Experiment on Photoelectron Instability at BEPC and KEKB

8th ICFA Beam dynamics Mini-Workshop on Two-Stream Instabilities in Particle Accelerators and Storage Rings

16th Feb. 2000

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1.Experiment on Photoelectron Instability at BEPC

2.Vertical Beam Blow-up at KEKB LER

Experiment on Photoelectron Instability at BEPC

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1.Introduction

- A vertical coupled-bunch instability was observed in a positron beam at KEK PF years ago.

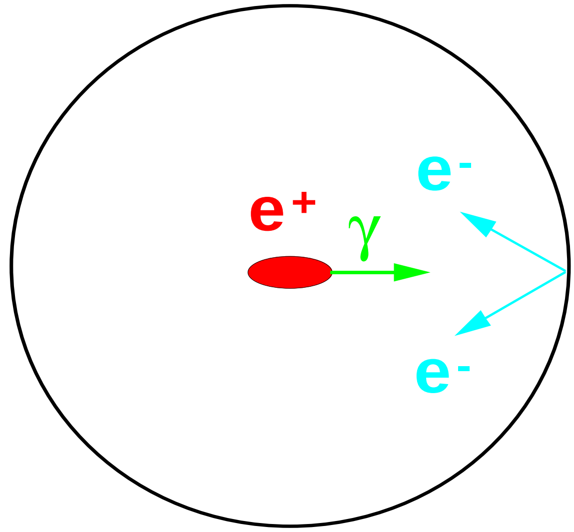
- Characteristics of the instability in PF are
  1)Coupled oscillation,
  2)Low threshold current(15-20mA),
  3)Broad distribution of betatron sidebands,
  4) 3) is not observed in a electron beam,
  5)The threshold current depends on bunch spacing,
  6)Betatron sideband distribution changes as the beam current changes.

- To explain the observation the experimenters proposed,
  1)the instability is caused by electrons,
  2)the force, which causes the instability, has a semi-long range about 10 bunch spacing.

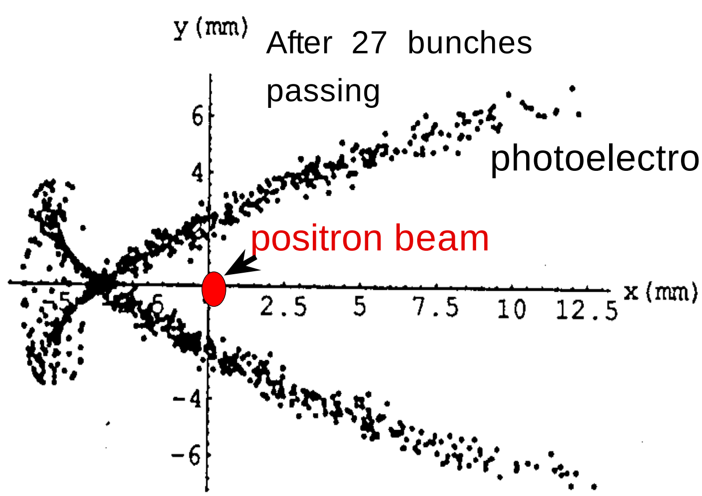
- K. Ohmi proposed a model to explain the experiment in KEK PF.

Model of PEI by K. Ohmi

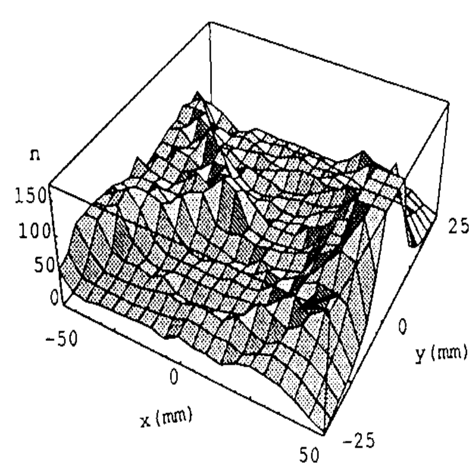
1)Synchrotron light produces photoelectrons.



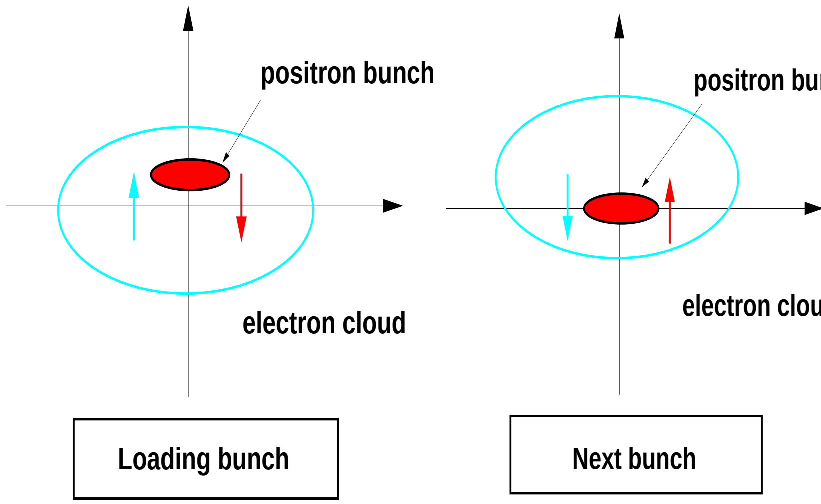
2)Photoelectrons (PE's) are attracted by positron beam.



3)Continuous production and absorption of PE's make a stational distribution.

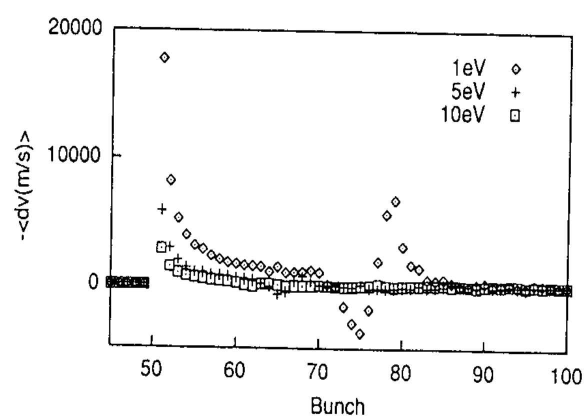


4)If a loading bunch is shifted, following bunches receive kicks by the electron cloud.

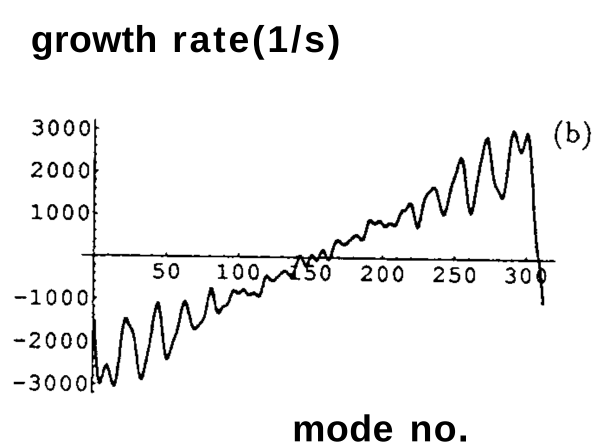


Force received by a bunch is expressed by a wake.

short range wake



5)Growth time is calculated by the conventional instability theory.



- To investigate the PEI further a series of experiments has been carried out in BEPC at IHEP in the collaboration between IHEP and KEK.

BEPC : electron-positron collider in IHEP ,Beijing

Machine parameters of BEPC

Energy	1.55-2.2 GeV
Circumference	240 m
RF frequency	200 MHz
Harmonic number	160
Current	40-150mA
Damping time(x,y)	4.6 ms

2.Observation of betatron sideband of the instability

•At an early stage of the experiments, a vertical instability was observed in positron accumulation. Characteristics of the instability are

1)Coupled oscillation,

2)Low threshold current(9 mA),

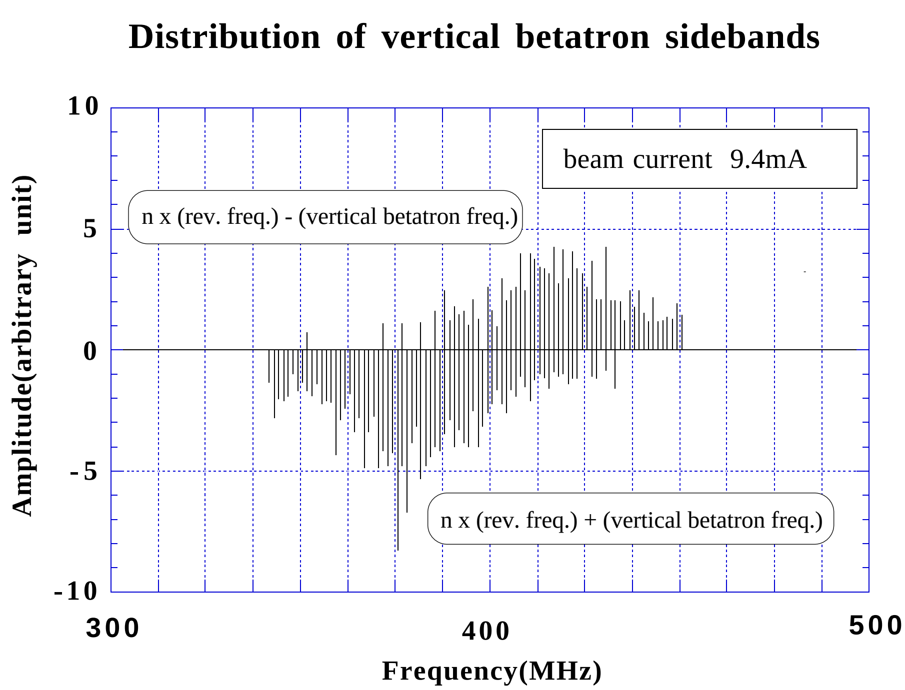
3)Broad distribution of betatron sidebands,

4) 3) is not observed in a electron beam,

5)The threshold current depends on bunch spacing,

When bunch spacing increased from 5ns to 10 ns, threshold current increased higher than 40 mA.

Observed instability is very similar to that in PF.



3.Observation of the instability by the single pass beam position monitor system

1)Experimental setup

- Single pass beam position monitor system(SBPM) was introduced to observe the transverse oscillation of every bunch.
  SPBPM system consists of BPM, FADC with 500MHz and 20 Mbyte memory board which has a capability to store the beam position data of 160 bunch x 16000 turns.

- Experiment condition

Beam energy	1.3 GeV
Nominal betatron tune	5.82 (H) and 6.74 (V)
Nominal chromaticity	4 (H) and 4 (V)
Natural emittance	0.134 mm mr
RF voltage	290 kV
Filling pattern	160 bunches
Beam current	about 10 mA
Damping time	86 ms (transverse)

2)Mode analysis

A)Procedures

To find a mode distribution of the oscillation mode analysis was performed as follows.

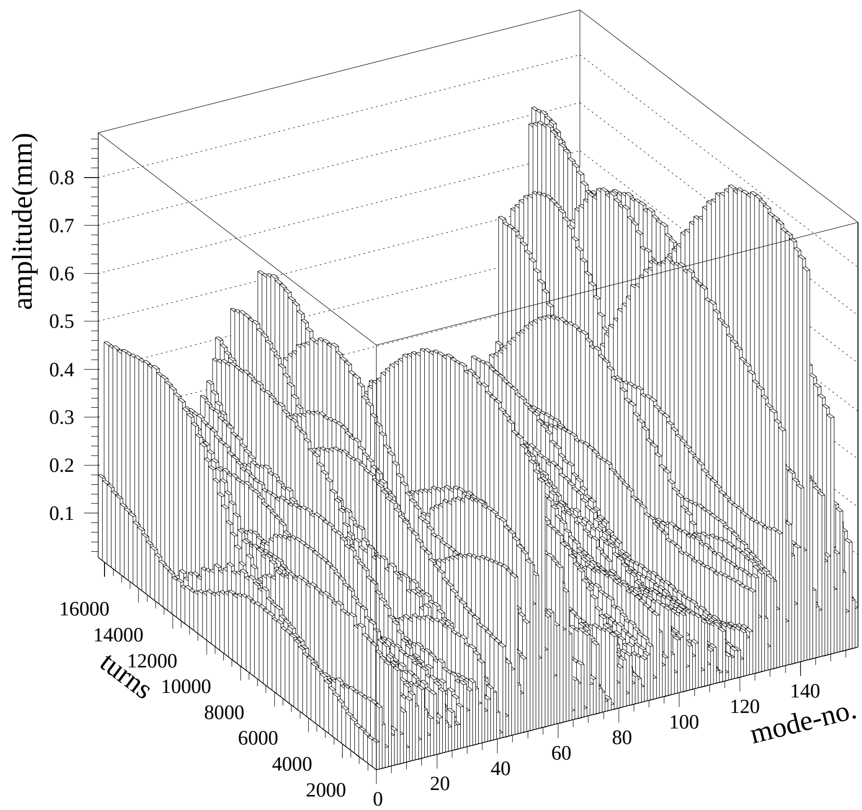
- Dividing 16000 turns data into 256 turns for each bunch,
- Fourier analyzing for 160 bunch x 256 turns data,
- Getting the distribution of betatron sidebands,
- Plotting the time development of modes.

B)Result

a)Positron beam

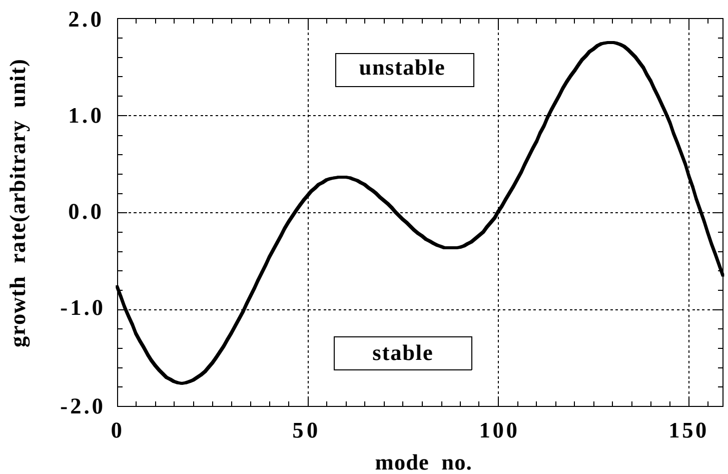
For the data of 160 bunch uniform filling and beam current of 12mA,

•Mode distribution has two broad peaks around 55th mode and 145th mode.



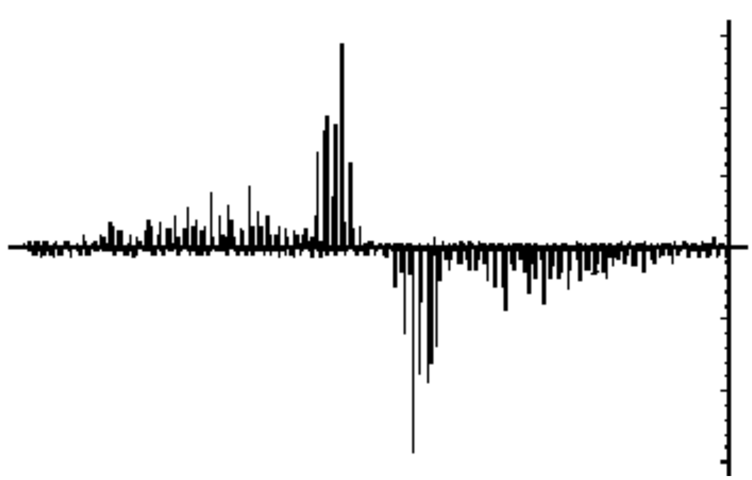
•Simple phenomenological model shows that two broad peaks appears if range of wake is two bunch spacing.

$$\tau_g = \mathrm{Im}[A\sum_{p=1}^{l} F(-pD)\exp\{i2p\pi(\mu+\nu_b)/M\}]$$



•Simulation based on PEI model also shows two broad peaks, but position and width of peaks slightly different from the observation.

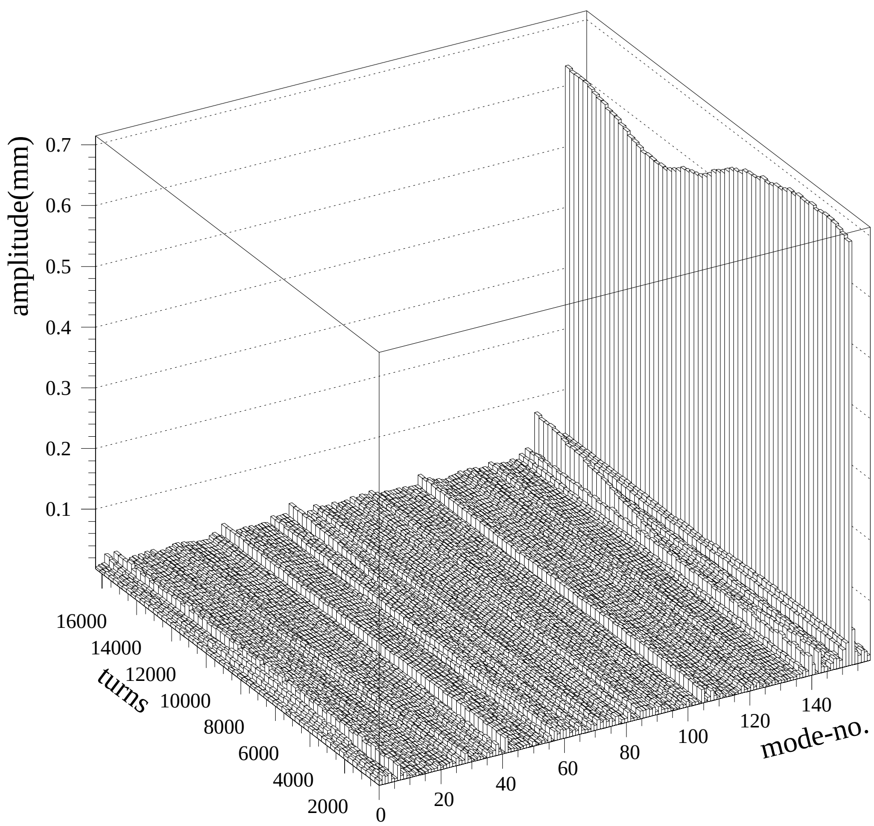
E=1.3 GeV



b)Electron beam

For the data of 160 bunch uniform filling and beam current of 12mA,

- Mode distribution has a peak at 153th mode.
- This peak can be explained by ion trapping.



3)Measurement of growth rate

A)Generals

- Octupole introduces an amplitude dependent tune shift which cause a smear in phase space (Landau damping).
- Smear cause the damping of center of mass motion of a bunch which suppress the instability.
- This enable us to measure the growth rate of the instability by measuring the strength at which the instability is damped.

B)Result

- Oscillation due to the instability stopped when the octupole was excited by K3 =-33 m^{-3}.
- A calculation based on perturbation theory shows that the damping time by the octupole is 6.5 ms which should be the estimate of the growth time of the instability.
- A simulation based on PEI model gives the growth time of about 10 ms which is consistent with estimated growth time by the measurement.

4.Summary

- Photoelectron instability was studied experimentally at BEPC.
- The vertical coupled bunch instability which is very similar to that observed at KEK PF was also observed in BEPC.
- Observed mode spectrum and the growth time measured by the octupole excitation are consistent with the simulation of the PEI model.

Vertical Beam Blow-up at KEKB LER

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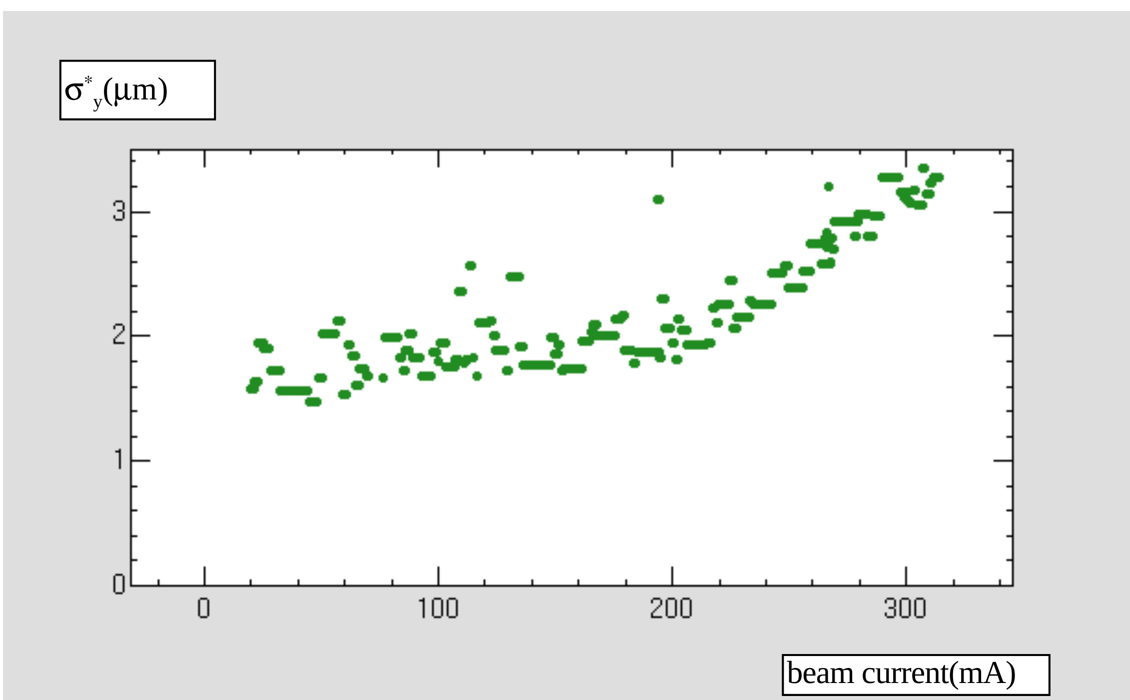
1. Introduction
2. Characteristics of beam blow-up observed by the interferometer
3. Beam break-up(BBU)/head-tail instability by the photoelectron cloud
    - A. Model
    - B. Experiment
4. Summary

1. Introduction

- Vertical blow-up of beam size is observed in LER.

- The beam size as a function of beam current starts to increase at a threshold beam current and is almost doubled by 300 mA under typical operating conditions.

- Thus the blow-up is one of the most serious problems limiting the luminosity of KEKB.



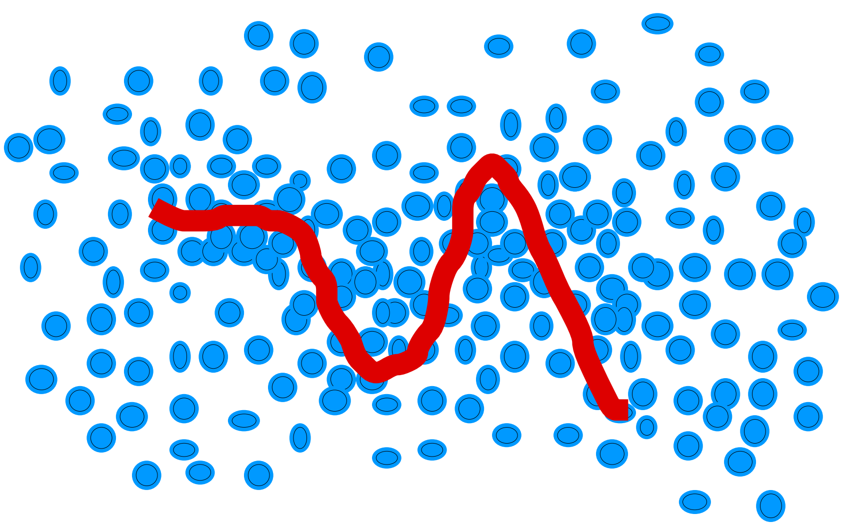
2. Characteristics of beam blow-up observed by the interferometer

1) Single beam and multibunch effect.
2) The effect is confined in a train, if the separation between trains is sufficiently long (longer than about 160 buckets).
3) The blow-up has a threshold which is determined by the charge density (bunch current/bunch spacing).
4) The blow-up does not change much for the chromaticity.
5) Almost independent on betatron tunes.
6) No dependence on vacuum pressure (especially on hydrogen) in the arc.
7) No dependence on the position of the vertical masks.
8) No dependence on the excitation of the wigglers.

3.Beam break-up(BBU)/Head-tail instability by the photoelectron cloud

To explain the blow-up, the beam break up/head-tail instability in a bunch caused by the electron cloud is proposed.

A. Model (F. Zimmermann, K. Ohmi)



- Electrons which is generated by the synchrotron radiation form a cloud by the attractive force of multi-bunch positron beam.

- Beam breakup/head-tail oscillation in a bunch occurs by the mediation of the cloud.

i)Formation of electron cloud (F. Zimmermann)

Simulation results for the KEKB LER show,

• Electron cloud builds up in 10 to 20 passages of the bunches, then the number of electrons is saturated. The equilibrium density of electrons is almost equal to the neutralization density.

$$n_{cloud,sat} \approx \frac{1}{\pi r_p^2 l} \frac{N_{e,tot}}{l} \approx 1.4 \times 10^{12} m^{-3}, \quad n_{neutr} \approx \frac{1}{\pi r_p^2} \frac{N_b}{s_b} \approx 1.5 \times 10^{12} m^{-3}$$

$\Rightarrow$ $n_{\text{cloud, sat}} \propto$ charge density of the beam

l: lenght of drift space, N_b: positrons in a bunch, s_b: bunch spacing,
N_b / s_b: charge density of the beam

• Field gradient in the cloud induces a tune shift along the train.

$$\Delta\nu_y \approx \frac{1}{4\pi} \langle \beta_y \rangle e \frac{dE_y}{dy} C \frac{1}{\gamma mc^2}$$

$$\frac{dE_y}{dy} \approx \frac{e n_{neutr}}{2\varepsilon_0} \approx \frac{e}{2\varepsilon_0} \frac{1}{\pi r_p^2} \frac{N_b}{s_b}, \qquad \frac{dE_y}{dy} \approx 12000 V/m^2 \Rightarrow \Delta\nu_y \approx 0.012$$

$\Rightarrow$Tune shift is proportional to the charge density of the beam if the neutralization is reached.

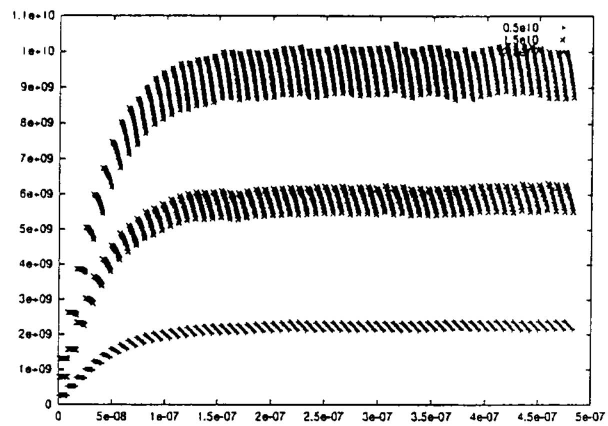


Figure 3: Build up of the electron cloud (total charge per meter) as a function of time (in s) for three different bunch populations and a constant bunch spacing of 4 rf buckets. The photoelectron yield is assumed to be 0.05 per positron per meter.

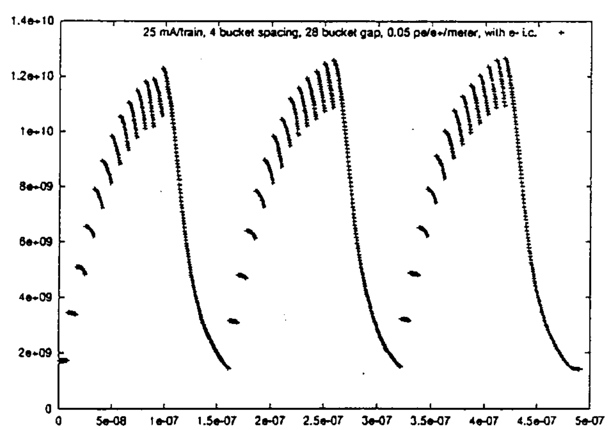
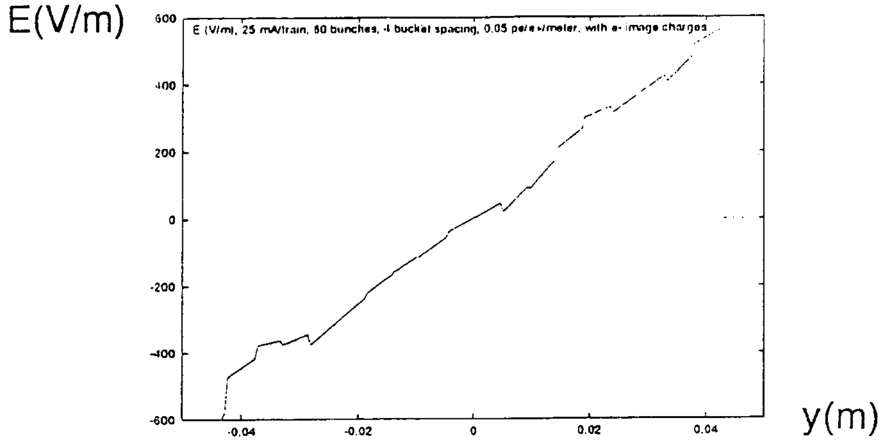


Figure 4: Electron-cloud build up for trains of 13 bunches with 4 bucket spacing, with trains separated by 28-bucket gaps. The electron cloud is cleared almost completely in the gap between trains.

F. Zimmermann



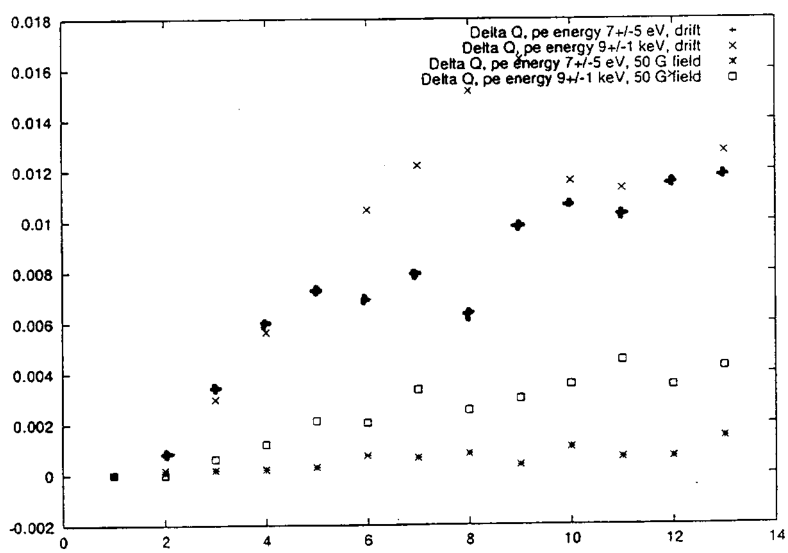


Figure 10: Tune shift ΔQ as a function of bunch number along the train, comparing cases with and without magnetic field and for two different distributions of initial photoelectron energies. The first distribution is centered at 7 eV with 5 eV rms, the second is centered at 9 keV with 1 keV rms width. The bunch spacing is 4 rf buckets (2.4 m) and the bunch population 2.5×10^{10}.

ii) Blow-up mechanism

a) Linear theory of BBU(F. Zimmermann)

Growth rate

$$\frac{1}{\tau} = 4\pi n_{cloud} \frac{N_b^{-1/2} r_e^{3/2} \sigma_z^{1/2} \sigma_x \beta_y c}{\gamma \sigma_y^{1/2} (\sigma_x + \sigma_y)^{3/2}} \approx 25\mu\text{sec}$$

Oscillation frequency of an electron inside the bunch

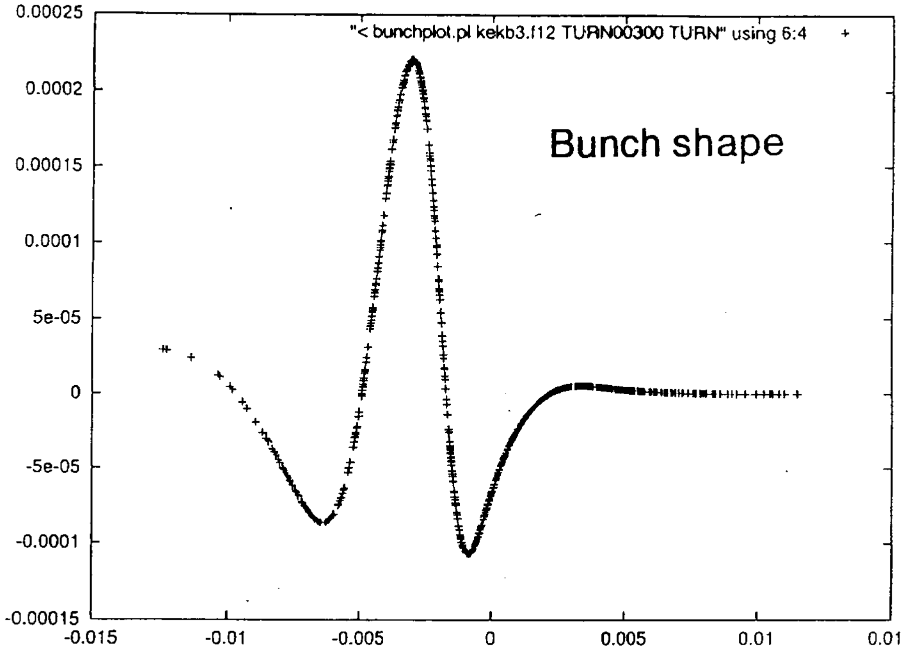
$$f_i = \frac{c}{2\pi} \left[\frac{4 N_b r_e}{3\sigma_y (\sigma_x + \sigma_y) \sqrt{2\pi} \sigma_z} \right]^{1/2} \approx 15\text{GHz}$$

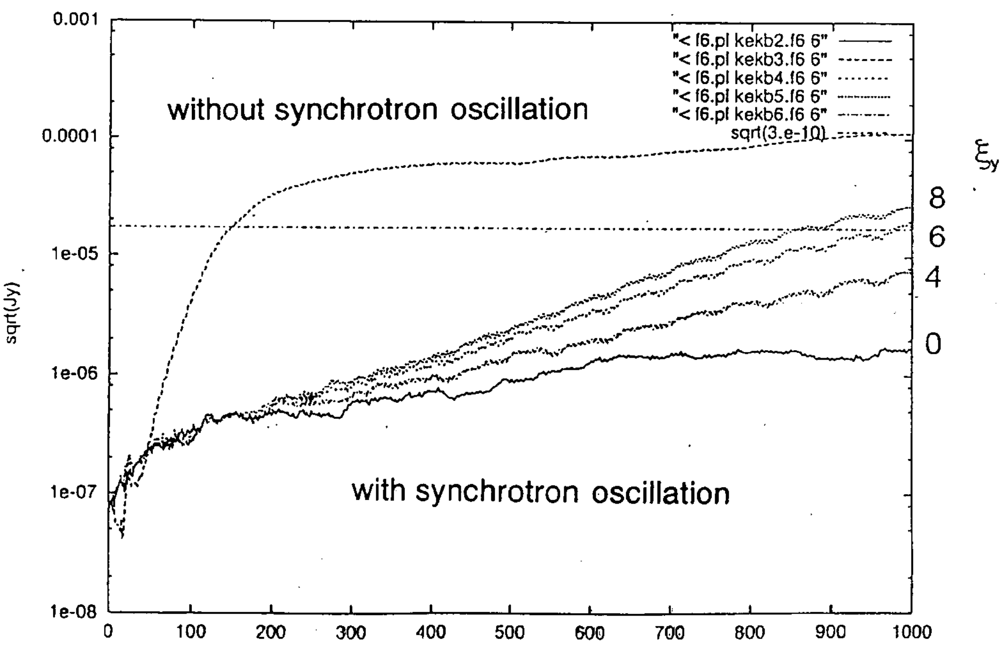
b) Simulation(K. Ohmi)

- Simulation shows,
  - ♦ beam break up instability appears,
  - ♦ growth is relaxed taking into account of synchrotron oscillation.

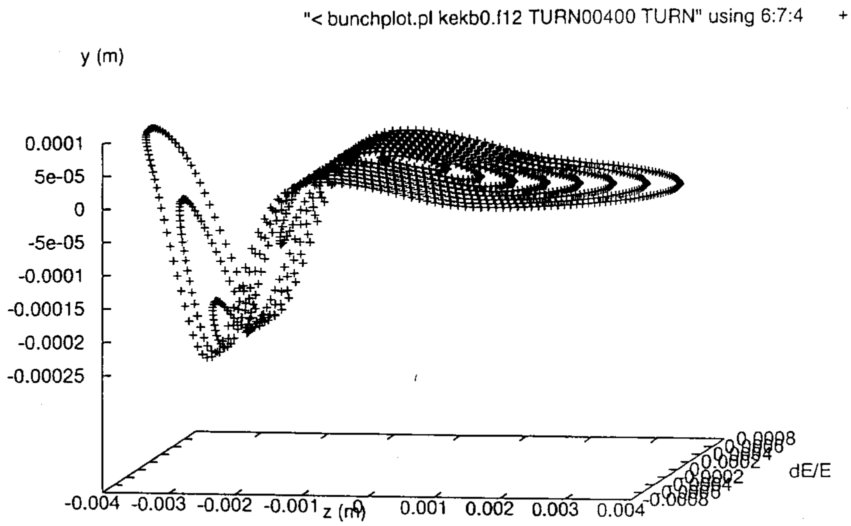
preliminary

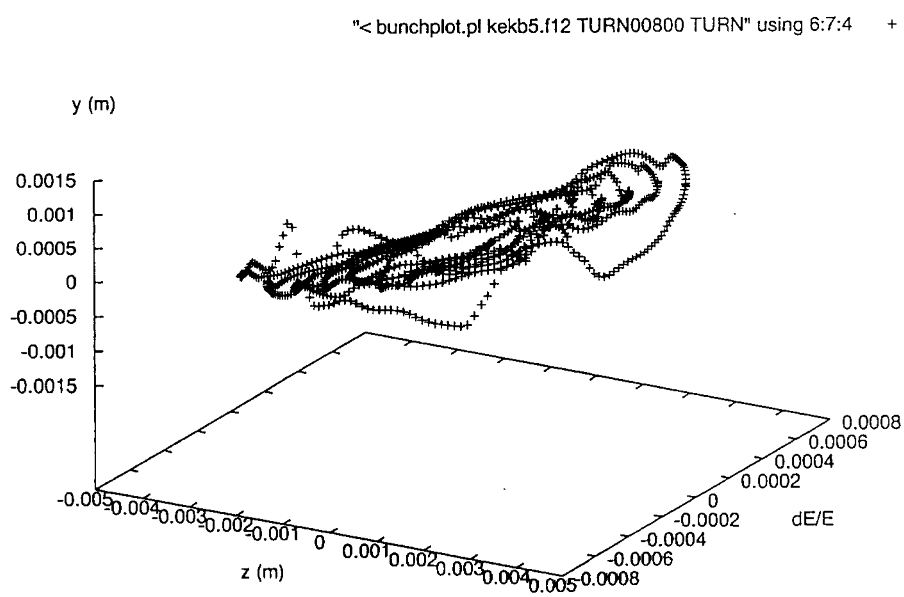
K. Ohmi





K. Ohmi preliminary





B. Experiment

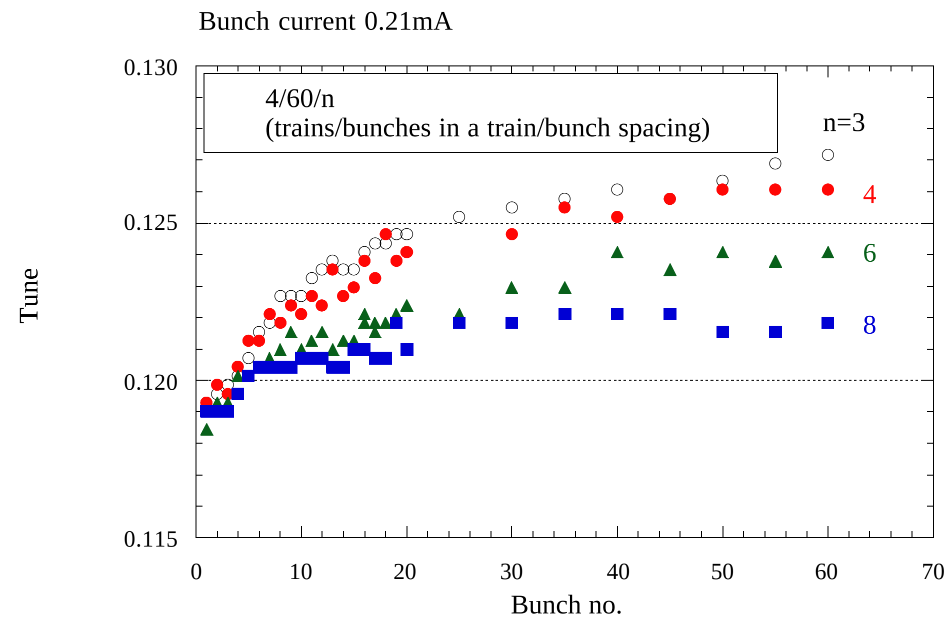
i) Tune along the train

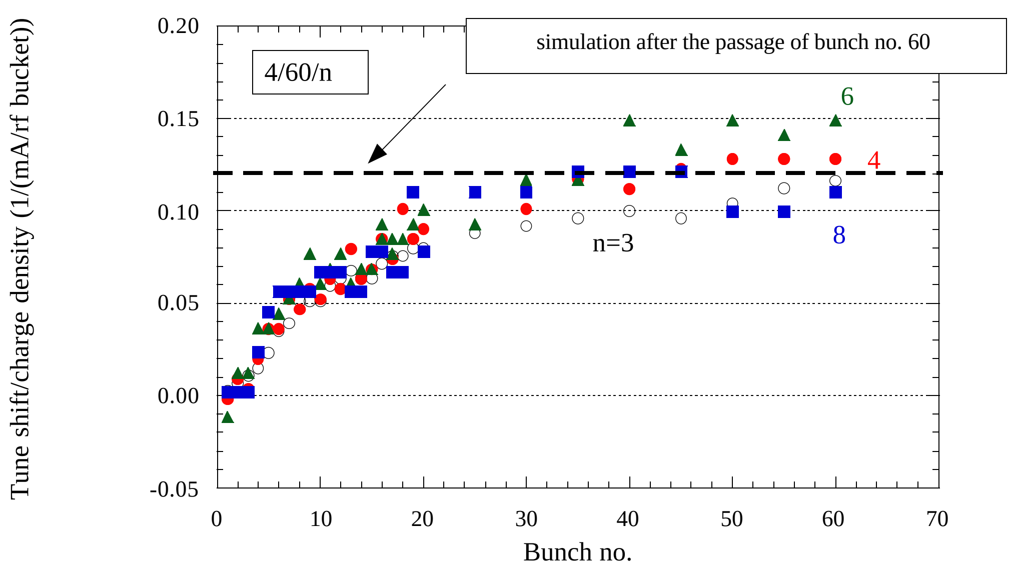
- Vertical betatron tune of the bunches along the train was measured by the gated tune meter.

- The data show that

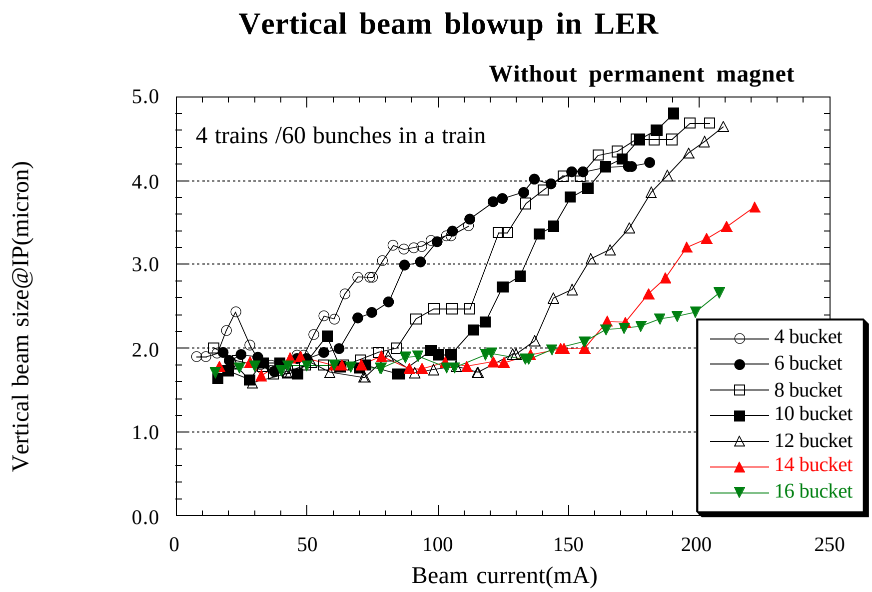
  1) tune increases along the train,
  2) tune almost saturates at about 20th bunch,
  3) tune shift is proportional to the charge density of the beam and (saturated tune shift) / (charge density) is about 0.12 which is consistent with the simulation.

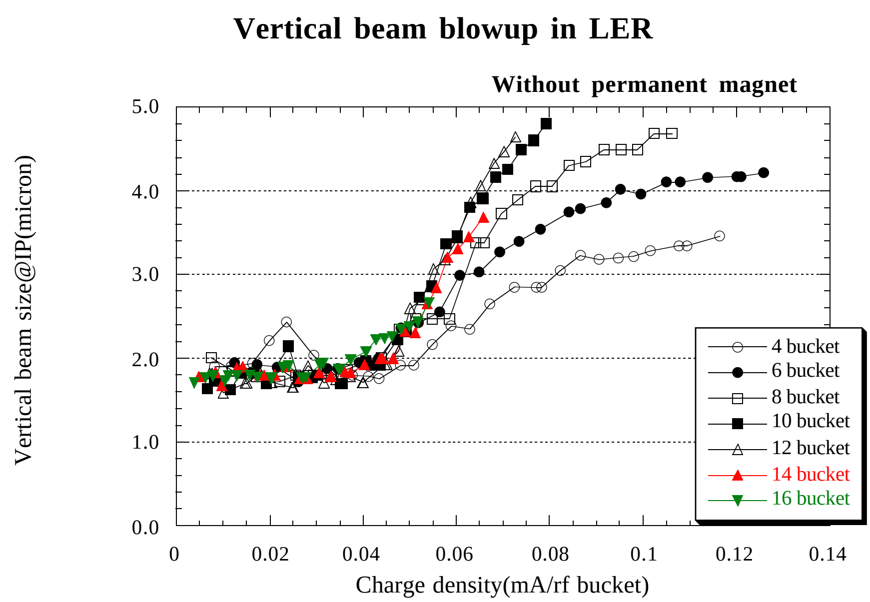
  1), 2) and 3) support the simulation by F.Z..


Bunch current 0.21mA
4/60/n
(trains/bunches in a train/bunch spacing)
n=3
4
6
8
Tune
0.130
0.125
0.120
0.115
0
10
20
30
40
50
60
70
Bunch no.


simulation after the passage of bunch no. 60
4/60/n
6
4
n=3
8
Tune shift/charge density (1/(mA/rf bucket))
0.20
0.15
0.10
0.05
0.00
-0.05
0
10
20
30
40
50
60
70
Bunch no.

ii) Threshold intensity of the blow-up





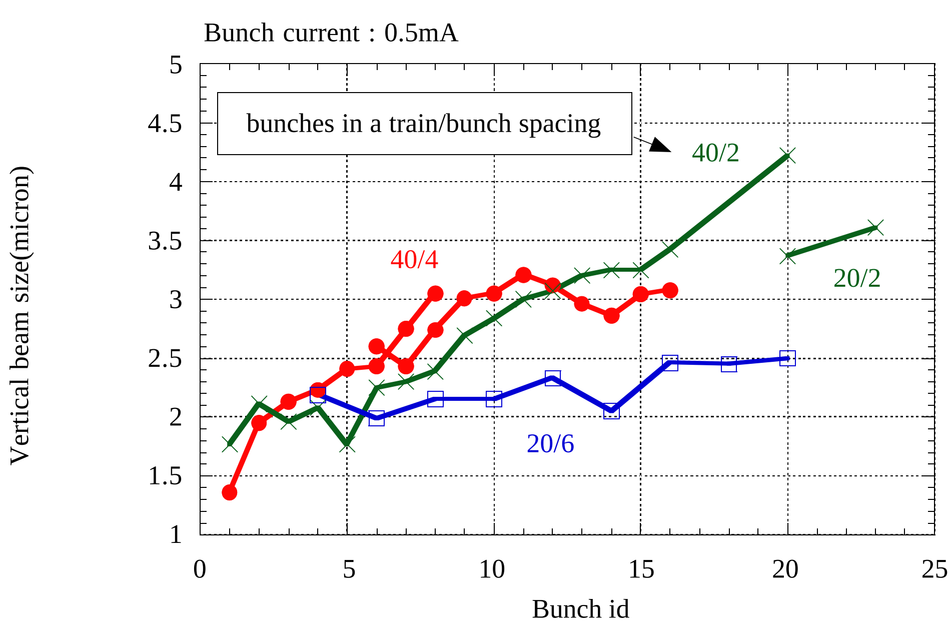
- Threshold intensity is determined by the charge density of the beam. This fact suggests the blow-up starts at a critical density of the cloud. But why the threshold is not dependent on the bunch intensity is an open question.

iii) Beam size of each bunch

If the blow-up is caused by the electron cloud, we expect the beam size increases along the train because the density of the cloud also increases along the train.

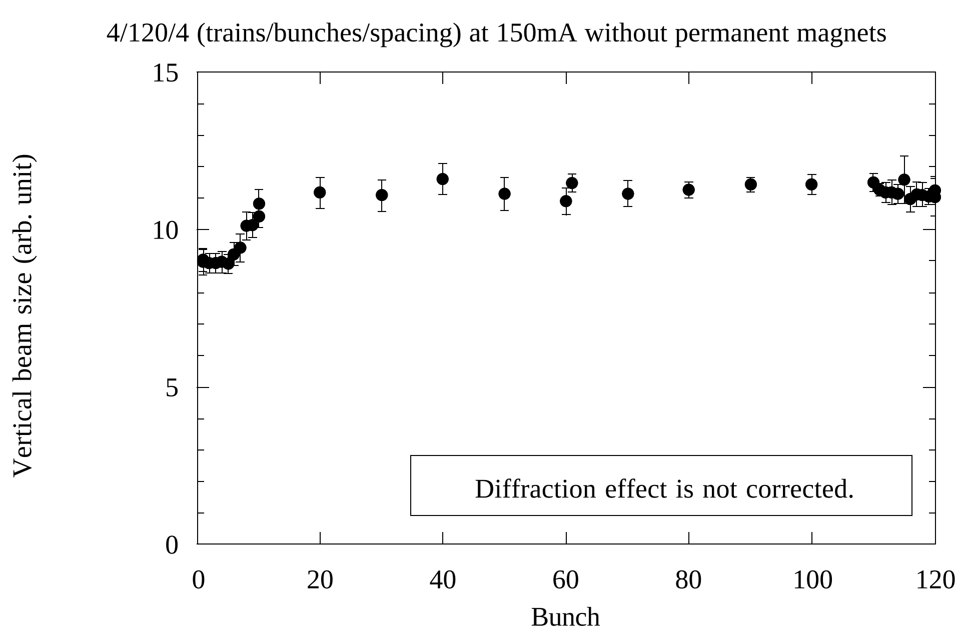
a) Average beam size

- Beam size was measured by the interferometer by adding the bunch one by one to the train.
- The data shows that the average beam size increases as the length of the train increases.



b) Measurement by the Fast Gated Camera

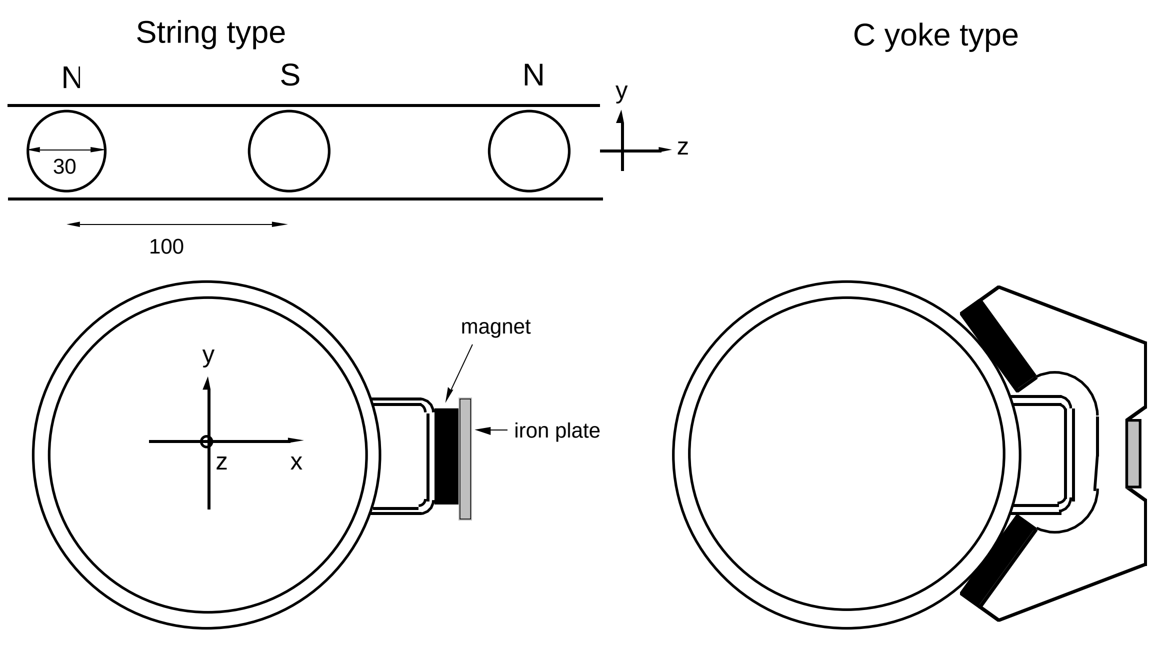
- We are trying the direct measurement of the beam size by the fast gated camera.
- The data show that the beam size increases along the train and the beam size almost saturates at 10 to 20th bunch.
- But a data showed that the blow-up changed after adjusting the focus of the light image. The reason is not clear. We are planning to construct the simultaneous measurement system of the interferometer and the fast gated camera. It will enable us to watch the beam size continuously during the measurement by the FGC and calibrate the data of the FGC.



iv) Effect of magnetic field

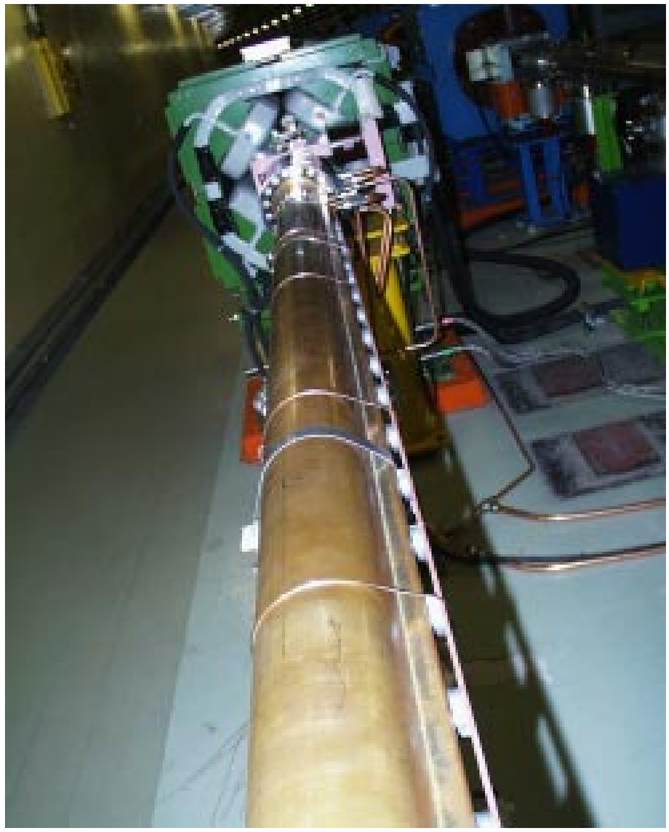
- To remove the electrons, about 5000 permanent magnets were attached on the outer-lateral side of the vacuum chambers where the synchrotron radiation irradiate.
- The magnets are attached in every 10 cm of the LER drift space within 7 m downstream from bending magnets.
- We tried two type of magnets , i.e. string type and C yoke type. At first string type magnets were tried. Then they were replaced with C yoke magnets because the blow-up still remained and a strange instability appeared around 20 mA.

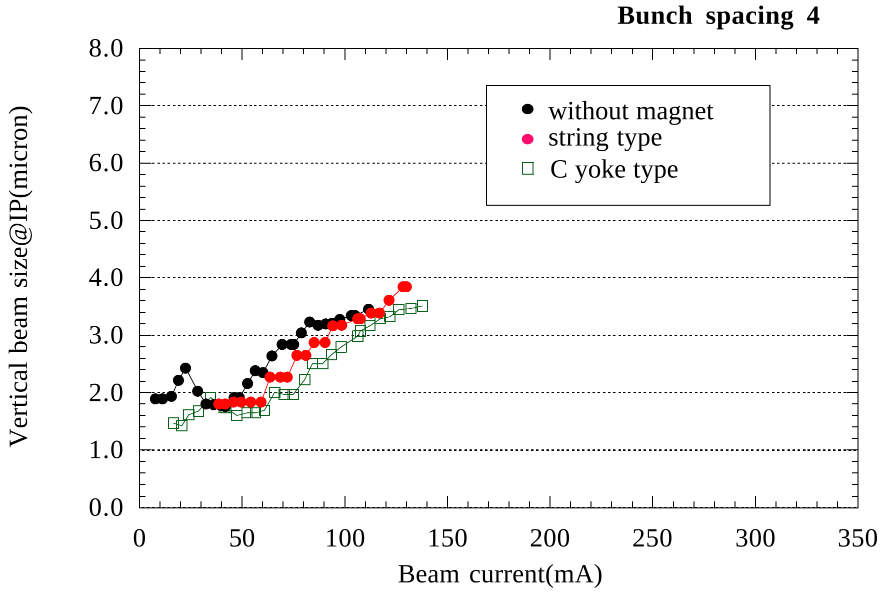
Permanent magnet

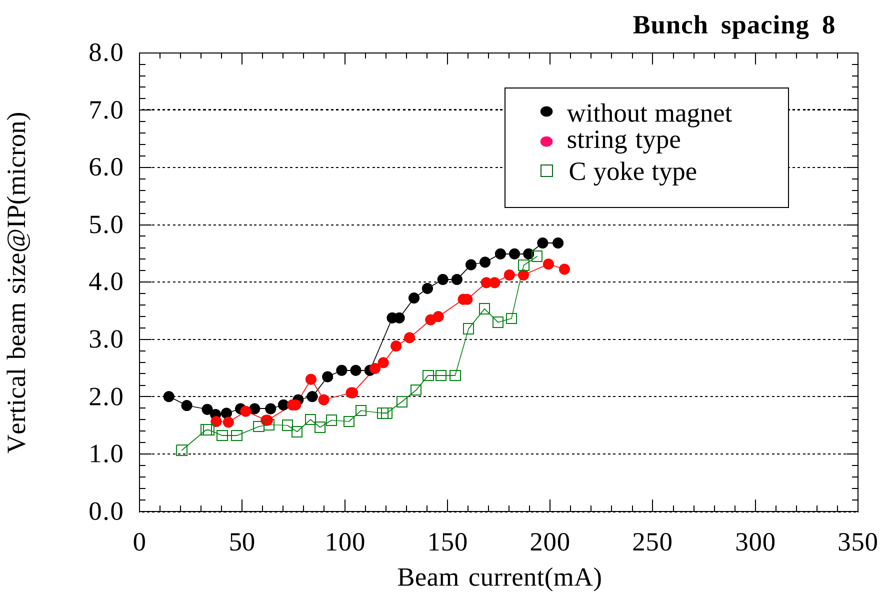


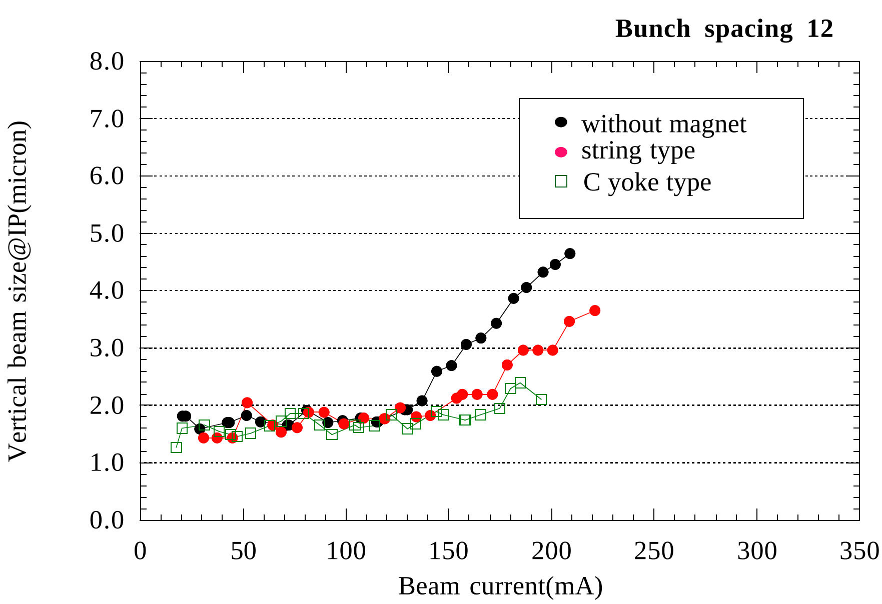
Bz=50G on inner wall of chamber
Bz=14G at center of chamber

By=350G on inner wall of chamber
By=40G at center of chamber




Bunch spacing 4
Vertical beam size@IP(micron)
Beam current(mA)
without magnet
string type
C yoke type
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
0
50
100
150
200
250
300
350


Bunch spacing 8
Vertical beam size@IP(micron)
Beam current(mA)
without magnet
string type
C yoke type
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
0
50
100
150
200
250
300
350


Bunch spacing 12
Vertical beam size@IP(micron)
Beam current(mA)
without magnet
string type
C yoke type
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
0
50
100
150
200
250
300
350

- Two hypotheses are proposed to explain why the effect of the magnets are not dramatic if the blow-up is caused by the electron cloud.

  1) Reflective light hits the inner-lateral side of the chamber where the magnets are not attached and it generates the electrons.

  2) High energy photoelectrons (several keV) ,which are not swept out by the magnetic field, are produced due to shallow incident angle.

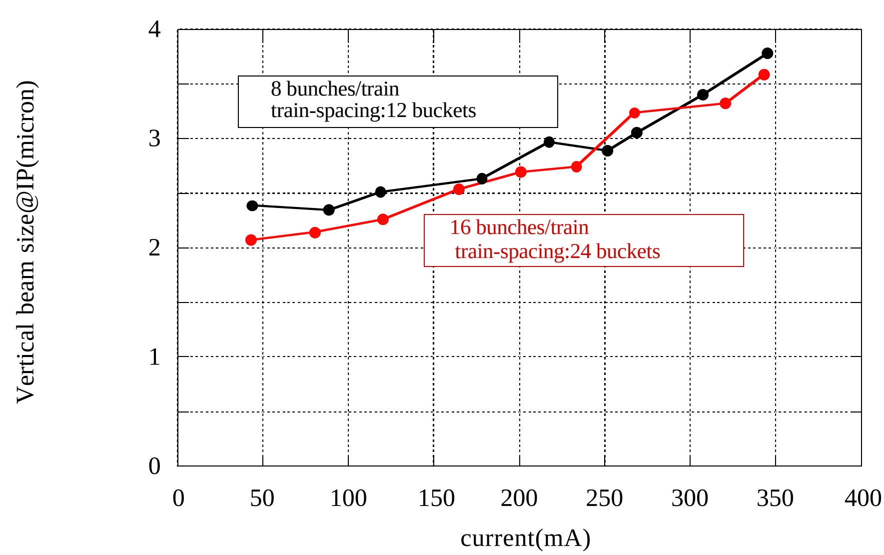
To examine the hypotheses,

1) the measurement of the current through BPM electrodes are in progress and

2) the measurement of reflectivity of light and energy distribution of photoelectrons is planned at KEK PF.

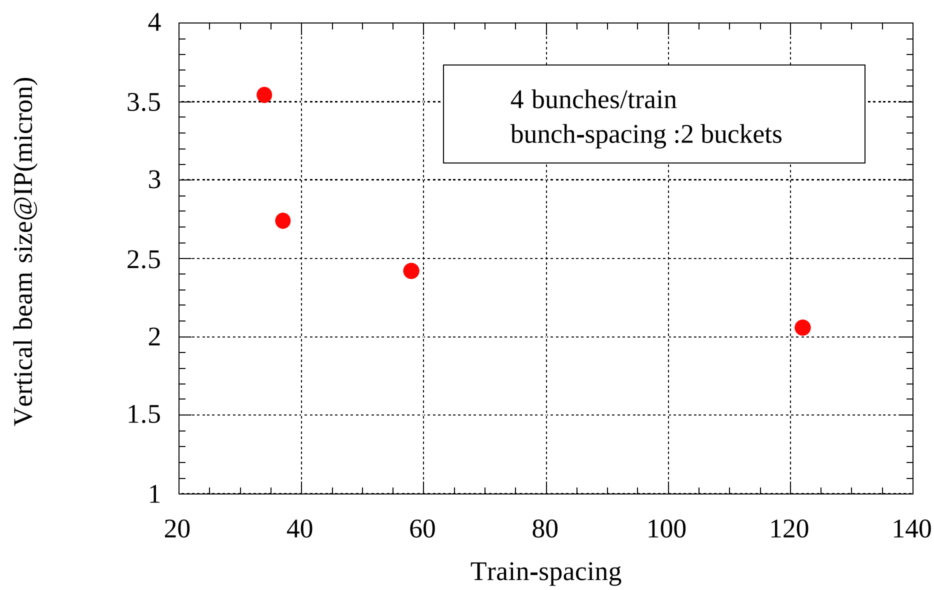
v) Fill pattern

- Short and many bunch trains were tried expecting the blow-up would stop before saturation.
- Bunch current and the number of bunches were set to 0.5mA and about 1000 respectively, because actual operation uses these parameters. To accommodate these constraints and to take a long train spacing of 24 buckets, we set the bunch spacing to 2 rf buckets.
- The measurement showed that the blow-up still remained. This fact implies train spacing is not enough to suppress the blow-up.



• In fact a measurement showed that the blow-up was remarkable if the train spacing was shorter than 35 rf buckets.

At present we do not find a fill pattern to suppress the blow-up.



4.Summary

1)A blow-up of the vertical beam size is observed in -the KEKB positron ring (LER). The beam size starts to increase at a threshold beam current and is almost doubled by 300 mA under typical operating conditions. The blow-up is one of the most serious problems limiting the luminosity of KEKB.

2)The beam break up/head tail instability in a bunch caused by the electron cloud is suspected as the cause of the blow-up.
At present there is no clear experimental evidence against this hypothesis.

3)We are planning

- the measurement of reflectivity of light and energy distribution of photoelectrons is planned at KEK PF,
- putting more C yoke permanent magnets in the ring,
- observation of bunch shape by the streak camera,
- measurement of the current through BPM electrodes and so on.