The Fast Beam-Ion Instability and Measurements at the ALS

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SLAC

- Fast Beam-Ion Instability
- Simulation Code
- Results from ALS

References:

T. Raubenheimer, F. Zimmermann, Phys. Rev. E, **52:** 5487 (1995)
G. Stupakov, T. Raubenheimer, F. Zimmermann, Phys. Rev. E, **52:** 5499 (1995)
J. Byrd, *et al.*, Phys. Rev. Let., **79:** 79 (1996)
M. Kwon, *et al.*, Phys. Rev. E, **57:** 6016 (1998)
J. Huang, *et al.*, Phys. Rev. Let., **81:** 4388 (1998)
D. Pestrikov, Phys. Rev. ST-AB, **2:** 044403 (1999)
G. Stupakov, Phys. Rev. ST-AB, **3:** 019401 (2000)

Introduction

- "Standard" ion effects arise when ions are trapped in the potential well of the beam.

- Ions accumulate until stabilized by neutralization, second ionization, ...

- The normal cures are the introduction of a gap in the bunch train to make the ion motion unstable and beam shaking which drives the ions resonantly to large amplitudes.

- BUT, in high current rings (or linacs) with long bunch trains and small emittances, ions accumulated during a single passage of the beam can generate an instability.

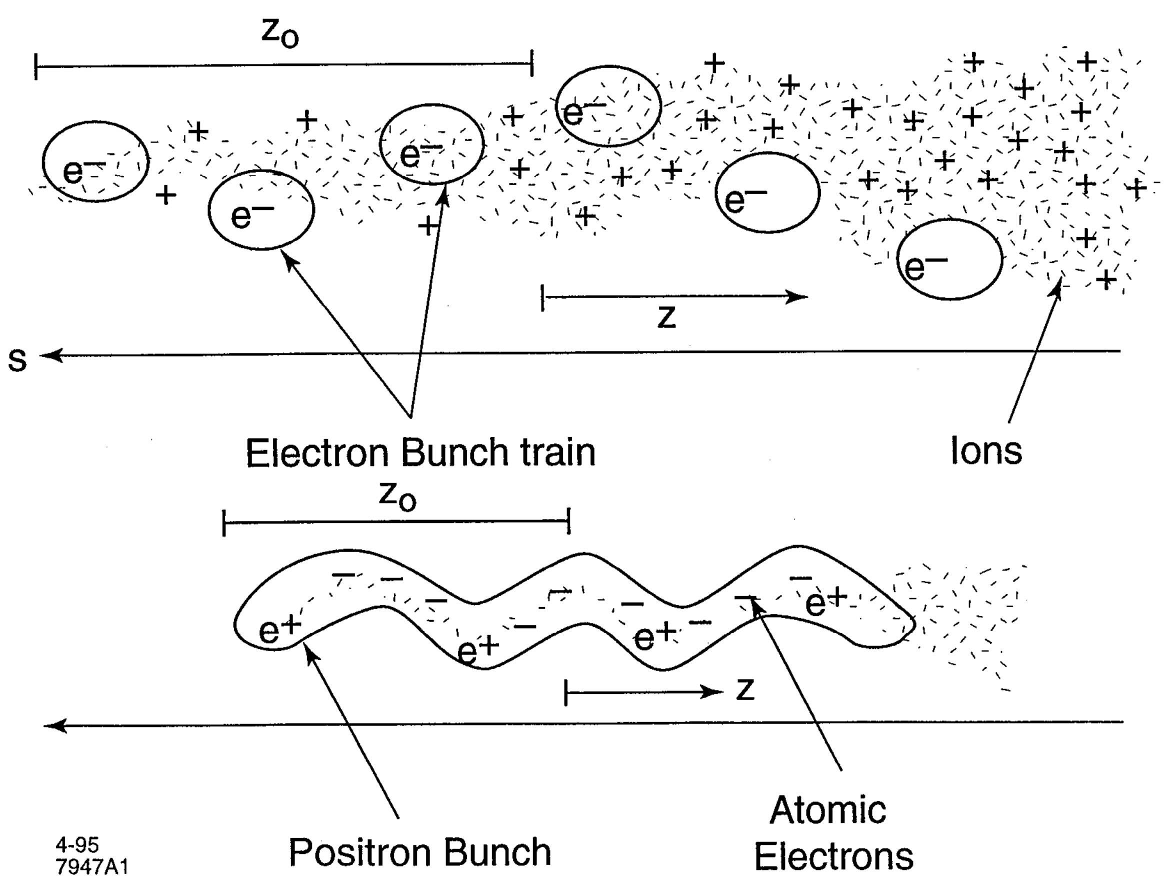
- The instability is like beam-breakup in a linac rather than a storage ring coupled-bunch instability

- Trapping between passages of the bunch train is not required.

Introduction

- Trapped particles oscillate within the beam modulating the beam at the oscillation frequency $\Rightarrow$ quasi-exponential growth — can occur in ring or linac/transport line.

- Can arise with either electrons trapped in a positron bunch or ions trapped in an electron beam or electrons trapped in a proton beam.



Fast Beam-Ion Instability

Simple linear theory for dipole oscillations – two coupled equations

$$\frac{d^2 y_b(s,z)}{ds^2} + \omega_\beta^2 y_b(s,z) = K[y_i(s,s+z) - y_b(s,z)] \int_{-\infty}^{z} \rho dz'$$

$$\frac{d^2 \tilde{y}_i(s,t)}{dt^2} + \omega_i^2(z)[\tilde{y}_i(s,t) - y_b(s,z)] = 0$$

$$y_i(s,t) = \frac{\int_{-\infty}^{z} dz' \rho \tilde{y}_i(s,t)}{\int_{-\infty}^{z} dz' \rho}$$

$$K \equiv \frac{2\lambda_{ion} e_e}{\gamma \Sigma_y (\Sigma_x + \Sigma_y)} \qquad \omega_i(z) \equiv \sqrt{\frac{2 N_b r_p}{L_{sep} A \Sigma_y (\Sigma_x + \Sigma_y)}}$$

- Ions generated in the beam by collisional ionization
- Assume that trapped particles are stable in train and have small initial velocities

$$y_b \sim \frac{y_0 e^{\sqrt{t/\tau_c}}}{(t/\tau_c)^{1/4}} \qquad \frac{1}{\tau_c} \approx \frac{n_{gas} \sigma_i r_p^{1/2}}{A^{1/2}} \frac{N_b^{3/2} n_b^2 r_e L_{sep}^{1/2} c}{\gamma \sigma_y^{3/2} (\sigma_x + \sigma_y)^{3/2}}$$

Fast Beam-Ion Instability

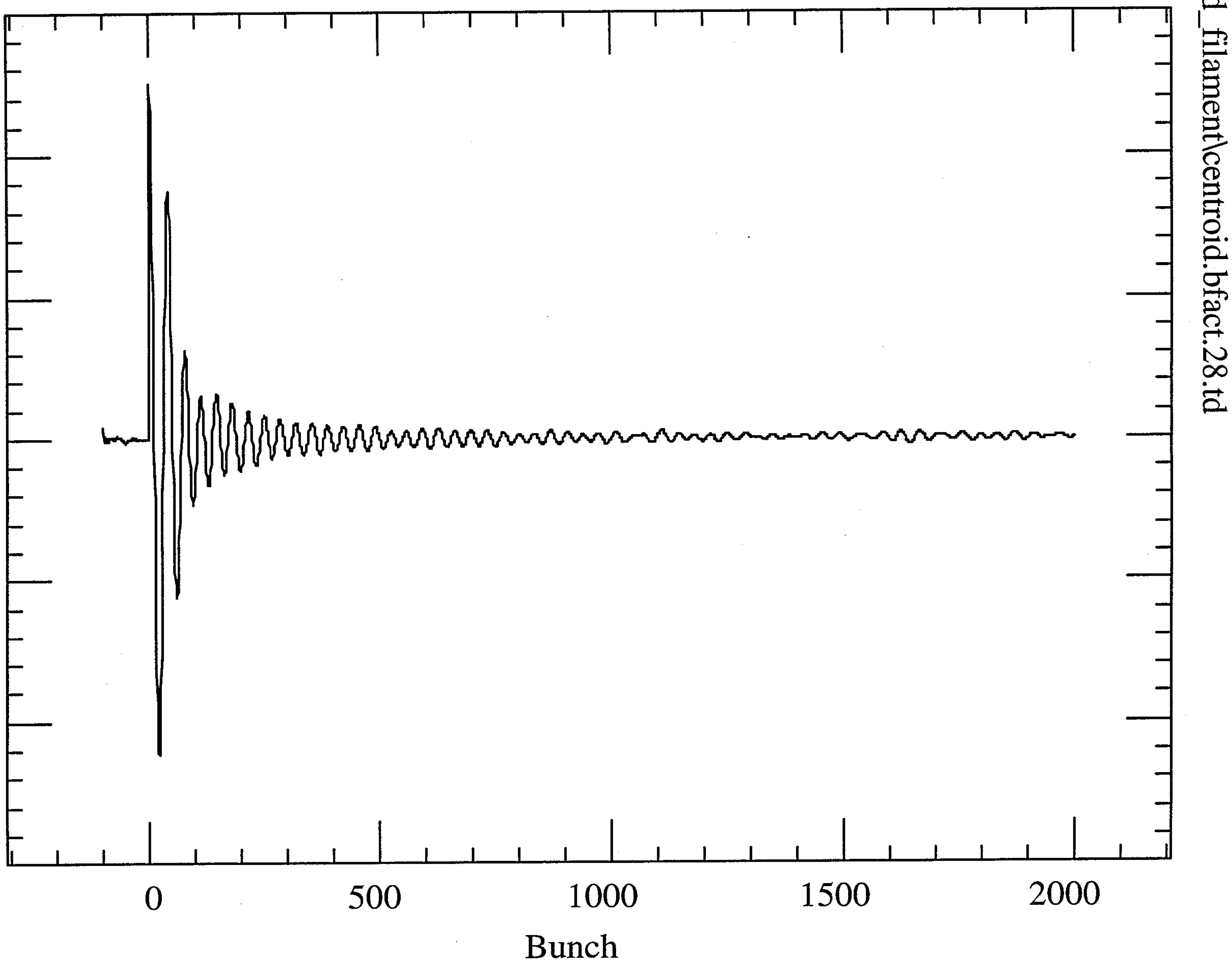
Linear model does not include:

- Beam-ion non-linearity:
  - Growth saturates at $\hat{y} \sim \sigma_y \quad \Rightarrow \quad$ filamentation and slower growth
  - Decoherence of ion oscillations – $F_y(x) \propto e^{x^2/2\sigma_x^2}$ – slows growth rate
- Optics variation which causes ω_i to vary
- Synchrotron motion — leads to threshold
- Charged particle halo:
  - Six main processes: collisional ionization, tunneling ionization, photo-ionization, photo-electrons, field emission, and secondary electrons—the first two processes generate ions/electrons within the beam while the later effects are in the vacuum or at the walls and generate a halo

Ion decoherence and lattice variation can be approximated:

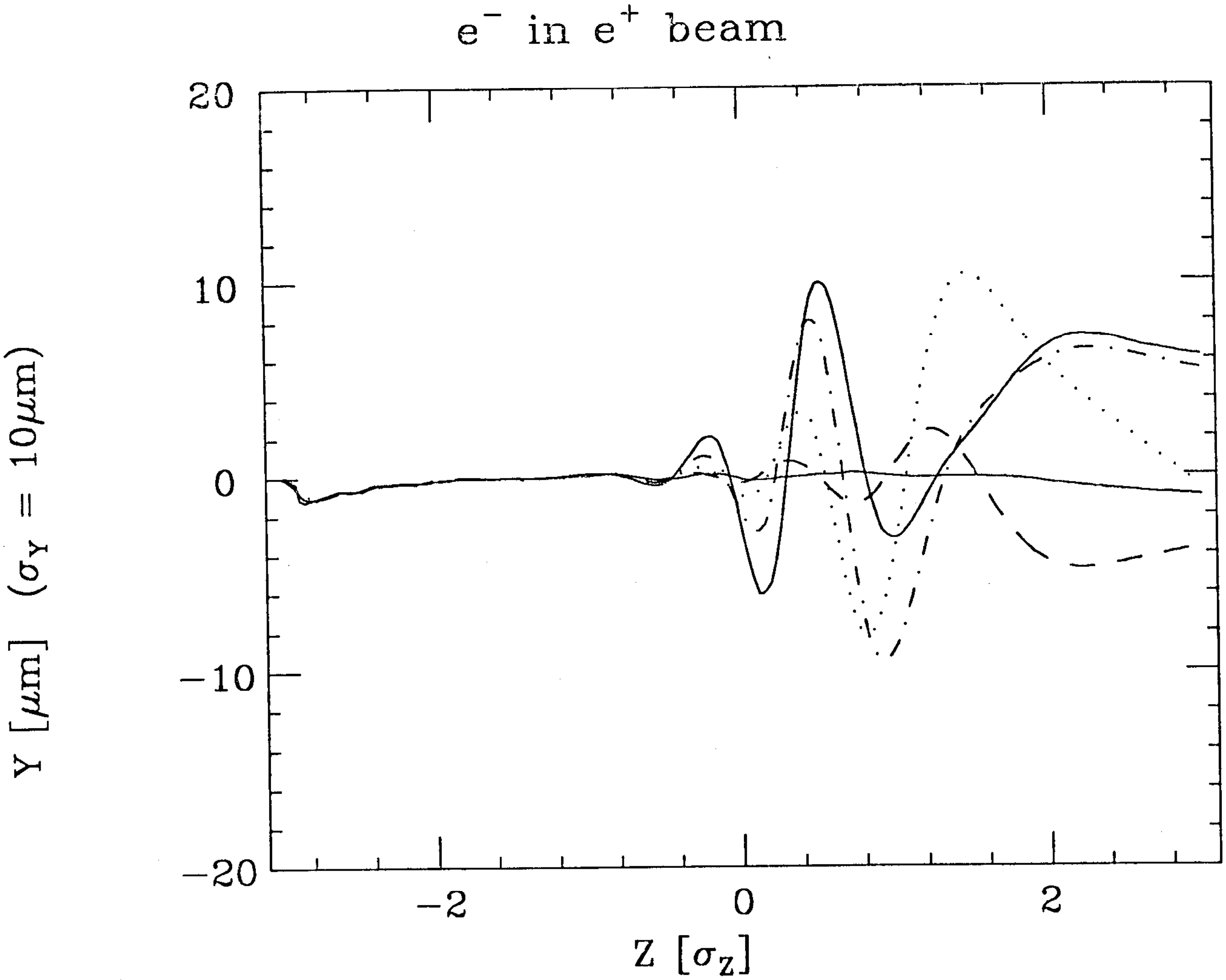
$$y_b \sim y_0 e^{t/\tau_e} \qquad\qquad \frac{1}{\tau_e} \approx \frac{1}{\tau_c} \frac{c}{2\sqrt{2} n_b L_{sep} (\Delta\omega_i)_{rms}}$$

Y_ave in B-fact for Y0 = 0.5 sig_Y



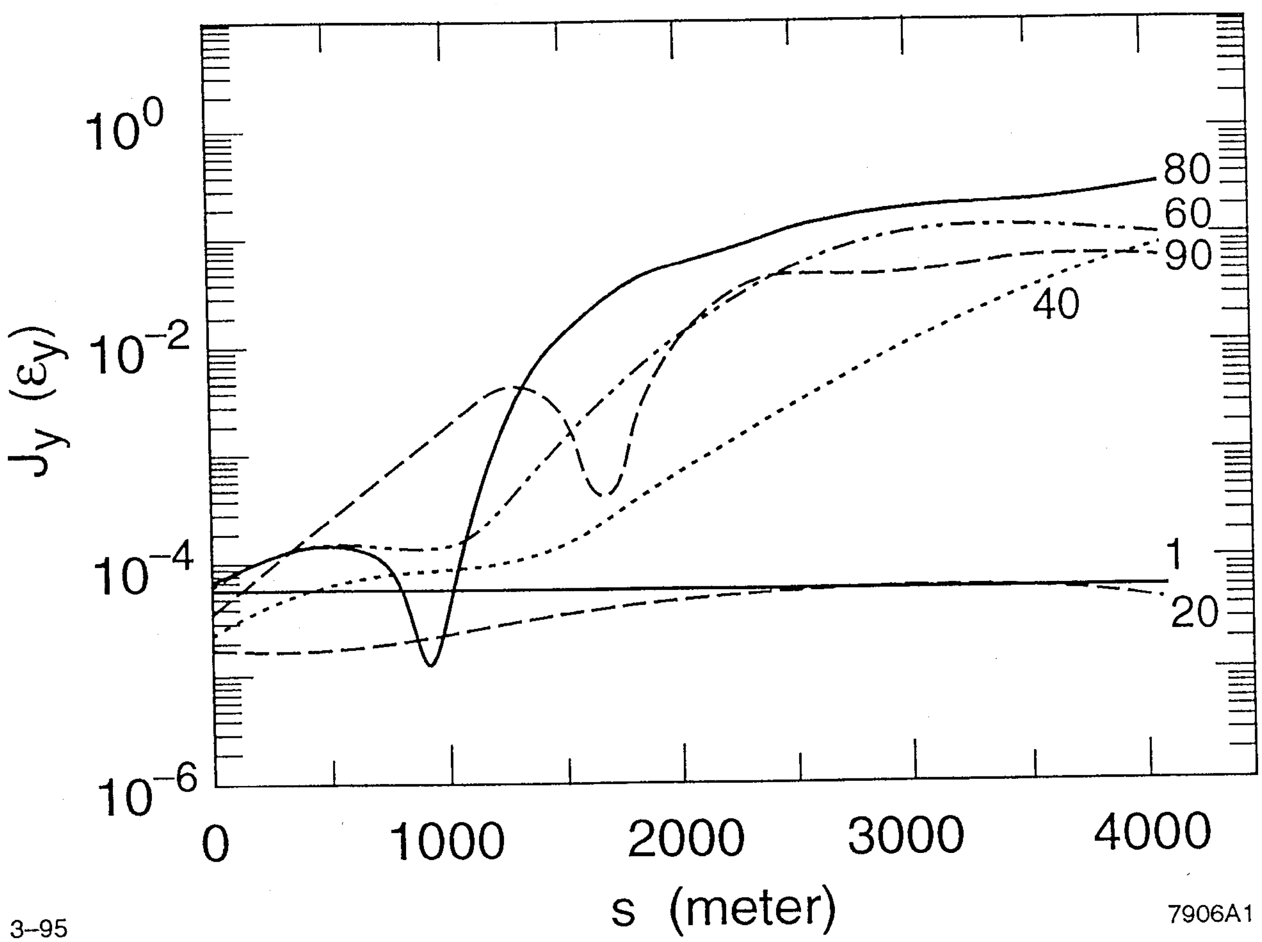
Macro-Particle Simulations

- Beam (electrons or positrons) and ions/electrons represented by macro-particles (typically 100,000 per train)
- Steps through lattice as defined by a MAD deck
- Beam is assumed Gaussian when calculating forces
- Ion/electron fields are calculated from Coulomb law or 2-D FFT
- Fields are mapped onto a grid (typically 25x25) — ions/electrons are created on grid points and allow to oscillate in fields
- Ions/electrons are generated at rest
- Non-relativistic transverse motion is assumed for ions /electrons
- Synchrotron motion can be included for the beam but there is no longitudinal motion of ions/electrons
- Ions/electrons are discarded after bunch train — no coupling from turn-to-turn
- Code is running on parallel system of 64-linked Linux boxes


e⁻ in e⁺ beam
20
10
0
−10
−20
−2
0
2
Z [σ_Z]
Y [μm] (σ_Y = 10μm)

Beam-Ion in NLC DR

- 10^{-8} torr CO gas
- Optics replaced with smooth FODO array having roughly correct beta function but without injection/ectraction and wiggler section



Expected Growth Rates

	ALS	ESRF	NLC DR	PEP-II HER	ALS Experiment
Circ. C [m]	200	844	220	2200	200
Energy E_0 [GeV]	1.5	6	2	9	1.5
N/Bunch N [10^{10}]	0.7	1.0	1.5	3.0	0.2 – 0.4
$\overline{\beta_0}$ [m]	2.5,4	4,12	2,2	25,20	2.5,4
$\gamma\epsilon_x$ [10^{-6} m-rad]	12	73	3	500	12
$\gamma\epsilon_y$ [10^{-6} m-rad]	0.2	0.7	0.03	25	0.4
Bunches n_b	320	300	90	1658	1 – 240
Bunch Sep. ΔL [m]	0.6	1	0.42	0.6	1.2
Vac. Pres. P [nTorr]	1	2	1	5	80
Ion Freq. f_i [MHz]	20	25	176	3	40
τ_c [μs]	18	0.7	0.5	2	1
τ_e [μs]	4000	300	20	74 – 740	28 – 280

- Assumed pressures are CO equivalent gas except for ALS experiment which was He — this may overestimate the growth rates

Experimental Observations

- FBII has been seen at the ALS, KEK AR, PLS, and KEK-B
- All experiments increased vacuum pressure to observe instability
- Similar effect has been in high current induction linac studies
- Something also seen in PSR with trapped electrons in proton beam

ALS Ion Experiments

J. Byrd, A. Chao, S. Heifets, M. Minty, T.O. Raubenheimer
J. Seeman, G. Stupakov, J. Thomson, F. Zimmermann

- Add > 25 nTorr He gas to ALS vacuum – nominal vacuum ~1 nTorr

- Fill ring less than 3/4 (240/328 bunches) full — With 1 mA / bunch, ions are unstable with a 7 bucket gap

  ⇒ Ion growth rate: $\tau_c \sim 1\,\mu s$ and $\tau \sim$ 10–100 μs with 160 bunches

- Measure betatron sidebands with and without He – show charactistic peak at expected ion frequency *sometimes!*

- Measure beam size using VUV SR with and without He versus bunch train length

- Observe current after scraping

- Measure beam size with different bunch train lengths, with and w/o gaps, and with and w/o transverse feedback

ALS Ion Experiments

- Observe increase in vertical beam size roughly as expected ($2\sigma_y$)

- This occurs in a regime where the gap is expected to completely clear the ions

- Sometimes we have observed betatron sidebands that are consistant with the ion instability and sometime we do not. They seem to disappear when the bunch train is decreased or the bunch current is increased. Could this be a quadrupole rather than dipole instability??

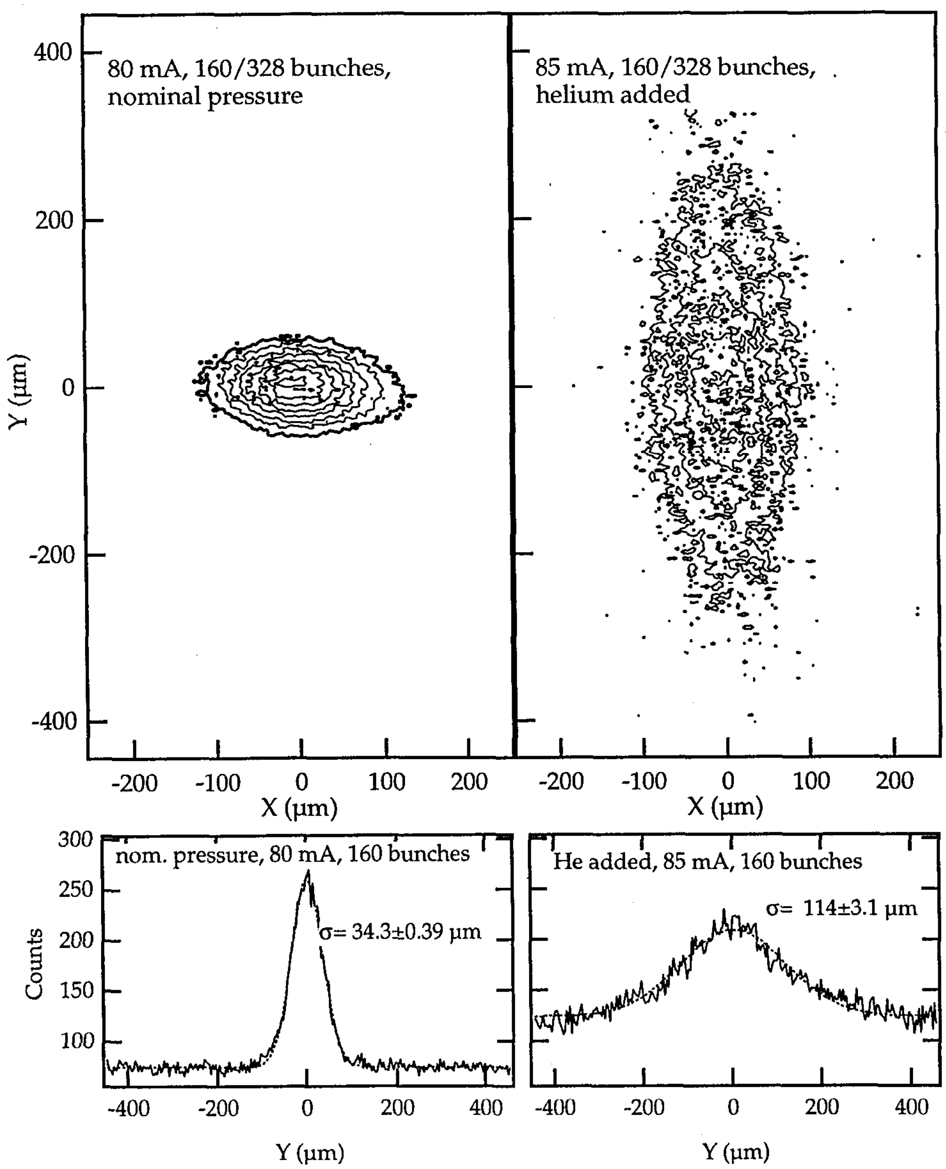
- Observe decreasing current after scraping implying large amplitude motion at end of train

- See little effect of transverse feedback, implying fast growth

- Have not measured growth rates but based on the *expected* feedback damping rate, the onset of the instability is "consistent" with the theory

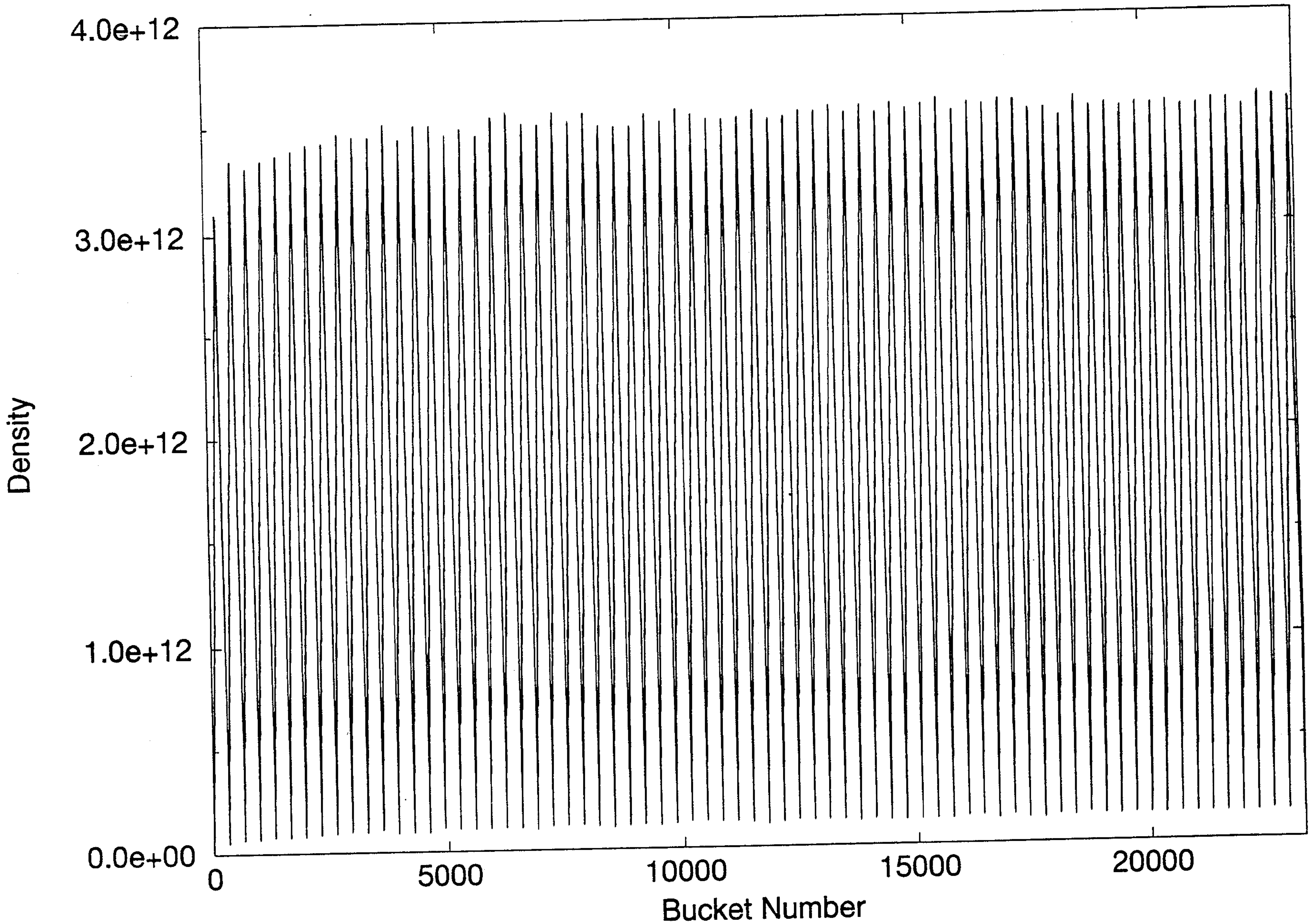
ALS Ion Experiments

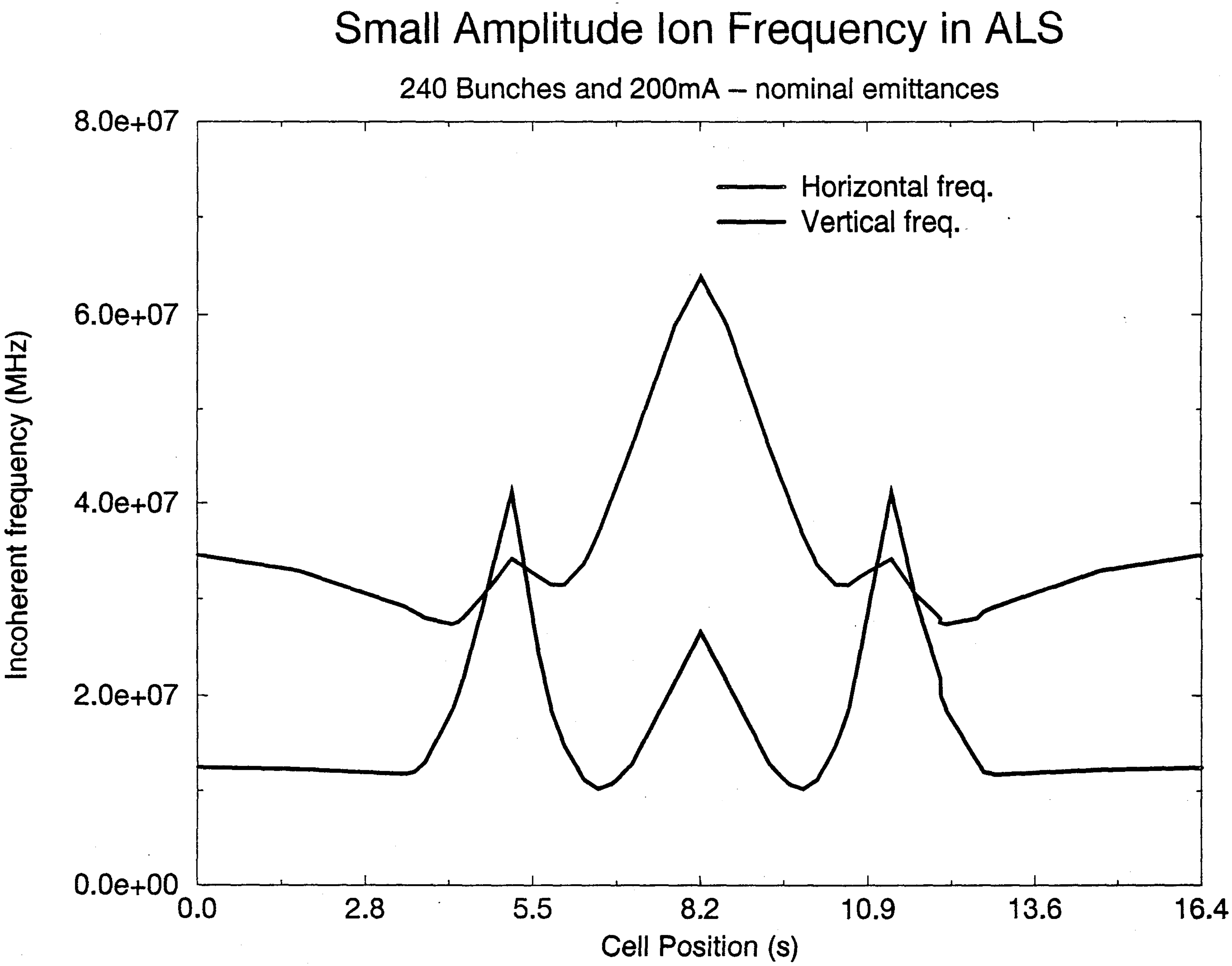
- Observe increase in projected vertical beam size when He is added–single bunch beam size was increased by $\sim 20\%$



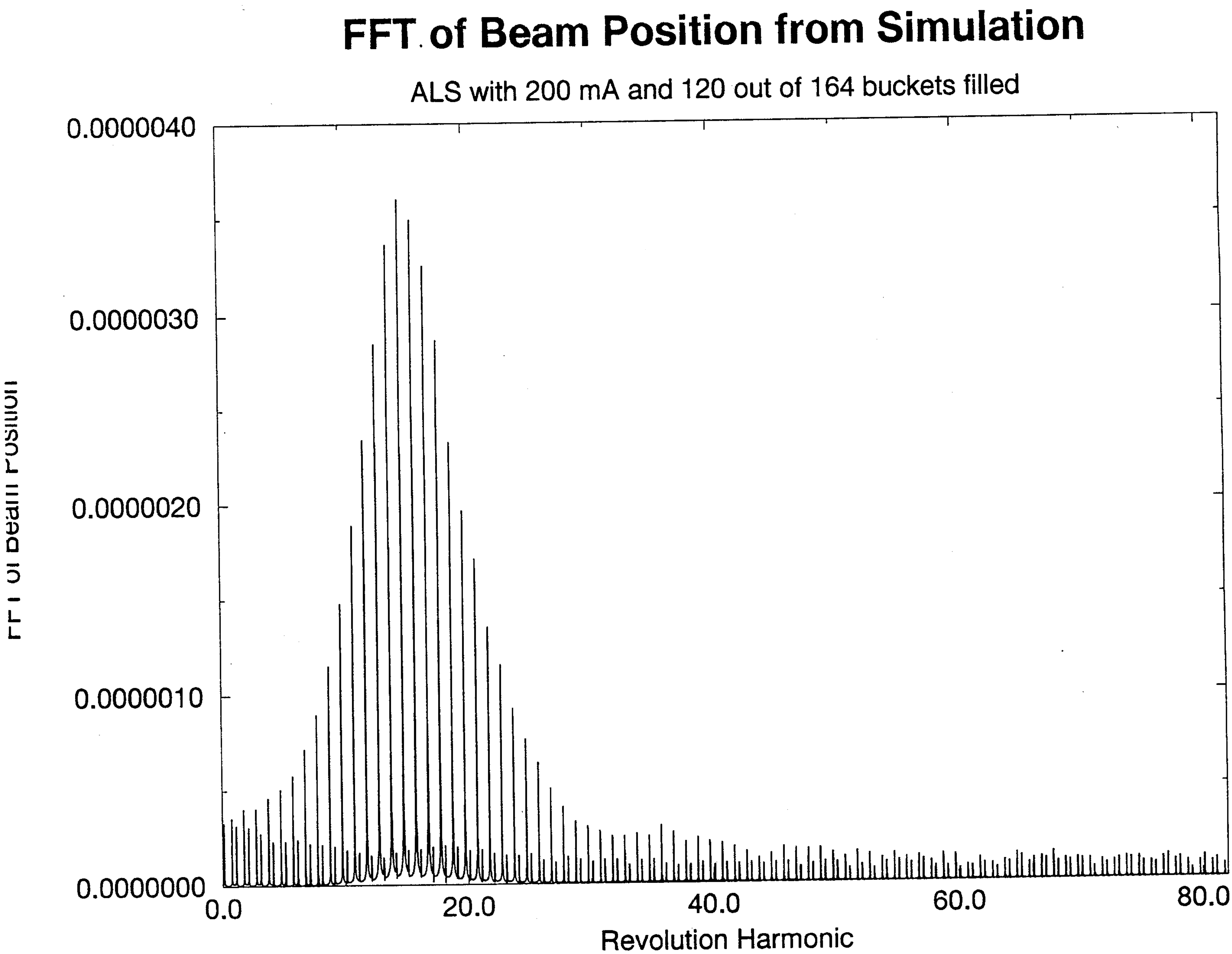
Ion Density versus Turns in ALS

240 Bunches with 200 mA at s = 0

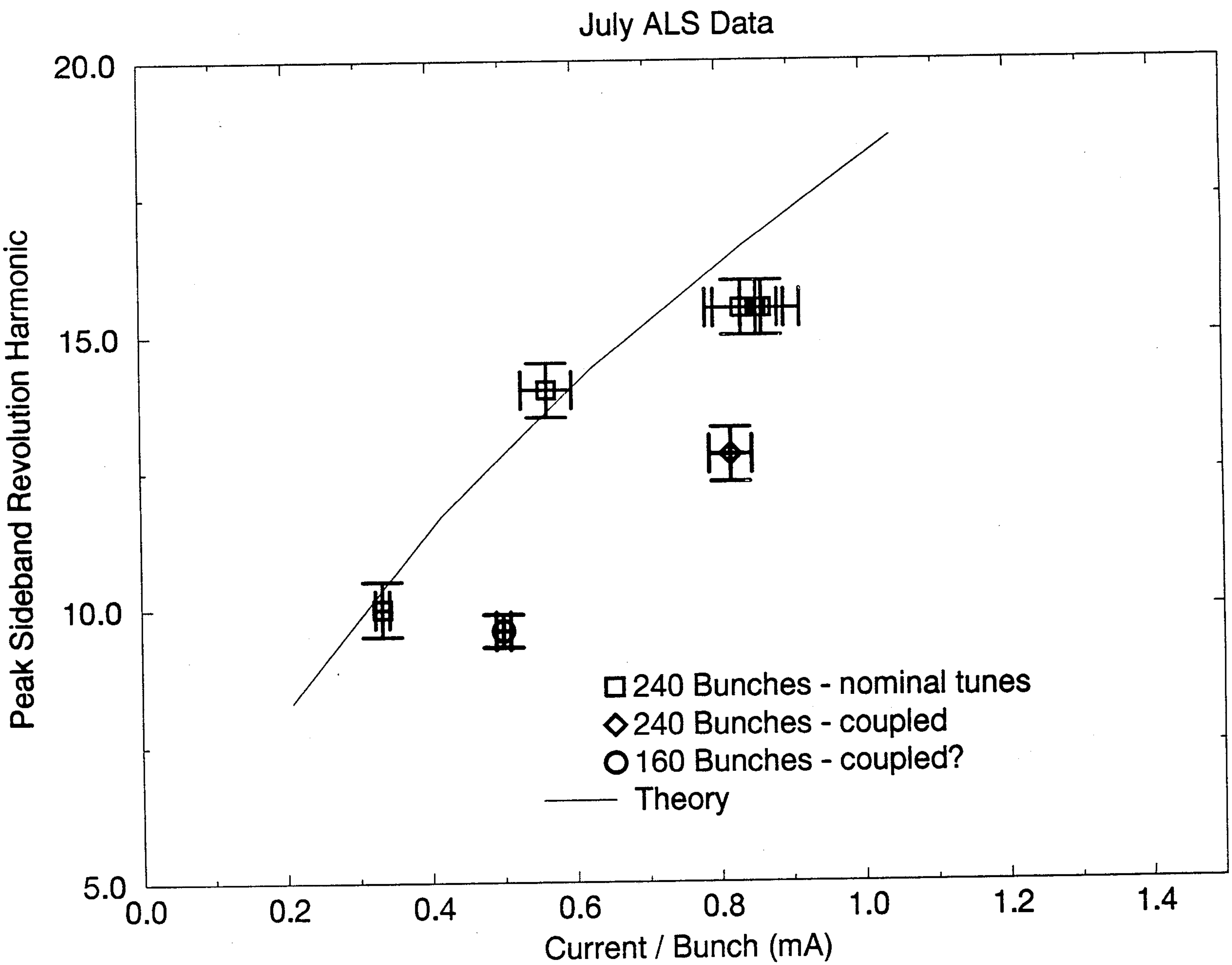




Small Amplitude Ion Frequency in ALS
240 Bunches and 200mA – nominal emittances
Horizontal freq.
Vertical freq.
Incoherent frequency (MHz)
8.0e+07
6.0e+07
4.0e+07
2.0e+07
0.0e+00
0.0
2.8
5.5
8.2
10.9
13.6
16.4
Cell Position (s)

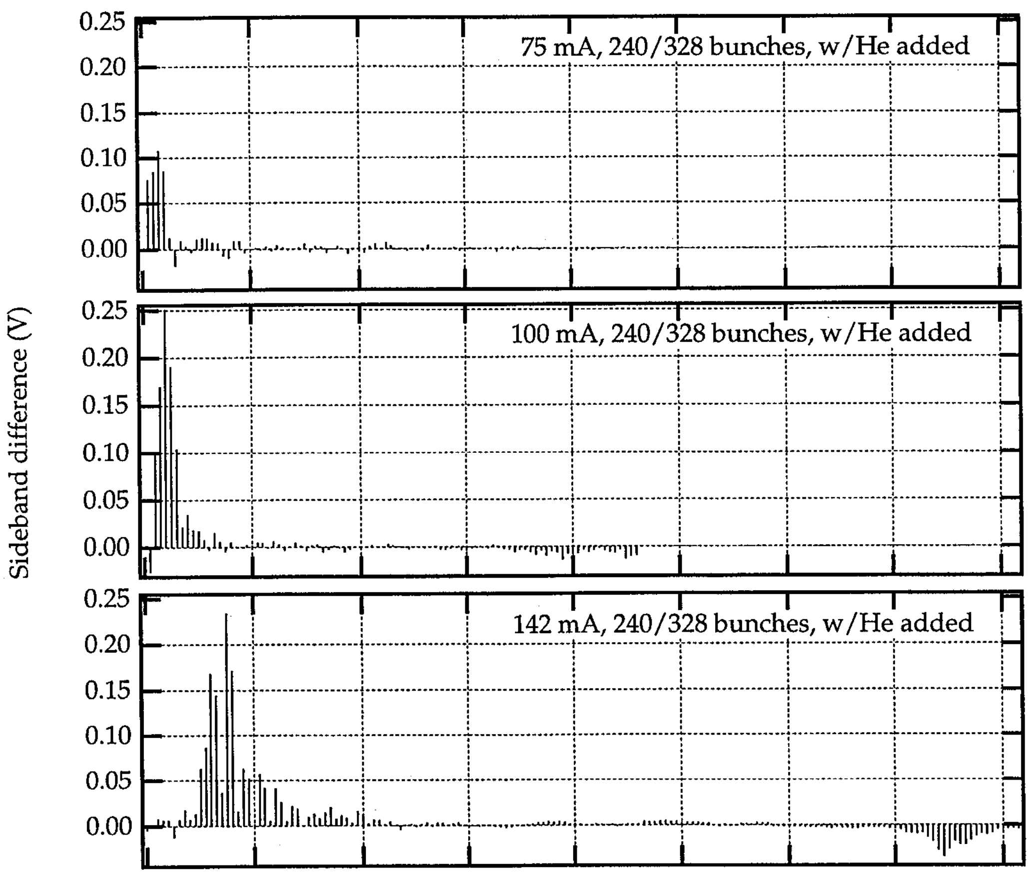

FFT of Beam Position from Simulation
ALS with 200 mA and 120 out of 164 buckets filled
0.0000040
0.0000030
0.0000020
0.0000010
0.0000000
FFT of Beam Position
0.0
20.0
40.0
60.0
80.0
Revolution Harmonic

Sideband Frequency versus Current per Bunch



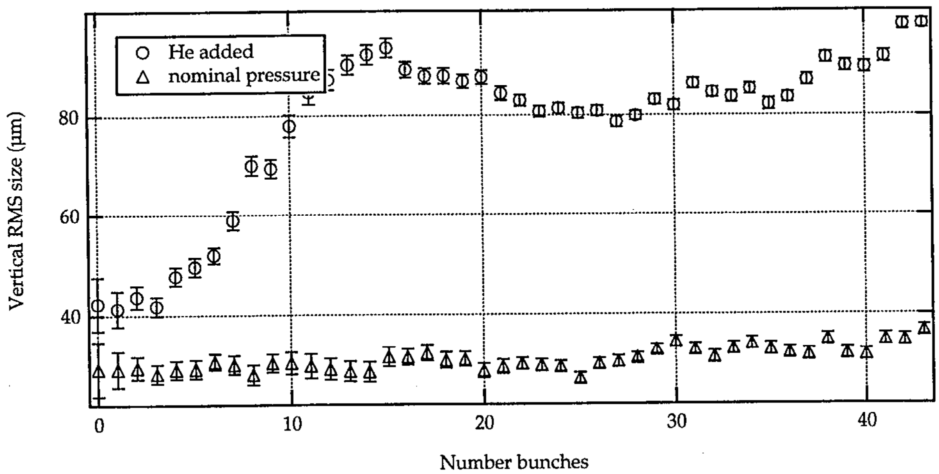
ALS Ion Experiments

- Betatron sidebands measured for 240 bunches with different currents–note increase in sideband frequency with current



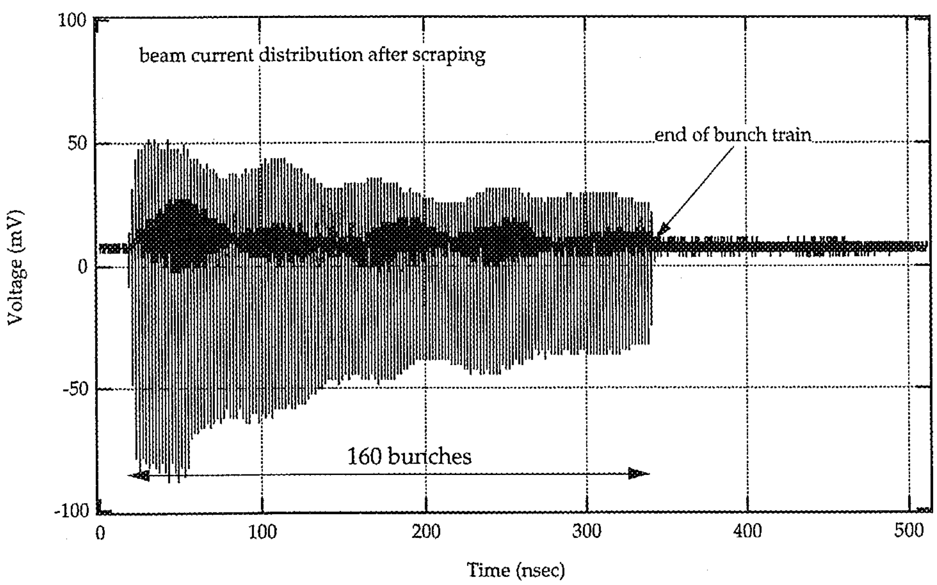
ALS Ion Experiments

- Projected beam size of bunch train depended on train length–oscillation grows along the length of the bunch train



ALS Ion Experiments

- Beam current for 160 bunch train after moving a vertical aperture close to the beam--implies oscillation amplitude increases along bunch train



Summary

- Single pass beam-ion instablity may be important for future colliders and light sources — Instability is not eliminated with the use of a gap
- Instability is like beam-breakup and can occur in linacs and transport lines as well as storage rings
- Many qualitative experimental verifications of dipole instability (ALS, PLS, KEK AR, KEKB??) — quantitative verifcation not complete but results are "consistent" with theory
- Still questions regarding effect of decoherence and possible quadrupole modes
- No quantitative observations in the PEP-II HER.
- Measurements have not (I think!) yet compared growth rates with simulation results