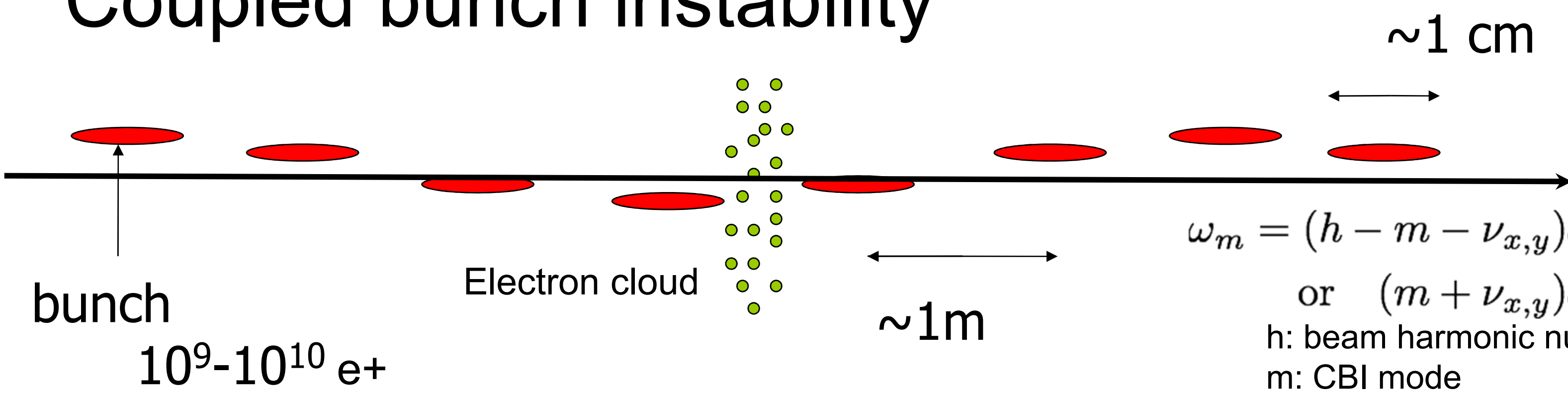
Electron cloud effects, codes & simulations

K. Ohmi (KEK)

ICAP12, 20-24 Aug, 2012
Rostock

Observation of electron cloud effects

- Coupled bunch instability



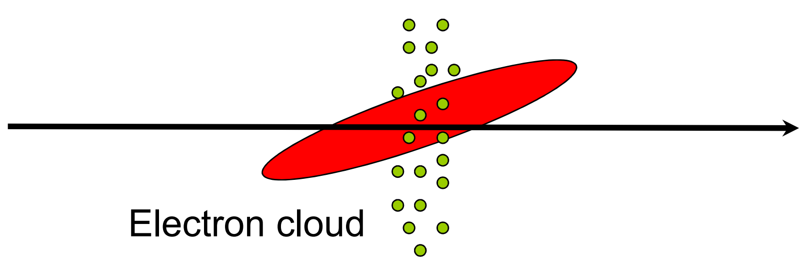
$$\omega_m = (h - m - \nu_{x,y})\omega_0$$

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

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

Part I
Coupled bunch instability due to electron cloud

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

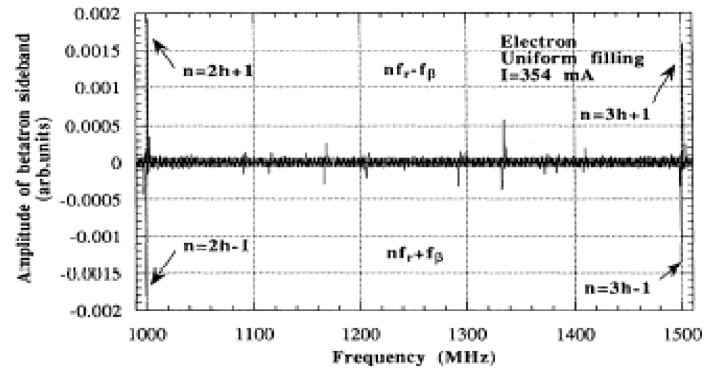


FIG. 1. Distribution of the betatron sidebands observed during electron multibunch operation with uniform filling.

Positron 324 mA & 240 mA

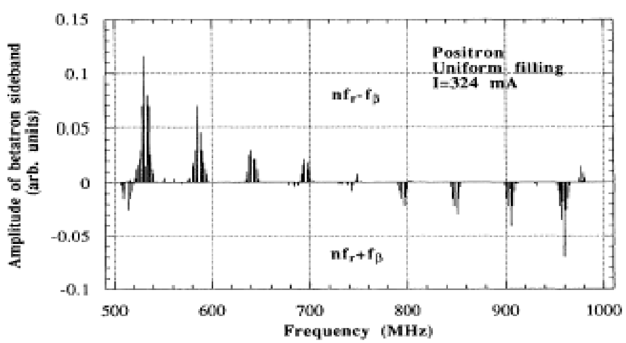


FIG. 2. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling.

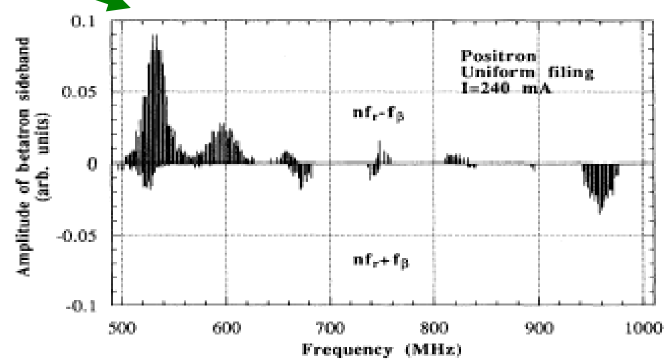


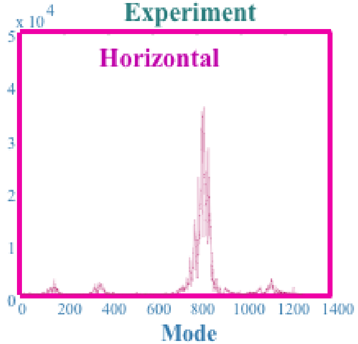
FIG. 3. Distribution of the betatron sidebands observed during positron multibunch operation with uniform filling. Only the stored current is different from Fig. 2.

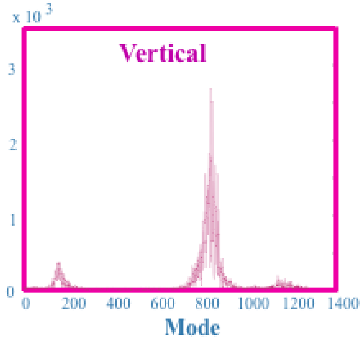
Different spectra are observed for e+ or e- storage. Mode spectra depend on beam current.

Measurement in KEKB

- CBI mode spectra in KEKB Solenoid-Off

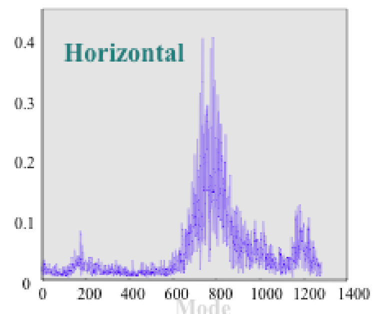
Experiment

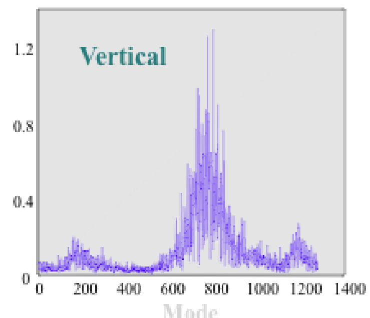




Bunches are filled every 4 bucket.

Simulation





Su Su Win et al,(EC200

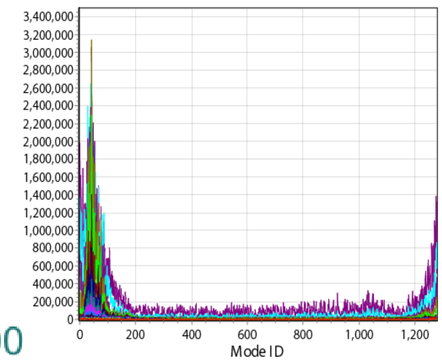
Solenoid ON

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

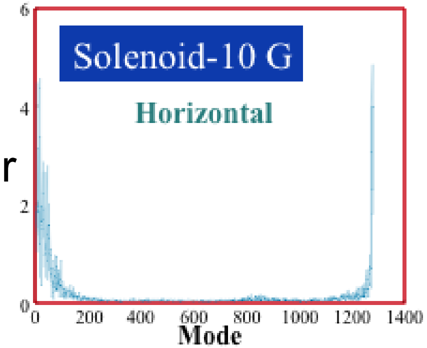
$$\text{or} \quad (m + \nu_{x,y})\omega_0$$

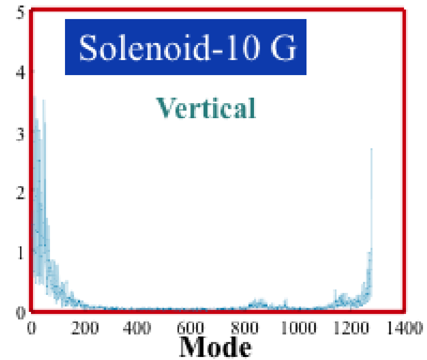
h: beam harmonic number
m: CBI mode

measurement



Simulation



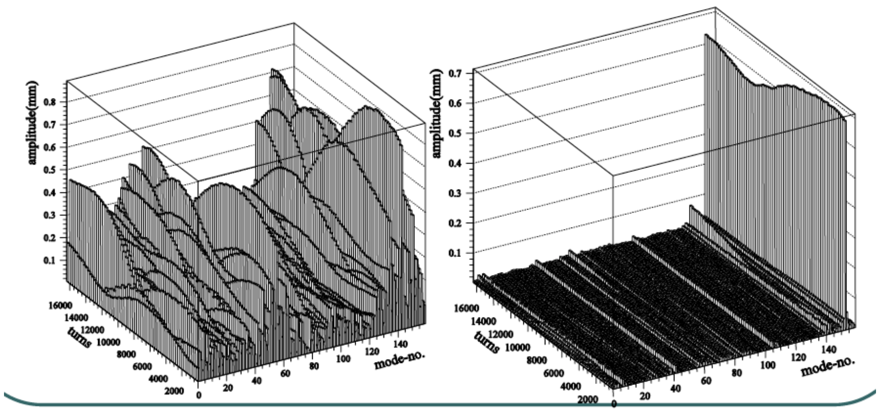


Solenoid is installed to protects electron cloud near the beam. The mode of the coupled bunch instability depends on the solenoid ON/OFF.

Measurement in BEPC & DAFNE

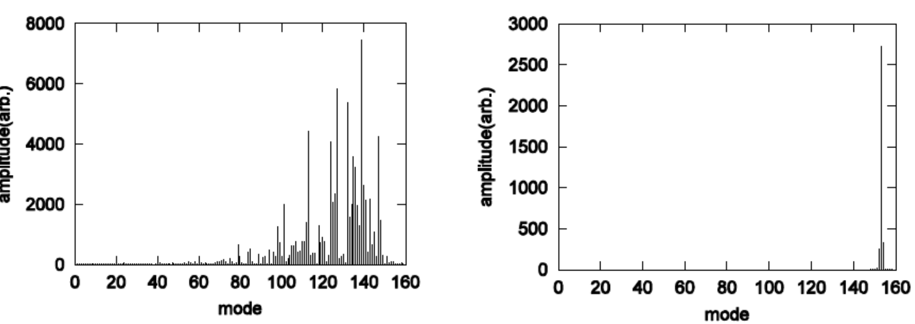
Vertical coupled bunch instability in BEPC

Positron electron



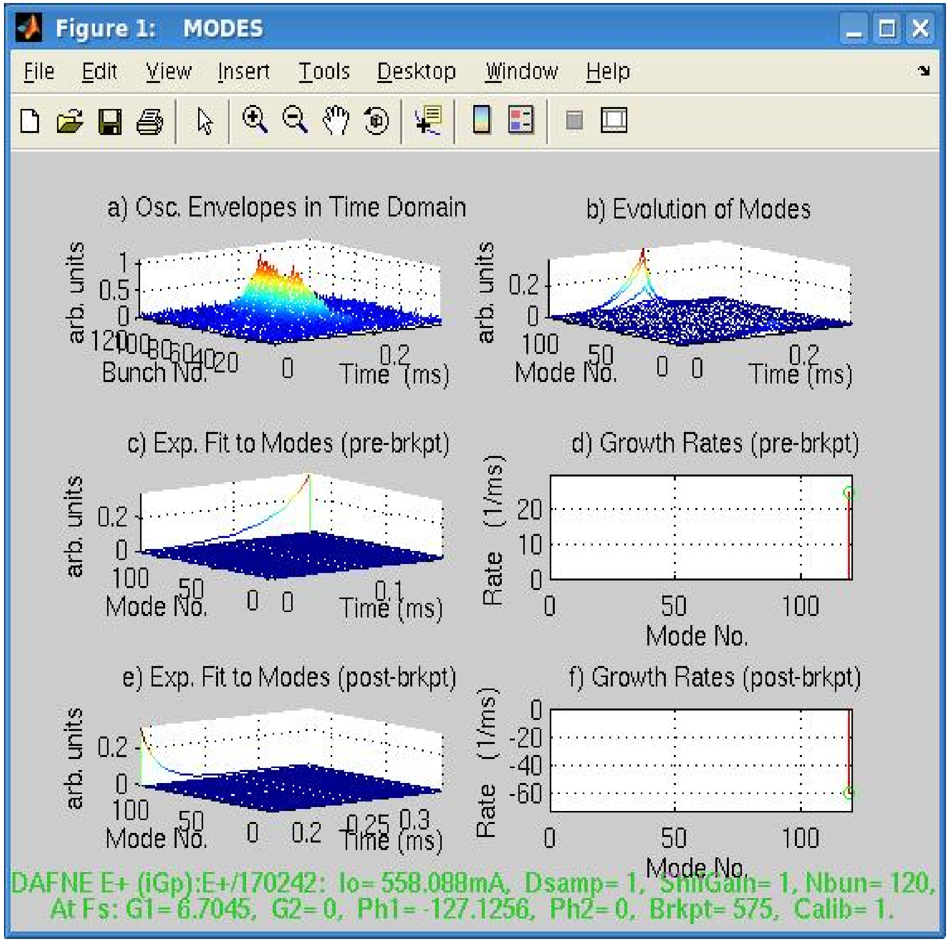
Guo, et al, PRST (2002).

Positron electron



Horizontal coupled bunch instability in DAFNE

M. Zobov, ECLOUD12



BEPC measurement is consistent with that of KEK-PF

Slowest mode of horizontal instability is observed in DAFNE.

Measurement in LHC

. Bartosik et al., ECloud'12

Observations with 25ns beam in the LHC

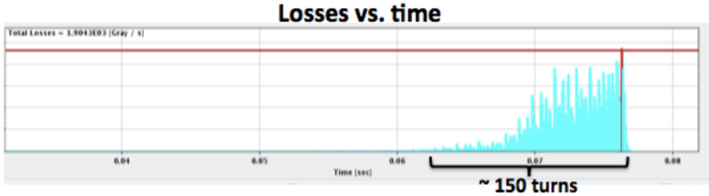
June 29th: **24 bunches: strong emittance growth, but no instability**

August 26th: **48 bunches on beam 2 with 1e11p/b and standard chromaticity ($Q'_x \approx Q'_y \approx 2$)**

- **Injection with transverse damper → dumped after ~1000 turns (beam excursion)**
- **Injection without transverse damper → dumped after ~500 turns (fast beam loss)**

} Suitable to benchmark simulation codes

Losses vs. time



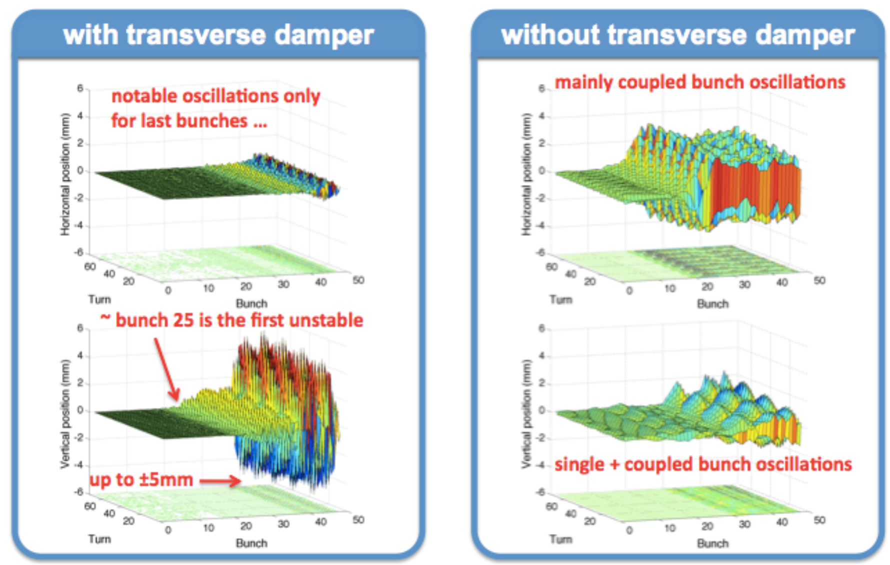
Further MDs in October: **up to 288 bunches injected**

- **high chromaticity ($Q'_x \approx Q'_y \approx 15$) needed for stabilizing the beam**
- **Clear signature of electron cloud effects: pressure rise, heat load, emittance growt the bunch train, losses …**

Beam dump has been observed at 25 ns spacing operation. The present physics run is adopted 50 ns spacing, while the design is 25 ns spacing.

Post mortem of the 2 beam dumps on August 26th

The ~last 73 turns before the beam dump are stored in the post mortem …

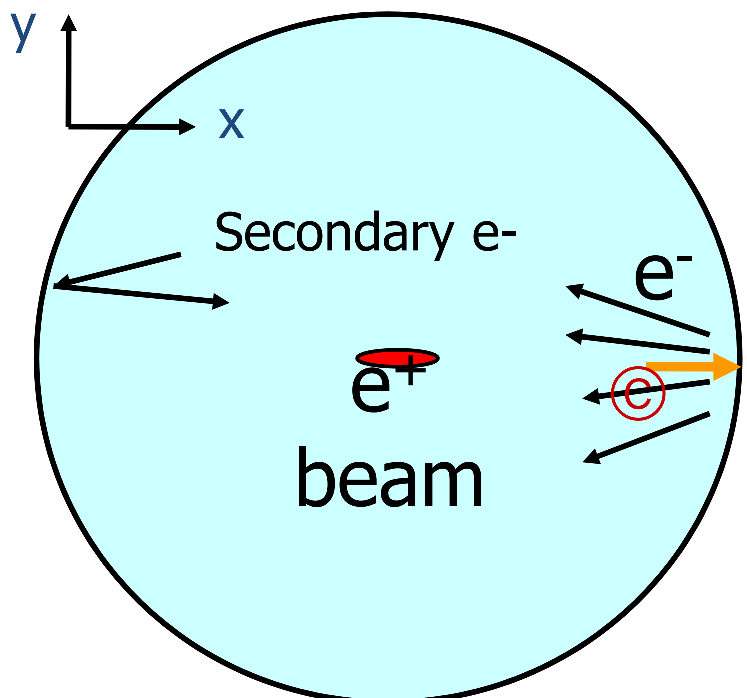


→ explains why 24 bunches could be injected and stored …

Horizontal coupled bunch and vertical single bunch instabilities are observed in LHC & SPS.

Simulation of Electron cloud build-up

Model



Beam chamber

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

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

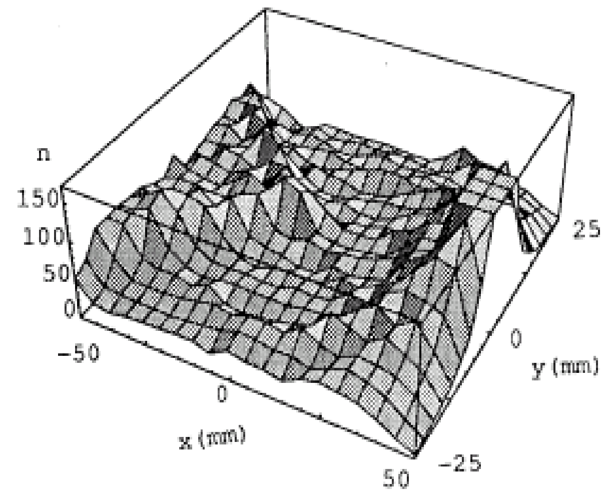


FIG. 2. A stationary distribution of photoelectrons with $\epsilon_0 = 5$ eV.

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 $2 \times 10^6\ cm^{-3}$. 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.

Simulation of coupled bunch instability

K.Ohmi, PRE55,7550 (1997)

K.Ohmi, PAC97, pp1667.

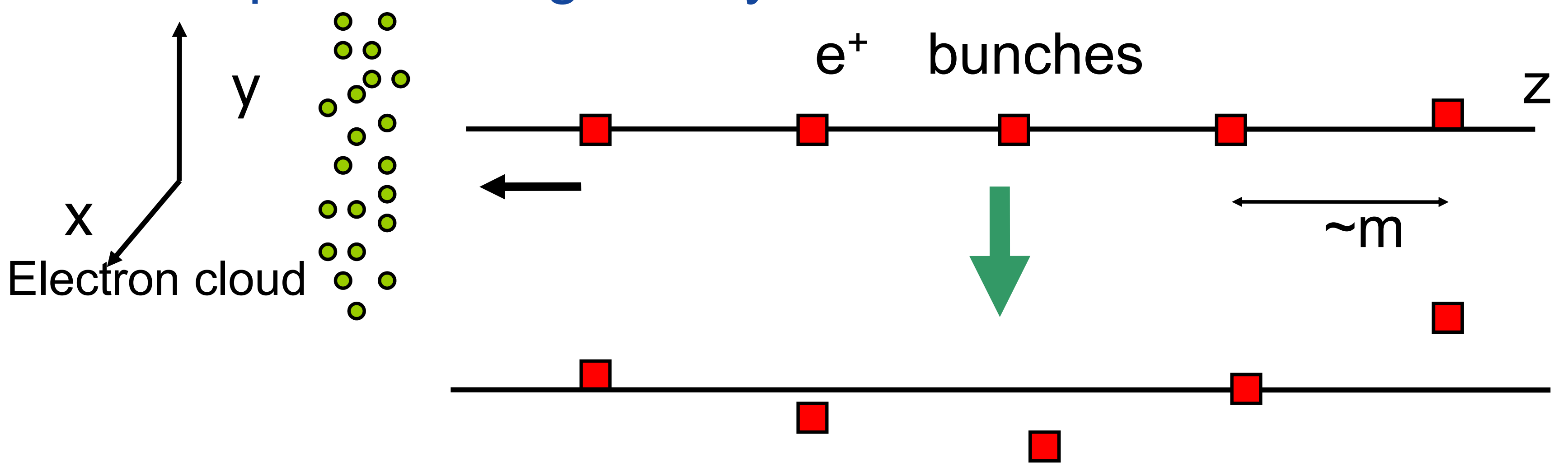
Solve both equations of beam and electrons simultaneously

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

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

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

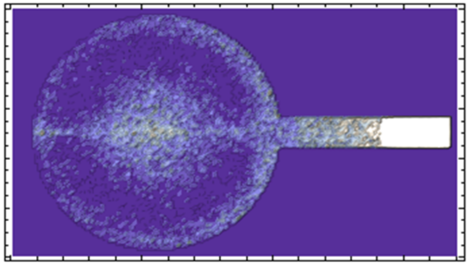
Mode spectrum is given by FFT of bunch motion



Electric(Magnetic) filed, Potential solver

- Beam-electron force
  1. Basetti-Erskine formula and mirror beam
  2. Poisson solver
- Electron space charge, 2D Poisson solver
  1. Solve Finite difference equation for cylindrical and rectangular chamber
  2. Finite Element Method for ante-chamber

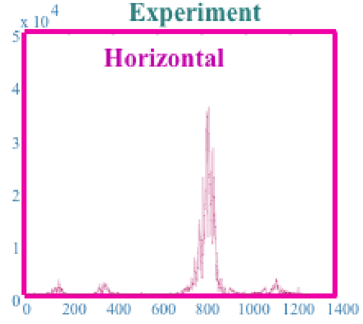
- No correlation of the electron distribution for s. Longitudinal velocity of electron is negligible for beam velocity.
- Electron distribution depends only on z=s-ct.
- In 3D simulation, boundary condition for s is ambiguous.

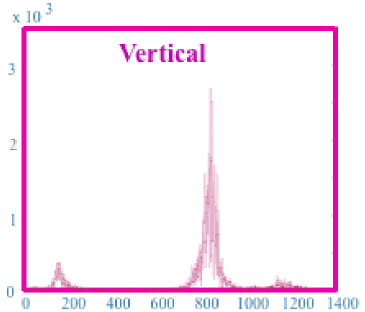


Measurement in KEKB

CBI mode spectra in KEKB Solenoid-Off

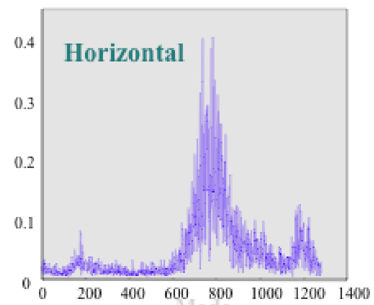
Experiment

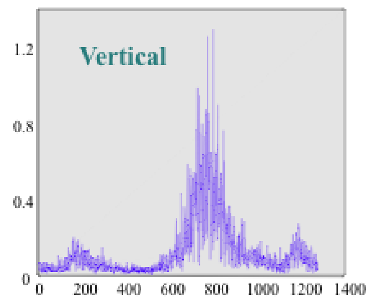




Bunches are filled every 4 bucket.

Simulation





Su Su Win et al,(EC200

Solenoid ON

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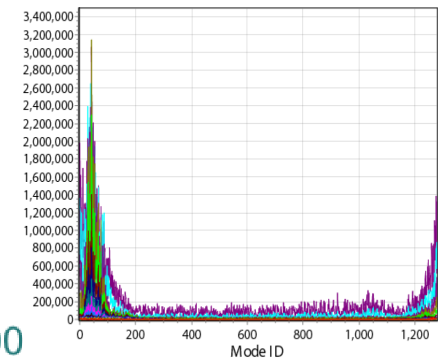
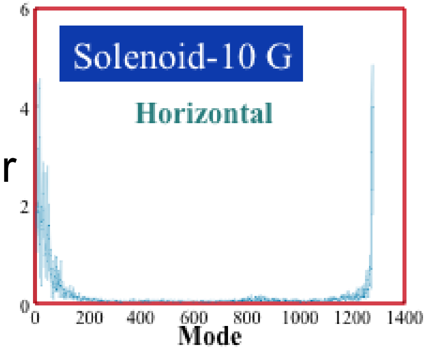
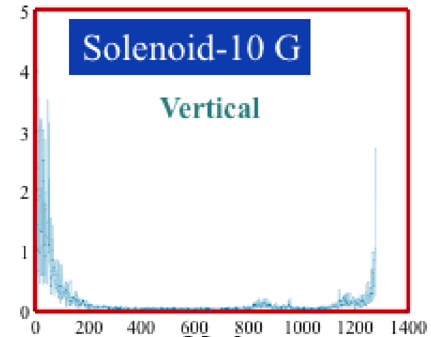
measurement



Simulation

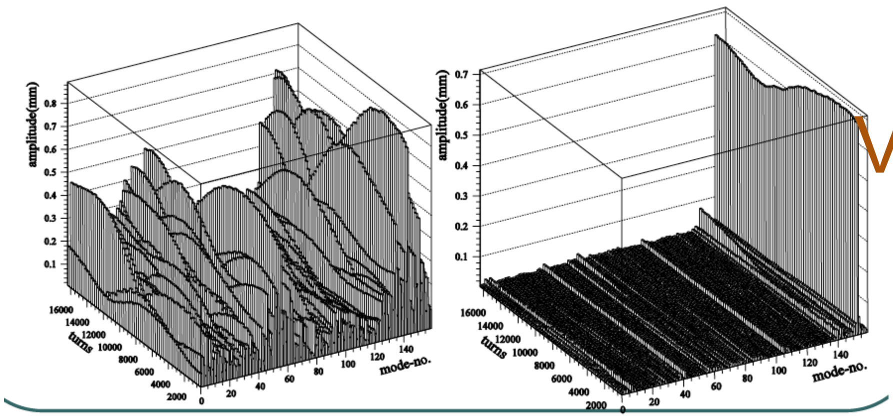




Solenoid is installed to protects electron cloud near the beam. The mode of the coupled bunch instability depends on the solenoid ON/OFF.

Measurement and simulation for BEPC

Positron electron

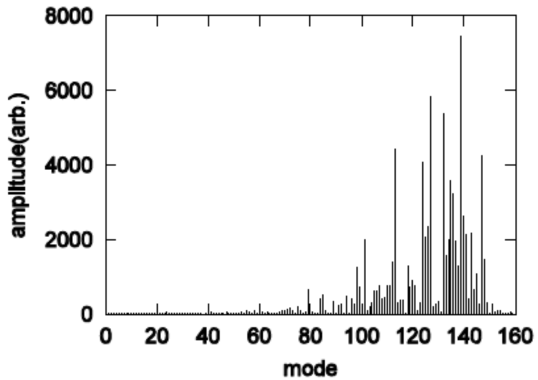


Guo, et al, PRST (2002).

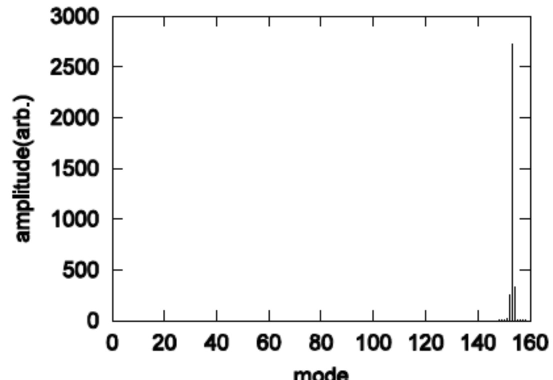
Vertical instability was observed.

- Mode spectra for electron cloud and ion instabilities

Positron



electron

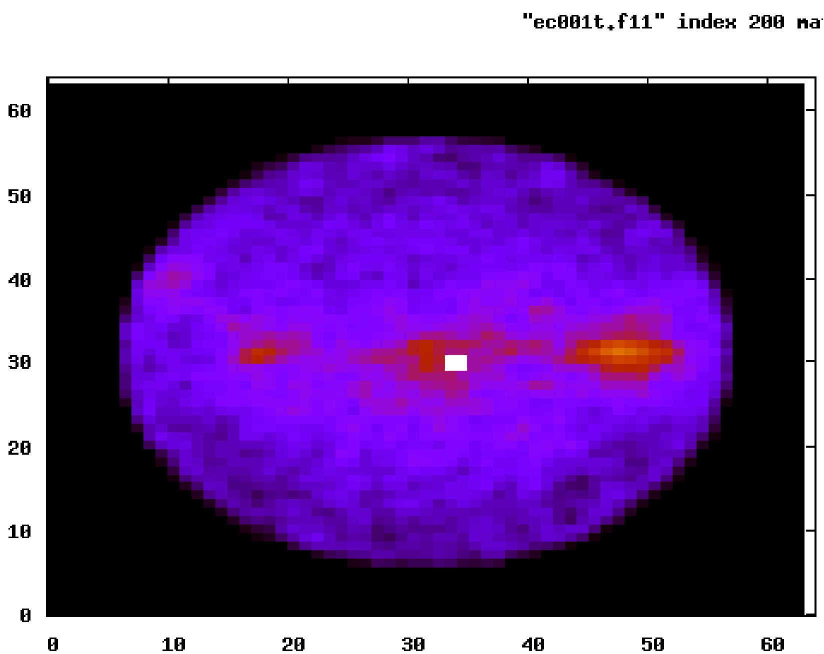


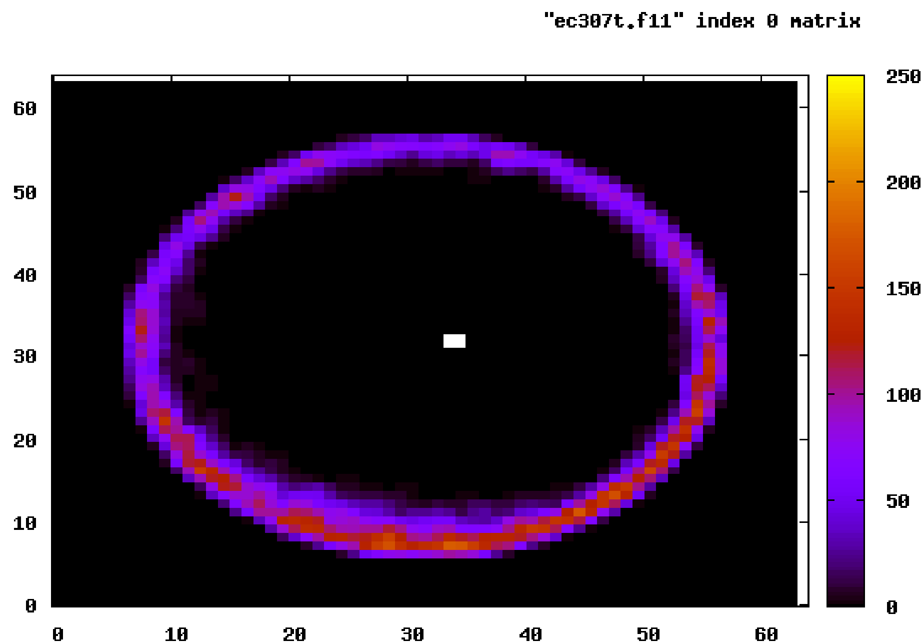
FFT of y_p

Electron distribution and Coupled bunch motion

- Drift Solenoid

White point: beam position passing through the chamber

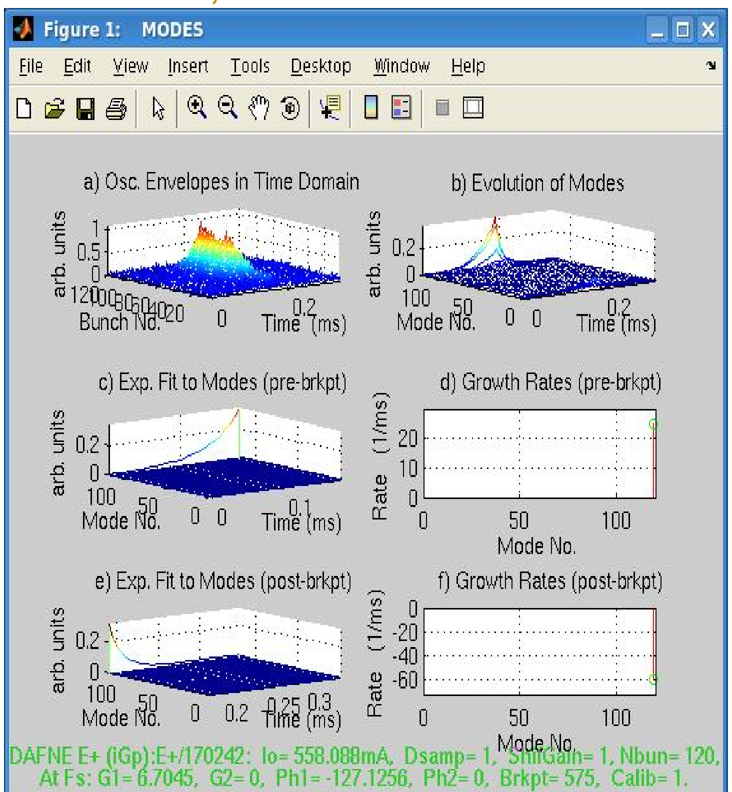




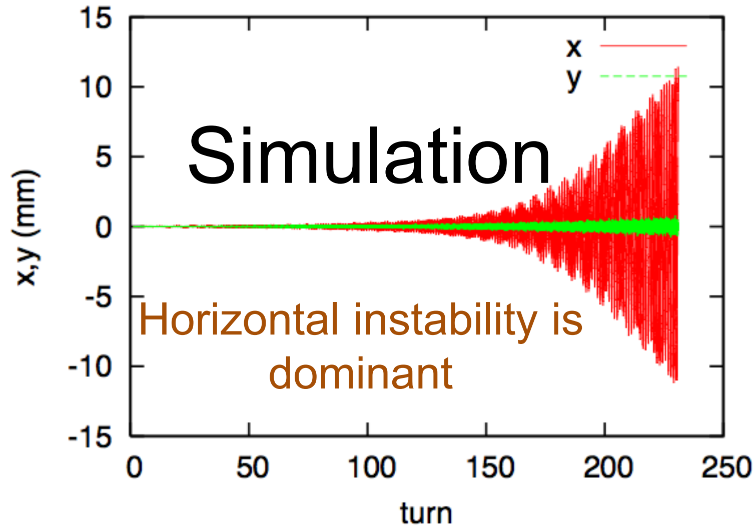
Coupled bunch instability due to electron cloud in bending field

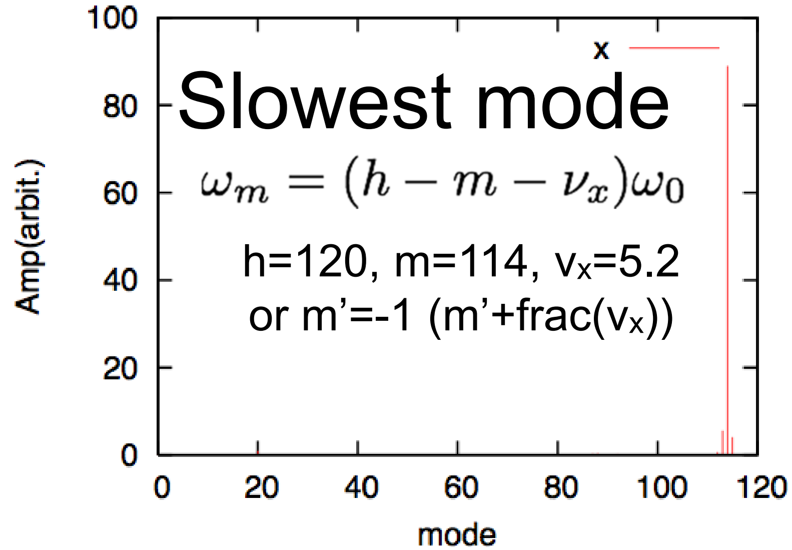
Measurement in DAFNE

M. Zobov, ECLOUD12



Horizontal coupled bunch instability

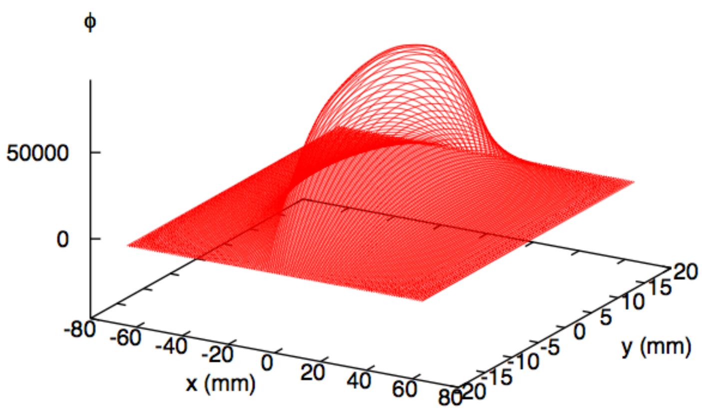


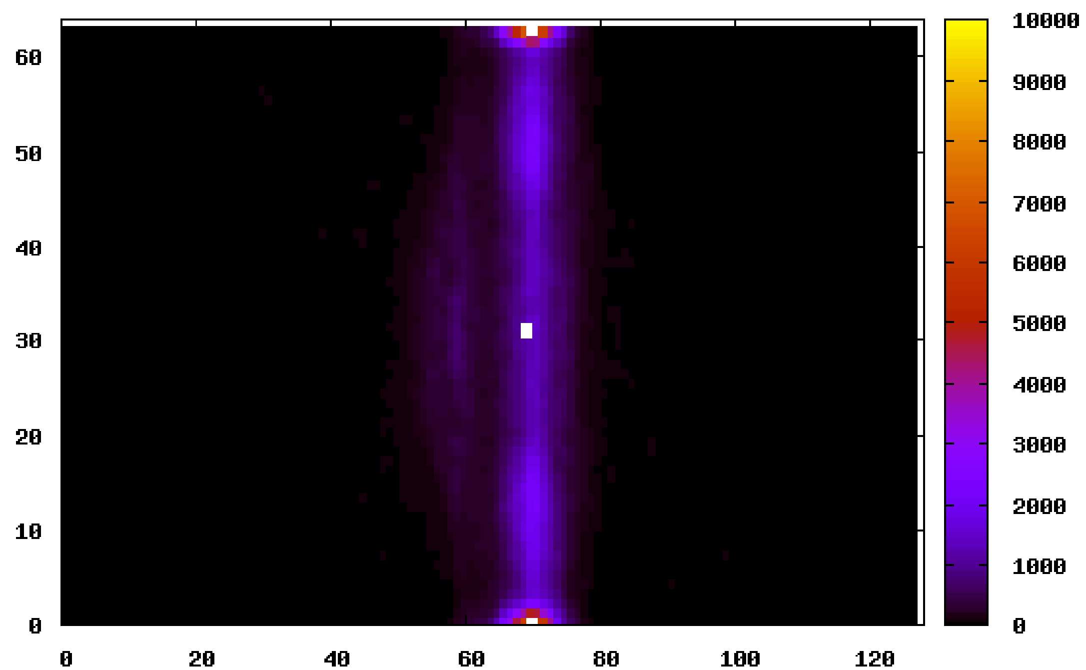


Coherent motion of beam and electron stripe

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

Electron potential



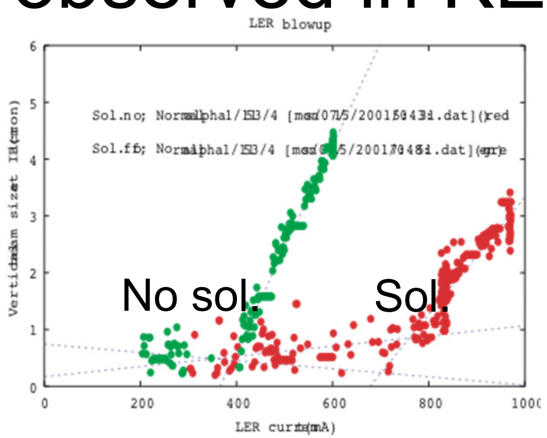


Part II
Single bunch instability due to electron cloud

PEHT & PEHTS

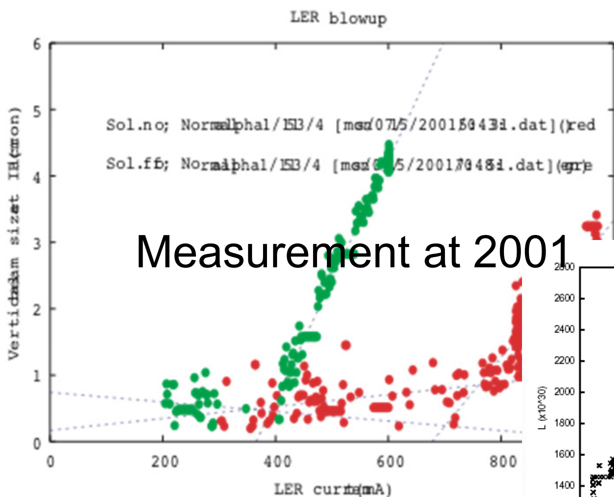
The same purpose code: HEADTAIL, C-MAD, WARP...

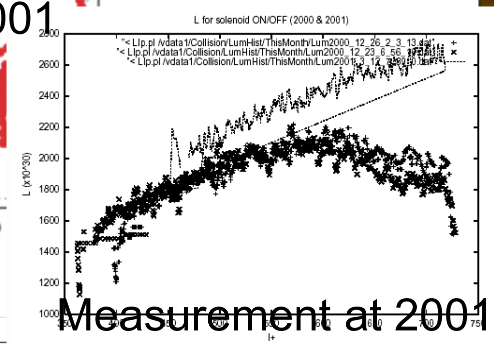
- Simulation of Fast head-tail instability caused by electron cloud
- Incoherent emittance growth using PEHTS
- Purpose: to explain beam size blow up observed in KEKB.

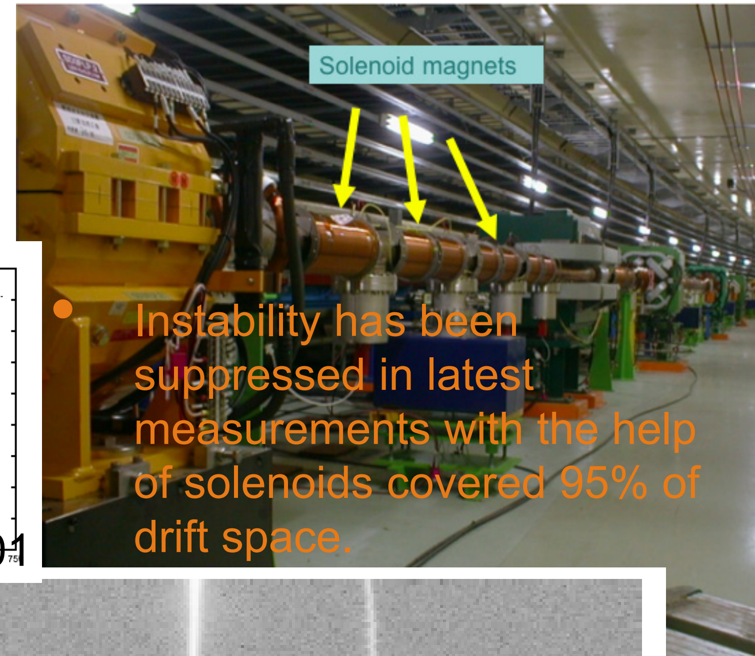


Fukuma et al. measurement at 2001

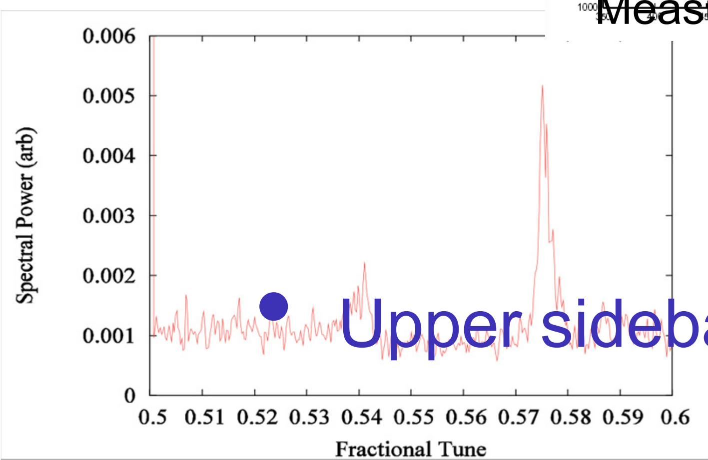
Observations in KEKB







- Instability has been suppressed in latest measurements with the help of solenoids covered 95% of drift space.



- Upper sideband $\nu_y + a\nu_s$ $(1<a<2)$ is seen.

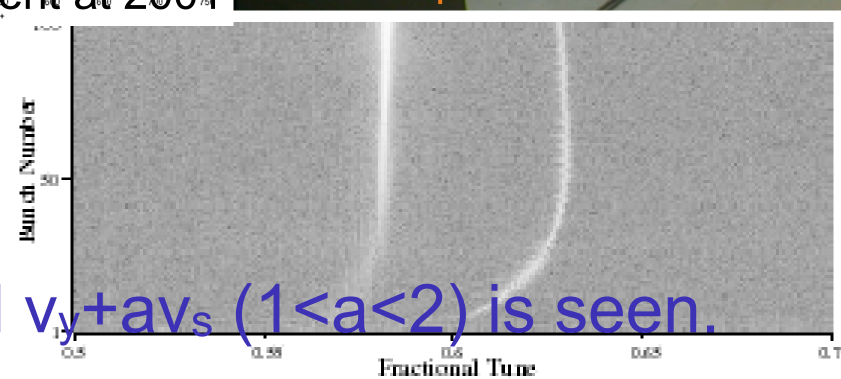
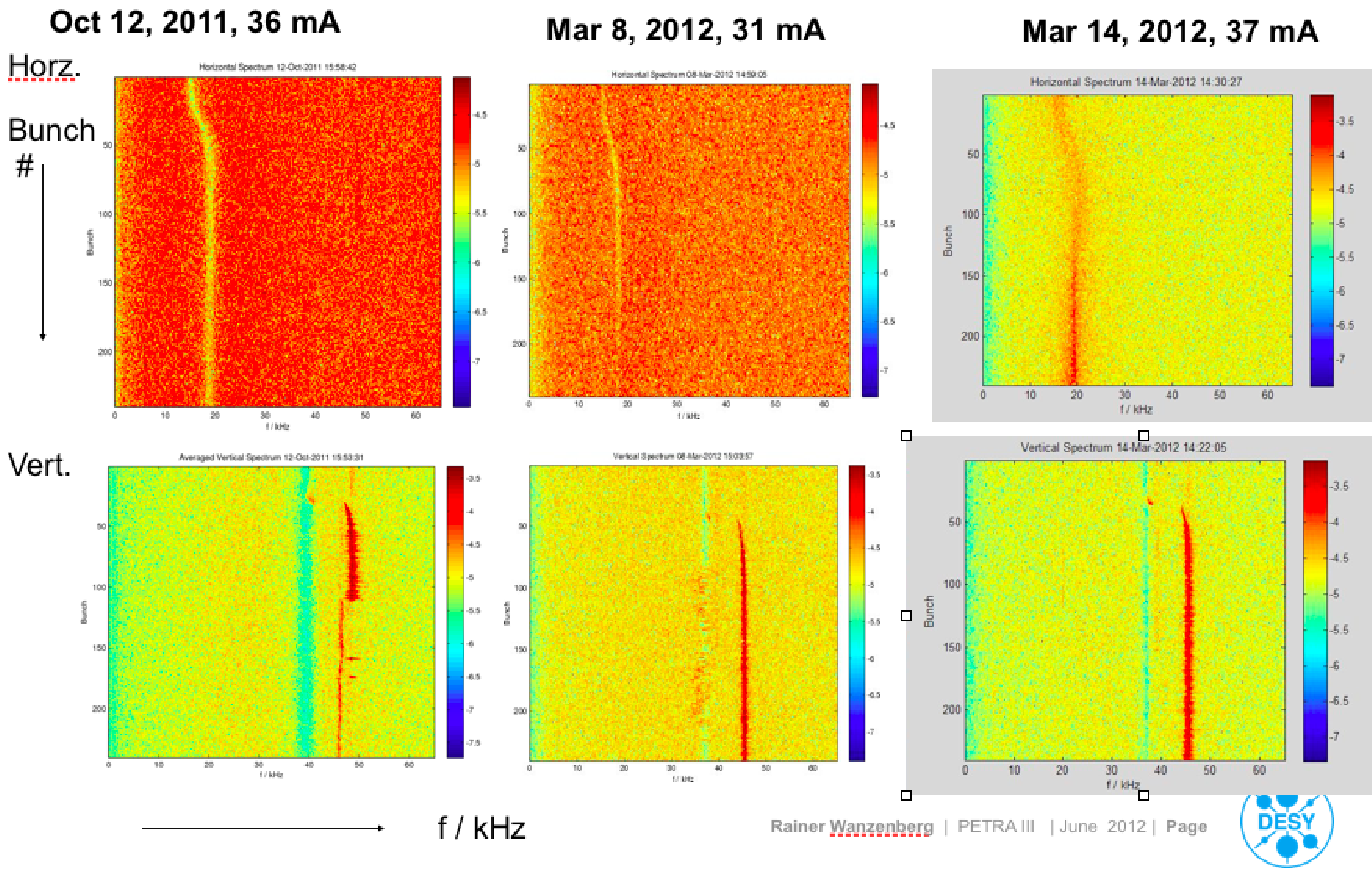


FIG. 1. Two-dimensional plot of vertical bunch spectrum versus bunch number. The horizontal axis is the fractional tune, from 0.5 on the left edge to 0.7 on the right edge. The vertical axis is the bunch number in the train, from 1 on the bottom edge to 100 on the top edge. The bunches in the train are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

Observations in PETRA III

R. Wanzenberg, ECLOUD12

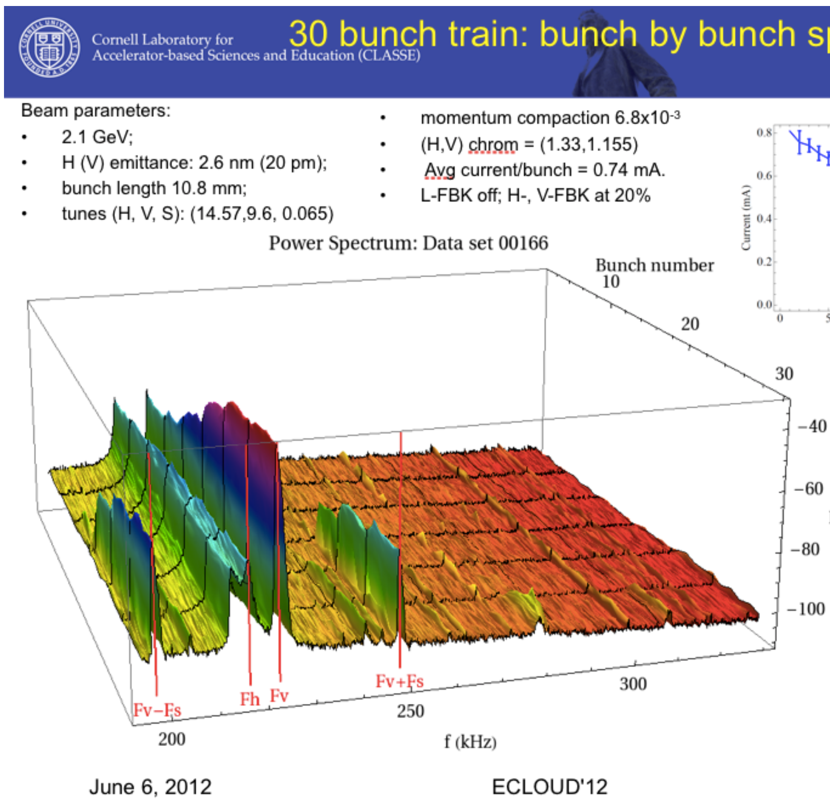
240 bunches (8 ns bunch spacing) ε_y=5pm->100pm

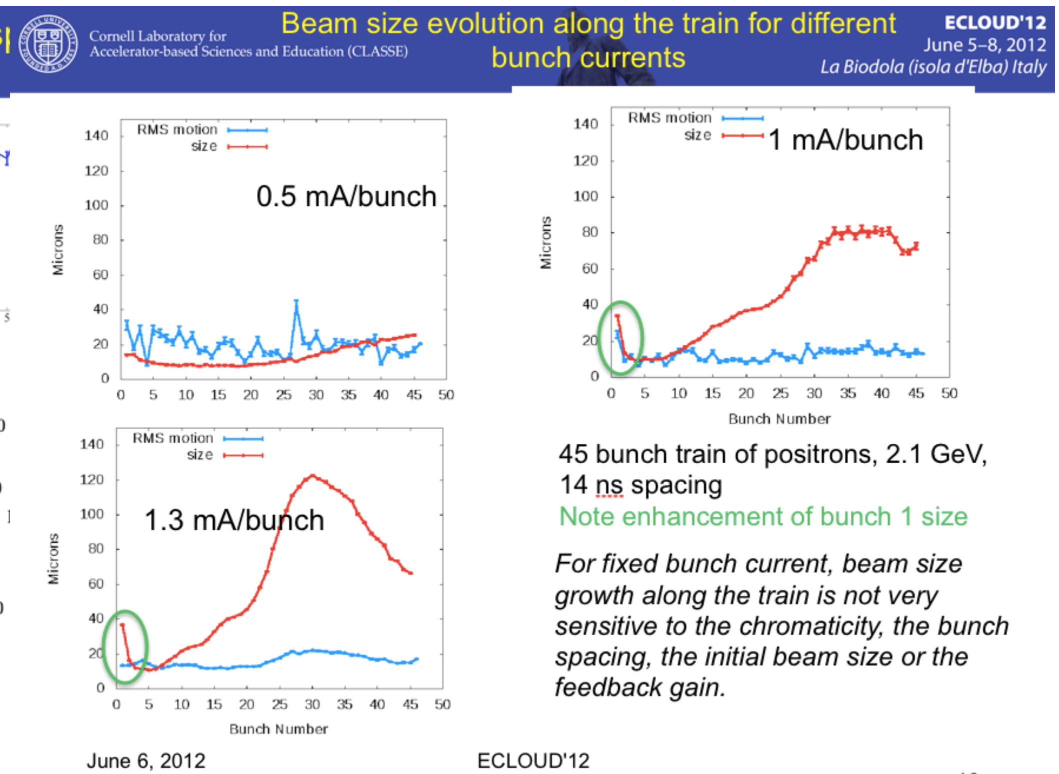


- Upper sideband $\nu_y + a\nu_s$ (1<a<2) is seen like KEKB.

Observations in CesrTA

G. Dugan, ECLOUD12



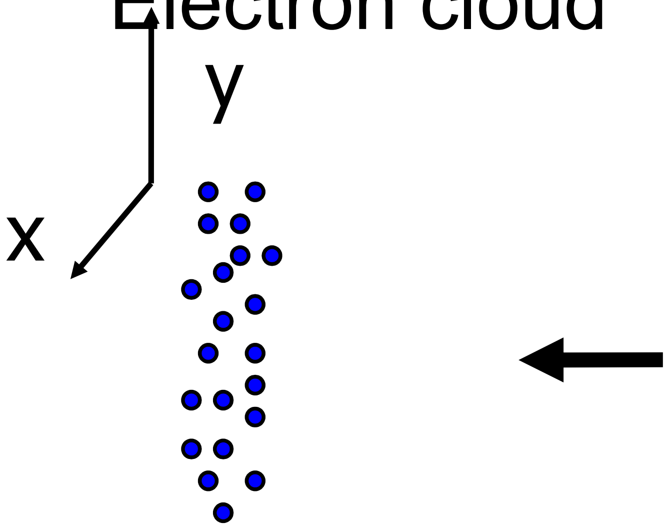


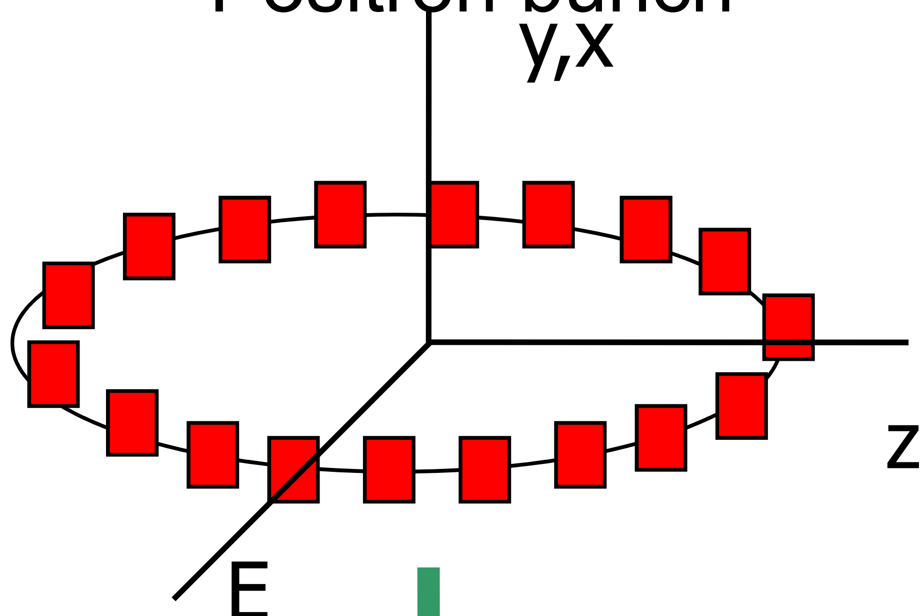
- Lower sideband ν_y-$a\nu_s$ (a~1) is seen contrast with KEKB and PETRA III.

Simple modeling (PEHT code)

Simulation using Gaussian micro-bunch model

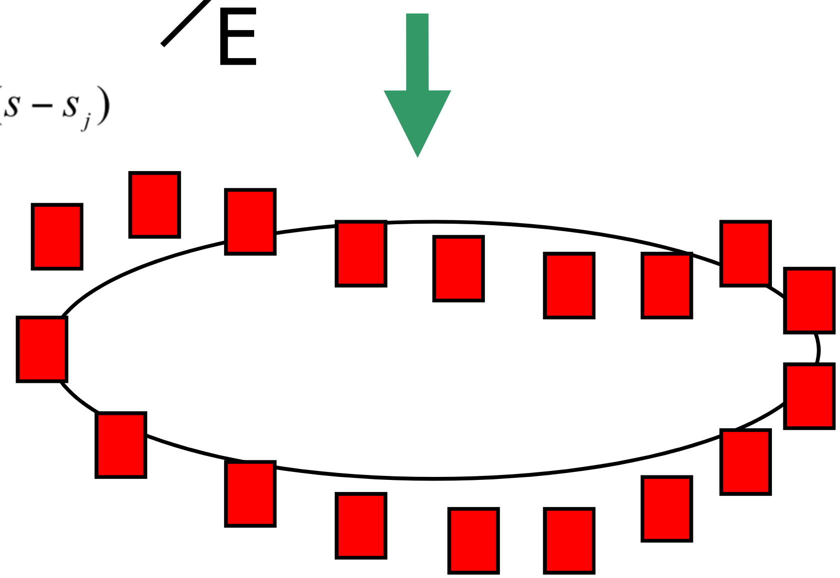
- Electron cloud Positron bunch





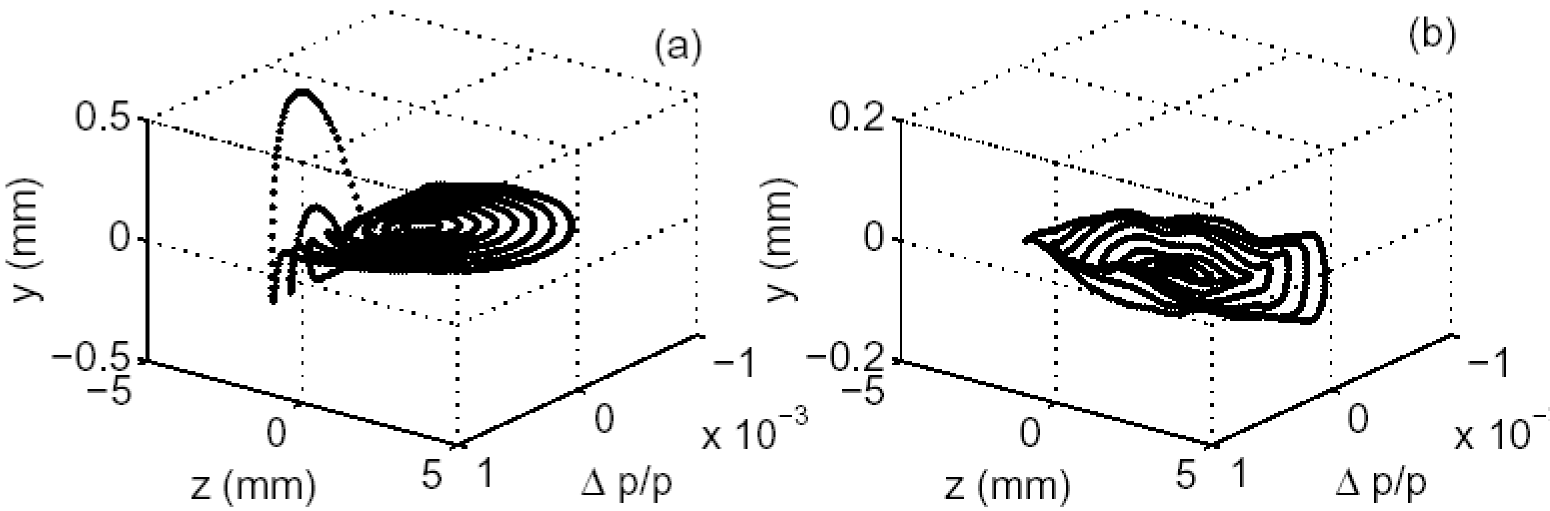
$$\frac{d^2\mathbf{x}_{+,a}}{ds^2} + K(s)\mathbf{x}_{+,a} = \frac{2r_e}{\gamma}\sum_{j=1}^{N_i}\mathbf{F}_G(\mathbf{x}_{+,a} - \mathbf{x}_{e,j};\sigma(s))\delta(s - s_j)$$

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



PEHT results

- Bunch head-tail motion w/wo synchrotron

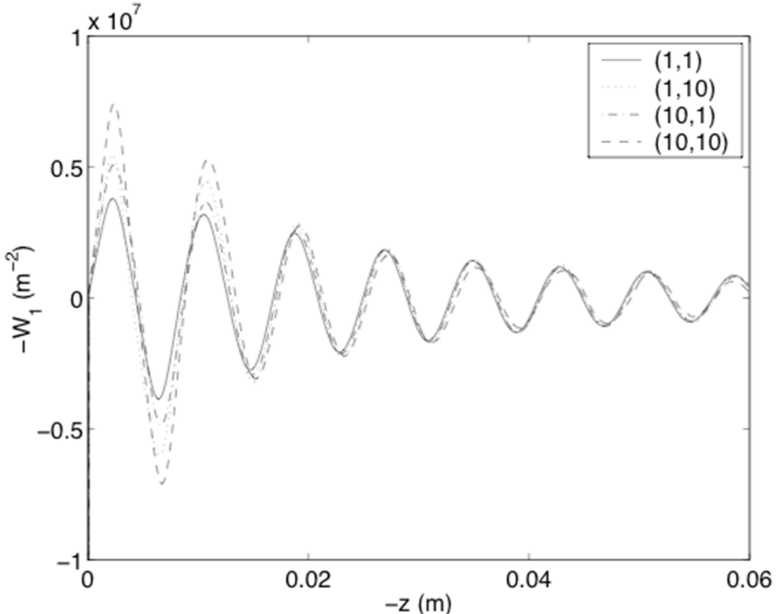


Vertical amplitude of the macro-particles in the longitudinal phase space are plotted. Multi-airbag model (z-™) is used to visualize in these figures.

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)

PIC code (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.

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)

Simulation (PEHTS)

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

Betatron sideband

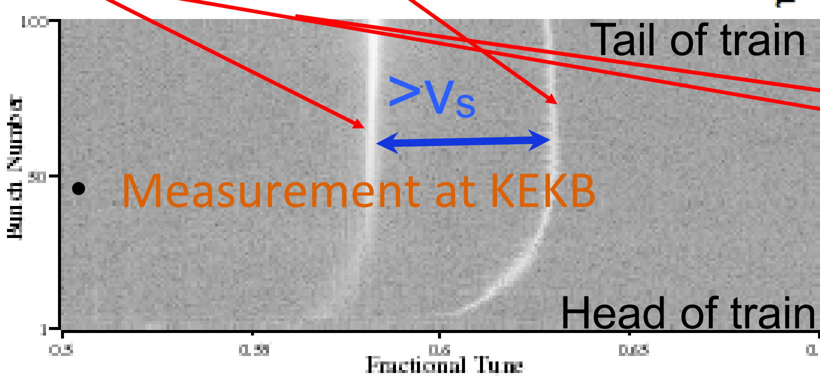
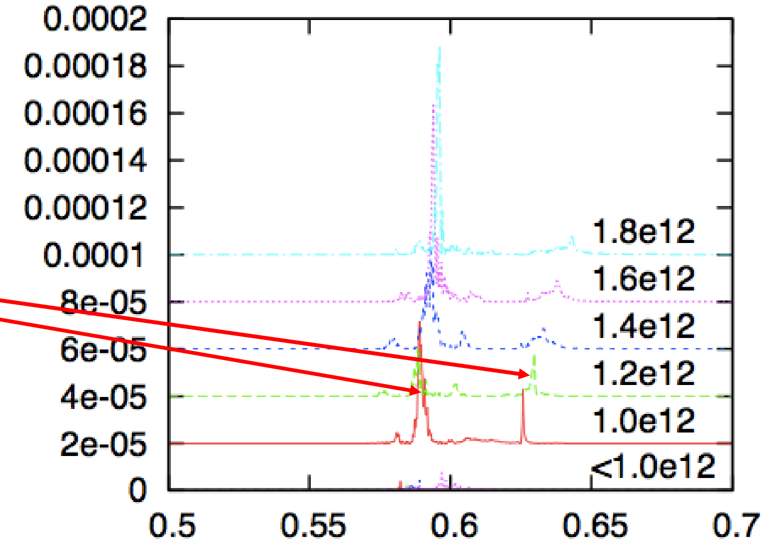
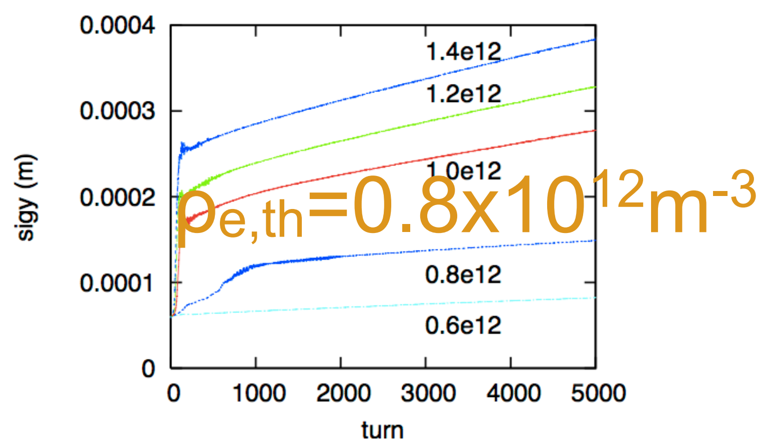


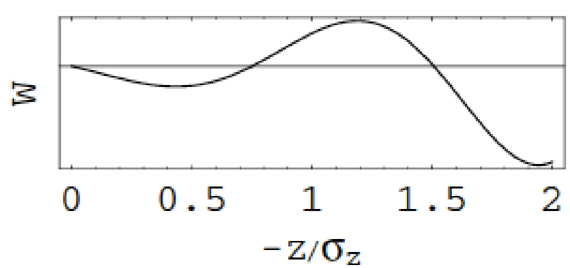
FIG. 1. Two-dimensional plot of vertical bunch spectrum versus bunch number. The horizontal axis is the fractional tune, from 0.5 on the left edge to 0.7 on the right edge. The vertical axis is the bunch number in the train, from 1 on the bottom edge to 100 on the top edge. The bunches in the train are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





Possible explanation for the sideband

Electron pinching may enlarge the wake field strength.



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

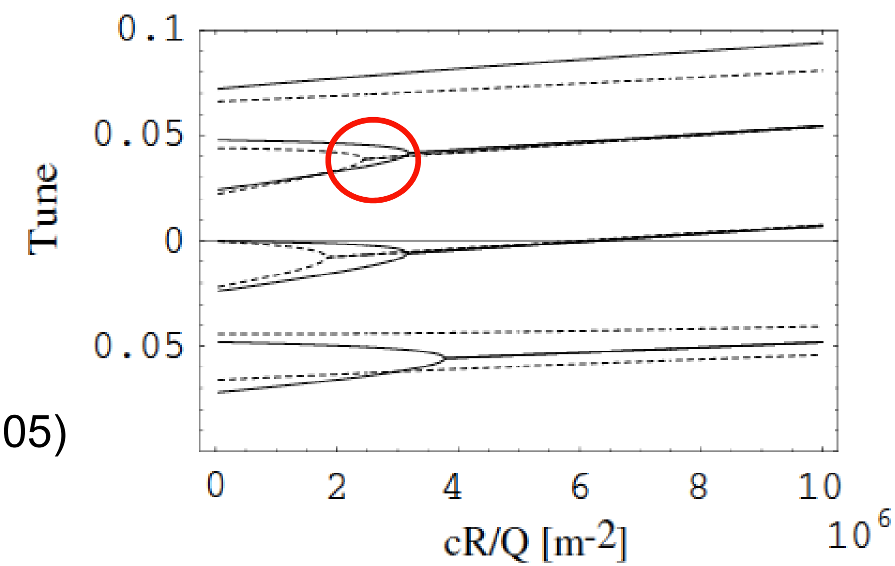


FIG. 6. Example mode spectrum for model focusing wake at $\nu_s = 0.022$ (dashed lines) and $\nu_s = 0.024$ (solid lines).

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.

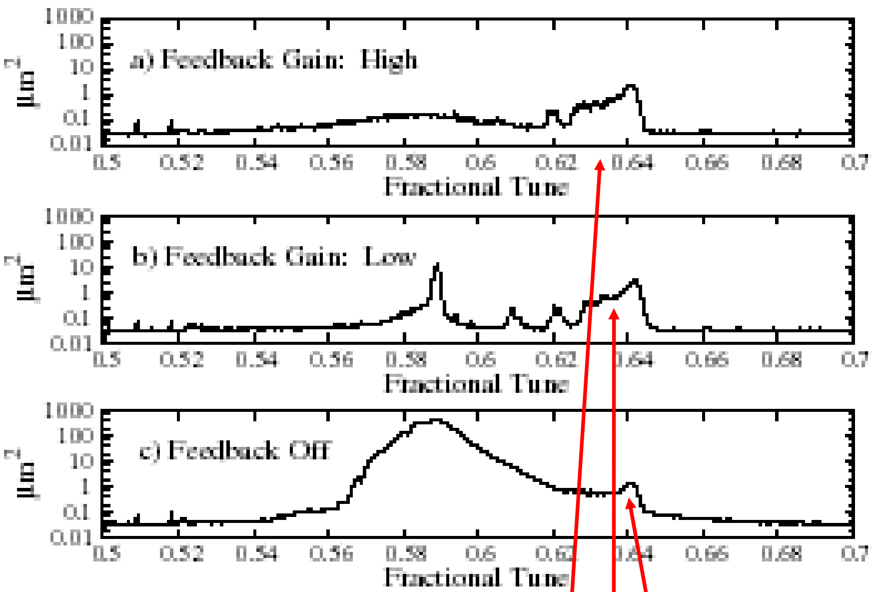
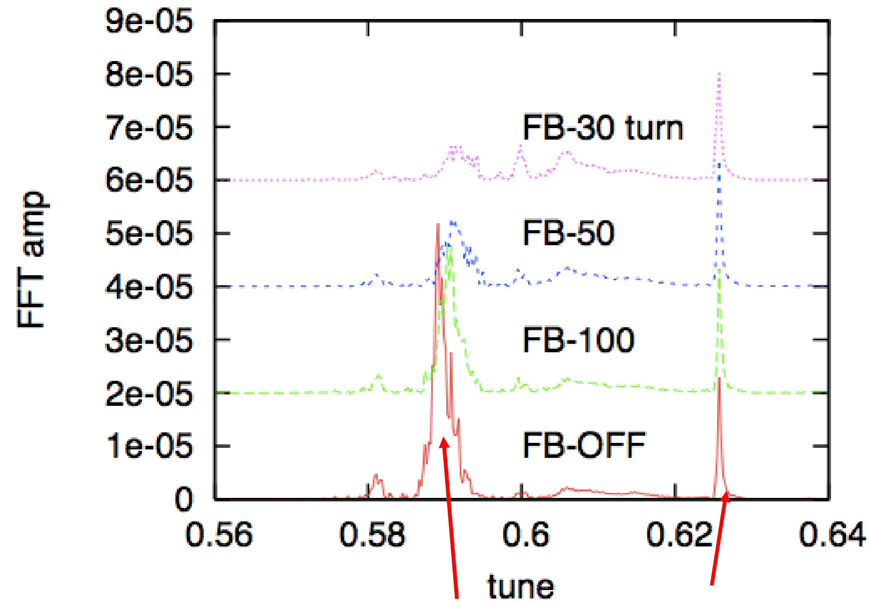


FIG. 2. Averaged spectra of all bunches with the feedback gain (a) high, (b) low, and (c) set to zero. The vertical betatron peak is visible at 0.588, and the sideband peak can be seen around 0.64.



Betatron sideband

Simulation (PEHTS)

Sideband signal is Integrated over the train

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.
- Horizontal coupled bunch instability in DAFNE is reproduce by a simulation. Instability in SPS and LHC will be reproduced
- Simulations and theory explained the phenomena. The agreement is good.
- 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 ....

Thank you for your attention