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

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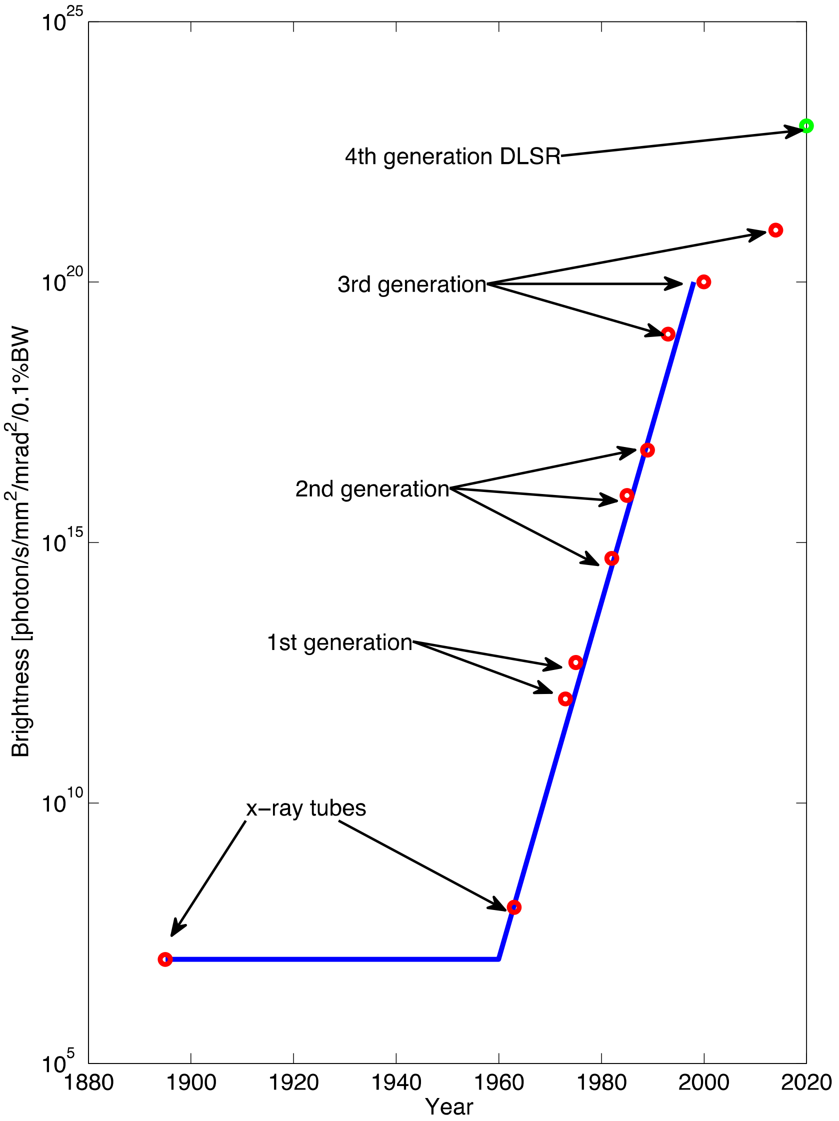
Outline

- APS upgrade ("APS-U") overview
- APS-U requirements
- Review of storage ring collective effects
- Modeling methods
- Review of predictions for single-bunch instabilities
- Results for multi-particle, multi-bunch simulations
  - Stability for uniform fills
  - Stability for non-uniform fills
  - Stability under loss of a bunch
  - Instabilities while filling the ring
- Plans and conclusions

Next-Generation Storage Ring X-Ray Sources

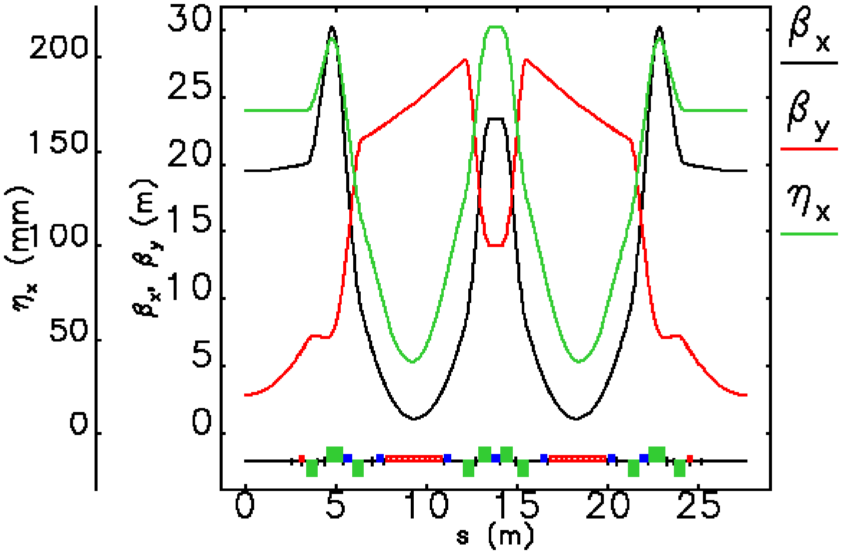
- High-brightness "4th generation" rings under development world-wide[1,2,3,4,5]
- Require very strong magnets with small bores
- Vacuum bore R much smaller
- Geometric and resistive wakefields scale like $1/R^2$ to $1/R^3$
- Collective instabilities in 4GSRs must be carefully modeled and solutions anticipated

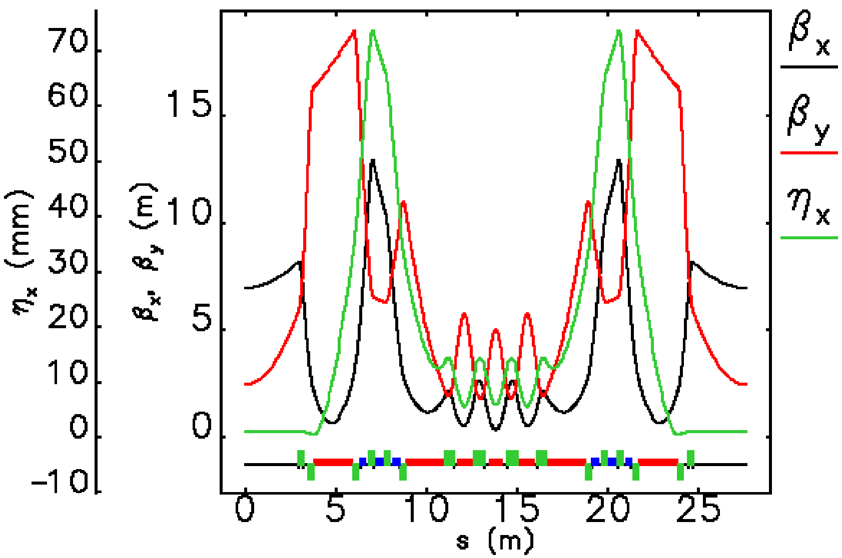


Courtesy C. Steier, ALS.

1: S. Leemann *et al.*, PRSTAB 12, 120701 (2009).
2: L. Liu et al., IPAC14, 191 (2014).
3: C. Steier, SRN 27, 19 (2014).
4: L. Farvacque *et al.*, IPAC13, 79 (2013).
5: G. Decker, SRN 27, 13 (2014).

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





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

	APS	MBA	
Betatron motion			
ν_x	36.205	95.125	
ν_y	19.272	36.122	
$\xi_{x,nat}$	-90.340	-138.580	
$\xi_{y,nat}$	-43.319	-108.477	
Lattice functions			
Maximum β_x	30.2	12.9	m
Maximum β_y	27.8	18.9	m
Maximum η_x	0.216	0.074	m
Average β_x	13.2	4.2	m
Average β_y	15.9	7.8	m
Average η_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			
β_x	19.5	7.0	m
η_x	171.88	1.11	mm
β_y	2.9	2.4	m
$\epsilon_{x,eff}$	3142.7	67.0	pm
Miscellaneous parameters			
Momentum compaction	2.84×10^{-4}	5.66×10^{-5}	
Damping partition J_x	1.00	1.61	
Damping partition J_y	1.00	1.00	
Damping partition J_δ	2.00	1.39	

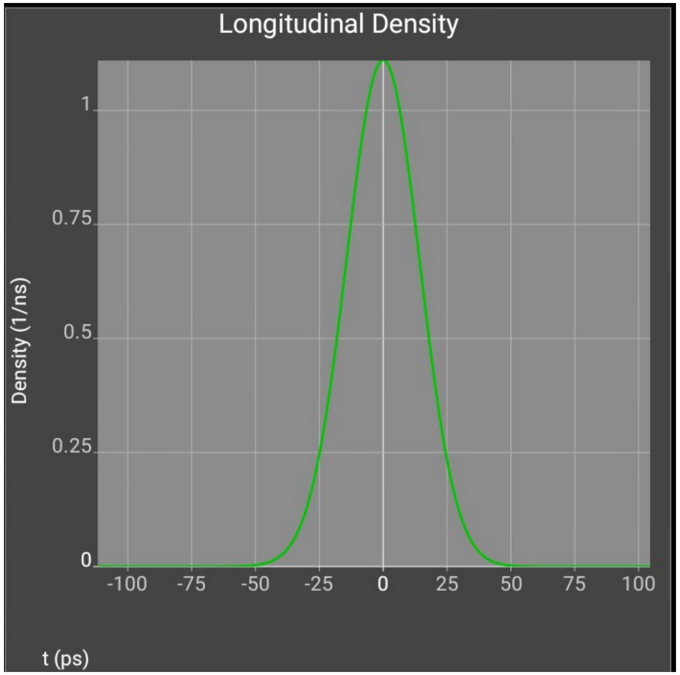
1: D. Einfeld et al., SPIES 2013, 201 (1993).
2: M. Borland et al., IPAC15, 1776 (2015).

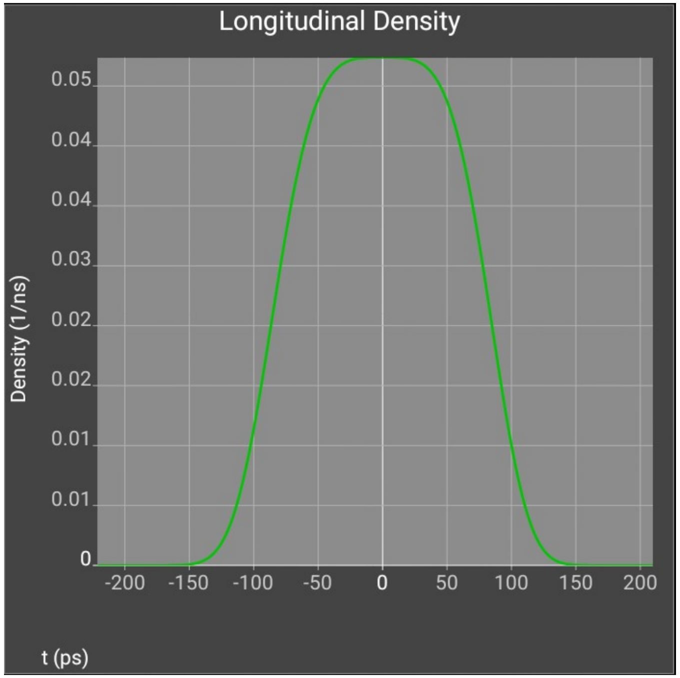
Planned APS-U operating modes

- Single-bunch on-axis swap-out injection
  - Each bucket is filled by a single shot from the injector
  - Accommodates small aperture, unusual insertion devices
  - Implies injection of 15 nC (4.2 mA) bunches
- Targeting 200 mA in various fill patterns
  - 324-bunch uniform
    - Desirable for long lifetime and highest brightness
    - Limit of present fast kicker technology
  - 48-bunch uniform
    - Desirable for timing experiments
  - Possible hybrid or non-uniform modes under study

Intrabeam scattering and Touschek lifetime

- Low emittance beams have high particle density in bunches, leading to
  - Emittance growth due to intrabeam scattering (IBS)
  - More rapid particle loss due to Touschek scattering
- Counter-measures
  - Many weak bunches
  - Running with "round beams," i.e., $\kappa=\varepsilon_y/\varepsilon_x\approx 1$
  - <u>Bunch-lengthening using a higher harmonic cavity (HHC)</u>





Computations from TAPAs, tinyurl.com/borlandTAPAs

APS-U requirements drive modeling goals

- Requirement: single-bunch intensity limit >4.2 mA
  - Modeling must specify required chromaticity
  - Modeling must assess microwave instability
  - Modeling must guide vacuum system design, choice of materials
- Requirement: multi-bunch instabilities absent or controlled by feedback
  - Modeling must specify feedback requirements
  - Modeling must guide choices related to cavity HOM damping, may impact choice of materials
- Requirement: Flexibility, reliability, and fault tolerance
  - Modeling must assess robustness of operating modes
  - Modeling must assess impact of likely faults
- Requirement: bunch lengthening to mitigate scattering
  - Modeling must predict bunch distributions with passive HHC
  - Modeling must determine impact of HHC on instabilities

Review of impedances & wakefields in electron storage rings

- Impedances/wakefields characterize how electrons interact with each others' electromagnetic fields in the ring
  - Geometric wakefields are generated by changes in the vacuum chamber cross section
  - Resistive wall wakefield is due to the finite conductivity of chamber walls
- Resonances (e.g. HOMs) are a special case of geometric wakefields

	Longitudinal	Transverse
Effects due to short-term wakefields	Heating of vacuum chamber Bunch lengthening Microwave instability	Source of orbit change Tune shift Transverse instabilities
Effects due to long-term wakefields	Heating of cavities Multi-bunch instability	Heating of cavities Multi-bunch instability
Most worrisome effect(s)	Single bunch rf heating Multi-bunch stability	Single bunch stability at 4.2 mA

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]
  - All features described are in the present release
- Post-processing and visualization
  - SDDS[6]
  - ImageMagick

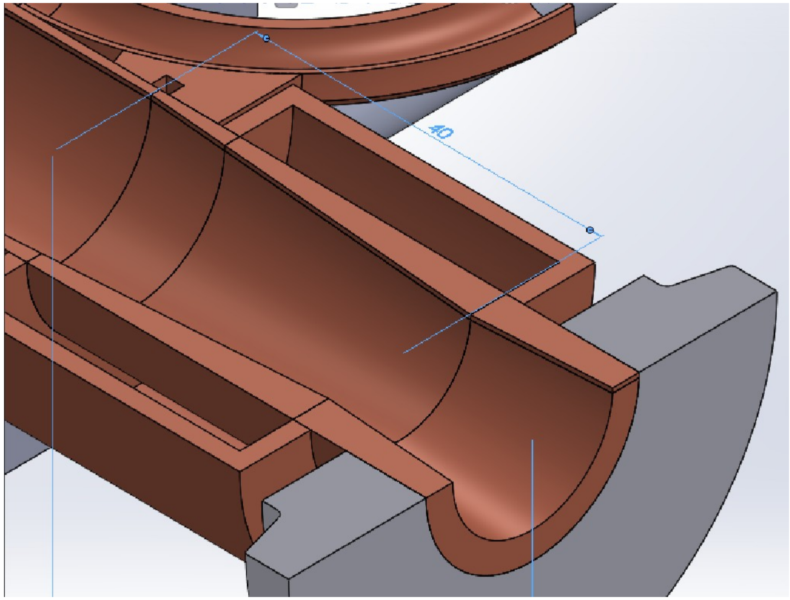
1: W. Bruns, Linac 2002, 418.
2: I. A. Zagorodnov et al. PRSTAB 8, 042001.
3: T. Weiland, NIM 216, 329 (1983).
4: Y. Wang et al., PAC07, 3456.
5: M. Borland et al., IPAC15, 549.
6: R. Soliday et al., PAC03, 3473.

Simulation of short-range wakes

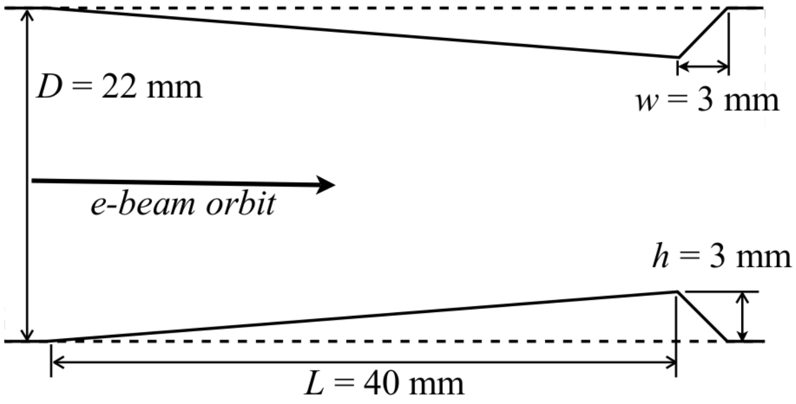
- Short-range wakes produce intra-bunch effects, e.g.,
  - Head-tail instability
  - Microwave instability
- APS-U simulations include
  - Resistive wakes from analytical expressions
    - Longitudinal monopole wake
    - Transverse dipole wakes
  - Geometric wake potentials
    - Longitudinal wake
    - 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

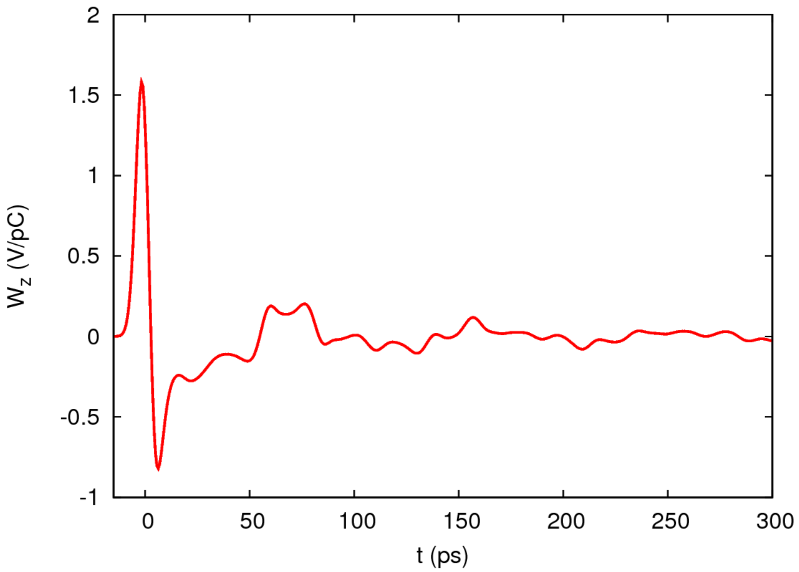
Example of a short-range wake (ECHO)

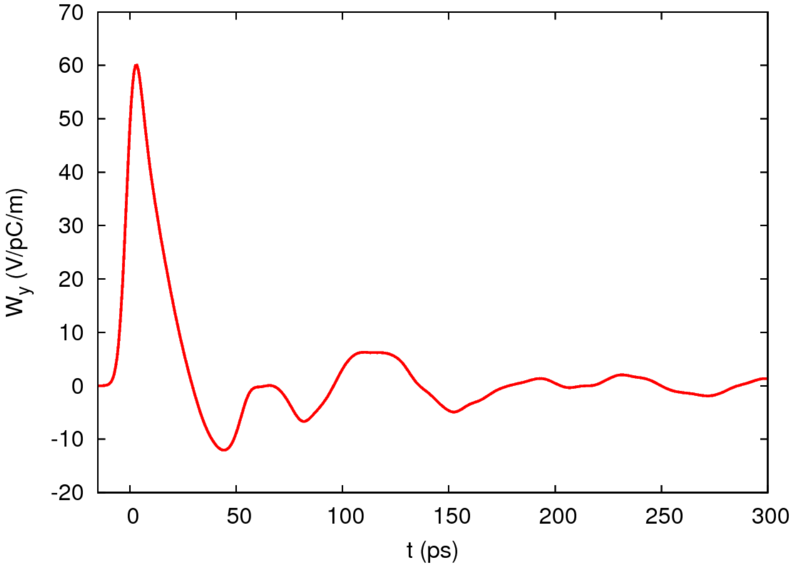
CAD model of flange absorber



ECHO model for wakefield calculations







APS-Upgrade short-range impedance model

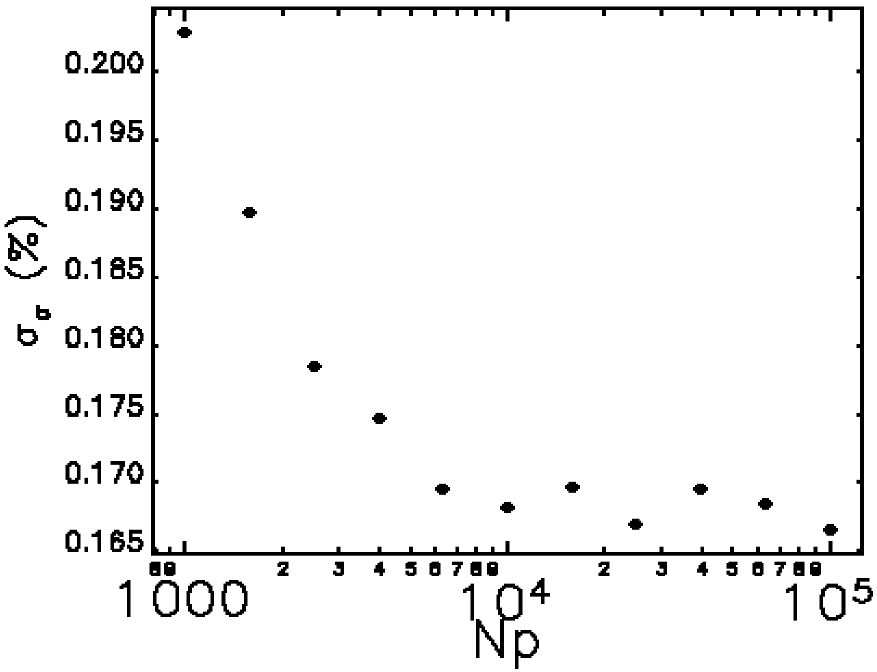
- Total wakefield/impedance found by summing over all contributions weighted by the local beta function
- Single-bunch tracking can be used to assess
  - Microwave instability
  - Single bunch intensity limit

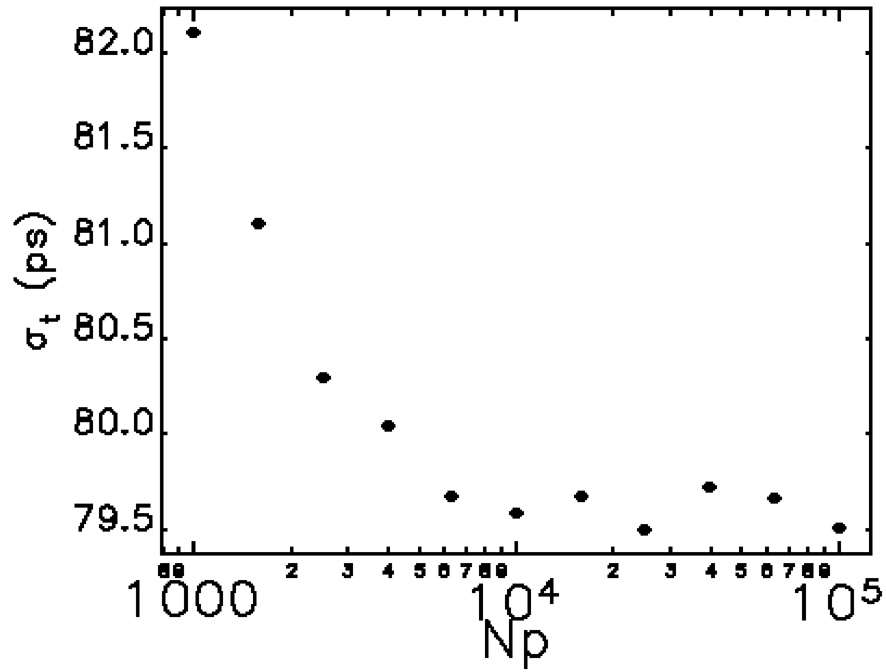
Impedance elements used in model

Resistive wall			Geometric contributions			
			Sector ($\times 40$)		Ring	
Metal	**Diameter**	**Length**	**Element**	**Number**	**Element**	**Number**
Cu	22 mm	224 m	Regular BPM	12	Injection kicker	4
Al	22 mm	605 m	ID BPM	2	Extraction kicker	4
SS	22 mm	80 m	ID transition	1	Feedback	2
Al	6 mm	50 m	Bellow	14	Stripline	1
Al	6×20 mm	125 m	Flange	52	Aperture	2
Al	140 mm	20 m	Crotch absorber	2	Fundamental cavity	12
			In-line absorber	12	Rf transition	4
			Gate valve	4	4^{th} harmonic cavity	1

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

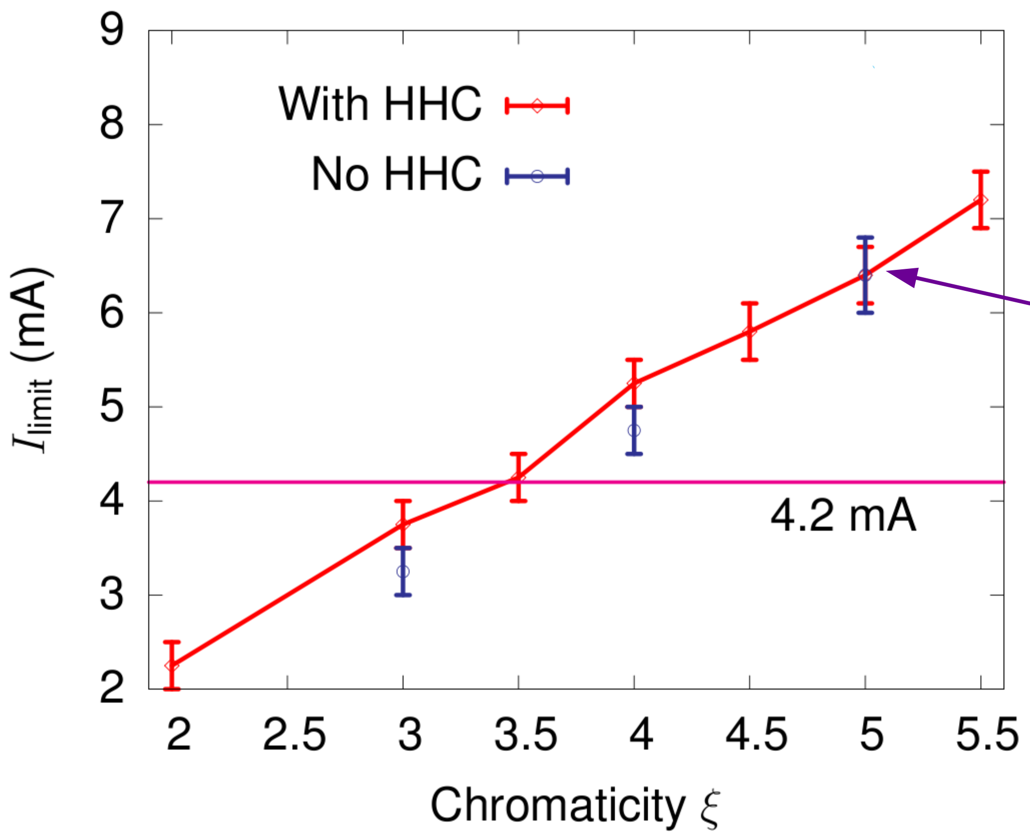
Microwave instability simulation convergence





- Studied convergence for 48 bunches
- ~10k particles per bunch are needed for stable results
  - With 48 bunches, at least 0.5 M particles total
- Implications for subsequent computations
  - Must track 20k-30k turns to assess stability
  - Upwards of 10^{10} particle-turns per simulation
  - Strongly motivates use of lumped-element modeling

Single bunch current limit predicted to be safely above 4.2 mA



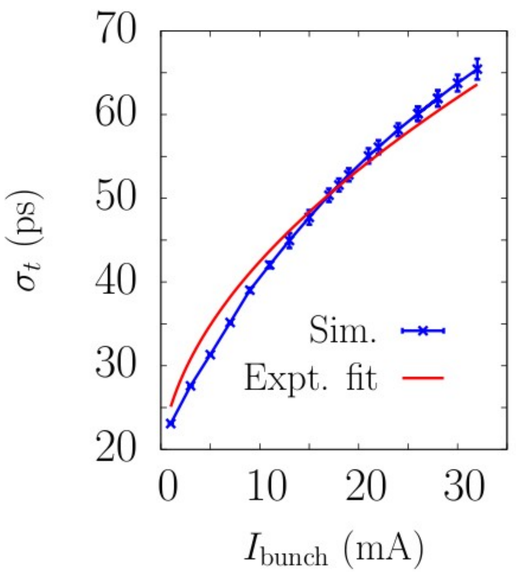
Planned operating point with $\xi = 5$: $I_{limit} = 6.2$ mA

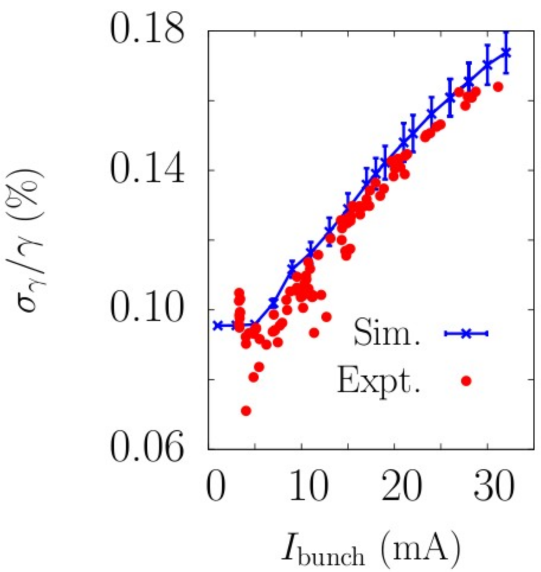
- Higher-harmonic cavity (HHC) increases limit by ~0.5 mA if $\xi \leq 4$
- At higher chromaticity, the limit is dominated by losses at injection

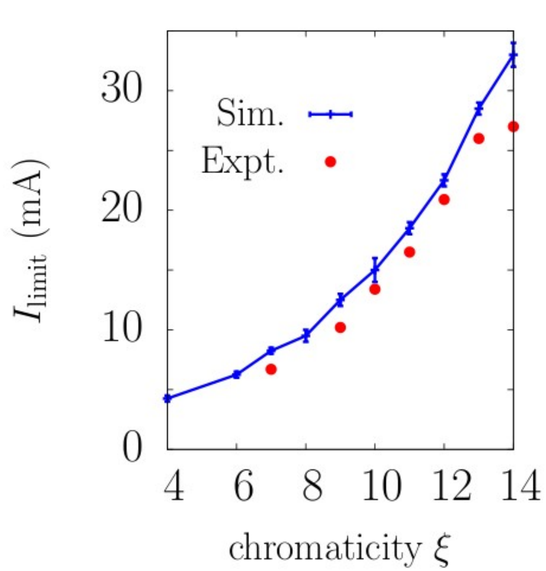
R. Lindberg et al., IPAC15, 1823-1825.

Bench-marking with present-day APS

- Modeling of single-bunch effects for existing ring uses the same approach
- Agreement with experiment is good[1]
- Several successful predictions of effects of changes
  - Reduced intensity limit after adding several ID chambers
  - Variation of intensity limit with beta function changes[2]





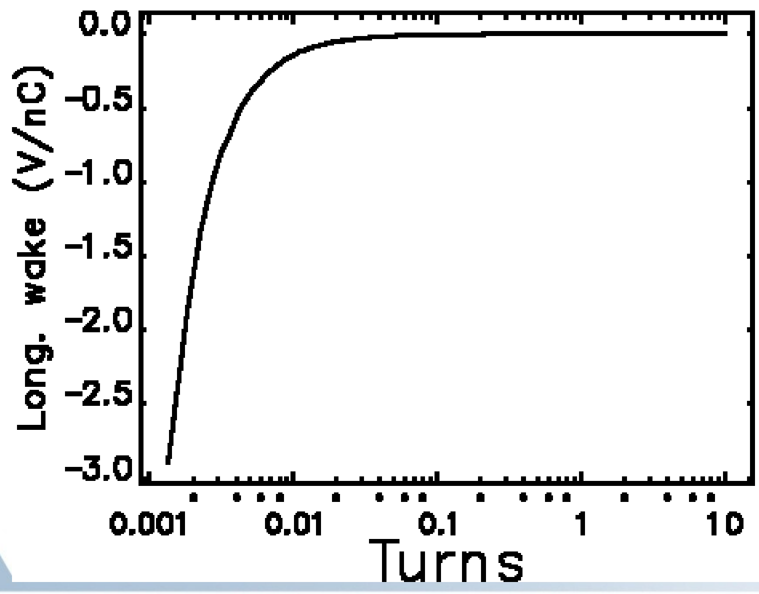


1: R. Lindberg et al., IPAC15, 1823.
2: V. Sajaev, PAC13, 405.

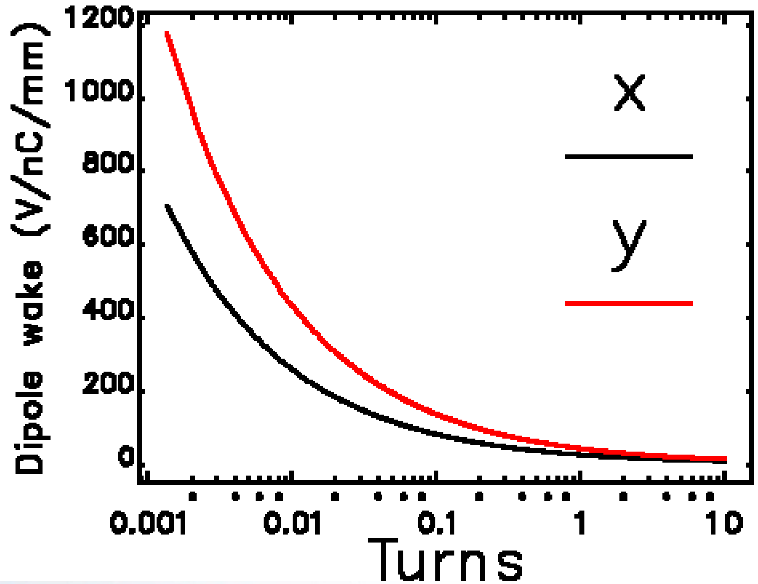
Long-range non-resonant wakes

- 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 wake and transverse dipole wakes

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



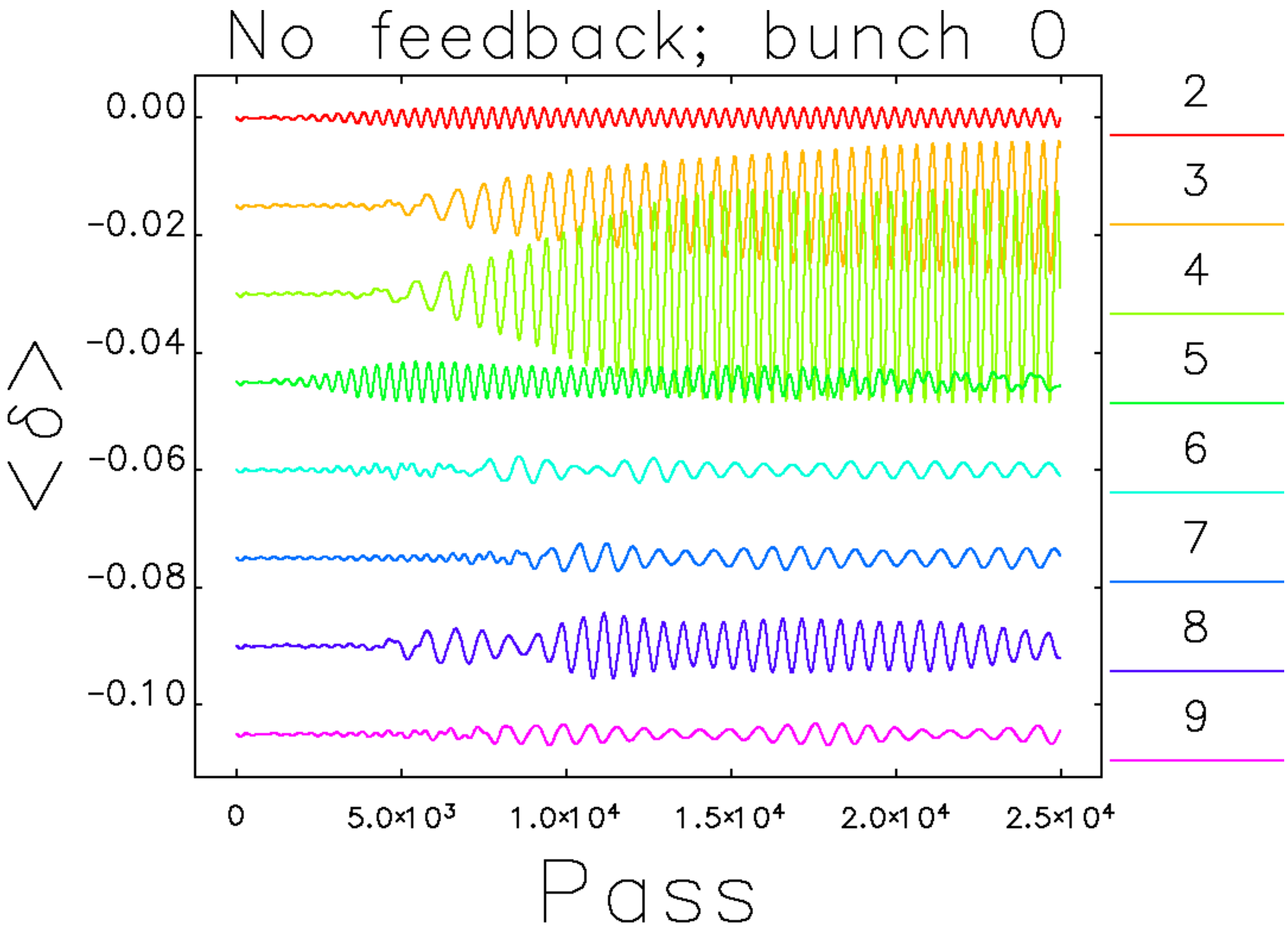
$$W_{y,D}(z) \approx \frac{cL\sqrt{\pi Z_0 \rho_{\rm res}}}{12b^3|z|^{1/2}}$$



Resonant wakes

- Resonances have both intra- and inter-bunch effects
- We include only cavity modes
  - 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 HHC (RFMODE)
  - 120 parasitic monopole modes in main cavities (FRFMODE)
  - 168 parasitic dipole modes in main cavities (FTRFMODE)
  - 12 beam-loaded, generator-driven main cavities with feedback

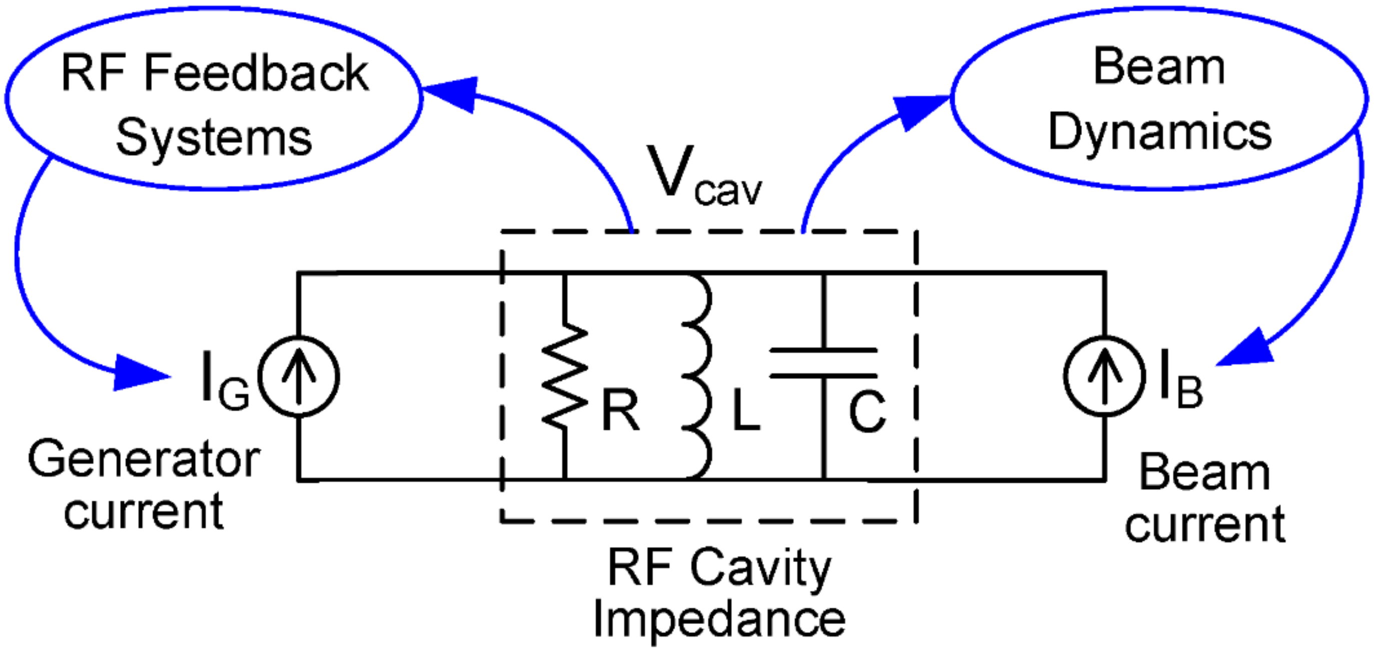
Monopole HOMs expected to drive longitudinal instability



- HOM frequencies not well known, so must study statistically.
- Curves show 8 possible cases (offset for clarity)
- Without feedback, longitudinal instability is likely
- Landau damping from HHC present, but doesn't resolve this.

L. Emery et al., IPAC2015, 1784-1786.

Coupling of Rf Feedback and Beam Dynamics[1]



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

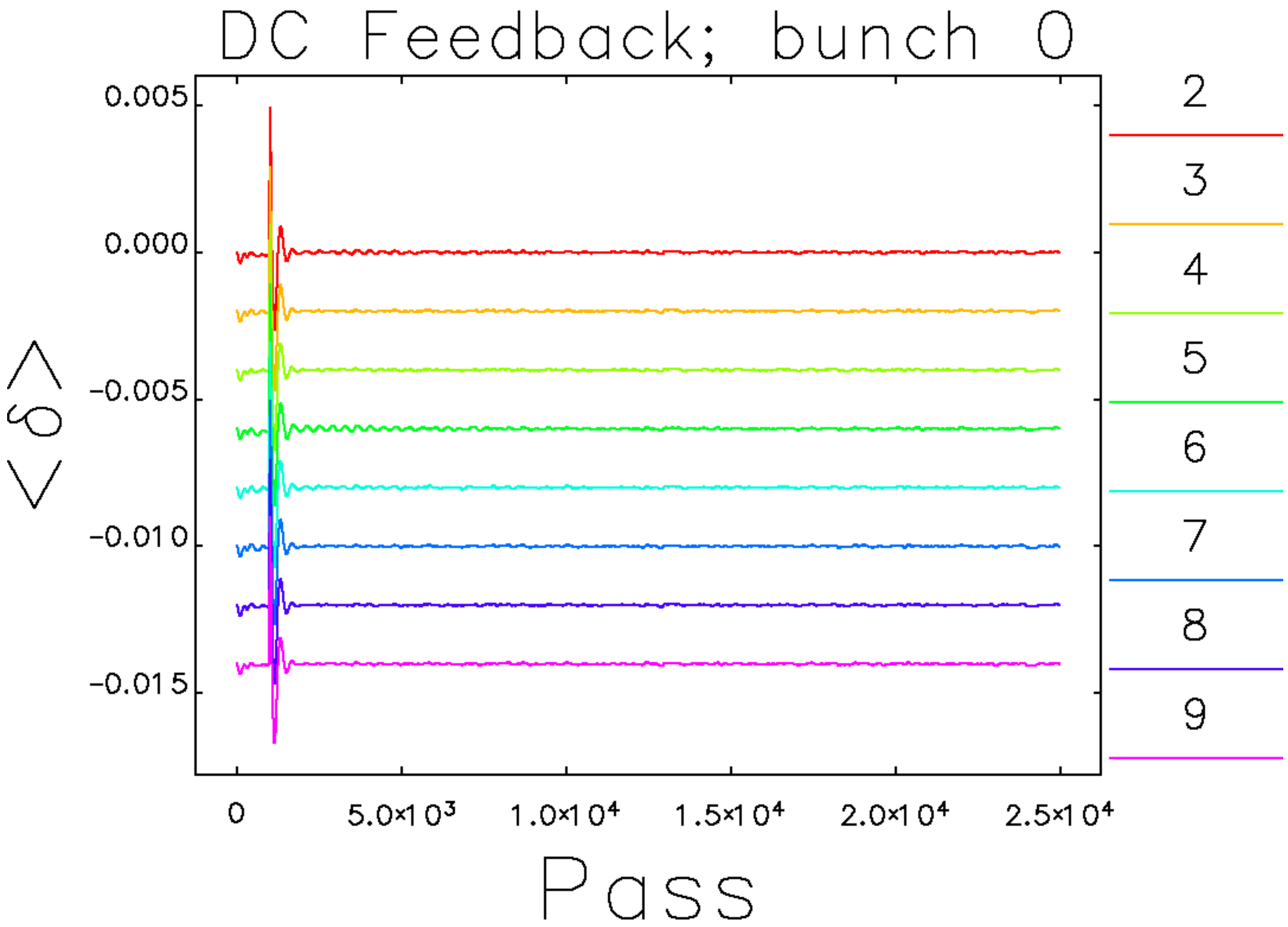
1: T. Berenc *et al.*, IPAC15, 540.

Other simulation components

- Bunch-by-bunch feedback
  - Longitudinal and transverse pickup and driver elements
  - TFBDRIVER computes kicks using FIR filter to process TFBPICKUP signals
- Beam transport
  - ILMATRIX used for single-element simulation of ring lattice
    - Includes chromaticity and nonlinear momentum compaction
  - SREFFECTS used for single-element simulation of synchrotron radiation damping and quantum excitation
- 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.

FIR feedback with DC gain gives stability



- Longitudinal bunch-by-bunch feedback can stabilize beam
- Must have gain at DC because of suppression of synchrotron tune by the HHC
- Not a typical configuration for longitudinal feedback

L. Emery et al., IPAC2015, 1784-1786.

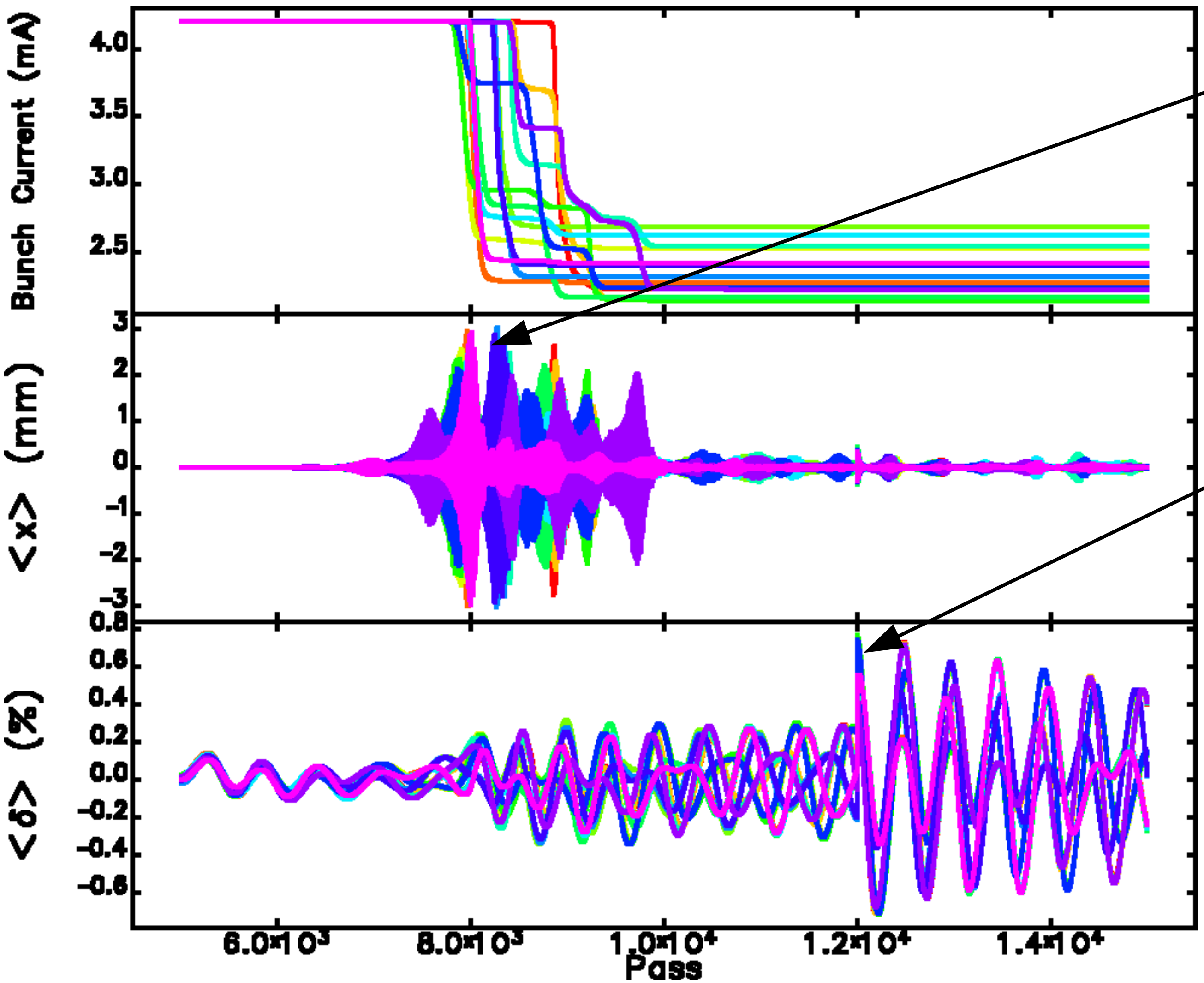
Simulations of operational scenarios

- We've simulated four operational scenarios
  1) Idealized, uniform 48-bunch fill
  2) 1+45 hybrid (or “camshaft”) fill
  3) Uniform 48 bunch fill after one bunch gets lost due to swap-out failure
  4) Filling the ring from zero
- Used typical set of “randomized” HOMs
  - Expect longitudinal instability if no feedback
  - Expect transverse stability even if no feedback
    - High coherent damping rate from chromaticity and short-range wake

1: 48-bunch uniform fill pattern

- Questions to answer
  - Is the beam stable without transverse feedback?
  - If not, what drives instability?
  - What are feedback requirements?
- "Quiet start" is important
  - Ramp simulated beam current from 0 to 200 mA in ~5000 turns
    - About 1 damping time
    - Sufficient time for rf feedback to respond
  - Wait ~7000 turns for full equilibriation
  - Give longitudinal and transverse kicks to the beam
    - Assess stability
    - Observe damping/growth rates

Horizontal instability w/o transverse feedback

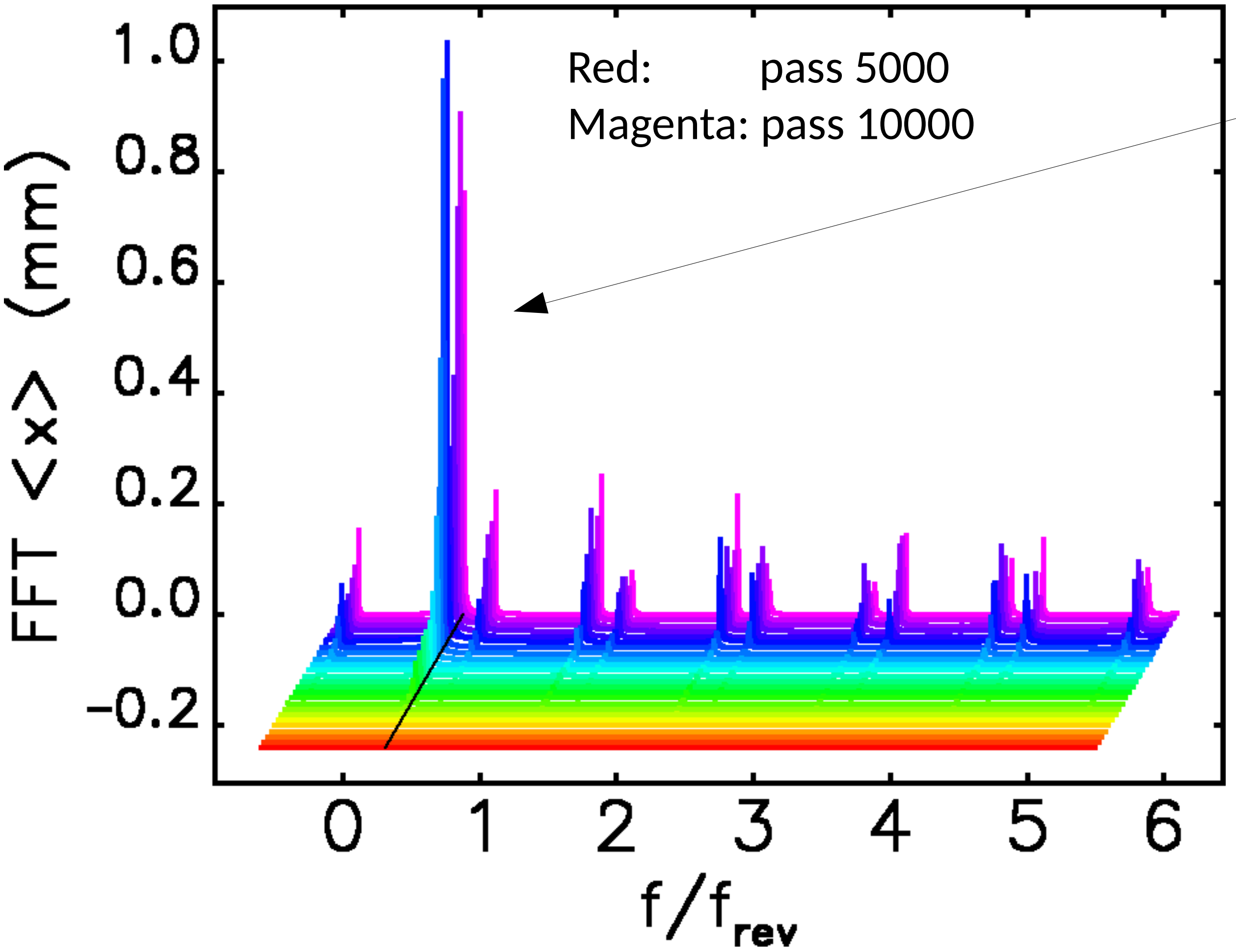


Colors show data for a selection of the 48 bunches

- See unexpected instability in horizontal plane
- Anticipated that chromaticity would suppress this
- Beam loss begins before the beam is kicked
  - Noise is sufficent to seed instability

Show movie #1

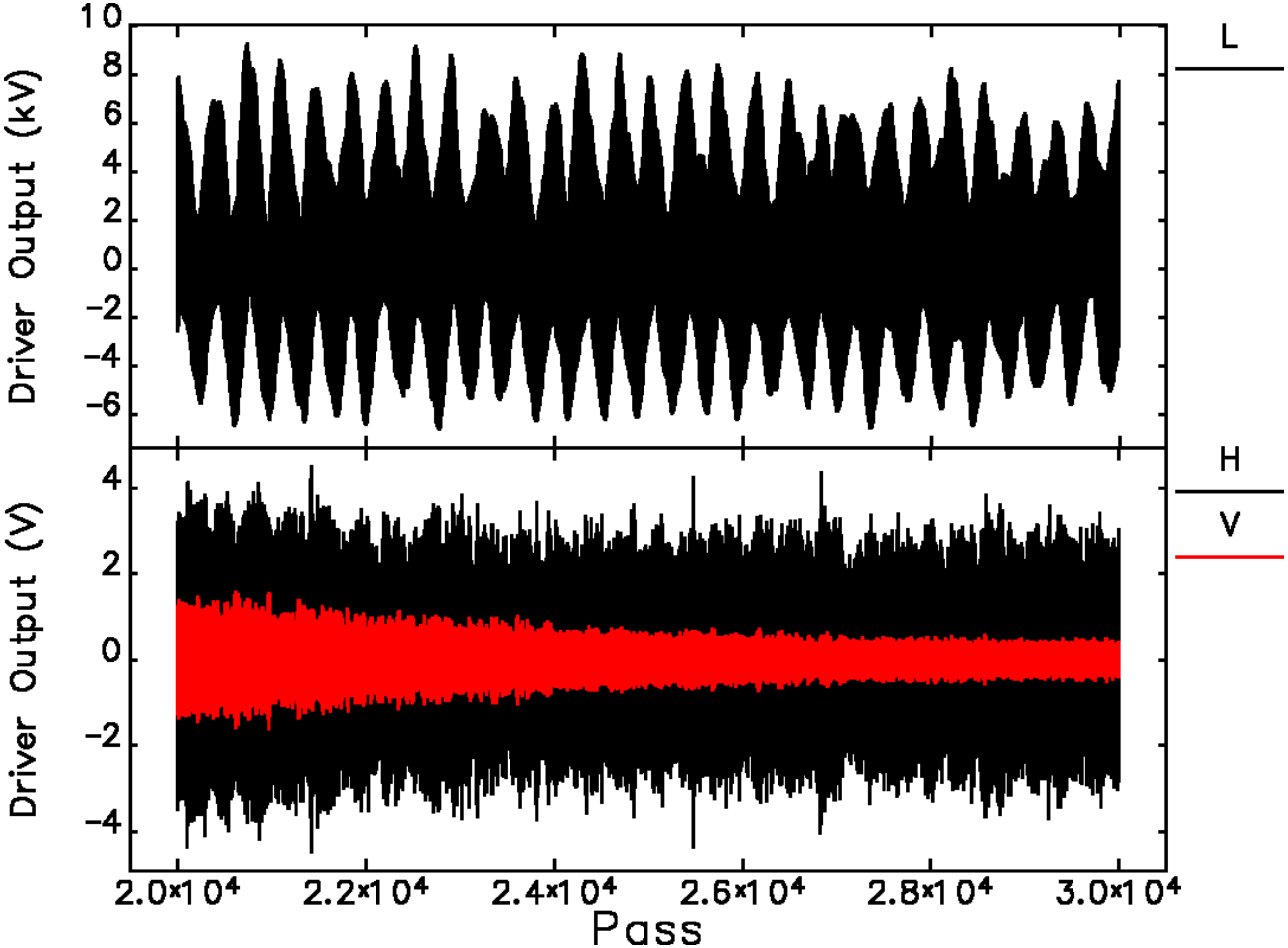
Long-range resistive wall instability



- FFT of bunch motion shows a line at $1-\nu_x$ that grows as instability builds
- Characteristic of long-range RW instability[1]
- Confirmed by absence of instability if this component is removed
- Conclusion: transverse feedback not optional, unlike APS today

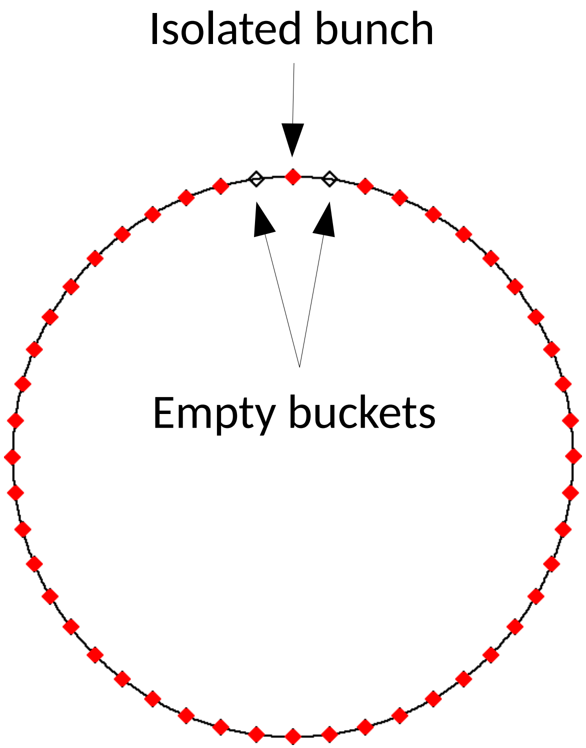
1: F. Sacherer, 9th Conf. On High Energy Accel., 347 (1974).

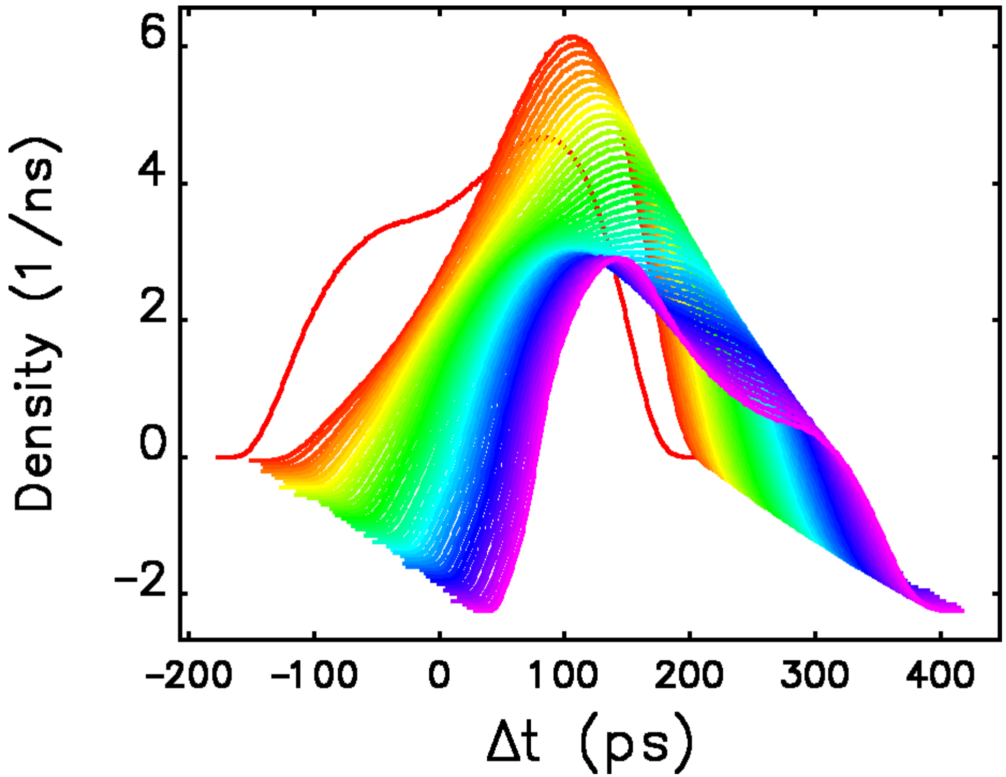
Feedback effort for quiet conditions



- 10kV longitudinal feedback effort is significant
- Can be "capped" to some degree
- Modest transverse feedback effort needed to suppress LRRW instability

2: Nonuniform fill mode: 1+45

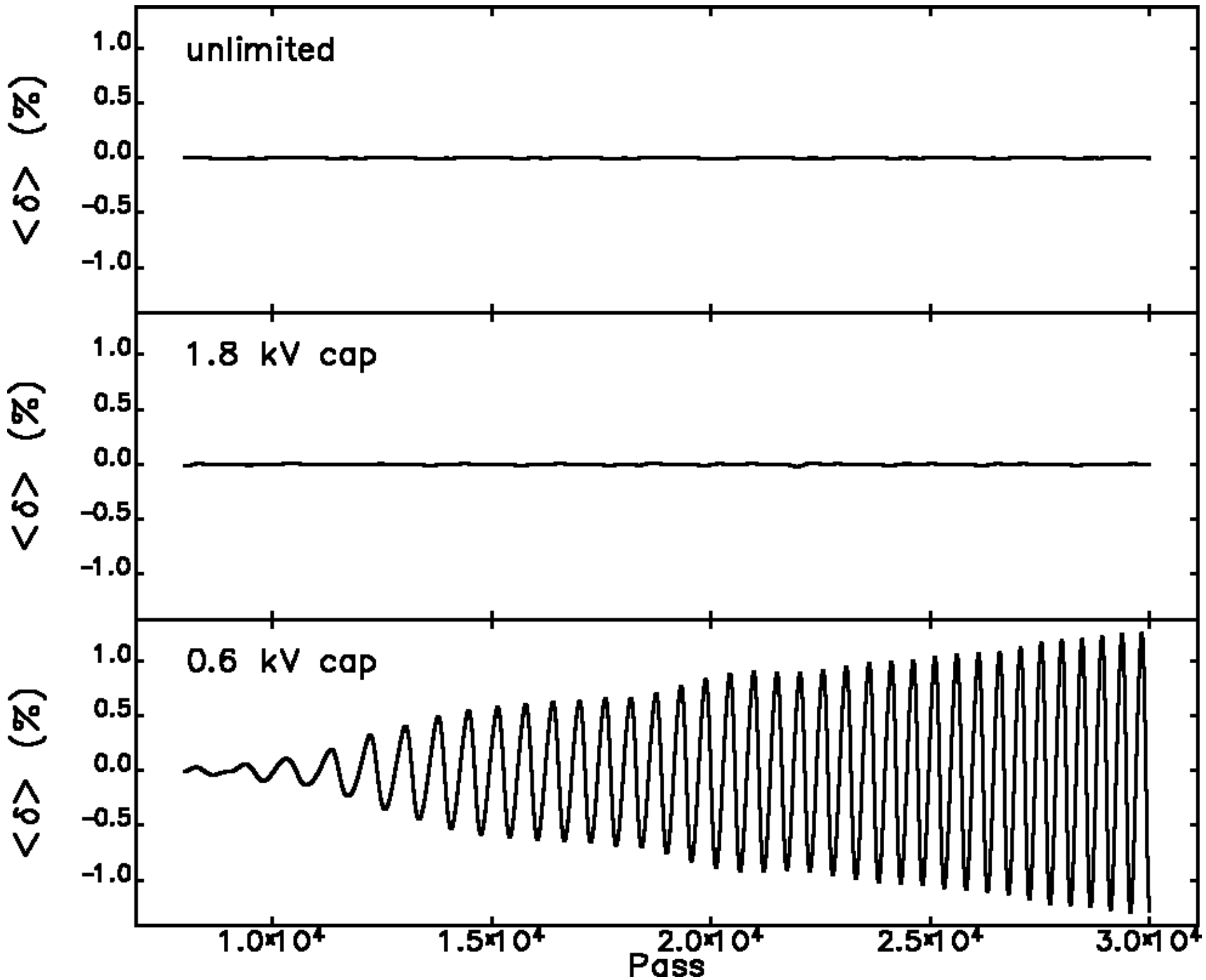




- Predict main rf voltage transient
  - ~8 μs filling time of main cavities coupled with slow rf feedback
- Bunches slew in phase
  - Considerable variation in bunch shape
  - HHC voltage is reduced

Can limit LFB effort to some degree

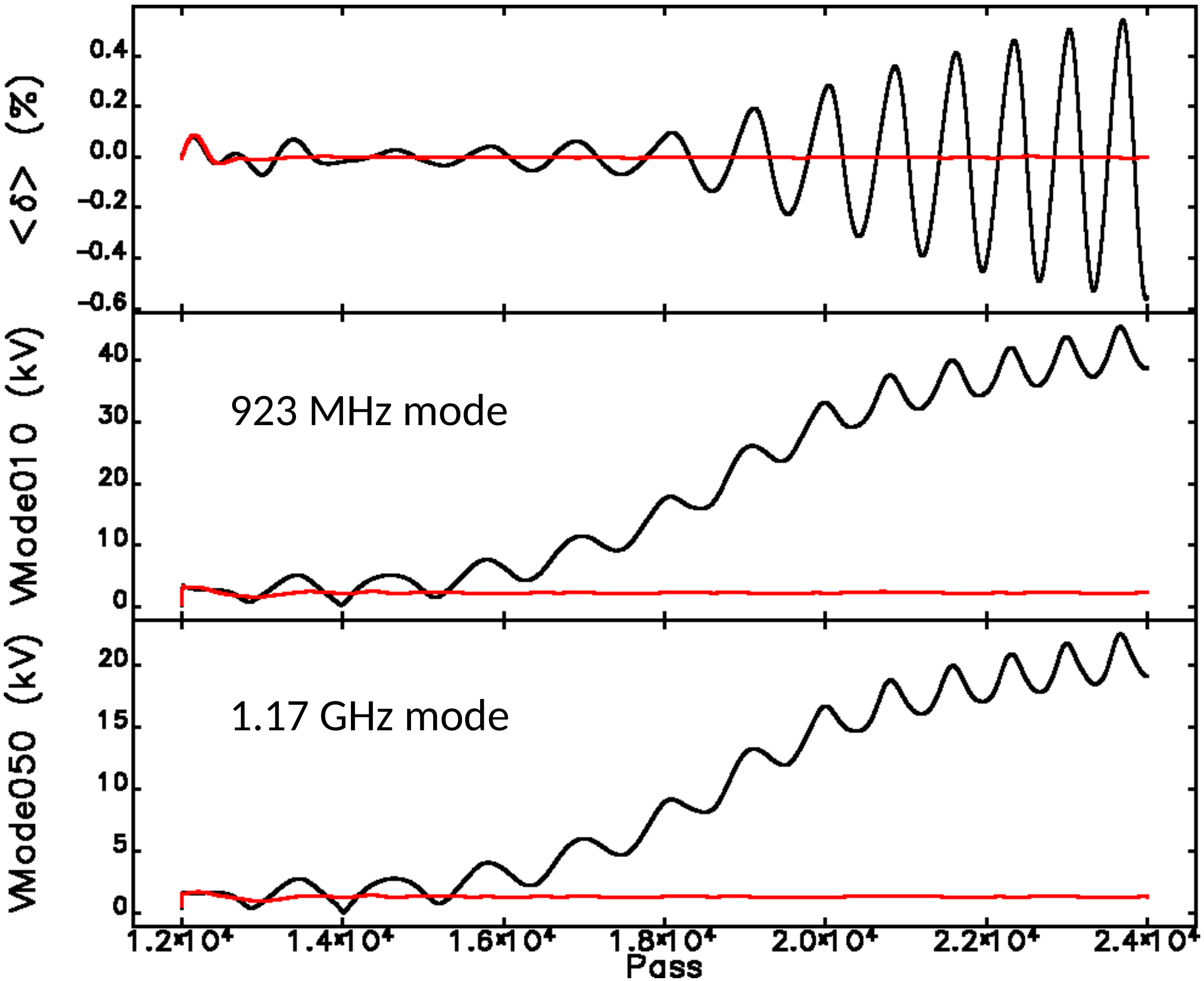
Results for 1+45 mode



- ELEGANT can "cap" the feedback effort to simulate amplifier limitations
- A 1.8 kV cap is consistent with stability
- 0.6 kV is adequate for 48U

M. Borland et al., IPAC2015, 543-545.

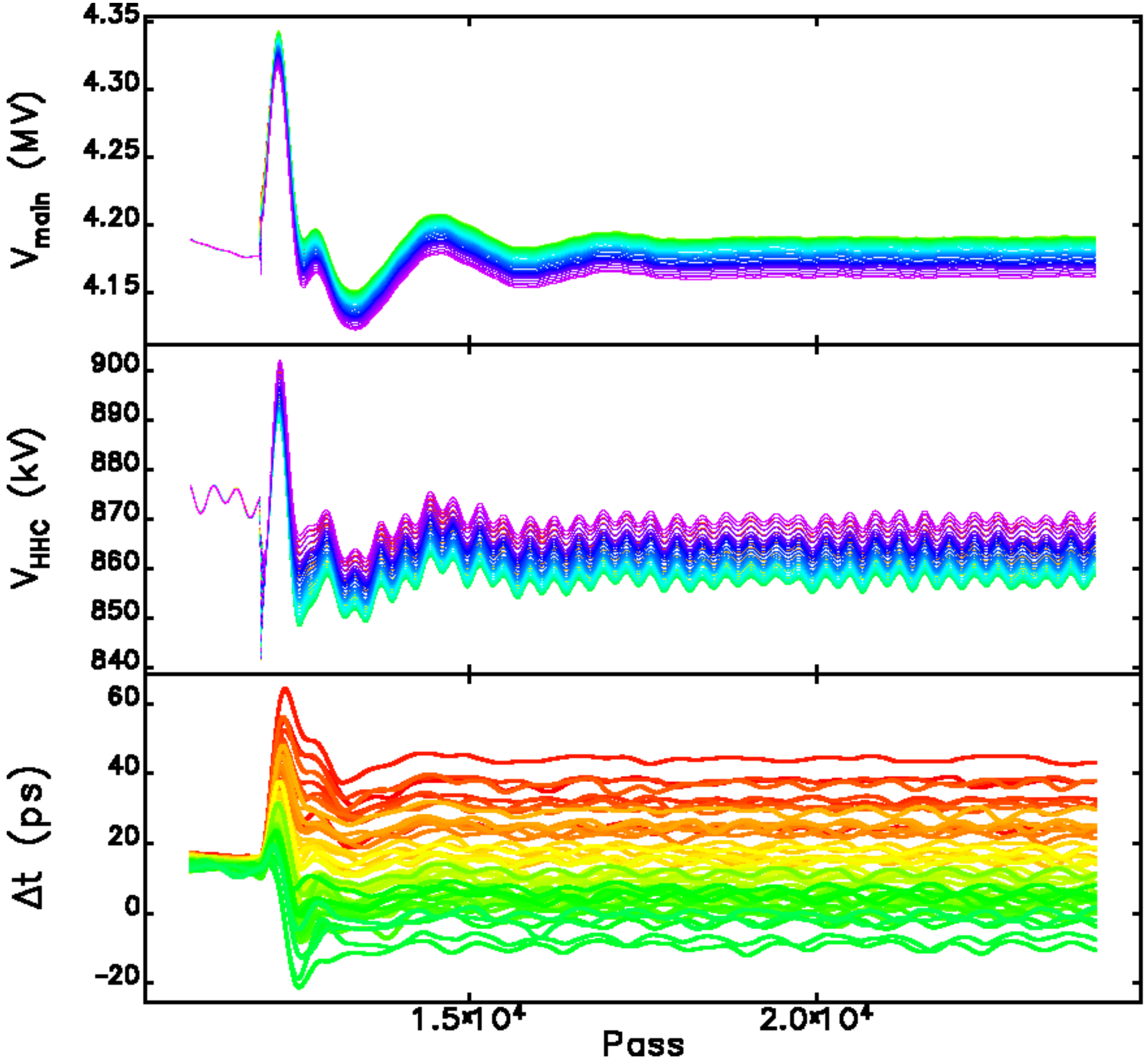
3: Impact of a lost bunch (failed swap-out)



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 equilibiration
- Without adequate longitudinal feedback strength, beam is lost
- Suspect involvement of two monopole HOMs
- Strength needed is ~3x higher than for 1+45 pattern

Variation voltage and bunch phase

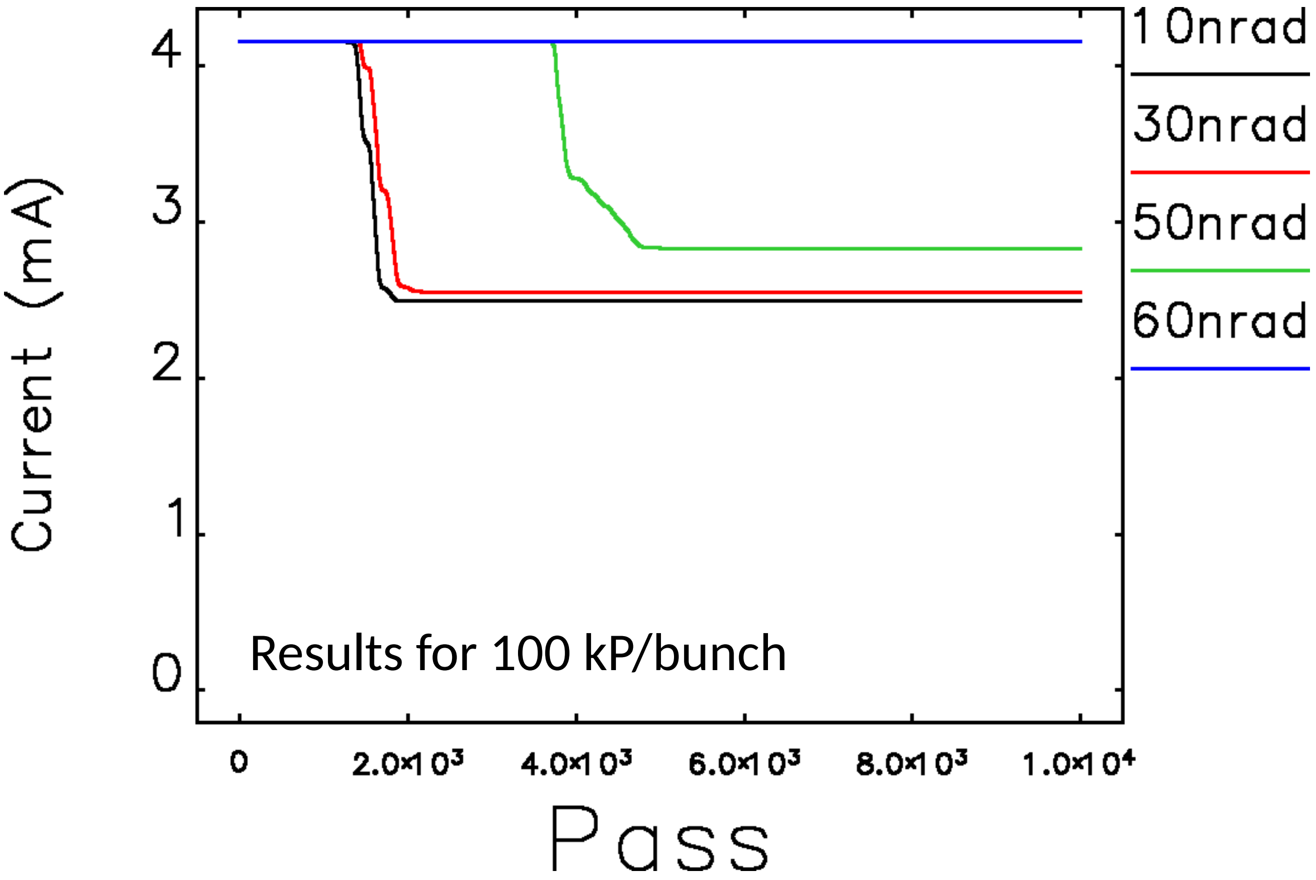


- Simulations show slewing of bunches in time
- Results from sawtooth voltage variation in main rf cavities
- Bunch length also varies due to variation in phase in the harmonic cavity

4: Filling from zero

- We must inject one full-current bunch into each target bucket
  - Will this work?
  - What feedback effort is needed?
- 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

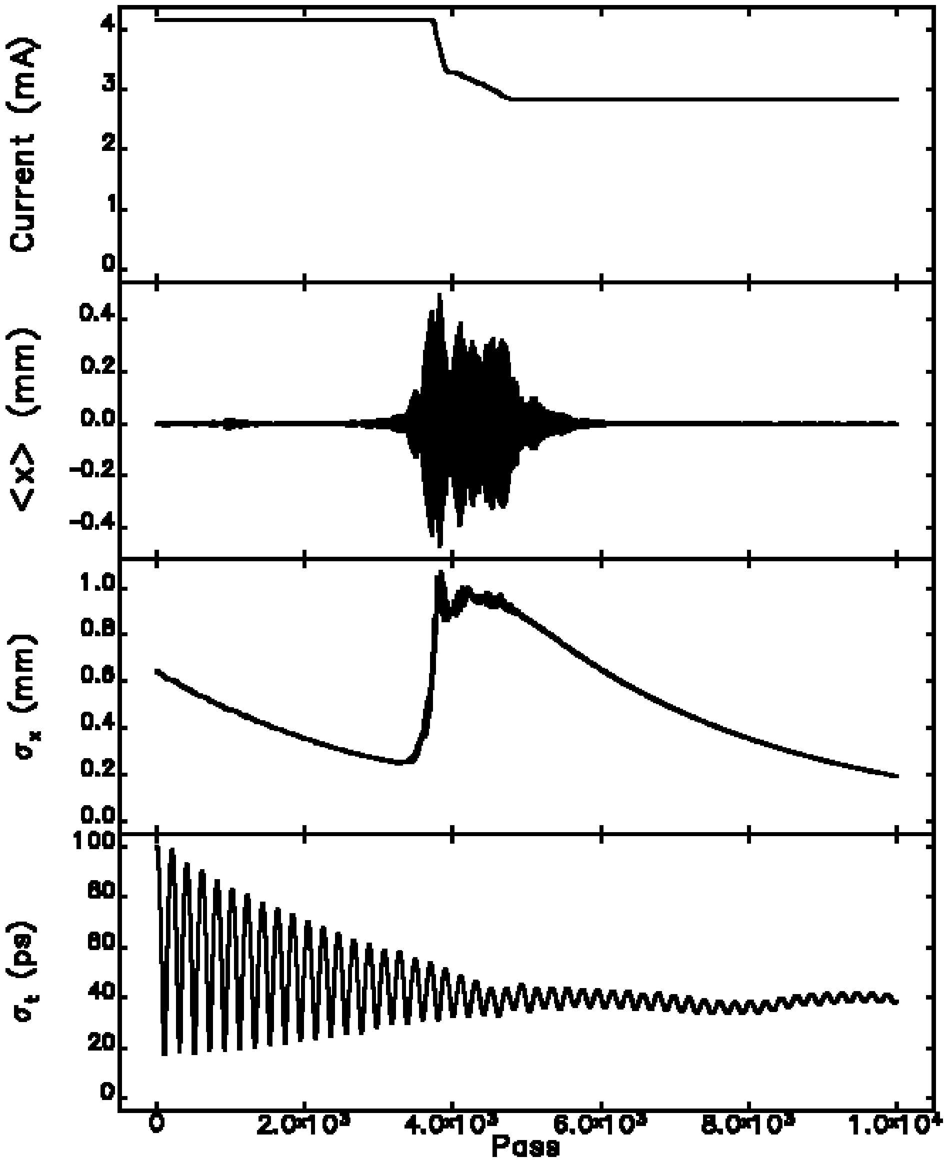
Losses occur for first injected bunch

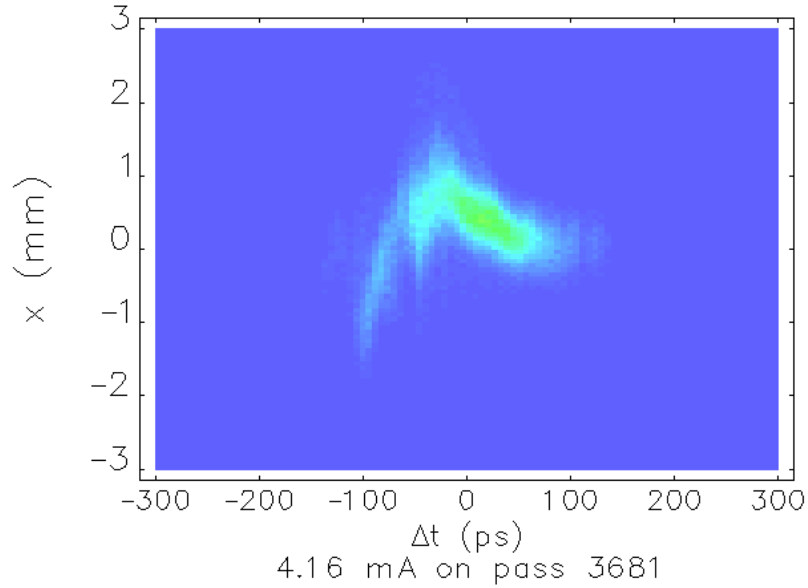


- Need transverse feedback strength of >50 nrad to prevent beam loss
  - Level depends on number of particles, converges for ~100k
- Indicated ~300 V for a bunch-by-bunch system not challenging[1]
  - Interesting to explore instability *assuming* feedback is more limited

1: C.-Y. Yao, private communication

Head-tail instability at injection (50nrad)

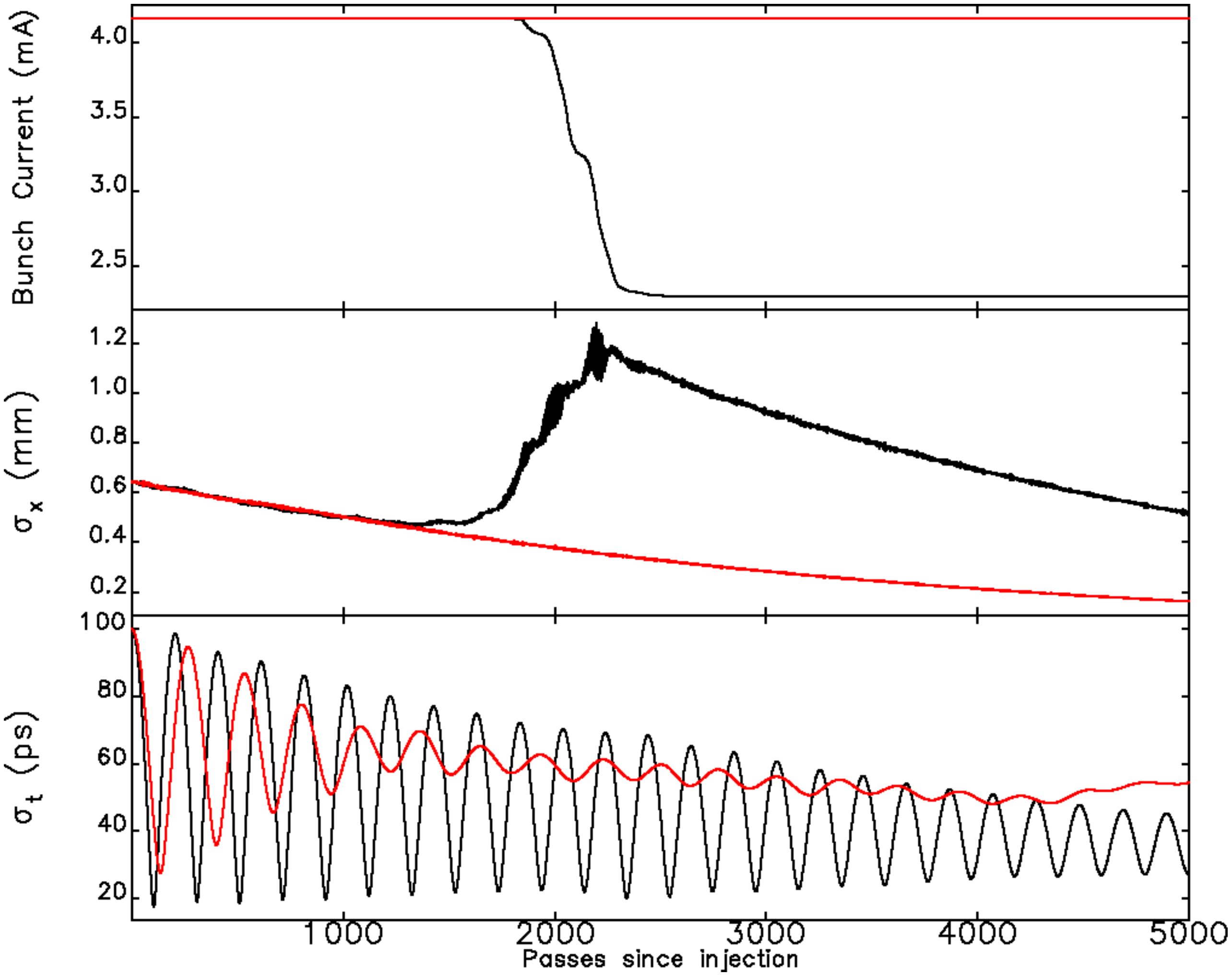




- Head-tail instability driven by horizontal dipole wake
- Bunch-length oscillations due to initial longitudinal mismatch appear relevant

Show movie #2

Instability suppressed by bunch lengthening



- As HHC voltage builds, longitudinal injection mismatch is reduced
- Bunch length no longer oscillates dramatically
- Peak currents reduced, as are wakefields

Show movie #3

Black: bunch 0 (bucket 0); HHC voltage ~0
Red: bunch 24 (bucket 1242); HHC voltage ~400kV

NB: simulations with 10 kP

Plans

- Model for existing ring needs enhancement
  - Refine measurements of existing-cavity HOMs
  - Extend model to include long-range wakes, HOMs
  - Add simulation of existing bunch-by-bunch feedback
  - Bench-mark tracking studies with measurements
- APS upgrade
  - Refine impedance model
    - Iterate with vacuum engineers to reduce longitudinal impedance
    - Add long-range resistive quadrupole wakes
    - Use refined data for cavity HOMs, add HHC HOMs
  - Study feedback requirements more thoroughly
    - Sensitivity to number of simulation particles
    - Sensitivity to simulated readback noise

Conclusions

- Simulation of collective effects for an APS upgrade are well advance
  - Short- and long-range resonant and non-resonant impedances included
  - Full multi-bunch, multi-particle per bunch tracking
  - Beam and rf feedback systems
- Single-bunch limit is comfortably above required 4.2 mA
  - Initial injection requires transverse feedback to suppress head-ta instability
- Multi-bunch instabilities must be suppressed with feedback
  - Longitudinal instability from cavity HOMs
  - Transverse instability from long-range resistive wall
  - Longitudinal feedback is challenging when swap-out fails
- Plan to improve model for existing ring and extend bench-marking