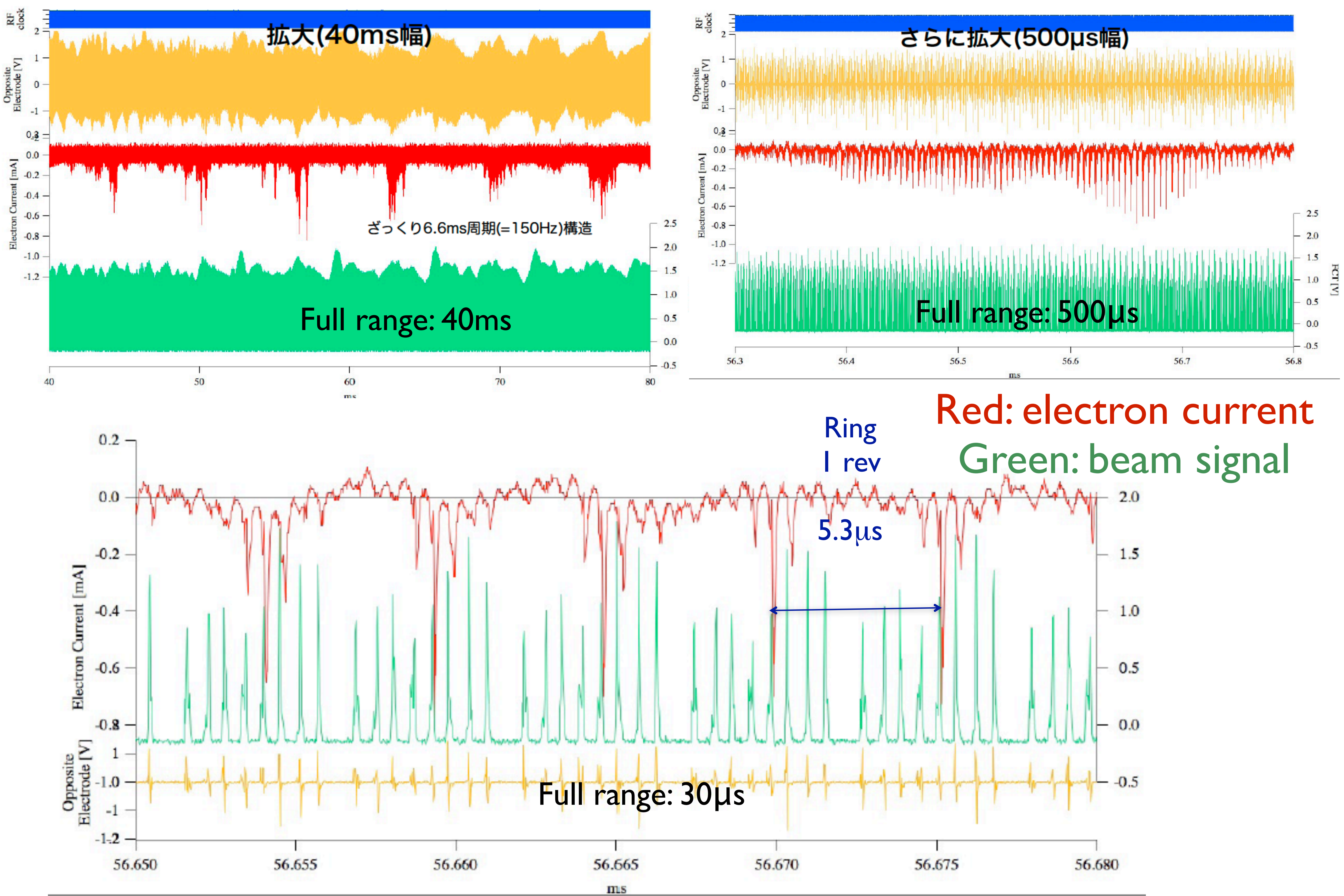
chamber radius =6.5cm
Monitor effective surface =13cm²

Electron production rate=$0.97\times10^8\times2\pi\times6.5\times100$
=4.0×10^{11} /m/passage (including secondary emission)
Electron production rate=4.0×10^{11} /1.25×10^{13}
=0.032/m/p/passage (including secondary emission)









拡大(40ms幅)
ざっくり6.6ms周期(=150Hz)構造
Full range: 40ms
さらに拡大(500μs幅)
Full range: 500μs
Ring
1 rev
5.3μs
Full range: 30μs
Red: electron current
Green: beam signal

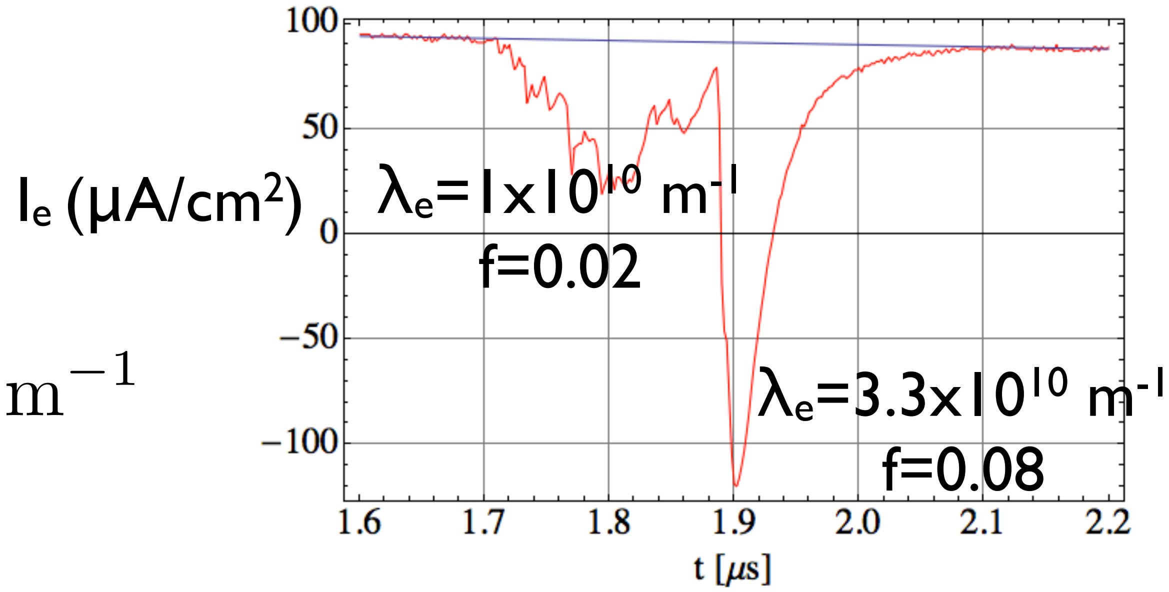
Estimation of Cloud density

$$\lambda_e = \frac{2\pi R^2 I_e}{e v_e}$$ electron line density

$$\boxed{\lambda_{e,peak} = 3.3 \times 10^{10}} > \lambda_{e,th}$$

- R=0.065m, $v_e = 10^7$ m/s (300eV)

$$\int_0^{L/h} 2\pi R I_e(s) ds/c = 4 \times 10^{11} e \text{ m}^{-1}$$



- Threshold of electron cloud density for the instability

$$\lambda_{e,th} = \frac{2\gamma_p \omega_e |\eta_p| \sigma_p (\sigma_x + \sigma_y)\sigma_y}{\sqrt{3} c Q r_p \beta_y}$$

$$\boxed{\lambda_{e,th} = 1.1 \times 10^{10}} \quad \lambda_p = 4.4 \times 10^{11} \quad f = \lambda_{e,th}/\lambda_p = 0.025$$

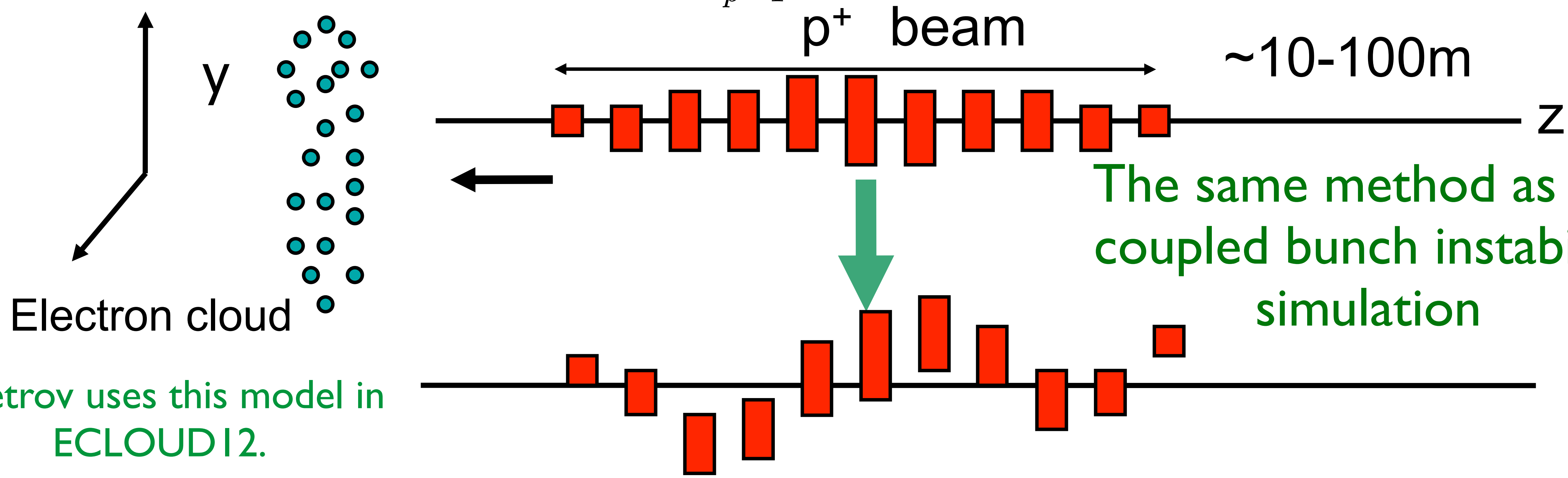
- Proton beam does not exist at the peak density. Proton beam experiences $\lambda_e = 1\times10^{10}$ m^{-1}, critical for the instability.

Tracking simulation, code EPI

- Solve both equations of beam and electrons simultaneously and self consistently.
- Electrons are produced and tracked with the correct initial condition and boundary condition.
- Landau damping is taken into account by comparison of the growth (Gr) and damping (D_L) rates, because of no synchrotron motion in this modeling.

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

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



The same method as the coupled bunch instability simulation

F. Petrov uses this model in ECLOUD12.

Example of Landau damping

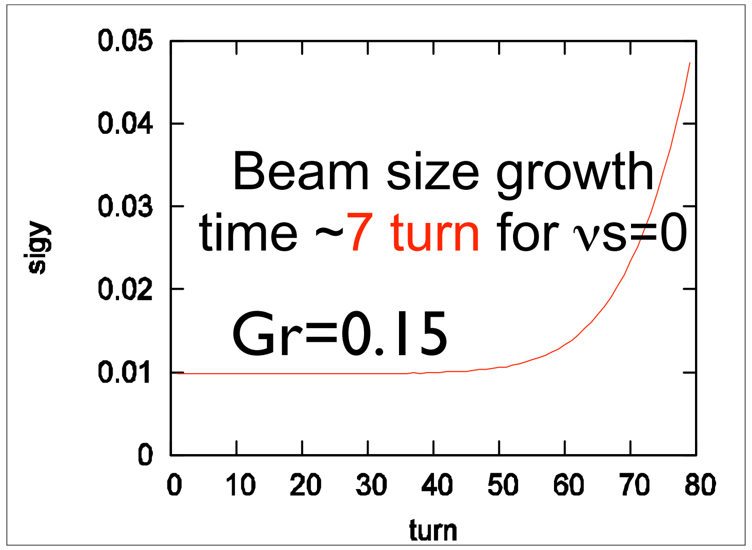
- Landau damping due to energy spread (slippage).

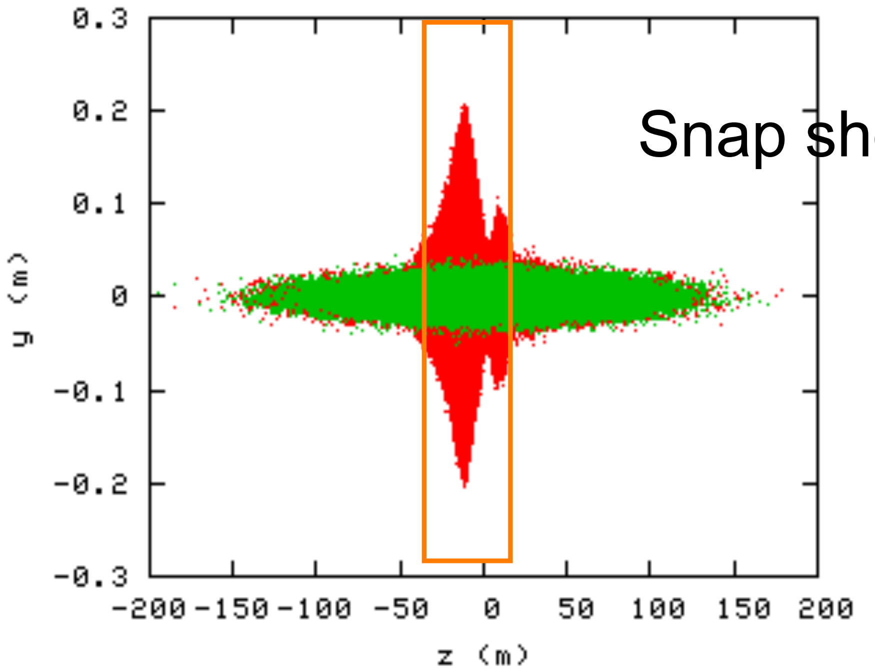
- Landau damping works very well as is expected!

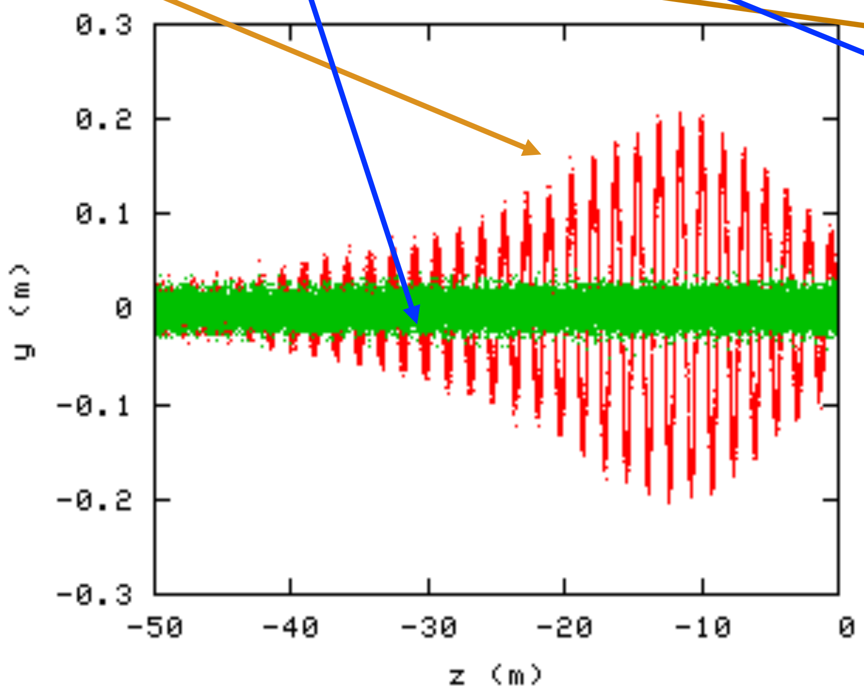
$$D_L = \frac{\nu_s \omega_e \sigma_z}{\sqrt{3}c}$$

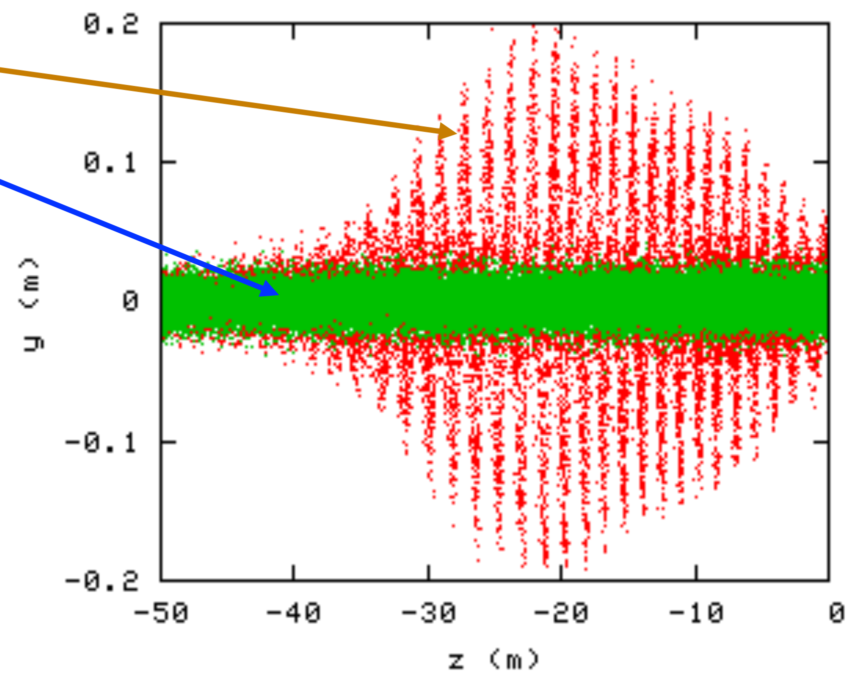
Green ν_s=0.0002(U=Gr/D_L=1.07)

Red ν_s=0 or 0.0001(U=Gr/D_L=2.14)

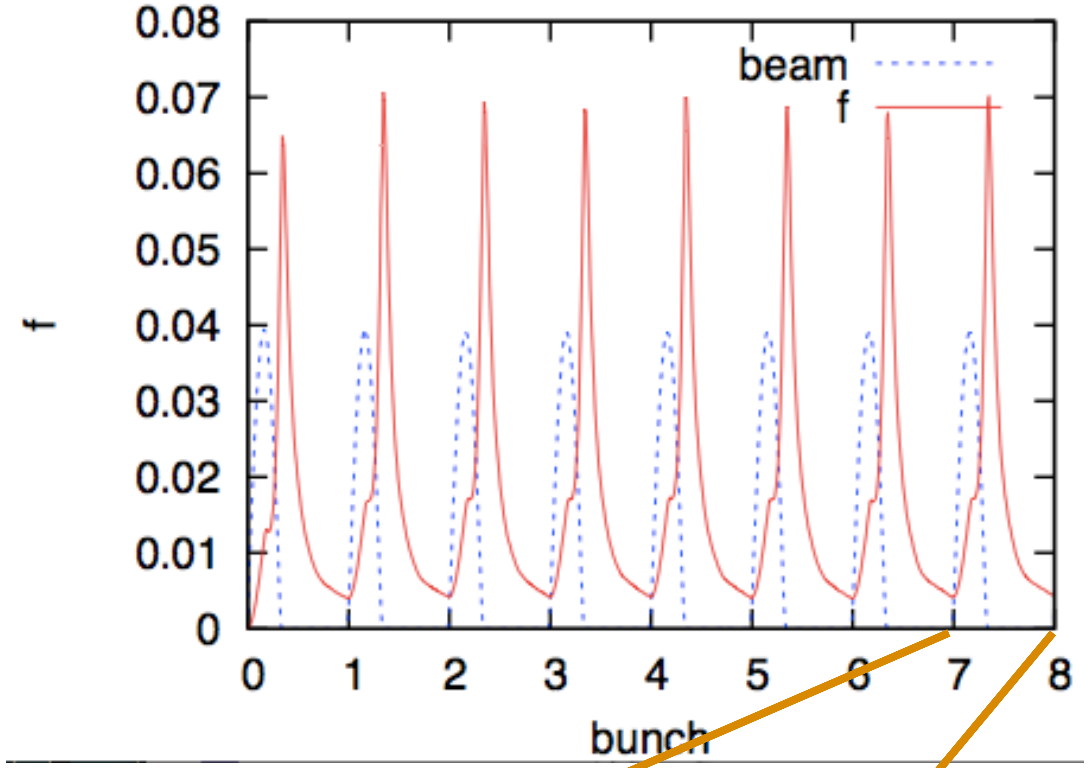








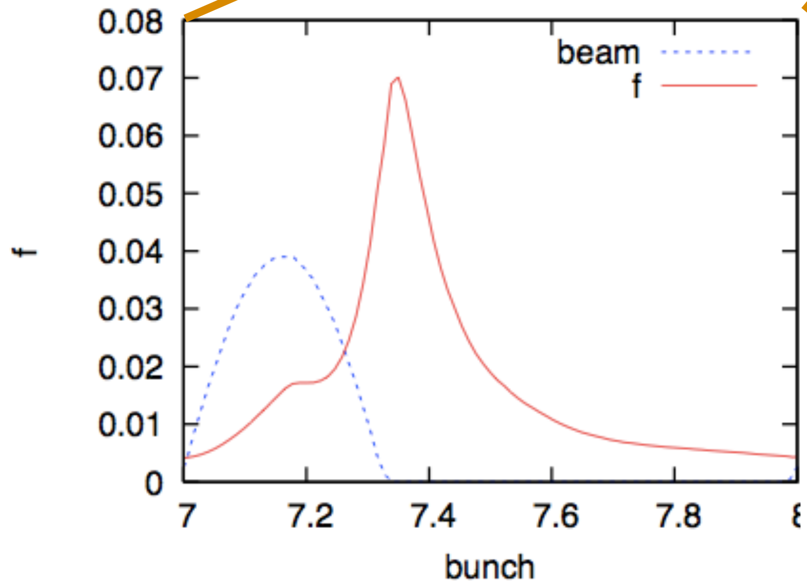
Simulation with similar electron profile

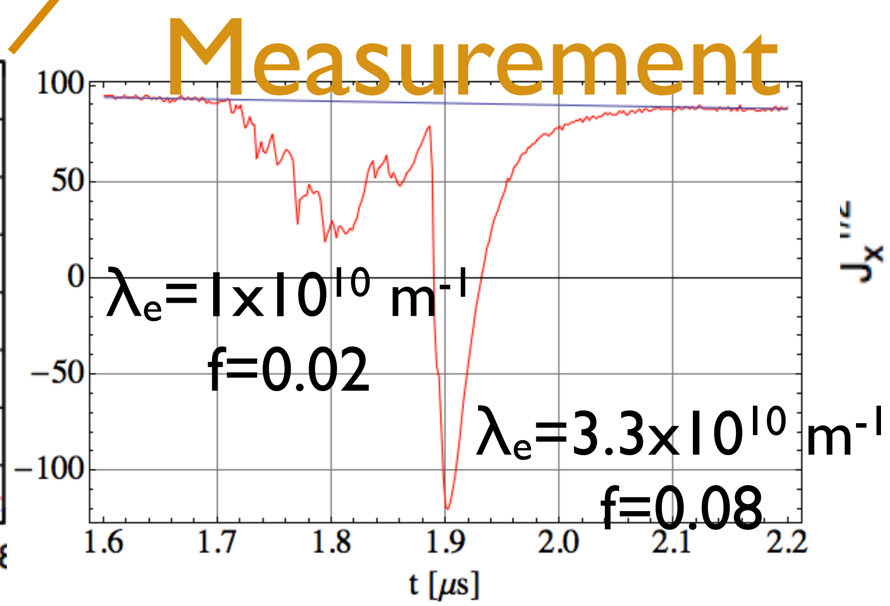


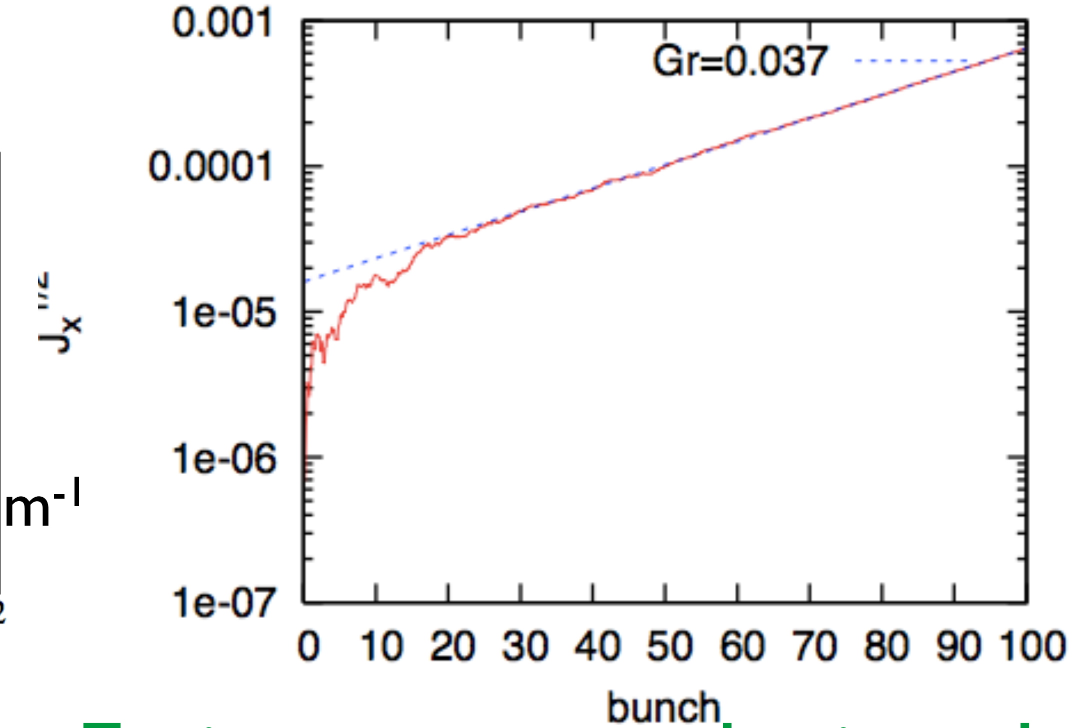
- Gr=0.037

$$D_L = \frac{\nu_s \omega_e \sigma_z}{\sqrt{3}c} = 0.088$$

- U= Gr/D_L=0.4
- Critical situation







Emittance growth given by the tracking

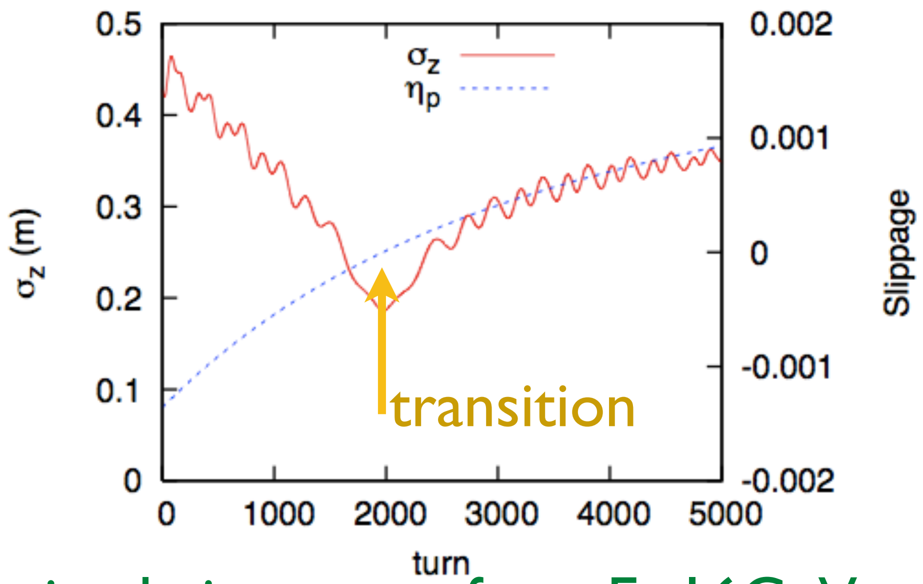
Measurement at Fermilab Main Injector

$$\lambda_e = \frac{2\pi R^2 I_e}{e v_e} \qquad \rho_e = \frac{2 I_e}{e v_e}$$

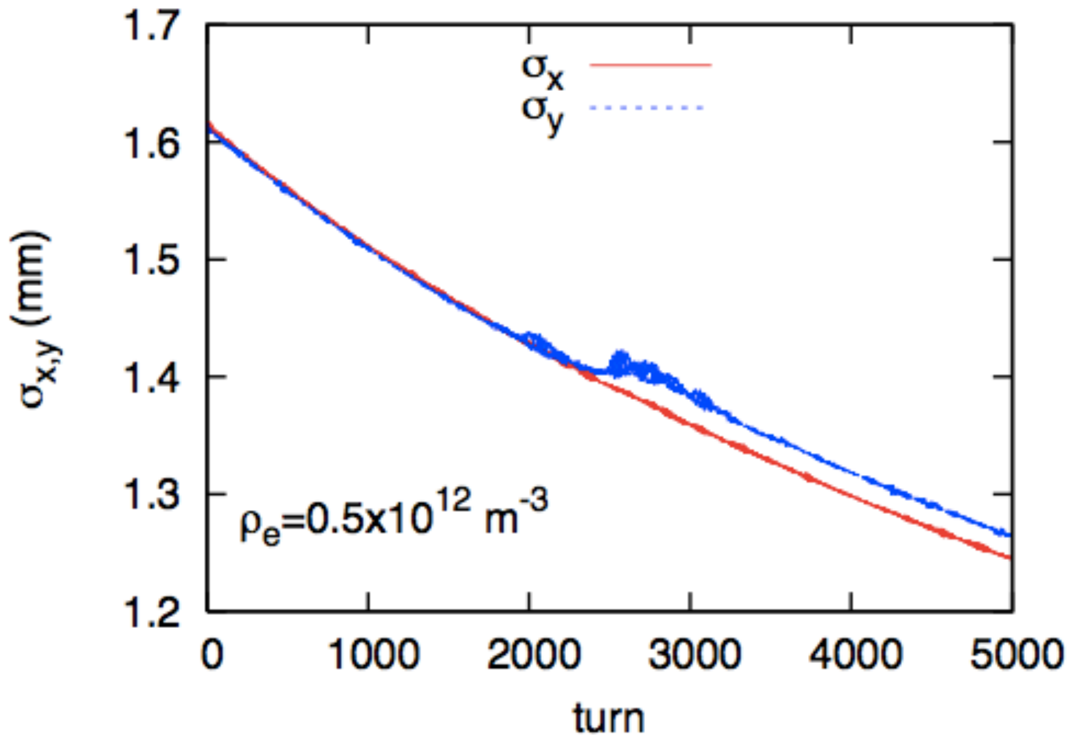
Steel pipe without coating

- Electron current is observed near the transition

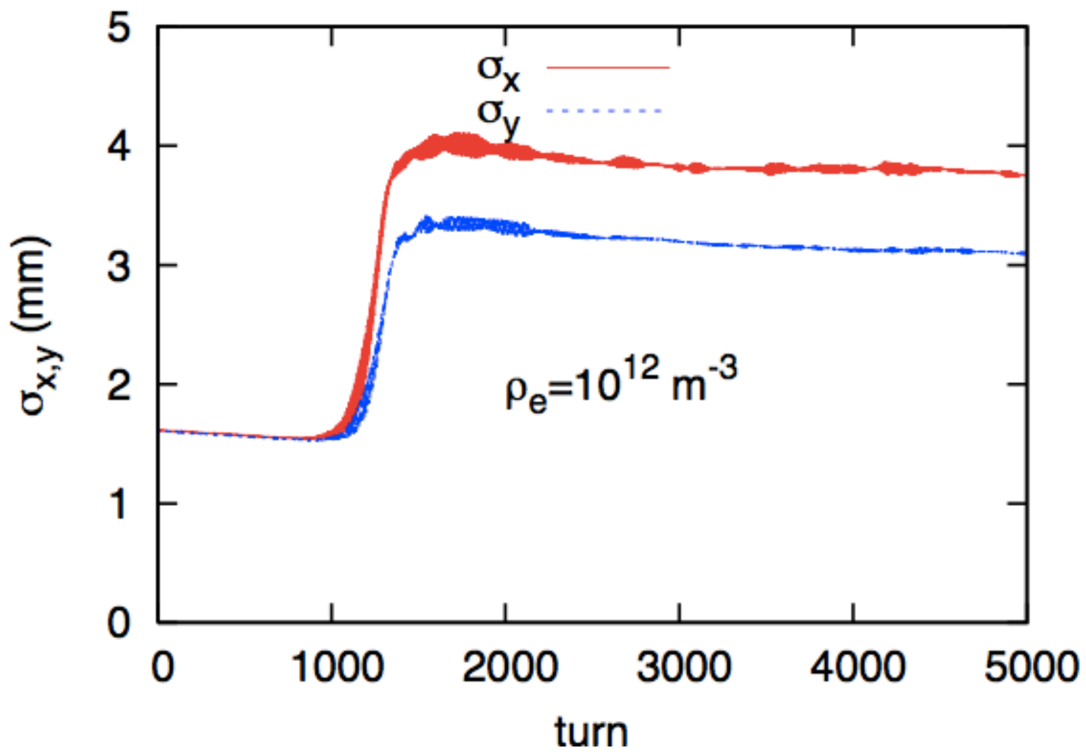
Instability near the transition



The simulation starts from E=16GeV, and the beam is accelerated 2.29MeV/turn.



- Bunch length (0.2m) is shorter compare than bunch spacing (5.65m).
- Decoupling coupled bunch and single bunch effects. PEHTS modeling is available.
- Bunch length and slippage vary turn-by-turn.
- $\rho_{th}=5\text{x}10^{11}\text{m}^{-3}$, $I_{e,th}=40\mu A/cm^2$.



Growth of coupled bunch instability is also fast

$Gr=0.1$/turn at $I_e=40\mu A/cm^2$.

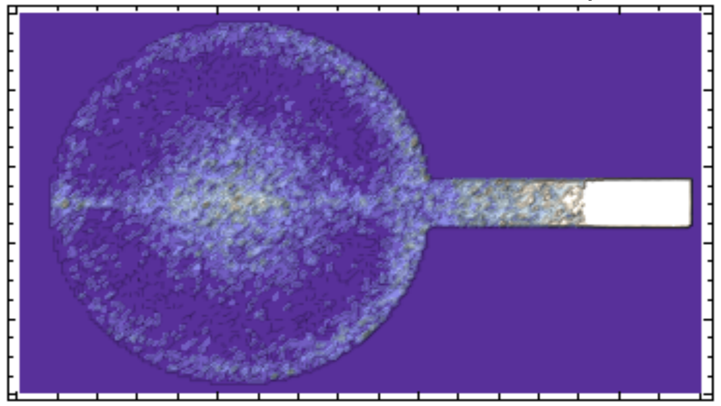
Summary

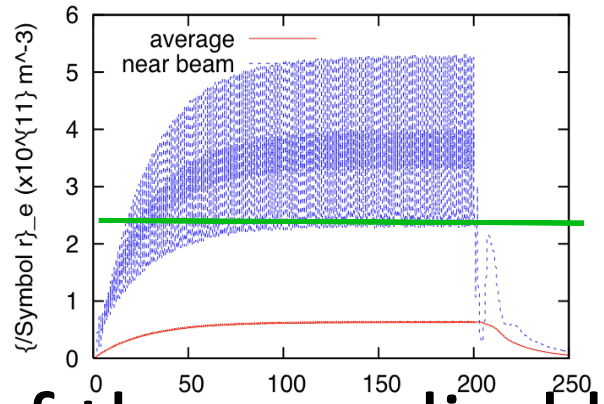
- Mode spectra due to the coupled bunch instability and synchrotron sideband due to the fast head-tail instability are prominent results of the electron cloud instability.
- Simulations and theory explained the phenomena. The agreement is not bad.
- Upper sideband spectrum is solid in experiments, while is sometimes fragile in simulations. Spectrum seen in Cesr-TA has different feature. Simulation can reproduce the spectrum, m=0 mode dominates for $\omega_e\sigma_z/c>>1$. But ....
- I am also interested in DAFNE instability and in SPS, LHC...
- Prominent signal for the EC instability in Proton rings, J-PARC; Instability threshold, beam frequency spectra ....

Thank you for your attention

Estimation of cloud density and coupled bunch instability in SuperKEKB

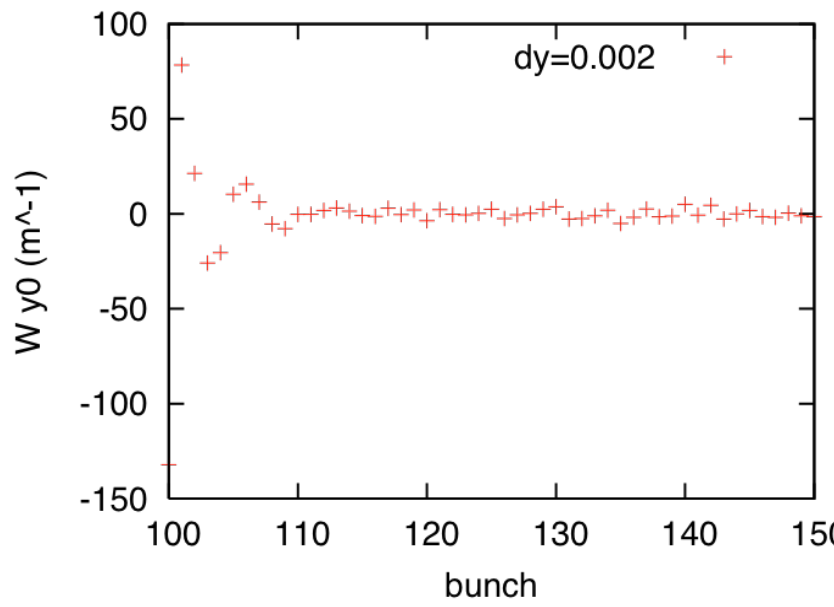
- Ante-chamber, $\delta_{2,max}$=1.2 without special structure like groove

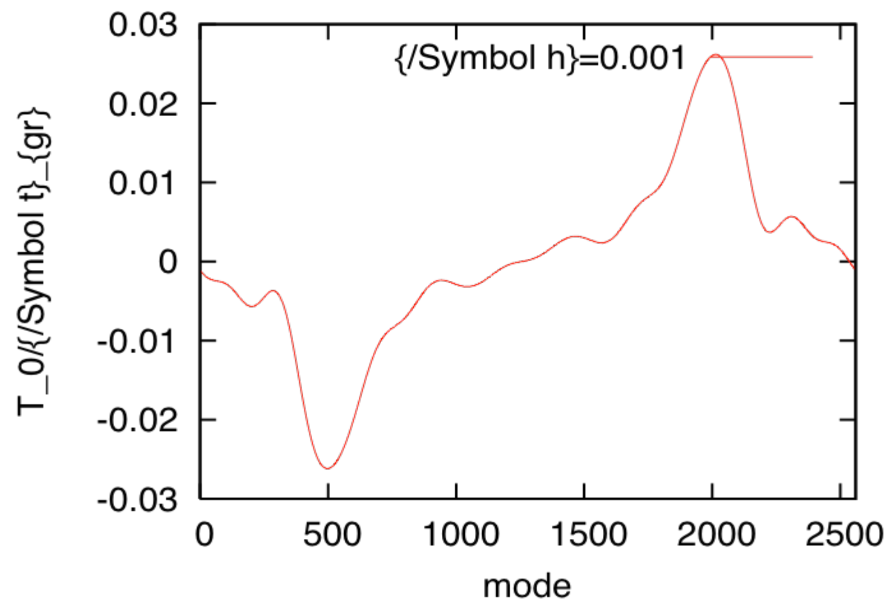




$\rho_e = 2.2 \times 10^{11}\ m^{-3}$

- Wake field and growth rate of the coupled bunch instability.

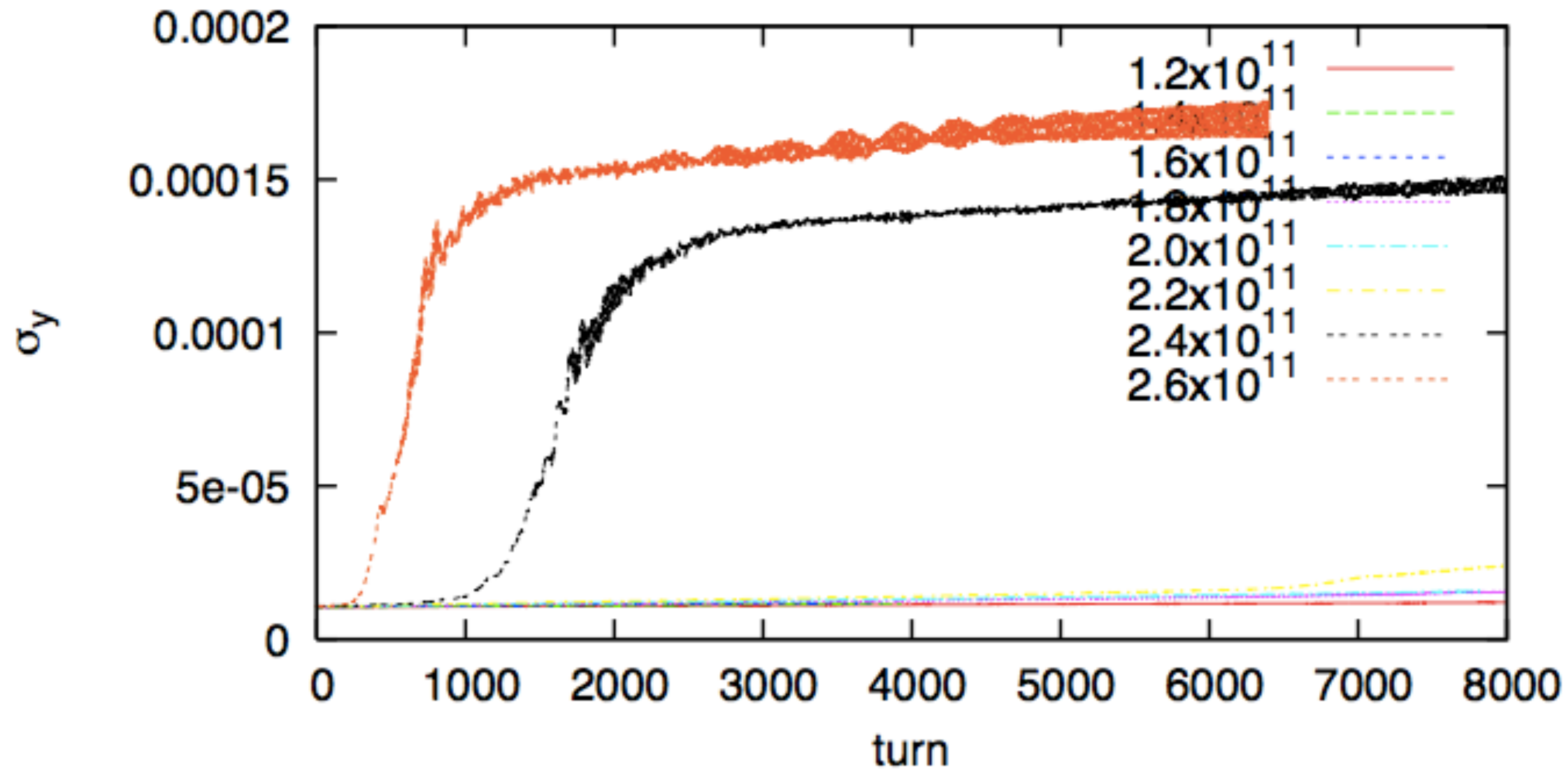




Growth time is 40 turns. It should be suppressed at $\rho_e = 1 \times 10^{11}\ m^{-3}$.

- Suetsugu-san estimates the density based on measurements and is designing the chamber to achieve density.

SuperKEKB



- Simulation ρ_{th}=2.2x10^{11} m^{-3}.
- Analytic ρ_{th}=2.7x10^{11} m^{-3}.
- Take care of high β section. Effects are enhanced.

Vacuum system designed to be ρ_e=1x10^{11} m^{-3}

$$\oint \rho_e \beta_y ds/L = 10^{11} \times 10 \ \mathrm{m}^{-2}$$

Parameters for e^+ machines

Table 1: Basic parameters of the positron rings

Lattice		KEKB	Cesr-TA	PETRA-III	SuperKEKB	Super B
Circumference	L (m)	3,016	768	2304	3016	1260
Energy	E (GeV)	3.5	2-5	6	4.0	6.7
Bunch population	$N_+(10^{10})$	8	2	0.5	9	5
Beam current	I_+ (A)	1.7	-	0.1	3.6	1.9
Emittance	ε_x(nm)	18	2.3	1	3.2	2
	ε_y(nm)	0.18	0.023	0.01	0.01	0.005
Momentum compaction	$\alpha(10^{-4})$	3.4	68	12.2	3.5	
Bunch length	σ_z(mm)	6	6.8	12	6	5
RMS energy spread	$\sigma_E/E(10^{-3})$	0.73	0.8		0.8	0.64
Synchrotron tune	ν_s	0.025	0.067	0.049	0.0256	0.0126
Damping time	τ_x(ms)	40	56.4	16	43	26

Table 2: Threshold of the B factories positron rings and others

		KEKB (no sol.)	KEKB (50 G sol.)	Cesr-TA	PETRA-III	SuperKEKB	SuperB
Bunch population	$N_+(10^{10})$	3	8	2		8	5
Beam current	I_+ (A)	0.5	1.7	-	0.1	3.6	1.9
Bunch spacing	ℓ_{sp}(ns)	8	7	4-14	8	4	4
Electron frequency	$\omega_e/2\pi$(GHz)	28	40	43	35	150	175
Phase angle	$\omega_e\sigma_z/c$	3.6	5.9	11.0	8.8	18.8	18.3
Threshold	ρ_e $(10^{12}$ m$^{-3})$	0.63	0.38	1.7	1.2	0.27	0.54