Machine Impedance and Instabilities in the APS Storage Ring

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Preface

Talk focused on effects most important for anticipated near-term (1-2 yrs) performance: many details left out

Emphasis on how to overcome present limits

NOT discussed:

- Consequences of high I_b , e.g. thermal heating of accelerator components by I_b^2R or radiation (see L. Emery's SR R&D presentation 2002 jan 11)
- Instability theory

Acknowledgements

Y.-C. Chae

L. Emery

Z. Huang

E. Lessner

B. Yang

Impedance, Instability, Feedback Task Force

M. Borland, S. Milton, N. Sereno, A. Lumpkin

Outline

- Introduction, definitions
- Single bunch limits
  - o Accumulation limit vs injection transients
  - o Horizontal mode-coupling instability
  - o Measured $\Delta(\sigma_z, \delta, \langle x \rangle, \sigma_x, \varepsilon_x)/\Delta I_b$ (representative data set, 7.5 nm-rad lattice)
- Cures to achieve higher I_b
- Multibunch limits
- Resources required
- Summary

What is Impedance?

Machine coupling impedance, Z(ω), is the frequency-domain equivalent of the time-dependent wake field

$$Z(\omega) = -V(\omega)/I(\omega)$$

Energy loss from resistive impedance: growth rate

Frequency shift (detuning) from reactive impedance

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 is the ring radius and $\bar{Z}_\perp(\omega)$ is the effective impedance (convolution of impedance with beam frequency distrib)

What are Instabilities?

Beam instabilities are **intensity-dependent collective effects** that arise as a result of the electromagnetic wake fields generated by the beam as it interacts with its environment.

Coherent oscillations appear above some **threshold current** when the induced wake field forces overwhelm the natural damping of the electron beam from either frequency spread or synchrotron radiation.

The oscillation amplitude **grows exponentially** in time until either the beam is lost or nonlinearities in the system limit the growth.

Items in **bold** and characteristic instability **mode frequencies** ($m\nu_\beta$, $m\nu_s$) distinguish beam instabilities from Glenn's orbit stability.

Main Sources of Impedance in the SR

Single bunch instabilities

- small-gap chambers
  - o resistive wall impedance
  - o geometric impedance (transitions)
- other discontinuities: rf fingers, kickers, scraper “cavity”

Multibunch instabilities

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

Single Bunch: Limiting instabilities

Two kinds of limits

Accumulation limit

Injection rate = loss rate

Beam losses on vertical aperture due to coupling of horizontal injection transients

Transverse mode-coupling instability limit

Horizontal centroid betatron oscillations above threshold bunch current (±1 mm)

Effective horizontal emittance blowup

Machine parameters allow accum limit > TMCI limit

Bunch lengthening and energy spread increase due to **longitudinal potential well distortion** and **microwave instability** do not limit I_b but may be important to some Users

Comparison of lattices and effect of 5-mm gap vacuum chambers

Chromaticities ($\xi = \Delta\nu/\delta$) approx constant = (4, 6)

rf Voltage 9.4 MV

	7.5 nm-rad	7.5 nm-rad	3.3 nm-rad
# 8-mm vc [1]	20	19	21
# 5-mm vc [2]	0	2	2
accum. limit (mA)	12	8	8
horiz instab thresh. (mA)	~5	4.8	6.3

[1] equiv 5-m long small-gap vc's

[2] vertical scrapers at 5-mm gap resulted in same accum limit as single 5-mm vc (9 mA);

addition of second 5-mm vc reduced accum limit to 8 mA

Results with vertical scraper show accumulation limited by losses on vertical aperture.

Horiz. instability not very sensitive to tune slope change from 5-mm vc's; more sensitive to addition of dispersion at all small-gap vc's

Horizontal injection transients couple to vertical plane

Gated camera measurements (x-y) of the first 12 turns after pulsing kickers with stored beam (B. Yang, M. Borland, A. Lumpkin)

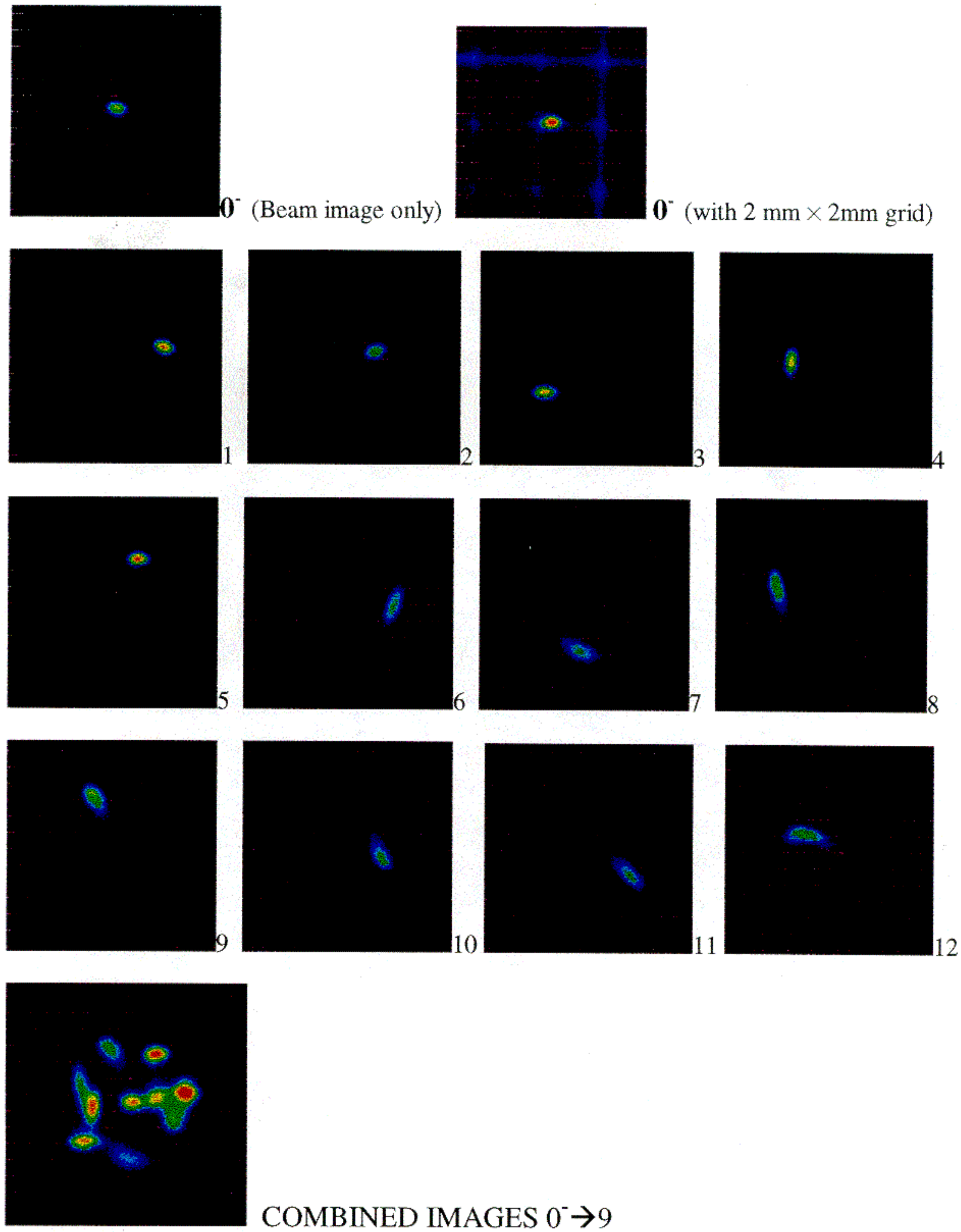
> Significant <y> offset on 3rd turn: losses on smallest small-gap aperture
>
> Used as a diagnostic for measuring coupling
>
> Data shown are **NOT** for minimum coupling conditions; <y> offset is much smaller for standard, “small” coupling in User configuration (per Bingxin)
>
> Diagnostics logbook for these studies (section 4.11): http://www.aps4.anl.gov/diagnostics/diag_log/9801_archive/980119-2.frame.html

Possible remedy: Off-energy injection (Y.-C. Chae, L. Emery, S. Milton)

> Reduces the horizontal betatron oscillation, Δx_β; instead introducing a dispersion insertion to bump (using Δx_δ) the off-energy injected beam near the stored beam

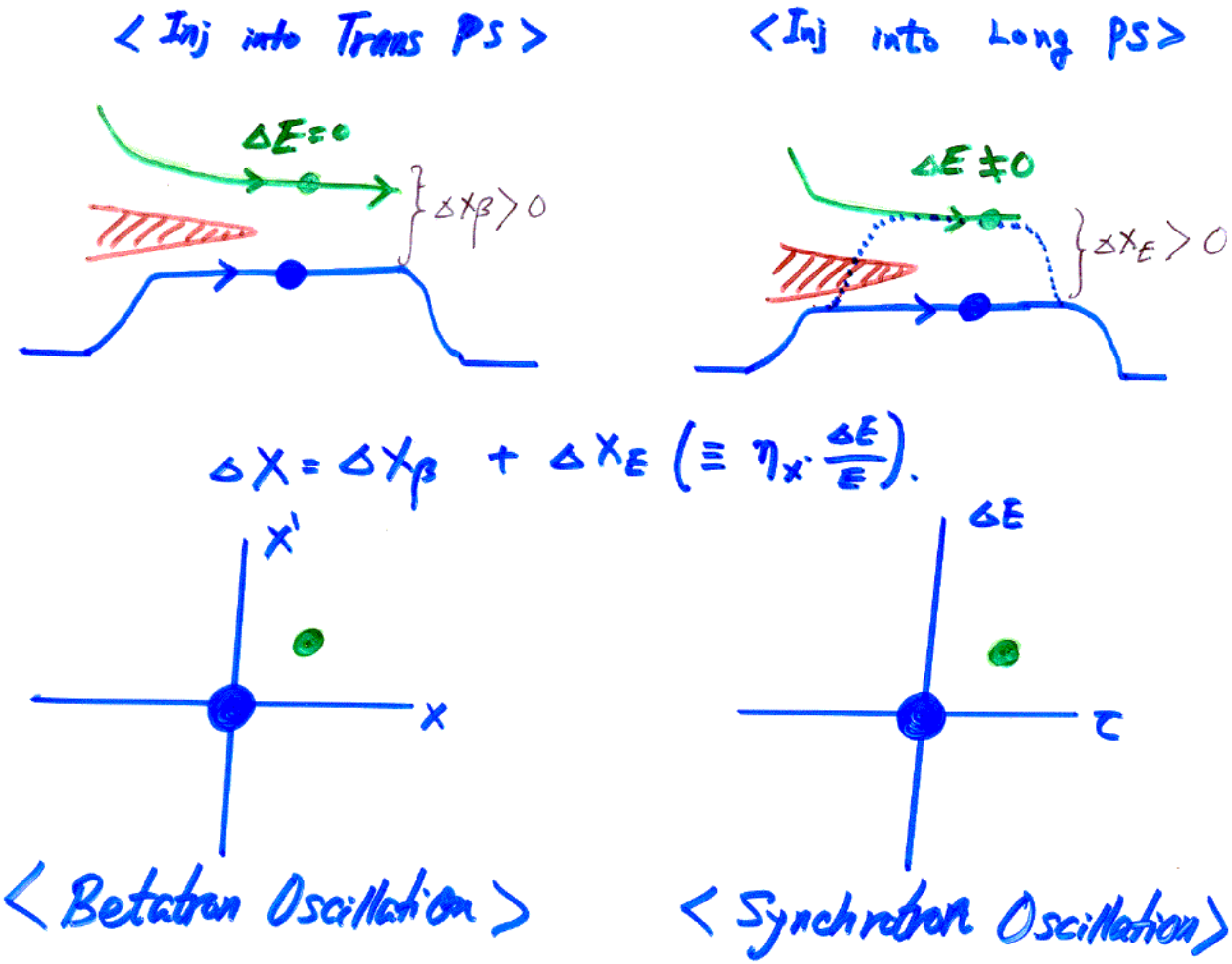
GATED CAMERA IMAGES FOR KICKER INDUCED TRANSIENT (1/19/98)

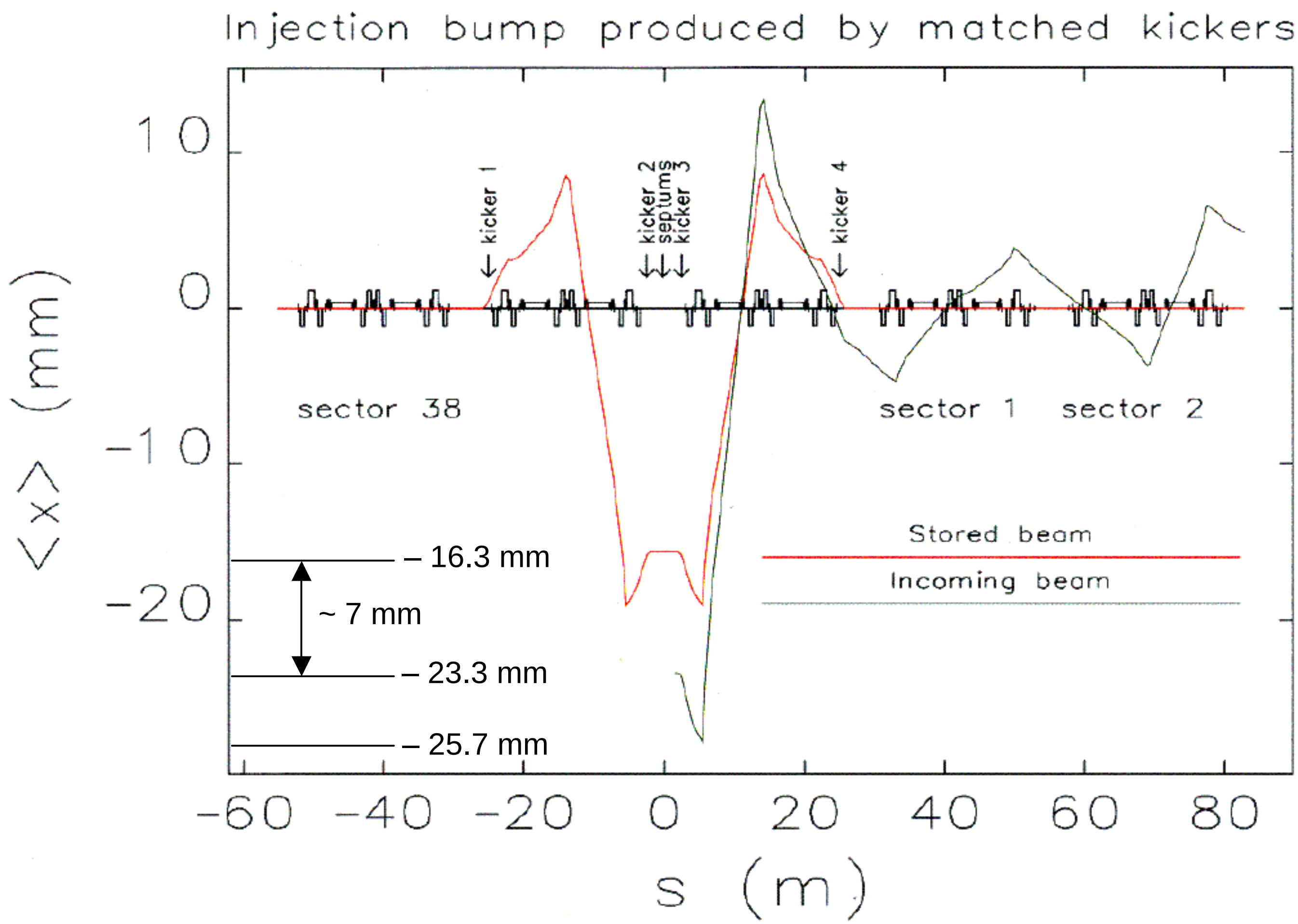
Single turn images (first 12 turns, file 02 .. 15):



From Bingxin Yang: kick stored beam, large x-y coupling

Off-energy injection (from Y.-C. Chae)





Clearance ~7 mm

$\delta = \Delta E/E$ ~1%

η_x ~60 cm

Δx_δ ~6 mm

Δx_β ~1 mm

Realistic parameters!

figure: L. Emery

calc's: Y.-C. Chae

Note: in practice, bump mismatched to share Δx_β perturbation between injected and stored beam

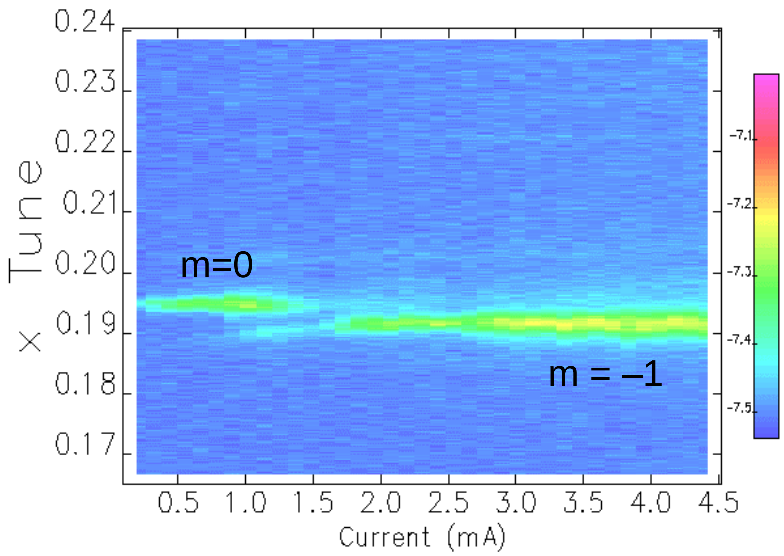
Single bunch instability: transverse mode coupling instability

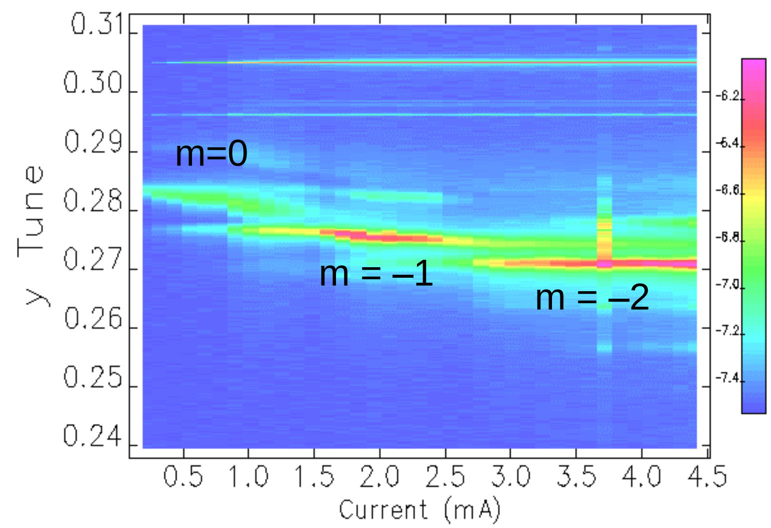
Force due to transverse wake defocuses beam, i.e. detunes betatron frequency

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

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

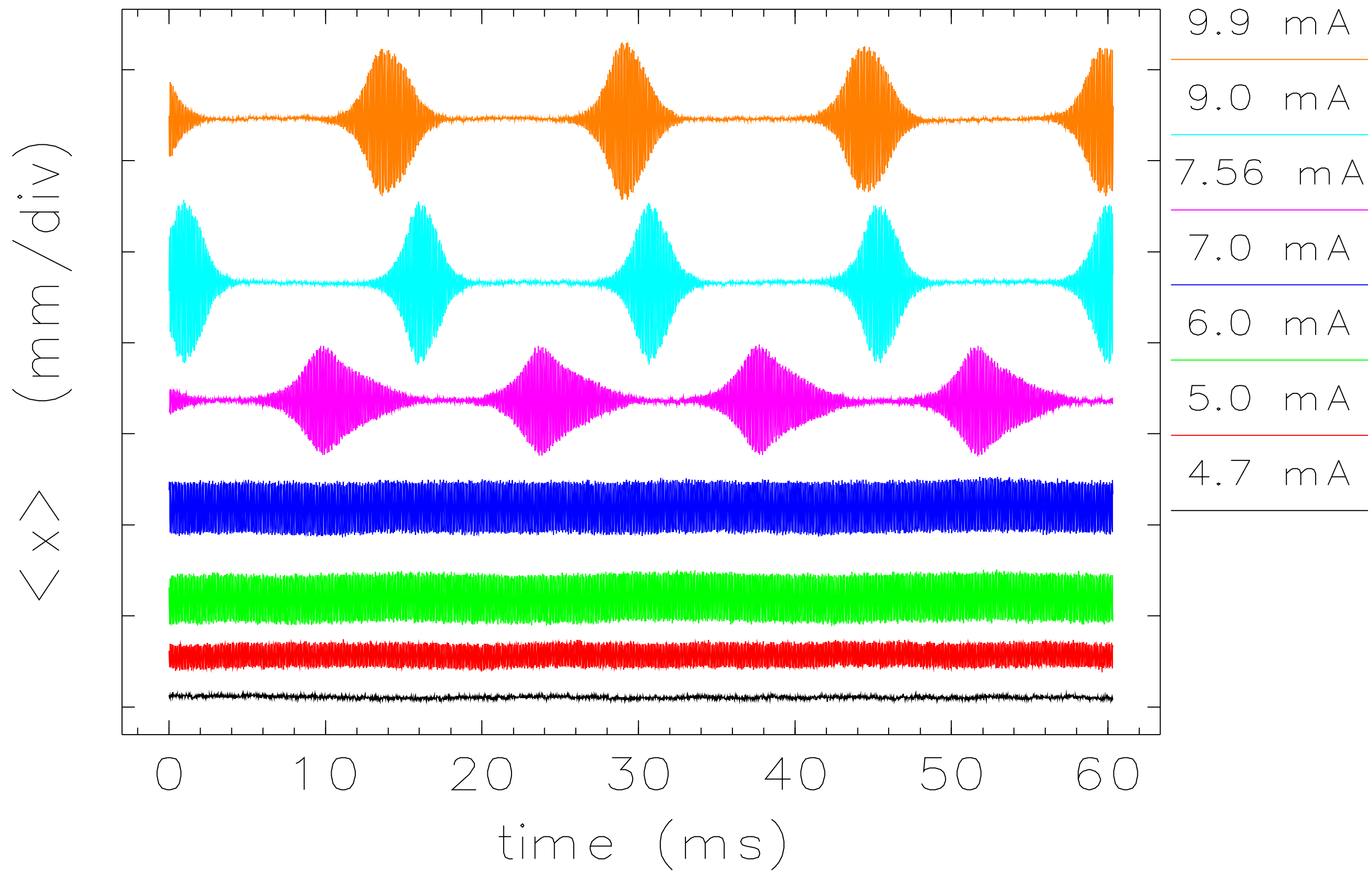
Horizontal **Vertical** (L. Emery)





$\Delta\nu_x/\Delta I$ = -8x10^{-4}/mA $\Delta\nu_y/\Delta I$ = -2.6x10^{-3}/mA

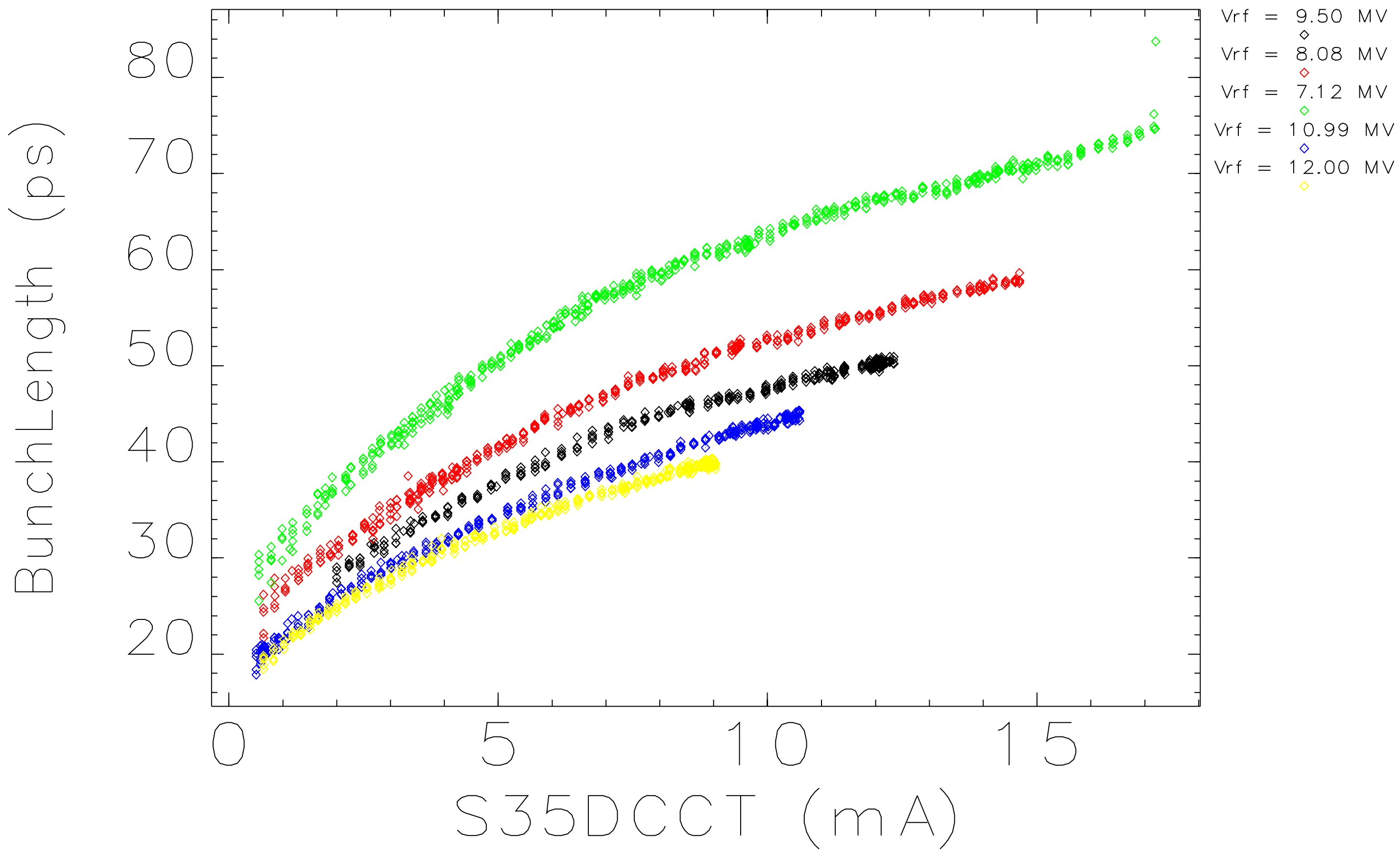
Large <x> oscillations above mode-merging threshold (V_{rf} 9.4 MV case shown): some Users will observe an effective emittance blowup, $\Delta\varepsilon_x$



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))

Measured bunch lengthening vs V_{rf}

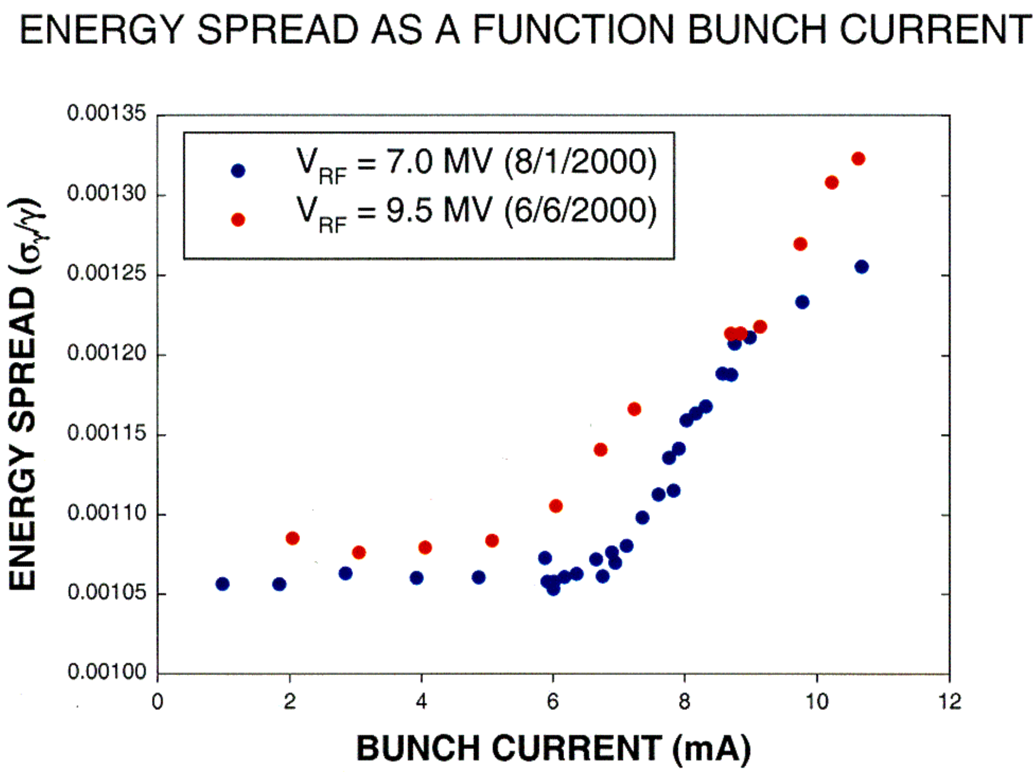
(L. Emery, M. Borland, A. Lumpkin)



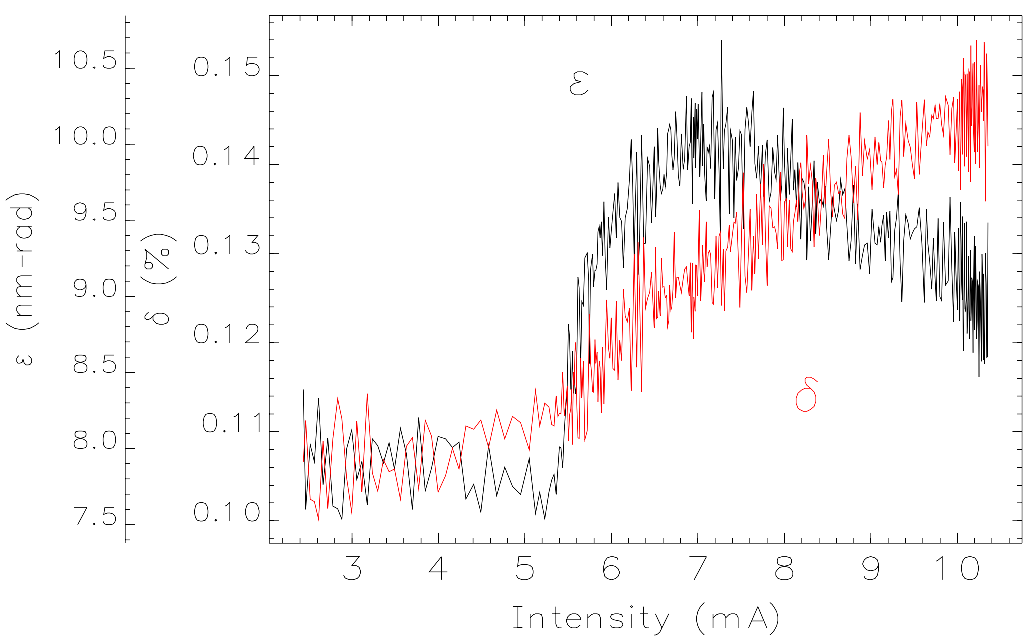
no 5-mm chambers (March 2000)

$Z_{||}/n \approx 0.5\ \Omega$ (estimated, Y.-C. Chae, et al., PAC01)

Measured δ (two methods: note $\xi_{x,y}$ differ) and ε_x vs I_b



ξ_x higher than normal (B. Yang, L. Emery, Y.-C. Chae, K. Harkay)



V_{rf} 7 MV, nominal $\xi_{x,y}$ (B. Yang, K. Harkay, E. Lessner, A. Lumpkin)

Small-gap ID vacuum chamber impedance

Estimated four ways:

1. Z_y determined experimentally from change in tune slope, $\Delta\nu/\Delta I$, as a function of no. of chambers [PAC97, 1700]:

$$Z_y = 50\ \text{k}\Omega/\text{m per chamber x } 20 = 1\ \text{M}\Omega/\text{m}$$

2. Simulations of broad-band resonator impedance model reproduced measured tune slope and threshold for TMCI [PAC99, 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 $\propto 1/b^3$ and geometric according to [Bane and Krinsky PAC93, 3375]

ratio of resistive wall to geometric:

x large : 1 **y** 1 : 1

4. MAFIA calculations of wake potentials: extracted tune slopes for resistive and geometric components (very preliminary) (Chae)

ratio of resistive wall to geometric:

x 7 : 1 **y** 2 : 1

Cures

Injection losses/transients

- Redesigned 8-mm gap vc (Trakhtenberg, Emery, Harkay)
- Off-energy injection (Chae, Milton, Emery)

Lower rf voltage

Higher chromaticity

- increase β at location of sextupoles
- upgrade sextupole power supplies

Active bunch-by-bunch feedback

- instability growth (e-folding) time ~1 ms
- pick-ups and kickers already exist, at least to test prototype

Cures Pros/Cons

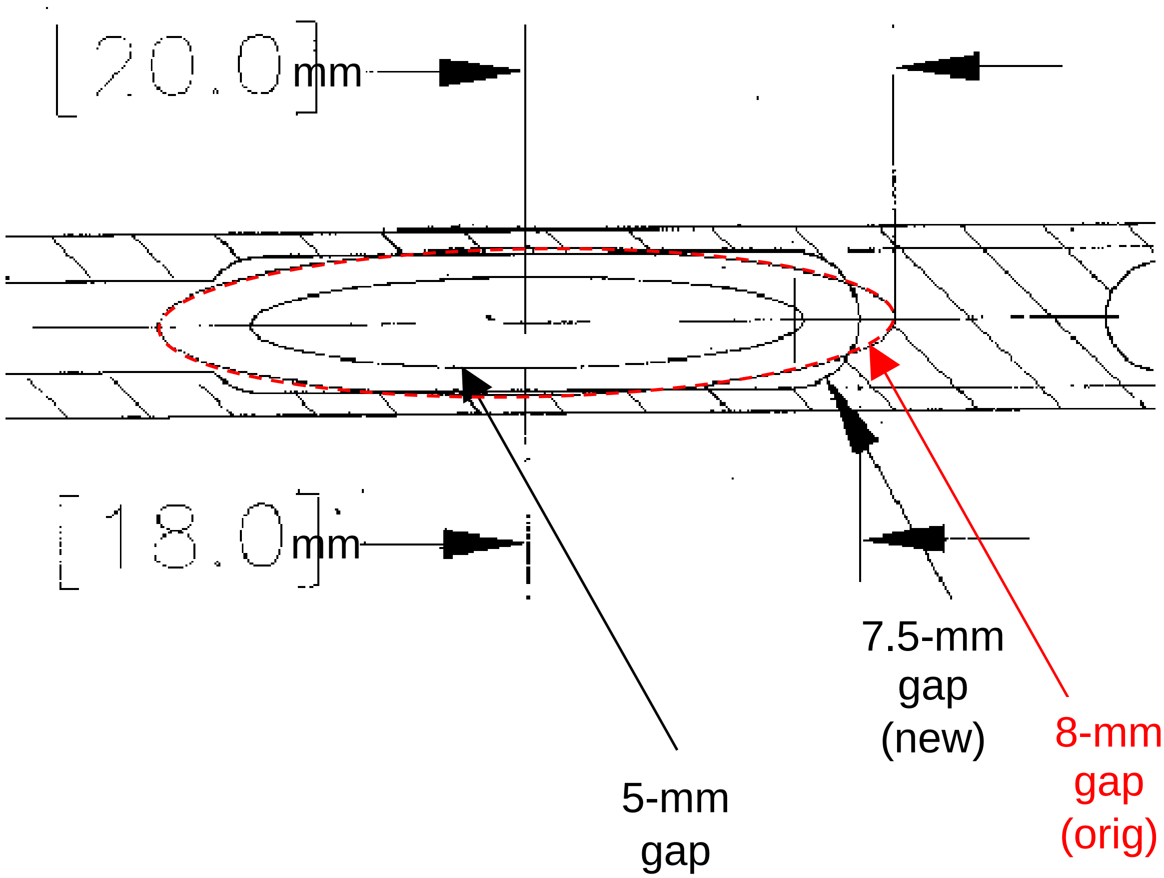
	Pro	Con
Redesigned 8-mm chamber	Incr y aperture at large x: incr accum limit	Time/cost to fabricate/install
Off-energy inject	Δx_β is minimized: • reduce beam losses from x-y coupling + small gap vc • incr accum limit • top-up more transparent • less sensitive to lattice perturb by injection bump	—
Lower V_{rf}	Incr accum limit	• Lifetime degrad • TMCI threshold not sensitive
High ξ $\Delta\nu = \xi\delta$	High I_b by raising TMCI threshold	• Lifetime degrad • dynamic aperture degrad. for asym-metric lattices • Some sextupoles near saturation (PS near limits)
Active bunch-by-bunch feedback	High I_b up to accum limit w/o requiring high ξ	cost

Redesigned 8-mm vacuum chambers

(Trakhtenberg, Emery, Harkay)

New chambers were being designed anyway for 90° rotated bpm's:
original, ellipsoidal 8-mm gap vc (red) being replaced
by more rectangular cross-section 7.5-mm gap vc

5-mm gap vc shown for reference



Issues: increasing chromaticity

7.5 nm-rad lattice

- ΔS3 and ΔS4 contribute to $\Delta\xi_y$, $\Delta\xi_x$
- S3 near saturation; near limit of 250 A (~225 A)

3.3 nm-rad lattice

- S3 near saturation; at limit of 250 A
- TMCI threshold higher for same value of ξ_x as above
- Dispersion (η_δ) everywhere: now ΔS1 and ΔS2 also contribute to $\Delta\xi_x$, $\Delta\xi_y$
- S3 power supply limit no longer as critical
- ΔS1 and ΔS2 also change the amplitude-dependent tune; now mixed with ξ

Ongoing studies

- Coupling impedance (Chae, Emery)
    - Local bump method (PAC01 – Z_y)
    - Local tune shift ($Z_{x,y}$)
    - MAFIA calculations (PAC01 – Z_z)
- Characterize long. instability (Chae, Emery, Yang)
    - Apply $Z_{||}$ calc'd from MAFIA to elegant to reproduce $\Delta\sigma_t/\Delta I$ and $\Delta\delta/\Delta I$
- Characterize transv. instability (Harkay, Lessner, Huang)
    - Instab. threshold, growth rate, and saturation amplitude vs V_{rf}, ξ, $\Delta\nu_x/x^2$, η_δ
    - Use Panofsky-Wenzel theorem to extract Z_{tr} from $Z_{||}$ to reproduce steady-state and bursting bunch dynamics and observed decoherence
- Instability photon diagnostics (Yang, Harkay)
    - Details of decoherence
- Other supporting analysis
    - Amplitude-dependent tune (Crosbie)
    - Tune shift over bursting mode (Sajaev)

Multiple Bunch limiting instabilities

Accumulation limit vs bunch spacing

Bunch pattern, 100+ mA

- Few-bunch operation limited by single-bunch limits
- Somewhere between 80 and 160 buckets, bunches couple to one another transversely and full single-bunch accumulation limit cannot be reached (nominal singlets spacing is 154 buckets)
- In bunch trains shorter than 10-15 bunches, large transverse oscillations seen in tail bunches. Driving impedance source not yet identified.
- Longitudinal coupled-bunch instability observed for particular bunch patterns. Better model needed to predict unstable fill patterns (C. Schwartz, A. Nassiri, K. Harkay)
    - o driven by rf cavity HOMs
    - o fairly easily avoided through choice of spacing of groups of bunch trains (see hybrid mode)
    - o easily cured by changing rf cavity water temperature
- HOM damper prototypes under test (70 dB rejection of fundamental)

Resources Required

- Accelerator physics:
  - machine studies and data analysis
  - modeling in elegant
  - analytical models to describe transverse bursting behavior
  - predict instability thresholds and growth rates for full suite of small-gap chambers
  - evaluate options to decrease β_x to decrease tune slope (raise TMCI threshold) or increase chromatic correction through increasing $\beta_{x,y}$ at sextupoles

- Engineering:
  - Design of active feedback system
  - Evaluate existing pick-ups and kickers

Summary

- Single bunch instability (TMCI) threshold below current limit for positive chromaticity: I_{TMCI} is effective limit due to centroid oscillations
- Trade-offs required between passive (chromaticity, Vrf) and active damping
- Certain limits of passive options are almost reached; however, for example, beam lifetime may not be a serious limit in top-up operation
- Multi-bunch operation up to 200-300 mA not an issue for low current/bunch
- Multi-bunch operation with few bunches a challenge in 7.5 nm-rad lattice if much more than 5 mA/bunch required; appears okay in 3.3 nm-rad lattice up to at least 130 mA in 1+22S.
- Characterizing single bunch thru impedance modeling:
  - Z_{tr} from tune slope and BBR model fit some aspects of data, but not the instability dynamics above the I_{TMCI} threshold
  - $Z_{||}$ from MAFIA calculations of detailed vacuum chamber component inventory (Y.-C. Chae, L. Emery); R-L-C model
  - Modeling with calculated $Z_{||}$ to be compared with measured bunch lengthening and energy spread
  - We hope to derive the calculated Z_{tr} next and try to reproduce TMC instability data