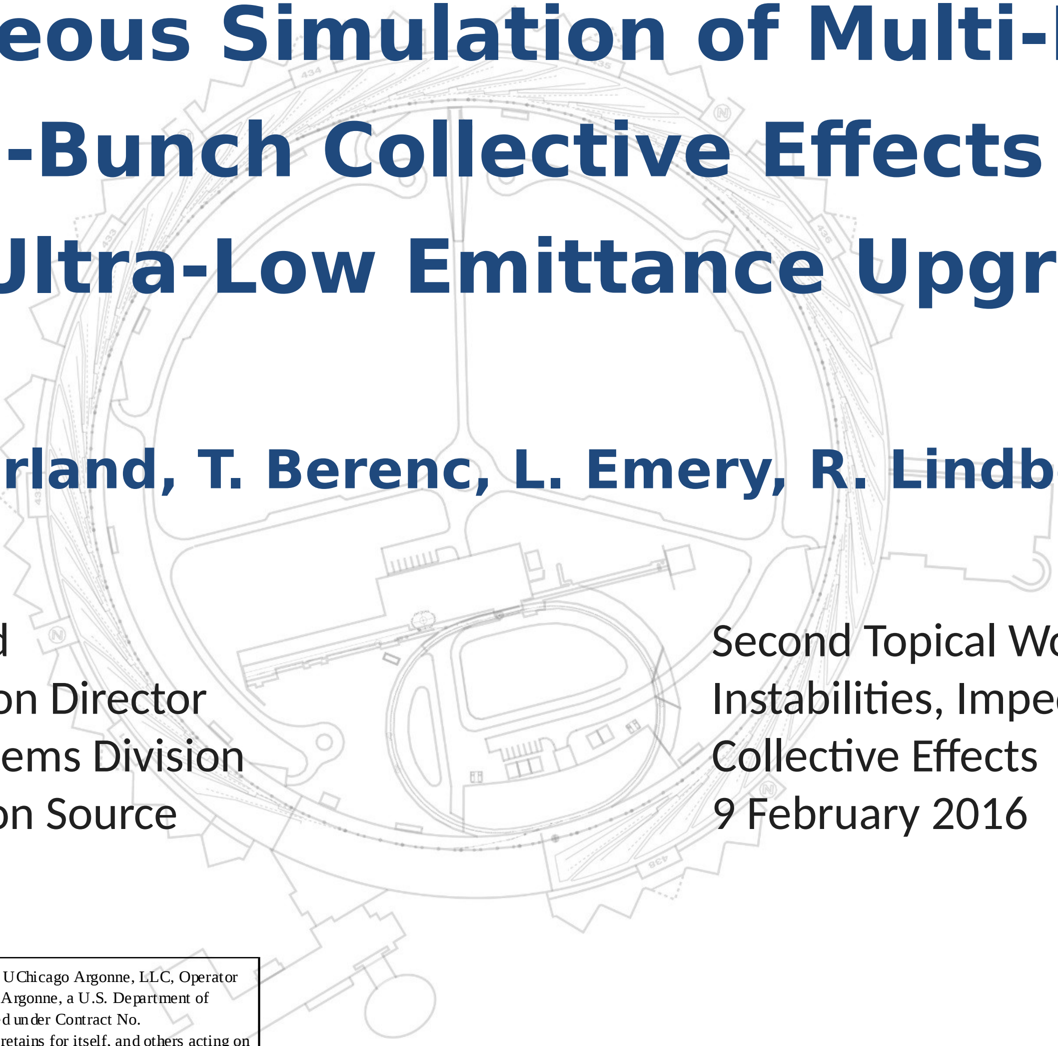
# Simultaneous Simulation of Multi-Particle and Multi-Bunch Collective Effects for the APS Ultra-Low Emittance Upgrade



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Second Topical Workshop on
Instabilities, Impedance, and
Collective Effects
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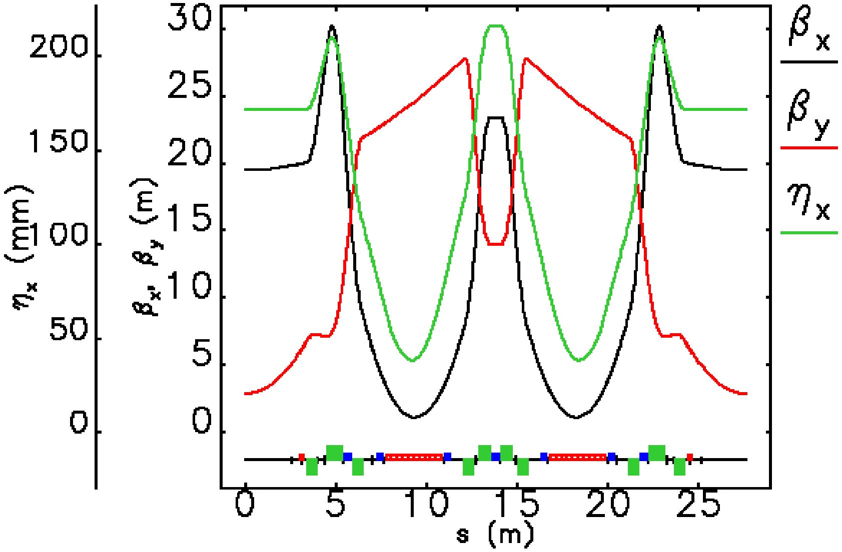
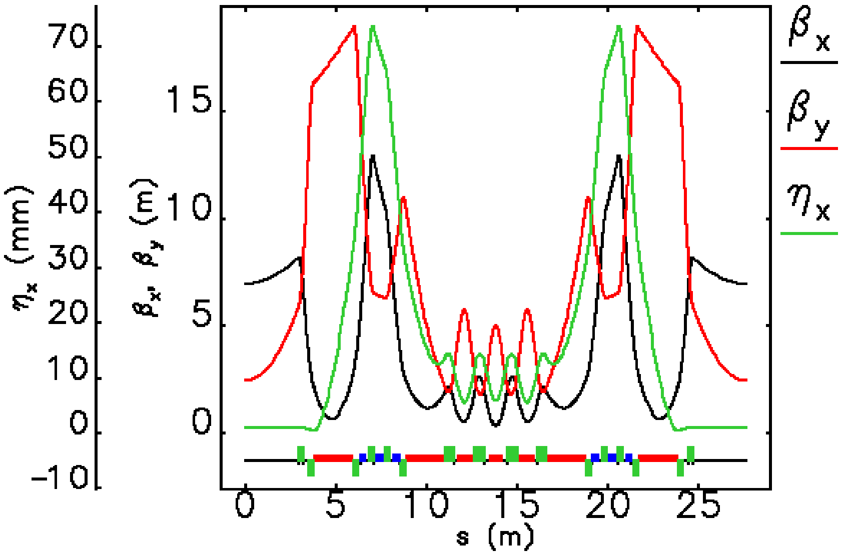
# Outline

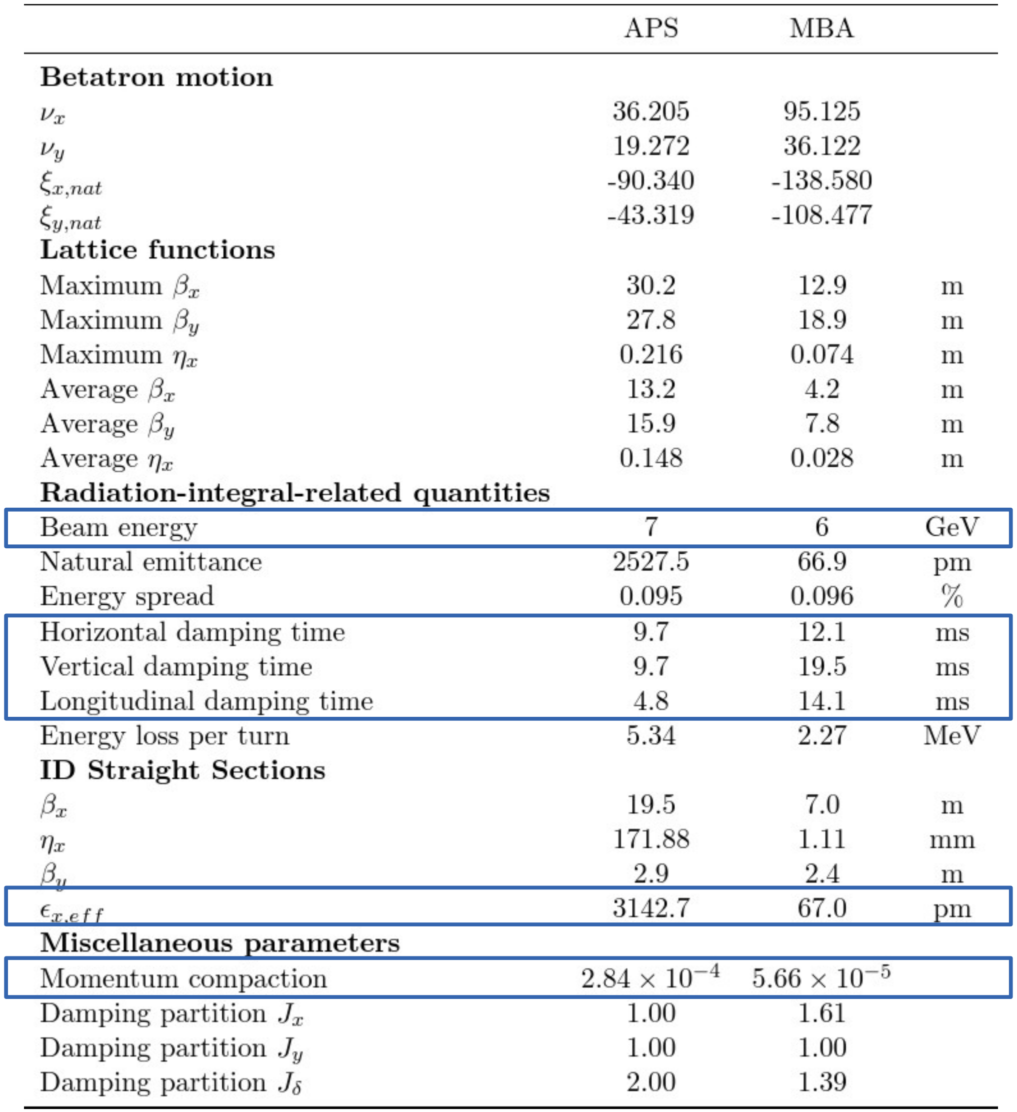
- APS upgrade ("APS-U") overview
- Modeling tools and methods
- Results for multi-particle, multi-bunch simulations
    - Stability for uniform fills
    - Stability under loss of a bunch
    - Stability while filling the ring
- Conclusion

# Multi-bend achromat lattice[1] for APS-U[2]





H7BA lattice based on L. Farvacque *et al.*, IPAC13, 79.



| | APS | MBA | |
|---|---|---|---|
| **Betatron motion** | | | |
| $\nu_x$ | 36.205 | 95.125 | |
| $\nu_y$ | 19.272 | 36.122 | |
| $\xi_{x,nat}$ | -90.340 | -138.580 | |
| $\xi_{y,nat}$ | -43.319 | -108.477 | |
| **Lattice functions** | | | |
| Maximum $\beta_x$ | 30.2 | 12.9 | m |
| Maximum $\beta_y$ | 27.8 | 18.9 | m |
| Maximum $\eta_x$ | 0.216 | 0.074 | m |
| Average $\beta_x$ | 13.2 | 4.2 | m |
| Average $\beta_y$ | 15.9 | 7.8 | m |
| Average $\eta_x$ | 0.148 | 0.028 | m |
| **Radiation-integral-related quantities** | | | |
| Beam energy | 7 | 6 | GeV |
| Natural emittance | 2527.5 | 66.9 | pm |
| Energy spread | 0.095 | 0.096 | % |
| Horizontal damping time | 9.7 | 12.1 | ms |
| Vertical damping time | 9.7 | 19.5 | ms |
| Longitudinal damping time | 4.8 | 14.1 | ms |
| Energy loss per turn | 5.34 | 2.27 | MeV |
| **ID Straight Sections** | | | |
| $\beta_x$ | 19.5 | 7.0 | m |
| $\eta_x$ | 171.88 | 1.11 | mm |
| $\beta_y$ | 2.9 | 2.4 | m |
| $\epsilon_{x,eff}$ | 3142.7 | 67.0 | pm |
| **Miscellaneous parameters** | | | |
| Momentum compaction | $2.84 \times 10^{-4}$ | $5.66 \times 10^{-5}$ | |
| Damping partition $J_x$ | 1.00 | 1.61 | |
| Damping partition $J_y$ | 1.00 | 1.00 | |
| Damping partition $J_\delta$ | 2.00 | 1.39 | |

1: D. Einfeld et al., SPIES 2013, 201 (1993).
2: M. Borland et al., IPAC15, 1776 (2015).

# Planned APS-U operating modes

- Single-bunch on-axis swap-out injection
  - Each bucket is filled by a single shot from the injector
  - Accommodates small apertures, unusual insertion devices
- Targeting 200 mA in various fill patterns
  - 324-bunch uniform
    - Desirable for long lifetime and highest brightness
    - Close to limit of present fast kicker technology
    - 2.2 nC/bunch
  - 48-bunch uniform
    - Desirable for timing experiments
    - 15 nC/bunch
  - Possible hybrid or non-uniform modes under study
- Passive higher-harmonic cavity (HHC) required to lengthen bunch
  - Reduce intrabeam scattering, increase Touschek lifetime

# Simulation tools

- Computation of geometric wakes
  - GdfidL[1]
  - ECHO[2]
- Computation of cavity modes
  - URMEL[3]
  - Measurement
- Tracking with collective effects
  - Parallel version of **`elegant`**[4,5]
- Setup, post-processing, and visualization
  - clinchor[6]
  - TAPAs[7]
  - SDDS[8]
  - ImageMagick
- Blues cluster at Argonne LCRC

1: W. Bruns, Linac 2002, 418.
2: I. A. Zagorodnov et al. PRSTAB 8, 042001.
3: T. Weiland, NIM 216, 329 (1983).
4: Y. Wang et al., PAC07, 3456.
5: M. Borland et al., IPAC15, 549.
6: L. Emery, PAC93, 3360.
6: M. Borland, PAC2013, 1364.
7: R. Soliday et al., PAC03, 3473.

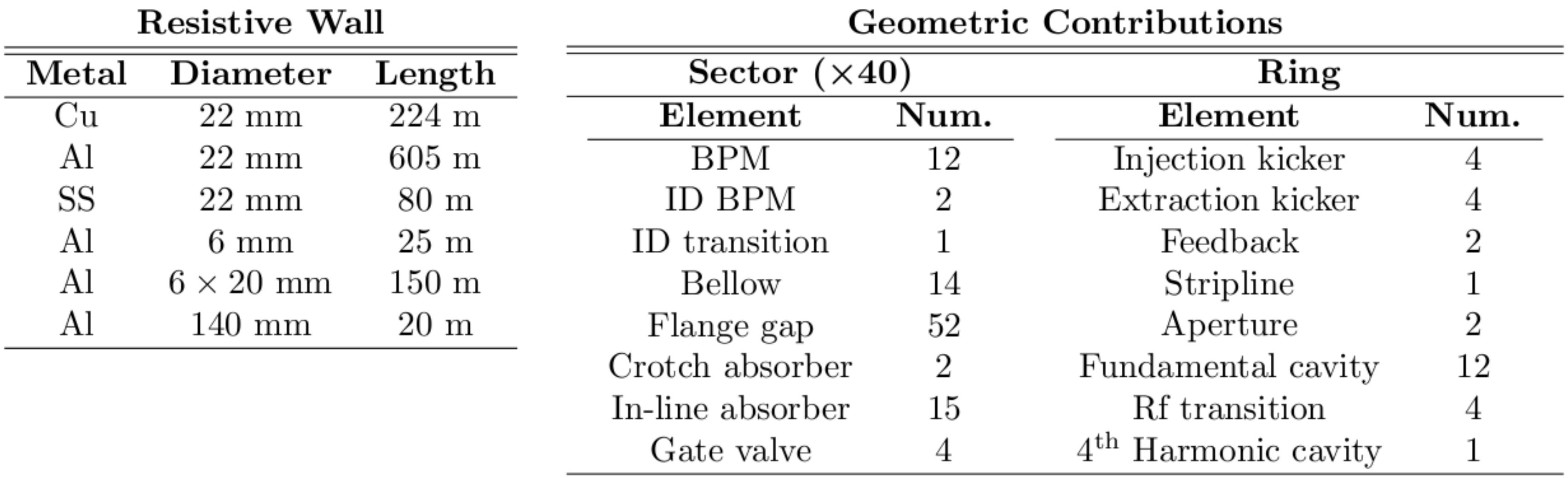
# Simulation of short-range wakes

- Simulations include
  - Resistive wakes from analytical expressions
    - Longitudinal wake
    - Transverse dipole wakes
  - Geometric wake potentials
    - Longitudinal wake
    - Transverse dipole and quadrupole wakes
- Used in `elegant` via impedance formalism
  - FFT-based convolution of time-dependent charge-weighted moments of beam distribution with the wake potentials
  - ZLONGIT and ZTRANSVERSE elements in `elegant`

# APS-Upgrade short-range impedance model

- Total wakefield/impedance found by summing over all contributions weighted by the local beta function
- More details in R. Lindberg's presentation

**Impedance elements used in model**



**Resistive Wall**

| Metal | Diameter | Length |
|---|---|---|
| Cu | 22 mm | 224 m |
| Al | 22 mm | 605 m |
| SS | 22 mm | 80 m |
| Al | 6 mm | 25 m |
| Al | $6 \times 20$ mm | 150 m |
| Al | 140 mm | 20 m |

**Geometric Contributions**

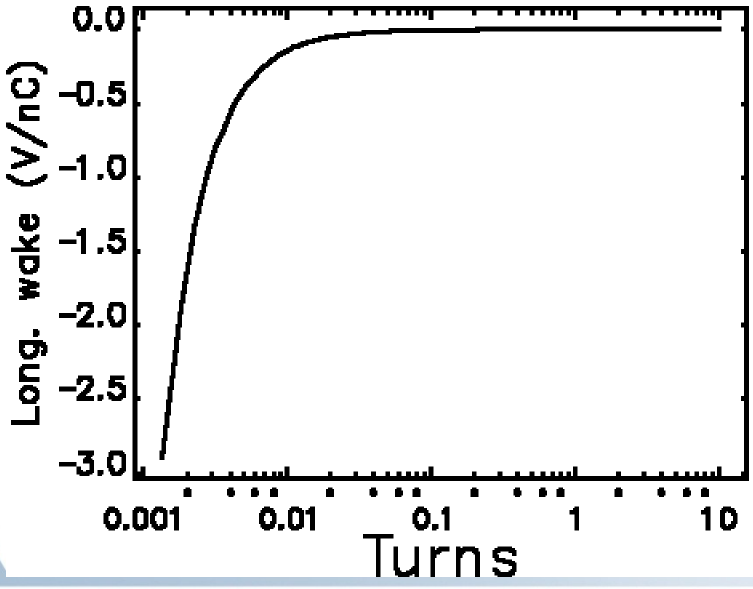
| Sector ($\times 40$) | | Ring | |
|---|---|---|---|
| **Element** | **Num.** | **Element** | **Num.** |
| BPM | 12 | Injection kicker | 4 |
| ID BPM | 2 | Extraction kicker | 4 |
| ID transition | 1 | Feedback | 2 |
| Bellow | 14 | Stripline | 1 |
| Flange gap | 52 | Aperture | 2 |
| Crotch absorber | 2 | Fundamental cavity | 12 |
| In-line absorber | 15 | Rf transition | 4 |
| Gate valve | 4 | $4^{\text{th}}$ Harmonic cavity | 1 |

R. Lindberg et al., IPAC15, 1823-1825.

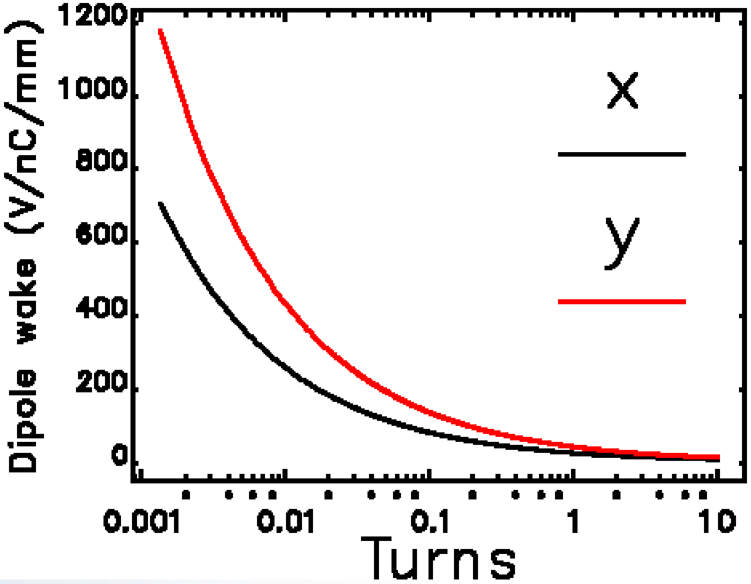
# Long-range non-resonant wakes

- Resistive wall effects can extend over many bunches and turns
- Modeled using LRWAKE element in **`elegant`**
  - Time domain computation
  - Point-bunch approximation
- For APS-U simulations, wakes extended over 10 turns (37 µs)
  - Include longitudinal and transverse dipole wakes

$$W_z(z) \approx -\frac{cL\sqrt{\pi Z_0 \rho_{\mathrm{res}}}}{4\pi^2 b|z|^{3/2}}$$



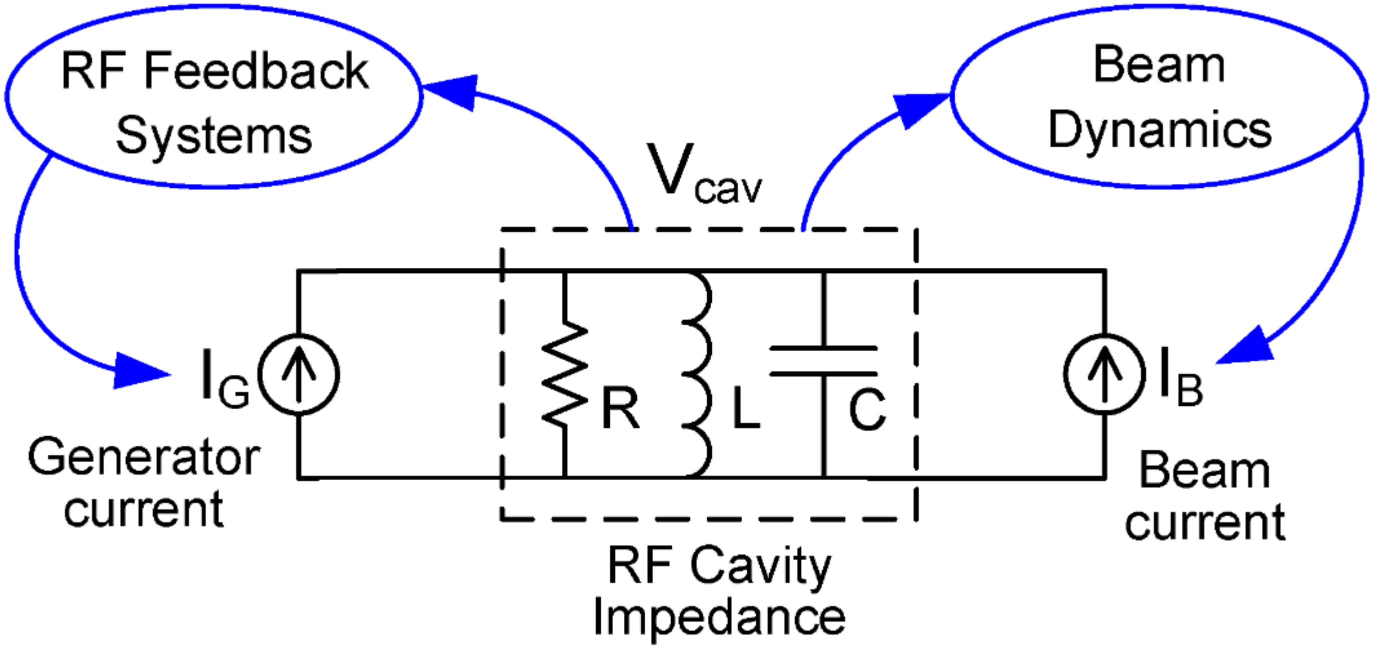
$$W_{y,D}(z) \approx \frac{cL\sqrt{\pi Z_0 \rho_{\mathrm{res}}}}{12b^3|z|^{1/2}}$$



# Resonant wakes

- We include only cavity modes in this category
  - Characterized by frequency, Q, and shunt impedance
  - RFMODE and TRFMODE elements for single monopole and dipole modes
  - FRFMODE and FTRFMODE for multiple modes from a file
- Implemented using fundamental theorem of beam loading and phasors
  - Modes driven by time-dependent charge-weighted moments of each passing bunch
  - Phasor rotation and damping used to advance fields
- For APS-U, use this method to include
  - Passive 1.4 GHz Higher Harmonic Cavity (RFMODE)
  - 120 parasitic monopole modes in main cavities (FRFMODE)
  - 168 parasitic dipole modes in main cavities (FTRFMODE)
  - 12 beam-loaded, generator-driven, 352-MHz main cavities with feedback

# Coupling of Rf Feedback and Beam Dynamics[1]



- Rf system feedback changes cavity impedance seen by beam
  - Can affect stability
- RFMODE element accepts voltage and phase setpoints for rf feedback systems
  - Feedback is configured by user-supplied IIR filters
  - APS-U simulations use filters that emulate existing APS systems

[1] T. Berenc *et al.*, IPAC15, 540.

# Feedback on the beam

- Bunch-by-bunch feedback is included
  - Longitudinal and transverse pickup and driver elements
  - TFBDRIVER computes kicks using FIR filter to process TFBPICKUP signals
  - Noise may be injected into input or output (not used here)
- Longitudinal feedback is unusual[1]
  - Needs gain at DC because HHC depresses the synchrotron tune
  - During filling, bunches slew in phase due to sawtooth variation of voltage in the cavities
    - There's no simple “correct” phase for the bunches in this situation
    - Doing feedback is easiest using a pickup that reads the momentum offset, not the beam phase

[1] M. Borland *et al*., ICAP15, to be published.

# Other simulation components

- Beam transport
  - ILMATRIX used for fast single-element simulation of ring lattice
    - Includes nonlinear chromaticity and nonlinear momentum compaction
    - Can also include tune shift with amplitude (not used here)
  - SREFFECTS used for single-element simulation of synchrotron radiation damping and quantum excitation
  - Simulations can also use element-by-element tracking and synchrotron radiation
    - Much slower, but interesting as a cross-check (R. Lindberg's talk)
- Output data
  - Bunch-by-bunch, turn-by-turn particle data, histograms, moments
  - Feedback pickup and driver data
  - Data from rf cavity modes and feedback
  - Written using parallel I/O to SDDS files[1]

[1] H. Shang *et al.*, ICAP09, 347.

# Simulations of operational scenarios

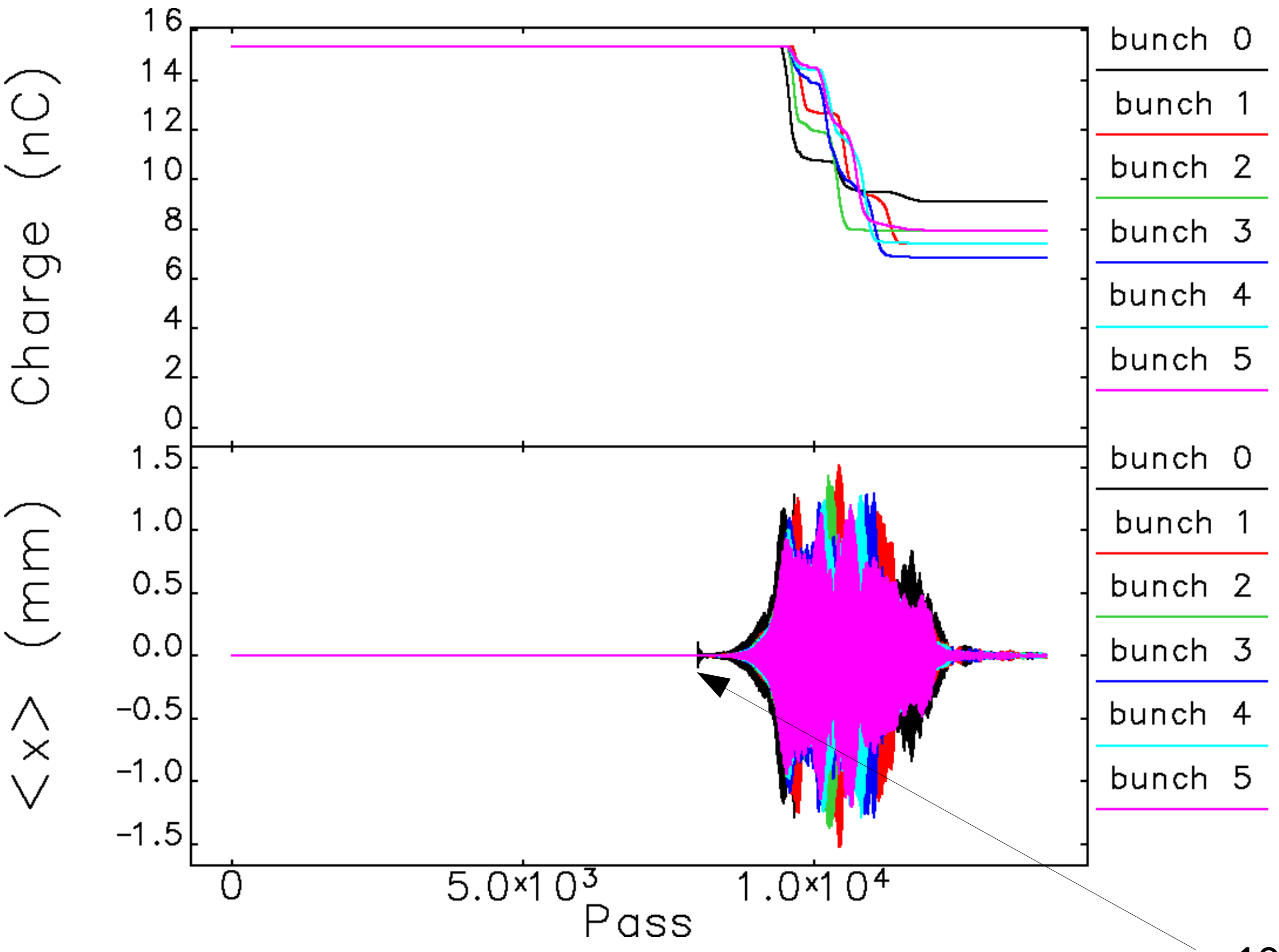
- We've simulated several operational scenarios[1], including
  1) Idealized, uniform 48-bunch fill
  2) Uniform 48-bunch fill after one bunch gets lost due to swap-out failure
  3) Filling the ring from zero
- Used typical set of “randomized” HOMs
  - Expect longitudinal instability if no feedback[2]
    - Landau damping from the HHC is not sufficient for longitudinal stability
  - Expect transverse stability even if no feedback
    - High coherent damping rate from chromaticity and short-range wake

1: M. Borland *et al*., ICAP15, to be published.
2: L. Emery et al., IPAC15, 1784.

# 1: 48-bunch uniform fill pattern

- Questions to answer
  - Is the beam stable without transverse/longitudinal feedback?
  - If not, what are feedback requirements?
- Noise control and “quiet start” is important
  - Use 100,000 particles per bunch
  - Preload rf cavity modes and rf feedback with expected voltage, phase
  - Prepare bunch with expected non-gaussian longitudinal distribution due to HHC
  - Ramp impedance up to full strength in 5000 turns
    - About 1 damping time
    - Sufficient time for rf feedback to respond
    - Beam adiabatically responds to the short-range wake
  - Wait ~2000 turns for full(er) equilibriation
  - Give longitudinal and transverse kicks to the beam to assess stability

# Horizontal instability w/weak transverse feedback

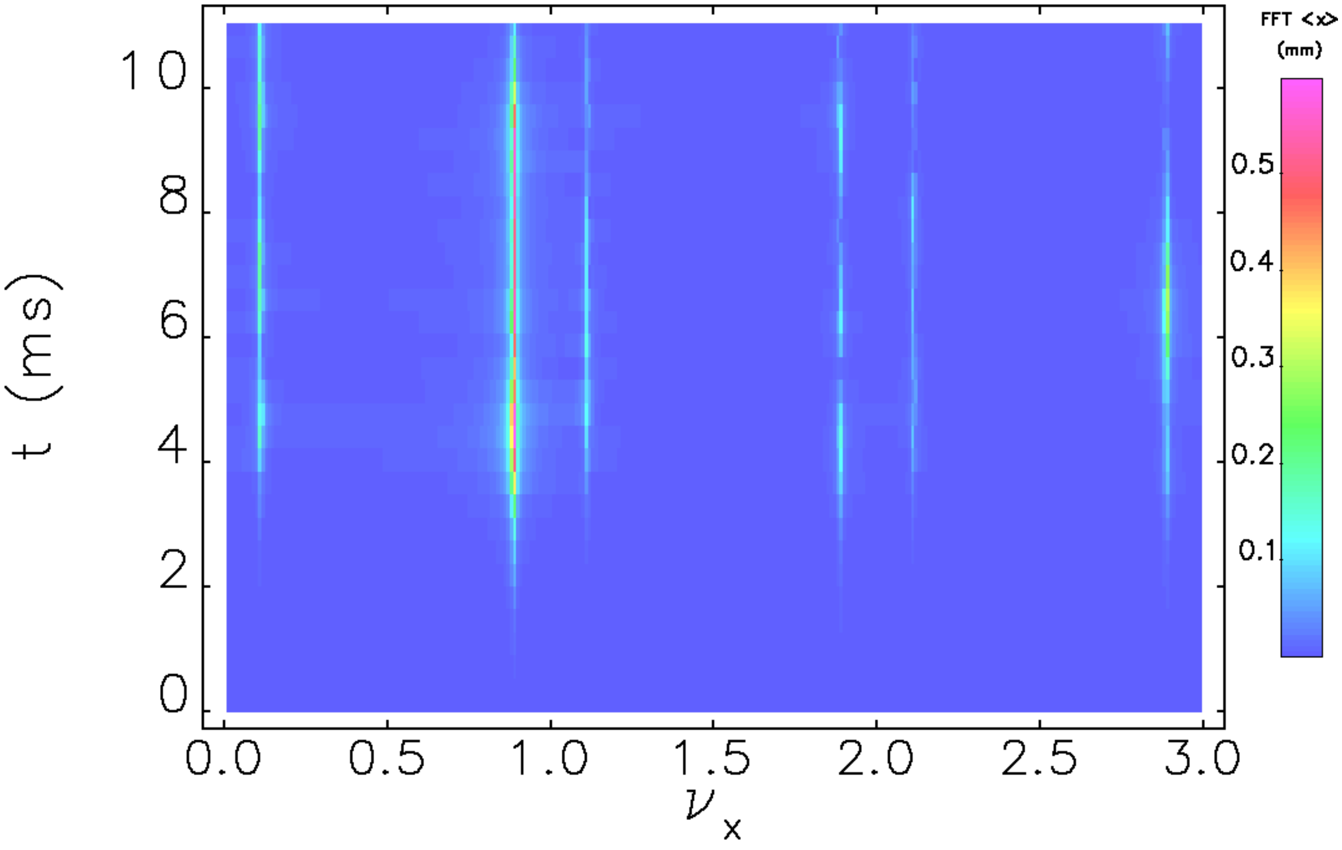


- With TFB limited at 1 nrad pk, see unexpected instability in horizontal plane
- Without *any* TFB, beam is unstable even before getting pinged
- Anticipated that chromaticity would suppress this

100 micron x and y ping
0.1% energy ping

For clarity, data for only 6 of 48 bunches show.

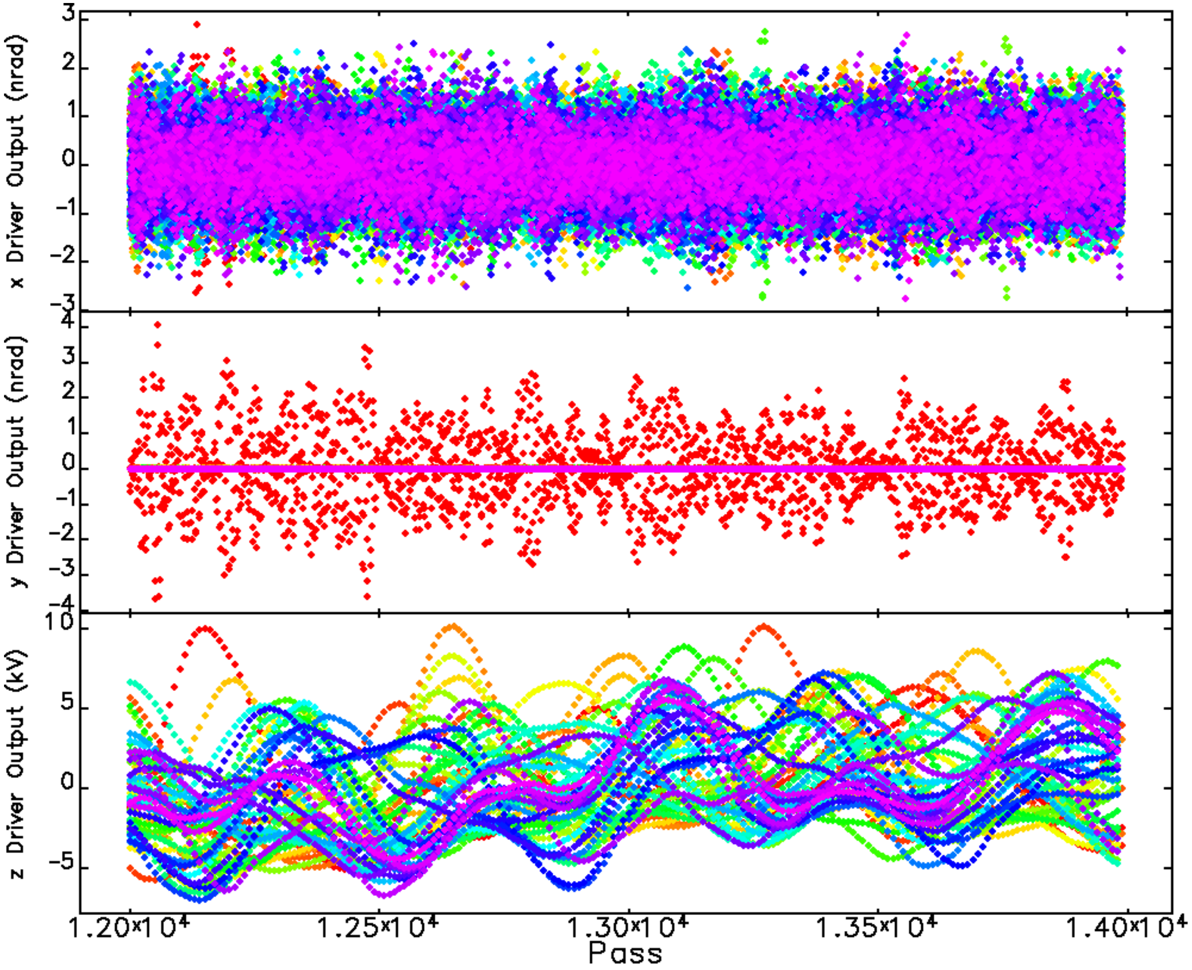
# Long-range resistive wall instability



- Bunch motion shows growing line at 1-$\nu_x$
- Characteristic of long-range RW instability[1]
- Instability absent if long-range RW wake removed from simulation
- Conclusion: TFB not optional, unlike APS today

[1] F. Sacherer, 9th Conf. On High Energy Accel., 347 (1974).

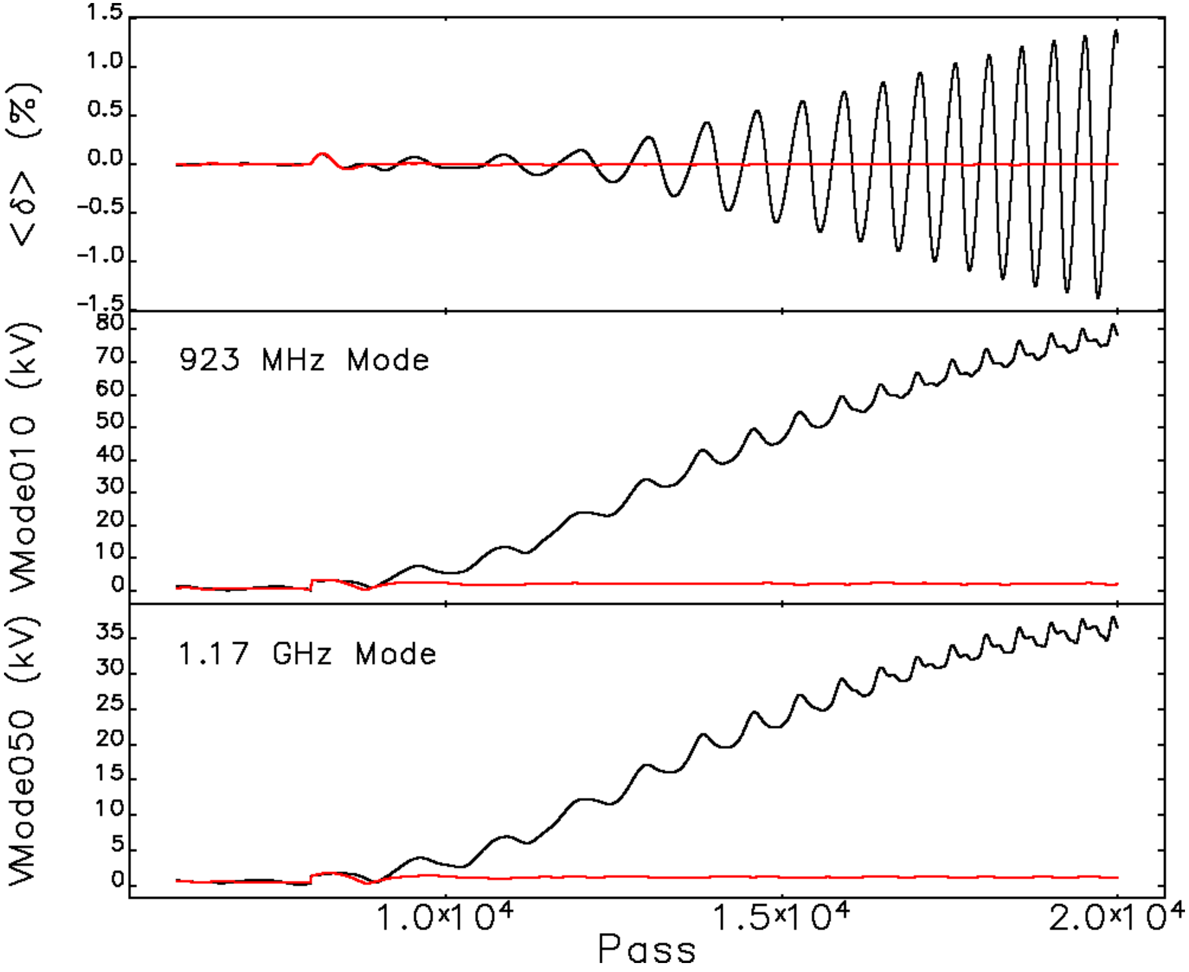
# Feedback effort for quiet conditions



- 3-4 nrad TFB effort sufficient to maintain stability

- 10kV longitudinal feedback effort is significant
- For undisturbed beam, can “cap” at 1.8 kV without loss of stability

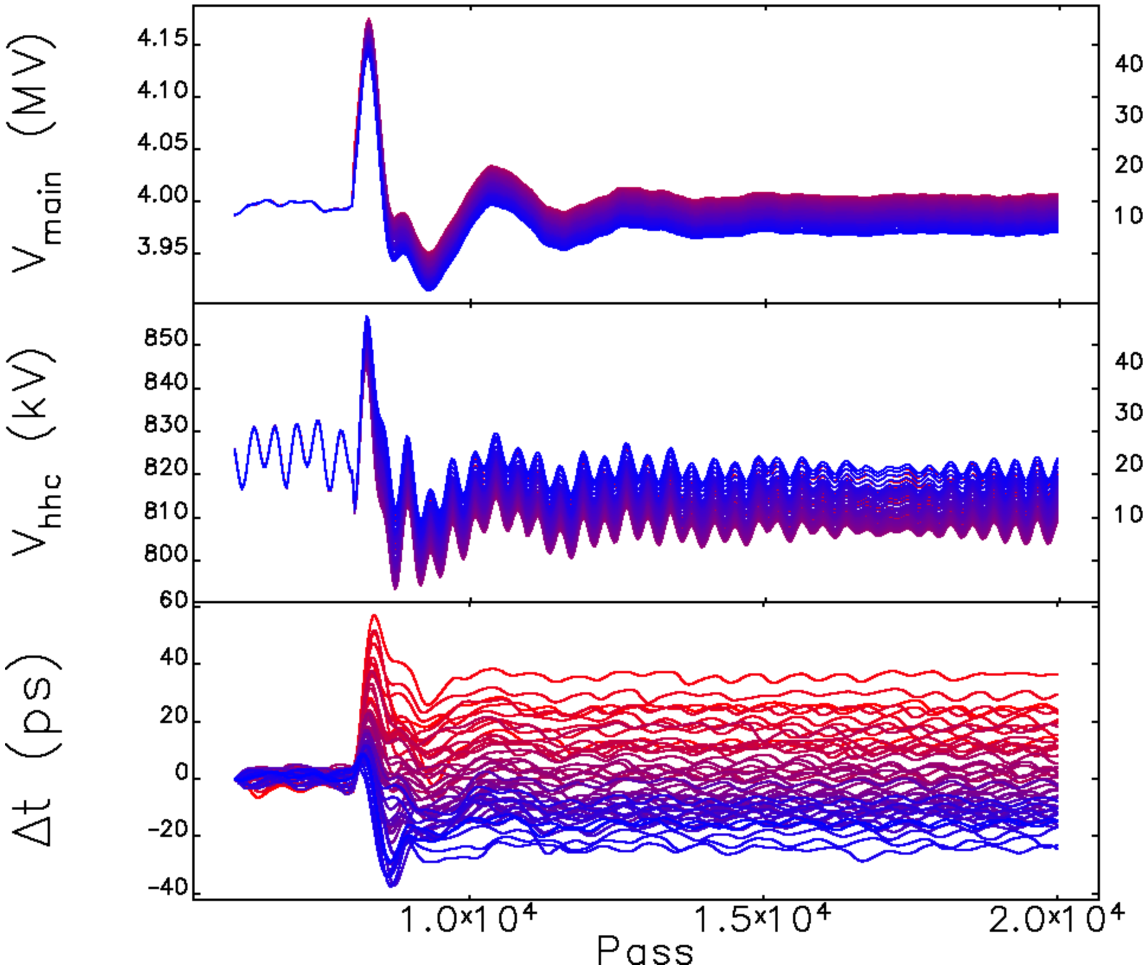
# 2: Impact of a lost bunch (failed swap-out)



Black: 1.8 kV LFB cap
Red: 6 kV LFB cap

- Swap-out uses very fast kickers to extract one bunch and inject a replacement
- What if replacement fails to arrive?
- Simulated using a kicker to kill one bunch after equilibriation
- Without adequate longitudinal feedback strength, beam is lost
- Suspect involvement of two monopole HOMs
- This gives more realistic estimate of required LFB strength

# Variation in voltage and bunch phase

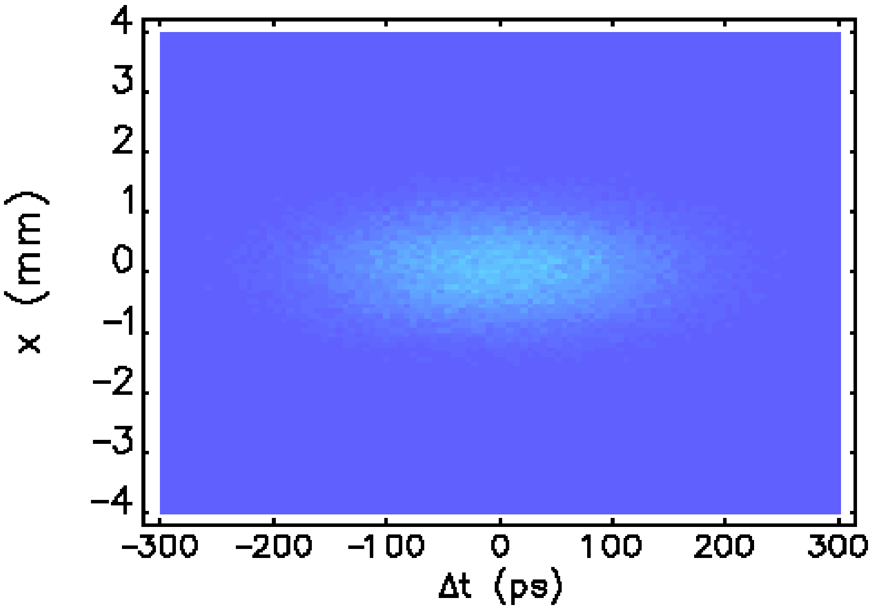


- Gap in bunch train results in sawtooth voltage variation in main rf cavities
- Also get variation in HHC voltage
- Bunches slew in time due to sawtooth voltage variation

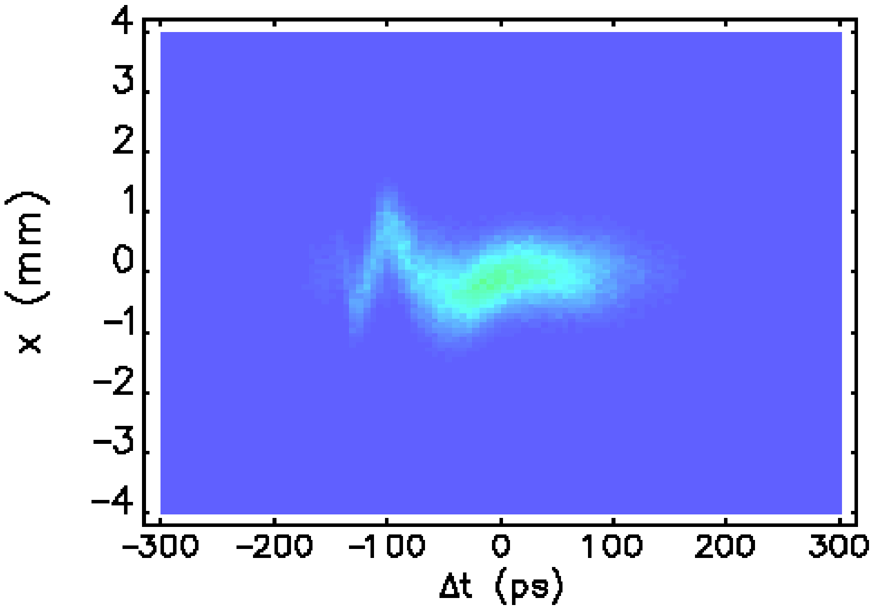
# 3: Filling from zero

- We must inject one full-current bunch into each target bucket
- Simulated this using a “balanced” fill order
  - Intended to reduce sawtooth variation of rf voltage
- Simulations inject one bunch every 5000 turns or 18 ms
  - Interval is far shorter than in reality
  - More than a damping time in horizontal, longitudinal planes
  - About the same as the rf feedback response time
- This simulation relies on **`elegant`**'s SCRIPT element
  - Allows arbitrary modification of a beam with an external program/script
  - In this case, the “modification” is to add a bunch

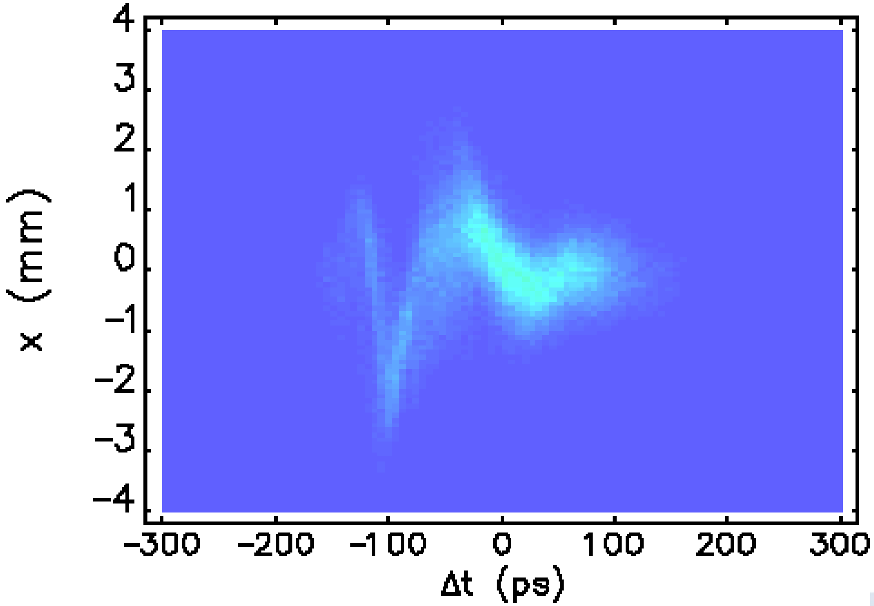
# Head-tail instability for the first bunch



Turn 0 15.344 nC



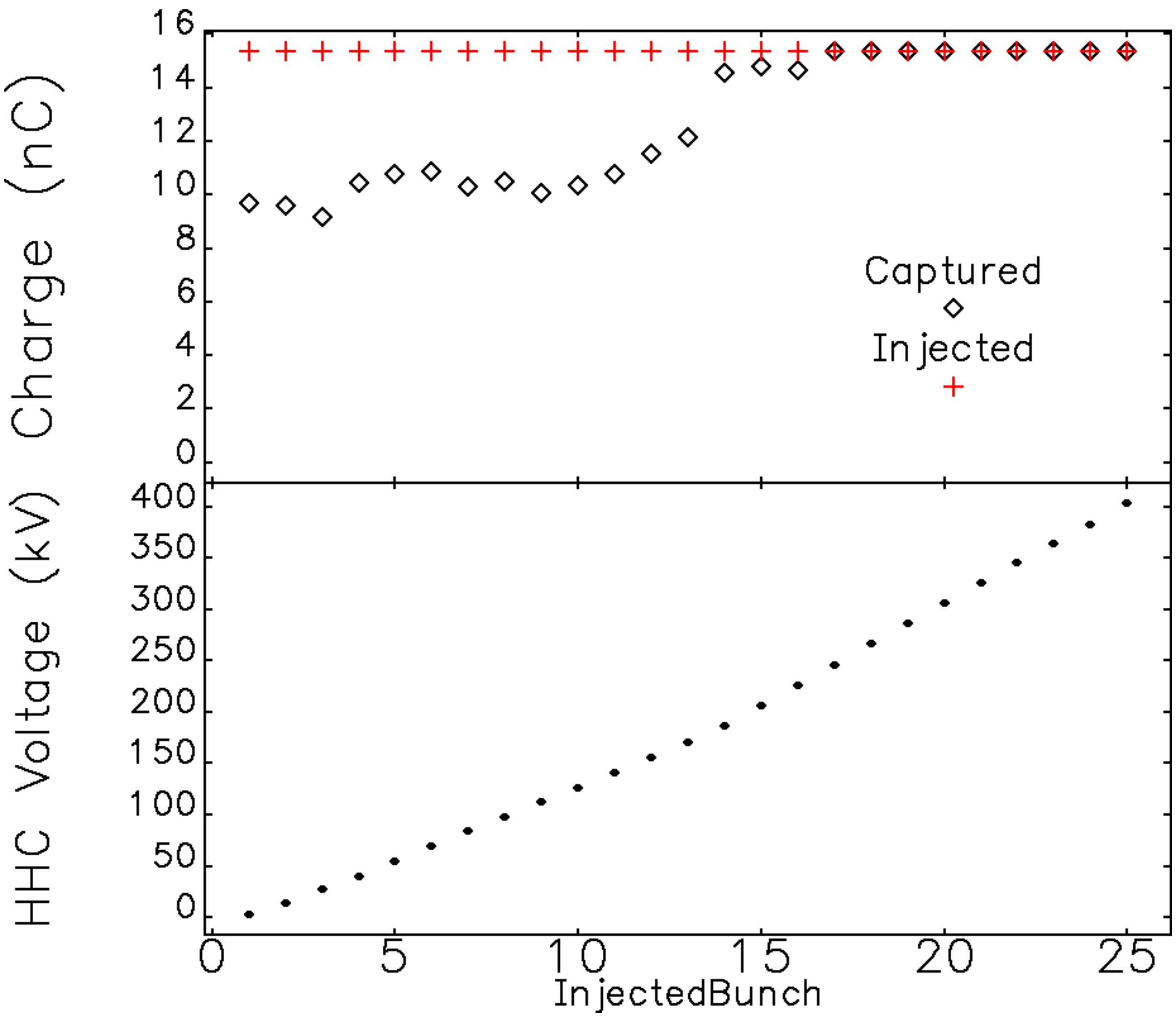
Turn 2250 15.344 nC



Turn 2475 15.344 nC

- Beam is eventually scraped on the horizontal physical aperture (±10mm assumed)
- TFB is not effective at suppressing this instability
  - Needs further study, optimization

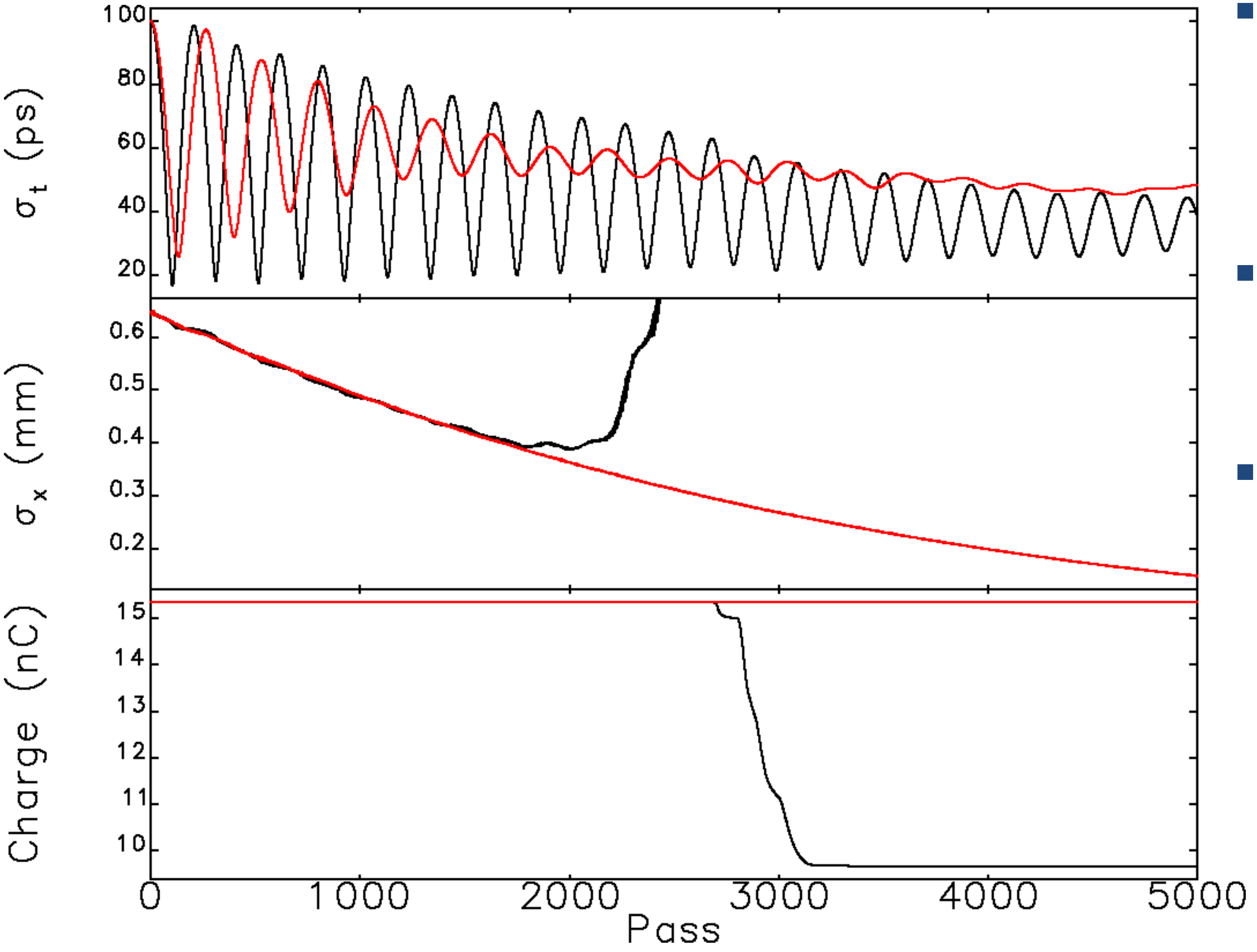
# Capture Improves as HHC Voltage Builds



- First 13 bunches injected suffer significant losses
- Later bunches are captured with 100% efficiency
- This corresponds to build-up in the voltage in the passive harmonic cavity

M. Borland et al., TWIICE 2, Feb. 2016

# HHC Reduces Bunch-Length Oscillations



- As HHC voltage builds, bunch length oscillates less, settles to longer value
- Effects of high-frequency horizontal impedance reduced
- Multi-stage swap-out will help, e.g.,
  - Inject 48, 5nC bunches
  - Replace with 10nC bunches
  - Finally replace with 15nC bunches

Black: bunch 1 (bucket 0); initial HHC voltage: 0

Red: bunch 23 (bucket 621); initial HHC voltage: 400kV

# Conclusions

- Simulation of collective effects for APS upgrade well advanced
  - Single-particle dynamics include higher-order chromaticity and momentum compaction
  - Multi-bunch, multi-particle per bunch tracking
  - Short- and long-range resonant and non-resonant impedances
  - Beam and rf feedback systems
- Simulated operational scenarios for 48-bunch mode, including
  - Stored beam with a small imposed disturbance
  - Stored beam with swap-out fault
  - Filling from zero
- Findings
  - Modest transverse feedback is required
  - Longitudinal MBI suppression requires strong feedback
  - Filling from zero with passive HHC presents some problems
    - Multi-stage swap-out should resolve this
    - Better tuning of transverse feedback may help