Argonne NATIONAL LABORATORY

... for a brighter future

U.S. Department of Energy

UChicago ▶ Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

Impedance Database Computation and Prediction of Single-Bunch Instability

Yong-Chul Chae

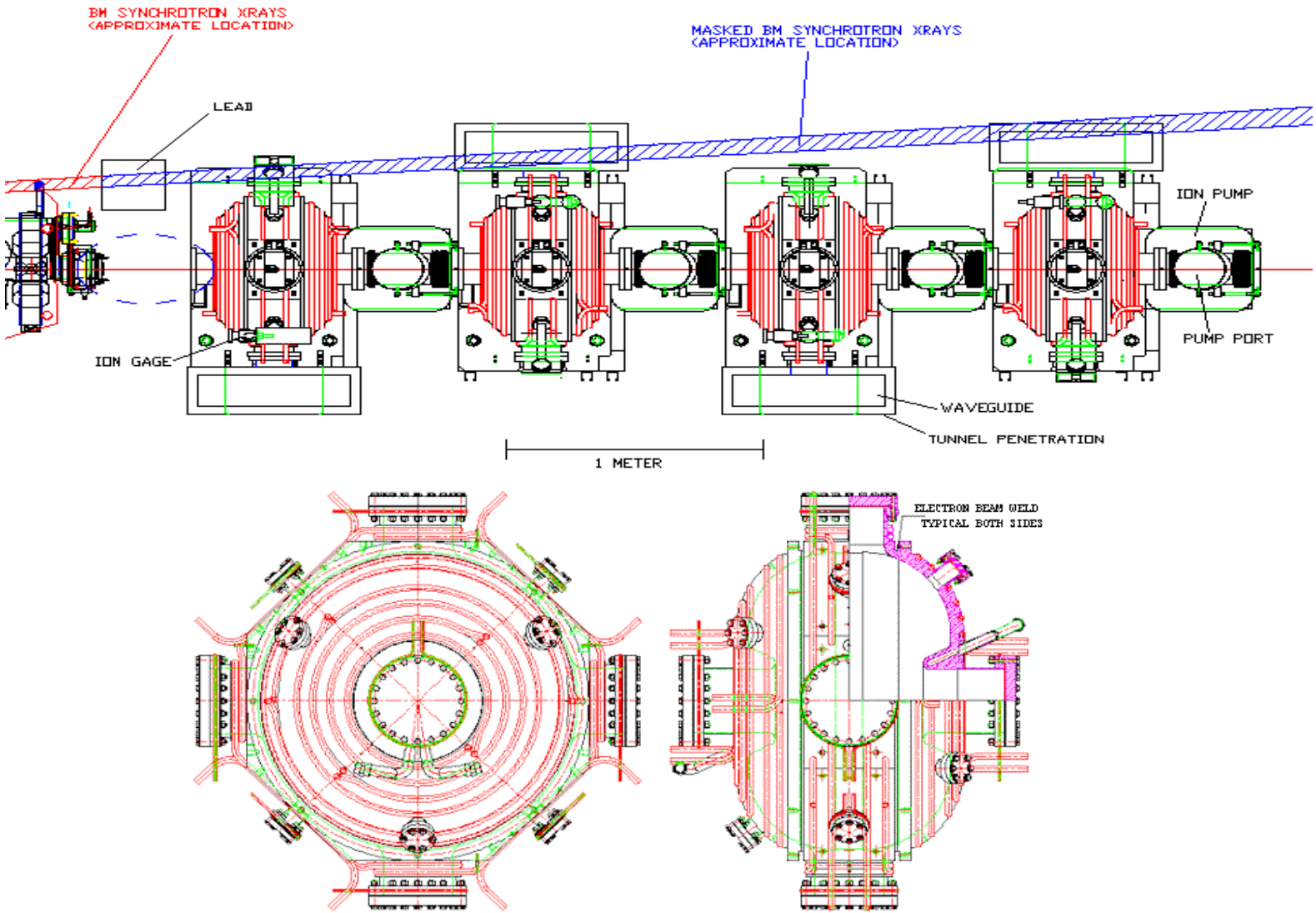
Advanced Photon Source

PAC07, Albuquerque, New Mexico, June 25-29, 2007.

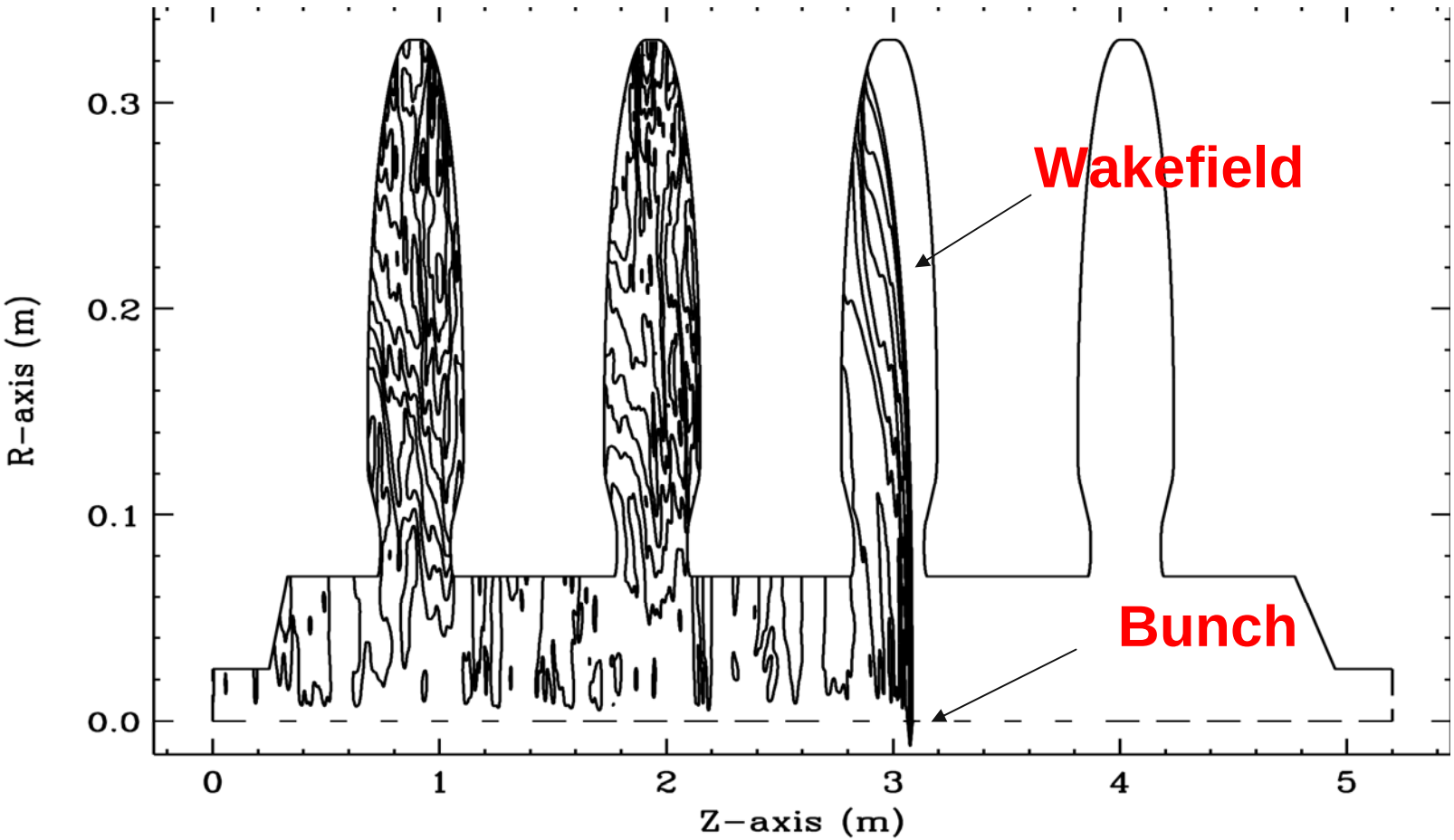
Outline

- Impedance Database (σ_z = 5 mm)
- Application: understanding observed instability
  - Longitudinal Microwave Instability
  - Horizontal Saw-Tooth Instability
  - Vertical TMCI Instability
  - Injection Process
- Impedance Database II (σ_z = 1 mm)
  - Improvement
  - Accumulation Limit
- Plan for the future APS Upgrade
  - Energy Recovery Linac

APS RF Cavity

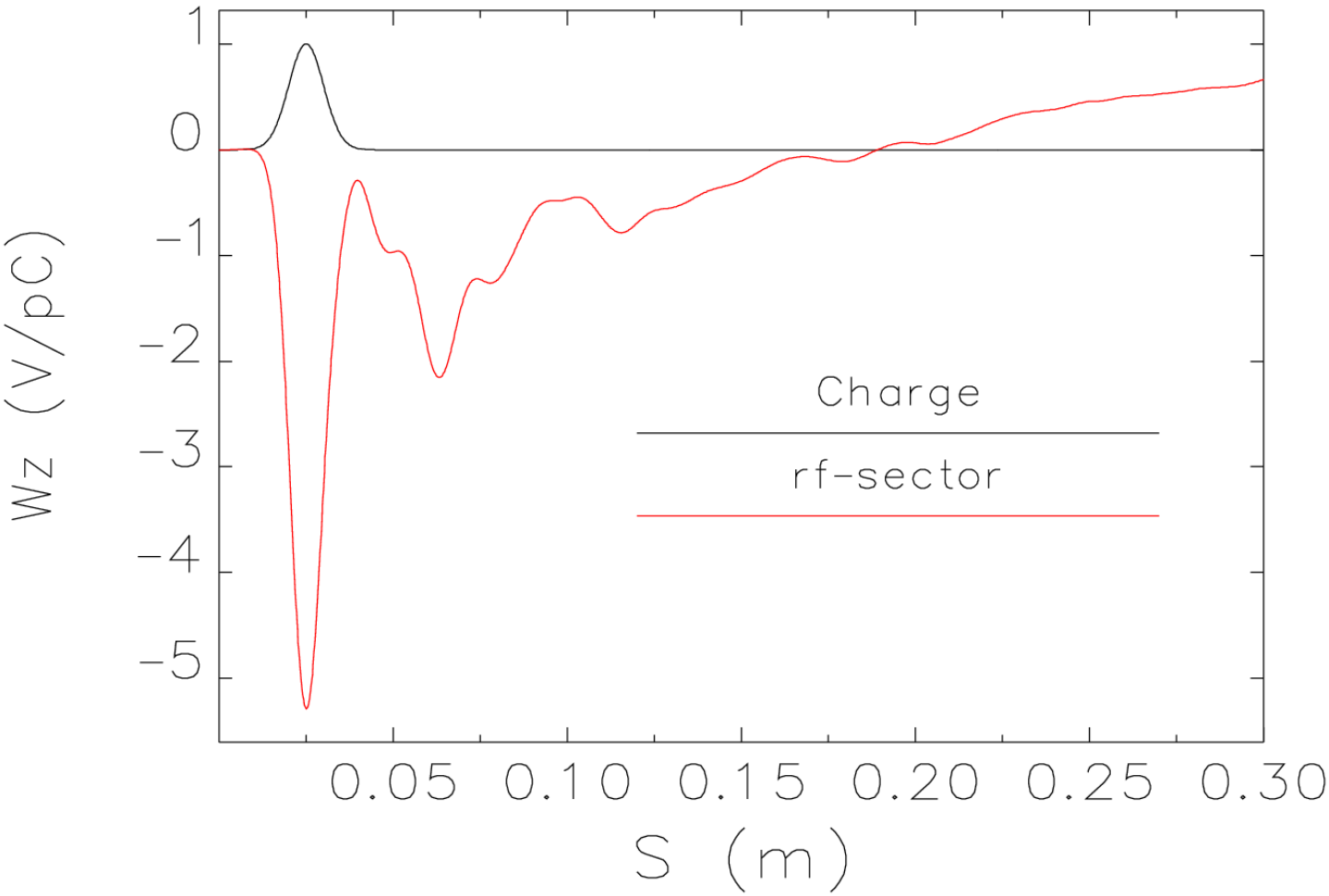


APS RF Cavity: Wakefield



2-D ABCI simulation

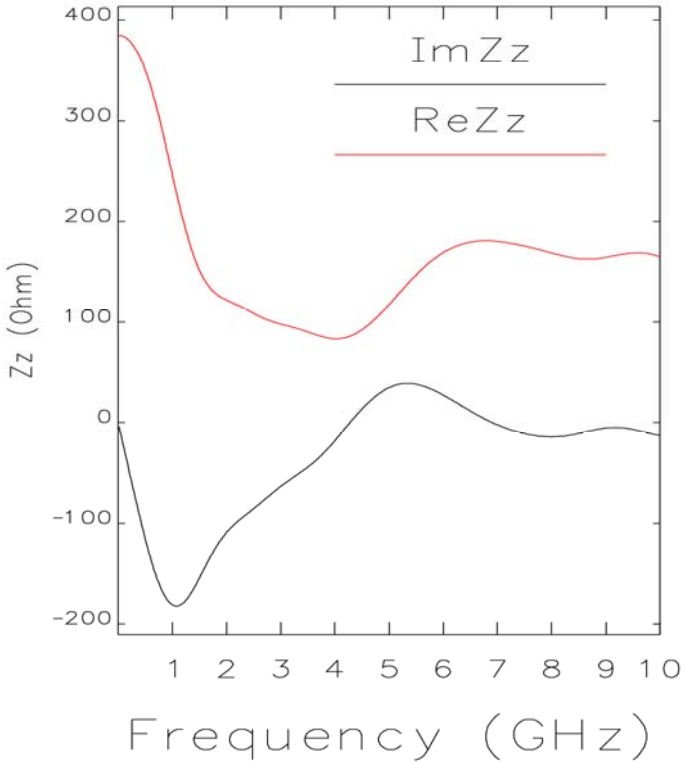
APS RF Cavity: Wakepotential

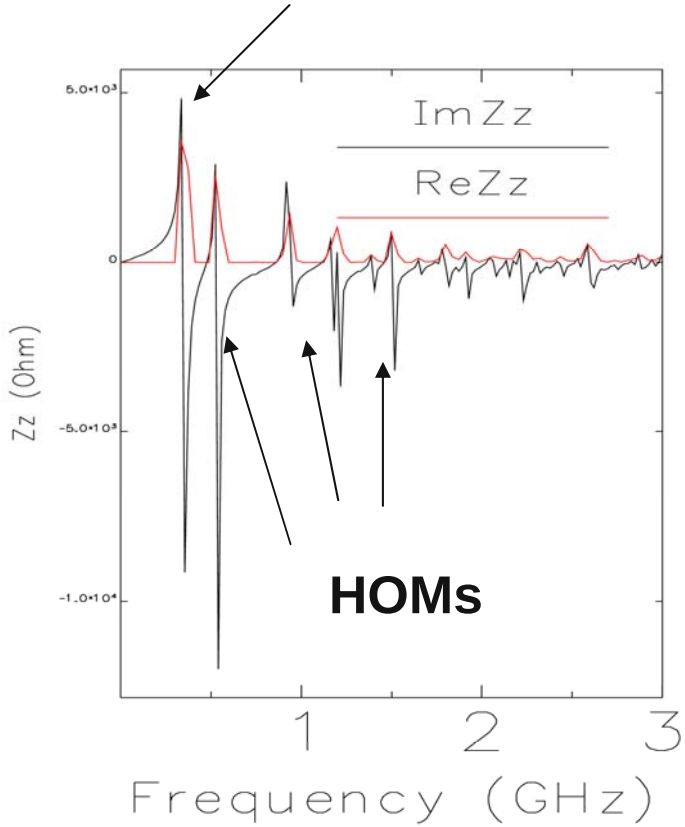


2-D ABCI simulation

APS RF Cavity: Impedance

352 Mhz fundamental





Broadband: **short range including beam loading**

Narrowband: **long range including beam loading**

Impedance Database

GOAL:
Total Wake Potential

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

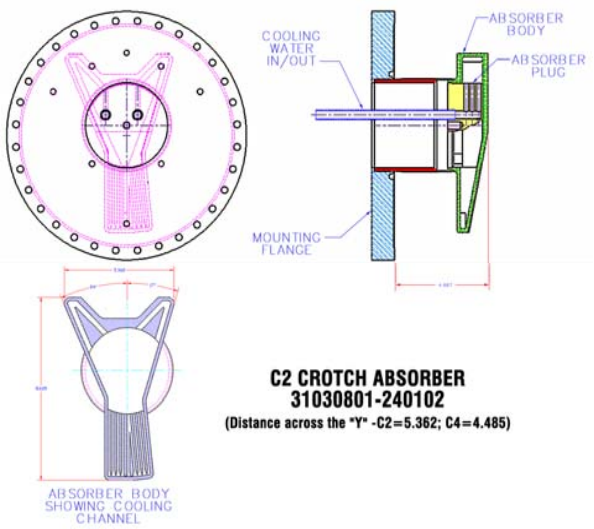
W_{total} = total wake-potential of the ring,

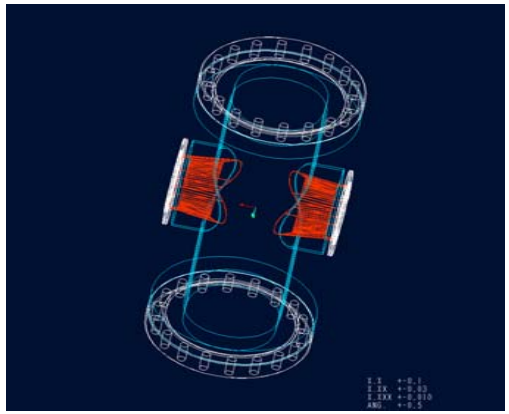
N_i = number of the element in the ring,

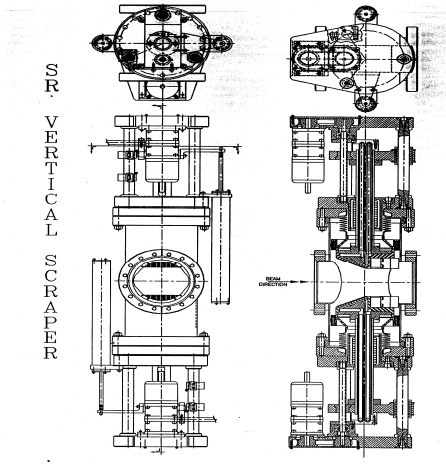
W_i = wake-potential of the element,

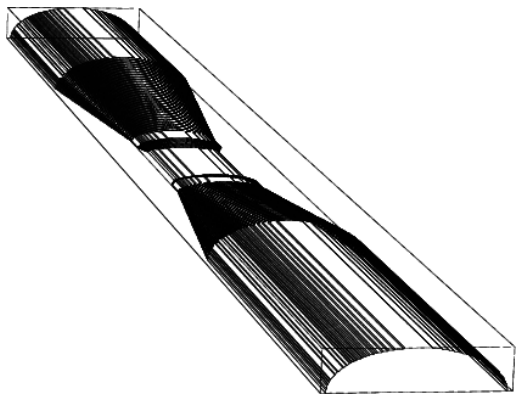
a_i = weight of the element.

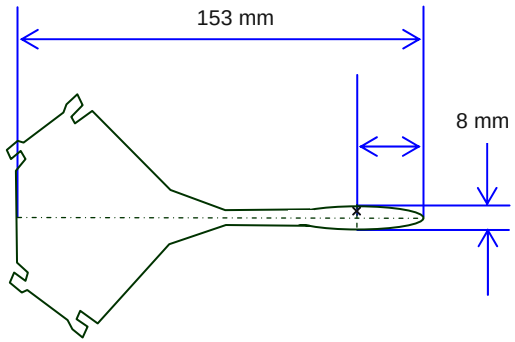
Impedance Elements

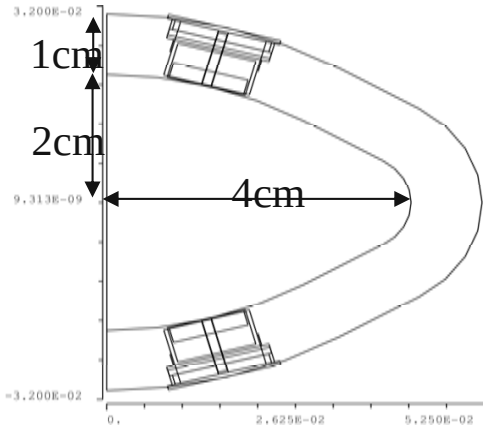




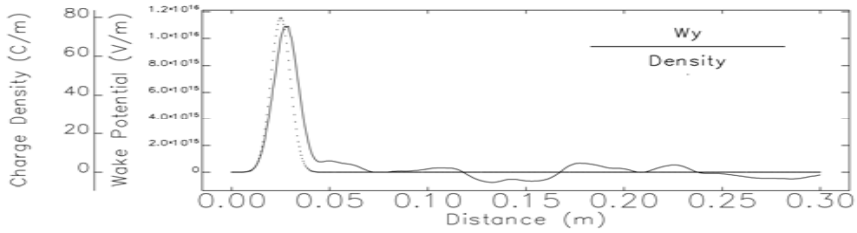


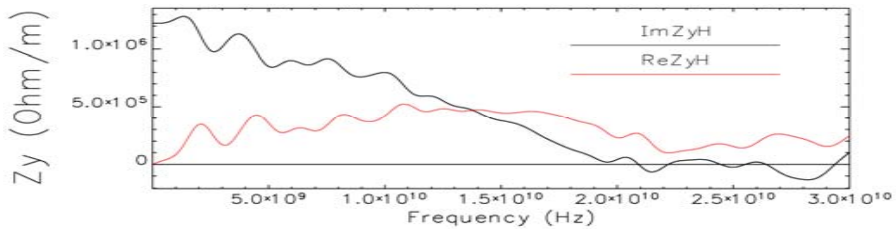




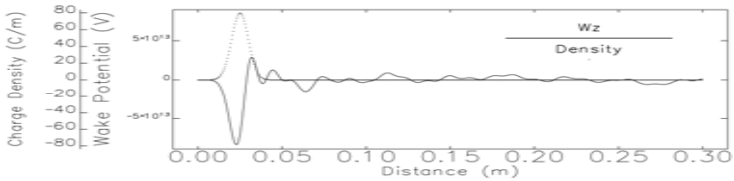


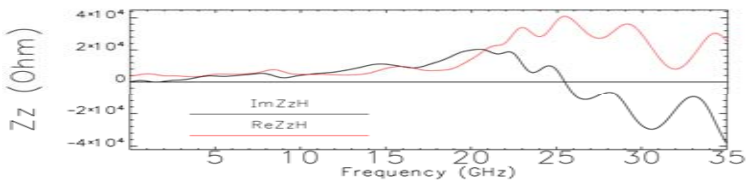
Total Impedance of the APS Storage Ring



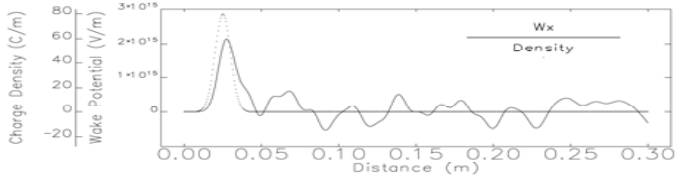


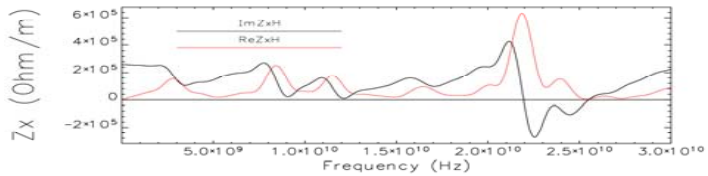
VERTICAL





LONGITUDINAL

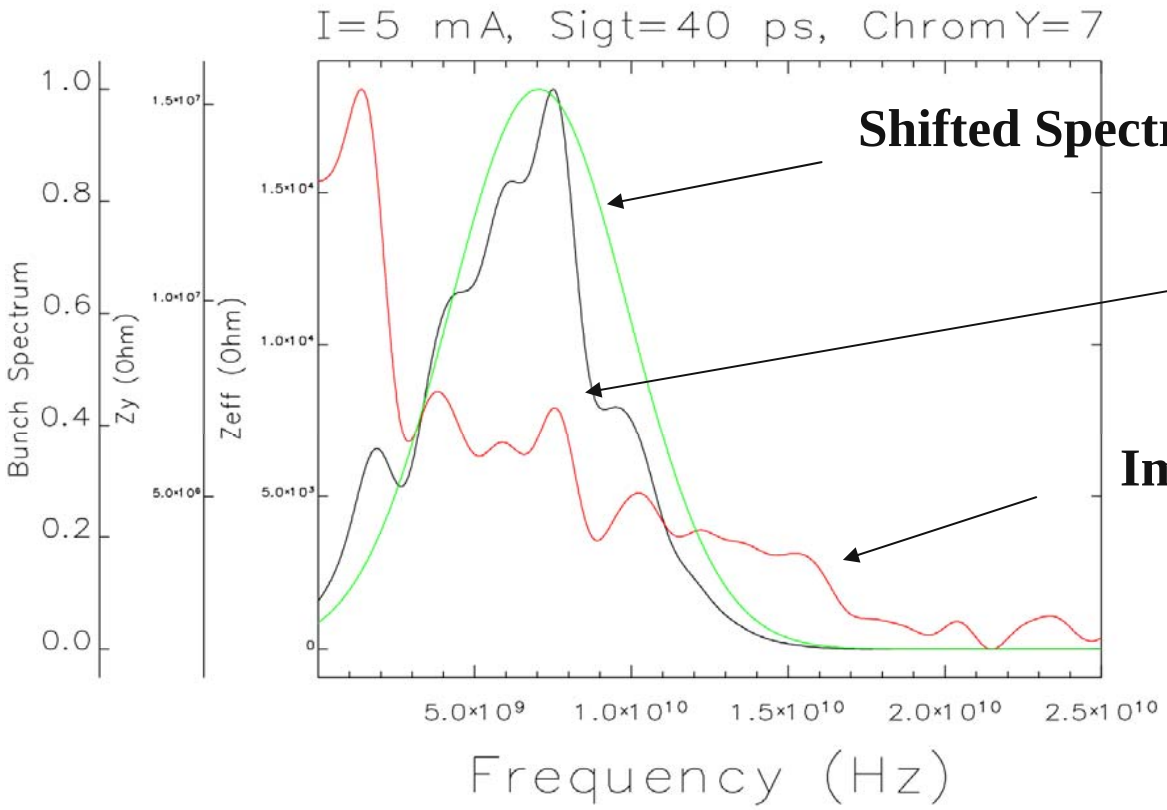




HORIZONTAL

Tune Shift: Formula

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

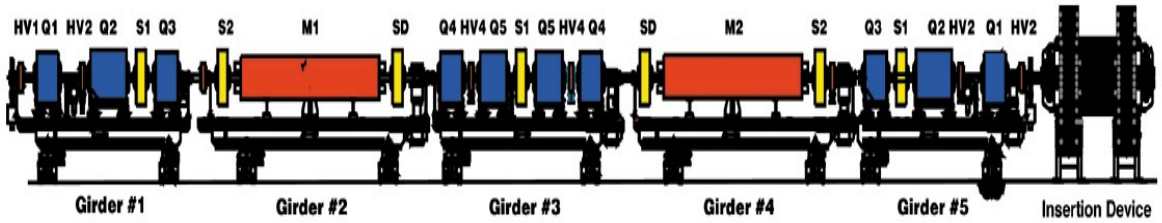


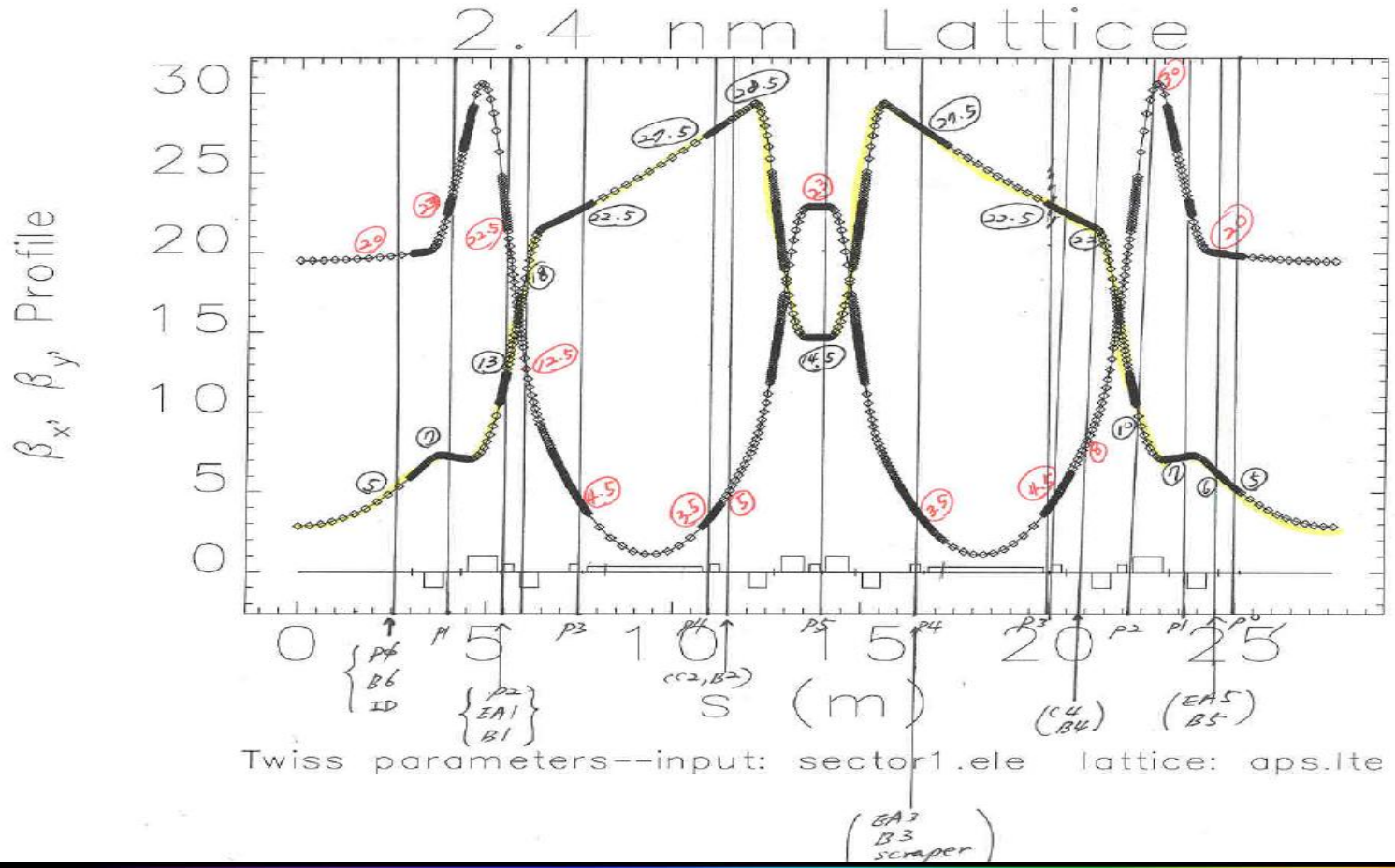
Shifted Spectrum, H0(ξ)

Zeff=H0*Zy

Impedance, Zy

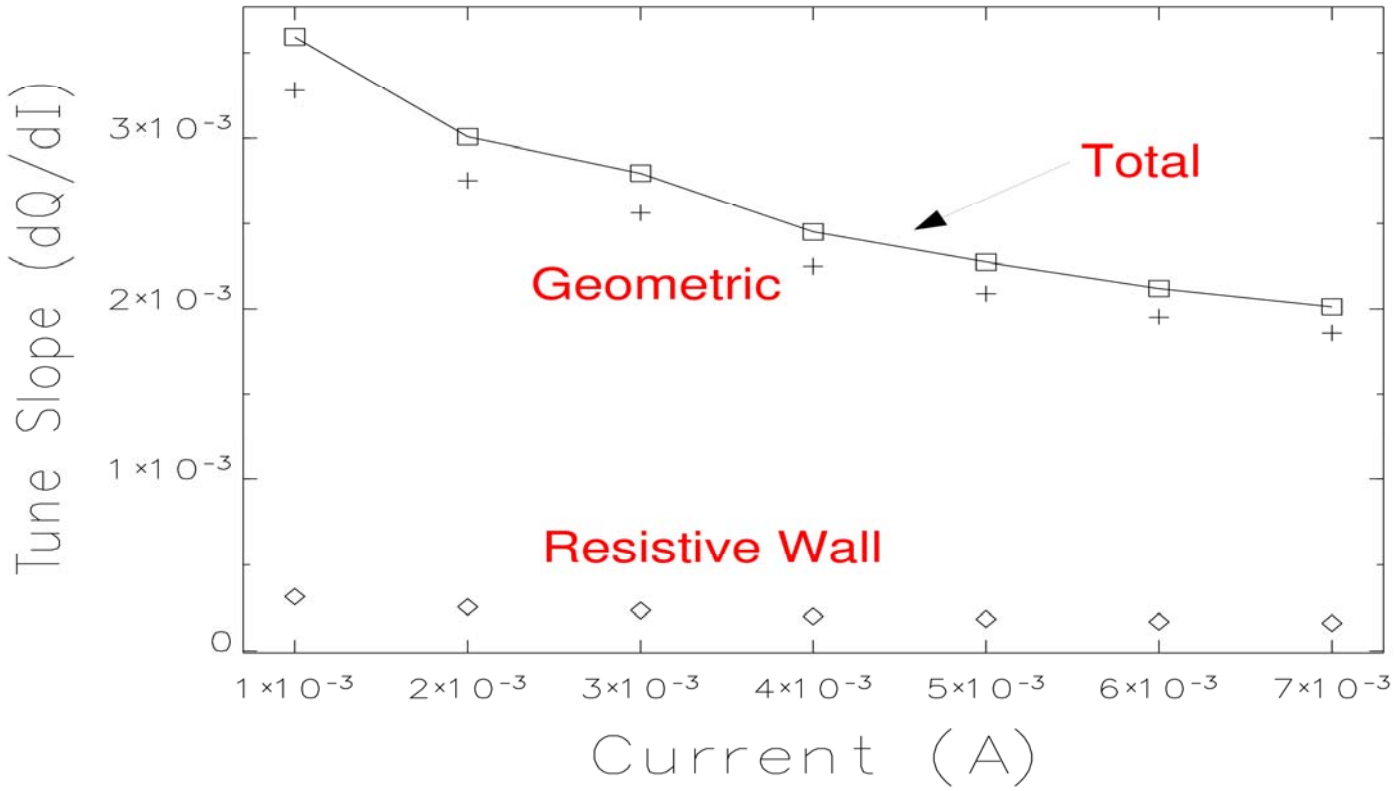
APS Low Emittance Lattice



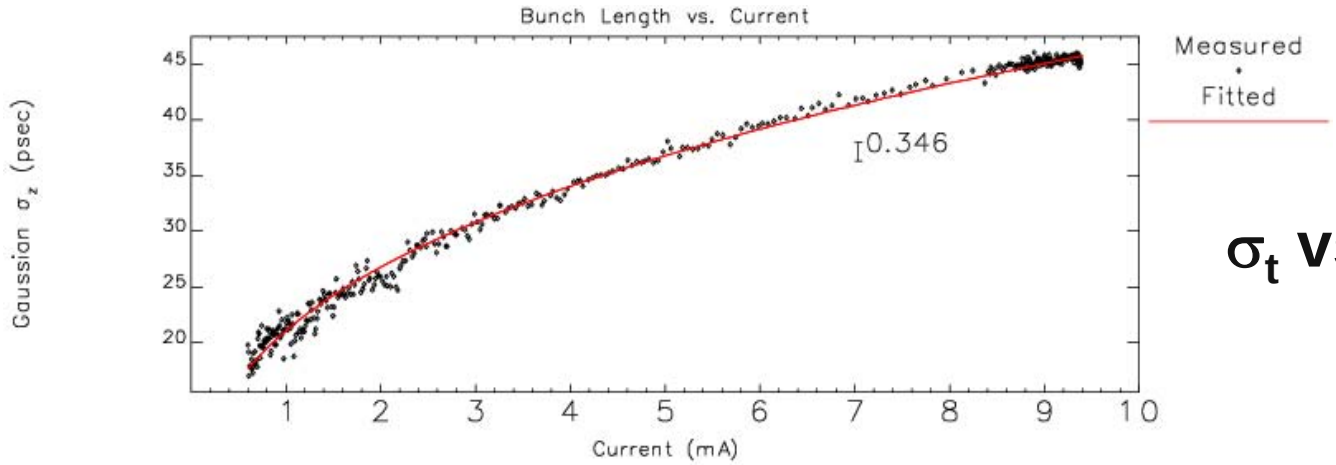


Tune Shift: Vertical

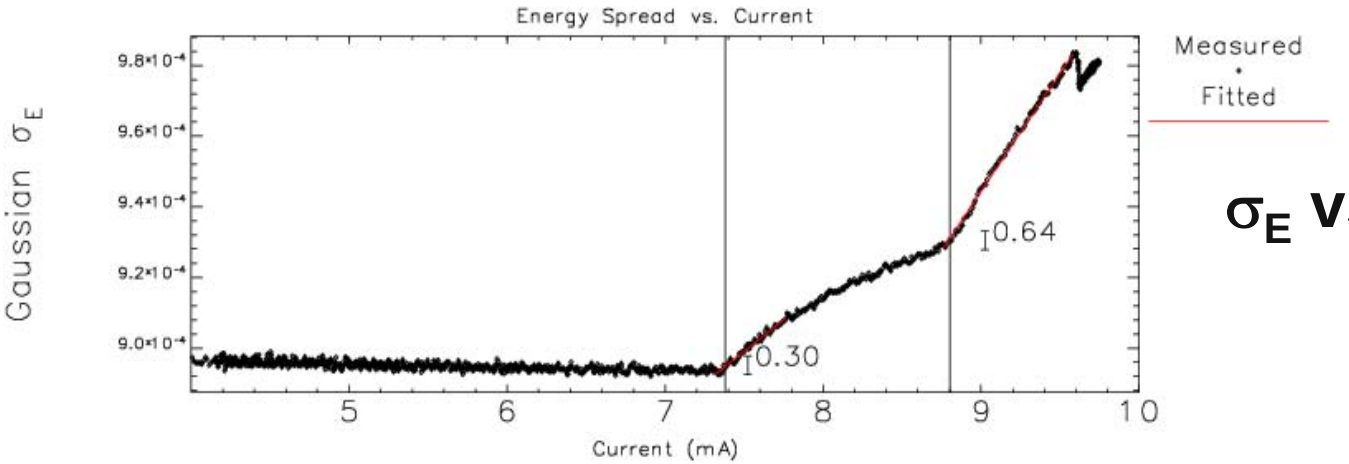
Calculated Tune Slope = 2.2e-3/mA
Measured Tune Slope = 2.4e-3/mA



Longitudinal MW: Measurement



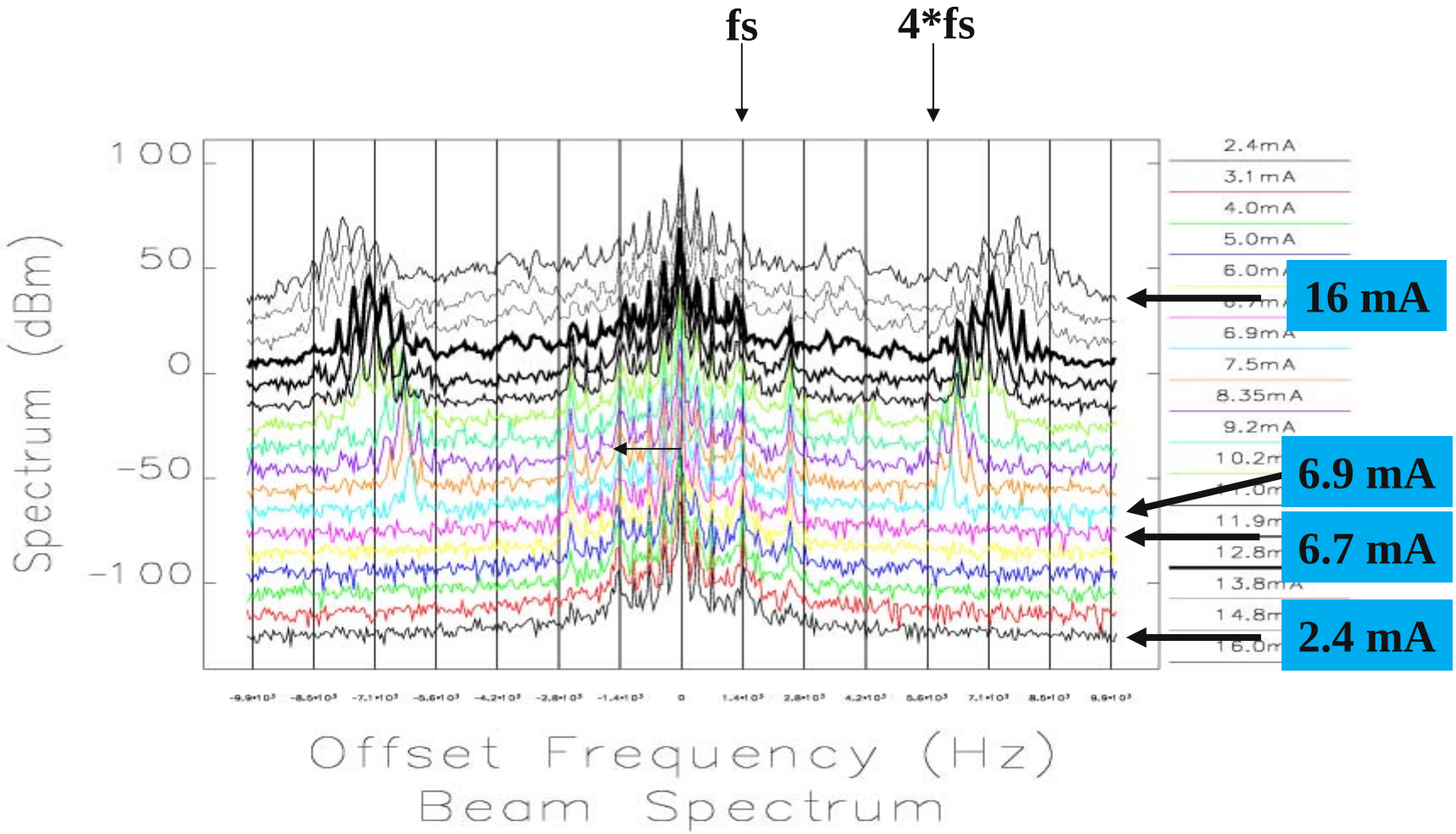
σ_t vs. I



σ_E vs. I

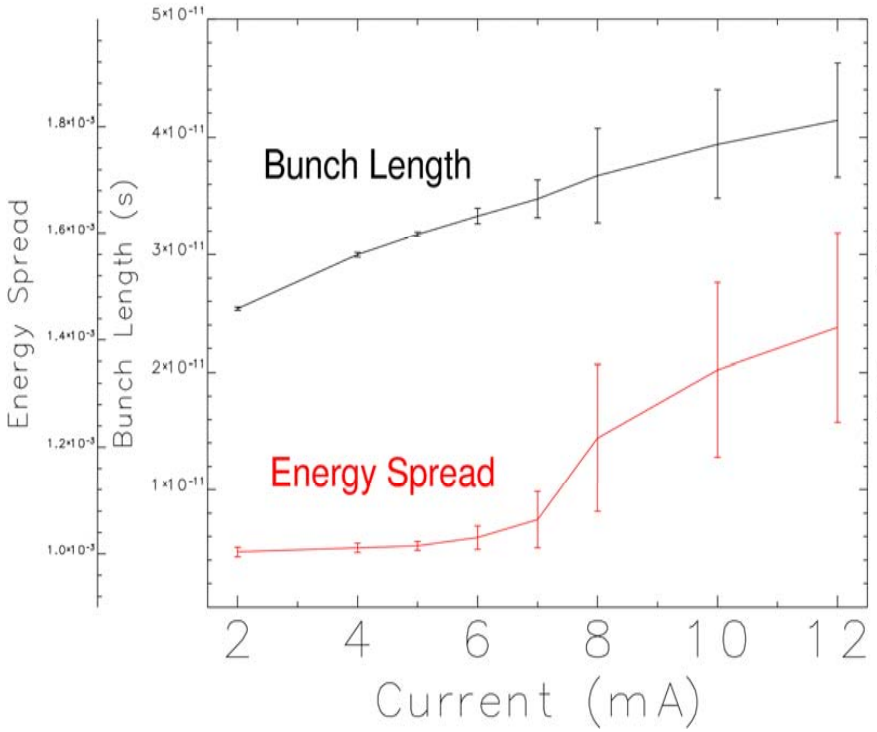
(Y.Chae, L.Emery, A.Lumpkin, J.Song, PAC'01)

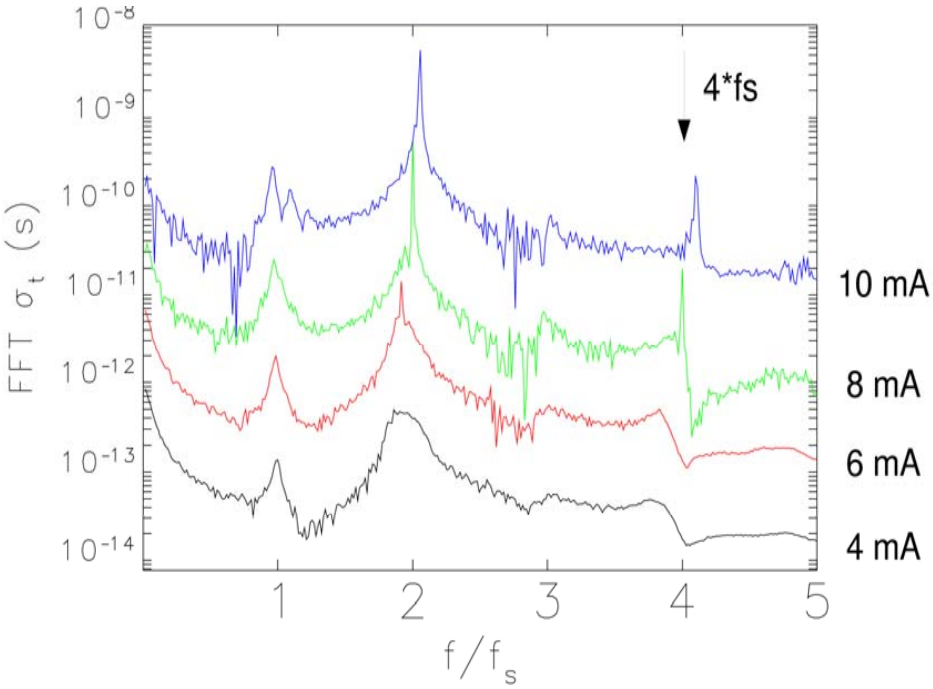
Longitudinal MW: Measurement



Mosnier: 8 $f_r \sigma_t = 1 + m$ ➔ f_r=25 GHz, σ_t=40 ps ➔ m = 7

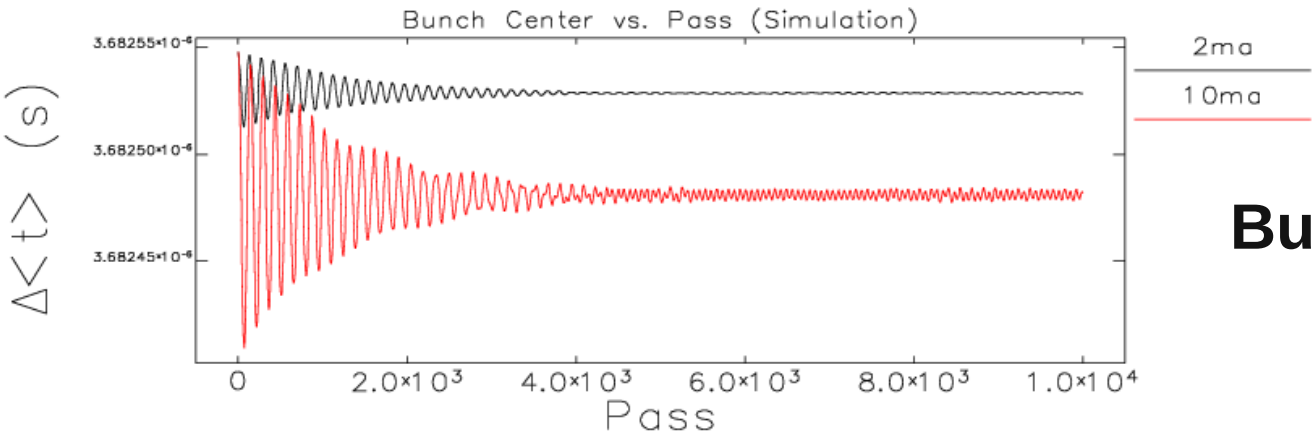
Longitudinal MW: Simulation



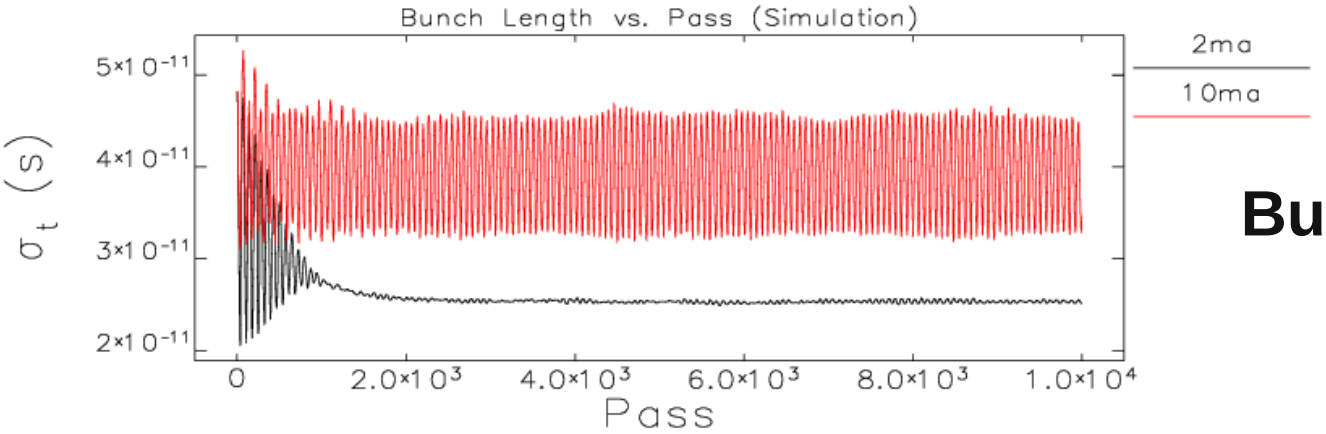


Bunch Length/Energy Spread **Bunch Length Oscillation**

Longitudinal MW: Simulation



Bunch Center



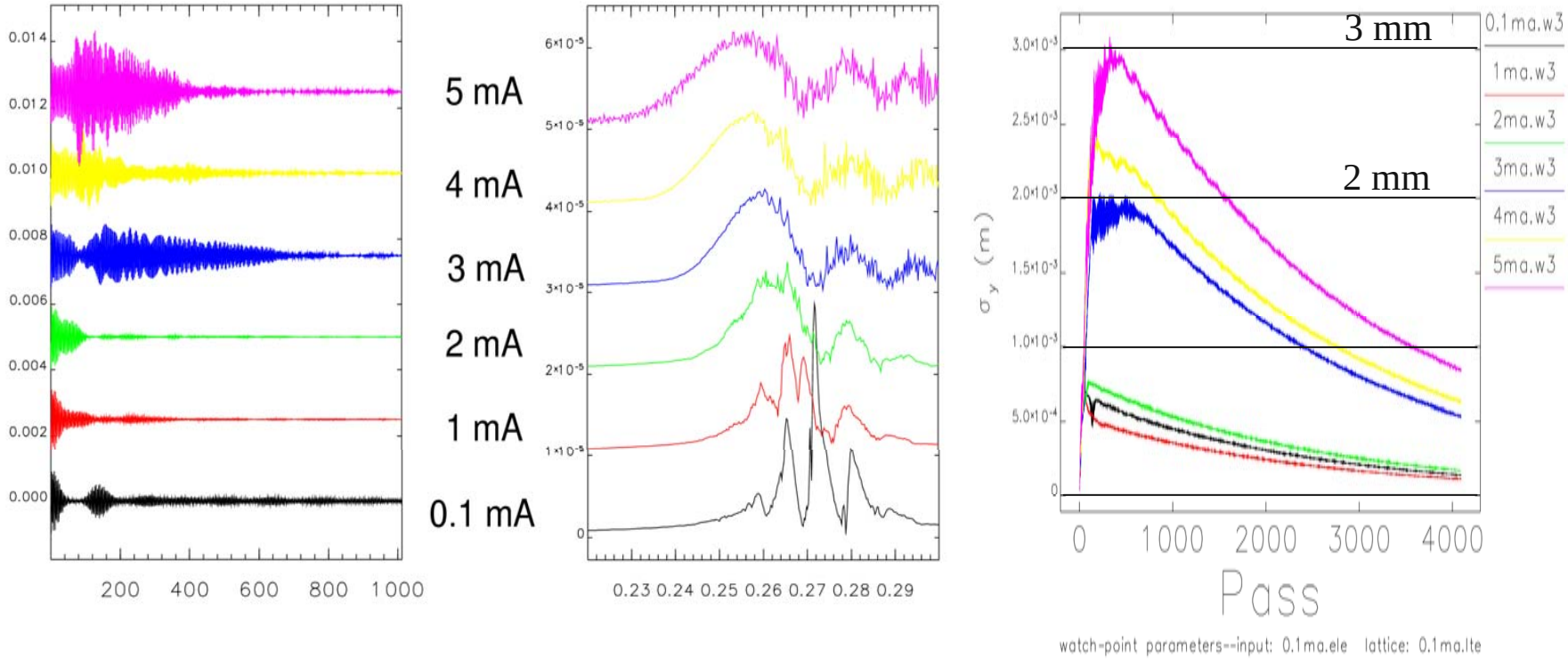
Bunch Length

What limits the single-bunch current?

- **Accumulation Limit was 6-8 mA at low chromaticity at 5-7.**
- **Chromaticity was limited by sextupole strength until the pole tip was modified.**
- **Higher chromaticity (> 10) achieved with modified sextupoles.**
- **Accumulation Limit is 20 mA at high chromaticity at 10.**

Vertical TMCI: Simulation

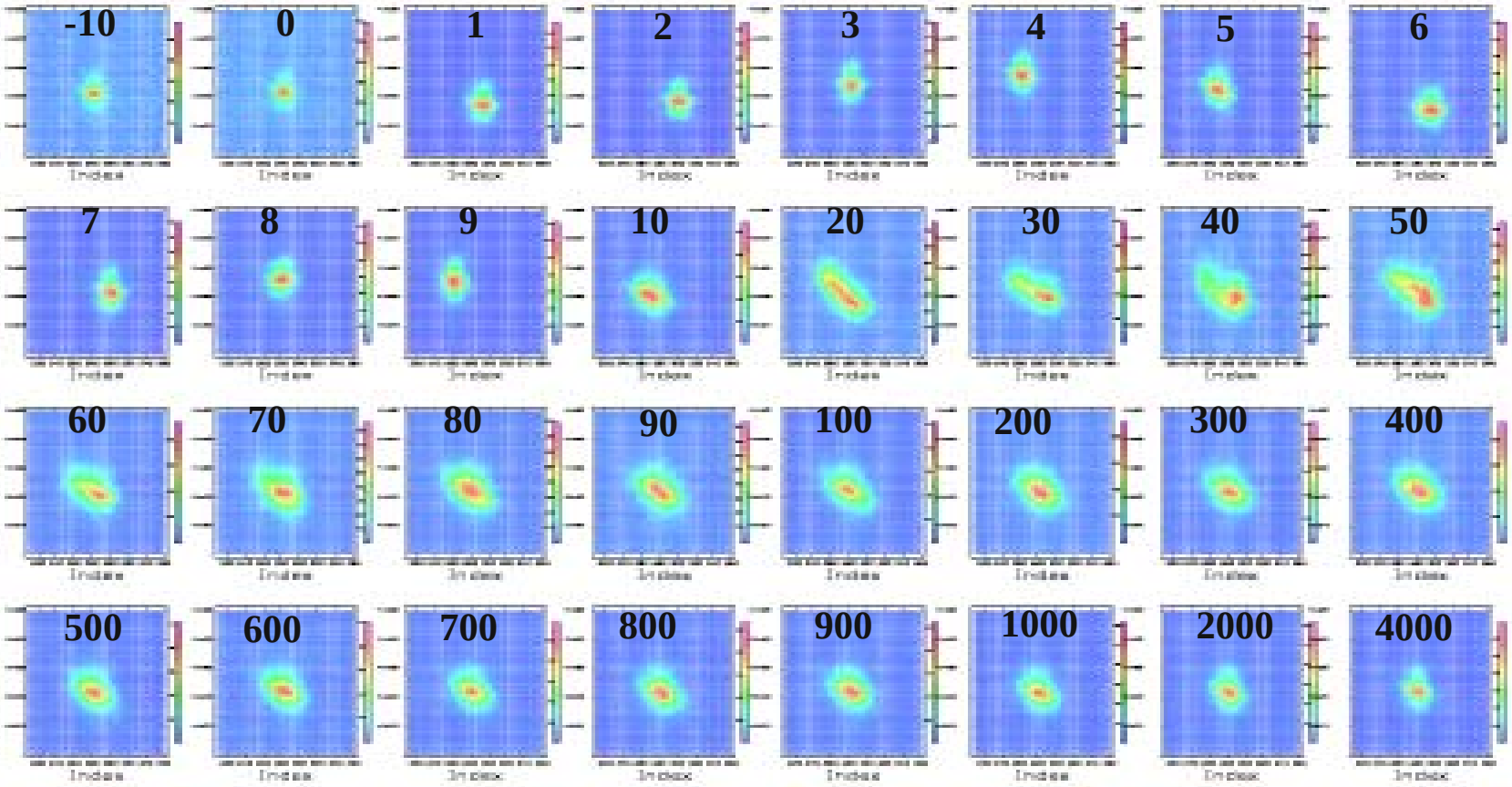
Centroid Kick Δy=1mm | **Spectrum** | **Vertical Beam Size**



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 Insertion Device Chamber**

Turn-by-Turn Images

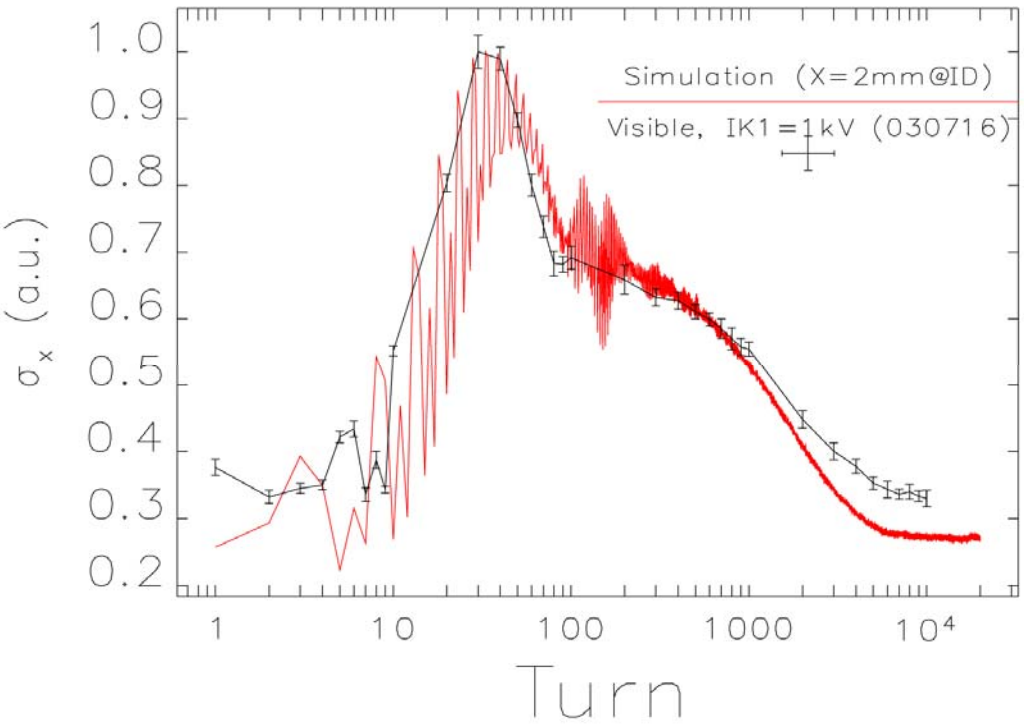
Gated Camera Images: I=1 mA, IK1=1 kV



- Gated Camera and Kicker are synchronized
- Kick the beam; Capture single image; Wait for damping; Repeat

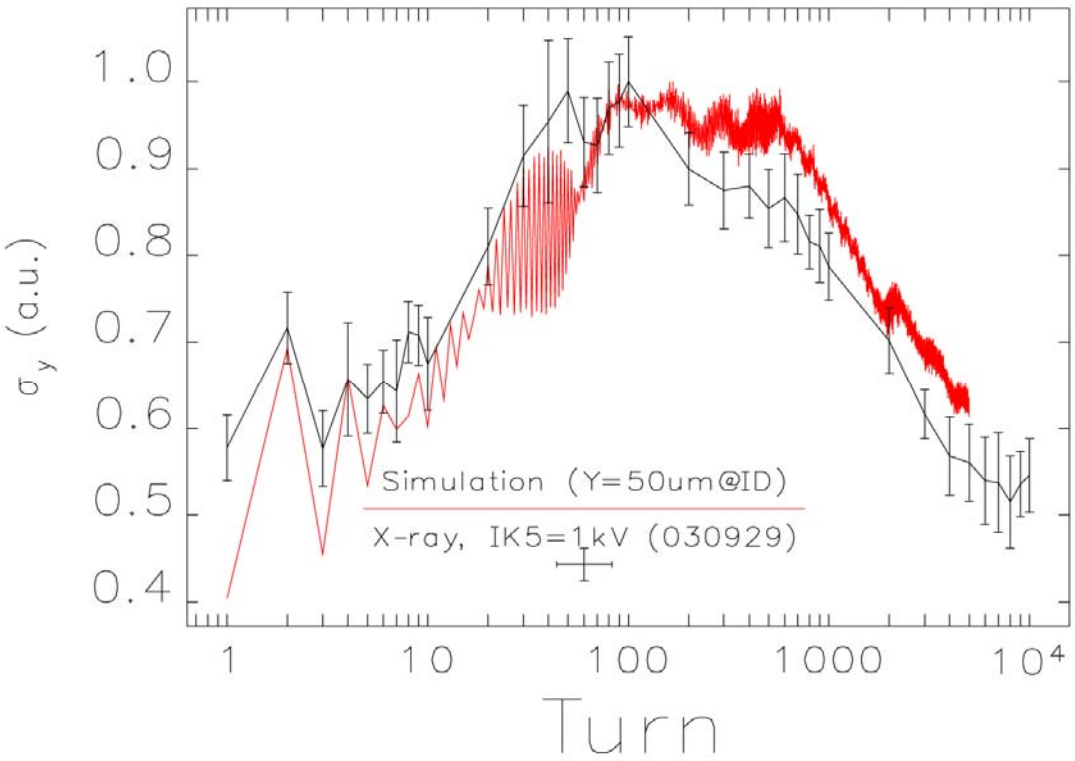
Horizontal Beam Size: Low Current (1 mA)

- **Measurement: BM Visible, IK1=1 kV, 030716**
- **Simulation: ID, BBR-1, ∆x=2 mm**
- **Beam size normalized by the maximum for comparison**



Vertical Beam Size: High Current (5 mA)

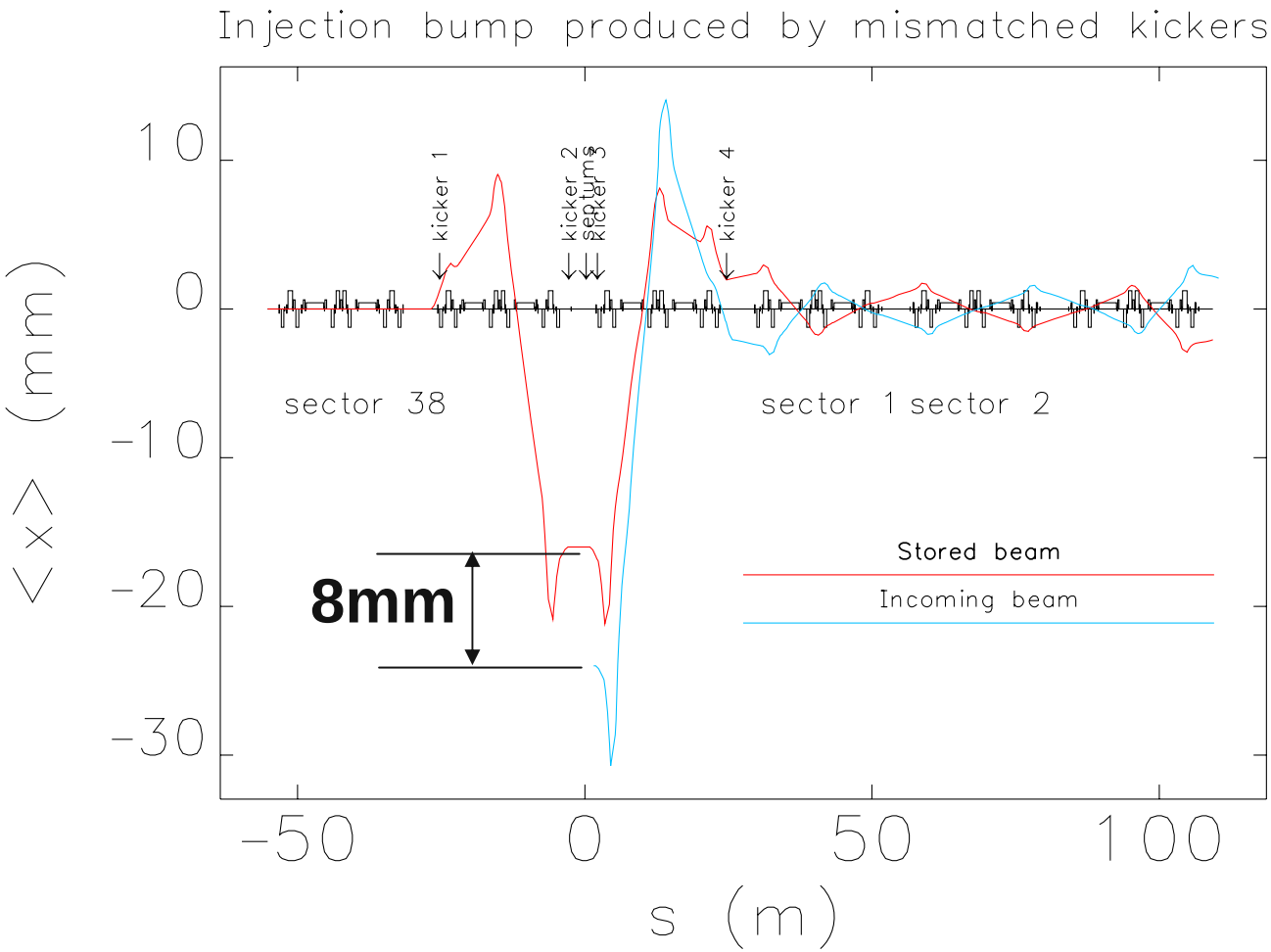
- **Measurement: ID x-ray pinhole, IK5=1 kV, 030929**
- **Simulation: ID, BBR-1, Δy=50 μm**
- **Beam size normalized by the maximum for comparison**



Simulation of Injection Process

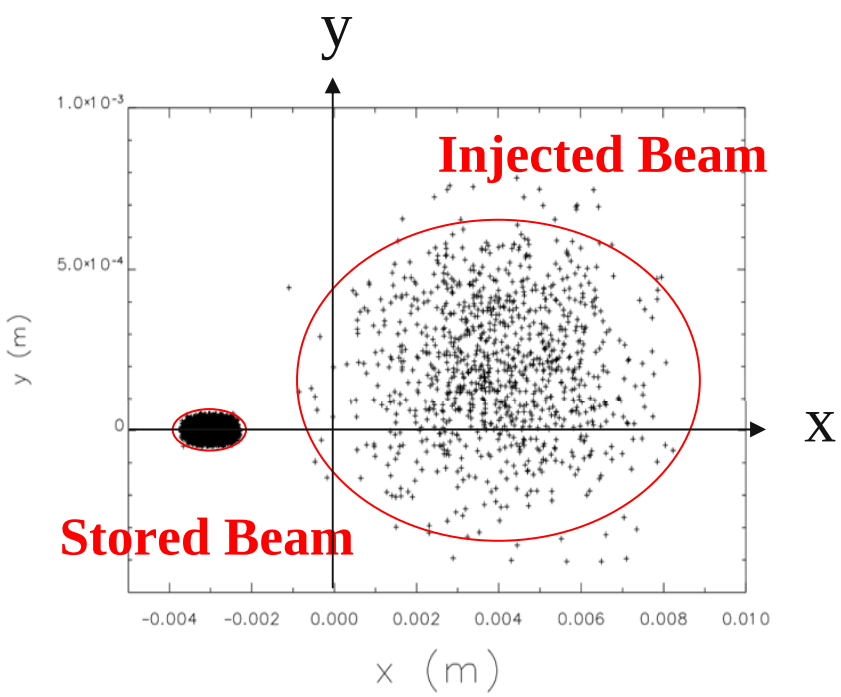
- Purpose is to improve the accumulation limit above 8 mA at low chromaticity setting
  - Injection by matched kicker bumps
  - Injection by mismatched kicker bumps (current)
  - Longitudinal injection (proposed)

Injection by Mismatched Kicker Bump



From Louis Emery (APS/OAG)

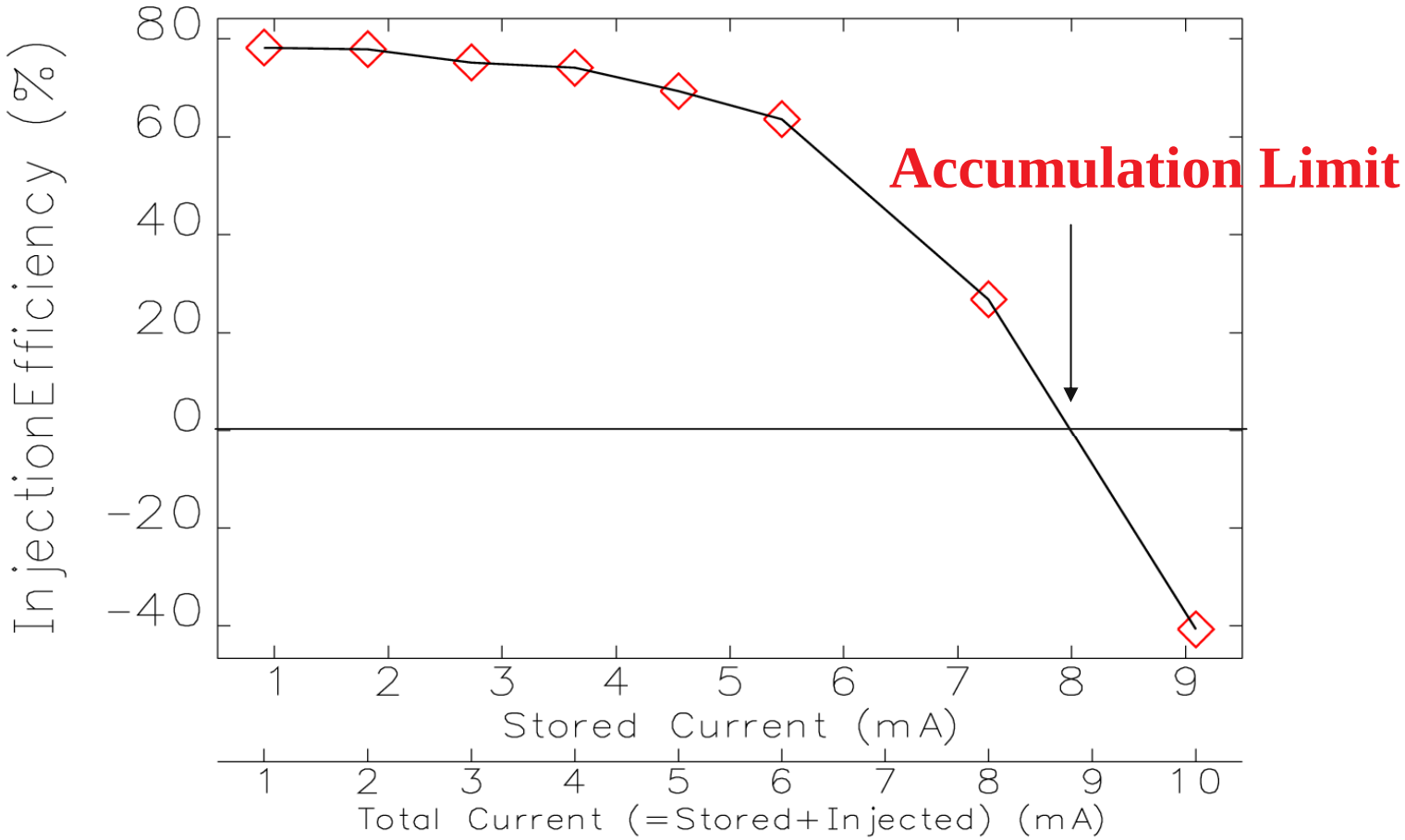
Initial Condition of Beam Simulating Current Injection Scheme



Coordinates of Initial Beam at the center of ID straight

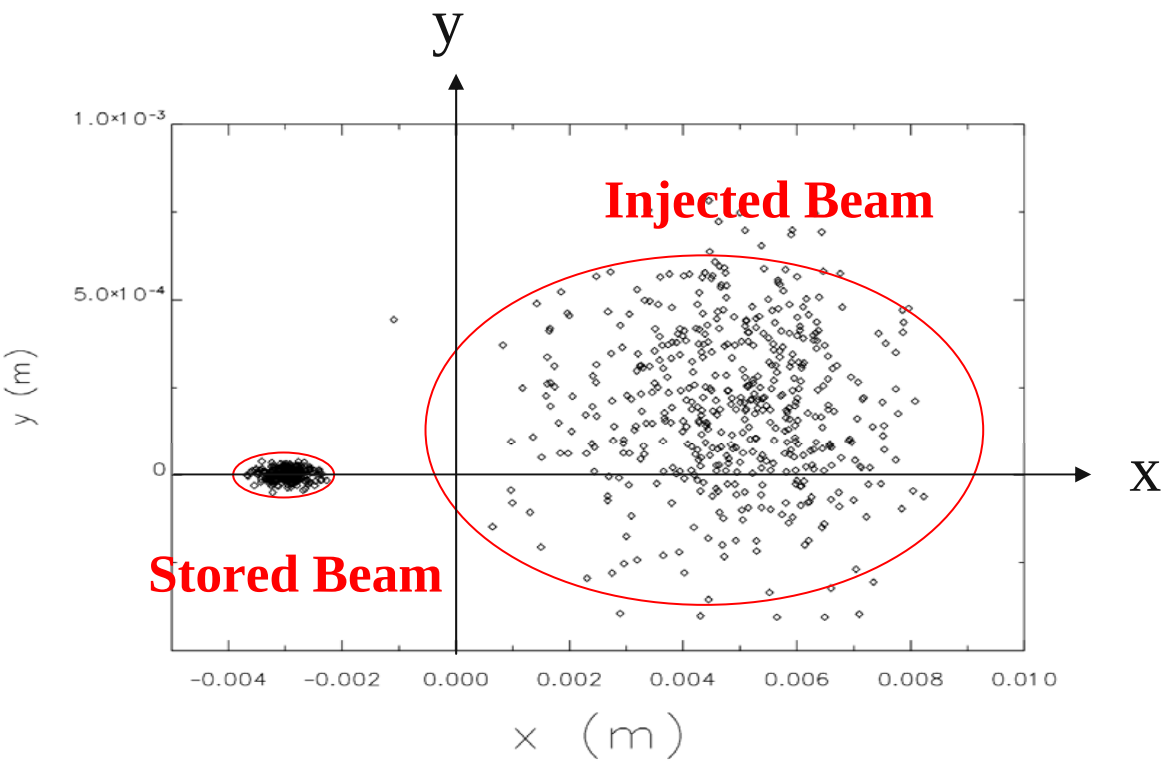
	Stored beam	Injected beam
Δx (mm)	3	4
Δy (mm)	0	0.2
ε_x (m)	3e-9	1.5e-7
$\varepsilon_y/\varepsilon_x$ (%)	3	10
β_x (m)	20	20
β_y (m)	3	3
σ_s (mm)	7 - 12	24
σ_p (%)	0.1- 0.13	0.1

Injection Efficiency vs. Current



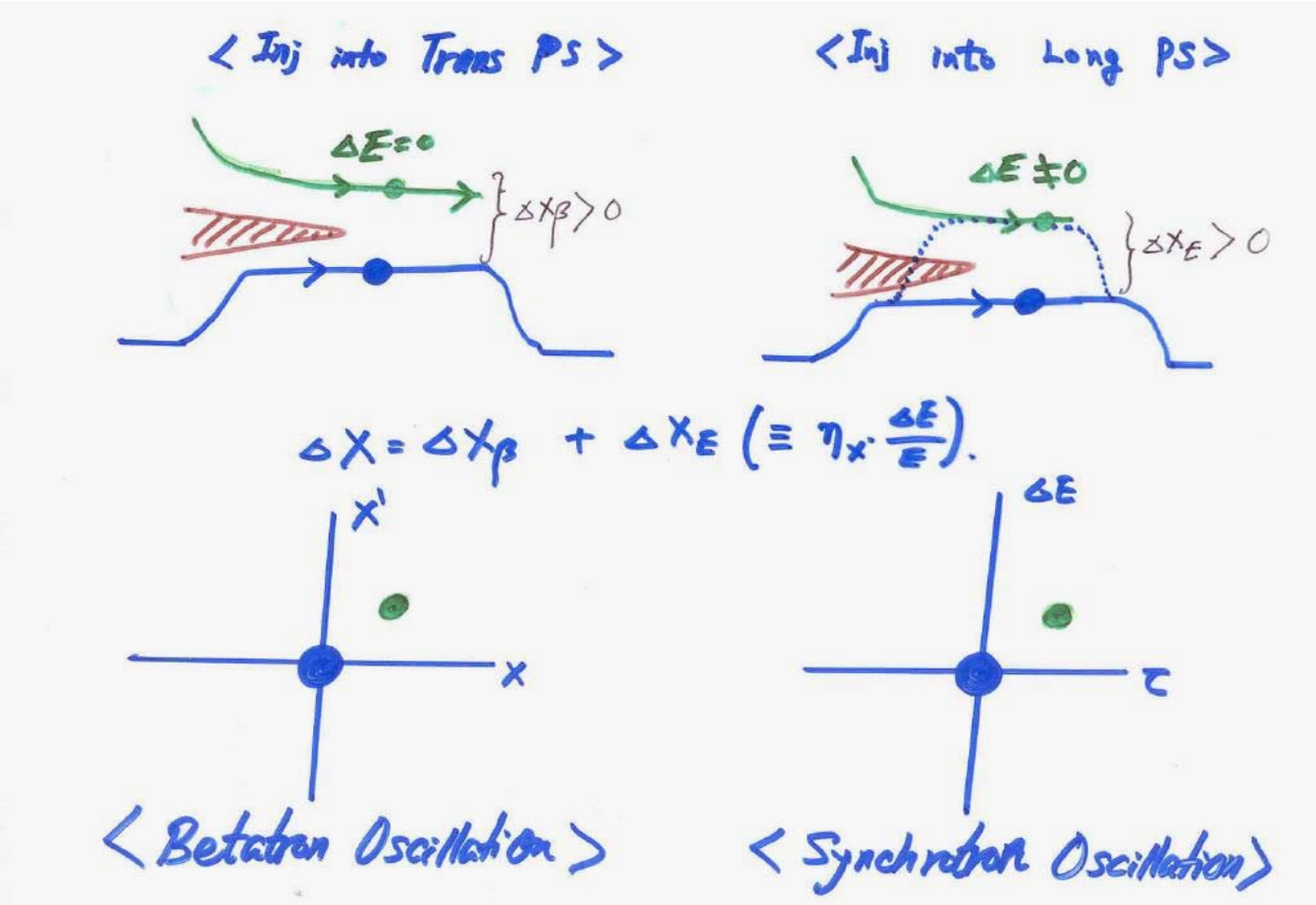
Measured Accumulation Limit < 8 mA

Initial Coordinates of Lost Beam

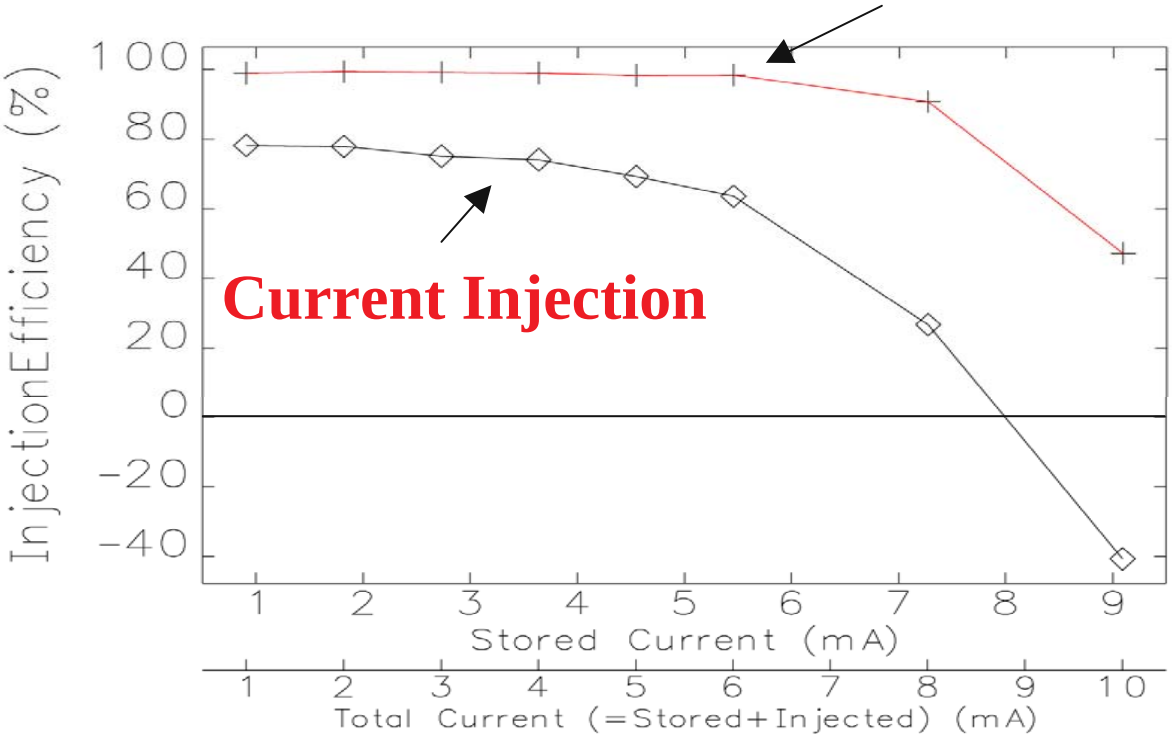


- Significant amount of stored beam is lost during the injection process
- Reduce the Beam Loss ➔ Reduce the Separation ➔ Longitudinal Injection

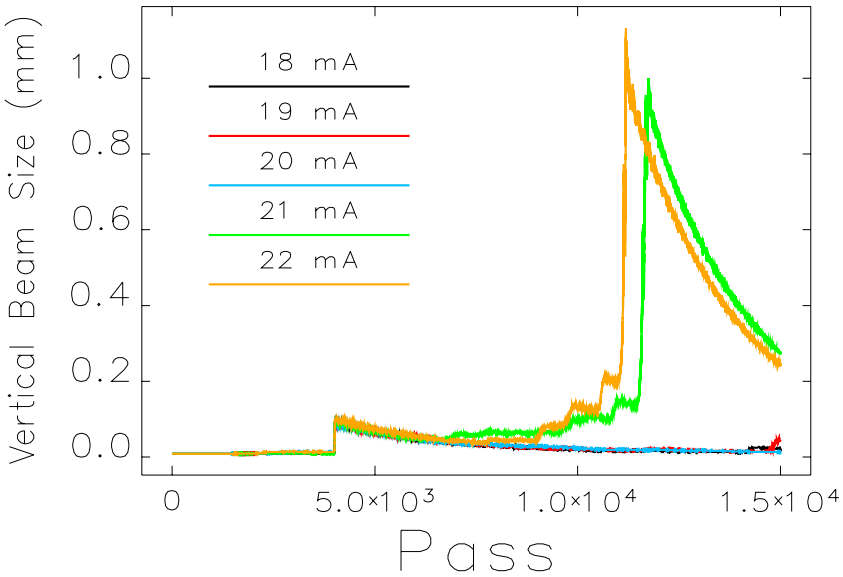
Longitudinal Injection Scheme

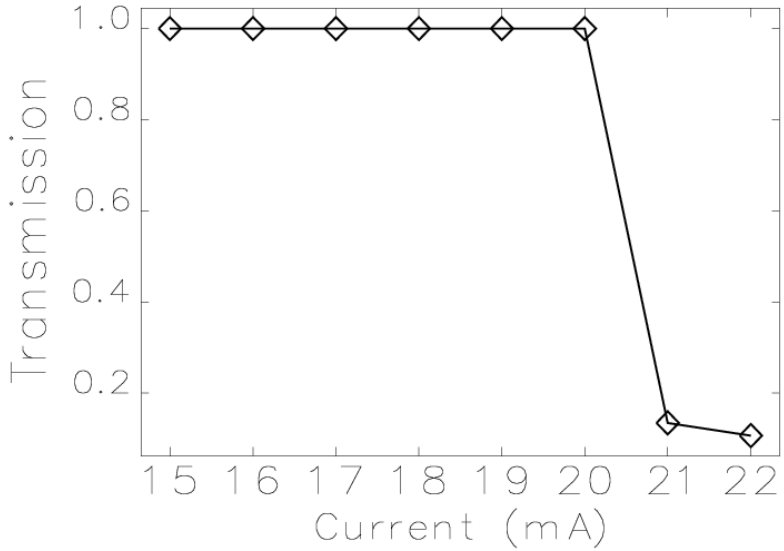


Injection Efficiency vs. Current



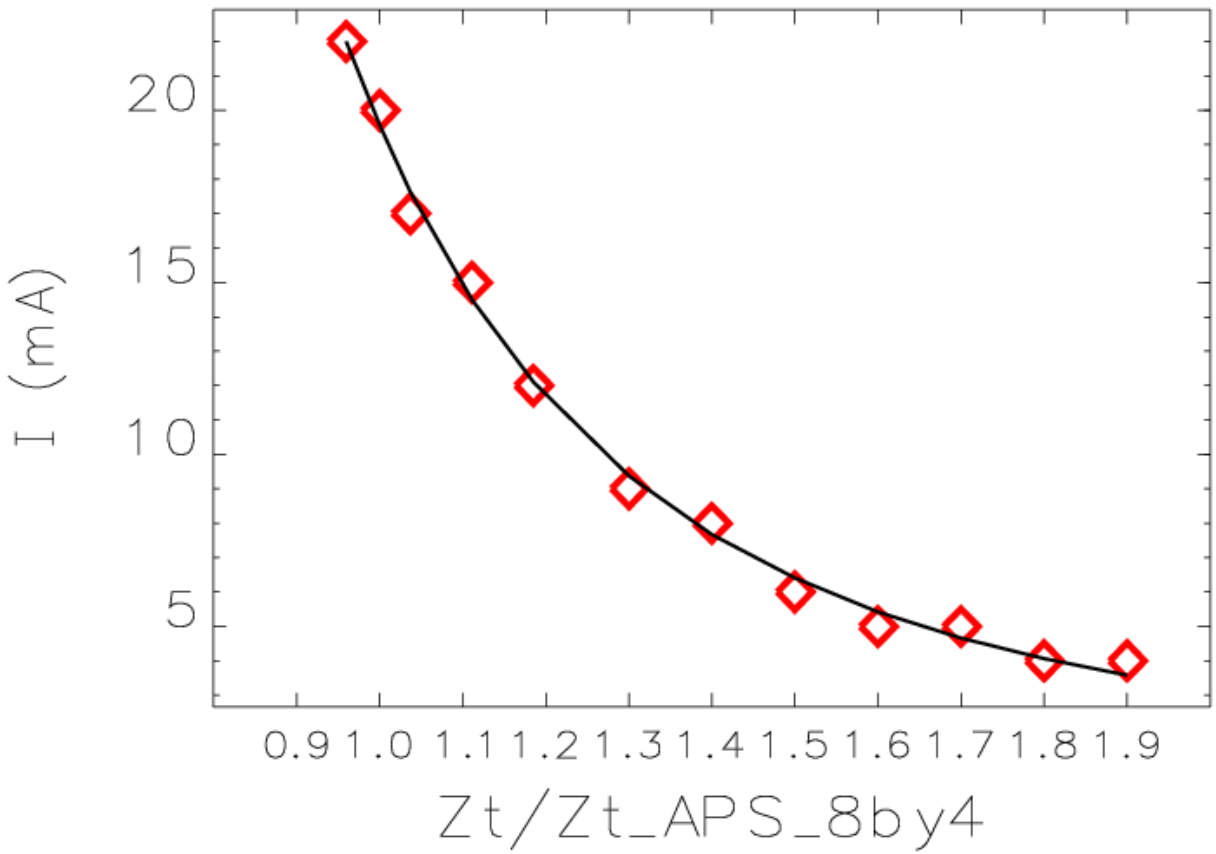
Prediction of Accumulation Limit: High Chromaticity





- **Threshold current is 20 mA determined by simulation**
  - **Vertical beam size blow-up**
- **Simulation reproduced the accumulation limit at 20 mA observed in the APS storage ring**

Single Bunch: Prediction for the APS



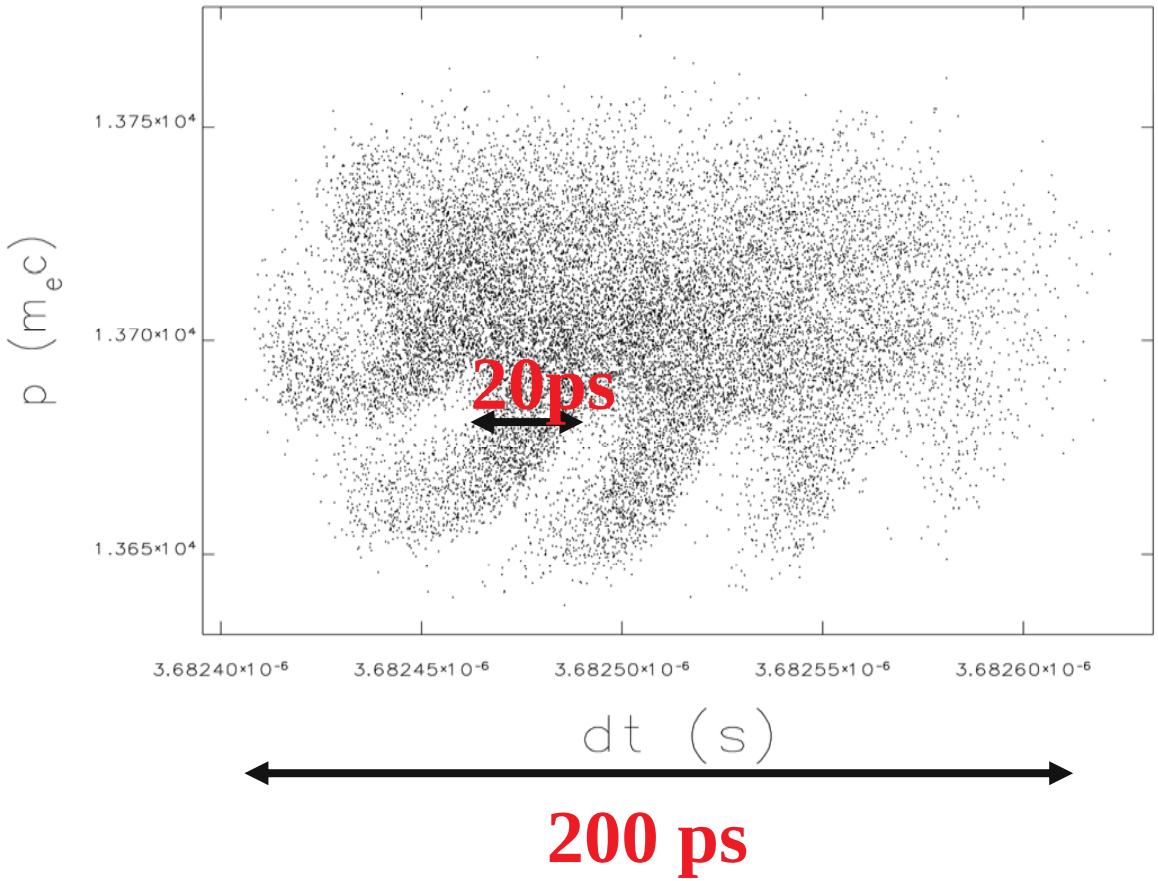
- **We can now predict the effect of small gap chambers.**

So far so good, but some problems to be fixed

- The impedance to produced good agreement was NOT true impedance BUT "Working Impedance"
  - We add imaginary Z/n=0.1 Ω to the computed impedance
  - This is necessary to compensate missing impedance above 30-40 GHz
- Bunch length oscillation of 5-ps amplitude had never been verified by streak camera measurement with 2-ps resolution.
- If the accumulation is limited by a vertical TMCI, why our injection efficiency is sensitive to the HORIZONTAL injection kicker setting in a high chromaticity operation?

So far so good, but problems to be fixed (2)

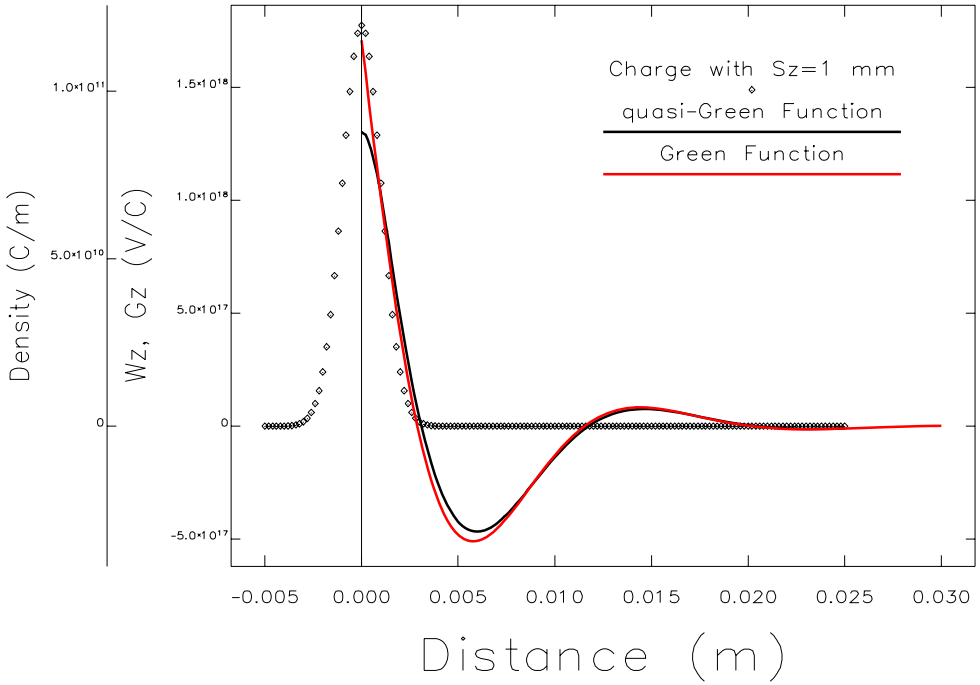
- **Phase space modulation is questionable.**



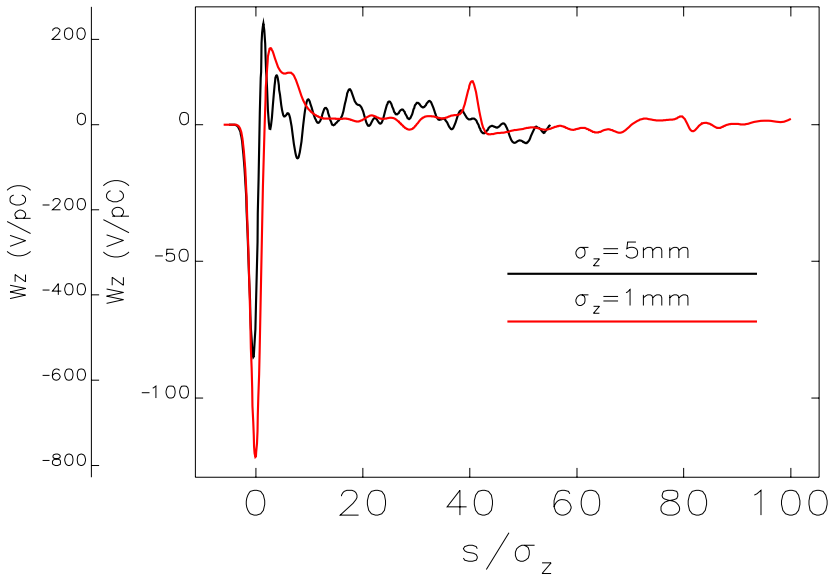
Impedance Database II: Choice of Bunch Length

- **Remove "ad-hoc" modification made to IDB-1 by improving the impedance bandwidth**
- **Use short bunch to calculate wake potential!**

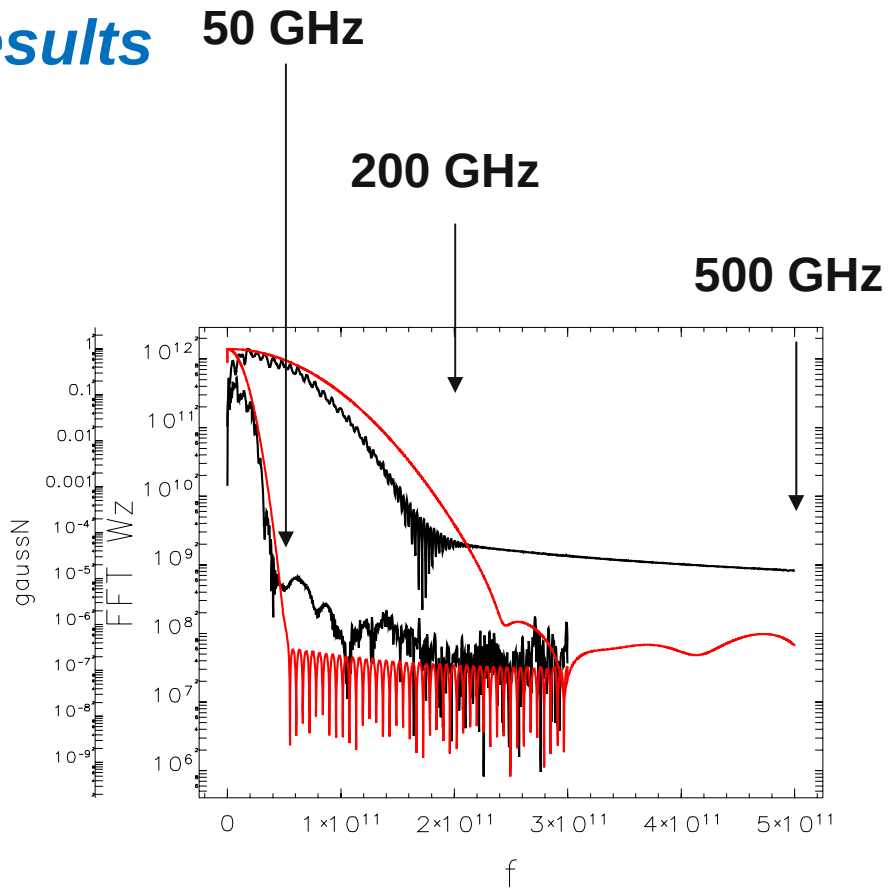
- The shorter, the better.
- But, computer resources are limited.
- **We choose σ_z=1 mm**
  - quasi-Green Function
- We purchased 60-node cluster equipped with 240 GB of memory
- We purchased GdfidL



Impedance Database II: Results



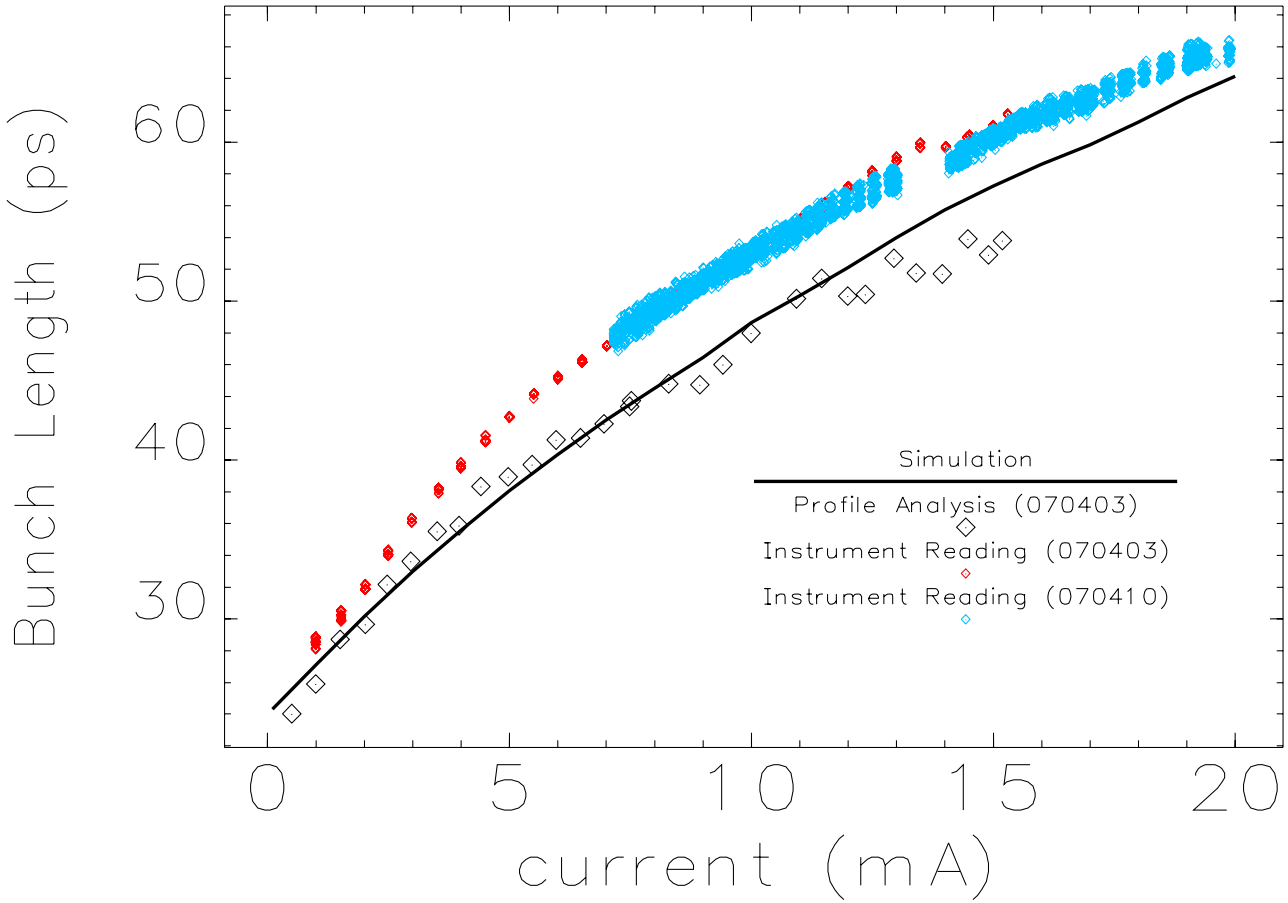
W_z (V/pC)



| FFT(W_z)|

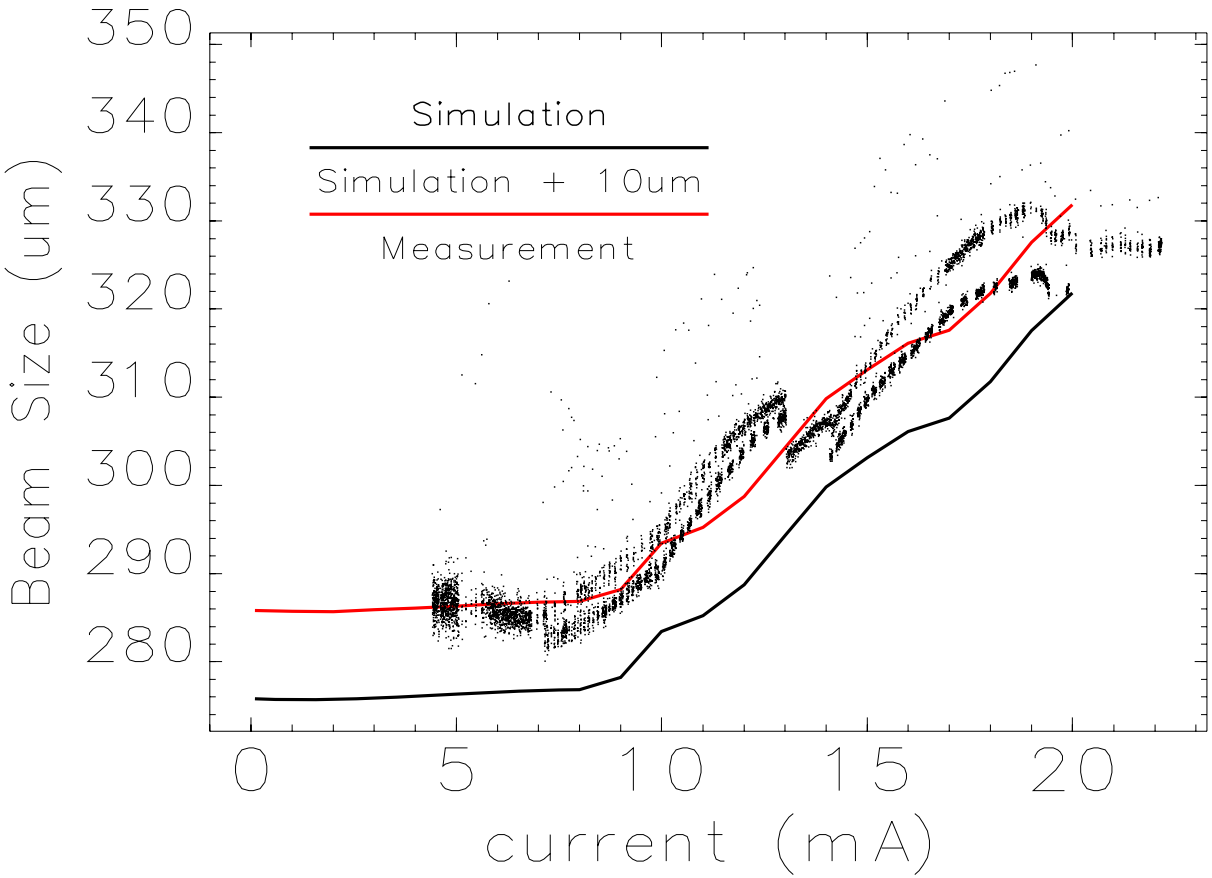
- Bandwidth increased from 40 to 200 GHz!

Bunch Length Measurement



- Simulation results was obtained by a raw impedance.

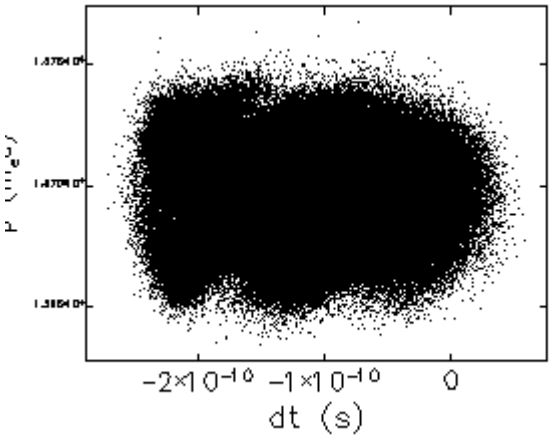
Energy Spread Measurement

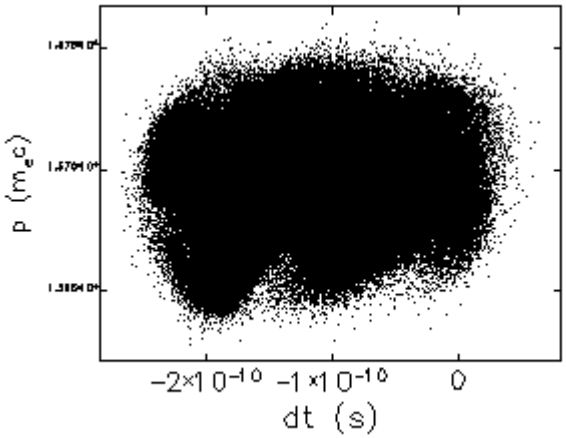


- The difference is only 2% if we include 40 um resolution.

Phase space is smoothed

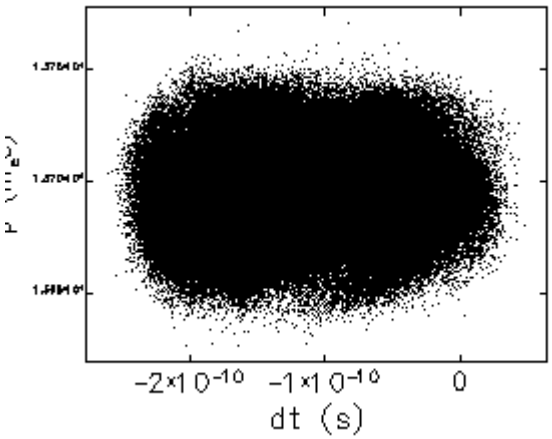
P=6500

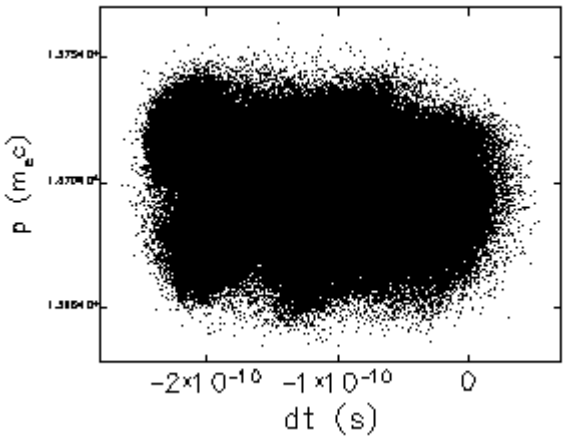




P=7000

P=7500

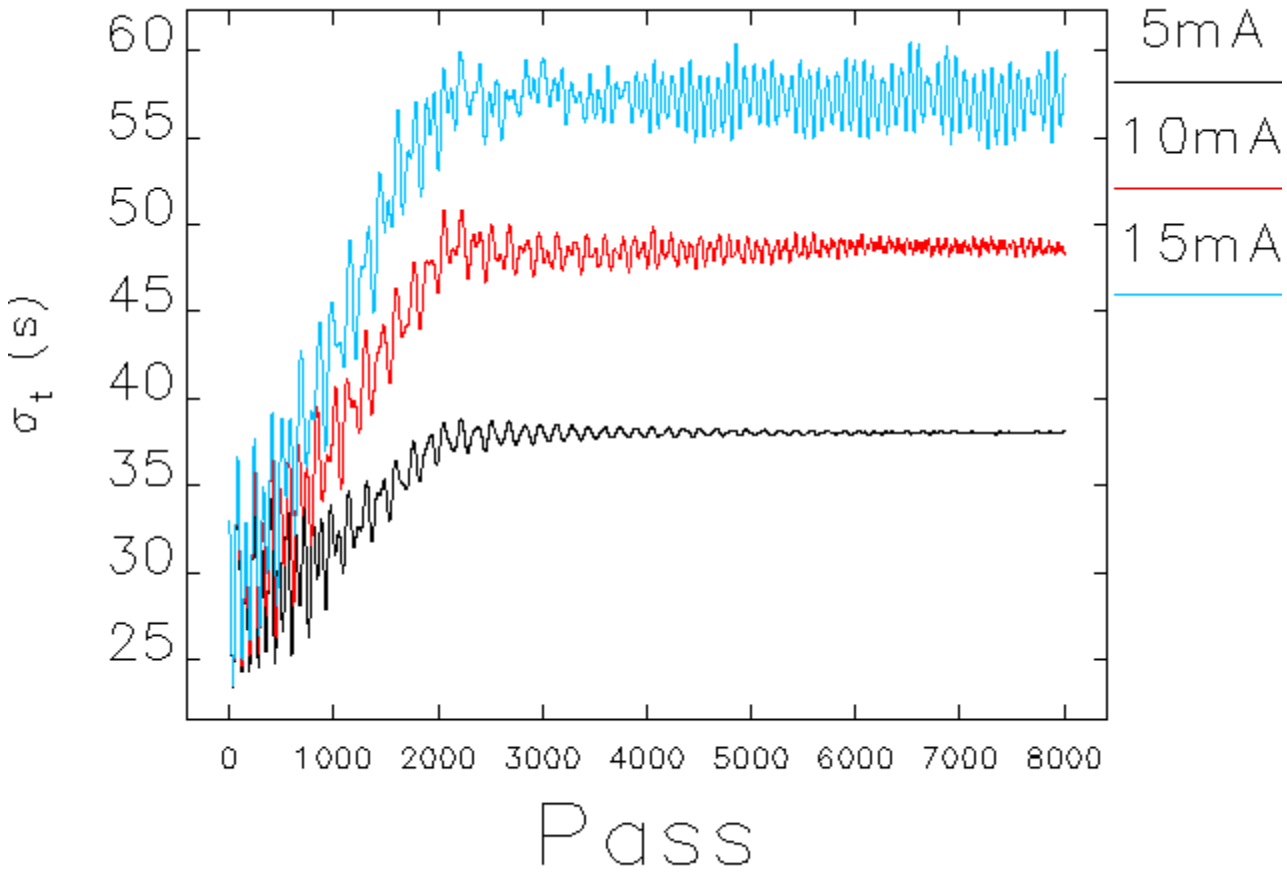




P=8000

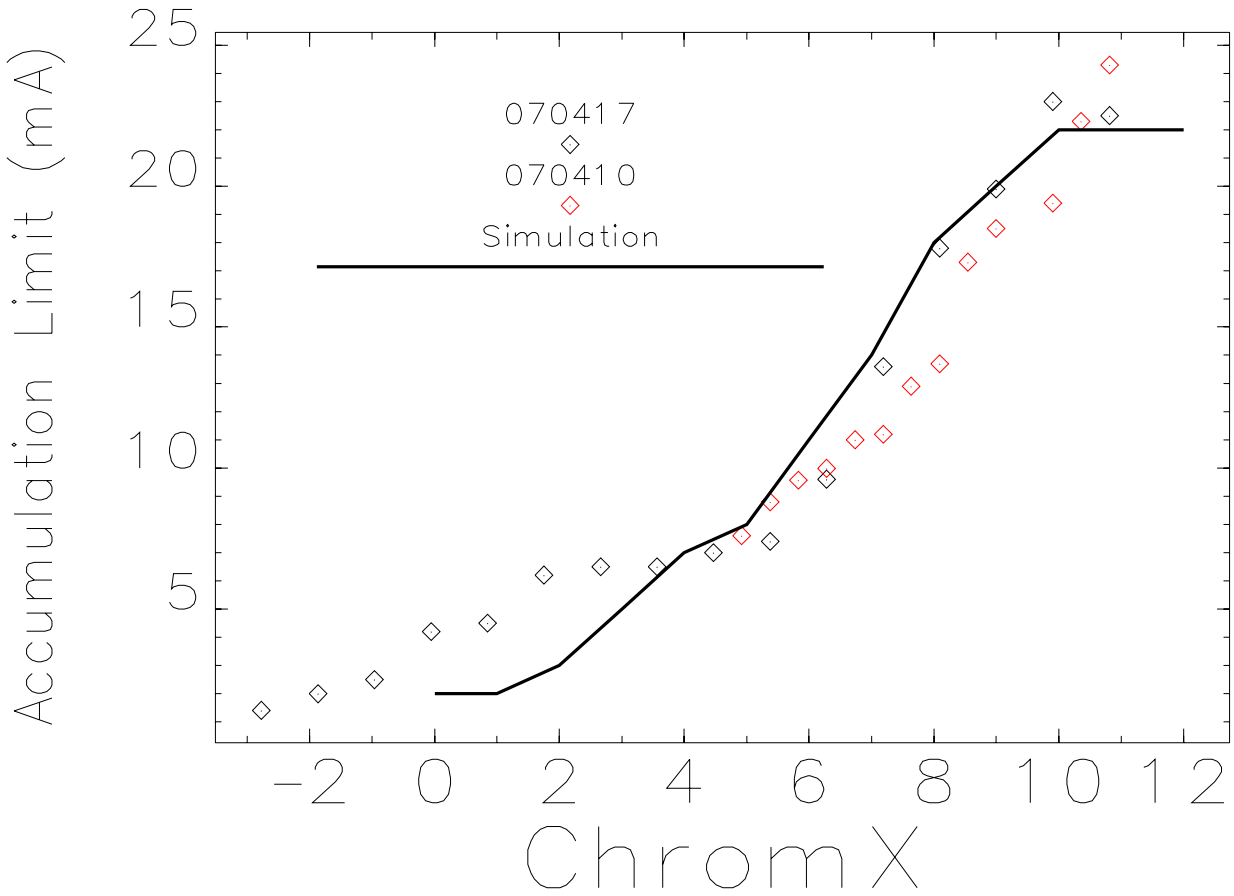
- The pronounced paw-like structure is smoothed.

Bunch Length Variation is reduced.



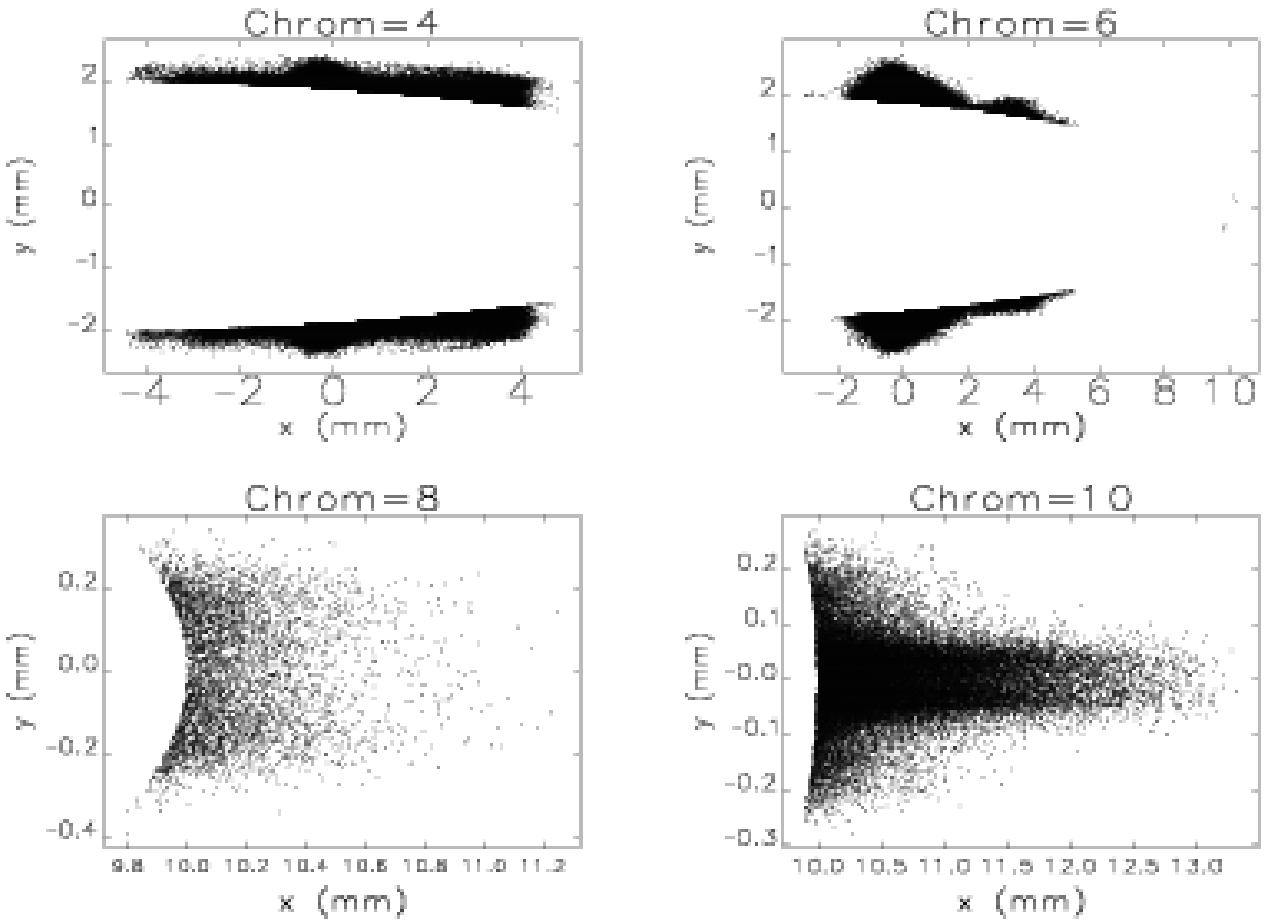
- The oscillation amplitude is about 2 ps close to the APS streak camera limit.

Accumulation Limit



- This is the first time we compare accumulation limit at different values of chromaticity.

Beam Loss



Vertical TMCI

Horizontal TMCI

- **Effect of amplitude dependent tune shirt changes beam-loss plane from vertical to horizontal plane.**

Single Bunch Current of the Future APS Ring

	Add (%)	Total (%)	Current (mA)	Note
Reference	0.00	100	20.0	1*5-mm + 29*8-mm + Others
Short pulse sector	1.33	101.33	19.3	1*3-cell + 2*9-cell (r=23.5 mm), T1+T2
8-mm gap	1.54	102.87	18.6	Replacing EMW @ S11
4*8-mm gap	6.16	109.03	15.8	New addition
7-mm gap	0.64 (2.18)	109.67	15.6	Replacing 8mm 3.5 m long SC ID
6-mm gap	1.71 (3.25)	111.38	14.9	Replacing 8mm 5 m long ID @ S1

Plan for the APS Upgrade

- We consider upgrading the current 3rd generation storage ring to an Energy-Recovery-Linac based 4th generation light source.
  - Need to estimate the wake field of the 100-fs bunched beam passing through linac and all impedance elements.
- We are developing a high-order 3D wake-potential program based on a spectral-element discontinuous Galerkin method
  - Recently computed the wake potential of 1-ps bunched beam up to 7th order accuracy (Misun Min, THPAN091)
- We are developing a high-order 3D time-dependent PIC code in collaboration with Brown University
  - Initially we will simulate 1-m long structure
  - Eventually we will simulate 1-km long accelerator without any approximation
  - This is in the LDRD proposal with strong support from ANL's petaflop computing.

Summary

- Impedance Database was proved as a useful tool to investigate the single-bunch instability in the APS:
  - The APS storage ring (Y. Chae et al., FRPMN104)
  - The 1-nm storage ring with smaller chamber (Y. Chae et al., FRPMN103)
  - The APS storage ring with crab cavities for short x-ray pulse (Y. Chae et al., FRPMN105).
- Found that 3D computation was essential because the APS storage ring's chamber is smooth.
- Very short bunch in the ERL based APS Upgrade required to develop a new high-order 3D wake-potential code (M. Min et al., THPAN090,THPAN091)

Acknowledgement

Taking Data

M. Borland, L. Emery, K. Harkay, A. Lumpkin, N. Sereno, V. Sajaev, J. Song, C. Yao, B. Yang, APS Operators

Computer Software/Hardware

M. Borland, B. Soliday, Y. Wang, A. Xiao, W. Bruns (GdfidL)

Drawings

P. Choi, G. Goepner, L. Morris, E. Rossi, S. Sharma

Support

R. Gerig, K. Harkay, K. Kim, S. Milton

Discussion

S. Krinsky, B. Podobedov, J. Wang (NSLS)

R. Nagaoka (SOLEIL), M. Blaskiewicz (BNL)