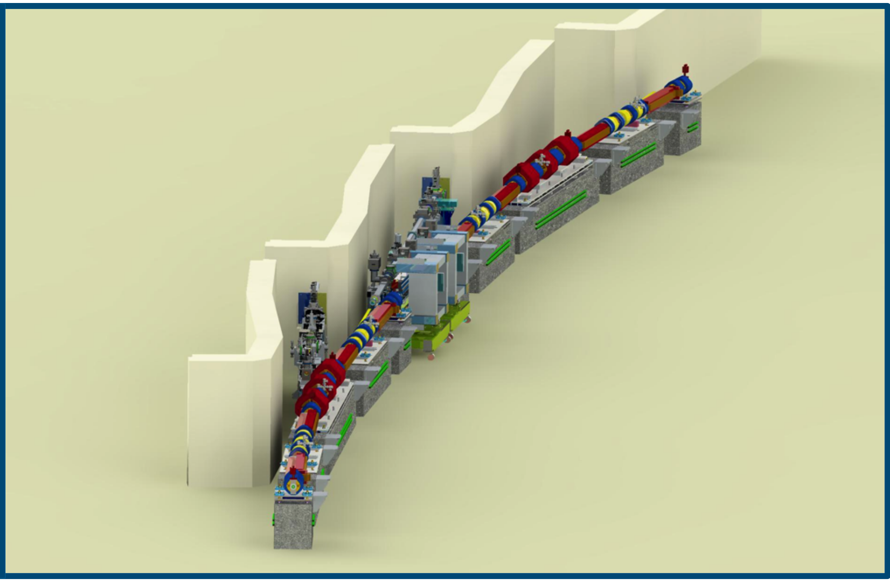
Collective effects in APS-U injection



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Topical Workshop on Injection and Injection Systems
Berlin, Germany
August 28, 2017

Acknowledgments

- Michael Borland
- Joe Calvey
- Louis Emery
- Ben Stillwell
- Uli Wienands
- Alexei Blednykh (NSLS-II)
- Yong-Chul Chae (now at DESY)
- Medani Sangroula (IIT)
- Blues cluster at ANL/LCRC

Introduction and motivation

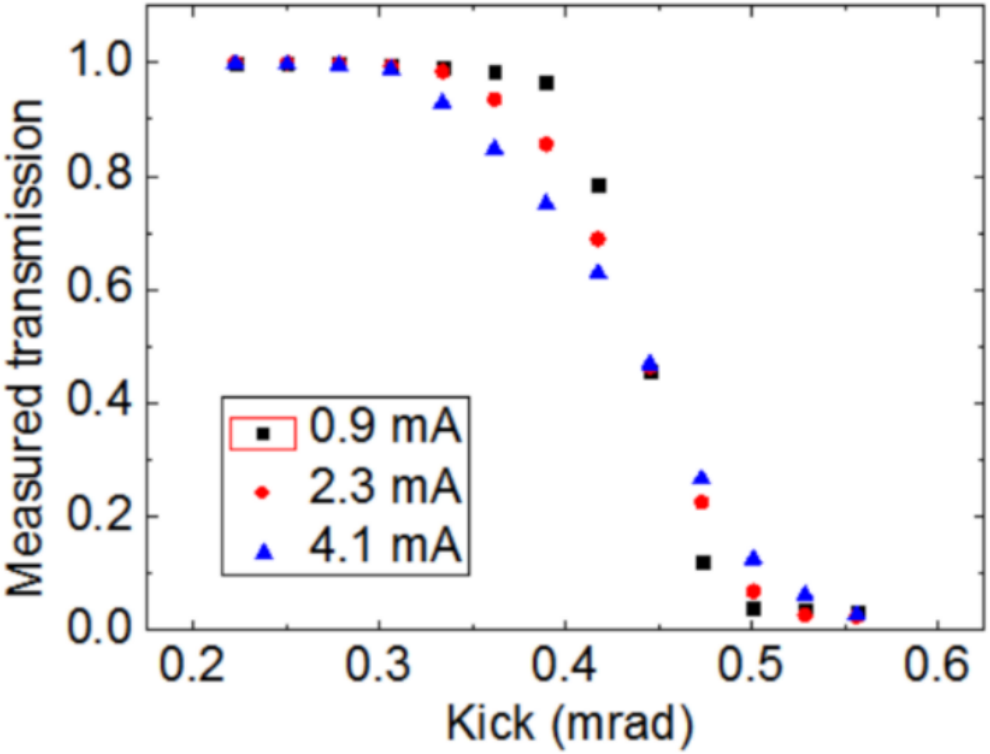
- Injection performance is traditionally analyzed using single particle dynamics
  - Usual dynamic aperture determined by nonlinear dynamics
  - Injection efficiency computed using the dynamic aperture and injector parameters (injected/stored 6D size, kicker specifications, etc.)
- Collective effects may further degrade injection performance
  - Increase beam size/emittance beyond dynamic aperture
  - Result in beam loading of rf cavities that may reduce acceptance
  - Drive transient single bunch instabilities and beam loss during injection
- Collective effects are particularly important when
  1. Injected and/or stored charge is large
  2. Required phase space area for injection ~ dynamic aperture
- Both of these conditions apply to the multi-bend achromat (MBA) lattice planned for the APS-U

Outline

- Measurements and simulations of injection-related collective effects at the present APS
- Particle tracking approach including collective effects
- Simulations of collective effects during off-axis accumulation in the 90-pm MBA lattice
- Simulations of collective effects for on-axis injection in the 42-pm MBA lattice
- Conclusions

Measurements of charge-dependent injection efficiency at the APS

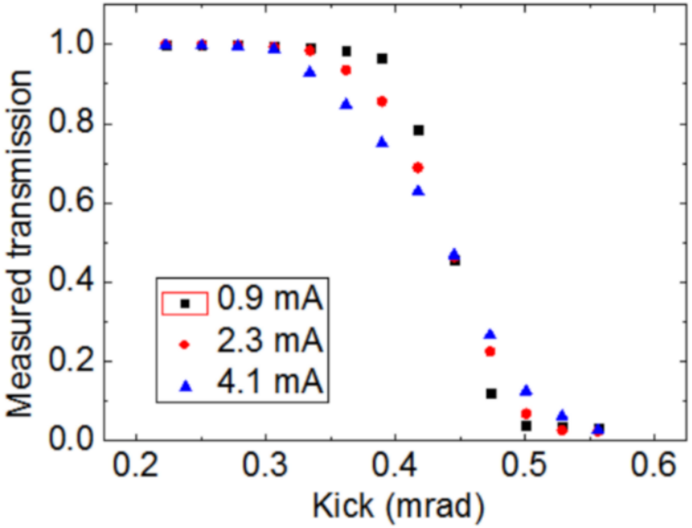
- Experimental procedure for a given charge:
  1. Kick stored beam with one injection kicker
  2. Measure transmission (fraction of particles remaining)
  3. Replenish beam if necessary
  4. Repeat with different kick strength
- Measurements made at 0.9, 2.3, and 4.1 mA (3.3, 8.4, and 15 nC)
- Dynamic aperture sets the horizontal kick limit at around 0.42 mrad



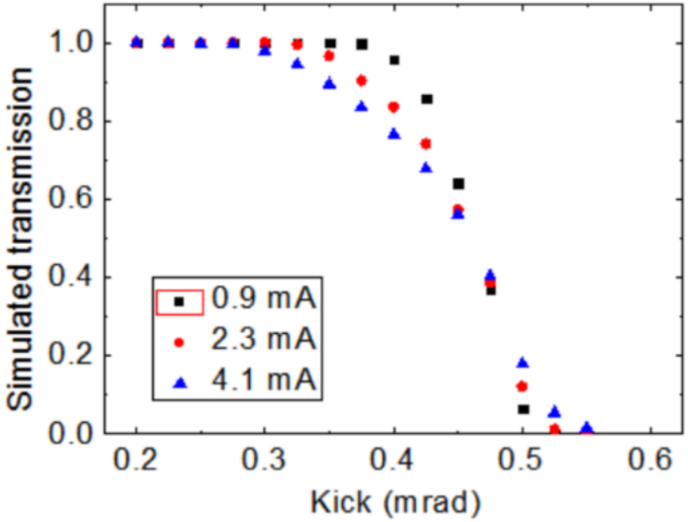
Experiments by V. Sajaev (APS) and S. Shin (PAL)

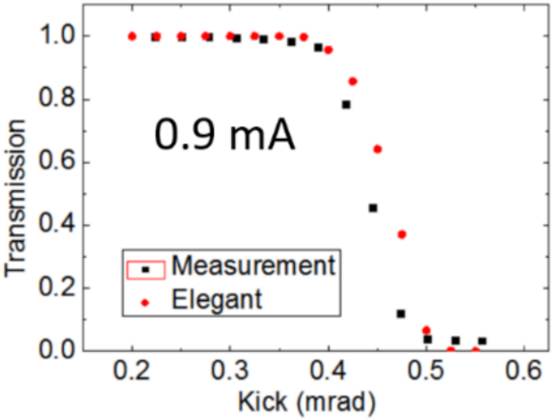
Simulations can predict injection dynamics

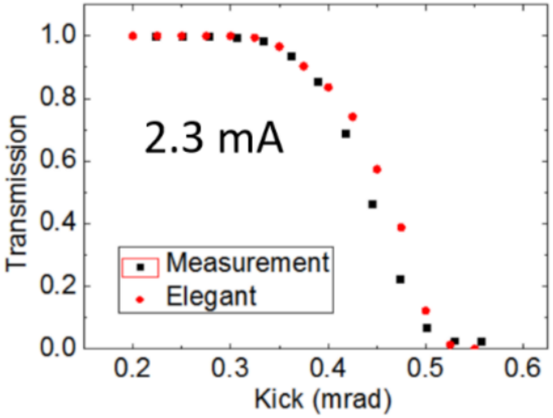
- Experiment at the APS to measure particle transmission as a function of kick strength.

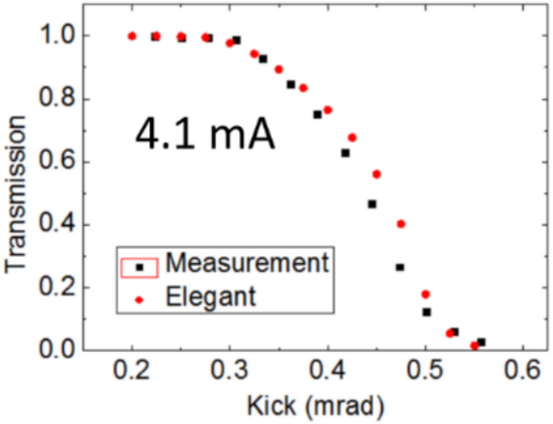


- Element-by-element `elegant` tracking using calibrated lattice and impedance model





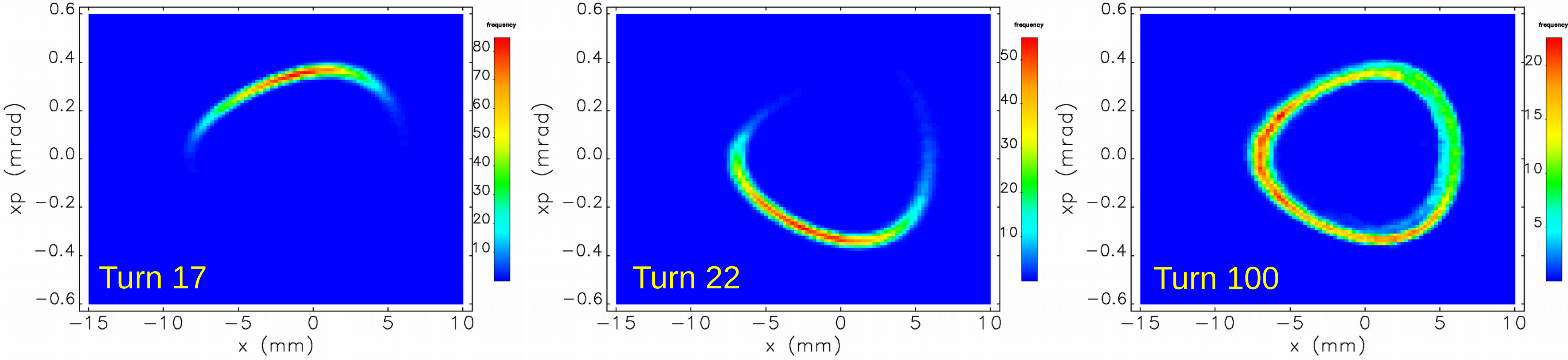




Experiments by V. Sajaev (APS) and S. Shin (PAL), simulations by S. Shin (PAL) and R. Lindberg (APS)

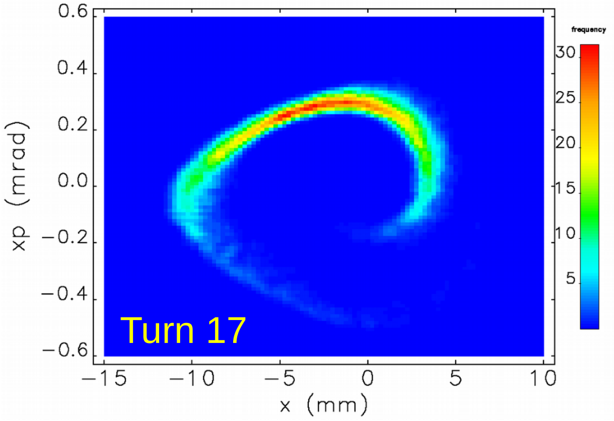
Collective effects increase phase space area and increase losses at large amplitude

Simulation of APS with no collective effects (0.35 mrad kick @ 0 mA)

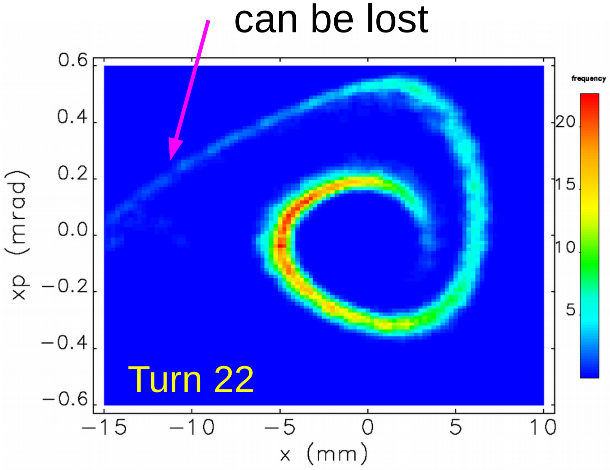


Simulation of APS with collective effects (0.35 mrad kick @ 4.1 mA)

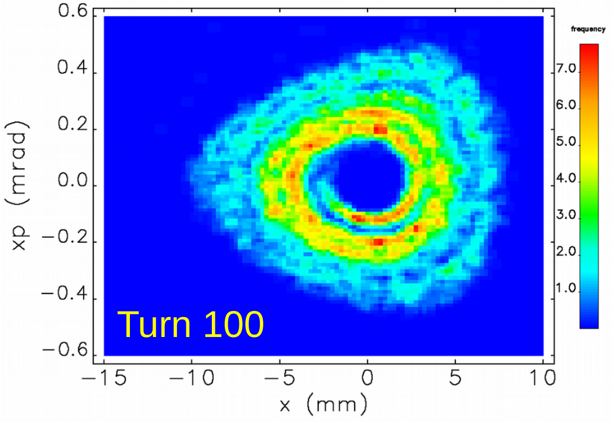
Collective effects blow up the phase space, creating tails in the distribution



Particles that are in the impedance-driven “tails” can be lost



Collective effects result in a beam that fills the stable phase space after many turns



Collective effects at injection in MBA lattices

- Collective effects do not typically play an important role during injection at the present APS
  - APS dynamic aperture is much larger than what is required for injection
  - Kick after top-up (~0.2 mrad) < Kick where efficiency drops (~0.3 mrad @ 4.1 mA)
- This conclusion depends upon the impedance, the charge, and both the dynamic and physical aperture
- All these factors can become more challenging in MBA upgrades
- Two MBA lattices considered for APS-U:
  - 90 pm MBA lattice[†] with traditional accumulation
    - Horizontal dynamic aperture: ±6 mm (median), ±4 mm (10%)
    - Physical aperture: ±4 mm for helical superconducting undulator
  - 42 pm MBA lattice[§] using on-axis, swap-out injection
    - Horizontal dynamic aperture: ±2.7 mm (median), ±2.2 mm (10%)

[†] Y.-P. Sun, M. Borland, R. Lindberg, and V. Sajaev, Proc. of NAPAC 2016

[§] Present project baseline, PDR report of 2017.

Simulating collective effects at injection

(These methods were originally developed @ APS by Y.-C. Chae)

1. Identify geometric and resistive wall sources of impedance
2. Compute the resistive wall impedance using analytic formulas
3. Calculate the geometric impedance using the numerical codes `ECHO`† and `GdfidL`§
   - Model point-particle Green function by the wakefield of a σ_b =1-mm bunch
   - Equivalent to applying a frequency filter $\exp[-(\sigma_b\omega)^2/2]$ to impedance
4. Weight transverse dipole/quadrupole wakefield by local beta function and sum over components every ~2 meters per sector (15 total impedance elements/sector)
5. Take FFT of "locally summed wakefield" in each plane to get the "locally summed impedance" in each plane
6. Track particles in `elegant`¥
   - Element-by-element tracking including synchrotron emission
   - Idealized higher-harmonic rf cavity potential using `RFCA` element
   - Apply local impedance elements in 15 locations/sector using `ZLONGIT` and `ZTRANSVERSE` elements

† I. A. Zagorodnov and T. Weiland. PRST-AB, **8**, 042001 (2005).
§ W. Bruns. The GdfidL Electromagnetic Field simulator.
¥ M. Borland. ANL/APS LS-287, Advanced Photon Source (2000)

MBA impedance summary

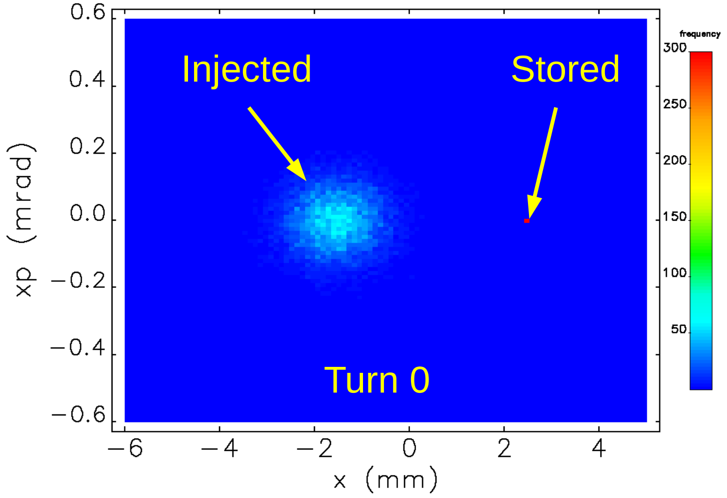
Impedance source	Number	$\Im(Z_{\parallel})/n$ (Ω)	$k_{\text{loss}}(\sigma_t = 50$ ps) (V/pC)
BPM-bellows	560	0.048	0.090
In-line absorber	760	0.060	0.045
Gate valve	160	0.020	0.002
Flange	1880	0.011	$< 10^{-3}$
ID transition	40	0.0018	$< 10^{-3}$
Crotch absorber	80	0.0070	0.002
Pumping cross	200	0.0015	$< 10^{-3}$
Inj/ext kickers	8	0.0075	0.94
Small-gap ID BPM	30	0.0013	0.008
352 MHz rf-cavity	10	0.001	3.8
Rf transitions	3	0.018	0.84
Resistive wall	NA	NA	2.18
Total	NA	0.18	7.9

Resistive Wall

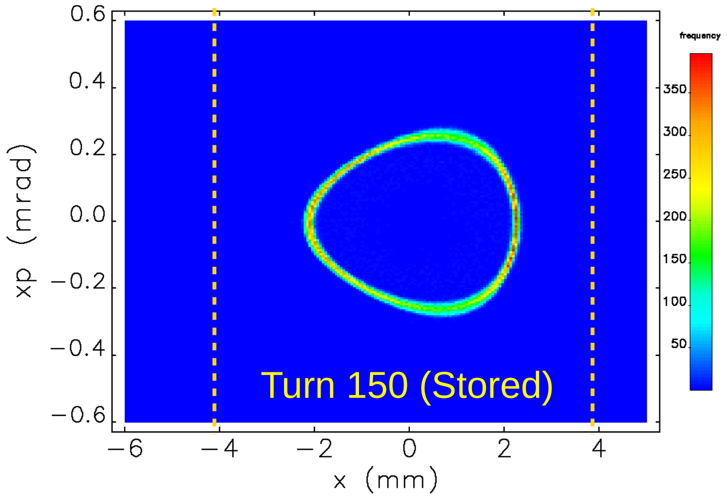
Metal	Diameter	Length
Cu	22 mm	224 m
Al	22 mm	605 m
SS	22 mm	80 m
Al	6 mm	25 m
Al	20×6 mm (H×V)	150 m
Al	140 mm	20 m

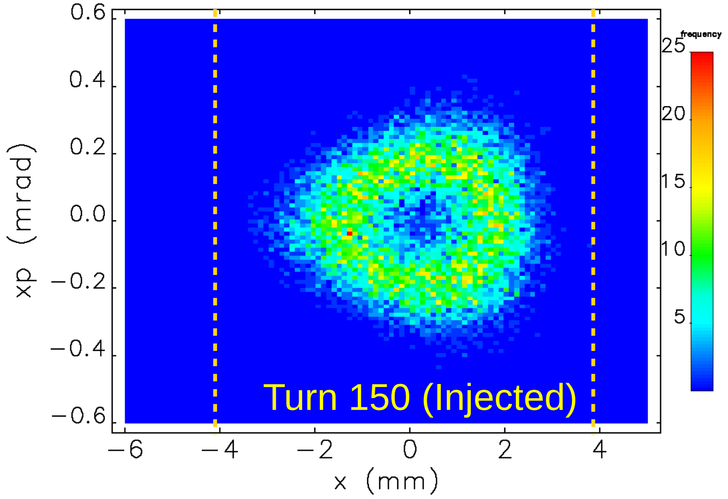
- Dominant source of transverse impedance is from the resistive wall of the narrow-gap ID chambers
- In-line photon absorbers are the second largest transverse impedance source

Single particle tracking shows accumulation is possible in the 90 pm MBA lattice†



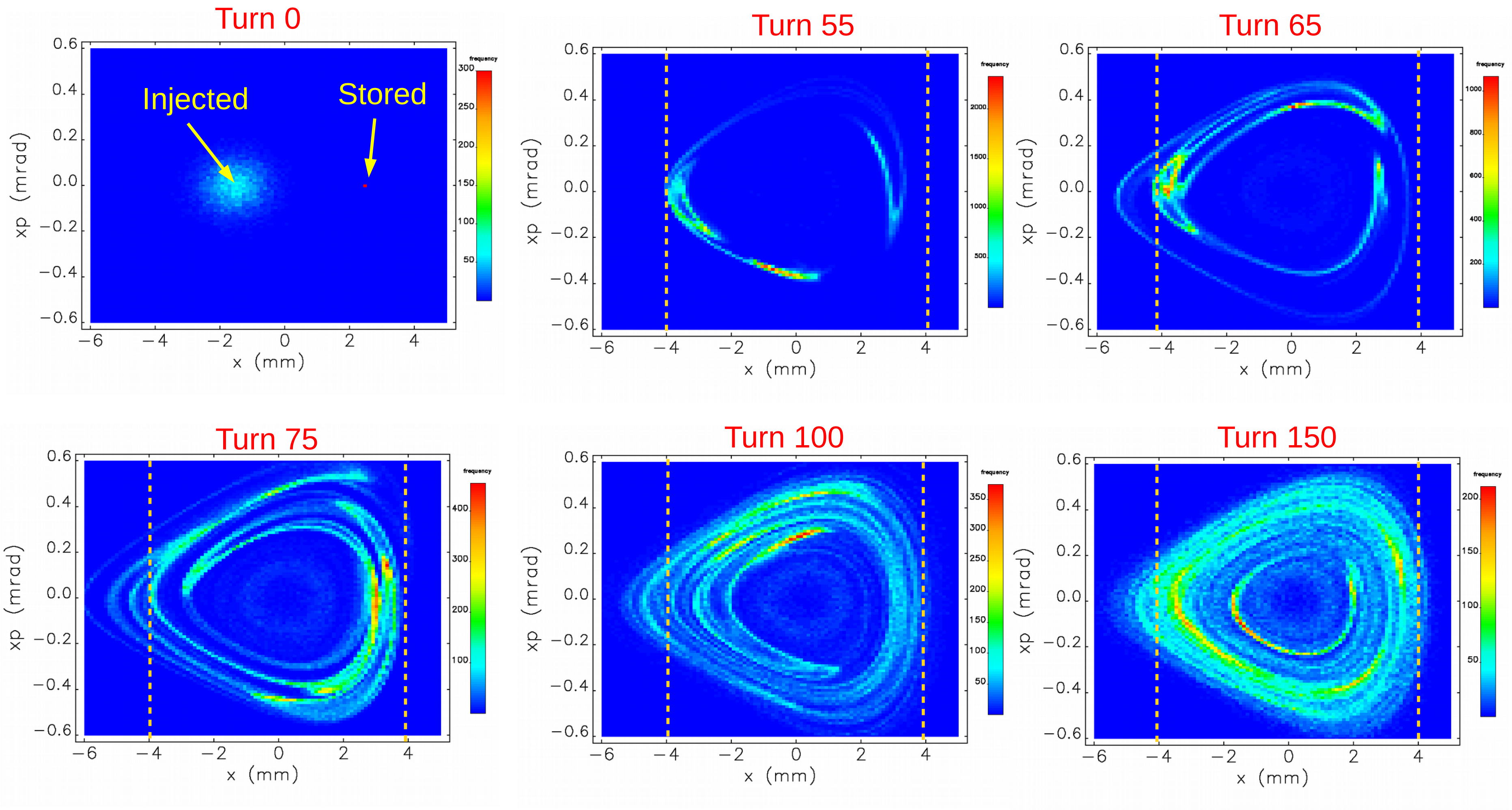
- Element-by element tracking
- Booster bunch injected at x = –2 mm with $\varepsilon_x \times \varepsilon_y$ = (60 nm)×(16 nm)
- Stored bunch begins at x = +2 mm
- No lattice errors, no impedance
- Will this work at 4.2 mA/bunch including collective effects?





† Y.-P. Sun, M. Borland, R. Lindberg, and V. Sajaev, Proc. of NAPAC 2016

Collective effects at 4.2 mA/bunch precludes accumulation in the 90 pm MBA



R. Lindberg, M. Borland, and A. Blednykh. Proc. of NAPAC 2016

Some bullets about on-axis, swap-out injection

- MBA lattices have strong focusing, are very nonlinear, and consequently have small dynamic apertures
- Recent advances in fast, high-voltage pulser technology permit on-axis, swap out injection
- Ideally, on-axis injection allows for efficient injection if the dynamic aperture is a few times the injected beam size
  - Allowance must be made for errors in injection systems
  - How do collective effects change the requirements?

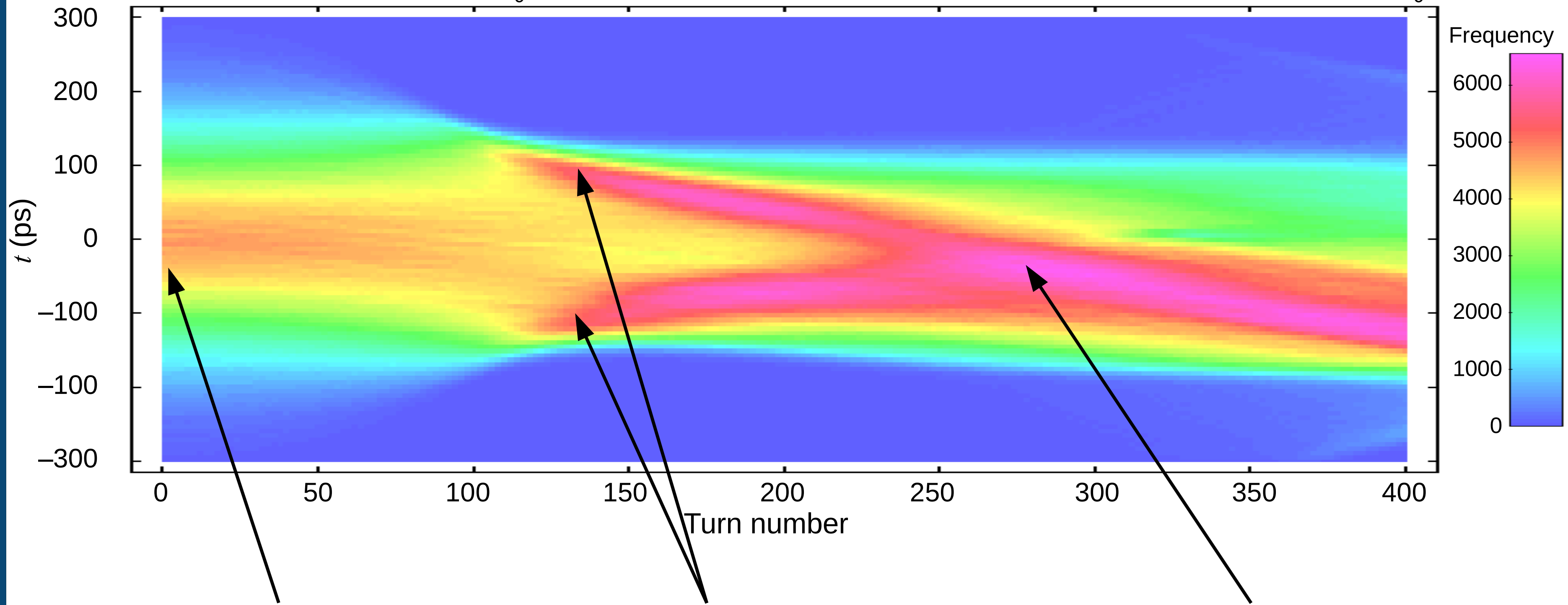
Collective effects at injection can be significant and may ultimately limit the current

- Collective effects can reduce injection efficiency, even for on-axis injection†
  - Errors in the injection system will result in initial e-beam offsets of up to 200 microns in both planes that can seed transverse instabilities
  - Longitudinal phase-space mismatch between booster Gaussian beam and storage ring non-Gaussian beam with HHC (flat potential or otherwise) results in longitudinal oscillations/structure which can generate large transverse wakefields
  - Transverse wakefields can drive transverse oscillations, emittance growth, and particle loss within a few synchrotron oscillations
- Nonlinear resonances of the large-emittance injected beam tends to cause even larger transverse oscillations
- Lattice errors can further exacerbate the problem
- Improving the longitudinal phase-space matching can reduce the longitudinal tumbling and transient transverse instability
- Transverse feedback can cure the instability and prevent particle loss

† M. Borland, T. Berenc, L. Emery, R. Lindberg. Proc. of ICAP 2015, Shanghai, China, pp 61; R.R. Lindberg, M. Borland, and A. Blednyk. Proc. of NAPAC 2016, p. 901 (WEPOB08).

Injection from the booster results in longitudinal dynamics that can drive transverse instabilities

Booster beam is a Gaussian with σ_δ = 0.12% while the equilibrium at 4.2 mA is non-Gaussian with σ_δ = 0.15%



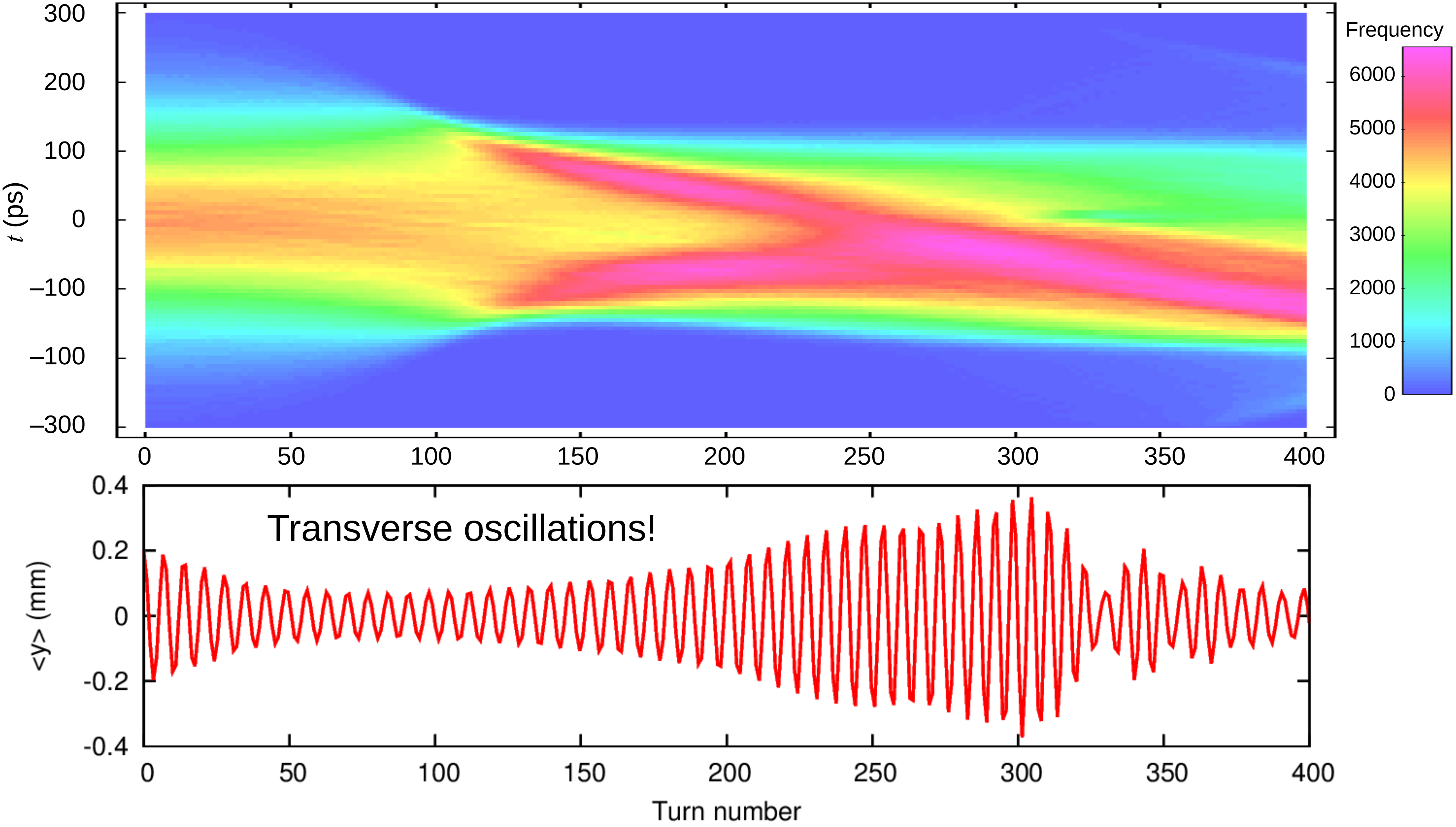
Initial, on-axis Gaussian bunch from booster

Turbulent onset and current peaks driven by the longitudinal impedance

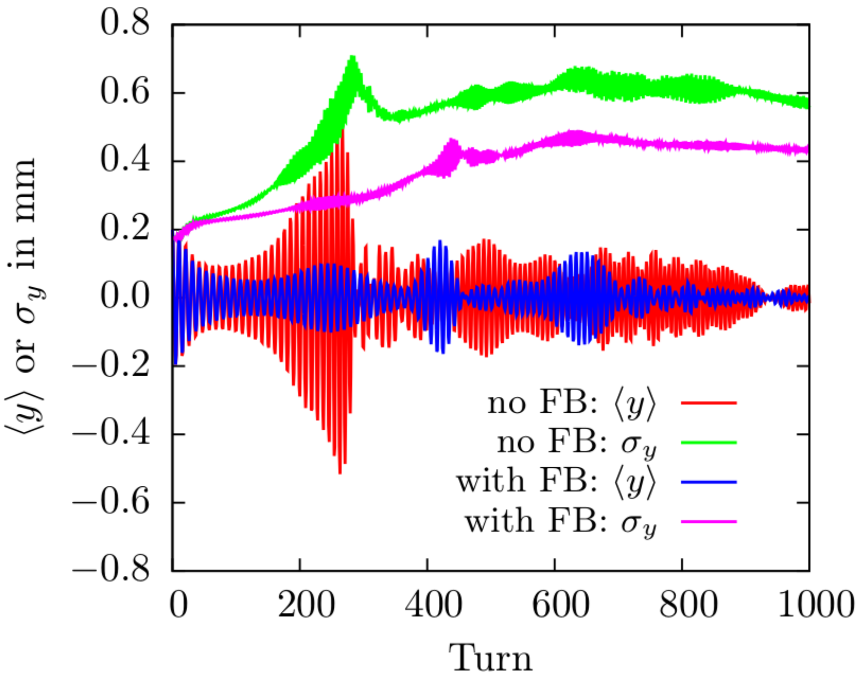
Local minimum of the bunch length and maximum of the peak current

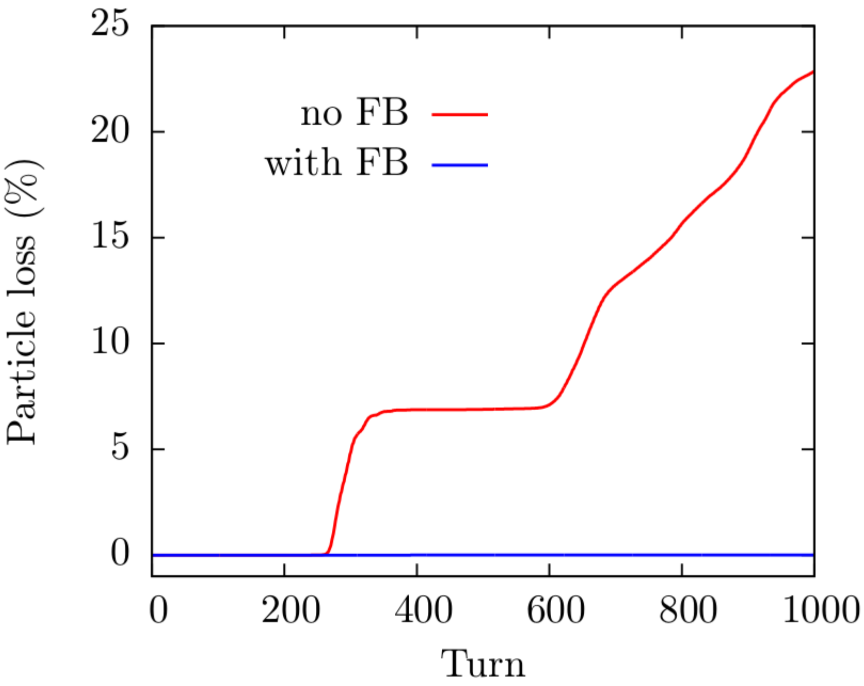
Injection from the booster results in longitudinal dynamics that can drive transverse instabilities

Booster beam is a Gaussian with σ_δ = 0.12%, while the equilibrium at 4.2 mA is non-Gaussian with σ_δ = 0.15%



Transverse feedback can control the transient instability at injection

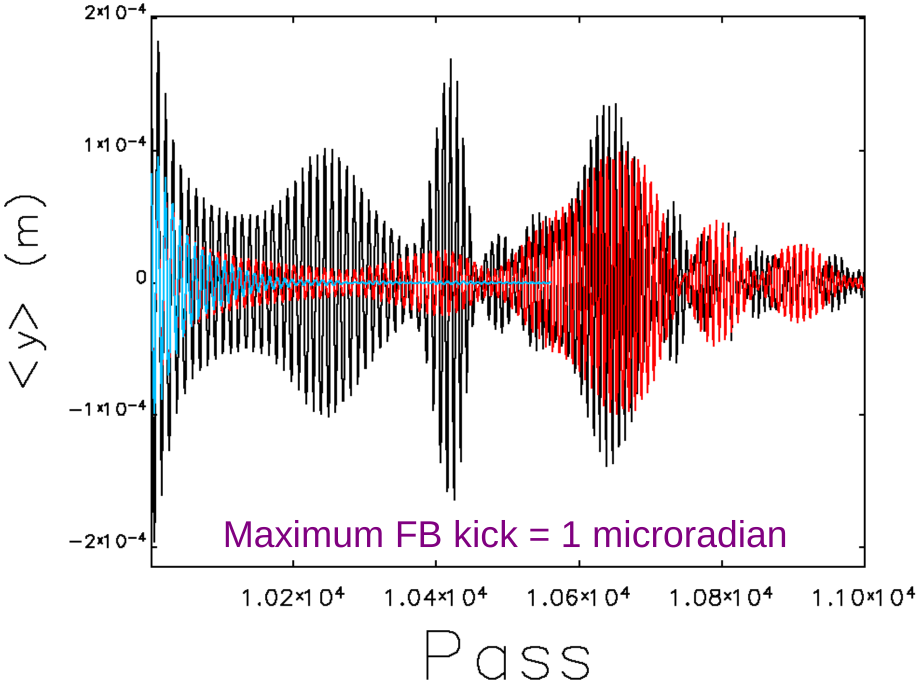




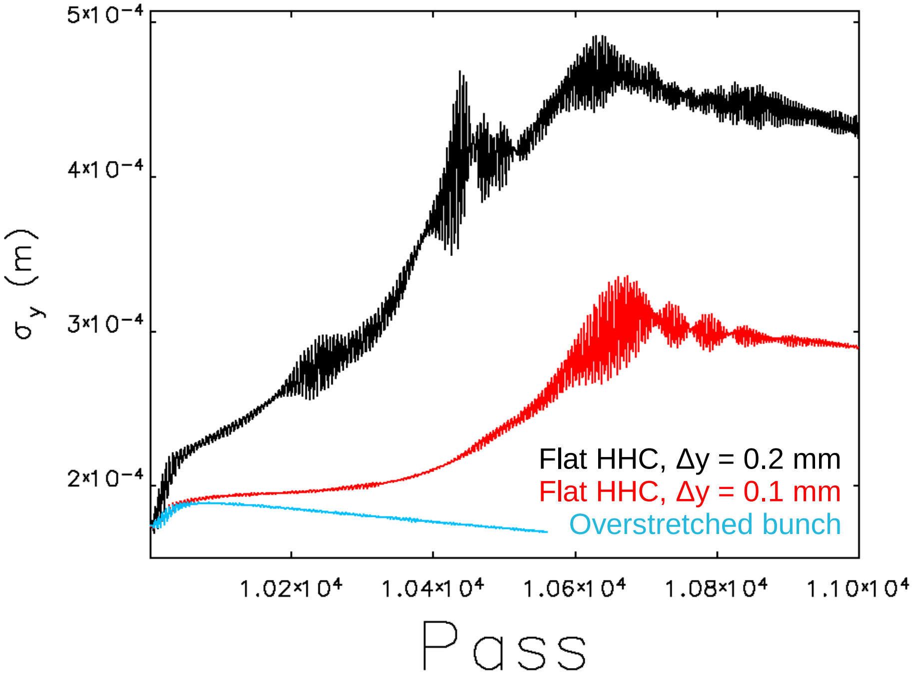
- Element-by-element tracking with prescribed higher harmonic cavity voltage set to flatten rf potential
- The transverse feedback is limited to 1 microradian maximum kick

Overstretching the bunch with the HHC further reduces injection oscillations

- We plan to use the HHC to “overstretch” the bunch to maximize lifetime
- This increases the length while decreasing the energy spread
  - Better longitudinal matching of storage ring to injected booster beam
- Simulation uses element-by-element tracking of all 48 bunches
- Flat HHC equil.: σ_t = 75 ps, σ_δ = 0.17%; Overstretched equil.: σ_t = 100 ps, σ_δ = 0.15%



Maximum FB kick = 1 microradian



Conclusions

- We have had significant success modeling collective effects at the APS during at injection time
- We examined how impedances plus small dynamic aperture can limit injection with accumulation and also on-axis injection
- In APS-U we seem to have pushed lattice, impedance and injection to some overall limit