Experimental Study of Fast Beam-Ion Instability at PLS

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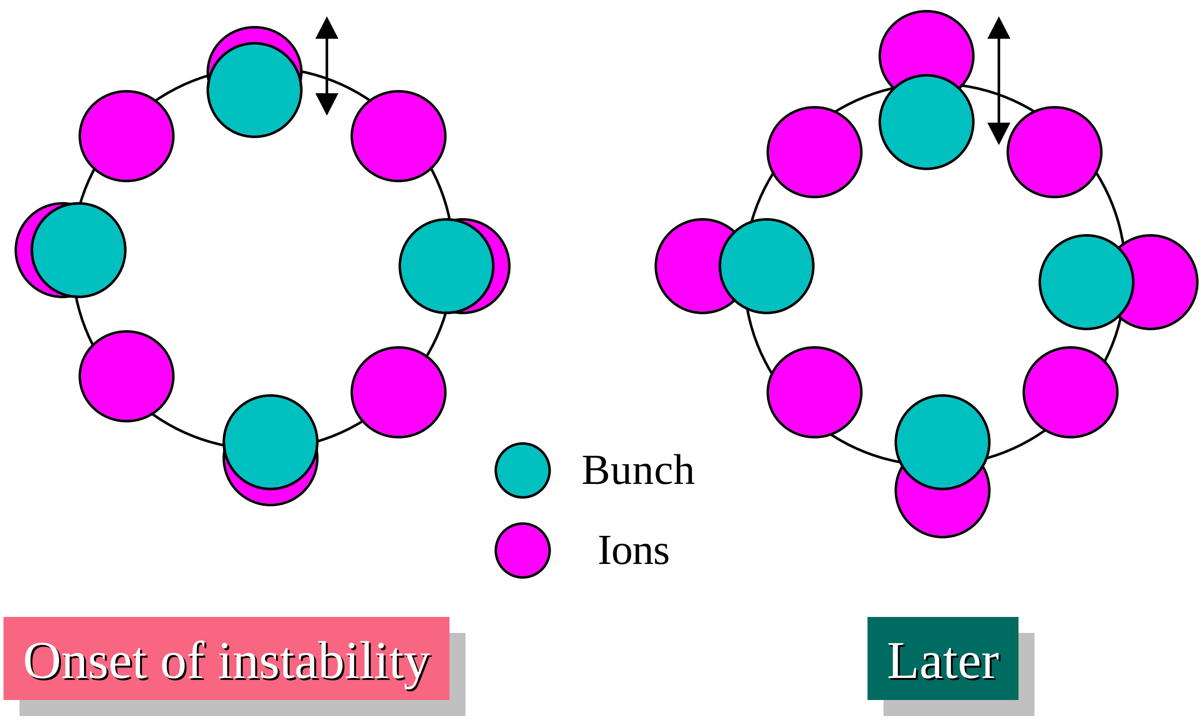
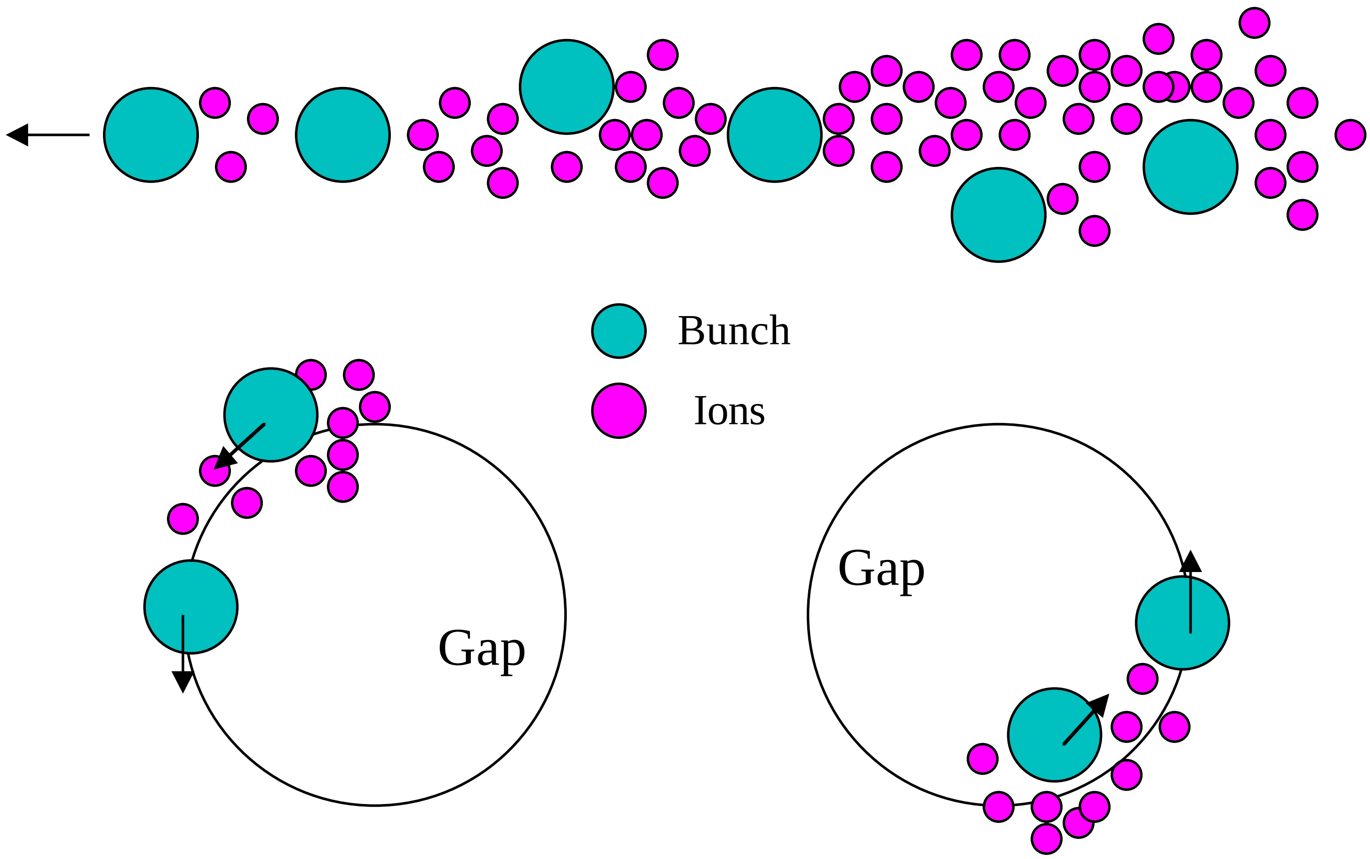
Introduction

- Ion-related instabilities at electron rings
  - Ion trapping
  - Fast Beam-Ion Instability (FBII)
- Ion trapping
  - Uniform filling of a beam
  - No clearing of ions (saturation of ion population)
  - Stationary state (even though unstable)
  - Existence of threshold for onset of instability
  - Narrow-band spectrum



- (Transient) Fast Beam-Ion Instability
  - Ions are cleared out by a gap
  - Transient (single pass) phenomenon
  - Broad-band spectrum



At one moment

A half turn later

Trapping Condition

- Ion oscillation frequency

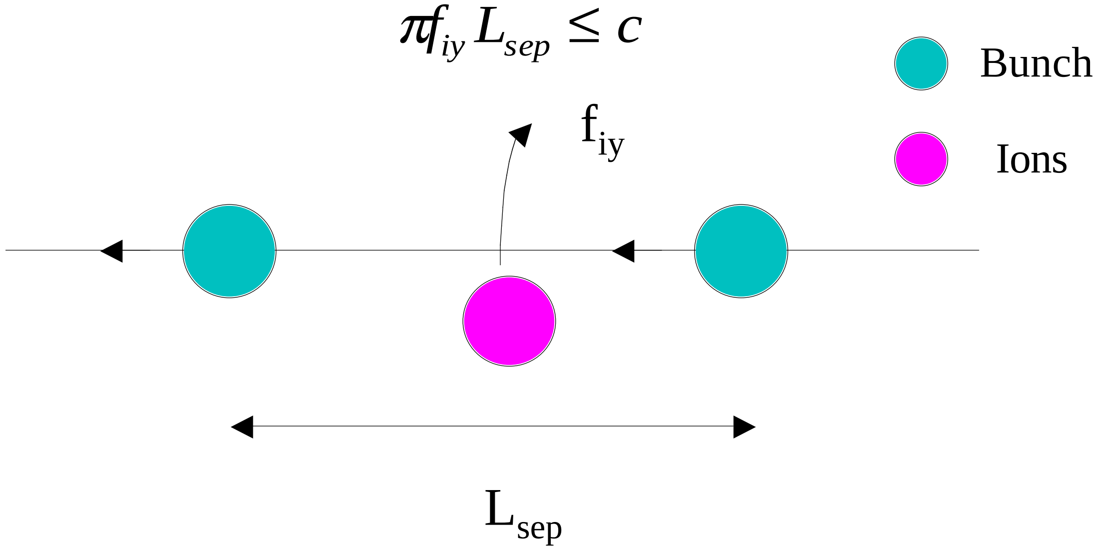
$$f_{iy} = \frac{c}{2\pi}\sqrt{\frac{4Nr_p}{3L_{sep}\sigma_y(\sigma_x+\sigma_y)A}}$$

where

- N=number of particles in a bunch
- L_{sep}=distance between bunches
- σ_x, σ_y=horizontal and vertical beam sizes
- r_p=classical proton radius

- Ions can be trapped within a bunch train if

$$\pi f_{iy} L_{sep} \le c$$



Rise-time Formula for FBII

- Modified linear theory (Stupakov, Zimmerman)

$$y \approx \exp(t / \tau_e)$$

$$\frac{1}{\tau_e} = \frac{1}{\tau_c} \cdot \frac{c}{2\sqrt{2}\, l_{train}\, \Delta\omega_i^{rms}}$$

where

$$\frac{1}{\tau_c} = \sqrt{\frac{2m_e}{m_N}}\, \frac{\beta_y L_{sep}^{1/2}}{c\gamma}\, \frac{n_g \sigma_i}{\sqrt{A}}\, \left(\frac{2r_e zN}{3\sigma_y \sigma_x}\right)^{3/2} n^2$$

Here,

- m_e, m_N=electron and nucleon masses
- β_y=average beta-function
- γ=gamma factor
- r_e=classical electron radius
- z, A=electrovalence and mass number of ion
- n=number of bunches
- n_g=residual gas density
- σ_i=ionization cross-section
- l_{train}=length of a bunch train
- $\Delta\omega_i$=spread in ion frequency

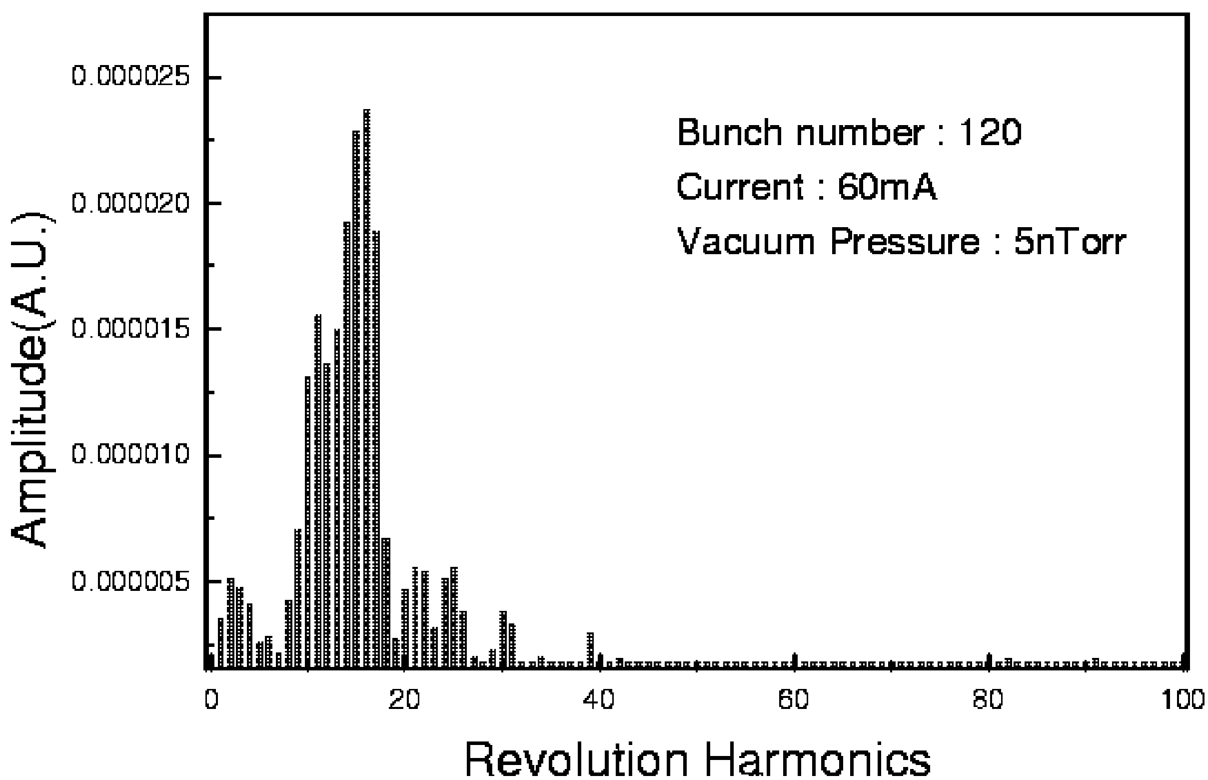
Summary of the 2nd Experiment

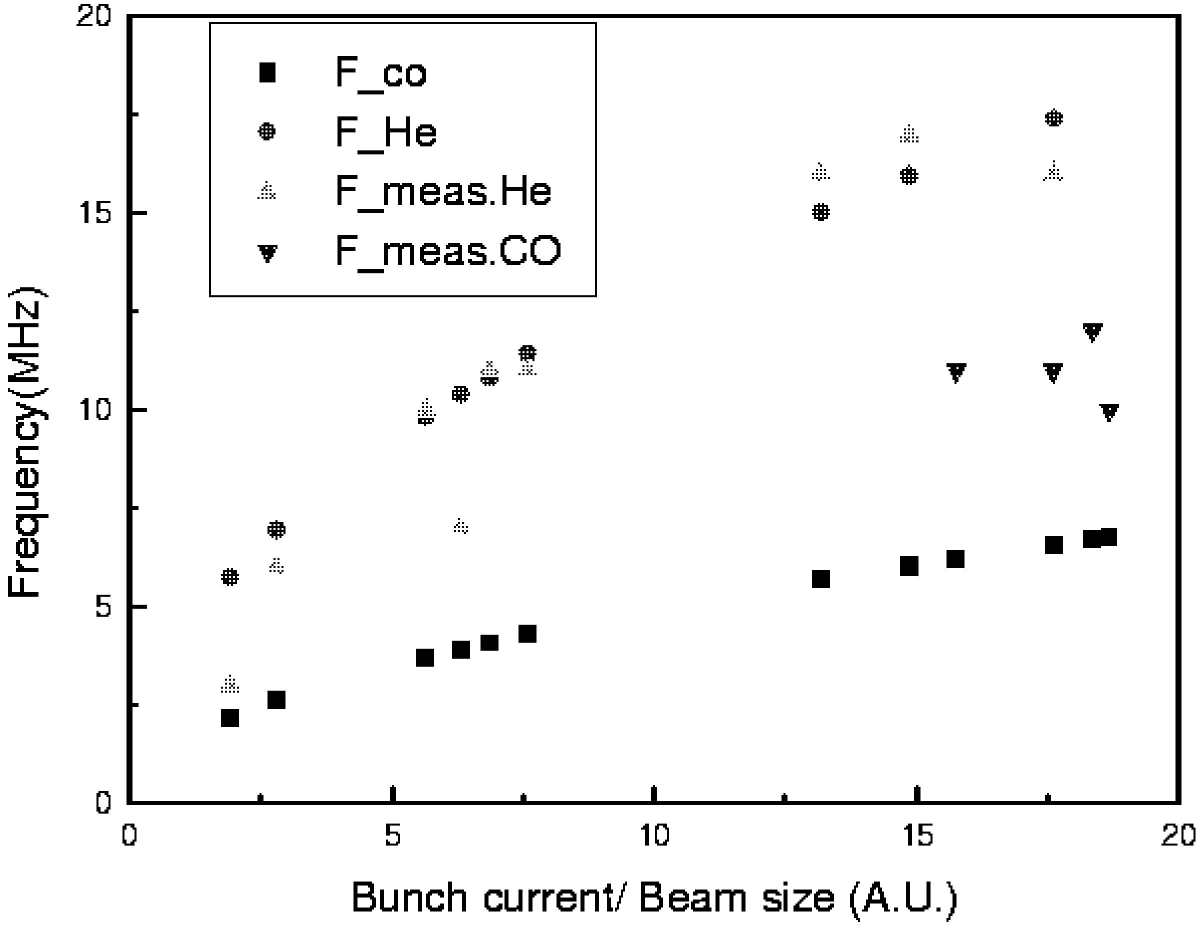
- The 2nd experiment on FBII has been conducted on June 26 - 29, 1997 at PLS
  - Participants:
    - KEK: Y. H. Chin , H. Fukuma, M. Isawa, K. Ohmi, M. Tobiyama
    - PAL: M. Kwon, J. Y. Huang, and T.Y. Lee, J. W. Lee, M. K. Park, H. J. Park, C. D. Park, I. S. Ko
- PLS (Pohang Light Source in Korea) parameters
  - E=2.0GeV
  - C=280.56m
  - TBA lattice
  - h=468 (f_{RF}=500.082MHz)
  - L_{sep}=2ns
  - I_{max}=440mA
  - ε_x=12.1 nm
  - ε_y=0.12 nm
  - σ_x=0.35mm
  - σ_y=0.035mm
  - Q_x=14.28
  - Q_y=8.18

- Spectrum analysis
  - Clear ion peaks are visible even at normal pressure.
  - The He gas injection enhances the spectrum amplitude
    - Most of measurement have been done at P=5nTorr with He.
  - The frequency of He peak scales with the bunch current/beam size in a good agreement with calculated ion frequency.
  - Peaks disappeared when the beam size was doubled.

Conclusion 1

Observed vertical beam oscillations are indeed due to interaction with ions.


Bunch number : 120
Current : 60mA
Vacuum Pressure : 5nTorr
Amplitude(A.U.)
0.000025
0.000020
0.000015
0.000010
0.000005
0
20
40
60
80
100
Revolution Harmonics



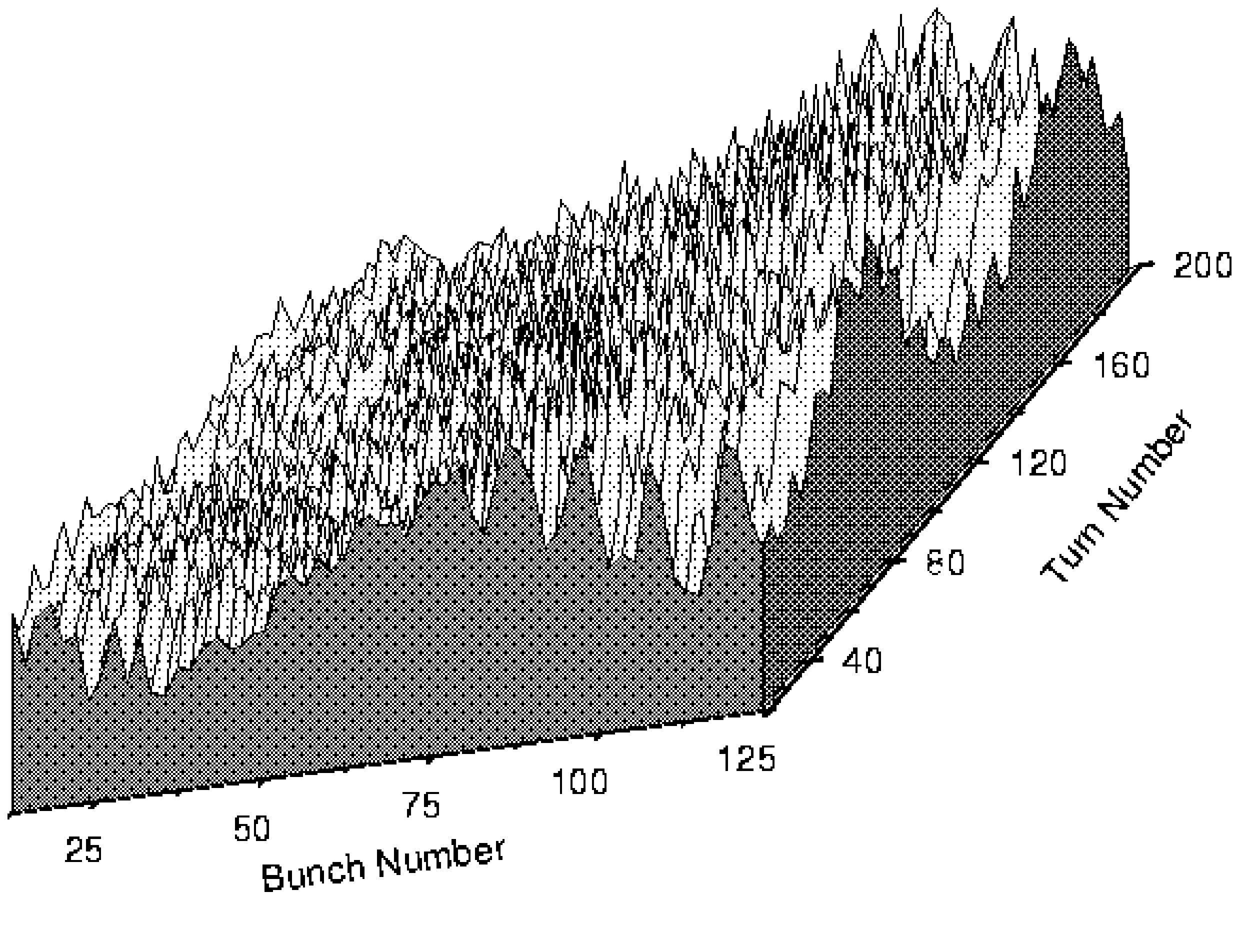
F_co
F_He
F_meas.He
F_meas.CO
Frequency(MHz)
Bunch current/ Beam size (A.U.)
0
5
10
15
20

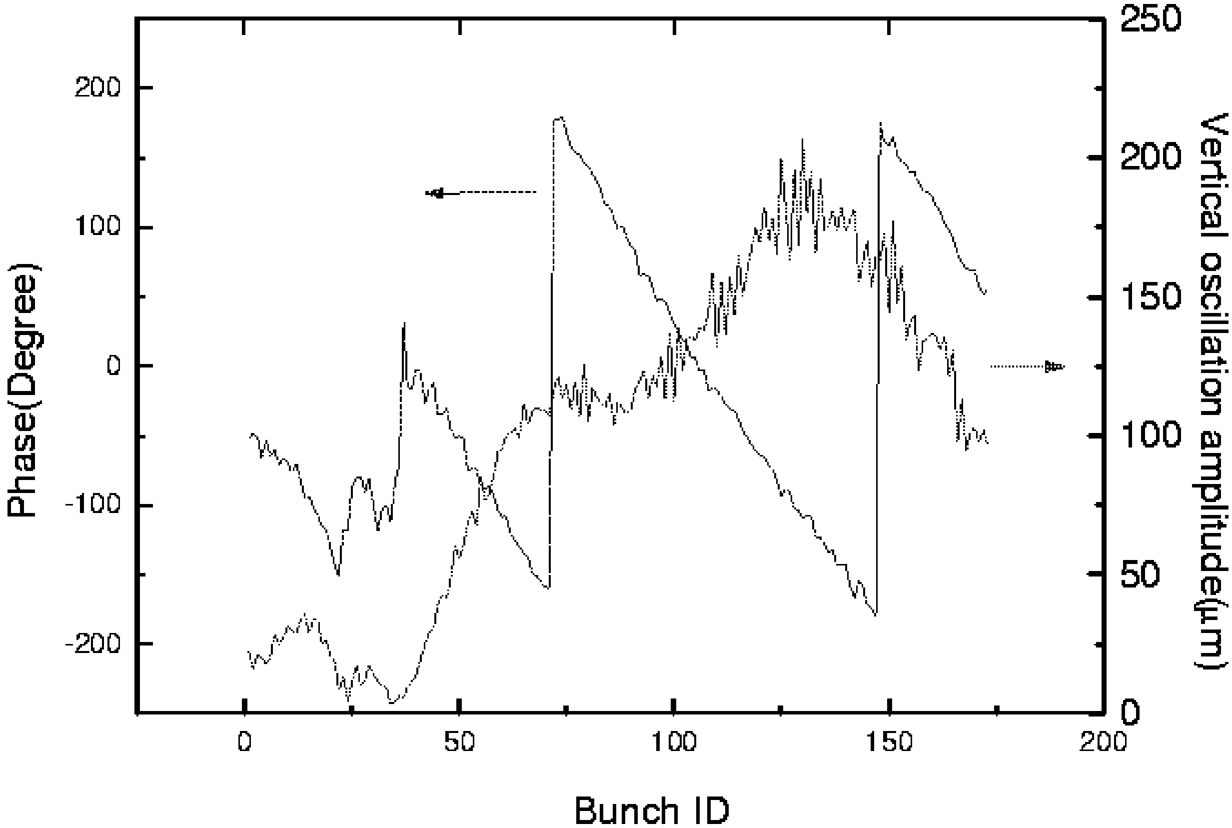
- Bunch oscillation analysis
  - at 180 bunches, 90mA and P=5nTorr

- The oscillation amplitude grows toward the tail of bunch train.
- The maximum oscillation amplitude is about 200mm
- The oscillation phase decreases toward the tail of bunch train (4π rad)
- The simulation result with the increased vertical beam size shows also about 2 oscillations along the bunch train, in a reasonable agreement with the above measurement.

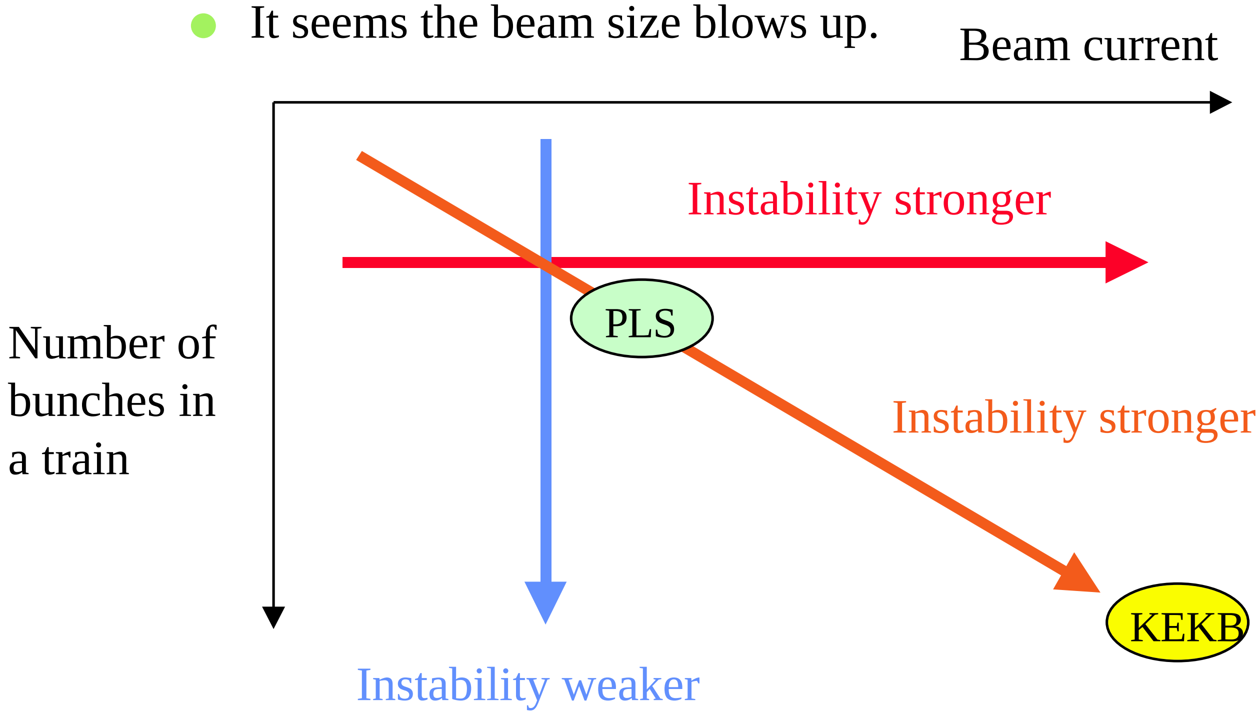
<u>Conclusion 2</u>

Observed oscillation patterns of bunch train are consistent with FBII


200
160
120
80
40
Turn Number
25
50
75
100
125
Bunch Number


Phase(Degree)
200
100
0
-100
-200
Vertical oscillation amplitude(μm)
250
200
150
100
50
0
0
50
100
150
200
Bunch ID

- Characteristics of FBII and its impact on a beam
  - For the same number of bunches, the larger the beam current, the stronger the instability.
  - For the same bunch current, the larger the number of bunches, the stronger the instability.
  - For the same beam current, the larger the number of bunches, the weaker the instability (in agreement with StupakovÕs theory).
  - The oscillation amplitude saturates at 2-3 σ_y.
  - It seems the beam size blows up.



- Scaling to KEK B-Factory
  - The beam areas ($\sigma_x\sigma_y$) are similar.
  - The bunch separations are both 2ns.
  - The normal pressure of PLS is lower than that of KEKB by a factor of a few.
  - The beam energy ratio is 2/8.
  - The number of particles in a bunch at KEKB is equal to that when the bunch current = 2mA at PLS.
  - A beam is very unstable vertically at PLS even with 180 bunches when the bunch current = 2mA (radiation damping time = 16ms).

cancel each other

Conclusion 3

The growth time of FBII at KEKB with a bunch train of 500 bunches will be much shorter than 16 msec. The transverse feedback is inevitable

Summary of the 3rd Experiment

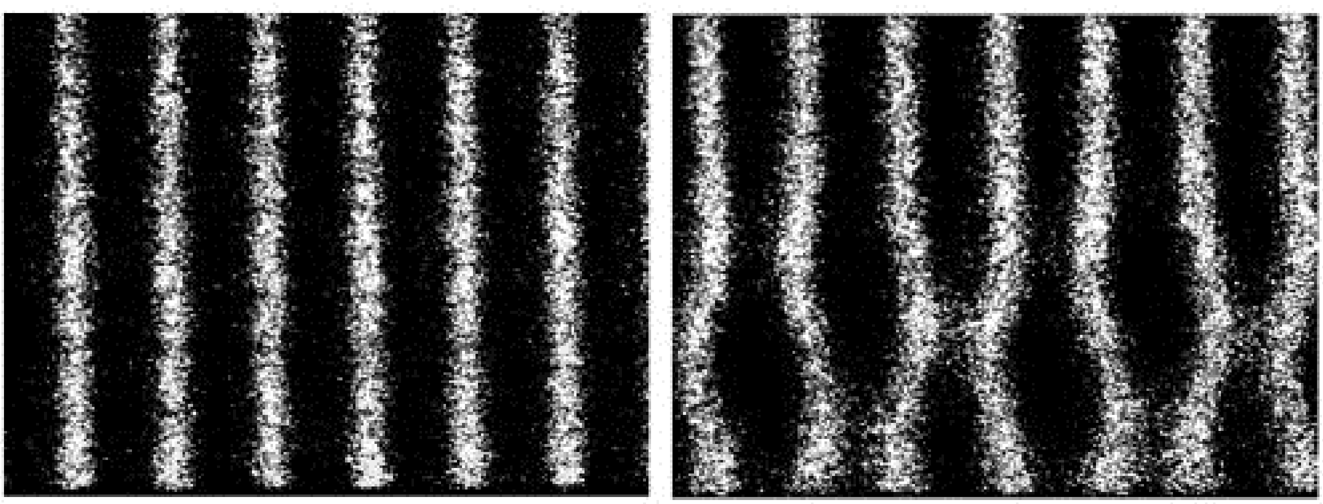
- The 3rd experiment has been done by PAL people in December, 1997.
  - The aim is a direct observation of the FBII from the snapshots of the bunch train taken by a streak camera.
  - The amplitude and the phase of the oscillation of a bunch train and the vertical beam size were also measured using a fast BPM and a streak camera.
- The experimental condition:
  - A train of 250 bunches (0.72mA/bunch) and a gap with 218 empty buckets
  - Pressure
    - All ion pumps were turned off

      P=0.4 nTorr ---> 2.2 nTorr

      (P_{CO}=0.03 nTorr ---> 0.16 nTorr)
    - He gas was injected

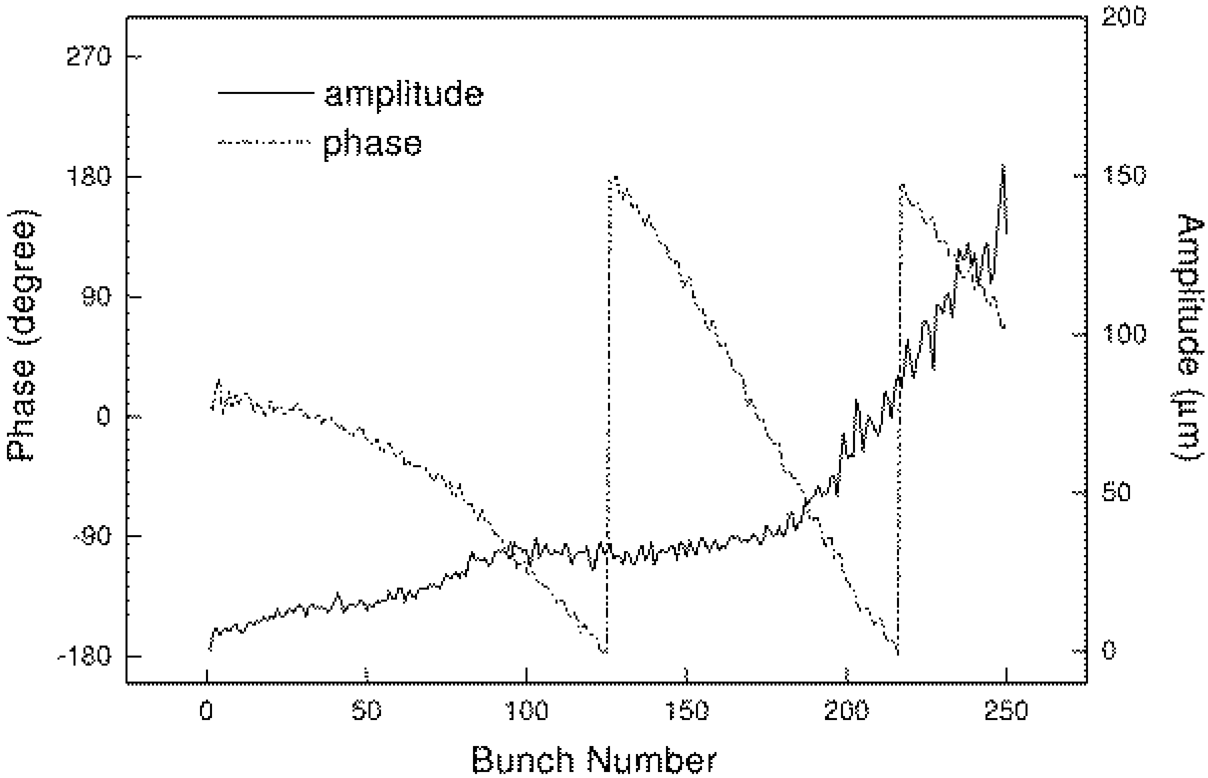
      P_{He}=0.2 nTorr, 1.2 nTorr, 2.1nTorr, 3.34 nTorr
  - No active feedback system on
  - A new cavity temperature control system:
    - A beam is stable upto 200 mA with 250 bunches without HOM induced instability.

- At P=1nTorr w/o He gas injection, a clear snake-tail oscillation of the bunch train with the wavelength of 57m appeared.
  - Each snapshot was taken every 4 turns
  - The snapshot looks almost periodic with a period of 3 ($\Delta Q_y \approx 1/6$)
  - The beam spectrum shows f=5.4 MHz <-- due to CO



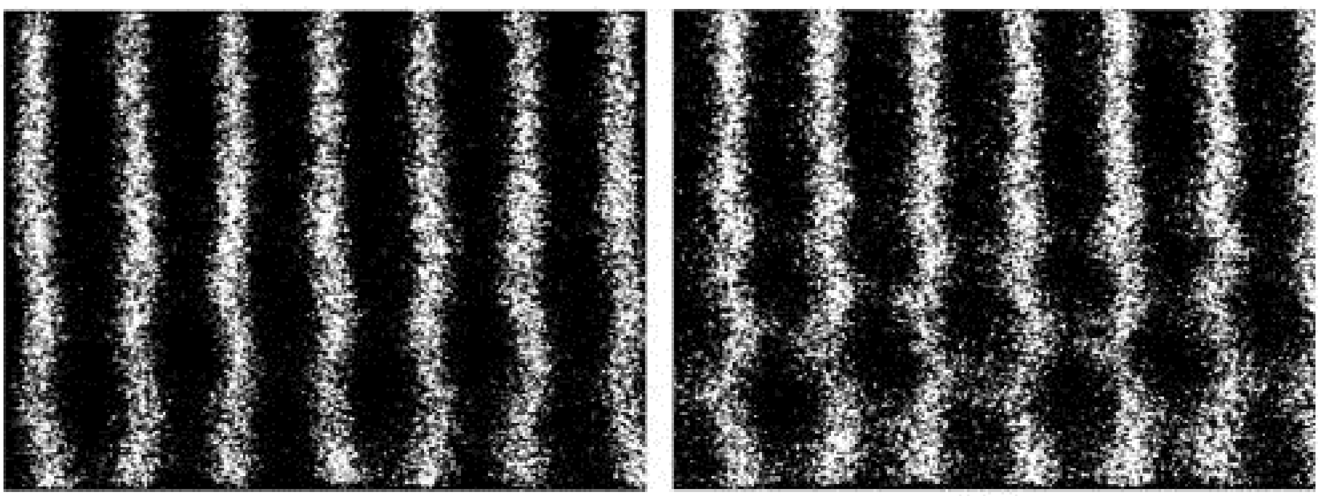
(a) P=0.4nTorr (normal)

(b) P=1nTorr w/o He injection



No bunch to bunch tune variation observed within the resolution of FFT(ΔQ_y<0.001)

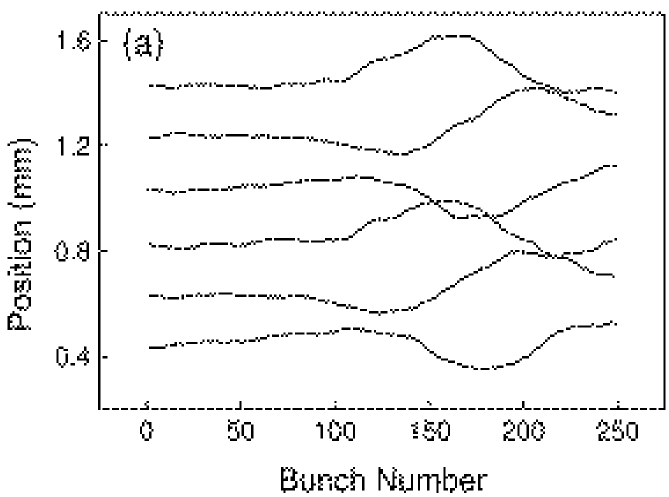
- After He gas injection, the higher ion frequency appeared at 7 MHz, indicating that the beam-He ion interaction becomes dominant.



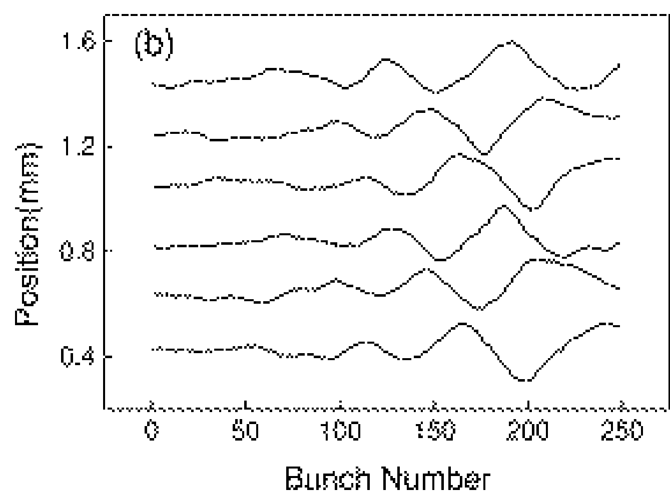
(a) P_{He}=0.2 nTorr

(b) P_{He}=3.34nTorr

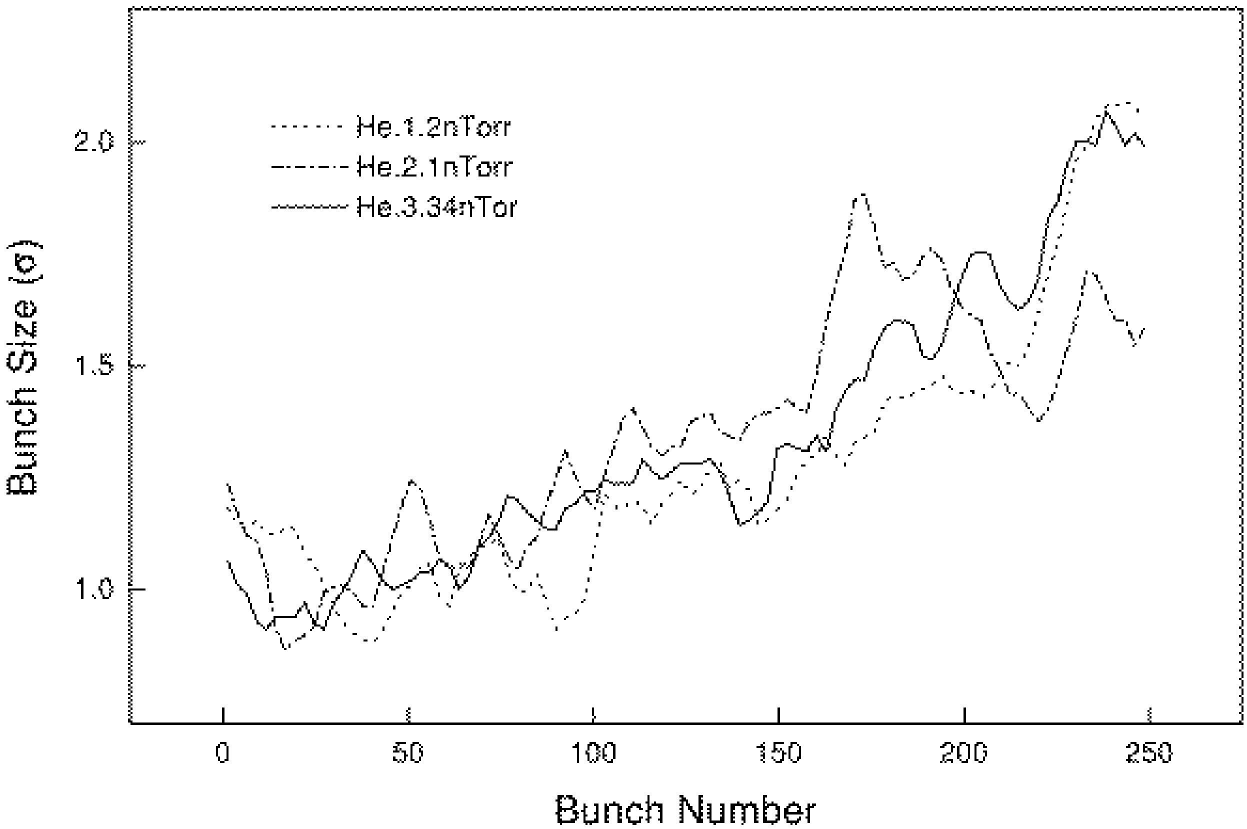
- Mountain views constructed from figures for P=1nTorr w/o He case and P_{He}=3.34nTorr.
  - The amplitude is 5 times magnified to see it clearly.
  - The nominal beam size was measured to be 95mm.



P=1nTorr
w/o He injection

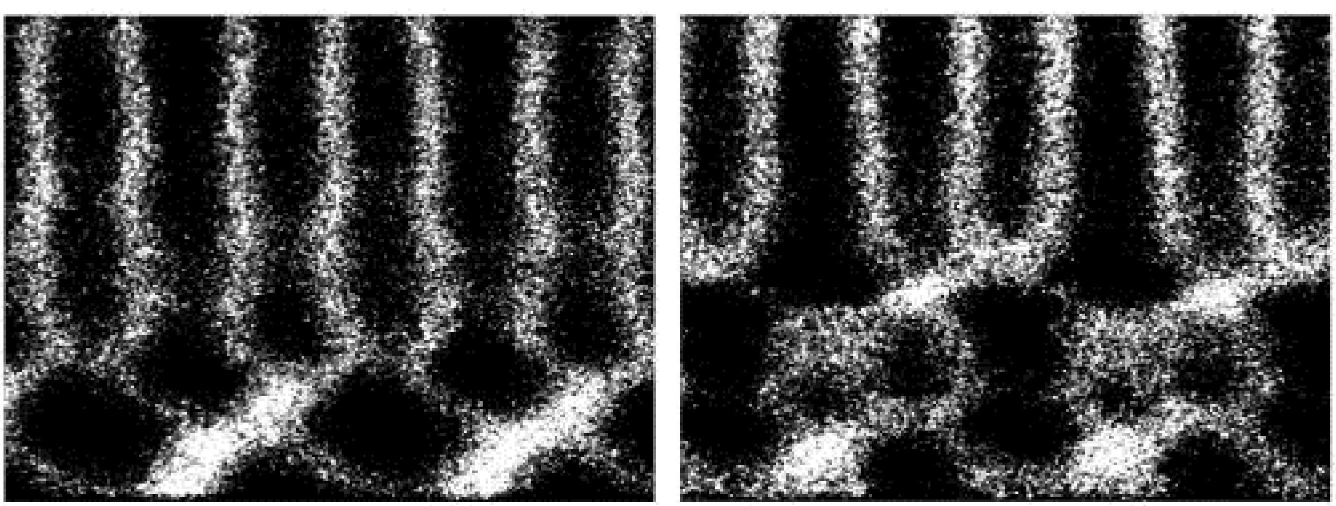


P_{He}=3.34nTorr



Calculated from the snapshots by slicing the bunch train into 96 pieces. The bunch size and the peak position were found by fitting it to a Gaussian bunch profile.

- Summary of the oscillation amplitude
  - σ_y at P_{He}=0.2nTorr
  - σ_y at P_{He}>1.2nTorr or P>1nTorr w/o He injection
    - Decoherence effect due to the competition between CO and He?
    - The triangular wave form may represent that the oscillation contains higher-harmonic components due to the nonlinearity of the beam-ion interaction?
  - When the He pressure is increased further, the bunch oscillation becomes turbulent:



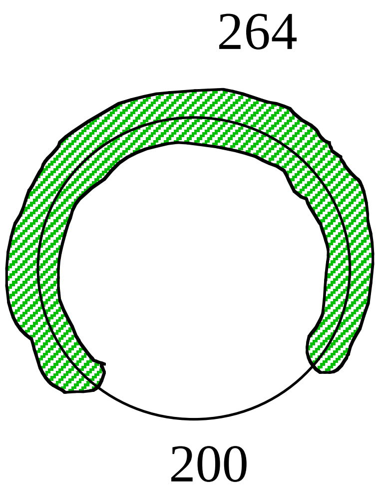
(a) (b)

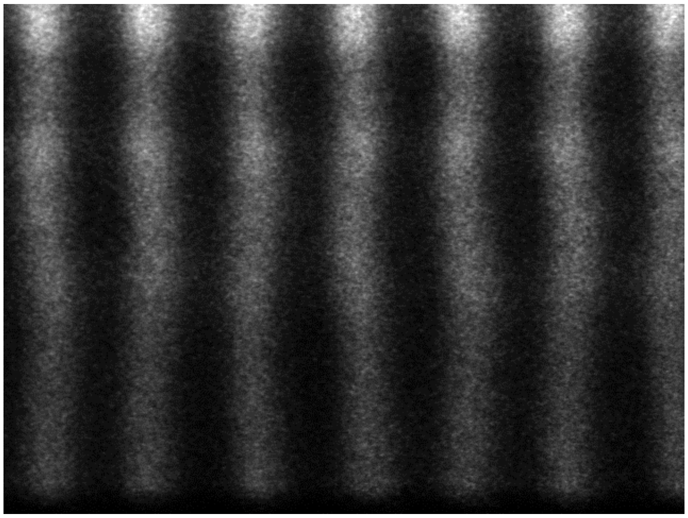
Summary of the 4th Experiment

- The 4th experiment was carried out on February 6-7, 1998. The participants from KEK include Y. H. Chin, T. Kasuga and A. Mochihashi.
  - The aims of this experiment were
    - to measure the growth time by using the transverse feedback system to control the FBII.
    - to study an effect of the gap using two bunch trains and by varying the gap sizes between them.
  - Unfortunately, the feedback system was not ÒstableÓ during the experiment, and thus we decided to concentrate on the study of gap effect.
- The experimental condition:
  - Pressure
    - All ion pumps were turned off

      P= 2.8 nTorr (P_{CO} =0.2 nTorr)
    - No He gas injection
      - Major ions are CO as in the case at KEKB

- Starting point:
  - 1 bunch train with 264 bunches
    - Total beam current = 150 mA (0.57mA/bunch)
  - 1 gap with 200 empty buckets

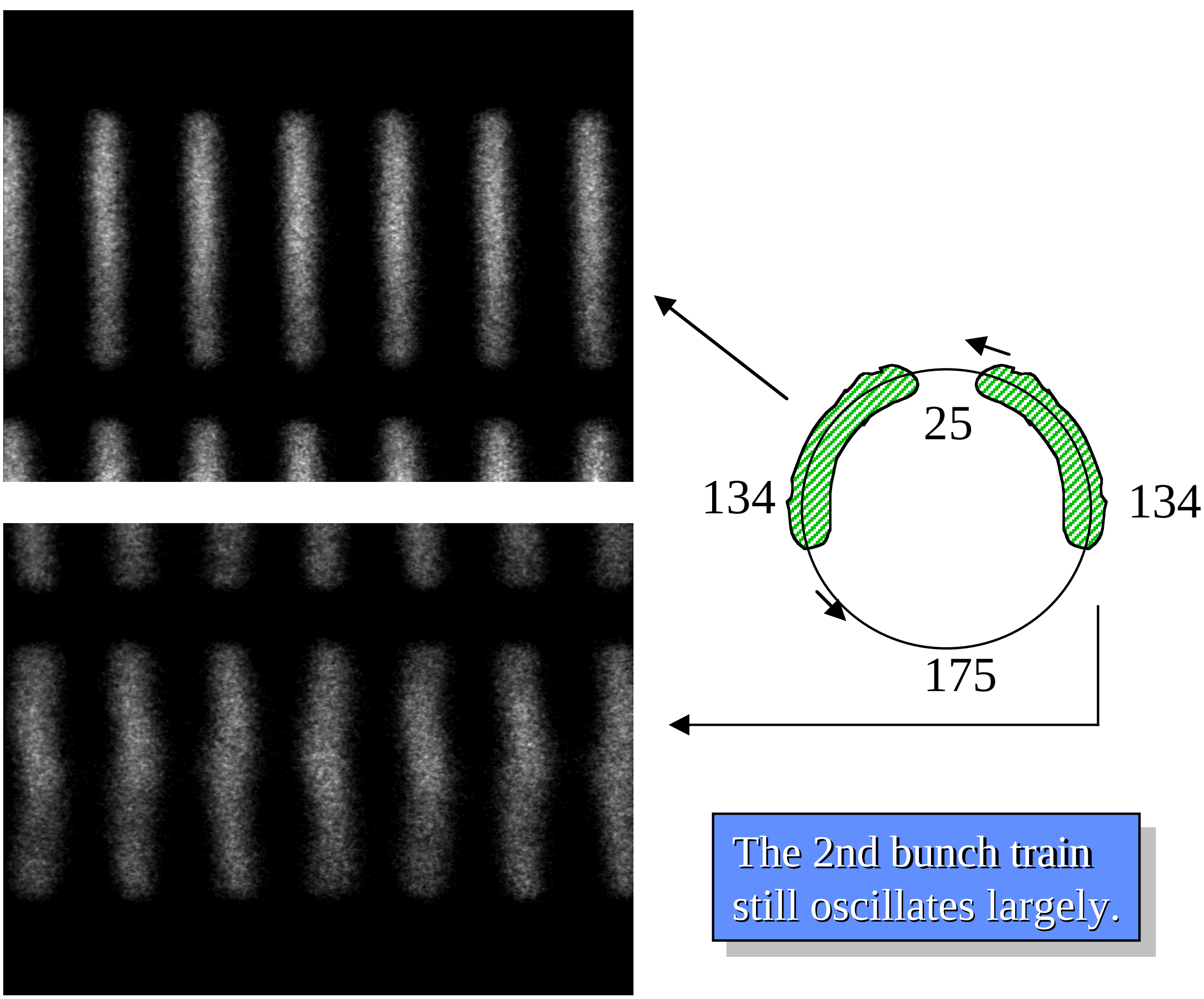




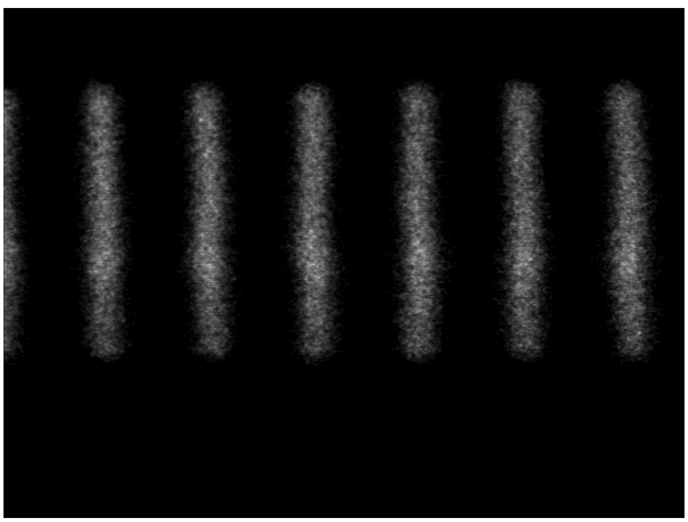
- 2nd step:

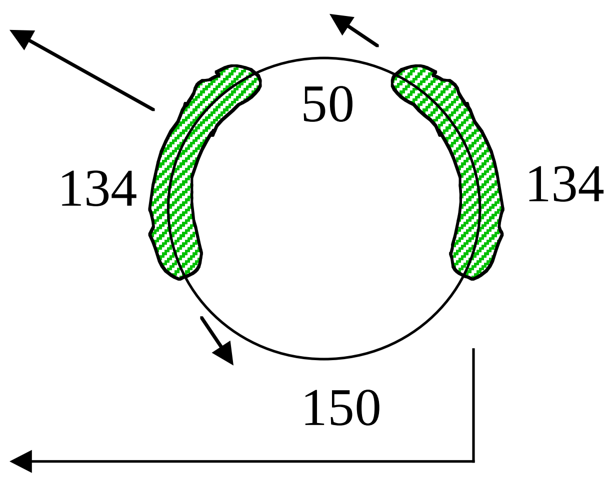
  We cut the bunch train to two identical ones

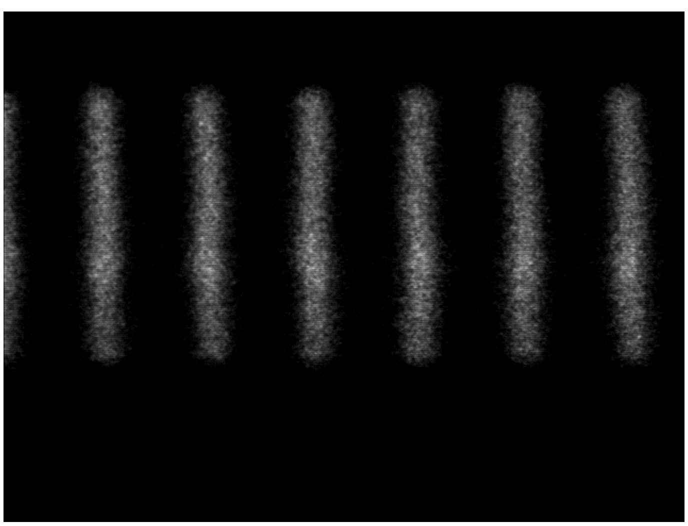
  - 2 bunch trains with 134 bunches each
  - 2 gaps with 25 empty buckets and 175 empty buckets, respectively.



- 3rd step:
  - 2 bunch trains with 134 bunches each
  - 2 gaps with 50 empty buckets and 150 empty buckets, respectively.

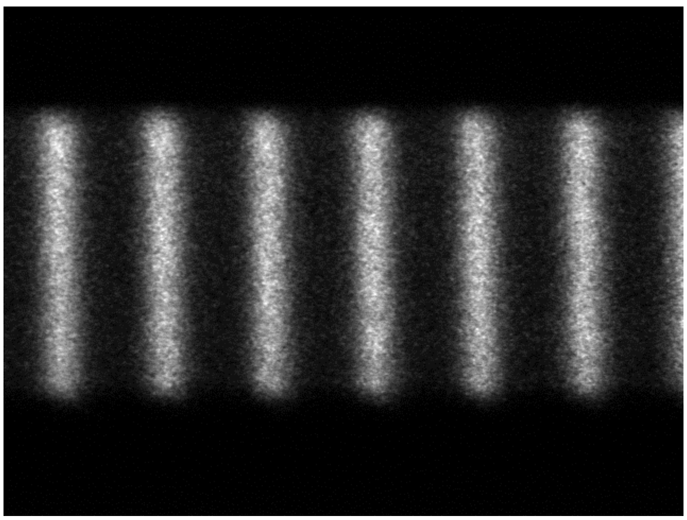


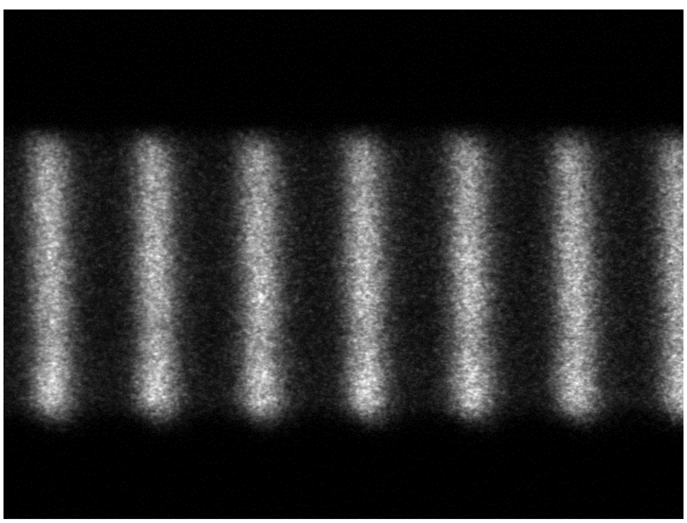


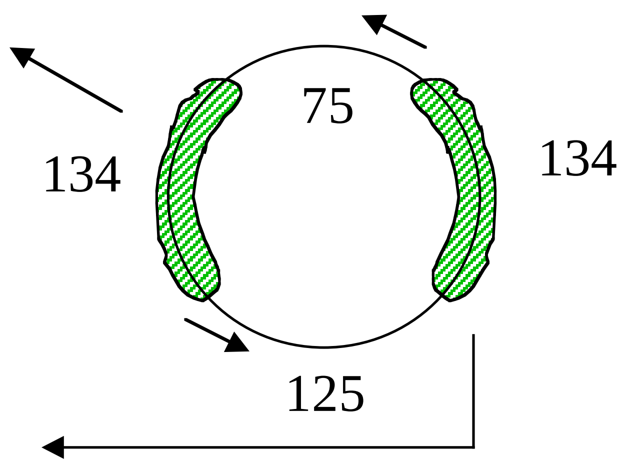


Now, the oscillation of the 2nd train becomes weaker.

- 4th step:
  - 2 bunch trains with 134 bunches each
  - 2 gaps with 75 empty buckets and 125 empty buckets, respectively.

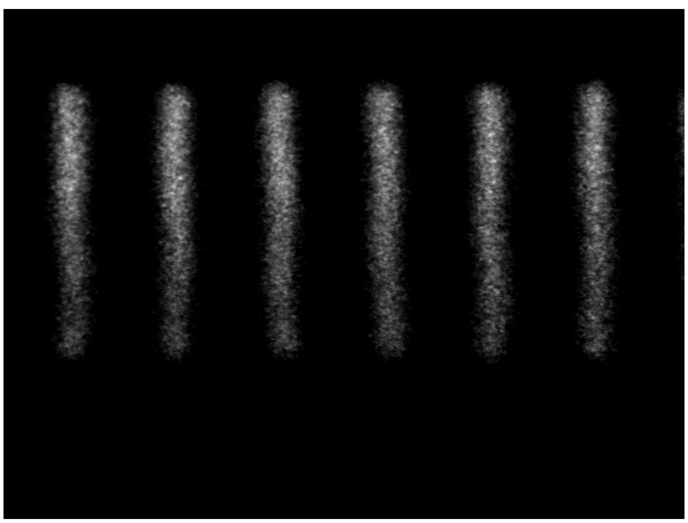


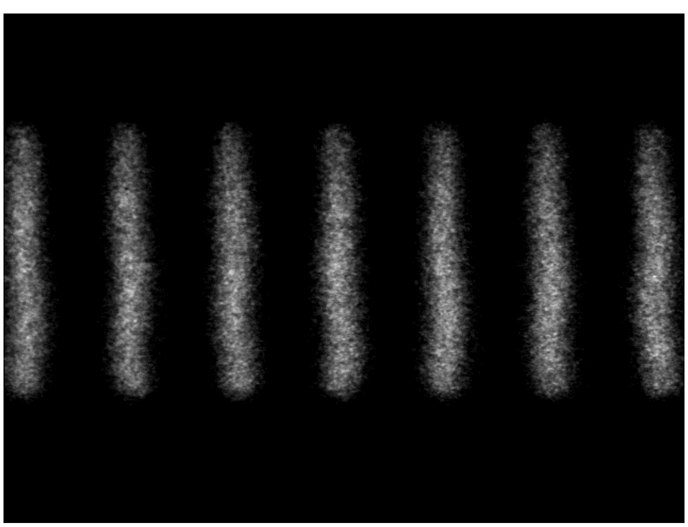


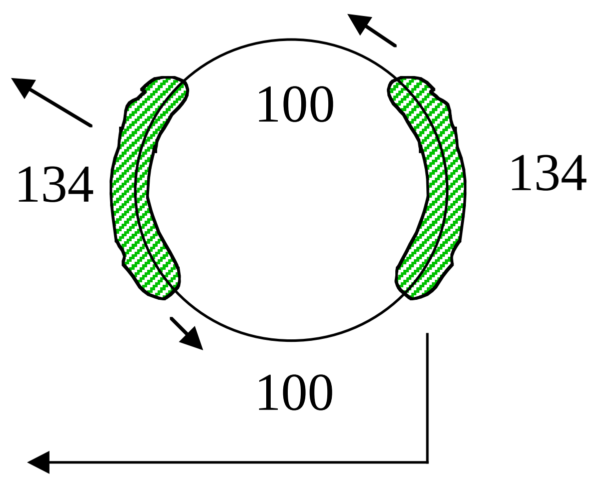


The oscillation of the 2nd train becomes even weaker.

- 5th step:
  - 2 bunch trains with 134 bunches each
  - 2 gaps with 100 empty buckets each







Ion trapping?

- Qualitative conclusions
  - A gap with empty 70-80 buckets was enough to clear ions substantially for the second bunch train to behave as the first one.
    - At KEKB, electrons/bunch is about 4 times more.
      - The ion oscillates twice faster
      - KEKB may need a smaller gap
    - The bunch train is about 4 times longer (N_b=500).
      - More ions (16 times) are created by a bunch train.
    - The combination of the above two effects may end up with a similar gap size to be needed.
  - It may be a good idea to have at least one ***BIG*** gap to make sure that all ions are cleared out in one turn to prevent a rise of the ion trapping at KEKB.
    - 200 - 300 empty buckets?