Instability due to Beam-Photoelectron interactions in LER

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A coupled bunch instability caused by photoelectron is discussed. Photoelectrons are produced by synchrotron radiation photons, when they hit the inner duct wall of beam pipe. The photoelectrons propagate toward the positron beam in the LER. In the multibunch operation, photoelectrons are supplied continuously into the beam pipe. Although each electron is not trapped around the beam, they form a flowing gas (cloud) of electrons. The electron gas acts as the media to transmit perturbative forces from a bunch onto subsequent bunches. The a coupled-bunch instability can emerge.

At the Photon Factory of KEK (PF), which is 2.5GeV electron-positron storage ring, a coupled bunch instability, which may be consistent with this mechanism, has been observed. At the PF, the threshold current of the instability is about 20mA. The problem in the LER may be serious, since its stored current will be much larger.

Synchrotron Radiation and Photoelectron

$$N_\gamma = \frac{5\pi}{\sqrt{3}} \alpha \gamma$$ in one revolution

α : fine-structure const $= \frac{1}{137}$

LER $\gamma = 6850$

$N_\gamma = 453$

$u_c \sim 6$ keV

Photoelectron production rate

0.02

Photoelectron energy

5 ± 15 eV

} Assumption

The number of photoelectron

$N_{p.e} = 9.1 /e^+$ $N_{pe.bunch} = 3 \times 10^{11} /bunch$

1 mA beam ≙ $2.58 \cdot 10^{17}$ photons s^{-1}

secondary electron yield, $\gamma = \dfrac{I_{ph}/I_{beam}}{1.6 \cdot 10^{-19} \cdot 2.58 \cdot 10^{17}}$

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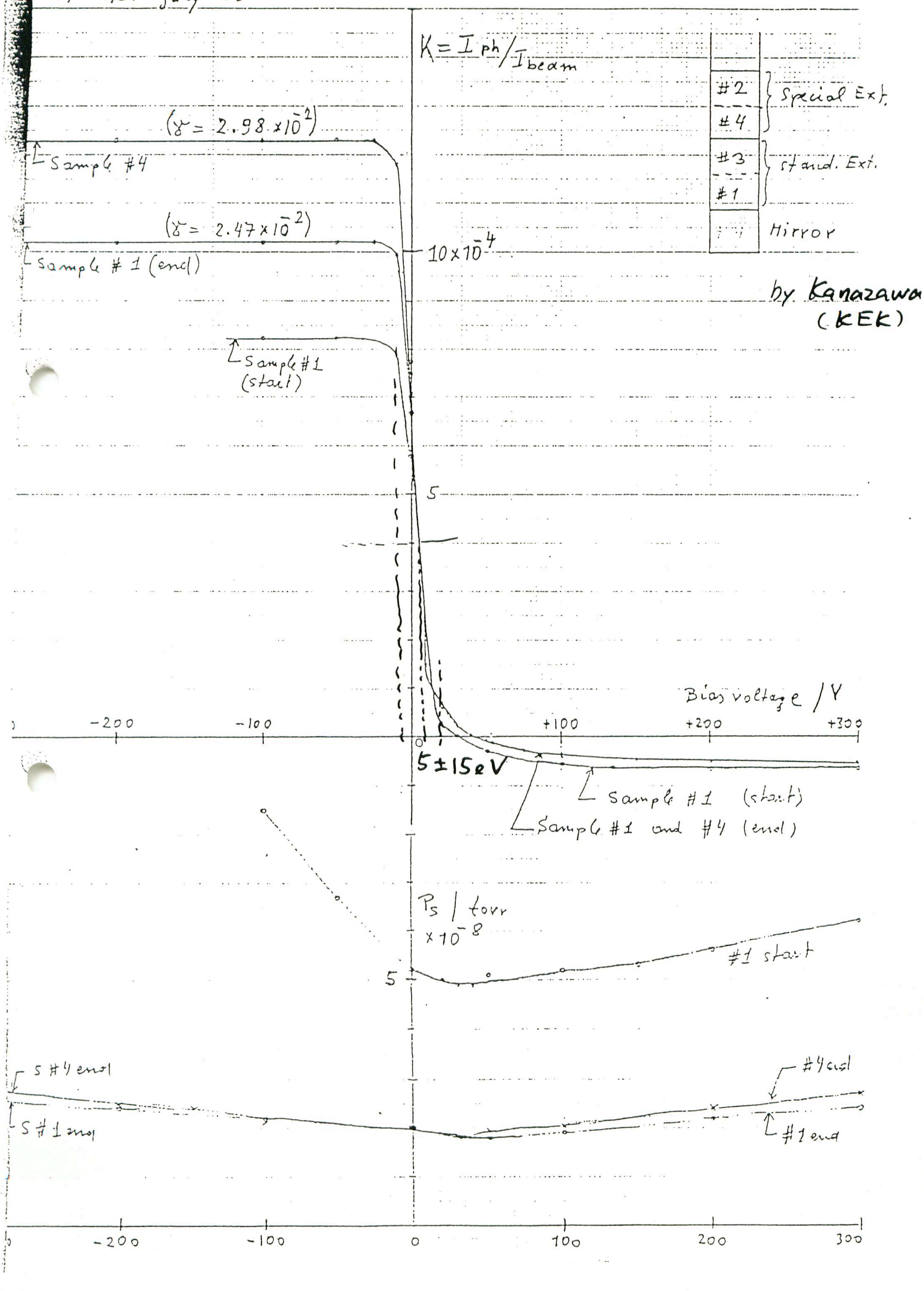

Photo-electron motion and its distribution obtained by a simulation

- 1000 virtual photo-electrons start from the duct.
- The photo-electrons propagate in the duct while receiving electric field of beam.

After receiving the beam interaction of following ~50 bunches, ~100nsec

- most of the photo-electrons are absorbed in the duct surface.

Photo-electrons are produced by the following bunches.
The photo-electron distribution is giving by summing the propagating distributions emitted by a bunch.

The distribution is stationary, but time dependent.
All of bunches always encounter the same photo-electron distribution.

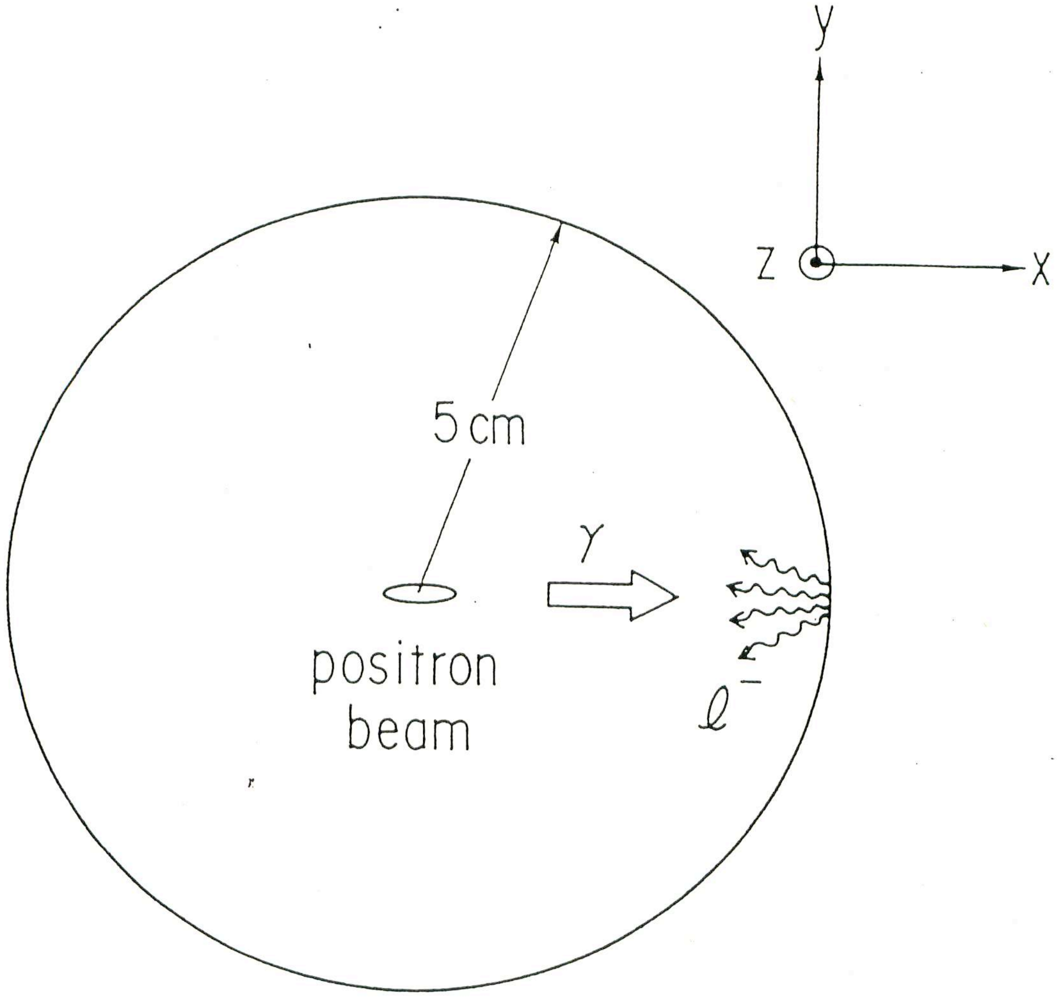

Fig.1. Model beam duct used for the simulation.

$$\psi(x, y, \epsilon, \theta; t_0) \sim \delta(x - x_{wall}) \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{(\epsilon-\epsilon_0)^2}{2\delta\epsilon^2}\right) \cos\theta$$

Model

beam rigid gaussian

photo-electron produced at the surface of beam duct

$\sim \cos\theta \, d\Omega$

Beam photo-electron force

$$\Delta v_y + i\Delta v_x = \frac{Ne^2}{2\pi \varepsilon_0 mc}\sqrt{\frac{\pi}{2(\sigma_x^2-\sigma_y^2)}}\left[W\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right) W\left(\frac{\frac{\sigma_y}{\sigma_x}x + i\frac{\sigma_x}{\sigma_y}y}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

Drift

B(Magnetic field) = 0

$$\Delta x = v_x \tau$$
$$\Delta y = v_y \tau$$

$B \neq 0$

cychrotron motion

$$\omega_c = \frac{eB}{m}$$

$$\rho = \frac{mv}{eB}$$

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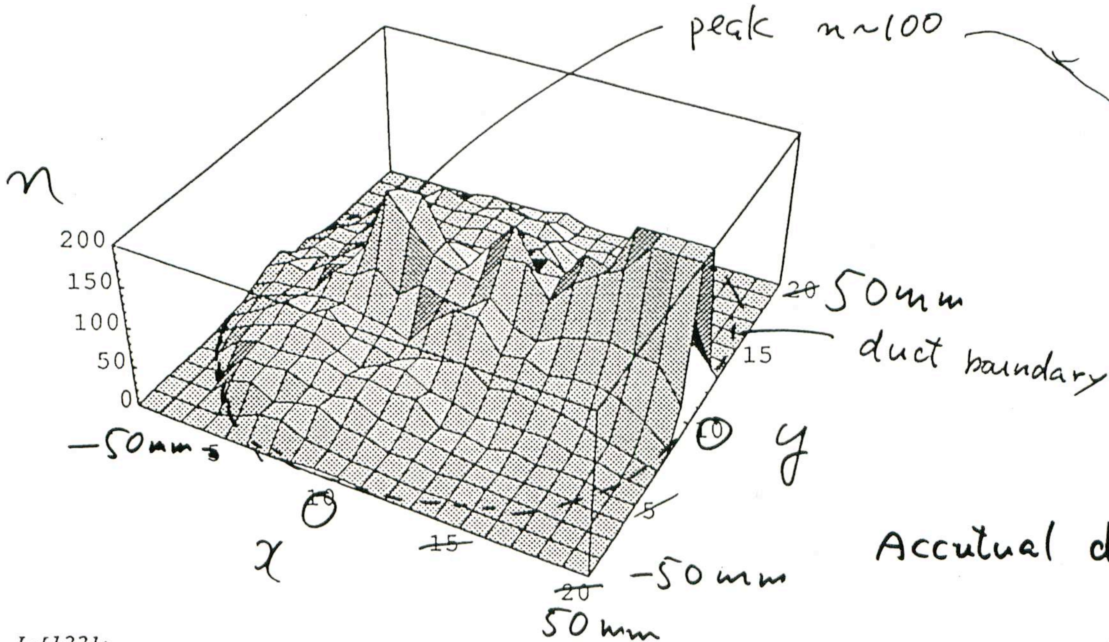

Accutual density of e^-

distributed along $z = 1000$m

$3 \times 10^{11} \times \frac{100}{1000} / 0.5 \times 0.5 \times 10^5$

$= \underline{1.2 \times 10^6 \text{ cm}^{-3}}$

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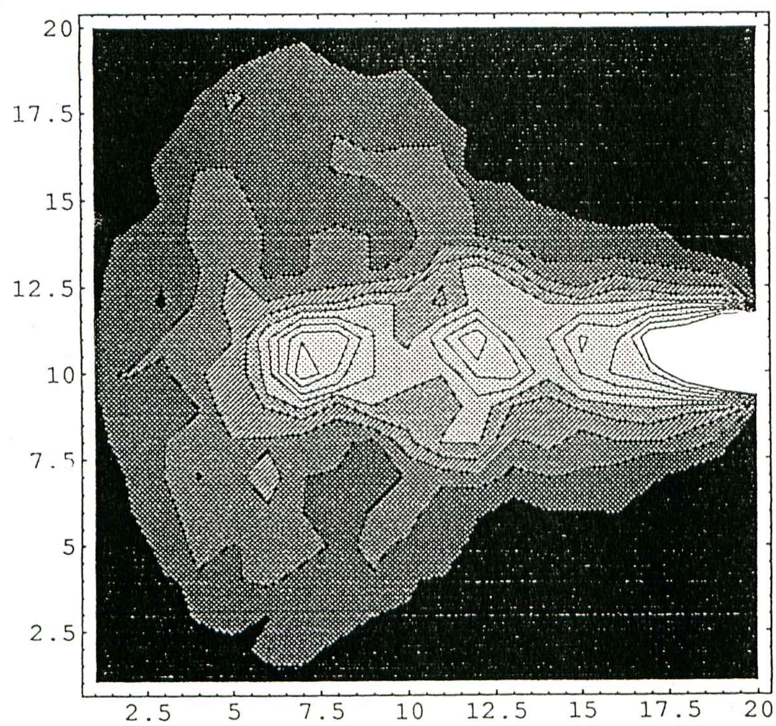


Wake force due to the photo-electron distribution

- Form the stationary distribution. using $2 \cdot 10^5$ macro particles
- A loading bunch having a vertical displacement passes through the stationary distribution.

  The distribution is disturbed, and has an effect on following bunches.

- Calculate beam kicks which the following bunches receive.

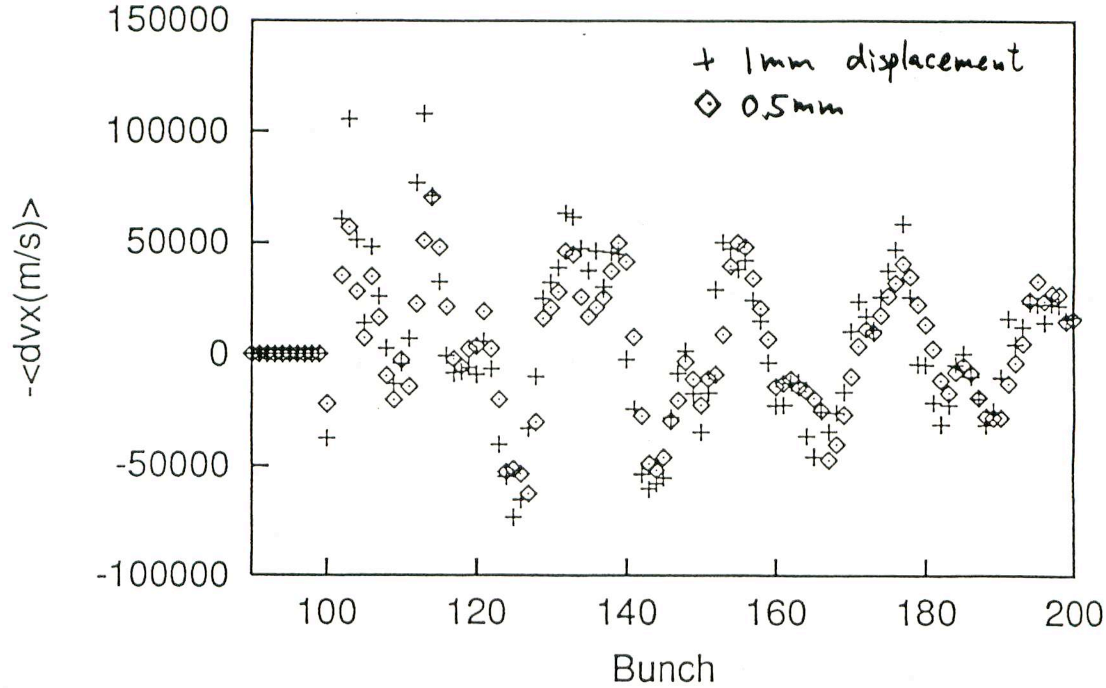
$\langle \Delta v_i \rangle$: Averaged velocity kick for photo-electrons from each rigid bunch including N_b e^+.

Loading displacement

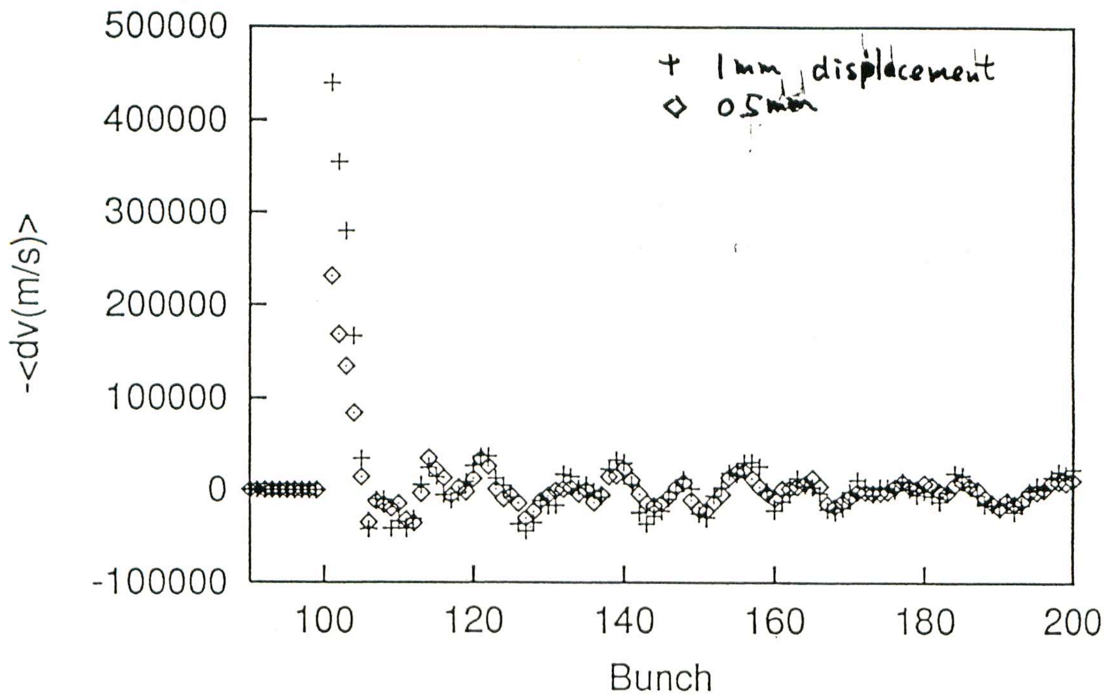
0.5mm

$\sim 3\sigma_y$ PF

$\sim 5\sigma_y$ KEKB



+ 1mm displacement
◇ 0,5mm
150000
100000
50000
0
-50000
-100000
-<dvx(m/s)>
100
120
140
160
180
200
Bunch



+ 1mm displacement
◇ 0,5mm
500000
400000
300000
200000
100000
0
-100000
-<dv(m/s)>
100
120
140
160
180
200
Bunch

Coupled bunch instability caused by the photo-electron's wake

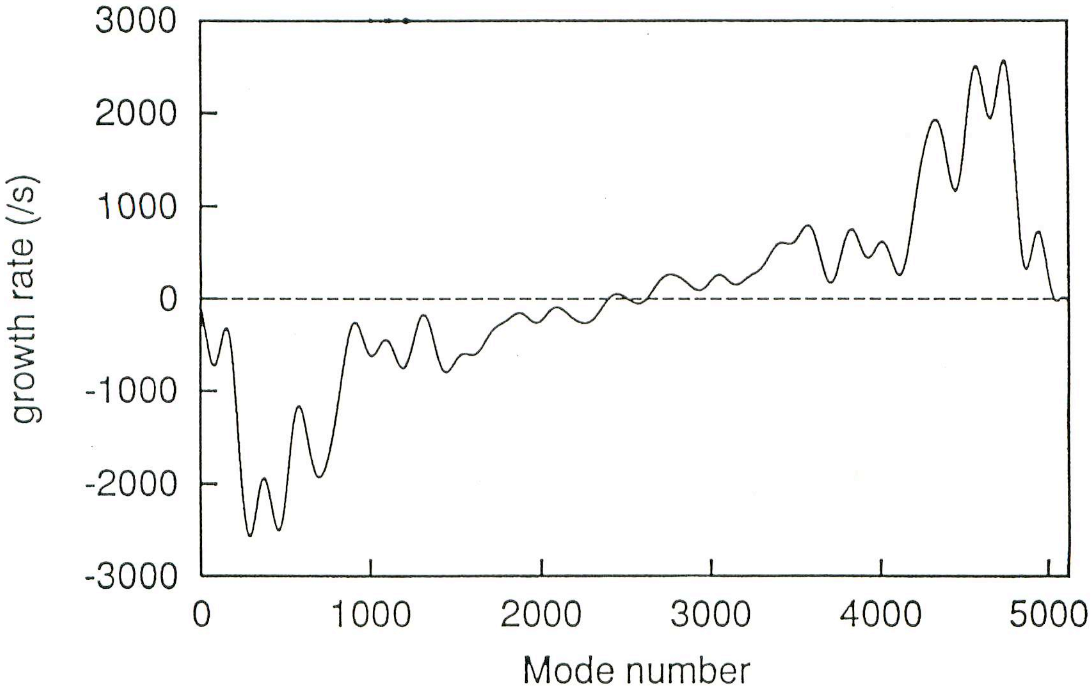
The equation of motion for a positron in a bunch

$$\frac{d^2 y_0}{dt^2} + \omega_\beta^2 y_0 = -\frac{N_{p.e.}}{N_b} \sum_{n=1}^{n_0} \frac{\Delta v_y\left(-\frac{nc}{h} T_{rev}\right)}{\gamma T_{rev}}$$

dispersion relation

$$\Omega_m - \omega_\beta = \frac{1}{4\pi \gamma \nu_y} \frac{N_{p.e.}}{N_b} \sum_{n=1}^{n_0} \frac{d v_y}{dy}(-nT_b)\, e^{2\pi i n(m+\nu_y)/h}$$

$$\left(\begin{array}{l} y_n^{(m)}(t) = e^{2\pi i m n/h}\, y_0^{(m)}(t) \\ y_j^{(m)}(t) = \tilde{y}_j^{(m)} e^{-i\Omega_m t} \end{array} \right)$$



3000
2000
1000
0
-1000
-2000
-3000
growth rate (/s)
0
1000
2000
3000
4000
5000
Mode number

This simulation has some ambiguities.

- The production rate of photoelectrons.
- Energy spectrum of photoelectrons.
- How many electrons contribute to the instability.

growthe rate $\propto N_{p.e\ bunch}$

$N_{p.e\ bunch} \propto \gamma N_b$

$\frac{dv}{dy} \propto N_b$

$\Omega_m - \omega_p \sim \frac{N_b}{\nu_y}$

If we identify this instability with that observed in PF.

	growth rate	I_{th}	ν_y
PF	100 s^{-1}	20 mA	3.3
KEKB LER	1000 s^{-1}	2.6 A	~50

$$\therefore \frac{2600}{20} \times \frac{3.3}{50} \sim 10$$

Roughly,
The growth rate of LER nearly equal to that of PF 200 mA.

Possible cures

If growth rate $< 1000 s^{-1}$ (1ms),

the instability can be cured by the bunch to bunch feedback.

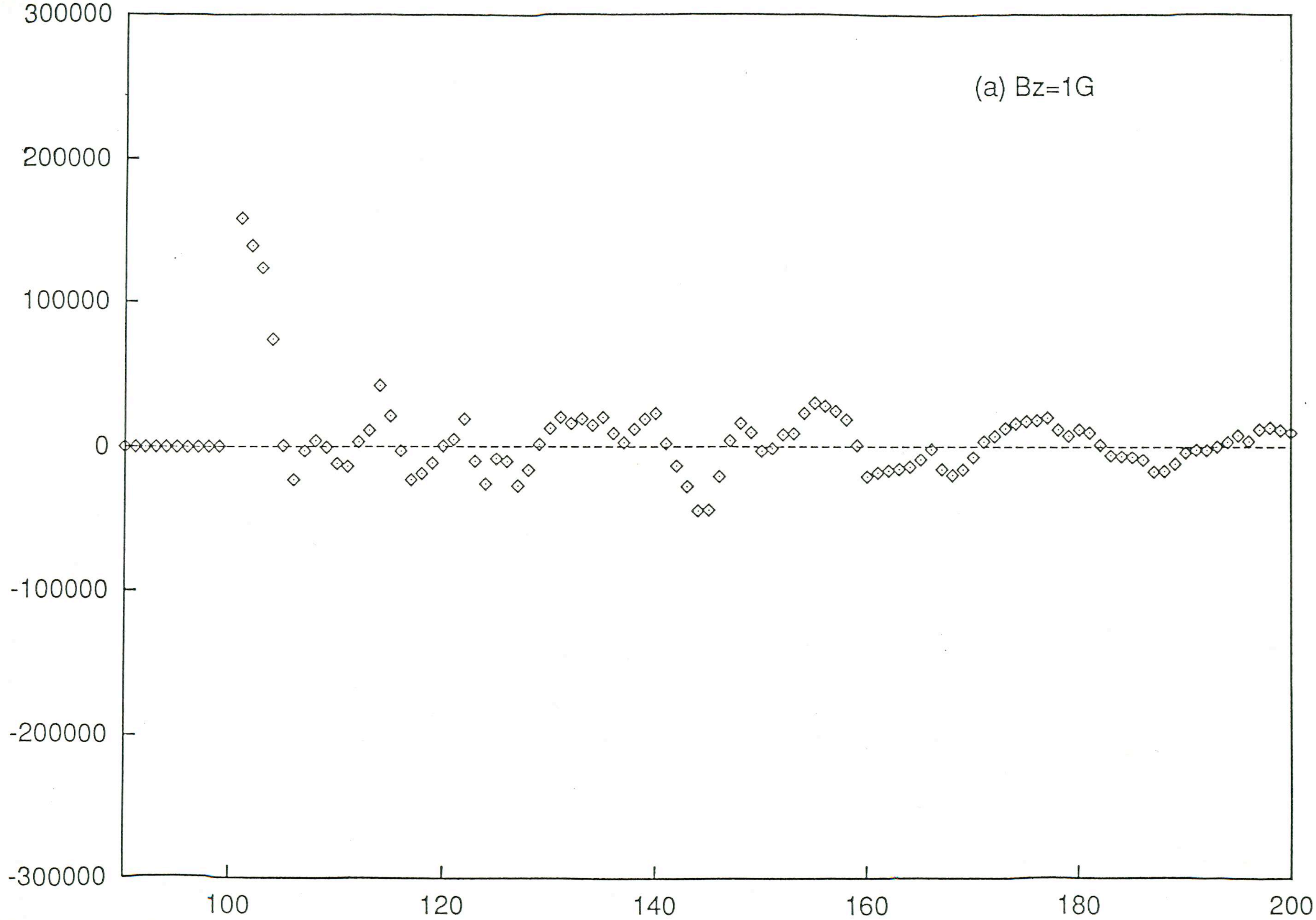
Another cure : magnetic fields

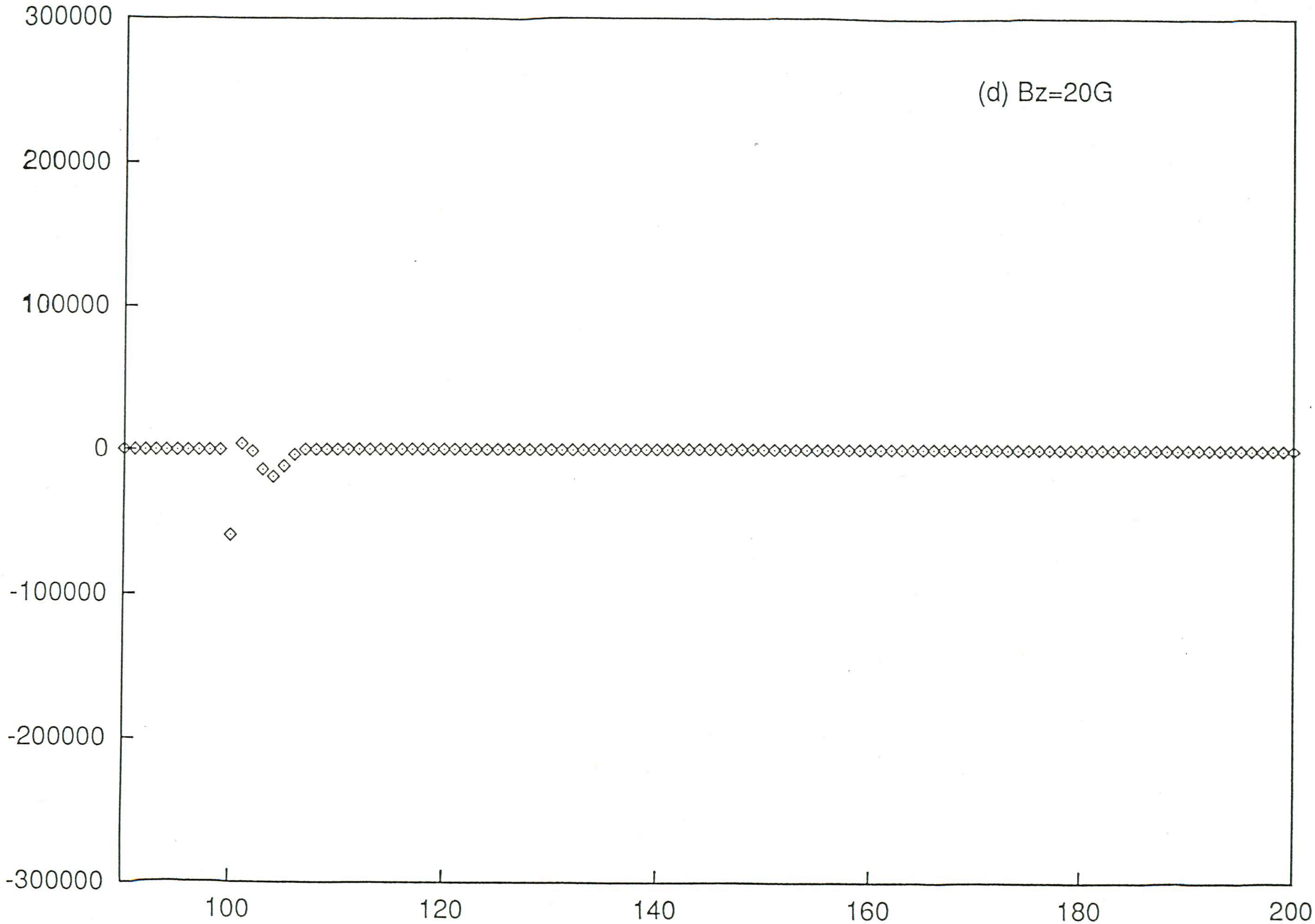
For example

$E_e = 10 eV \quad B = 10 G \longrightarrow \rho = 1.1 cm$

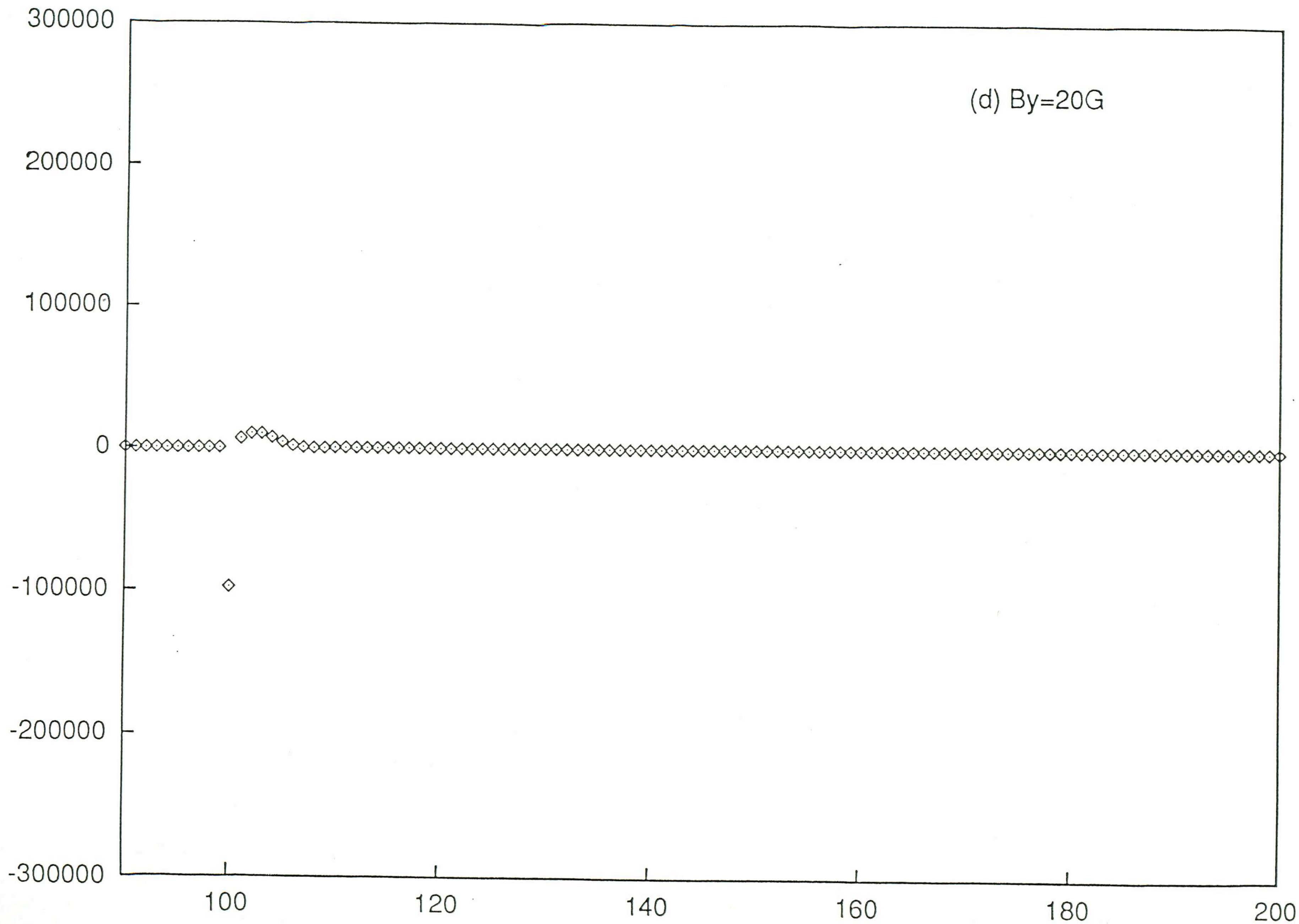
Photoelectrons can not propagate towards the beam

If the photoelectrons tend to reach the beam along a horizontal path, we can consider using a solenoid or vertical dipole fields.

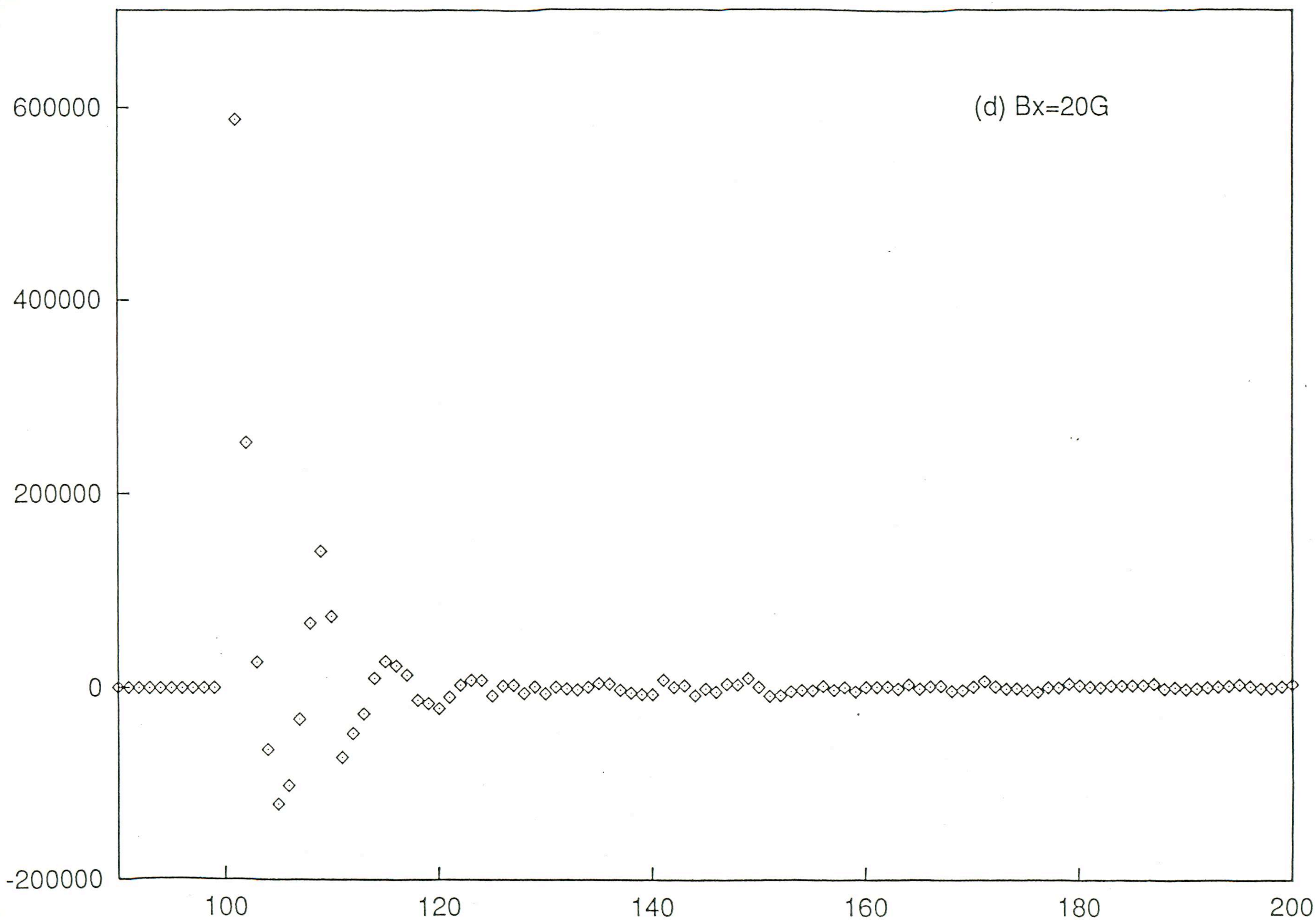

(a) Bz=1G
300000
200000
100000
0
-100000
-200000
-300000
100
120
140
160
180
200



(d) Bz=20G
300000
200000
100000
0
-100000
-200000
-300000
100
120
140
160
180
200



(d) By=20G
300000
200000
100000
0
-100000
-200000
-300000
100
120
140
160
180
200


(d) Bx=20G
600000
400000
200000
0
-200000
100
120
140
160
180
200

Conclusion

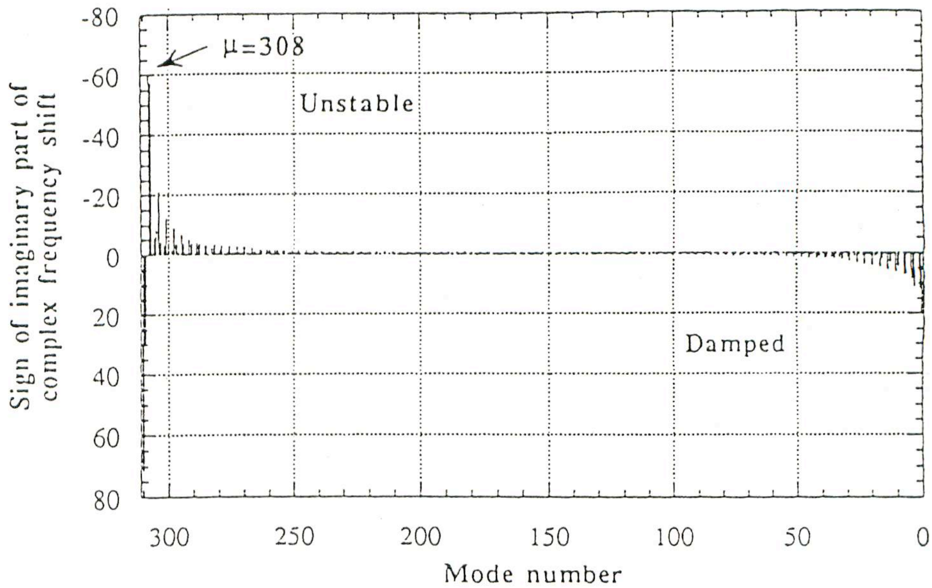
Effects of interactions between the positron beam and photoelectrons have been evaluated for the LER. The growth rate is estimated to be 2500 s^{-1}.

By applying solenoid or vertical magnetic field of 20 G, the growth rate will be reduced by one order which can be cured by the bunch-to-bunch feedback.

KEKB Feb.2.1995

100-Bunch までの long-range force のとき, Eq (4) で Im(Ω) が negative になる条件.

Unstable mode of coupled oscillation due to semi-long range (100 bunches) force



user Run 時

POSITRON STORAGE の場合

~~chromaticity~~

全 octapole が強くはいっている

$\xi_x \doteqdot 0$

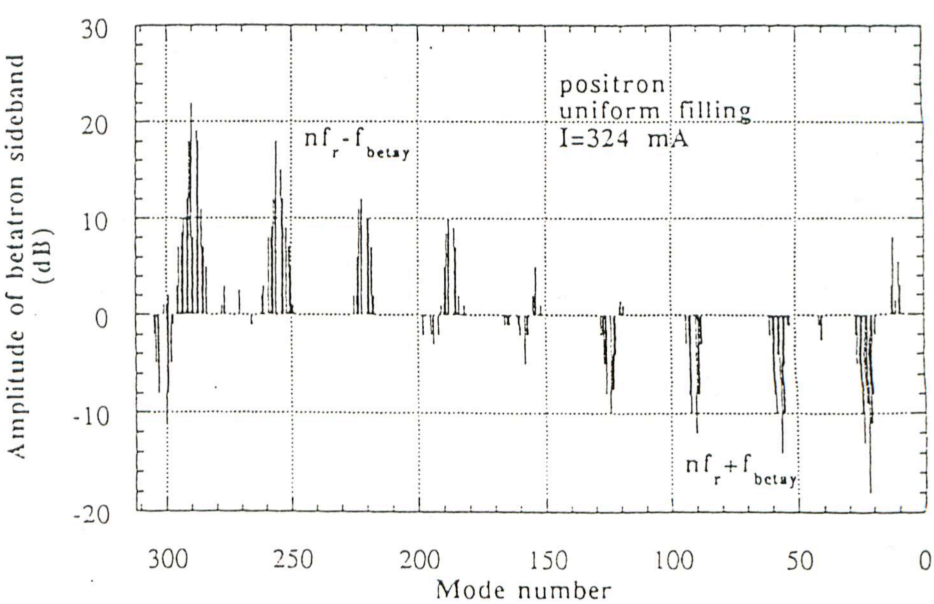
ξ_y やや ⊖

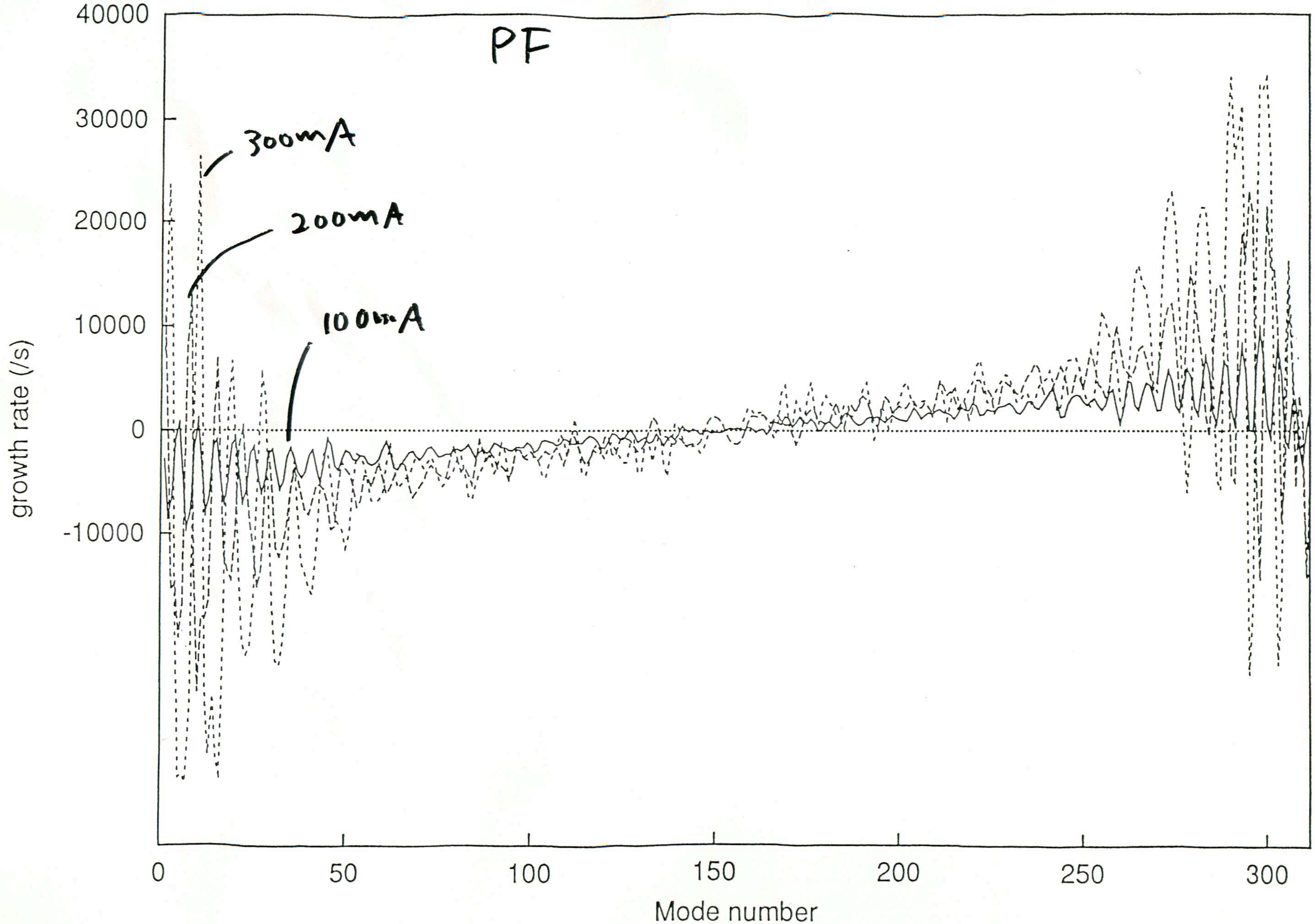
SF 3.4A

SD -3.7A.

-3A

Distribution of betatron sideband spectra




PF
300mA
200mA
100mA
40000
30000
20000
10000
0
-10000
growth rate (/s)
0
50
100
150
200
250
300
Mode number