Beam instability issues

10th Feb. 2000 KEKB-MAC

H. Fukuma, KEK

1. Single bunch effect

2. Transverse coupled bunch instability

3. Vertical beam blow-up

4. Summary

1. Single bunch effect

1.1 Longitudinal

- Loss factor was measured observing the dependence of synchronous phase on bunch current.
- Imaginary part of longitudinal coupling impedance was estimated from the data of bunch lengthening by the spectrum method.

- Result

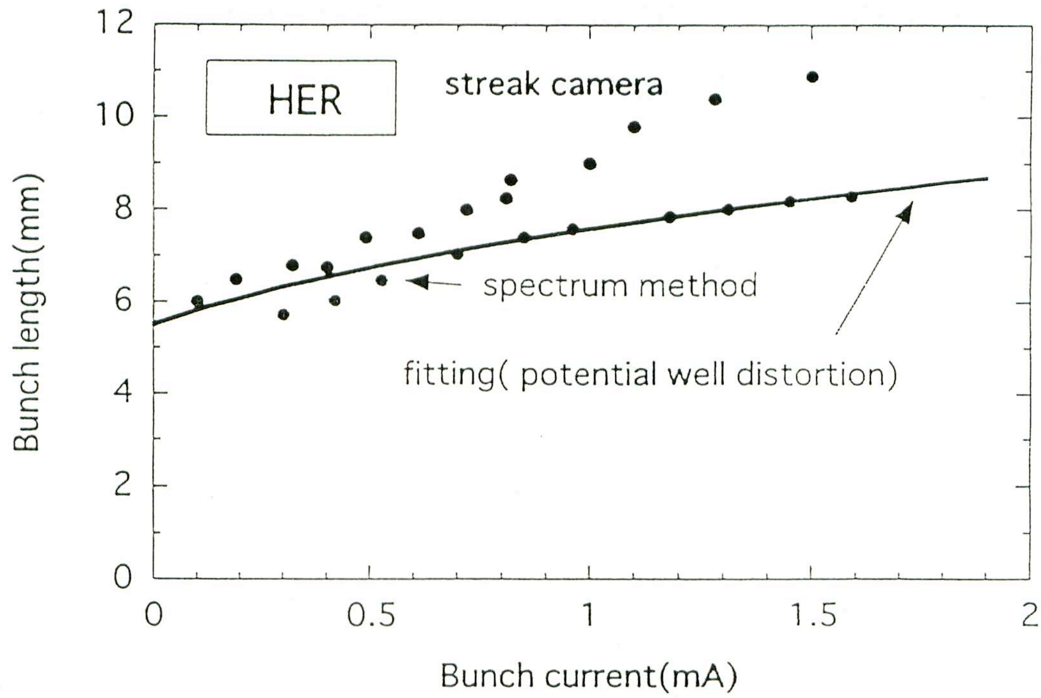
HER

	measurement	design
k(V/pC)	67 ± 16	28
$ImZ_{\parallel}/n(\Omega)$	0.076 ± 0.006	0.015

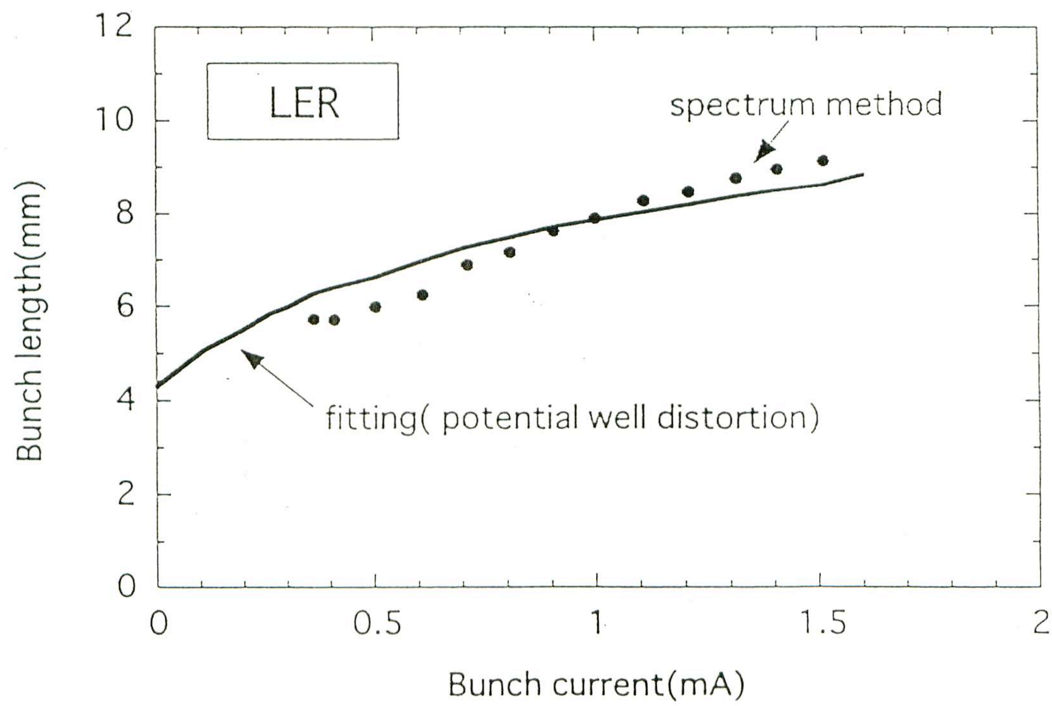
LER

	measurement	design
k(V/pC)	87 ± 30	25
$ImZ_{\parallel}/n(\Omega)$	0.072 ± 0.0011	0.015

Discrepancy is found between measured and design impedance.



HER
streak camera
spectrum method
fitting(potential well distortion)
Bunch length(mm)
Bunch current(mA)



LER
spectrum method
fitting(potential well distortion)
Bunch length(mm)
Bunch current(mA)

1.2 Transverse

- Transverse impedance was estimated by the measurement of the betatron tune shift as a function of bunch current.

- Result

HER

	measurement	
	hor.	ver.
Z_T (kΩ/m)	66.0	268.0

LER

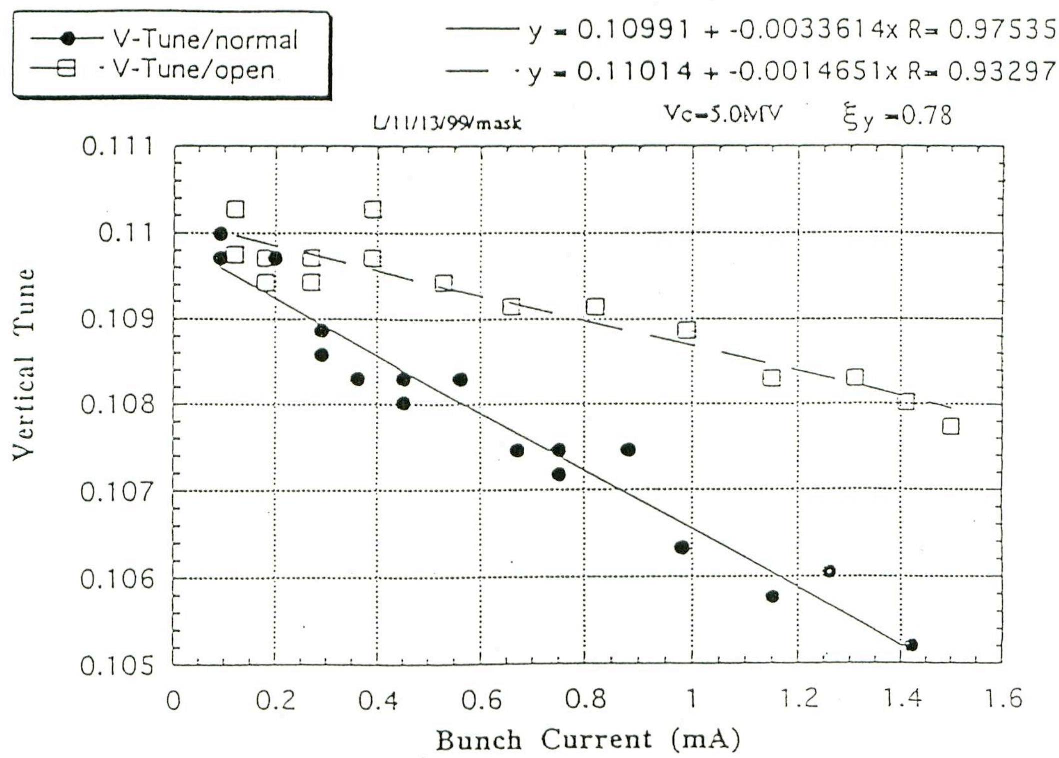
	measurement	
	hor.	ver.
Z_T (kΩ/m)	36.9 (mask:close)	80.6 (mask:close)
	24.6 (mask:open)	33.2 (mask:open)

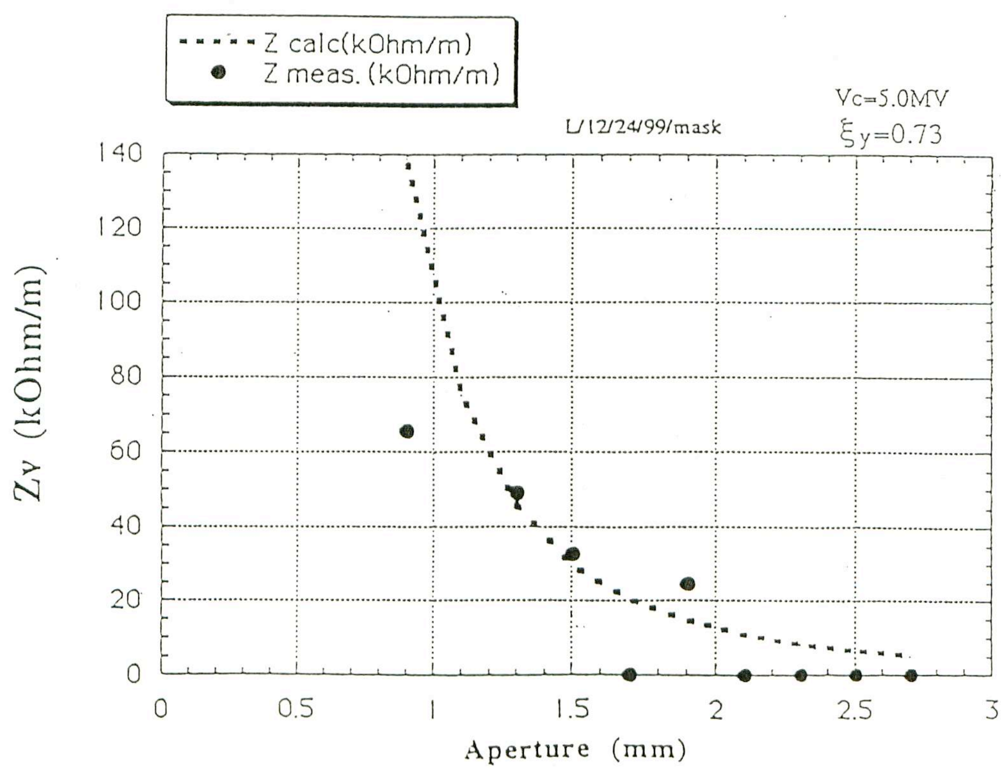
In LER half of the vertical impedance comes from masks which protect Belle detector from the background noise.

- Mode frequency vs. bunch current

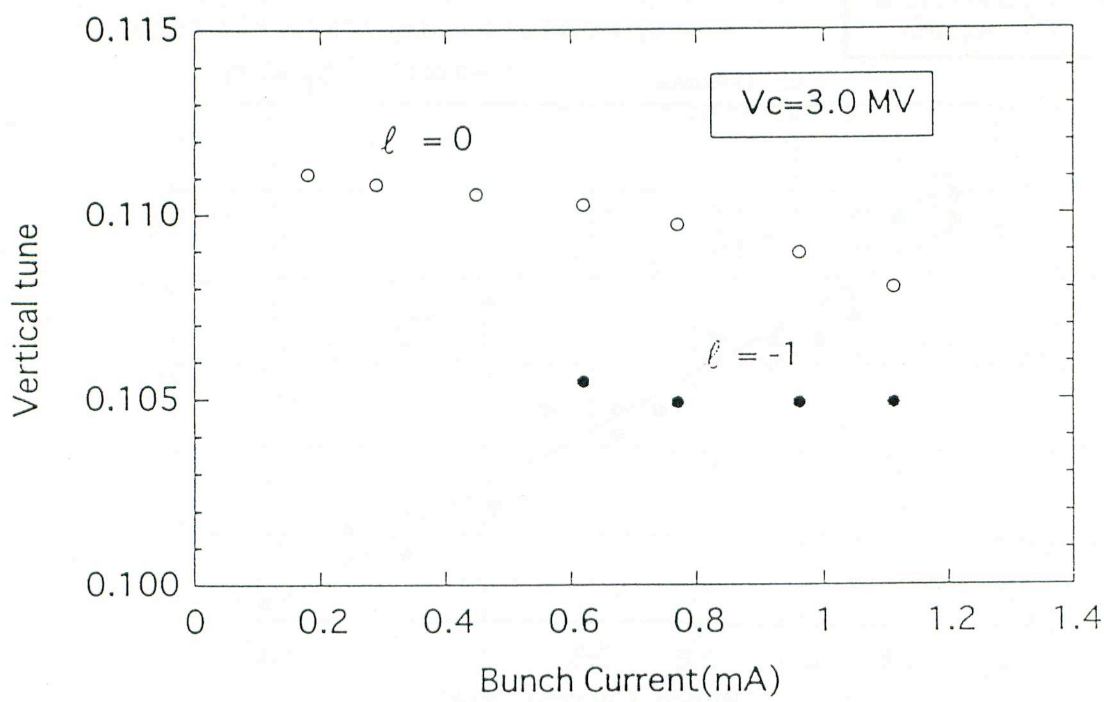
Mode frequency shift of l=0 and -1 mode was observed in LER.

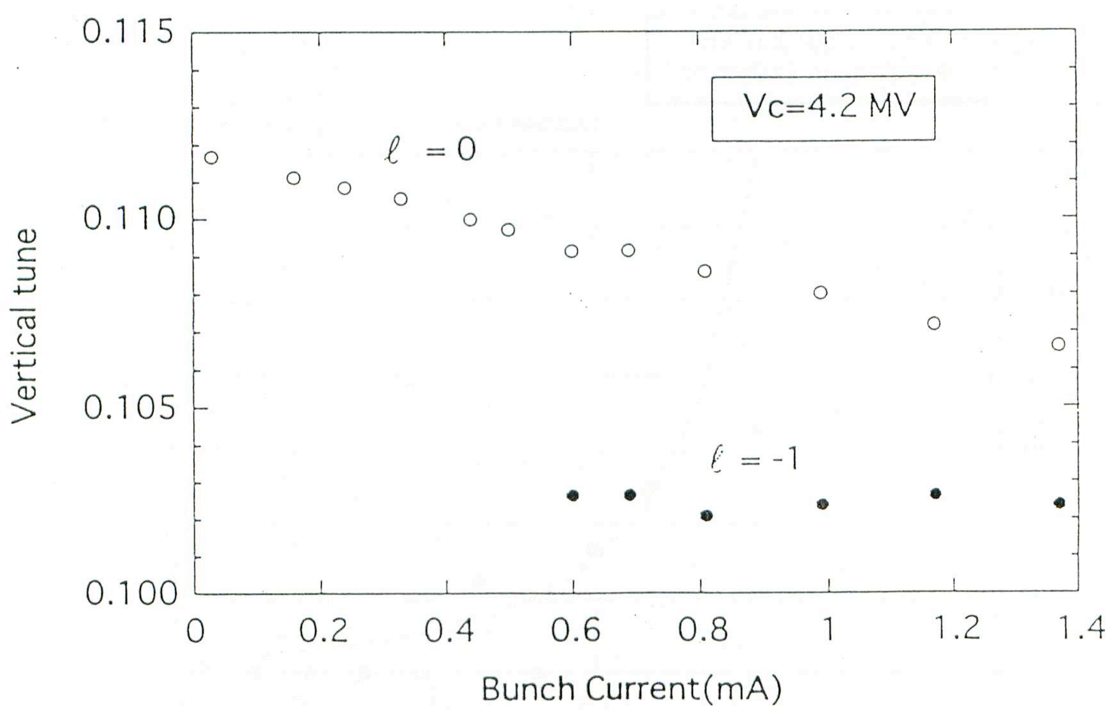
LER


V-Tune/normal
V-Tune/open
y = 0.10991 + -0.0033614x R= 0.97535
y = 0.11014 + -0.0014651x R= 0.93297
L/11/13/99/mask
Vc=5.0MV
ξy =0.78
Vertical Tune
Bunch Current (mA)
0.111
0.11
0.109
0.108
0.107
0.106
0.105
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6


Z calc(kOhm/m)
Z meas. (kOhm/m)
L/12/24/99/mask
Vc=5.0MV
ξy=0.73
Zv (kOhm/m)
Aperture (mm)
140
120
100
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3

Mode frequency vs. bunch current (LER)





2. Transverse coupled bunch instability

2.1 General

- In usual colliding operation such as,

  Fill pattern : 32/36/4 (trains/bunches in a train/bunch spacing in the unit of rf bucket)
  Beam current : 320 mA (HER), 560 mA(LER),

  coupled bunch instability(CBI) is completely suppressed by the bunch feedback system and large chromaticity. The chromaticity ξ_x / ξ_y is typically 5 / 8 in both rings.

- Largest current stored so far after Belle roll-in is

  600 mA in LER and 435 mA in HER.

  In LER the current is not limited by CBI. It is regulated to avoid the damage to the hardware.

  In HER beam loss occurs at the tail of a series of trains around 435 mA. CBI may be the cause of the beam loss.

2.2 Observation of CBI at large current

- In an experiment trying to store high beam current, bunch oscillation was measured by the Bunch Oscillation Recorder (single pass BPM + memory).
  BOR measures the transverse bunch position for 40 ms after turn-off the bunch feedback system.

- The beam conditions were,

  Fill pattern in both rings :
  32/36/4 (trains/bunches in a train/bunch spacing in the unit of rf bucket)
  Beam current:
  435 mA in HER, 600 mA in LER

•Result

1) Horizontal oscillation is much stronger than vertical in both rings.

2) As for the effect of train gap on horizontal oscillation to prevent CBI between trains,

it has an effect in LER but has almost no effect in HER.

3) Growth time

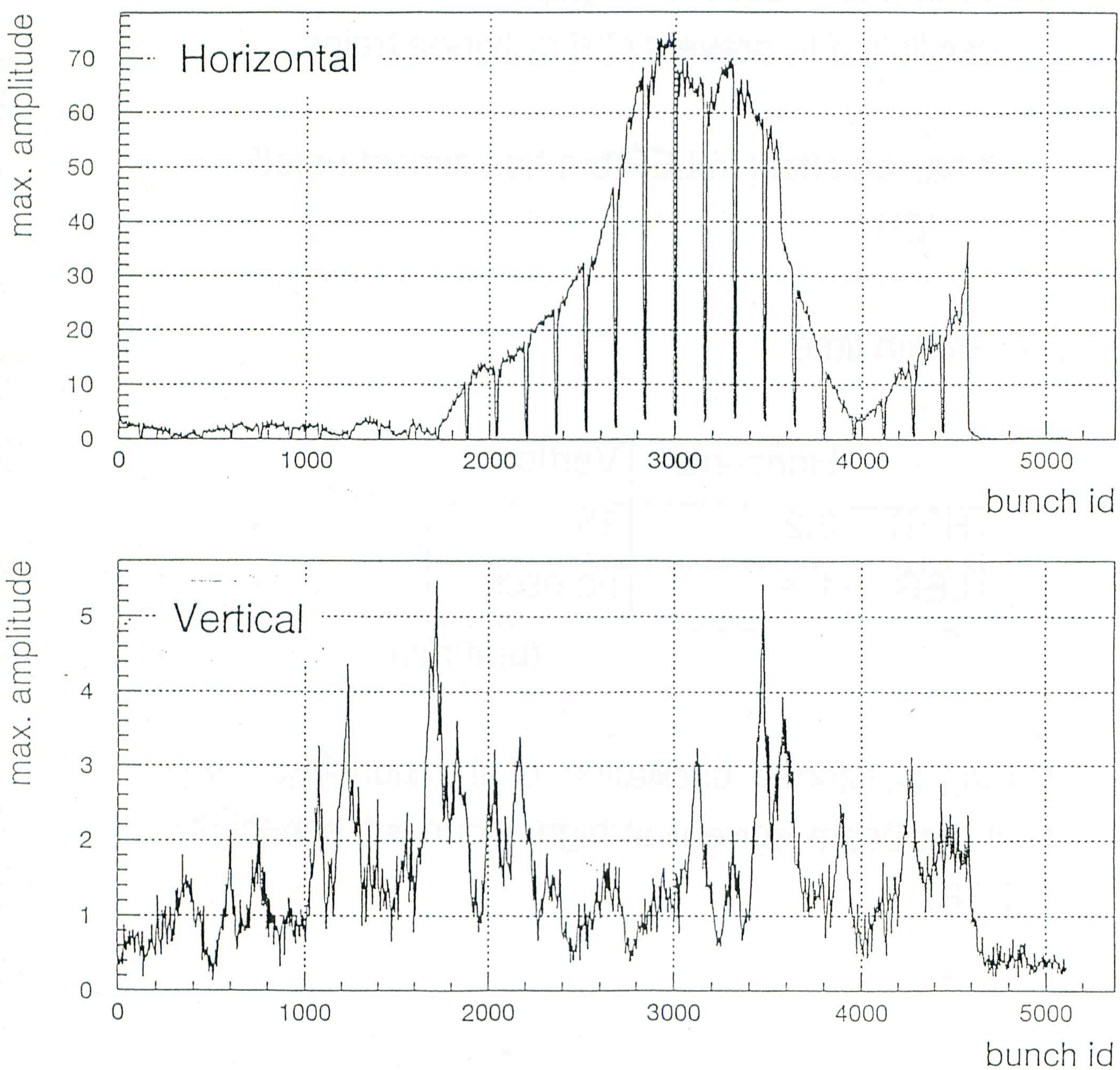
	Horizontal	Vertical
HER	3.2	13
LER	1.3	no osci.

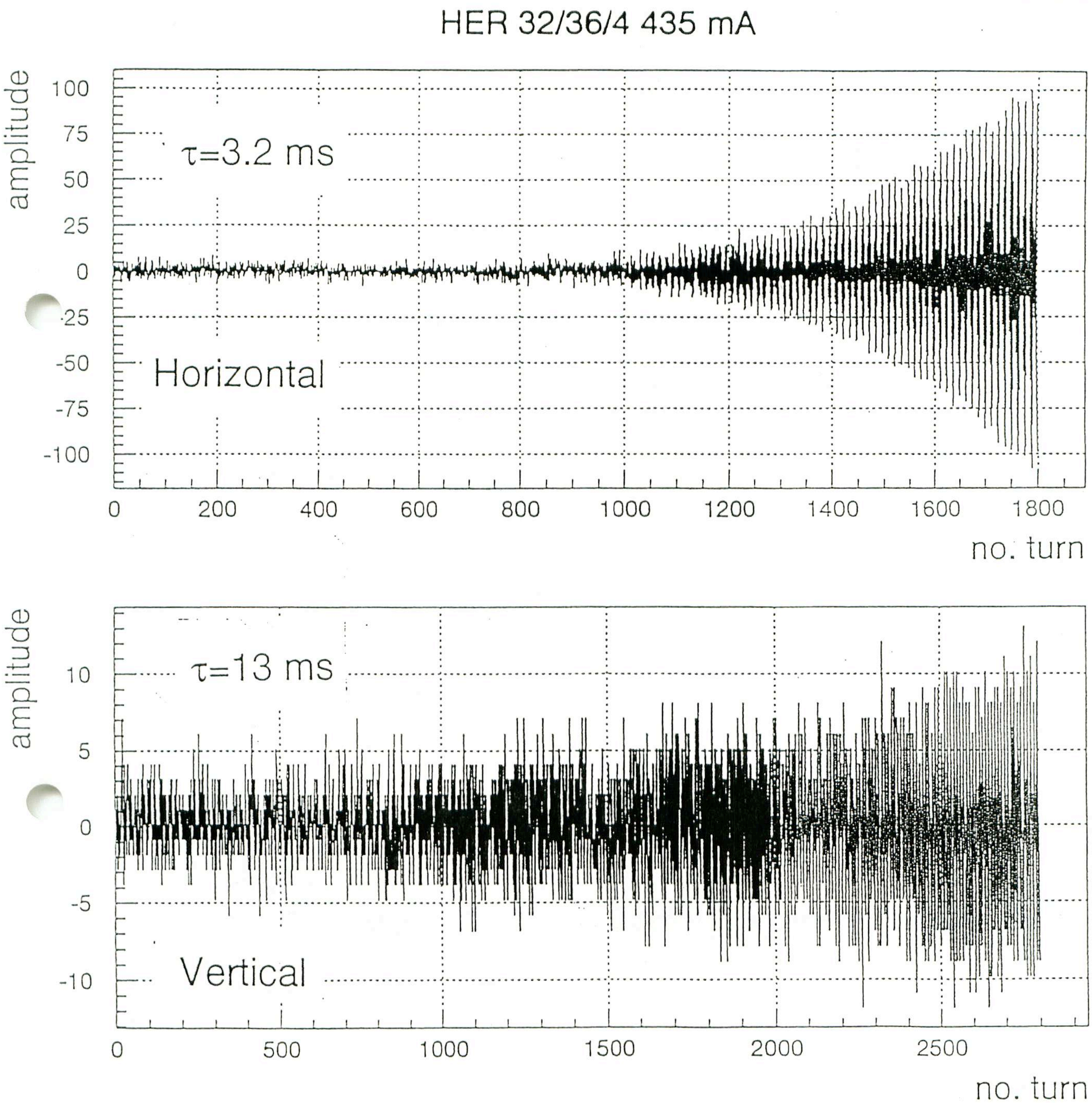
(unit:ms)

Strong horizontal oscillation of the bunches may limit the beam current at higher current especially in LER.

:0/02/07 02.08

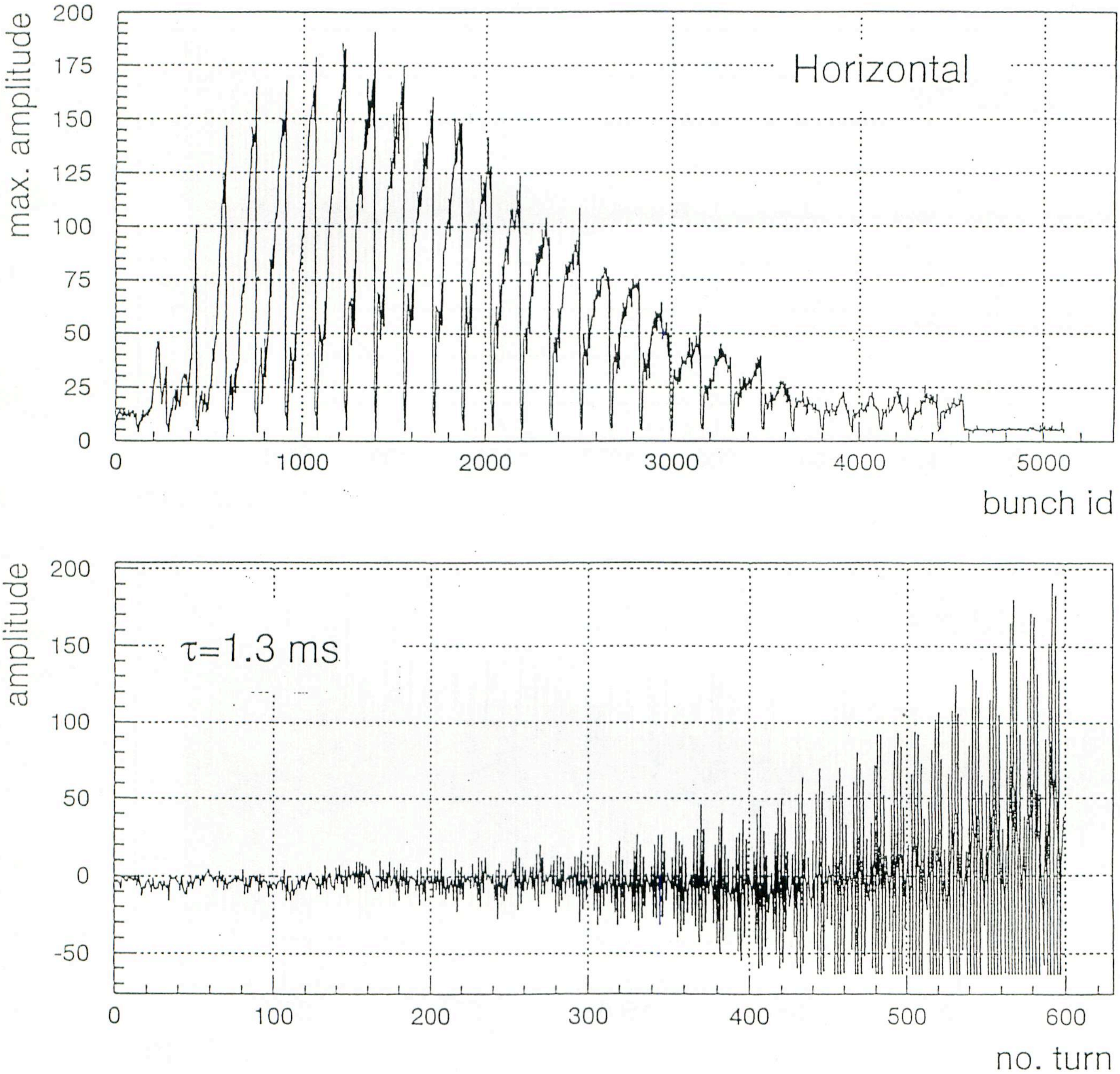
HER 32/36/4 435 mA




HER 32/36/4 435 mA
amplitude
τ=3.2 ms
Horizontal
100
75
50
25
0
-25
-50
-75
-100
0
200
400
600
800
1000
1200
1400
1600
1800
no. turn
amplitude
τ=13 ms
Vertical
10
5
0
-5
-10
0
500
1000
1500
2000
2500
no. turn

:0/02/07 10.52

LER 32/36/4 600 mA



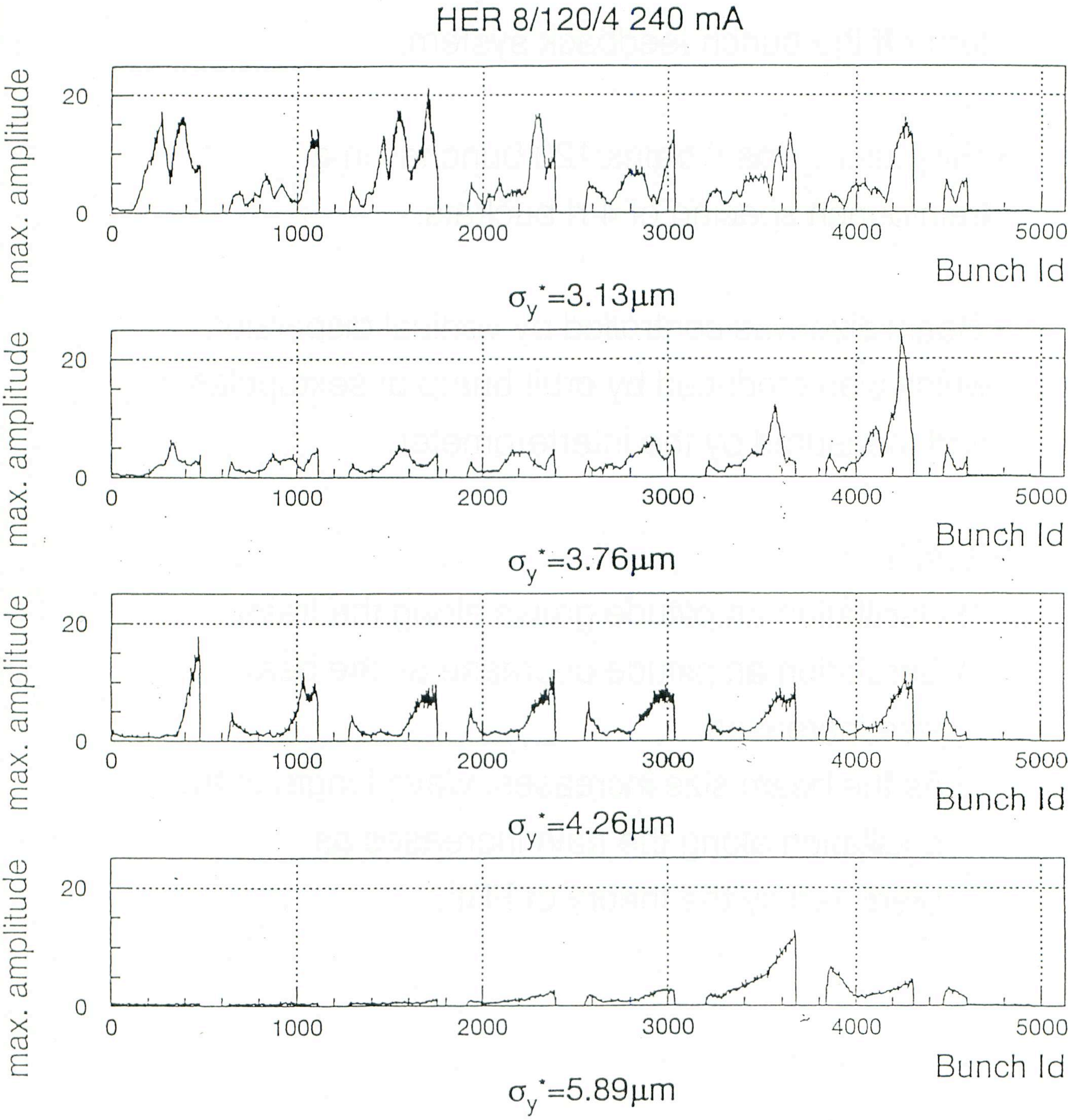
2.3 Observation of fast beam-ion instability in HER

- Vertical bunch oscillation was measured as a function of vertical beam size by the BOR after turn-off the bunch feedback system.

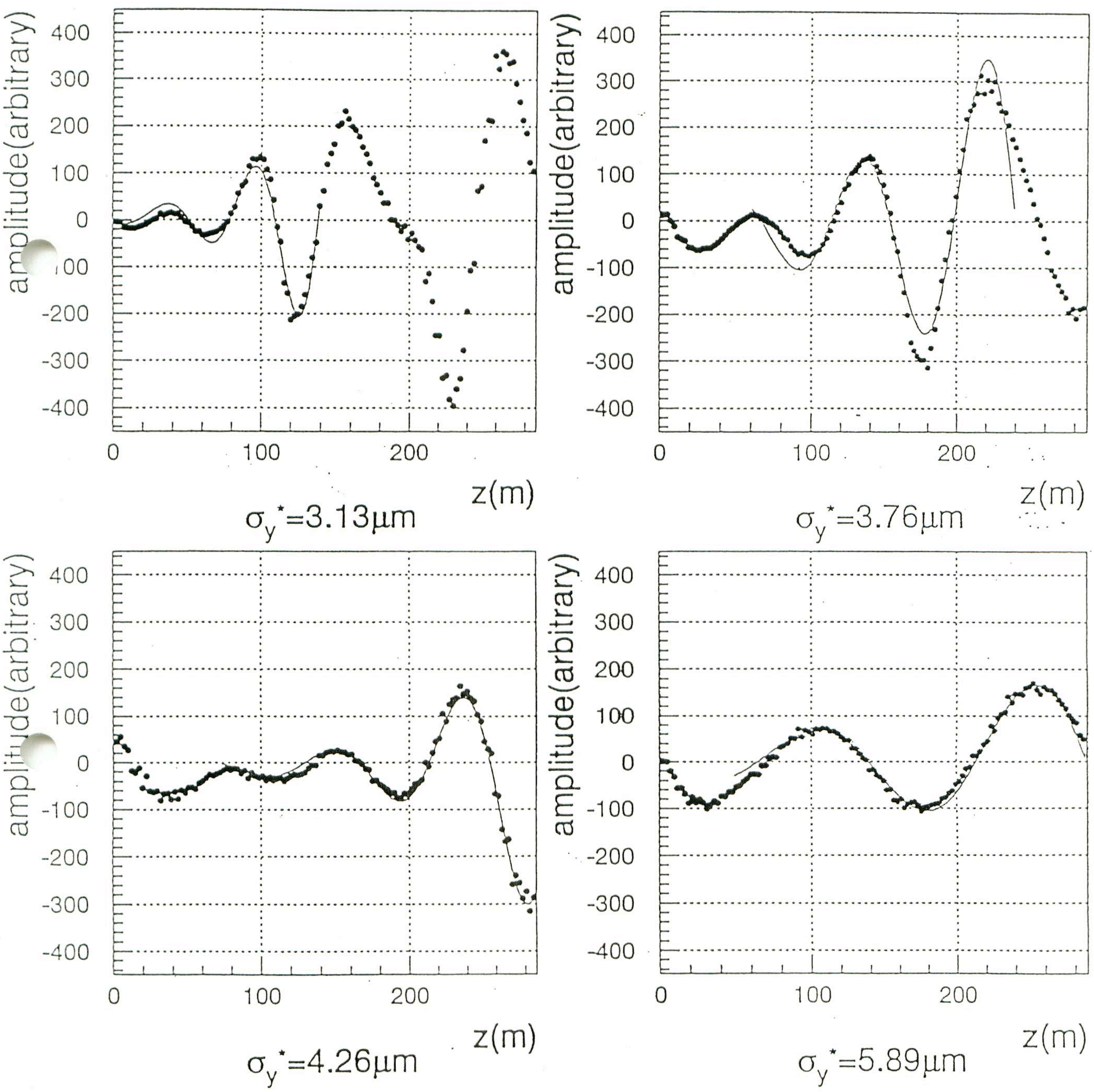
- Fill pattern was 8 trains/120 bunches in a train/bunch spacing of 4 rf buckets.

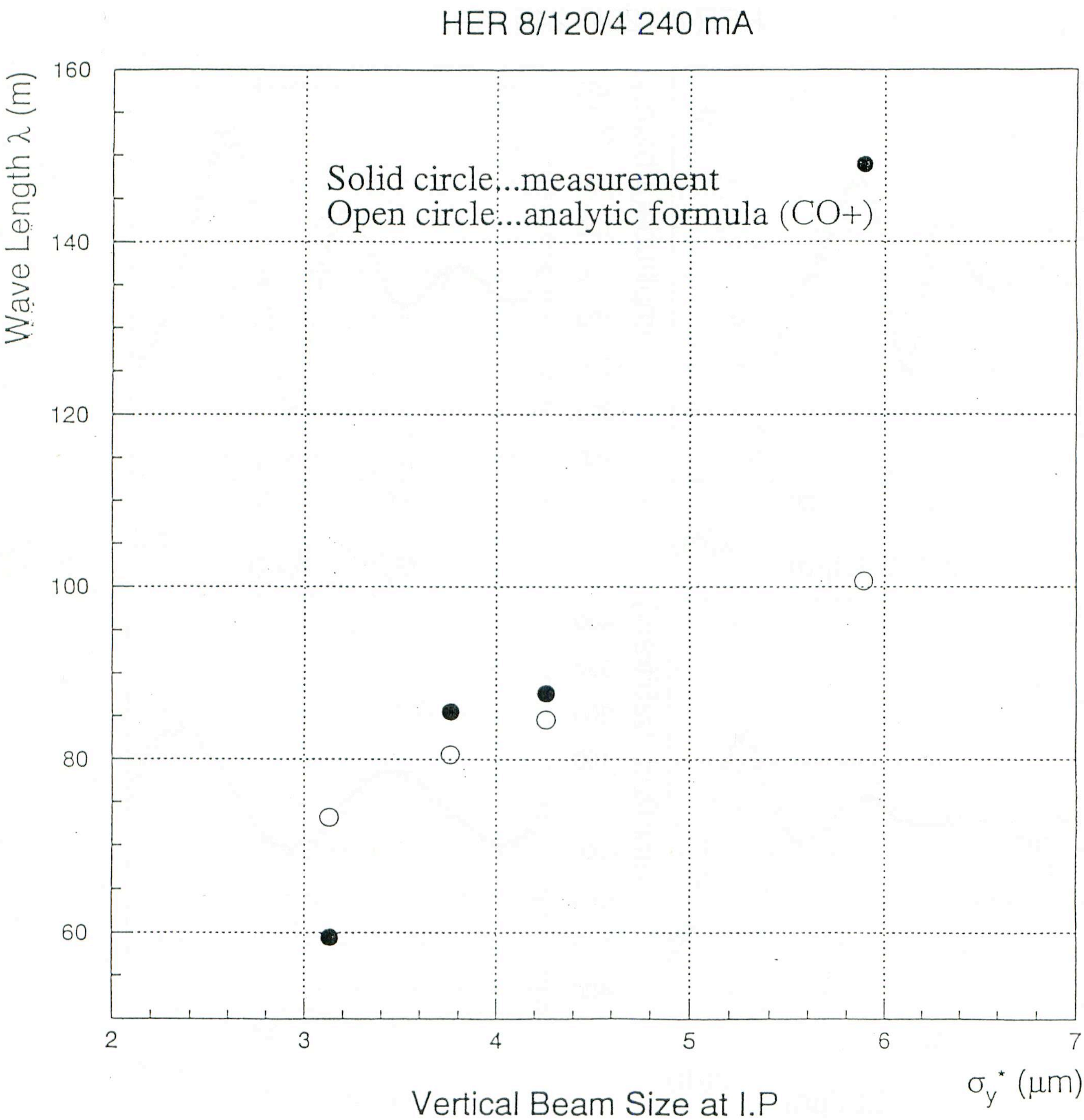
- Beam size was controlled by vertical dispersion which was produced by orbit bump at sextupoles and measured by the interferometer.

- Result
  1) Oscillation amplitude grows along the train.
  2) Oscillation amplitude decrease as the beam size increases.
  3) As the beam size increases, wave length of the oscillation along the train increases as predicted by the theory of FBII.


HER 8/120/4 240 mA
max. amplitude
0
20
0
1000
2000
3000
4000
5000
Bunch Id
σ_y^*=3.13μm
σ_y^*=3.76μm
σ_y^*=4.26μm
σ_y^*=5.89μm

HER 8/120/4 240 mA





HER 8/120/4 240 mA
Solid circle...measurement
Open circle...analytic formula (CO+)
Wave Length λ (m)
160
140
120
100
80
60
2
3
4
5
6
7
Vertical Beam Size at I.P
σy* (μm)

3. Vertical beam blow-up

3.1 Vertical beam blow-up in LER

- 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.

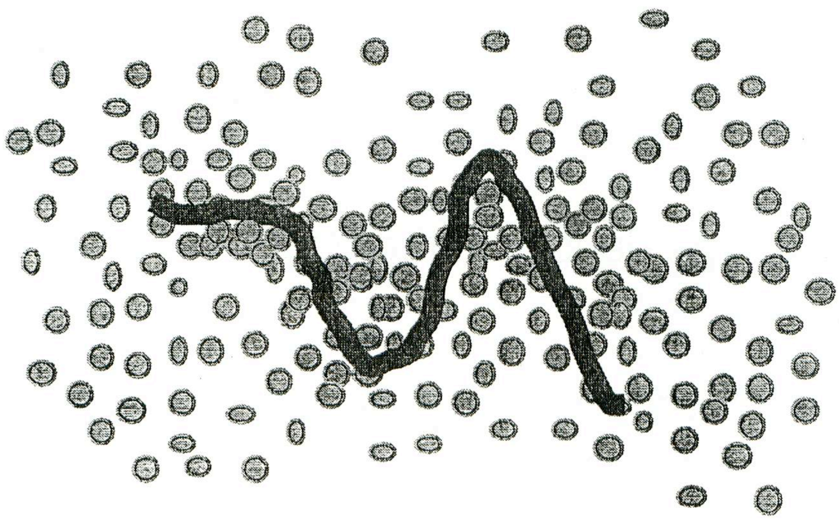
3.1.1 Characteristics of beam blow-up observed by the interferometer

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 between 5 and 8.
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.

3.1.2 Beam break-up(BBU) instability by the photoelectron cloud

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

A. Model <u>(F. Zimmermann, K. Ohmi)</u>



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

- Head-tail oscillation in a bunch occurs by the mediation of the cloud (very similar to the fast beam-ion instability).

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.

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

$\Rightarrow n_{\text{cloud, sat}} \approx$ 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.

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

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

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

F. Zimmermann

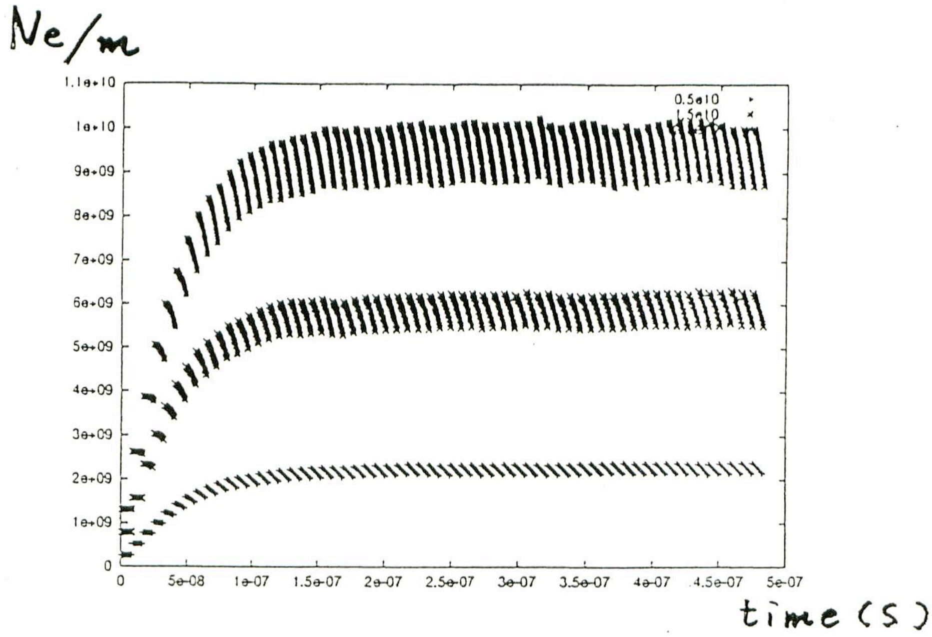


Figure 3: Build up of the electron cloud (total charge per meter) as a function of time (in s) for three different bunch populations and a constant bunch spacing of 4 rf buckets. The photoelectron yield is assumed to be 0.05 per positron per meter.

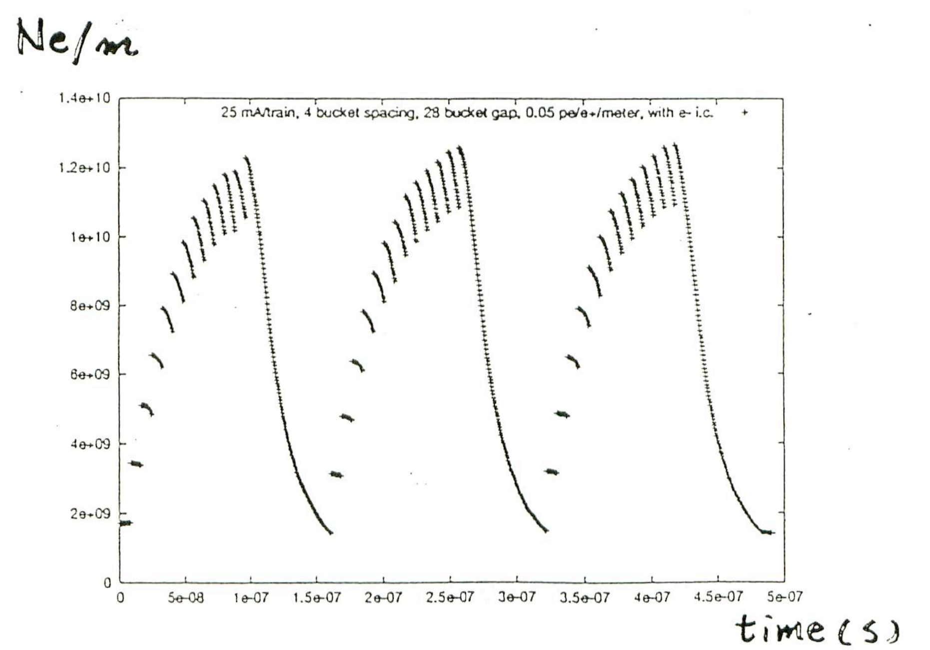
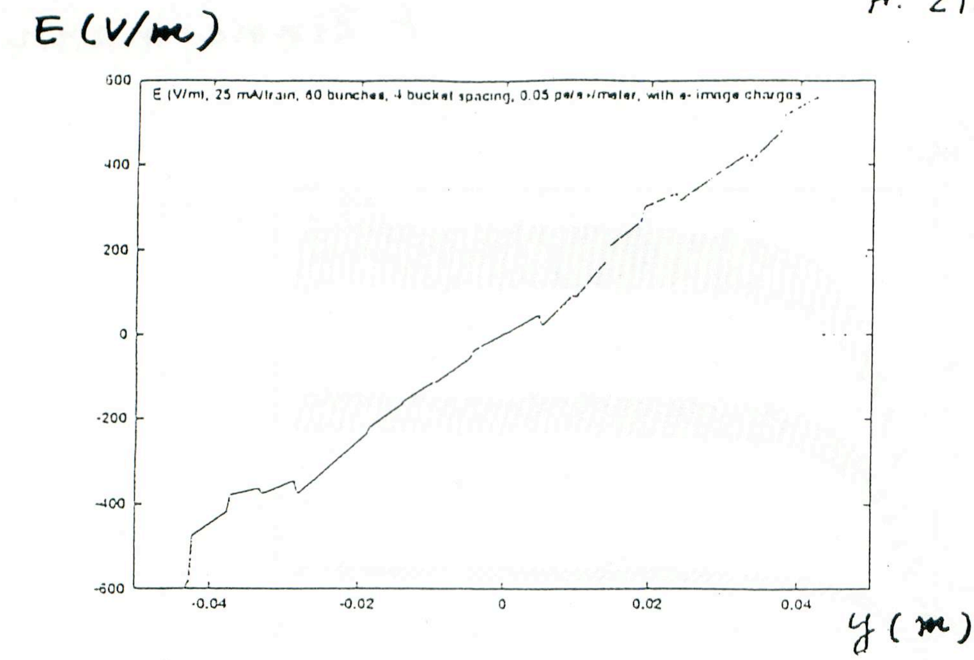


Figure 4: Electron-cloud build up for trains of 13 bunches with 4 bucket spacing, with trains separated by 28-bucket gaps. The electron cloud is cleared almost completely in the gap between trains.

F. Zimmermann



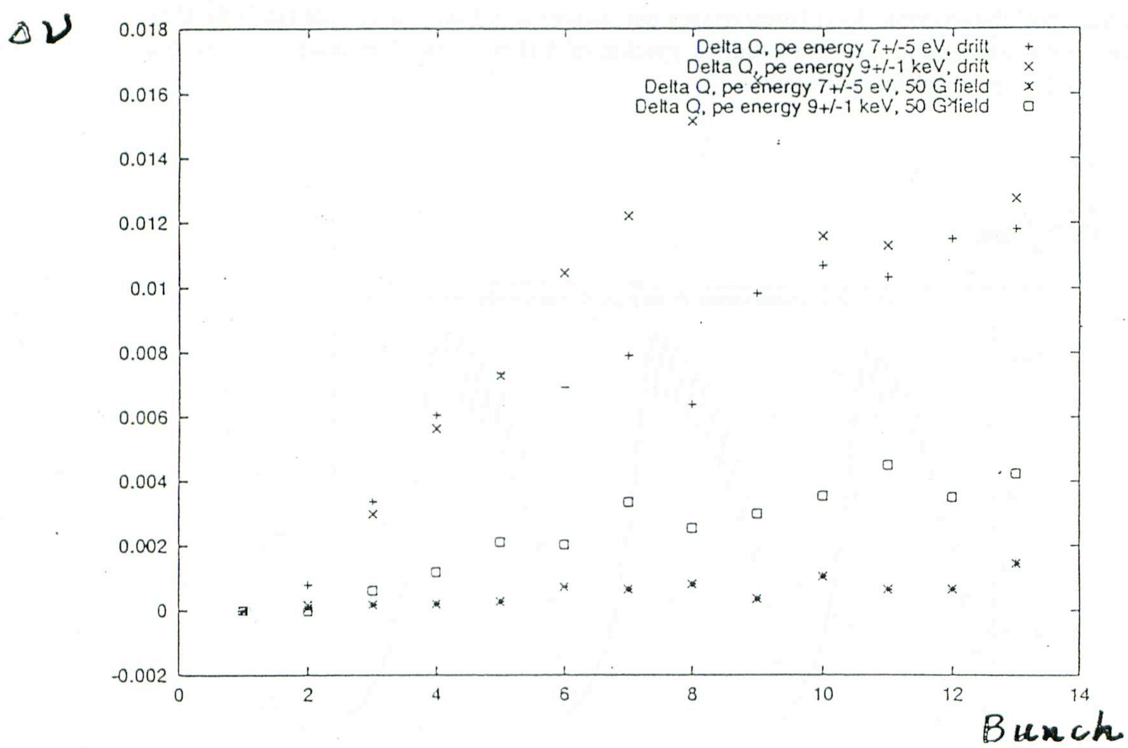


Figure 10: Tune shift ΔQ as a function of bunch number along the train, comparing cases with and without magnetic field and for two different distributions of initial photoelectron energies. The first distribution is centered at 7 eV with 5 eV rms, the second is centered at 9 keV with 1 keV rms width.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

ii) Beam break up

a) Linear theory(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

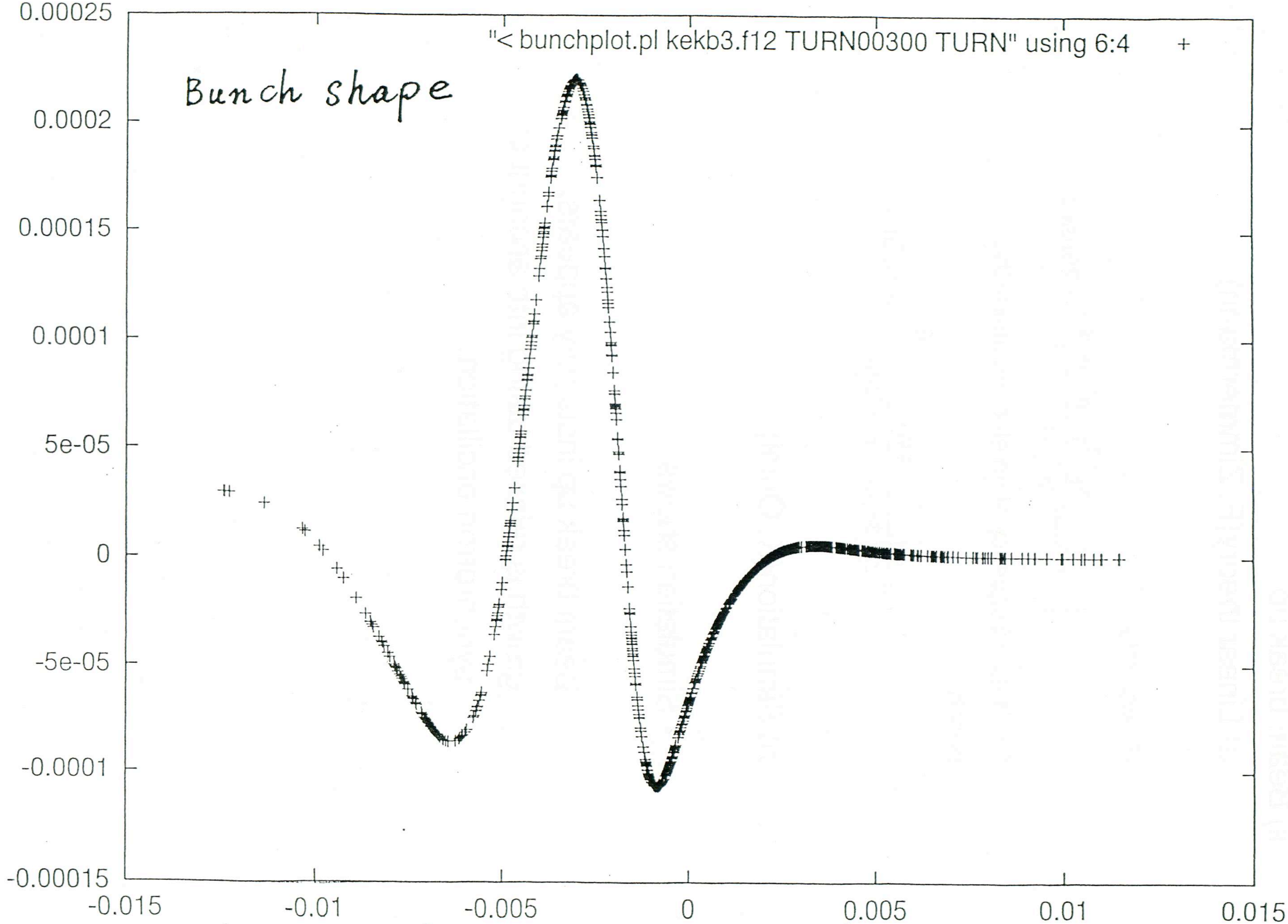
$$f_i = \frac{c}{2\pi}\left[\frac{4N_b r_e}{3\sigma_y(\sigma_x + \sigma_y)\sqrt{2\pi}\sigma_z}\right]^{1/2} \approx 15\text{GHz}$$

b) Simulation(K. Ohmi)

- Simulation shows,

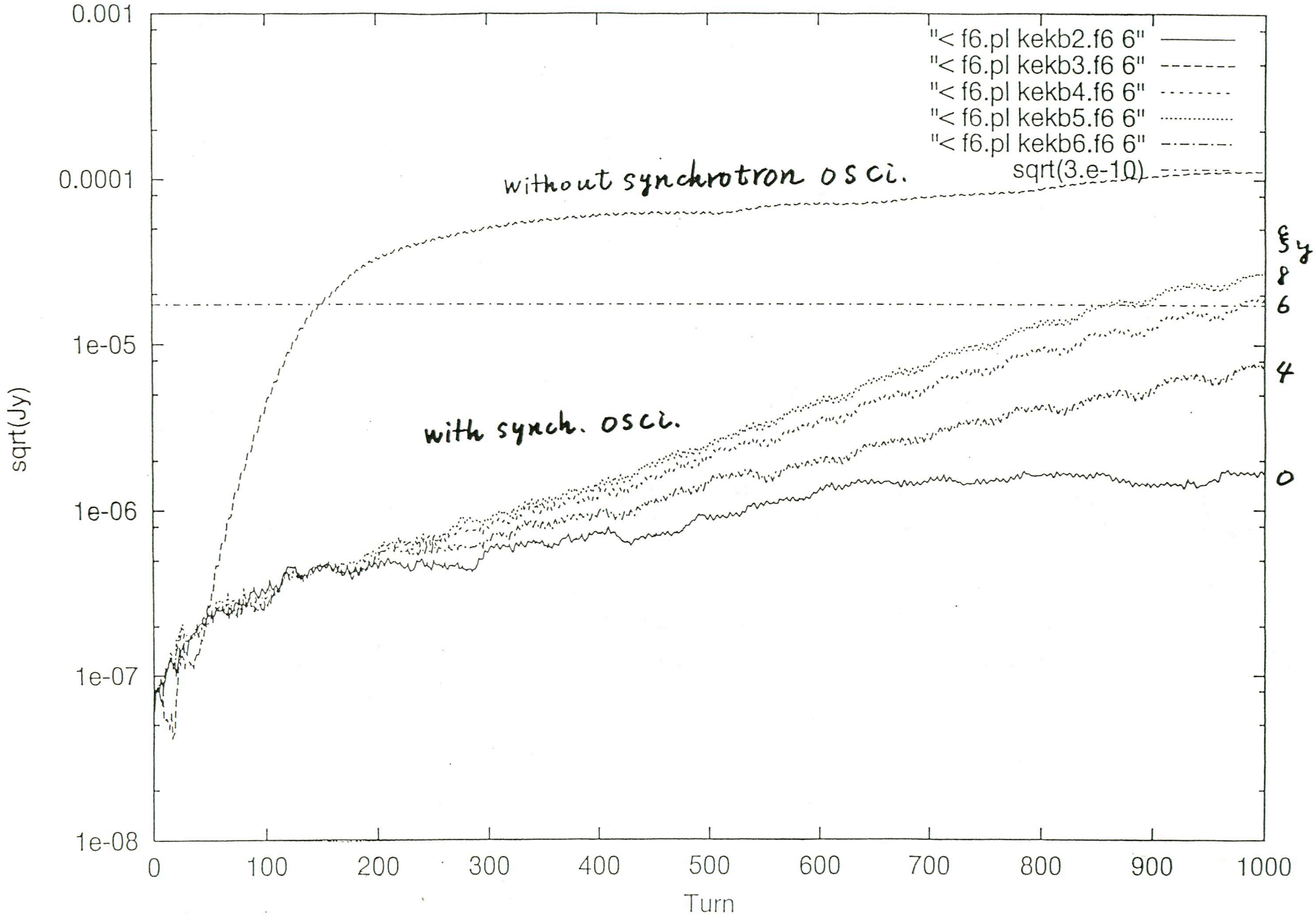
  beam break up instability appears,
  growth is relaxed taking into account of
  synchrotron oscillation.

K. Ohmi



Bunch shape
"< bunchplot.pl kekb3.f12 TURN00300 TURN" using 6:4
0.00025
0.0002
0.00015
0.0001
5e-05
0
-5e-05
-0.0001
-0.00015
-0.015
-0.01
-0.005
0
0.005
0.01
0.015

K. Ohmi



"< f6.pl kekb2.f6 6"
"< f6.pl kekb3.f6 6"
"< f6.pl kekb4.f6 6"
"< f6.pl kekb5.f6 6"
"< f6.pl kekb6.f6 6"
sqrt(3.e-10)
without synchrotron osci.
with synch. osci.
ξy
8
6
4
0
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
sqrt(Jy)
0
100
200
300
400
500
600
700
800
900
1000
Turn

B. Experiment

i) Formation of electron cloud

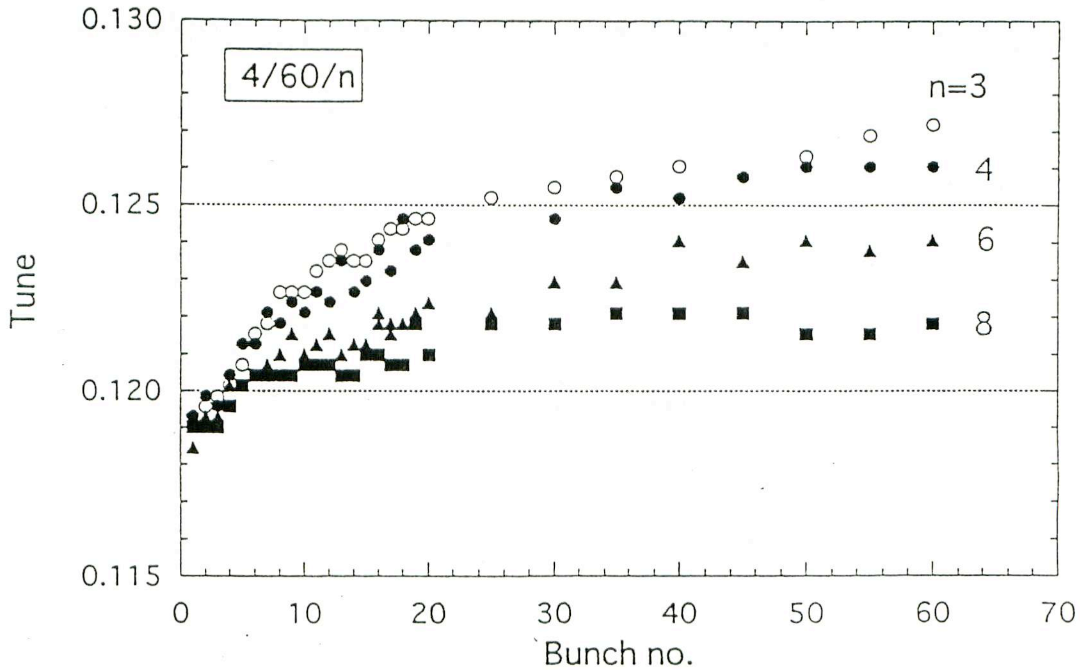
a) Tune along the train

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

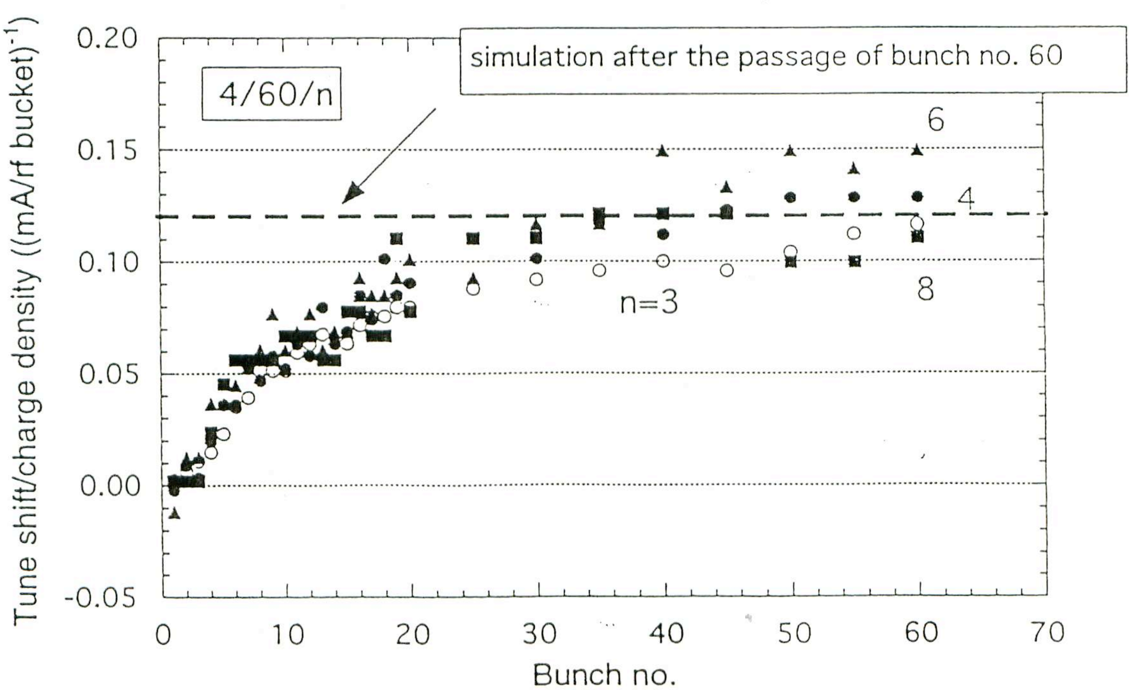
- The data show that

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..



4/60/n
n=3
4
6
8
Tune
0.130
0.125
0.120
0.115
0
10
20
30
40
50
60
70
Bunch no.

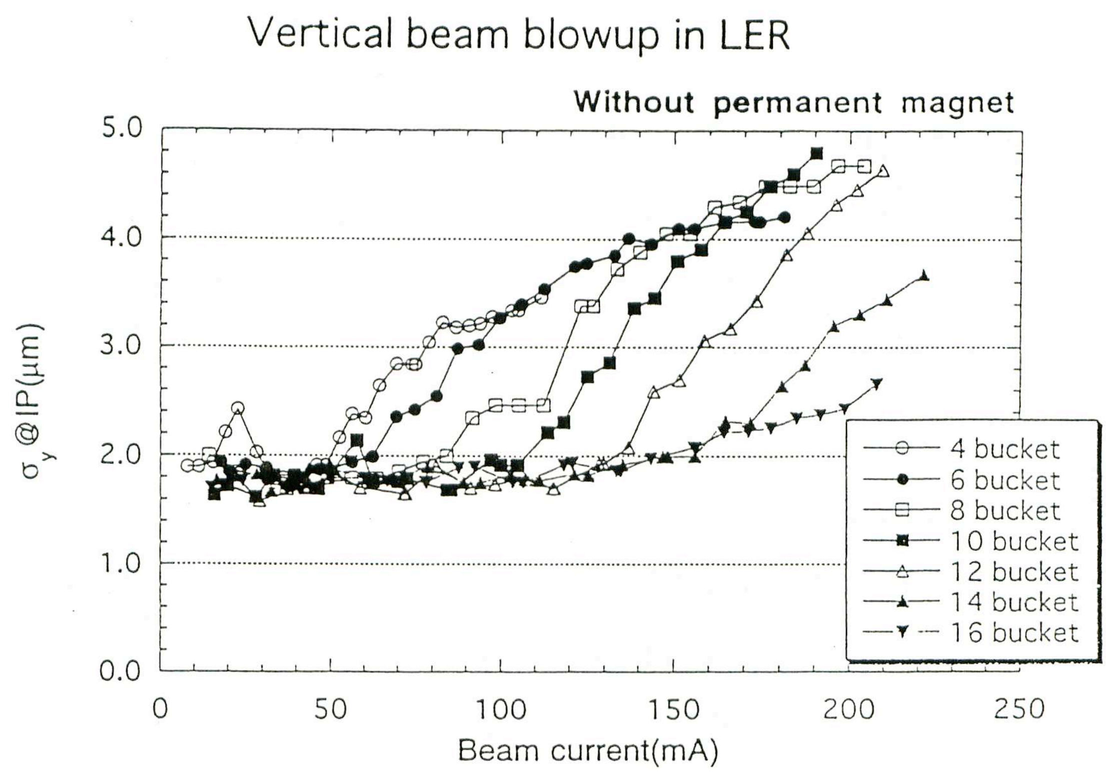


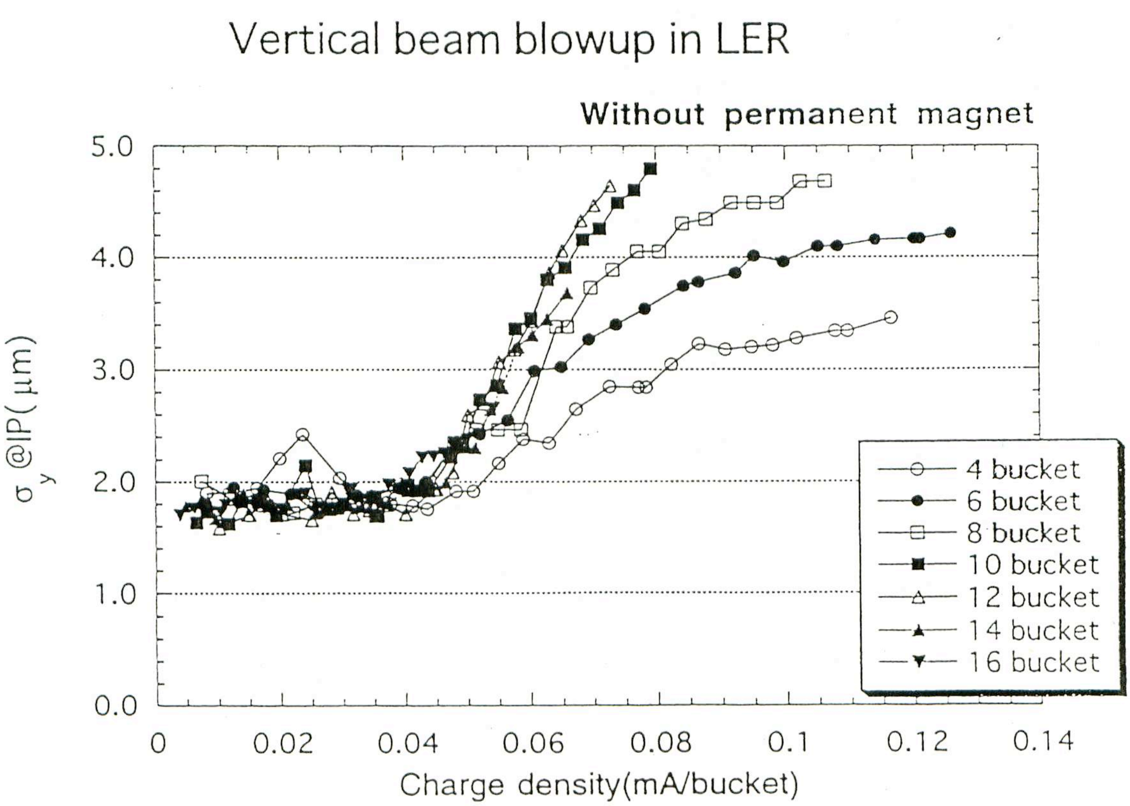
simulation after the passage of bunch no. 60
4/60/n
6
4
n=3
8
Tune shift/charge density ((mA/rf bucket)$^{-1}$)
0.20
0.15
0.10
0.05
0.00
-0.05
0
10
20
30
40
50
60
70
Bunch no.

b) Threshold intensity of the blow-up

- Threshold intensity is determined by the charge density of the beam. This fact supports the BBU model if the blow-up starts at a critical density of the cloud.

  (According to the simulation, density of the cloud is proportional to the charge density of the bunch if neutralization is reached).


Vertical beam blowup in LER
Without permanent magnet
σy @IP(μm)
5.0
4.0
3.0
2.0
1.0
0.0
0
50
100
150
200
250
Beam current(mA)
4 bucket
6 bucket
8 bucket
10 bucket
12 bucket
14 bucket
16 bucket


Vertical beam blowup in LER
Without permanent magnet
σy @IP(μm)
5.0
4.0
3.0
2.0
1.0
0.0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Charge density(mA/bucket)
4 bucket
6 bucket
8 bucket
10 bucket
12 bucket
14 bucket
16 bucket

ii) 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.

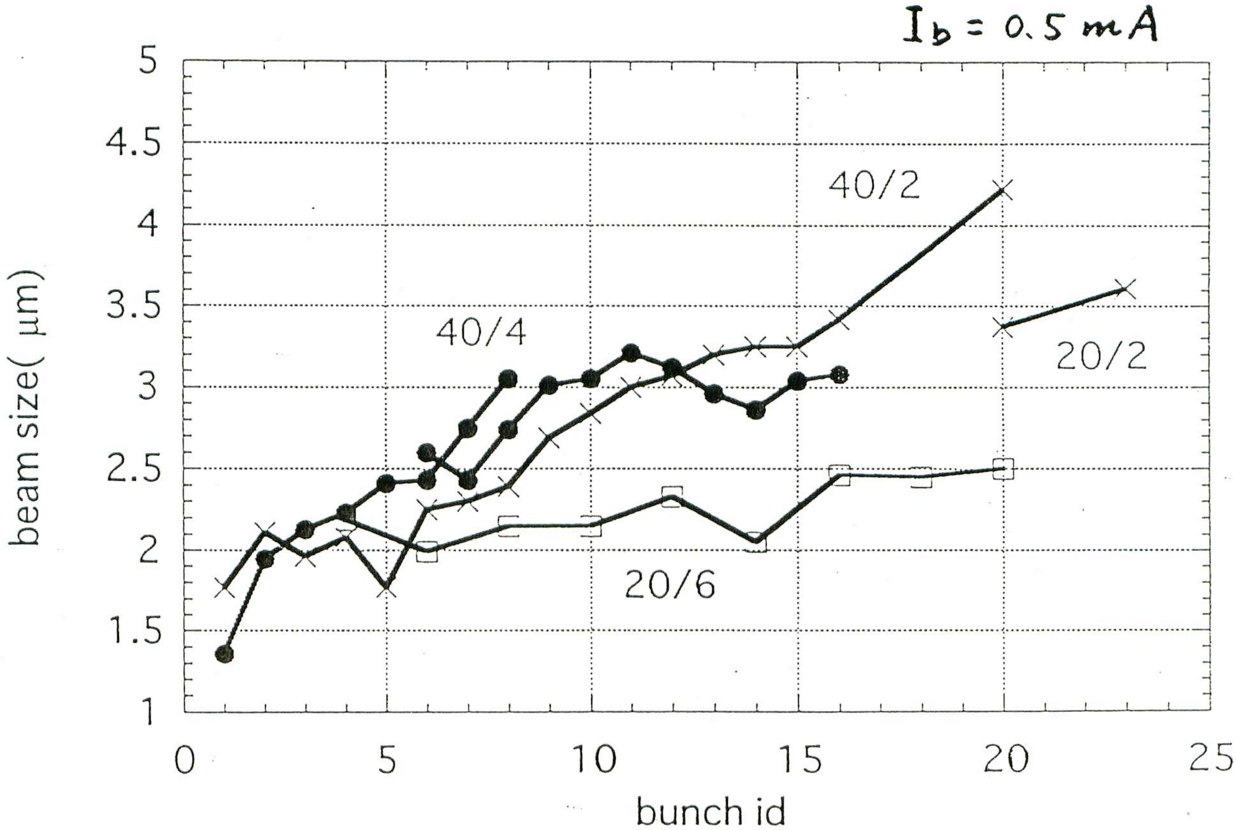
a) Average beam size

- 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

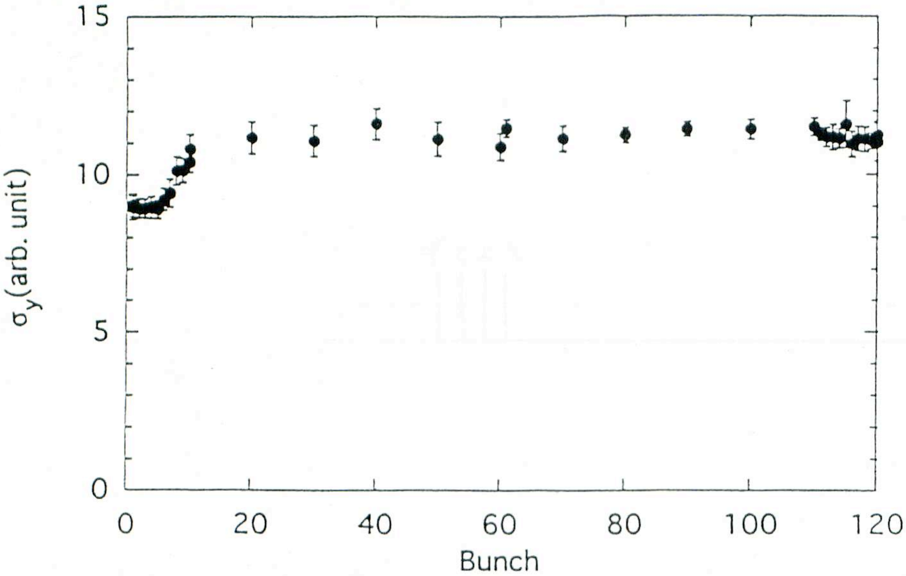
- We are trying the direct measurement of the beam size by the fast gated camera.
- The data shows that the beam size increases along the train and the beam size almost saturates at 20th bunch.
- But a data showed that the blow-up changed after adjusting the focus of the light image. The reason is not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


1 2 3 4
1 2 3 4

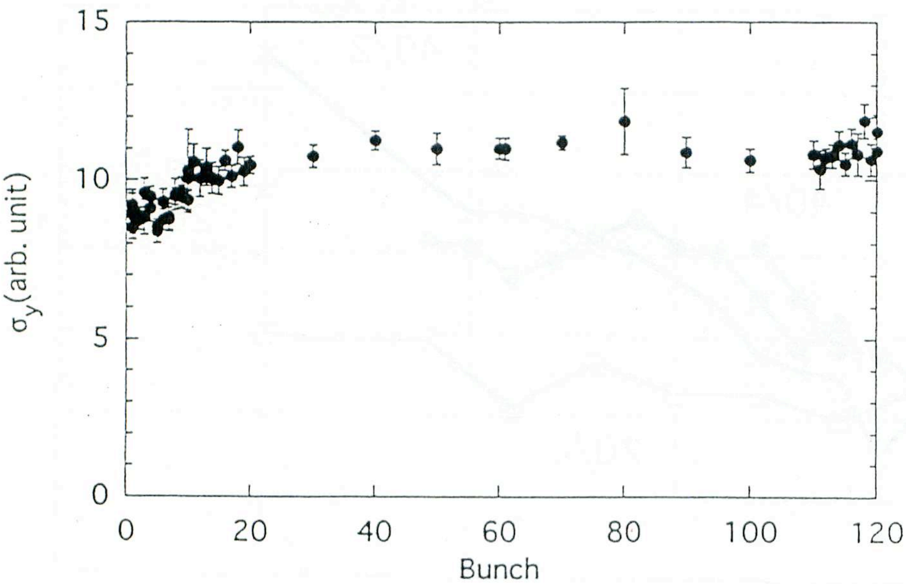

$I_b = 0.5$ mA
beam size(μm)
bunch id
40/2
40/4
20/2
20/6
5
4.5
4
3.5
3
2.5
2
1.5
1
0
5
10
15
20
25

Fast gated camera

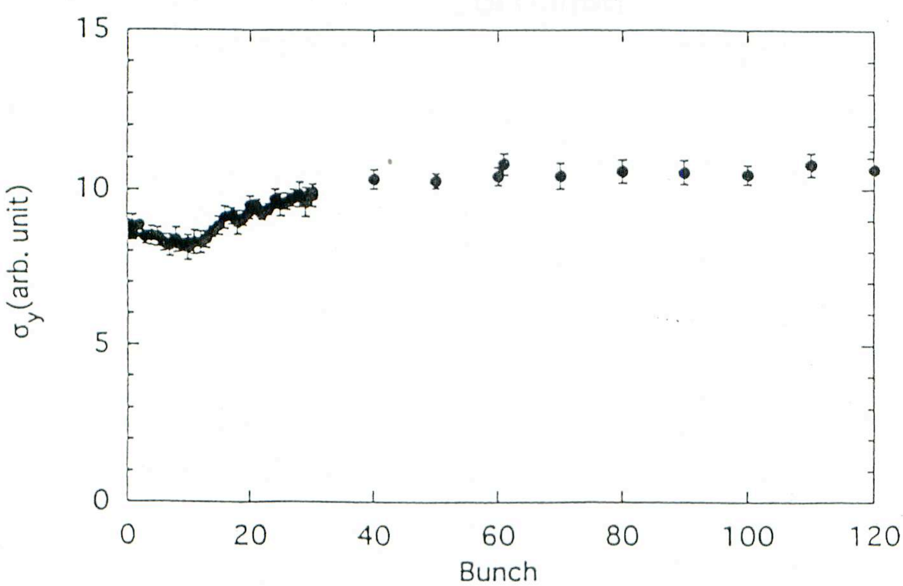
4/120/4 (trains/bunches/spacing) at 150mA without permanent magnets



4/120/4 at 150mA with string type magnets



4/120/4 at 150mA with C-yoke type magnets



iii) 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.

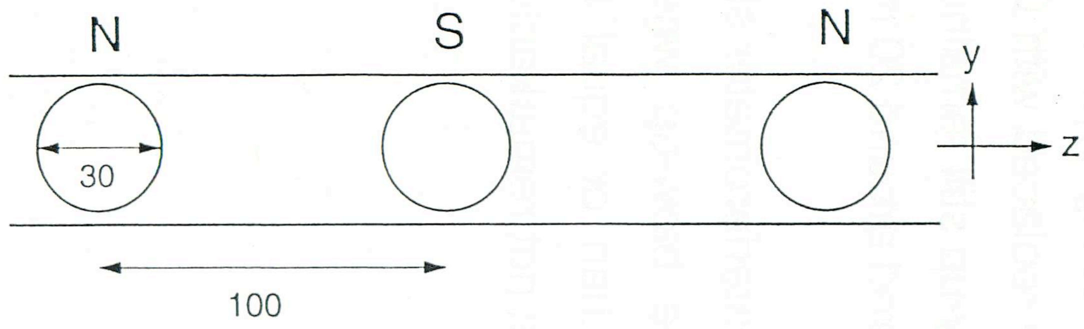
- The magnets are attached in every 10 cm of the LER drift space within 7 m downstream from bending magnets.

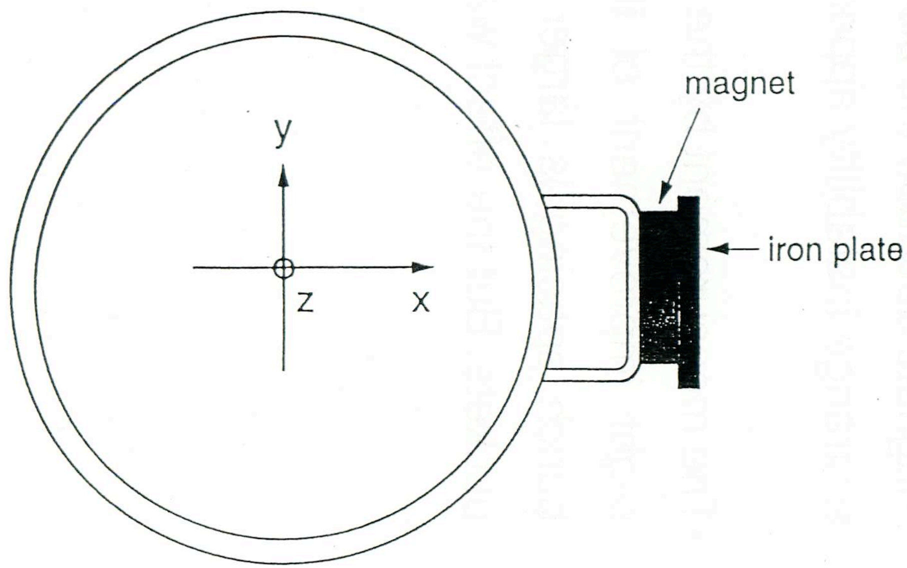
- We tried two type of magnets , i.e. string type and C yoke type. At first string type magnets were tried. Then they were replaced with C yoke magnets because the blow-up still remained and a strange instability appeared around 20 mA.

- The measurement by the interferometer showed slight improvement of the blow-up when the bunch spacing is larger than or equal to 8 rf buckets. But the effect was not remarkable.

Permanent magnet

String type

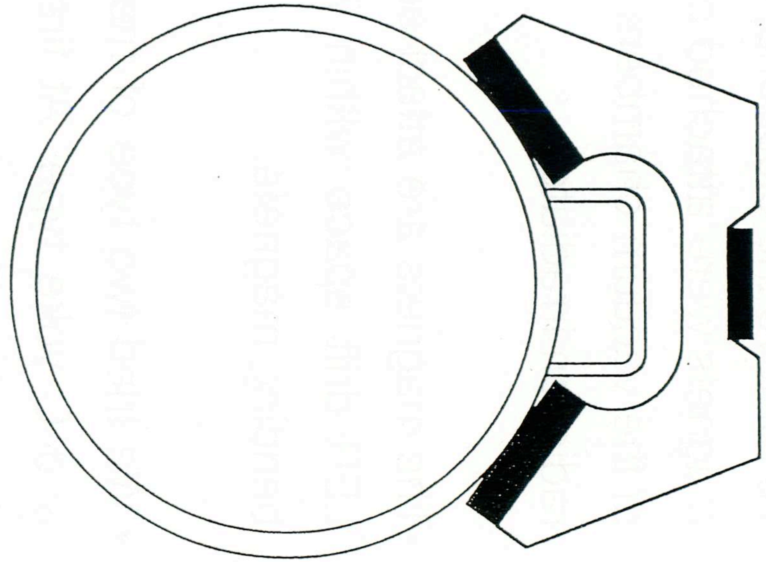




Bz=50G on inner wall of chamber

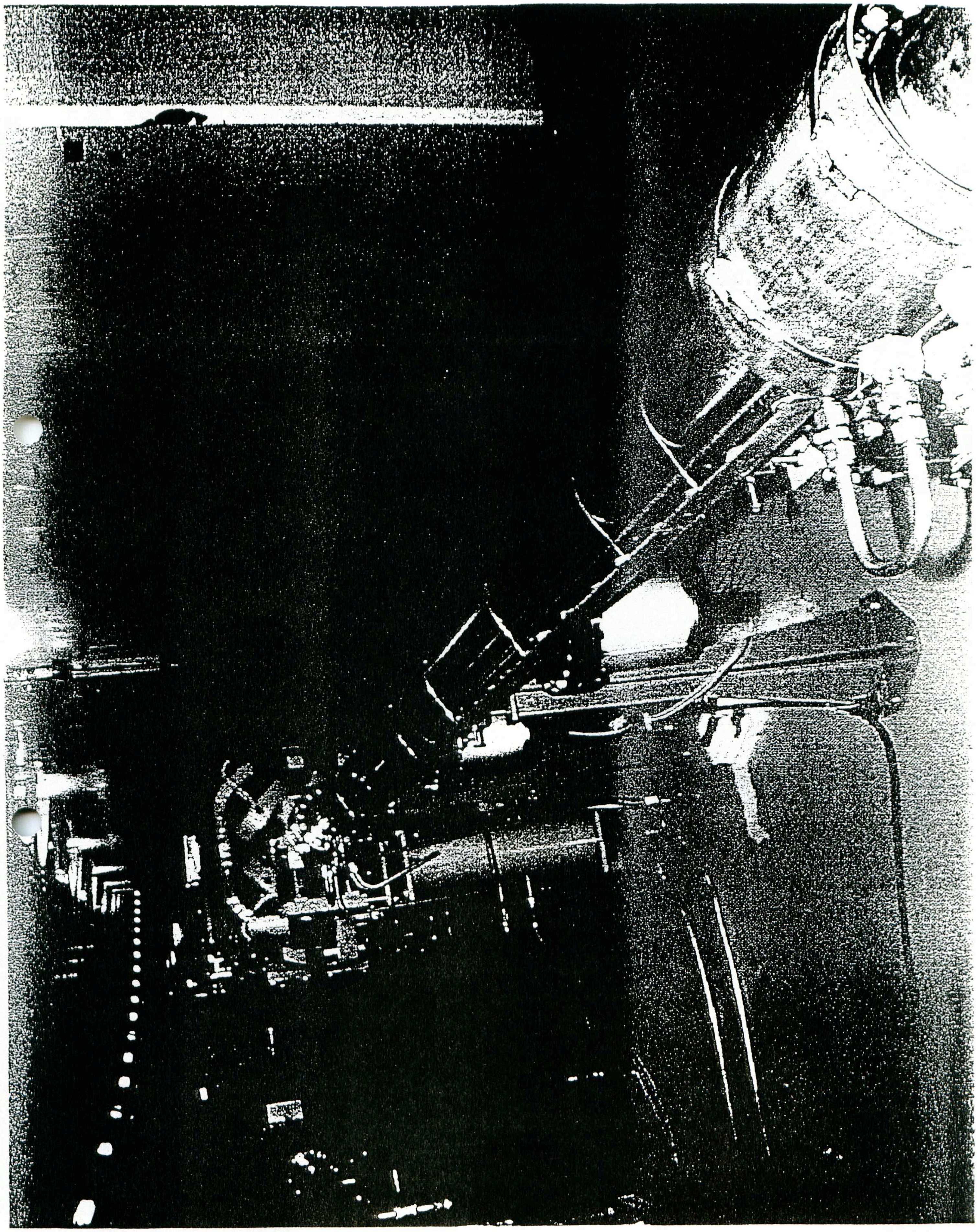
Bz=14G at center of chamber

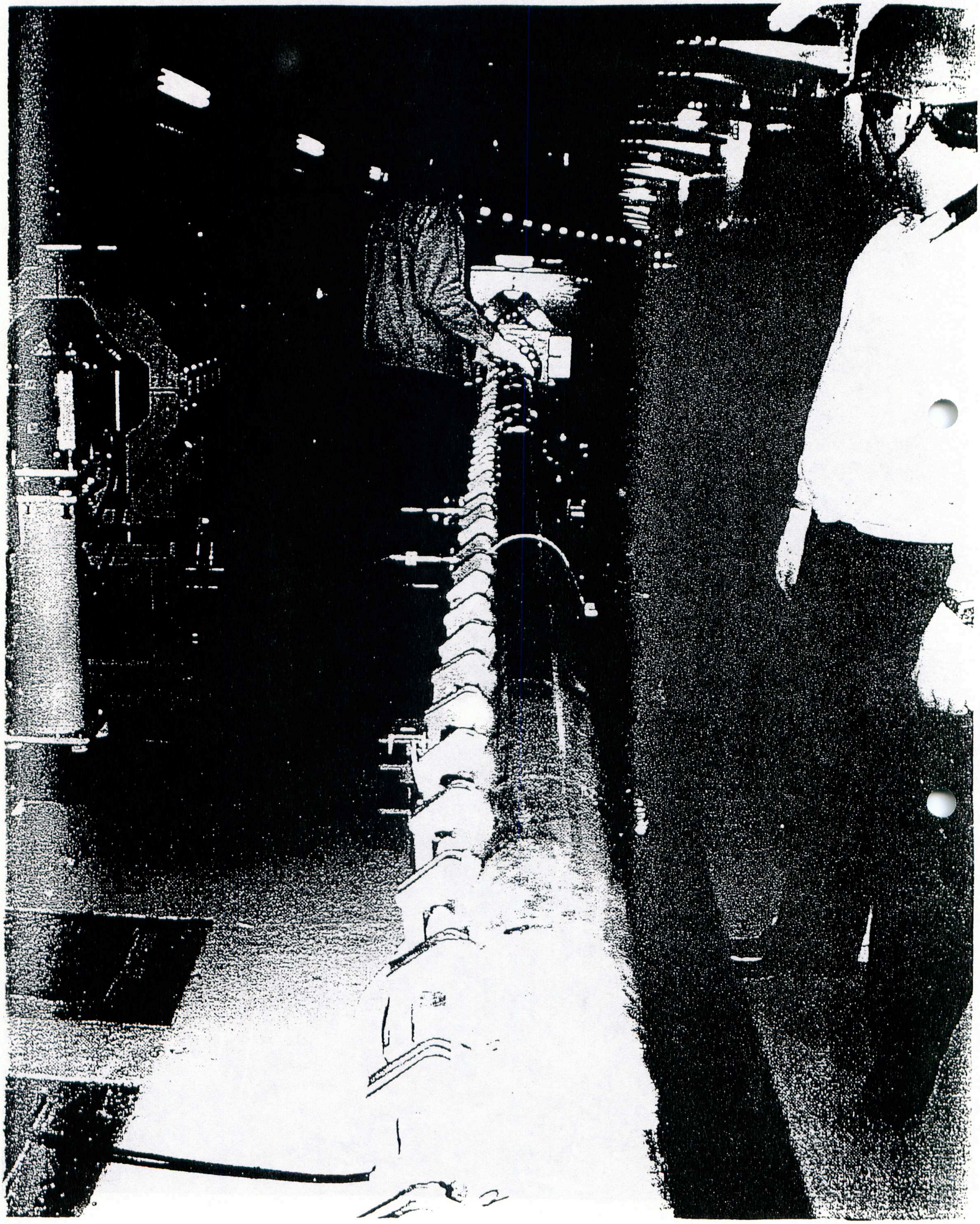
C yoke type



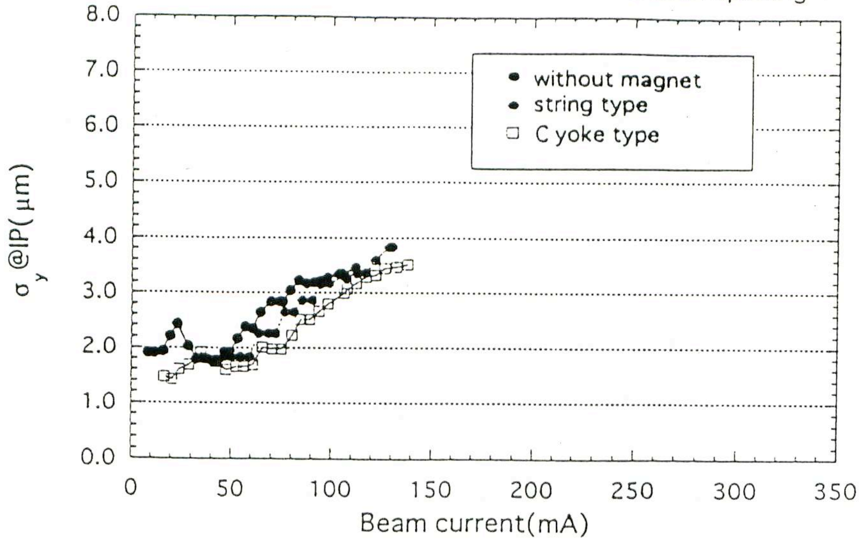
By=350G on inner wall of chamber

By=40G at center of chamber

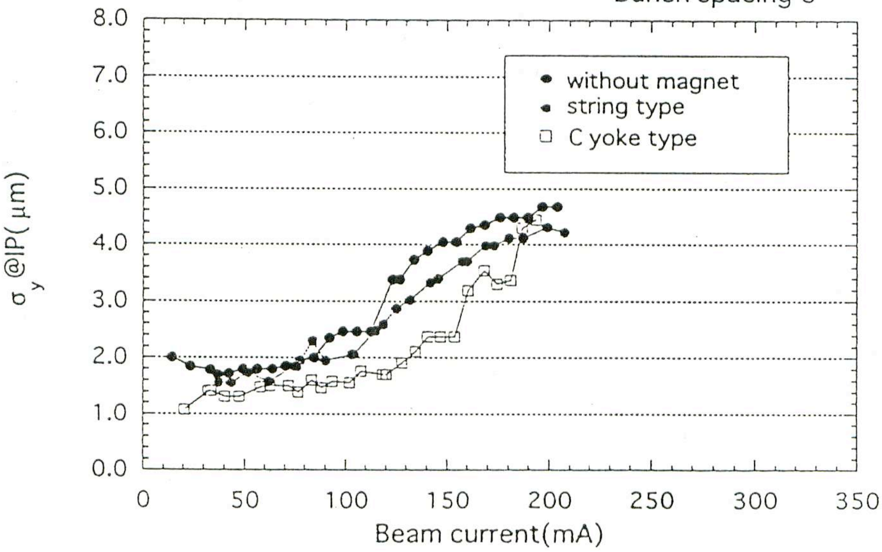




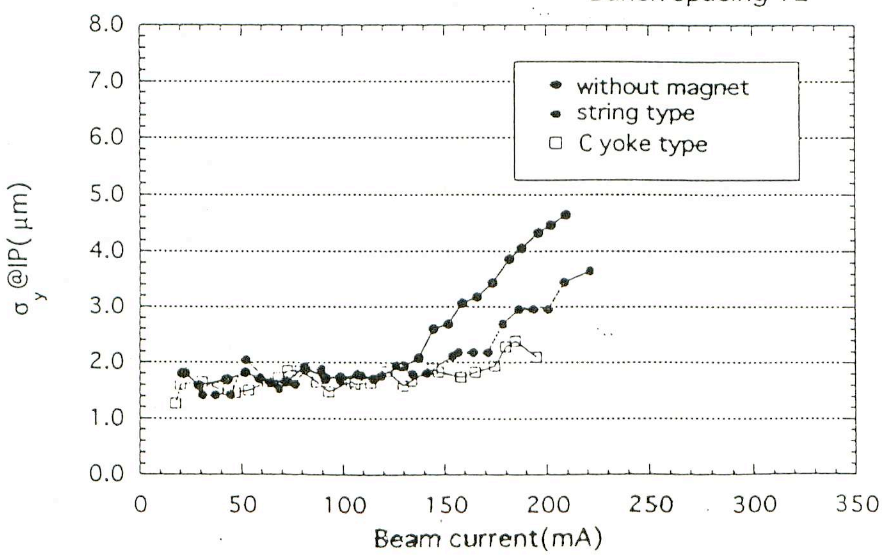
Bunch spacing 4



Bunch spacing 8



Bunch spacing 12



•Two hypotheses are proposed to explain why the magnets are not effective 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.

At present there is no clear experimental evidence against BBU model.

3.1.3 Measures

1) Fill pattern

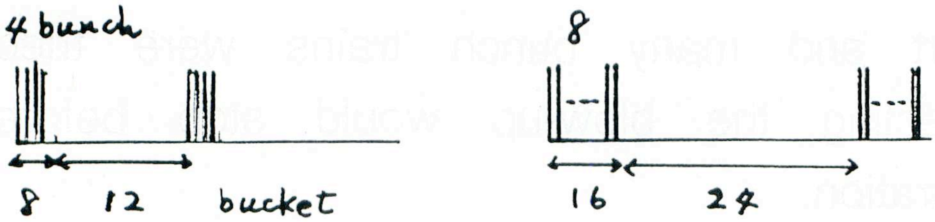
- Short and many bunch trains were tried expecting the blow-up would stop before saturation.

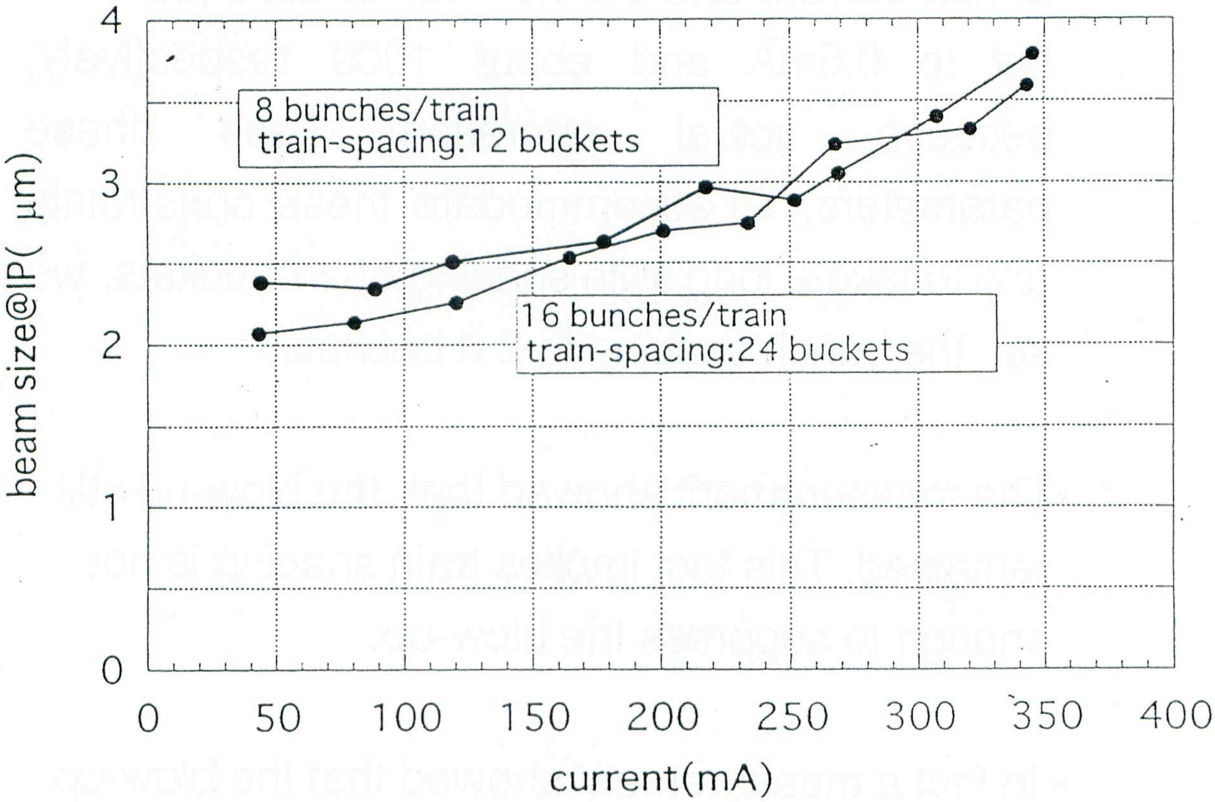
- Bunch current and the number of bunches were set to 0.5mA and about 1000 respectively, because actual operation uses these parameters. To accommodate these constraints and to take a long train spacing of 24 buckets, we set the bunch spacing to 2 rf buckets.

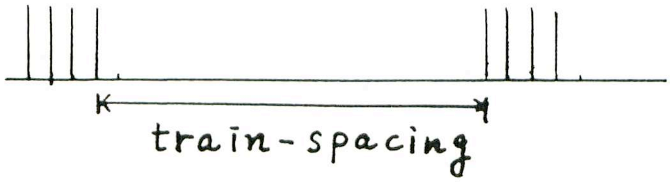
- The measurement showed that the blow-up still remained. This fact implies train spacing is not enough to suppress the blow-up.

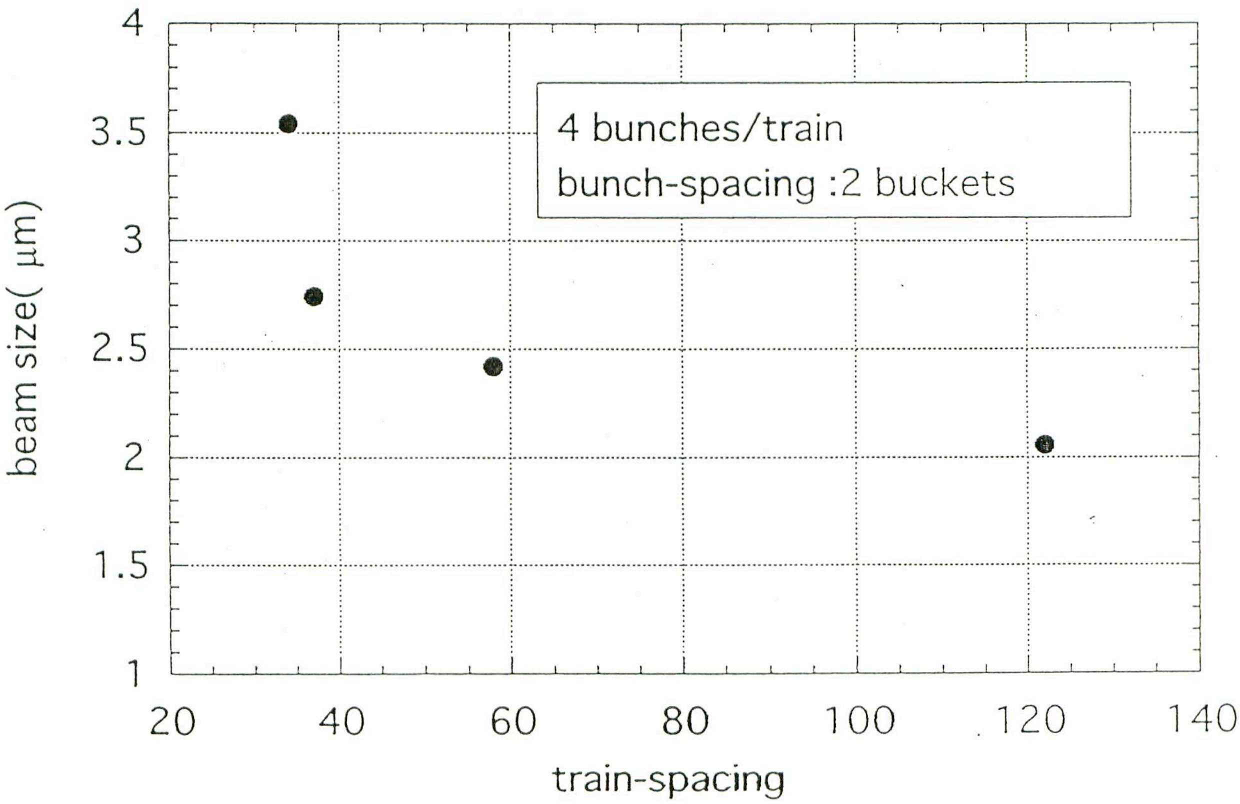
- In fact a measurement showed that the blow-up was remarkable if the train spacing was shorter than 35 rf buckets.

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


4 bunch
8
12
bucket
8
16
24


8 bunches/train
train-spacing:12 buckets
16 bunches/train
train-spacing:24 buckets
beam size@IP(μm)
current(mA)
0
1
2
3
4
0
50
100
150
200
250
300
350
400


train-spacing


4 bunches/train
bunch-spacing :2 buckets
beam size(μm)
train-spacing
4
3.5
3
2.5
2
1.5
1
20
40
60
80
100
120
140

2) Measurement of characteristics of photoelectrons

- As described before, the measurement of reflectivity of light and energy distribution of photoelectrons is planned at KEK PF(⇒Y. Suetsugu's talk).

3) More C yoke permanent magnets

- To examine the effect of reflective light, we are planning to add more C yoke magnets on the inner-lateral side of the chambers and on the chambers further down stream of the beam line.

4) Plan to remove the photoelectrons

a) Improvement of the vacuum chambers

ante-chamber

mask to absorb the synchrotron radiation

saw-tooth surface to reduce the reflective light

⇒Y. Suetsugu's talk

b) Electro-magnetic C yoke magnets
To make magnetic field variable and to obtain better field quality than permanent magnet, electro-magnetic C yoke magnets are discussed in a task force.

4) Machine study

•Following machine studies are planned,

a) simultaneous measurement of beam size by the interferometer and the fast gated camera,
b) observation of bunch shape by the streak camera,
c) measurement of the current through BPM electrodes.

3.2 Vertical beam blow-up in HER

- Vertical beam blow-up is observed in HER by the interferometer.

- Observation shows,

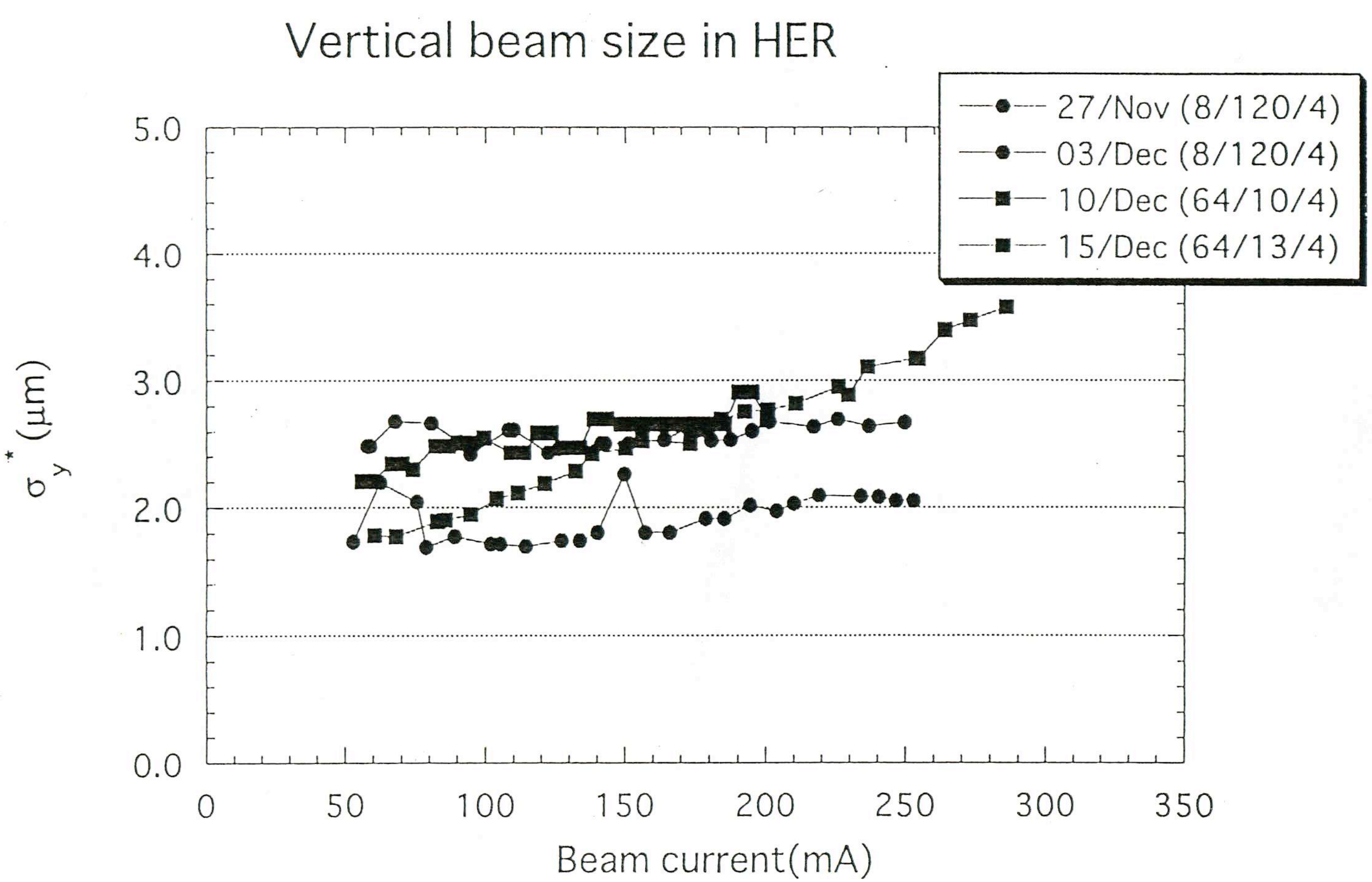
  1) Beam size increases linearly with beam current (no threshold).
  2) Blow-up rate of beam size σ^*_y at IP is typically 3.2×10^{-3} mm /mA. And $\delta \sigma^*_y / \sigma^*_y$ is 40 % (50 - 300 mA).
  3) Blow-up rate is affected by optics.

  1) and 3) shows that blow-up in HER is different phenomena from that in LER.

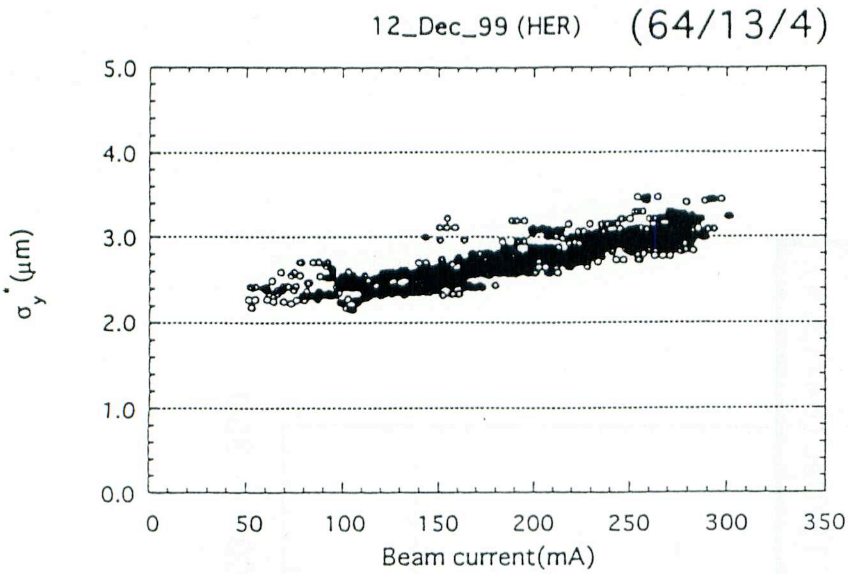
- Dipole oscillation is a candidate of the blow-up.

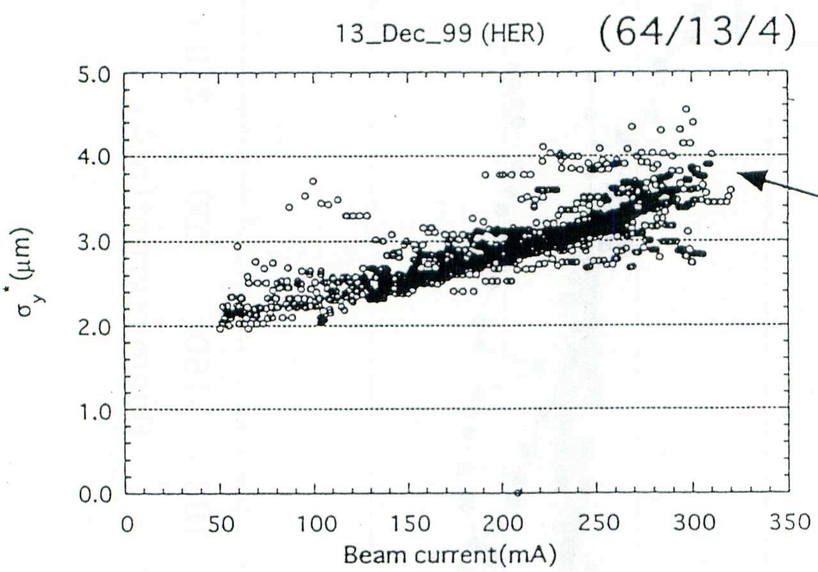
- Planned machine studies are

  a) Observation of dipole oscillation by a spectrum analyzer and
  b) Observation of the blow-up by the fast gated camera.

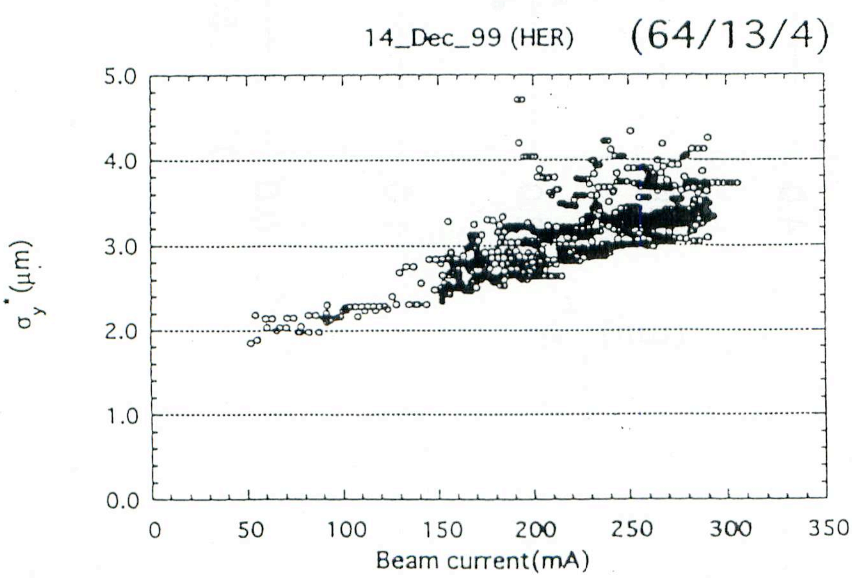

Vertical beam size in HER
27/Nov (8/120/4)
03/Dec (8/120/4)
10/Dec (64/10/4)
15/Dec (64/13/4)
σ_y^* (μm)
5.0
4.0
3.0
2.0
1.0
0.0
0
50
100
150
200
250
300
350
Beam current(mA)

Vertical beam size in HER





Dispersion &
X-Y coupling
correction



4. Summary

1) Most serious problem concerning to the beam instability is vertical beam size blow-up in LER.

   The beam break up 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.

   Measures against the blow-up such as the application of the magnetic field, improvement of the vacuum chamber and so on are discussed.

2) In present operation, transverse coupled bunch instability is not limiting factor of the beam current. It is suppressed by the bunch feedback system and large chromaticity.

   Observation at largest beam current so far achieved shows strong horizontal oscillation of the bunches which may limit the beam current at higher current.