Impedance Database and its Application to the APS Storage Ring

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Outline of Talk

Impedance Database: construction

- Goal/Method
- Examples
- Total Impedance

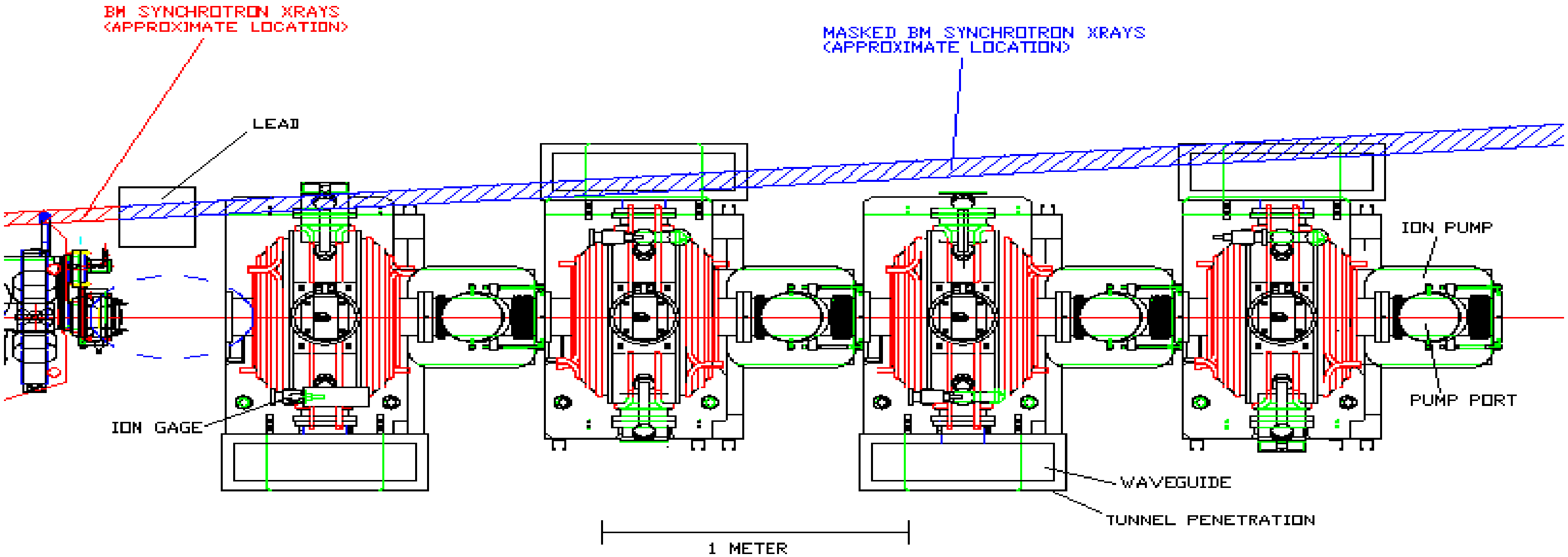
Application: understanding observed instabilities

- Longitudinal: Microwave
- Horizontal: Saw-tooth
- Vertical: TMCI

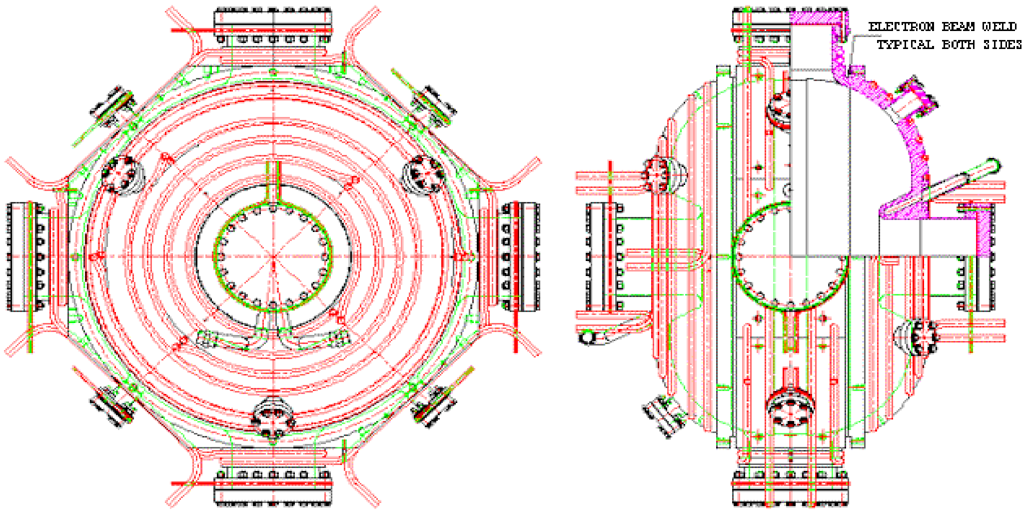
Application: mitigation of instabilities

- Impedance reduction: redesign ID chamber transition
- Transverse: longitudinal injection, negative α lattice
- Longitudinal: rf-voltage modulation

RF Cavity

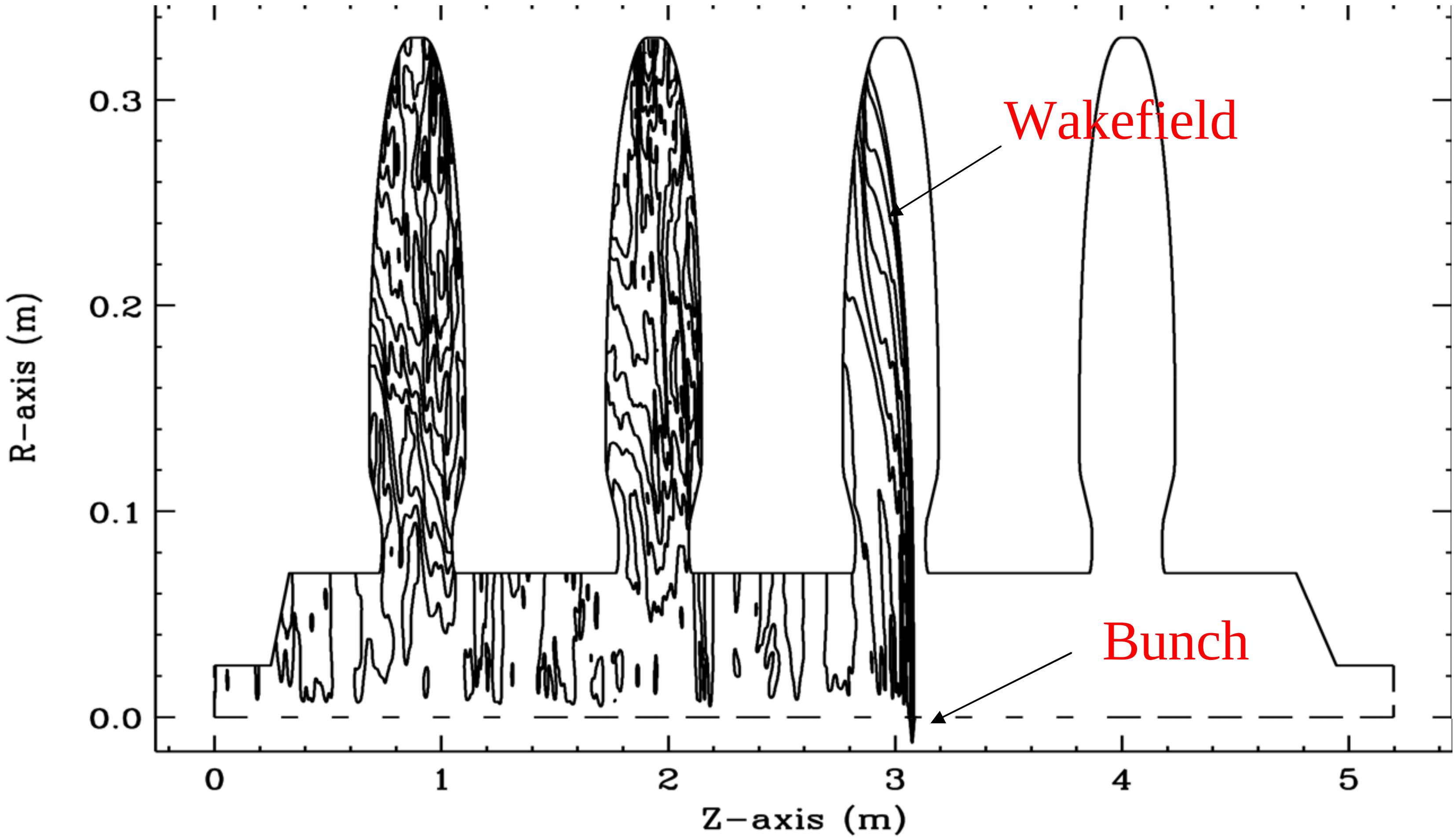


BM SYNCHROTRON XRAYS
(APPROXIMATE LOCATION)
MASKED BM SYNCHROTRON XRAYS
(APPROXIMATE LOCATION)
LEAD
ION PUMP
PUMP PORT
ION GAGE
WAVEGUIDE
TUNNEL PENETRATION
1 METER



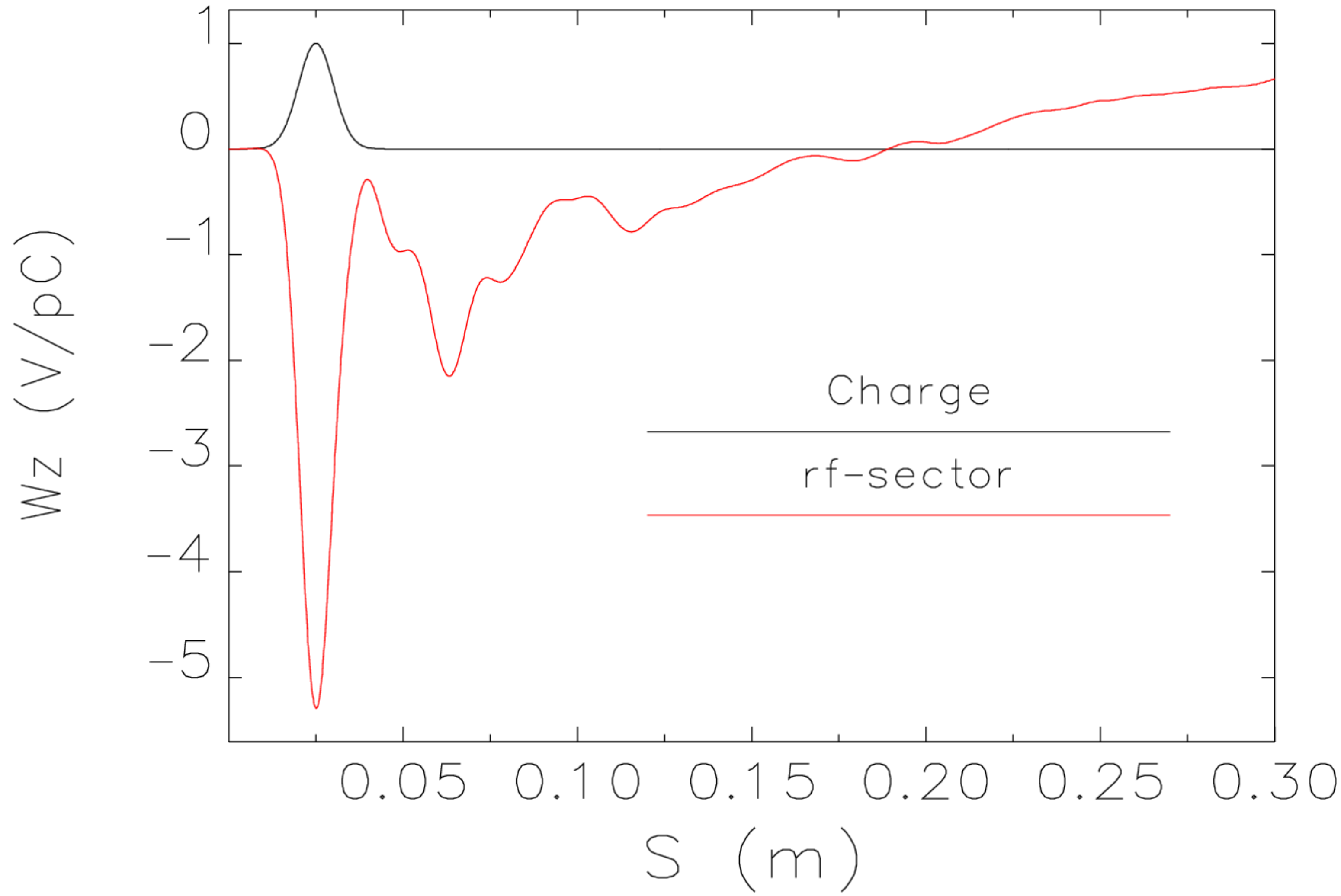
ELECTRON BEAM WELD
TYPICAL BOTH SIDES

RF Cavity: Wakefield



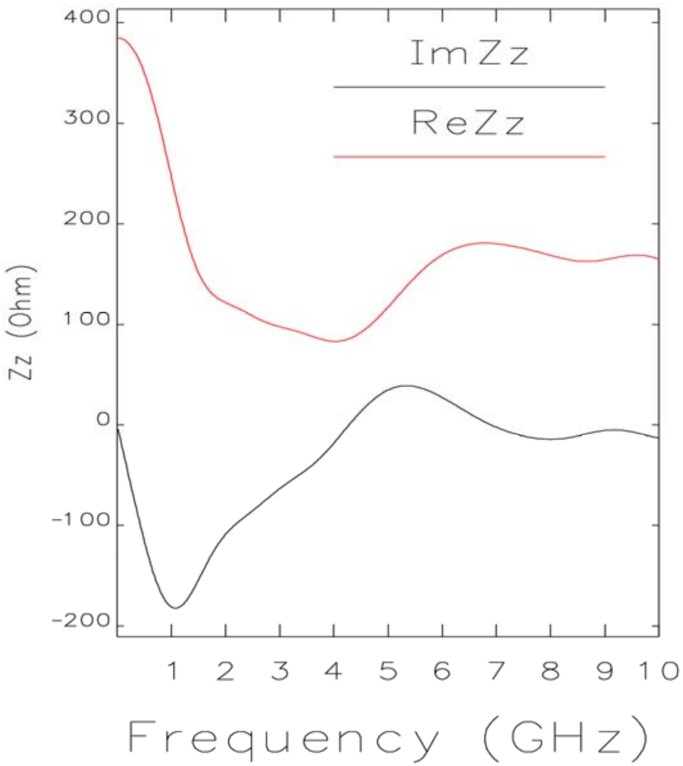
2-D ABCI simulation

RF Cavity: Wakepotential

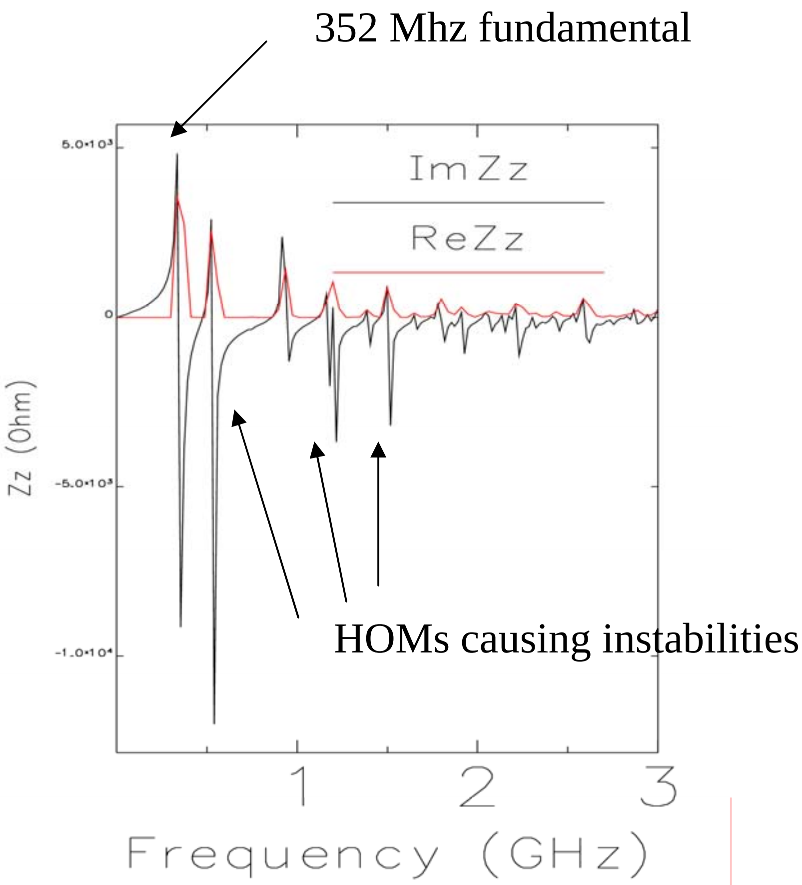


2-D ABCI simulation

RF Cavity: Impedance



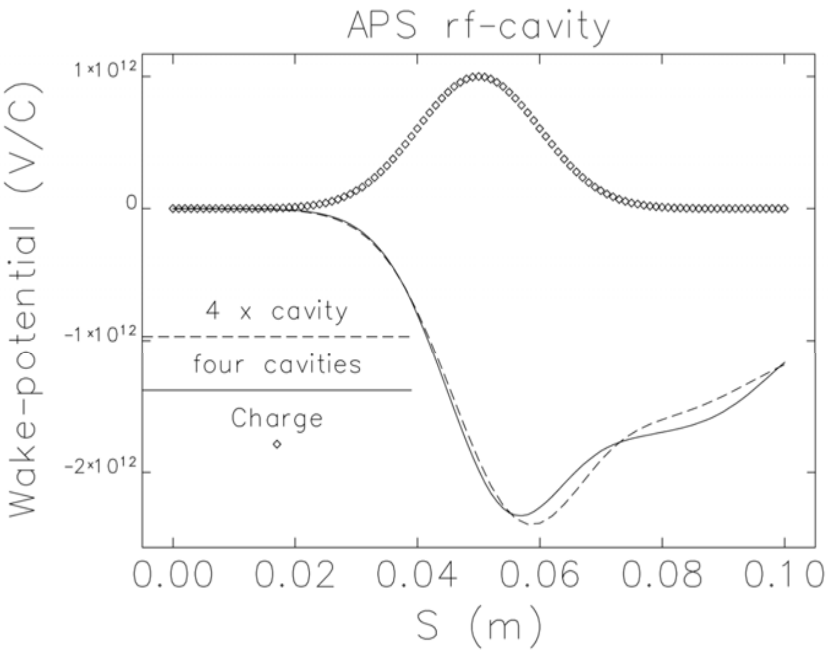
Broadband: short range including beam loading

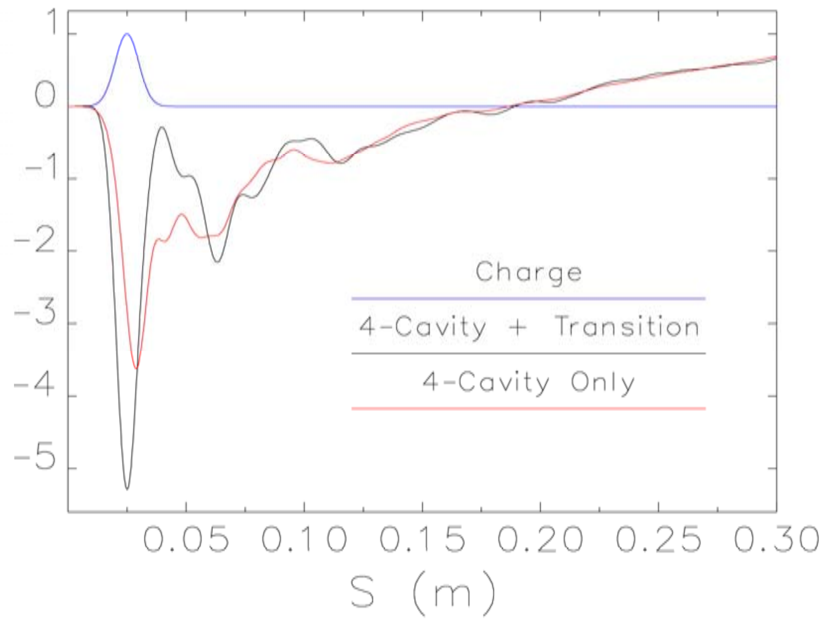


Narrowband: long range including beam loading

RF Cavity: Interference

Interference between cavities





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

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

Wakepotential/Impedance

- wakefield, long-range wake, short-range wake, broadband impedance, narrowband impedance, interference effects

- How to compile/store/manage all these concepts/data in useful form

- OLD Approach: Impedance Budget

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,

α_i = weight of the element.

Method:
Standard Wake Potential

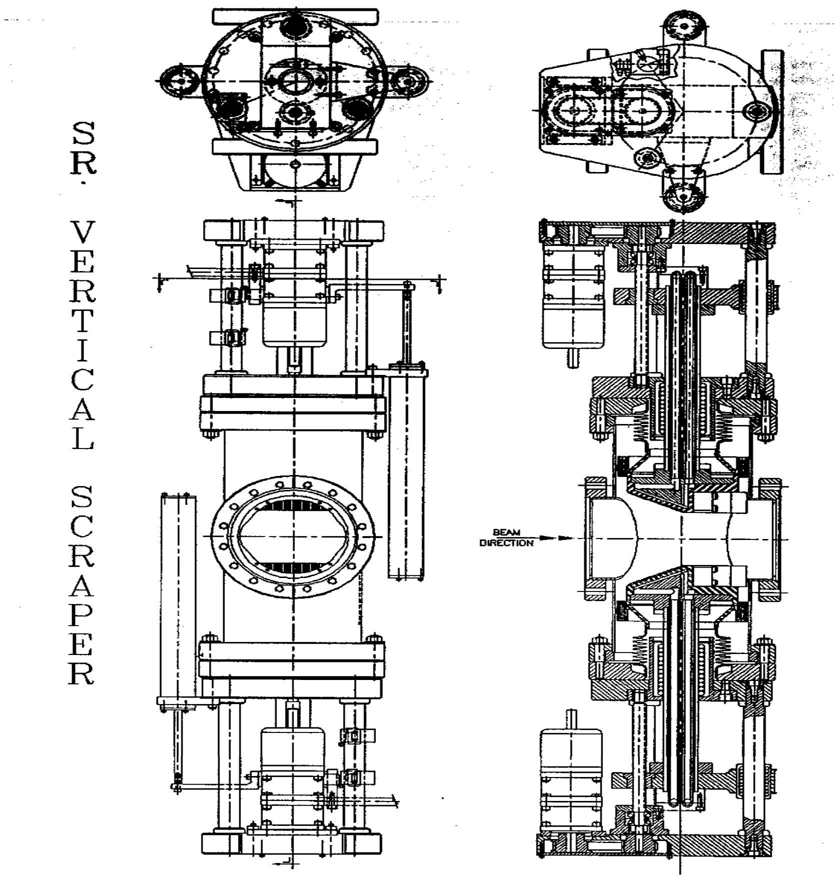
1. Data in SDDS forms: s, Wx, Wy, Wz
2. Uniform Simulation Condition
   - Rms bunch length = 5mm
   - Mesh size smaller than 0.5 mm
   - Wake length larger than 0.3 m
3. Deposit the authorized wake potentials in the designated directory
   ➔ Available to everyone who has access

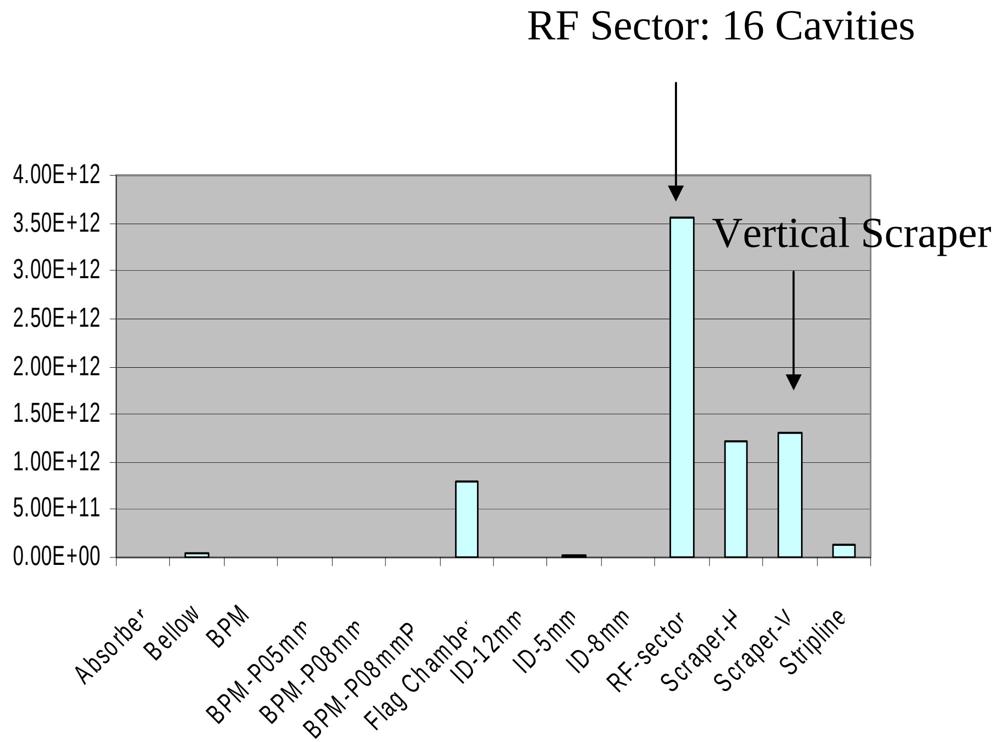
Vertical Scraper

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.

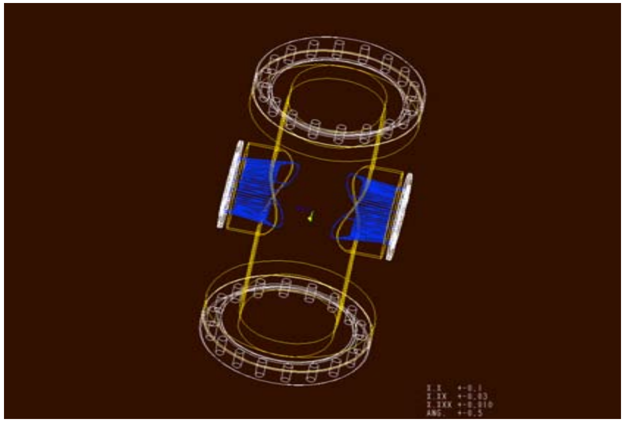


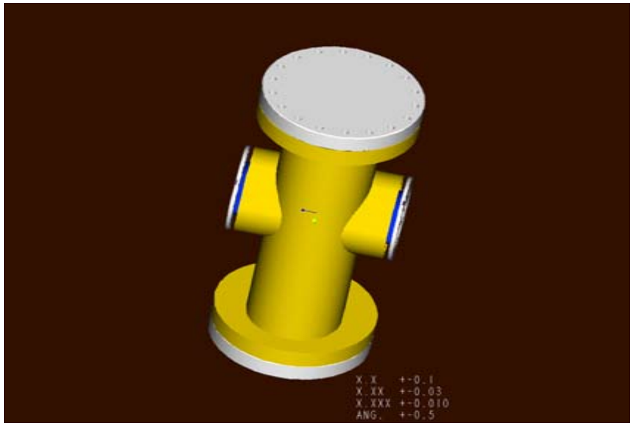


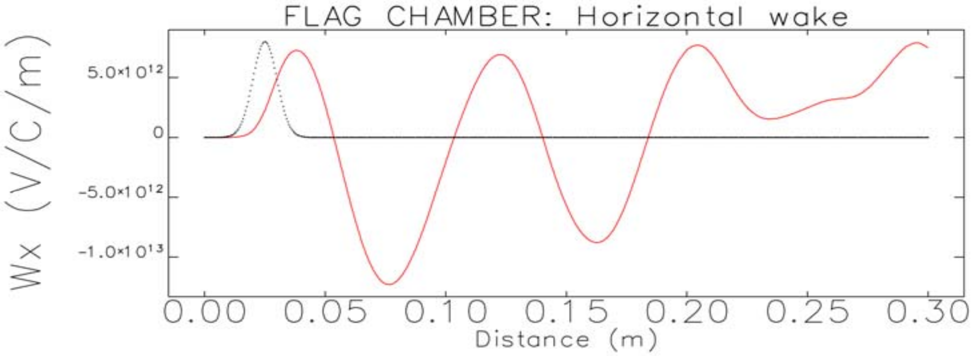
Loss Factor of Each Element

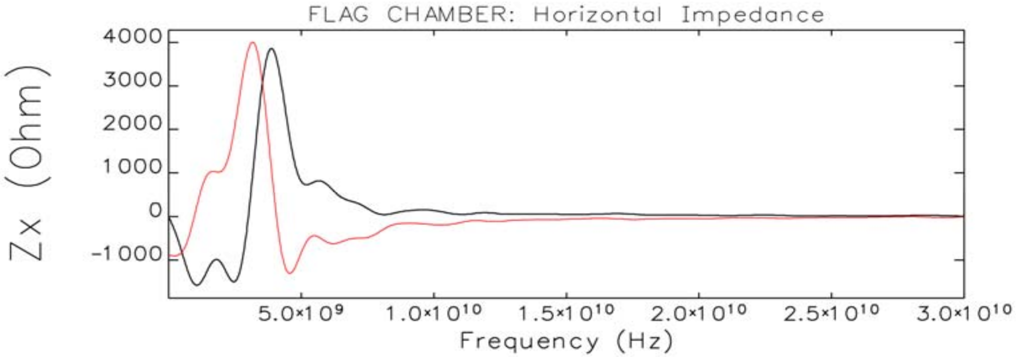
Flag Chamber

FLAG CHAMBER WAS SURPRISE
IN THE APS STORAGE RING.



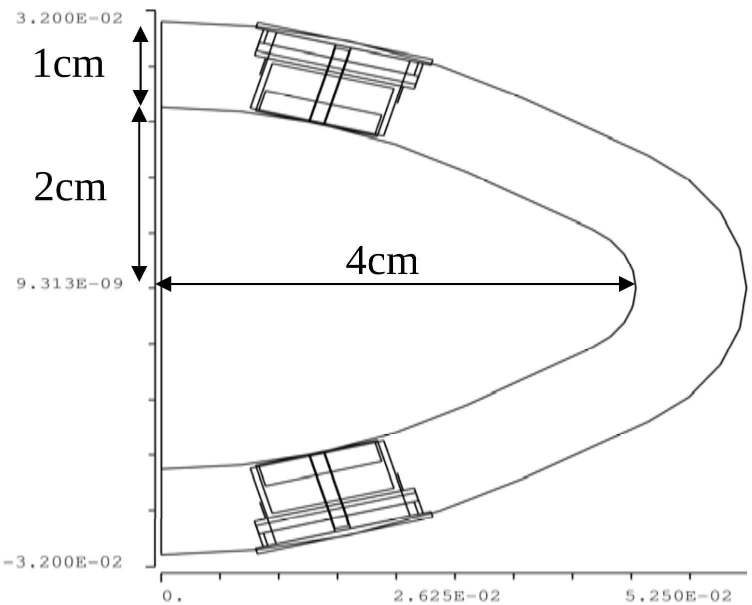


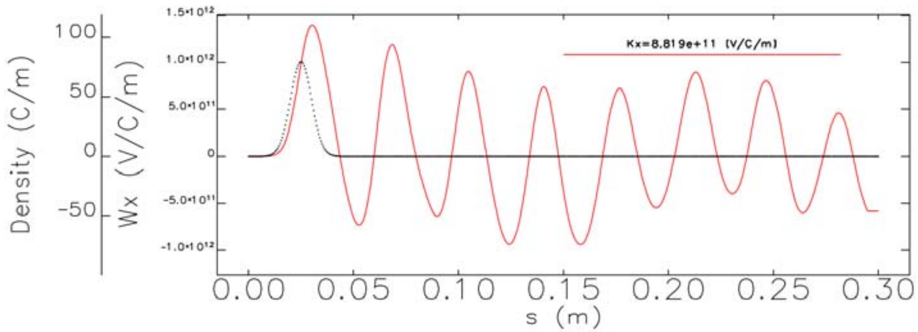


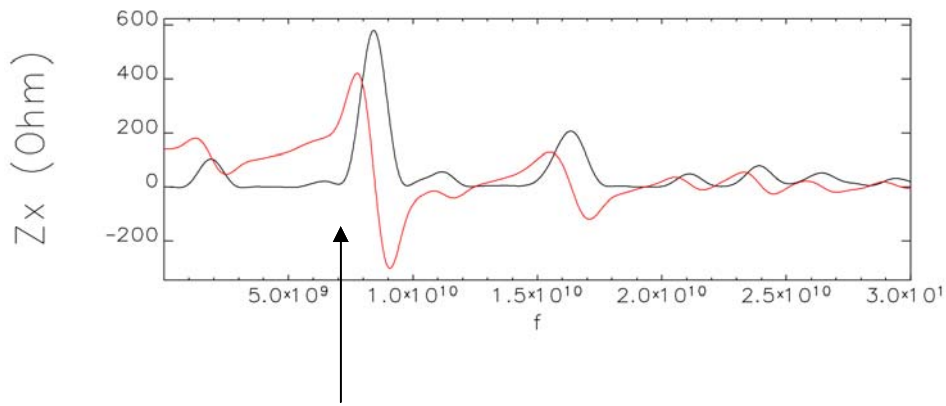


BPM: Regular Chamber

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



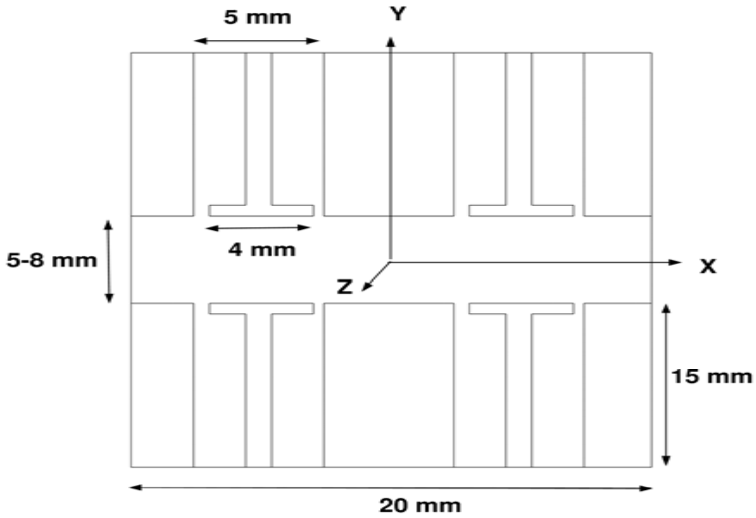


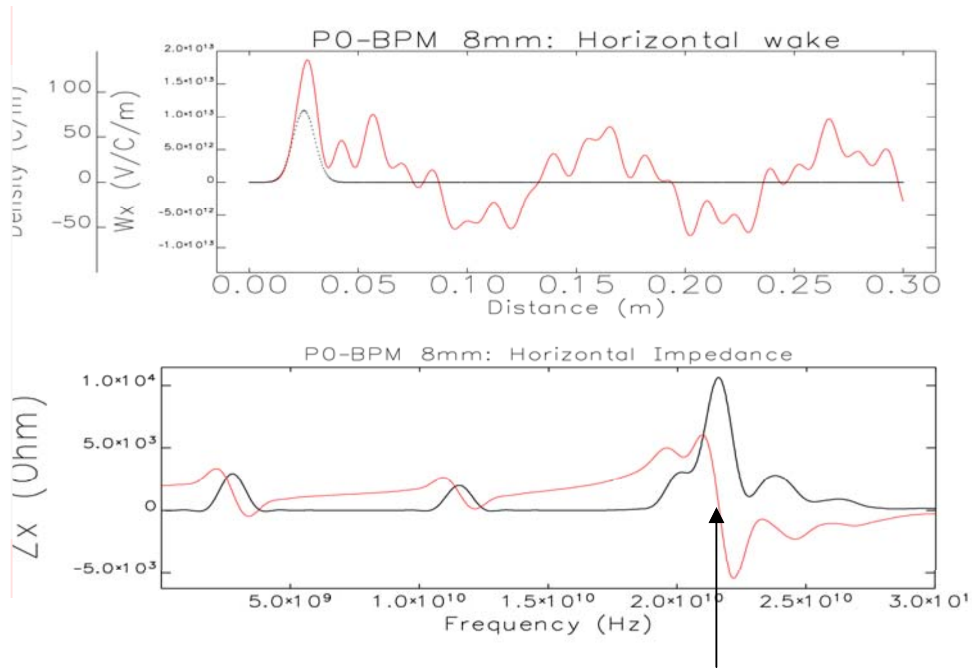


Fr=8Ghz, BW=1Ghz, Q=4

P0-BPM: 5mm, 8mm, 8mmR

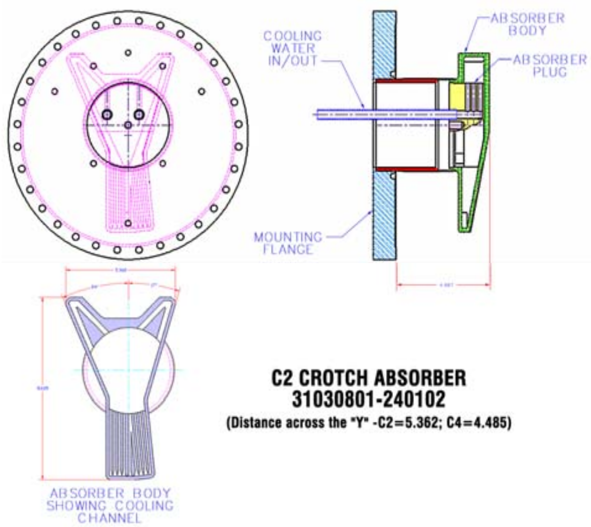
P0-BPMs are a major source of horizontal impedance in the ring!

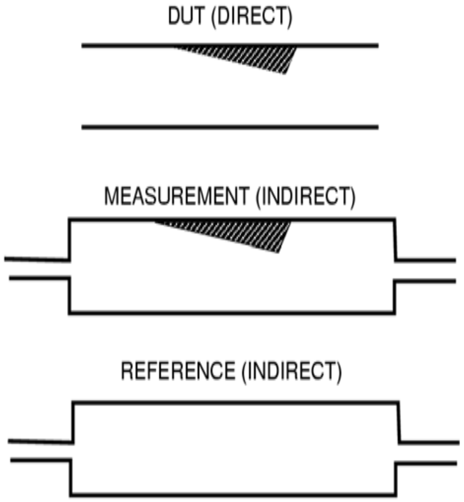


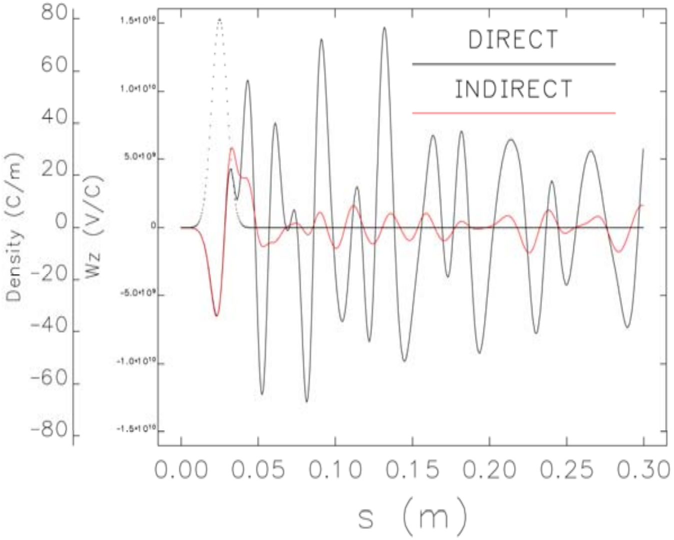


Fr=22Ghz, BW=2Ghz, Q=5

Radiation Absorber





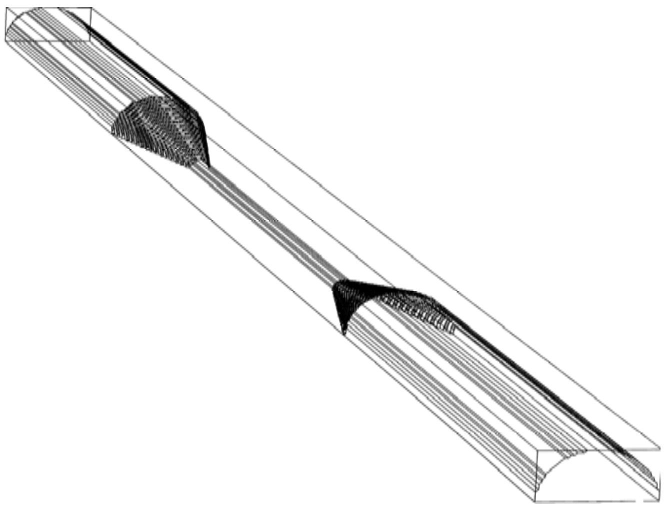


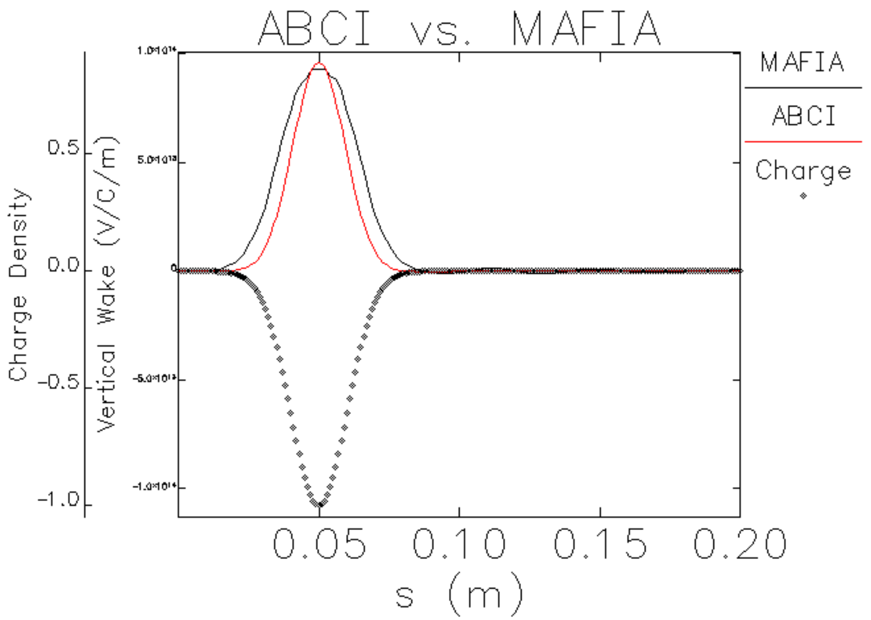
component

method

result

ID Chamber
3-D MAFIA vs. 2-D ABCI



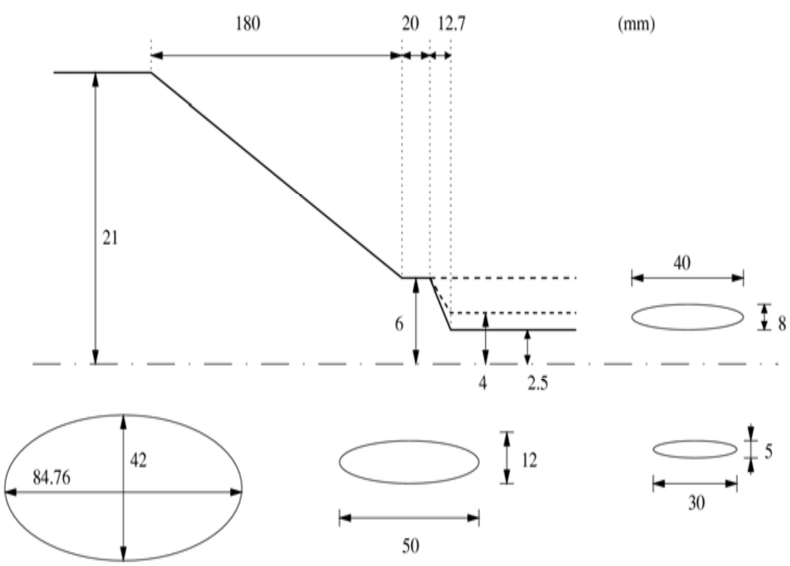


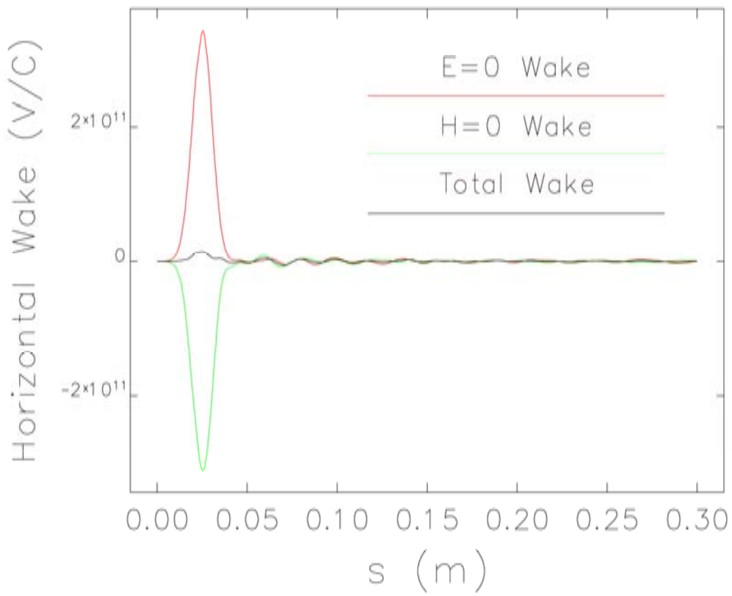
Geometry: Circular transition
Simulation: MAFIA 3-D, ABCI 2-D

Good agreements ➔
Confidence in 3-D MAFIA simulation

ID Chamber: Horizontal

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

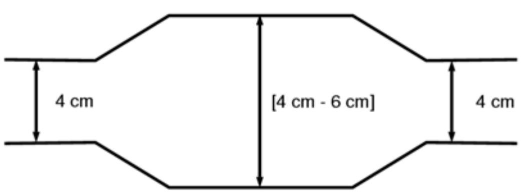




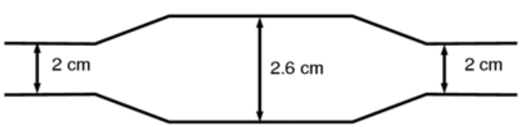
Transverse Focusing Wake

CONJECTURE

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

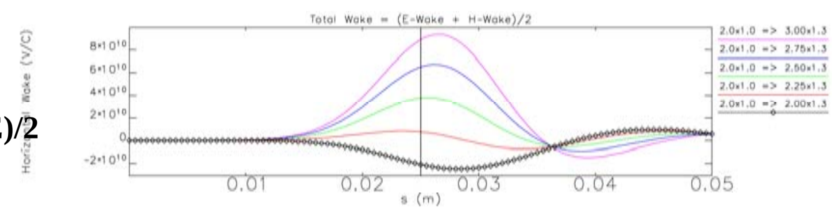


HORIZONTAL TAPER

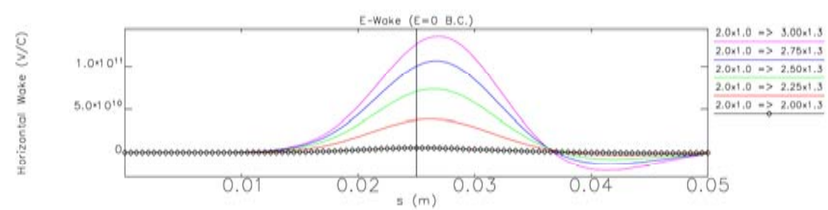


VERTICAL TAPER

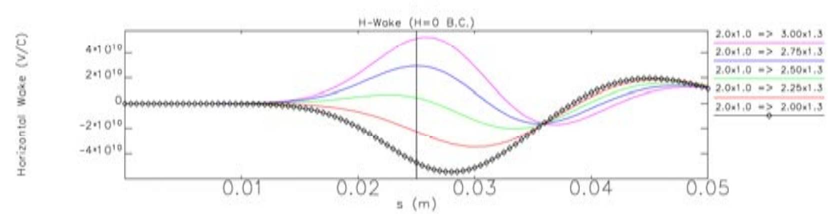
TOTAL= (E-WAKE+H-WAKE)/2



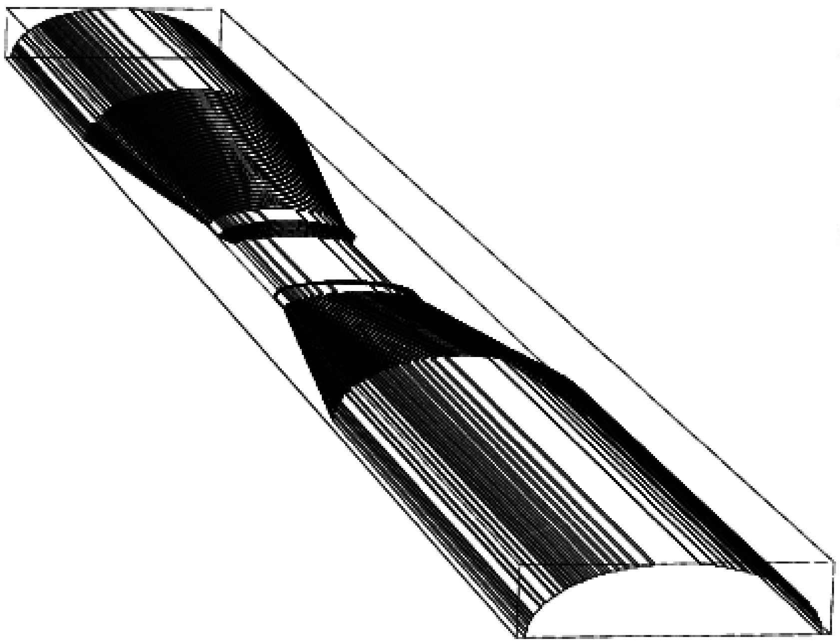
E-WAKE



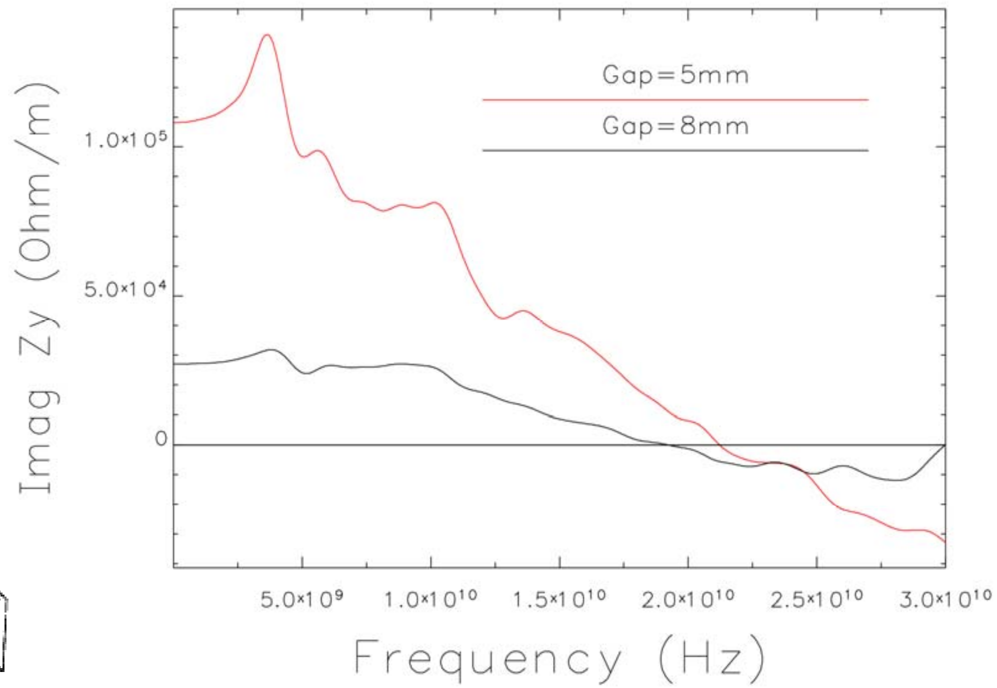
H-WAKE



ID Chamber: Vertical

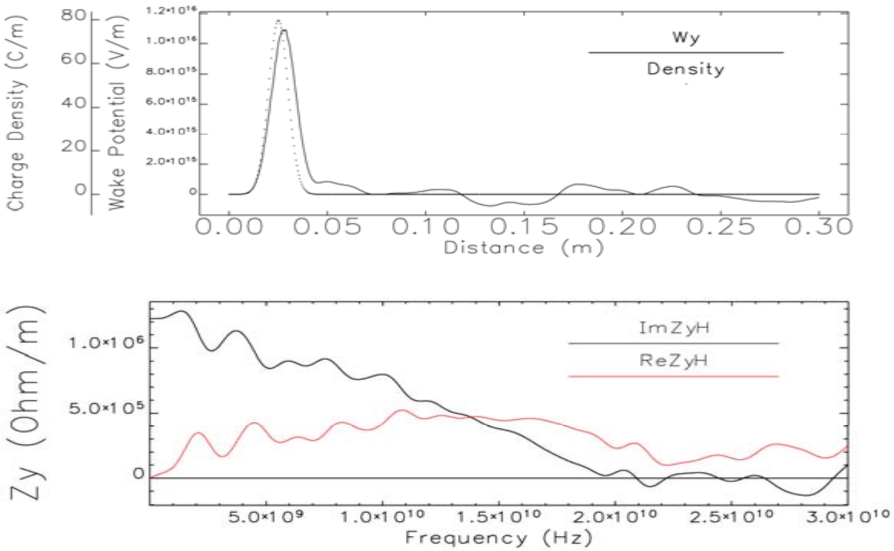


Geometry

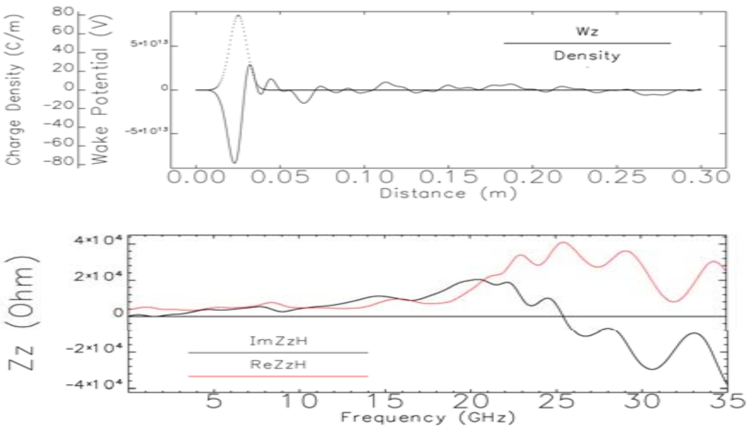


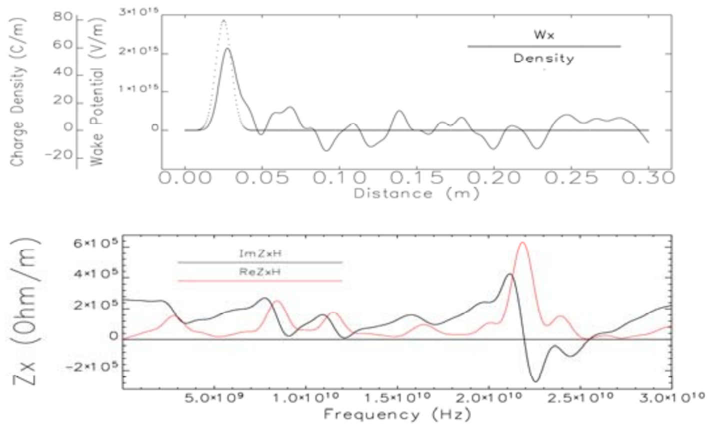
Impedance ∝ 1/b**3

Total Impedance



VERTICAL

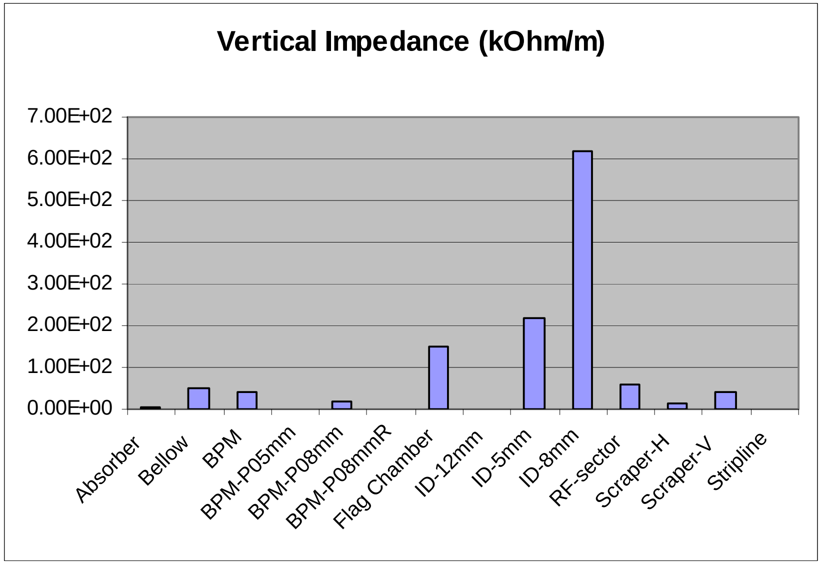


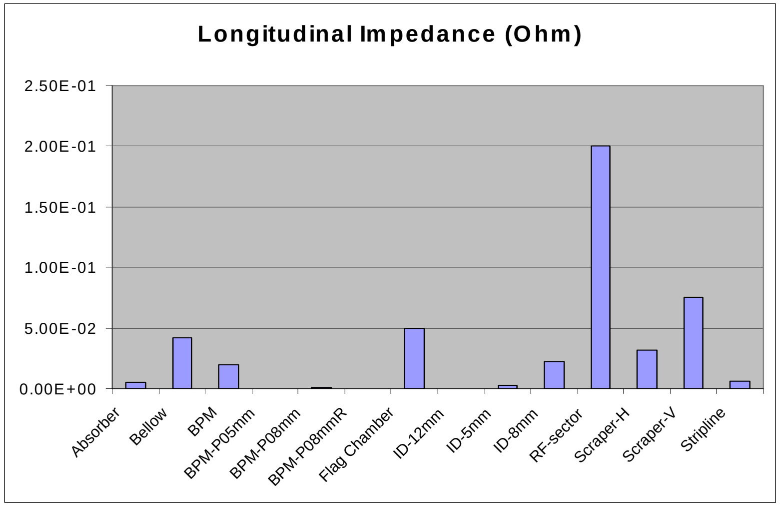


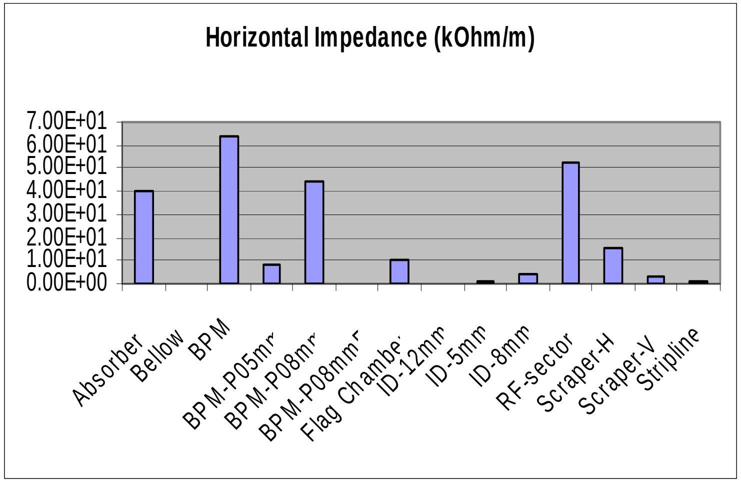
LONGITUDINAL

HORIZONTAL

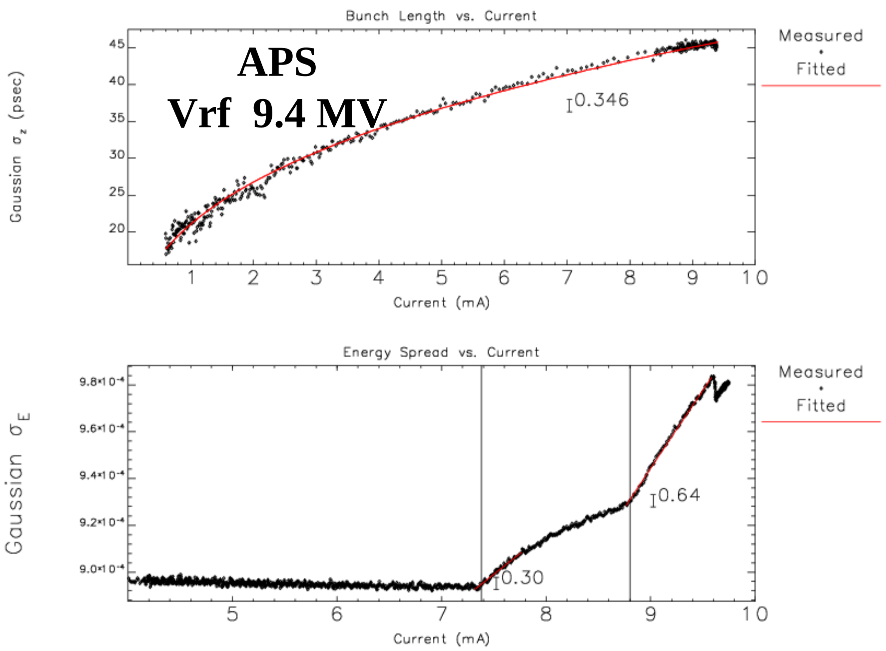
Impedance Budget

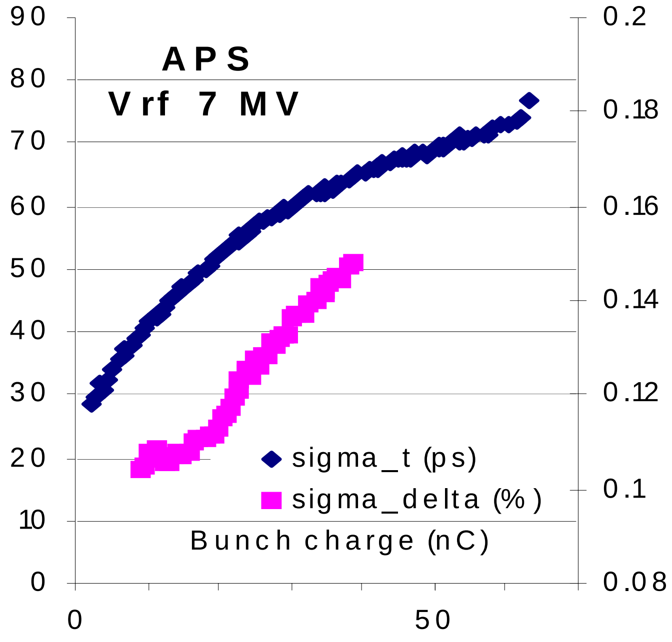






Longitudinal MW: Measurement

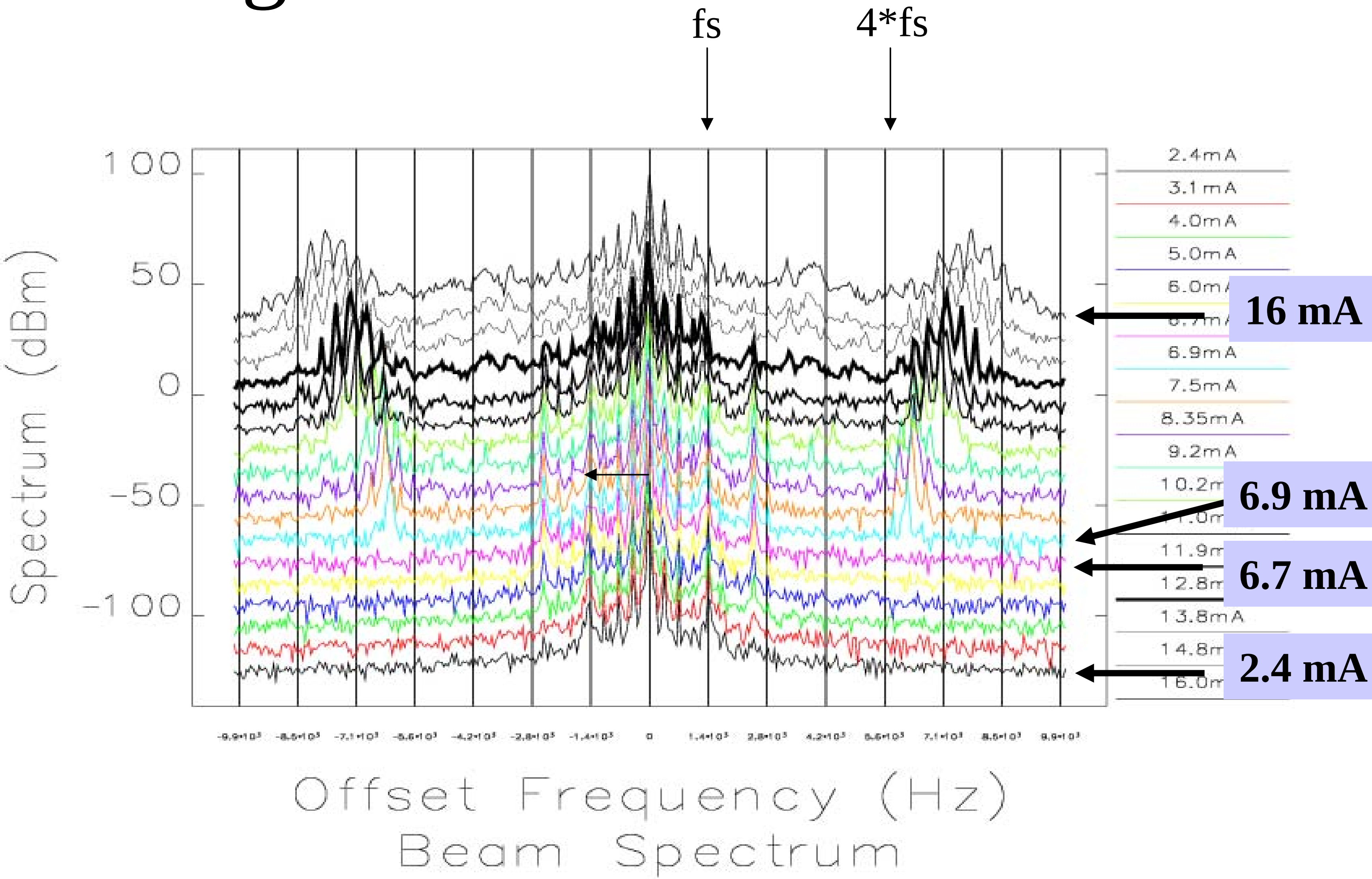




(Y.Chae, L.Emery, A.Lumpkin, J.Song, PAC'01)

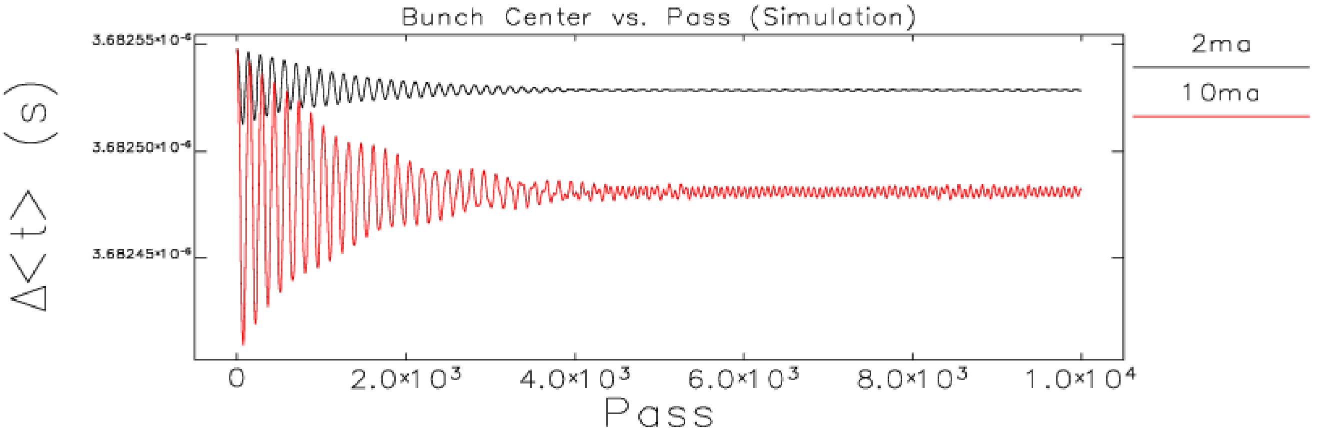
(Courtesy of K.Harkay, B.Yang)

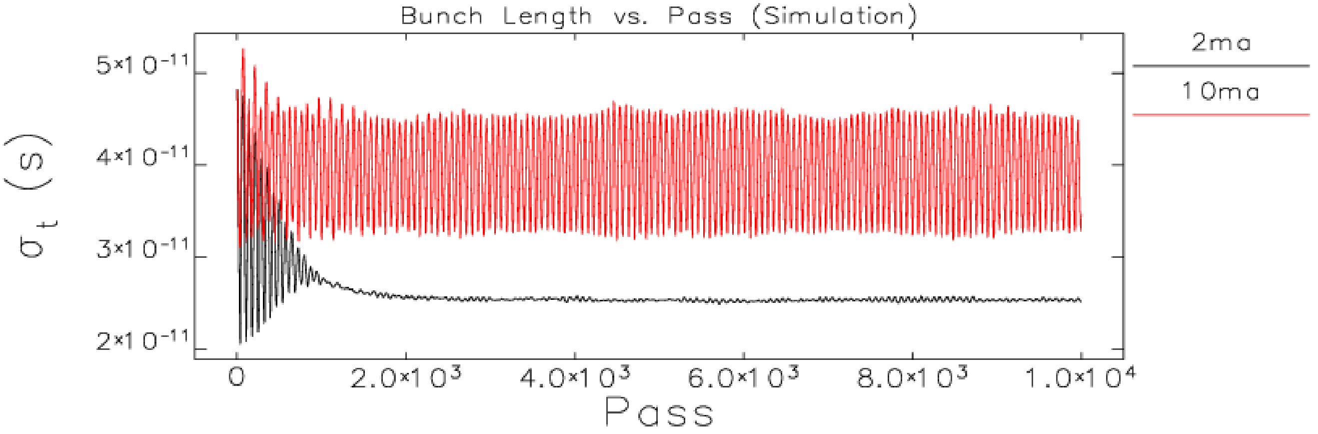
Longitudinal MW: Measurement



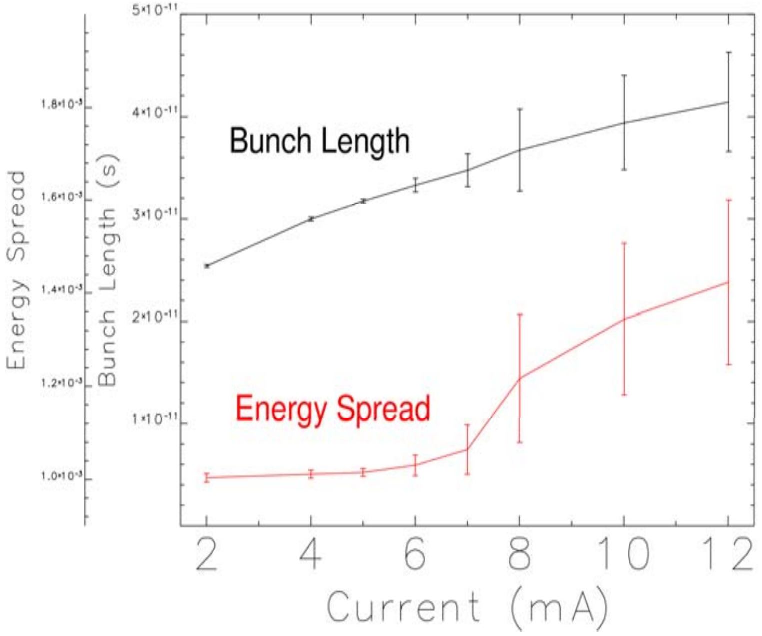
(Y.Chae, L.Emery, A.Lumpkin, J.Song, PAC’01)

Longitudinal MW: Simulation

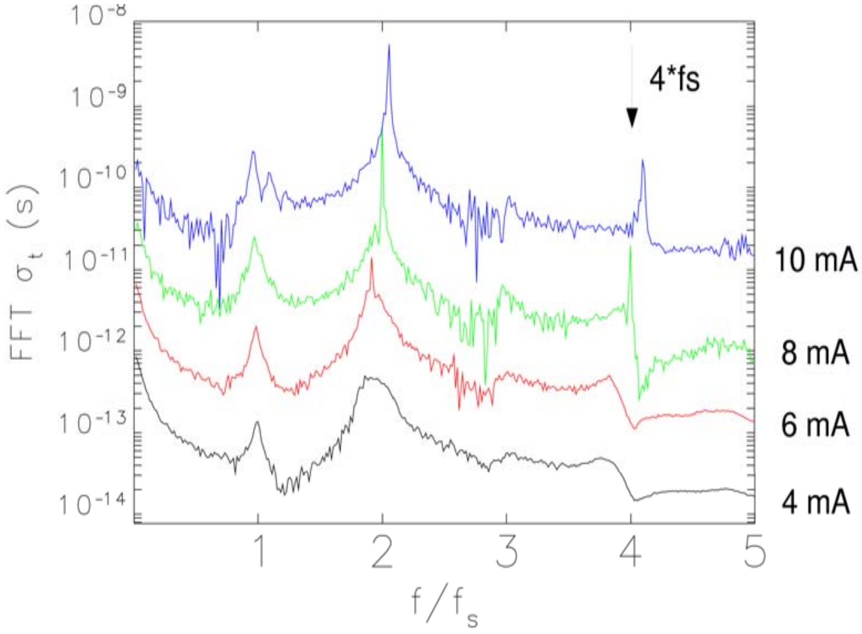




Longitudinal MW: Simulation



Bunch Length/Energy Spread



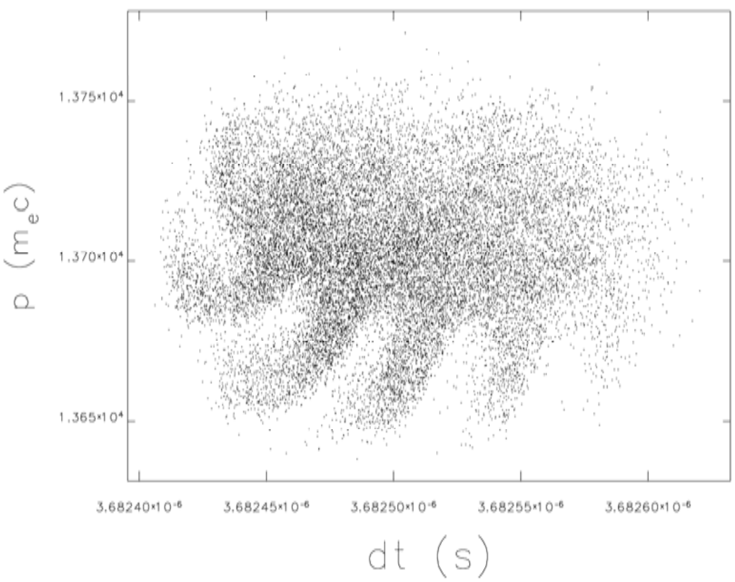
Bunch Length Oscillation

Longitudinal MW: Discussion

1. Good agreement was obtained by impedance 80 % larger than the calculated total impedance

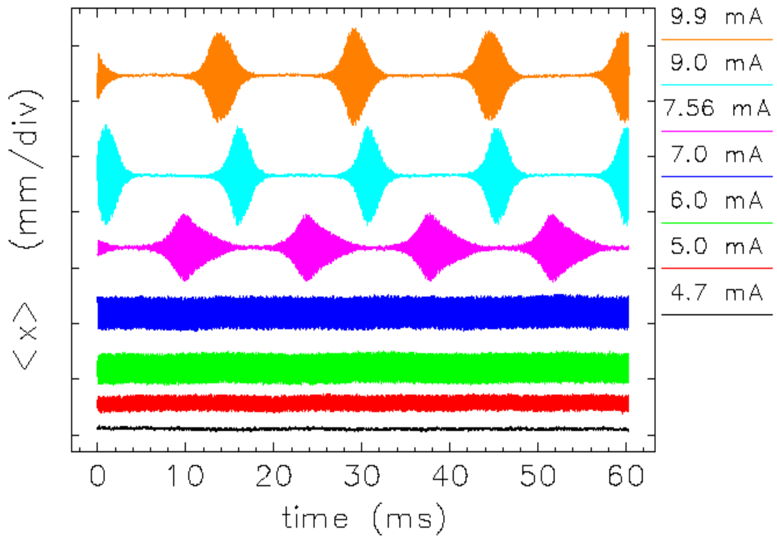
2. Bunch length oscillation could be verified by streak camera measurement

3. Sometimes we are getting this from the simulation:

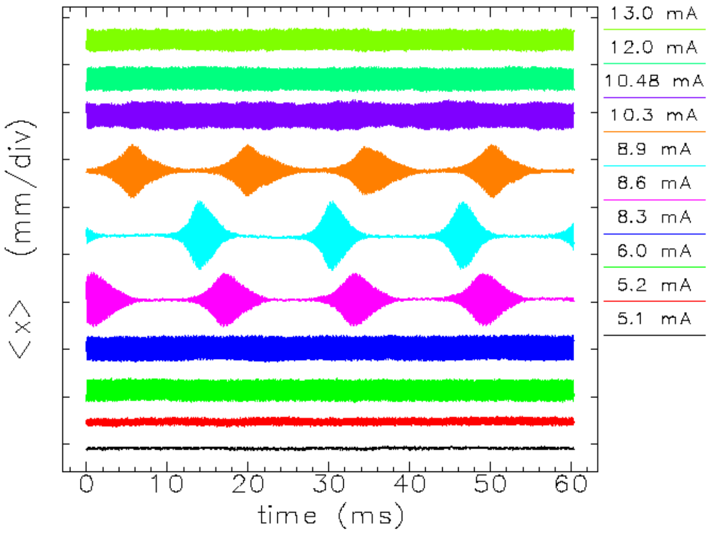


Horizontal Saw-Tooth: Measurement

7.5 nm lattice, Vrf=9.4 MV

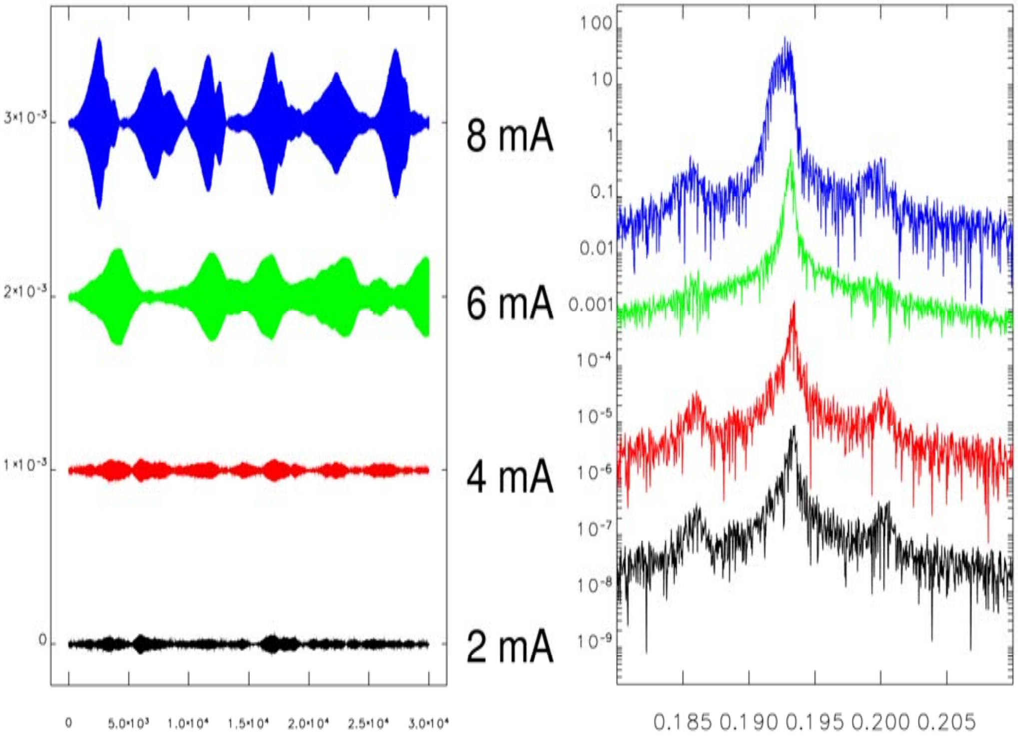


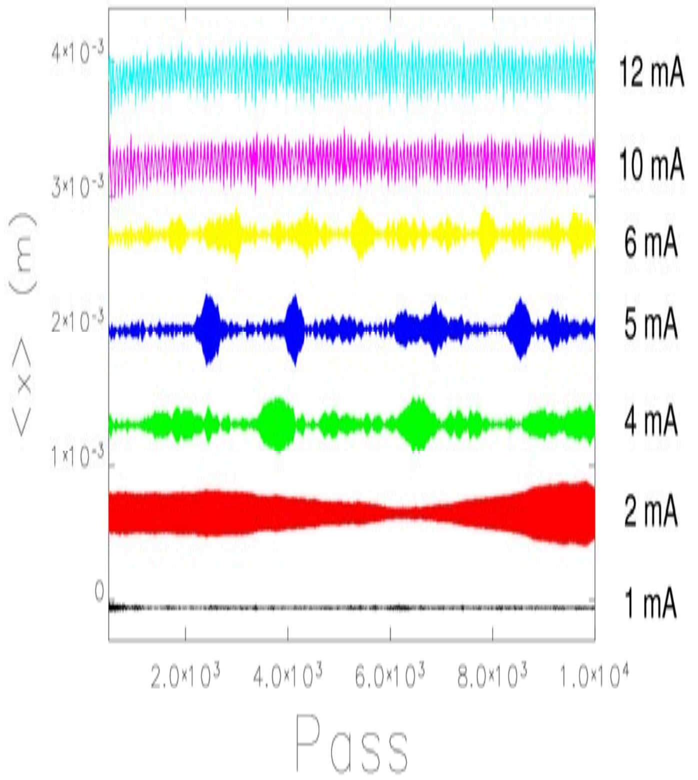
7.5 nm lattice, Vrf=7.0 MV



(Courtesy of K. Harkay, PAC'01)

Horizontal Saw-Tooth: Simulation

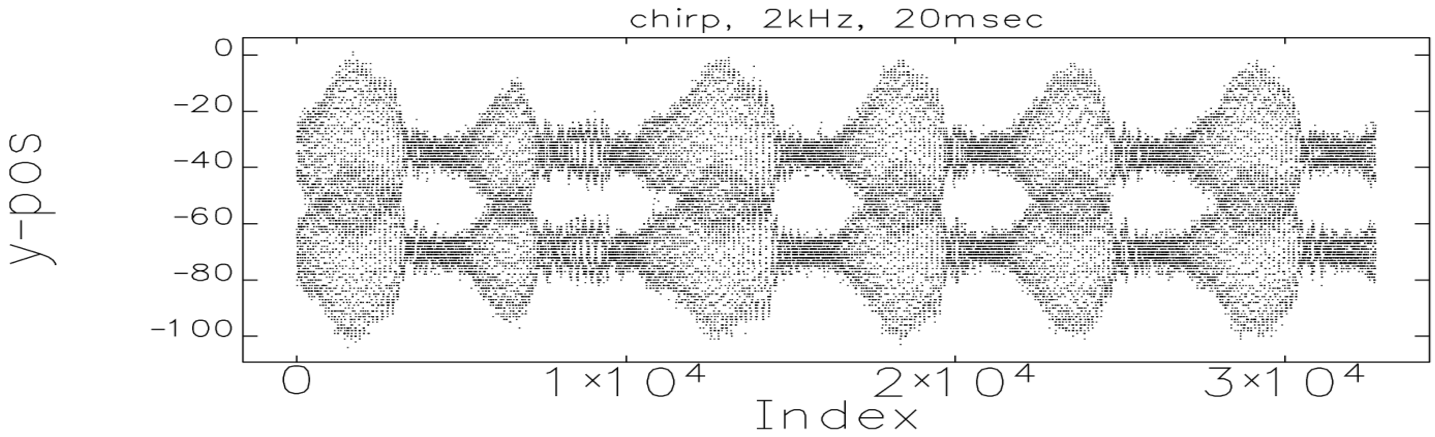




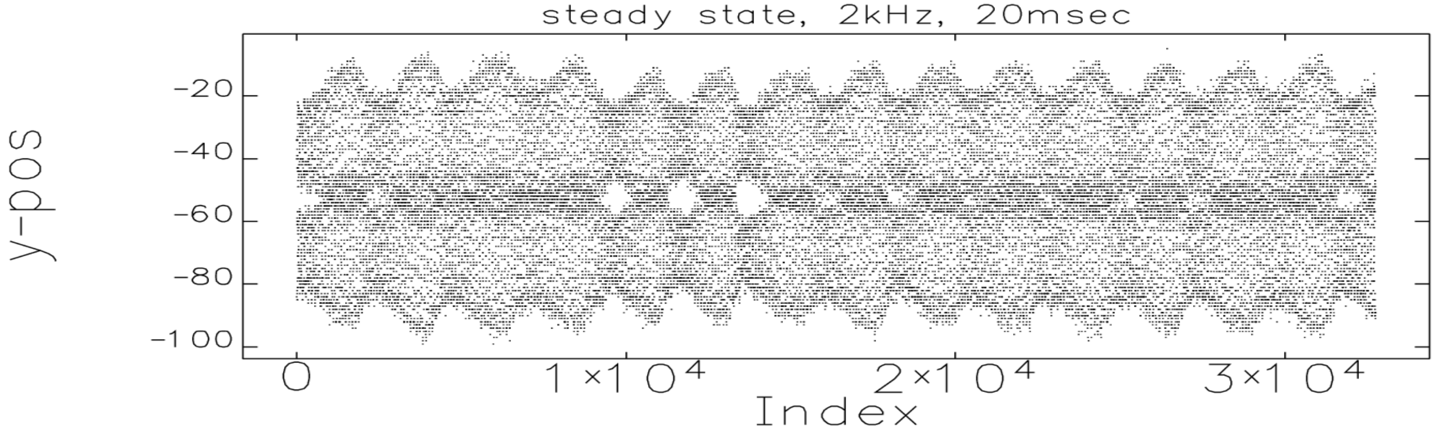
Bursting mode excited by the narrowband impedance

Bursting mode excited by the broadband impedance

Measurement of Driving Beam Response



CHIRP



Steady State

(C.Yao, Y.Chae, B.Yang, A.Lumpkin)

Horizontal Saw-Tooth: Discussion

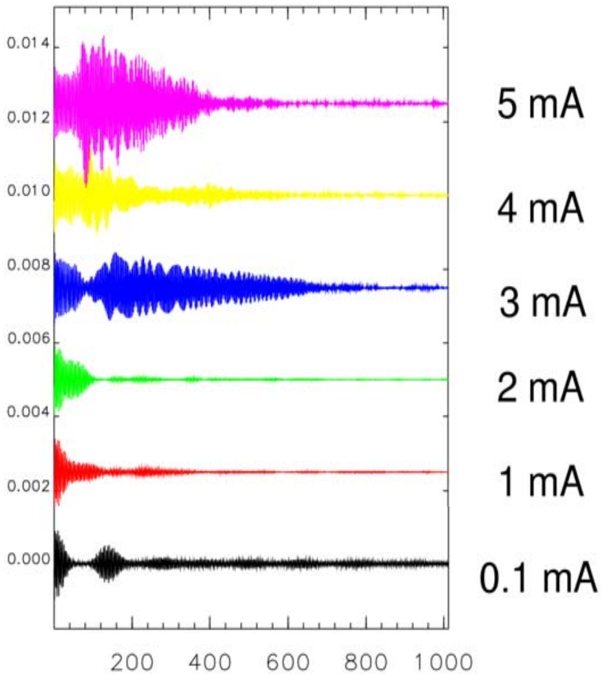
1. **Need to verify the source of excitation**
   - Resistive wall
   - HOM of rf cavities
   - Broadband impedance

2. **Understanding driving-beam-experiment is important**
   - Controllable source
   - Nonlinear effect
   - Damping effect

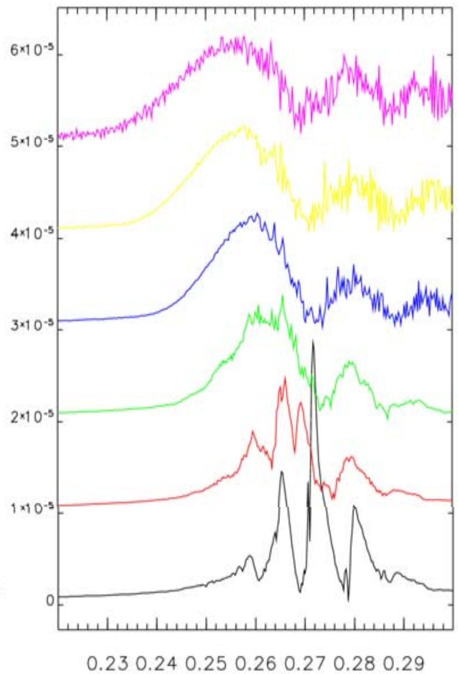
Vertical TMCI: Simulation

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

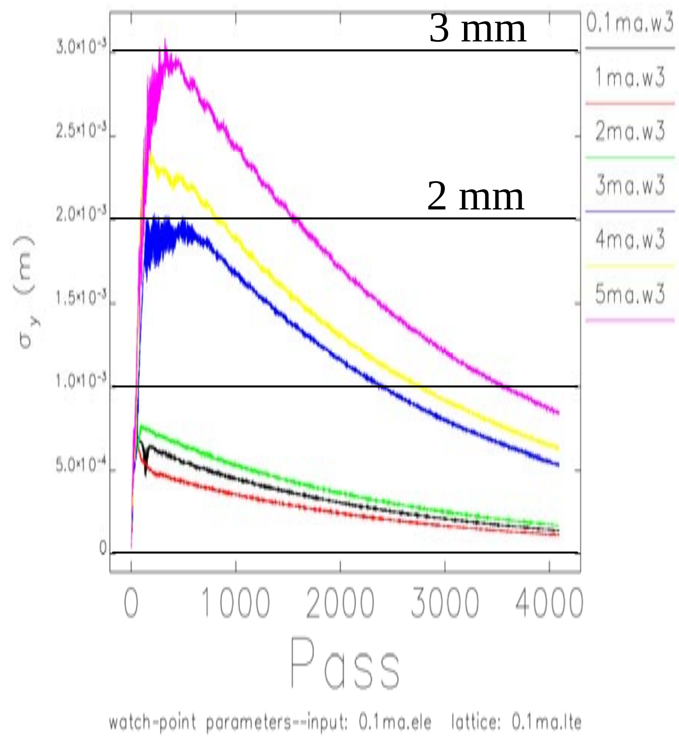
Centroid Kick Δy=1mm



Spectrum



Vertical Beam Size



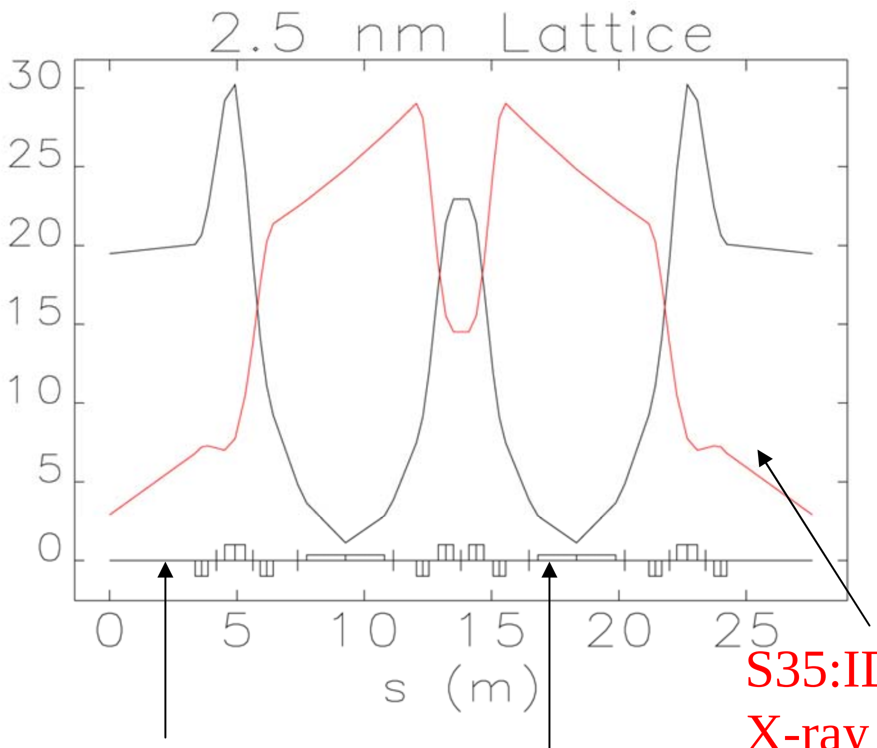
1. **Well known decoherence behavior at low current**
2. **Mode coupling completes 3 mA**
3. **Beam size blow-up above mode coupling ➔ Beam Loss due to 5-mm Insertion Device Chamber**

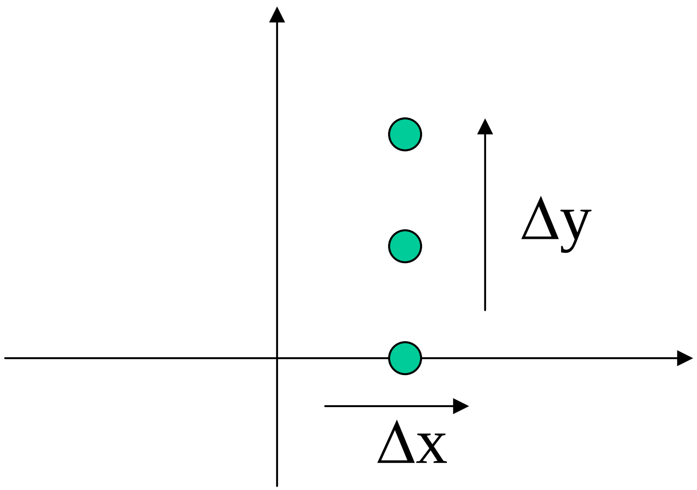
Machine Studies

Date	Studier	Data Source	Method
05/26/03	Y.Chae, A.Lumpkin	BM x-ray pinhole	Stored Beam, Average
06/24/03	Y.Chae, B.Yang, C. Yao	BM x-ray pinhole	Kicker, Average
07/16/03	Y.Chae, B.Yang	BM visible	Kicker, Single Turn
09/29/03	B.Yang	ID x-ray	Kicker, Single Turn
10/14/03	Y.Chae C.Wang	BPM	Kicker, MIA

Transient Beam Profile Measurement

Purpose: Current Dependent Beam Size Blow-up





Kicker Calibration (rough)

	a_x (m/kV)	a_y (m/kV)	$a_{y/}$ a_x (%)
IK1/IK4	$1.8\text{x}10^{-7}$	$8.0\text{x}10^{-9}$	4.5
IK2/IK3			
IK5	~ 0	$8.3\text{x}10^{-10}$	na

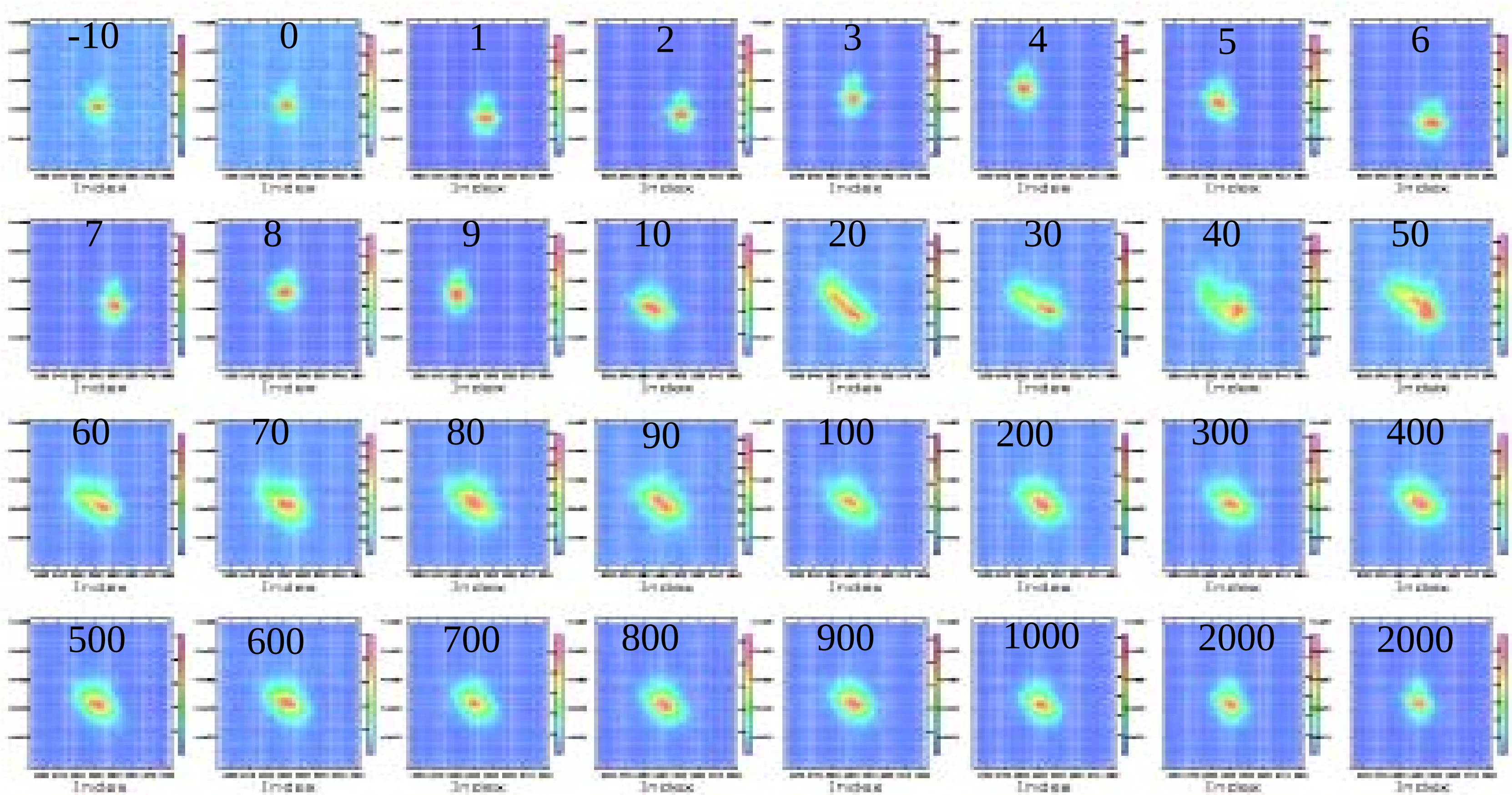
Lattice Functions at Source Point

	β_x (m)	β_y (m)	η_x (m)
BM	2.0 (0.10mm)	20.0 (0.035mm)	0.07
ID (center)	19.5 (0.27mm)	2.9 (0.014mm)	0.17
ID (avg)	14.4 (0.24mm)	4.0 (0.015mm)	0.12

- Kicker is calibrated based on the beam centeroid measured by BM gated camera
- IK1=1kV ➔ 0.6 mm at BM and ~2 mm at ID center in x
- IK5=1kV ➔ 130 μm at BM and ~50 μm at ID in y
- Precise calibration based on MIA method is under way (C.Wang, Y.Chae)

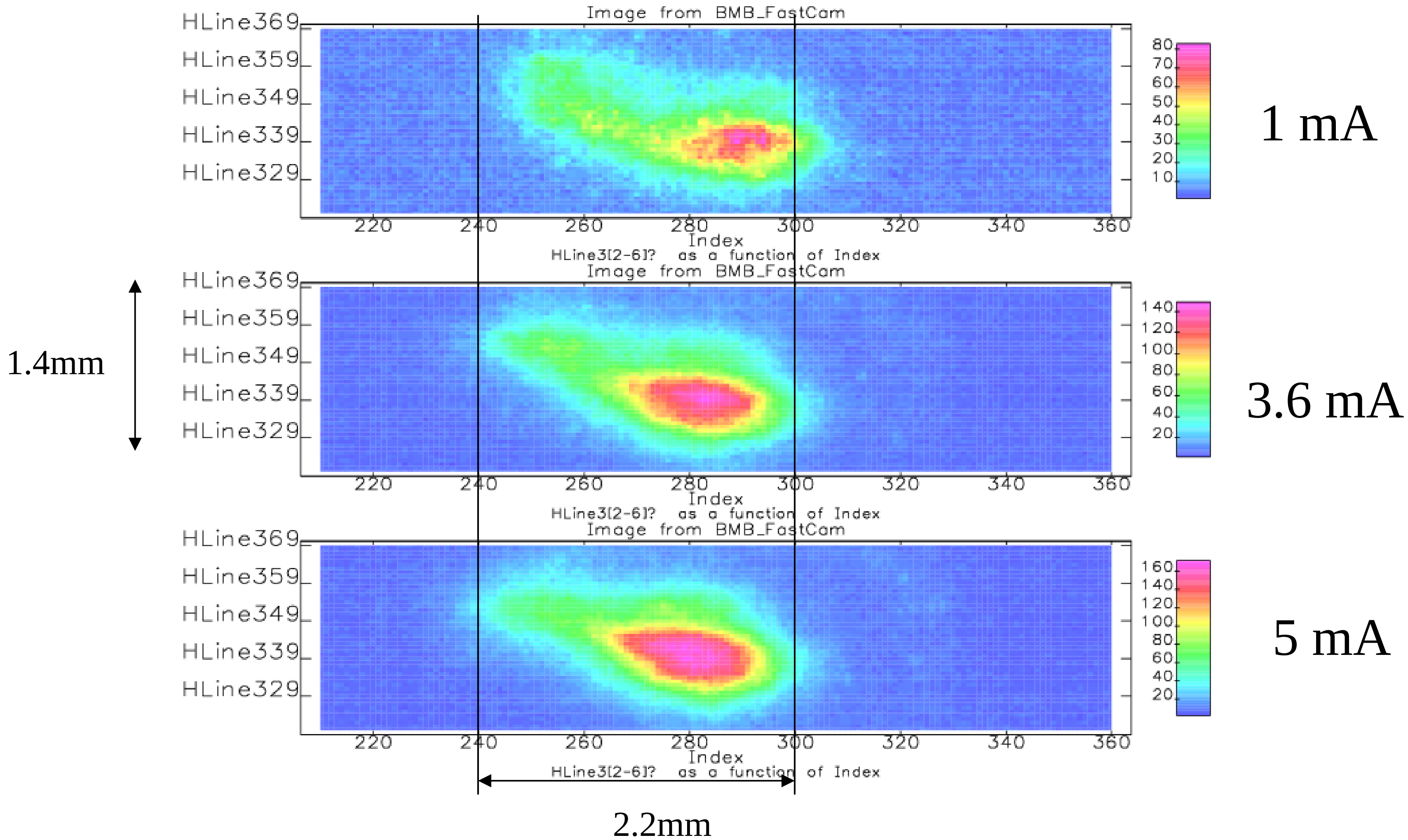
Turn-by-Turn Images

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

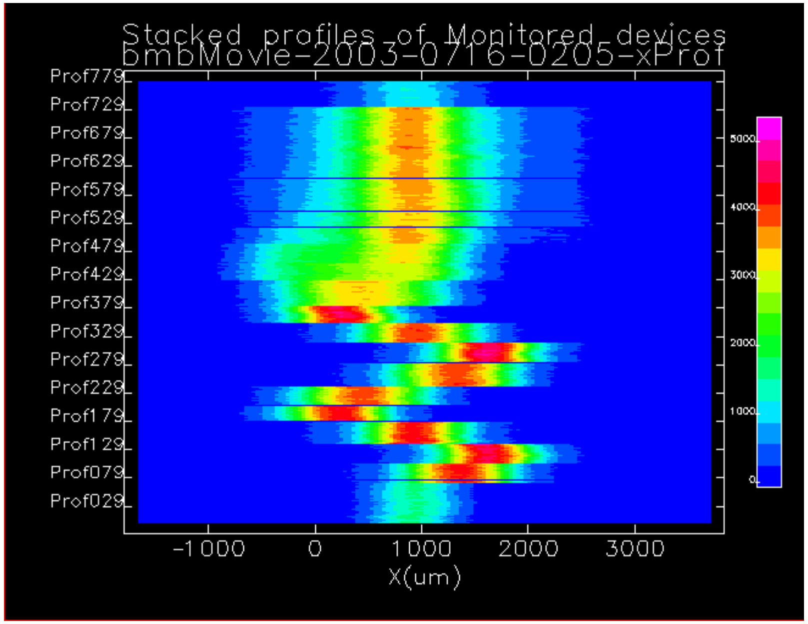
40th Turn Image: Peak Beam Size



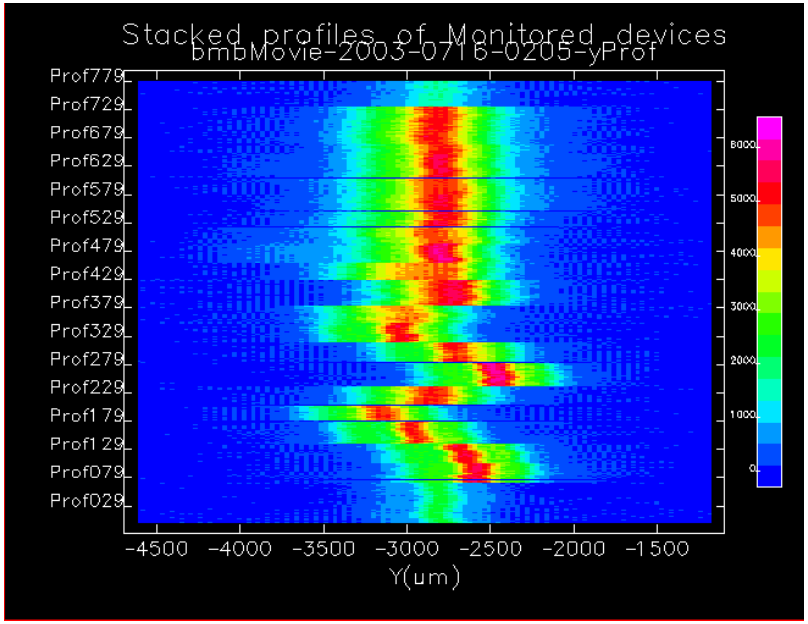
*pixel resolution: x/y= 36/28 um

Turn-by-Turn Images

Streak-like Beam Images: I=5 mA, IK1=1 kV



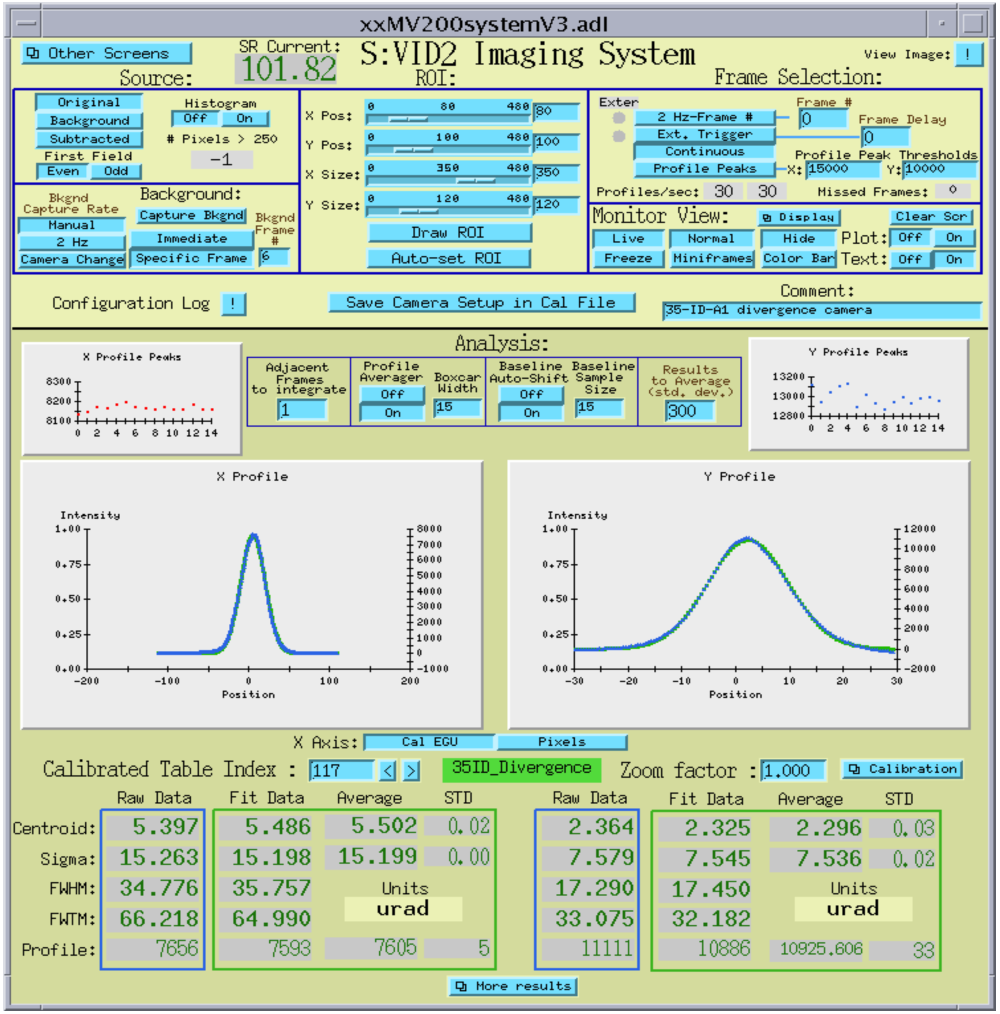
Horizontal Profile



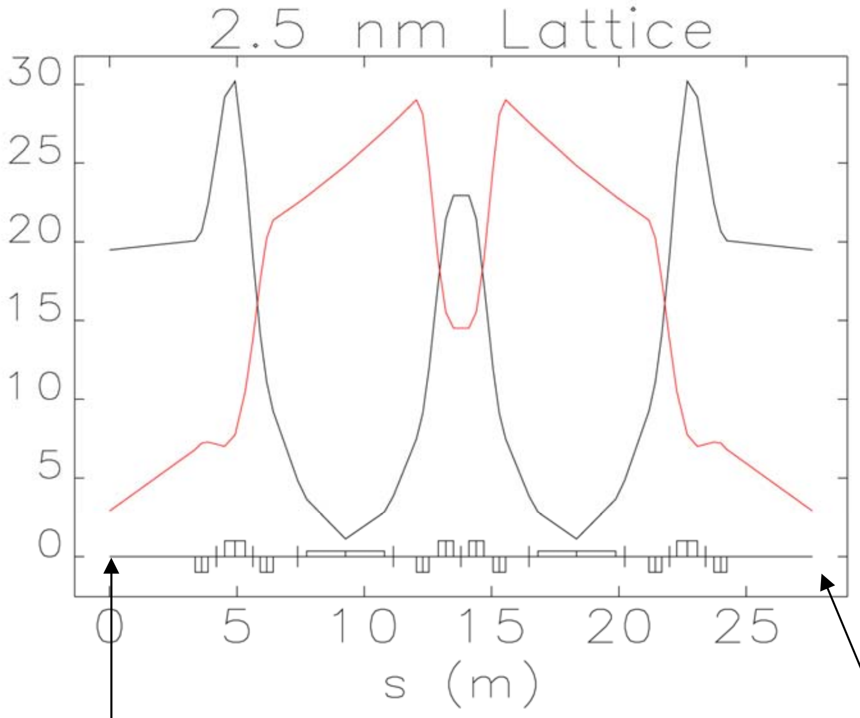
Vertical Profile

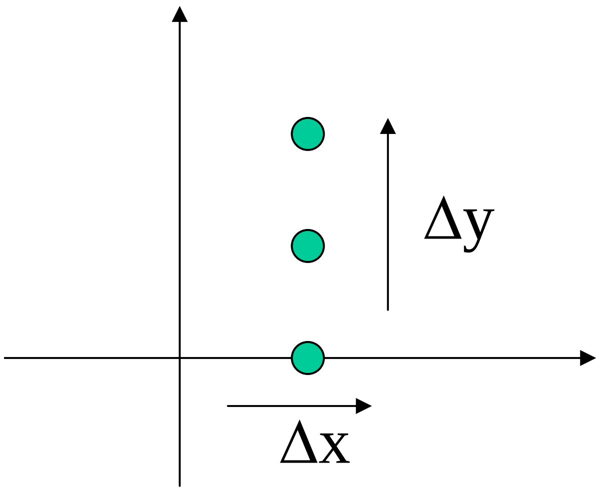
MEDM Screen

Profile data from VID4: 30-40 data points at each turn



2.5 nm Lattice and Initial Condition





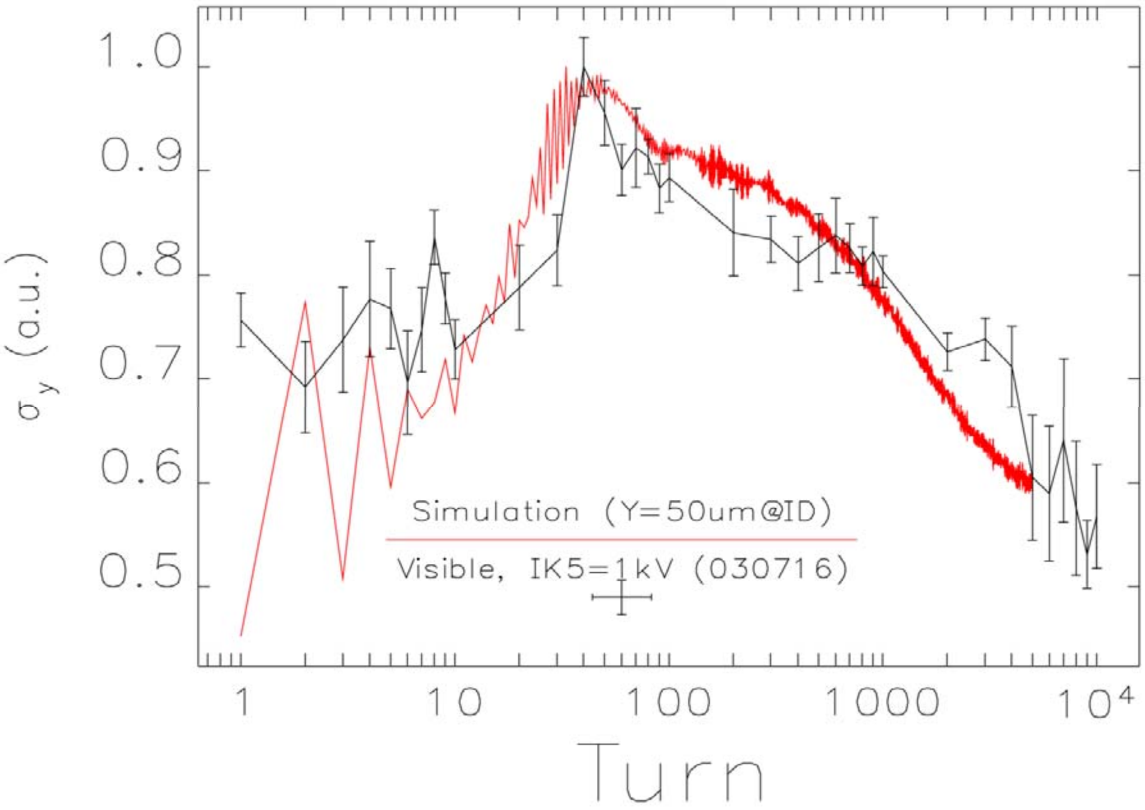
Injection Point: (Δx, Δy)
Watch Point: (x,x',y,y',σ_x,σ_y,)

Aperture;
Impedance element (BBR-1, BBR-2)

* 2.5nm lattice; chromaticity: ξx=6, ξy=6

Vertical Beam Size: Low Current (1 mA)

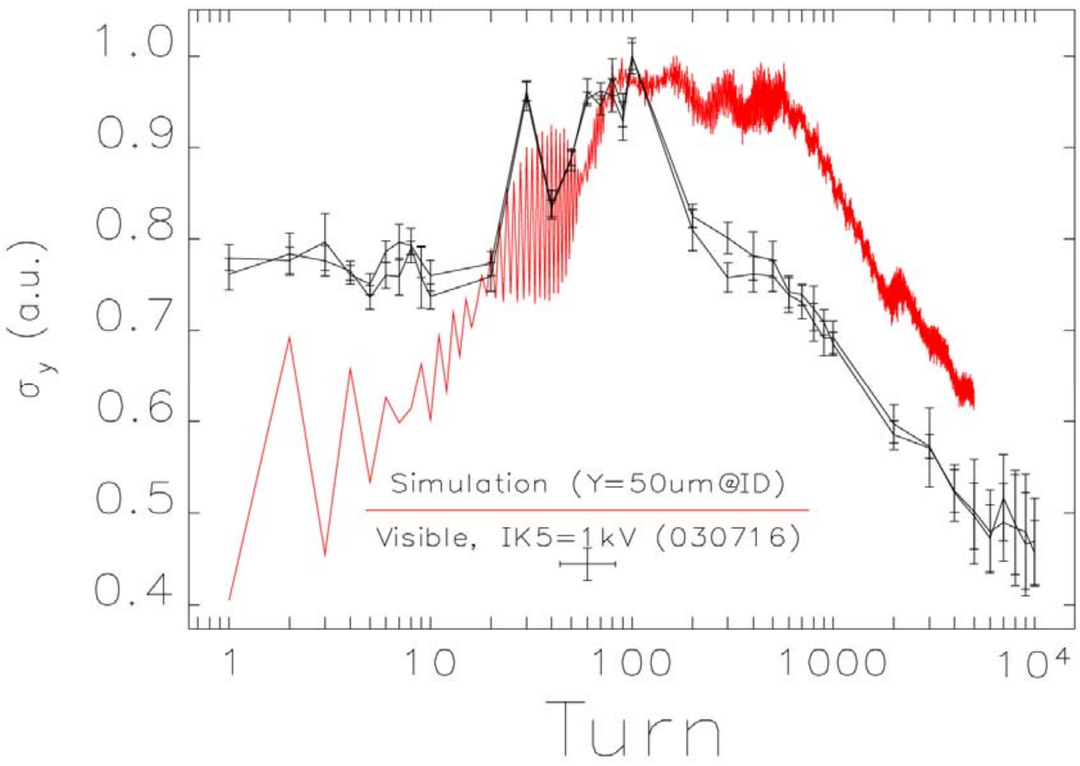
- Measurement: BM Visible, IK5=1 kV, 030716
- Simulation: ID, BBR-1, Δy=50 μm
- Beam size normalized by the maximum for comparison



Good agreement!

Vertical Beam Size: High Current (5 mA)

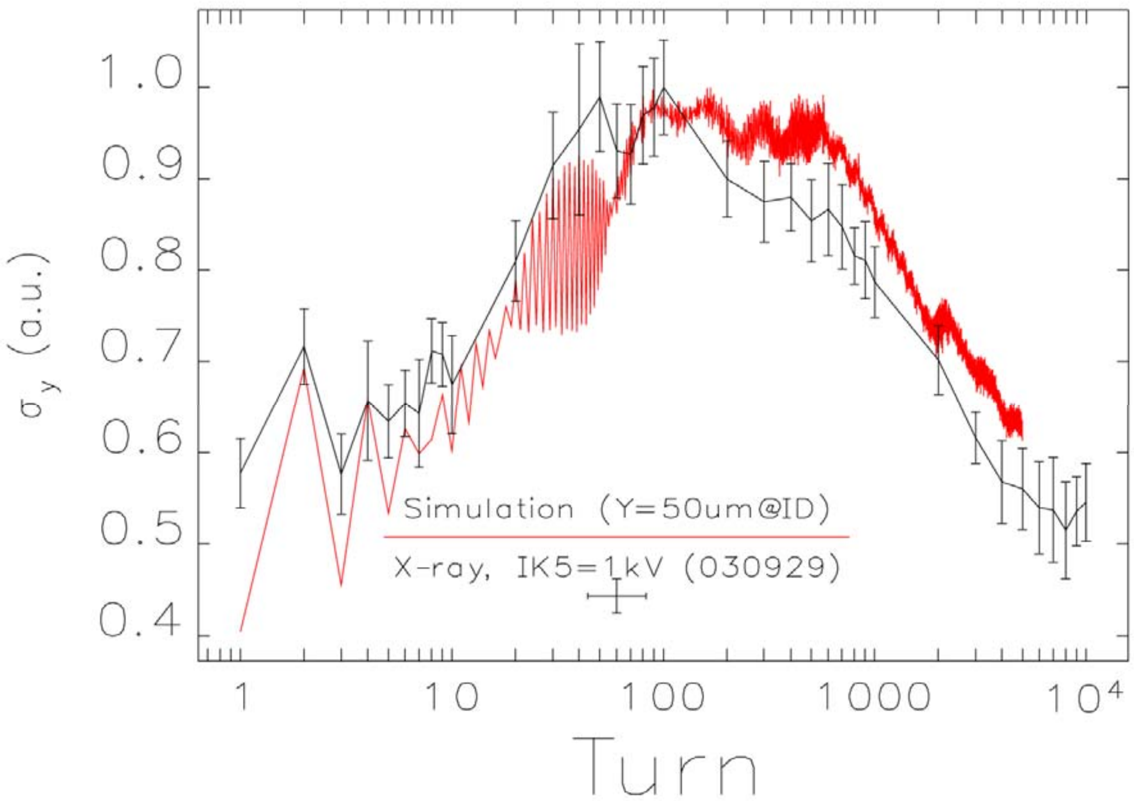
- Measurement: BM Visible, IK5=1 kV, 030716
- Simulation: ID, BBR-1, Δy=50 μm
- Beam size normalized by the maximum for comparison



- Measurements are re-producible
- Not a good agreement ➔ ID x-ray measurement

Vertical Beam Size: High Current (5 mA)

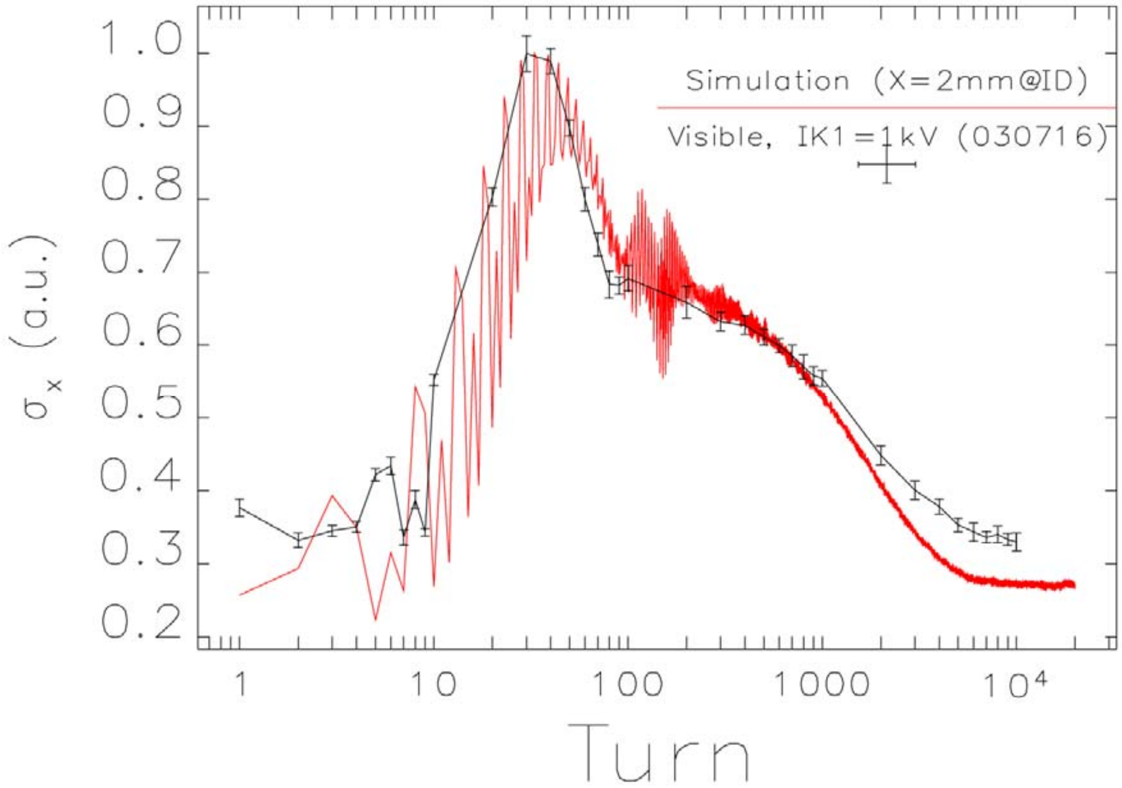
- Measurement: ID x-ray pinhole, IK5=1 kV, 030929
- Simulation: ID, BBR-1, Δy=50 μm
- Beam size normalized by the maximum for comparison



ID x-ray source provides better agreements with simulation!

Horizontal Beam Size: Low Current (1 mA)

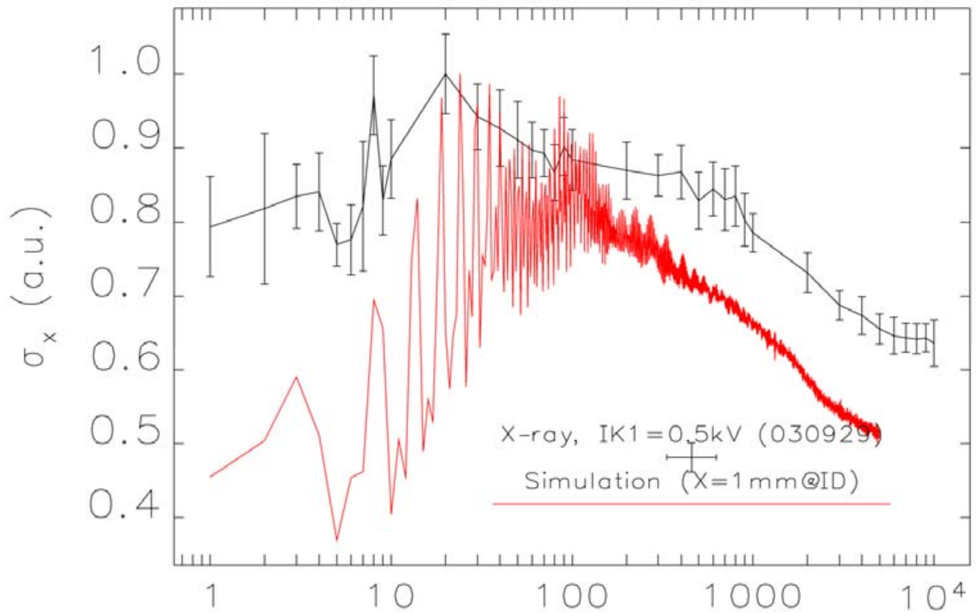
- Measurement: BM Visible, IK1=1 kV, 030716
- Simulation: ID, BBR-1, Δx=2 mm
- Beam size normalized by the maximum for comparison



Good agreement!

Horizontal Beam Size: High Current (5 mA)

- Measurement: ID x-ray pinhole, IK1=0.5 kV, 030929
- Simulation: ID, BBR-2, Δx=1 mm
- Beam size normalized by the maximum for comparison



- BBR parameter adjusted ➔ BBR-2 is 50% smaller than BBR-1➔ Much better agreement!
- BBR-1 and BBR-2 parameters published in PAC'03

Vertical TMCI: Discussion

- **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

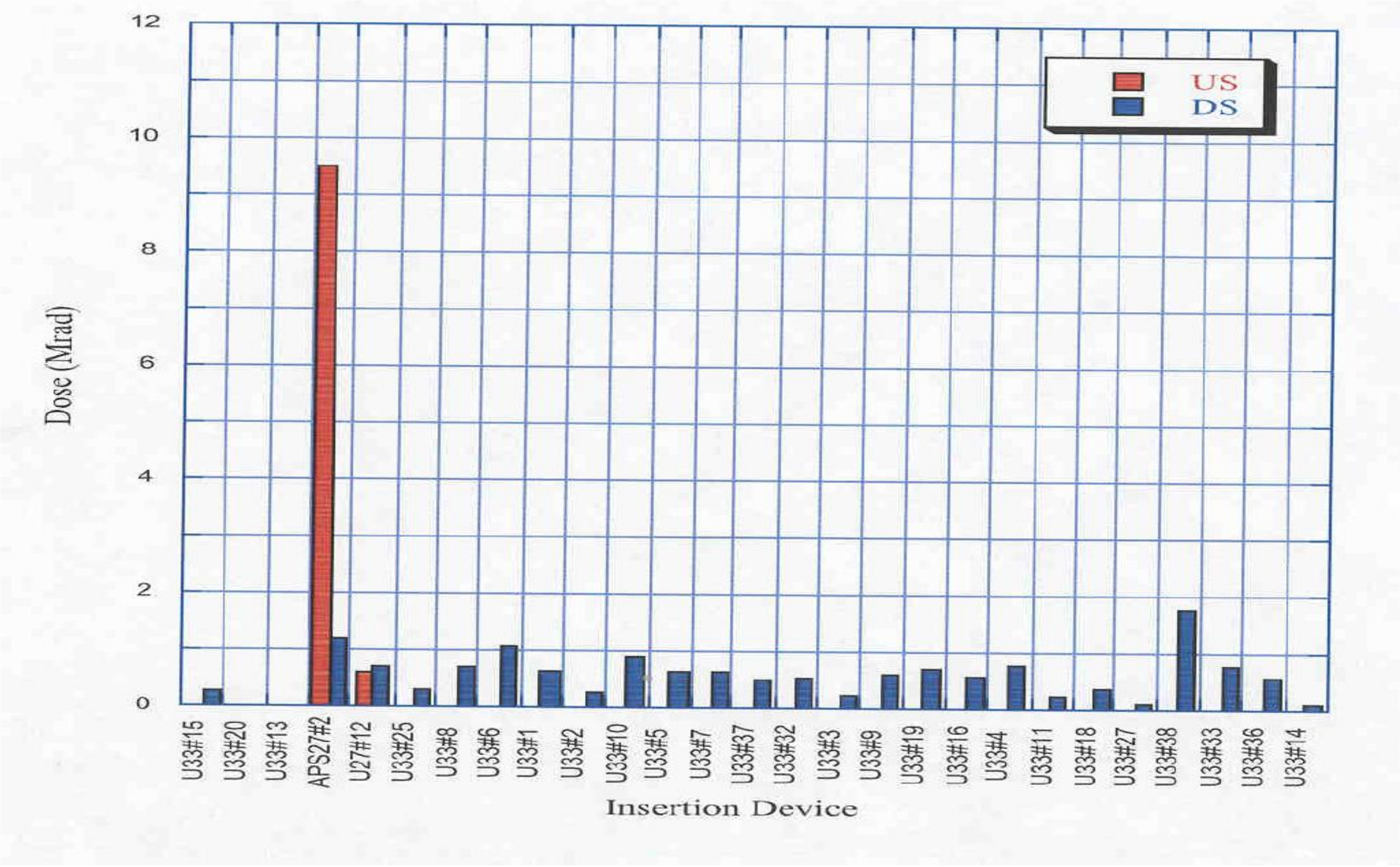
- **Reduce the Impedance**
  - 8 cm x 4 cm ➔ 2 cm x 5 mm (present)
  - 2 cm x 1 cm ➔ 2 cm x 5 mm (1/3 of the present Zy)
  - Optimize the taper

Feedback damper (?)

Simulation of Injection Process

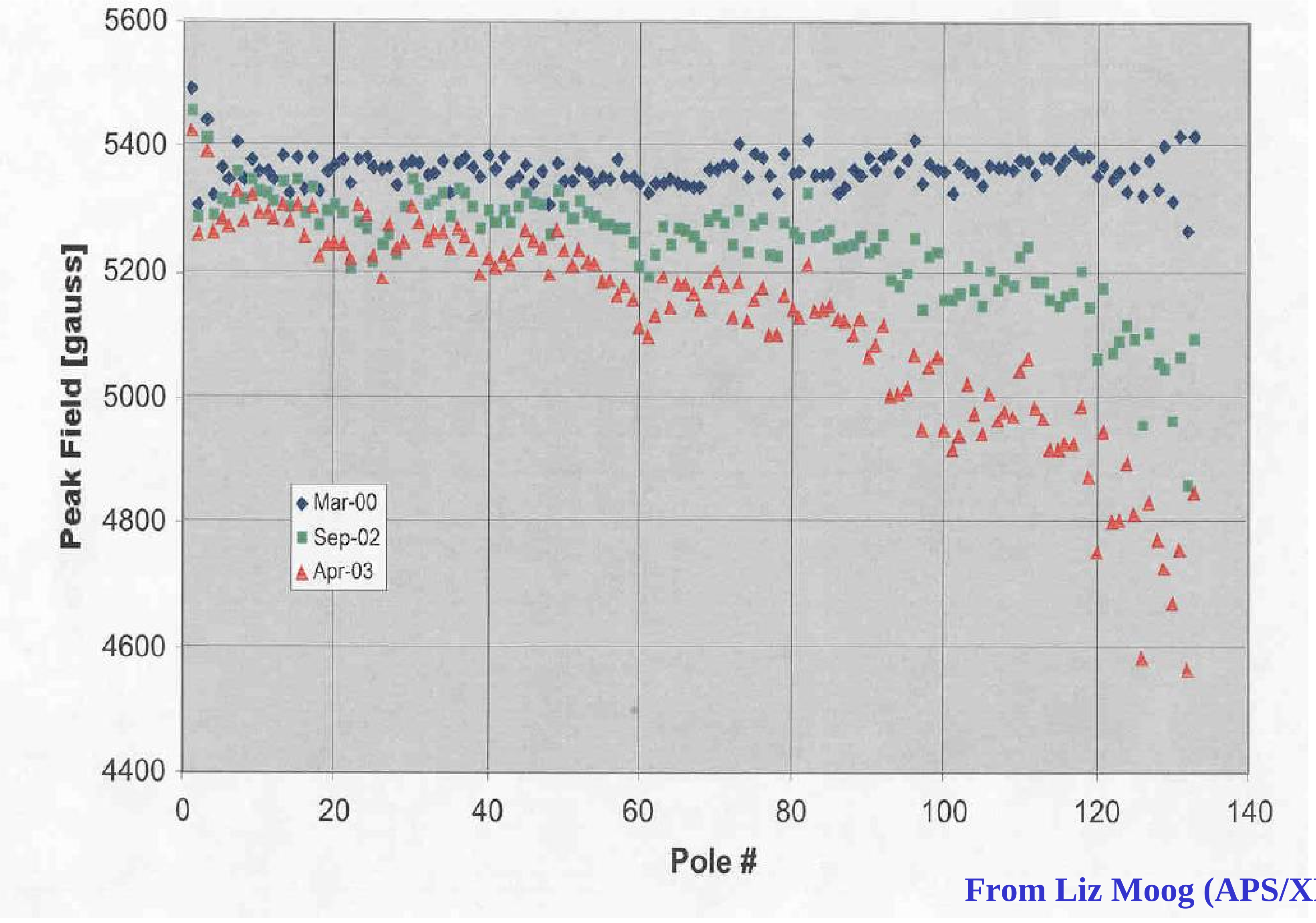
- Accumulation Limit is 8 mA
- Radiation Damage to Insertion Devices

Run 2003-1 ID Dose (alanine)



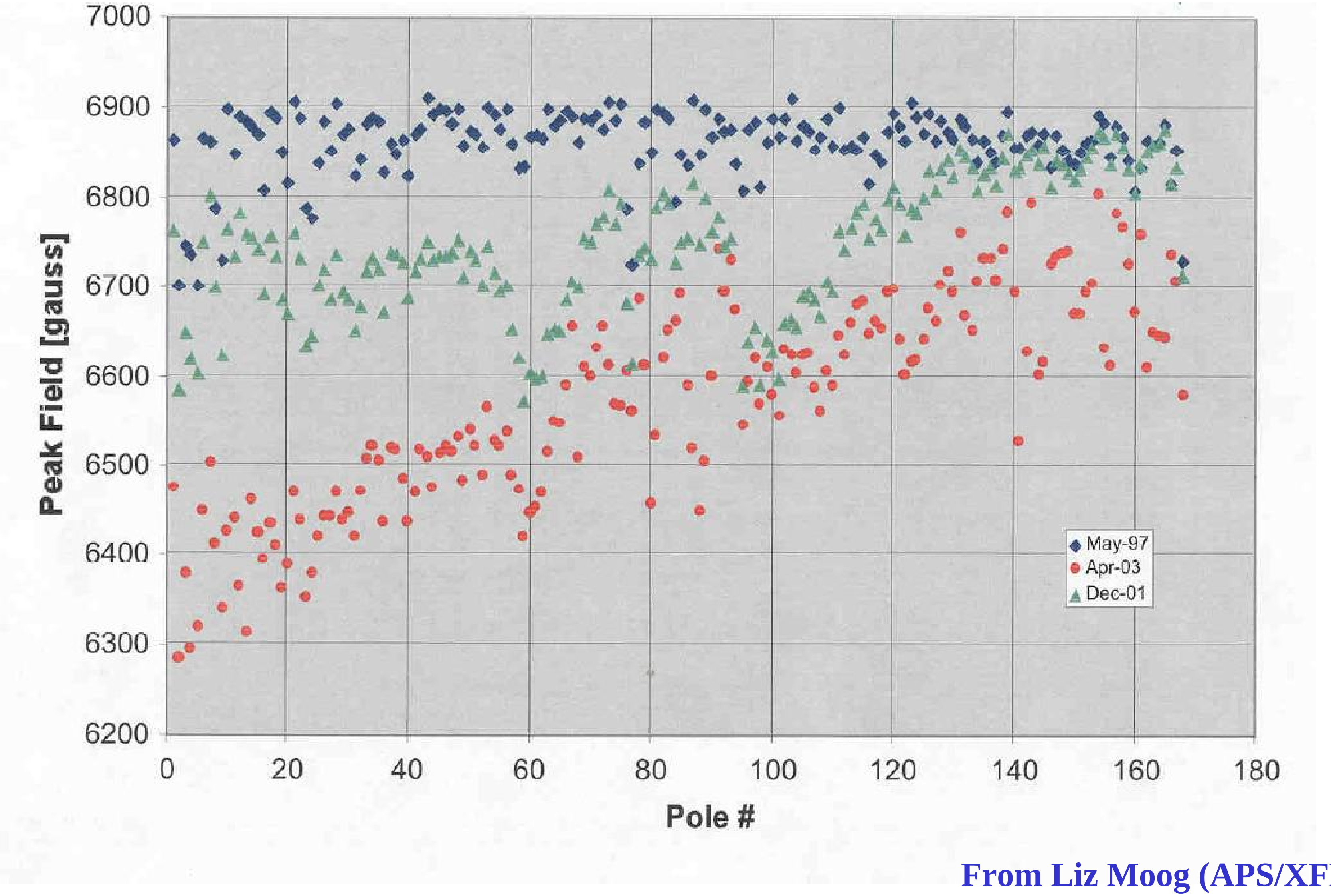
From Liz Moog (APS/XFD)

APS27#2 Damage Sequence



From Liz Moog (APS/XFD)

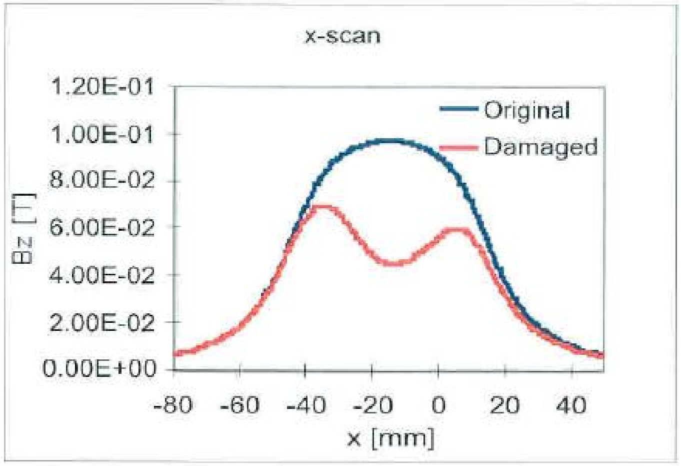
U27#12 Damage Sequence

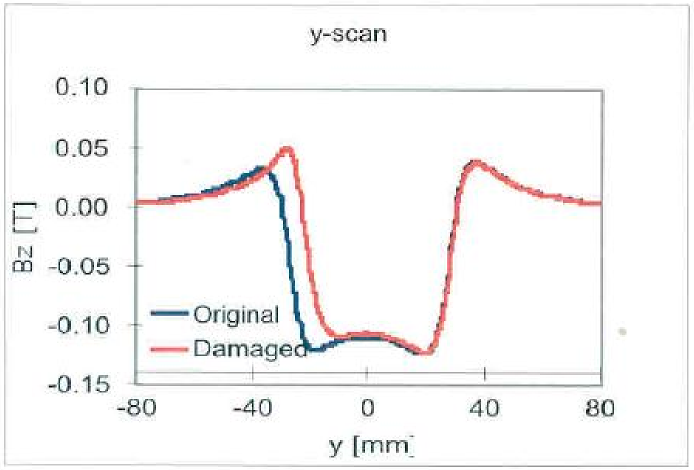


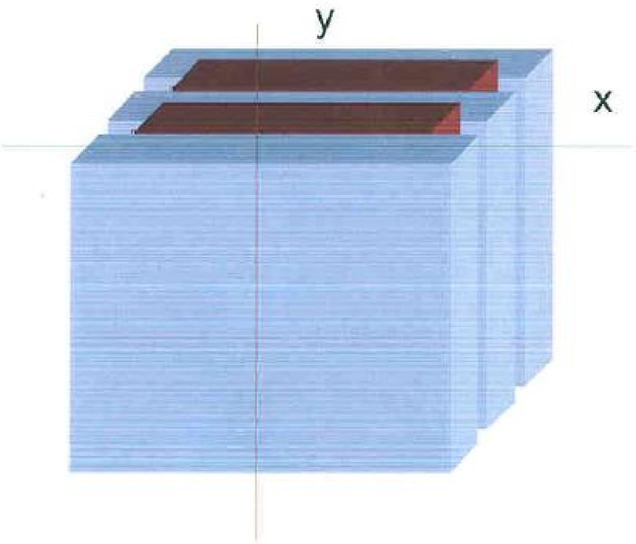
From Liz Moog (APS/XFD)

Damage Distribution in Magnet Block

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







From Liz Moog (APS/XFD)

Damage Assessment

U27#12 — Gap 10.5mm — Sector 3 DS

Date	RMS Phase error	3rd harm., % of ideal	notes
1997 June 23	5.45	82.6	reference
2001 Dec. 31	36.5	35.2	damaged
2002 Jan. 3	9.29	69.0	tuned, taper 0.160mm
2002 May 6	14.14	52	more damage
2002 May 7	10.81	62.4	tuned, taper 0.185mm
2002 Sept 12	15.00	49.2	more damage
2002 Sept 13	6.9	75.2	tuned, taper 0.235
2003 Jan 3	13.68	56.6	more damage
2003 Jan 3	6.4	80.4	tuned, taper 0.315 mm
2003 April	6.56	78.1 (1st 95.3%)	tuned, taper 0.47 mm, more shims

APS27#2 — Gap 11.5mm — Sector 3 US

2000 June 23	2.62	91.5	reference
2002 Jan. 8	10.79	64.2	damaged
2002 Jan. 8	3.67	86.1	tuned, taper -0.150 mm
2002 Sept 18	32.9	30.9	more damage
2002 Sept 18	5.90	74.1	tuned, taper -0.4 mm
2003 Jan 3	32.7	28 (1st 69.5%)	more damage
2003 Jan 3	5.62	76.3	tuned, taper –0.9 mm; 3% weaker Beff overall
2003 May 8	3.87	89.7 (1st 100%)	replace 36 magnets with spares; turn rest of magnets in US half; remove taper

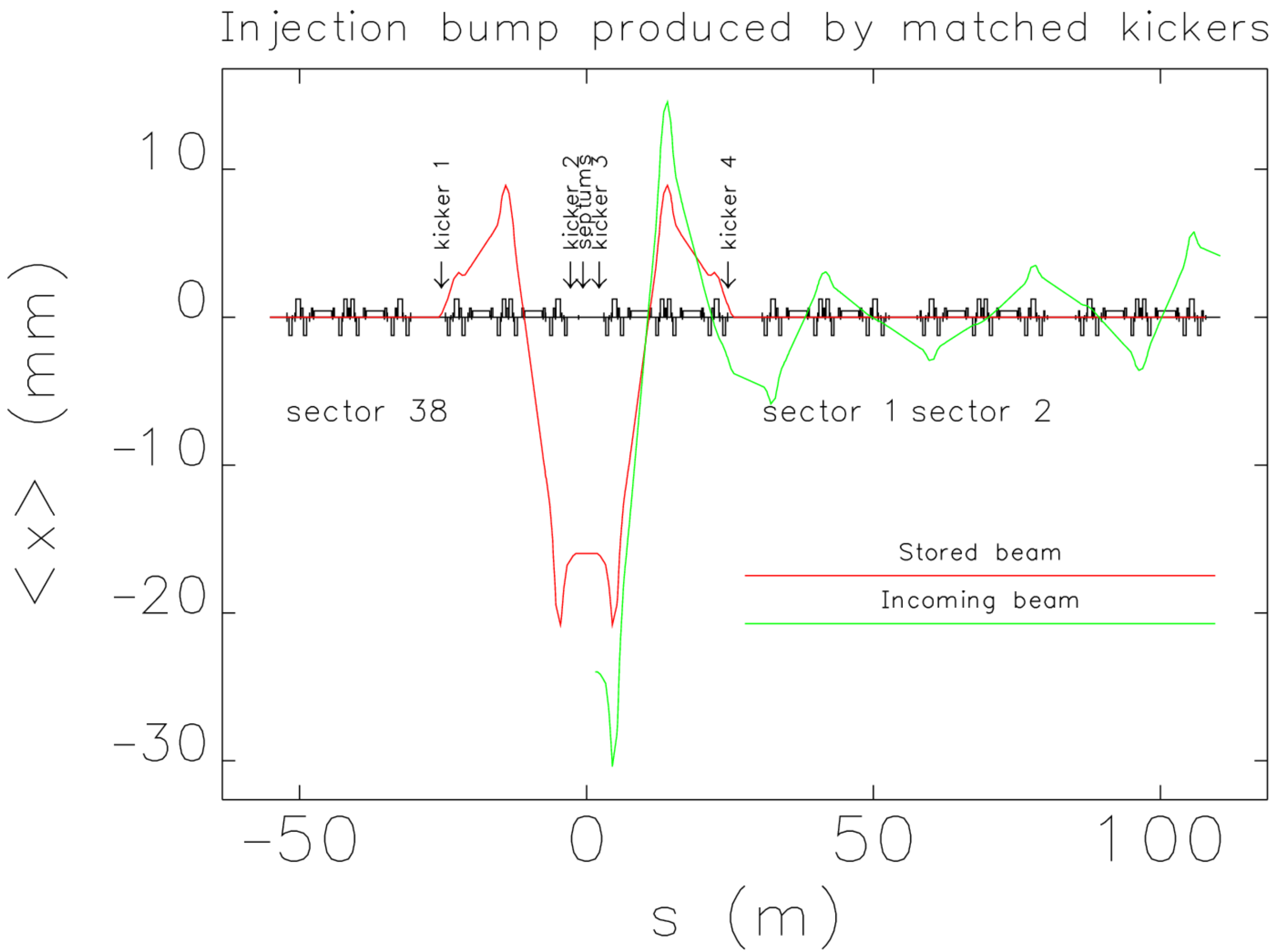
From Liz Moog (APS/XFD)

Simulation of Injection Process

- Injection by matched kicker bumps
- Injection by mismatched kicker bumps

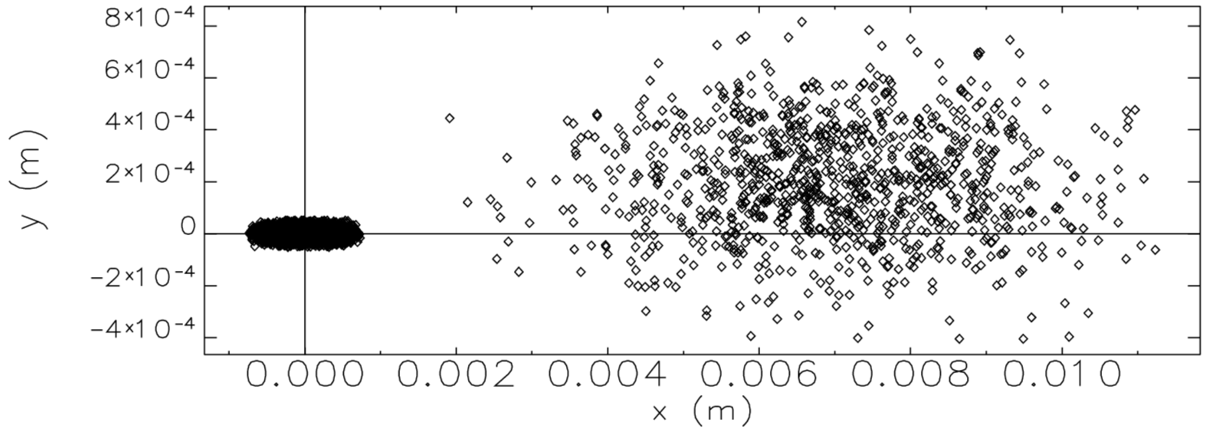
  (current injection scheme)
- Longitudinal injection

Injection by Matched Kickers

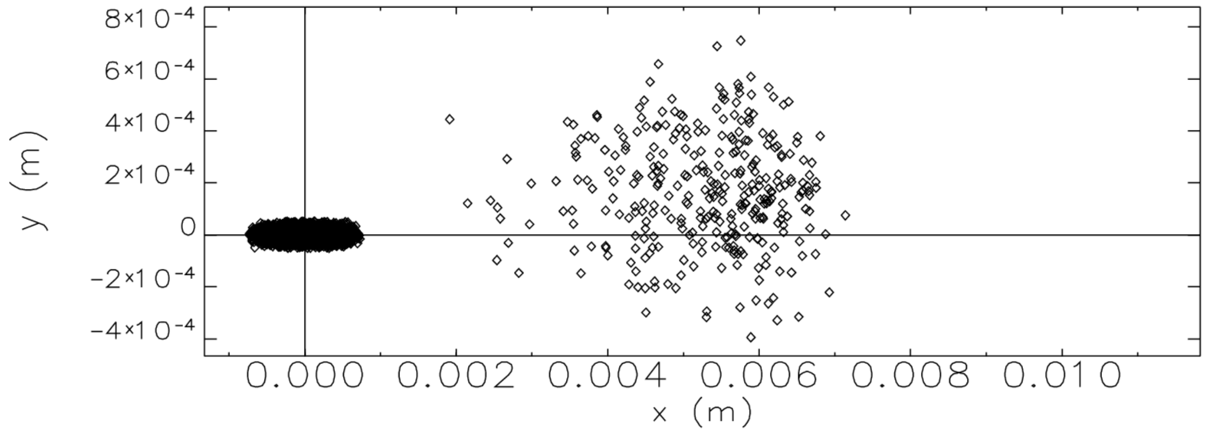


From Louis Emery (APS/AOD)

Simulation of Matched Kicker Injection



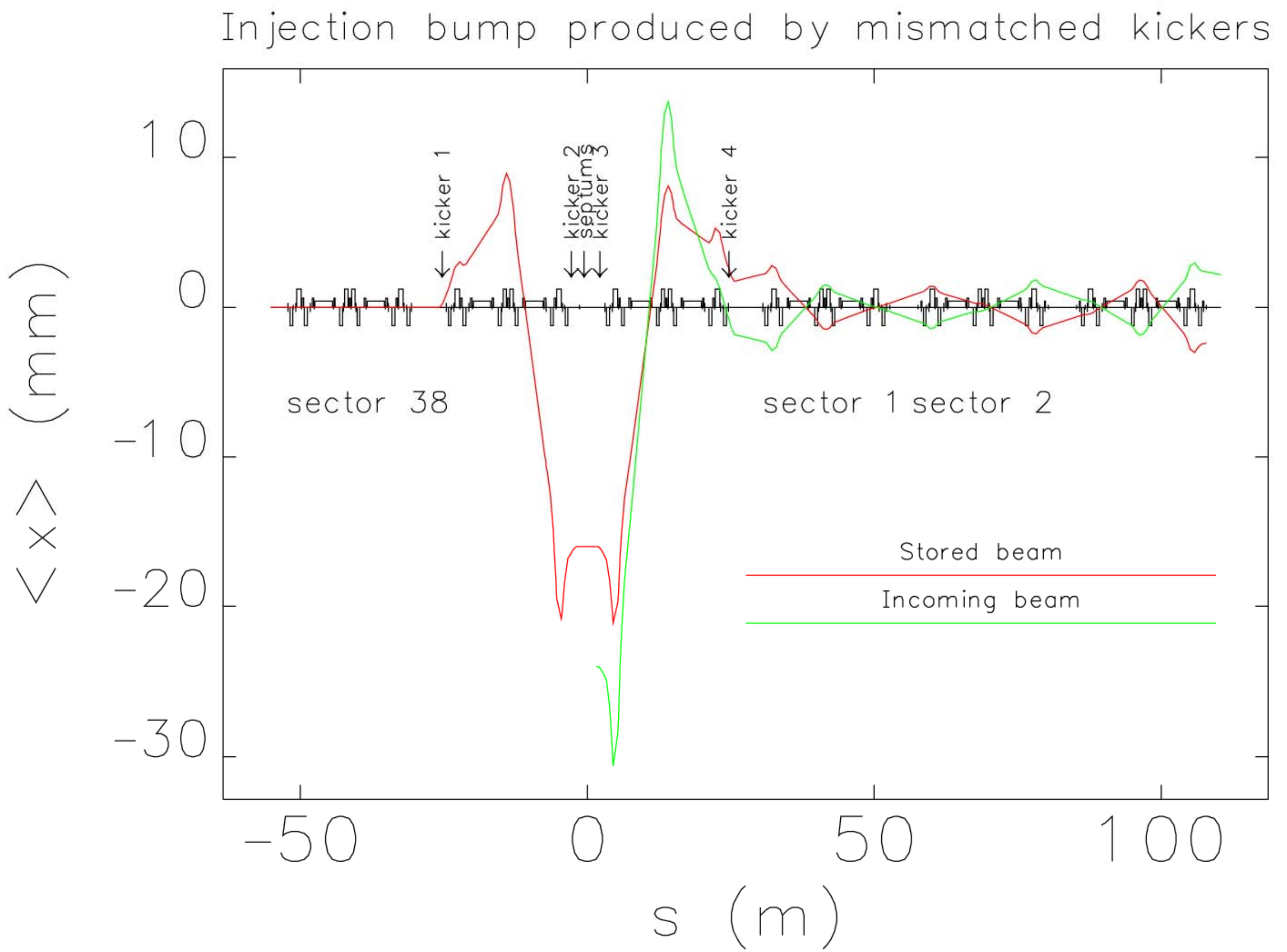
Initial beam



Survived beam

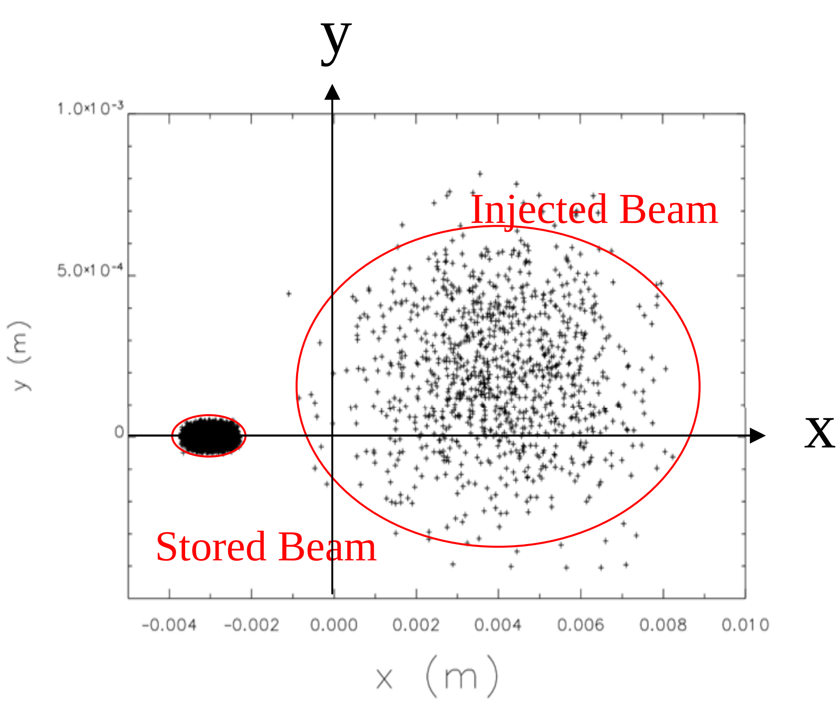
- Particle lost by dynamic aperture ➔ single particle effect
- Injection efficiency less than 50% ➔ constant up to 8 mA

Current Injection Scheme



From Louis Emery (APS/AOD)

Initial Condition of Beam Simulating Current Injection Scheme

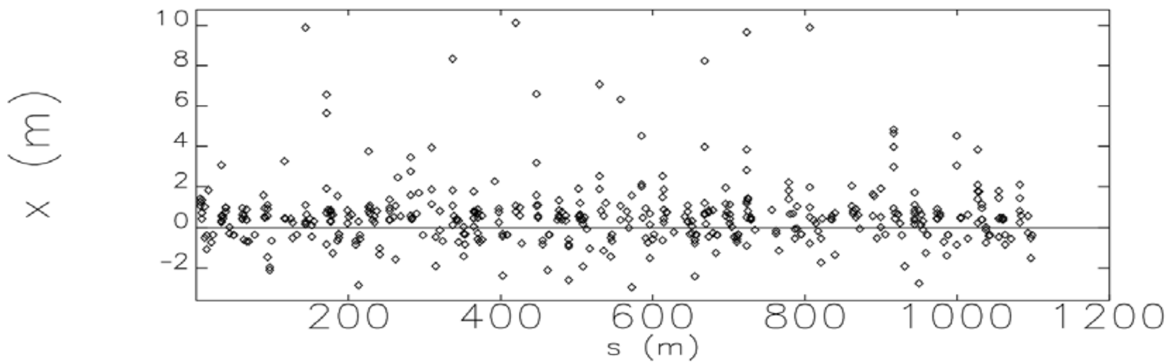


Coordinates of Initial Beam at the center of ID straight

	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

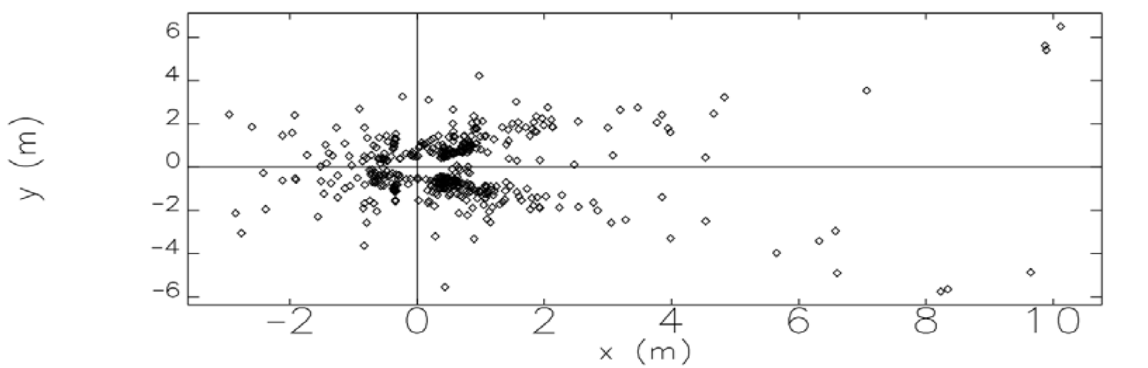
Particle Loss: Dynamic Aperture

x vs. s



Particle loss around ring

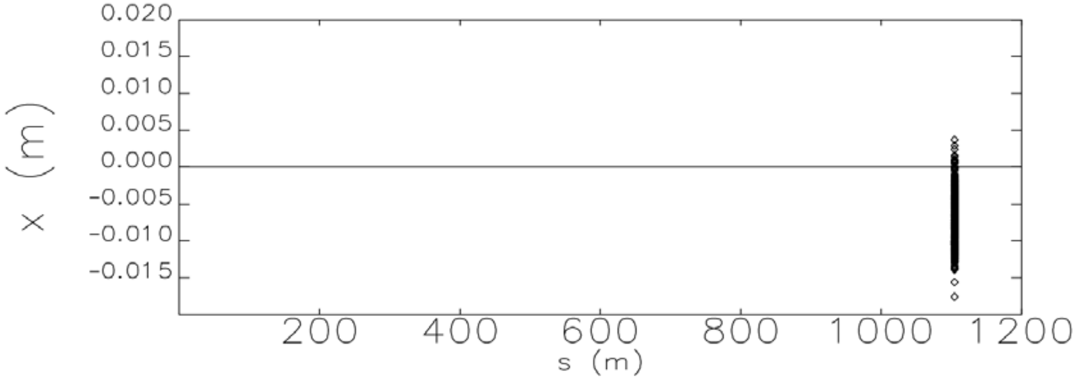
x vs. y



Coordinates of the lost particles

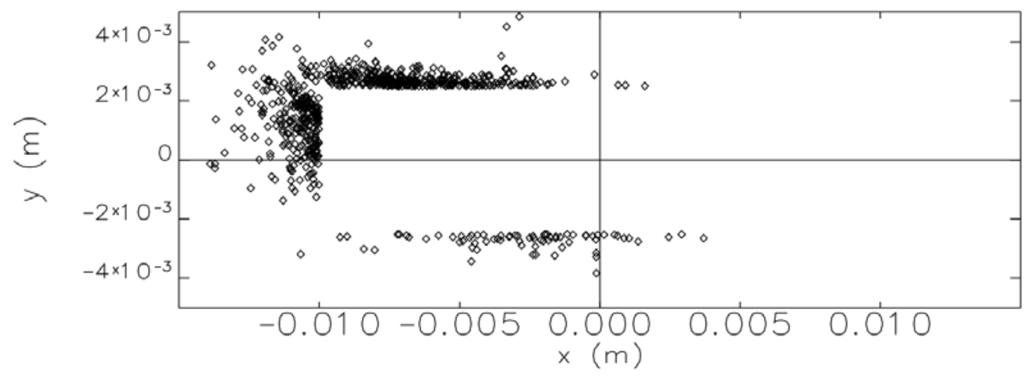
Particle Loss: Physical Aperture

x vs. s



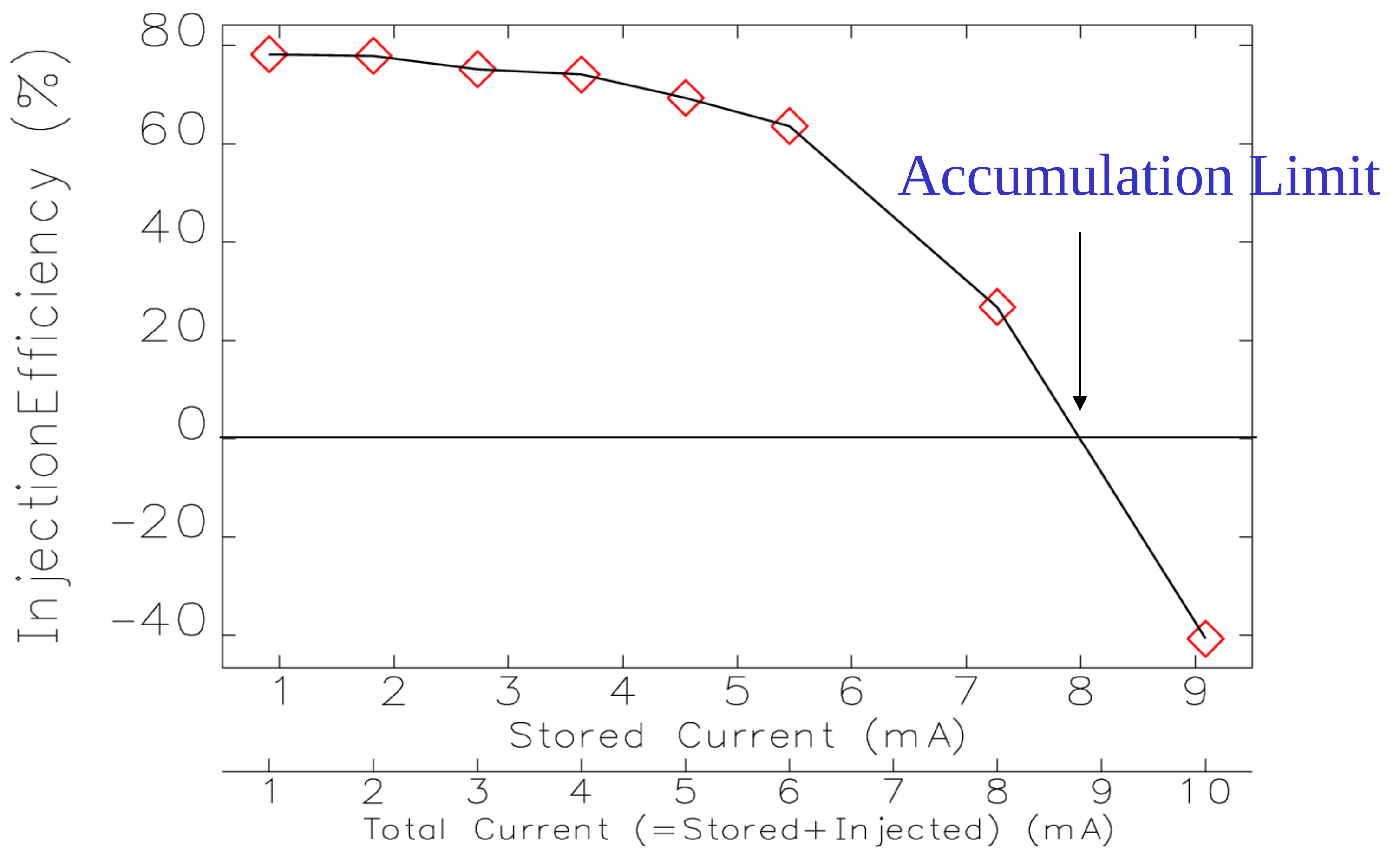
Particle loss localized by aperture

x vs. y



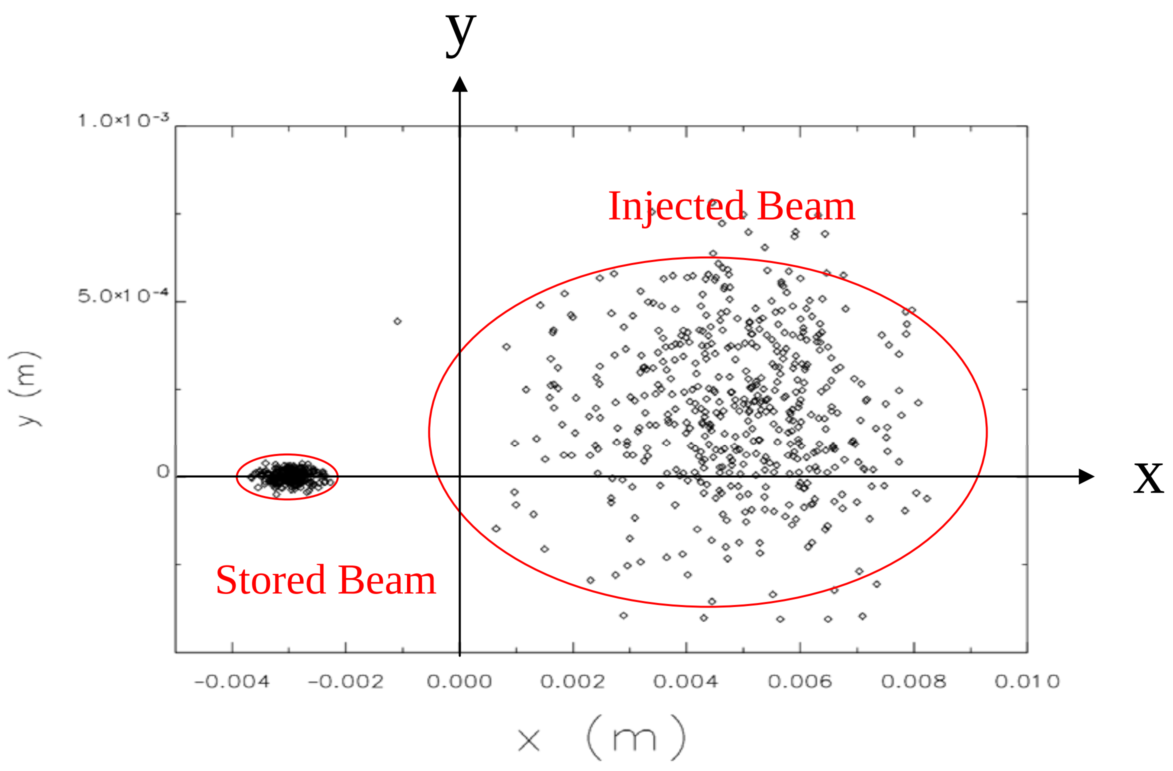
Coordinates of the lost particles

Injection Efficiency vs. Current



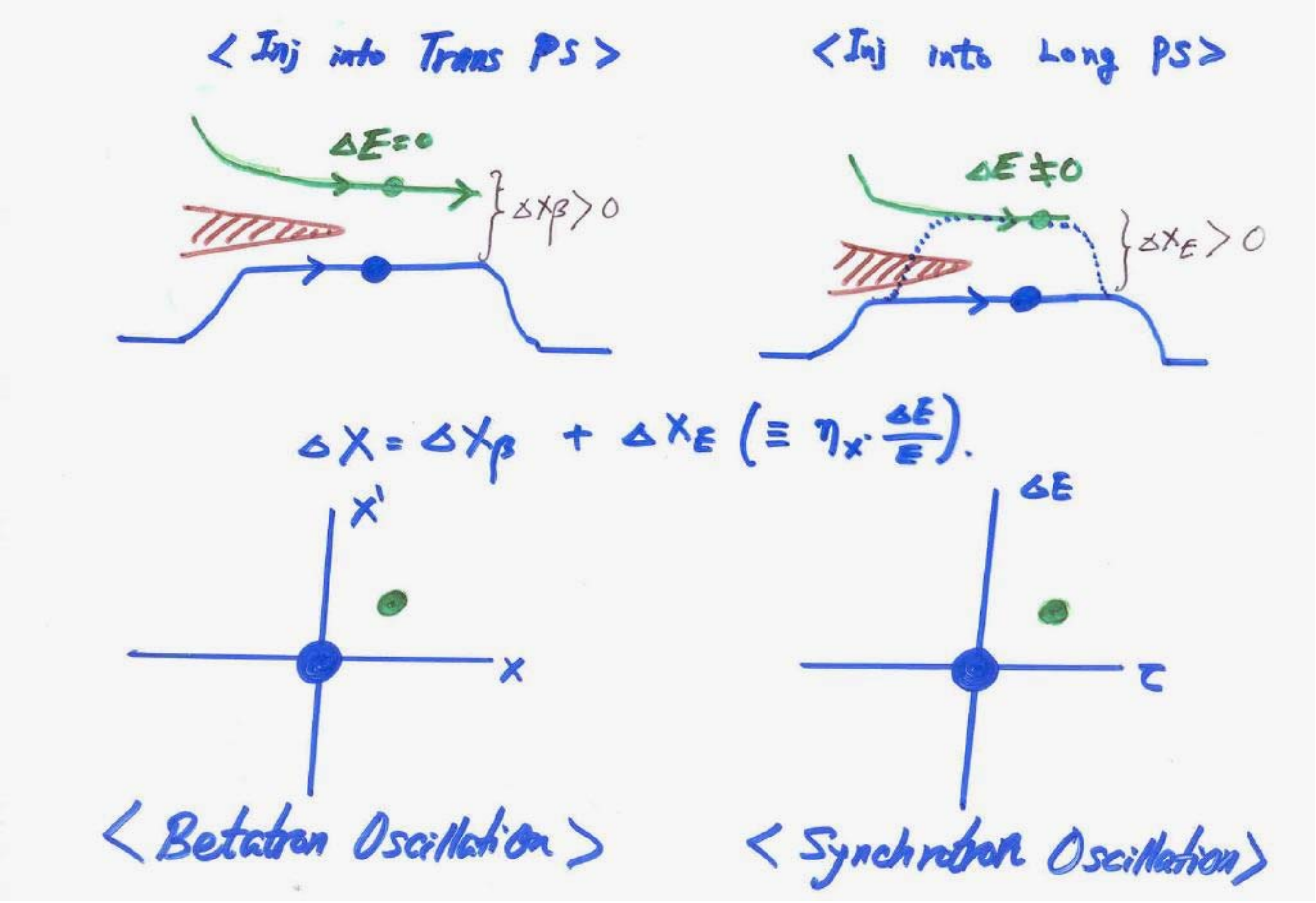
Measured Accumulation Limit < 8 mA

Initial Coordinates of Lost Beam: High Stored Current

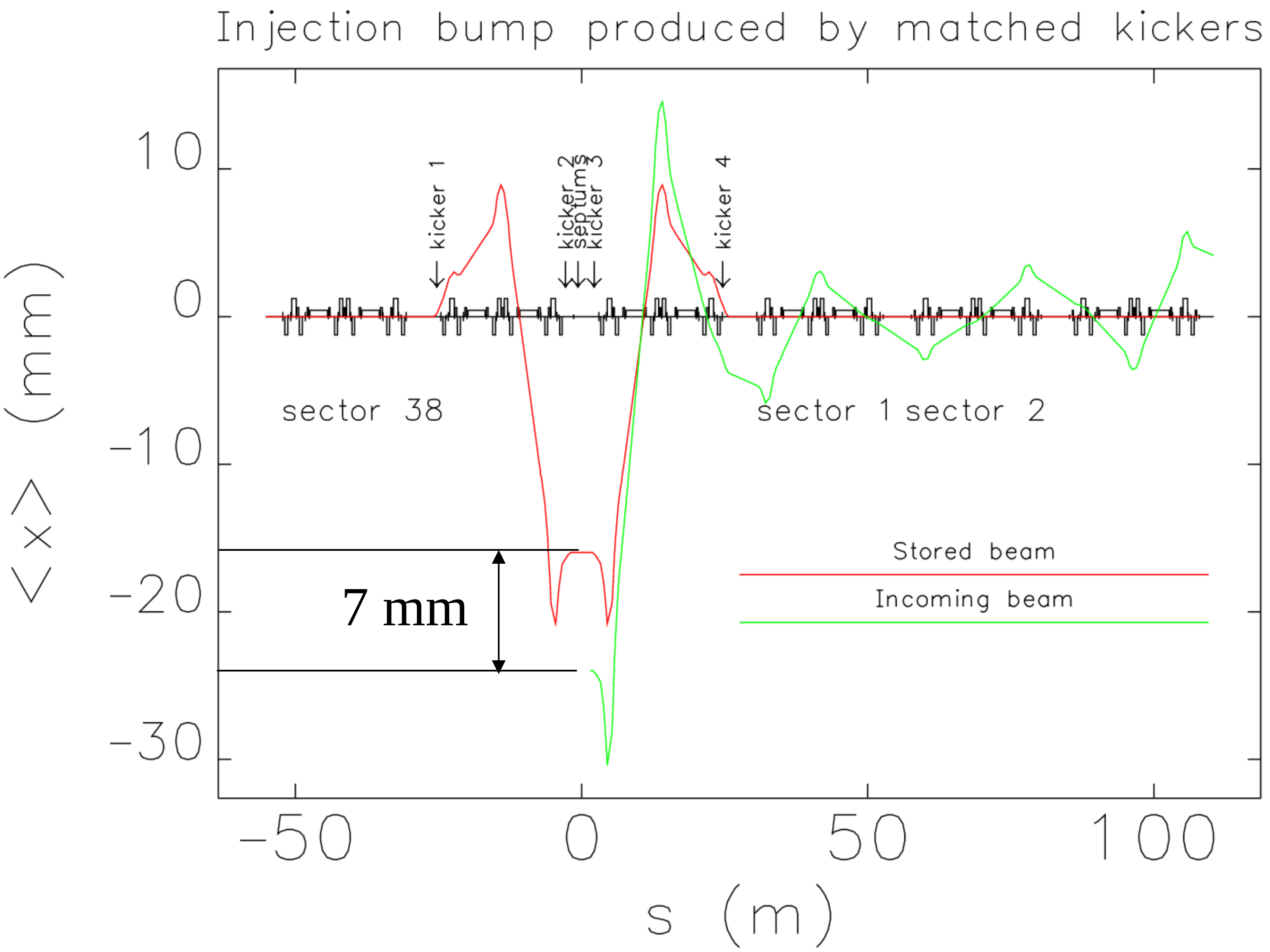


- **Significant amount of stored beam is lost during the injection process**
- **Reduce the Beam Loss ➔ Reduce the Separation ➔ Longitudinal Injection**

Longitudinal Injection Scheme



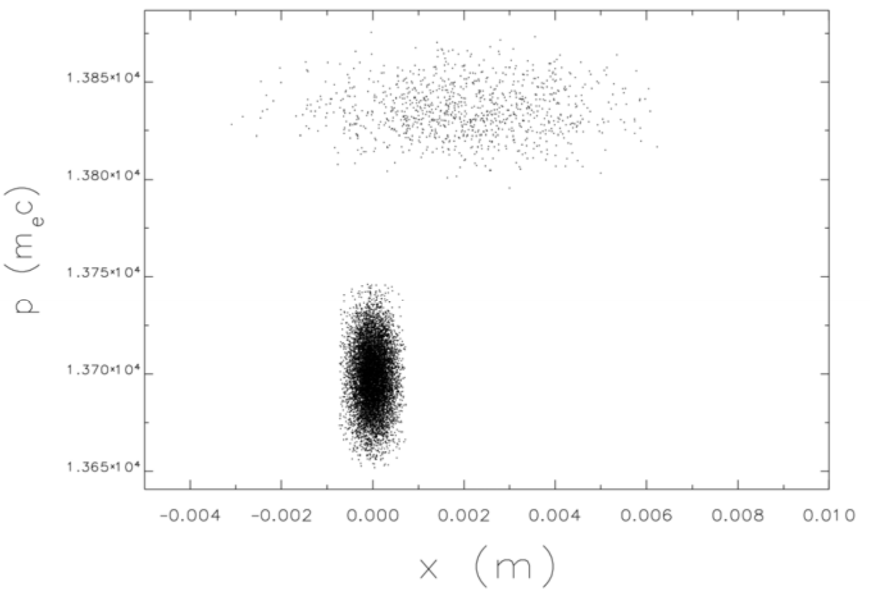
Injection by Matched Kickers



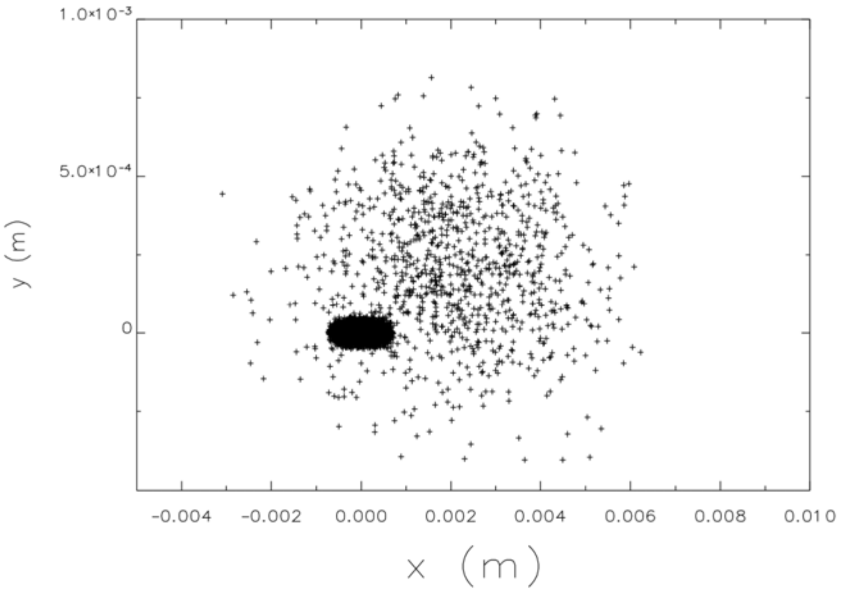
η_x= 40 cm
$\Delta E/E$=-1%
X_β=3 mm

Simulation of Longitudinal Injection Scheme

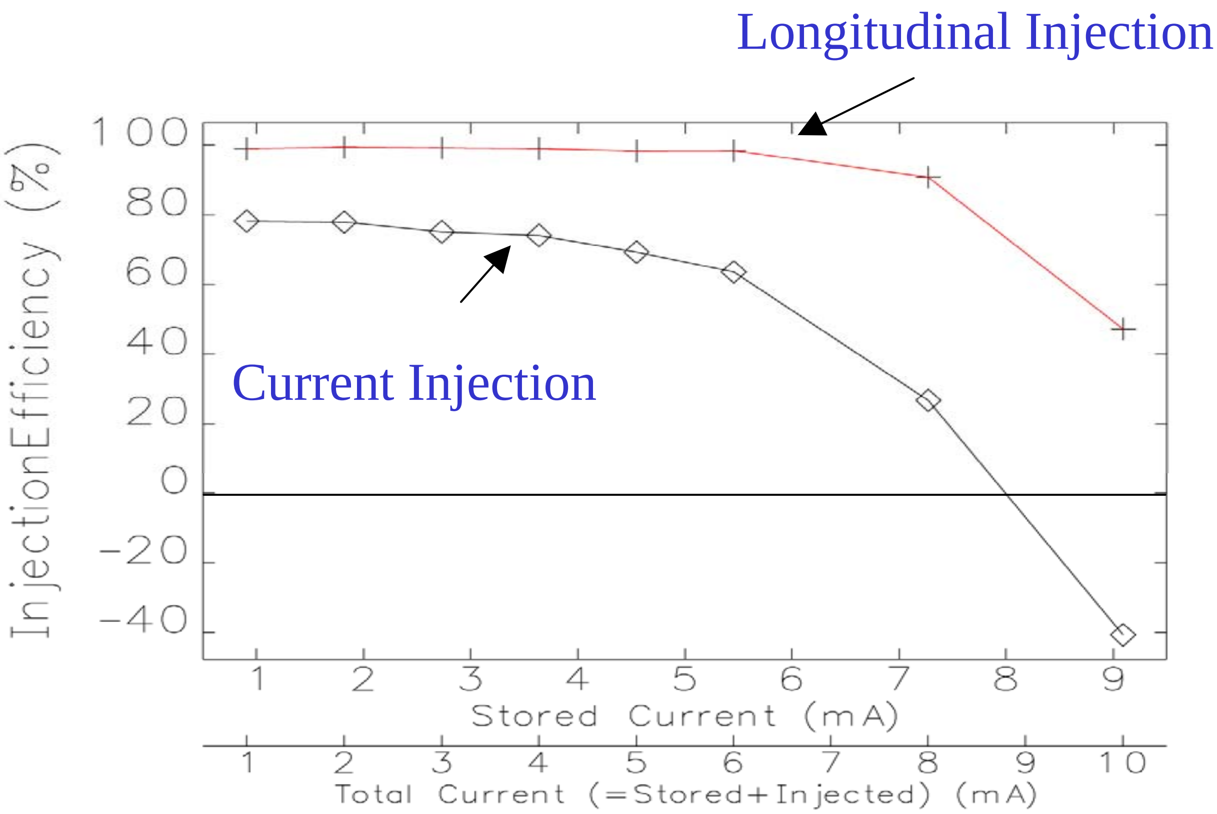
x-p space



x-y space



Injection Efficiency vs. Current



Injection Efficiency Improved in simulation !

CONCLUSION

- We completed the initial construction of Impedance Database for the APS storage ring.
- We reproduced quantitatively/qualitatively the instabilities observed in the APS storage ring by *elegant* simulations which include the impedance elements in the multi-particle tracking .
- We showed by simulation that the longitudinal injection scheme could reduce the injection loss; we hope it could reduce the radiation damage to undulators.
- The effects of small gap chamber is still under investigation
  - Current dependent
  - Lattice dependent

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- K. Harkay, V. Sajaev, C. Wang from Accel Phy Group
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- X. Sun, G. Decker, O. Singh, A. Lumpkin, B. Yang, L. Erwin from Diag Group
- C. Yao from Operations Group