Single Bunch Sawtooth Instability in the APS Storage Ring

K. Harkay

Advanced Photon Source
Accelerator & FEL Physics Group
Argonne National Laboratory

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Preface

Talk not meant as an overview of accelerator R&D

in the AP group – rather, an overview of

one of the top AP group priorities: to understand the observed single bunch instability

Acknowledgements

AP Group: Y.-C. Chae, Z. Huang, E. Lessner, S. Milton,
V. Sajaev, C.-X. Wang

Other APS groups: M. Borland, L. Emery, A. Lumpkin,
N. Sereno, B. Yang

APS Impedance, Instability, Feedback Task Force

Outline

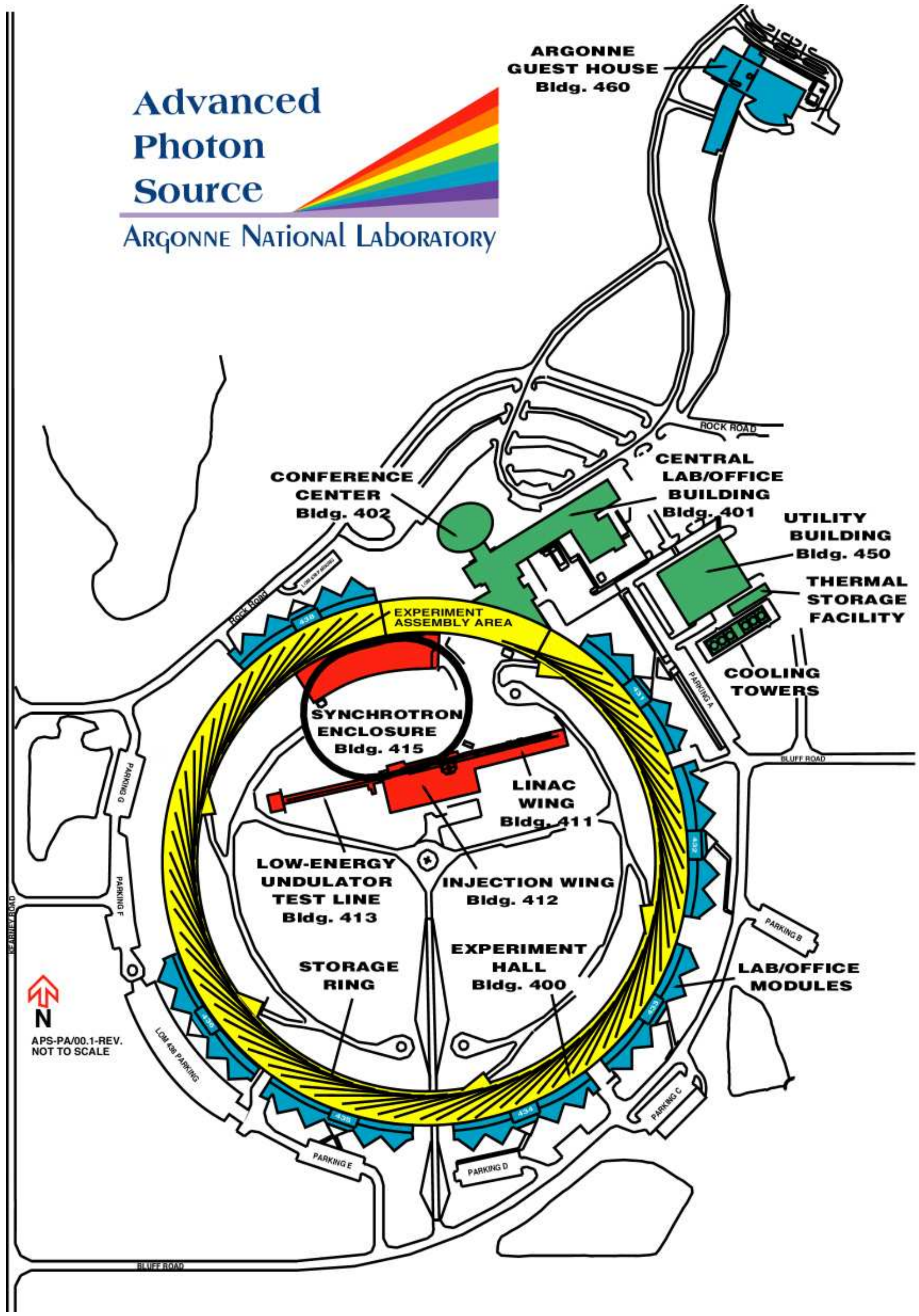
- Motivation
- Sources of machine coupling impedance
- Experimental observations
- Theoretical speculations
- Future R&D

Motivation

- Typically deliver 100 mA electron beam in 23 bunches (4.3 mA/bunch) for normal operation for users
- Horizontal instability (centroid oscillations) observed above about 5 mA/bunch – this is above the transverse mode-coupling instability (TMCI) threshold
- Normal operation with high positive chromaticity allows a single bunch intensity limit > TMCI limit: up to about 10 mA. However, beam properties (effective emittance) degraded above TMCI limit.
- Addition over time of small-gap insertion device chambers, a major source of coupling impedance, has
    - resulted in lowered single bunch instability and intensity limit
    - required operation with higher chromaticity and smaller beta functions to restore
- Need to understand physics and how to control instability in order to
    - satisfy anticipated future user requirement for higher bunch current
    - anticipate effect of additional small-gap insertion device chambers *and influence design*
    - mitigate instability while preserving beam quality, in particular, beam lifetime (e.g. effect of high chromaticity)

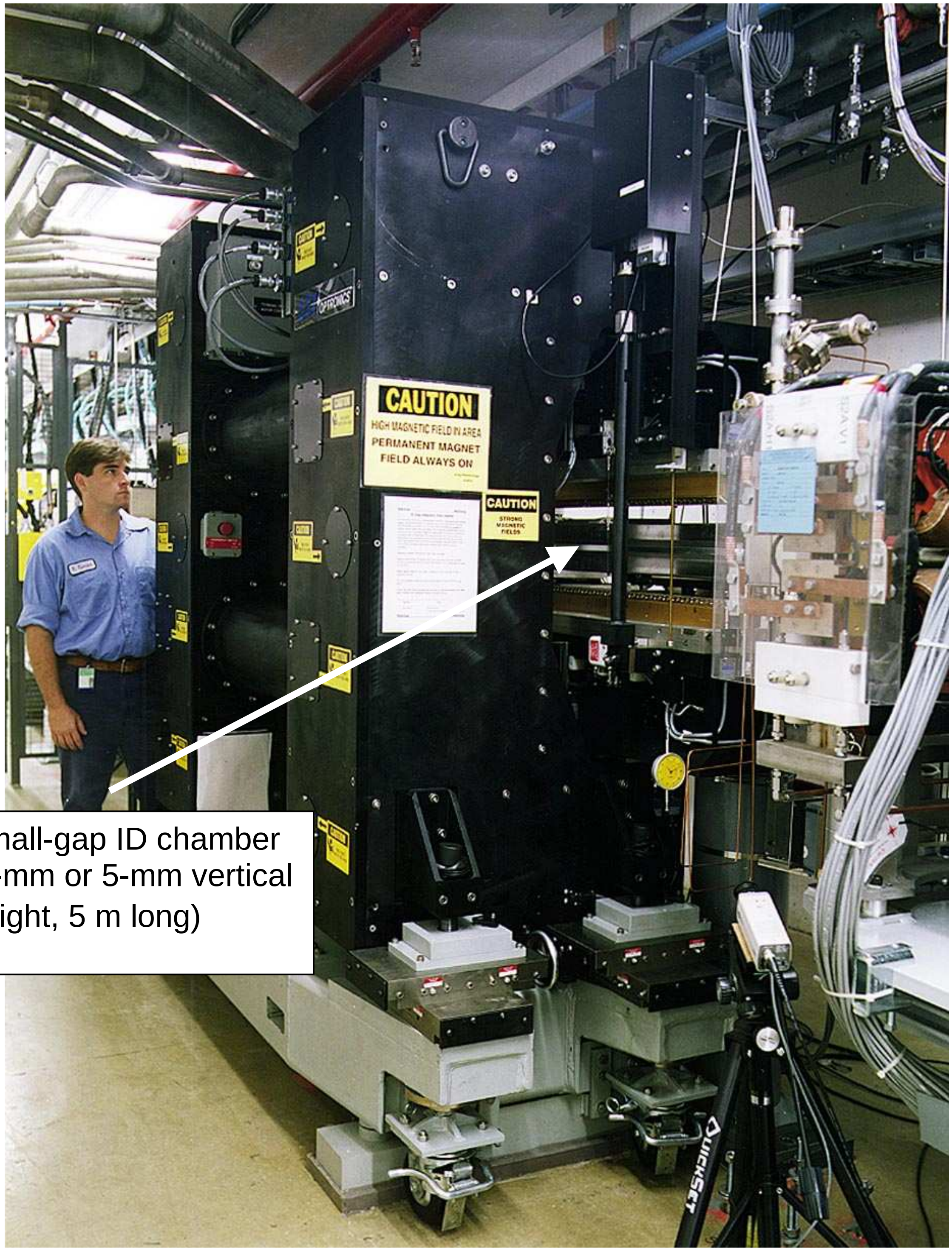
Advanced Photon Source site

25 of 40 sectors are occupied with photon beamlines: bending magnet and insertion device (ID) synchrotron radiation



Typical APS storage ring sector

Insertion Device (undulator magnet) with ID chamber



Main Sources of Impedance in the SR

Single bunch instabilities

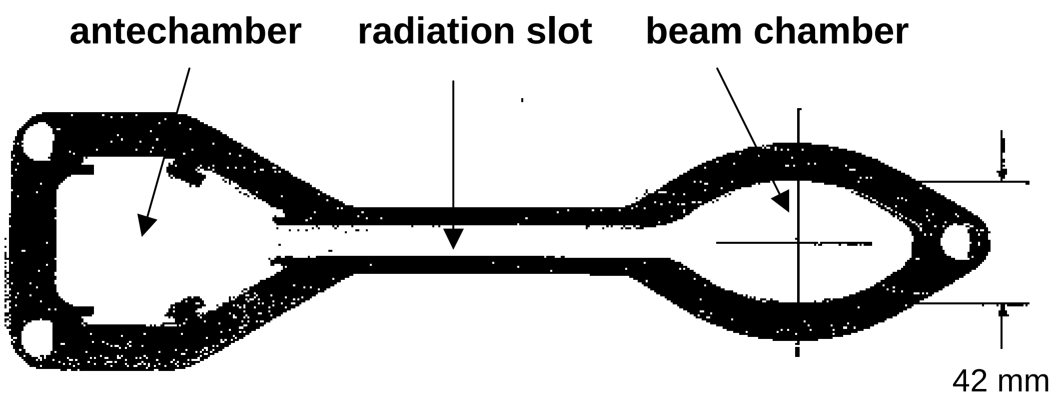
- small-gap ID chambers
  - resistive wall impedance
  - geometric impedance (transitions)
- other discontinuities: rf fingers, kickers, scraper “cavity”
- “trapped” chamber modes?

Multibunch instabilities

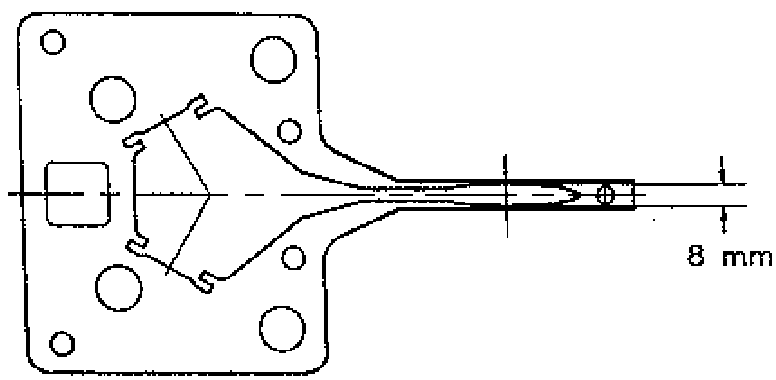
- rf cavity higher-order modes
- other discontinuities: scraper “cavity”
- “trapped” chamber modes?

APS Storage Ring chambers

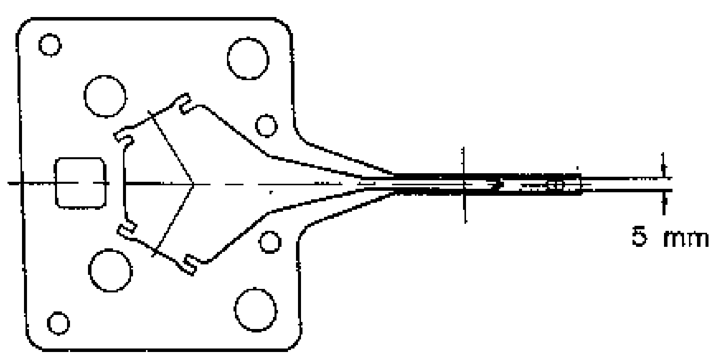
Standard



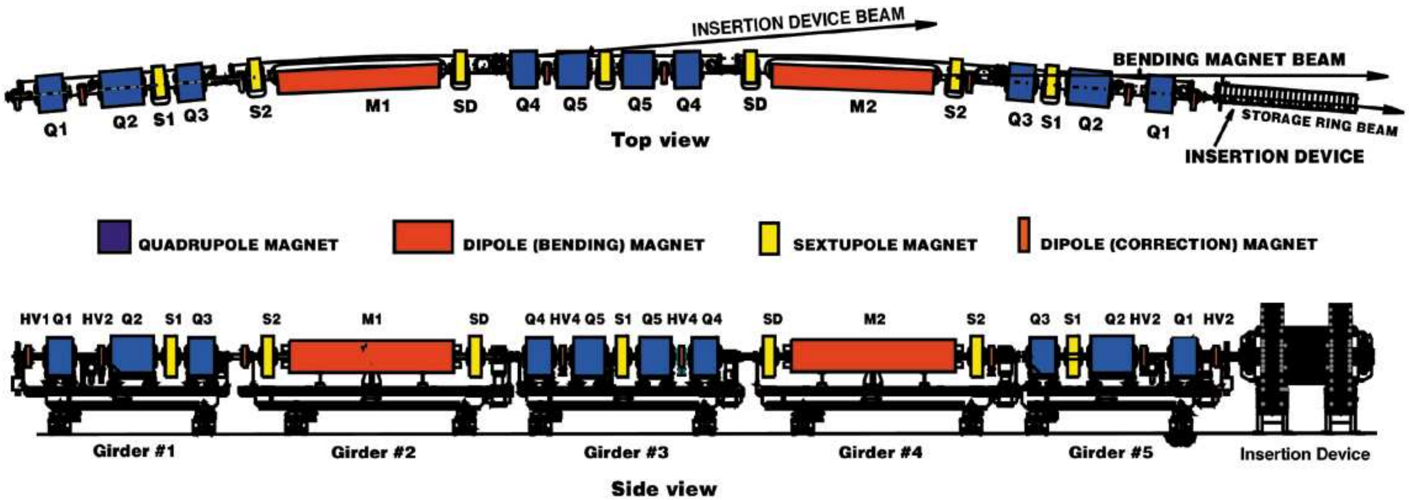
8-mm gap ID chamber



5-mm gap ID chamber



One Sector of the Advanced Photon Source Storage Ring



Small-gap ID chambers are located in 5-m straight sections

(total no.: 22 with 8-mm gap, 2 with 5-mm gap, 1 with 19.6-mm gap)

Transverse Mode-Coupling Instability

(a.k.a. strong head-tail, fast head-tail, transverse turbulence)

from A. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators, John Wiley & Sons (1993):

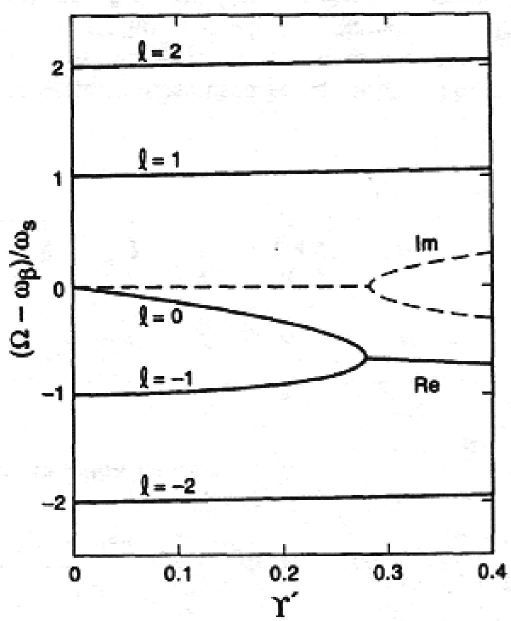


Figure 6.36. Transverse mode frequencies $(\Omega - \omega_\beta)/\omega_s$ versus the parameter Υ' for an air-bag beam with the impedance (6.224). The instability threshold is located at $\Upsilon'_{th} \approx 0.28$, where the modes $l = 0$ and -1 become degenerate. The dashed curves give the imaginary part of the mode frequencies for $l = 0$ and $l = -1$.

BB: $Z_1^{\perp}(\omega) = \dfrac{2c}{b^2\omega_0} R_0 \left|\dfrac{\omega_0}{\omega}\right|^{3/2} \left[\mathrm{sgn}(\omega) - j\right]$

$$\Upsilon' = \frac{N r_0 c^2 R_0}{\gamma T_0 \omega_\beta \omega_s b^2} \sqrt{\frac{\hat{z}}{c T_0}}$$

Tune slope, $\Delta\nu/\Delta I$, from transverse reactive wake:

$$\frac{\Delta\nu}{\Delta I} \propto \frac{\nu_0}{\sigma_z} \frac{\langle\beta\rangle R}{E/e} \bar{Z}_\perp(\omega)$$

where R = ring radius, $\bar{Z}_\perp(\omega)$ = effective impedance

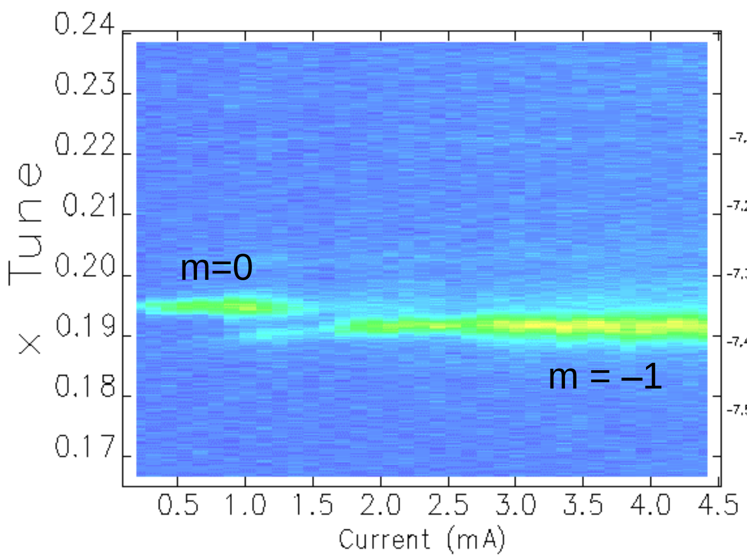
Single bunch instability: transverse mode coupling instability

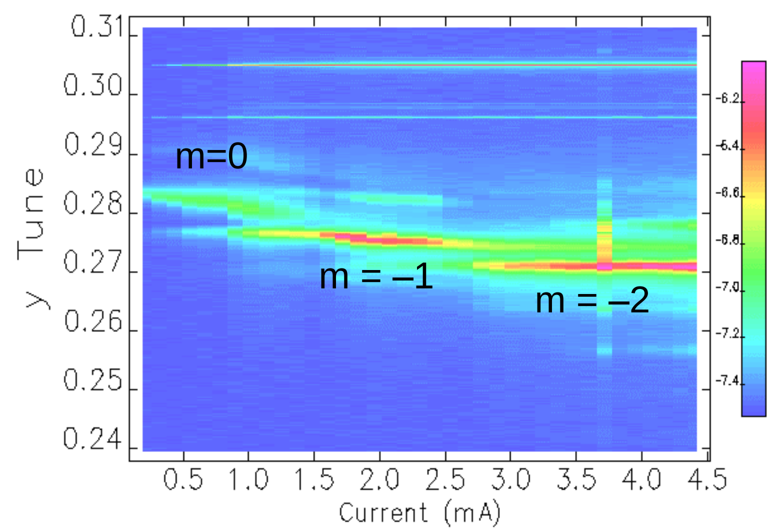
Force due to transverse wake defocuses beam, i.e., detunes betatron frequency.

When ν_β crosses ($m\nu_s$) modulation sidebands, synchrotron motion can couple to transverse plane and beam can be lost unless chromaticity sufficiently large/positive.

Tune slope increases with no. of small gap chambers: mode merging threshold decreases.

Horizontal $\xi_x > 1.3$, $\xi_y \approx 4$ **Vertical**

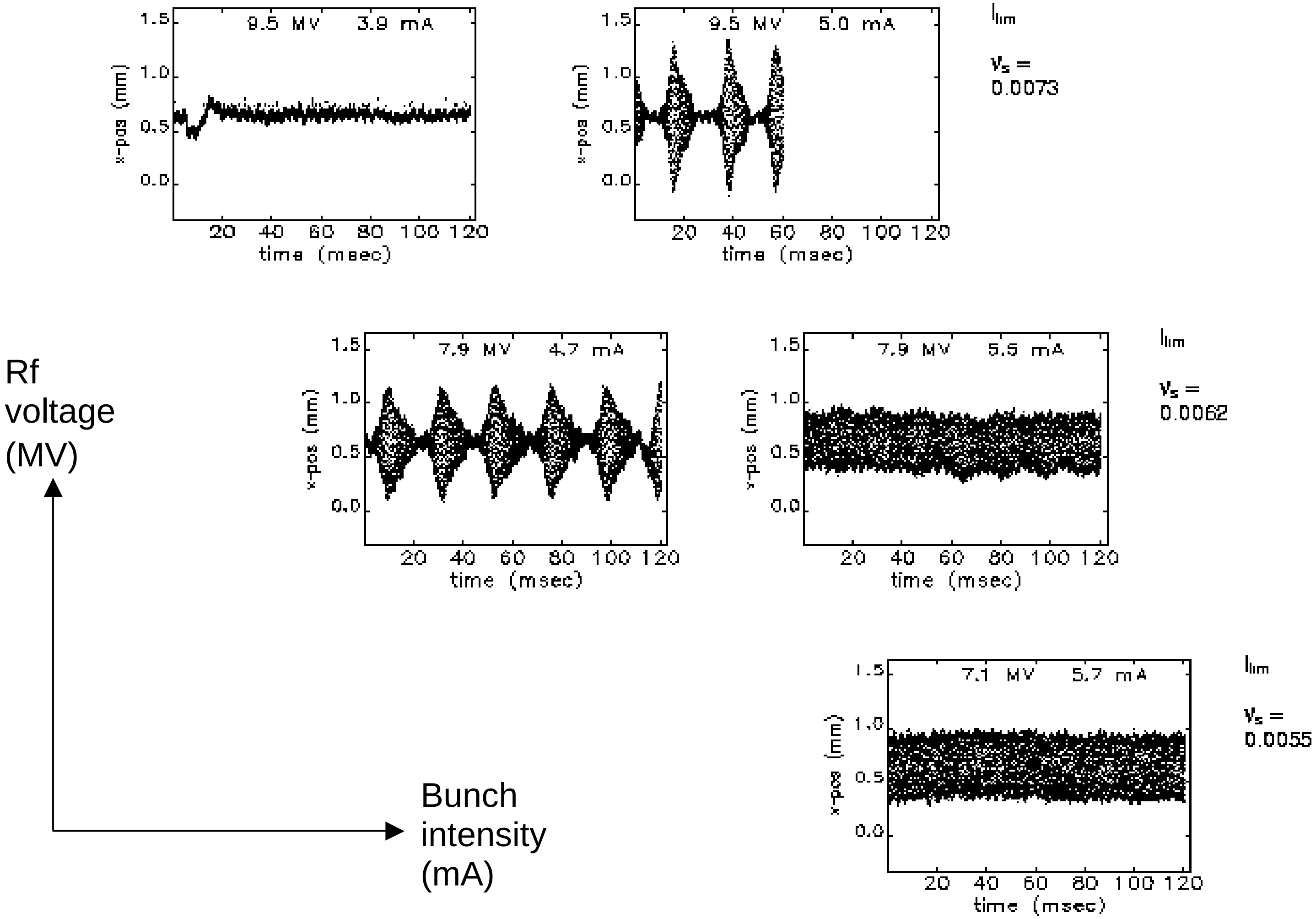




$\Delta\nu_x/\Delta I = -8\times10^{-4}$/mA

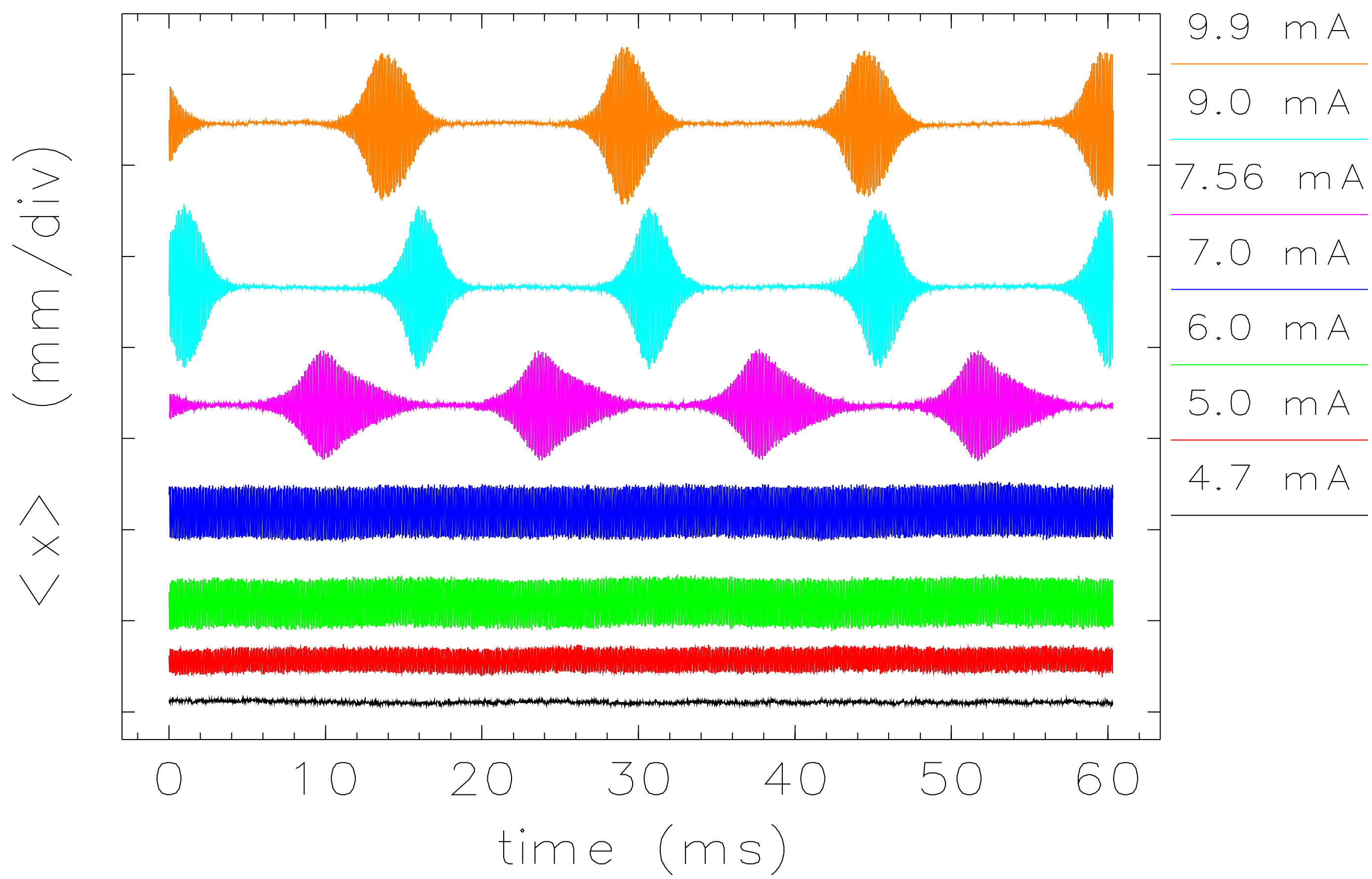
$\Delta\nu_y/\Delta I = -2.6\times10^{-3}$/mA

(data courtesy of L. Emery [K. Harkay et al., Proc. of 1999 PAC, 1644])



Early data using beam position monitor turn-by-turn histories showed horizontal centroid oscillations whose bunch intensity instability onset and mode (bursting vs. steady-state amplitude) varied with rf voltage (chromaticities: $\xi_x = 1.3$, $\xi_y = 3.9$) (2/15/1999)

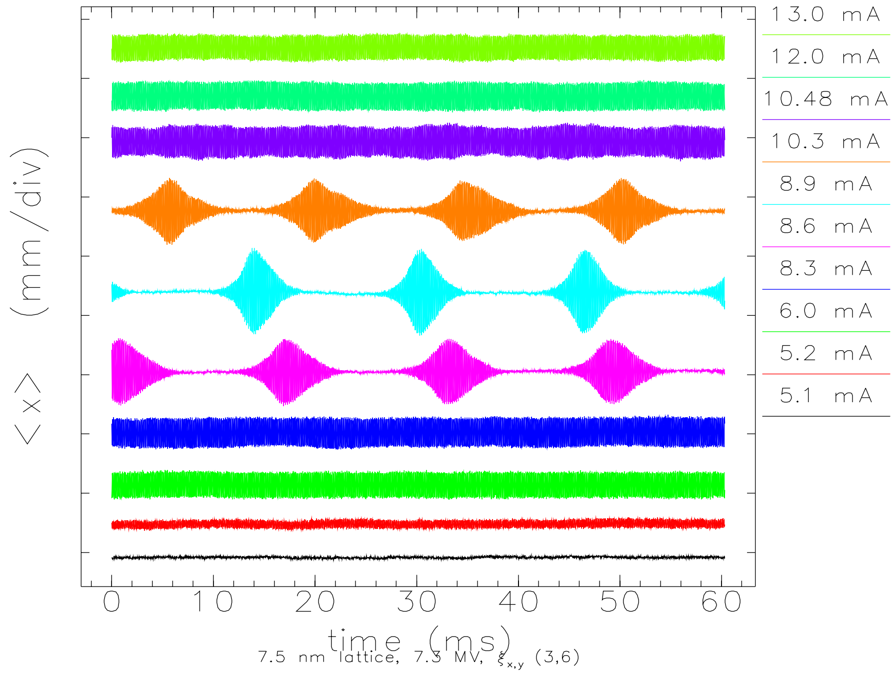
Large <x> oscillations above mode-merging threshold (V_{rf} 9.4 MV case shown): some Users will observe an effective emittance blowup, $\Delta\varepsilon_x$



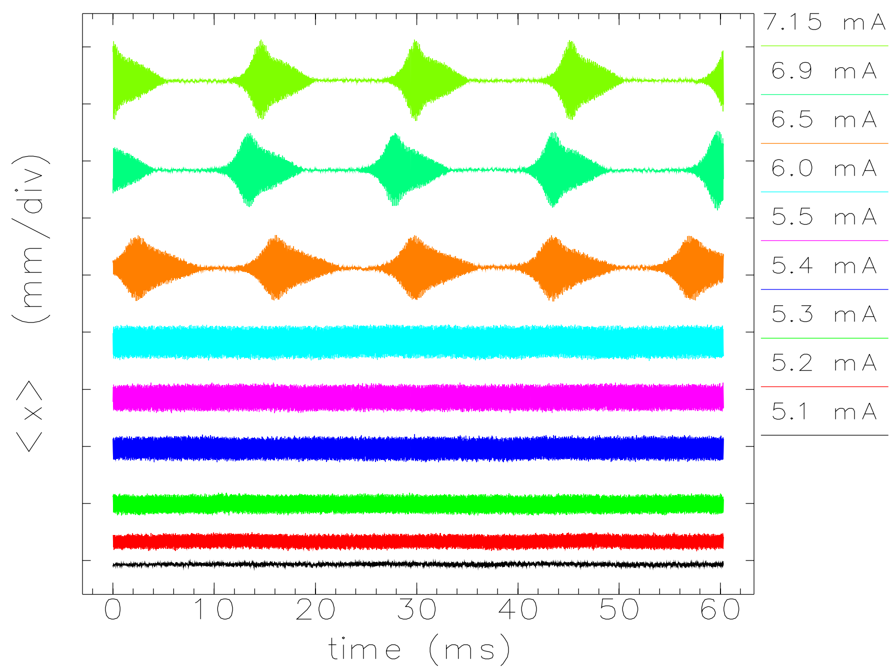
Note: bunch length σ_z, energy spread δ, and emittance ε_x also vary with current (ε_x decoherence NOT 100% of <x> oscillation amplitude; σ_x = 220 µm (7.5 nm-r lattice))

Variations with different machine parameters

7.5 nm lattice, Vrf = 7.3 MV, $\xi_{x,y}$ = (3,6)

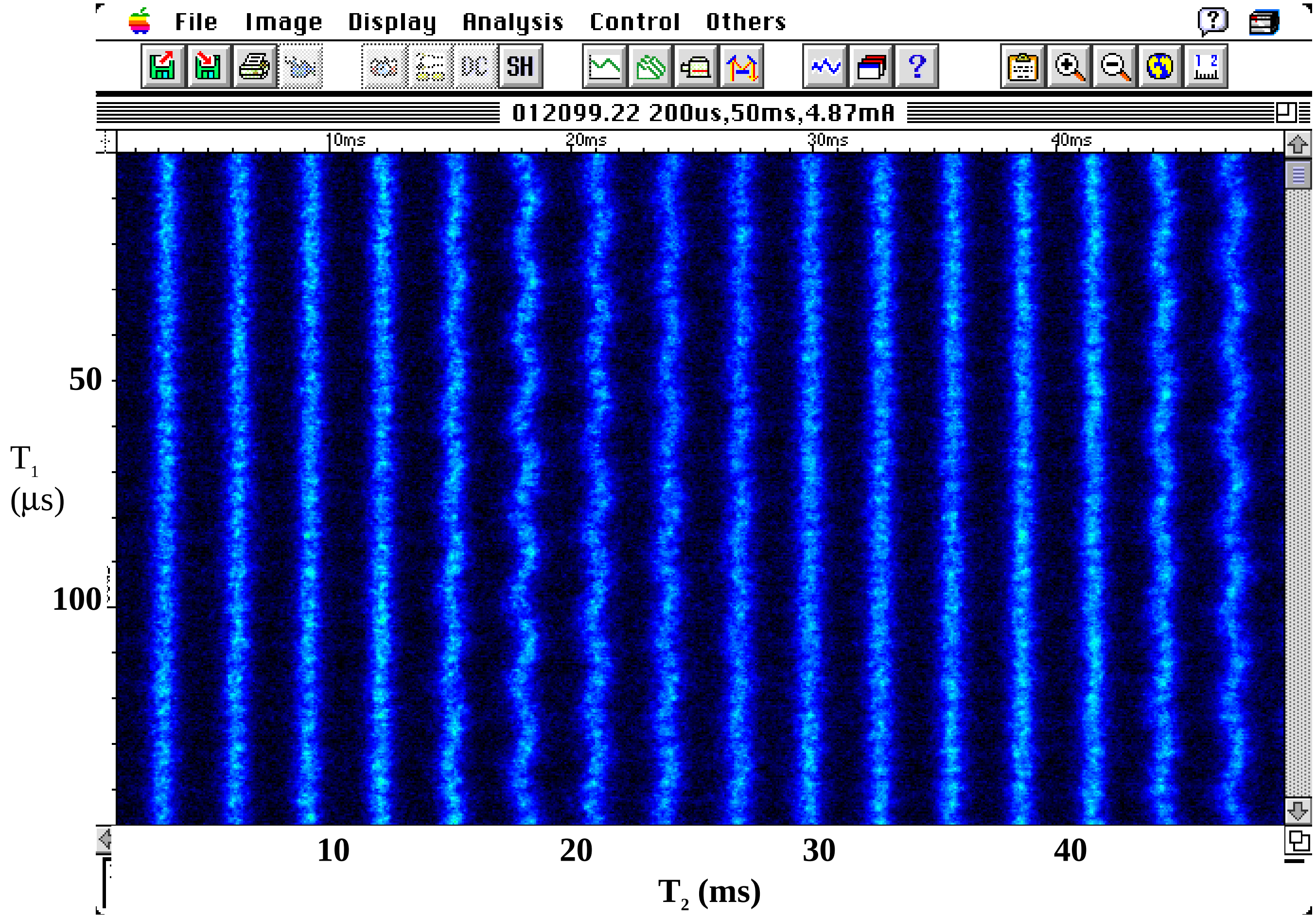


3.9 nm lattice, Vrf = 9.5 MV, $\xi_{x,y}$ = (3.2,5.8)

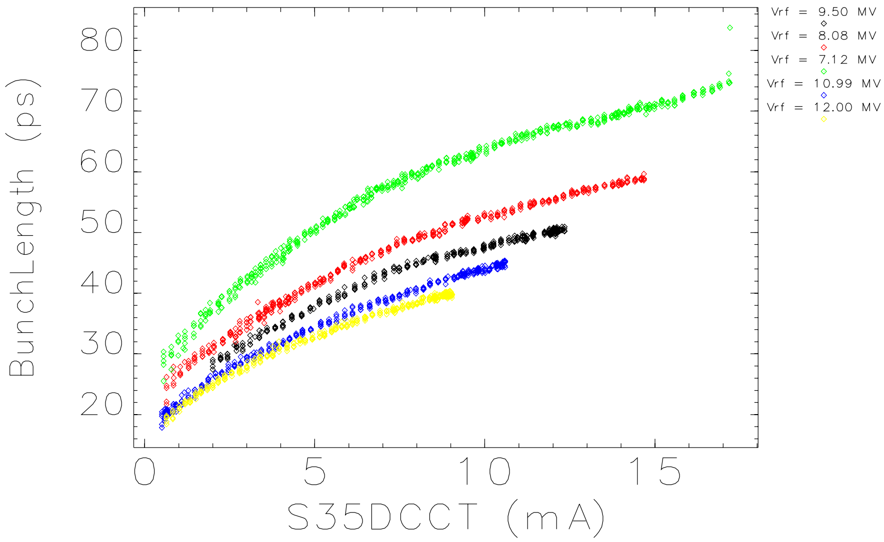


Dual-sweep streak camera horizontal image of single bunch undergoing coherent horizontal oscillations in bursting mode: bunch does not completely decohere

[data courtesy of B. Yang; K. Harkay et al., Proc of 1999 PAC, 1644]



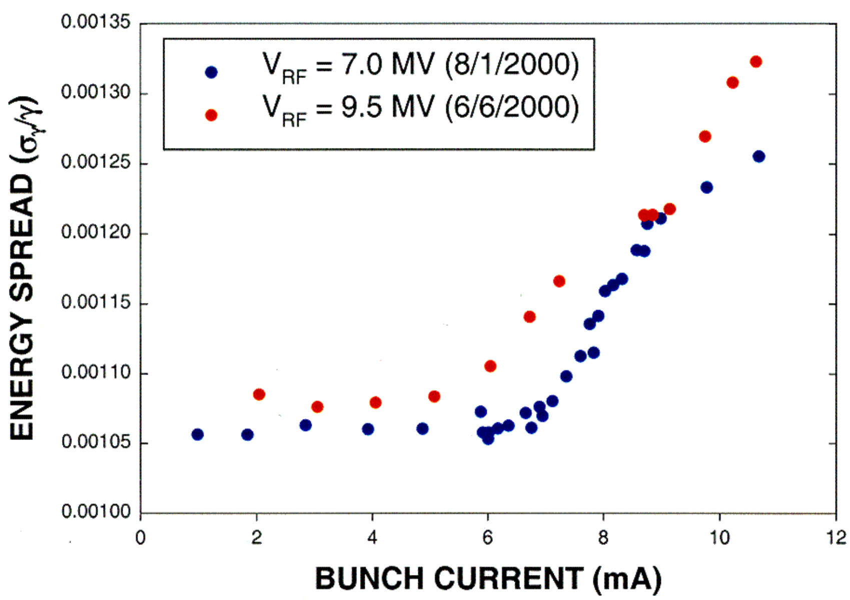
Measured bunch lengthening vs V_{rf}
(L. Emery, M. Borland, A. Lumpkin)



no 5-mm chambers (March 2000)

$Z_{||}/n \approx 0.5\ \Omega$ [estimated, Y.-C. Chae et al., Proc. of 2001 PAC, 1817]

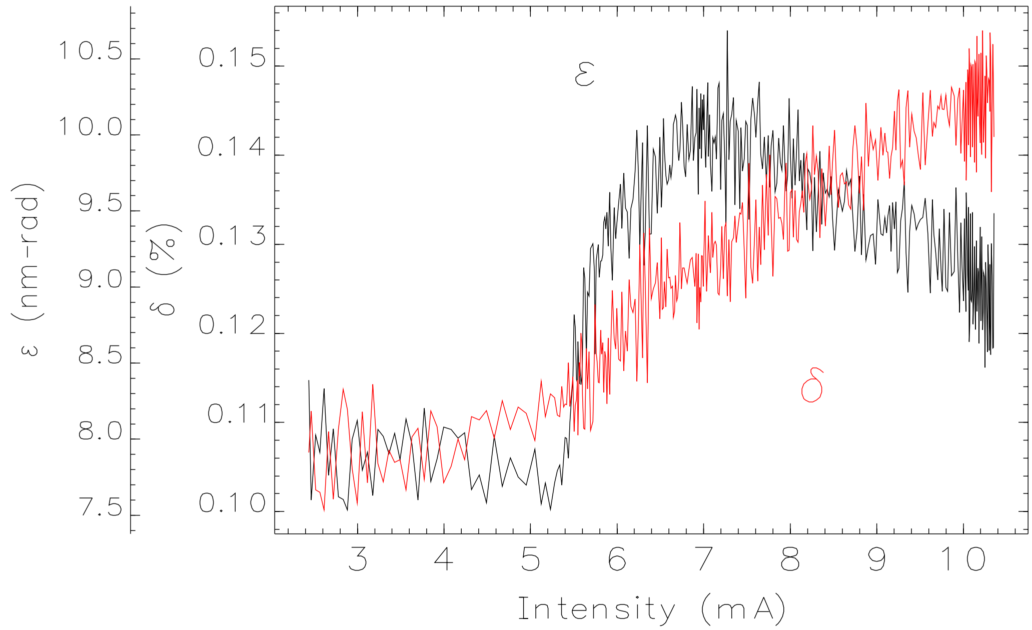
ENERGY SPREAD AS A FUNCTION BUNCH CURRENT



high ξ_x (B. Yang, L. Emery, Y.-C. Chae, K. Harkay)

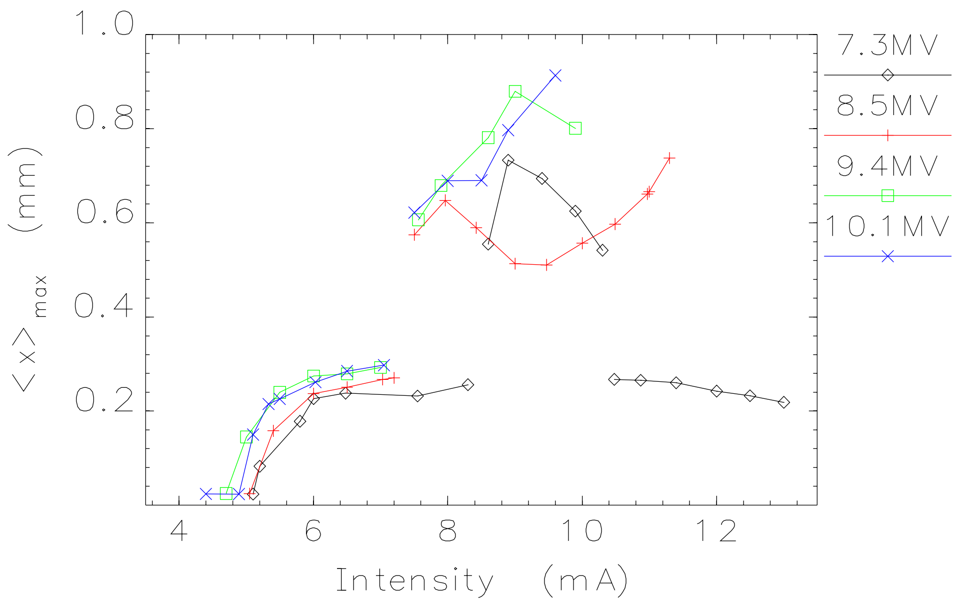
Measured δ and ε_x vs I_b

(another method: note $\xi_{x,y}$ differs from the previous figure)



V_{rf} 7 MV, nominal $\xi_{x,y}$ (B. Yang, K. Harkay, E. Lessner, A. Lumpkin [K. Harkay et al., Proc. of 2001 PAC, 1915])

Maximum amplitude of horizontal centroid oscillations as a function of Vrf



8-mm gap ID vacuum chamber impedance

Z_y (effective) estimated five ways:

1. $Z_y = (Z_{RW} + Z_{geom})$ determined experimentally from change in tune slope, $\Delta\nu/\Delta I$, as a function of no. of chambers [N. Sereno et al, Proc. of 1997 PAC, 1700]:

$$Z_y = 53\ \text{k}\Omega/\text{m per chamber x } 20 = 1.1\ \text{M}\Omega/\text{m}$$

2. Simulations with Z_y represented by broad-band resonator impedance model reproduced measured tune slope and intensity threshold for TMCI at low chromaticity [K. Harkay et al, Proc. of 1999 PAC, 1644]:

exp:	$\Delta\nu_x/\Delta I = -8\text{x}10^{-4}$/mA	$\Delta\nu_y/\Delta I = -2.6\text{x}10^{-3}$/mA
model:	0.2 MΩ/m	1.2 MΩ/m
I_{TMCI} thresh:	4.4 mA	2.2 mA

3. Impedance calculated: resistive wall and geometric

a. resistive wall $\propto 1/b^3$

$$\frac{Z^{\perp}_{1_{x,y}}}{L} = \frac{c}{\omega}\frac{1+\text{sgn}(\omega)\,j}{\pi b^3 \delta\sigma} G_{1_{x,y}} \quad \Rightarrow \quad Z^{\perp}_{1_{x,y}}\left[\frac{\text{k}\Omega}{\text{m}}\right] = \left(1+\text{sgn}(\omega)\,j\right)\frac{25500}{b[\text{mm}]^3\sqrt{f\,[\text{MHz}]}} G_{1_{x,y}}$$

f = cutoff frequency = $c/2\pi b$ = 13 GHz

G_{1y} = 0.825 [Gluckstern and van Zeijts, CERN SL/AP 92-25, Jun 1992]

Z_{RW} (per 8-mm chamber, L = 5 m) = 3.4 kΩ/m

b. geometric (transition): assuming a perfectly conducting circularly cylindrical tube of half-height b=4 mm, angle θ [Bane and Krinsky, Proc. of 1993 PAC, 3375]

$$W_{\perp} = \frac{Z_0 c}{\pi b}\left(\frac{2\theta}{\pi}\right)^{1/2} \frac{1}{\sqrt{2\pi}\sigma_s} \exp\left(\frac{-s^2}{2\sigma_s^2}\right) = 4 \times 10^{14}\ \Omega/\text{m-s per transition}$$

$Z_\theta = 2 \times (\sigma_s/c)W_\perp = 26$ kΩ/m (5-mm: $Z_\theta = 55$ kΩ/m)

$Z_\theta = 20 \times 26 = 0.5$ MΩ/m

c. total per 8-mm chamber:

$Z_y = Z_{RW} + Z_\theta = 3.4 + 26 = 30$ kΩ/m

c. total per 5-mm chamber:

$Z_y = Z_{RW} + Z_\theta = 12 + (2.1 \times 26) = 67$ kΩ/m

4. MAFIA calculations of wake potentials: Z_θ from extracted tune slopes for geometric component (Y.-C. Chae)

(next talk)

5. Local bump method Z_y measurements [L. Emery, G. Decker, J. Galayda, Proc. of 2001 PAC, 1823]

5-mm: Z_y [kΩ/m] = 96 $\pm$ 8 (ID3); 78 $\pm$ 14 (ID4)

8-mm: Z_y = 16 kΩ/m

6. Local betatron phase shift [V. Sajaev]

Work in progress: preliminary results in agreement with #4 & #5

Progress/speculation in understanding collective transverse behavior above TMCI threshold

- Transverse instability occurring simultaneously with longitudinal instabilities: bunch lengthening due to potential well distortion and growth in energy spread due to microwave instability – attempt to separate bunch length dependence (peak current), resonance between betatron and synchrotron tunes, and Landau damping due to energy spread (i.e., tune spread)
- Transverse instability growth rate not linear with bunch current – nonlinear effects
- Transverse oscillation amplitude dependence
  - saturates with increasing current in steady-state mode (due to amplitude-dependent tune)
  - no simple dependence of amplitude on rf voltage or beam current in bursting mode (resonant effect?)
- Explore possibility of coupling of transverse and longitudinal collective motion described in literature:
  - R.D. Kohaupt (DESY reports, ca. 1985)
  - C. Besnier, D. Brandt, B. Zotter (Particle Accelerators *17*, 1985)
  - Yong Ho Chin (DESY 86-081, 1986)

TBD: Transverse driving impedance from linear instability theory

Coasting beam equation of motion [B. Zotter and F. Sacherer, CERN 77-13, 1977]:

$$\ddot{x} + \nu^2 \omega_0^2 x = -j \frac{c^2 \beta_x}{E/e} \frac{Z_\perp(\omega) I}{2\pi R} x \,.$$

Assuming a time dependence of exp(jωt), where $\omega = \omega_p = (p + \nu)\omega_0 + \Delta\omega$:

frequency shift: $$\Re(\Delta\omega) = \frac{j}{2\nu\omega_0} \frac{c^2 \beta_x}{E/e} \frac{\Im(Z_\perp(\omega)) I}{2\pi R}$$

growth rate: $$1/\tau = -\Im(\Delta\omega) \propto \Re(Z_\perp(\omega))$$

For bunched beam, need to sum over bunch spectrum

frequency shift: $$\Re(\Delta\omega)_m = \frac{1}{(1+m)} \frac{j}{2\nu\omega_0} \frac{c^2 \beta_x}{E/e} \frac{I_b}{\sigma_z} \Im(Z_{eff})$$

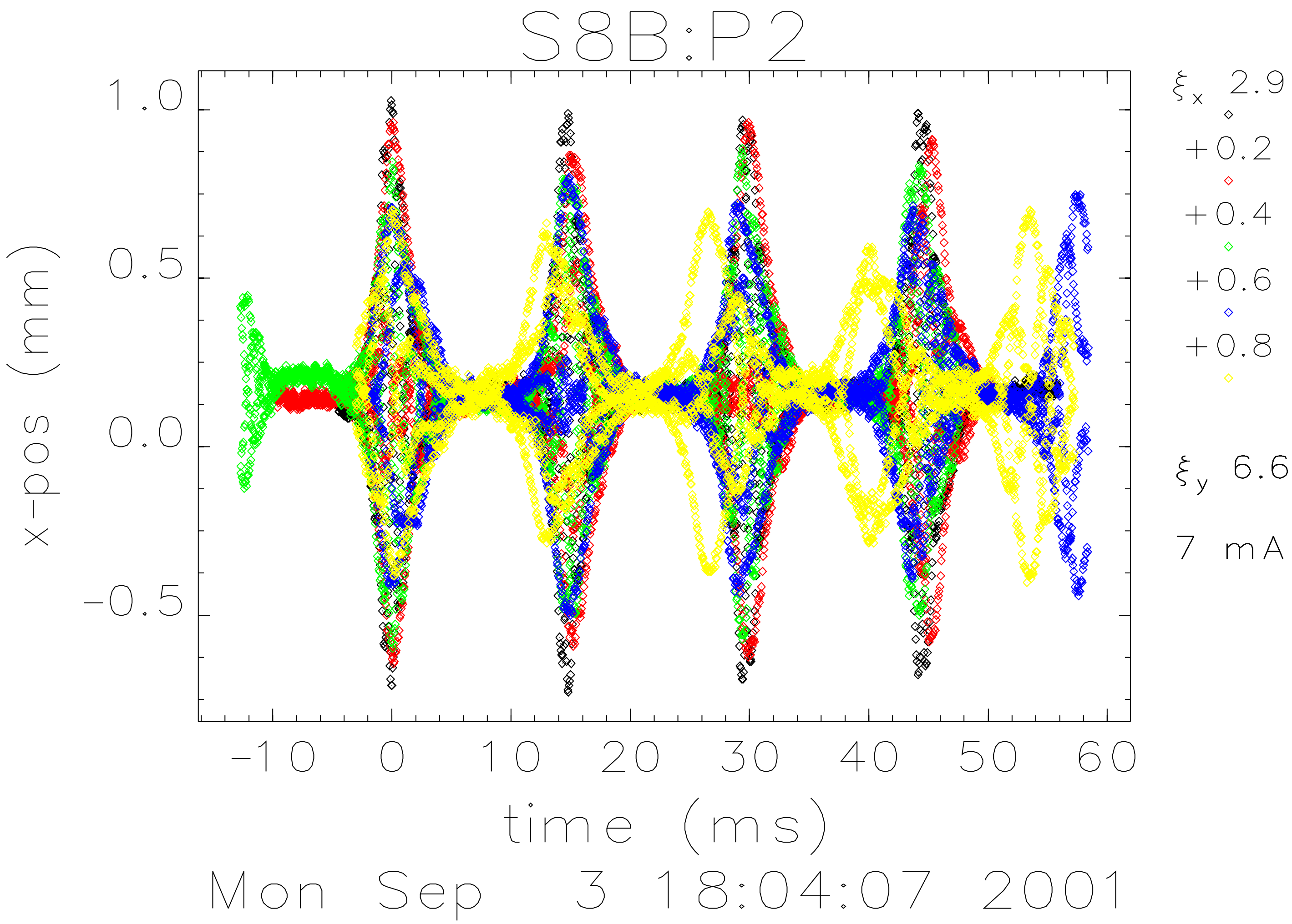
where $Z_{eff} = \dfrac{\sum_p Z_\perp(\omega_p) h_m(\omega_p - \omega_\xi)}{\sum_p h_m(\omega_p - \omega_\xi)}$, I_b = current/bunch, $\omega_\xi = \dfrac{\xi}{\alpha}\omega_0$

For a broadband impedance, where $Z_\perp$ smooth (approx. true for ID chamber impedance):

$$\Re(\Delta\omega) = \frac{j}{2\nu\omega_0} \frac{c^2 \beta_x}{E/e} \frac{I_b}{\sigma_z} \Im(Z_\perp(\omega_\xi))$$

This is almost the coasting beam result. If ω_ξ can be varied, $\Re(Z_\perp(\omega))$ can be deduced by measuring the growth rate $\Im(Z_\perp(\omega))$

Measured growth rate as a function of horizontal chromaticity (bursting mode)



Rise time:

0.7 ms

0.8

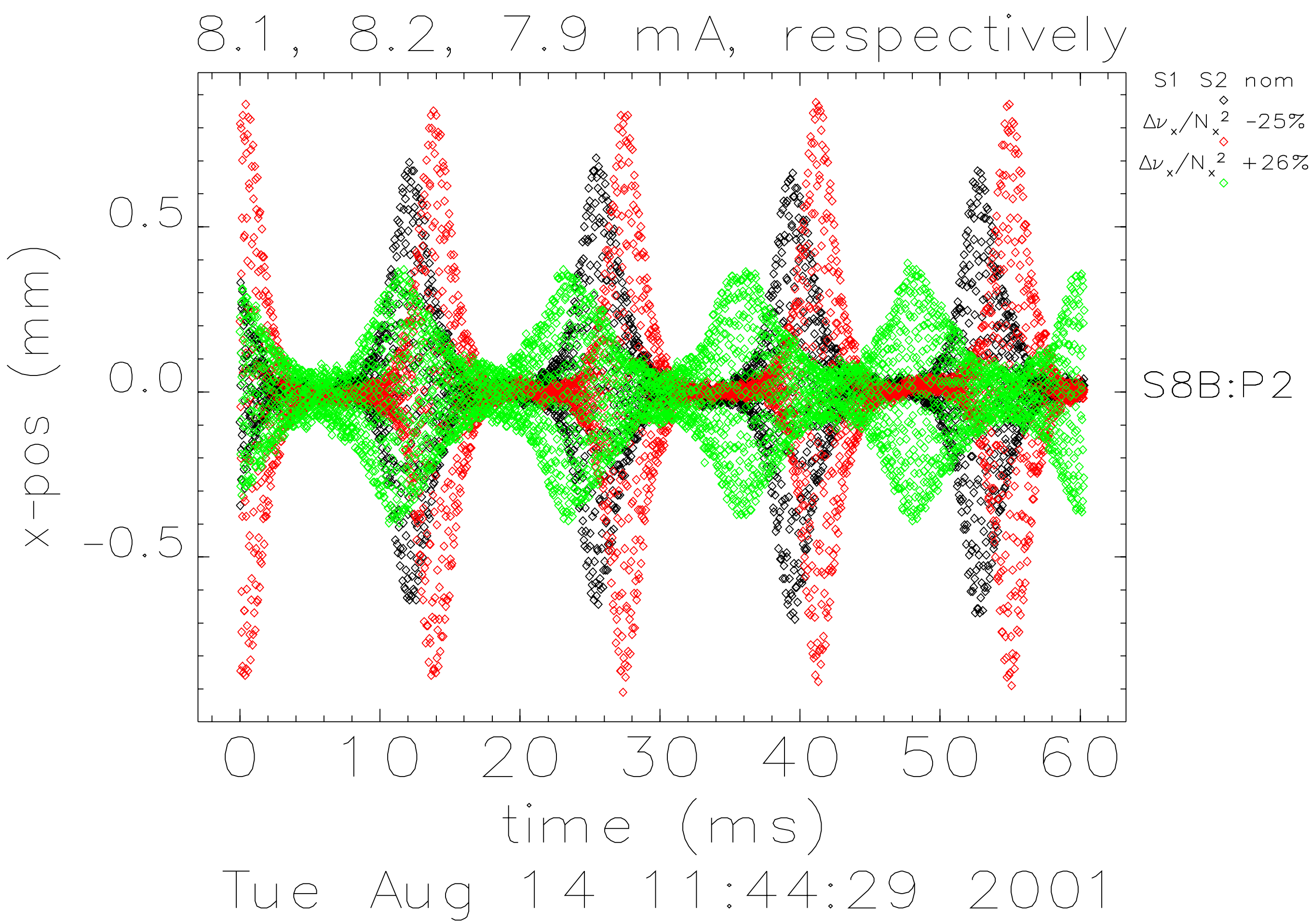
0.9

1.2

1.2

Saturation amplitude varies with change in amplitude-dependent tune, $\Delta\nu_x/N_x^2$, in expected direction (N_x = x-amplitude) (rise time approx. constant: 1 ms)

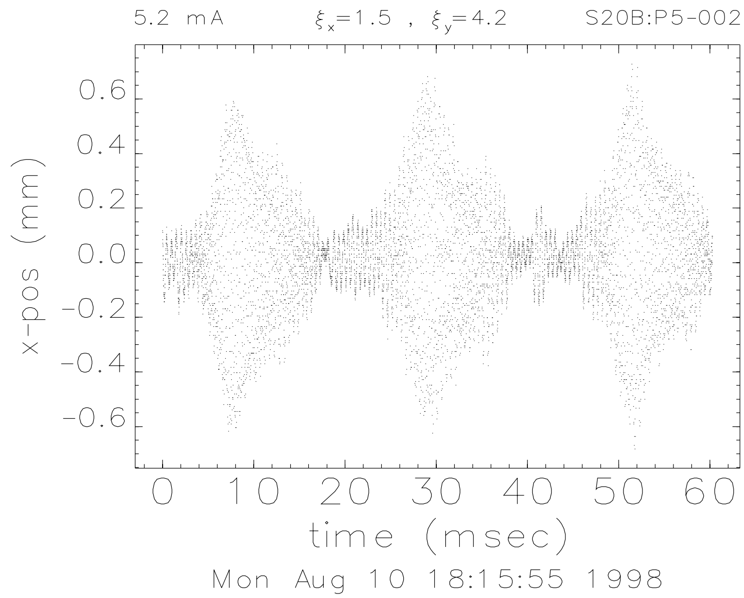
(second-order effect of changing harmonic-correcting sextupoles S1, S2 – coefficients per E. Crosbie)

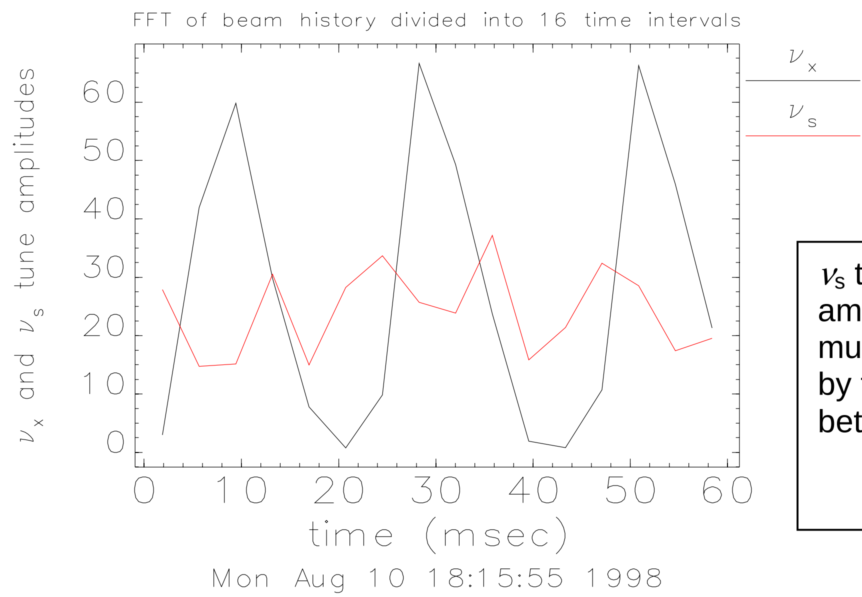


N_x max:
+ 20%
- 50%

Possible x-z parametric resonance?

Self-excited ν_x and ν_s tune lines appear to vary out-of-phase over a burst.





ν_s tune amplitude multiplied by two for better clarity

Middle burst: ν_s appears to rise first, then drops as ν_x reaches a peak. After the peak, ν_s rises again as ν_x drops, then ν_s also drops.

Future R&D

- Coupling impedance database (Chae et al.)
  - Local bump method (PAC01 – Z_y)
  - Local tune shift (V. Sajaev, C.-X. Wang – $Z_{x,y}$)
  - MAFIA calculations (PAC01 – Z_z)
- Characterize longitudinal instability – validate $Z_{||}$
  - Apply $Z_{||}$ calculated from MAFIA to model with *elegant* code to reproduce bunch lengthening, $\Delta\sigma_t/\Delta I$, and microwave instability, $\Delta\delta/\Delta I$
- Characterize transverse instability – validate $Z_\perp$
  - Instability threshold, growth rate, and saturation amplitude vs V_{rf}, ξ, $\Delta\nu_x/N_x^2$, dispersion
- Instability photon diagnostics
  - Details of decoherence over bursts
- Other supporting analysis
  - Amplitude-dependent tune
  - Measure frequency spectrum evolution to look for mode-coupling and/or parametric resonance signatures