CLNS 97-1487

Proceedings of the Mini-Symposium on Photoelectron and Ion Instabilities at PAC 97

May 15, 1997

compiled by
J. Rogers and E. Camdzic
Laboratory of Nuclear Studies
Cornell University

Preface

The Minisymposium on Photoelectron and Ion Instabilities was organized as a satellite meeting of the 1997 Particle Accelerator Conference by J. Rogers, Y.H. Chin, and J. Byrd. We had two purposes in organizing this minisymposium. First, in recent months there has been exciting and encouraging progress in observing and understanding the fast ion and photoelectron instabilities of electron and positron storage rings. The Vancouver PAC was an opportunity to bring together many of the researchers in these fields to discuss these recent developments. Second, the minisymposium served as an organizational meeting for the International Workshop on Multibunch Instabilities in Future Electron and Positron Colliders, to be held July 15-18, 1997 at KEK.

The speakers at the minisymposium were Y. Funakoshi (KEK), Y.H. Chin (KEK), G. Stupakov (SLAC), H. Fukuma (KEK), M. Kwon (PAL), J. Byrd (LBNL), M. Furman (LBNL), Z.Y. Guo (BEPC), and P. Krejcik (SLAC). The speakers very kindly supplied copies of their transparencies, which form the report you see here. This is an experiment in electronic publishing: this report is intended to be entirely electronic, available in PDF format on the World Wide Web at http://www.lns.cornell.edu/~jtr/minisymposium.html. We hope that we have set a speed record for distributing the proceedings of a meeting.

We wish to thank the participants of the minisymposium for providing copies of their transparencies, M. Craddock and E. Driessen of TRIUMF for making the meeting possible, and M. Roman and R. Helmke of Cornell for computer support.

J. Rogers
E. Camdzic
Laboratory of Nuclear Studies
Cornell University
May 26, 1997

Contents

Overview of the

International Workshop on Multibunch Instabilities in Future Electron and Positron Accelerators KEK, Tsukuba, Japan 15 - 18 July, 1997

Y. Funakoshi, KEK

Goal:

The goal of the workshop is to review the results of the theoretical and experimental studies on the multibunch instabilities in future electron and positron accelerators. We also plan to discuss about further studies and effective counter-measures such as fast feedback systems. Although an emphasis will be placed on the fast ion and photo electron instabilities, discussions on other multibunch instabilities in the workshop will also be encouraged.

The Program Advisory Committee:

S. Kurokawa (KEK, chair), A. Chao (SLAC),
J. Rogers (Cornell Univ.), J. Byrd (LBL), F. Zimmermann (SLAC),
R. J. Macek (LANL), N. Dikansky (INP), S. H. Wang (IHEP),
M. Kwon (PAL), F. Ruggiero (CERN), T.Yamazaki (ETL),
H. Fukuma (KEK), M. Isawa (KEK), Y. H. Chin (KEK) and
Y. Funakoshi (KEK)

Schedule:

Date: 15 - 18 July, 1997 ➜ fixed
Place: KEK, Tsukuba, Japan ➜ fixed
Program ➜ tentative

	9:00 am-12:30 pm	2:00 pm-5:30 pm	evening
Mon., 14 July		Registration	get together party
Tues., 15 July	Session	Session	Reception
Wed., 16 July	Session	Excursion	
Thu., 17 July	Session	Session	
Fri., 18 July	Session	Concluding plenary	

Please discuss about the program. We will pay a close attention to the results of the discussion in this symposium.

We are looking forward to seeing you in Tsukuba in July!

Announcement:

If you know anyone that should be included in the mailing list for the future correspondence, please let me know.

I brought some copies of the poster for the workshop. If you need them, please ask me.

Ion-Related Instabilities and Photoelectron Instabilities: Theory and Simulations at KEK

KEK
Yong Ho Chin

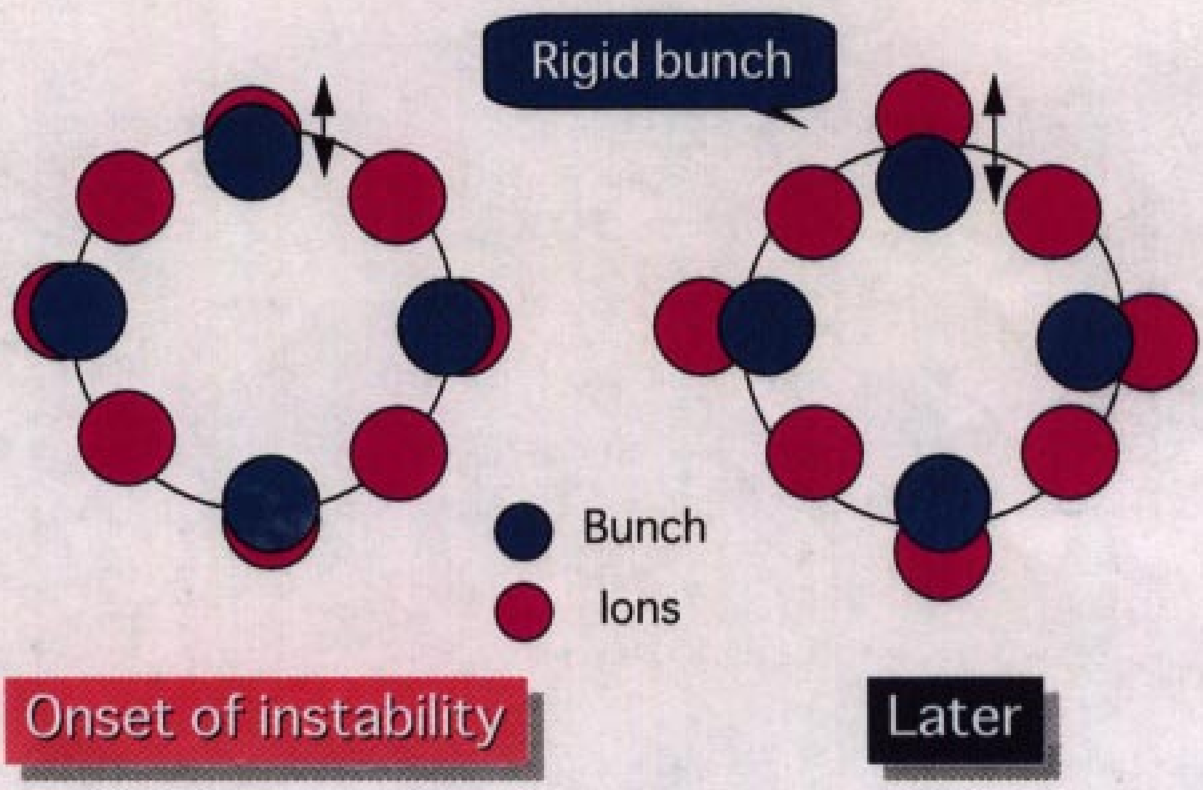
Mini-Symposium on
Photoelectron and Ion Instabilities
at PAC97
Vancouver, B.C., Canada
May 15, 1997

Relevant Machines

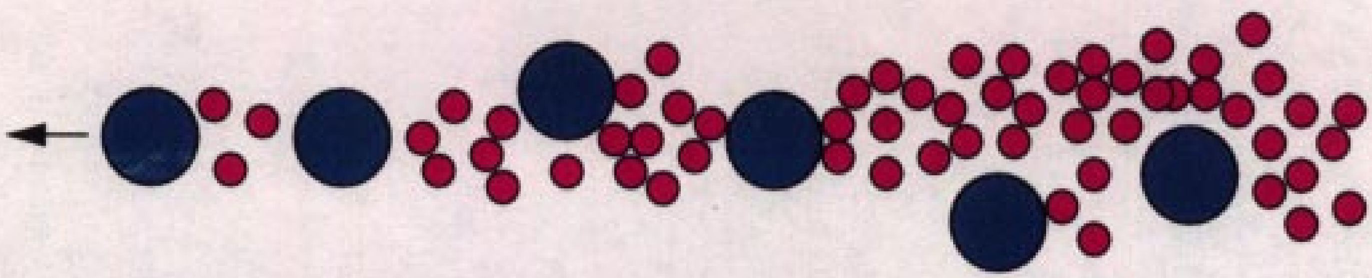
- Ion-related instabilities at electron rings
  - Ion trapping
    - KEK PF, PLS?,...
  - Fast Ion Instability (FII)
    - KEK B-factory, PEP-II, LCs, LC damping rings, KEK PF, ALS, PLS, APS?, ~~ESRF~~, ...
- Photoelectron instabilities at positron rings
  - Ohmi-type photoelectron instabilities
    - KEK B-factory, PEP-II, BEPC, BTCF,...
  - DIP instabilities
    - CESR,...

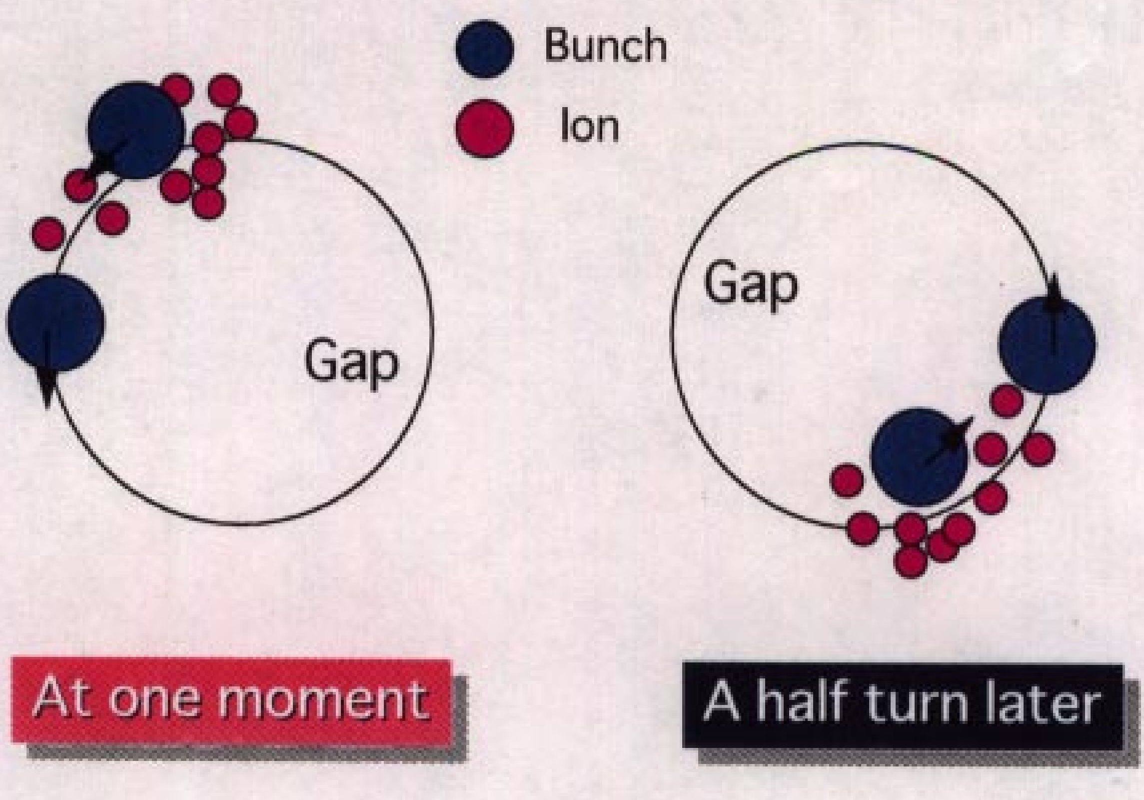
Ion-Related Instabilities

- 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

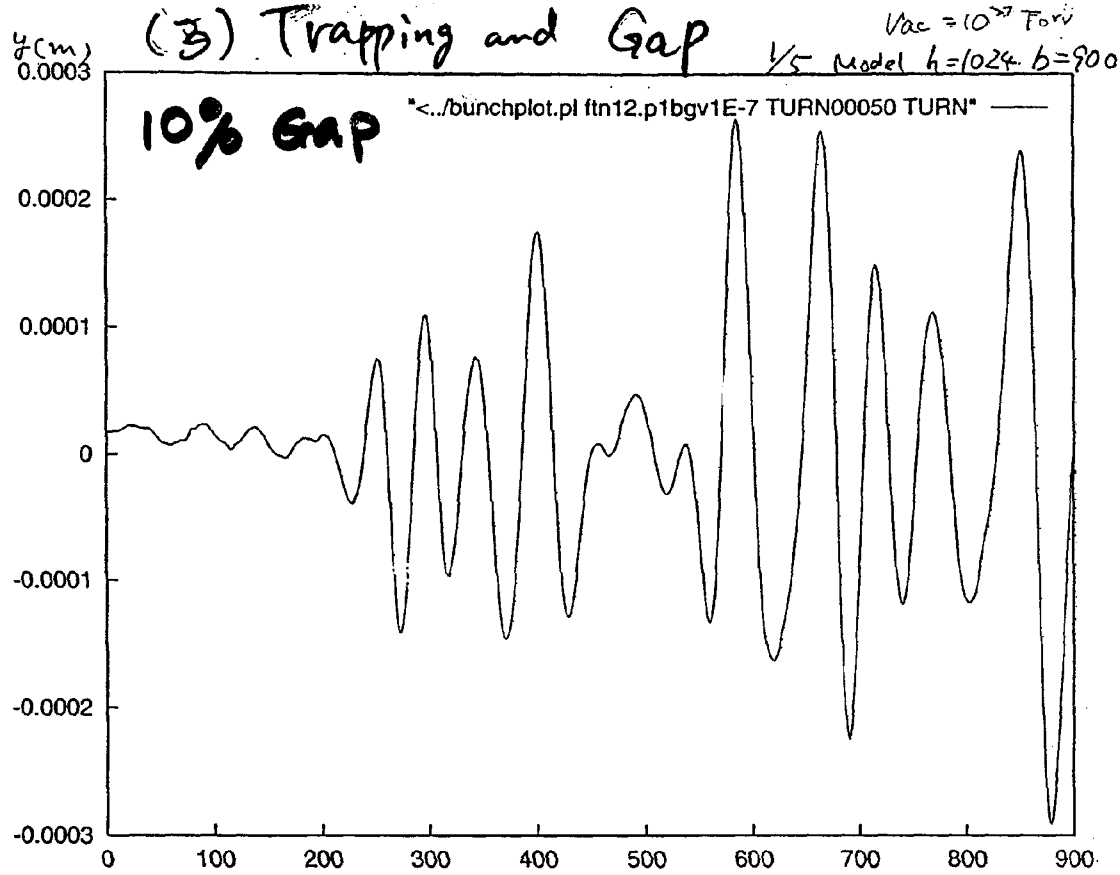


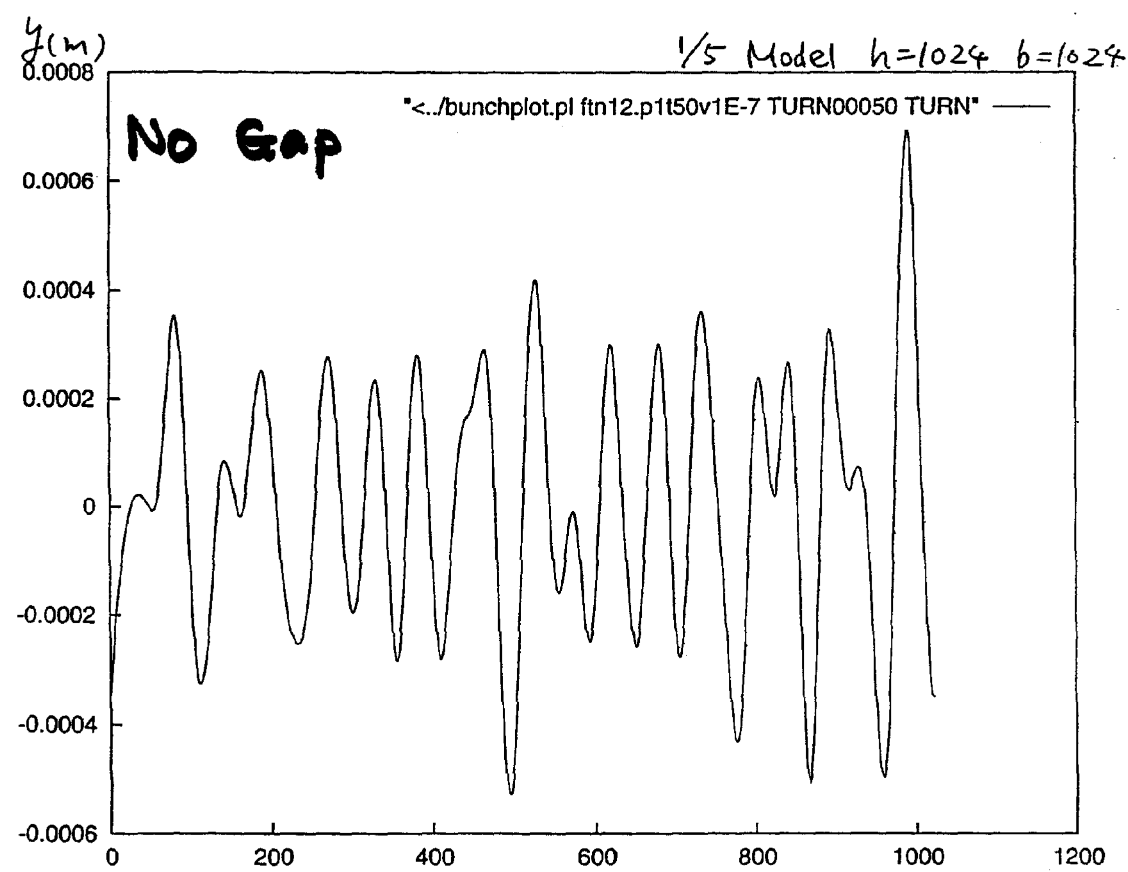
- (Transient) Fast Ion Instability
  - Ions are cleared out by a gap
  - Transient (single pass) phenomenon
  - Broad-band spectrum





(B) Trapping and Gap





Summary of Linear Theory for FII

- Ion oscillation frequency

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

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

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

- Average number of ions per passage of a bunch

$$n_i = N n_g \sigma_i$$

where

  - n_g=residual gas density
  - σ_i=ionization cross-section

- Amplitude growth factor for the n-th bunch after running over distance s

$$G = 1 + \frac{1}{\Gamma} e^{\sqrt{\Gamma}}$$

$$\Gamma = \sqrt{\frac{2m_e}{m_N} \frac{\beta_y L_{sep}^{1/2}}{\gamma} \frac{n_g \sigma_i}{\sqrt{A}} \left[\frac{2r_e zN}{3\sigma_y \sigma_x} \right]^{3/2}} sn^2$$

where

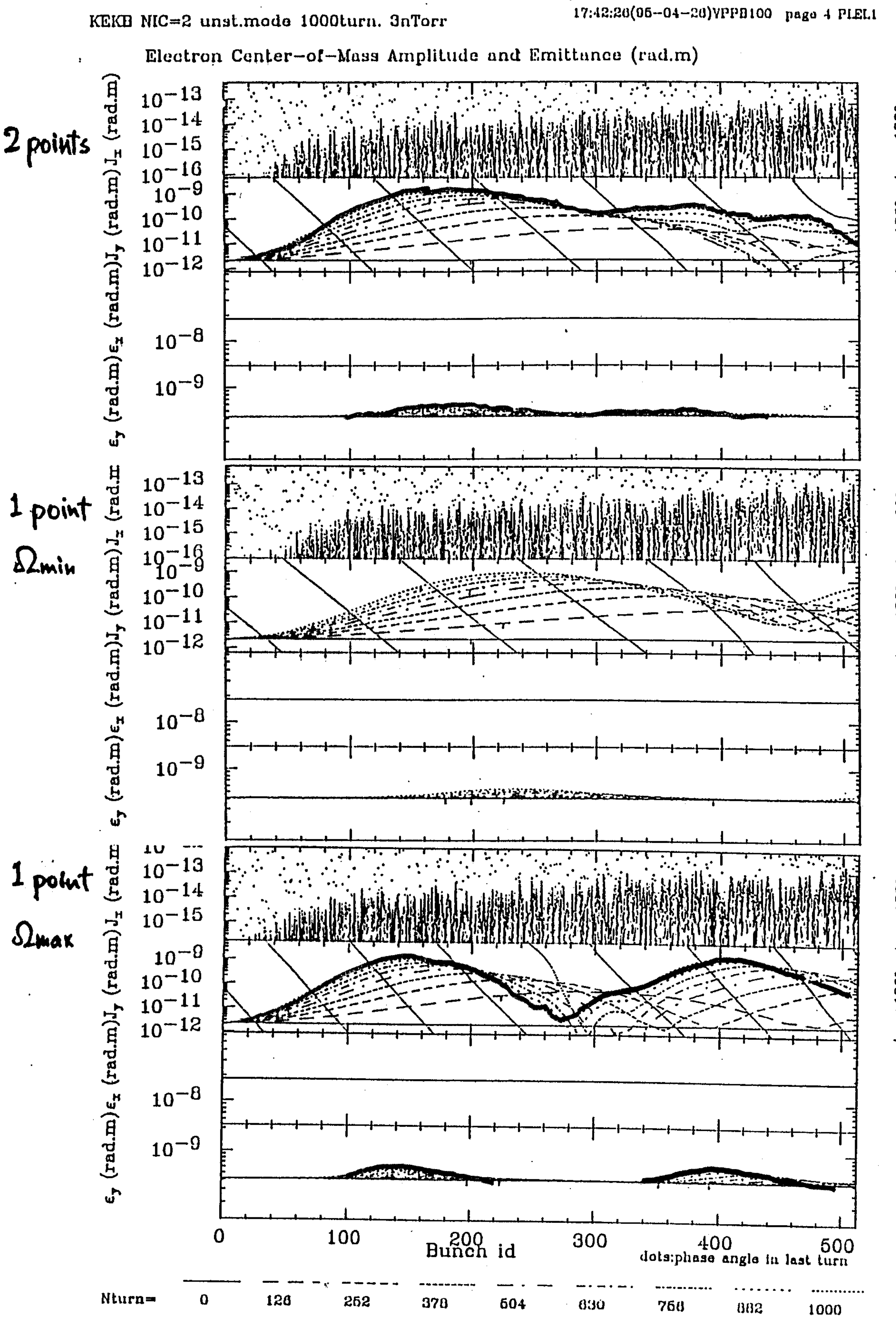
- m_e, m_N=electron and nucleon masses
- β_y=average beta-function
- γ=gamma factor
- r_e=classical electron radius
- z, A=electrovalence and mass number of ion

Simulation Results of FII for KEKB

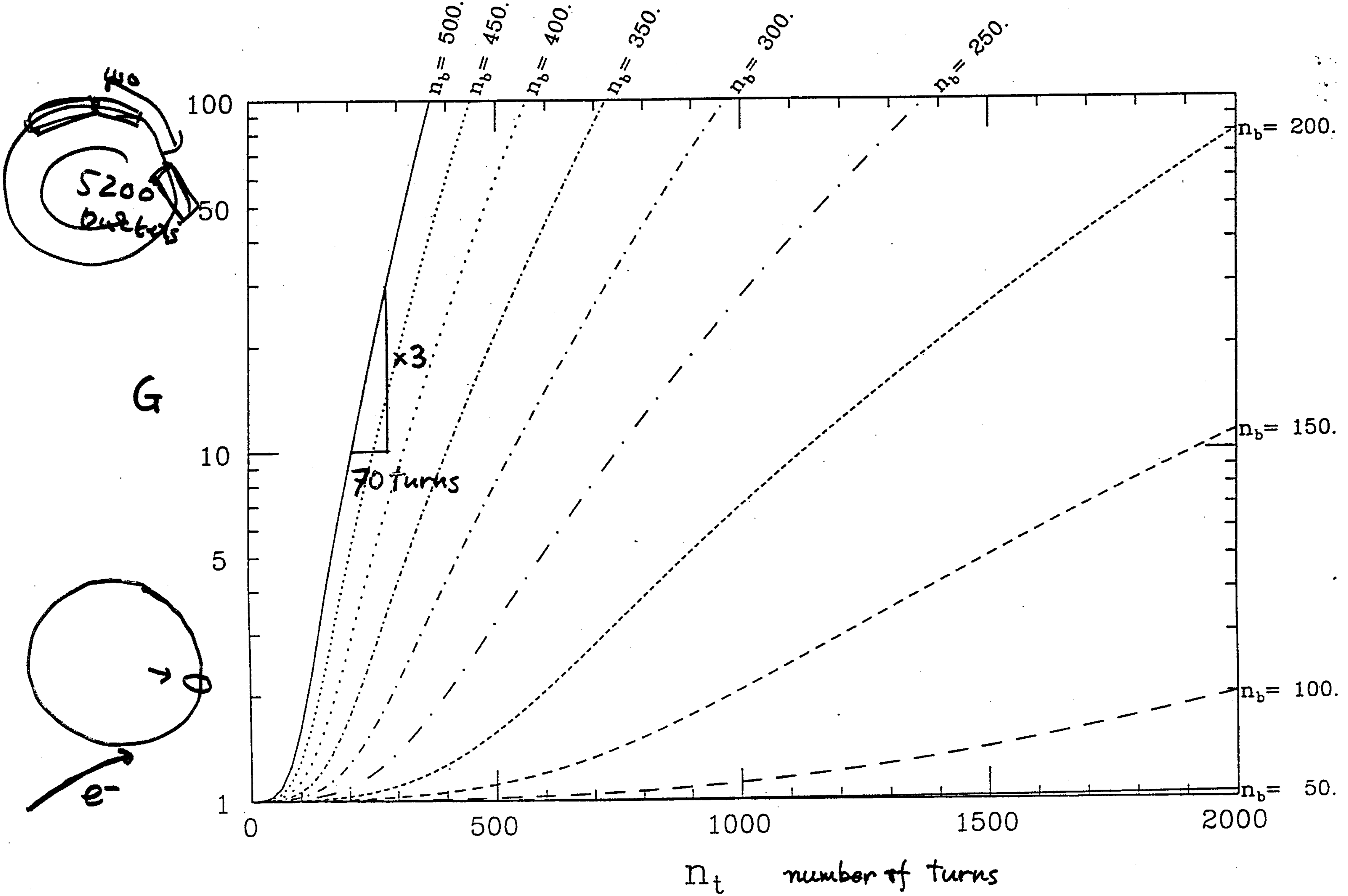
- Ion trapping
  - $E=8GeV$
  - $C=3016m$
  - $I=1.1A$
  - $N=1.4x10^{10}$
  - $L_{sep}=2ns$
  - $n_b=5120$
  - $P=1nTorr$ (CO gas)
  - $\sigma_x=0.4mm$
  - $\sigma_y=0.06mm$
    - $\eta_{th}=N_i/N_e=5x10^{-6}$
    - $\tau=2.3$ turns

- FII
  - Number of ions created by a bunch=100/m (1nTorr)
    - $N_i=5x10^5$/m after 5000 bunches
    - $N_e=2.4x10^{10}$/m
    - $\eta= N_i/N_e=2x10^{-5} >> \eta_{th}$
  - FII becomes ion trapping in one turn and the growth is too fast
  - Simulations show that a bunch train with 500 bunches gives a growth time of 100 turns

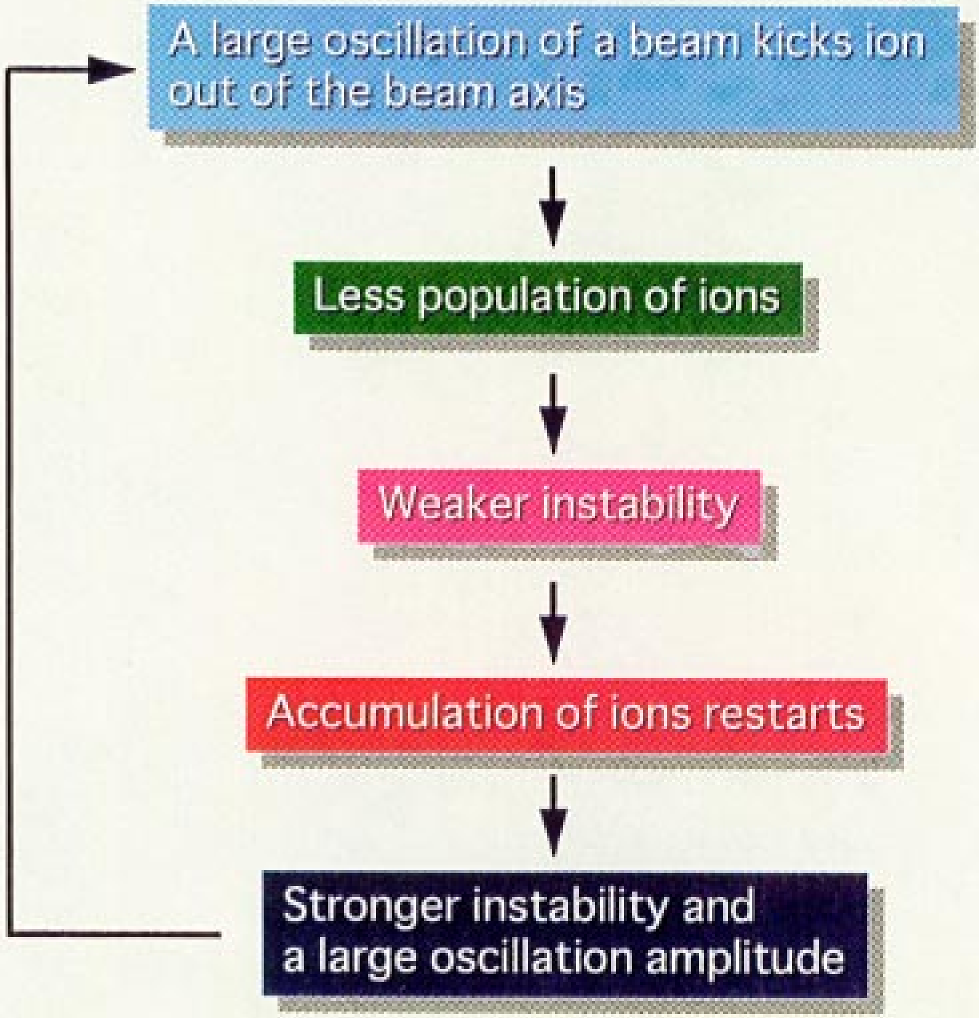
initial condiation $a = 0.1\,\sigma_y$. phase $e^{+i\Omega\tau}$

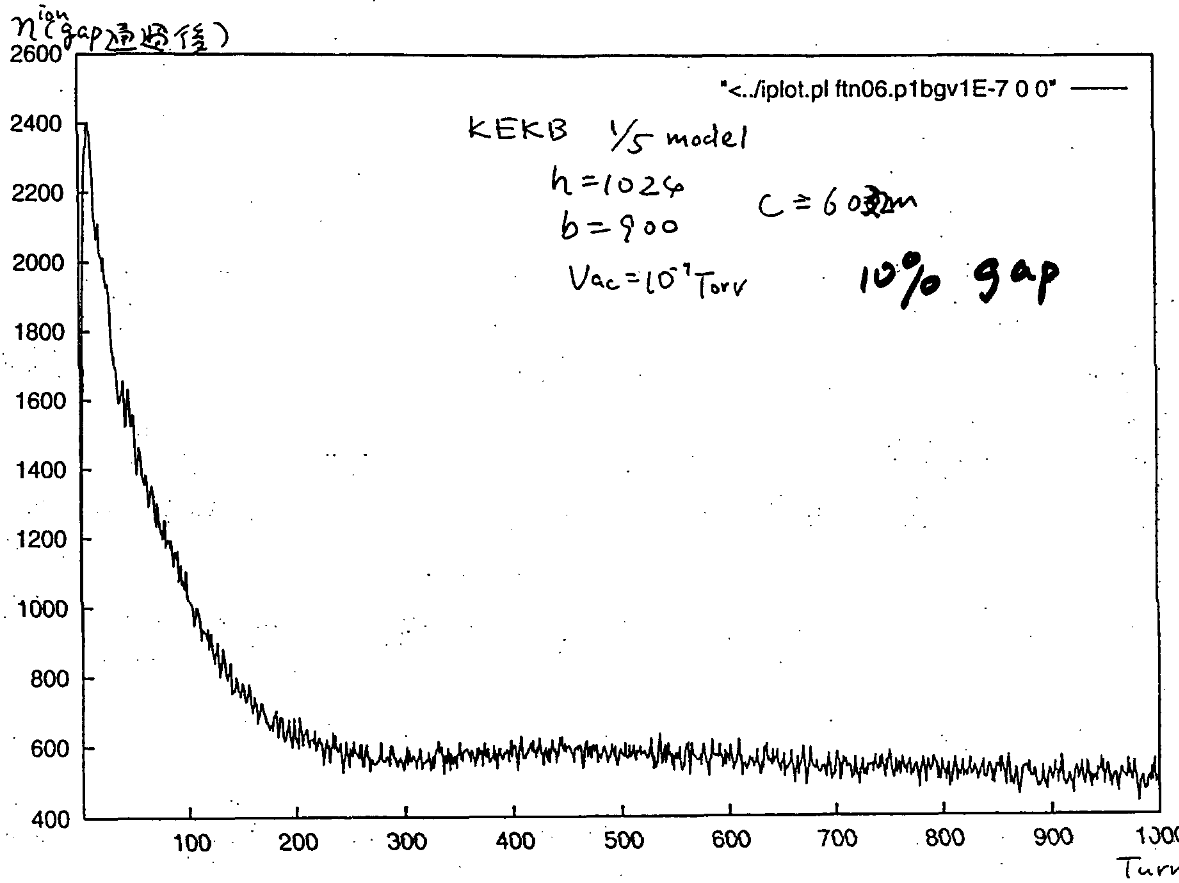


Amplitude Growth Factor (CO^+. 10^{-9} Torr)

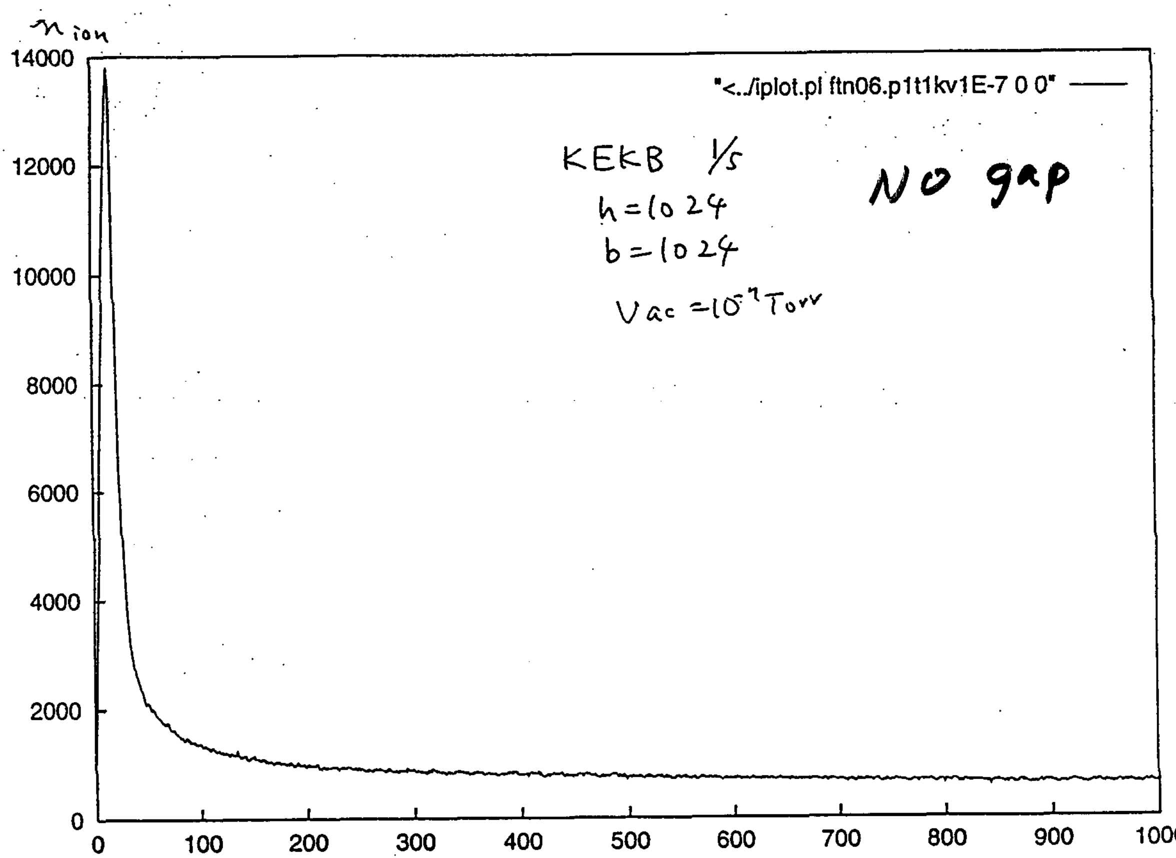


- Simulations for 1/5 KEKB model with a gap show
  - A 10% gap is effective to clear ions though not perfect.
  - A slow build-up and saturation of ion population near the beam axis and





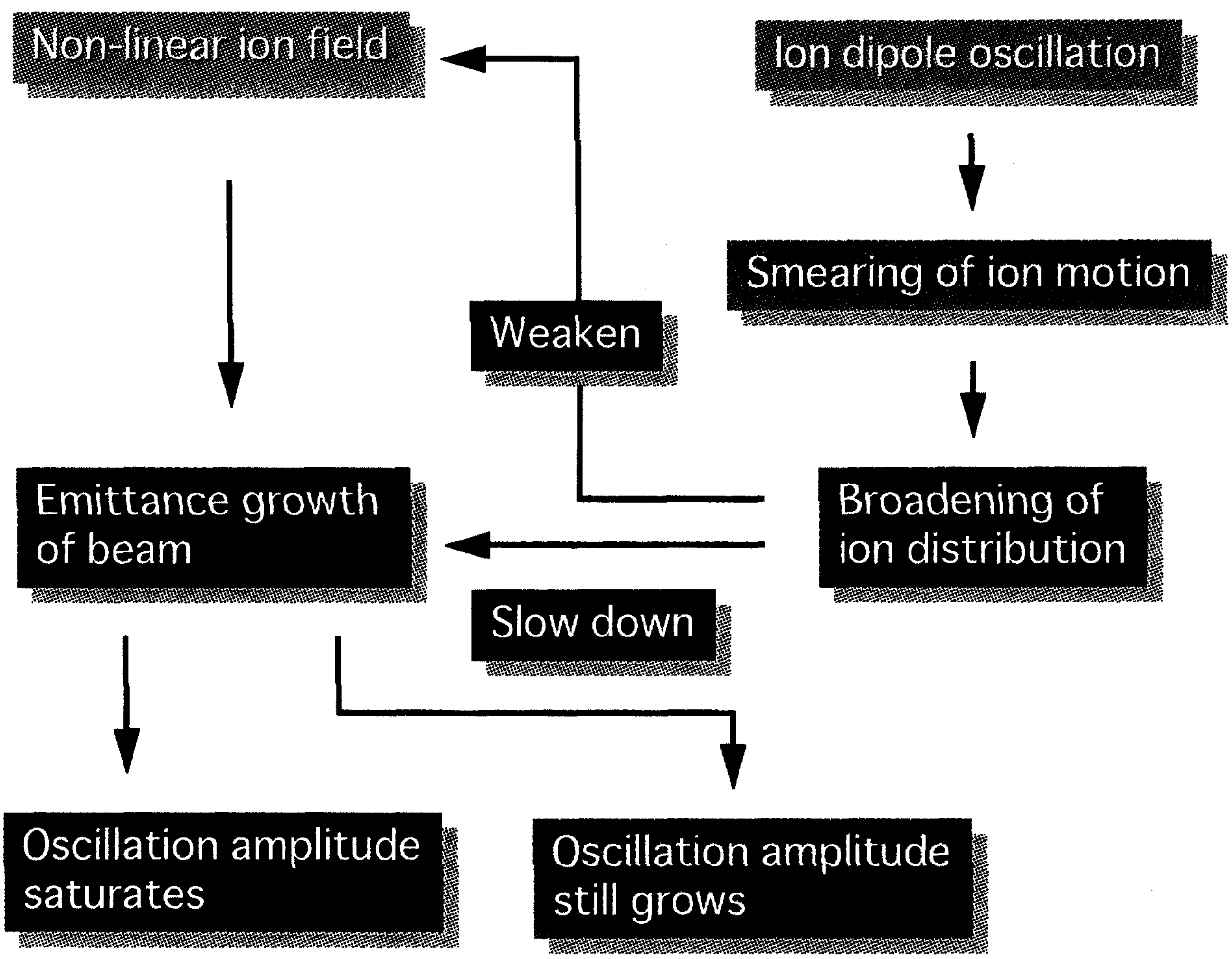
n^ion (gap通過後)
"<../iplot.pl ftn06.p1bgv1E-7 0 0"
KEKB 1/5 model
h=1024
b=900
Vac=10^-7 Torr
10% gap
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
100
200
300
400
500
600
700
800
900
1000
Turn



n ion
"<../iplot.pl ftn06.p1t1kv1E-7 0 0"
KEKB 1/5
h=1024
b=1024
Vac=10^-7 Torr
NO gap
14000
12000
10000
8000
6000
4000
2000
0
0
100
200
300
400
500
600
700
800
900
1000

- Saturation of the beam oscillation at a small amplitude?

  - Why no FII observed at ESRF or other SRs?
  - Extensive simulation studies show



参考資料

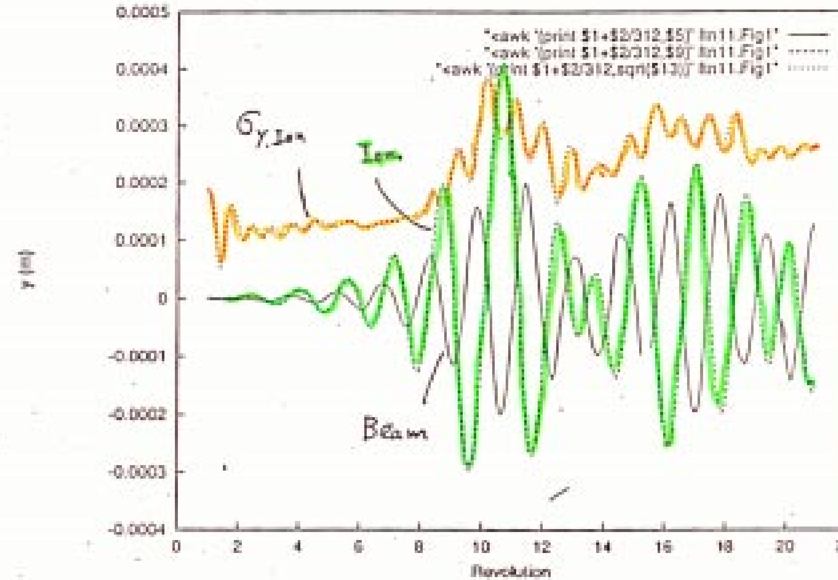
Numerical analysis of two beam instability due to ion in electron storage rings

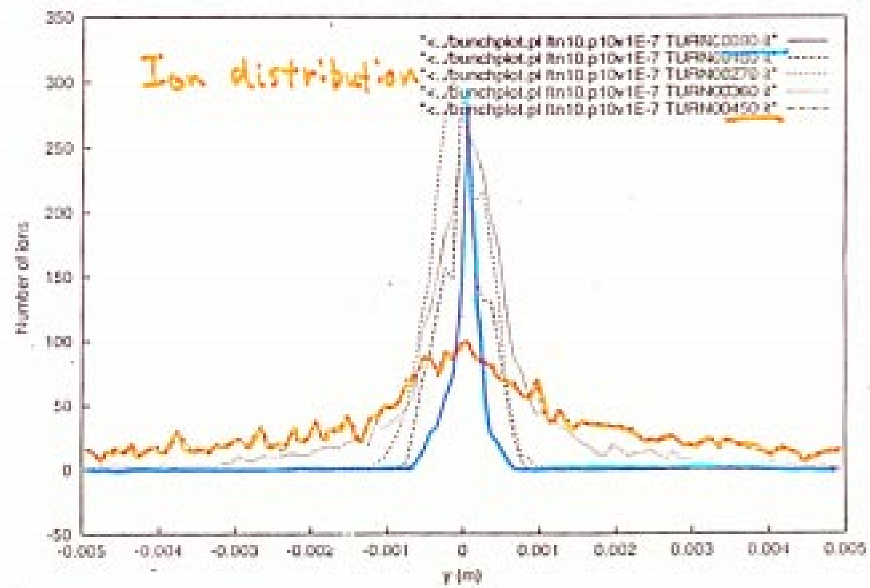
K.Ohmi (KEK-PF)

0. Characteristics of the two beam instability
   - Phase difference between beam and ion
   - Ion size
   - Smear of ion
   - Maximum amplitude
   - Smear of beam
   - Strong-weak and strong-strong simulations.

1. Examples of ion trapping
   - PF

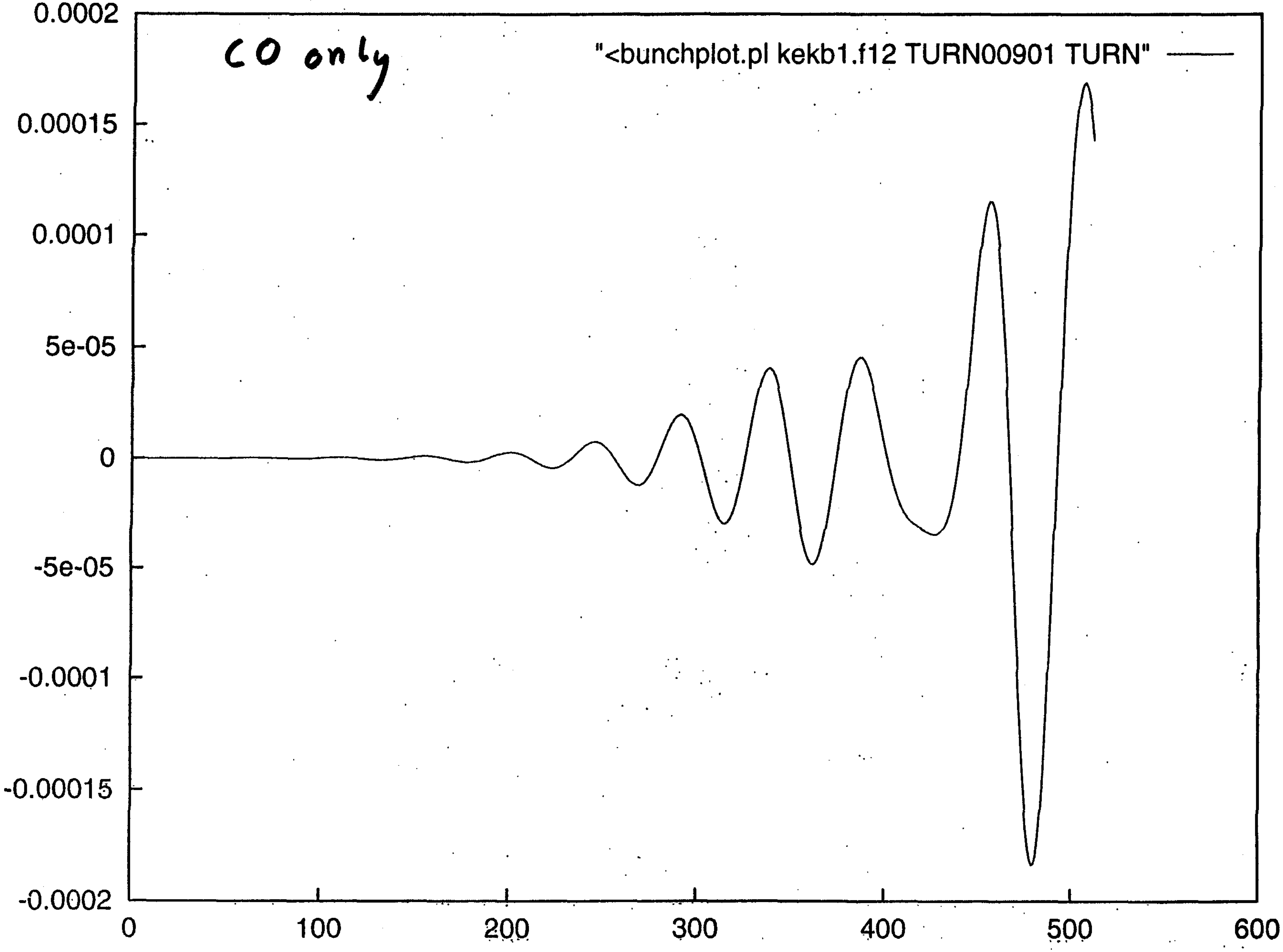
2. Examples of fast ion
   - PF
   - AR
   - KEKB

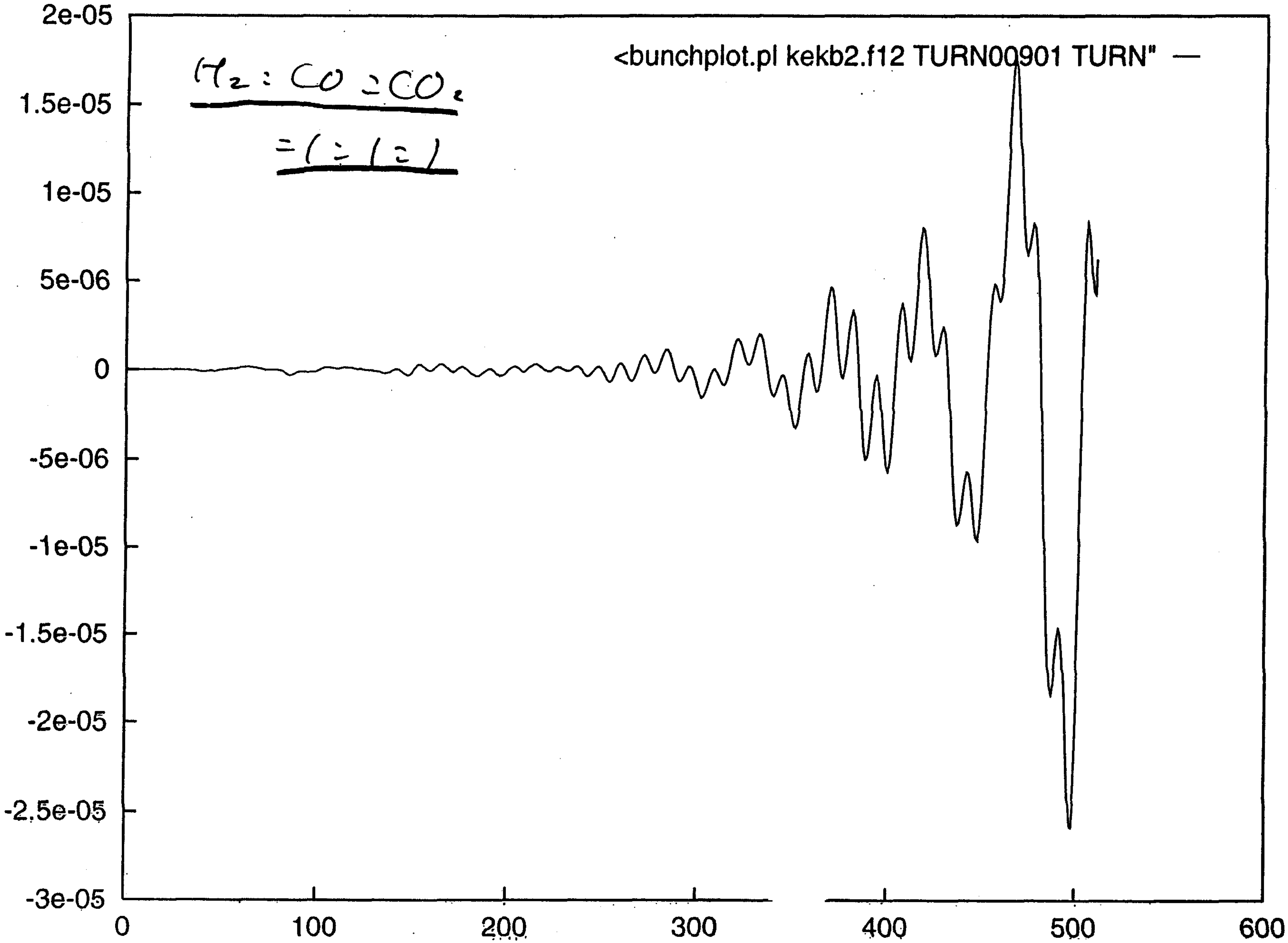




- Effects of ions of various species
  - Different ions have different plasma frequencies and resonate with a beam differently.
    - May disturb coherent oscillations of other ions (a kind of Landau damping?)
  - Simulations for total P=1nTorr, H_2:CO:CO_2=1:1:1 case
    - Almost no change in growth time from the CO only case.
    - A small ripple in the beam oscillation due to light H_2?
    - Their spectrum may be well separated
      - No interference?

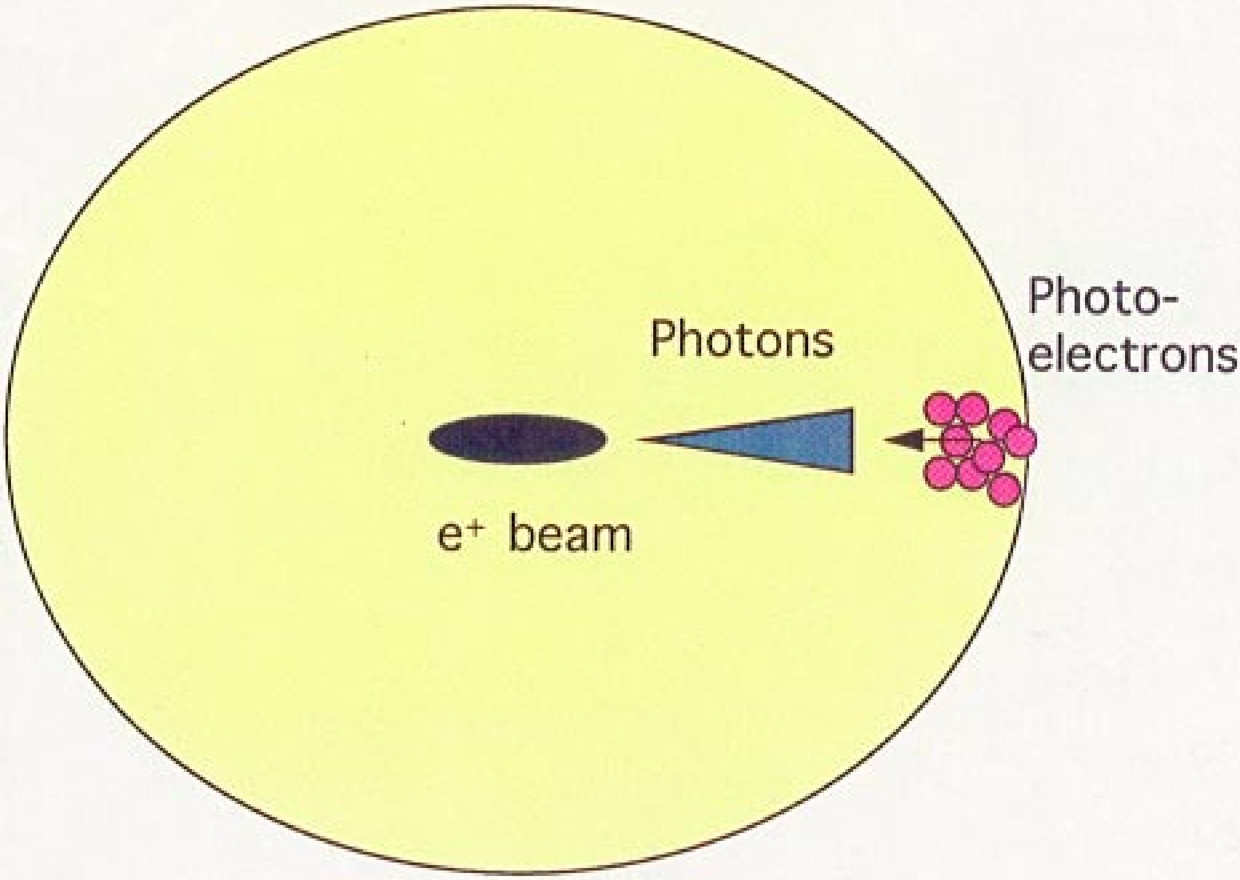
10^{-9} Torr   n=100 m



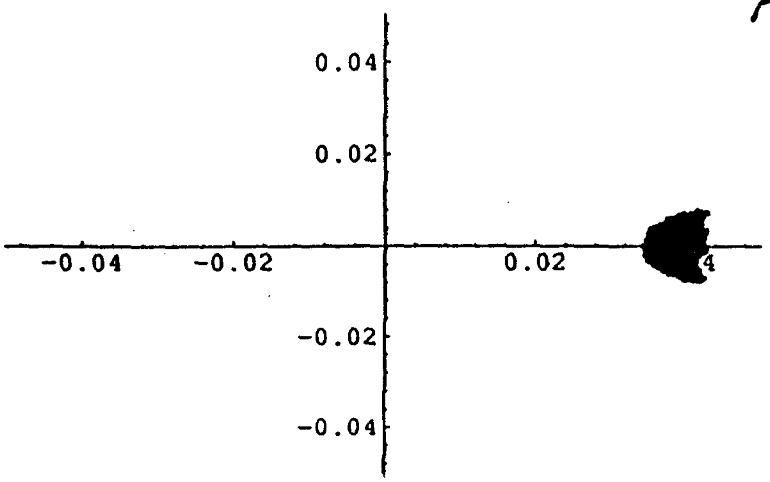

<bunchplot.pl kekb2.f12 TURN00901 TURN"
$H_2 : CO : CO_2$
$= 1 : 1 : 1$
2e-05
1.5e-05
1e-05
5e-06
0
-5e-06
-1e-05
-1.5e-05
-2e-05
-2.5e-05
-3e-05
0
100
200
300
400
500
600

Ohmi-type Photoelectron Instabilities (PEI)

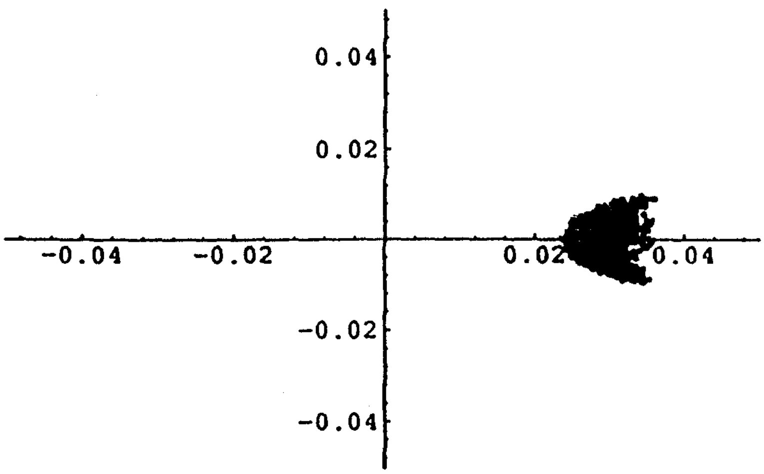
- Photo-electrons created by the synchrotron radiation hitting the chamber wall interact with a beam like the beam-beam interaction.



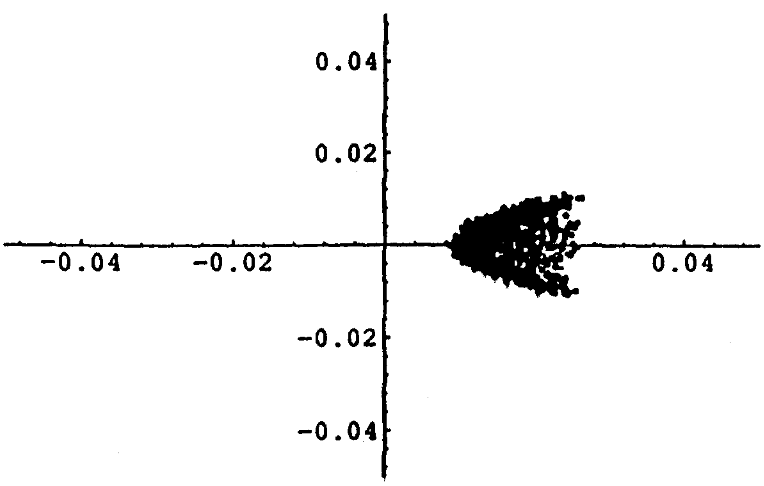
After 3 bunch passing
(6ns)

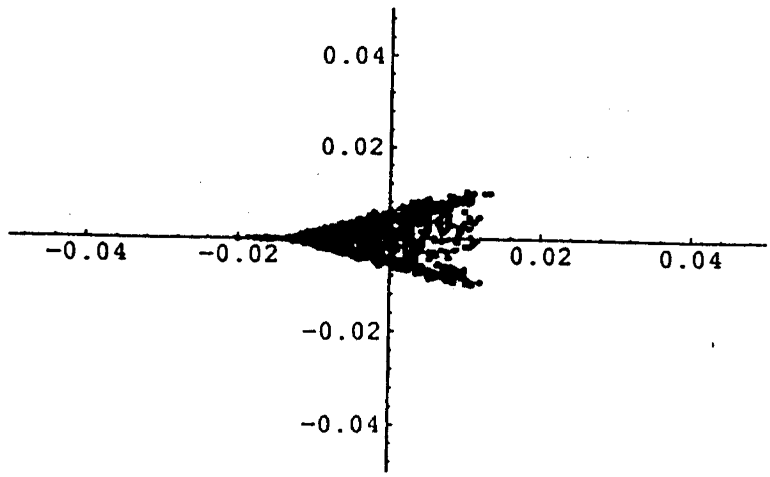


4 bunch
(8ns)

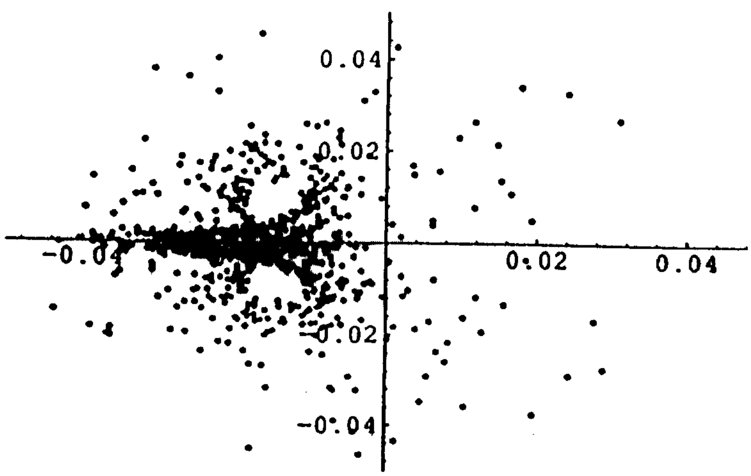


5 bunch
(10ns)

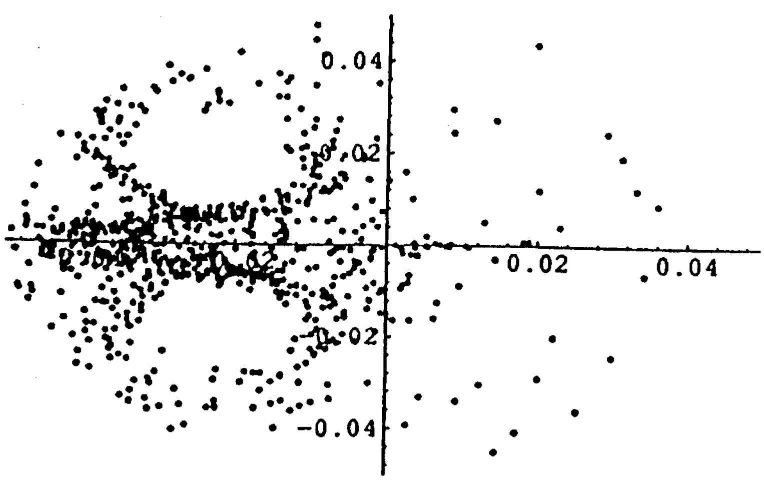




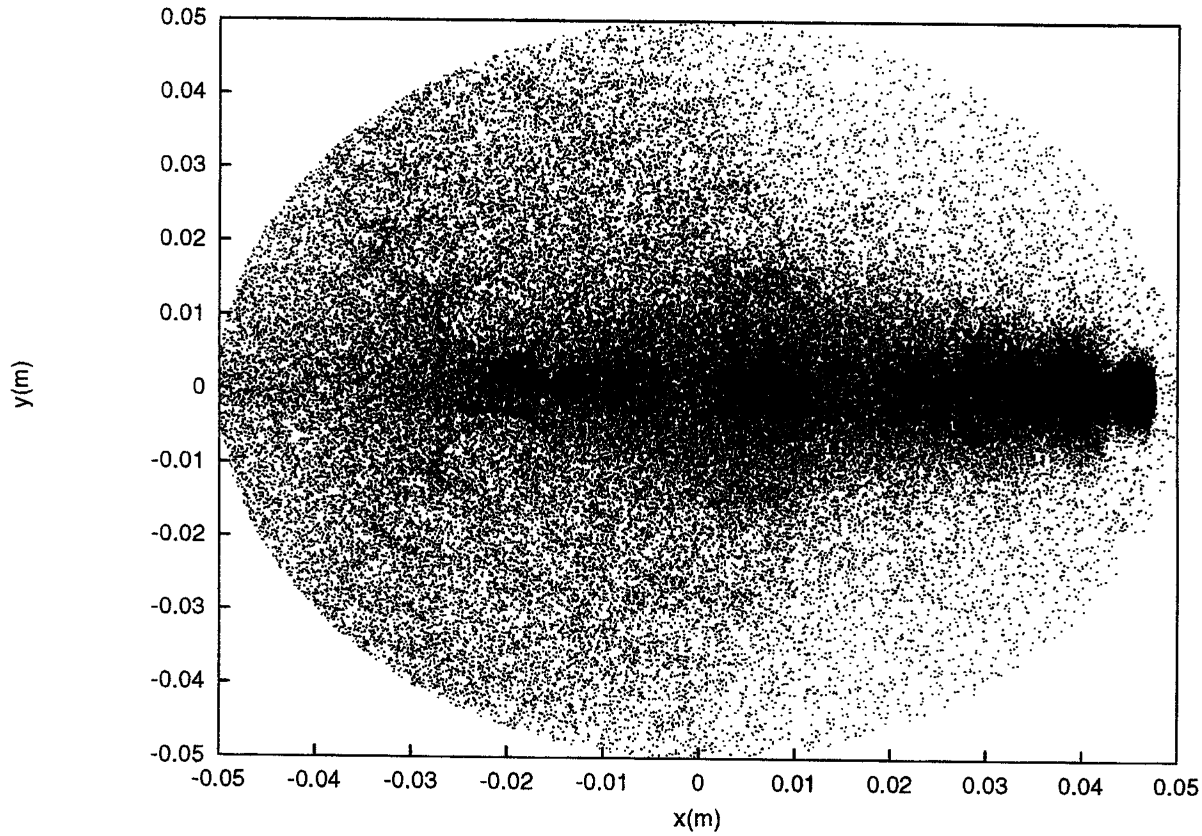
6 bunch
(12us)



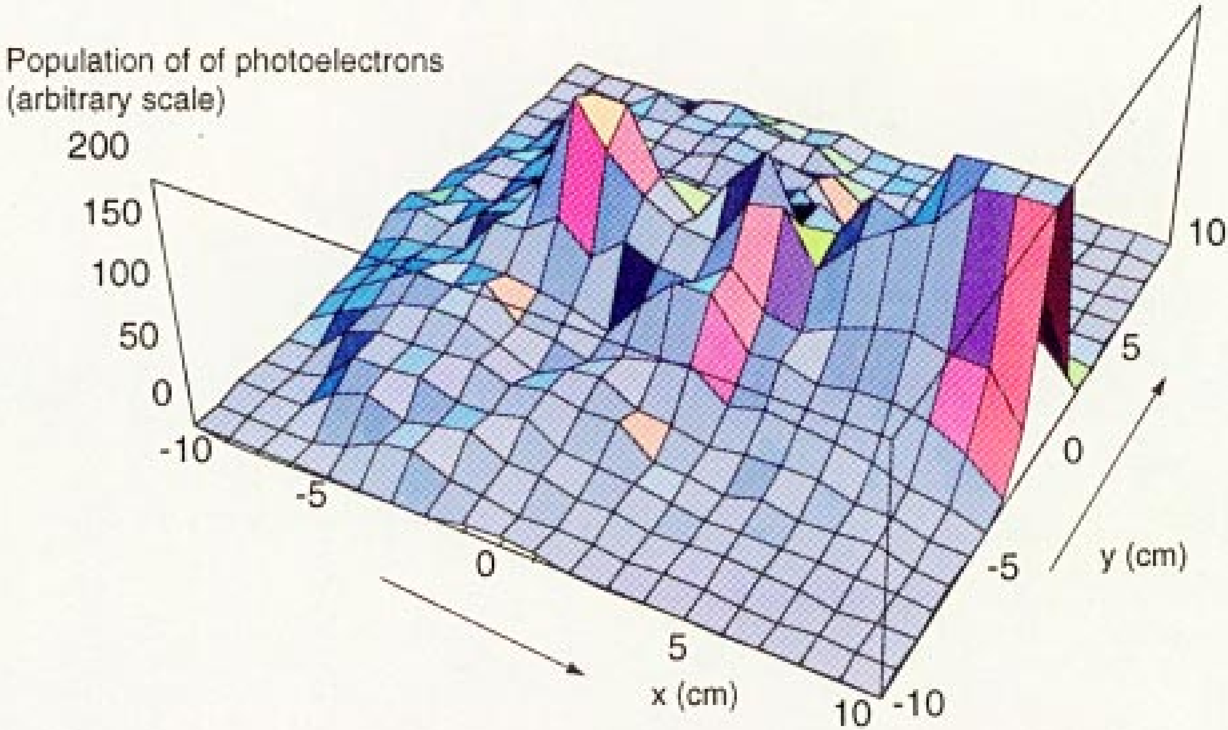
7 bunch
(14us)



8 bunch
(16us)

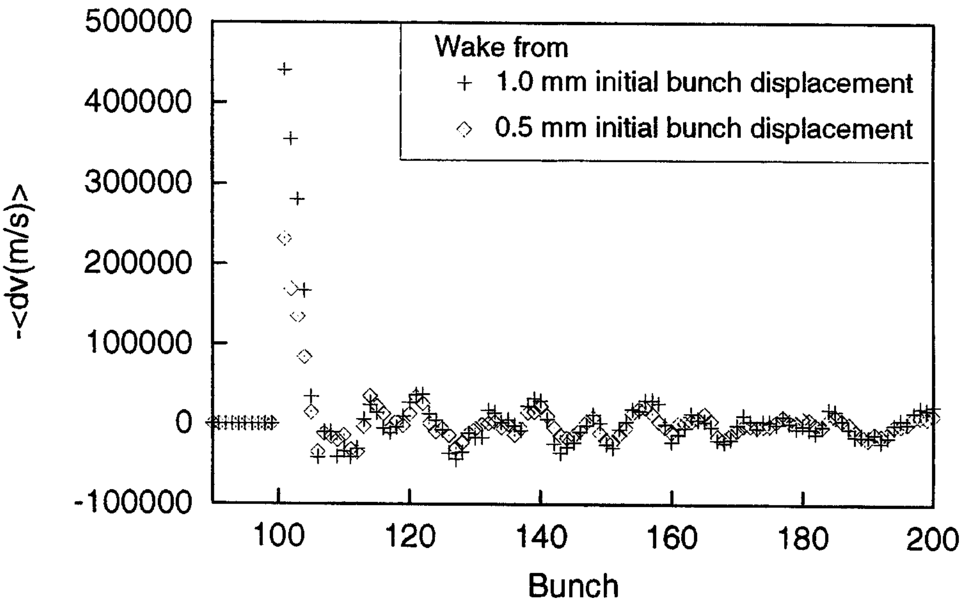


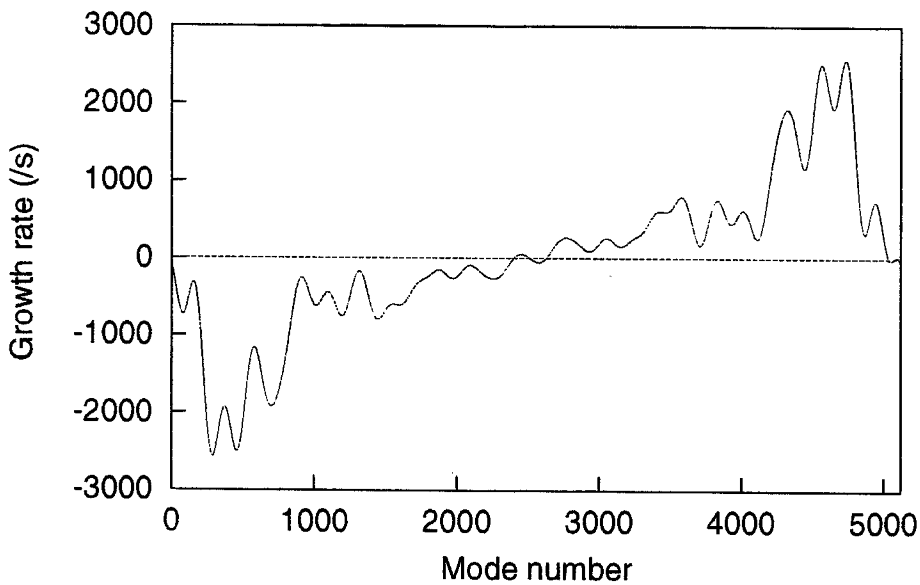
Stationary distribution of photoelectron without space charge and image charge effects taken into account.



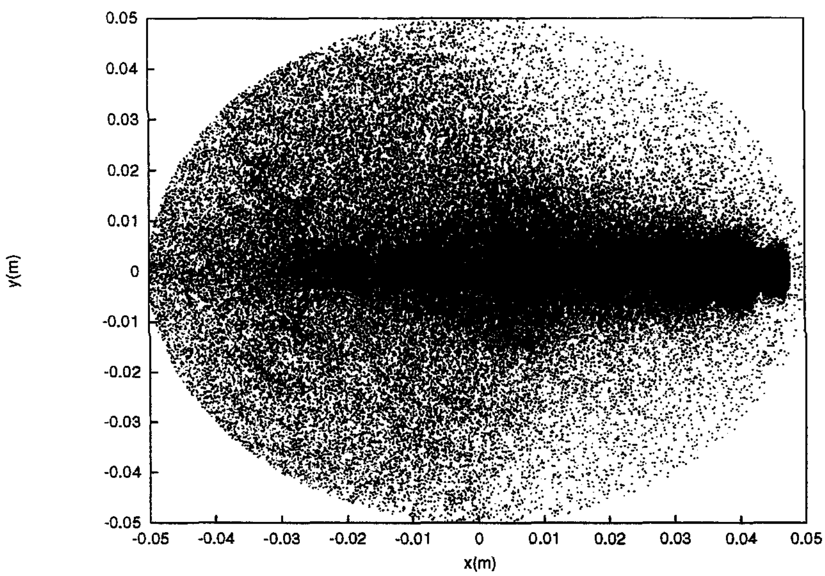
Stationary distribution of photoelectron without space charge and image charge effects taken into account.

- Old simulations without effects of the space charge and the image charge induced on the beam chamber have scared us by the extreme short growth time of 0.1 msec.

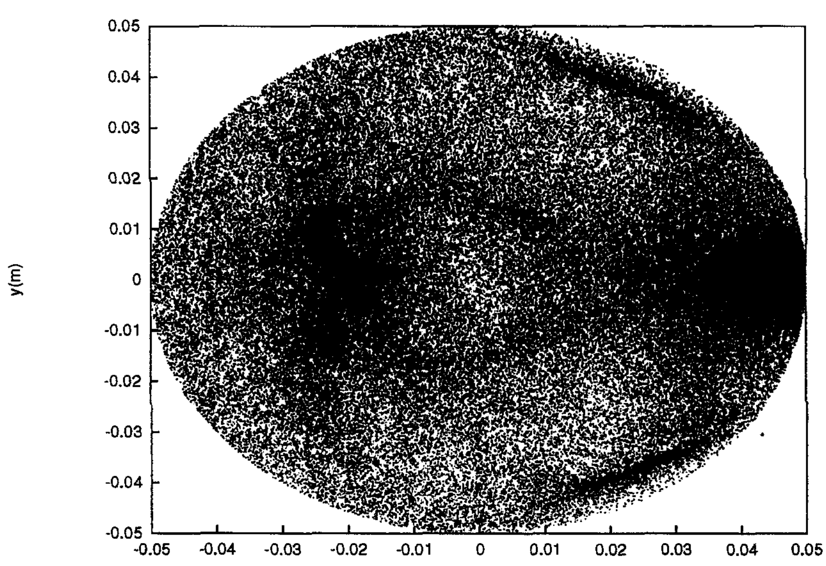




- New simulations including these effects show that the photo-electrons are highly populated near the chamber and the growth rate can be reduced by a factor of 10.



Without
space charge
and image charge



With
space charge
and image charge

- The solenoid magnetic field of 20 Gauss is enough to prevent photoelectrons from moving to the vicinity of a beam if E_{pe}<50eV.
  - 800 Turns/m, I=5A --> B_{max}=50 Gauss
  - Total length = 1200m

$E=5\pm10eV$

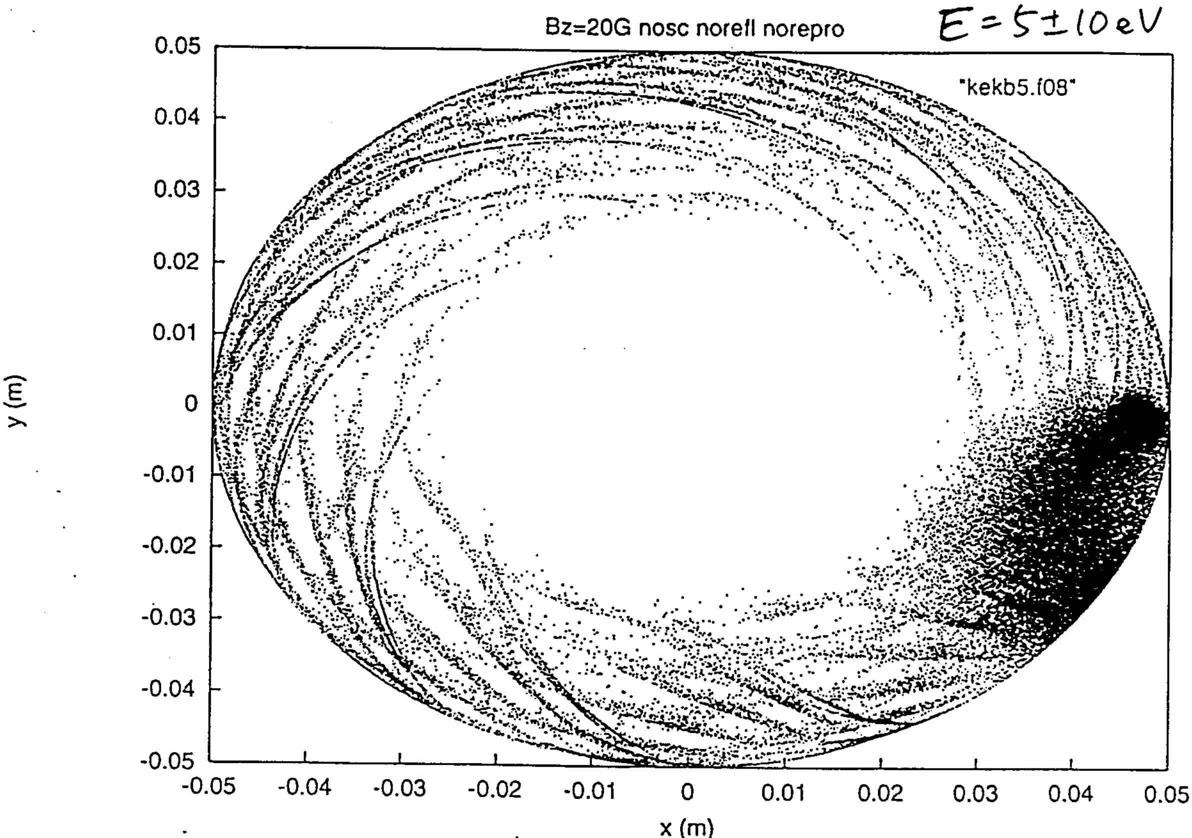


図1 $B_z=20G$ かけたときの光電子分布、~~スーエ~~ 空間電荷効果なし、一次電子のみ、
光電子の初期エネルギー $5\pm10eV$

$E=50\pm50eV$

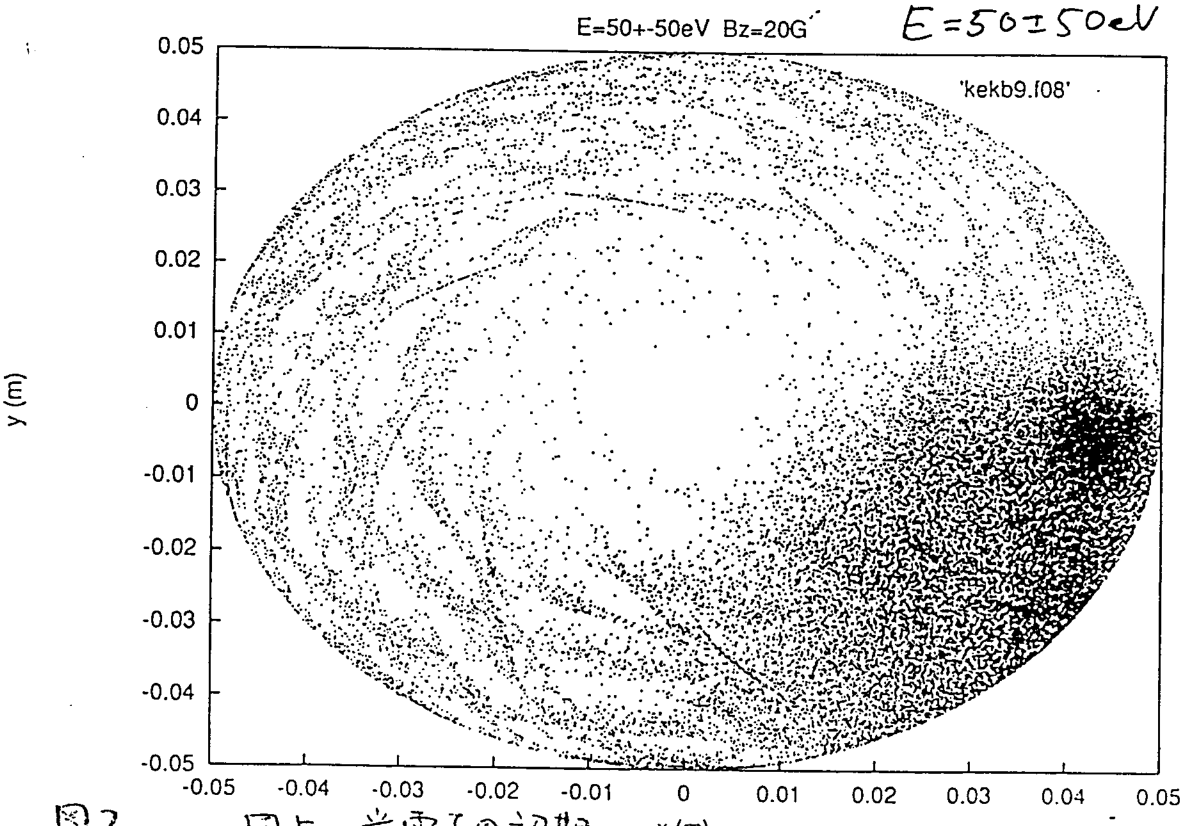


図2、 同上、光電子の初期エネルギー $50\pm50eV$

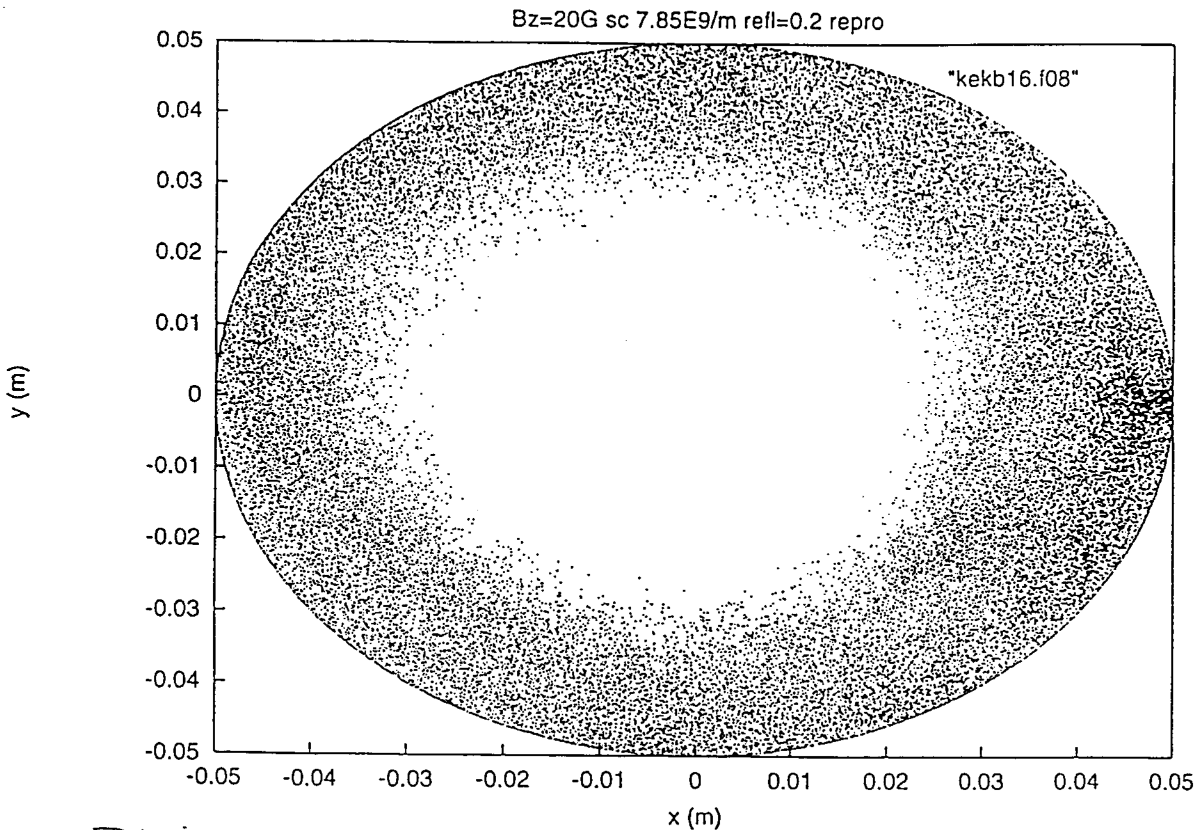


図15. 図11に対し Bz=20Gをかけたときの光電子分布

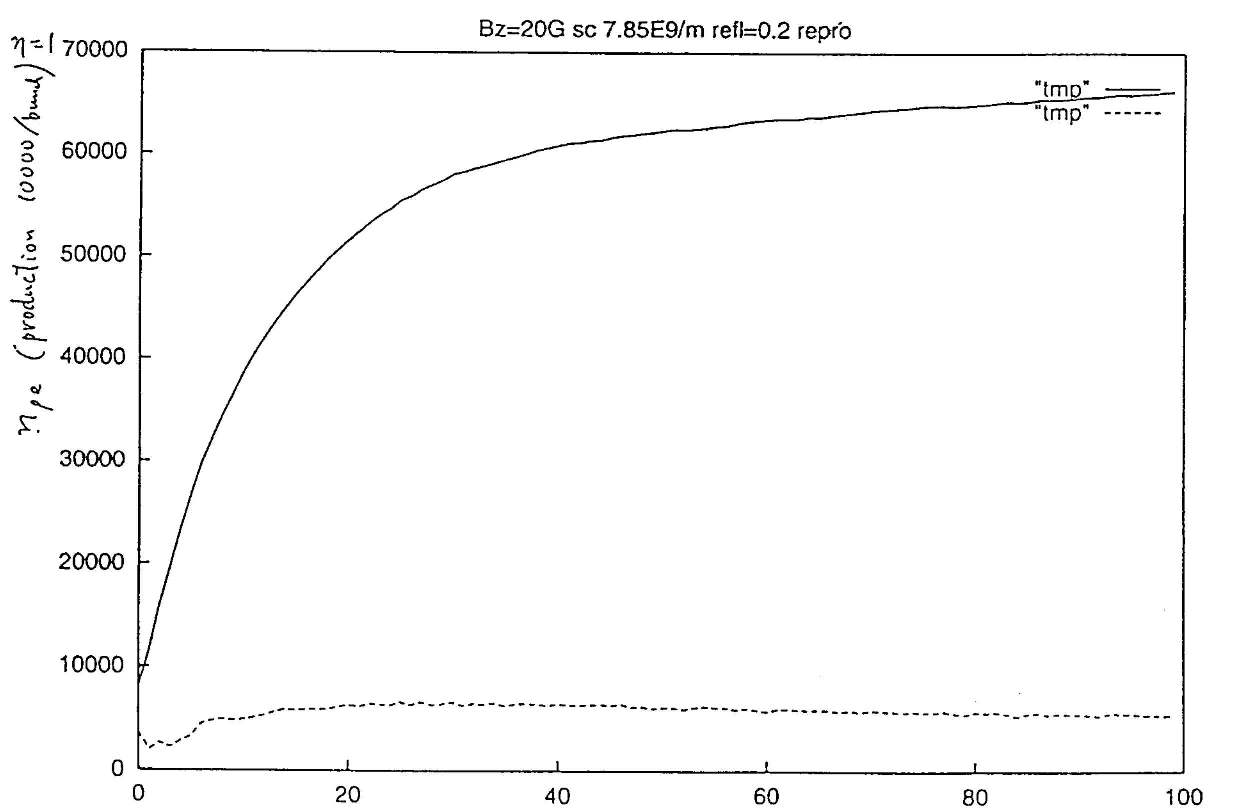


図16 バンチの通過による光電子数の増加

EFFECT OF BETA FUNCTION VARIATION ON FAST ION INSTABILITY GROWTH RATE

G. Stupakov

SLAC, Stanford University

Mini-Symposium on Photoelectron and Ion Instabilities at PAC 97

May 15, 1997

• In previous theoretical papers a constant focusing model was assumed

• In reality, variation of the beta function along the ring may be large, especially in synchrotron sources. This causes variation of the ion frequency,

$$\omega_i(s) = \left[\frac{4 n_e r_p c^2}{3 A \sigma_y(s)\left(\sigma_x(s) + \sigma_y(s)\right)} \right]^{1/2}$$

and breaking the synchronism between electron and ion oscillations.

Modification of the theory for the case of $\beta(s)$

$$\boxed{\frac{\partial^2 y(s,z)}{\partial s^2} + K(s)y(s,z) = -\kappa(s)\int z' \frac{\partial y(s,z')}{\partial z'} D(s,z-z')}$$

y – beam centroid offset
$z = ct - s$

$$\kappa = \frac{4\dot{\lambda}_{ion} r_e}{3\gamma c \sigma_y (\sigma_x + \sigma_y)}$$

$$\dot{\lambda}_{ion}[\mathrm{m}^{-1}\mathrm{s}^{-1}] \approx 9 \cdot 10^8 \sigma_i n_e p_{gas}$$

n_e – number of electrons per meter in the train
A – atomic mass number of the ions
$\dot{\lambda}_{ion}$ – number of ions per meter per unit time generated by the beam
σ_i – ionization cross section (in Mbarn)
p_{gas} – residual gas pressure (in torr)
$D(s,z) = \int d\omega_i \cos(\omega_i z/c) f_i(s,\omega_i)$ – decoherence function
$f_i(s,\omega_i)$ – ion distribution function over the frequency

Seek solution in the form

$$y(s,z) = \mathrm{Re}\, A(s,z)\sqrt{\beta(s)}e^{-i\psi(s)+i\omega_{i0}z/c}$$

where A is the amplitude, $\psi(s)$ is the betatron phase, and ω_{i0} is the averaged ion frequency.

Assume

$$f_i(s,\omega) = F(\omega - \omega_{i0} - \delta\omega_{i0}(s))$$

and $\delta\omega_{i0}(s) \ll \omega_{i0}$.

Equation for the amplitude

$$\frac{\partial A(s,z)}{\partial s} = \frac{\kappa\omega_{i0}\beta}{2c(2+i\beta')}\int_0^z z'A(s,z')\hat{D}(s,z-z')dz'$$

where

$$\hat{D}(s,z) = e^{i\delta\omega_i(s)z/c}D_0(z)$$

$$D_0(z) = \int d\omega F(\omega)e^{i\omega z} \approx (1 + i\alpha\omega_{i0}\, z/c)^{-1/2}$$

$\int_0^\infty D_0(z)dz = \infty$ – long-range interaction of electrons through ions.

Because of the presence of the oscillating factor $\exp\left(i\delta\omega_{i0}(s)z/c\right)$, the following integral converges,

$$l_d = \int_0^\infty \hat{D}(s,z')dz'$$

l_d – decoherence length, it has a meaning of the interaction length.

In the limit

$$l_d \ll l$$

equation for A reduces to

$$\frac{\partial A(s,z)}{\partial s} = \Lambda(s,z)A(s,z),$$

$$\Lambda(s,z) = \frac{\kappa\omega_{i0} z\beta l_d}{2c(2+i\beta')}$$

which means an exponential instability with the growth rate

$$\Gamma(z) = c\langle \mathrm{Re}\,\Lambda(s,z)\rangle$$

Scaling:

$$\Gamma \sim \frac{c\kappa\beta l}{4} \propto pn_b I_b = pI$$

(for constant beta function $\tau^{-1} \propto pn_b^2 I_b^{3/2}$).

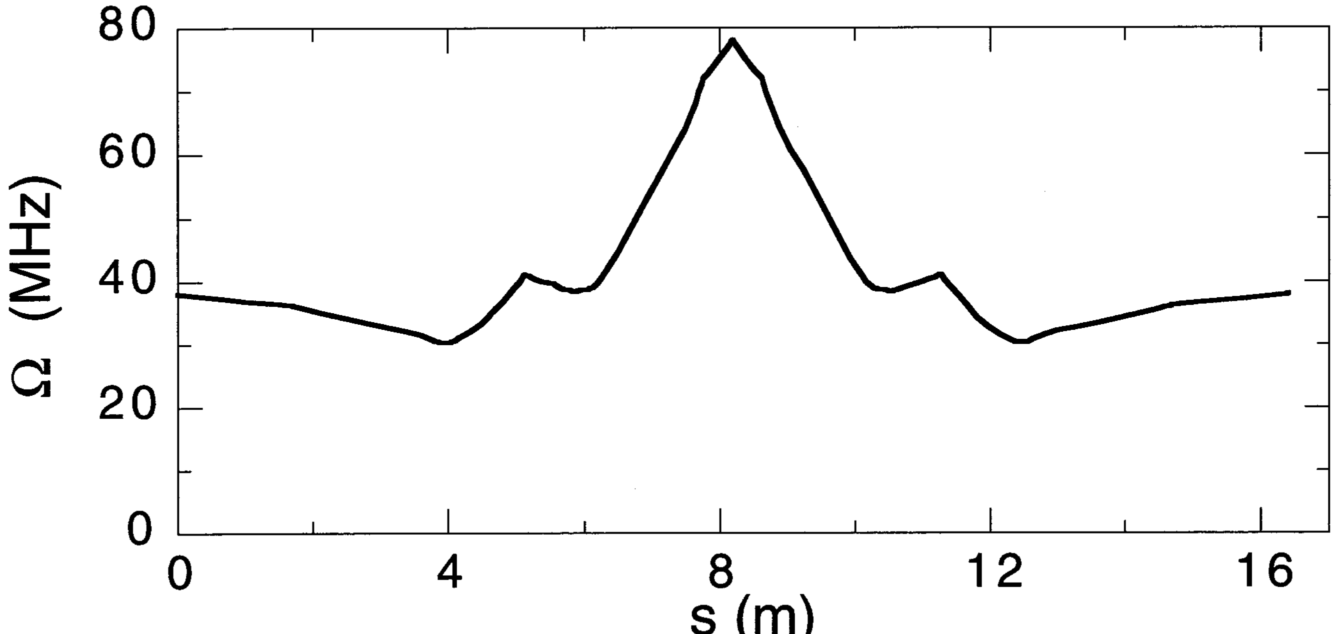
Growth times for the ALS experiment:

$E = 1.5$ GeV
$C = 196.8$ m
$\varepsilon_y = 9.4 \cdot 10^{-11}$ m
$\varepsilon_x = 4.1 \cdot 10^{-9}$ m
$p = 80$ nTorr, *He*
$\sigma_i = 0.15$ Mbarn

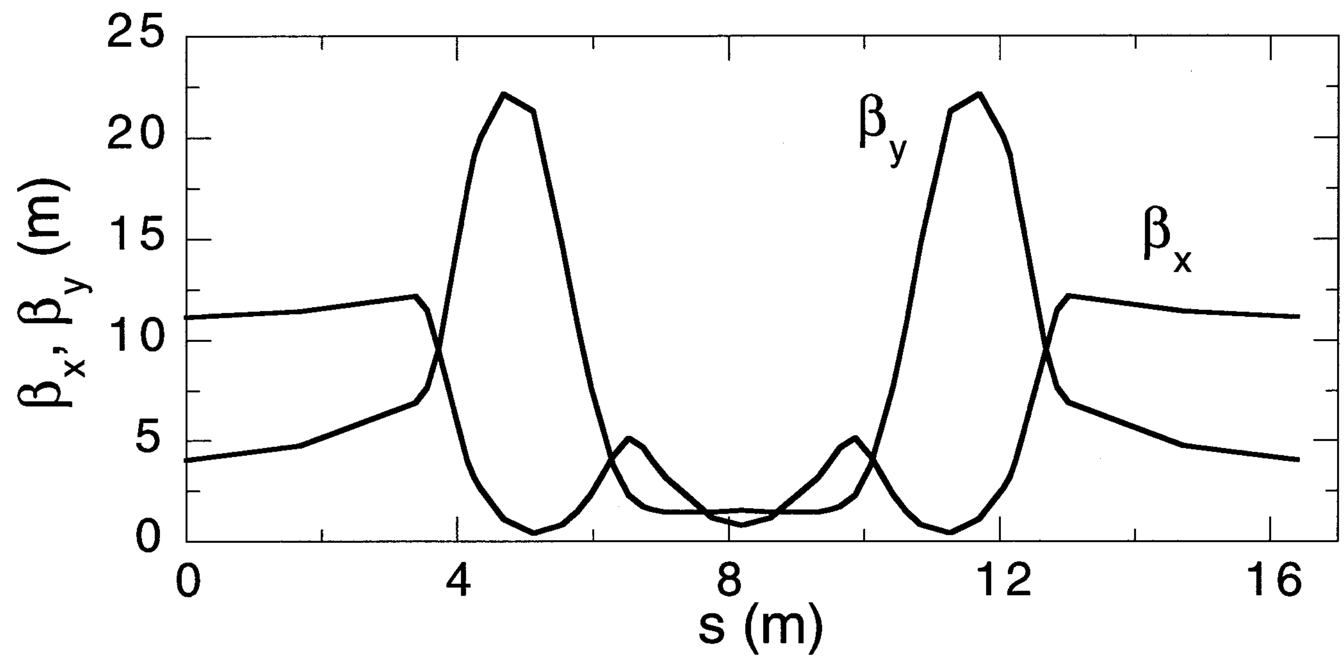
I, A	n_b	Γ^{-1}, ms
0.2	240	0.40
0.1	240	0.83
0.2	150	0.34
0.2	320	0.42

Conclusion

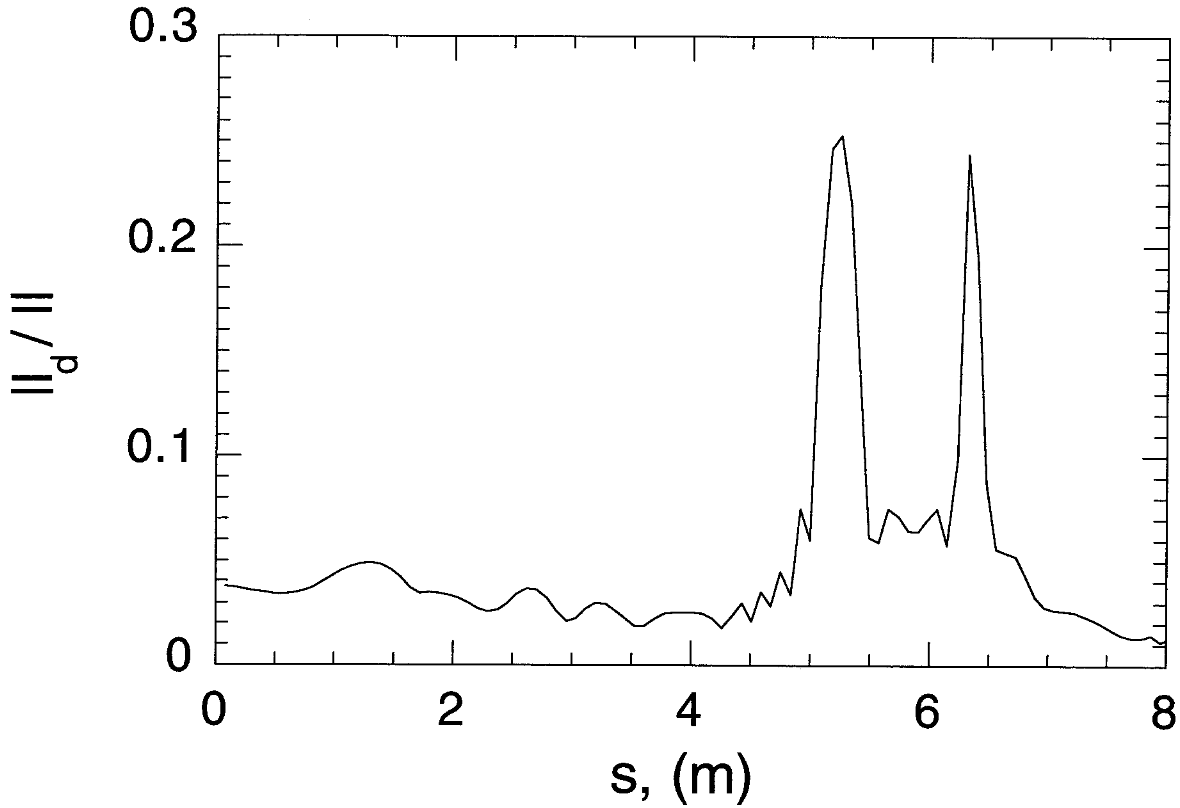
Large variations of the beta function in the ring substantially reduce the growth rate of the FII instability and change scalings.



Frequency of *He* ion oscillations as a function of position. Beam current $I = 0.2$ A, number of bunches 240.



Beta function in the ALS. Only one period of the lattice is shown.



Absolute value of the decoherence length for the ALS experiment.

Fast beam-ion experiment at the TRISTAN AR

Y.H. Chin, H. Fukuma, S. Kato, E. Kikutani,
S. Kurokawa, S. Matsumoto, K. Ohmi,
Y. Suetsugu, M. Tobiyama, K. Yokoya and
X.L. Zhang

KEK

(Presented by H. Fukuma)

1.Introduction

2.Experimental set up

3.Experimental procedure and results

4.Summary

1. Introduction

In high current and low emittance rings, new type of beam-ion instability named "fast beam-ion instability(FBII)" is proposed(T.O. Raubenheimer and F. Zimmermann, Phys. Rev. E 52, 5487(1995) and G.V. Stupakov, T.O. Raubenheimer and F. Zimmermann, Phys. Rev. E 52, 5499(1995)).

The FBII occurs in the single passage of the bunch train. The ions created by the head of the bunch train affect to the tail.

In the linear theory by K. Yokoya, the unstable mode of the oscillation is given by

$$y_n = a_o e^{i(\Theta n - ks)}, \quad \Theta = \sqrt{\frac{2 z N m r_e L}{A M_N \Sigma_y (\Sigma_x + \Sigma_y)}}$$

(n : bunch id)

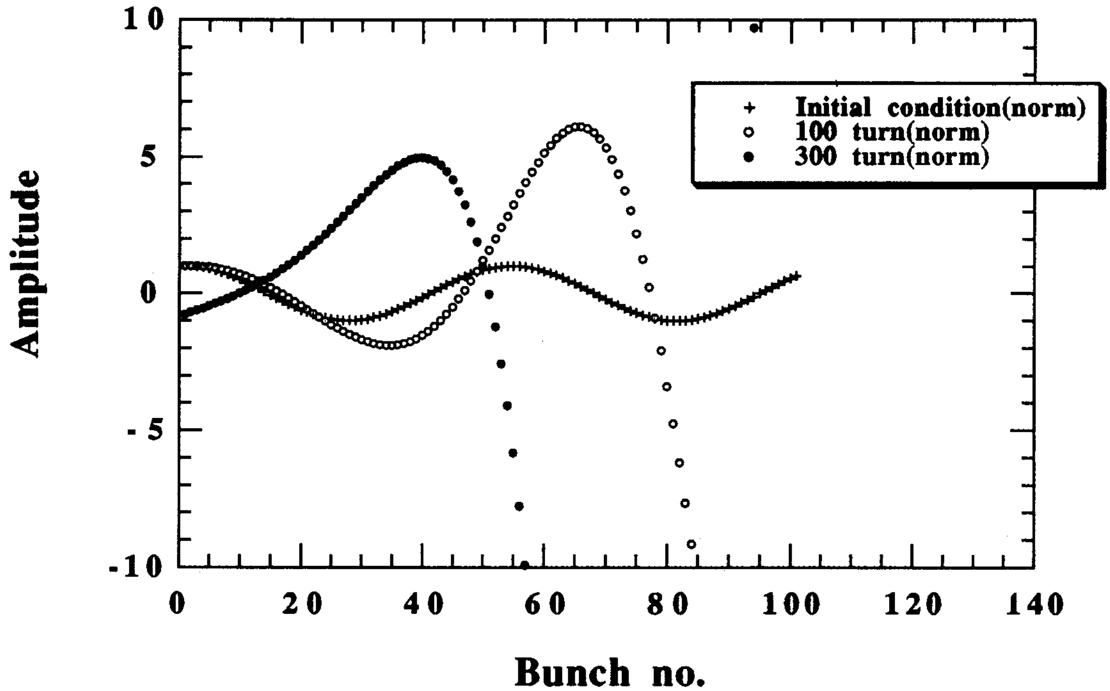
Amplitude growth factor G is given by

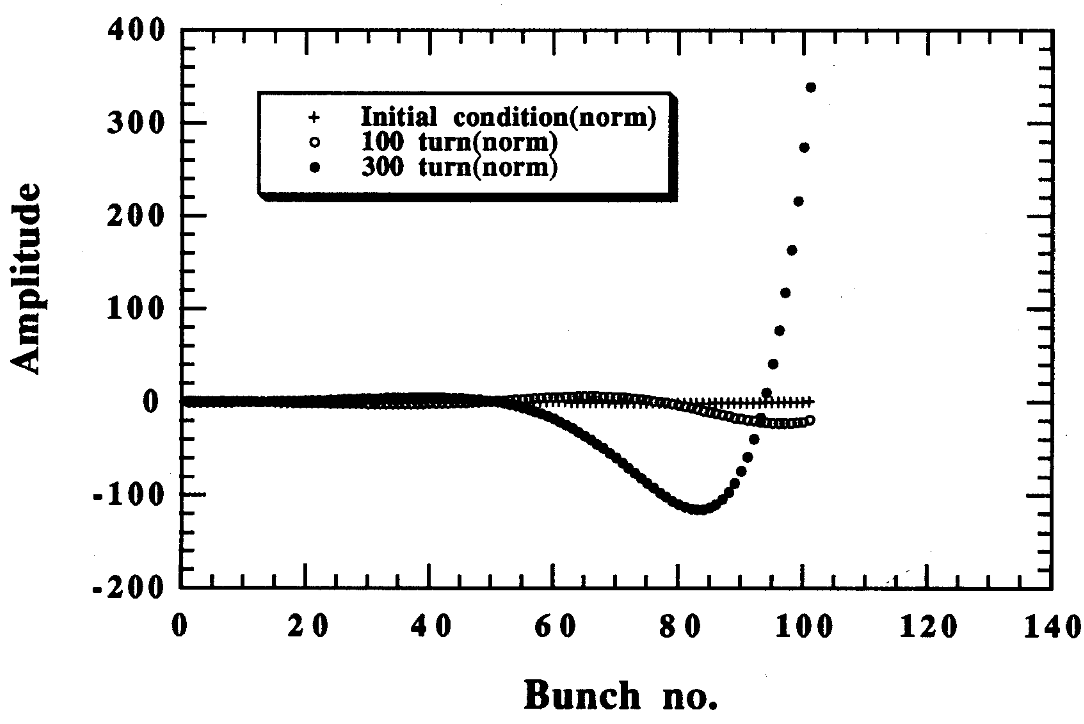
$$G = \left|\frac{a_n}{a_o}\right| \approx 1 + \frac{1}{\Gamma} e^{\sqrt{\Gamma}}, \quad \Gamma = \sqrt{\frac{2m}{M_N} \frac{\beta_y}{\gamma} \frac{\sqrt{L}\, n_g \sigma_i}{\sqrt{A}}} \left[\frac{r_e z N}{\Sigma_x \Sigma_y}\right]^{\frac{2}{3}} s n^2$$

L : distance between bunches, N : number of electrons / bunch,
m, M_N : electron and nucleon mass,
$\Sigma_{x,y}$: convolution of beam size of electrons and ions,
k : betatron wave number; σ_i : ionization cross section,
n_g : number density of the residual gas.

<u>Linear theory</u>

<u>AR</u>





Recently John Byrd et al. reported the experiments at the ALS where the results suggest that they observe the FBII with 10nTorr of He added to the vacuum (J. Byrd et al., SLAC-PUB-7389(1996)).

In KEKB the e-folding time of the amplitude growth is about 70 turns for the number of bunches of 500 and a pressure of 10^{-9} Torr.

2. Experimental set up

An experiment was carried out at the TRISTAN AR as a part of the ~~heigh~~ high beam current experiment in last Nov.-Dec..

Machine parameters of the AR are

Energy	2.5 GeV
Circumference	377 m
RF frequency	508 MHz
Harmonic number	640
Emittance	45nm
Damping time(H,V)	42ms
Average beta functions(H/V)	8.7 / 9.4
Betatron tunes(H/V)	10.14 / 10.25

1) Vacuum

The nitrogen gas was intentionally leaked into the vacuum duct to increase the growth rate of the FBII.

The pressure near the injection point of the gas was measured by a residual gas analyzer(RGA).

After the leak of the gas the partial pressure of the gas component whose atomic number is 28, P_{28}, was increased to 6.0×10^{-6} Torr at the RGA.

The pressure distribution around the injection point of the gas was calculated from the reading of the RGA and the pumping speed of the vacuum pumps.->Fig.

Together with the reading of CCGs the average value of P_{28} was obtained to be 8.4×10^{-8} Torr.

The vertical emittance growth by Coulomb scattering was estimated to be 3.8×10^{-10}m.

2) Beam position monitor(BPM) system

The BPM system which we used is a part of the trasverse feedback system.

The system has a filter board with 1Mb memory which is capable of storing the transverse position of every bunch up to 1600 turns after digitizing the signal by 8 bit ADC.

The ADC count U is expressed as $U = k_m \, y \, I_b$.
(y : the vertical beam position, I_b : the bunch current)
The constant k_m was determined to be 46 count/mm/mA by making orbit bumps at the pick up.

3) Spectrum analyzer

As an auxiliary instrument a spectrum analyzer HP8562E connected with a vertical button pick up was used for taking the beam spectrum.
The observed frequency range was $3f_{RF}$ to $4\ f_{RF}$.

From the noise level of the beam spectrum, detectable oscillation amplitude was estimated to be larger than 30μm at the beam current of 100mA.

4) Beam size

The beam size was measured by a photodiode arrays. At present we are not sure whether the monitor is reliable or not because it gives a horizontal beam size which is two times larger than design value in a single bunch.

The vertical-horizontal emittance ratio κ_m caused by the misalignment of quadrupoles and sextupoles was estimated by a simulation.

The r.m.s. value of the misalignment was estimated for the quadrupoles from the closed orbit(c.o.) without orbit correction which was obtained from the measured c.o. and corrector strength.

Assuming that the amount of the misalignment of the sextupoles is same as that of the quadrupoles, k_m was calculated to be less than 1 % after the orbit correction. Together with κ_m and the emittance growth by Coulomb scattering the ~~total~~ emittance *ratio is estimated to be several %.*

5) Bunch feedback system

Throughout the experiment the transverse feedback system was employed to store the beam current of several hundred mA. The damping time of the vertical feedback system was estimated to be 800 μs at the bunch current of 4mA.

Longitudinal feedback system(LFS) was not used because we used the filter board for the LFS to store the bunch oscillation.

the data of

3. Experimental procedure and results

A train of 100 bunches was stored with 2ns spacing.

A calculation based on the conventional ion trapping theory shows that the ions are not trapped in our experimental conditions, i.e. the trace of the ion motion matrix is larger than 2. absolute value of

Experimental steps are,

1) Before the leak of the nitrogen gas,
   we confirmed that the vertical betatron sidebands observed by the spectrum analyzer were disappeared at the beam current of 260 mA.

2) We leaked into the gas in the ring.
   The vertical betatron sidebands remained down to the beam current of 173 mA.

3) We added more gas.

   The beam was injected up to 190 mA.
   Vacuum pressure was 8.4×10^{-8} Torr.

   The intermittent vertical oscillation, which was not observed before and in the first leak of the gas, appeared in the synchrotron light(SL) monitor.

No beam loss accompanied with the oscillation was observed.

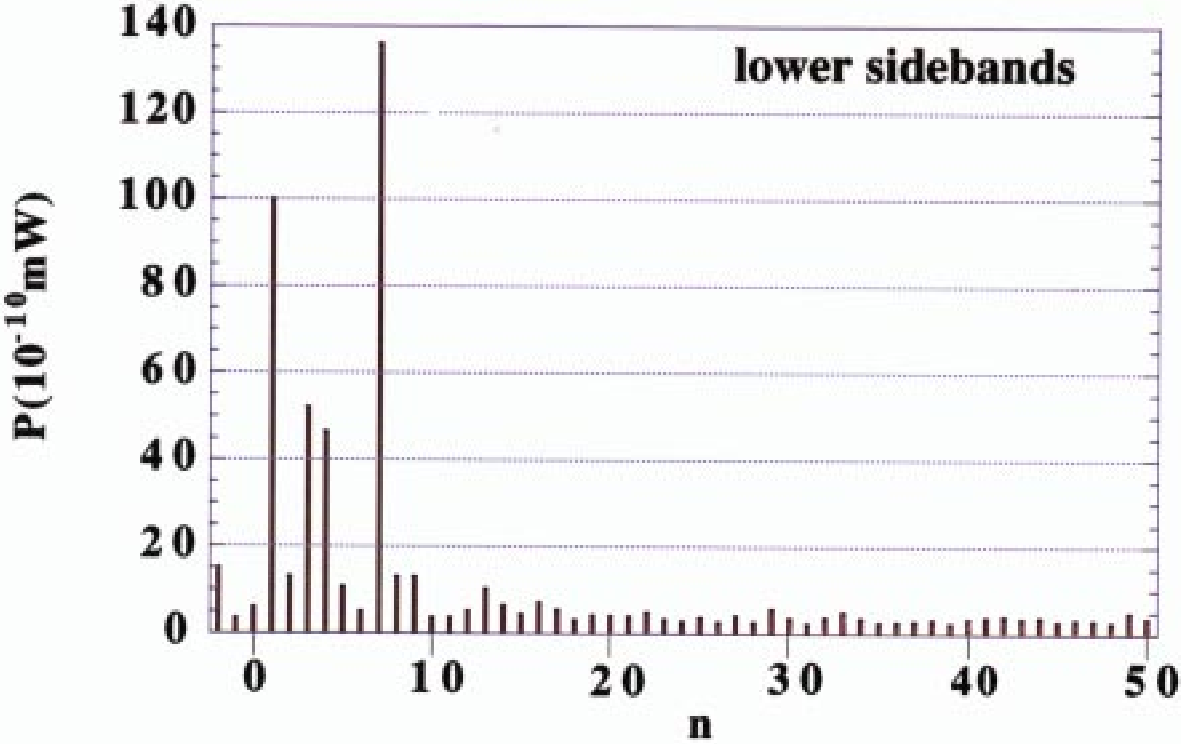
Beam Spectrum

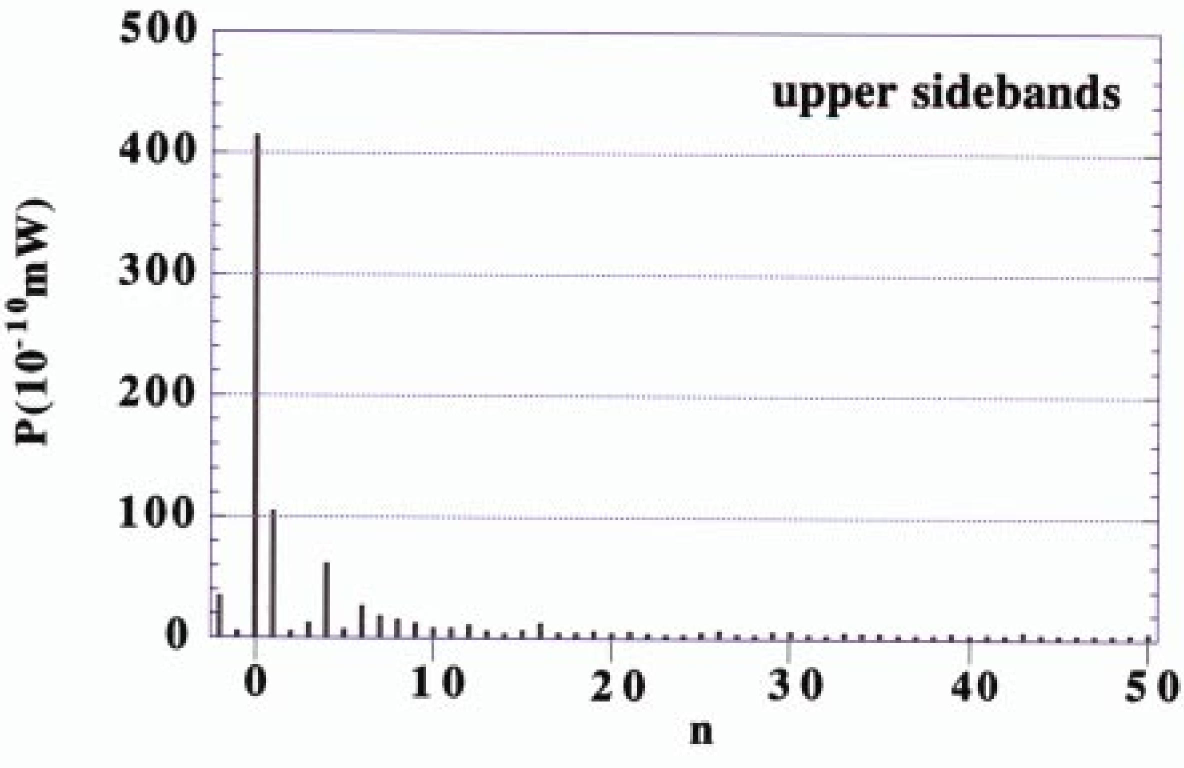
Strong vertical betatron sidebands were observed in the spectrum taken by the spectrum analyzer.

The spectrum distribution shows that the large lower sidebands appear below 10th revolution harmonics, which is expected by the theory.

We also observed upper sidebands whose origin is not understood yet.

- Spectrum of betatron sidebands at the frequency of $3\,f_{RF} + nf_r \pm f_\beta$





Bunch oscillation along the bunch train

The bunch oscillation was taken by the BPM system after adding the gas.

As the oscillation includes a large component of synchrotron oscillation we employed Fourier analysis for the data of 1600 turns.

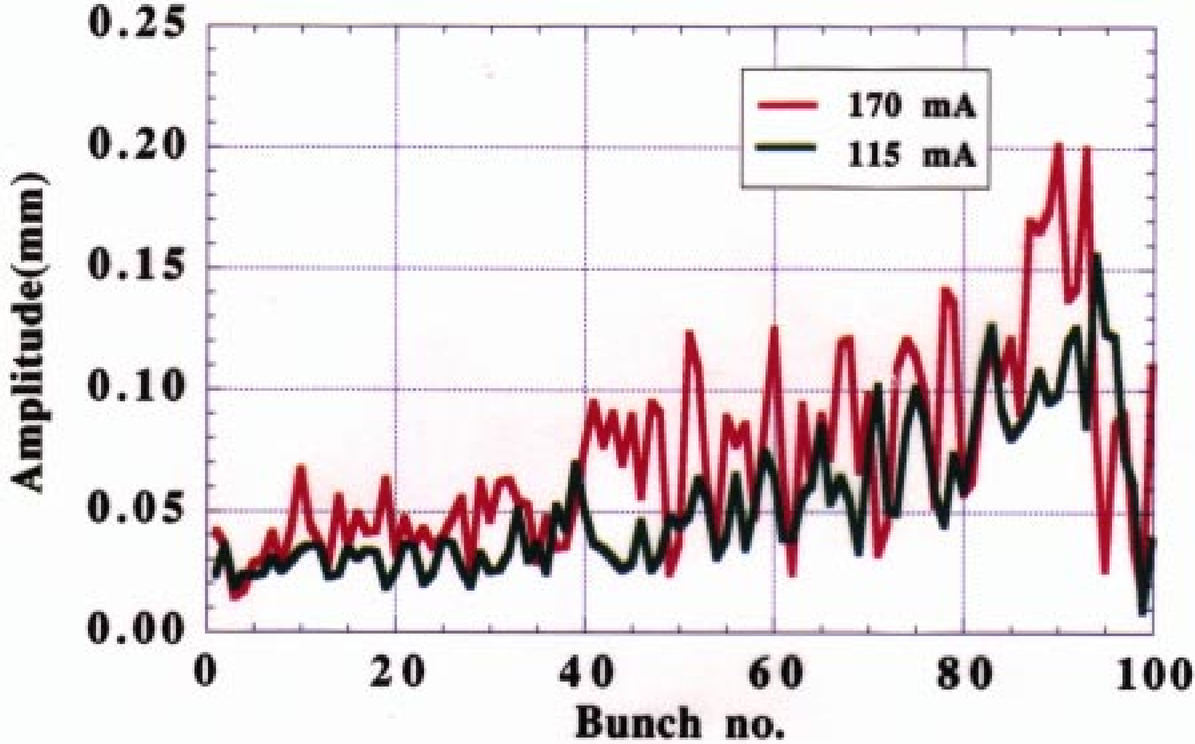
The amplitude were normalized by the bunch current because the distribution of the bunch current was not uniform due to the short beam life of about 10-14 min.

Amplitude

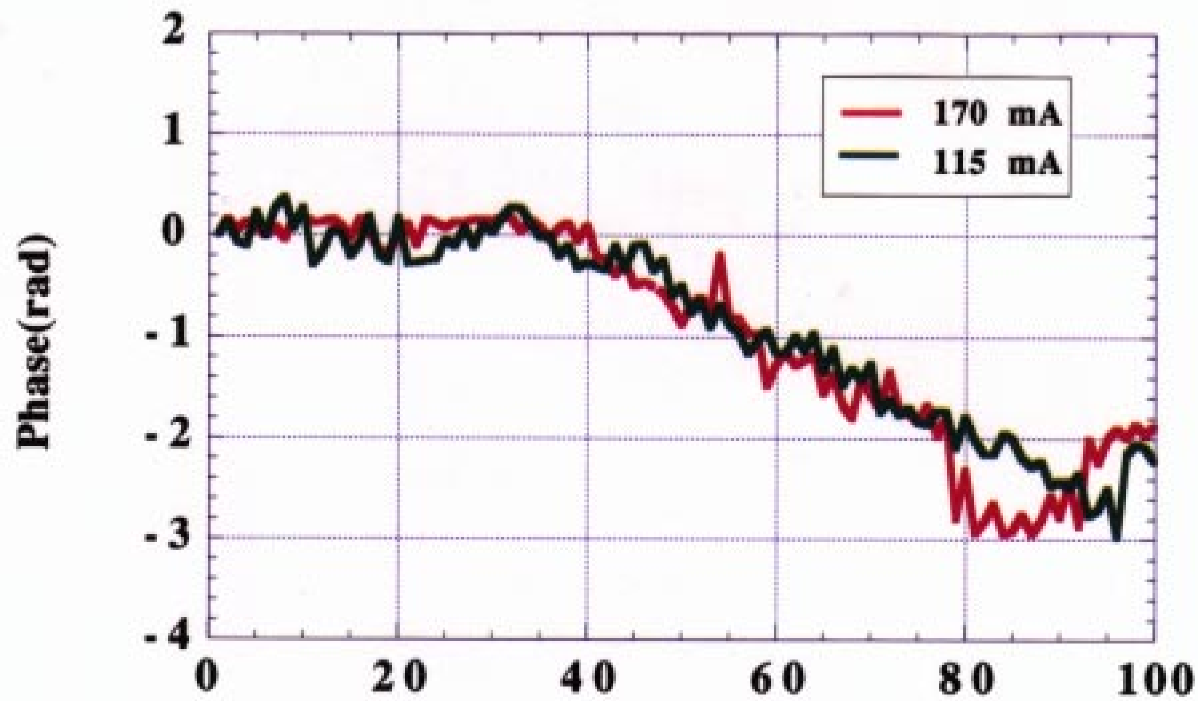
Analyzed data clearly shows the amplitude growth along the bunch train. The maximum amplitude is about 200μm.

As the amplitude of 200~~mm~~μm is well above the sensitivity of the spectrum analyser and the sidebands were not observed at almost same current before adding the gas, we conclude that the observed oscillation is caused by the addition of the gas.

Oscillation amplitude along the bunch train



Oscillation phase along the bunch train



Oscillation phase

The oscillation phase decreases along the bunch train, which exhibits the oscillation mode is unstable as expected by the theory.

The total phase shift from head to tail of the bunch train is about 3 radians.
Assuming the 2% coupling the linear theory gives three times larger phase shift than the observation.

The linear theory says that Θ is expected to be changed by 20% when the beam current decreases from 170 to 115 mA. But expected change of Θ is not clear.

4.Summary

An experiment for the search of the FBII was carried out at the TRISTAN AR.

Observed characteristics of the instability such as

1) Ion-related phemomena,
2) Growth of the oscillation amplitude along the bunch train,
3) Short growth time of the instability less than several ms,
4) Change of oscillation phase from the head to tail of the bunch train which agrees with the theory within a factor of the magnitude,

shows that the observed instability can be interpreted as the FBII.

Simulation study and more sofisticated data analysis such as analysing the tune shift along the bunch train are in progress.

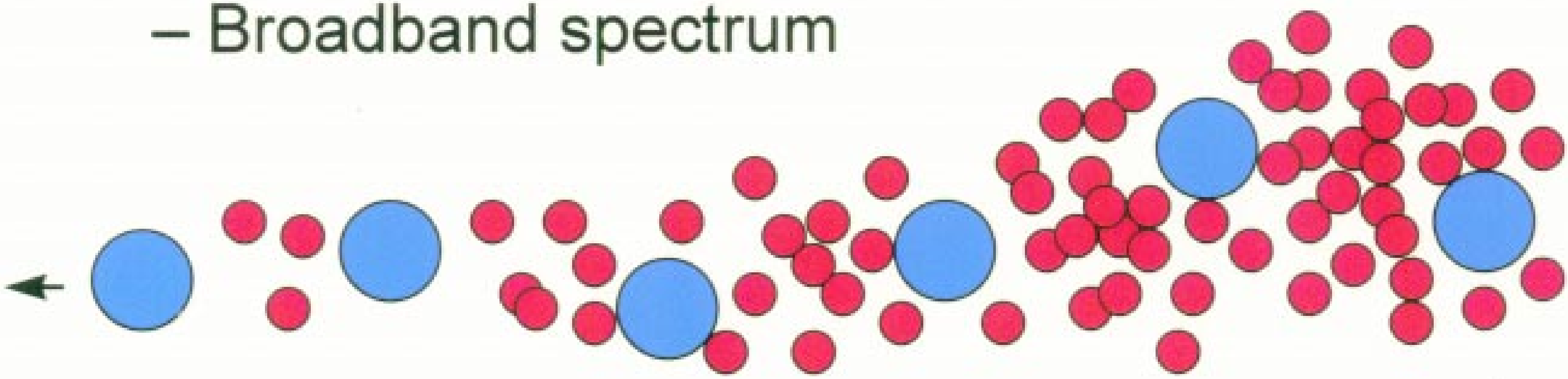
POHANG ACCELERATOR LABORATORY

Preliminary Experiments on the Fast Ion Instabilities at Pohang Light Source

M. Kwon, T. Y. Lee, J. Y. Huang, M. Yoon(PAL)
Yong Ho Chin, Y, Fukuma (KEK)

Introduction

- FAST ION INSTABILITY
  - Ions are cleared out by a gap
  - Transient phenomenon
  - Broadband spectrum



Linear Theory

- Ion oscillation frequency

$$f_{iy} = \frac{c}{2\pi}\left[\frac{4Nr_p}{3L_{sep}\sigma_y(\sigma_x + \sigma_y)A}\right]^{1/2}$$

where

- N=number of particles in a bunch
- L_{sep}=distance between bunches
- r_p=classical proton radius

- Ions can be trapped within a bunch train if

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

- Average number of ions per passage of a bunch

$$n_i = N n_g \sigma_i$$

where n_g=residual gas density

- Amplitude growth factor for the n-th bunch after running over distance s

$$G = 1 + \frac{1}{\Gamma} e^{\sqrt{\Gamma}}$$

$$\Gamma = \sqrt{\frac{2m_e}{m_N}} \frac{\beta_y L_{sep}^{1/2}}{\gamma} \frac{n_g \sigma_i}{\sqrt{A}} \left[\frac{2 r_e z N}{3 \sigma_y \sigma_x}\right]^{3/2} s n^2$$

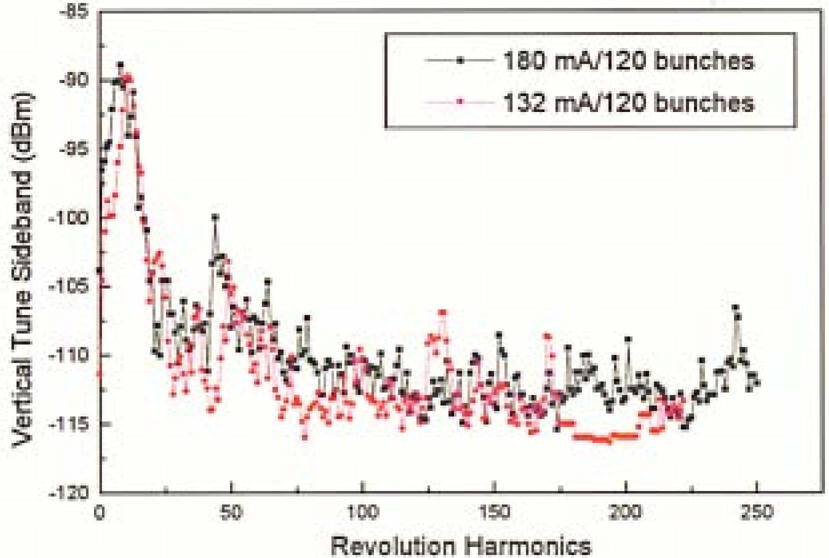
where β_y=average beta function and
r_e=classical electron radius

Experimental Setup

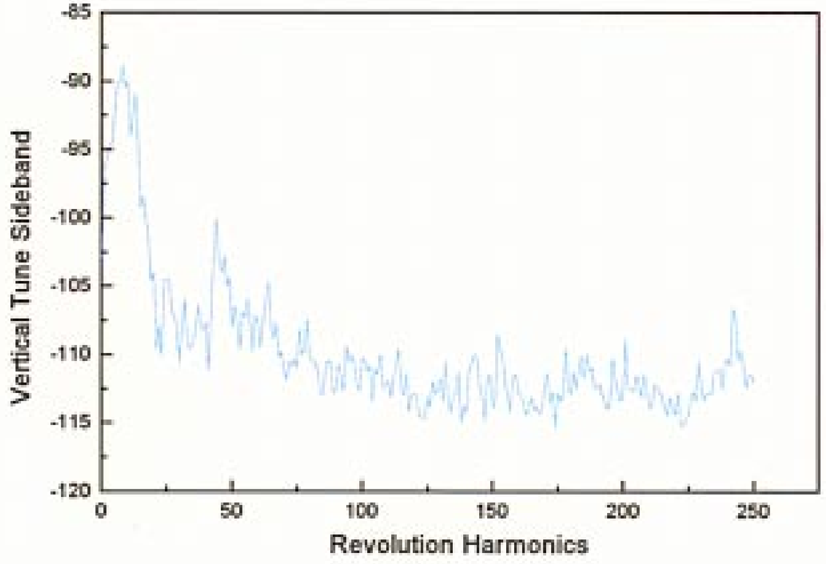
- Preliminary experiments on FII have been performed on Feb. 21 and 22, 1997 at PLS.
- Automatic scanning tool for measuring spontaneous vertical tune sideband.
- PLS beam parameters
  - $E=2.043$ GeV
  - $L_{sep}=2$ ns
  - beam size=0.3 mm(H)
    0.065 mm(V)
  - $Q_{x,y,s}=14.28, 8.18, 0.0105$
  - ion species=H_2(75%), CO(15%)

Experimental Results

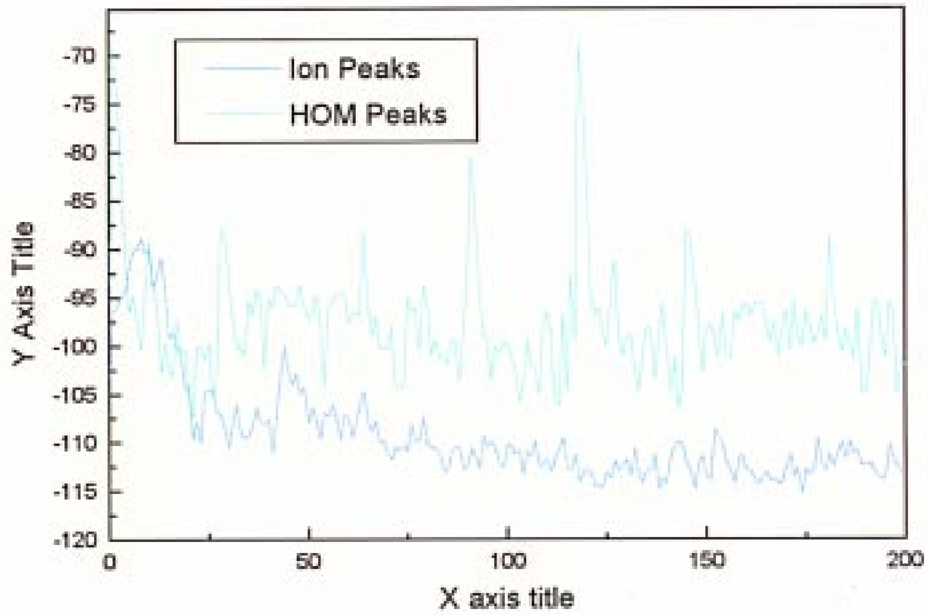
- Bunch beam current dependence
  - 50mA/60bunches or 100mA/120bunches
  :no spontaneous peaks
  - 132mA/120bunches 180mA/120bunches
  :Difference in freq. and amplitude



- Spectrum shows two distinct peaks corresponding to CO (13 MHz) and H_2 (50 MHz).



- Broad nature of peaks is different from HOM-induced ones.



- Pressure dependence : After DIP off, as pressure was doubled, the amplitude of the vertical sideband was enhanced.
- When the vertical beam size was doubled, the sideband disappeared.
- No effect of the vertical tune variation on spectrum was observed.

Summary and Future Plan

- Observed ion effects qualitatively.
- Second experiment for quantity measurements (last week in June).
  - gas injection experiment (He gas)
  - phase and amplitude measurements of the oscillation with fast BPM.
  - Growth rate measurements with TFS.
  - Precise emittance measurements

Experimental Observations of the Fast Beam-Ion Instability at the Advanced Light Source

John Byrd, John Thomson
Lawrence Berkeley National Laboratory

Alex Chao, Sam Heifets, Michiko Minty, Tor Raubenheimer, John Seeman, Gennady Stupakov, Frank Zimmerman
Stanford Linear Accelerator Center

Abstract

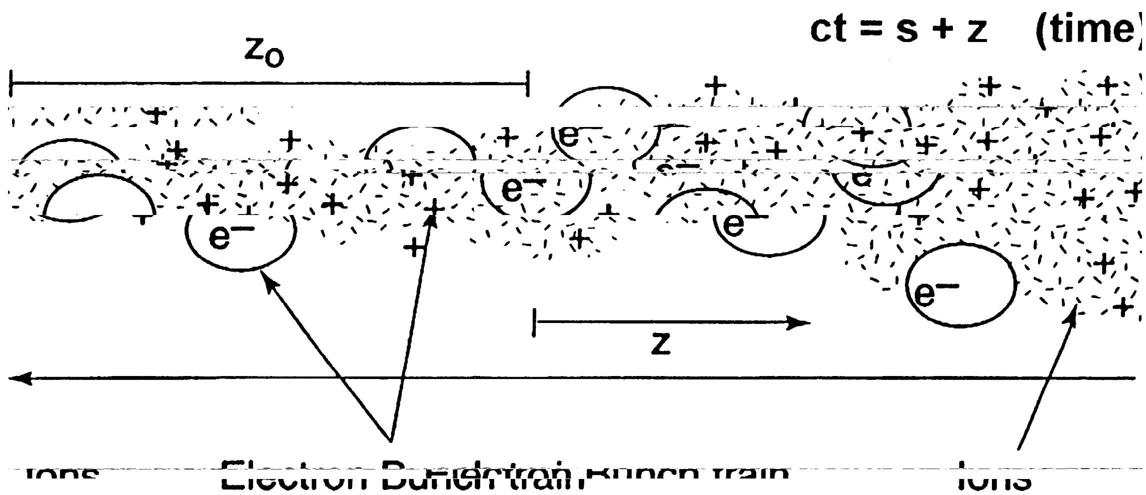
We present results of experimental observation of the fast beam-ion instability (FII). Results suggest that we observe the instability with ~80 ntorr of He added to the vacuum.

(see www-als.lbl.gov/~jbyrd for more information)

Introduction

•"classic" ion trapping occurs when the motion of ions is stable in the beam's potential well over many beam passages. The ion motion becomes unstable for large enough gap in the filling pattern (i.e. clearing gap). This is the typical "passive" solution for curing ion problems.

•For high currents and low emittances, transient interactions between the beam and ions can cause significant beam oscillations. Predicted to be important for flavor factories (PEP-II, KEKB, DAFNE), NLC linac and damping rings, next generation light sources. Similar effect predicted for positively charged bunch and atomic electrons.



J. Byrd, et. al., Fast beam-ion instability in the ALS

Advanced Light Source (ALS)

"3rd Generation Light Source"

A 1.5 GeV electron storage ring optimized for producing high brightness synchrotron radiation.

Energy	1.5 GeV	Circumference	196.8 m
F_{rf}	500 MHz	σ_δ	7e-4
I_{bunch}	1-2 mA	σ_l	5 mm
h	328	Q_s	0.0075
$\varepsilon_{x,y}$	4.1,0.12 nm-rad	$\langle\sigma_{x,y}\rangle$	160,30 μm
α	1.5e-3		

ALS is currently operating for users at design current. 5 ID's installed and 12 operational beamlines.

Under normal multibunch conditions, FB systems are used to control longitudinal and transverse coupled bunch instabilities driven by cavity HOMs and resistive wall impedance.

Experimental Procedure

- setup conditions where the FBII is expected with growth rates at least an order of magnitude above growth rates from cavity HOMs and resistive wall impedance **and** ion trapping of helium not expected. Add helium gas to vacuum to get large growth rates but minimize effects of Coulomb scattering. Helium also poorly pumped by passive titanium sublimation pumps.
- turn off all active pumping except for pumps on either side of RF cavities; add Helium to storage ring on either side of RF cavities and let it equilibrate in ring. Raise pressure to ~80 nTorr He.
- record transverse beam profile and beam spectrum for a variety of fill patterns at nominal and elevated storage ring vacuum pressure.
- Longitudinal, horizontal, and vertical coupled bunch FB systems are on for all measurements. Vertical damping rate ~(400 μsec)$^{-1}$/mA.

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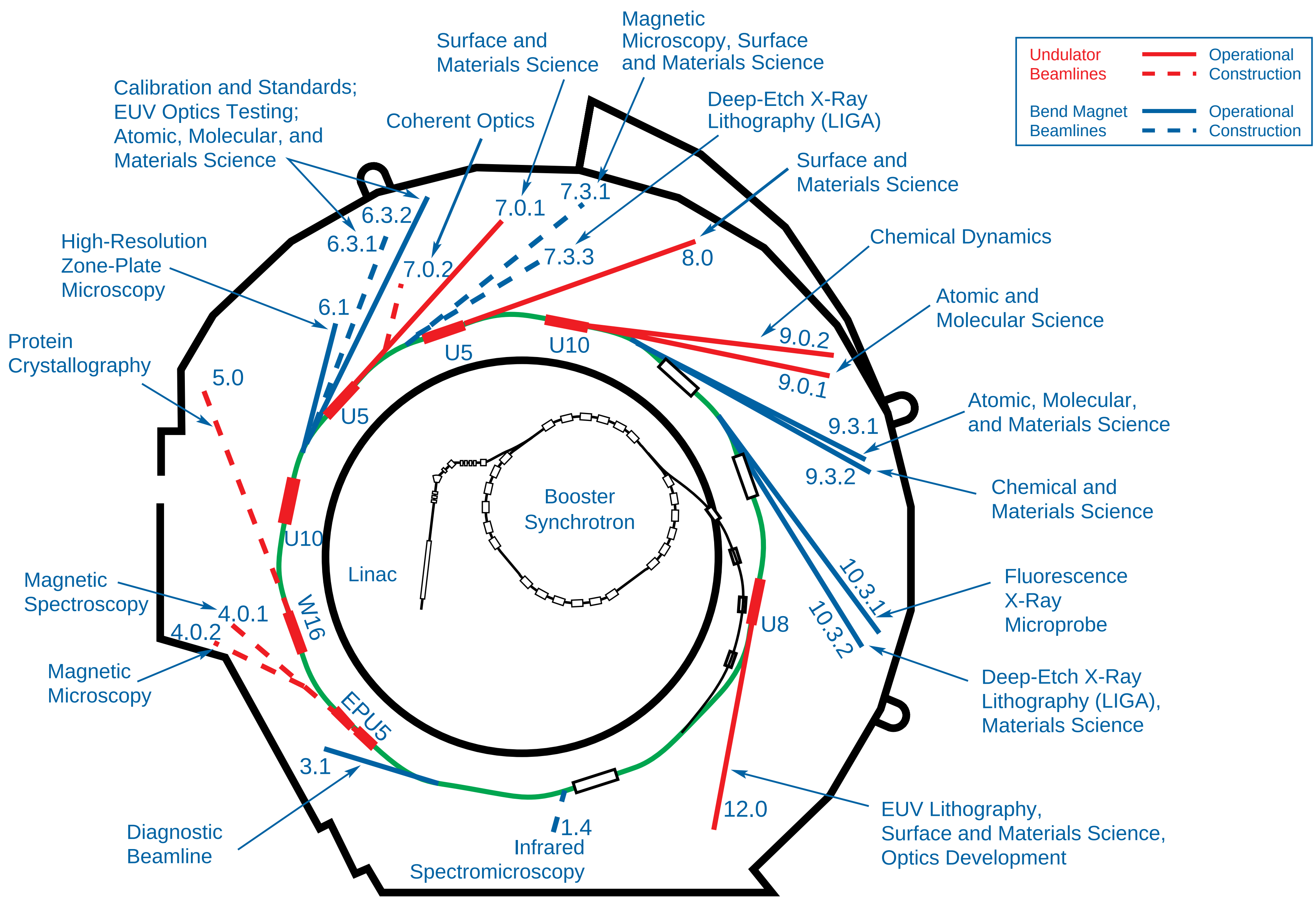

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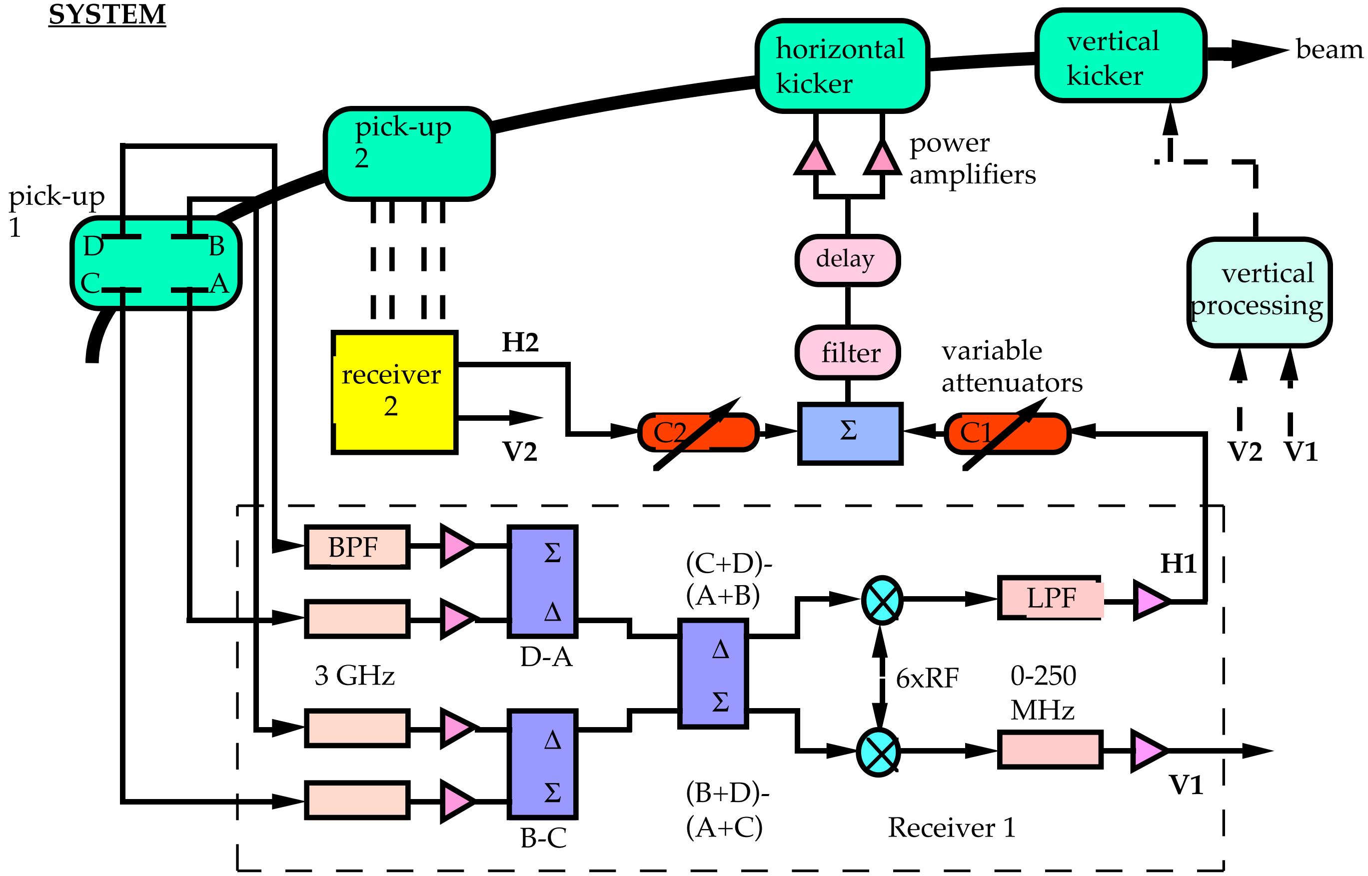
ALS TRANSVERSE FEEDBACK SYSTEM



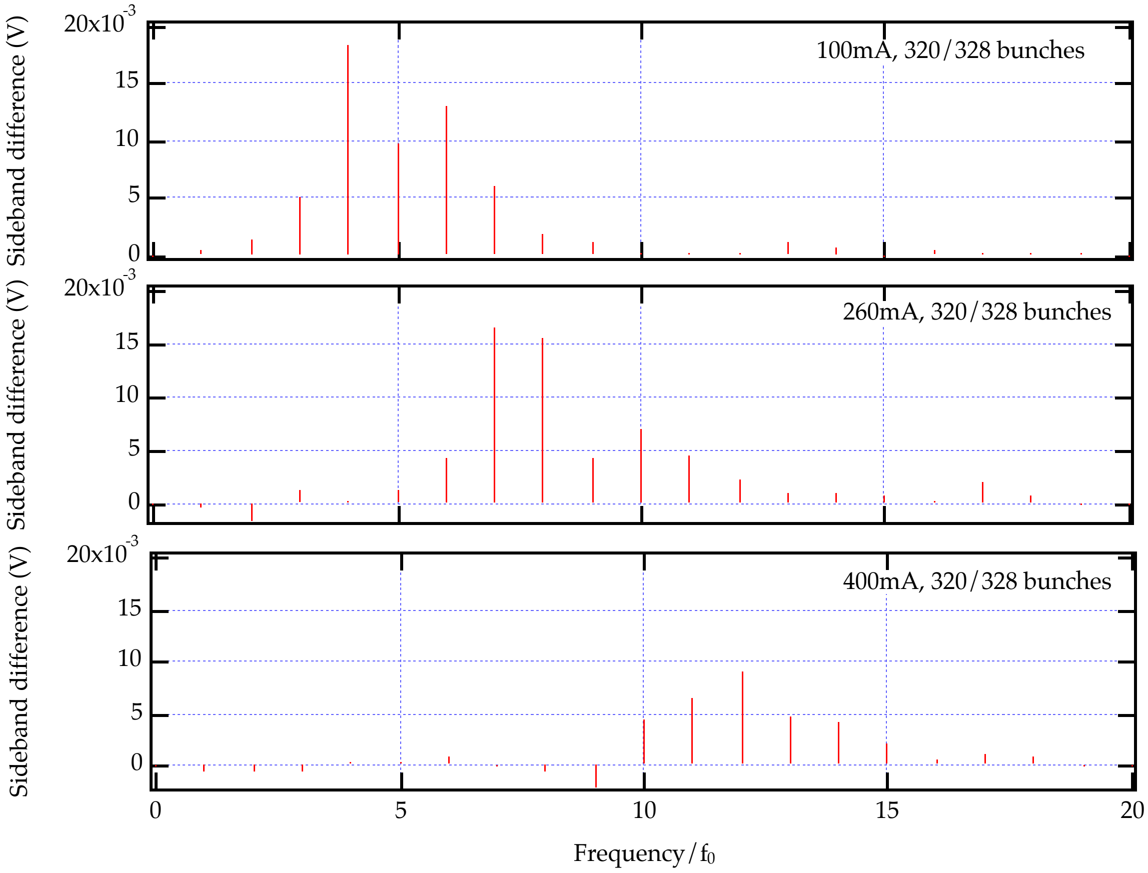
System Features:

- 100 kHz->250 (220) MHz BW
- high gain/low noise receivers (3 GHz heterodyne detection), current dependent gain
- 2 PUs w/quadrature processing, $\beta_{x1,2,k}$=12 m, $\beta_{y1,2,k}$=6 m, $\Delta\theta_{x1,2}/2\pi$=0.18, $\Delta\theta_{y1,2}/2\pi$=0.68, $\Delta\theta_{x2,k}/2\pi$=0.95, $\Delta\theta_{x2,k}/2\pi$=0.92, +/- variable attenuators (mixers in PIN diode mode)
- 150 W amplifiers driving stripline kickers (single plate only), maximum kick of ~1 kV
- 2-tap analog notch filter for removing DC orbit offsets

Experimental Results

Nominal Pressure

- longitudinal, horizontal, and vertical CB FB systems operational
- nominal vacuum pressure ~0.25 ntorr.
- 320/328 bunches filled (normal filling pattern for users)
- sideband signals disappear for 240/328 and 164/328 fill patterns.
- ~2-3% vertical beam size increase. Probably due to ion trapping of CO/N2.



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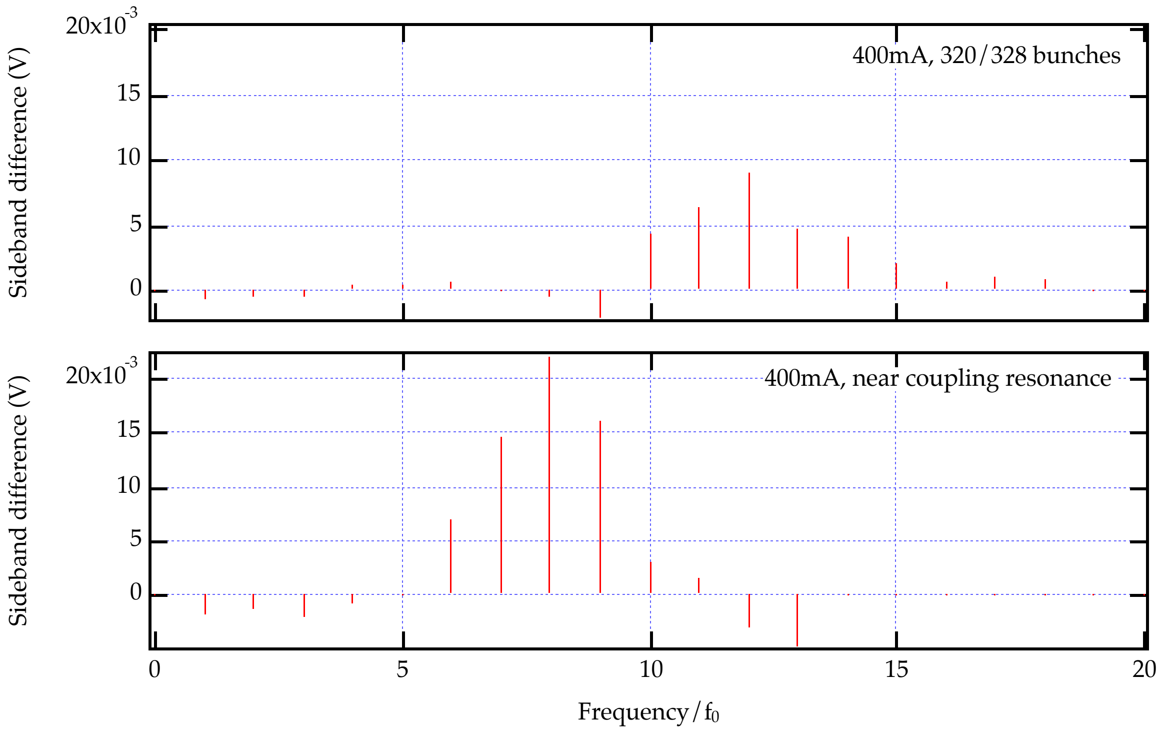
Initial Measurements (cont.)

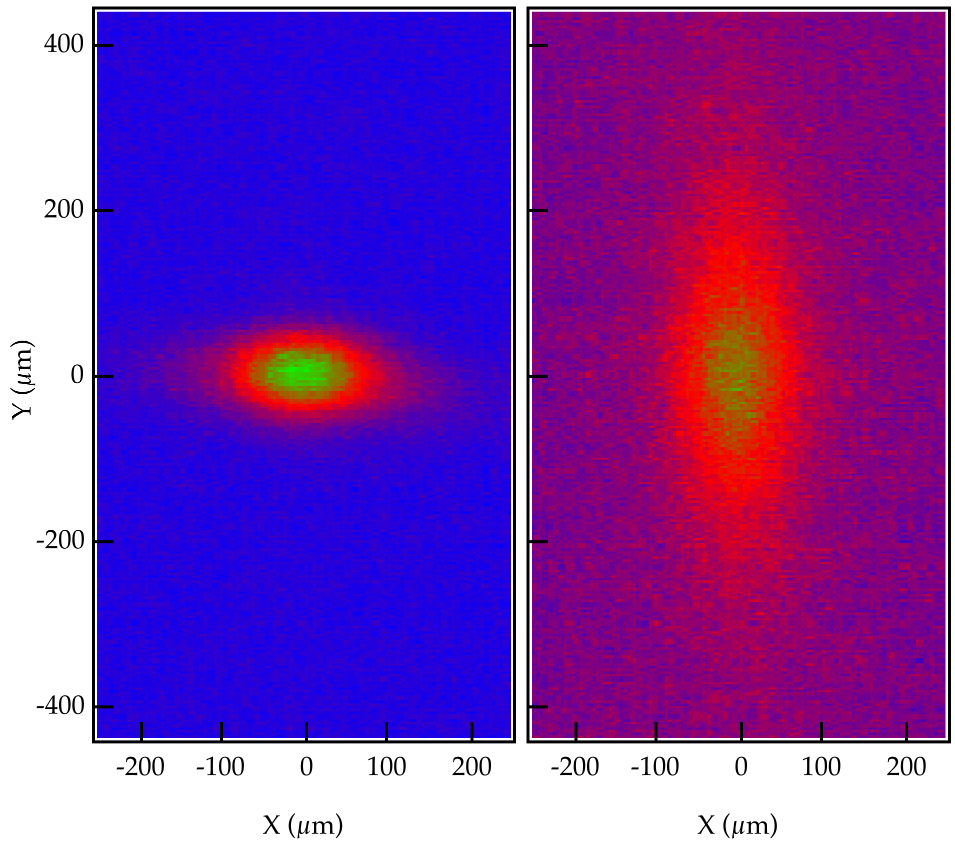
• near the betatron coupling resonance ($\sigma_y = 2^* \sigma_{y0}$), the frequency reduces as expected.



Elevated Pressure Results

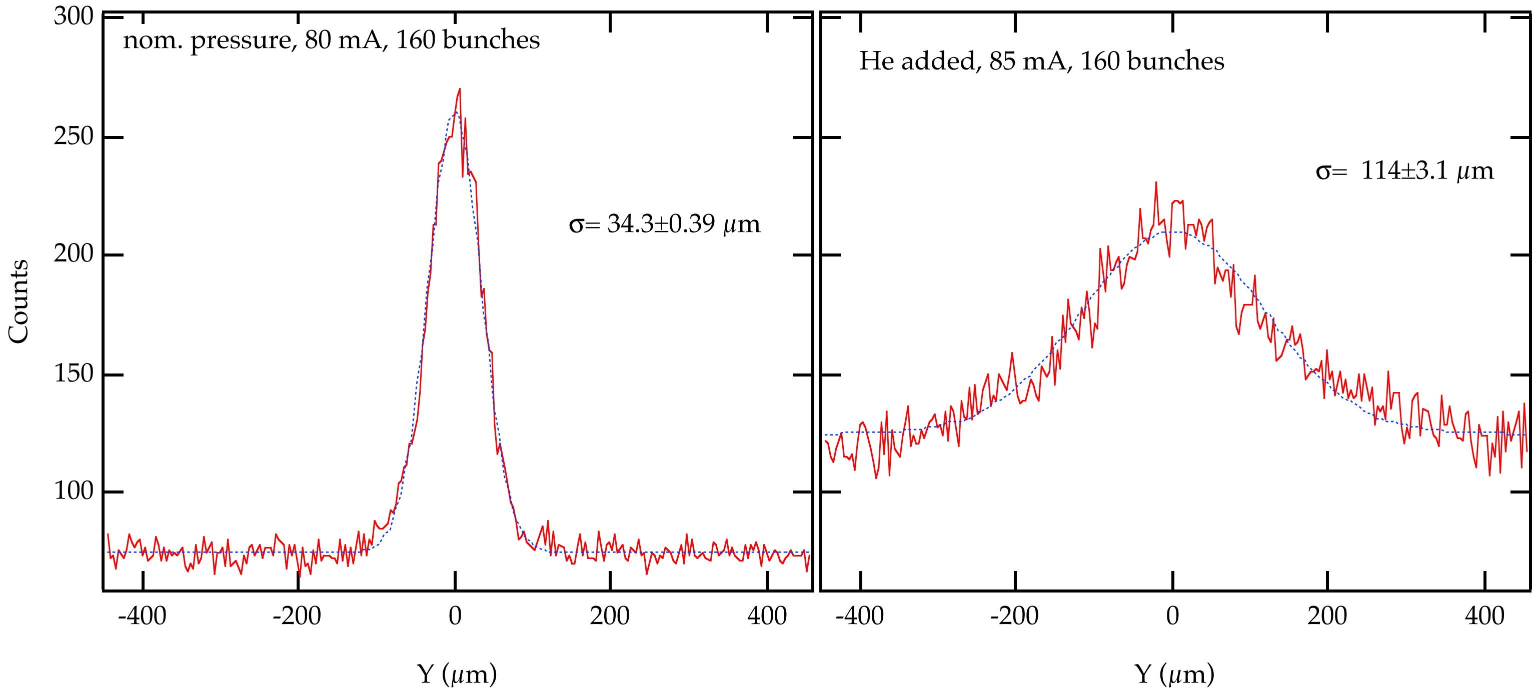
Vertical beam blowup

- dedicated diagnostic photon beam line measures average transverse beam cross section.
- β_X=0.35 m, β_Y=22 m, η_X=0.01 m



Each image is ~80 mA total beam current in 160 consecutive bunches (out of 328 possible)
The left is at nominal pressure and the right is with 80 ntorr He.

Synchrotron Light Images (cont.)

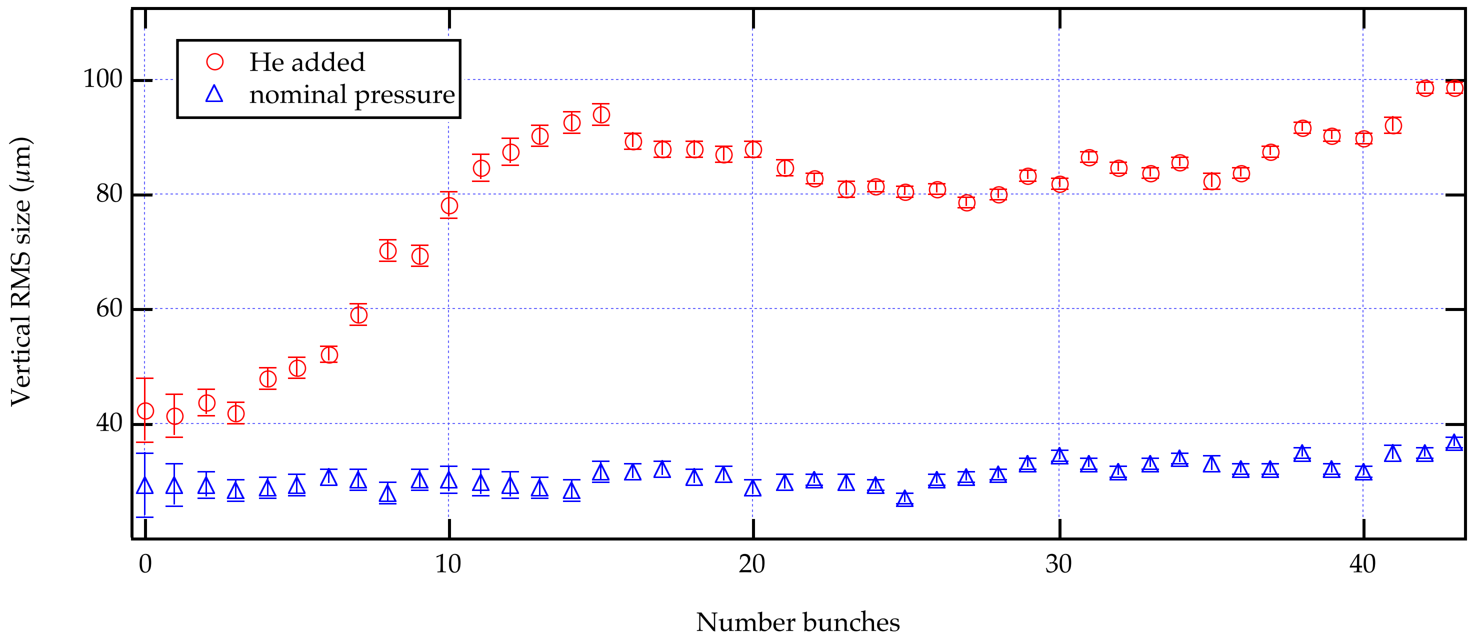


•We see between a factor 2-3 increase in average vertical beam size. Horizontal size is unaffected. Single bunch images show no increase with higher gas pressure.
•simulations show a similar saturation effect.
•variation of vertical FB gain has no effect on beam size or sidebands.

Observation of Instability Threshold

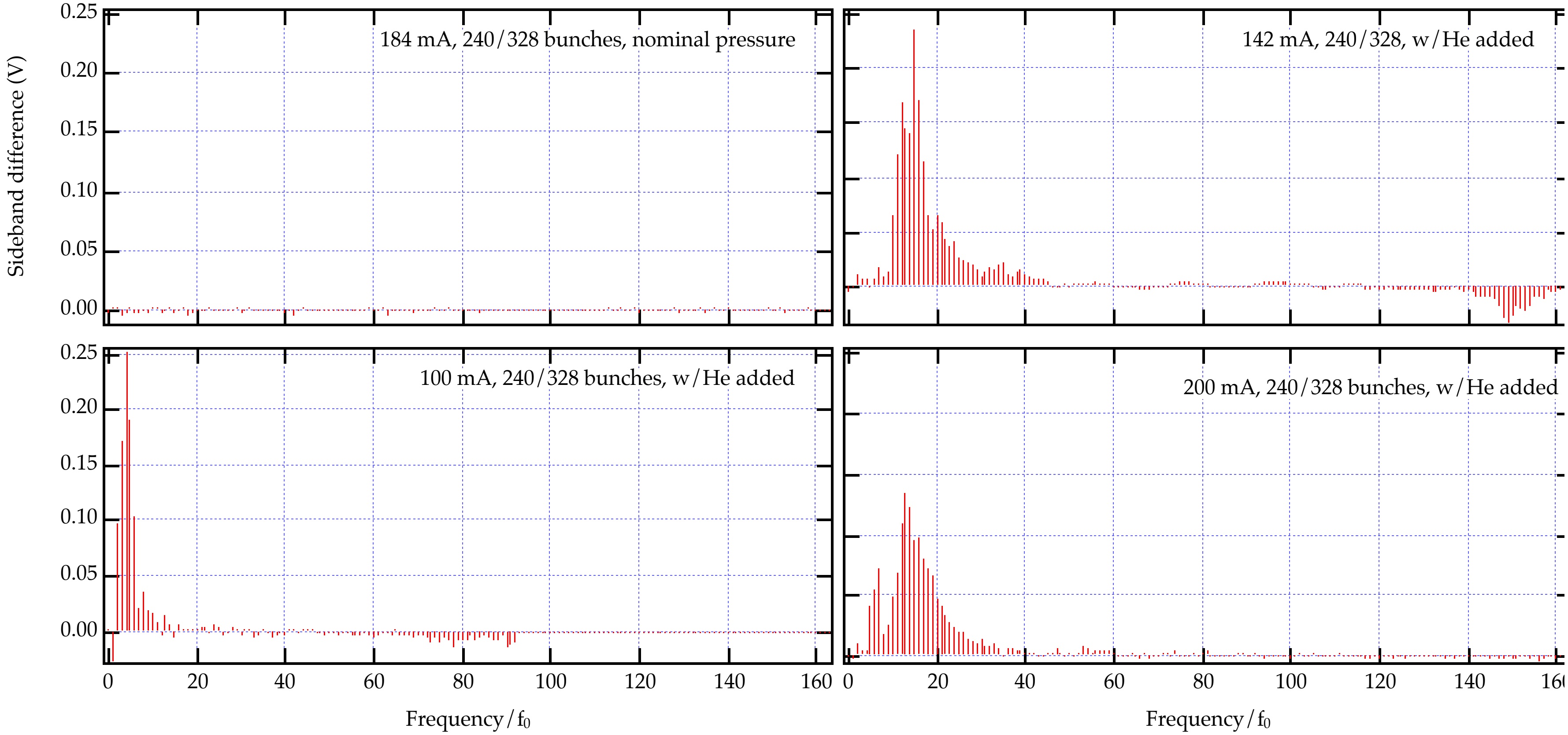
•at a given pressure, we can vary the instability growth rate by varying the length of the bunch train (using a fixed current/bunch)

•for the experimental conditions, the theory predicts a growth rate of ~1/msec at about 8 bunches. Our FB damping rate for 0.5 mA/bunch is ~1.2 msec.



Vertical beam spectrum

- record the amplitudes of all vert betatron sidebands over 250 MHz range
- plot the linear difference of lower-upper sideband amplitude
- peak frequency of sideband pattern agrees with calculated coherent ion frequency
- coherent oscillations not always observed (decoherence? 4-pole mode?)



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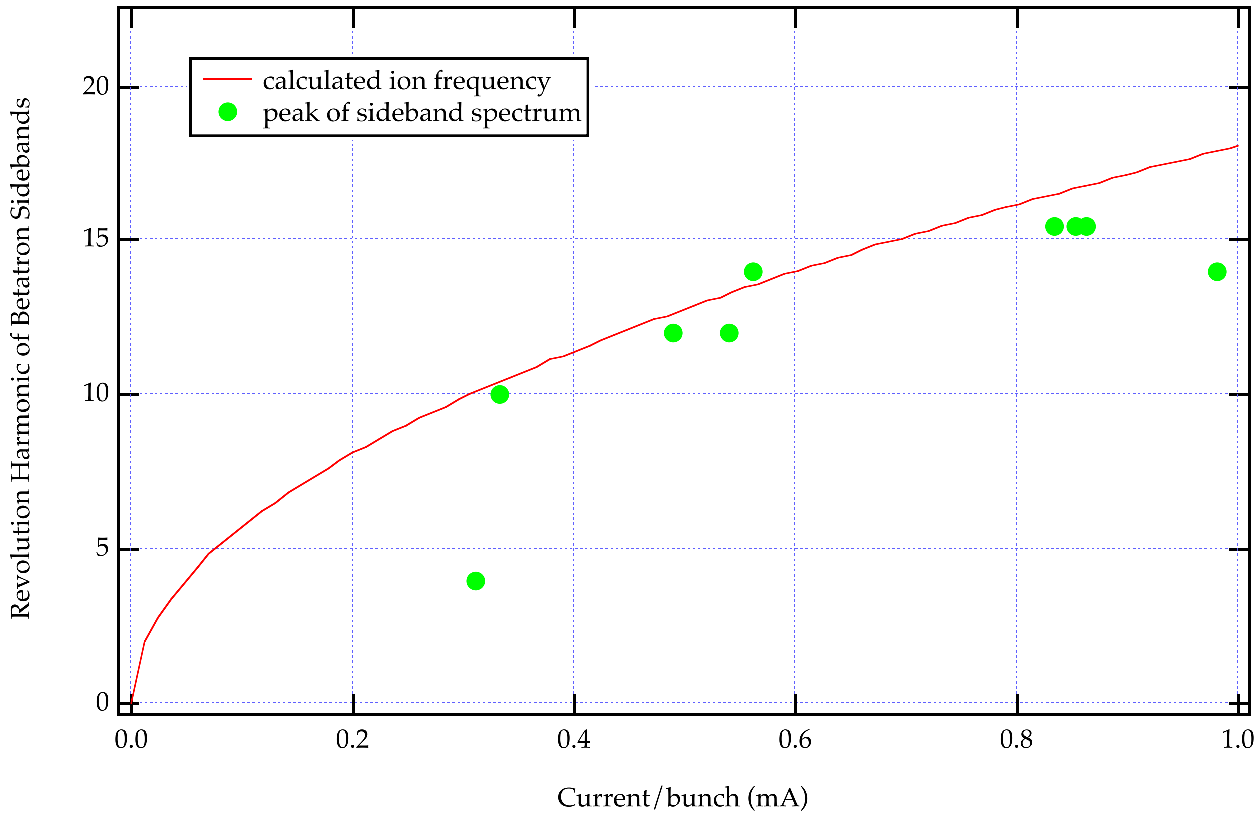
Frequency of sideband spectrum

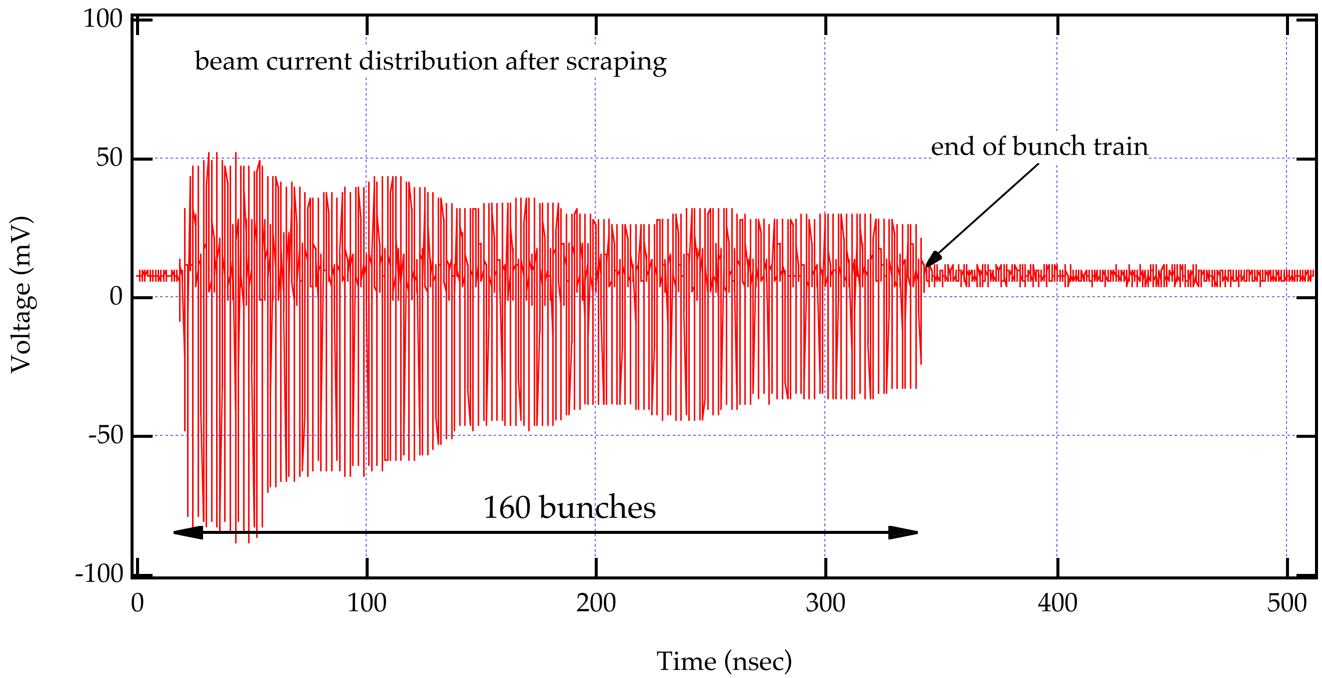
The frequency of the peak of the sideband spectrum shown previously shows fair agreement with the calculated ion frequency. However, detailed agreement requires precise knowledge of the vertical beam size which is difficult to determine when the beam is unstable. Also note that a coherent signal is not always visible on the spectrum analyzer, even though the beam is clearly unstable in the vertical direction.



Variation along bunch train

To measure the variation in vertical oscillation amplitude and/or vertical beam size along the bunch train, we measured the bunch intensity as the vertical aperture was reduced using a beam scraper.

The tail of the train is scraped more than the head, indicating that the tail is oscillating at larger amplitudes, as predicted by the theory. When the expt. is repeated at nominal pressure, the beam is scraped uniformly.



J. Byrd, et. al., Fast beam-ion instability in the ALS

Summary and Conclusions

•FBII probably not observed at nominal pressure.
•Vertical blowup observed when 80 ntorr helium is added in a regime where trapping not expected. Growth from gas scattering does not explain effect.
•Instability threshold at fixed pressure close to expected value.
•Frequency of coherent oscillations agrees with ion frequencies.
•Coherent oscillations increase along bunch train, demonstrating the transient nature of the effect.
•Growth saturates at 2-3*σ_v.
•Probably FBII but more studies necessary to extrapolate results to different regimes.

Future Plans

•next run planned for June 1997.
•vary gas pressure measure instability threshold.
•study effect of noise in TFB system
•measure tune and amplitude along bunch train.
•test potential damping mechanisms (i.e. fill with series of short trains)

Thanks to Alan Jackson and the ALS operations group

<u>The Electron-Cloud Effect in the PEP-II Positron Ring: An Update*</u>

M. Furman (+G. Lambertson)

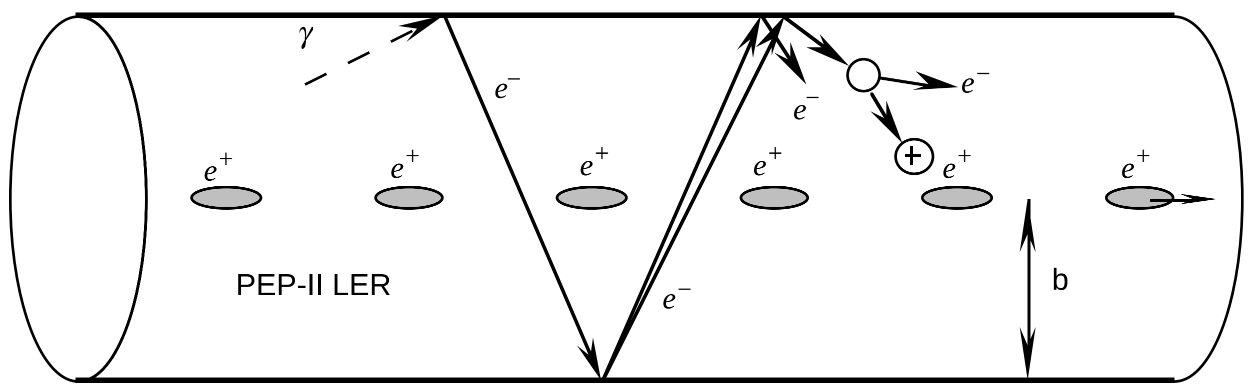
Lawrence Berkeley National Laboratory

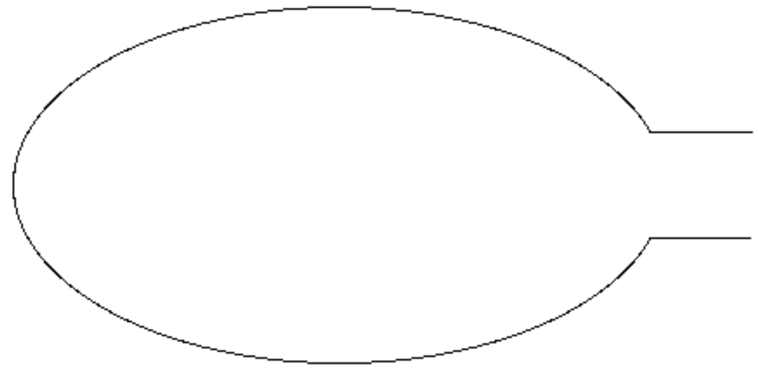
PAC97, Vancouver, May 12–16 1997

*this poster, as well as paper 2V015, can be found in http://www.lbl.gov/~miguel/

*Work supported by the U.S. Department of Energy under Contract no. DE-AC03-76SF00098.

Mechanism for the beam-induced electron cloud.





— **~99% of the photons escape**

~1% have low energy and large angle: these photons strike the wall and provide a supply of photoelectrons.

— **ionization of residual gas is a negligible source of electrons compared to photoelectrons**

PEP-II parameters:

— $N=5.6 \times 10^{10}$ particles/bunch

$s_B=1.26$ m

$\sigma_z=1$ cm

no. of bunches=1746 (max)

$I_{beam}=2.17$ A

— (see paper 7P37 for more details)

- The electron cloud couples the transverse motion of the bunches.

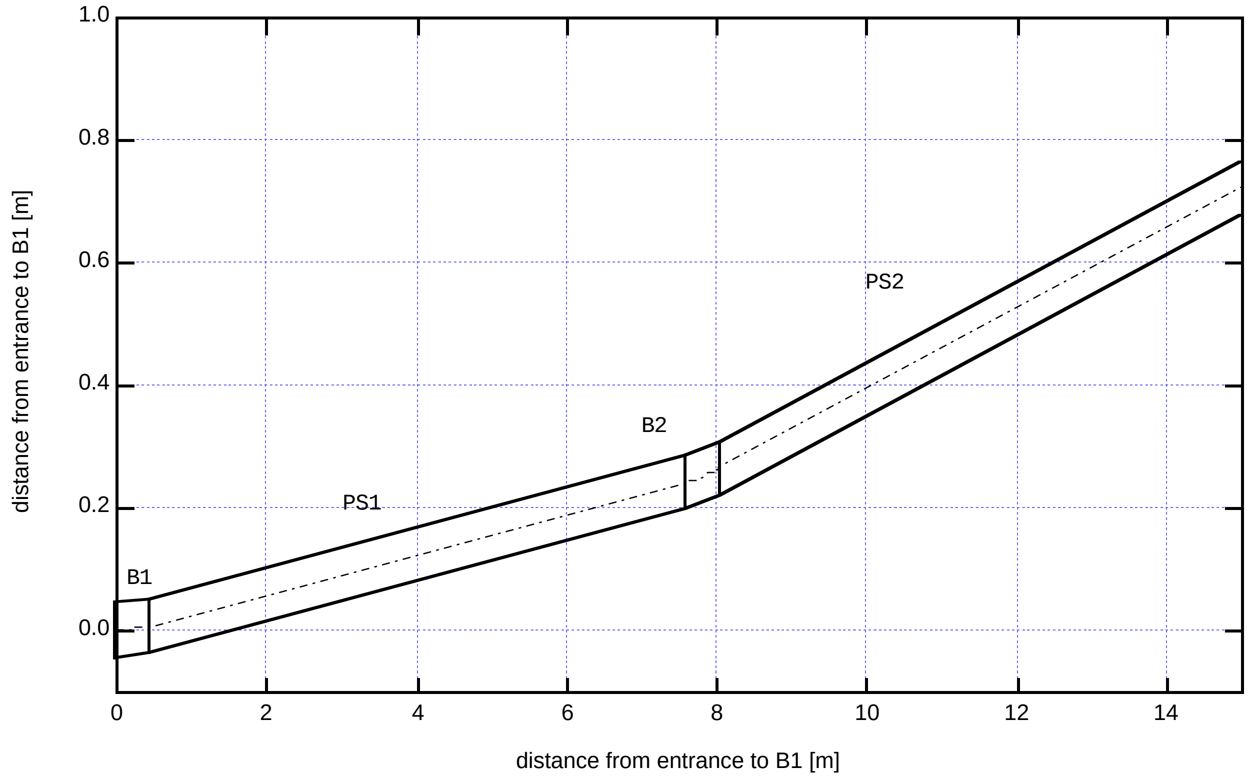
  - **Fast coupled-bunch instability**
  - **Unlike its cousin "beam-induced multipactoring effect," the electron-cloud effect is <u>not in principle resonant</u> in nature (although some subtle resonant effects can arise in the presence of a B-field)**
  - **M. Izawa, Y. Sato and T. Toyomasu, *Phys. Rev. Lett.* <u>74</u>, 5044 (1995): experimental evidence at the Photon Factory (KEK) when operated with positrons.**
    - ♦ **a beam gap does not reduce or eliminate the instability (but a large S_B does)**
  - **K. Ohmi, *Phys. Rev. Lett.* <u>75</u>, 1526 (1995): simulation of the electron cloud for the Photon Factory.**
    - ♦ **fast growth rate**
  - **Z. Y. Guo et al.: experiment carried out at BEPC (IHEP-KEK collaboration, EPAC96): similar characteristics as observed at the PF.**
  - **S. Heifets (SLAC) analytic approach to the problem for PEP-II.**
  - **F. Zimmermann (SLAC): recent preliminary simulations for the LHC.**
  - **a related instability at CESR: J. Rogers and T. Holmquist (J. Rogers talk 7'C2)**

Summary*

- PEP-II LER (positron beam)
- features of the simulation
- SEY data
- results for the pumping straight sections
- results for the bending magnets
- comments and conclusions

* this is a progress report; answers are not yet final!

PEP-II LER: plan view of a section of arc



- study the electron cloud separately in the pumping sections (PS's) and in the dipole bending magnets (B's)
  - **this is legitimate because the longitudinal motion (drift) of the cloud is very slow**
  - **compute separately the contributions to $W_1(z)$, then add them up; this is legitimate because range of $W_1(z)$ is much smaller than the betatron wavelength**

PEP-II simulations

- simulation code features:
  - **3-dimensional**
  - **elliptical vacuum chamber geometry (image charges included)**
  - **photoelectron emission is a very simplified model; this is a primary input**
  - **secondary electron yield (SEY) model included in detail (assume a low-emission coating such as TiN)**
  - **space-charge effects included**
  - **ionization of residual gas included (but not secondary ionization)**
- basic strategy of the simulation is:
  - **simulate the development of the cloud in one section (dipole magnet, or pumping section) due to passage of a train of e^+ bunches**
  - **when the cloud is established, displace one bunch by Δy (or Δx) and observe the resultant force on successive bunches**
  - **extract the dipole wake function $W_1(z)$**
  - **compute multibunch mode spectrum from $W_1(z)$ and read off growth rate**
- basic result:
  - **growth rate ~1 ms^{-1} dominated by the pumping sections**
  - **secondary emission is under control thanks to TiN coating**

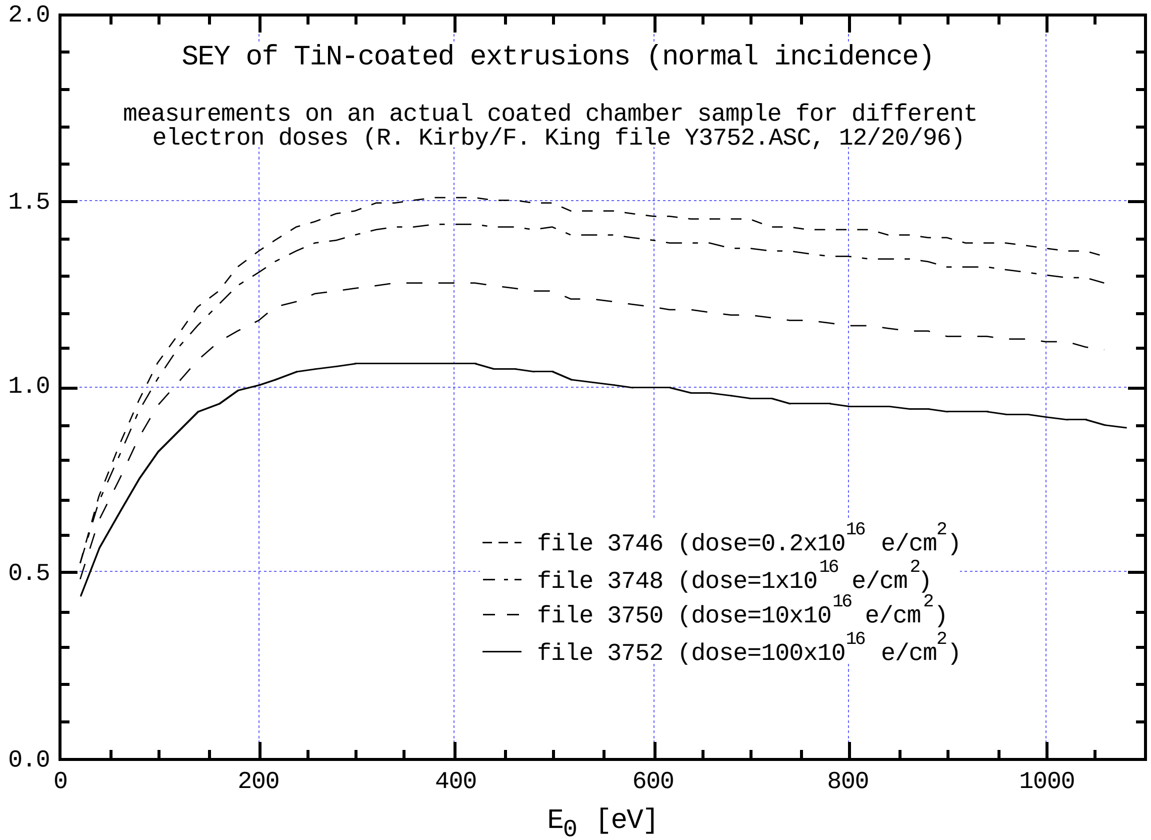
Secondary electron emission

- main quantity of interest is the secondary emission yield (SEY) δ:
  - — **δ=average number of ejected electrons per incident electron**
    - ♦ **function of: incident energy E_0, incident angle θ_0 and surface material**
    - ♦ **code uses semi-empirical model (H. Seiler, *J. Appl. Phys.* 54(11), p. R1, 1983)**
  - — **recent measurements by R. Kirby (SLAC) for TiN-coated extrusion sample at normal incidence also included**

- for the PEP-II LER the photon reflectivity *R* and quantum efficiency *Y* are also important, but not as much as the SEY
  - — **non-smooth behavior in δ but not in *R* or *Y***

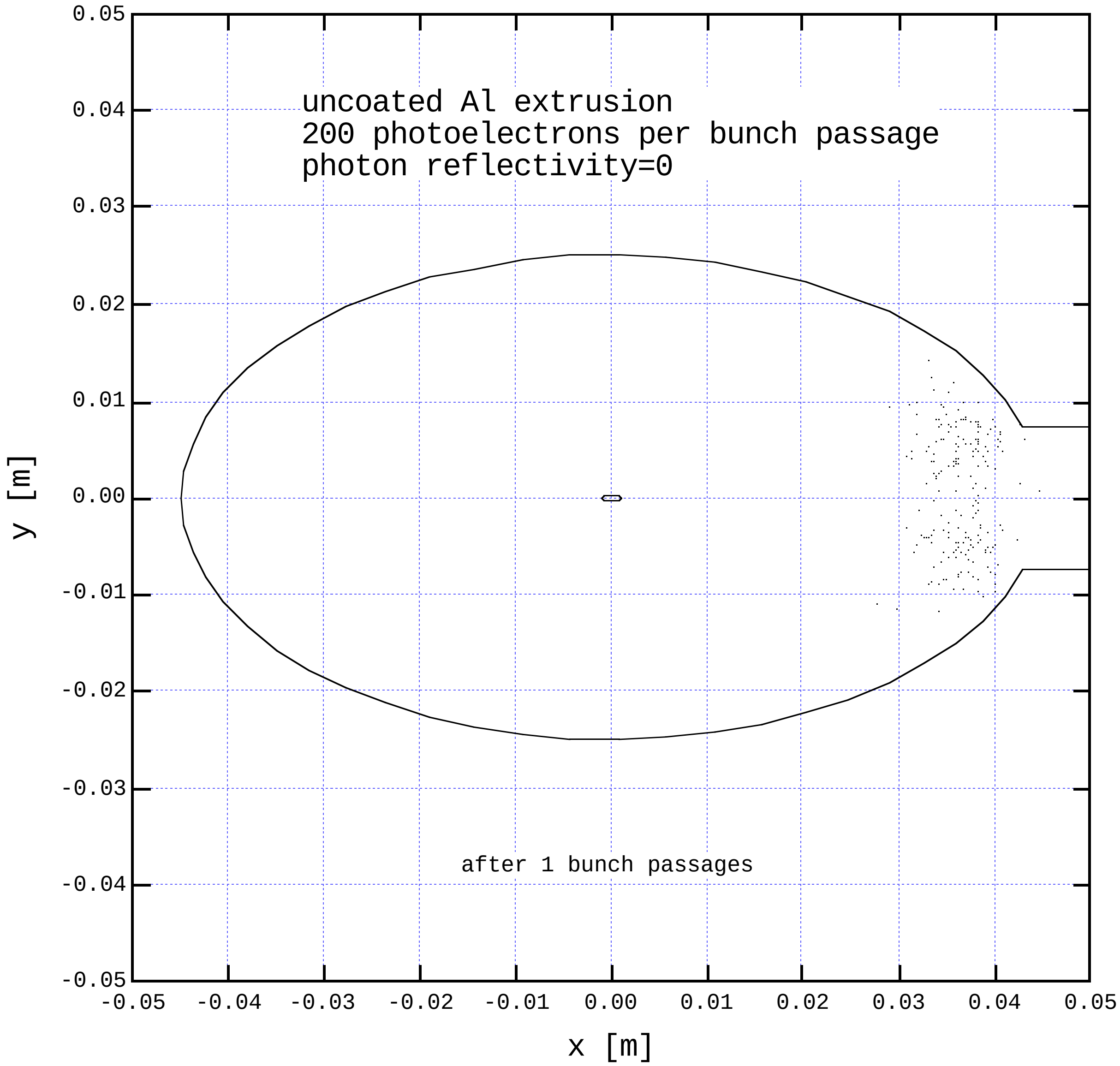
SEY measurements of Al extrusions at SLAC

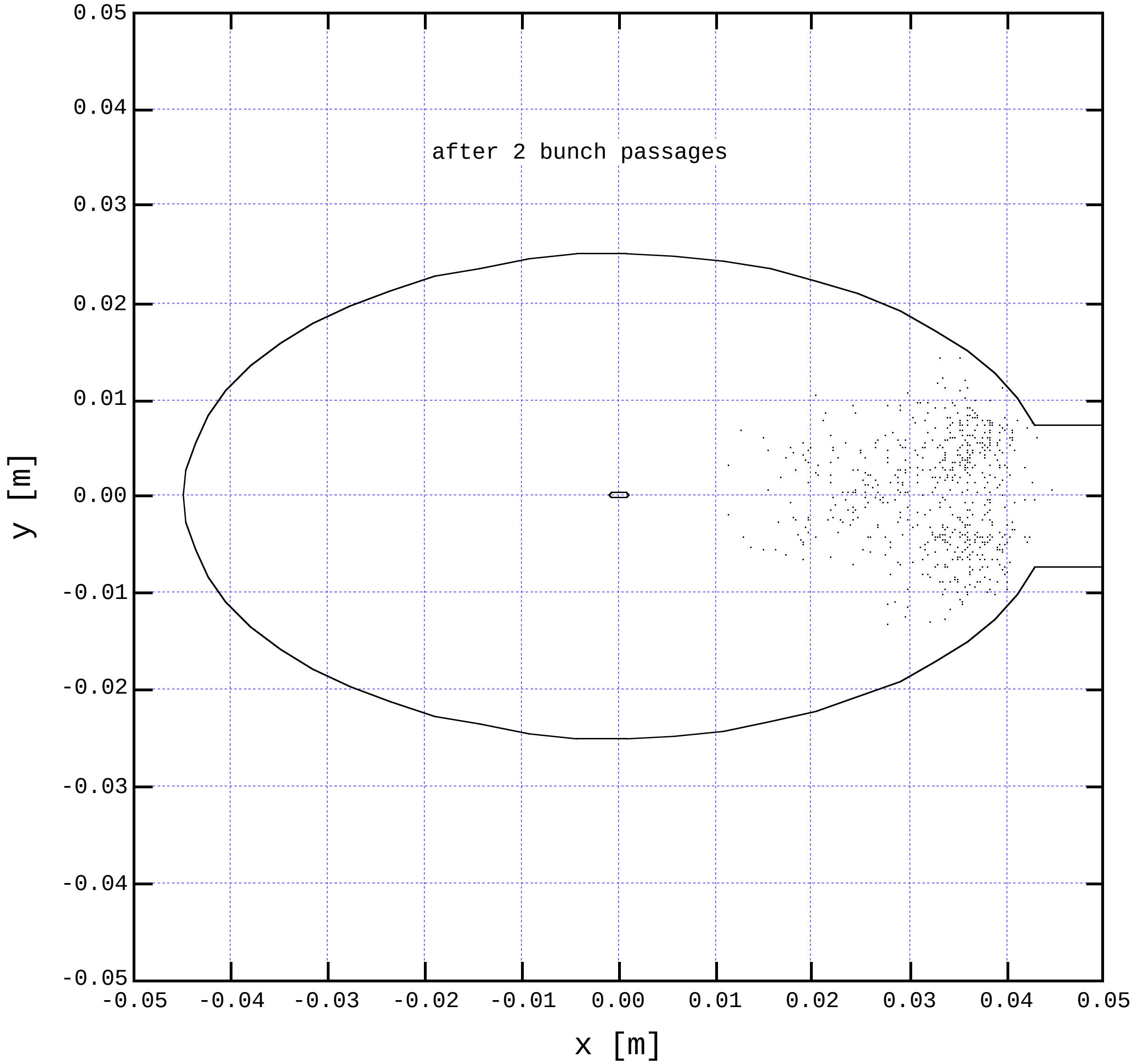
- TiN-coated, normal incidence (see paper 8C9)

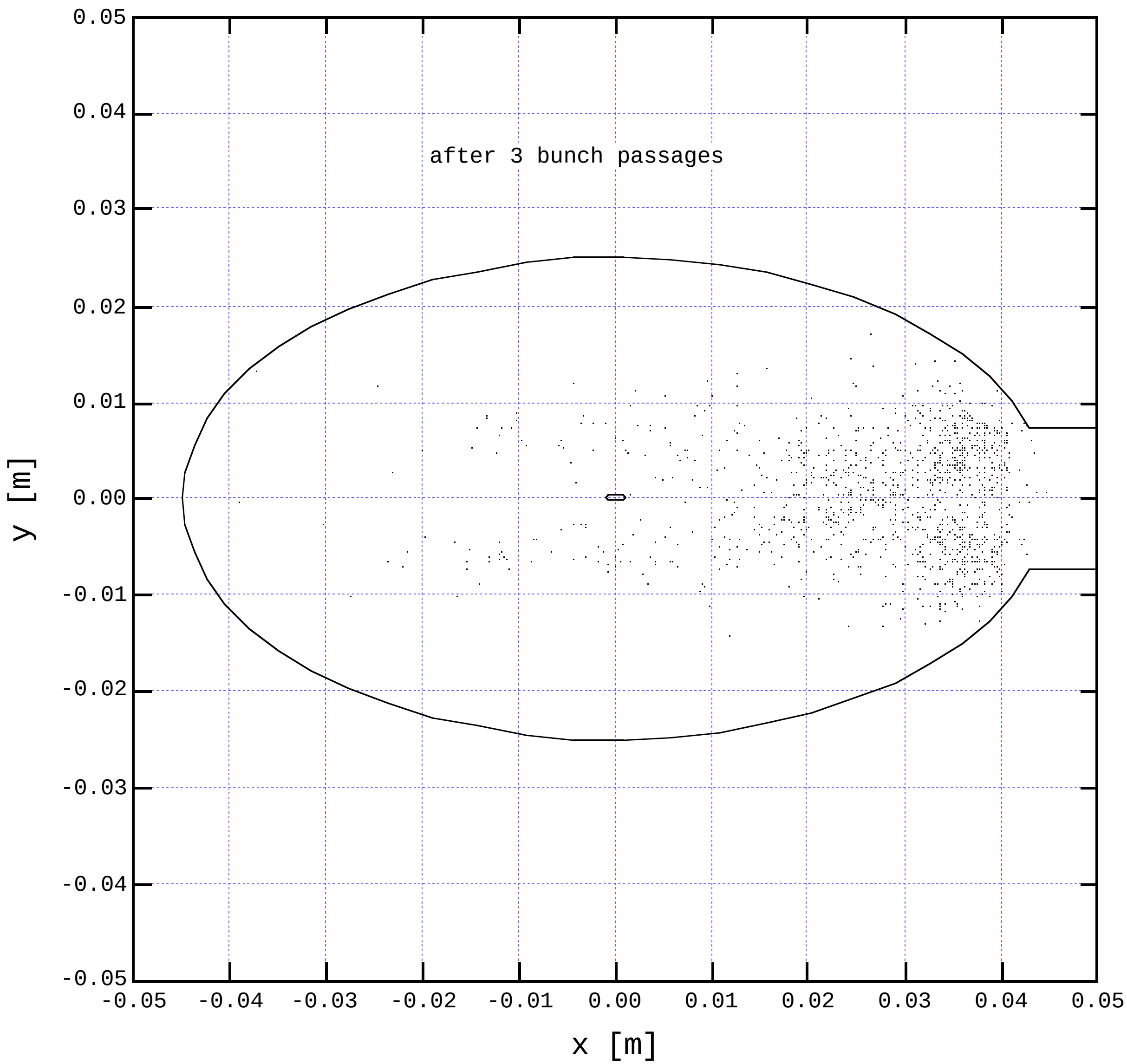


Baking and TiN-coating of vacuum chambers (paper 8C9)

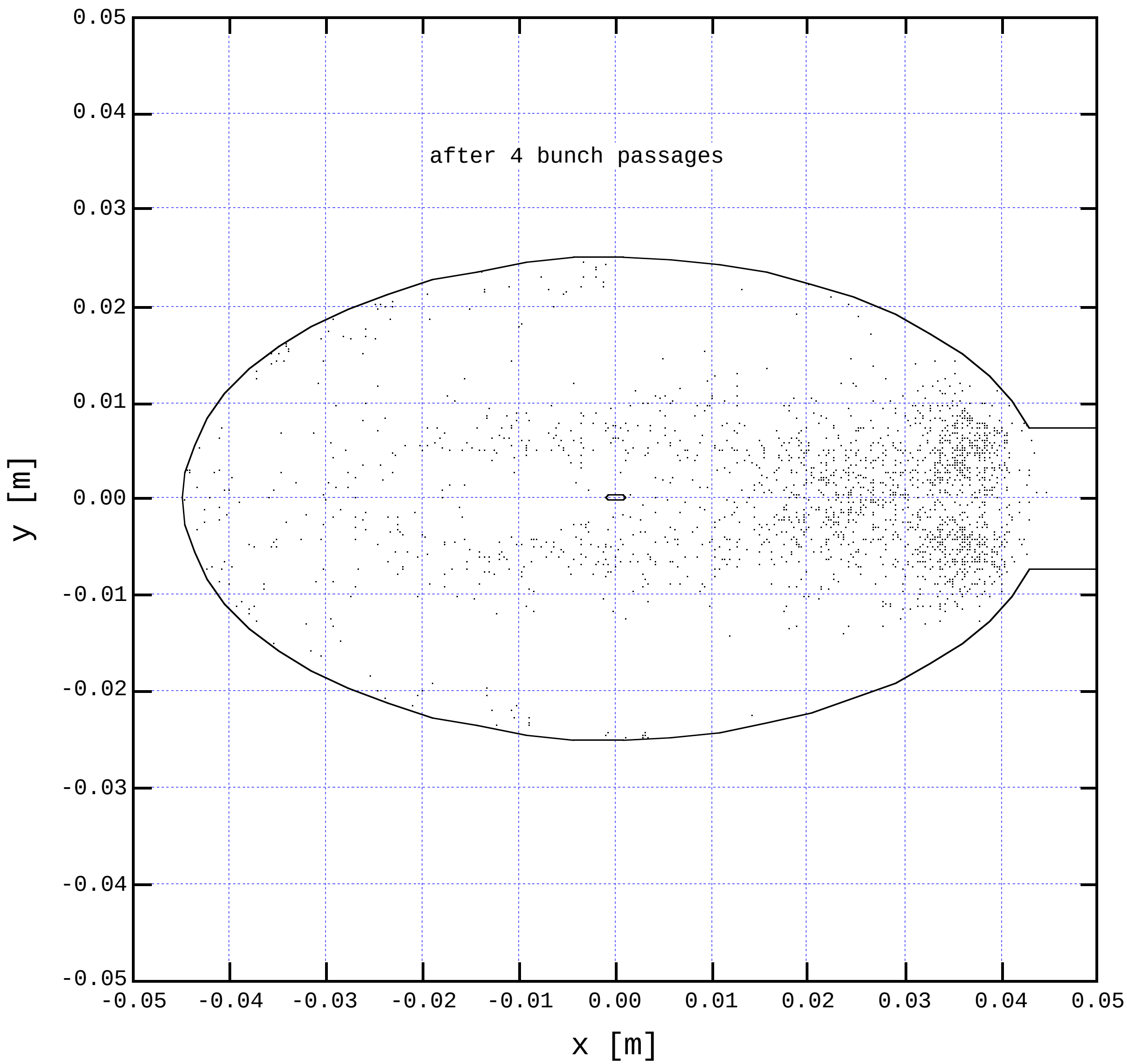
Pumping section: cloud build-up for *R*=0



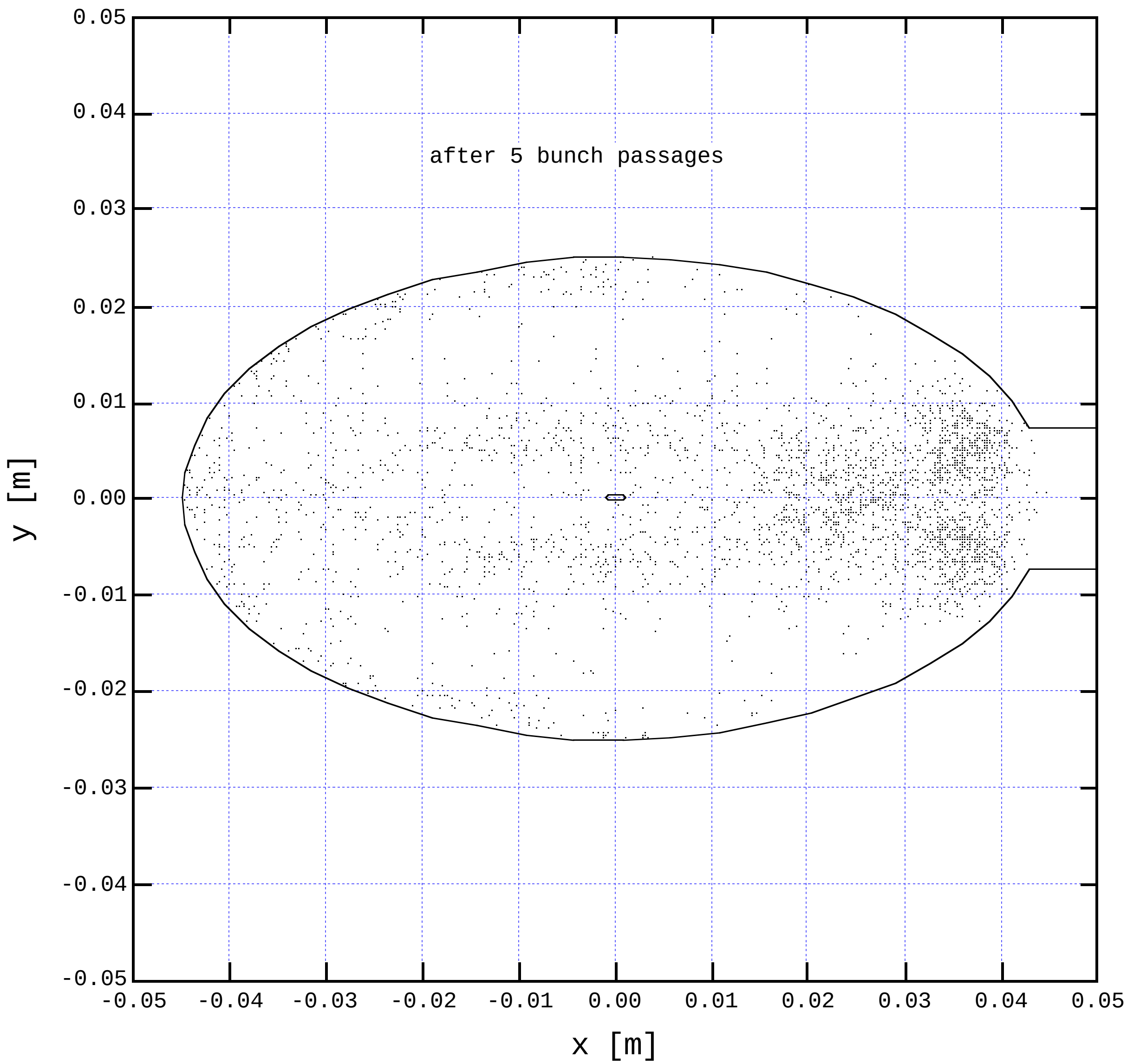

after 2 bunch passages
0.05
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
y [m]
-0.05
-0.04
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
0.05
x [m]



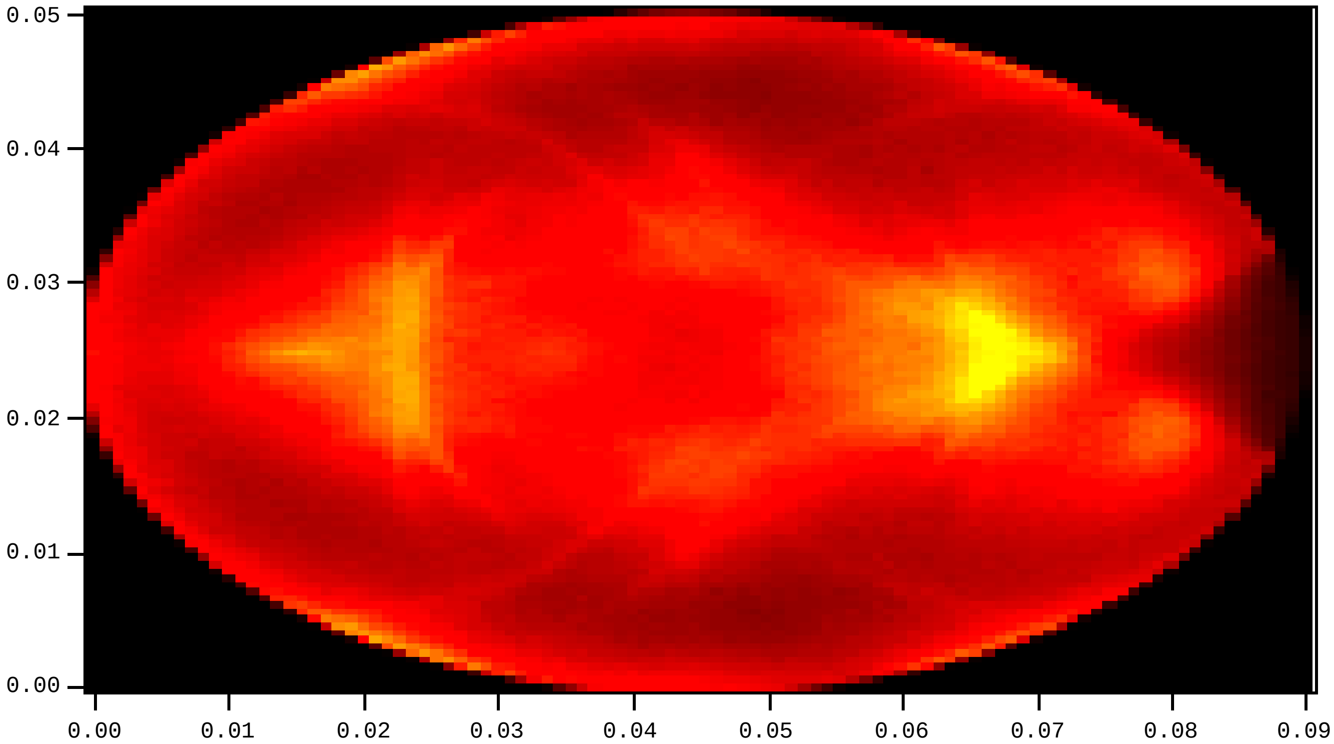
after 3 bunch passages
0.05
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
y [m]
-0.05
-0.04
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
0.05
x [m]



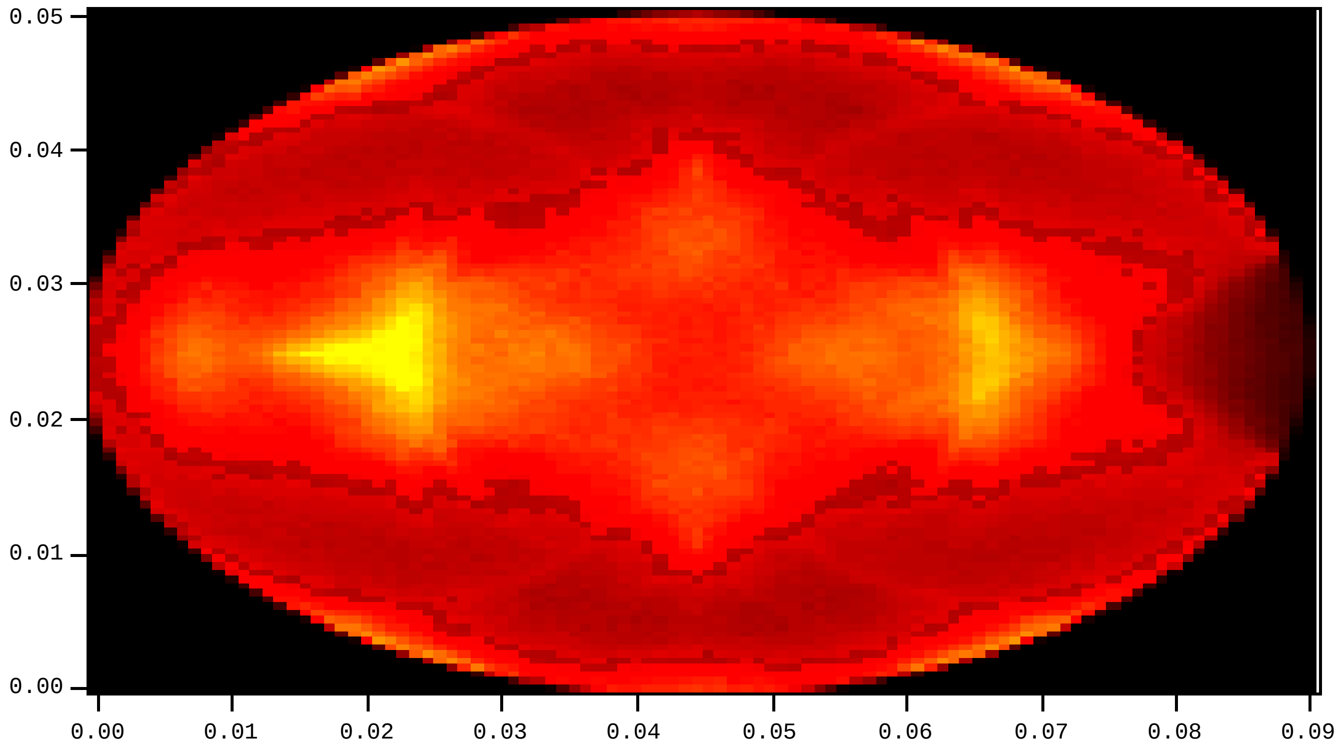
after 4 bunch passages
y [m]
x [m]
0.05
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.05
-0.04
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
0.05


after 5 bunch passages
0.05
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
y [m]
-0.05
-0.04
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
0.05
x [m]

Pumping section: equilibrium distribution for *R*=0



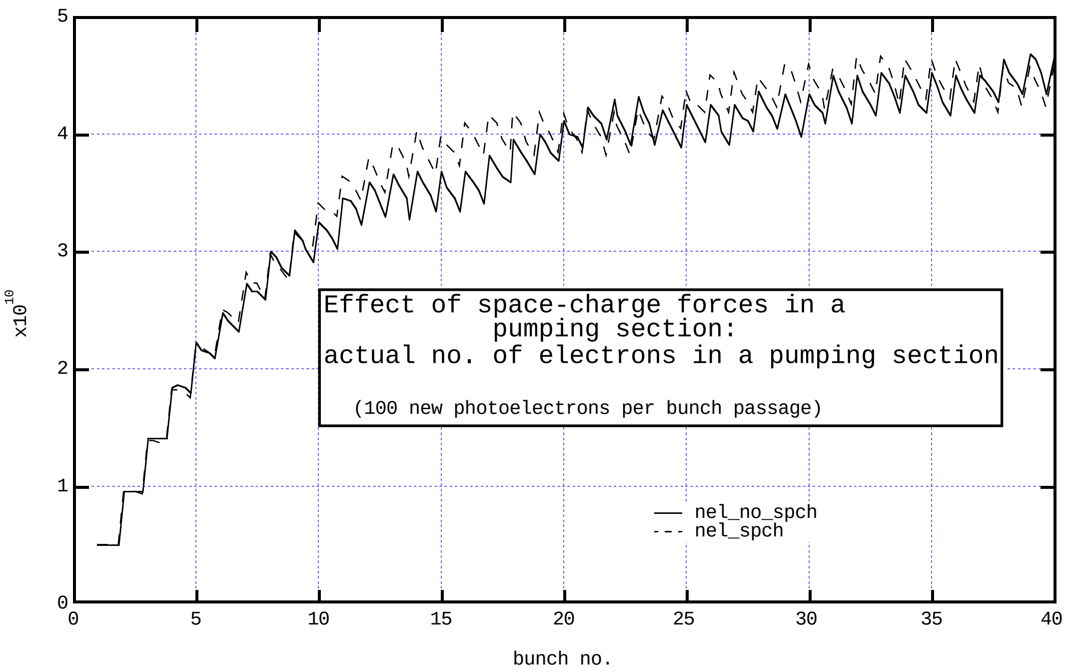
Pumping section: equilibrium distribution for *R*~1



Average (effective) emission yield:

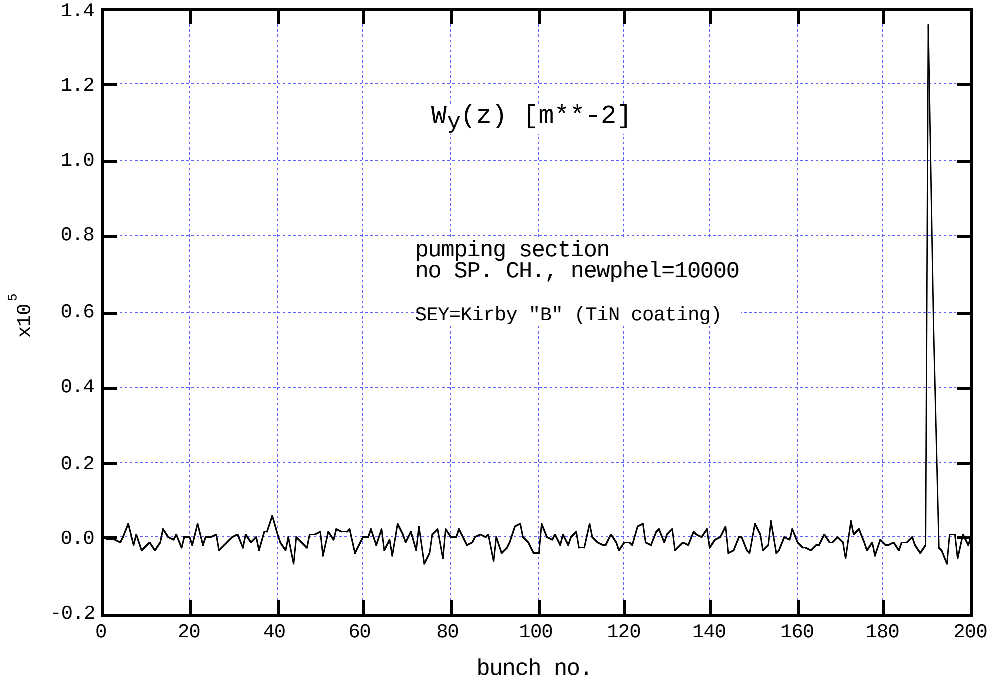
$$\bar{\delta} = \iint dE_0 \, d(\cos\theta_0)\rho(E_0, \cos\theta_0)\delta(E_0, \cos\theta_0)$$

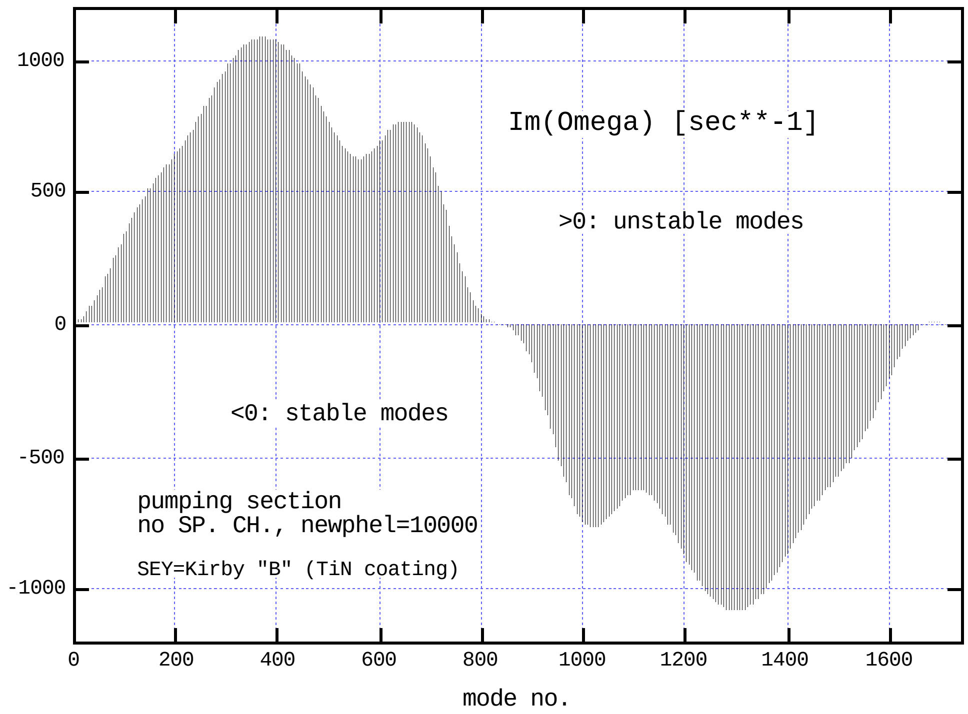
- find that $\bar{\delta} < 1$ in the pumping straight sections
  - — **walls act as a net absorber of electrons; an equilibrium is reached**



- at saturation, average electron density is ~4.7x10^5 e/cc
  - — **~1/27 of beam neutralization level**
  - — **can safely neglect space-charge (big computational savings!)**

Pumping straight section: wake function and multibunch spectrum.





- contribution from the PS's to the growth rate estimate: $\tau^{-1} \approx 1100\ s^{-1}$ for R~1

****

- if R=0, then $\tau^{-1} \approx 1400\ s^{-1}$; equilibrium density ~6x10^5 e/cc ~1/21 of beam neutralization level

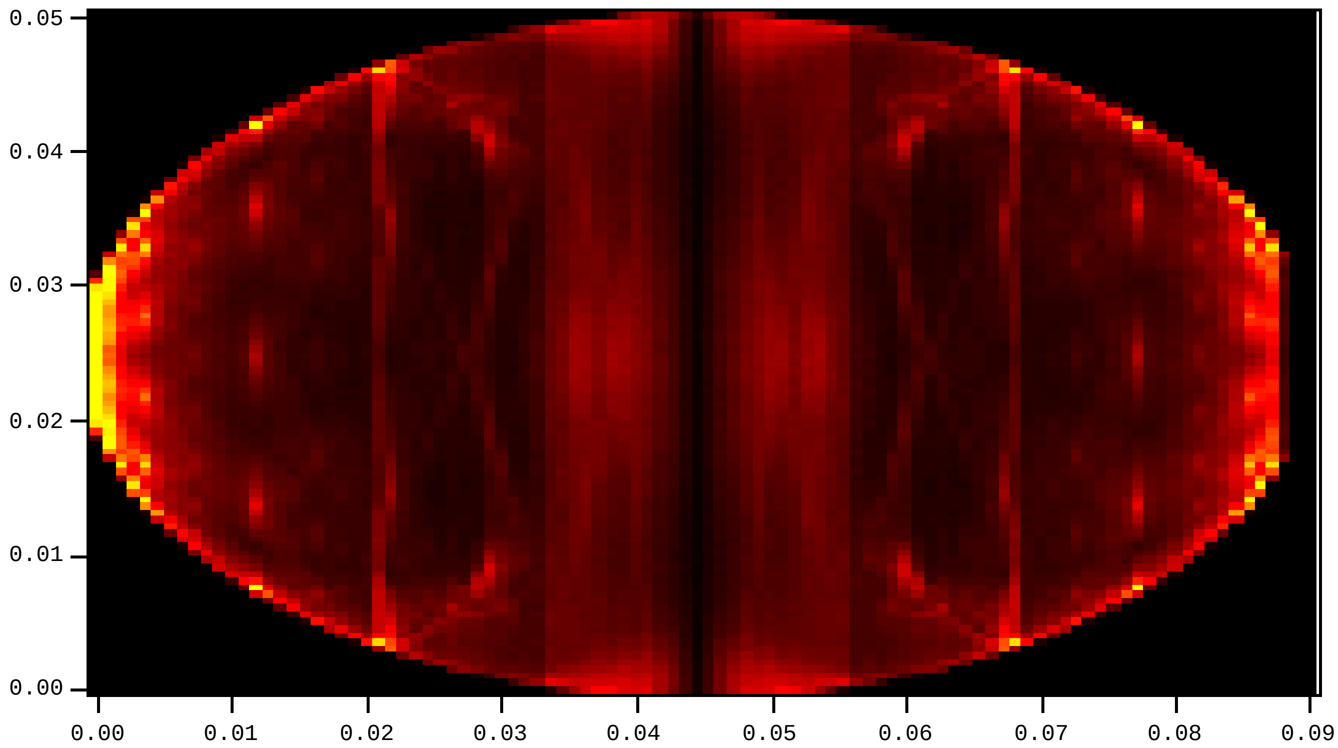
Dipole bending magnets.

- calculation is more complicated due to B-field
  - **B=0.75 T, L=0.45 m**
  - **electrons travel in tight vertical helices:**

$$\nu = \frac{eB}{2\pi mc} = 21\,\mathrm{GHz}, \qquad \rho = \frac{p_\perp}{eB} = 0.004 - 0.4\ \mathrm{mm}$$

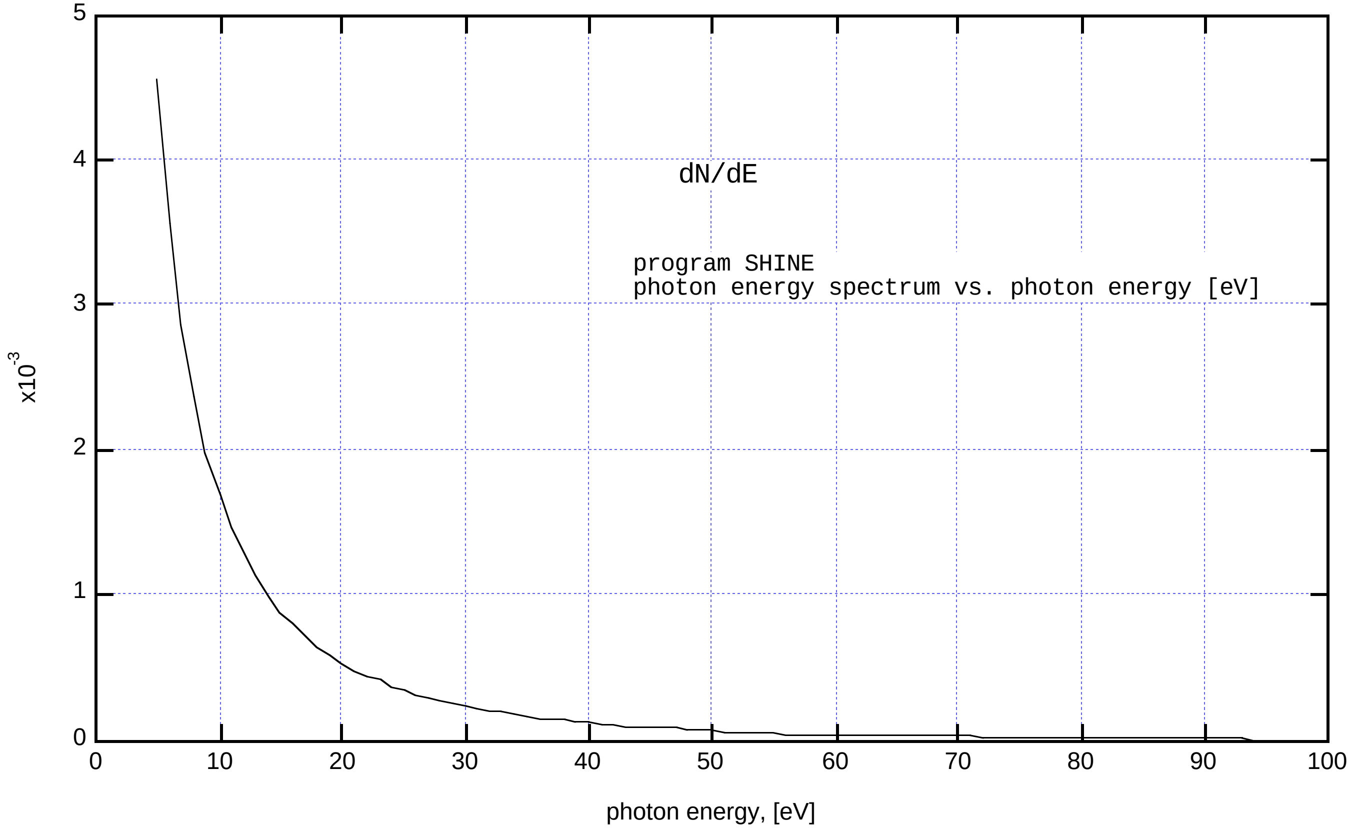
  - **bunch length effects are important!**
    - ♦ σ_t**=bunch length=33 ps**
    - ♦ **the fact that** $\nu\sigma_t > 1$ **has important consequences**
    - ♦ **impulse approximation yields overly pessimistic results**
    - ♦ **cyclotron-phase averaging of the beam-cloud interaction suppresses Δp_x by a factor** $\sim \exp\left(-(2\pi\nu\sigma_t)^2/2\right) = 5.9\times10^{-5}$ **relative to the impulse approximation**

Electron cloud distribution in a dipole bend (*R*~1)

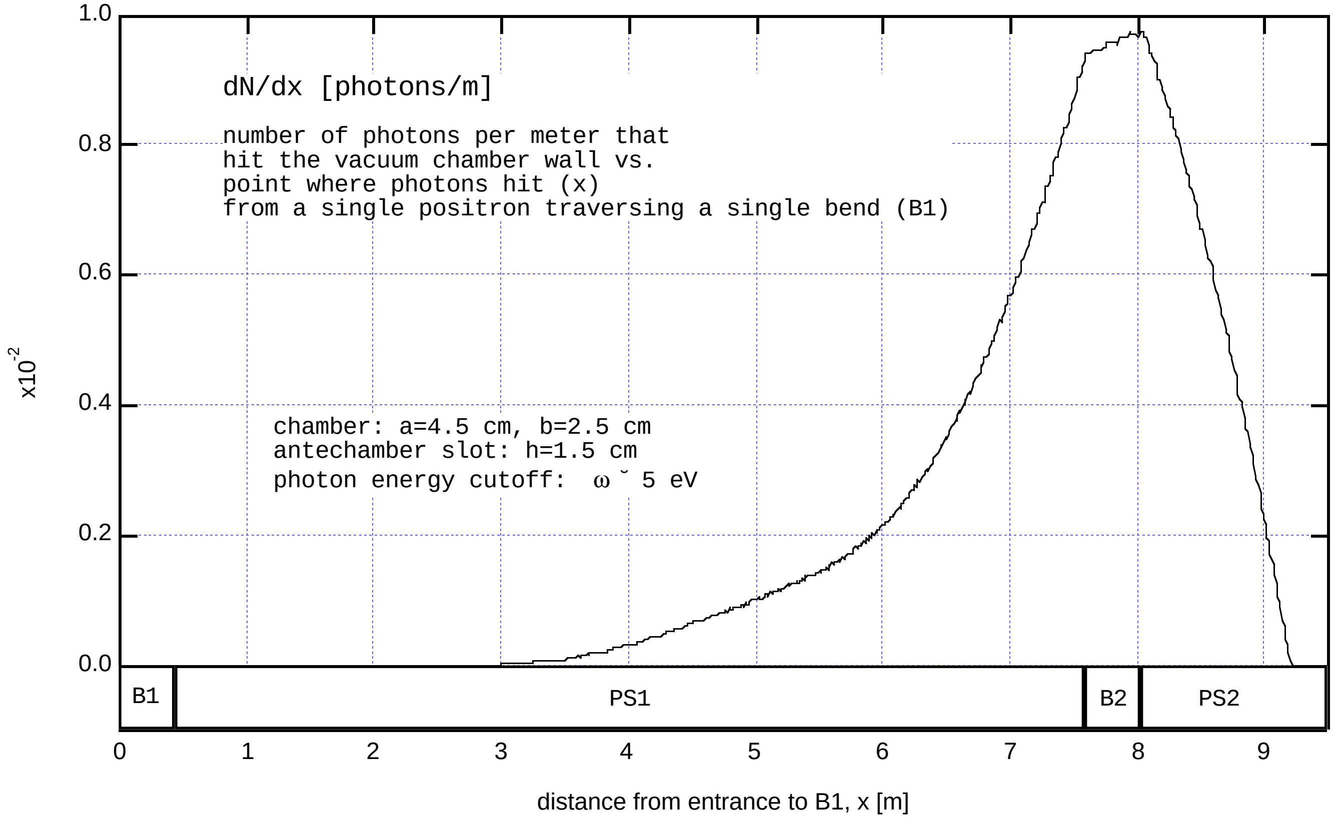


- $\bar{\delta} < 1$ in the dipole bending magnets
  - **equilibrium reached at an average density ~3.1x10^5 e/cc**
  - **~1/40 of beam neutralization level**
  - **can safely neglect space-charge**
- contribution from the bends to the growth rate estimate: $\tau^{-1} \sim 38\ s^{-1}$
- If *R*=0, $\tau^{-1} \sim 1.5\ s^{-1}$, even for residual gas at pressures ~150x nominal
  - **negligible because electrons trapped in a narrow region far way from the beam**

Photon spectrum



Photon geometry



Conclusions and comments

- present indications: growth rate ~1 ms^{-1}
  - — **will be controlled by the feedback system**
  - — **growth rate dominated by the pumping sections (much longer than dipoles)**
  - — **secondary emission is under control thanks to TiN coating**
- if chambers are uncoated, then:
  - — **δ_{max}~2; there is a chain reaction**
  - — **electron density grows until the beam is approximately neutralized on average (av. density ~1.3x10^7 e/cc)**
  - — **electron cloud is space-charge limited; detailed calculations much more computationally-expensive**
  - — **rough estimates: growth rates ~20-40 times larger than those above for TiN-coated surface**
- remaining issues: lots...
  - — **what is the actual photon reflectivity? (so far assumed *R* ~1 or *R*=0)**
  - — **what is the actual photoelectric yield? (so far assumed *Y*= 1 (yield per *penetrated* photon, not per *incident* photon))**
  - — **measure (and incorporate in the simulation) the angular dependence of the SEY**
  - — **if I_{beam} is high enough (higher than nominal), there is also a chain reaction; where is the edge?**

— **evaluate contribution from other magnets (quads, ...) and other regions of the ring (IR, ...)**
— **if coated chambers are accidentally exposed to air, the SEY becomes larger; how big a problem is it?**
— **study further numerical convergence issues (no. of macroparticles, space-charge grid size, time step,...)**
— **are higher-order modes excited?**
— **calibrate simulation against controlled experiment!**

Ion Effects
in the
SLC Electron Damping Ring

P. Krejcik,
D. Pritzkau, T. Raubenheimer,
M. Ross, F. Zimmermann,

SLAC.

Vacuum Conditions

An accidental failure of a kicker ceramic vacuum chamber resulted in us operating for several months with a contaminated vacuum system at pressures around $5 \bullet 10^{-7}$ Torr.

Beam Behavior

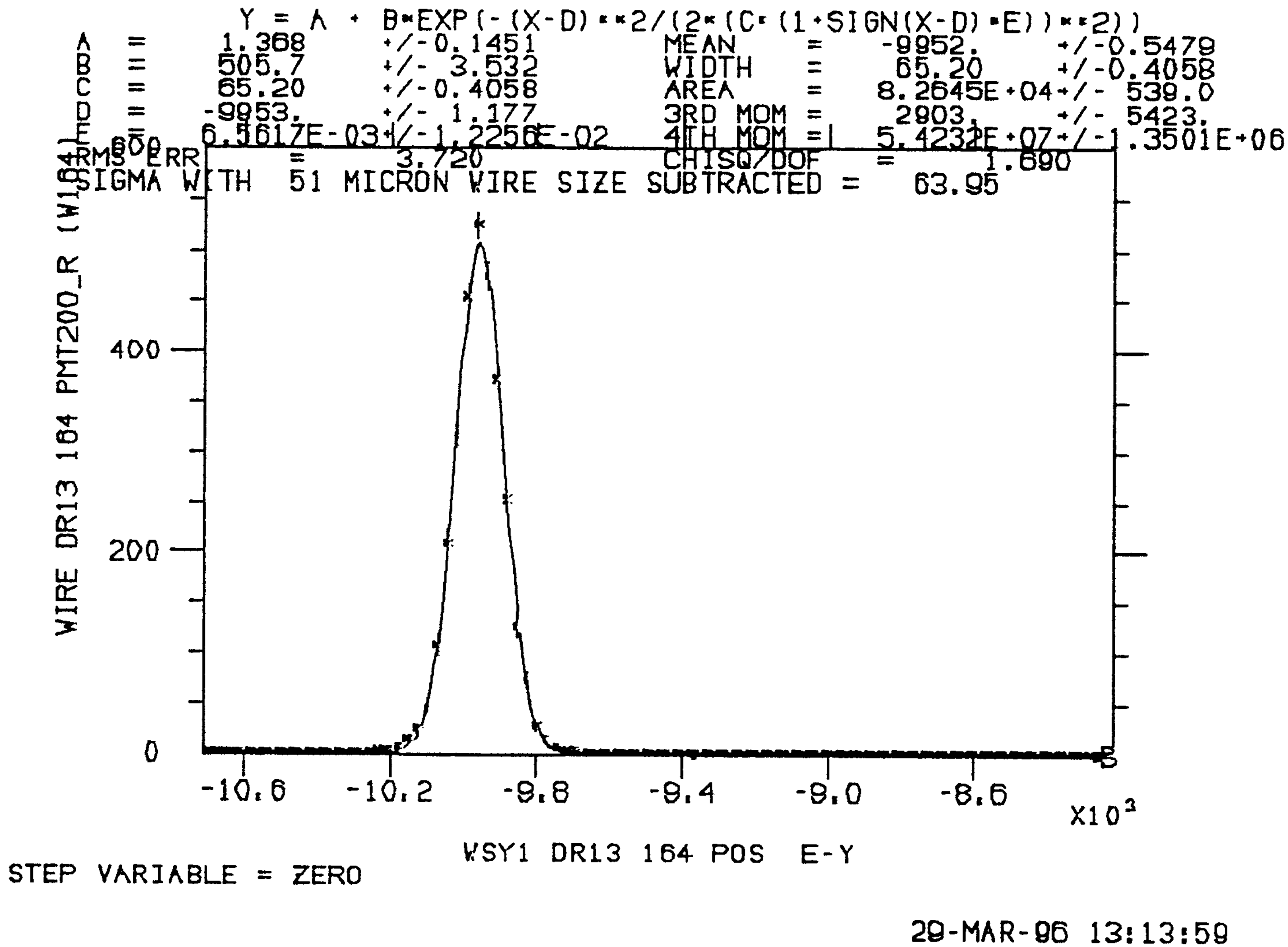
Large emittance growth and large pulse-to-pulse variations in beam size at extraction.

Variation in behavior associated with different outgassing rates changing with machine repetition rate and average beam current.

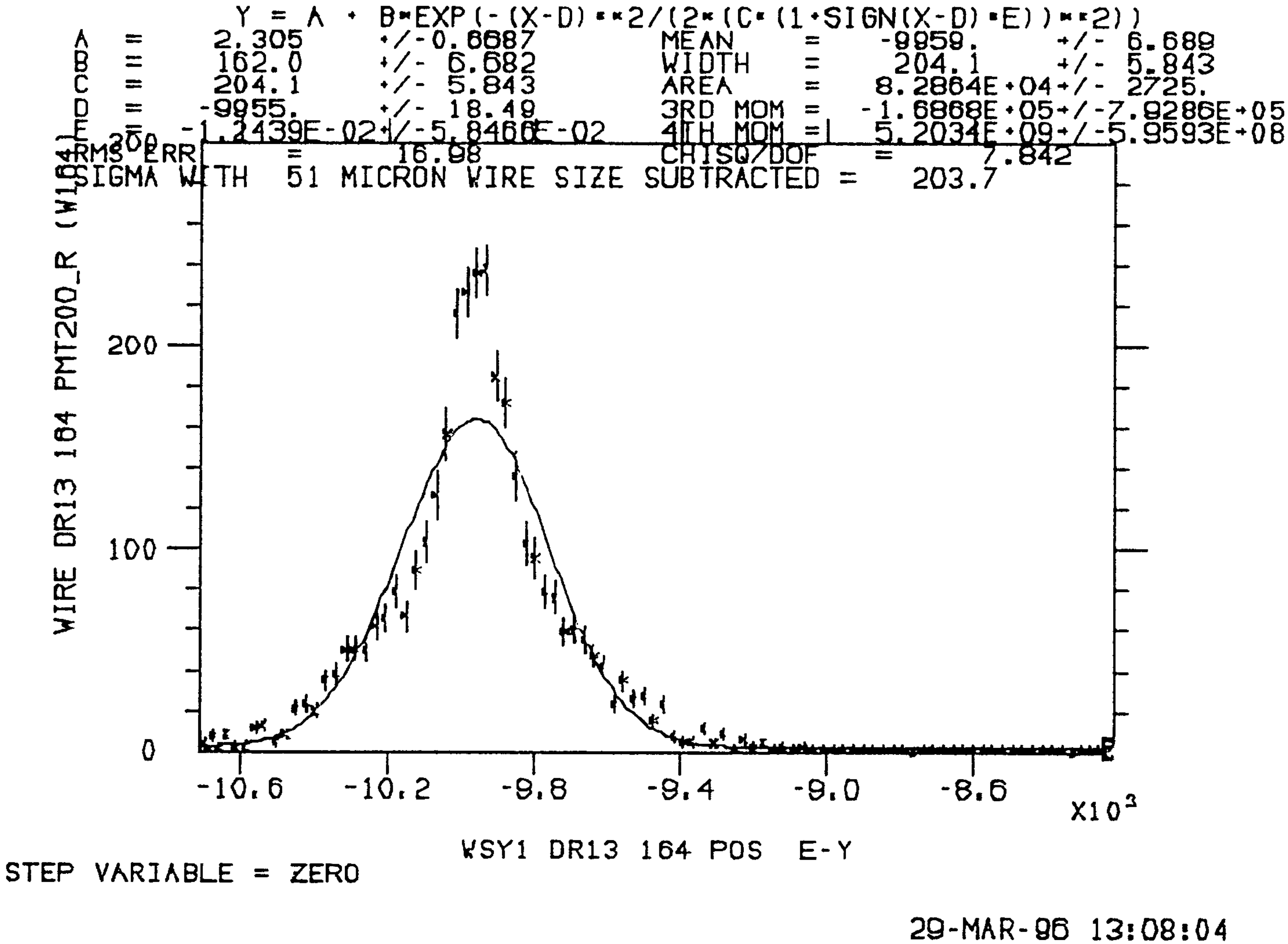
Vertical Emittance Growth

Growth due to instability only occurs with two bunches in the ring.

Observe the increase vertical profile monitor spot size and an increased, non-gaussian vertical wire scanner profile.



Single Bunch Vertical Beam Profile



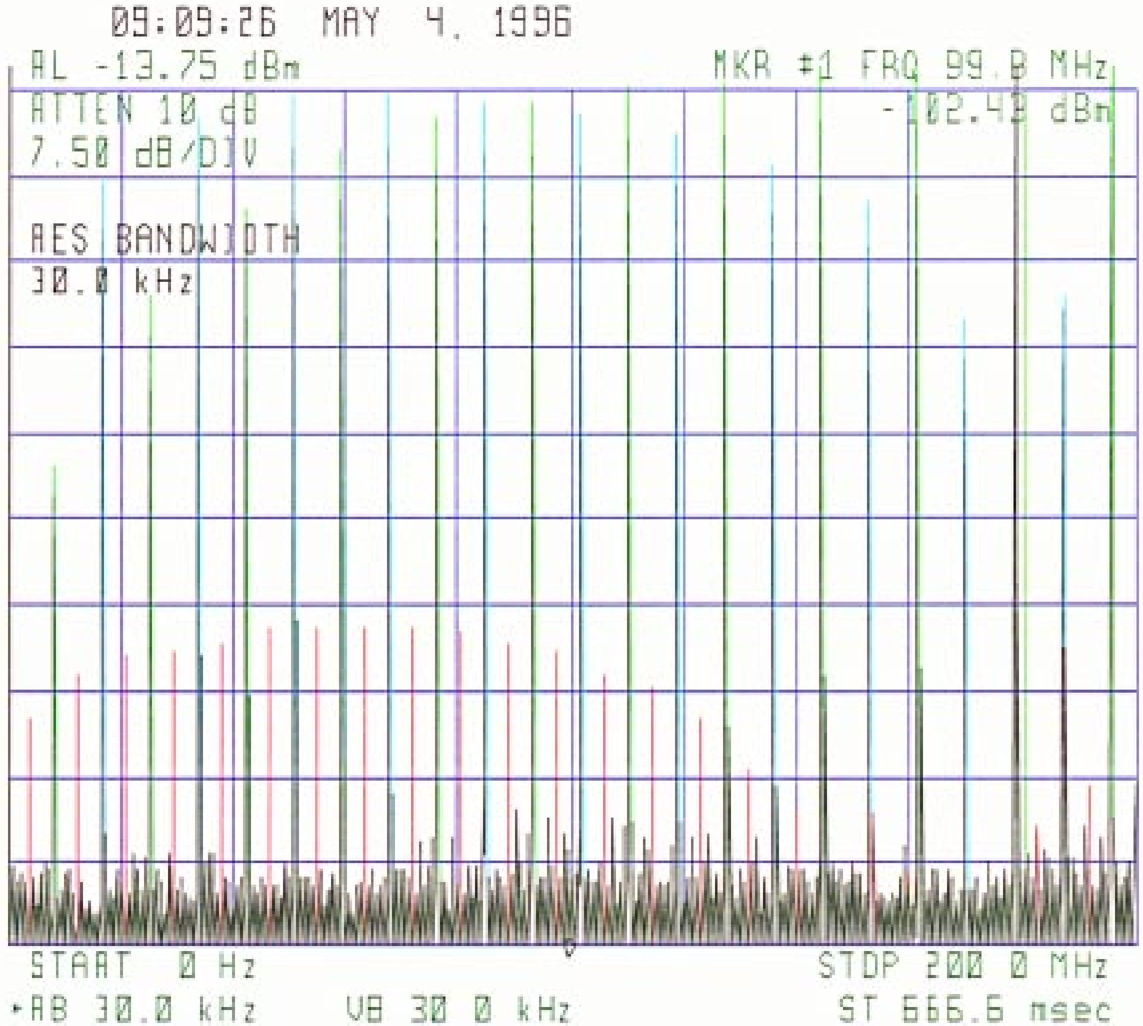
Two Bunch Vertical Beam Profile

Bunch Spectrum

Stored beam, 2 bunches.

Instability excites vertical betatron sidebands.

Betatron sidebands are generated over a broad range of frequencies.



Spectrum from 2 Bunches of 4E10 electrons each bunch
odd revolution harmonics (green)
even revolution harmonics (blue)
betatron sidebands (red) - self excited from the instability

Ionization rate

$$\dot{\lambda} \approx 4 \times 10^{11} m^{-1} s^{-1} \frac{p}{100 nTorr}$$

Critical mass

$$A_{crit} = \frac{N_{ot} C r_p Q}{n_b^2 2\sigma_y \left(\sigma_x + \sigma_y\right)}$$

Tune shift

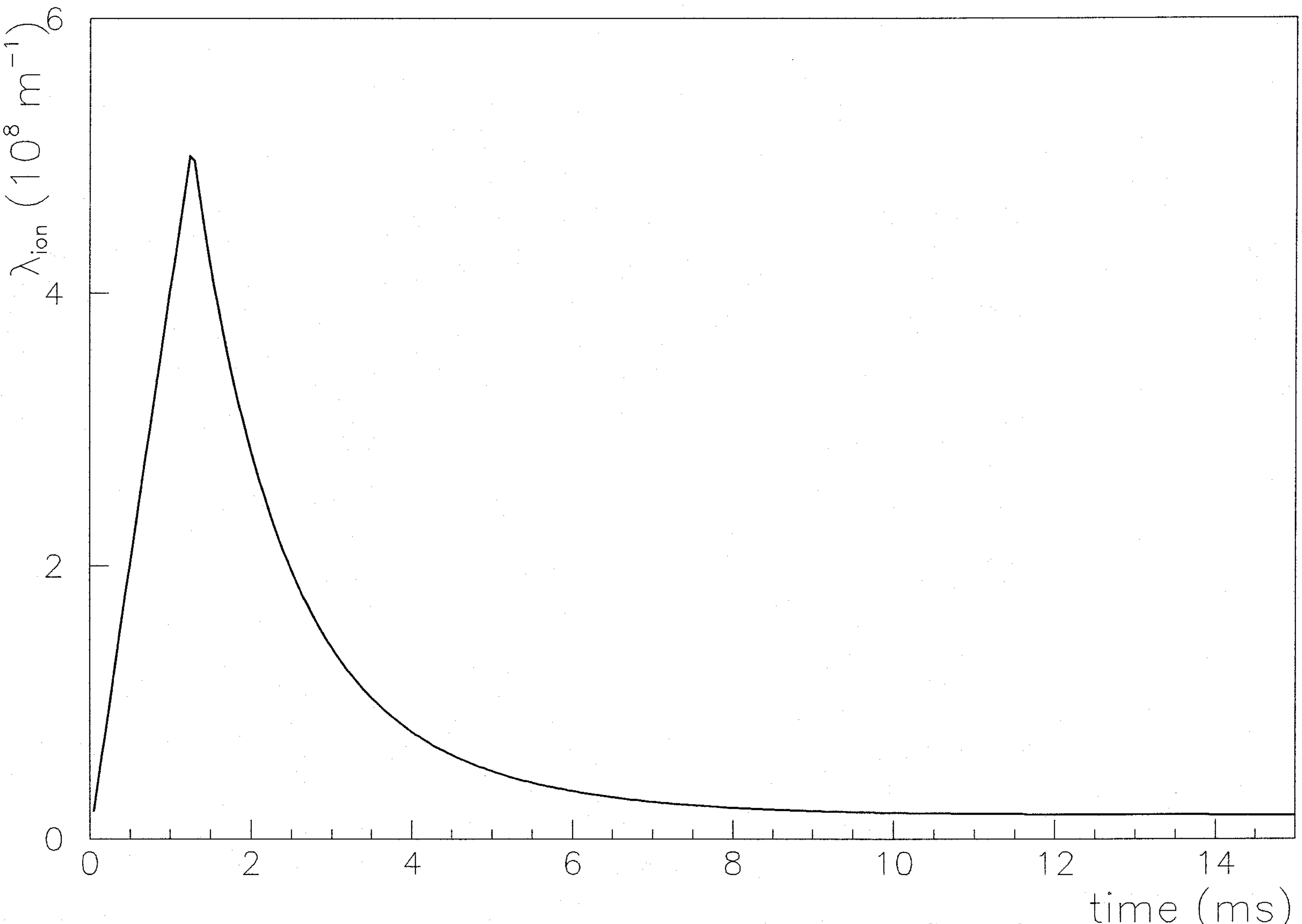
$$\Delta\nu_{x,y} = \frac{r_e \beta_{x,y} \lambda_{ion} C Q}{\gamma 2\pi \sigma_{x,y} \left(\sigma_x + \sigma_y\right)}$$

Ion frequencies

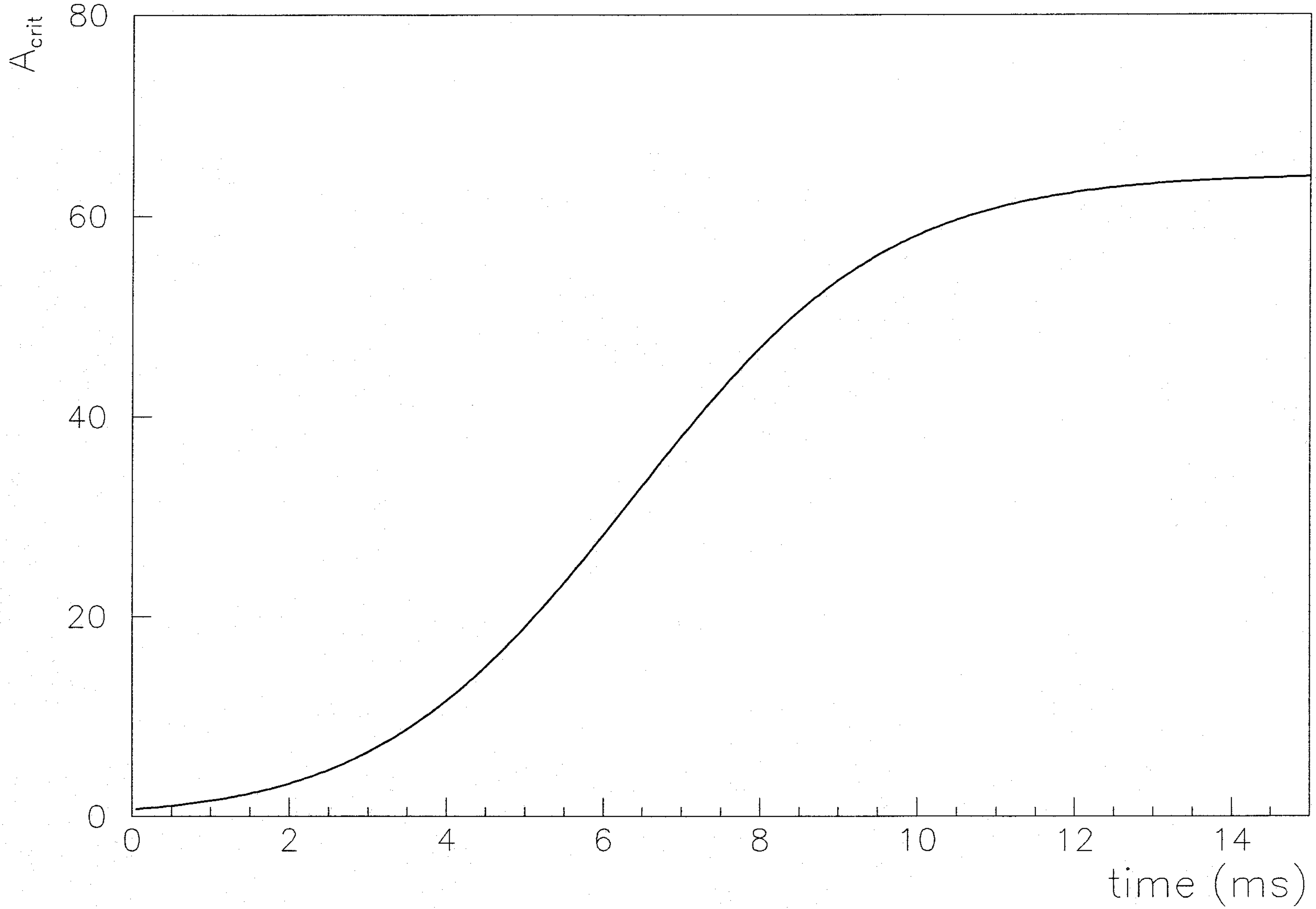
$$f_{x,y} = \frac{c}{2\pi} \left(\frac{N_{tot} 2 r_p \nu}{C \sigma_{x,y} \left(\sigma_x + \sigma_y\right) A} \right)^{1/2}$$

Coherent instabilities

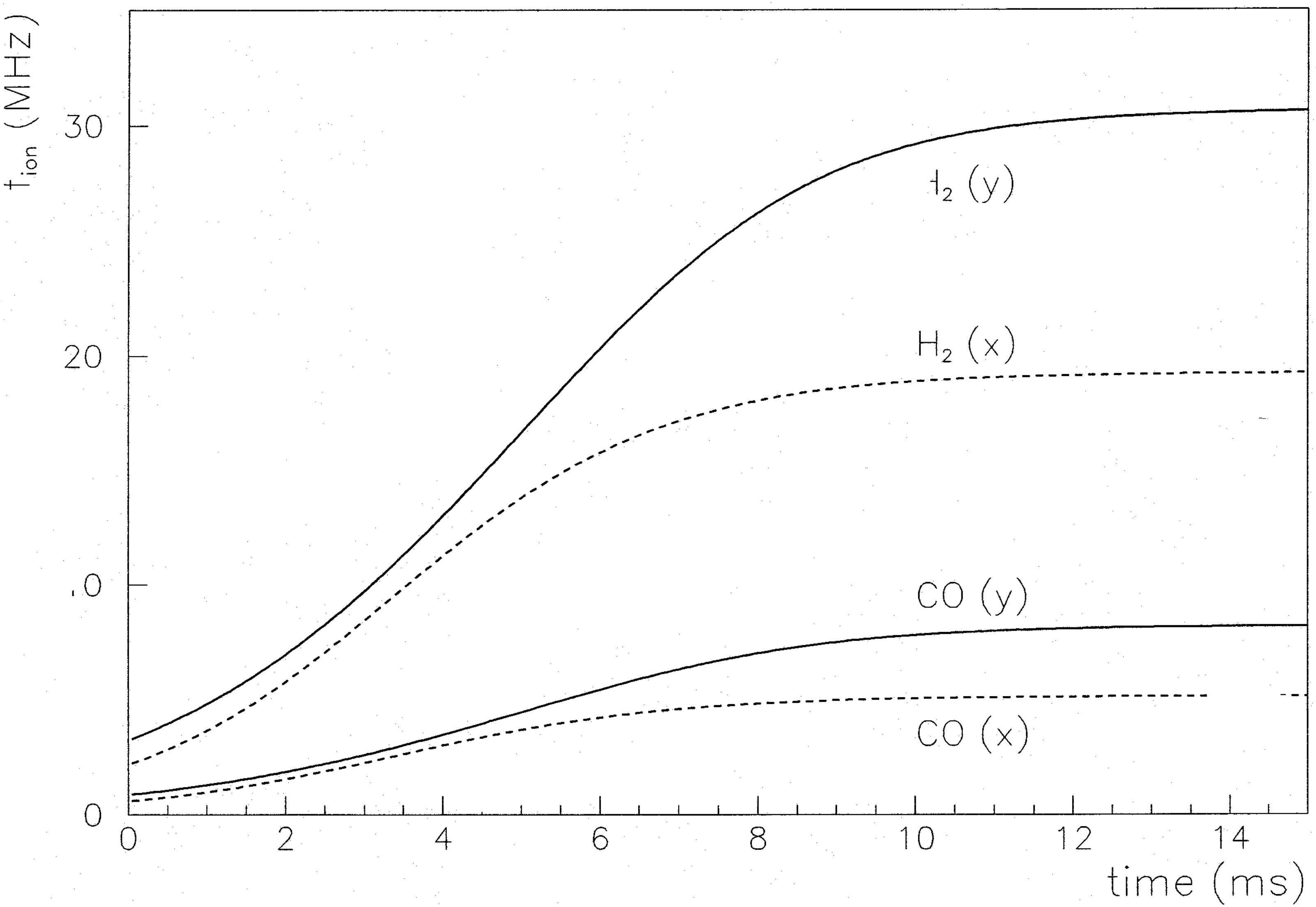
$$\delta\nu_y \delta\nu_{ion} \geq \left| \frac{\nu_c^2 q}{\nu_y} \right|$$



Predicted Ion Line Density (10^8 m^{-1})
as a function of store time [mS].



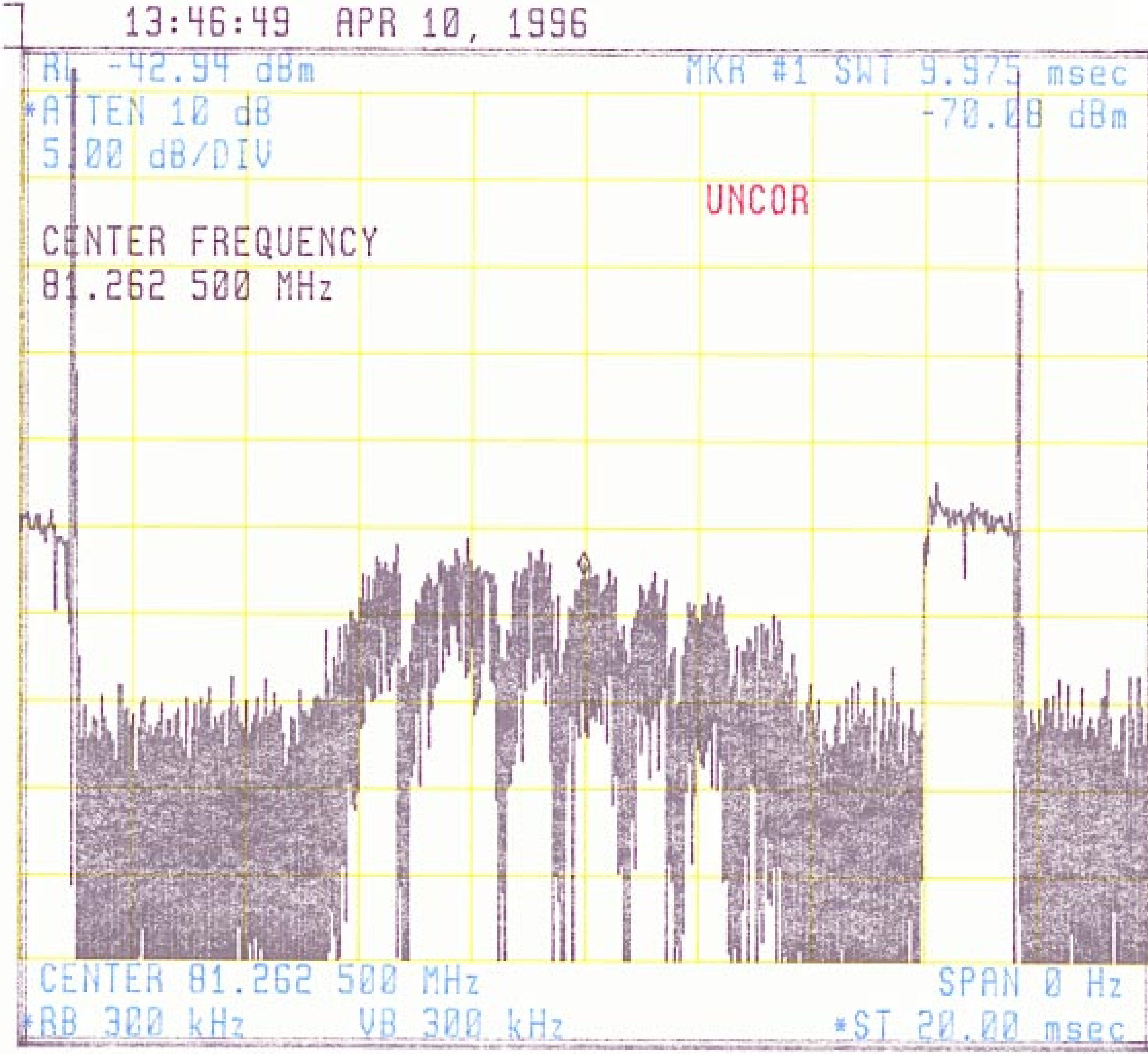
Critical ion mass (in a.m.u.)
as a function of elapsed time after injection.
Ions with $A > A_{crit}$ are trapped by the beam.



Predicted ion oscillation frequency as a function of elapsed time after injection, for carbon monoxide (A=28) and hydrogen(A=2) ions.

Instability evident in the time-evolution of the amplitude of the vertical betatron lower sideband at $10\, f_o - \nu_y$.

The tall peak corresponds to injection, the irregular bursts correspond to the instability.


13:46:49 APR 10, 1996
RL -42.94 dBm
*ATTEN 10 dB
5.00 dB/DIV
MKR #1 SWT 9.975 msec
-70.08 dBm
UNCOR
CENTER FREQUENCY
81.262 500 MHz
CENTER 81.262 500 MHz
SPAN 0 Hz
*RB 300 kHz
VB 300 kHz
*ST 20.00 msec

Experimental Observations

Most significant effect is the difference between 1 and 2 bunch response.

The 2 bunch data does not show any traits of a simple oscillator model.

Also studied:

- Intensity dependence.
- The mode response at odd and even revolution harmonics to distinguish 0 and pi modes.
- Comparison between vertical and horizontal response of the beam.
- The positron damping ring where ion trapping does not occur.

The ion instability described in the companion paper shows strong evidence for being a multi bunch effect only:

- does not occur with single bunch operation
- signature betatron lines in the bunch spectrum only present with 2 bunches, even at low intensity

Goal:

- develop measurement techniques
- and analysis techniques

to study the coupling process.

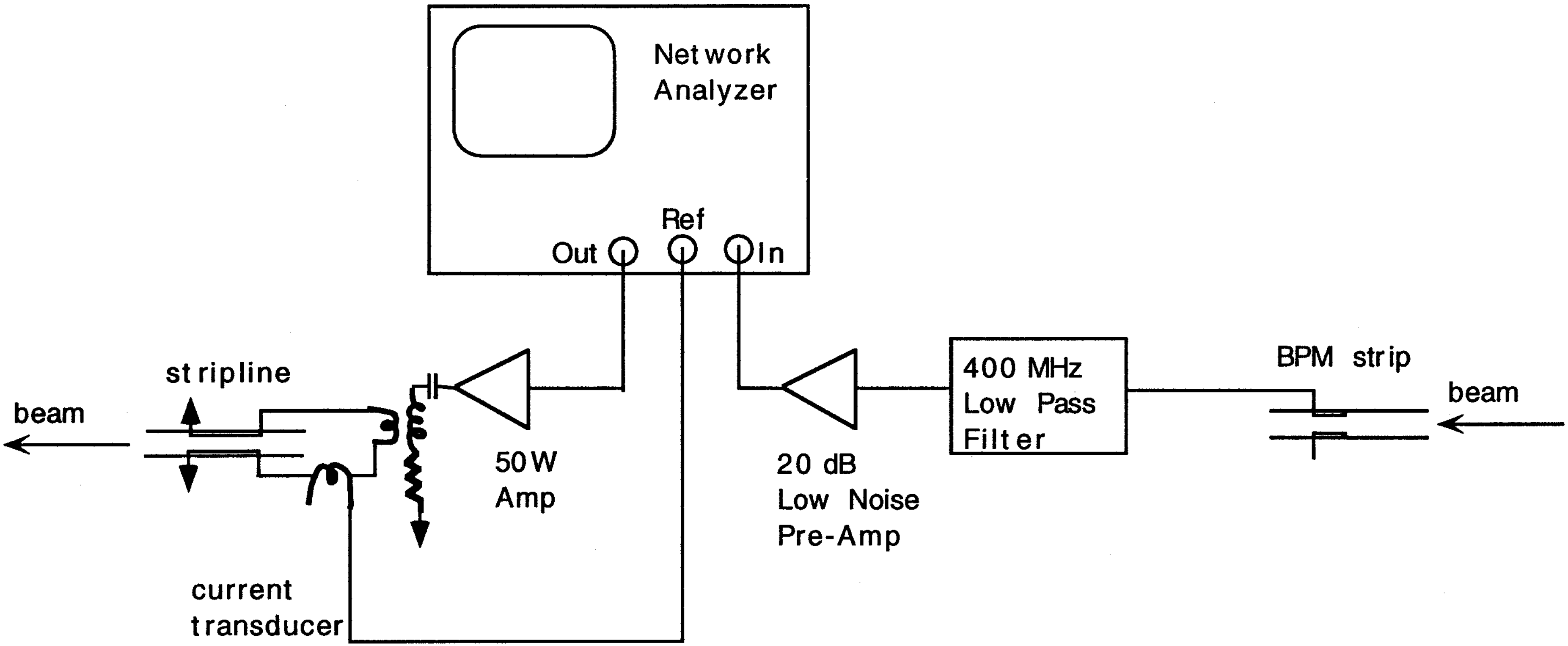
Measurement technique

Network analyzer drives amplifier to stripline kicker to excite transverse modes in the beam.

Beam response is measured at a beam position monitoring stripline.

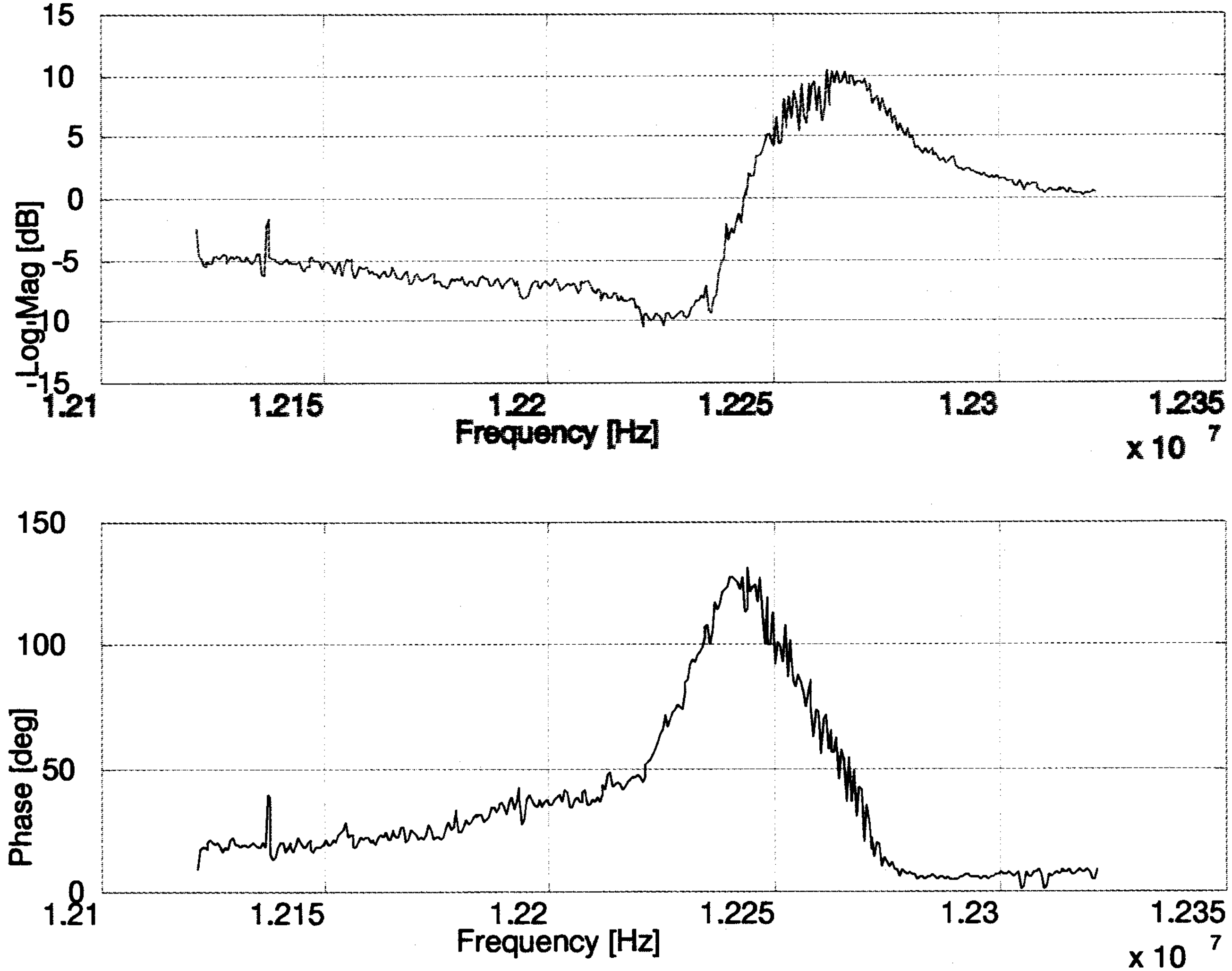
Low pass filter removes power at higher revolution harmonics.

Response of the beam is analyzed as a function of frequency.

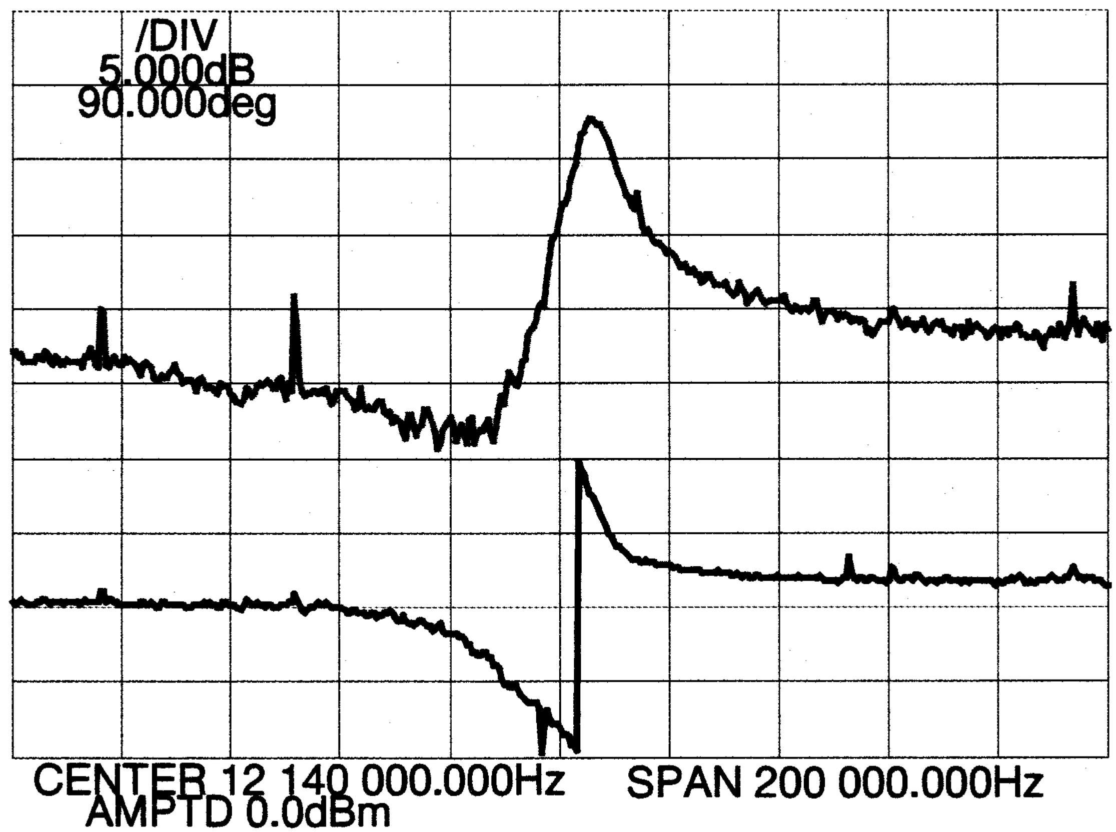


$$\text{Beam Transfer Function} = \frac{\text{Signal "In"}}{\text{Signal "Ref"}}$$

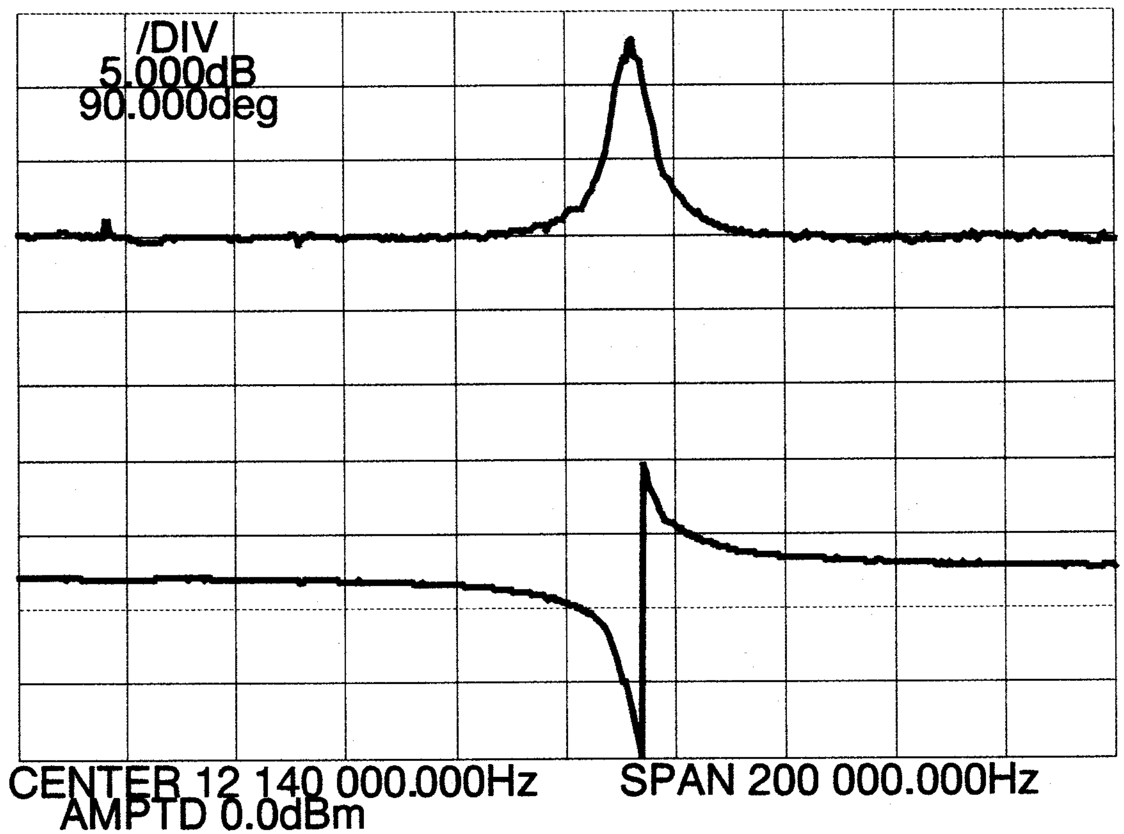
Two Bunch Magnitude Phase Response at $f_0+\nu_y$ for 8 10^{10} electrons



OneBunch Magnitude Phase Response at $f_0+\nu_y$ for 4 10^{10} electrons



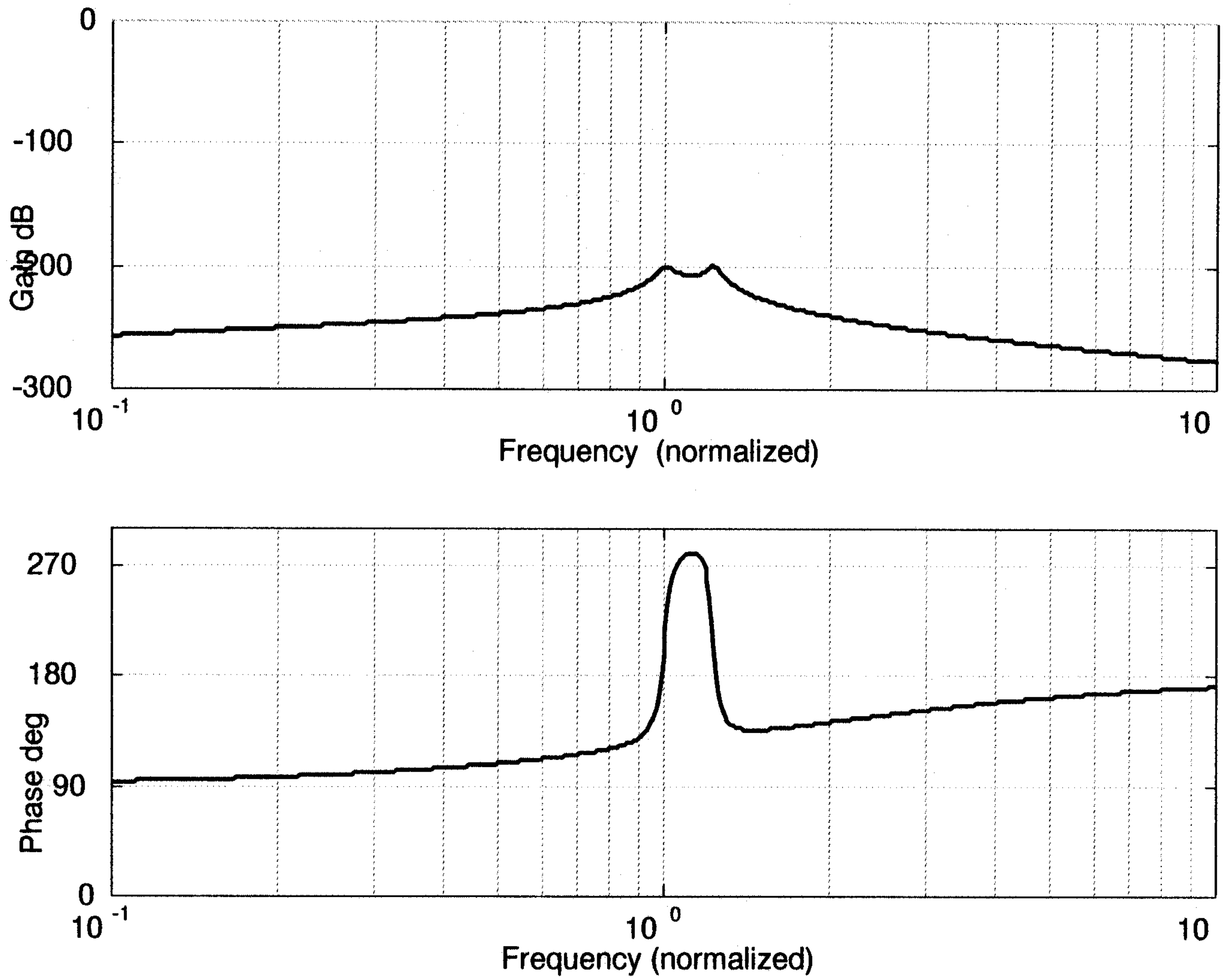
OneBunch Magnitude Phase Response at $f_0+\nu_y$ for 1 10^{10} electrons



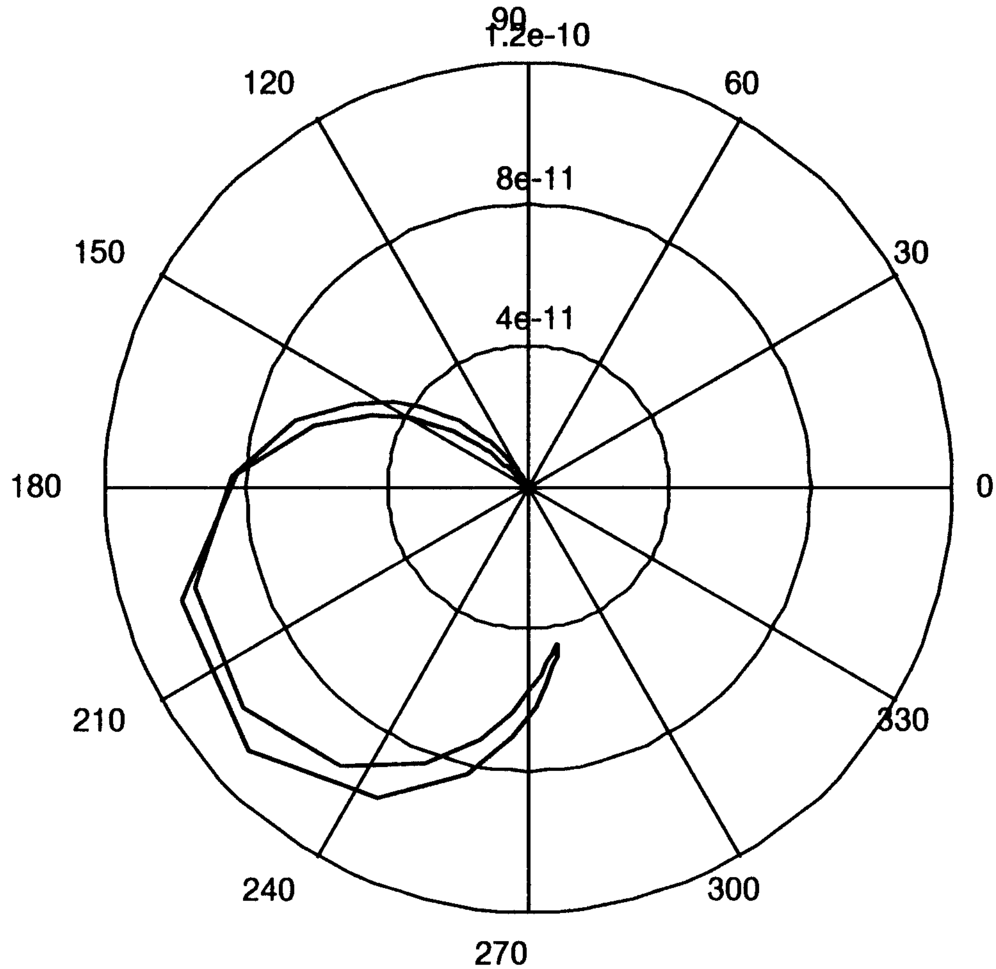
Modeling studies

The ion cloud, in addition to causing a tune shift through focusing, can oscillate in a transverse dipole mode about the electron bunch.
These dipole modes can couple to the other bunch.

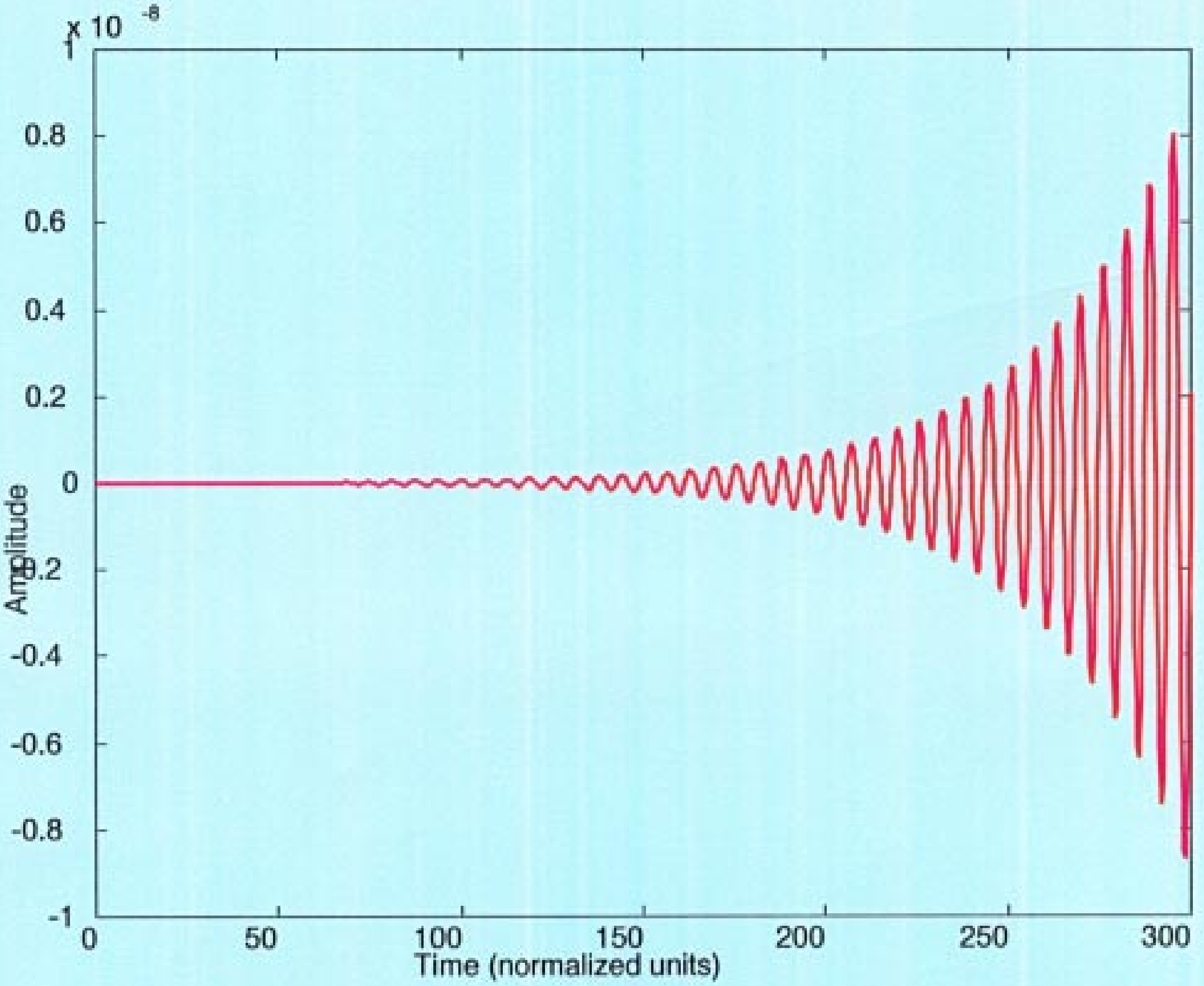
The frequency response of a damped coupled oscillator system is compared to the observed beam response.



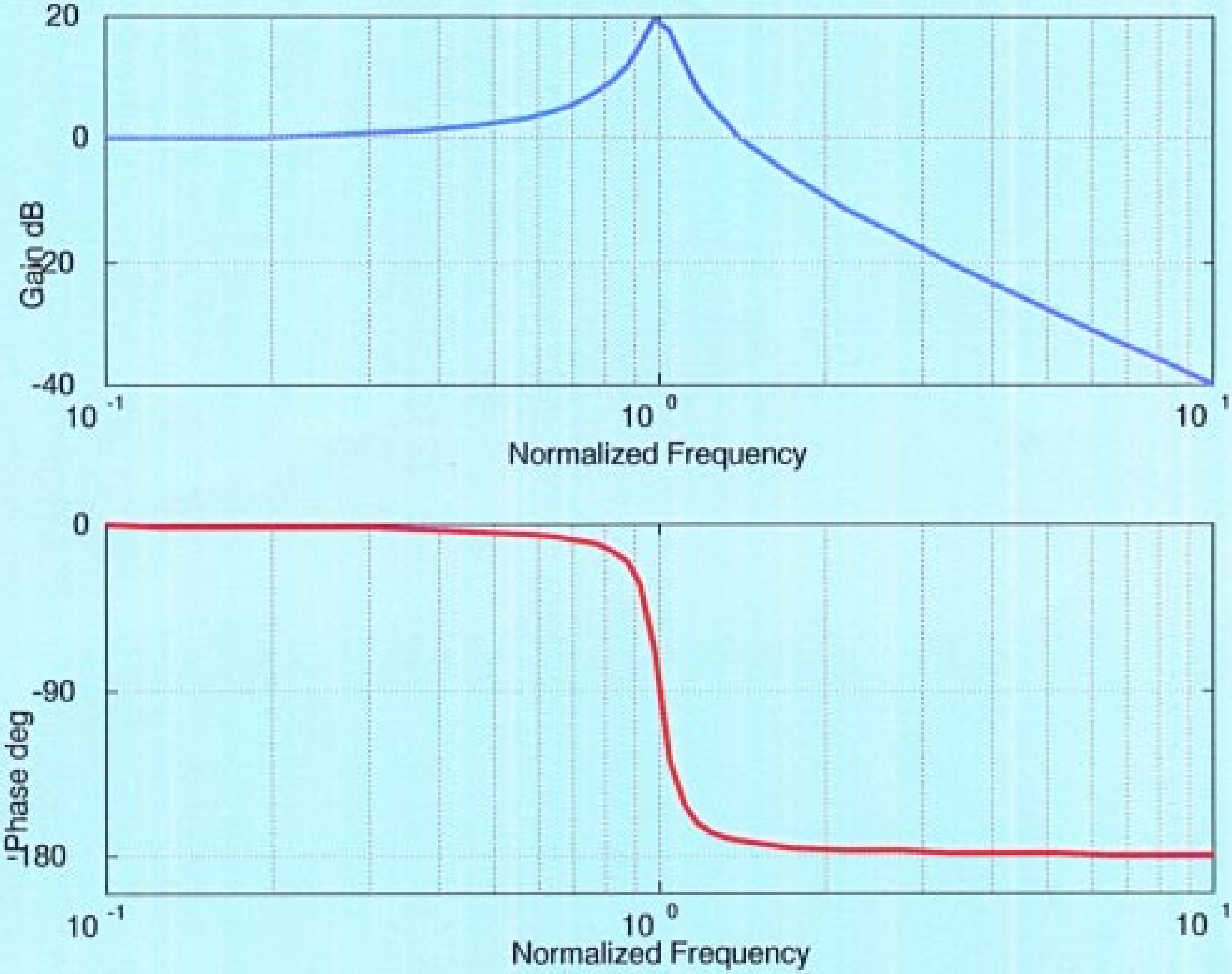
Phase and amplitude frequency response of the 4th order coupled oscillator model



Polar plot of phase and amplitude response of
the 4th order coupled oscillator model



Impulse response of
the 4th order coupled oscillator model



Frequency response of a second-order system
a single, damped oscillator

Damped coupled oscillators

$$\ddot{\phi}_1 + (\zeta + \zeta_c)\dot{\phi}_1 + \left(\omega_n^2 + \omega_c^2\right)\phi_1 + \omega_c^2\phi_2 + \zeta_c\dot{\phi}_2 = 0$$

$$\ddot{\phi}_2 + (\zeta + \zeta_c)\dot{\phi}_2 + \left(\omega_n^2 + \omega_c^2\right)\phi_2 + \omega_c^2\phi_1 + \zeta_c\dot{\phi}_1 = 0$$

A single damped oscillator is a second order system, described by a transfer function

$$G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

where ζ is the damping ratio and ω_n is the natural frequency.

Coupled oscillators can also be analyzed as two successive transfer functions:

$$G(s) \times G_c(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \times \frac{\omega_c^2}{s^2 + 2\zeta_c\omega_c s + \omega_c^2}$$

which leads straight forwardly to the 4th-order transfer function for the coupled oscillators.

Summary

- Poor vacuum resulted in significant ion trapping.
- Large emittance growth associated with transverse instability.
- We did not expect the small transverse beam size to be able to trap ions. Ions are probably trapped at injection when beam is large.
- The beam blowup only occured with 2 bunches in the ring, not with single bunches.
- A clearing mechanism for the ions occurs when the tune is just below 1/2 integer.