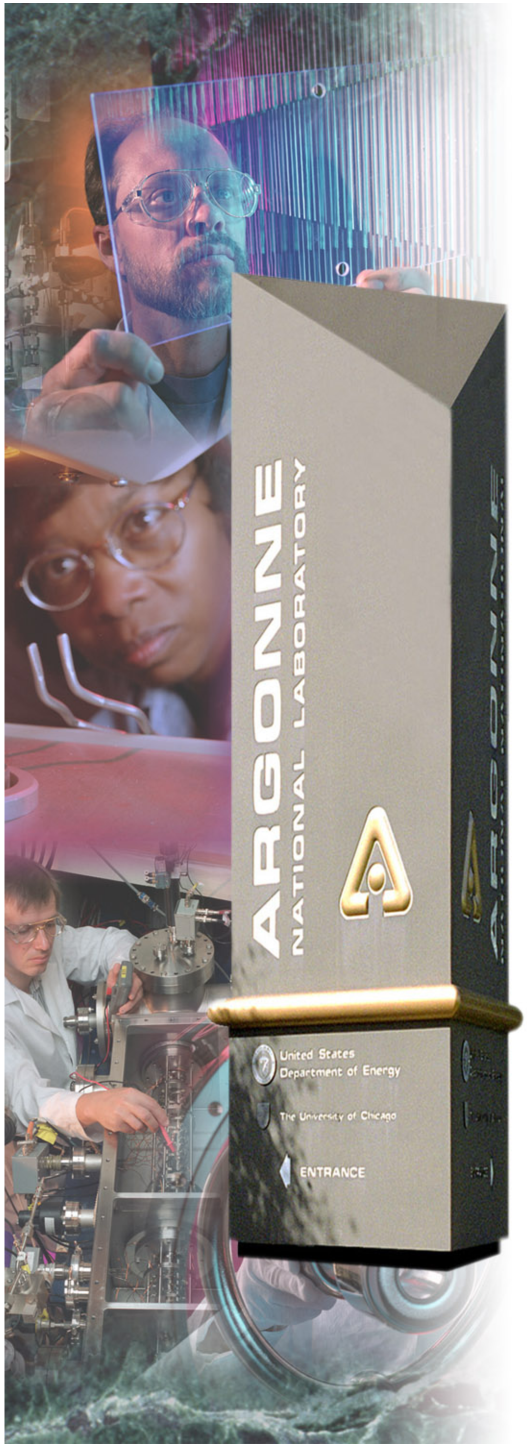


Characterizing the Impedance and Mitigating Instabilities at the APS

K.C. Harkay
Advanced Photon Source, ANL

Acceleratory Physics Seminar
DESY, 2004 Nov. 10

Office of Science
U.S. Department of Energy
A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Acknowledgements

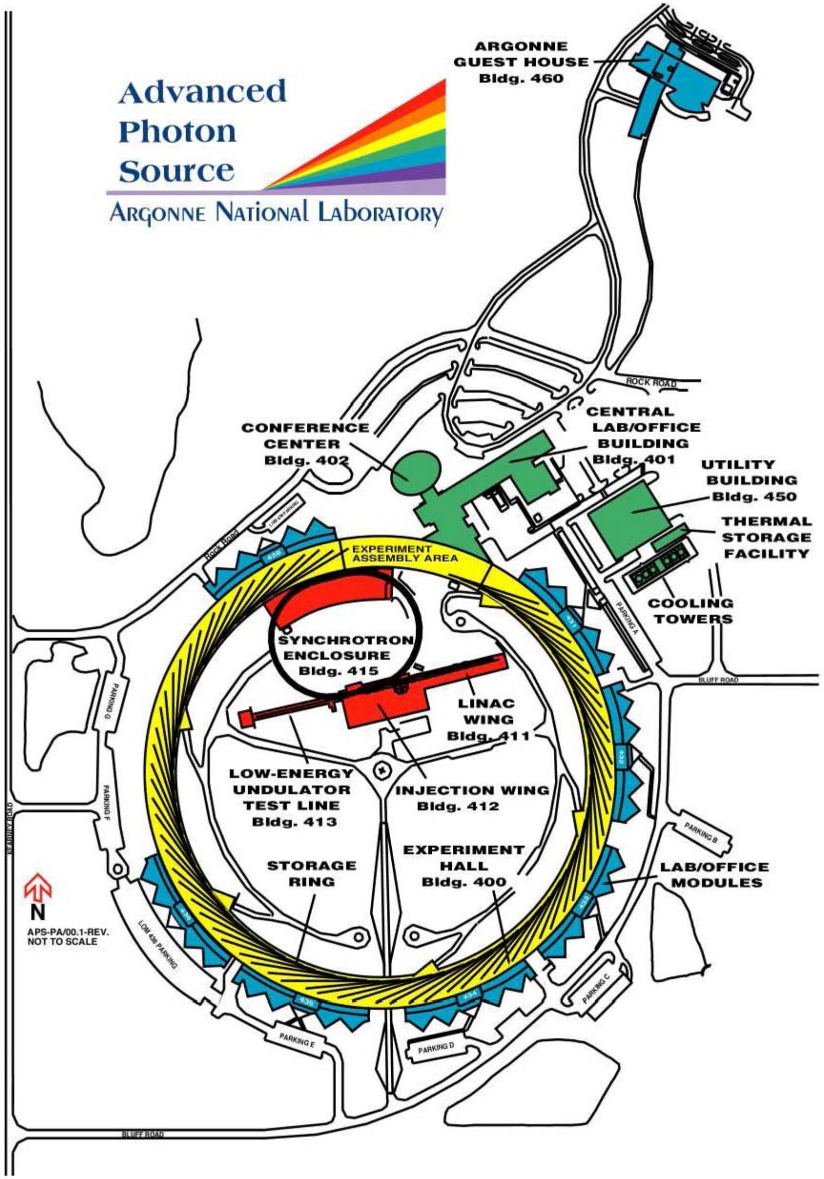
Thanks to many people

- M. Borland, L. Emery, H. Shang, R. Soliday, C. Yao from Operational Analysis Group (accelerator physics and Linux cluster & software)
- Y.C. Chae, V. Sajaev, C.X. Wang, from Accel Phy Group
- L. Loiacono from Loyola U.
- E. Moog, S. Milton, E. Trakhtenberg, R. Rosenberg from XFD
- M. Petra from AOD
- G. Waldschmidt, A. Nassiri, R. Kustom, Y. Kang (former) from Rf group
- S. Sharma, L. Morrison from Mech Eng Group
- P. Choi, E. Rossi from Design/Draft Group
- X. Sun, G. Decker, O. Singh, A. Lumpkin, B. Yang, L. Erwin from Diag Group
- APS Operations Group
- J. Galayda (former APS, now LCLS)

Outline

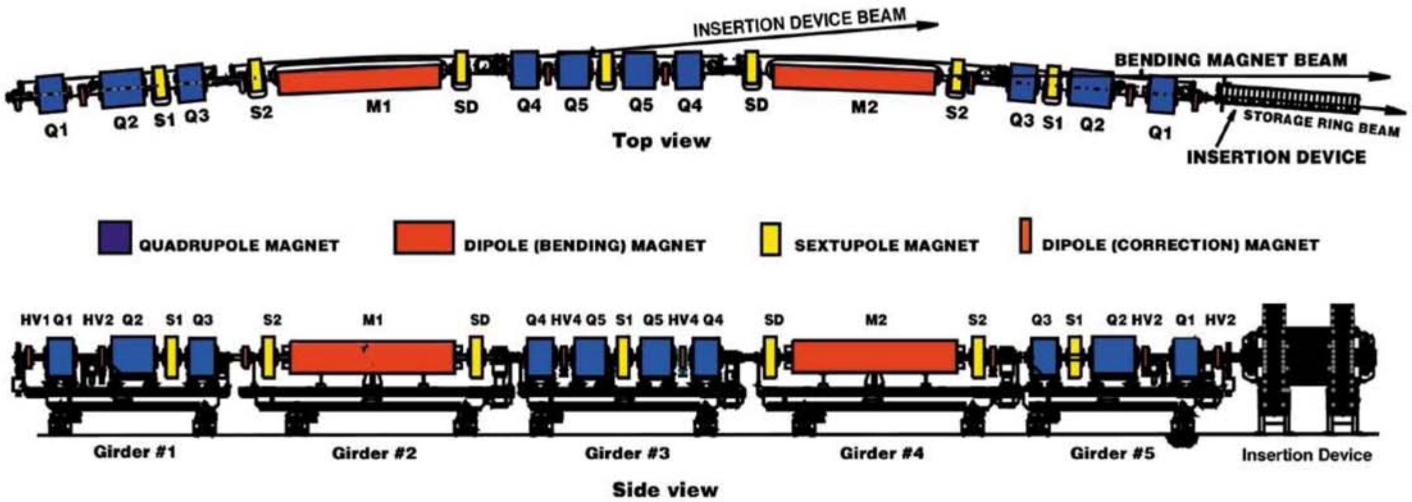
- **Introduction**
- **Recent performance enhancements**
- **Instabilities**
  - Single bunch
  - Multi-bunch
  - Feedback
  - Electron cloud, ions, dust
- **Impedance**
  - Impedance database
  - Beam-based measurements
- **Summary**

Advanced Photon Source site



Linac	325 / ≤450 MeV (APS / FEL)
	8 ns macropulse; 2.8 GHz
	3 nC/pulse (topup)
PAR	9.77 MHz, 117 MHz rf
Booster	7.0 GeV synchrotron
	352 MHz rf (2.84 ns)
	2 Hz rep rate
Storage Ring	7.0 GeV
	1104 m circumference
	h = 1296
	9.0 MV rf voltage (typ.)
	2.9e–4 momentum compaction
ε_x	2.4 nm (3.0 nm eff.)
	1% coupling
$\nu_x / \nu_y / \nu_z$	36.2 / 19.25 / 0.007
$\tau_x / \tau_y / \tau_z$	9.5 / 9.5 / 4.7 ms
$\xi_{x,y} = \Delta\nu_{x,y} / (\Delta p/p)$	6, 6 (typ.)
Total current	100 mA (typ.) 225/300 mA max/design
Single bunch limit	5 mA (8 mA higher ξ)

One Sector of the Advanced Photon Source Storage Ring



APS operation – 100 mA

- **Standard (~75%)**
  - 24 bunches, uniform spacing (54 λ_{rf})
  - 4.25 mA single-bunch current (τ ~ 7-9 h)
  - Top-up, 2-min intervals

- **Special operating modes (typ. 1-2 weeks ea. per run)**
  - Hybrid mode (1+56), top-up: 8 mA single bunch, $\pm$1.3 μs gap (τ ~ 25 h)
  - Many-bunch mode, non-top-up: 324 bunches, uniform spacing (4 λ_{rf}) (τ ~ 70 h)
  - Operator training, injector studies, FEL user experiments

Outline

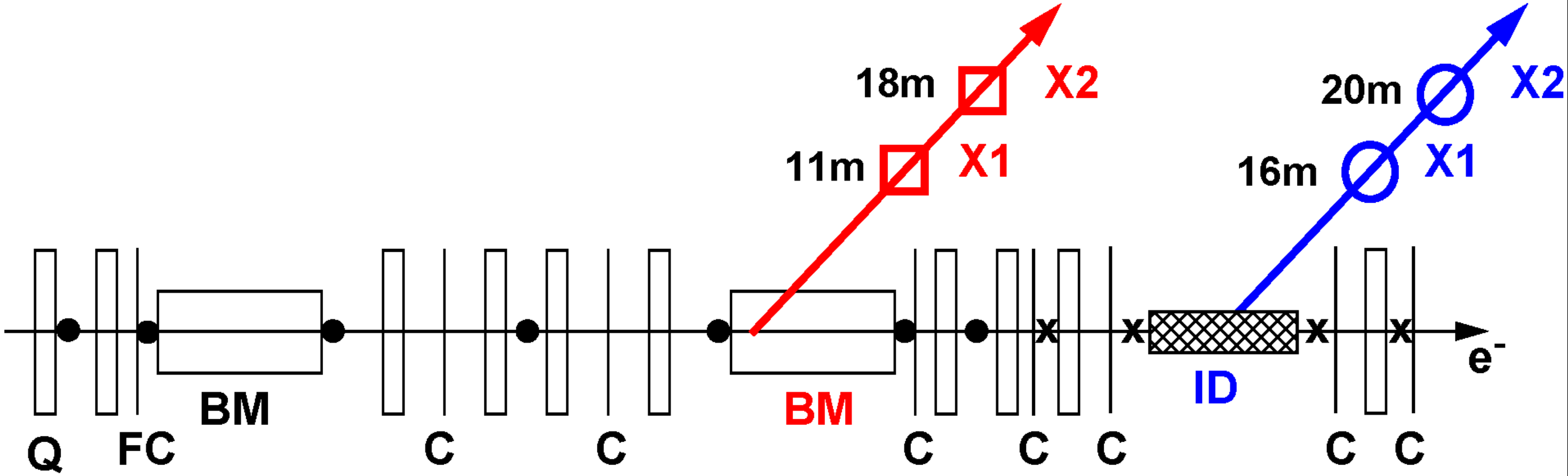
- Introduction
- **Recent performance enhancements**
- Instabilities
  - Single bunch
  - Multi-bunch
  - Feedback
  - Electron cloud, ions, dust
- Impedance
  - Impedance database
  - Beam-based measurements
- Summary

Recent performance enhancements…

… and indirect impact on or of instabilities

- Accurate machine model, lattice correction (orbit response matrix method), lifetime, top-up (V. Sajaev, L. Emery)
  - Ongoing improvements allow lower sextupole strength for given chromaticity; allowed 8 mA bunch in hybrid mode
  - Technique applied to measure local impedance: ID chambers
- Low emittance (V. Sajaev, M. Borland, L. Emery)
  - 324-bunch mode requires higher-than-expected chromaticity; gap raises threshold. Speculation: fast ions?
- 5-mm chambers and radiation damage of ID permanent magnets
- X-ray bpm's in orbit correction (G. Decker)
  - Improved long-term (24 h) stability to 1-2 μm rms
  - Ring distortions carried out over yrs; rf frequency evolution caused problems with HOM-driven CB instabilities

Beam Position Monitors and Magnets in One Sector



- ● : Broad-band RF Beam Position Monitors (7) (Turn-by-Turn)
- x : Narrow-band RF Beam Position Monitors (4) (~ 300 Hz)
- □ : BM X-ray Beam Position Monitors (2 - Vertical Only) (~165 Hz)
- ○ : ID X-ray Beam Position Monitors (2) (~165 Hz)
- FC : "Fast" Corrector Magnet (1) (~ 1000 Hz)
- C : "Slow" Corrector Magnets (7) (few Hz)
- Q : Quadrupole Magnets

“Chasing” HOMs

- **16 single-cell 352 MHz rf cavities**
- **HOM frequencies controlled through**
  1. Staggering cavity lengths
  2. Tuner set-point
  3. Cavity water temperature (per 4-cavity sector)
- **HOMs shift as rf frequency increased for each sector distortion (over years)**
  1. Staggering sufficient until ca. July 2002; longitudinal CBI driven by HOM near 540 MHz, 23(24)-bunch mode
  2. Detuning required to stabilize above 85 mA
  3. Detuning insufficient after ca. Spring 2003; increase water T, but beam unstable for low rf voltage (for better lifetime)
- **HOM dampers installed Sep 2004 – beam stable over wide range of rf voltage (study ongoing)**

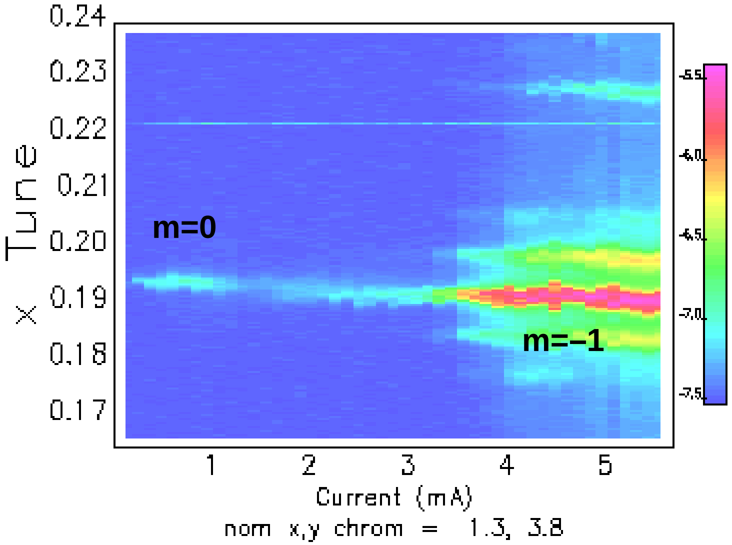
Outline

- Introduction
- Recent performance enhancements
- **Instabilities**
    - Single bunch
    - Multi-bunch
    - Feedback
    - Electron cloud, ions, dust
- Impedance
    - Impedance database
    - Beam-based measurements
- Summary

Single-bunch instability: transverse mode-coupling

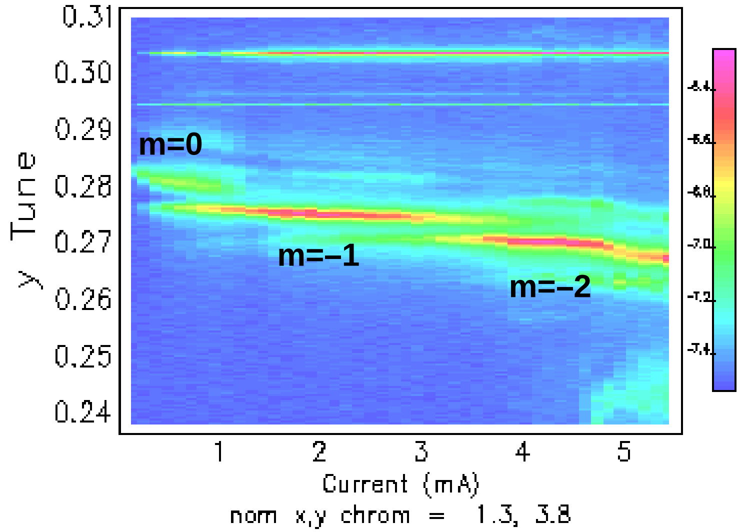
- **Transverse wake defocuses beam; i.e., detunes betatron frequency**
- **When ν_β crosses ($m\nu_s$) modulation sidebands, synchrotron motion can couple to transverse plane and beam can be lost unless chromaticity sufficiently large/positive**
- **Tune slope increases with number of ID chambers; mode merging threshold decreases, requiring ever-larger chromaticity to recover single bunch current.**

Horizontal



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

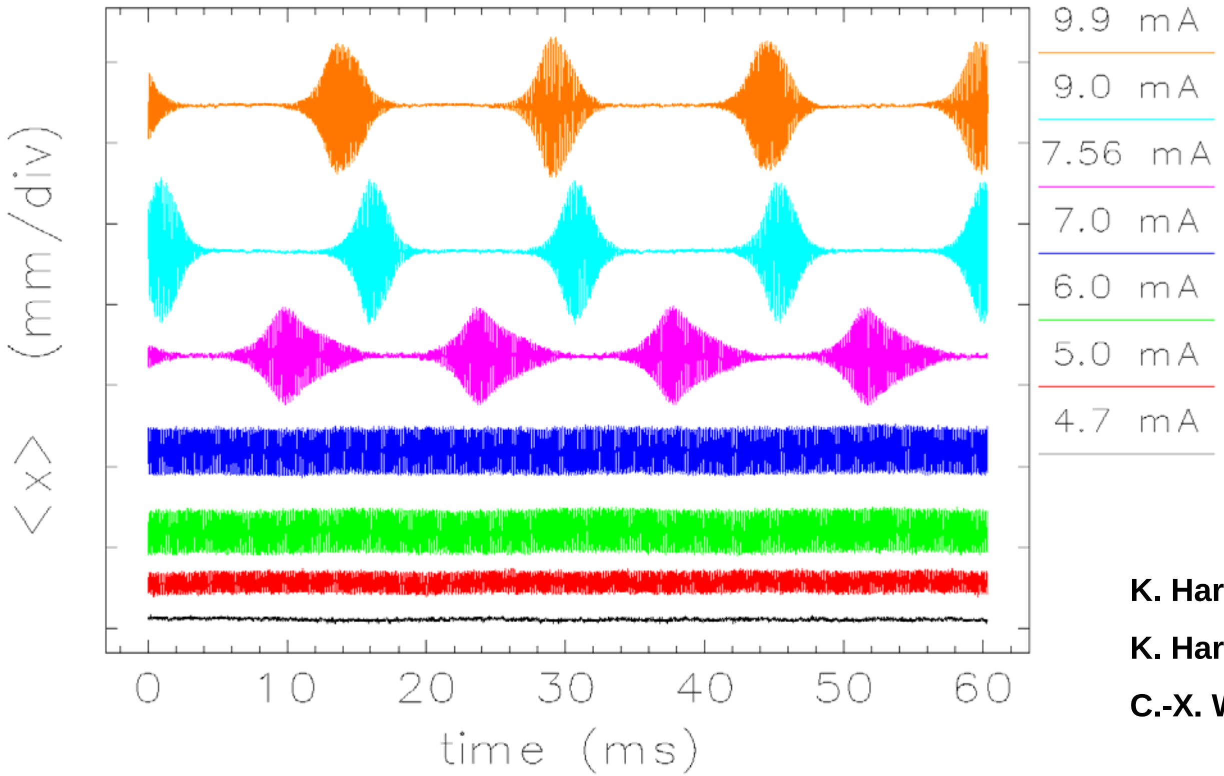
Vertical



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

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

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



K. Harkay et al., 1999 PAC, 1644.

K. Harkay et al., 2001 PAC, 1919.

C.-X. Wang, K. Harkay, 2002 EPAC.

Note: bunch length σ_z, energy spread δ, and emittance ε_x also vary with current

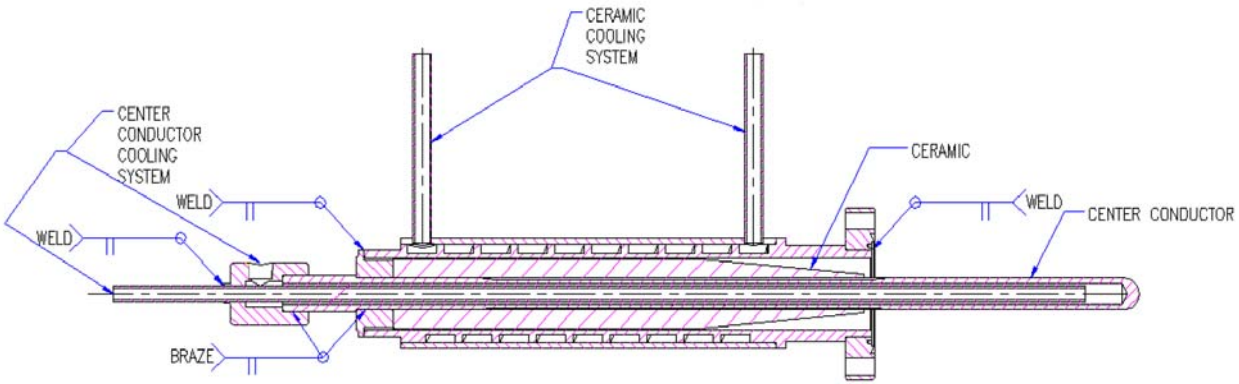
(ε_x decoherence NOT 100% of <x> oscillation amplitude; σ_x = 220 µm (7.5 nm-r lattice))

Outline

- Introduction
- Recent performance enhancements
- **Instabilities**
  - Single bunch
  - Multi-bunch
  - Feedback
  - Electron cloud, ions, dust
- Impedance
  - Impedance database
  - Beam-based measurements
- Summary

HOM dampers

- **Machine study identified HOM near 540 MHz as most responsible for CBI in 24-bunch mode; worst two cavities in same sector**
- **This mode identified as potentially dangerous in early 1990s analysis by R. Kustom et al., and by L. Emery. There are other HOMs as well.**
- **HOM dampers designed, high-power tested and installed in four cavities in same sector (Fig. courtesy G. Waldschmidt)**



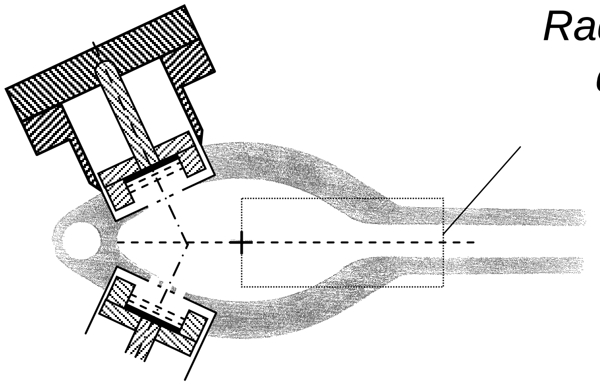
- **HOM power being monitored, preliminary results**

Fast Feedback

- **None presently exists (only orbit feedback up to 60 Hz)**
- **Multibunch**
  - Near-term strategy: pursue passive HOM damping
- **Single bunch: rise times ~0.5 ms.**
  - Preliminary feedback studies underway (simulation, prototype tests)
  - Overall strategy being developed (impedance reduction vs. active feedback)

Electron cloud at APS

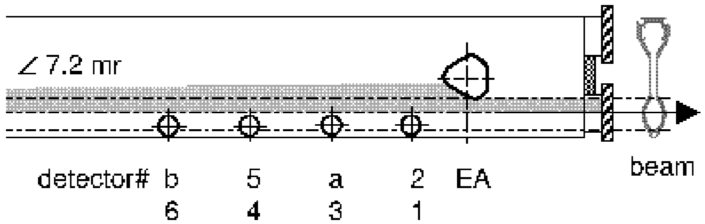
- Operated electron beam for first year, positron beam for two years, reverted back to electrons in 1998
- With positron beams, we were asked why we don't see electron cloud (EC) effects with Al chambers
- Installed RFA to measure distribution of EC colliding with walls



Radiation fan at det. #6 for $E_\gamma \geq 4$ eV

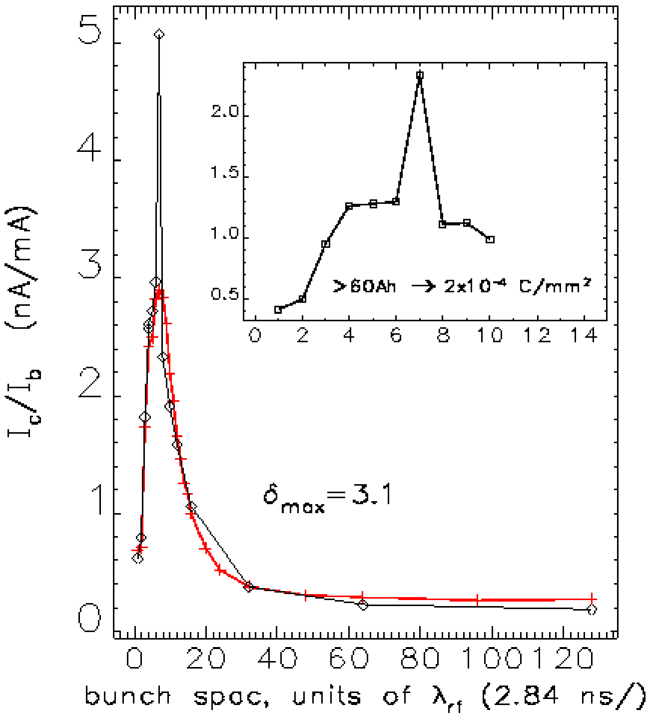
mounting on APS Al chamber ***behind vacuum penetration*** *(42* x *21 mm half-dim.)*

mounting on 5-m-long APS chamber, top view, showing radiation fan from downstream bending magnet

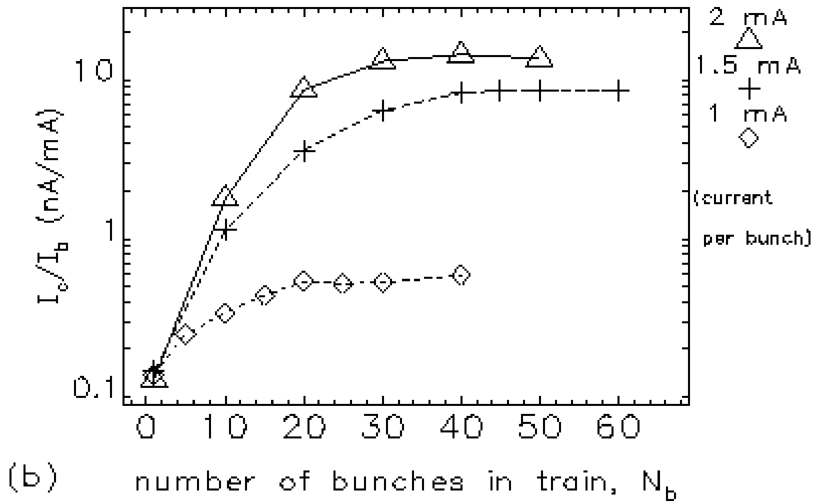


Cloud build-up and saturation: positrons

Black: RFA data; Red: POSINST simul. (LBL)



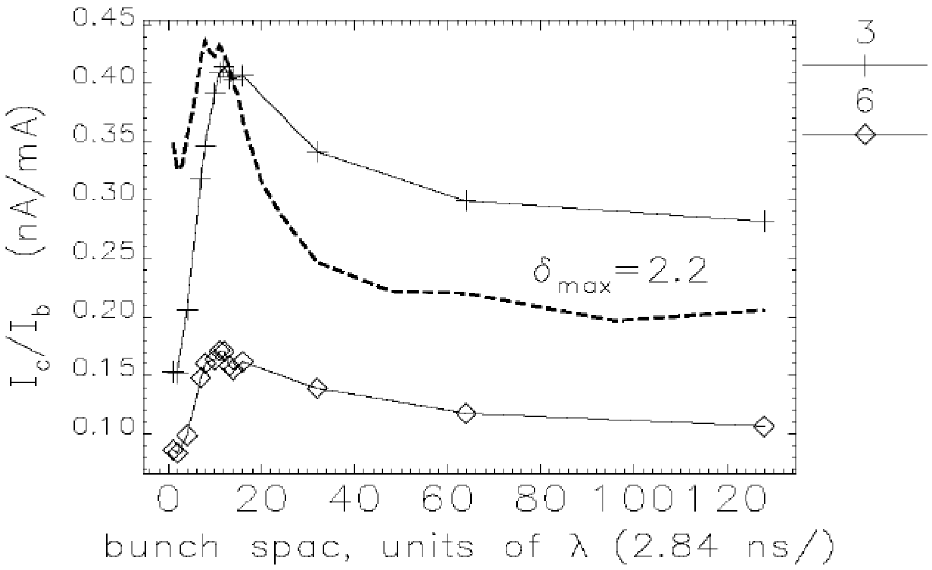
APS: EC saturates after 20-30 bunches (middle of straight); level varies nonlinearly with bunch current (7λ_{rf} bunch spacing)



Calculated EC density at saturation (e+ beam)

- **KEKB 6e11 m-3 (no solenoid)**
- **APS 10e10 m-3 (")**
- **PEPII 10e10 m-3 (between solenoids) (see Proc. ECLOUD'04)**

EC and electron beams



K. Harkay, ICFA Newsletter 33 (2004).

- EC signals down an order of magnitude compared to e+ beam
- Comparison of RFA data (solid) with POSINST (dashed) not as good as for e+ beam
- Did observe lifetime degradation for certain electron beam bunch trains (EC-stimulated gas desorption); effect now gone
- Used same input parameters to model EC wall flux for APS SC undulator design. Wall heating could reach 1 W/m, a potential impact on cryogenic cooling design. Experiments planned.

Ions, dust

- **Few dust events very early in APS operations**
- **NEG is well separated from beam chamber (possible source of dust in rings like PEP-II)**
- **Transverse coupled-bunch instability observed recently in many-bunch mode**
  - Not observed with high emittance many years ago (what else is different?)
  - 324-bunch mode required unexpectedly high chromaticity (too high for bunch current)
  - Gap in ring raised the threshold
  - Possible fast-ion instability (growth rate ~ $1/\sigma_y$)
  - Future machine study planned varying the coupling

Outline

- Introduction
- Recent performance enhancements
- Instabilities
  - Single bunch
  - Multi-bunch
  - Feedback
  - Electron cloud, ions, dust
- **Impedance**
  - Impedance database
  - Beam-based measurements
- Summary

Main contributions to impedance

Single-bunch instabilities

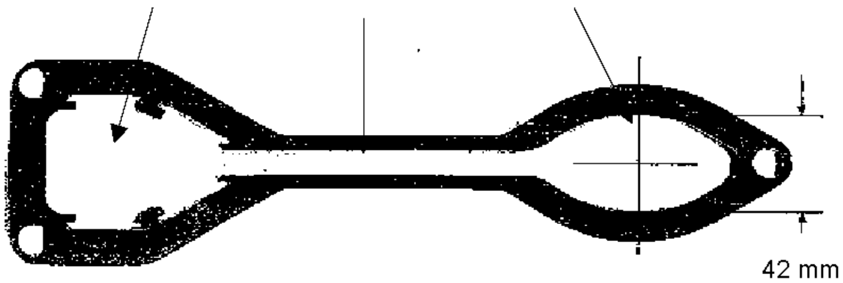
- **small-gap ID chambers**
- **resistive wall impedance (horizontal)**
- **geometric impedance (transitions) (vertical)**
- **other discontinuities: rf fingers, kickers, scraper "cavity"**
- **"trapped" chamber modes?**

Multibunch instabilities

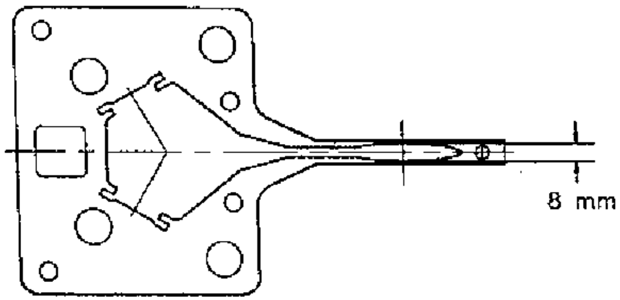
- **rf cavity higher-order modes (HOMs)**
- **other discontinuities: scraper "cavity"**
- **"trapped" chamber modes?**

APS ID chambers

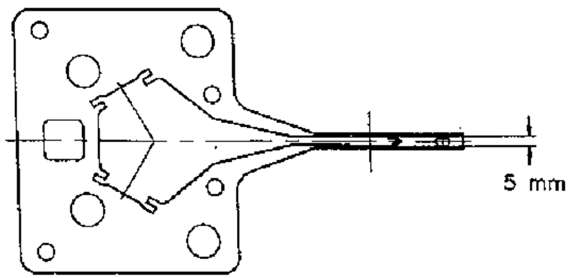
Standard

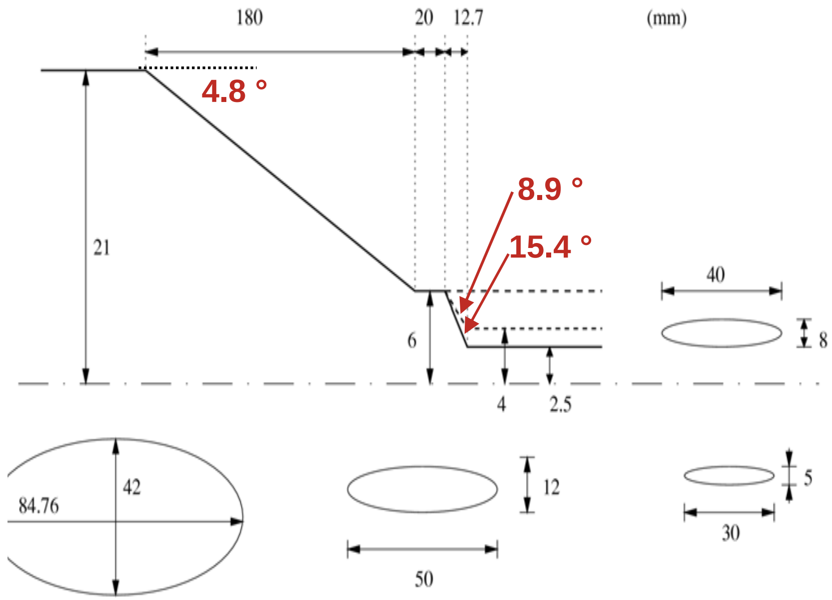


8-mm gap ID chamber



5-mm gap ID chamber





Impedance Database *(Y.C. Chae)*

GOAL:
Total Wake Potential

$$W_{total} = \sum_{Element} N_i * W_i * \alpha_i ,$$

W_{total} = total wake-potential of the ring,

N_i = number of the element in the ring,

W_i = wake-potential of the element,

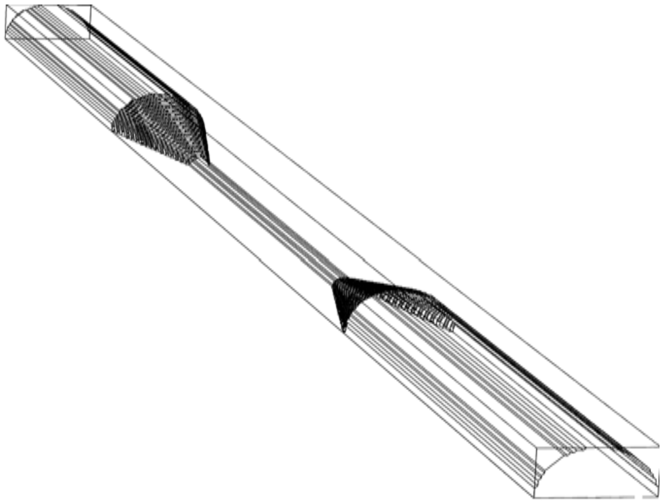
α_i = weight of the element.

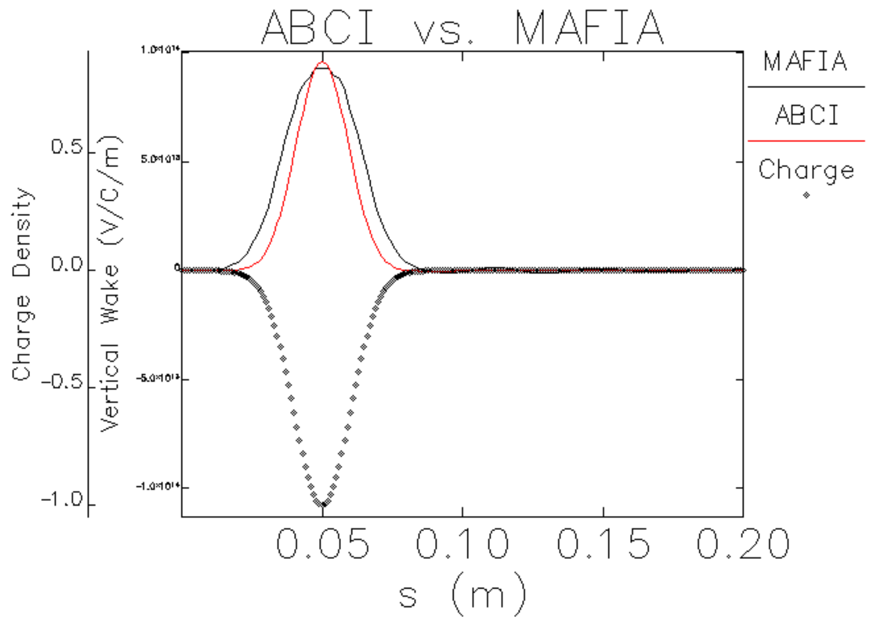
Method:
Standard Wake Potential

1. Data in SDDS forms: s, Wx, Wy, Wz
2. Uniform Simulation Condition
   - Rms bunch length = 5mm
   - Mesh size smaller than 0.5 mm
   - Wake length larger than 0.3 m
3. Deposit the authorized wake potentials in the designated directory
   ➔ Available to everyone who has access

After construction: validate through simulation and compare to measured results

ID Chamber: 3-D MAFIA vs. 2-D ABCI (Y.C. Chae)





Geometry: Circular transition
Simulation: MAFIA 3-D, ABCI 2-D

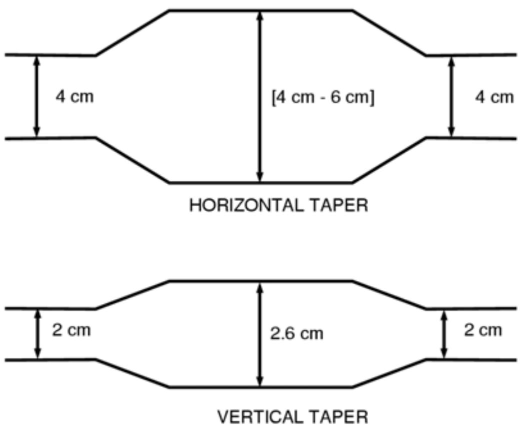
Good agreements ➔
Confidence in 3-D MAFIA simulation

ID Chamber: Horizontal (Y.C. Chae)

1. E-Wake is POSITIVE (DEFOCUSING)
2. H-Wake is NEGATIVE (FOCUSING)
3. Cancels Each Other ➔ Negligible!

CONJECTURE

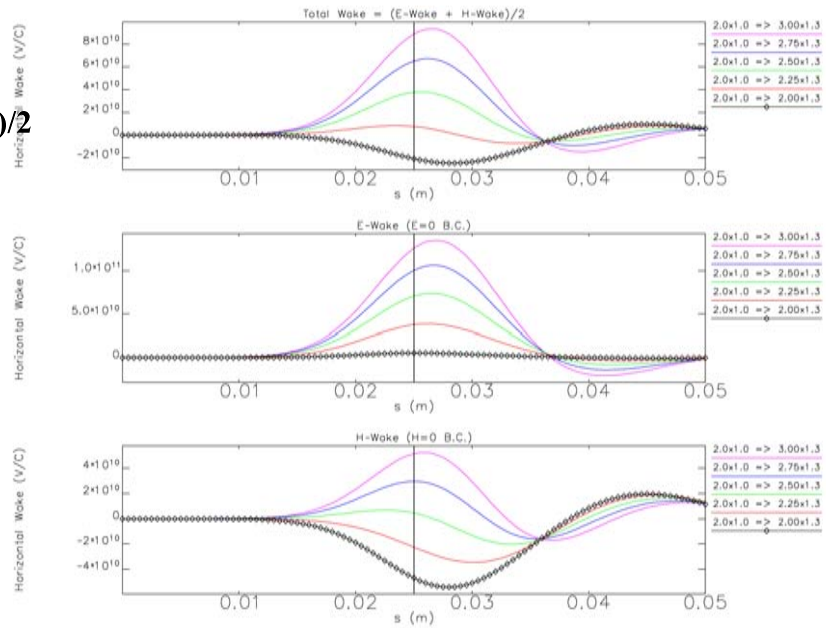
1. **The negative wake potential is a completely 3-D phenomena,**
2. **Can occur when degree of perturbation in one dim. greater than in the other,**
3. **The negative wake potential is in the plane of the smaller perturbation.**



TOTAL= (E-WAKE+H-WAKE)/2

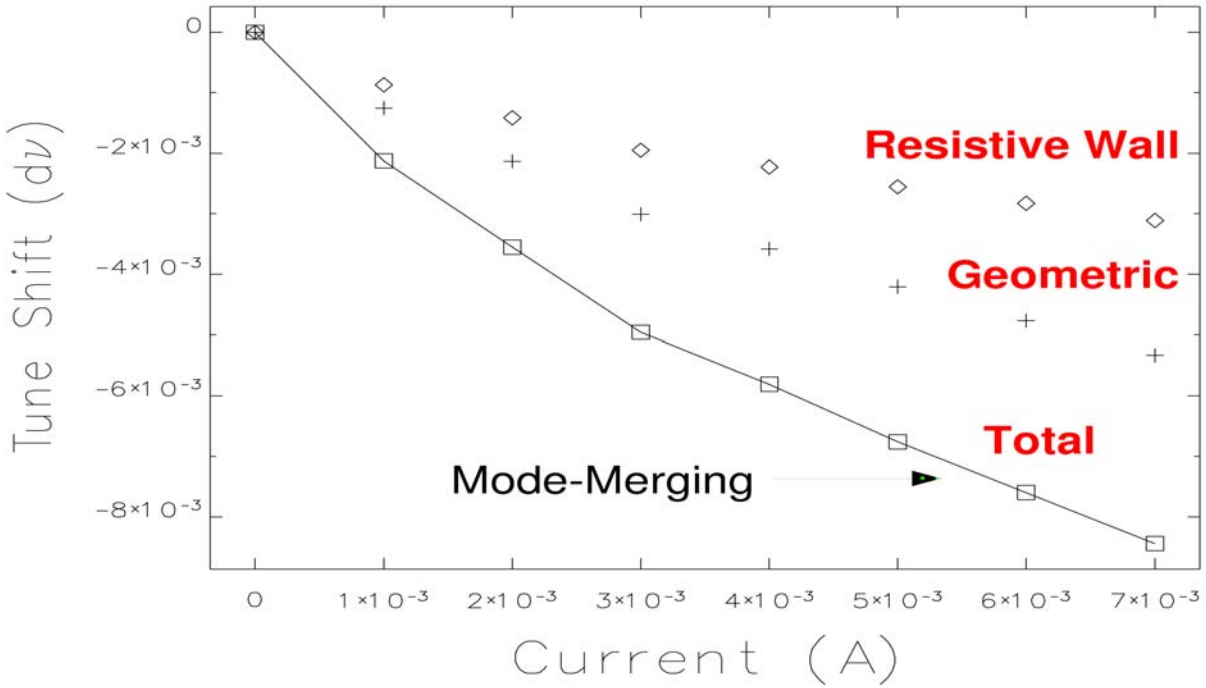
E-WAKE

H-WAKE



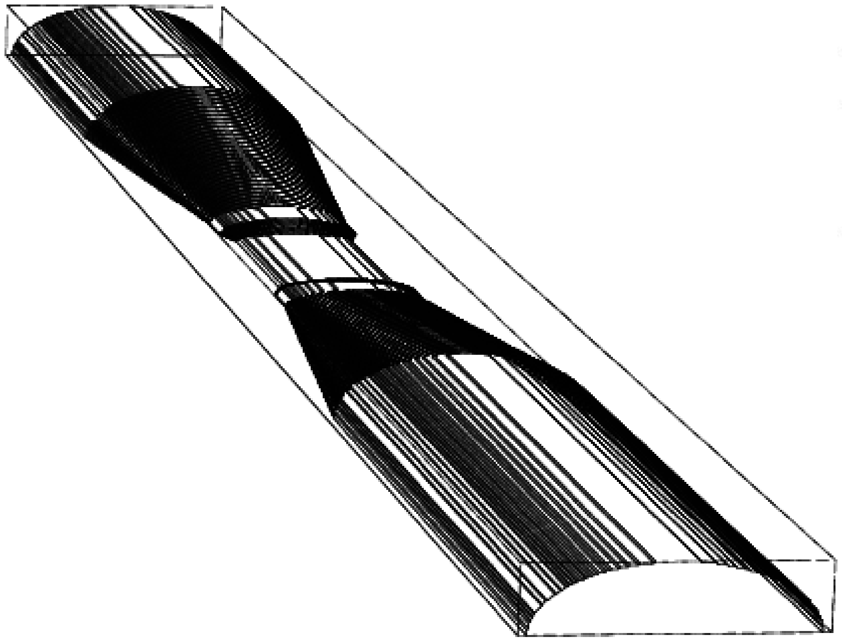
Tune Shift: Horizontal *(Y.C. Chae)*

Mode-merging about 5 mA

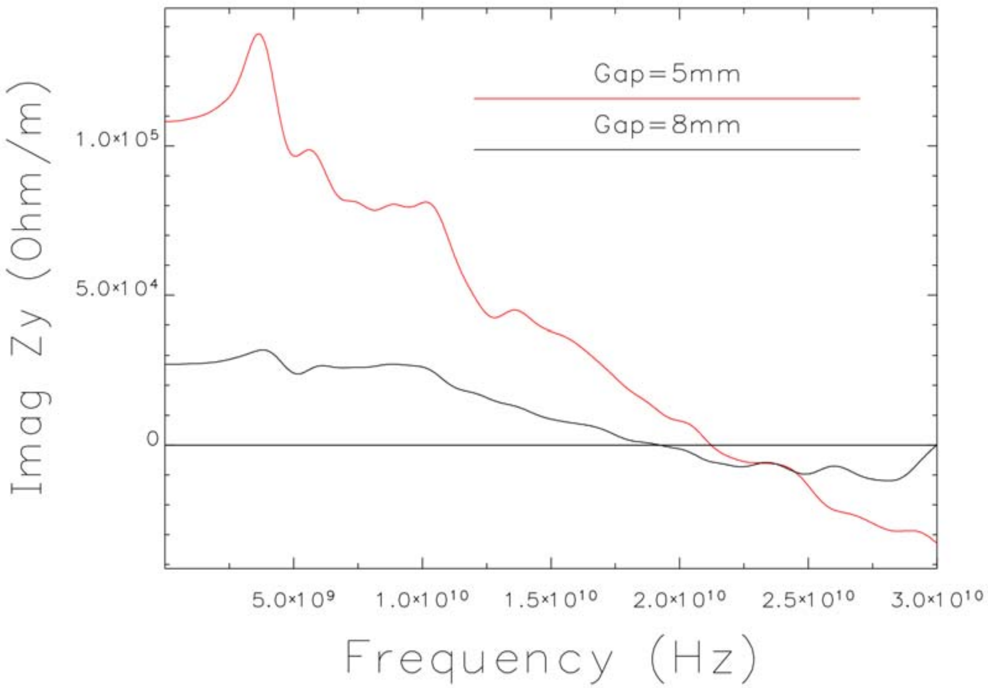


*Horizontal tune slope is difficult to measure; broad and weak.

***ID Chamber: Vertical** (Y.C. Chae)*



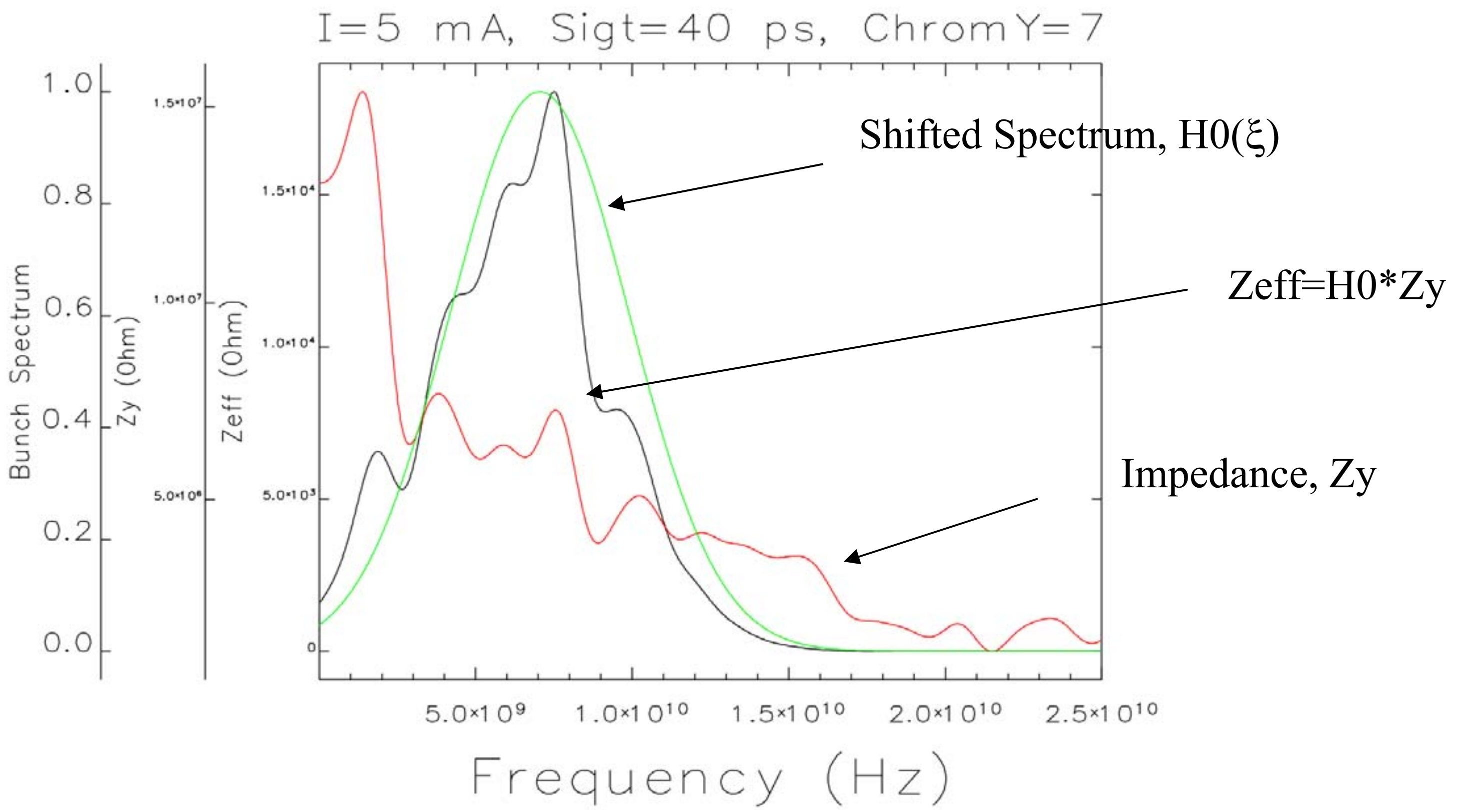
Geometry



Impedance ∝ 1/b**3

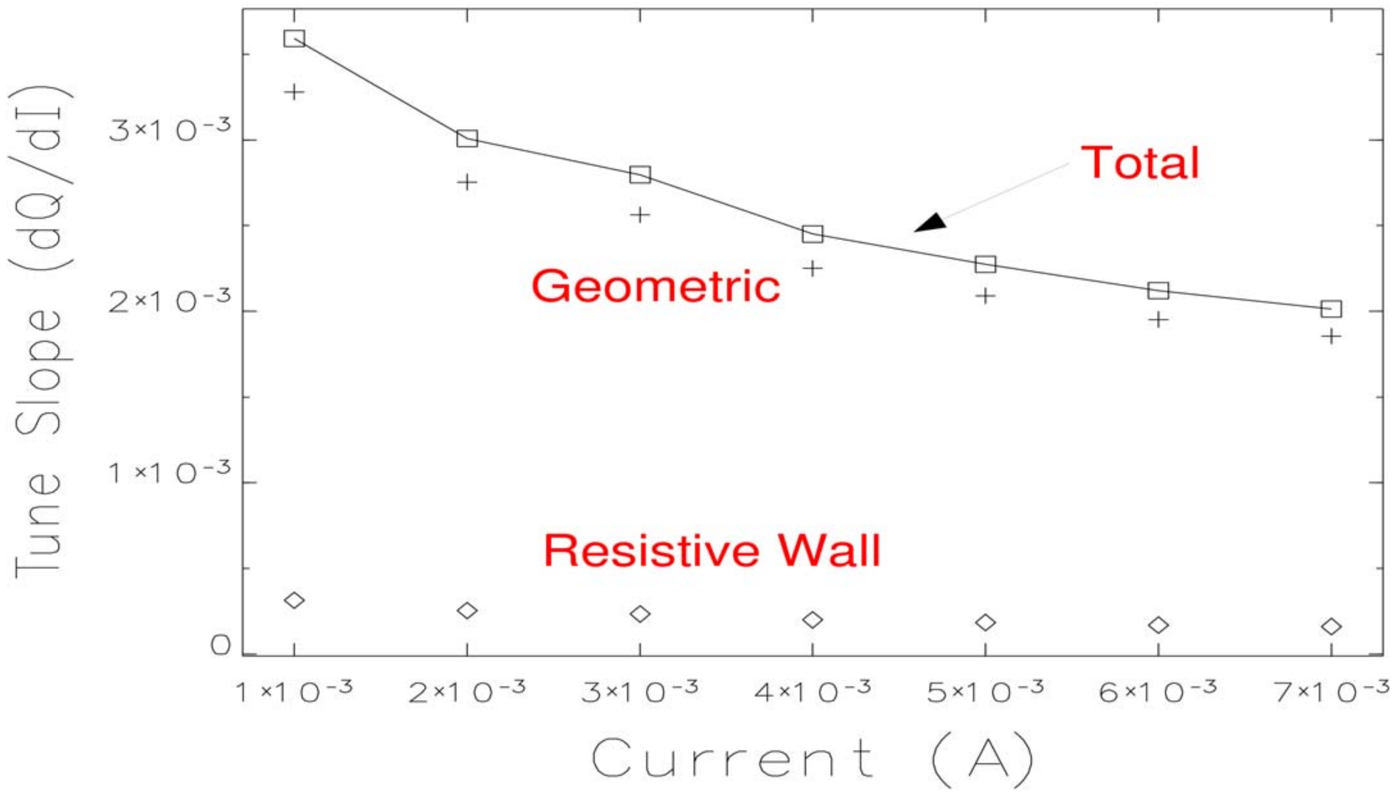
Tune Shift: Formula (Y.C. Chae)

$$\frac{d\nu}{dI} = \frac{R}{2\pi\sigma_s E/e} \sum_{Elements} \beta Z_{eff},$$



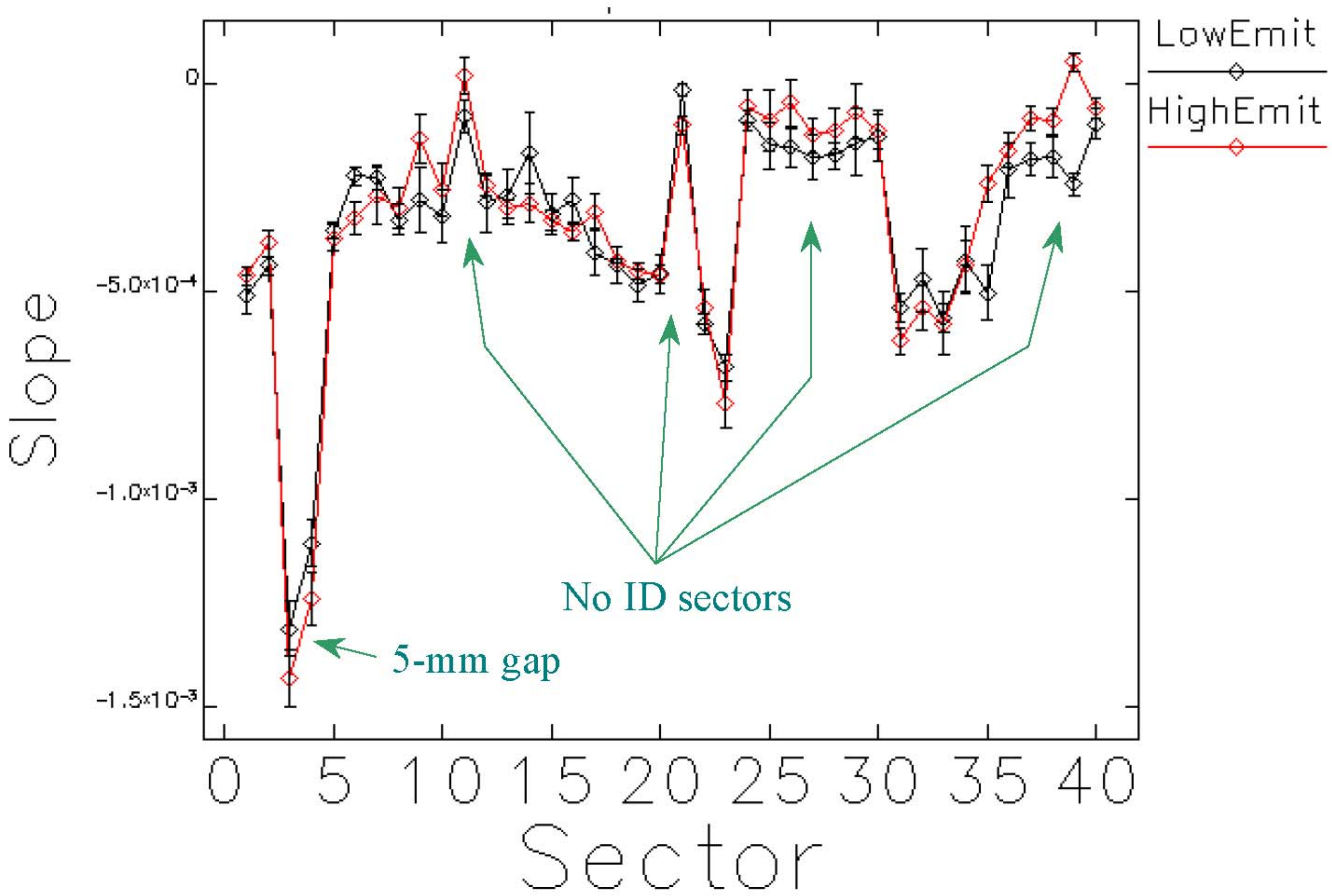
Tune Shift: Vertical

Calculated Tune Slope = 2.2e-3/mA
Measured Tune Slope = 2.4e-3/mA



Alternative method: obtain betatron phase difference for different bunch currents using orbit response matrix method

Vertical betatron phase slope distribution



Analysis courtesy V. Sajaev (2003 PAC)

Vertical impedance calculation

For a particular component, the effective impedance can be found from measured slopes of the phase advance:

$$Z_{eff}^{i} = \frac{E/_{e}\,\sigma_s}{R\beta_i}\frac{d\mu}{dI}$$

Analysis courtesy V. Sajaev (2003 PAC)

	Units	High emittance	Low emittance
$d\mu/dI_{no\ ID}$	A^{-1}	-0.09	-0.14
$d\mu/dI_{8mm}$	A^{-1}	-0.39	-0.40
$d\mu/dI_{5mm}$	A^{-1}	-1.33	-1.21
Z_{noID}^{eff}	kΩ/m	3.5	4.1
Z_{8mm}^{eff}	kΩ/m	31	34
Z_{5mm}^{eff}	kΩ/m	126	138
Z_{total}^{eff}	MΩ/m	1.1	1.2

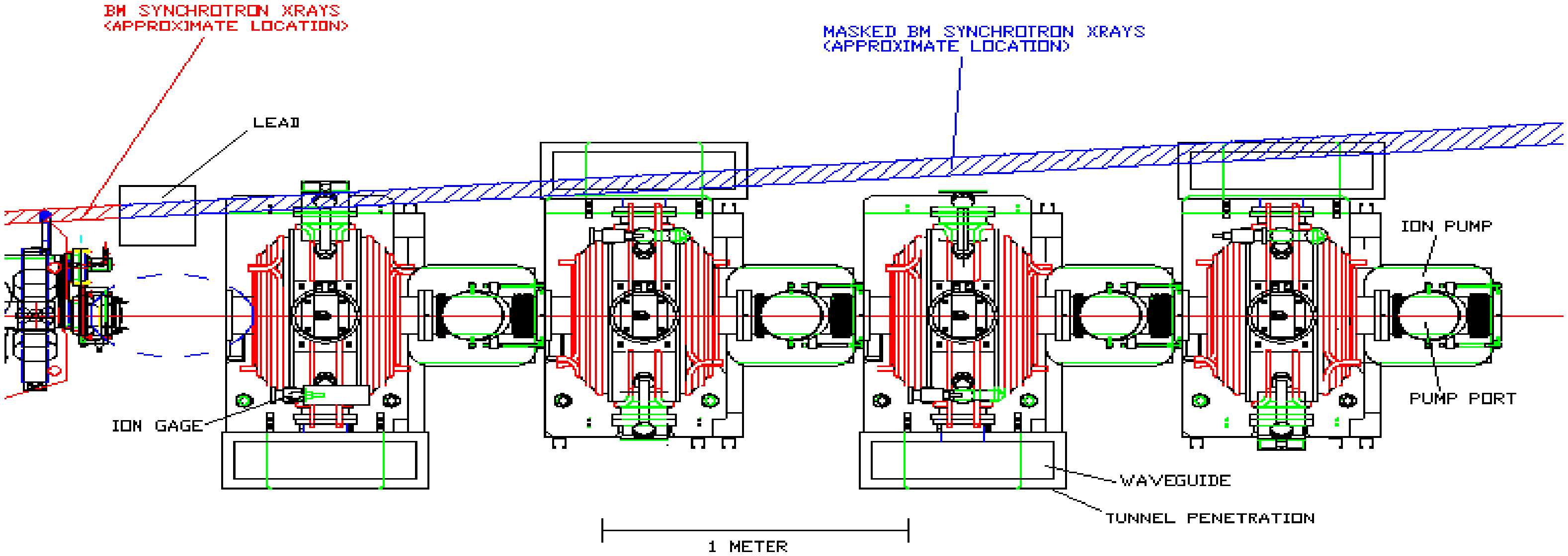
8-mm ID chamber vertical Z: comparison of five methods

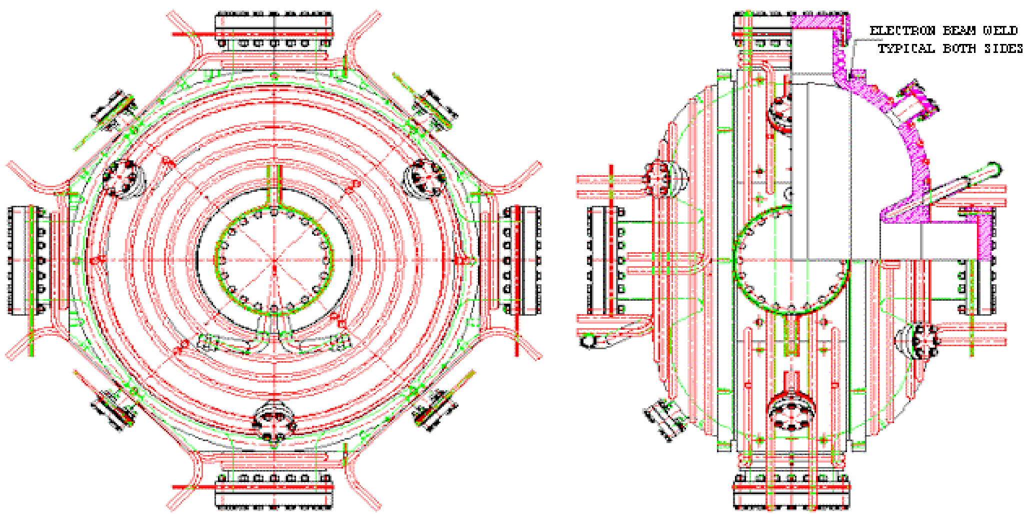
	8-mm ID	**5-mm ID**
Msrd $\Delta\nu/\Delta I$, as function of numbers of chambers [N. Sereno et al, Proc. of 1997 PAC, 1700]	53 kΩ/m per chamber x 20 = 1.1 MΩ/m	NA
Simulations with BBR model reproduced measured tune slope and intensity threshold for TMCI at low chromaticity [K. Harkay et al, Proc. of 1999 PAC, 1644]	1.2 MΩ/m $\Delta\nu_y/\Delta I = -2.6\text{x}10^{-3}$/ mA TBCI thresh: 2.2 mA	NA

8-mm ID chamber vertical Z: comparison of five methods (cont)

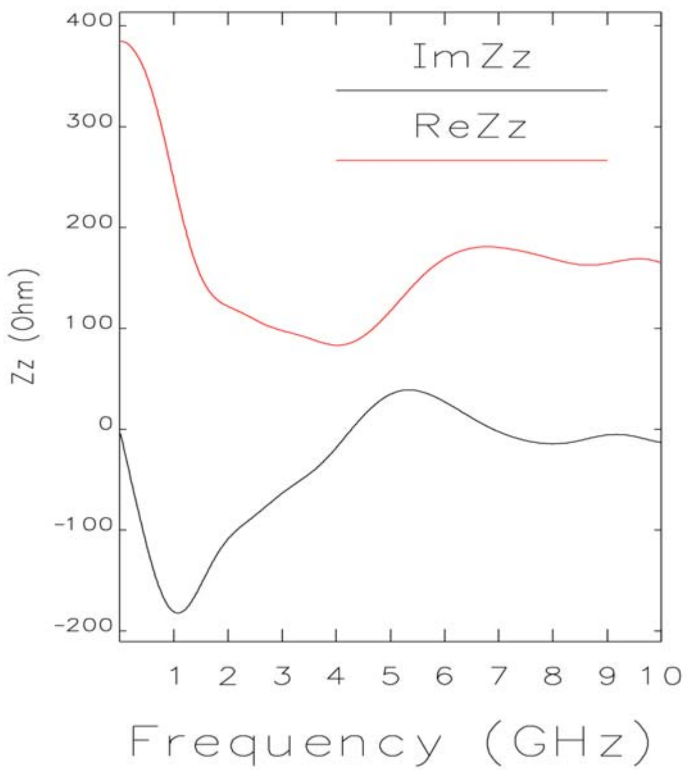
	8-mm ID	5-mm ID
Analytical calculations: Resistive wall [Gluckstern and van Zeijts, CERN SL/AP 92-25, Jun 1992] Geometric (transition): assuming perfectly conducting circularly cylindrical tube [Bane and Krinsky, Proc. of 1993 PAC, 3375]	$Z_{RW} + Z_\theta$ = 3.4 + 26 = 30 kΩ/m	$Z_{RW} + Z_\theta$ = 12 + (2.1 × 26) = 70 kΩ/m
MAFIA wake potentials: Z_θ from tune slopes for geometric comp. (Y.C. Chae)	20 kΩ/m	80 kΩ/m
Local bump method Z_y msmts [L. Emery, G. Decker, J. Galayda, Proc. of 2001 PAC, 1823]	16 kΩ/m	96 ± 8 kΩ/m 78 ± 14 kΩ/m
Orbit response matrix method [V. Sajaev, Proc. 2003 PAC]	32kΩ/m	130kΩ/m

RF Cavity (Y.C. Chae)

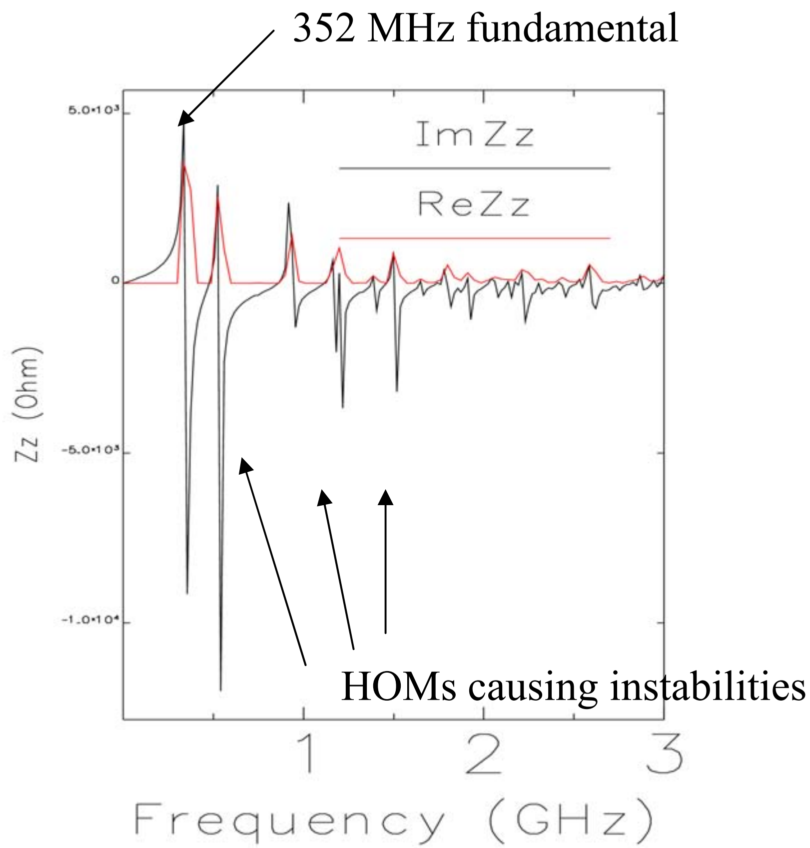




RF Cavity: Impedance (Y.C. Chae)



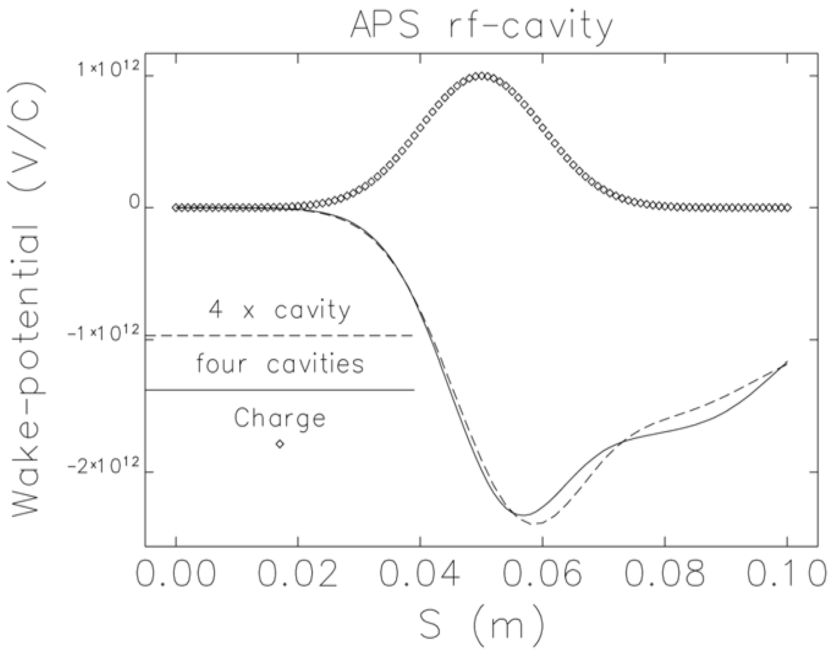
Broadband: short range including beam loading

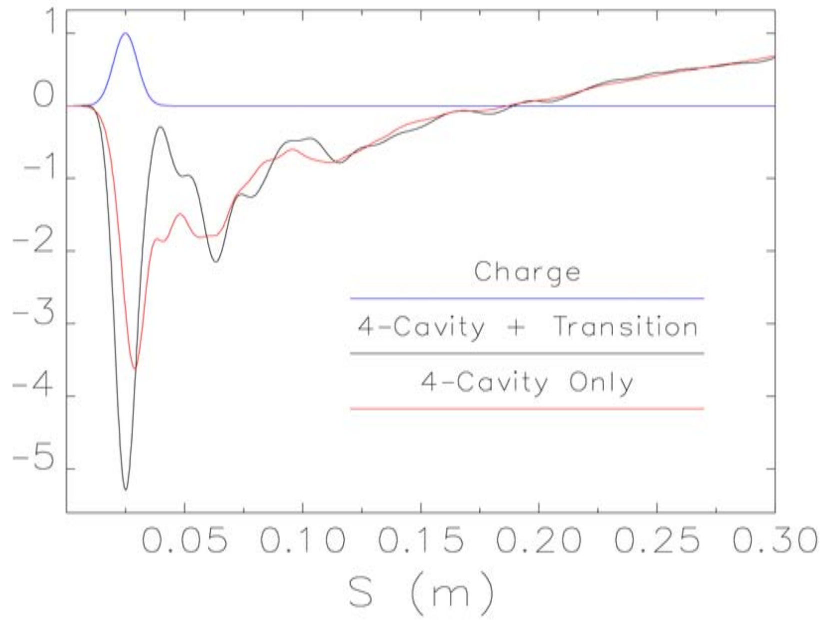


Narrowband: long range including beam loading

RF Cavity: Interference *(Y.C. Chae)*

Interference between cavities





4 x single cavity vs. 4-cavities in a row
➔ Interference small

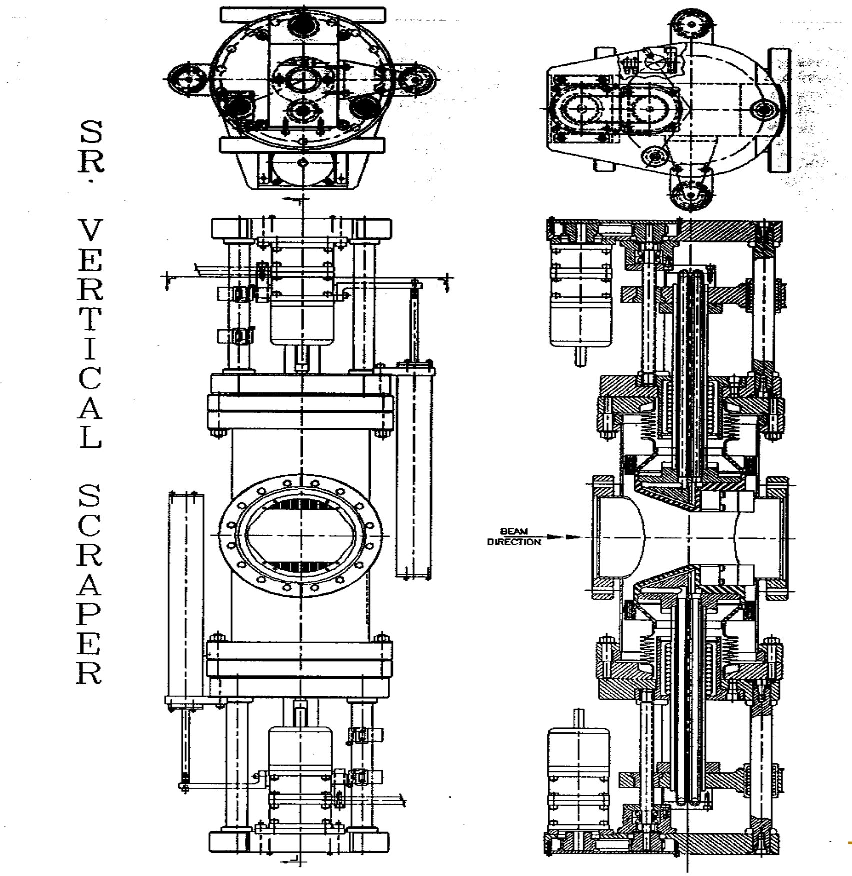
4-cavities in a row vs. ..+ transition
➔ Interference large

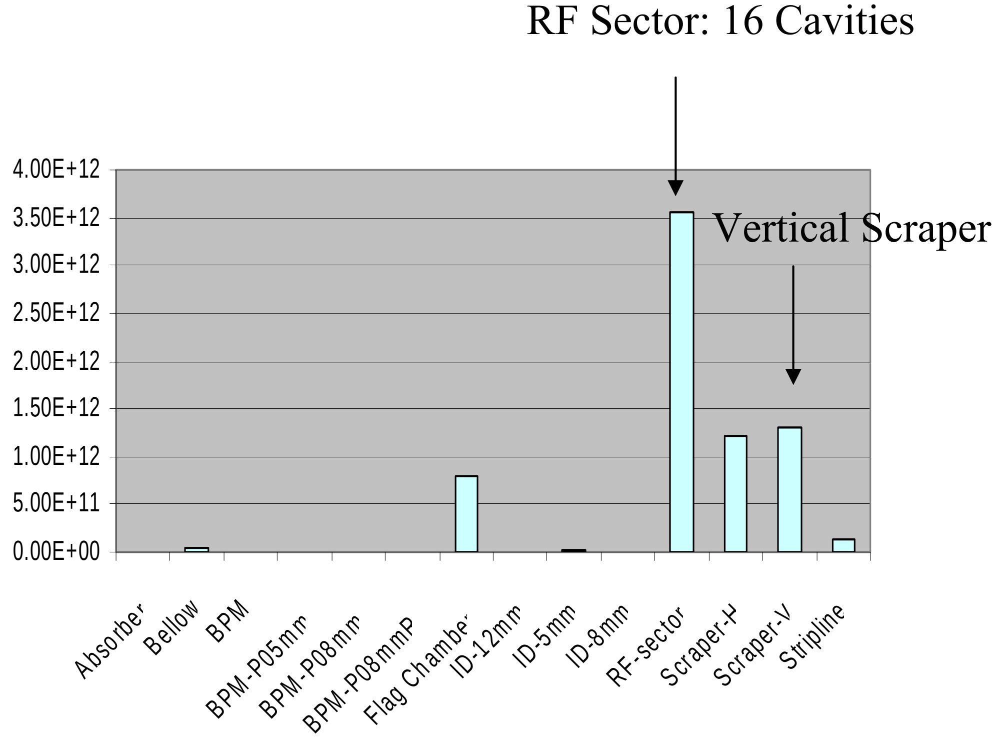
Vertical Scraper (Y.C. Chae)

VERTICAL SCRAPER IS HOT!!!

THE LOSS FACTOR IS 1.2 V/pC

The current 100 mA in 25 bunch will deposit 20 W into the small cavity area.

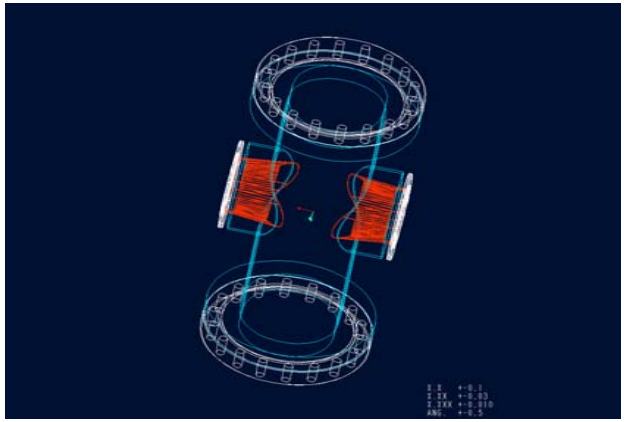


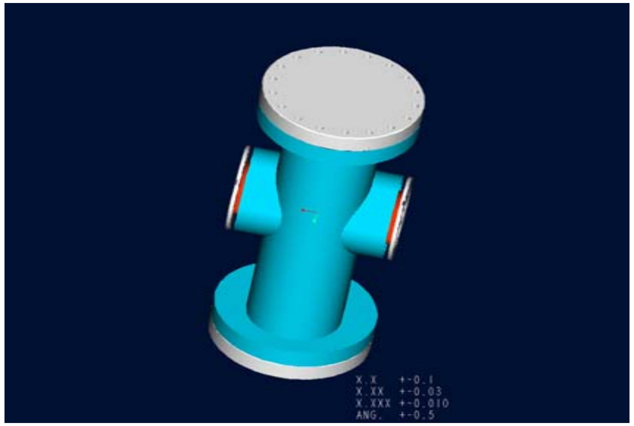


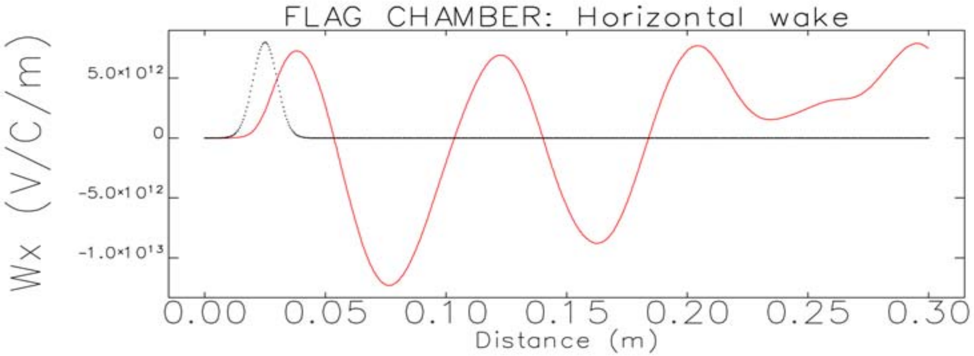
Loss Factor of Each Element

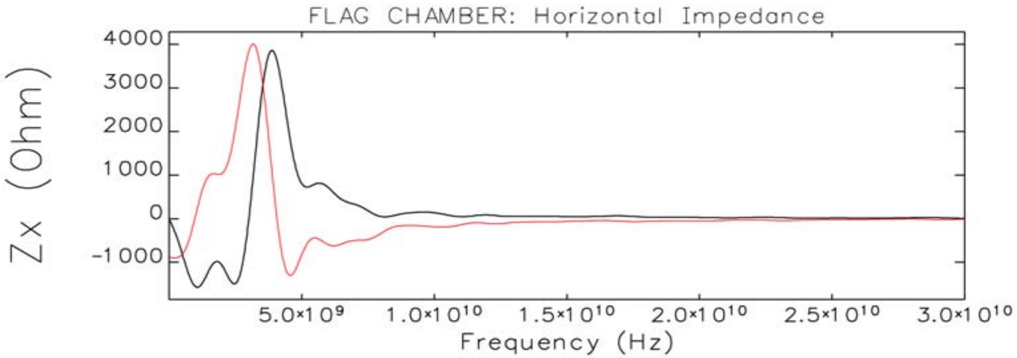
Flag Chamber (Y.C. Chae)

FLAG CHAMBER WAS SURPRISE IN THE APS STORAGE RING.



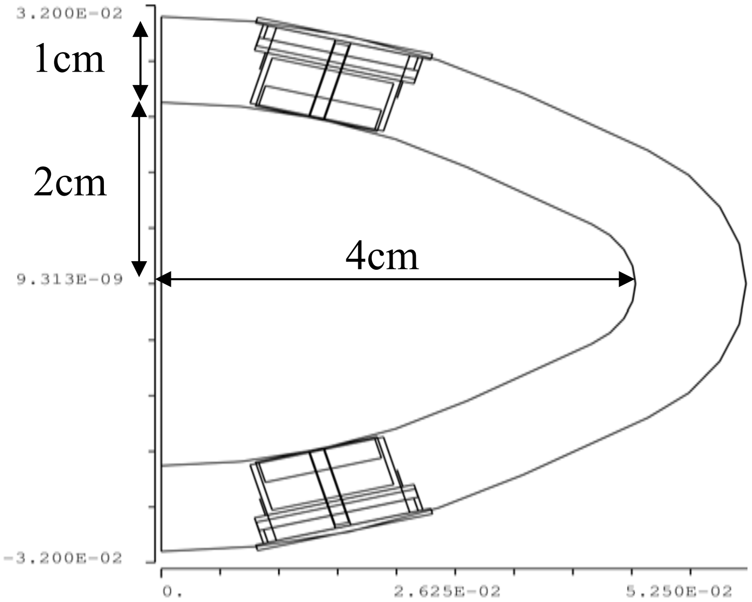


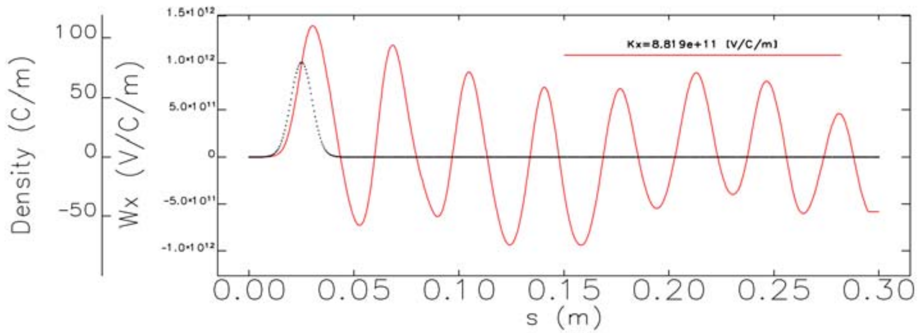


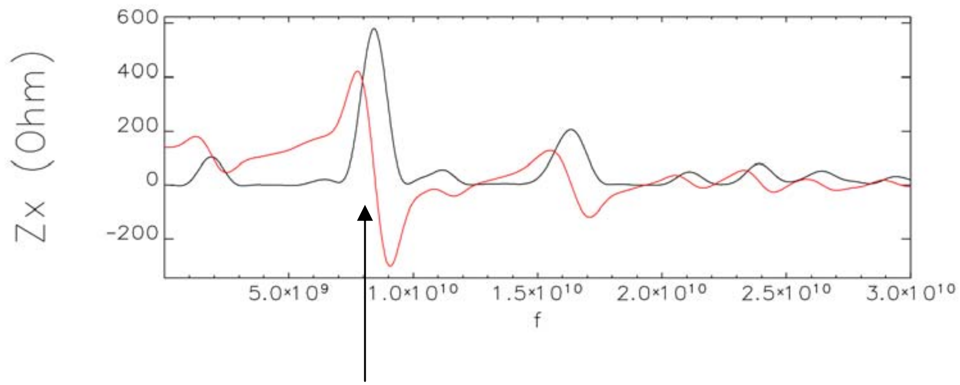


BPM: Regular Chamber (Y.C. Chae)

BPMs are a major source of horizontal impedance in the ring!



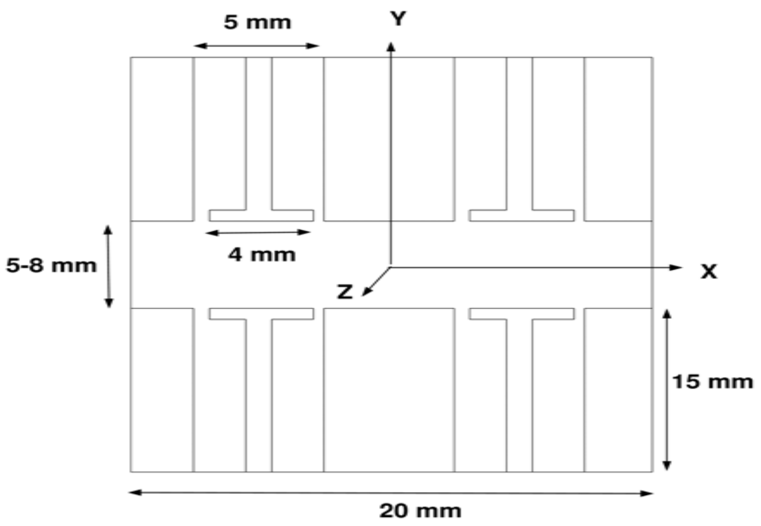


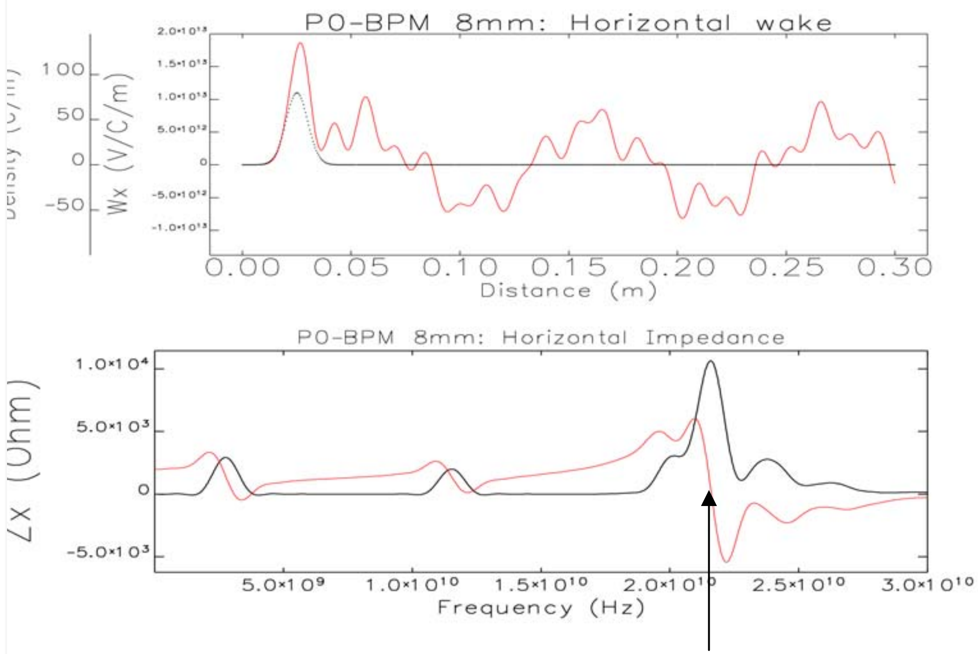


Fr=8GHz, BW=1GHz, Q=4

P0-BPM: 5mm, 8mm, 8mmR (Y.C. Chae)

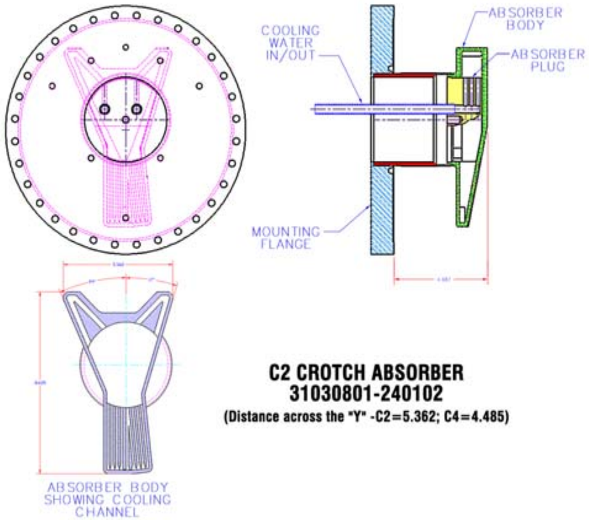
P0-BPMs are a major source of horizontal impedance in the ring!



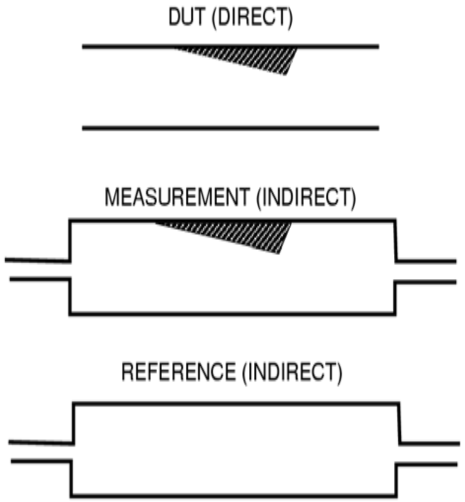


Fr=22GHz, BW=2GHz, Q=5

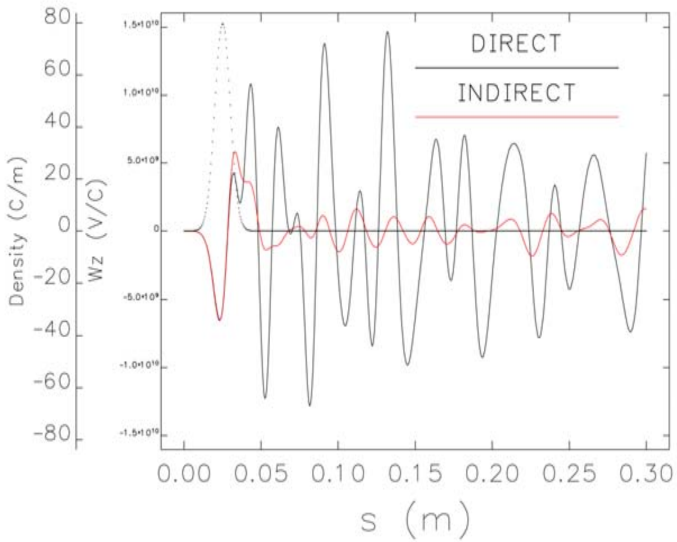
Radiation Absorber (Y.C. Chae)



component



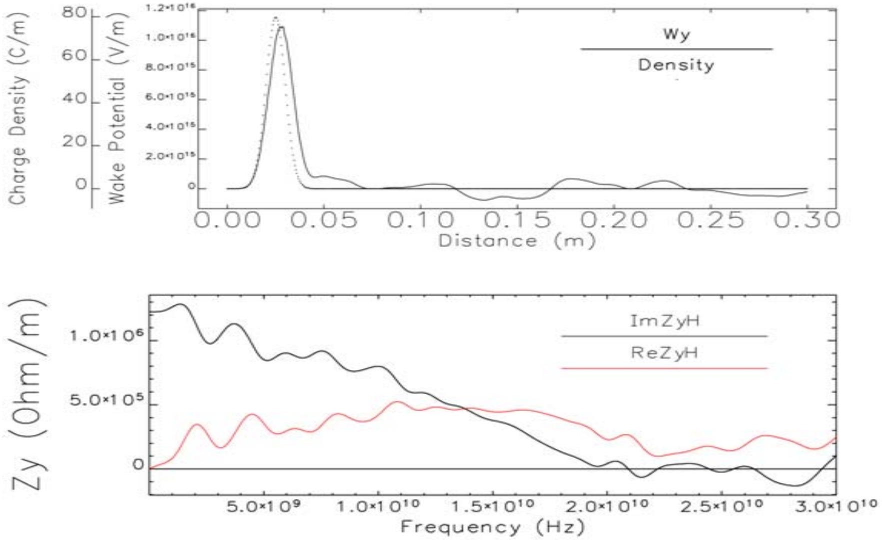
method



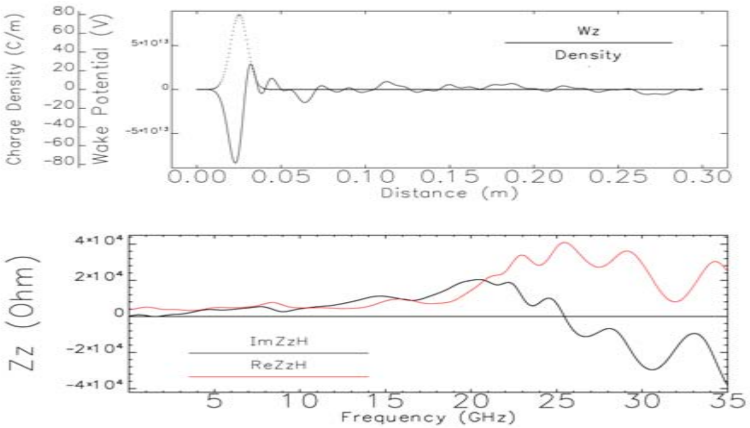
result

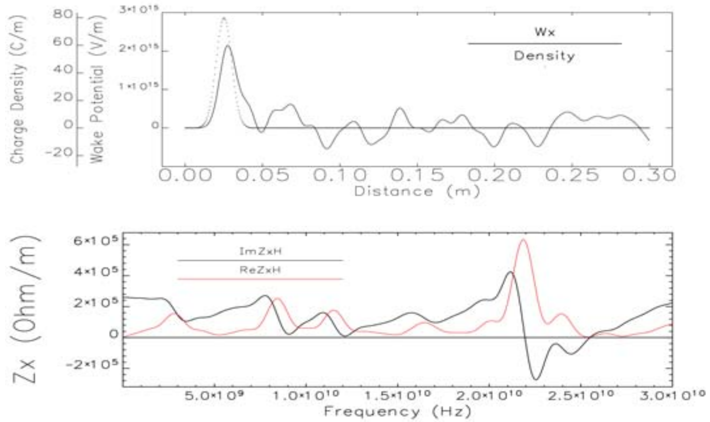
Total Impedance ***(Y.C. Chae)***

VERTICAL



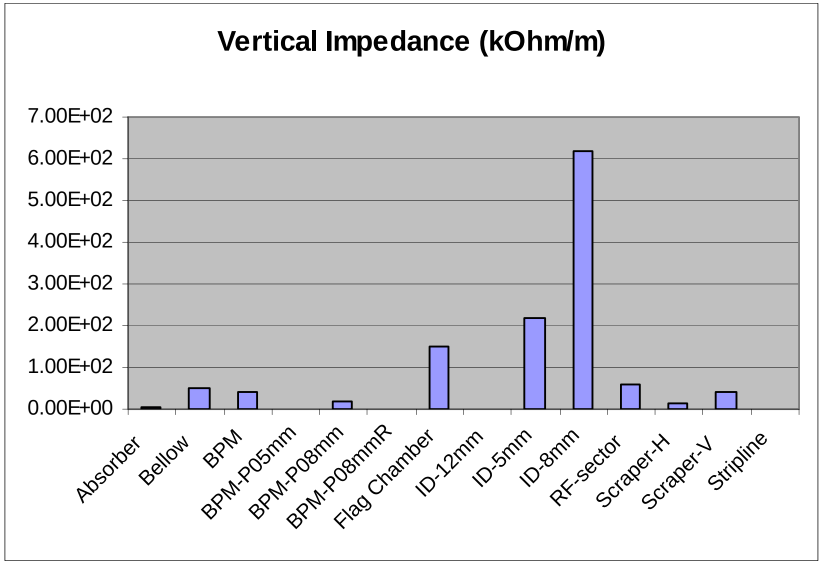
HORIZONTAL

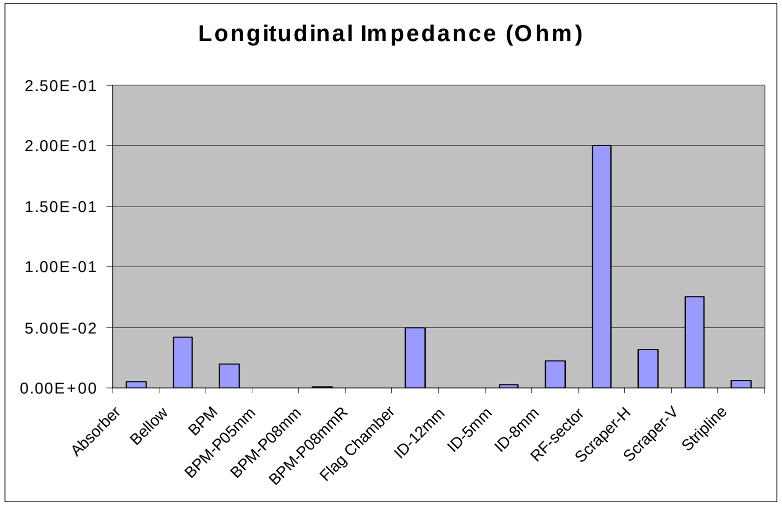


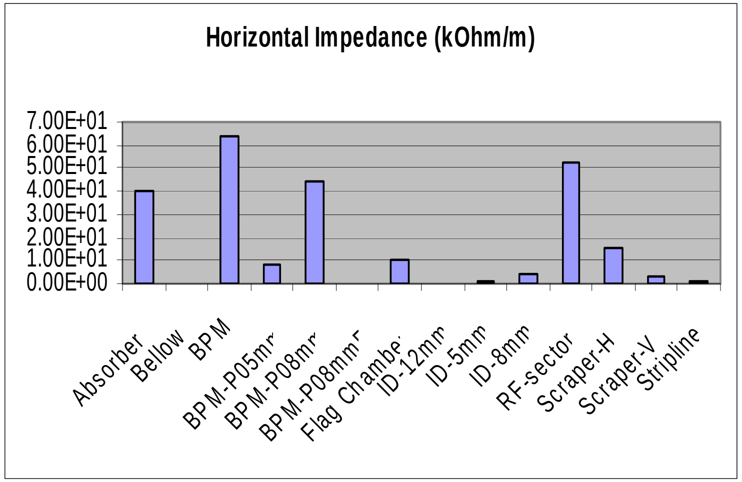


LONGITUDINAL

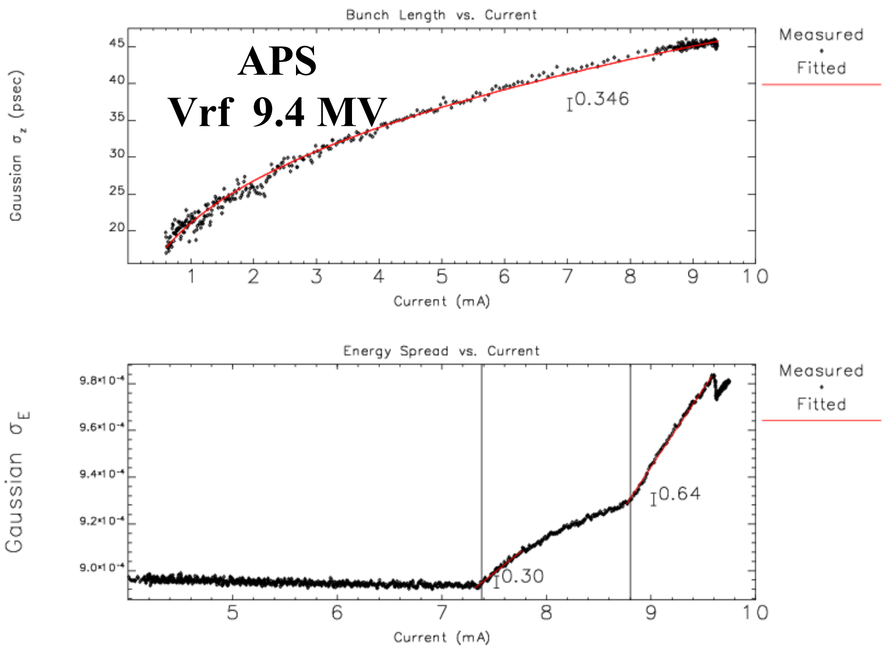
Impedance Budget (Y.C. Chae)



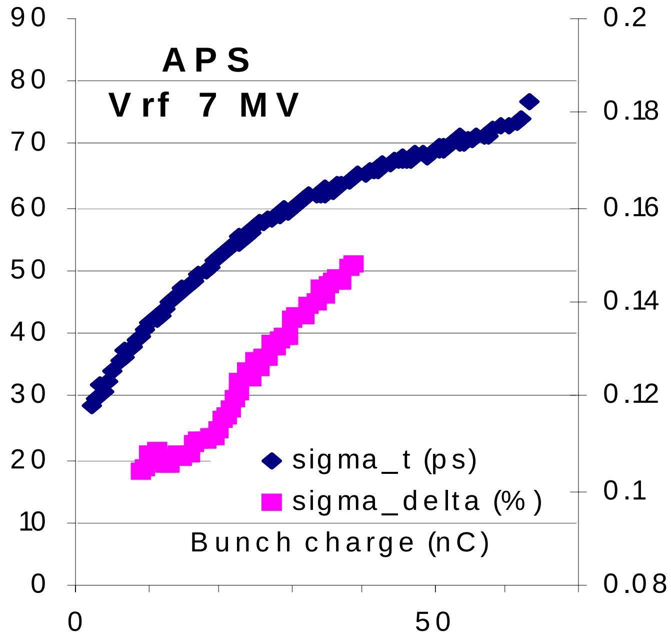




Longitudinal MW: Measurement



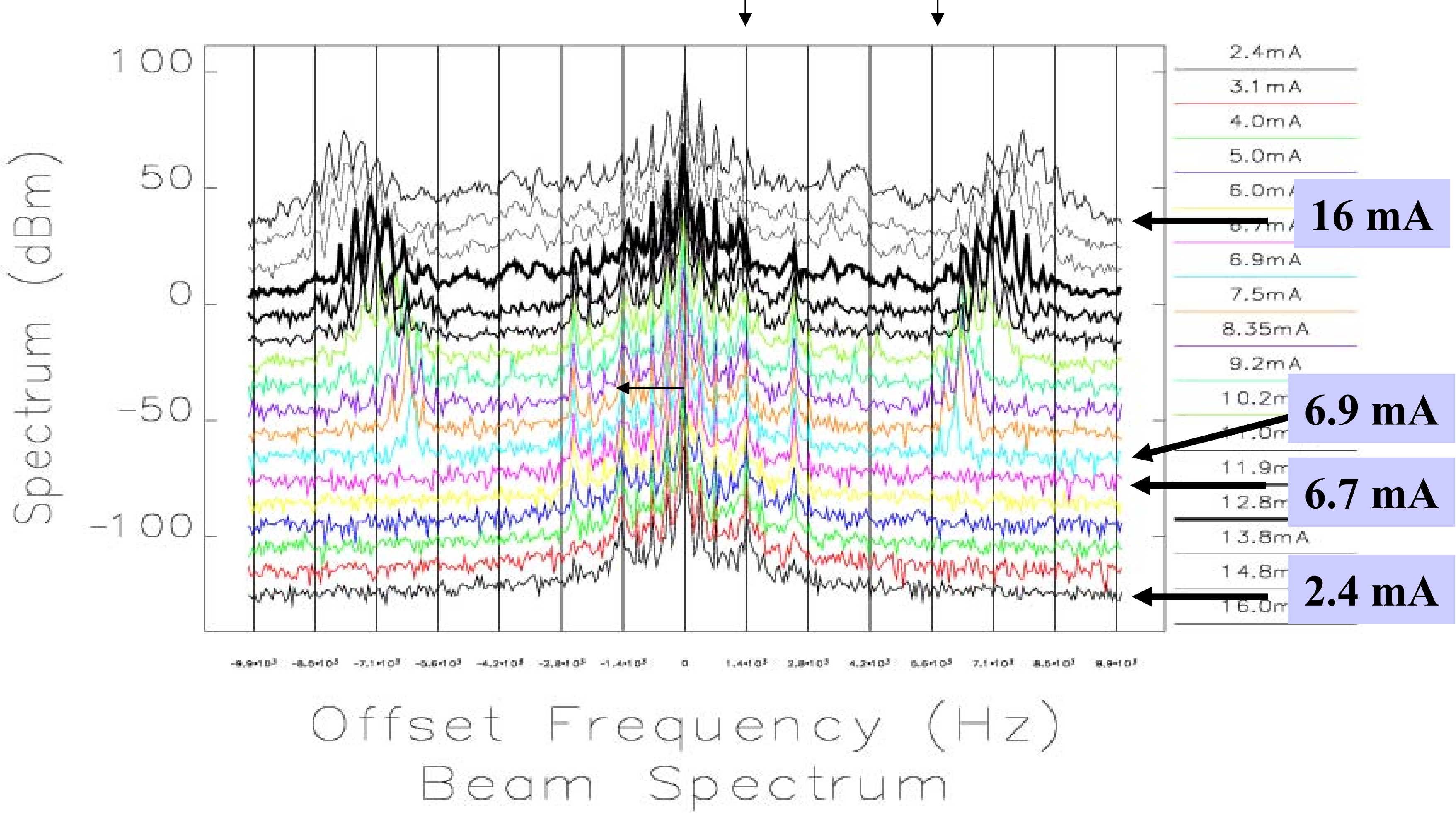
(Y.Chae, L.Emery, A.Lumpkin, J.Song, PAC'01)



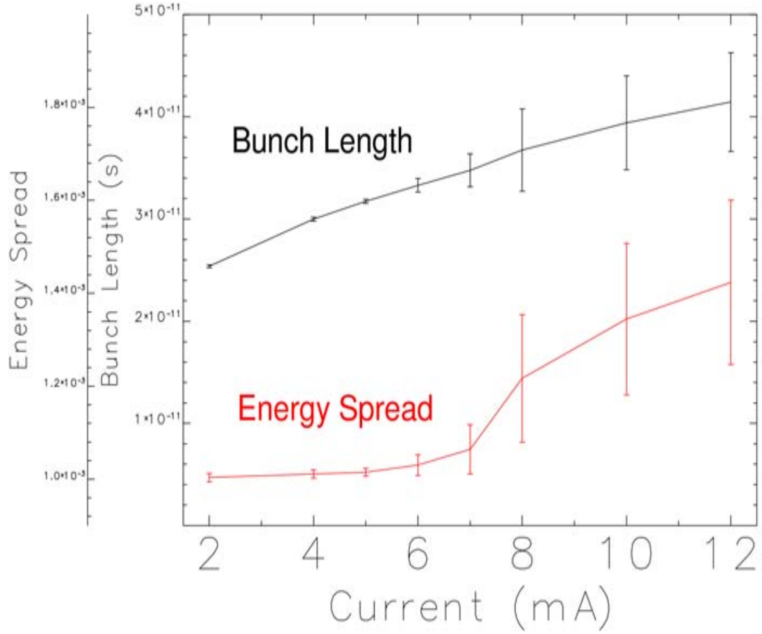
(Courtesy of K.Harkay, B.Yang)

Longitudinal MW: Measurement

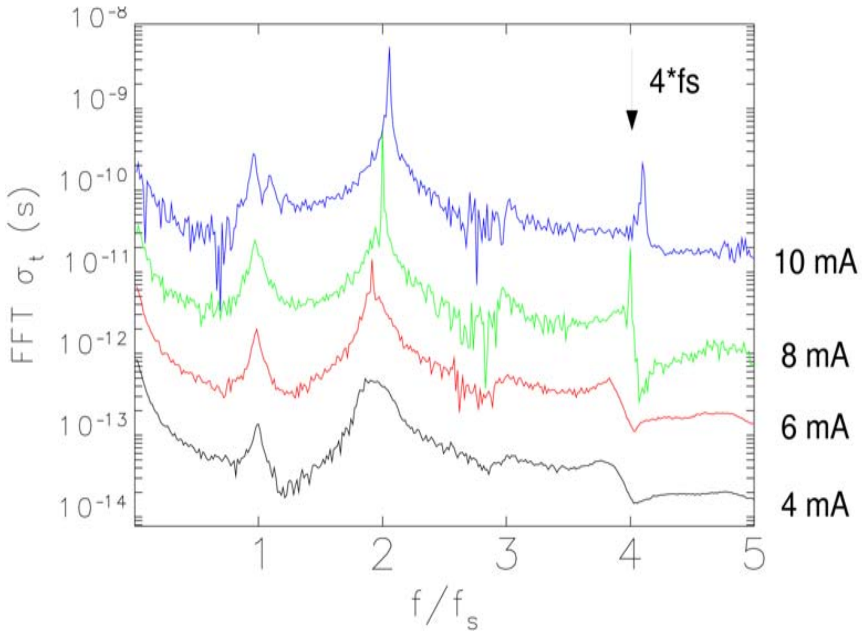
(Y.Chae, L.Emery, A.Lumpkin, J.Song, PAC'01)



Longitudinal MW: Simulation (Y.C. Chae)

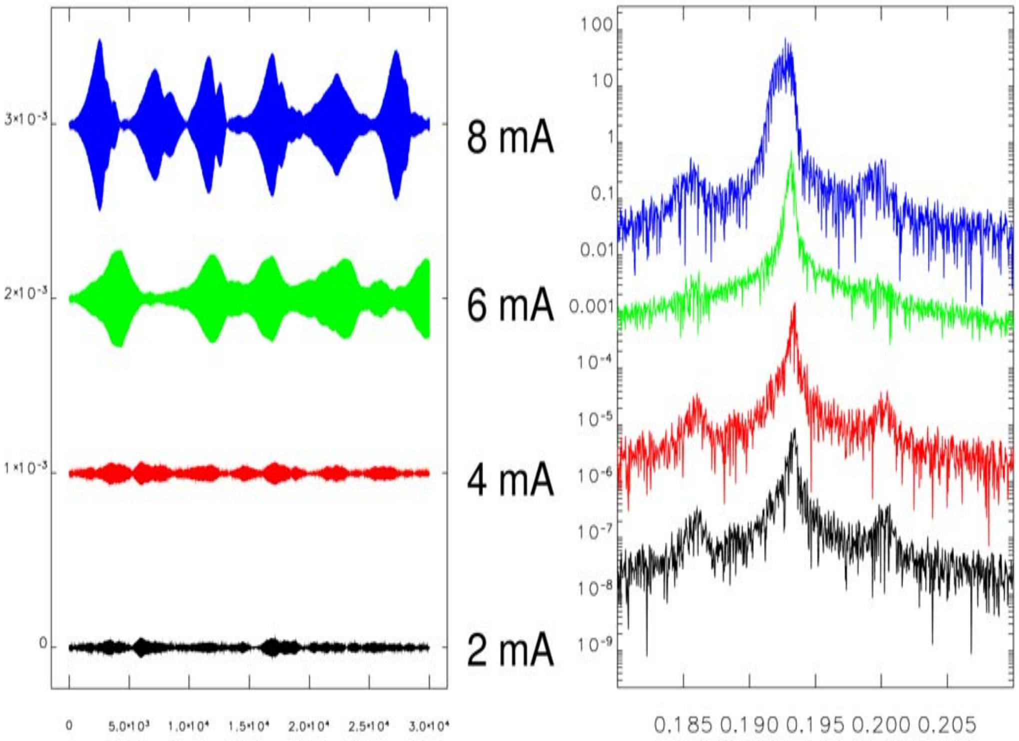


Bunch Length/Energy Spread
(Z scaled by 1.80 to match –
being investigated)

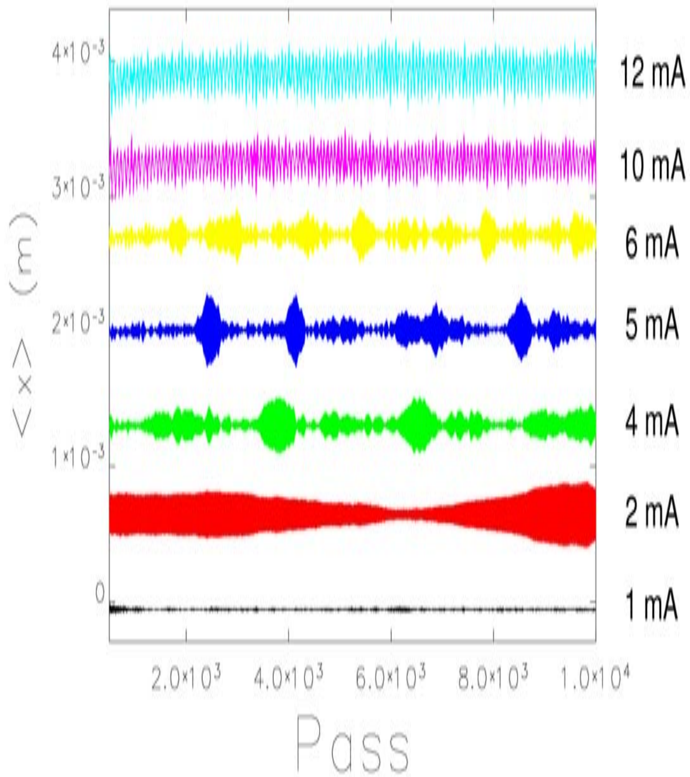


Bunch Length Oscillation

Horizontal Saw-Tooth: Simulation (Y.C. Chae)



Bursting mode excited by the narrowband impedance

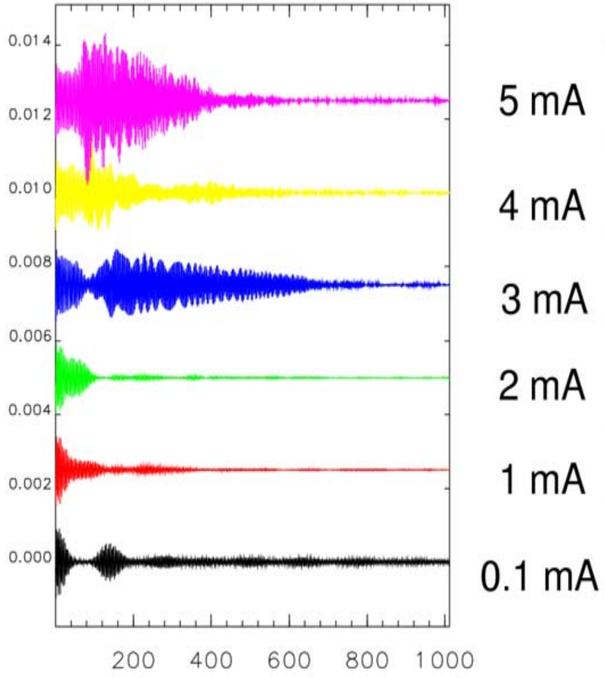


Bursting mode excited by the broadband impedance

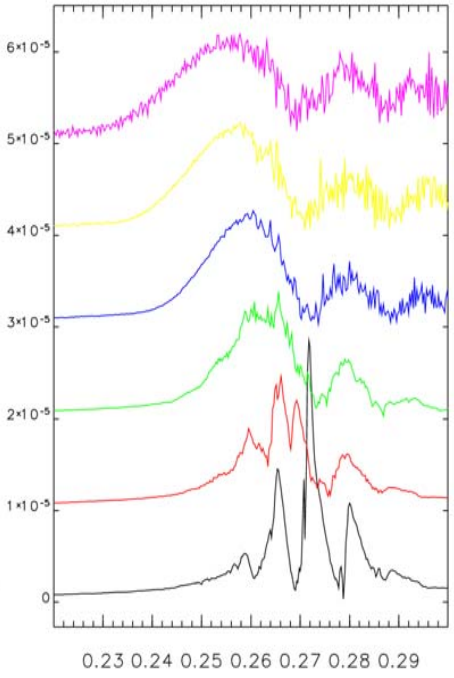
Vertical TMCI: Simulation (Y.C. Chae)

7.5 nm lattice; chromaticity: ξx=4, ξy=4

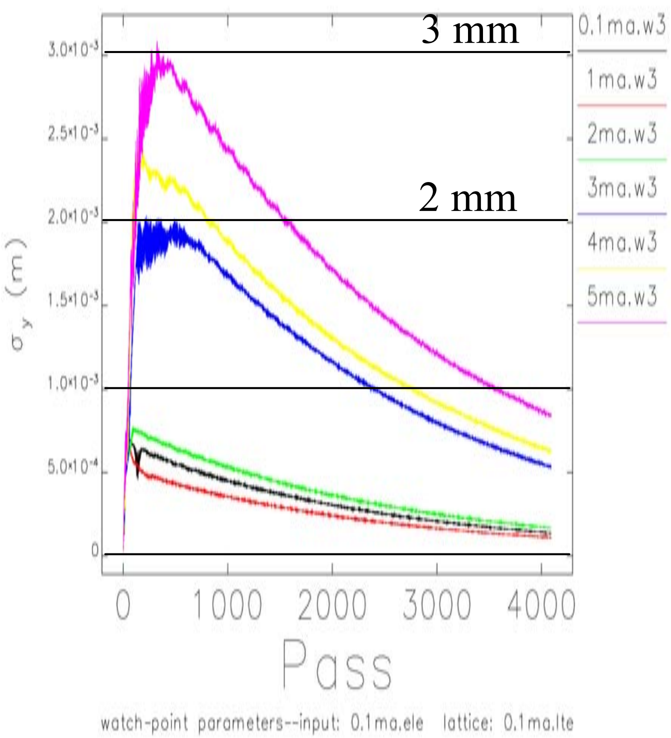
Centroid Kick Δy=1mm



Spectrum



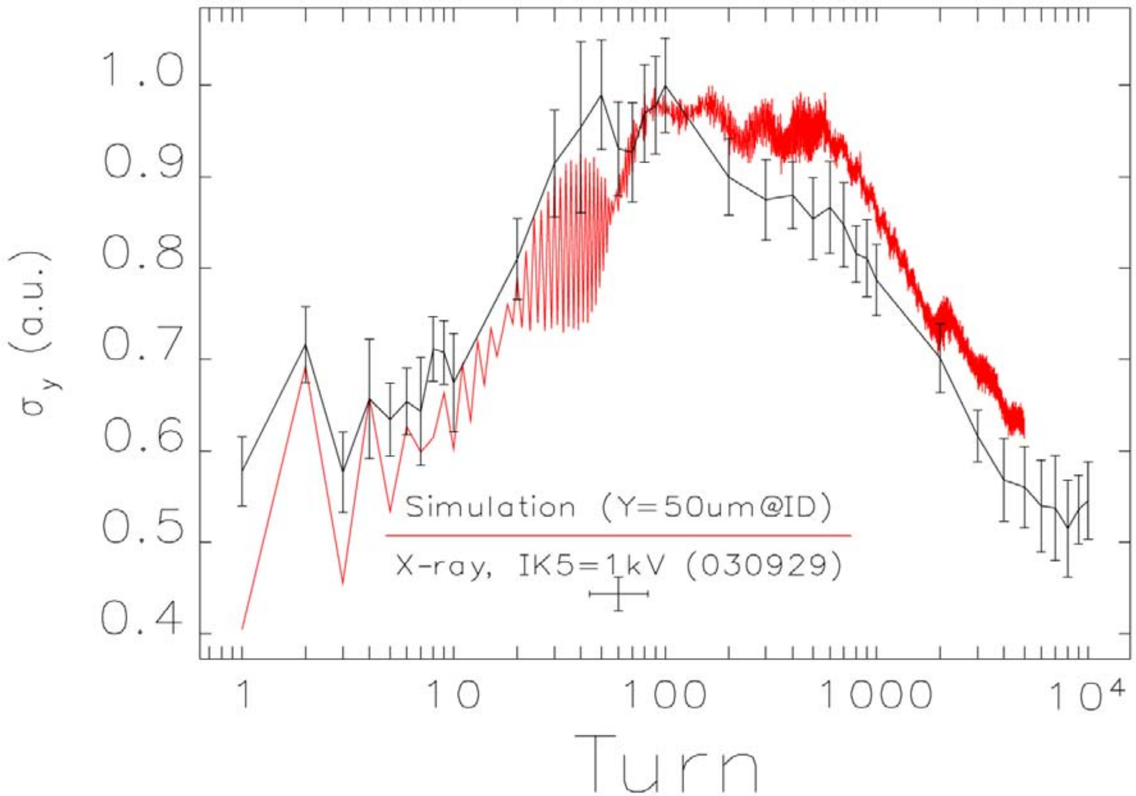
Vertical Beam Size



1. **Well known decoherence behavior at low current**
2. **Mode coupling completes 3 mA**
3. **Beam size blow-up above mode coupling ➔ Beam Loss due to 5-mm ID Chamber**

Vertical Beam Size: High Current (5 mA) (Y.C. Chae, B. Yang)

- Measurement: ID x-ray pinhole, IK5=1 kV, 030929
- Simulation: ID, BBR-1, Δy=50 μm
- Beam size normalized by the maximum for comparison



ID x-ray source provides better agreements with simulation!

Vertical TMCI: Discussion (Y.C. Chae)

- **Current Situation**
  - *24 x 8-mm and 2 x 5-mm chambers installed in the ring*
  - *Zy = 1 MW*
  - *Mode coupling at 3 mA and stability limit at 5 mA*

- **Worst Situation**
  - *34 x 5-mm chambers installed in the ring*
  - *Zy = 3.5 MW*
  - *Mode coupling at ~1 mA and stability limit at ~1.5 mA*

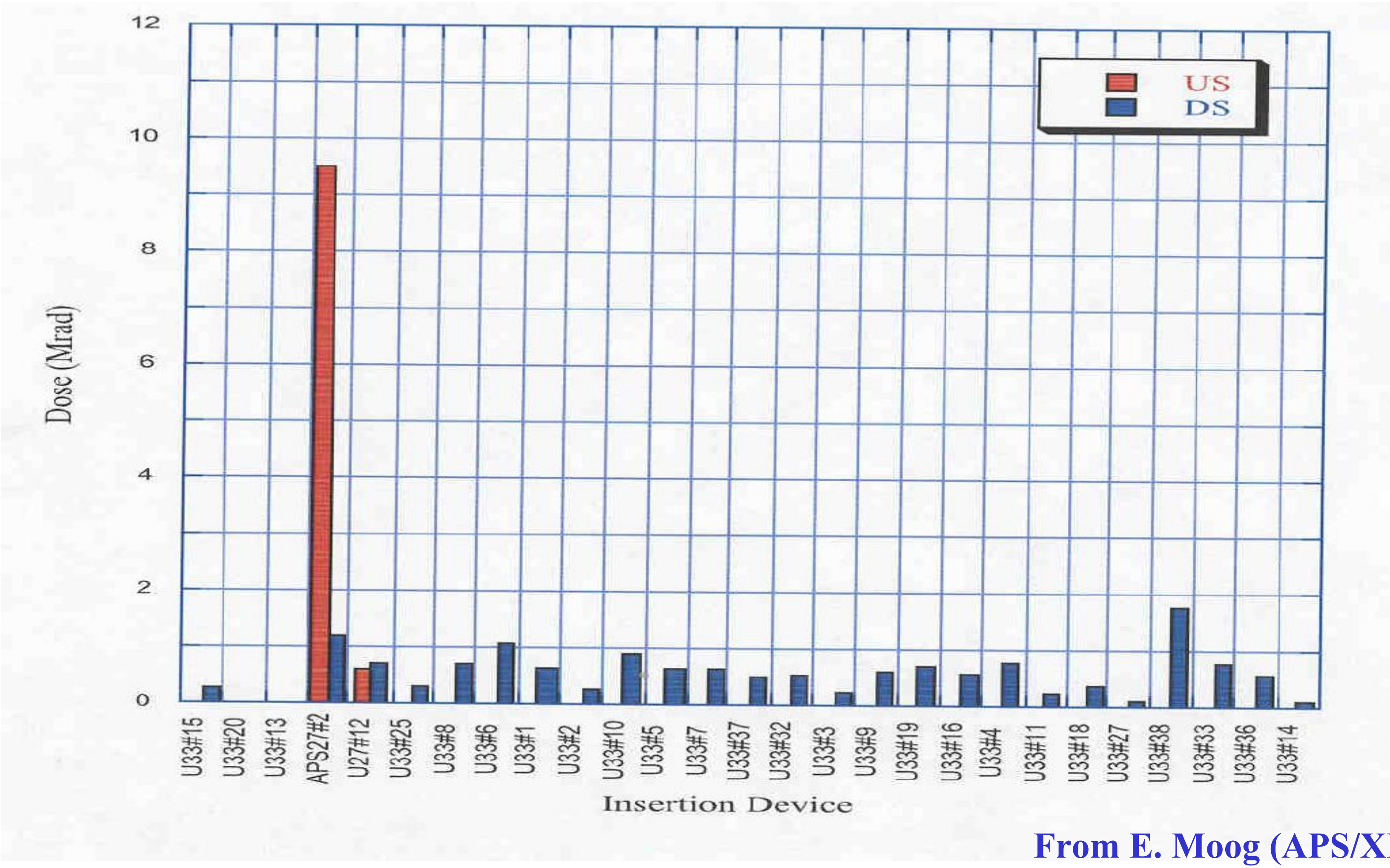
- **Reduce the Impedance**
  - *8 cm x 4 cm → 2 cm x 5 mm (present)*
  - *2 cm x 1 cm → 2 cm x 5 mm (1/3 of the present Zy)*
  - *Optimize the taper*

Feedback damper *(?)*

Simulation of Injection Process *(Y.C. Chae)*

- Accumulation Limit is 8 mA
- Radiation Damage to Insertion Devices

Run 2003-1 ID Dose (alanine)

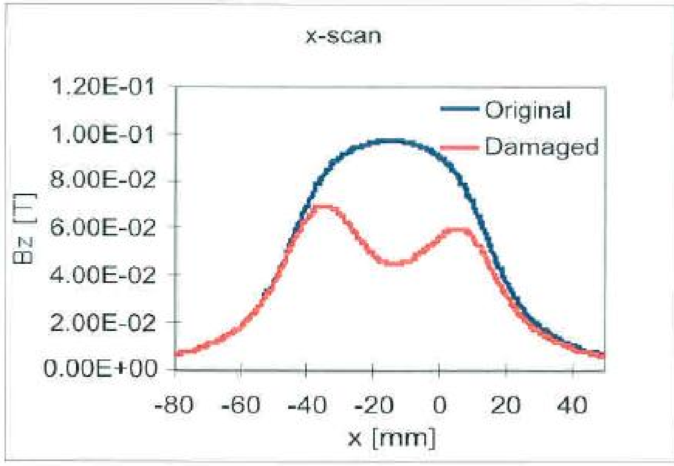


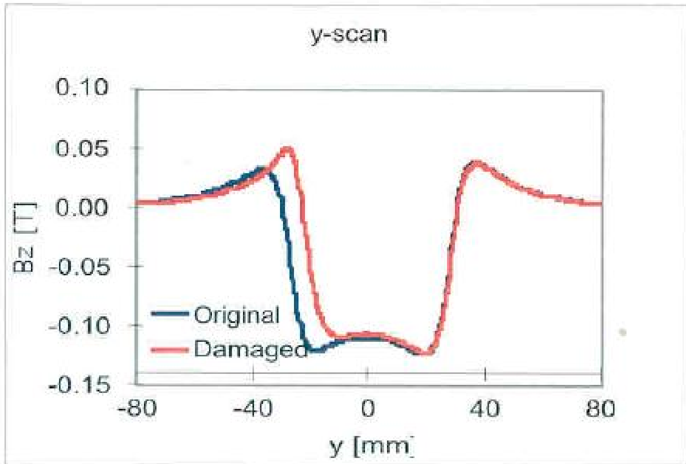
From E. Moog (APS/XFD)

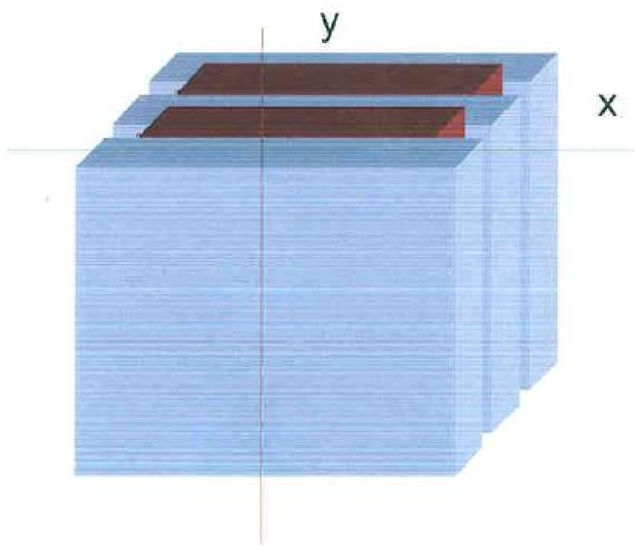
Damage Distribution in Magnet Block

From E. Moog (APS/XFD)

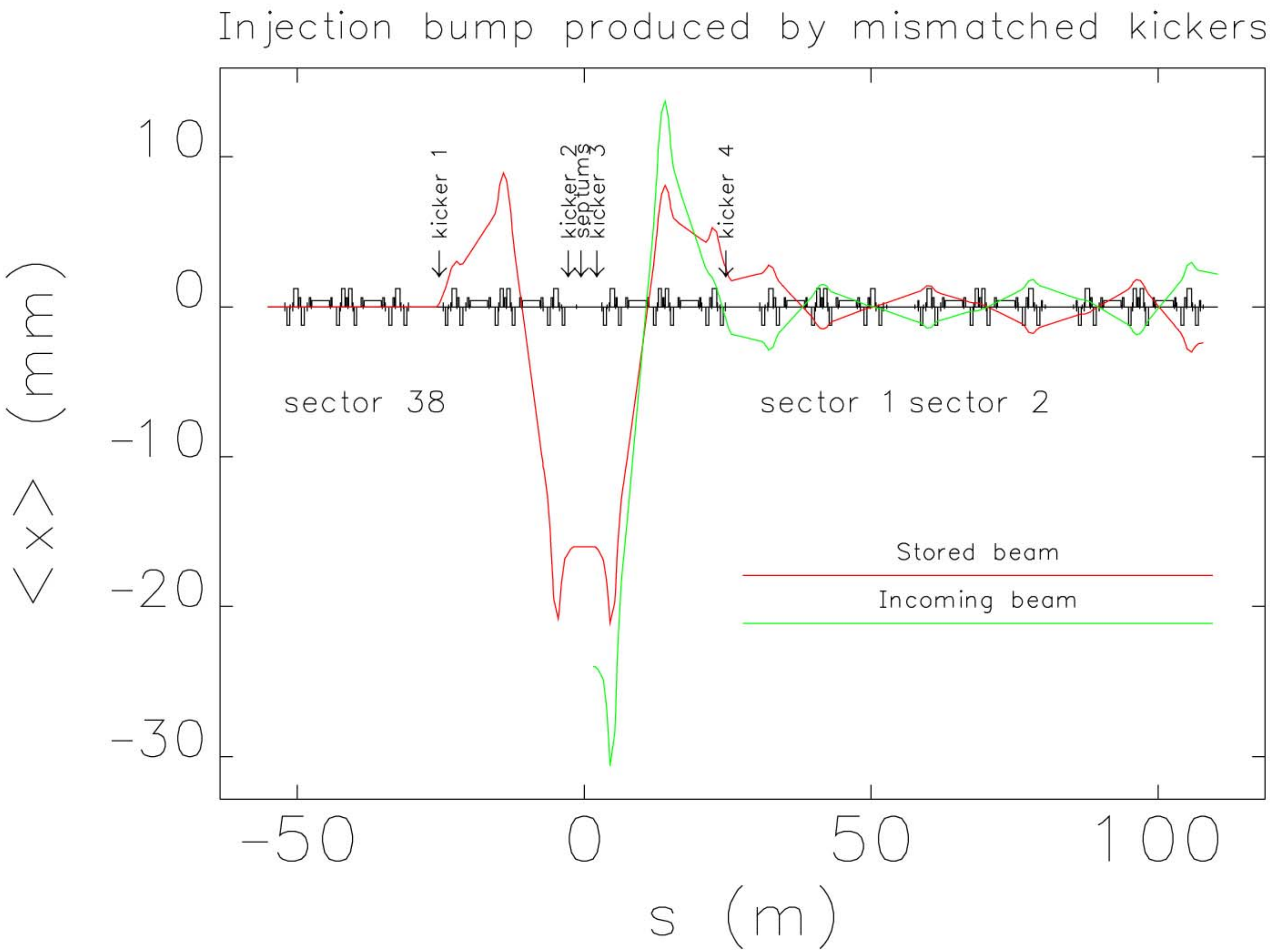
Magnet #6 from U/S end
of APS#2 Undulator







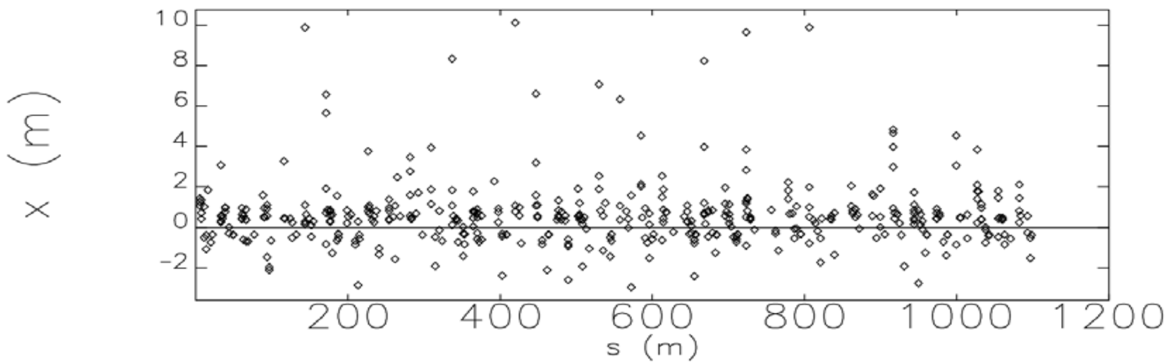
Current Injection Scheme



From Louis Emery (APS/AOD)

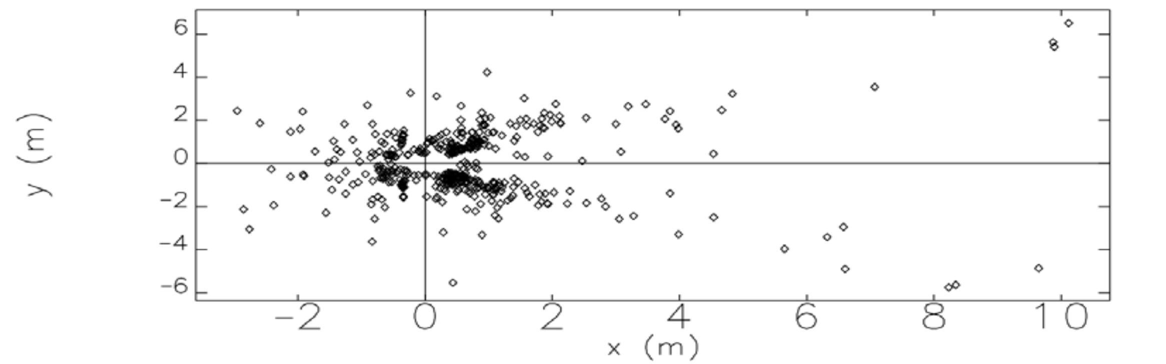
Particle Loss: Dynamic Aperture (Y.C. Chae)

x vs. s



Particle loss around ring

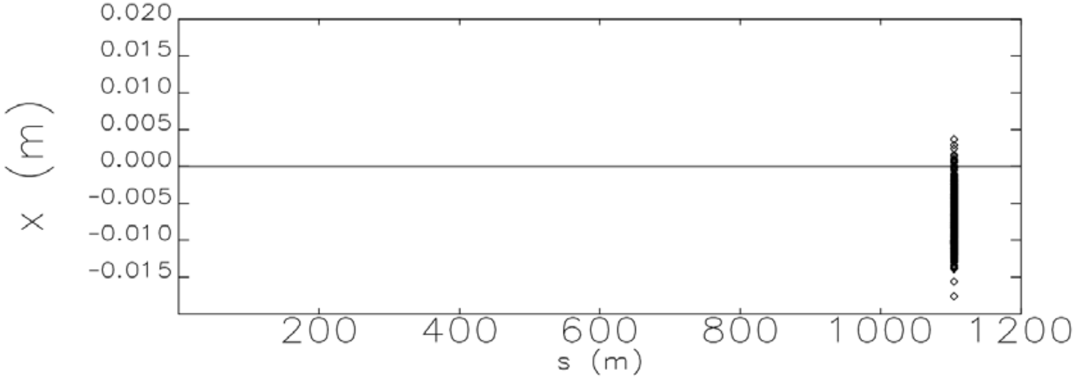
x vs. y



Coordinates of the lost particles

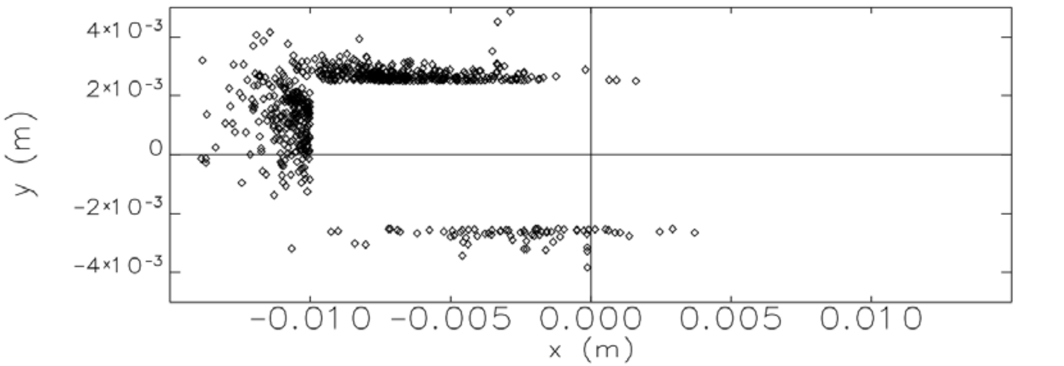
Particle Loss: Physical Aperture (Y.C. Chae)

x vs. s



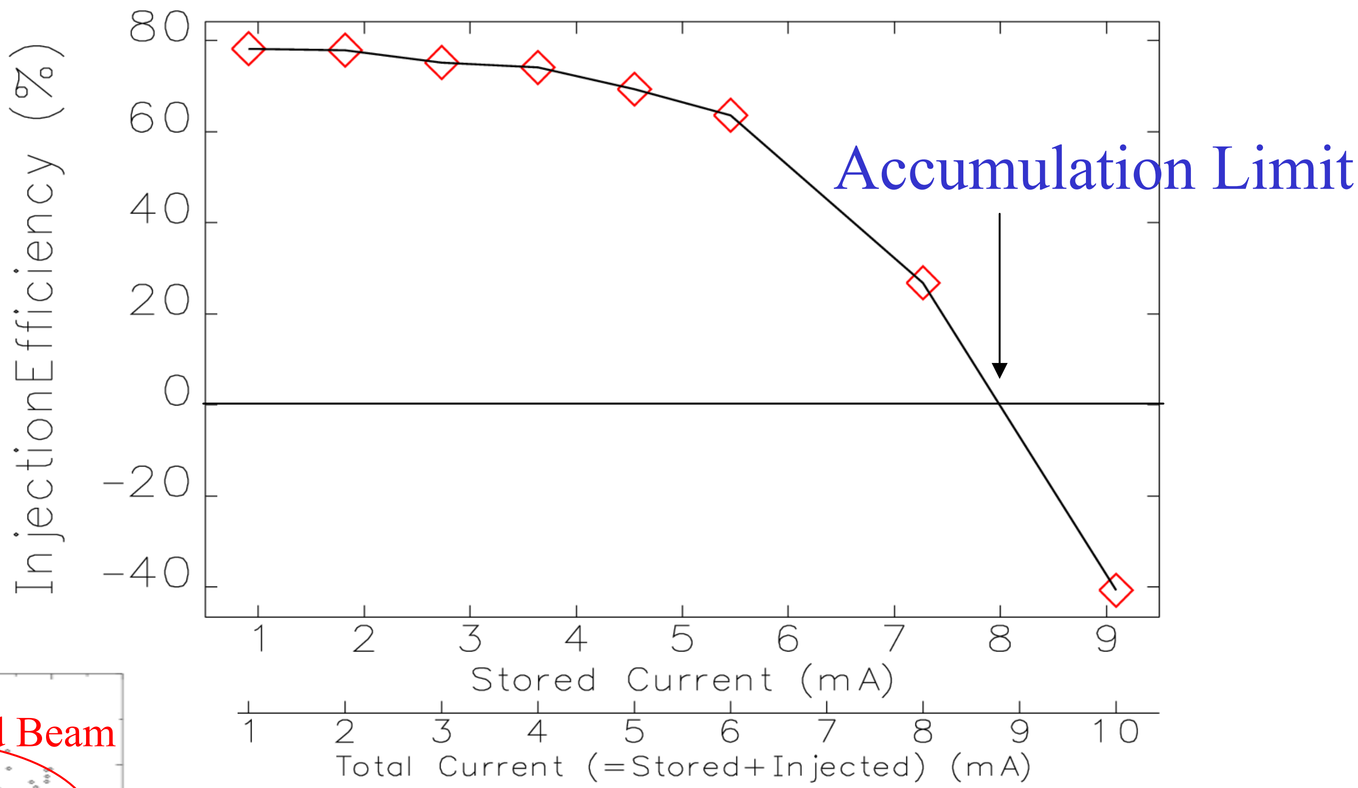
Particle loss localized by aperture

x vs. y

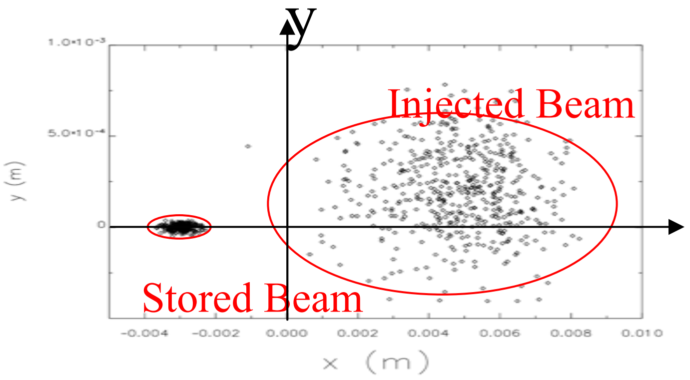


Coordinates of the lost particles

Injection Efficiency vs. Current (Y.C. Chae)



Initial coordinates,
lost particles



Measured Accumulation Limit < 8 mA

Summary

- Considerable effort dedicated to characterizing the APS impedance, comparing multiple methods for the ID chambers
- Completed the initial construction of Impedance Database for the APS storage ring
- Preliminary simulations using show good agreement with measurements of single bunch intensity-dependent effects
  - Tune slopes
  - Bunch lengthening
  - Microwave instability
  - Horizontal sawtooth instability (prelim)
  - Vertical TBCI (prelim)

Summary (cont)

- Several recent performance enhancements impacted instabilities, or were impacted by instabilities
  - Rf frequency evolution (for x-ray bpm's) lead to installation of HOM dampers to avoid longitudinal CB instabilities
  - Lattice correction method lead to very accurate beam-based local impedance measurement
  - Low emittance evolution opportunity to study possibility of fast ion instabilities for ultra-low emittance rings
- Other benefits of detailed impedance:
  - Good agreement simulating injection losses and single bunch accumulation limit; more work to quantify contribution to radiation damage