Modeling wakefields and collective effects for the APS-U

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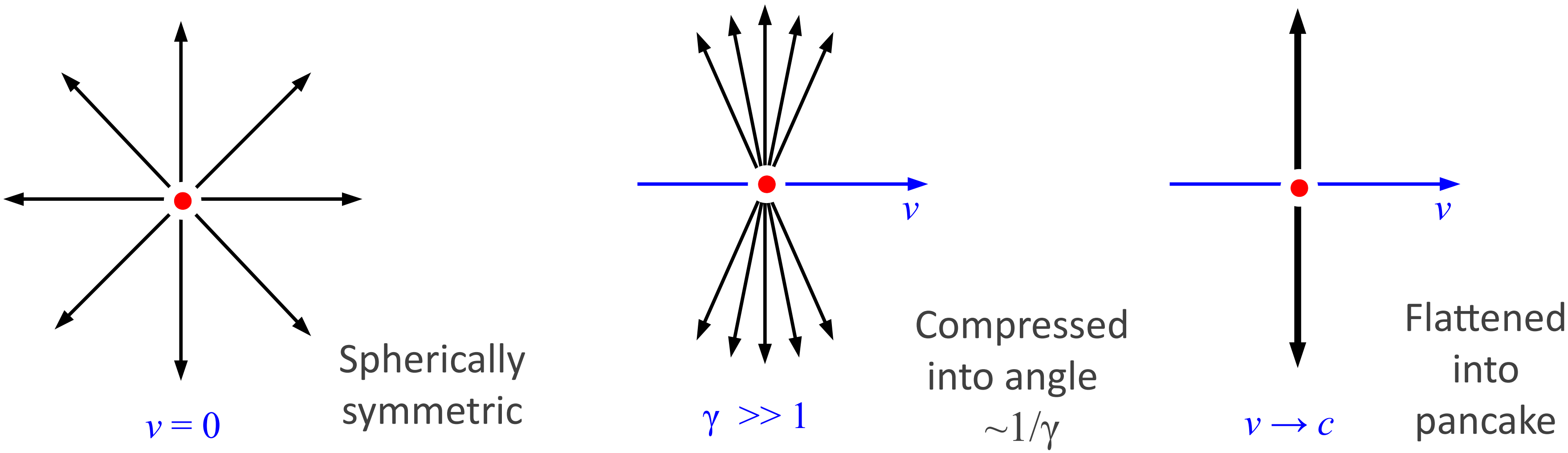
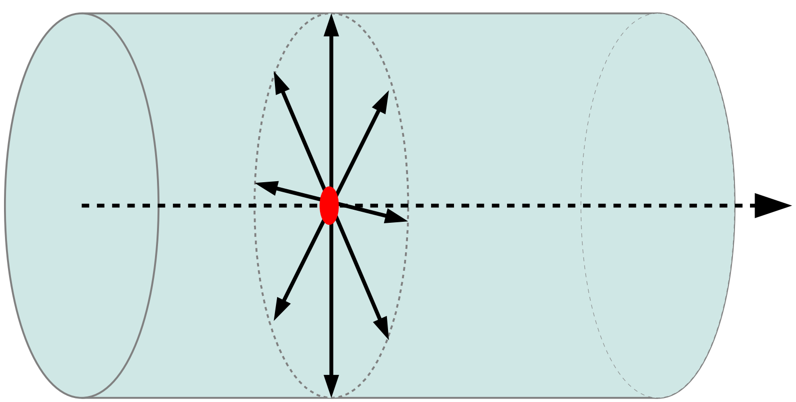
Outline

- Introduction to short-range wakefields
  - Geometric & resistive wall, longitudinal & transverse
  - Resulting current-dependent (collective) effects on beam
- Calculating wakefields/impedances
- Simulating collective effects at APS
- Impedance model for APS-U MBA
- Longitudinal collective effects at APS-U
- Transverse collective effects at APS-U
  - On-axis injection
  - Accumulation and feedback
- Future plans and outlook

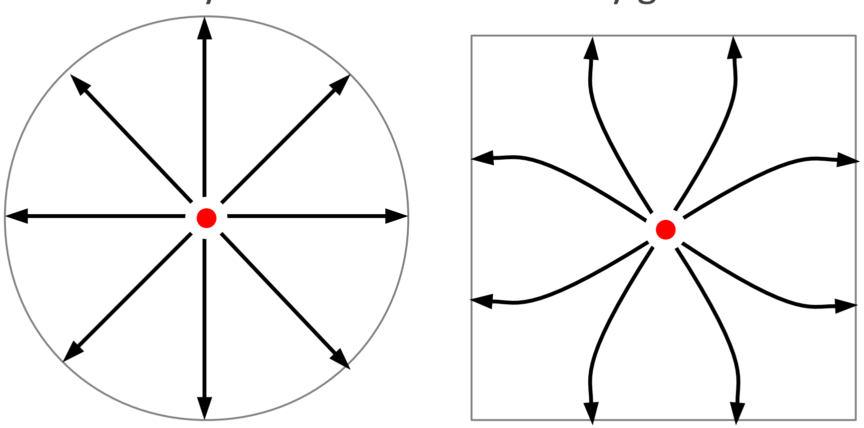
Coulomb field of a relativistic charge



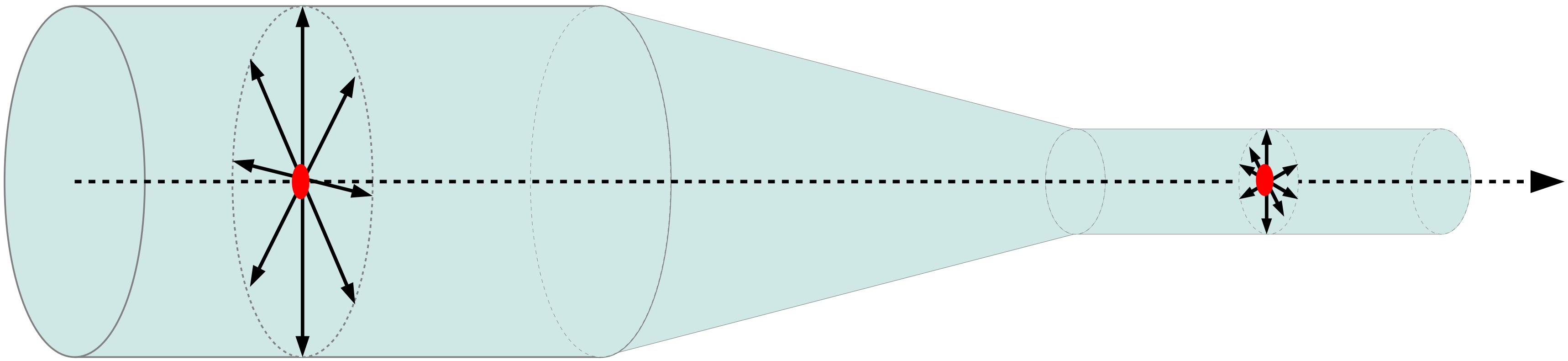
Perfectly conducting chamber



Field lines can be arranged to satisfy appropriate boundary conditions for arbitrary geometries



Geometric wakefields/impedance are generated by changes in the vacuum chamber cross section



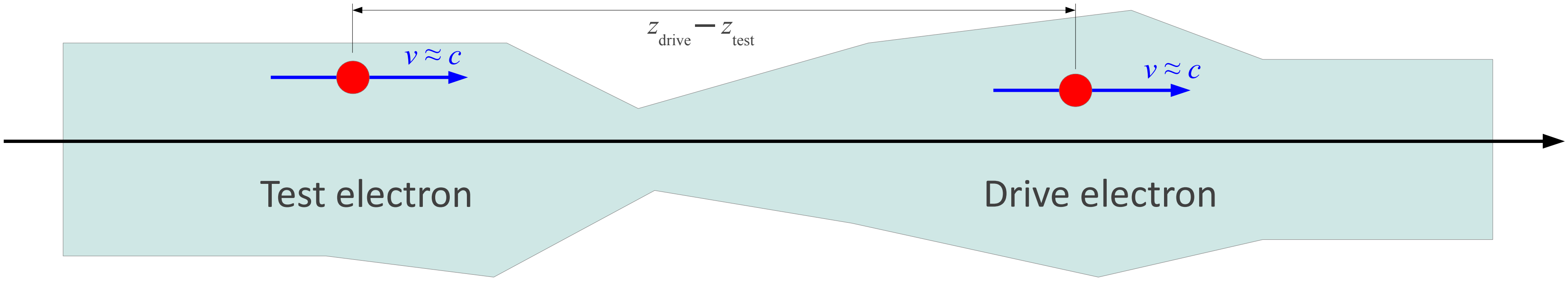
Changes in vacuum chamber cross section → Rearrangement of fields to satisfy new boundary conditions

These radiated fields lead to wakefields that are behind the exciting charge (since $v \approx c$)

Magnitude of the wakefield depends on the change in the chamber cross section and how fast that change occurs

In addition, there are resistive wall wakefields due to the finite resistivity of the chamber walls

Longitudinal wakefields and impedances



Longitudinal wakefields $W_{\parallel}$ change the test particle energy: $\Delta\gamma = -\frac{e}{mc^2}\int_{-\infty}^{\infty} ds\ E_{\parallel}(x, y, z; s) \equiv -\frac{e^2}{mc^2} W_{\parallel}(x, y, z)$

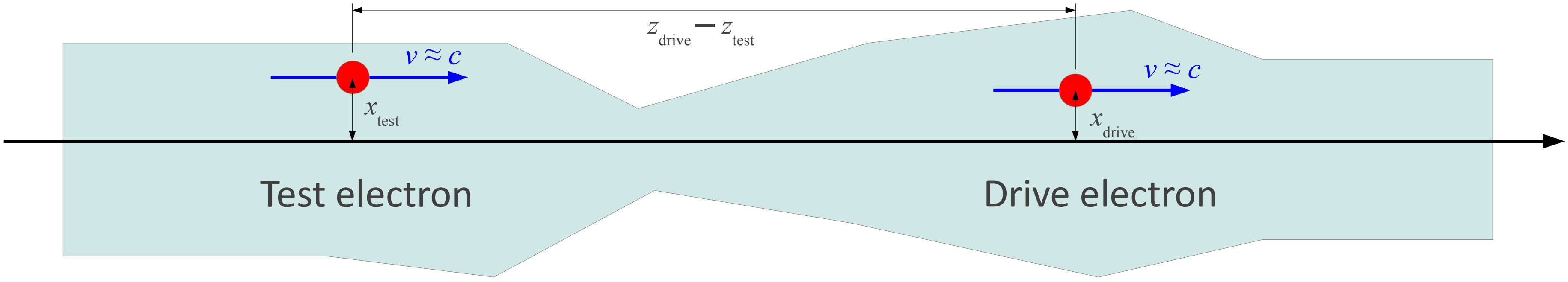
$W_{\parallel}$ is approximately a function of only the difference in longitudinal positions:

$$\Delta\gamma_{\text{test}} \approx -\frac{e}{mc^2} W_{\parallel}(z_{\text{drive}} - z_{\text{test}})$$

Impedance is the Fourier transform of the wakefield with respect to $\tau = z_{\text{drive}} - z_{\text{test}}$:

$$Z_{\parallel}(k) = \frac{1}{c}\int d\tau\ e^{-ik\tau} W_{\parallel}(\tau)$$

Transverse wakefields and impedances



Transverse wakefields $W_\perp$ change the test particle angle: $\Delta \boldsymbol{x}' = -\frac{e}{\gamma m c^2} \int_{-\infty}^{\infty} ds\, (\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})_\perp \equiv -\frac{e^2}{\gamma m c^2} \boldsymbol{W}_\perp(x, y, z)$

"Monopole" wakefield if chamber is not mirror symmetric in x; can cause emittance growth

Effect of "quadupole" wakefield scales with displacement of test electron; source of mainly tune shift

$$\Delta x'_{\text{test}} \approx -\frac{e}{\gamma m c^2}\left[W_{x,M}(z_{\text{drive}} - z_{\text{test}}) + x_{\text{drive}} W_{x,D}(z_{\text{drive}} - z_{\text{test}}) + x_{\text{test}} W_{x,Q}(z_{\text{drive}} - z_{\text{test}}) + \ldots \right]$$

Effect of "dipole" wakefield scales with displacement of drive electron; source of collective instabilities

Impedance is the Fourier transform of the wakefield with respect to $\tau = z_{\text{drive}} - z_{\text{test}}$:

$$Z_{x,D}(k) = \frac{i}{c} \int d\tau\, e^{-ik\tau} W_{x,D}(\tau)$$

Effects of wakefields/impedance

- Impedances/wakefields characterize how electrons interact 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
- Wakefields give rise to collective phenomena that can lead to rf heating of the vacuum chamber, changes in the electron beam distribution, and instabilities/beam loss

Component damage

	Short-term wakefields (single bunch, one turn)	Long-term wakefields (all bunches, many turns)
Longitudinal	Heating of vacuum chamber Bunch lengthening Microwave instability	Heating of cavities Multi-bunch instability
Transverse	Source of orbit change Tune shift Transverse instabilities	Heating of cavities Multi-bunch instability

Increase in emittance

Single bunch current limit
48 bunch mode: I = 4.2 mA

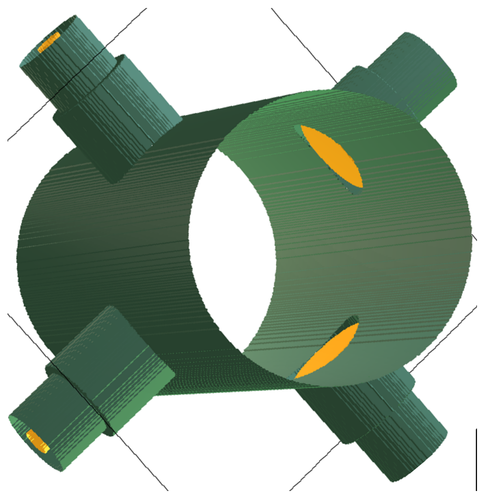
Calculating wakefields for vacuum components

- Resistive wall wakefield has analytic expressions for circular and elliptical chambers

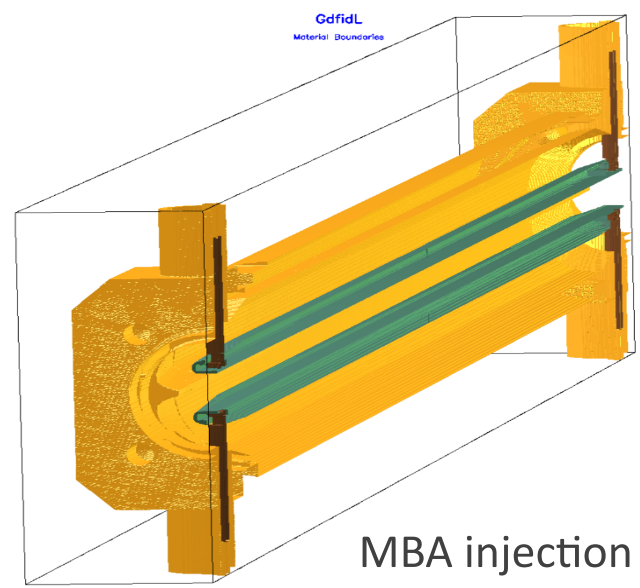
$$Z_{\|}(\omega) \propto |\omega|^{1/2} \frac{1}{b} \qquad Z_{\perp}(\omega) \propto \frac{1}{|\omega|^{1/2}} \frac{1}{b^3}$$

Narrow gap IDs contribute large impedance that can drive transverse instabilities

- Some analytic expressions exist for geometric wakefields in simple structures and/or in the low- or high-frequency regimes
- Impedance generated by realistic 3D structures typically require numerical calculation using finite-difference, finite-time electromagnetic solvers
  - ECHO, CST Microwave Studio, GdfidL, …



MBA BPM housing



MBA injection kicker

Simulating collective effects at the APS

(These methods were originally developed 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
   - Has effect of filtering Green function by Gaussian filter of width $1/\sigma_b$:

$$W_{\text{sim}}(t) = \int d\tau \, \frac{e^{-\tau^2/2\sigma_b^2}}{\sqrt{2\pi}\sigma_b} W_{\text{pt. charge}}(t-\tau) \quad \Rightarrow \quad Z_{\text{sim}}(\omega) = Z_{\text{pt. charge}}(\omega) e^{-\sigma_b^2\omega^2/2}$$

4. Weight transverse dipole/quadrupole wakefield by local beta function

$$\langle W_x(t) \rangle = \sum_{\text{elements } j} \beta_x(s_j) W_x(t; s_j) \qquad \langle W_y(t) \rangle = \sum_{\text{elements } j} \beta_y(s_j) W_y(t; s_j)$$

5. Take FFTs of wakefields to get impedances and sum to get "total impedance"
6. Track particles in `elegant`¥

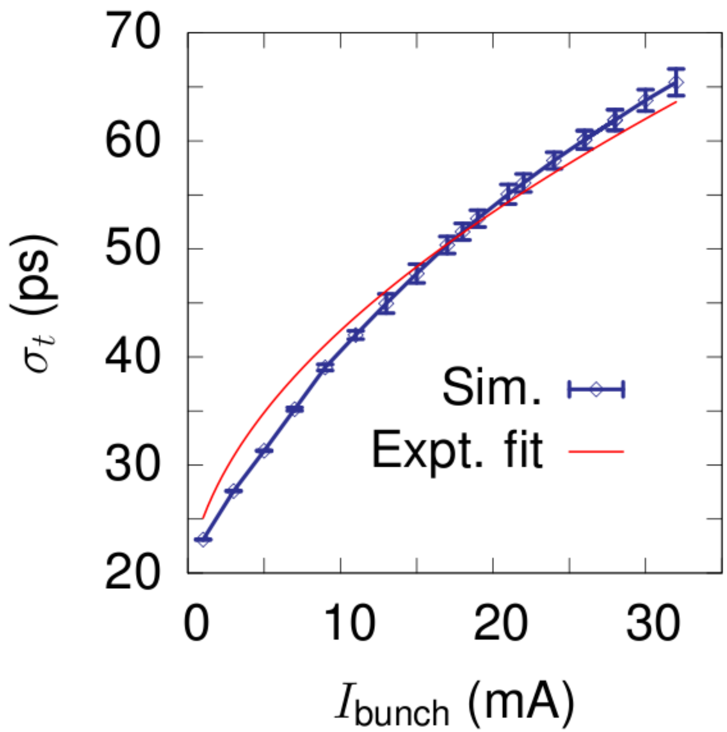
† I. A. Zagorodnov and T. Weiland. PRST-AB, **8**, 042001 (2005).
‡ W. Bruns. The GdfidL Electromagnetic Field simulator.
¥ M. Borland. ANL/APS LS-287, Advanced Photon Source (2000)

Particle tracking with collective effects in elegant

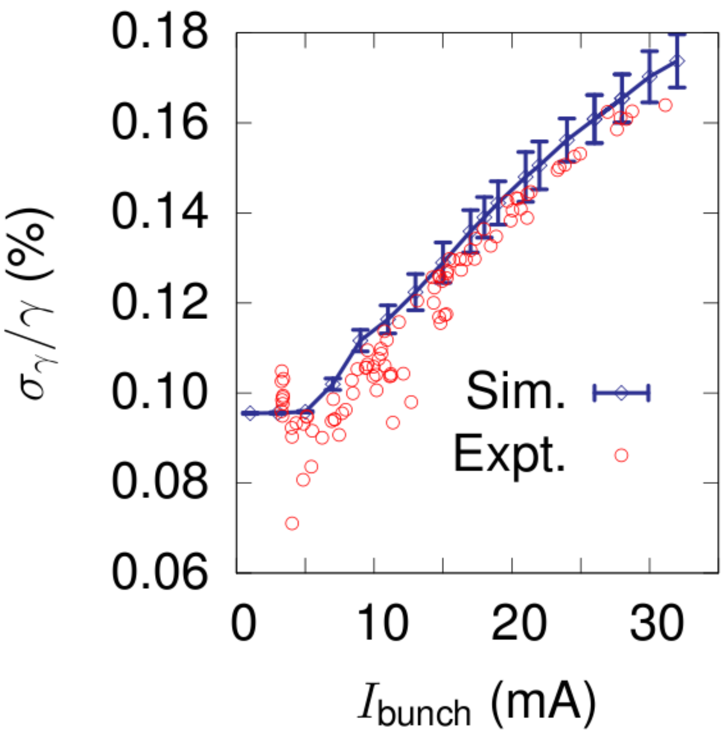
- Impedance is applied once/turn using `ZLONGIT` and `ZTRANSVERSE`
- RF acceleration is applied once/turn using `RFCA`
- Synchrotron emission modeled as lumped element using `SREFFECTS`
- Particles are tracked through lattice using `ILMATRIX` (individual linear matrix)
  - Includes nonlinear tune shift with amplitudes through second order
  - Includes chromatic effects through third order

Dynamics appear to be largely independent of these higher order effects

Simulation predictions for longitudinal dynamics are well-matched by measurements at present APS

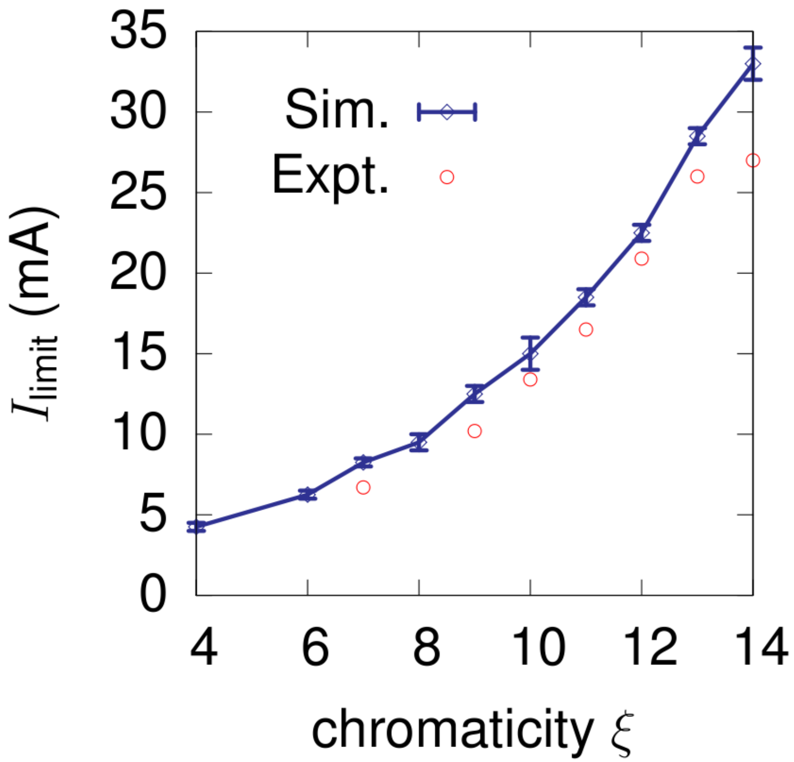


Bunch lengthening well-predicted



Onset of microwave instability and subsequent energy spread increase well-predicted

Simulation predictions of transverse instability threshold agree reasonably well with measurements at present APS



New constraints from upgrade

- Two operating modes/bunch patterns: 324 bunch mode with ~0.62mA/bunch and a 48 bunch mode with 4.2 mA/bunch
  - 48 bunch mode has largest single bunch current and largest single bunch collective effects
- Room for ~5 narrow horizontal gap IDs to be filled with some combination of helical undulators and vertical-gap linear undulator
  - Narrow gaps make accumulation very difficult → swap out injection preferred
  - Collective effects can make on-axis injection challenging in 48-bunch mode

Impedance model of APS-U MBA

Geometric contributions

Sector (×40)		Ring	
Element	**Number**	**Element**	**Number**
Regular BPM	12	Injection kicker	4
ID BPM	2	Extraction kicker	4
ID transition	1	Feedback	2
Bellow	14	Stripline	1
Flange	52	Aperture	2
Crotch absorber	2	Fundamental cavity	12
In-line absorber	15	Rf transition	4
Gate valve	4	4^{th} harmonic cavity	1

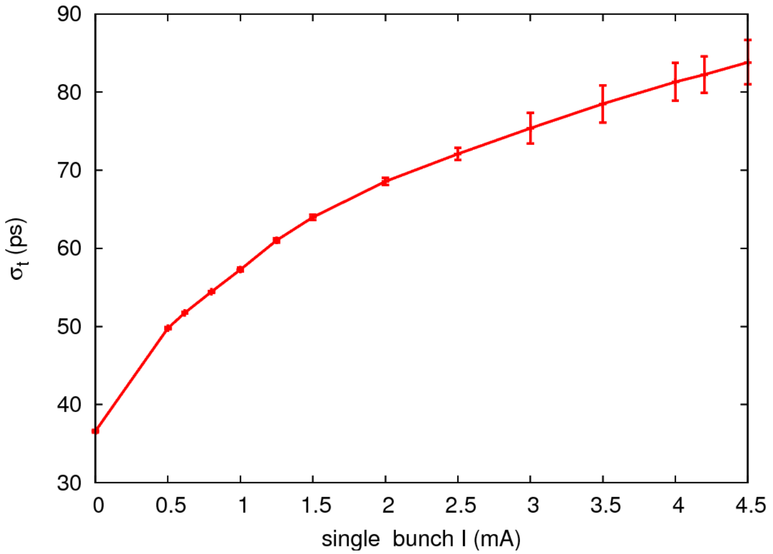
Dominant sources of longitudinal wakefields

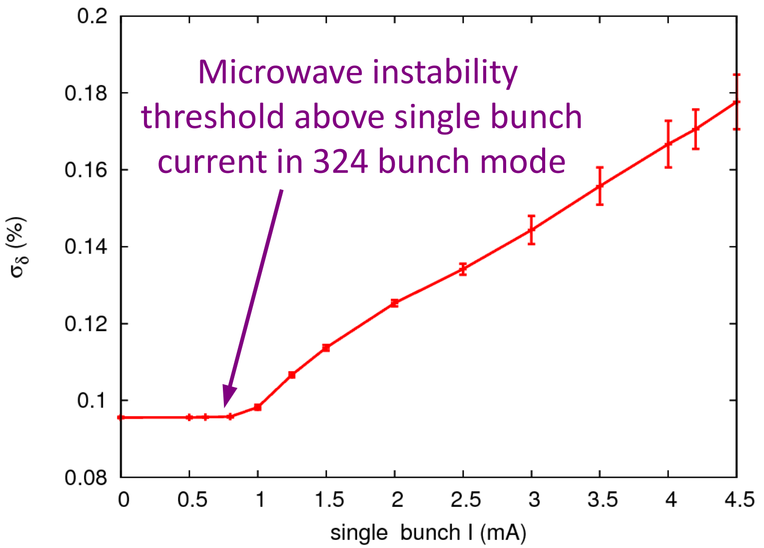
Resistive wall

Metal	Diameter	Length
Cu	22 mm	224 m
Al	22 mm	605 m
SS	22 mm	80 m
Al	6 mm	175 m
Al	140 mm	20 m

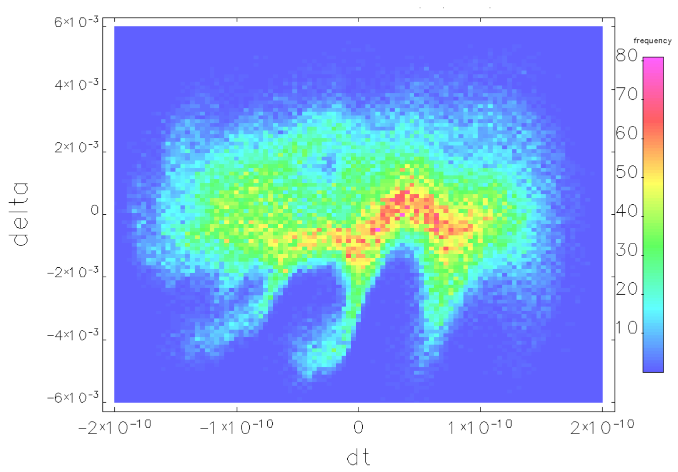
Dominant source of transverse wakefields

Longitudinal collective effects at the APS-U: bunch lengthening and energy spread increase



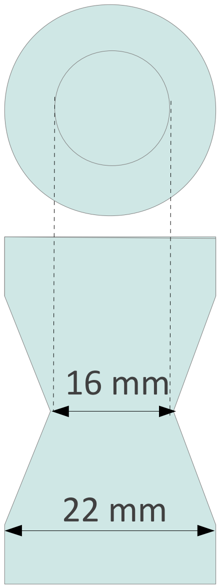


Longitudinal phase space at 4.2 mA/bunch is very turbulent with ~10% fluctuations in energy spread and bunch length

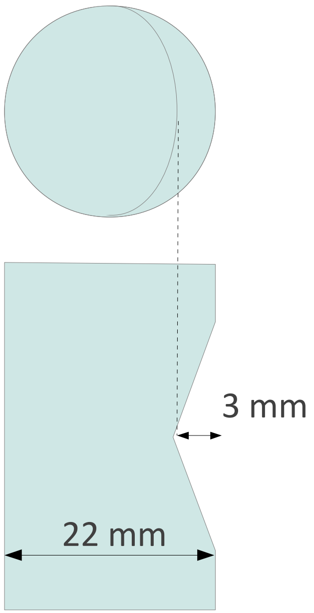


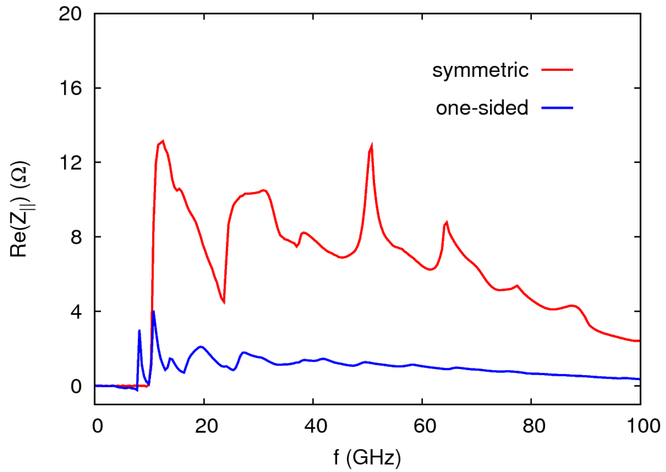
Reduction in longitudinal impedance by making in-line photon absorbers asymmetric

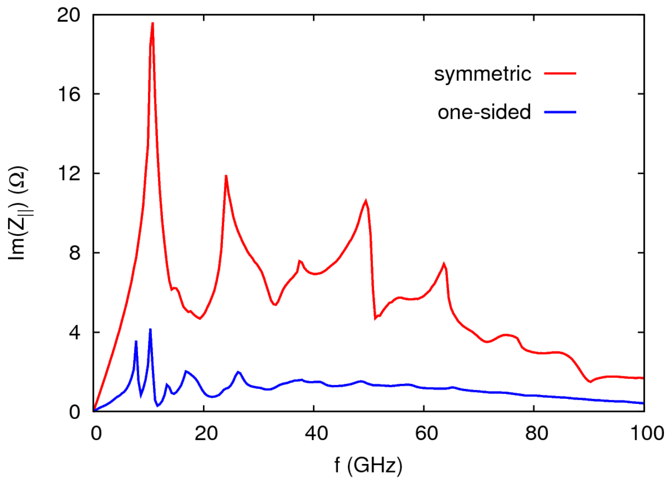
Nominal design:
Axially symmetric reduction from 22 mm diameter to 16 mm diameter
(3 mm absorber height)



Asymmetric design:
3 mm absorber constriction on one side only



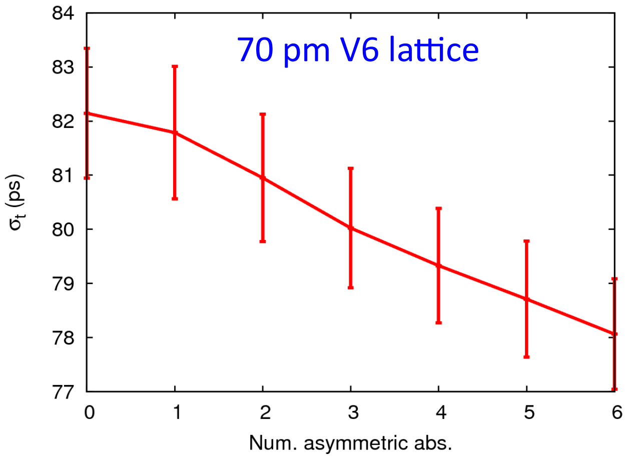


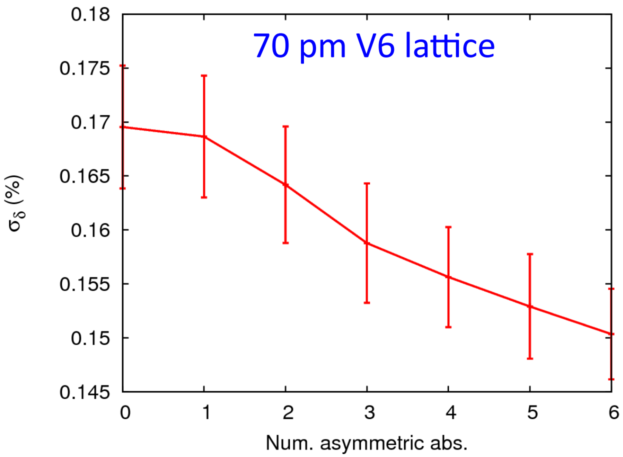


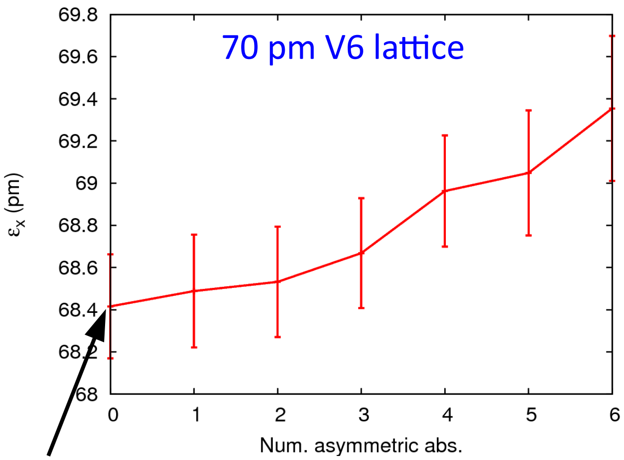
First suggested by vacuum group, but I was concerned with potential emittance growth

Asymmetric absorbers reduce effect of microwave instability while slightly increasing the emittance

- Simulation uses ILMATRIX + summed ring impedance to find equilibrium bunch length, energy spread, and emittance
- I have only considered changing absorbers whose local x-beta function is less than that of the ID – we expect the effect to scale $\sim \sqrt{\beta_x}$, but have not yet verified this







Includes monopole wakes from asymmetric crotch absorbers

Large energy spread and bunch lengthening lead to stability from usual transverse instabilities

- The various lattice options appear to stably store equilibrium bunches of almost 4 mA at a chromaticity of 3 units
- At the design chromaticity of 5 units, the lattices appear to be able to store > 7 mA/bunch in equilibrium
- However, simulations of injection from the booster give different answers since initial beam is NOT in equilibirum
  - Emittance is 10^3 times larger → stronger nonlinearities
  - Energy spread in 50% smaller → tumbling in longitudinal phase space
- While we saw some indication that the stability threshold does not equal the stably stored injection current, the effect appears to be larger then previously thought and to to depend on the method of simulation...

Including collective effects at injection appears to require high-fidelity simulations

- Previous experience at APS showed that transverse instability current thresholds are relatively insensitive to simulations specifics
  - True provided one has all relevant sources of longitudinal and transverse dipole/quadrupole impedance is identified
  - Linear dynamics ≈ nonlinear maps
  - Predictions are largely independent of initial phase space distribution/initial conditions
- MBA lattice has larger nonlinearities, more significant higher-ordedr chromatic effects, larger energy spread from microwave instability, and larger emittance mismatch from booster to ring
- Recent tracking simulations show that many of the previous assumptions are not valid for the MBA at injection
  - `ILMATRIX` does not appear to have enough physics...

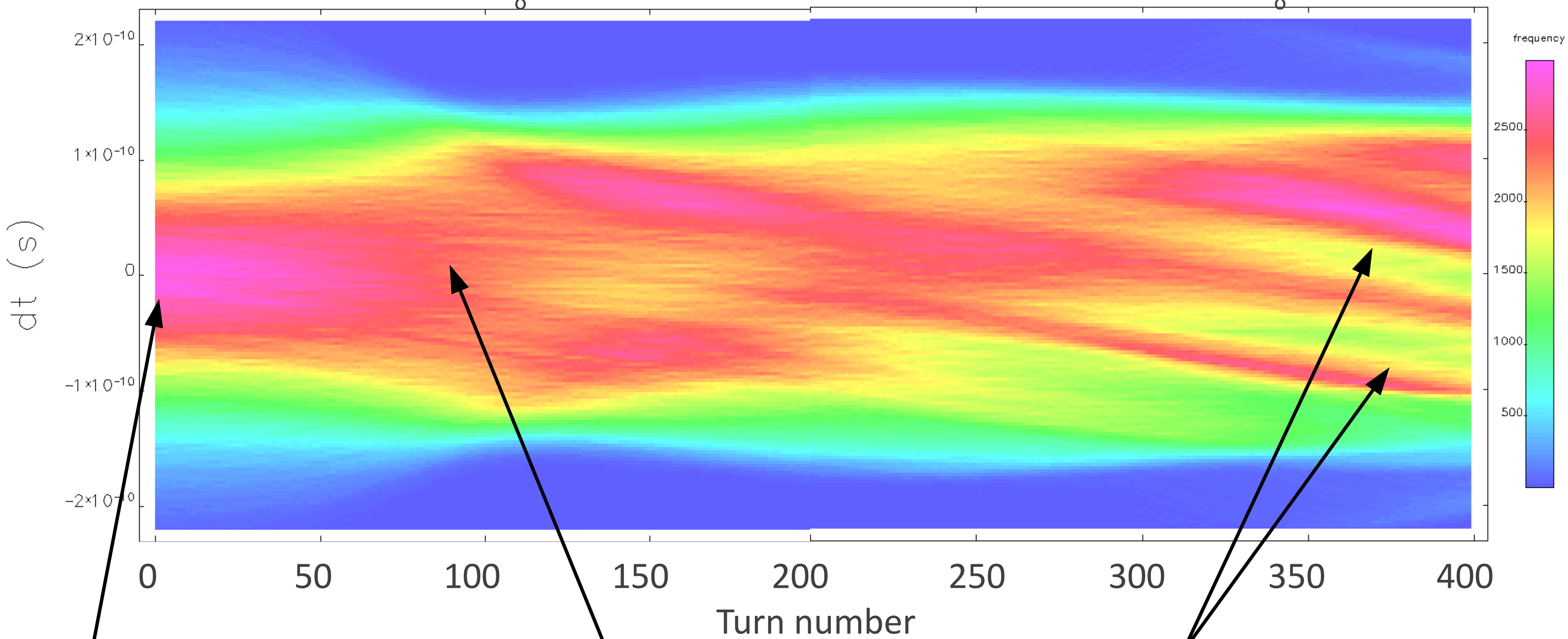
Since element-by-element tracking is so computationally intensive this claim is still under review

Simulating injection with collective effects

- Initialize phase space with the parameters from the booster
  - Gaussian with energy spread = 0.12%, bunch length = 24 mm, emittance = 60 nm
  - Include transverse offset of beam
    - 200 microns in x and y for on-axis injection to account for kicker errors
    - 2.1 mm in x if we are trying accumulation
- Track element-by-element through lattice
- Simulate synchrotron emission as a lumped SREFEECTS element
- Include impedance in several different ways
  - Once per turn as done previously
  - Once per sector
  - Include impedance elements within each sector at the following points
    - At each sector ID midpoint
    - At the 2 P0 (narrow gap) BPMs
    - At all 12 normal aperture BPMs
    - At one bonus absorber location in the FODO section
- Typically neglect physical apertures to see full dynamics w/o particle loss

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

Initial (booster) σ_δ = 0.12%, while at 4.2 mA the equilibrium σ_δ = 0.18%



Initial Gaussian bunch from booster

Turbulent onset from longitudinal impedance

Longitudinal structure from microwave instability

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

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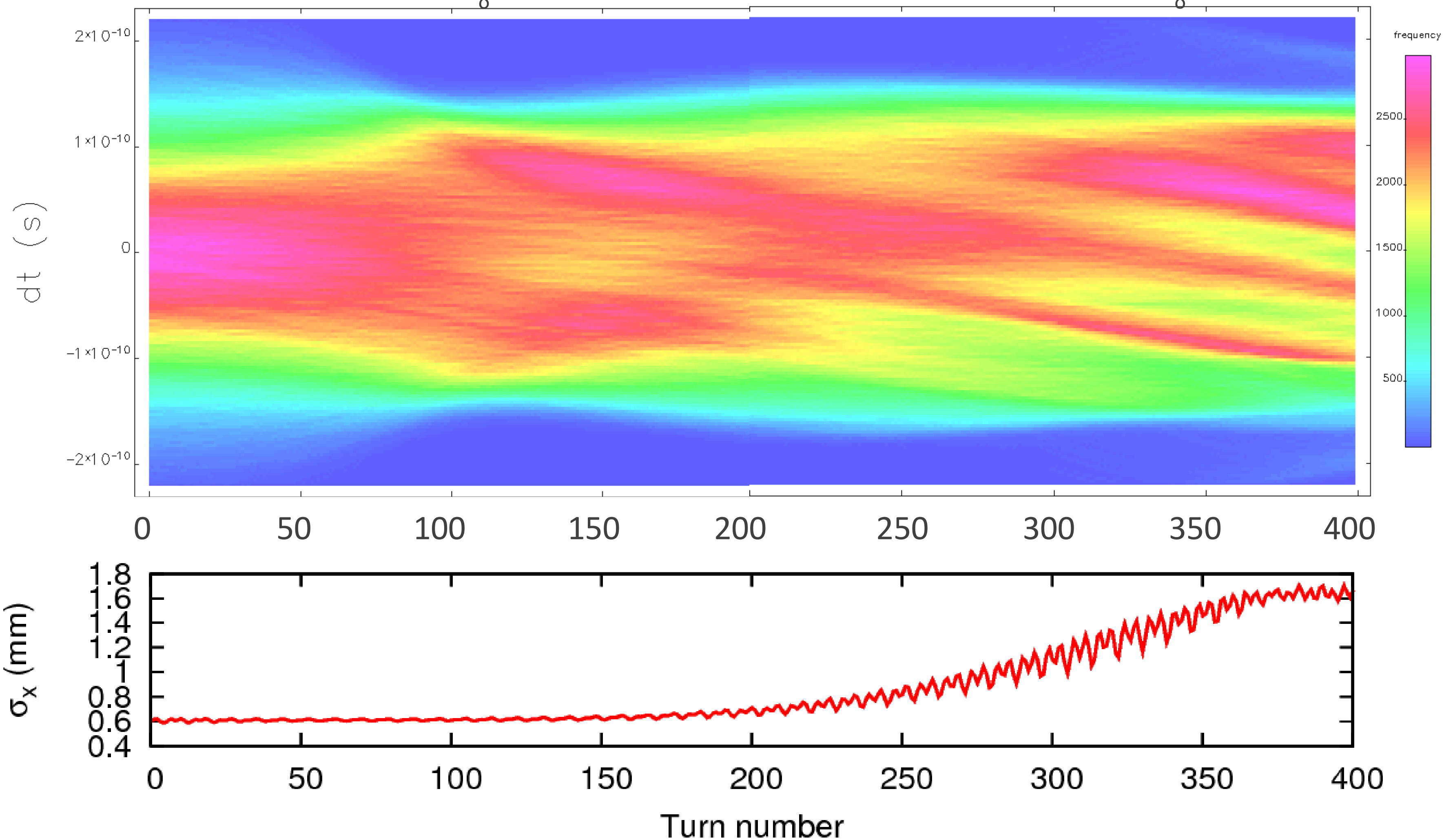
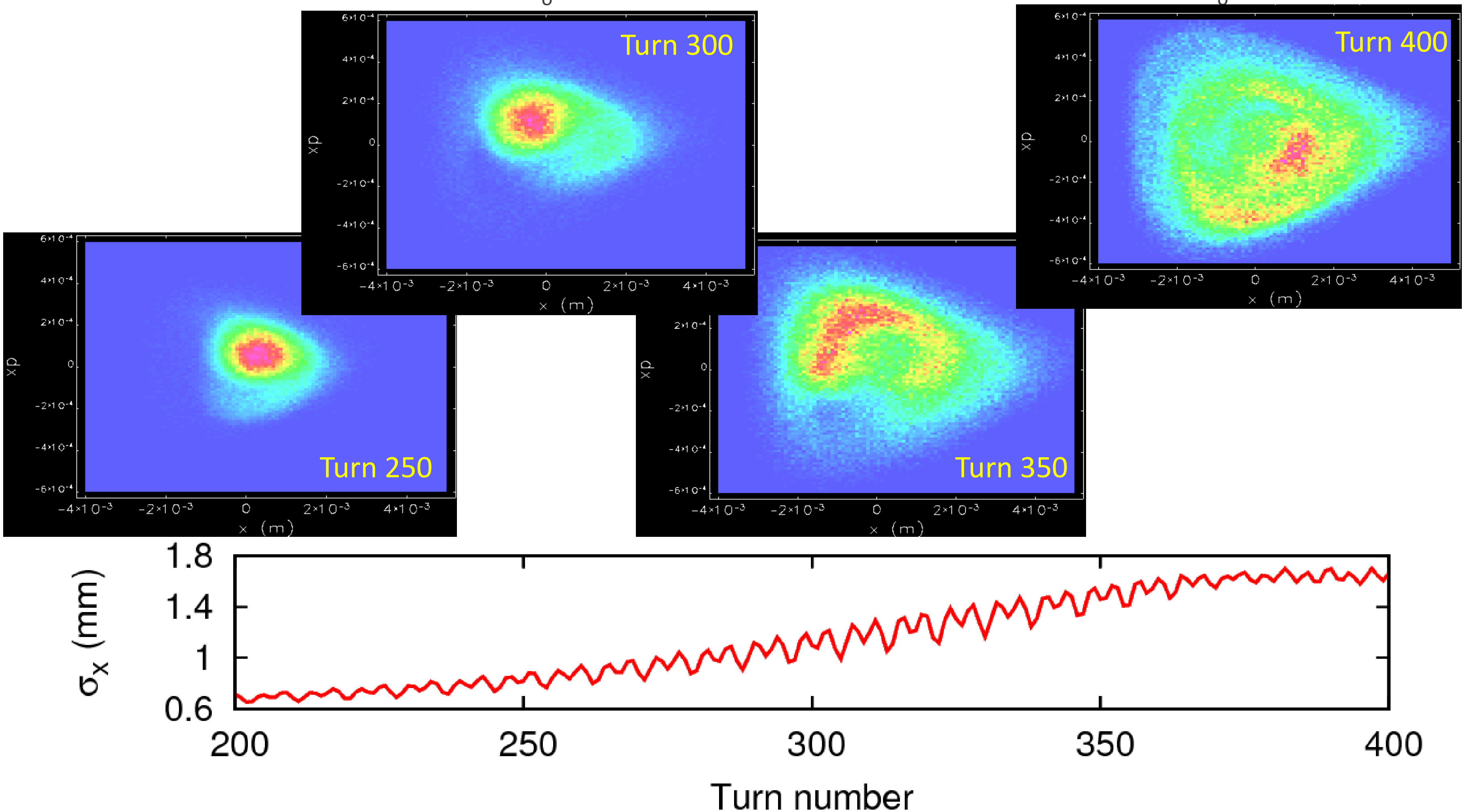


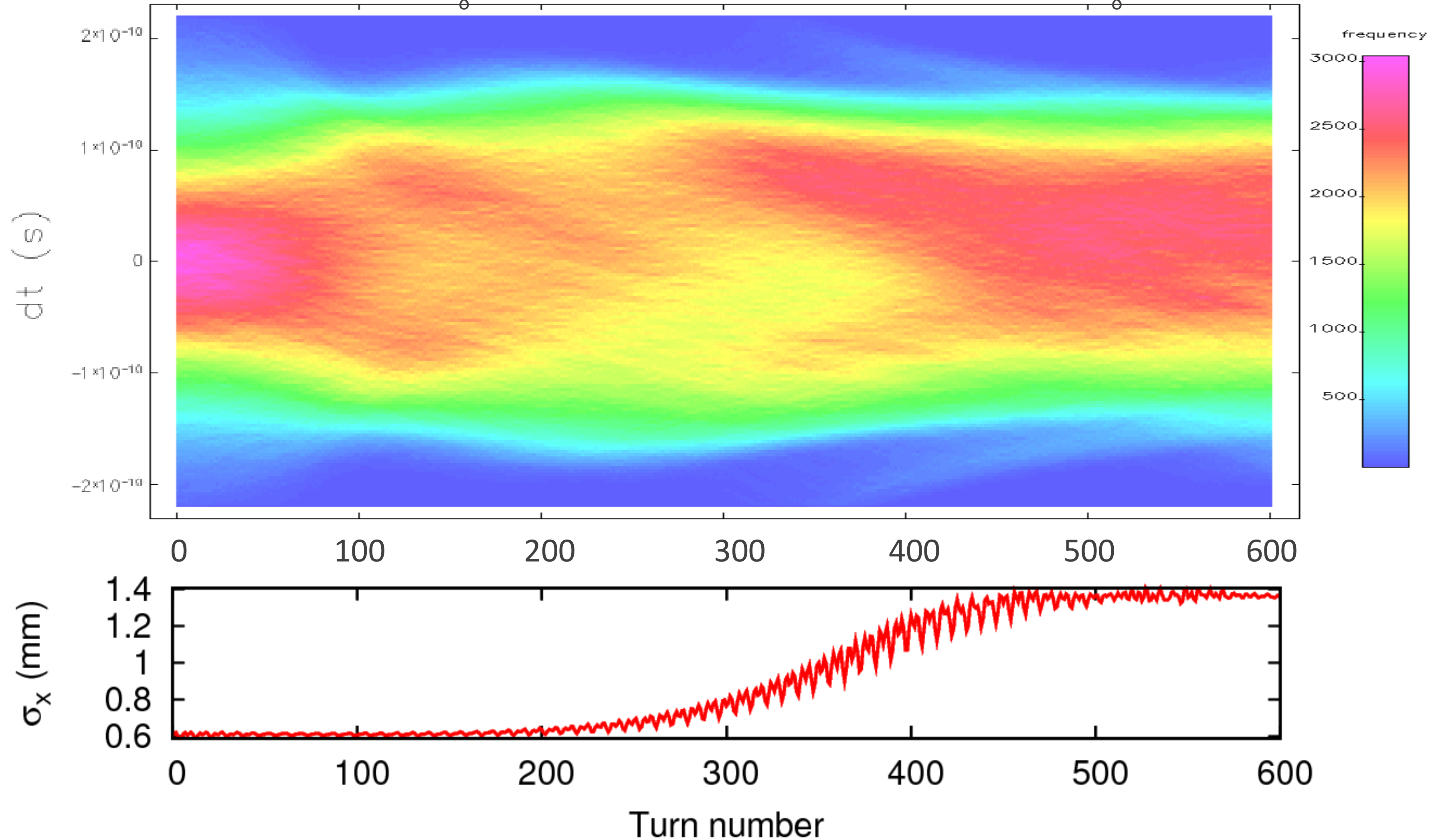
Longitudinal mismatch + impedance leads to longitudinal structure that drives emittance growth

Initial (booster) σ_δ = 0.12%, while at 4.2 mA the equilibrium σ_δ = 0.18%

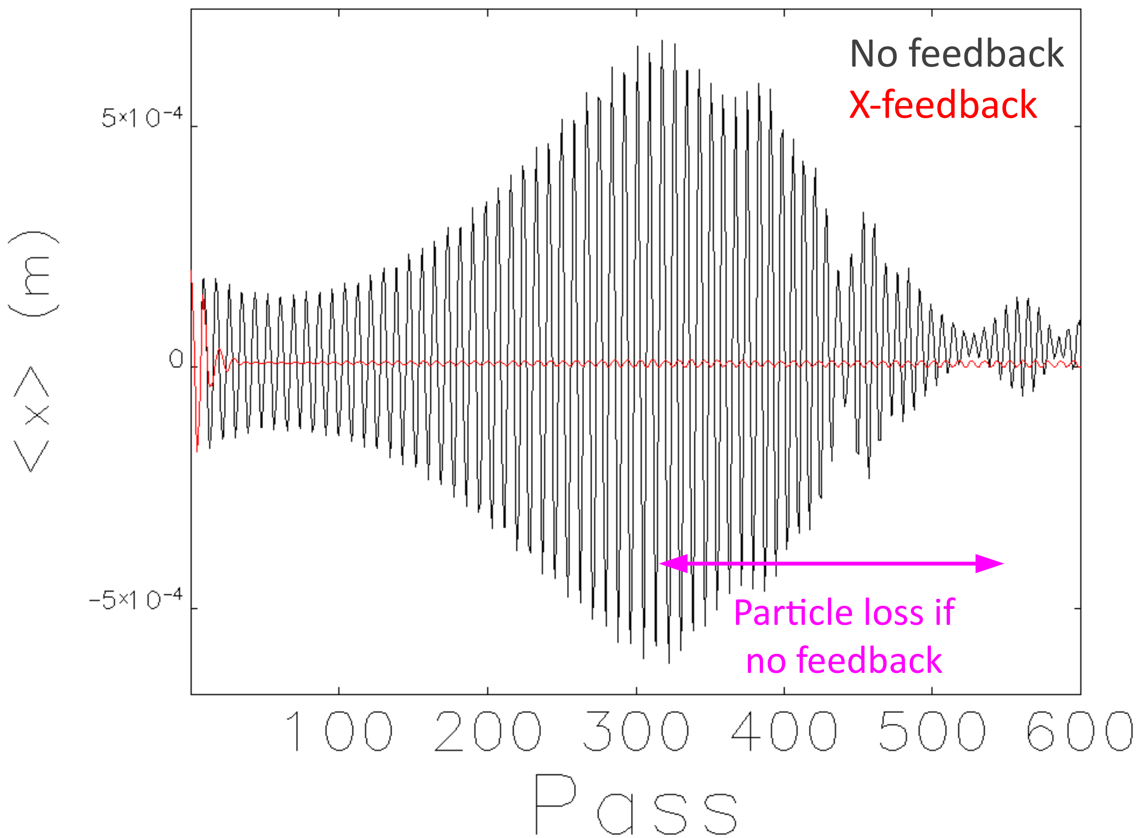


"Matching" longitudinal phase space reduces longitudinal structure and emittance growth

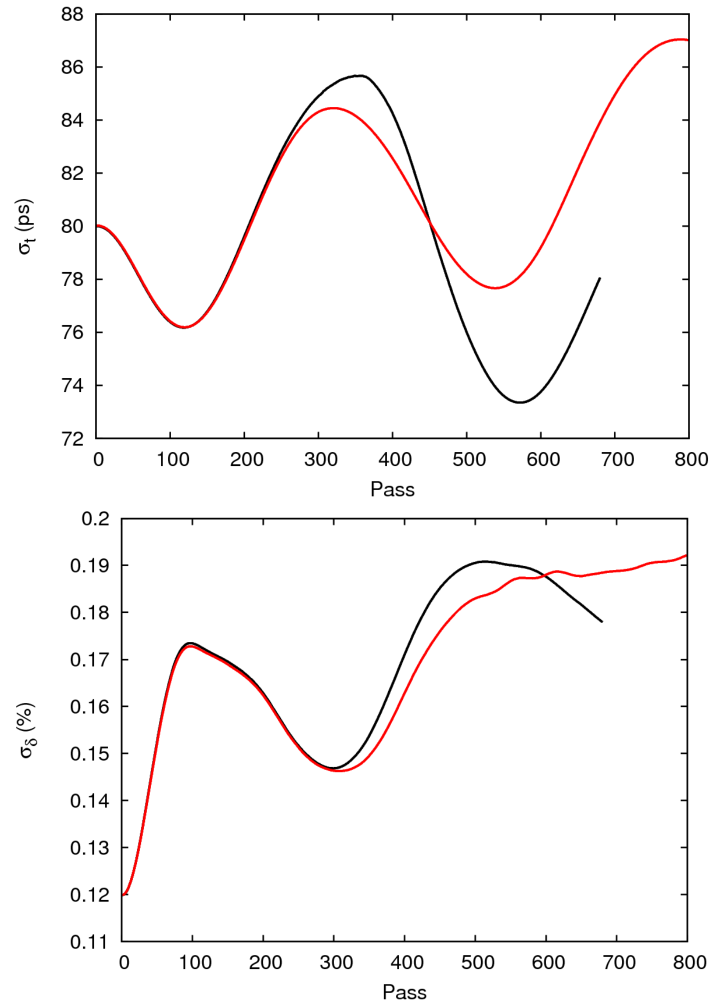
Initial (booster) σ_δ = 0.18% equals the 4.2 mA equilibrium σ_δ = 0.18%



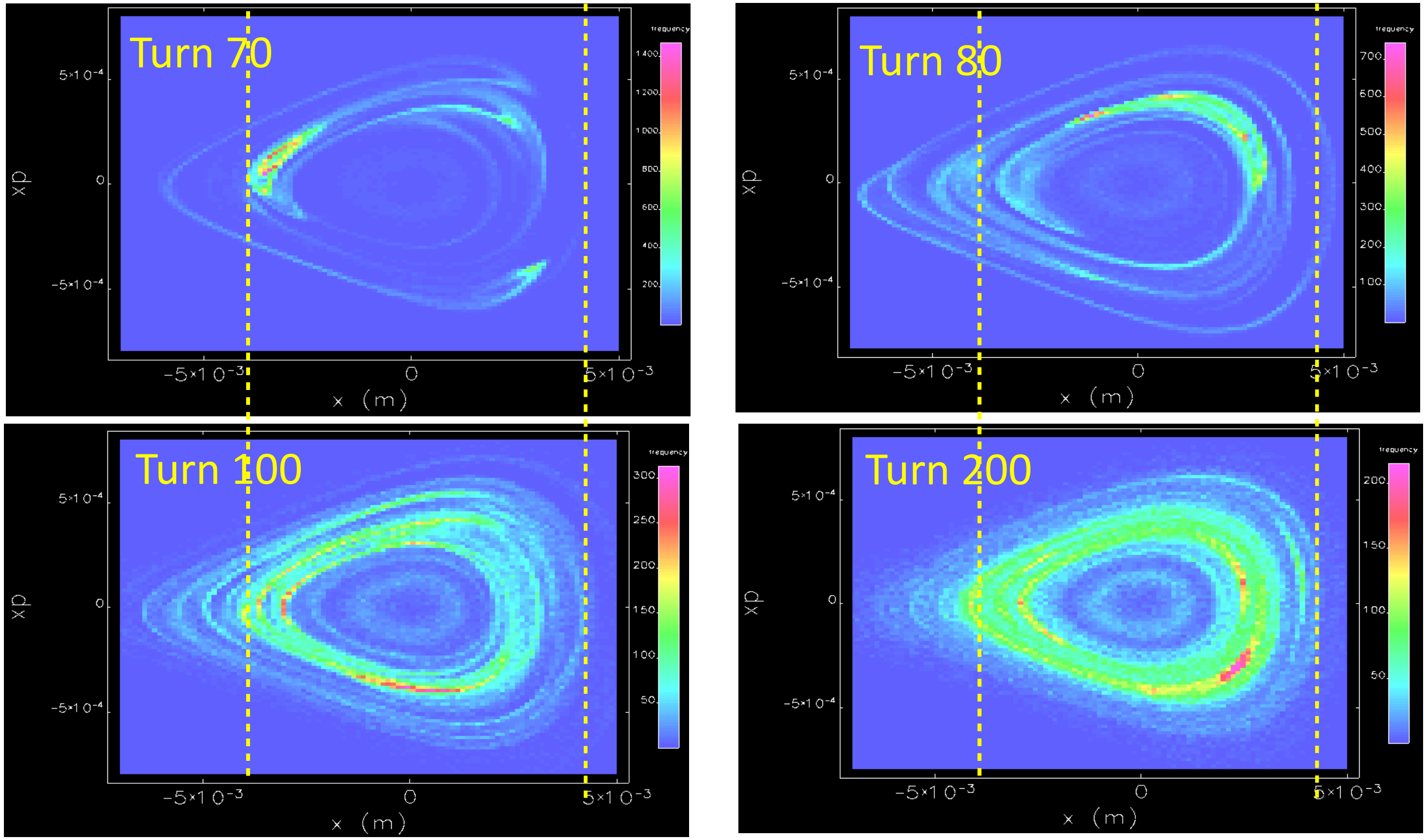
Transverse feedback can eliminate transverse oscillations and particle loss



Longitudinal evolution differs due to differing amounts of particle loss

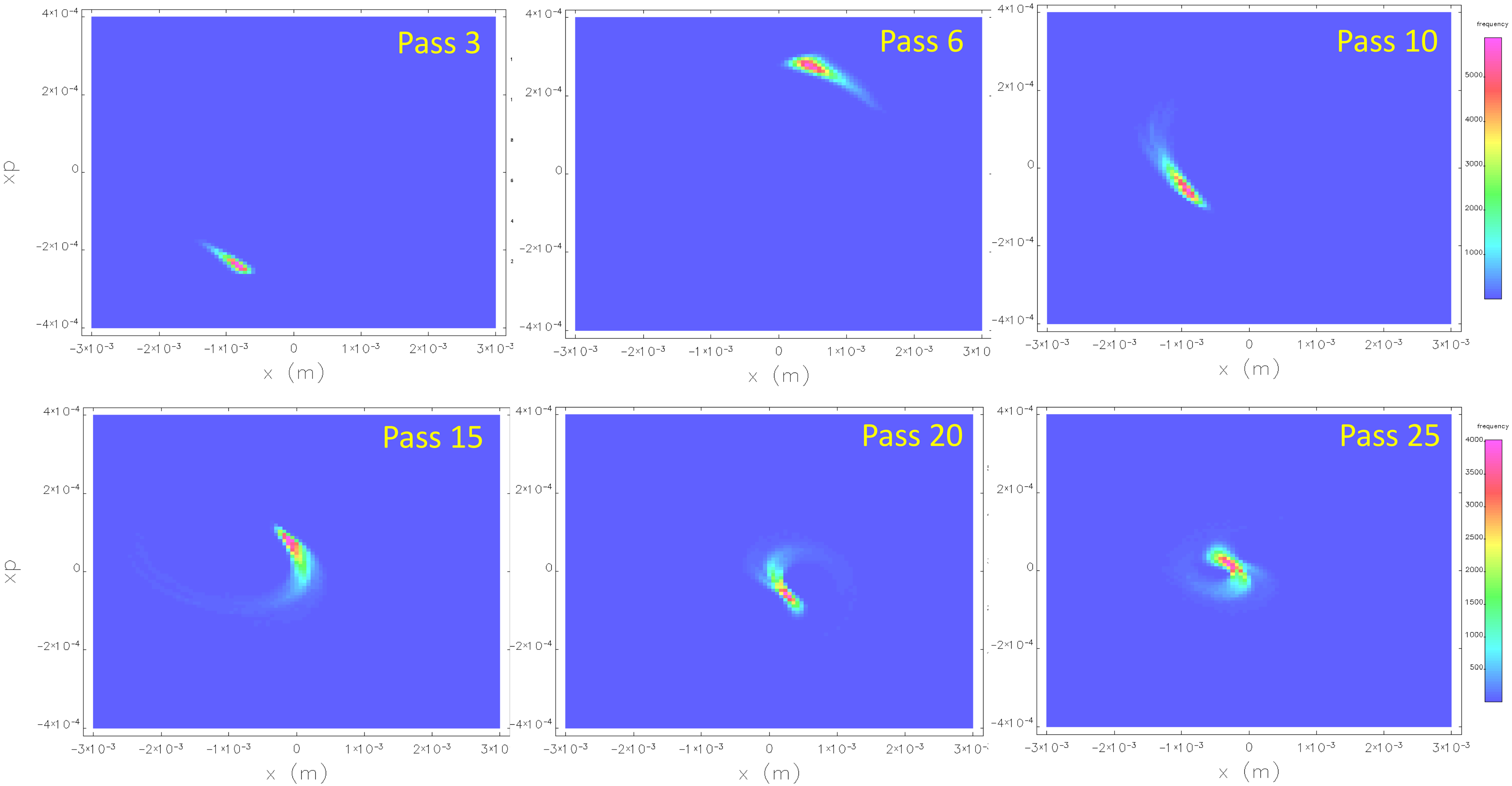


Collective effects make accumulation in 48 bunch mode (4.2 mA/bunch) very challenging (90 pm Alt)



- Basic physics could have been anticipated by previous APS measurements showing that the dynamic acceptance depends on the bunch charge
- These effects are unimportant in 324 bunch mode (0.62 mA/bunch)

Feedback greatly improves injection efficiency, and may make accumulation feasible



Still, 0.35 nC lost – I need to check if it's from the stored/injected/both, how it depends on the injected charge

Future plans and outlook

- We think we have a reasonably reliable method for simulating collective effects in 3rd generation storage rings
- We believe that this experience proves that we are able to identify and model the relevant sources of impedance and wakefields
- Simulations of the resulting collective effects in the ring are progressing
- Recent simulations indicate that collective effects are a real issue at injection
  - Large mismatch in booster and ring phase space
  - Feedback appears to cure instabilities for on-axis injection
  - Accumulation will be even more difficult: collective effects may preclude accumulating 4.2 mA/bunch in a ring with small horizontal gap apertures
- Now is an exciting (terrifying) time in simulating collective effects for ultra-low emittance storage rings
  - We are developing new simulation methods to attack these problems
  - We are learning a lot about complicated dynamics
  - We don’t yet have all the answers