Longitudinal Impedance Tuner Using New Material, 'FINEMET'.

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For the short bunch high intensity proton beam acceleration

problem: space charge effect

we have developed **"Impedance Tuner".**

Contents

Principle

Characteristic of 'FINEMET'

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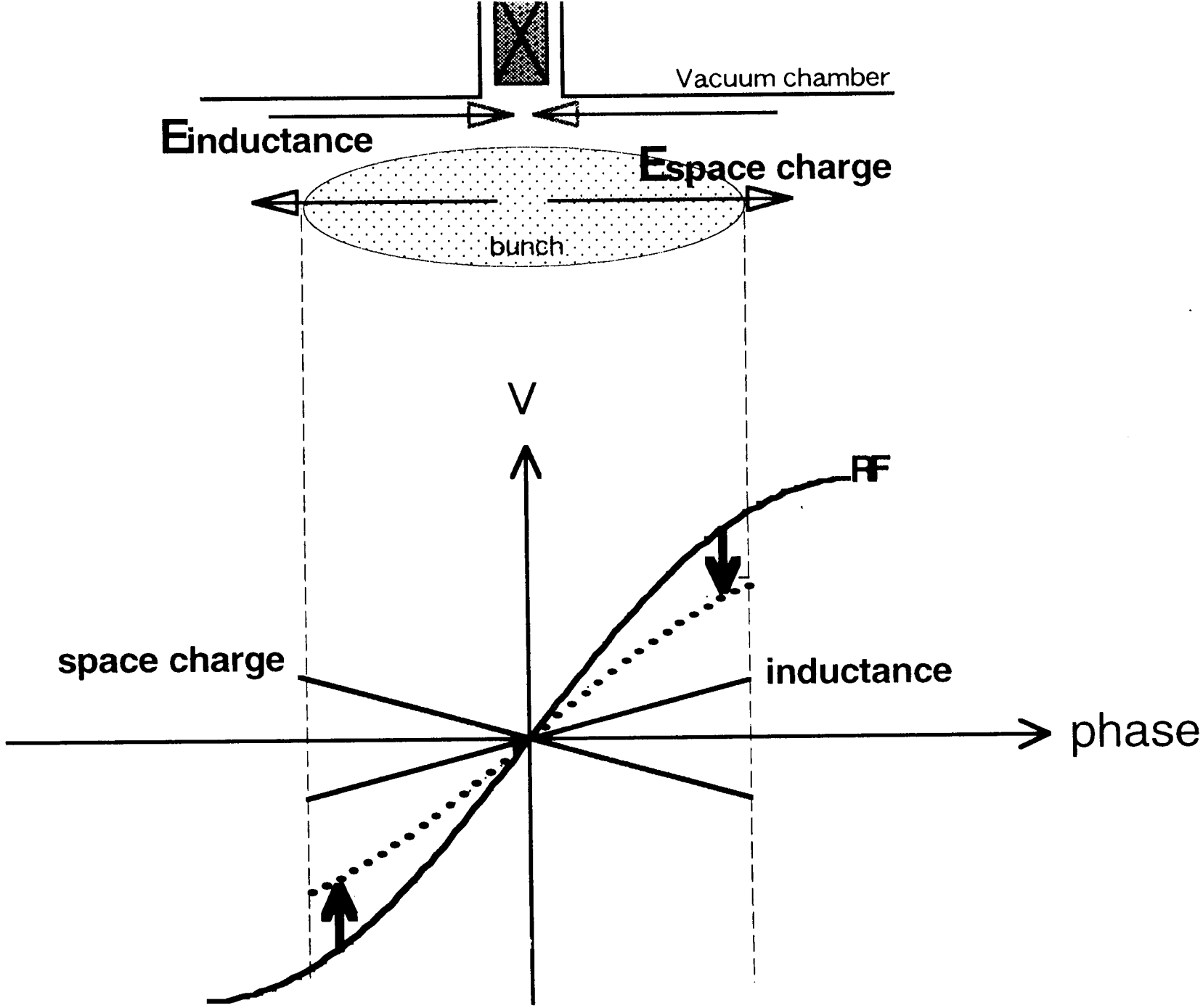

Vacuum chamber
Einductance
Espace charge
bunch
V
RF
space charge
inductance
phase

Induced voltage caused by space charge and inductor

$$V = -\frac{3ef_0}{\pi^2 h\cos\phi_s}\left(\frac{2\pi R}{\ell}\right)^3\left[\frac{g_0 Z_0}{2\beta\gamma^2} - \left|\frac{Z}{n}\right|\right]N\cdot\Delta\phi$$

$\beta\gamma$: Lorentz factor

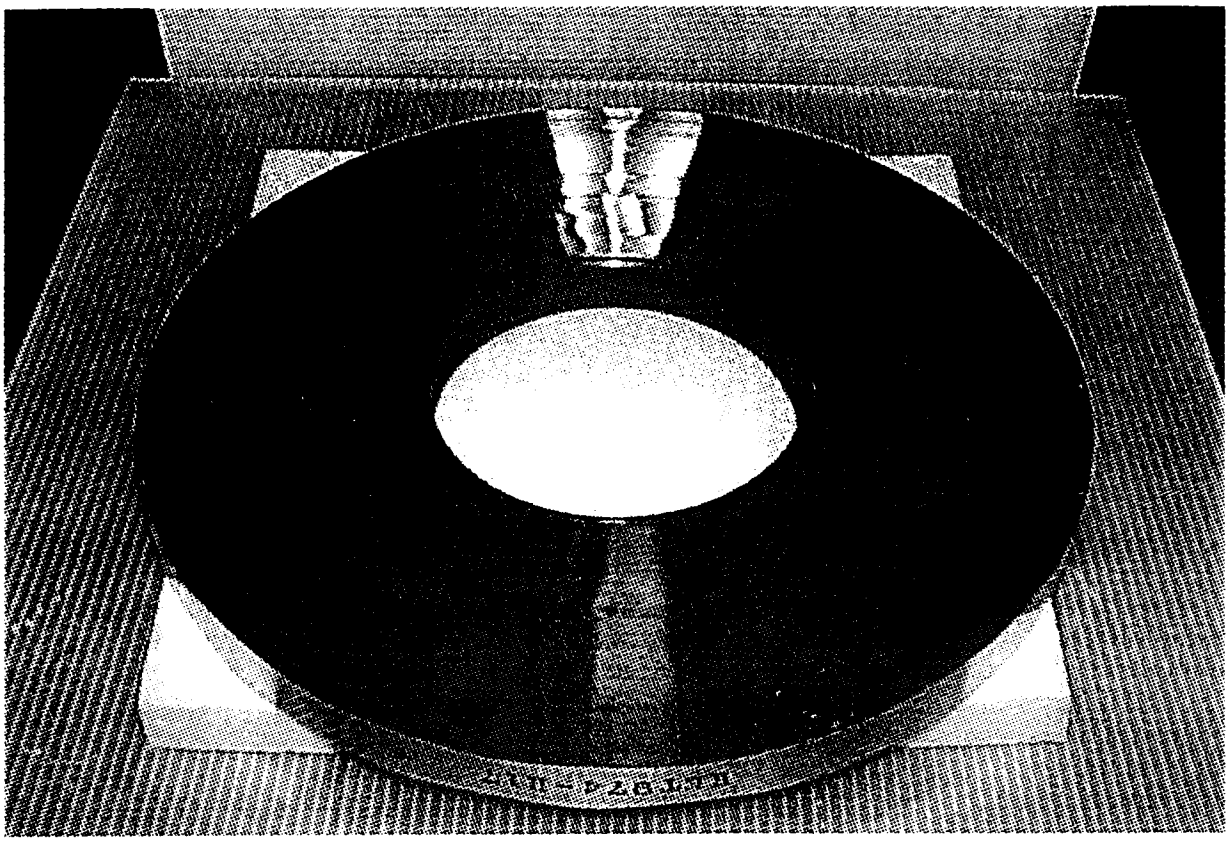
Space charge impedance $\frac{g_0 Z_0}{2\beta\gamma^2}$

Inductance $\left|\frac{Z}{n}\right| = \omega_0 L$

In order to clarify this experimentally,

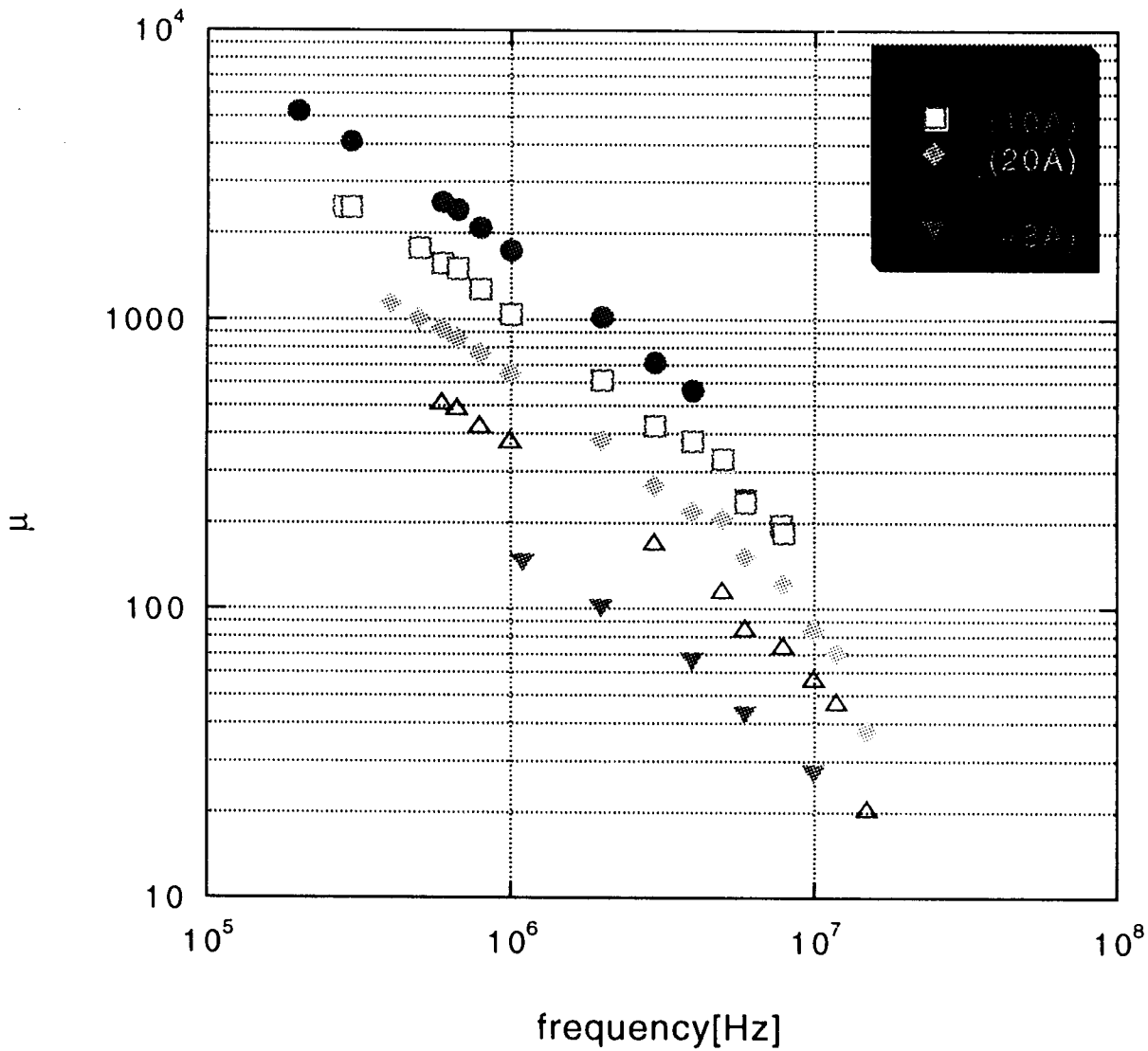
"IMPEDANCE TUNER" installed in the KEK-PS main ring

FINEMET



Outer diameter	:	340mm
Inner diameter	:	140mm
Thickness	:	25mm

Permeability of the "FINEMET" for different bias currents



KEK-PS main ring

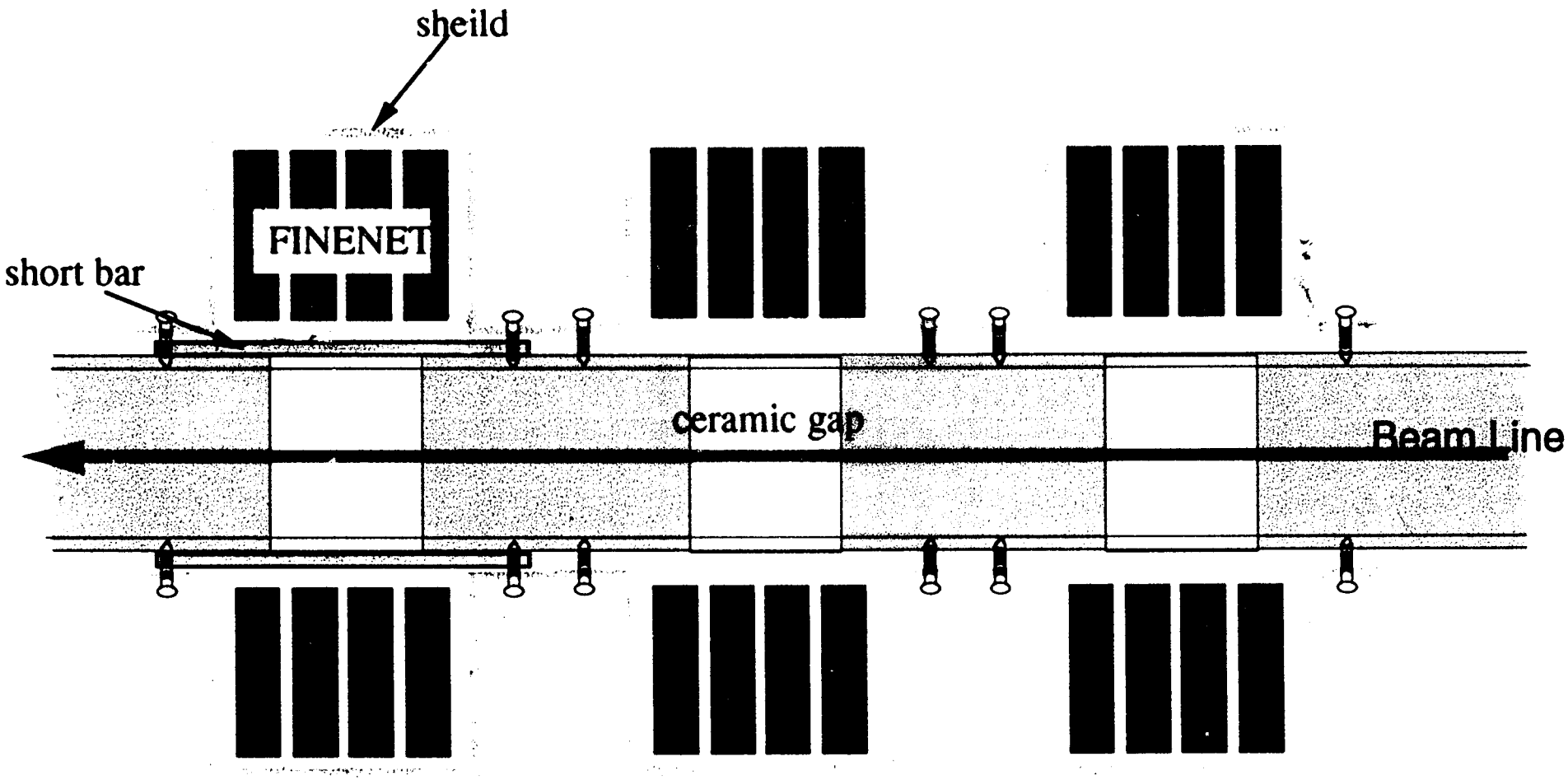
500MeV

667kHz

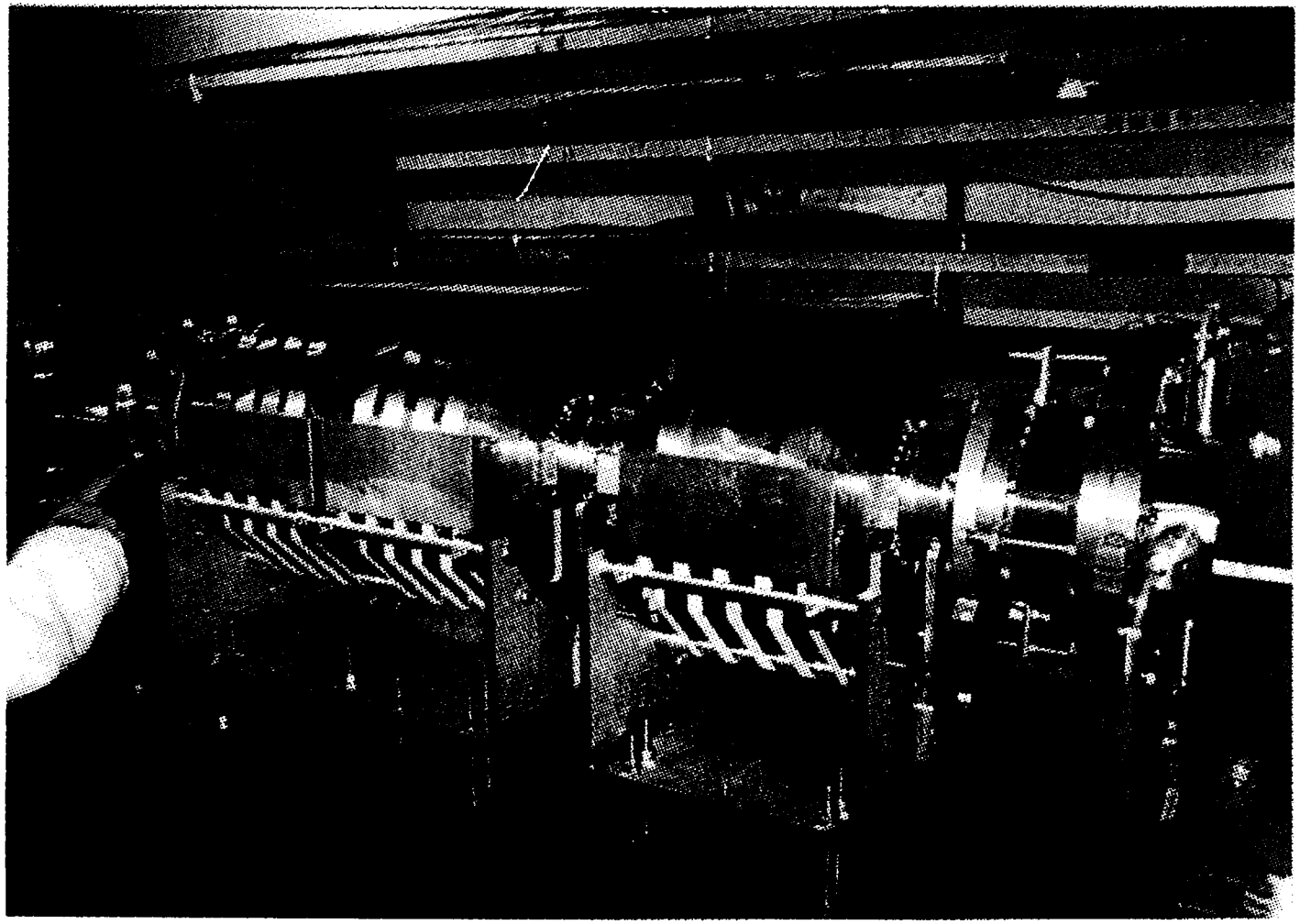
$$\frac{g_0 Z_0}{2\,\beta\gamma^2}$$ 310Ω

$$\left|\frac{Z}{n}\right| = \omega_0 L$$ 72 μH

11 pieces of "FINEMET" are need


sheild
FINENET
short bar
ceramic gap
Beam Line

IMPEDANCE TUNER #2



Measurement using the proton beam at KEK-PS

Synchrotron oscillation frequency is changed because the voltage modified by the impedance.

$$V_{sc} = -\frac{3ef_0}{\pi^2 h\cos\phi_s}\left(\frac{2\pi R}{\ell}\right)^3\left[\frac{g_0 Z_0}{2\beta\gamma^2} - \left|\frac{Z}{n}\right|\right] N\cdot\Delta\phi$$

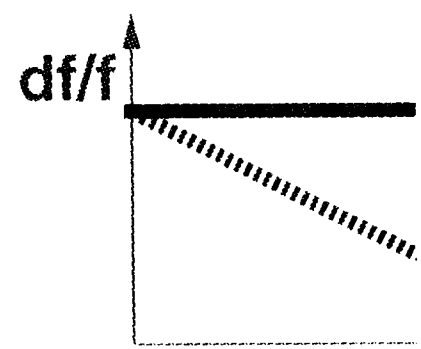
↓

To measure the impedance

we have to observe the **synchrotron frequency**.

frequency shift of synchrotron motion

$$\frac{\Delta f_s}{f_s} = -\frac{3ef_0}{2\pi^2 h V_{rf}\cos\phi_s}\left(\frac{2\pi R}{\ell}\right)^3\left[\frac{g_0 Z_0}{2\beta\gamma^2} - \left|\frac{Z}{n}\right|\right] N$$



How to measure the incoherent motion?

single particle motion (incoherent) can not be measured.

collective motion (coherent) can be measured.

dipole	$\Delta f \approx 0$
quadrupole	$\Delta f \approx \frac{1}{2}\Delta f_{s0}$

$$\frac{\Delta f_{2s}}{f_{2s0}} = \frac{1}{4}\frac{\Delta f_s}{f_{s0}}$$

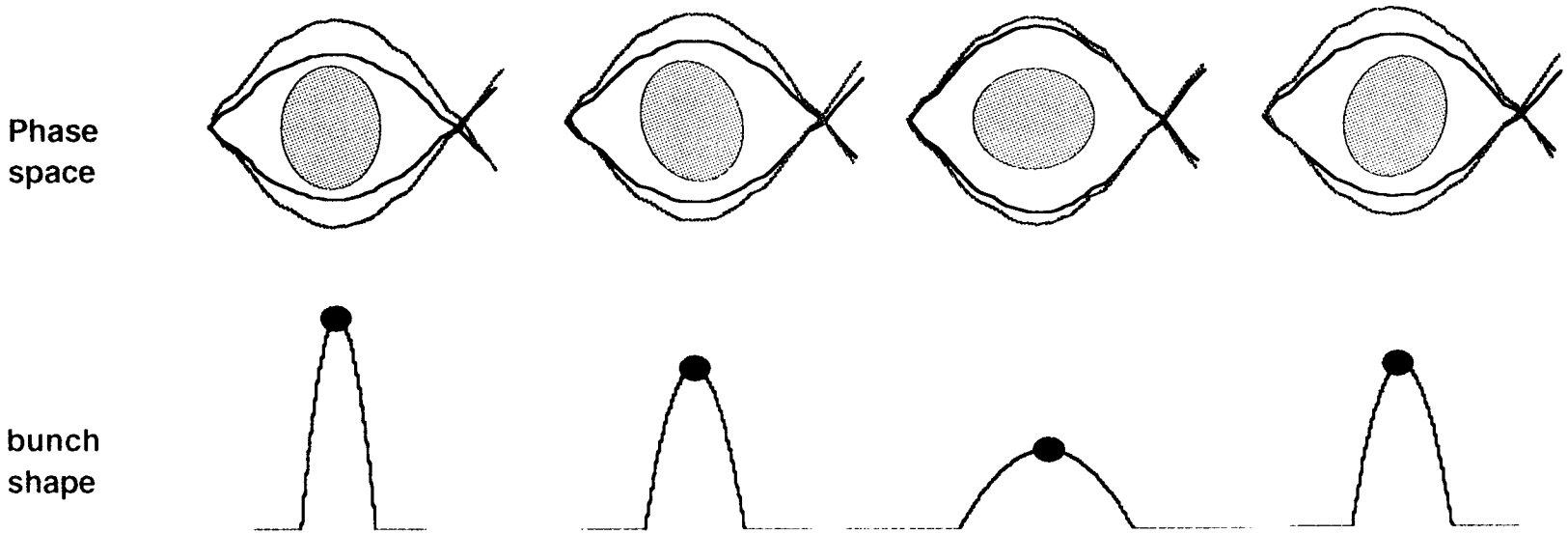
coherent quadrupole oscillation

incoherent

We can know the incoherent frequency shift
by measuring the **coherent quadrupole oscillation frequency**.

shift

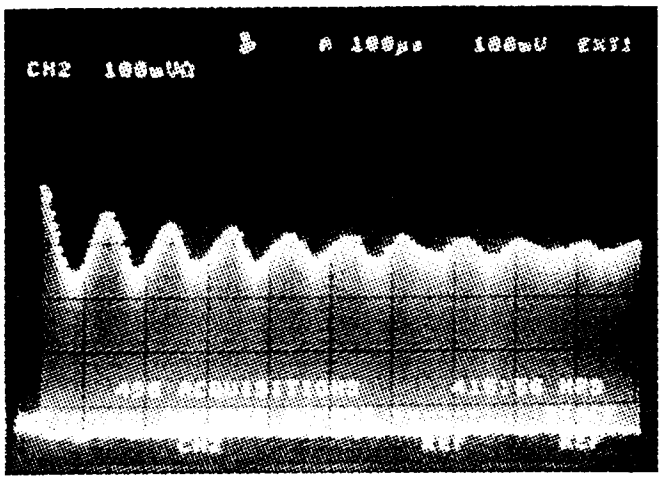
COHERENT : collective motion



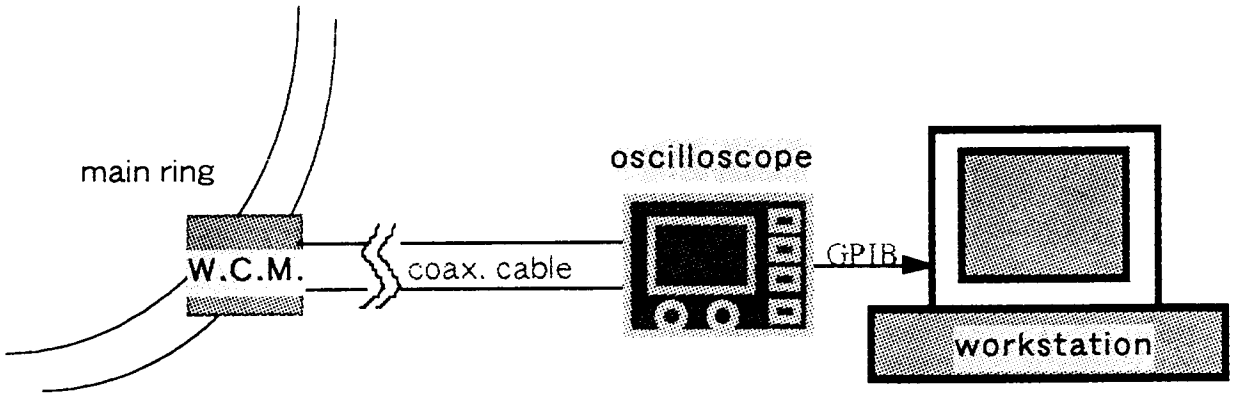
We can mesure the quadrupole oscillation
by obseving **the envelope oscillation of the bunch shape.**

Procedure of the data taking.

1 . Waveform detected by wall-current monitor



2 . deta taking

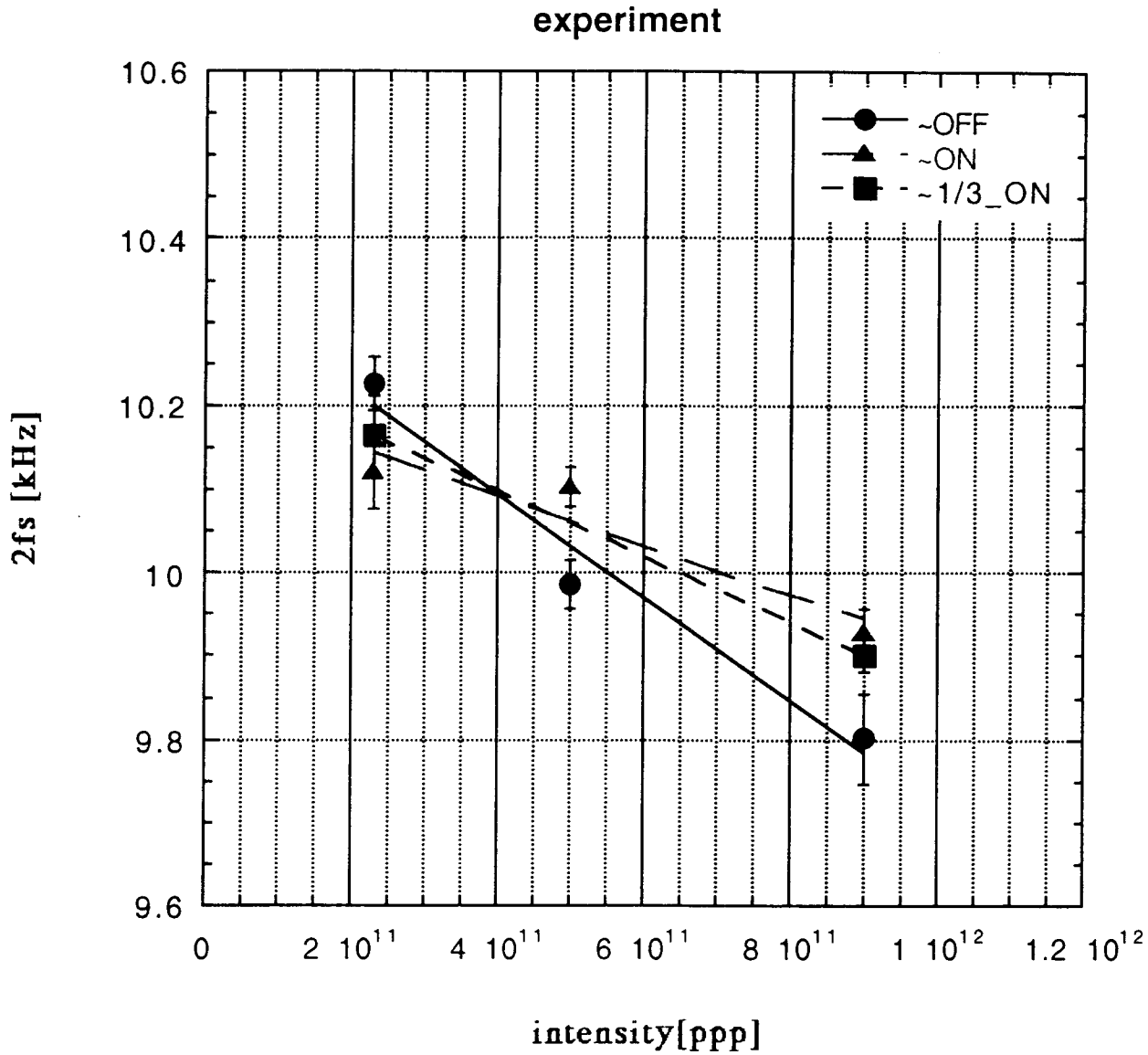


3 . frequency measuremnet

fit the bunch envelope to the equation,

$$y = a1 * \exp(a2 * x)\cos(2\pi \cdot a3 * x + a4) + a5$$

Experimantal Results



ON	1182	[ohm]
1/3ON	1554	
OFF	2475	

(space charge only)

Results

without Impedance Tuner

$$\mathrm{Im}Z = 2475\Omega$$

↓

with Impedance Tuner

$$\mathrm{Im}Z = 1182\Omega$$

That demonstrates
the space charge impedance is compensated with the Impedance Tune

?????Questions to the experimental results???'

------disagreement with calculations---------

- **Quadrupole frequency at "zero" beam current = 2 * synchrotron frequency**

calculation : 12.4kHz

$$f_{s0} = f_{rev}\sqrt{\frac{-\eta h}{2\pi\beta^2\varepsilon_s} eV_0 \cos}$$

$\neq$

measurement : 10.27kHz

~20% less

- **absolute value of the space charge impedance**

calculation : 310 ohm $= \boxed{\frac{g_0 Z_0}{2\beta\gamma^2}}$

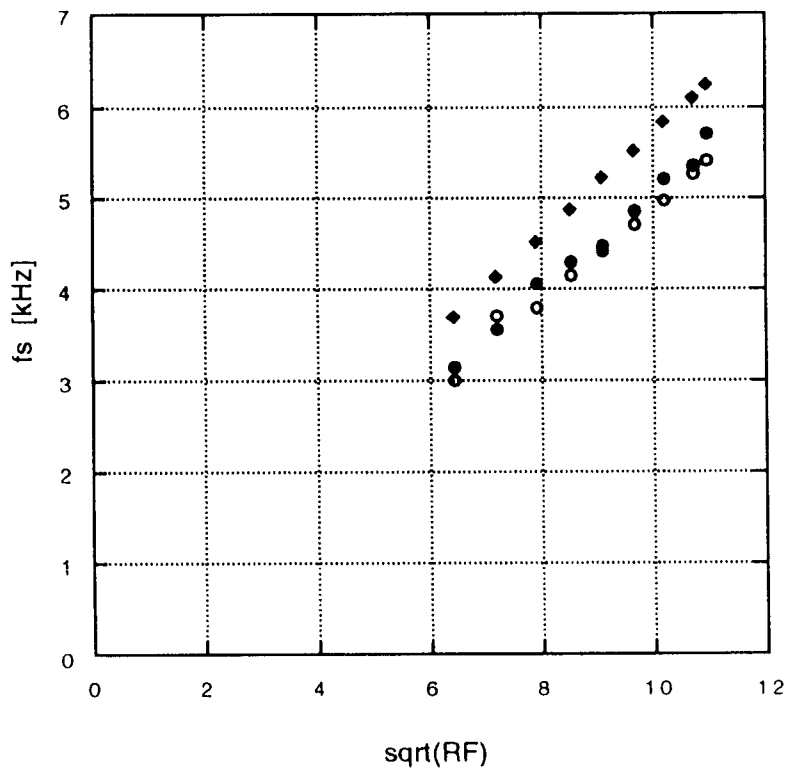
$\neq$

measurement : 2475 ohm

x8 times

Why these results do not agree with the calculation?

Another mesurement of the synchrotron frequency with **dipole osillation.**



fs = 5.3kHz

$2 \times f_s = 10.6$ kHz

calculation : 12.4kHz

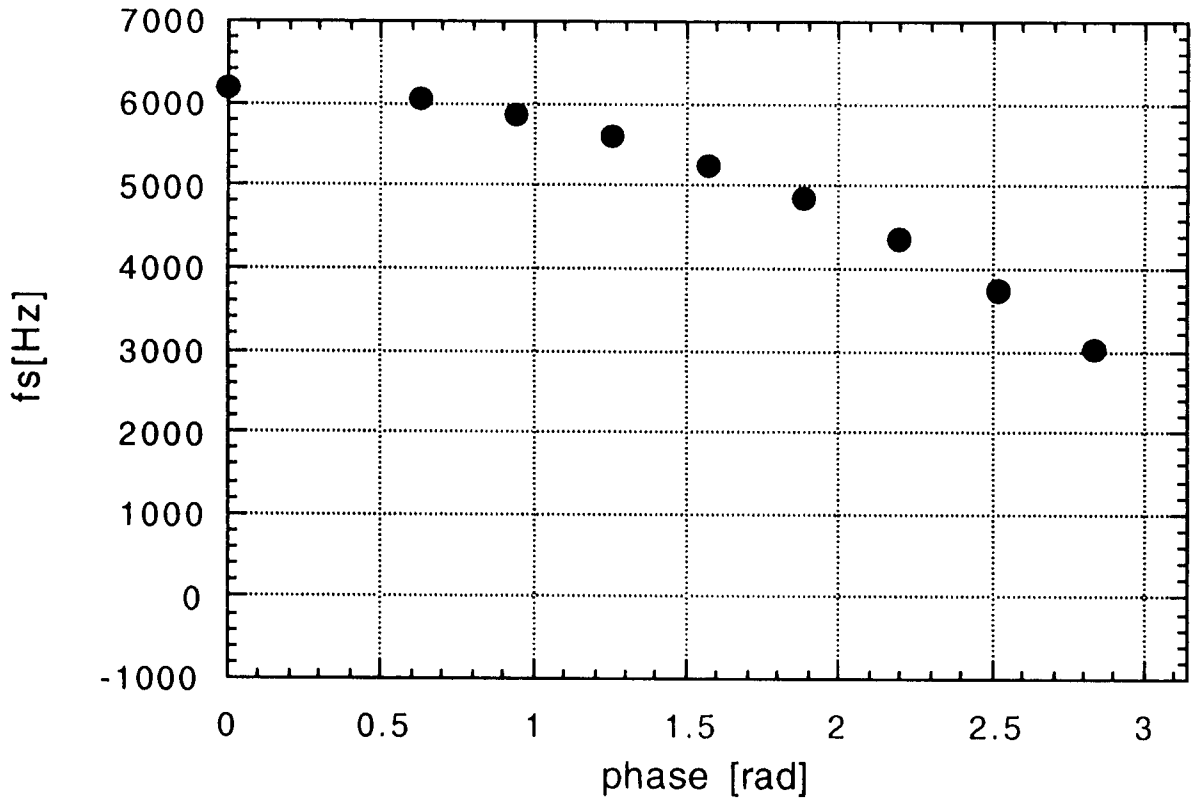
measurement : 10.27kHz

- This result dose not agree the caliclation, either.

Why?

Single particle motion

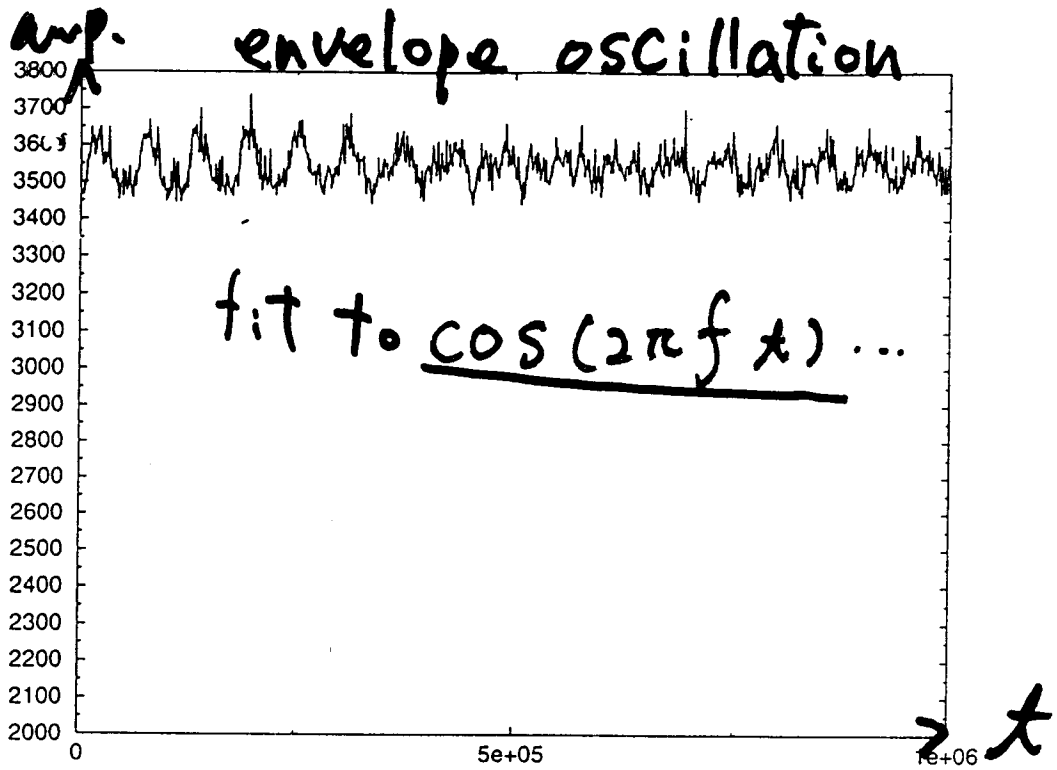
Each particle in the bunch has each incoherent synchrotron frequen
as a function of the amplitude.

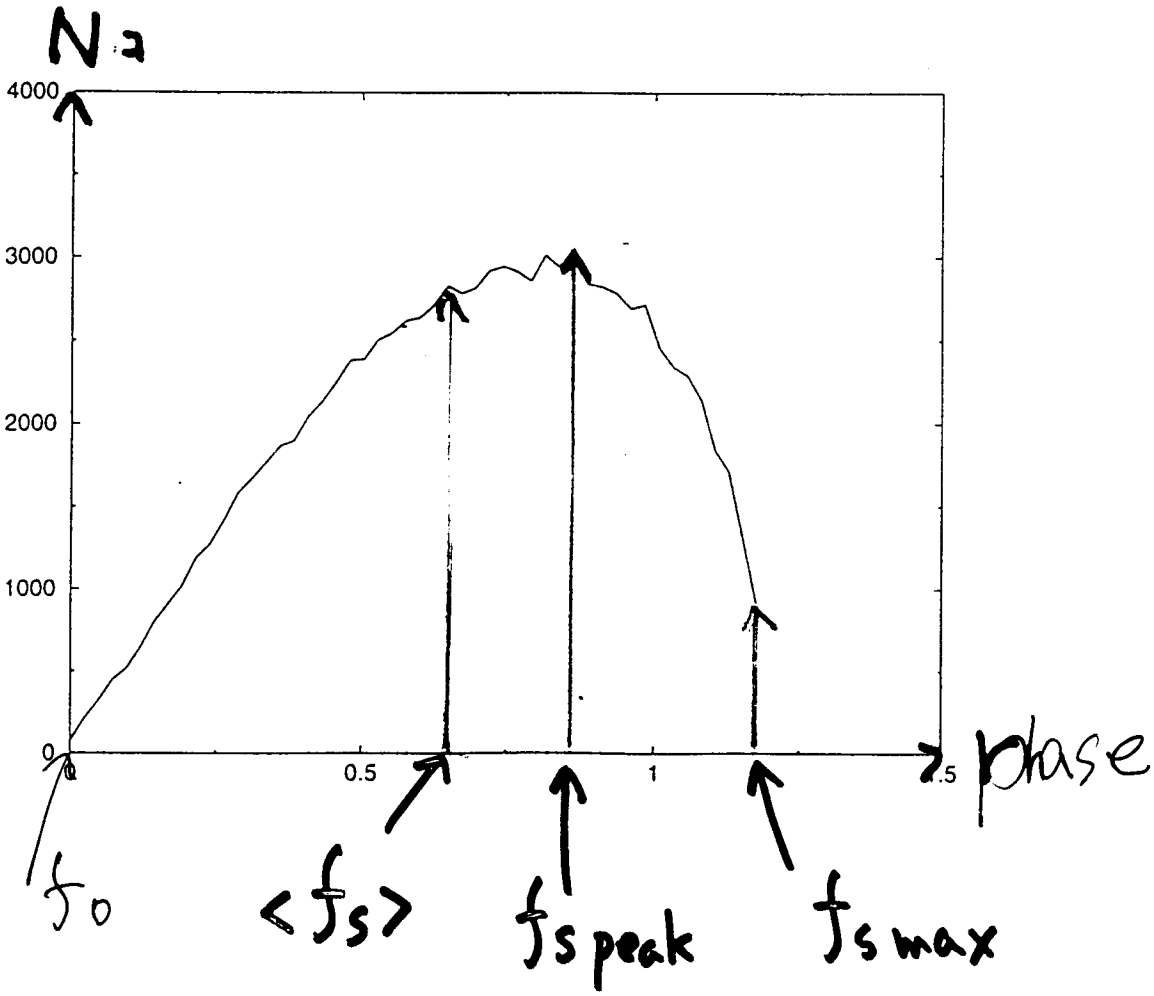


Multiparticle motion????

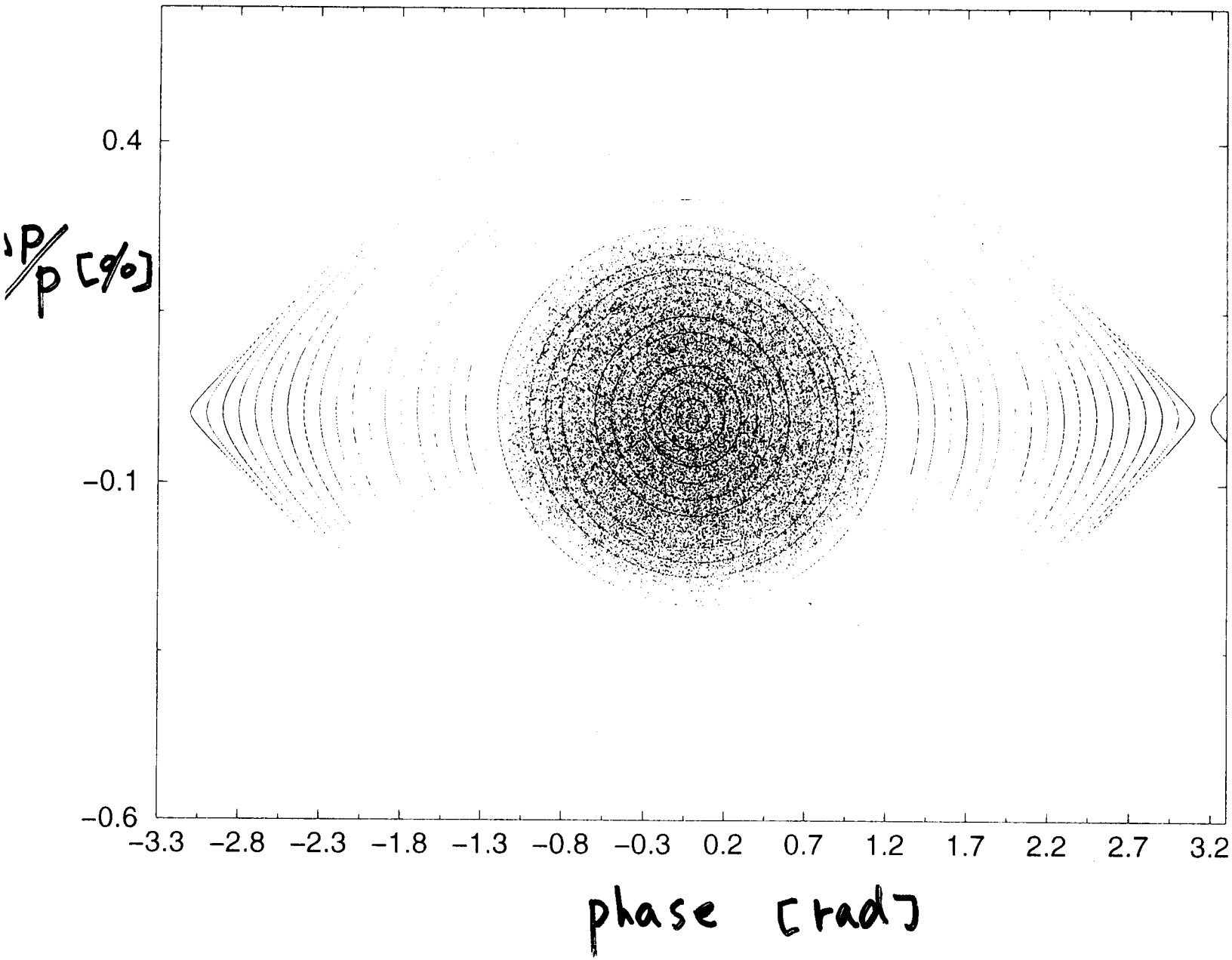
envelope oscillation frequency coused by the multiparticle motior

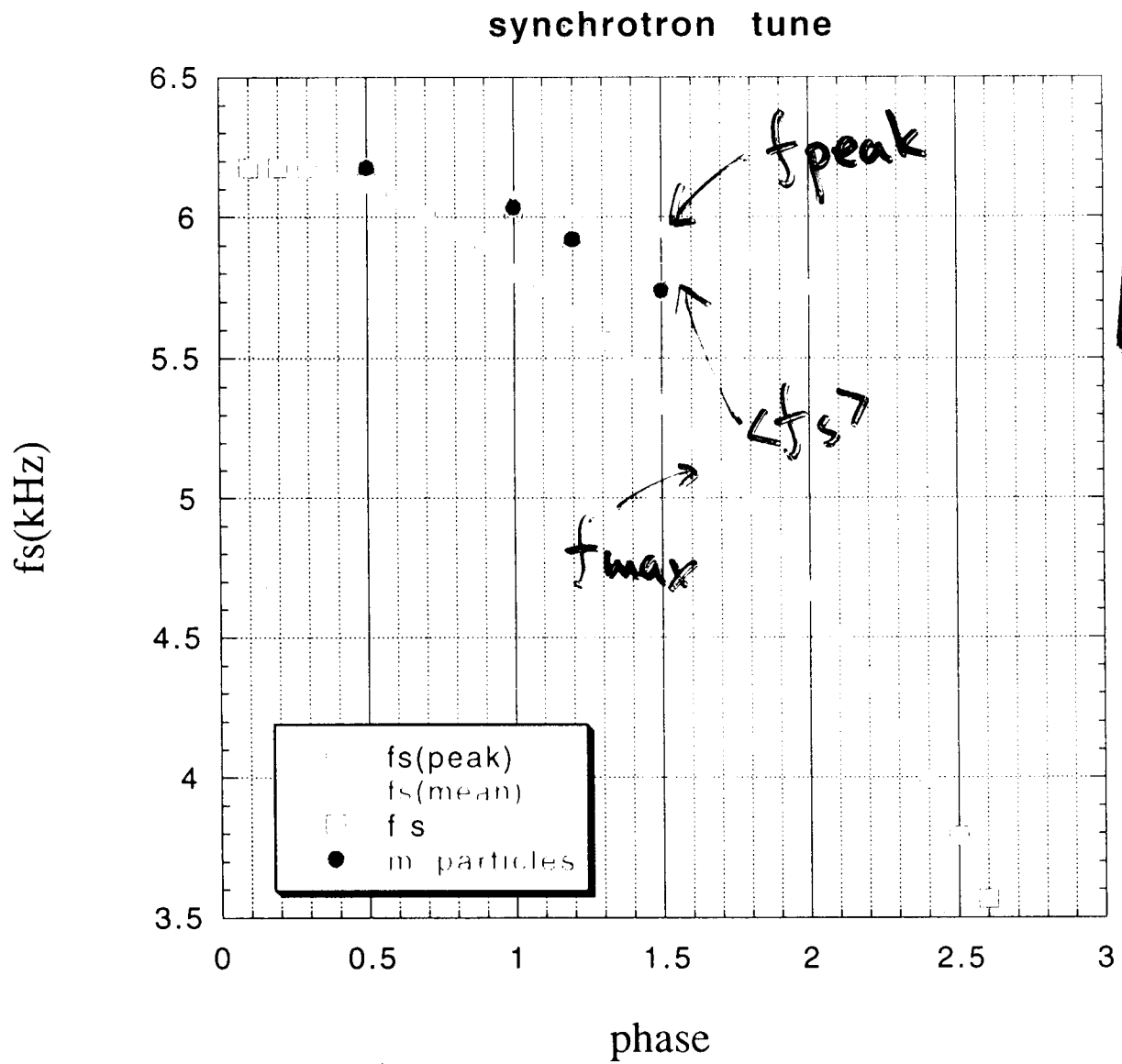
Simulation result





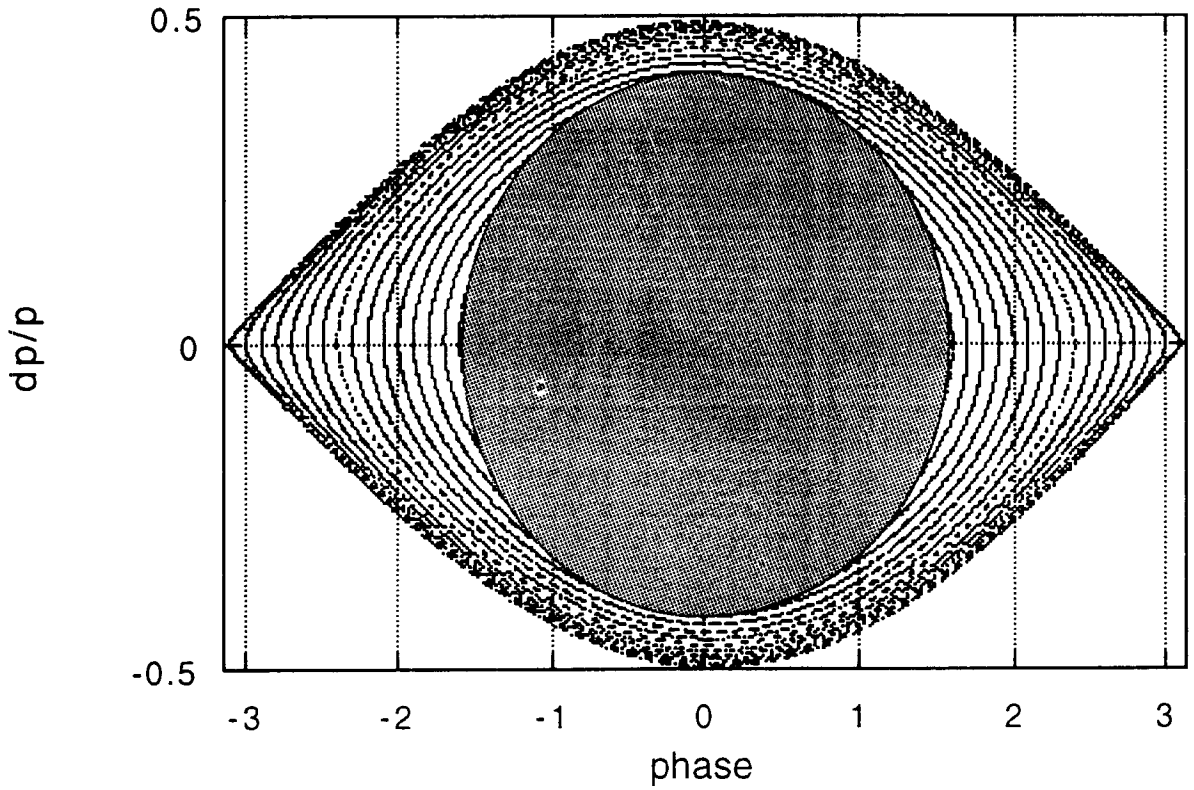
Multiparticle simulation with RF nonlinearity.





$\boxed{\text{env. } f_s \sim \langle f_s \rangle}$

phase space looks like this in the KEK-PS



real distribution

$a/2 = 0.409\%$ bunch length 101nsec

$b/2 = 1.59 rad$ bunch length 85nsec

The bunch is affected by **RF non-linearity.**

Q1: Quadrupole frequency at "zero" beam current
= 2 * synchrotron frequency

calculation : 12.4kHz

~20% less

measurement : 10.27kHz

Simulation with RF non-linearity : 10.6kHz

--->Ans. : The bunch is affected by the RF nonlinearity.
Because the RF voltage isn't enough at the KEK-PS.

before analysis

coherent ⟶ incoherent

$$\frac{\Delta f_{2s}}{f_{2s0}} = \frac{1}{4}\frac{\Delta f_s}{f_{s0}}$$

assumption linear RF field

longitudinal phase-space distribution

matched to RF bucket

However, real beam.....

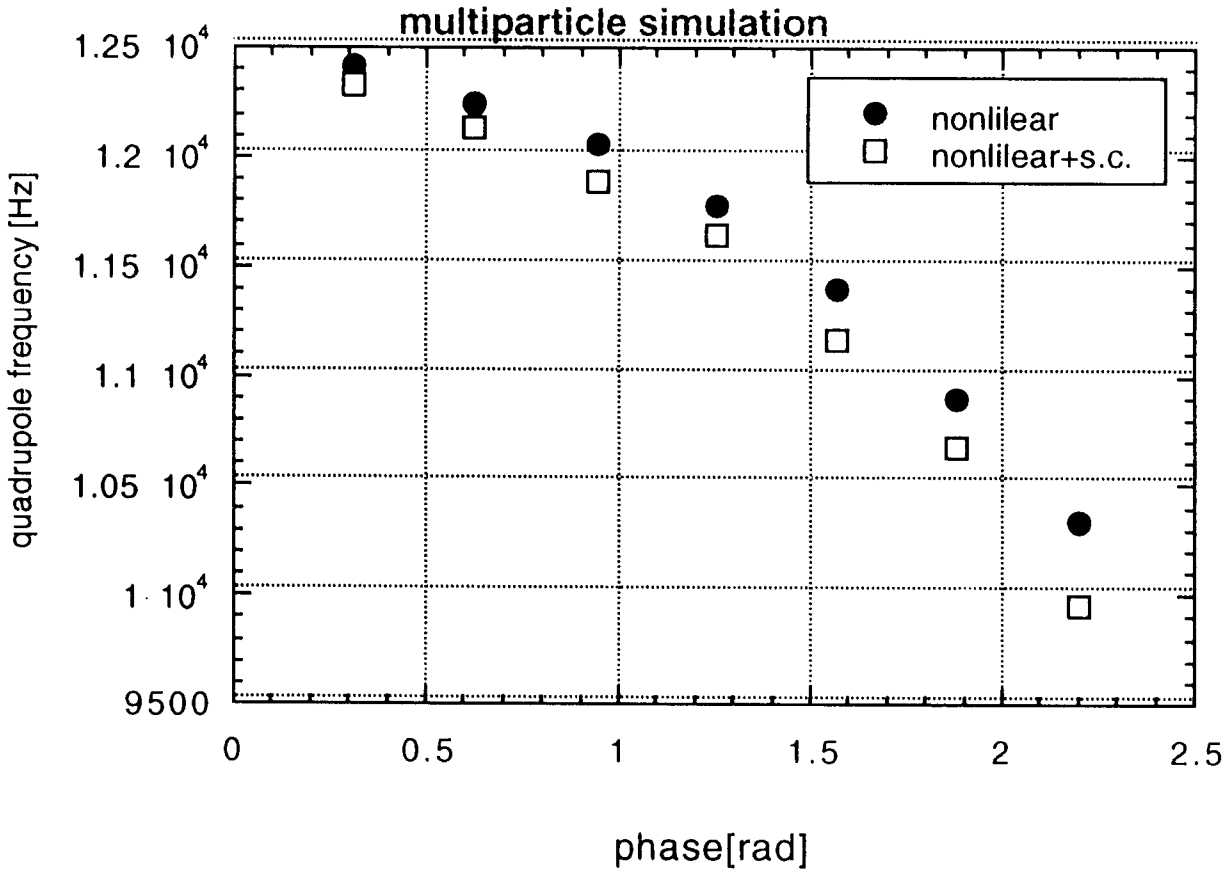
RF field ---> non-linear

mis-matching

Coherent quadrupole oscillation frequency shift.

space charge effects = const.

$$\frac{N}{\rho^3} = const.$$



$$\frac{\Delta f_{2s}}{f_{2s0}}$$

The frequency shift is a function of amplitude.

Simulation Result with real distribution in the KEK-PS

(3) non-linear RF field
without space charge

$f_{2s0} = 10.600\text{kHz}$

(4) non-linear RF field
without time-varying space charge force

$f_{2s} = 10.436\text{kHz}$

(5) non-linear RF field
with time-varying space charge force

$2\times f_s = 10.279\text{kHz}$

(3) -> (4) $$\frac{\Delta f_{2s}}{f_{2s0}} = \frac{10.600 - 10.436}{10.600} = 1.547\times 10^{-2}$$

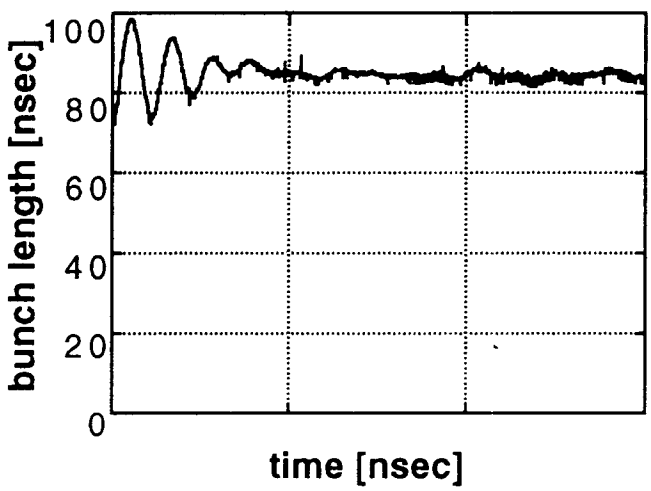
(3) -> (5) $$\frac{\Delta f_s}{f_{s0}} = \frac{10.600 - 10.279}{10.600} = 3.03\times 10^{-2}$$

$$\boxed{\frac{\Delta f_{2s}}{f_{2s0}} \approx \frac{1}{2}\frac{\Delta f_s}{f_{s0}}} \Leftarrow \frac{\Delta f_{2s}}{f_{2s0}} \approx \frac{1}{4}\frac{\Delta f_s}{f_{s0}}$$

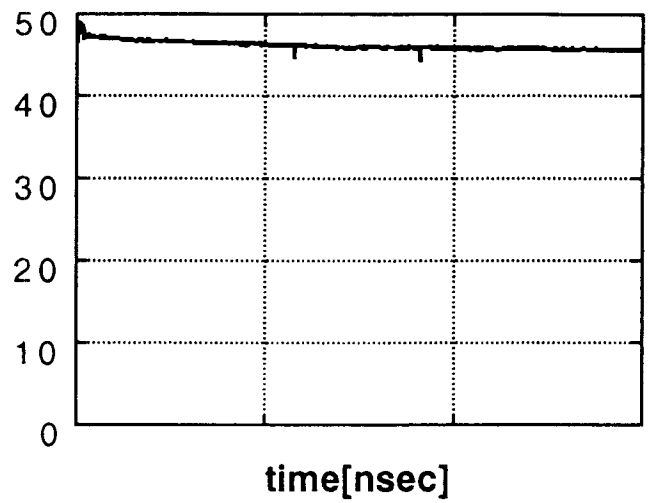
The frequency of the envelope oscillation is changing turn by turn.

$$\frac{\Delta f_s}{f_s} = -\frac{3ef_0}{2\pi^2 h V_{rf}\cos\phi_s}\left(\frac{2\pi R}{\ell}\right)^3\left[\frac{g_0 Z_0}{2\beta\gamma^2} - \left|\frac{Z}{n}\right|\right]N$$

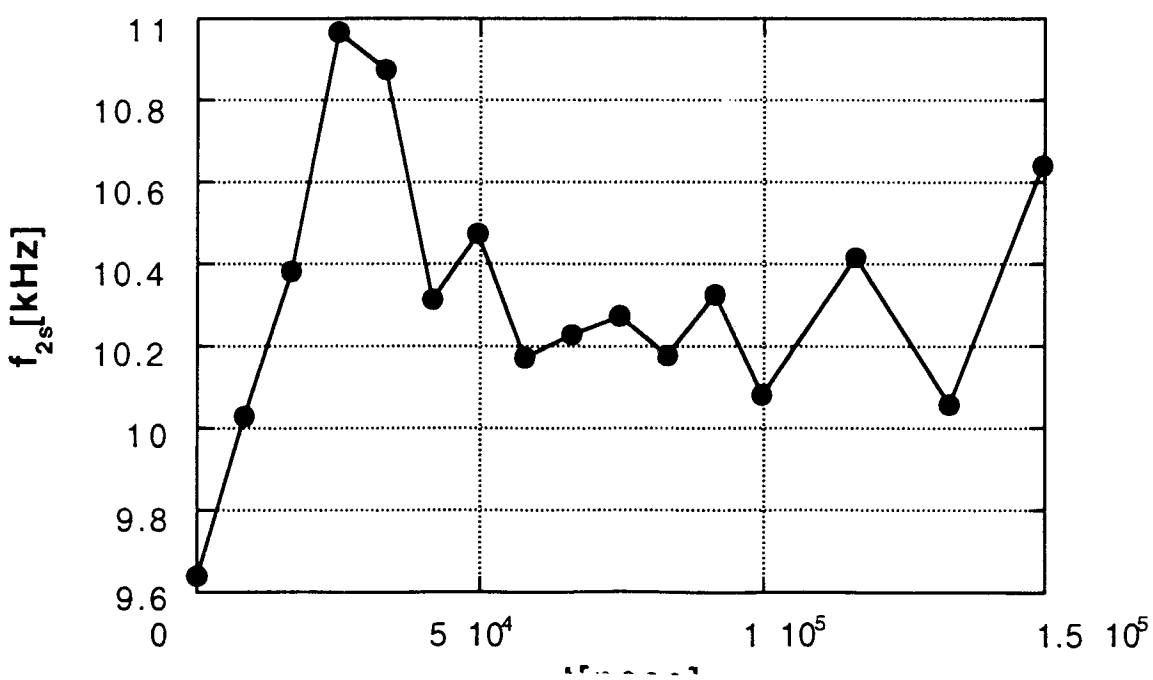
bunch length



beam intensity



frequency



We have to consider.....

RF non-linearity

the bunch distribution in the phase space

bunch length is changing(oscillating)

beam intensity is decreasing

Procedure of the new analysis

1. multi-particle simulation

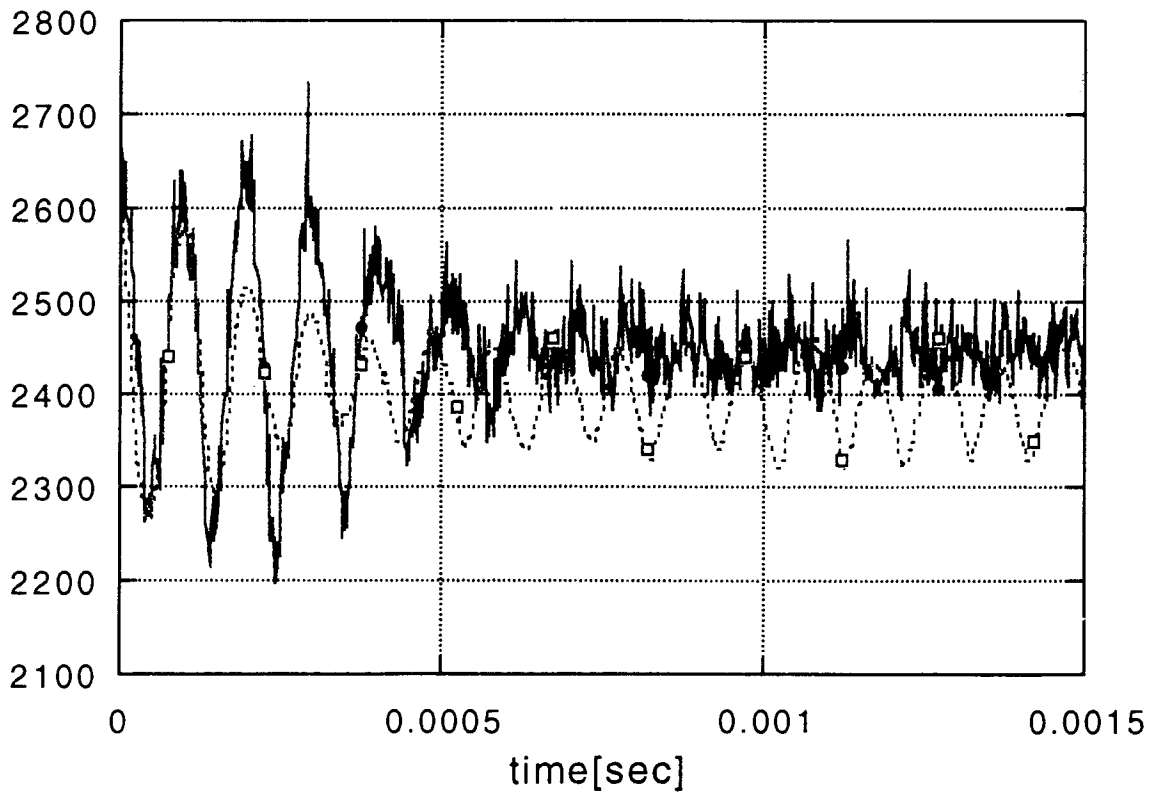
$$\frac{d\Delta\phi}{dn} = -2\eta\pi h\frac{1}{\beta^2}\frac{\Delta\varepsilon}{\varepsilon_s}$$

$$\frac{d\Delta\varepsilon}{dn} = eV_0\Delta\phi - eV_{sc}(\ell, N)\Delta\phi$$

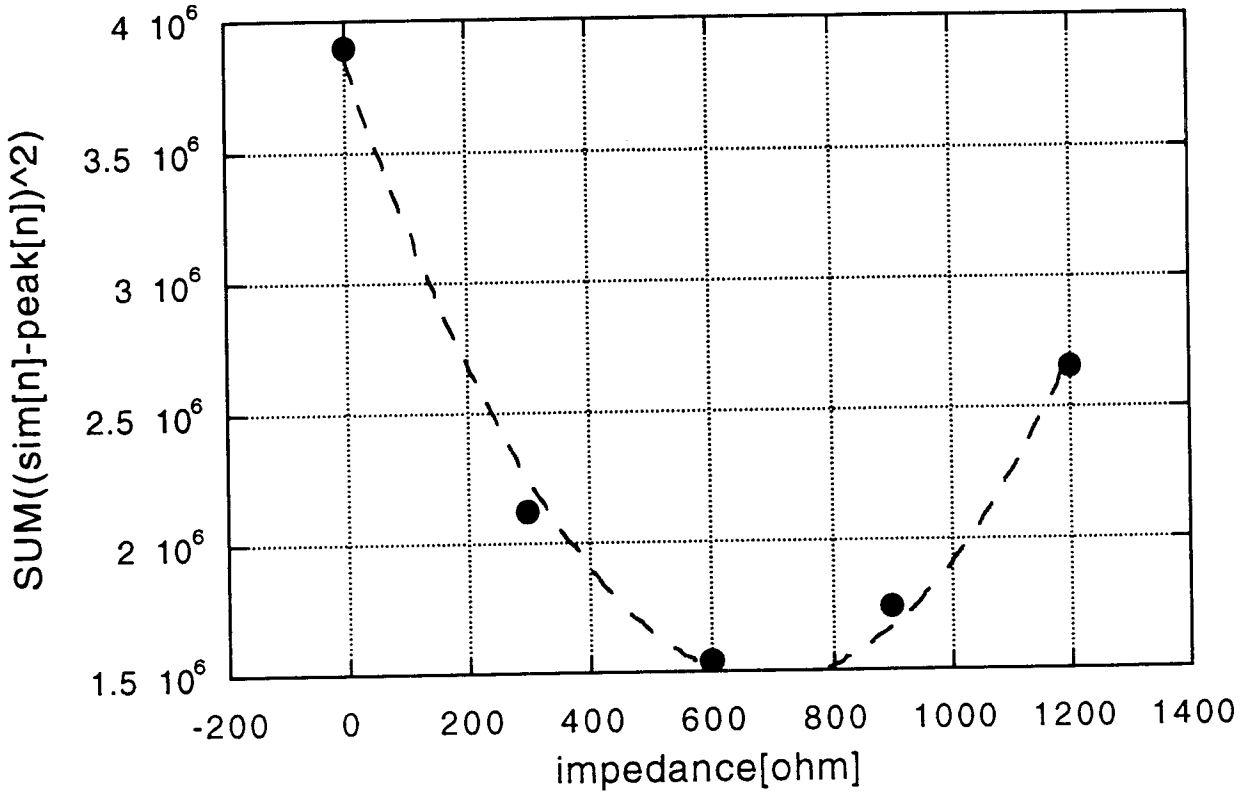
$$\therefore \frac{d^2\Delta\phi}{dn^2} \approx \frac{-2\eta\pi h}{\beta^2\varepsilon_s} e(V_0 - V_{sc}(\ell, N))\Delta\phi$$

$$V_{sc} = \frac{3ef_0}{\pi^2 h\cos\phi_s}\left(\frac{2\pi R}{\ell}\right)^3\left[\frac{g_0 Z_0}{2\beta\gamma^2} - \left|\frac{Z}{n}\right|\right]N$$

2. compared with experiment



$$\sum^{250}(peak\ [n] - sim\ [n])^2$$

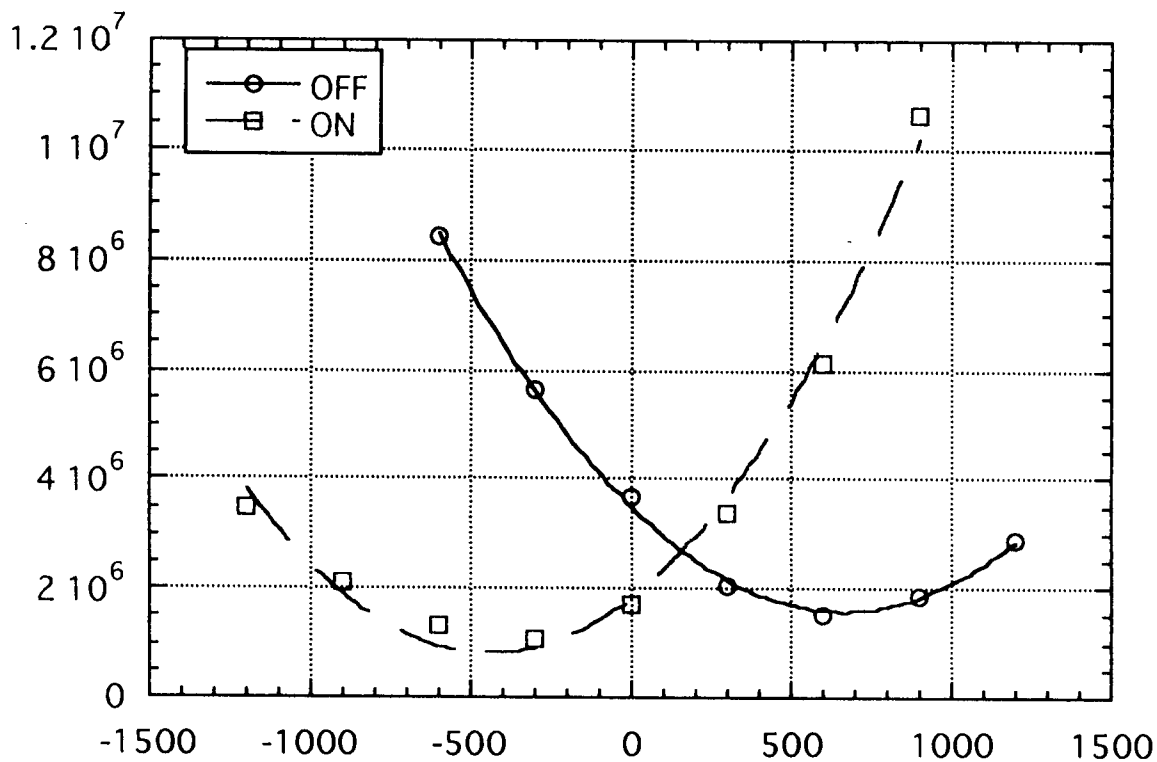


2475[ohm] Linear approximation analysis

660[ohm] Analysis including non-linear effect

310[ohm] Calculated space charge impedance

Result of the new analysis



without Impedance Tur

660.5 Ω

↓

with Impedance Tuner

-442.4 Ω

Q2: absolute value of the space charge impedance

calculation : 310 ohm

measurement : 2475 ohm

x8 times

--->Ans.

	before analysis	**new analysis**
without Impedance Tuner	$\mathrm{Im}Z = 2475\Omega$	$\mathrm{Im}Z = 660\Omega$
	↓	↓
with Impedance Tuner	$\mathrm{Im}Z = 1182\Omega$	$\mathrm{Im}Z = -442\Omega$

SUMMARY

We designed the impedance tuner consisting of the inductive materia FINEMET, to cancel the space charge impedance in the longitudinal direction. It was installed in the KEK PS main ring.

The measured impedance is reduced [redacted] by the impedance tun which consists of 12 pieces of the FINEMET cores. We demonstrated th space charge impedance is compensated by the impedance tuner.

We have analyzed the RF non-linear effect in detail with calculation simulation.