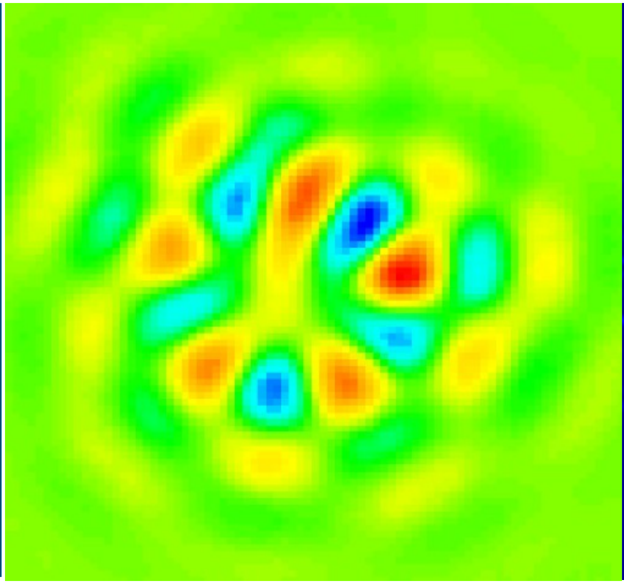
Collective effects at injection into small aperture storage rings: pros and cons of on-axis swap-out vs off-axis accumulation injection schemes



Ryan Lindberg

Accelerator Systems Division, Argonne National Laboratory

I.FAST Low Emittance Rings Workshop 2024
CERN, Geneva, Switzerland. Valentine's Day, 2024

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Outline and acknowledgments

- Some pros and cons of accumulation vs swap-out injection
- Collective effects during shared-oscillation accumulation
  - Emittance growth and reduction of dynamic acceptance
- Collective effects during swap-out injection
  - Transverse oscillations due to mismatch + wakefields
- Conclusions

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- Acknowledgments
  - Michael Borland, Joe Calvey, Louis Emery, and Vadim Sajaev (APS/ASD)
  - Seunghwan Shin (Pohang Accelerator Lab)
  - Weed cluster at ASD + `elegant` tracking code[1]

[1] M. Borland. "`elegant`: A Flexible SDDS-Compliant Code for Accelerator Simulation," LS-287 (2000)

Motivation

- Nonlinear dynamics present major challenges for ultra-low emittance lattices
  - Need adequate dynamic acceptance for high injection efficiency and long elastic gas scattering lifetime
  - Need adequate local momentum acceptance for long Touschek and inelastic gas scattering lifetimes
- Lower emittance is strongly correlated with reduced lifetime and injection aperture[2]

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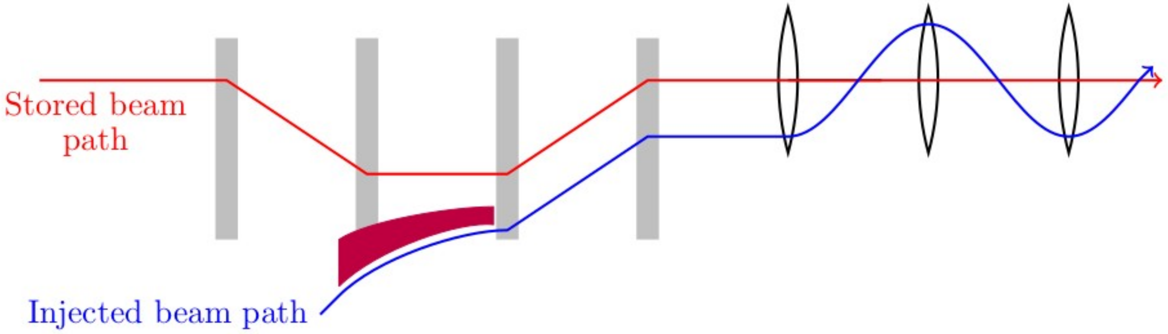

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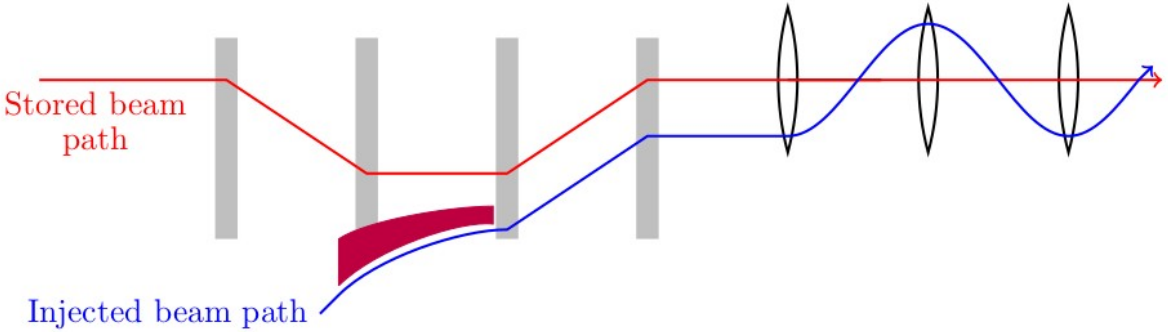
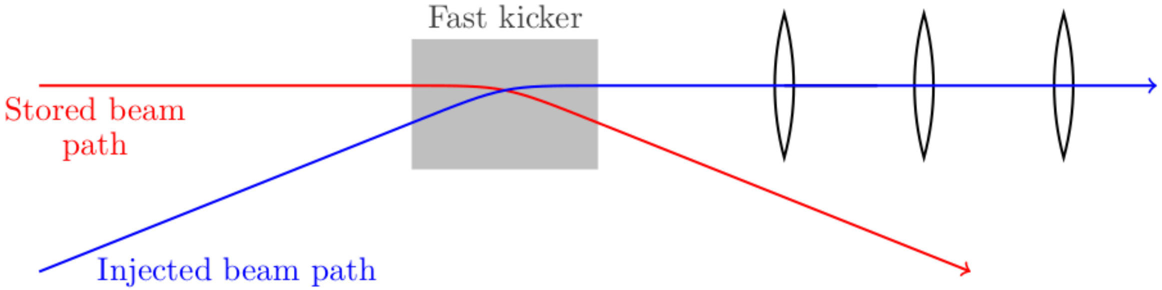
- Swap-out[5,6] accommodates drastically reduced injection aperture
  - Allows optimization that emphases Touschek lifetime over dynamic acceptance





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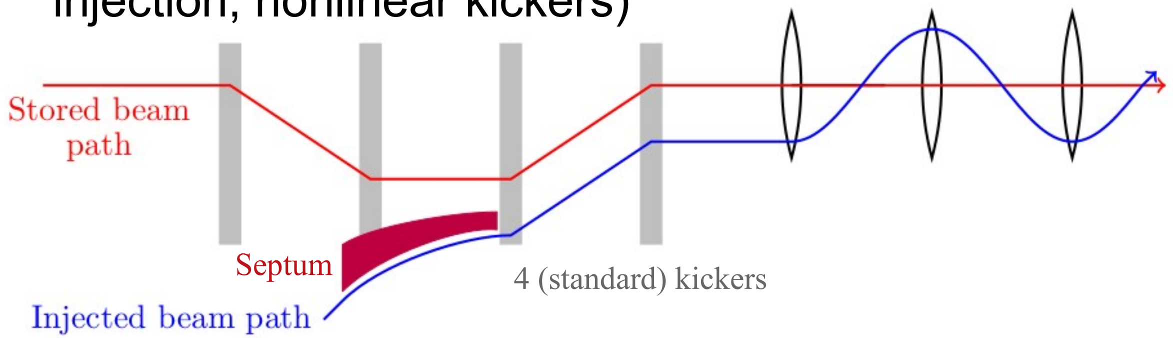
[5] R. Abela, W. Joho, P. Marchand, S.V. Milton, and L.Z. Rivkin. “Design Considerations for a Swiss Light Source (SLS),” Proc. of the 1992 European Particle Accel. Conf.,pp. 486.
[6] L. Emery and M. Borland. “Possible long-term improvements to the Advanced Photon Source,” Proc. of the 2003 Particle Accel. Conf. pp. 256..

Comparison of accumulation and swap-out

- Traditional accumulation (applies to multipole injection, nonlinear kickers)



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Modest injected charge/subsequent collective effects ☺
Requires largest dynamic aperture ☹

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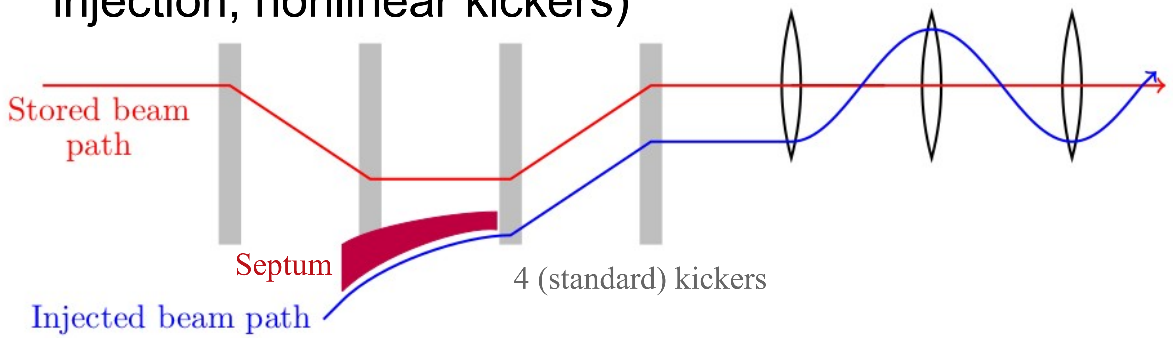

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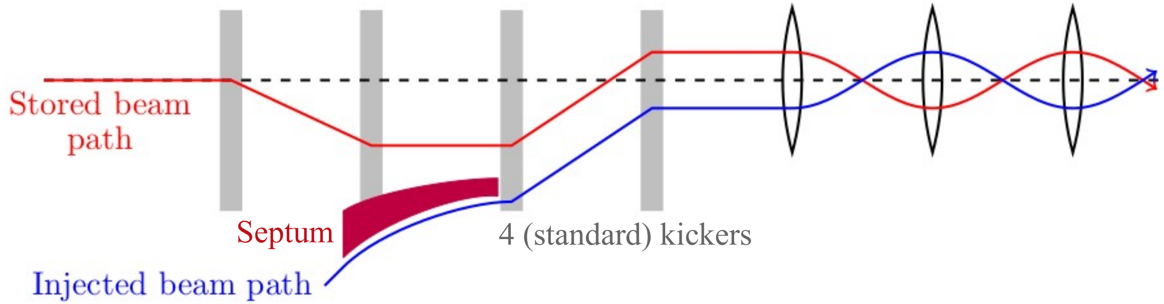

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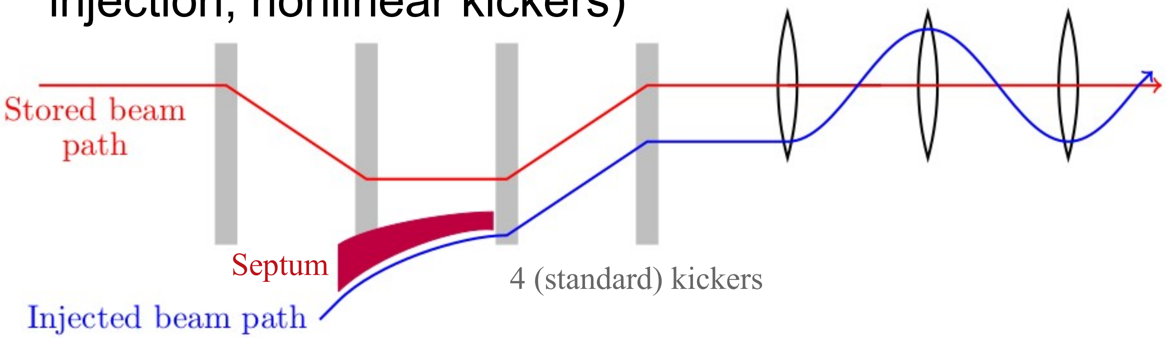

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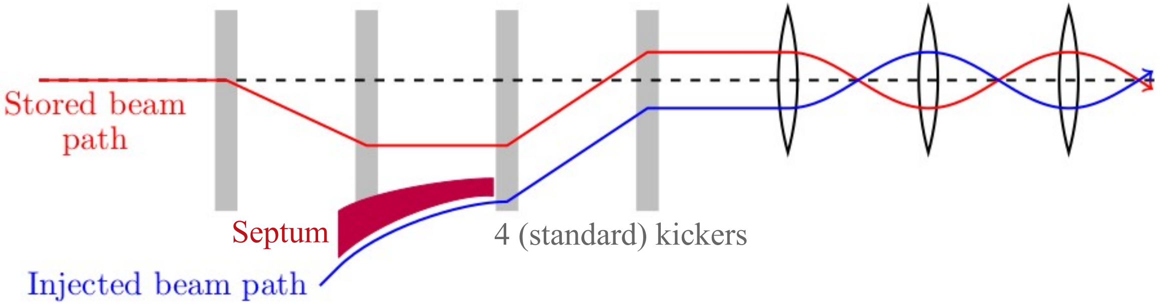

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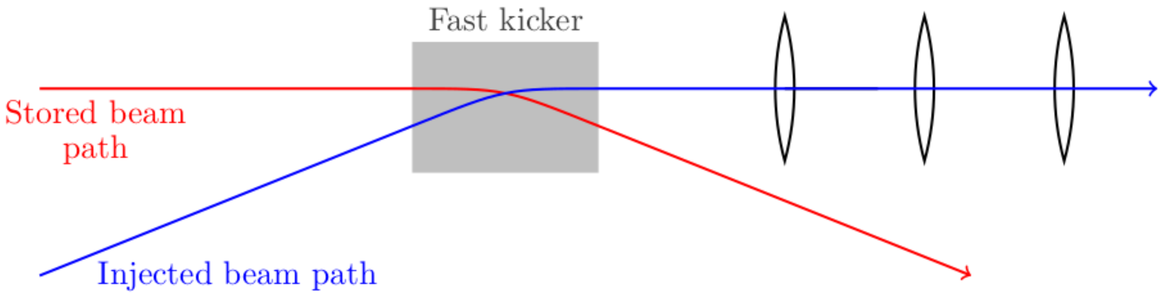

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On-axis collective effects are relatively small ☺
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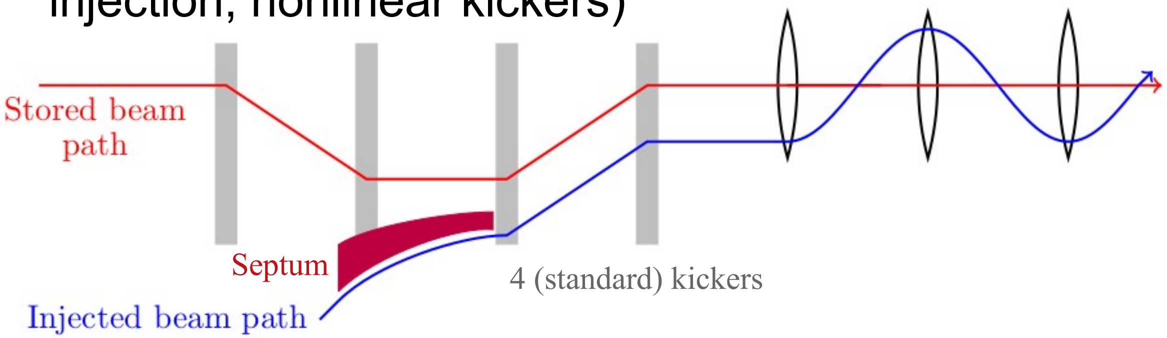

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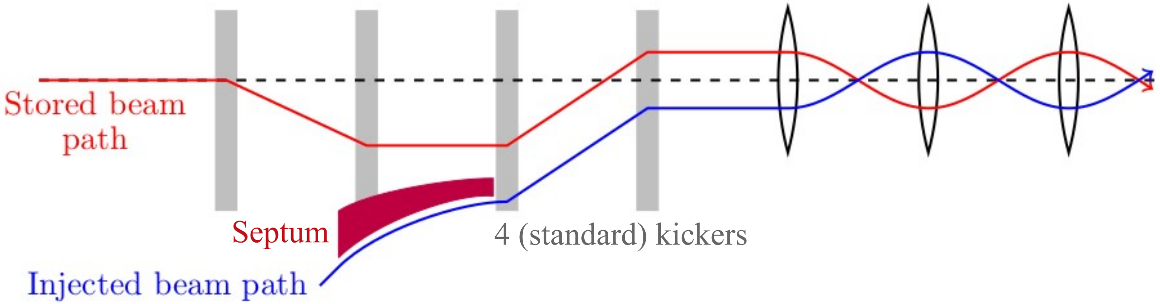

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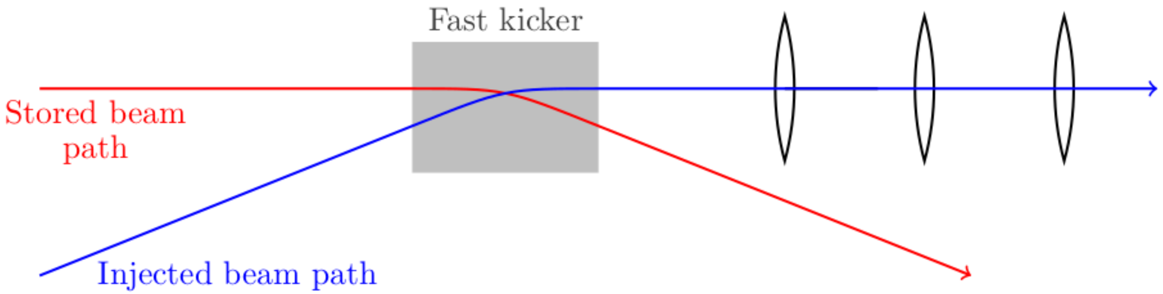

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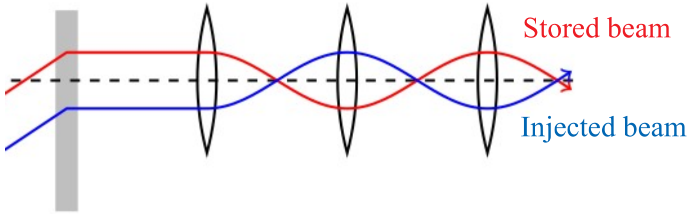
"If you can accumulate, you haven't pushed the lattice hard enough" – R. Hettel

At the very least, if you can accumulate, you could have pushed the lattice harder.

Collective effects can impact accumulation efficiency[7]

- The dynamic acceptance is typically considered from a single-particle perspective
- Transverse wakefields during traditional accumulation can reduce acceptance
  - Oscillating beam drives wakefields that can lead to emittance growth
  - Acceptance become “fuzzier” as charge increases
  - Net result will be a charge-dependent reduction of the injection efficiency



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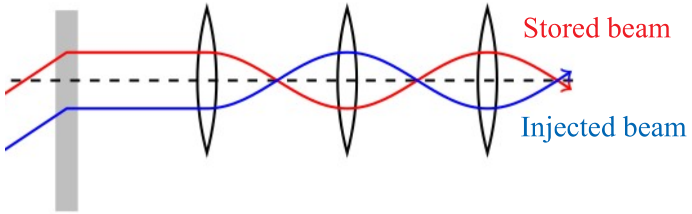

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  1. Inject fixed current (0.9, 2.3, and 4.1 mA) in a single bunch
     - Current is 0.63 mA (4.2 mA) in 324 (24) bunch mode
     - Stability limit during experiment was 5.3 mA
  2. Measure initial current with DC current transformer
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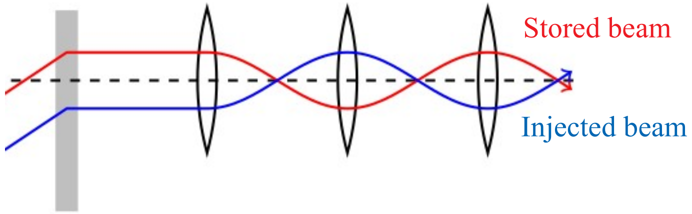

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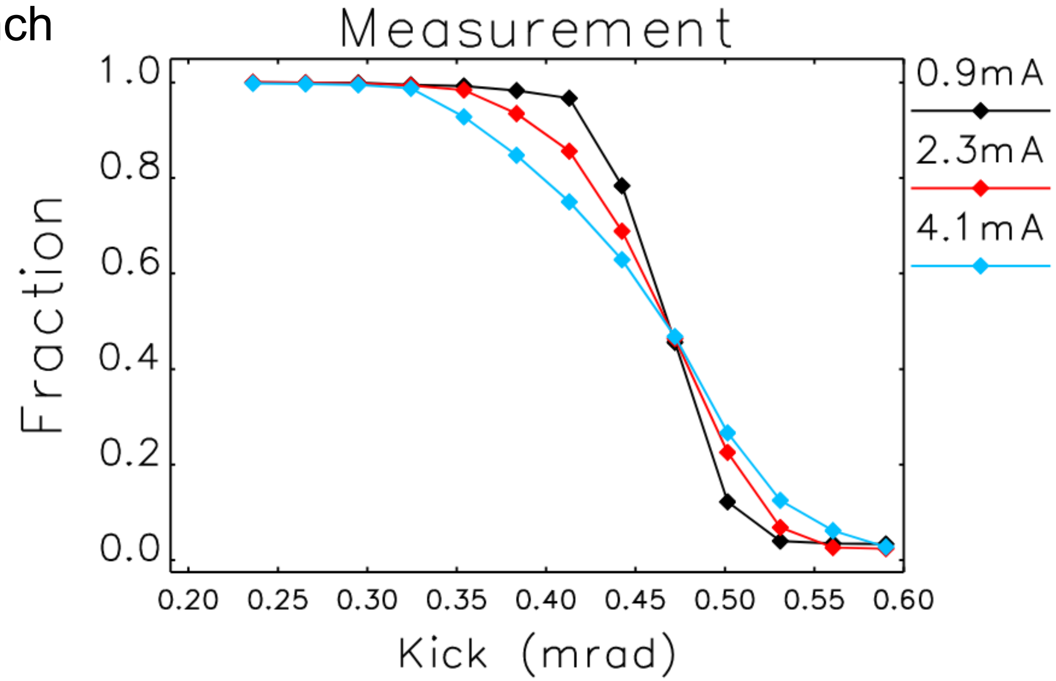

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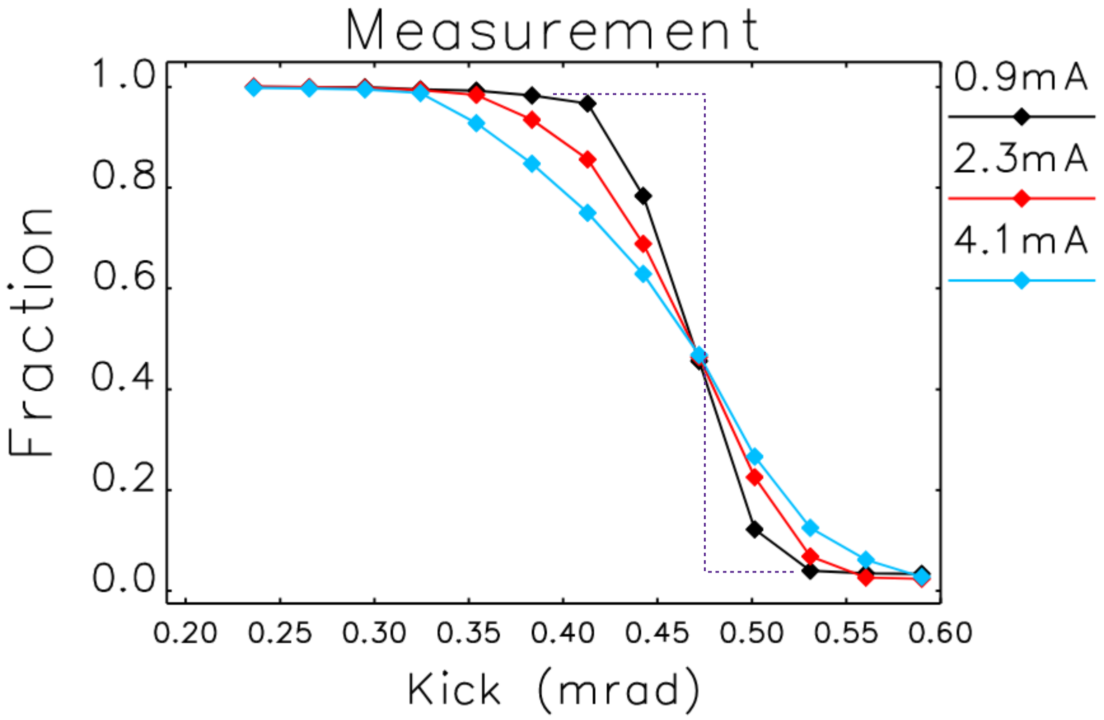
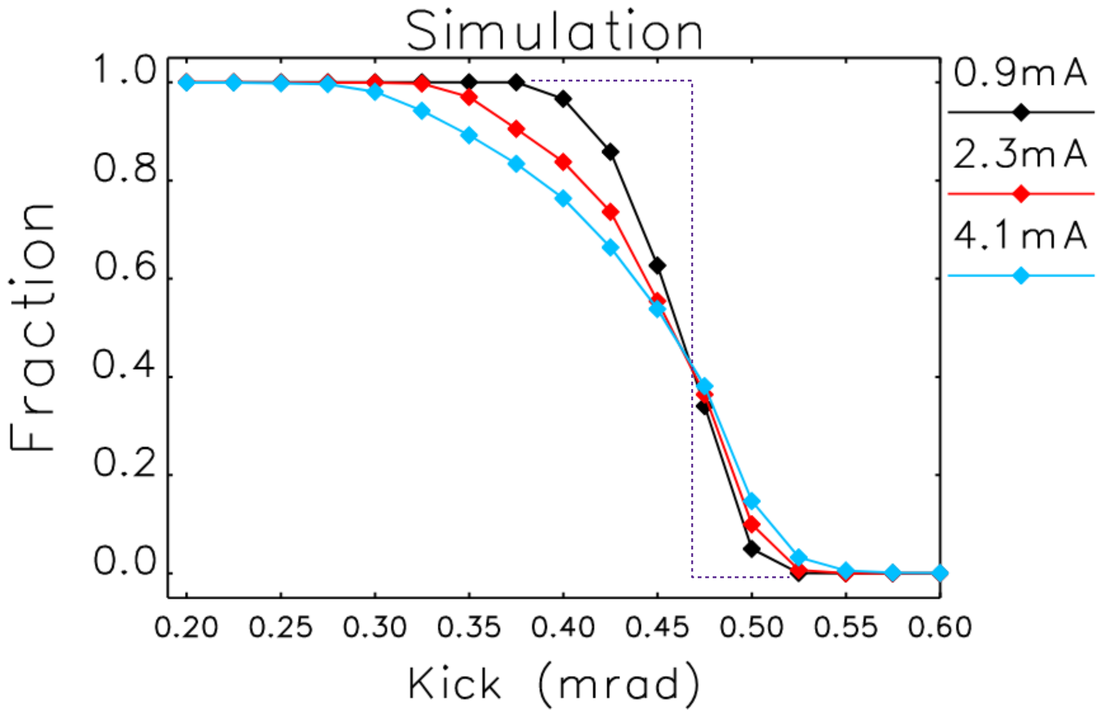
Measured and simulated dynamic acceptance





- “Single particle” result would be a sharp step function at ~0.47 mrad (purple dotted lines)
- “Zero charge” result is smoothed somewhat by the finite emittance of the injected beam
- Adding more charge smooths the distribution further due to projected emittance growth

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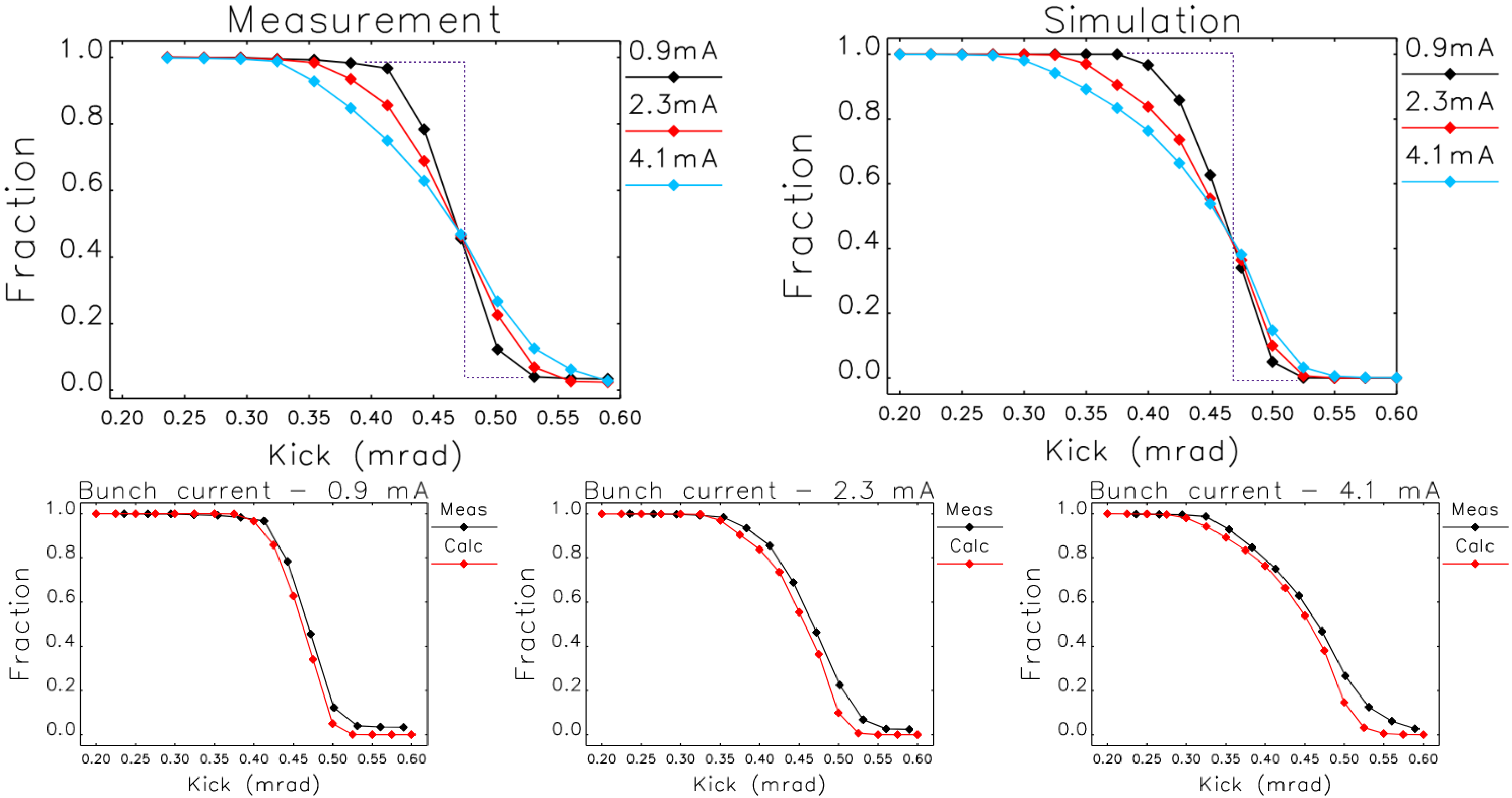
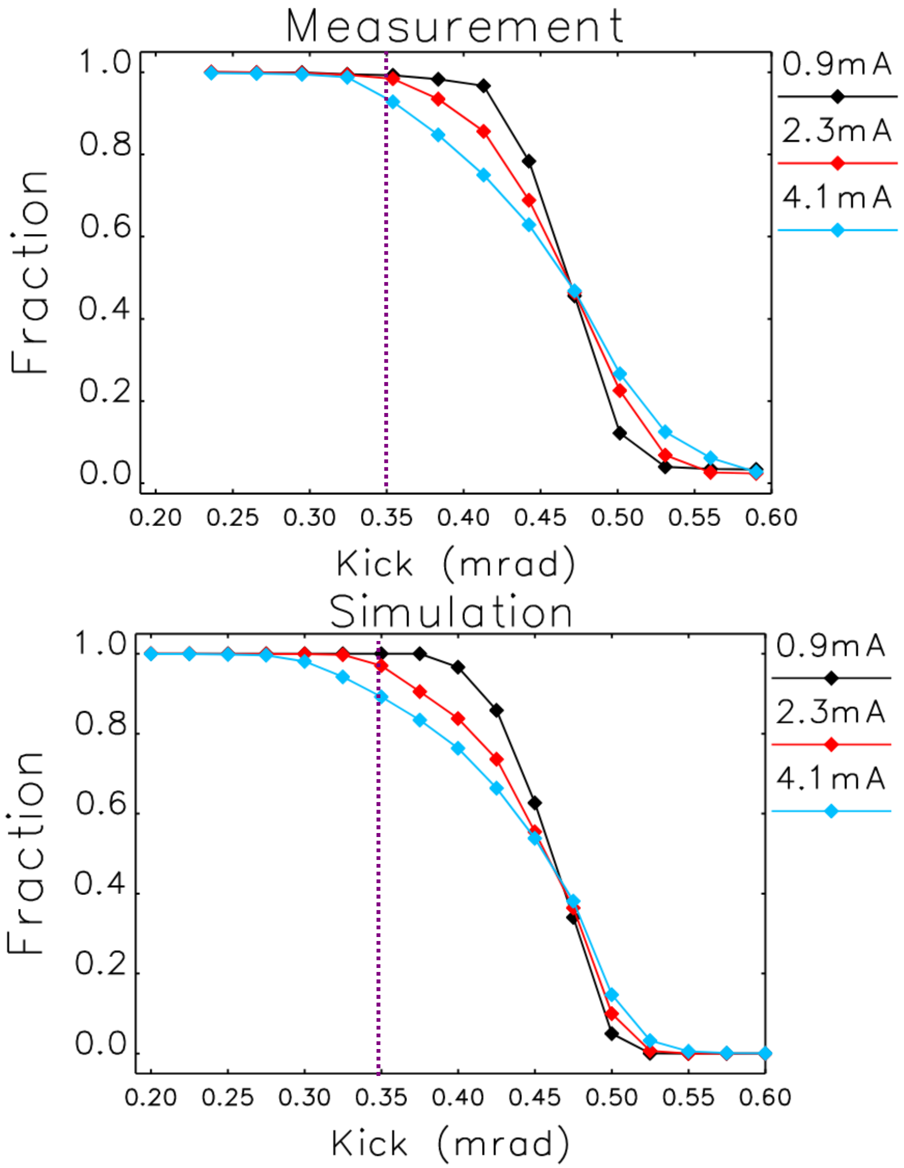
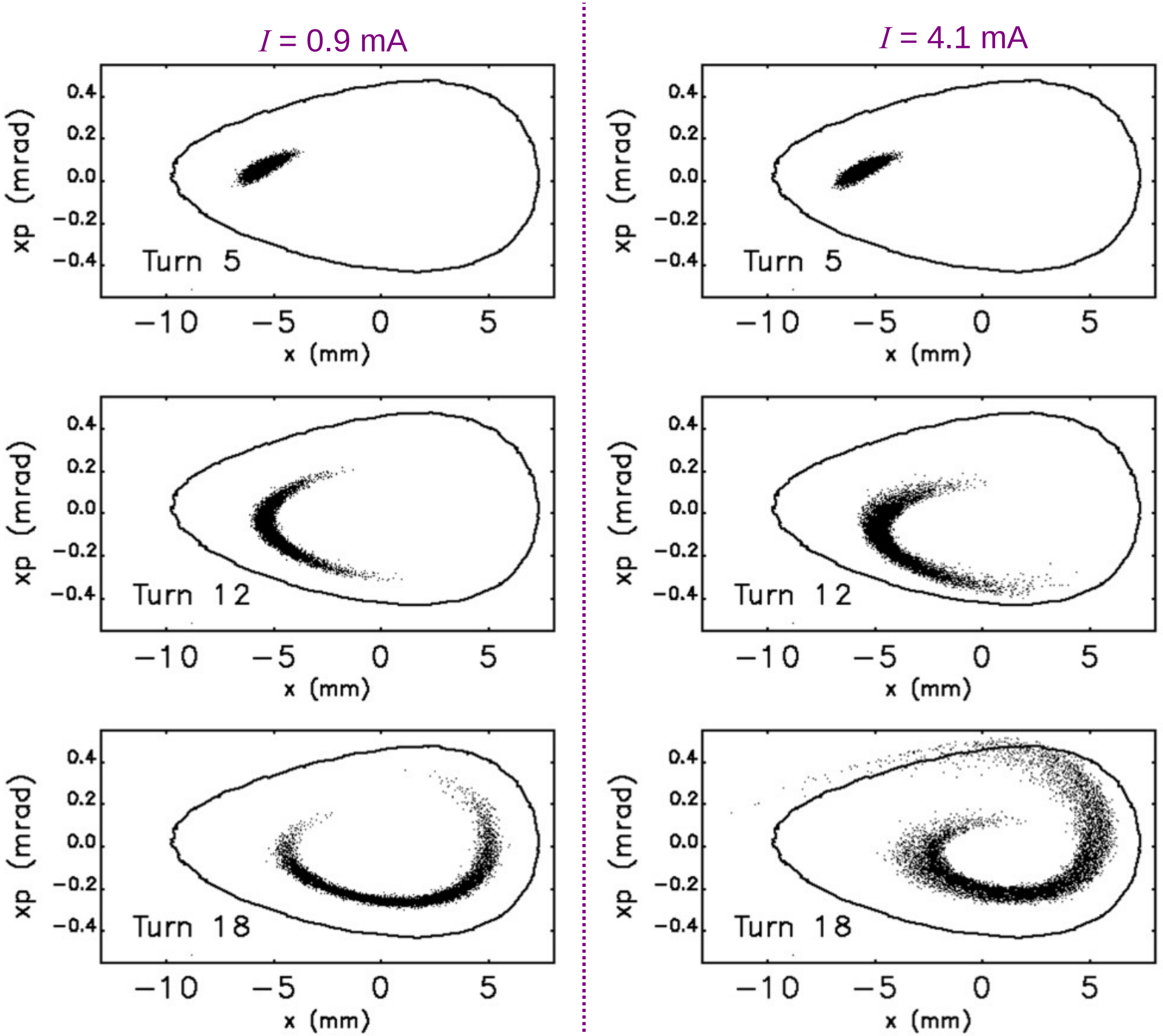


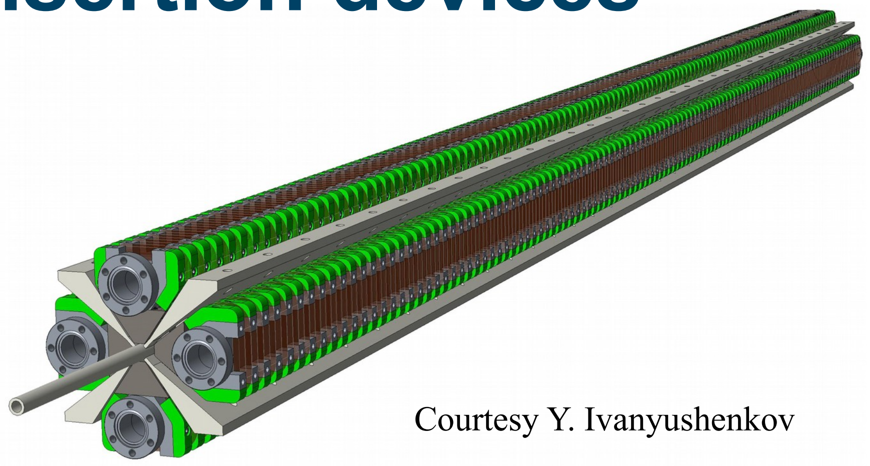
Particle dynamics for $\Delta x' = 0.35$ mrad





Collective effects during injection can limit dynamic acceptance and the choice of insertion devices

- Small dynamic aperture in low-emittance rings can naturally accommodate small physical apertures
- APS-U wants to install several narrow aperture devices like the Super Conducting Arbitrarily Polarized Emitter (SCAPE)
  - To achieve the required 10-mm (round) magnetic gap, chamber has a 6-mm inner diameter
- Could a 90 pm lattice accommodate this device with shared oscillation accumulation?



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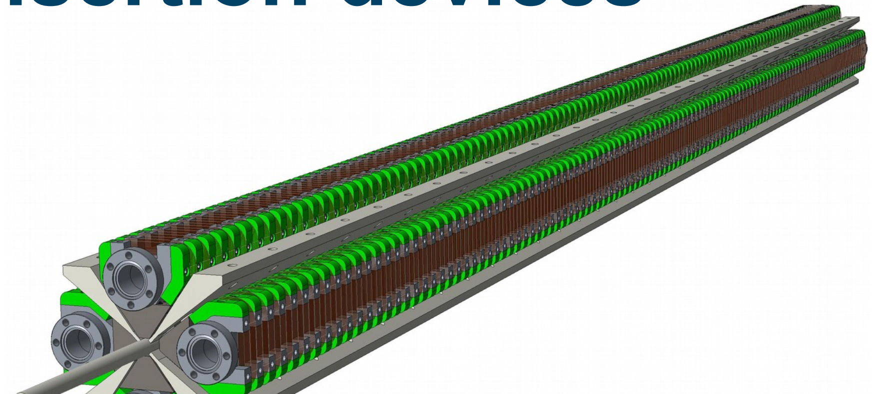

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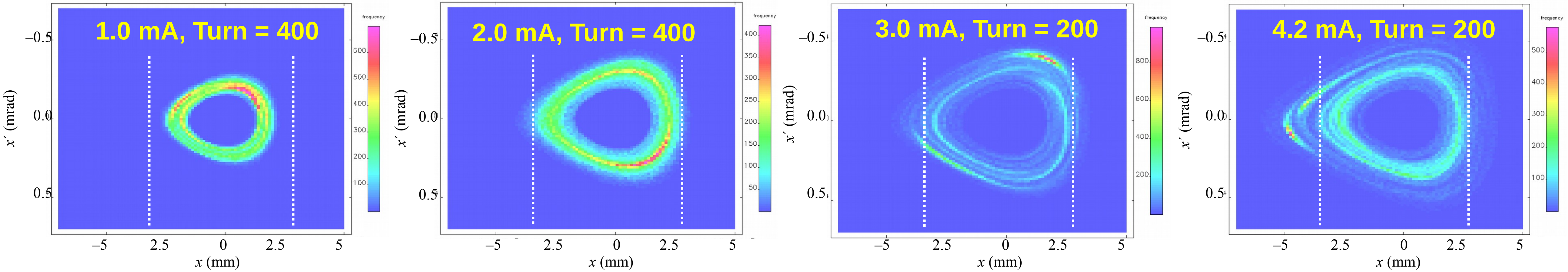
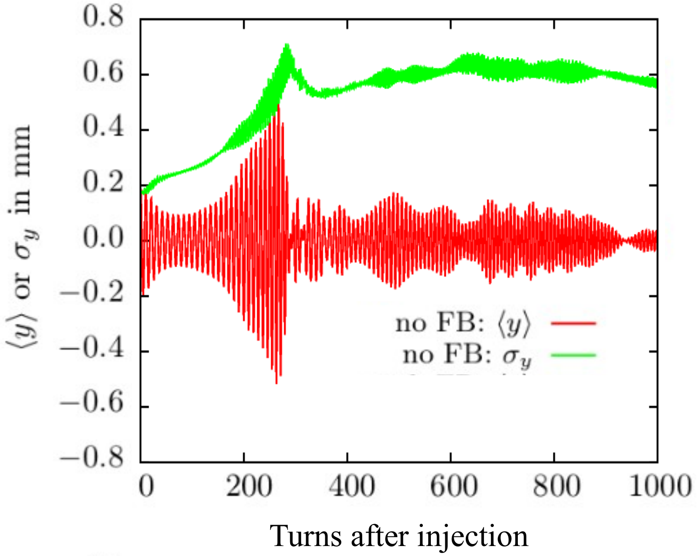
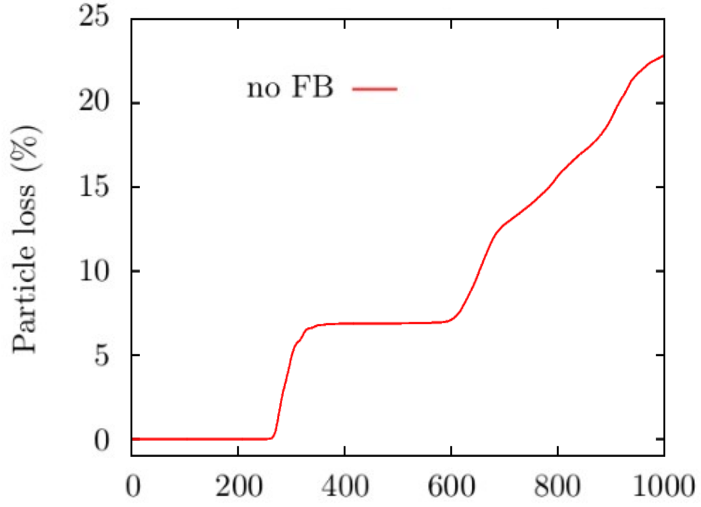


- Three mm aperture SCAPE would limit the current to < 2 mA/bunch
- Even doubling the aperture would only barely get us to 4.2 mA/bunch

Collective effects during swap-out injection are reduced, but not completely eliminated[8]

- One early APS-U lattice showed a transient instability that would lead to particle loss in 48 bunch mode (4.2 mA/bunch)
  - In equilibrium, the TMCI-like instability threshold ~ 10 mA
- The transient instability at injection depends on many factors
  1. Transverse impedance
  2. Initial transverse offset due to injection tolerances
  3. Nonlinear resonances experienced by particles in the large emittance injected beam/lattice errors
  4. Longitudinal mismatch between injected and stored beam





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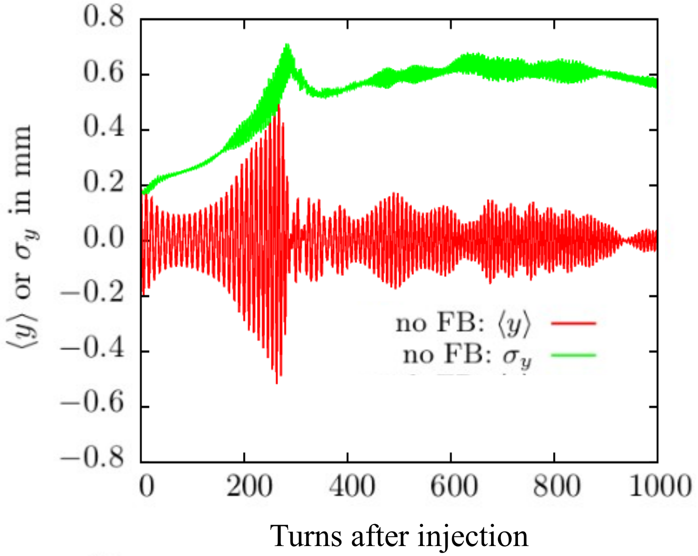
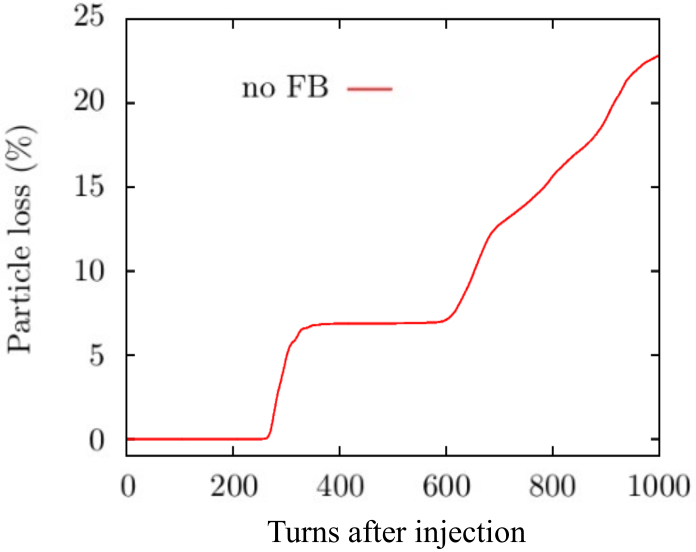
     - Bunch “tumbles” in rf bucket which leads to current spikes, which in turn drives anomalously high wakefields
     - Stability could be improved by better matching booster and storage ring bunch length and energy spread

Injected beam mismatch	$\Delta\sigma_\delta/\sigma_\delta$ = –40% $\Delta\sigma_t/\sigma_t$ = 15%	$\Delta\sigma_\delta/\sigma_\delta$ = –25% $\Delta\sigma_t/\sigma_t$ = 0%	$\Delta\sigma_\delta/\sigma_\delta$ = –10% $\Delta\sigma_t/\sigma_t$ = 15%	$\Delta\sigma_\delta/\sigma_\delta$ = 0% $\Delta\sigma_t/\sigma_t$ = 15%
Max. feedback kick needed to stabilize	1 μrad	0.5 μrad	0.5 μrad	0.4 μrad





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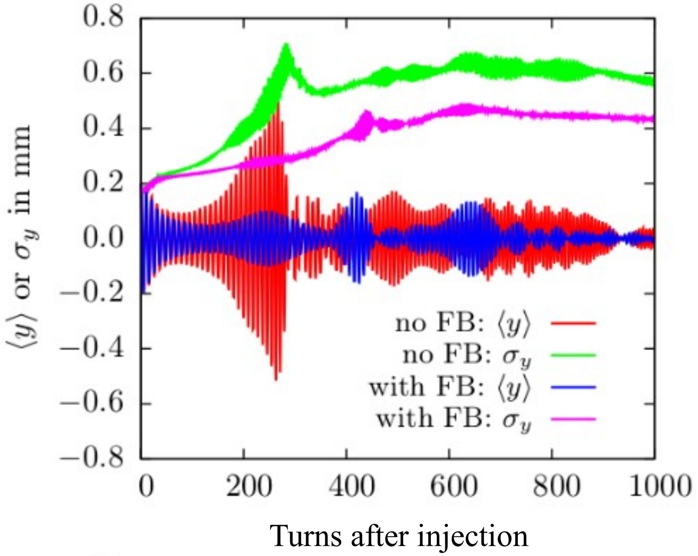
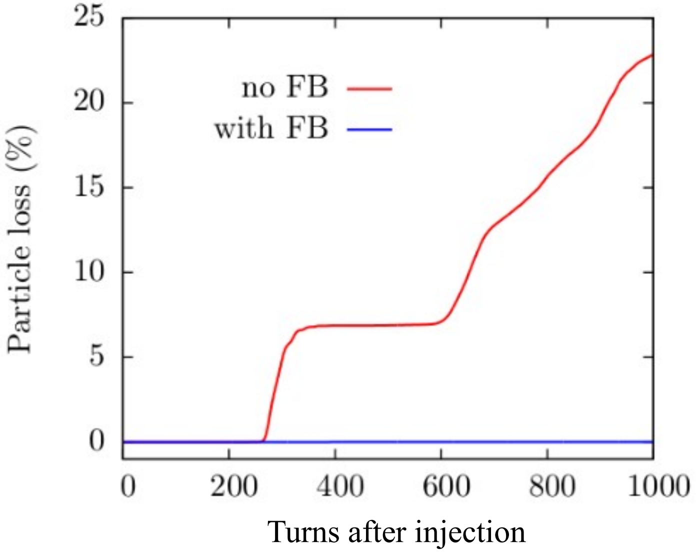
- The instability can be controlled with transverse feedback





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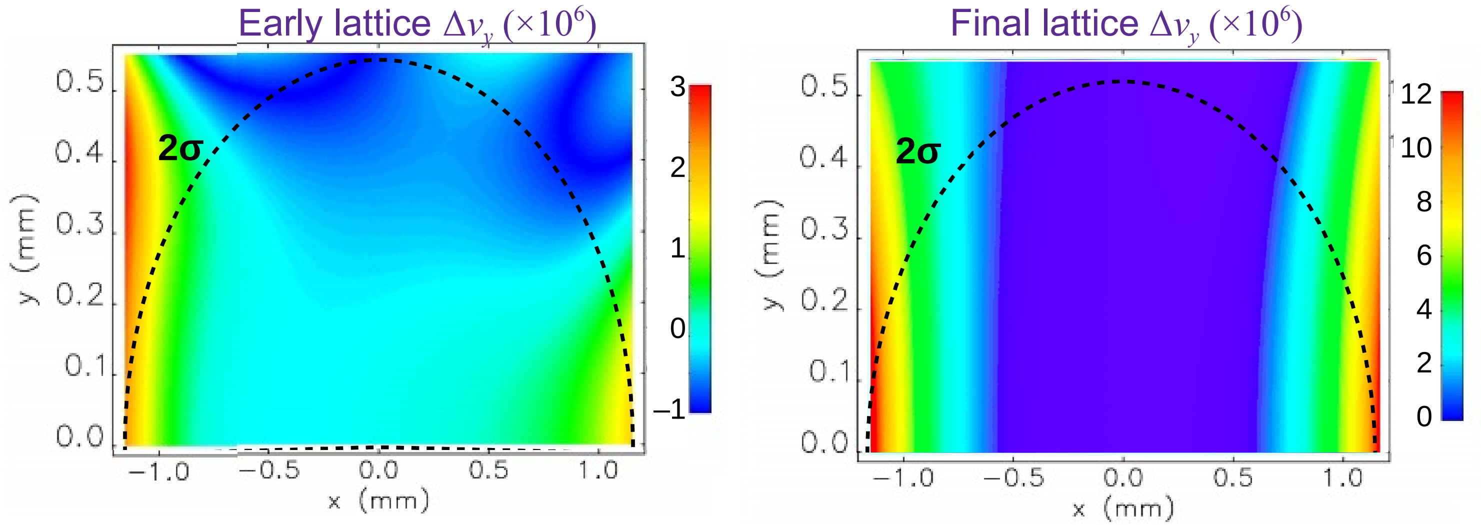
Tune shift with amplitude can help control instability[9]

- Subsequent iterations of the APS-U lattice showed no evidence of the instability at injection
- While most things were largely unchanged, the new lattice had a significantly larger tune-shift with amplitude
  - Tune spread over injected bunch was 3.5X higher in the new lattice



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  - Could octupoles be used to stabilize the previous lattice?

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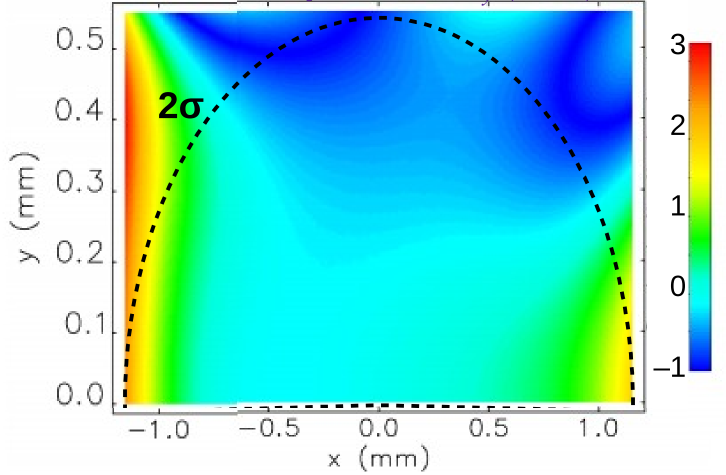
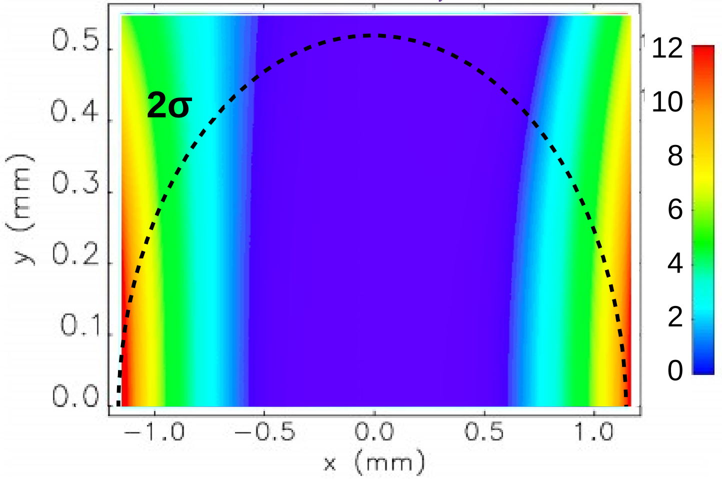
Early lattice $\Delta\nu_y$ $(\times 10^6)$



Final lattice $\Delta\nu_y$ $(\times 10^6)$



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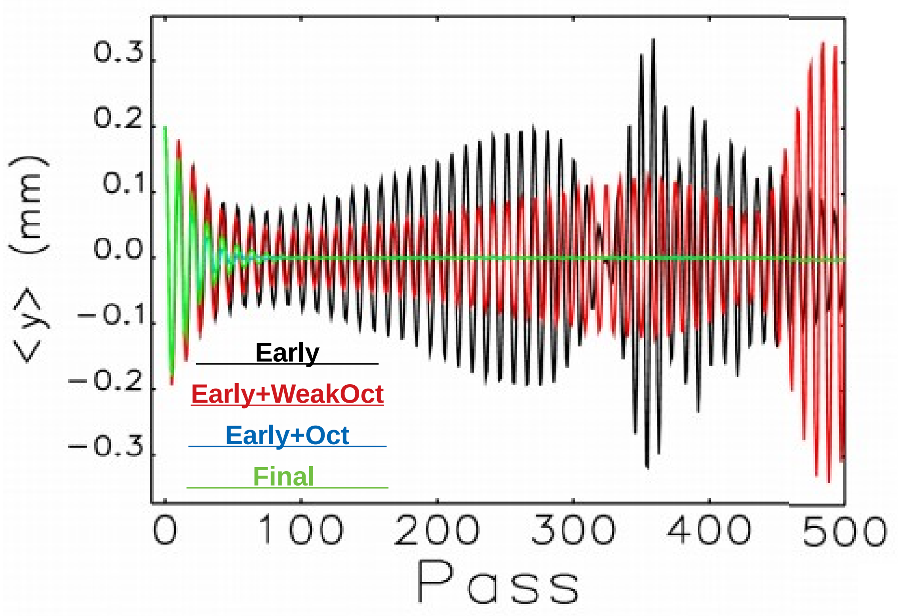
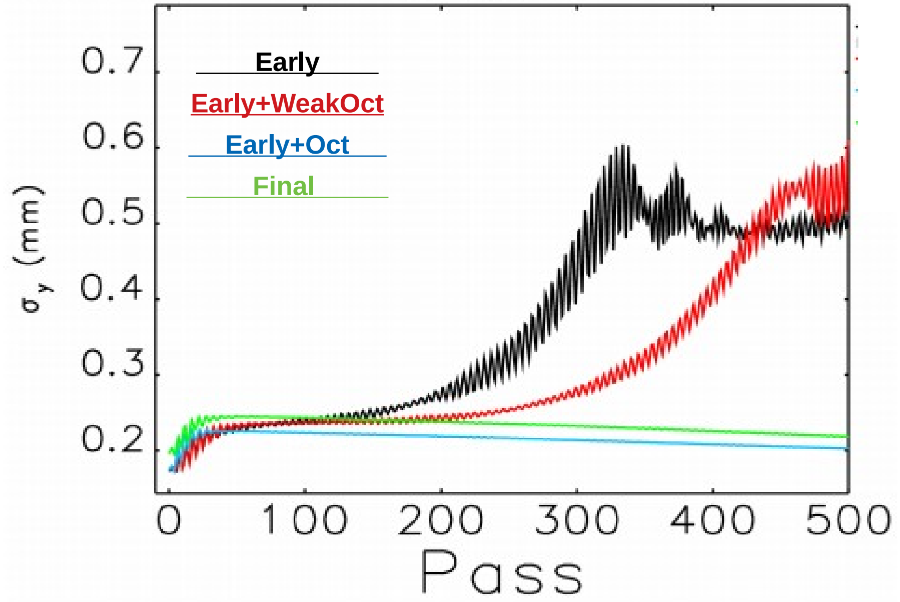
- Increasing the octupole strength (tune spread) helped stabilize injection transients





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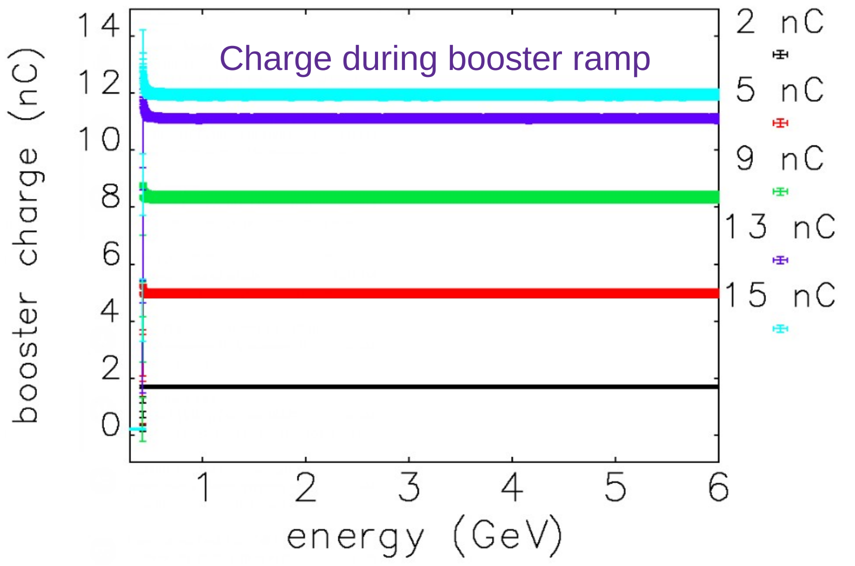
Stability of full-charge, swap-out bunches must be considered throughout the injector chain

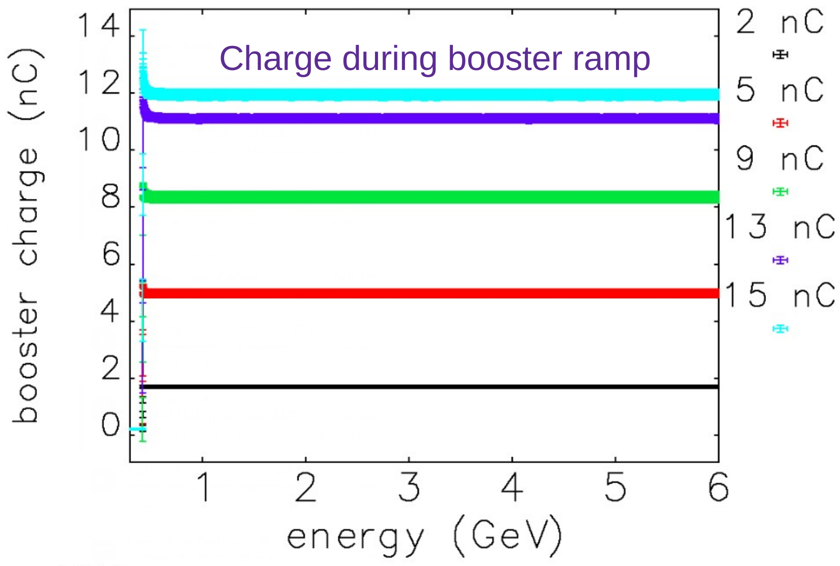
- While collective stability in the injector is always an issue, it becomes more pressing for the full-charge bunches needed for swap-out
- This has become important for the APS-U as we prepare our particle accumulator ring (PAR) and booster for high-charge swap-out[10]
  - Injectors were only designed to provide a few nC of charge for accumulation, while APS-U's 48-bunch mode needs 16 nC.
  - Over 20 nC have been stored in the PAR
  - 10 nC is reliably transmitted through the booster, while 12 nC is typically achievable during studies.

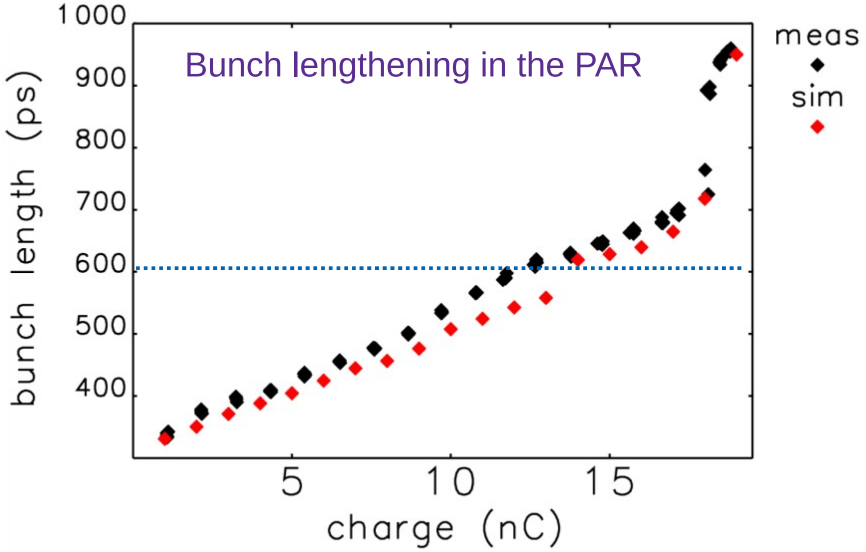


[10] J. Calvey, T. Fors, K. Harkay, U. Wienands, "Progress on the APS-U Injector Upgrade," in Proc. of the 2022 NAPAC pp. 859.

Stability of full-charge, swap-out bunches must be considered throughout the injector chain

- While collective stability in the injector is always an issue, it becomes more pressing for the full-charge bunches needed for swap-out
- This has become important for the APS-U as we prepare our particle accumulator ring (PAR) and booster for high-charge swap-out[10]
  - Injectors were only designed to provide a few nC of charge for accumulation, while APS-U's 48-bunch mode needs 16 nC.
  - Over 20 nC have been stored in the PAR
  - 10 nC is reliably transmitted through the booster, while 12 nC is typically achievable during studies.
  - Bunch length in the PAR has been identified as the present bottleneck
    - Longitudinal (microwave) instability in the PAR lengthens bunch
    - Efficiency in the booster drops when $\sigma_t > 600$ ps
  - Plans to combat PAR instability include lower impedance with new kicker chambers, increasing harmonic rf voltage, and raising PAR energy
  - Re-commissioning of injectors is going on now.
- Full-energy accumulator rings (ALS-U) can mitigate these issues





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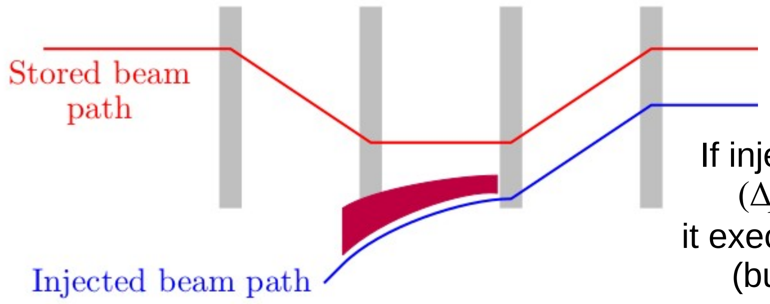
Brief comments on injection schemes we did not consider

- Synchrotron phase-space injection[11]
  - Relies on horizontal dispersion to inject an off-energy beam at non-zero horizontal location
  - Might be useful for certain low-emittance rings, but not those with small dispersion (multi-bend achromats)



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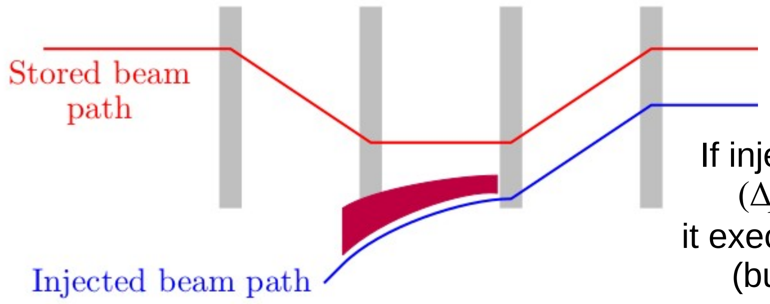

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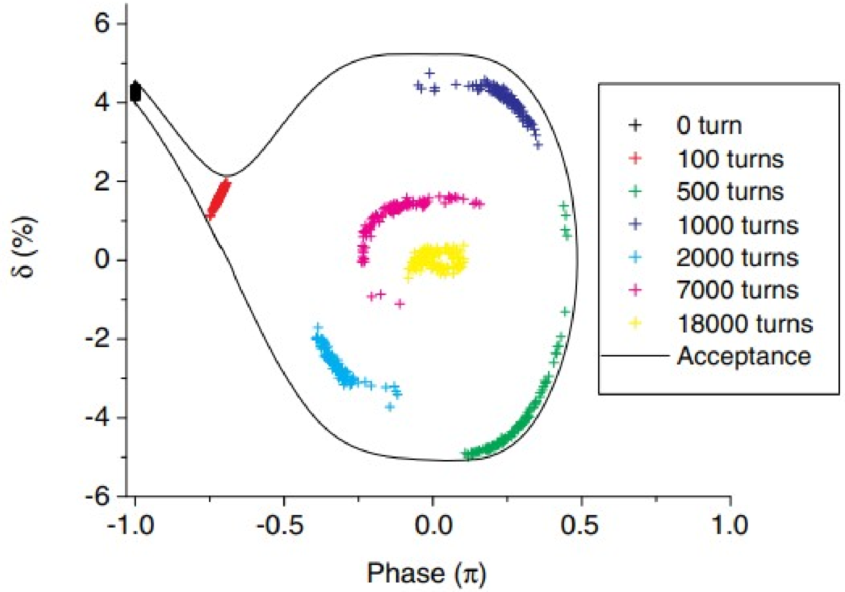
- Longitudinal injection[12]
  - Injects particles at an energy and phase such that they damp to oscillate about the equilibrium
  - Requires either an initially small horizontal emittance or complicated rf-gymnastics with multiple rf systems[13]
  - Short bunches or rf gymnastics will have transient beam loading effects that must be considered
  - Short bunches may also drive transverse wakefields and instabilities.



[11] P. Collier. "Synchrotron Phase Space Injection Into LEP," in Proc. of the 1995 Particle Accel. Conf., pp 551.
[12] M. Aiba, M. Böge, F. Marcellini, Á. Saá Hernández, and A. Streun. "Longitudinal injection scheme using short pulse kicker for small aperture electron storage rings," PRST-AB **18**, 020701 (2015).
[13] B.C. Jiang, Z.T. Zhao, S.Q. Tian, M.Z. Zhang, and Q.L. Zhang. "Using a double-frequency RF system to facilitate on-axis beam accumulation in a storage ring," NIMA **814**, 1 (2016).

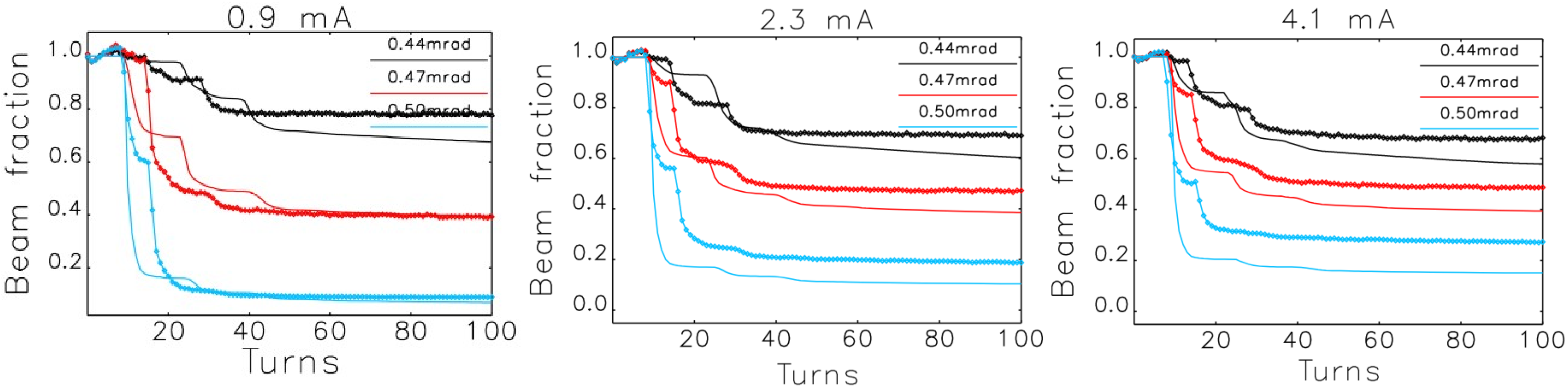
Conclusions

- Many factors influence the choice of injection
  - Pushing the lattice to peak performance → on-axis swap-out
  - Other goals and/or technological/injector constraints → accumulation
- Collective effects are small for traditional accumulation
- Collective effects for shared-oscillation accumulation may be important
  - Small aperture devices or small margins on dynamic aperture may be compromised
- Collective effects for swap-out injection may be an issue
  - Mismatches in emittances + wakefields + nonlinearities may drive transverse oscillations that could compromise high-charge operation
  - Tune-shift with amplitude (octupoles) can eliminate losses
- Collective effects through injector and during extraction may also be important

Extra slides

Dynamics during particle loss

- A more stringent test of the simulations compares beam loss as a function of turns in ring
  - Experiment uses calibrated vertical BPM sum signal
- General features are reproduced
  - Time scale of beam loss is < 40 turns
  - Loss pattern has odd step-like features



Connected symbols – measurements; Solid lines – `elegant` simulations

Simple theoretical explanation

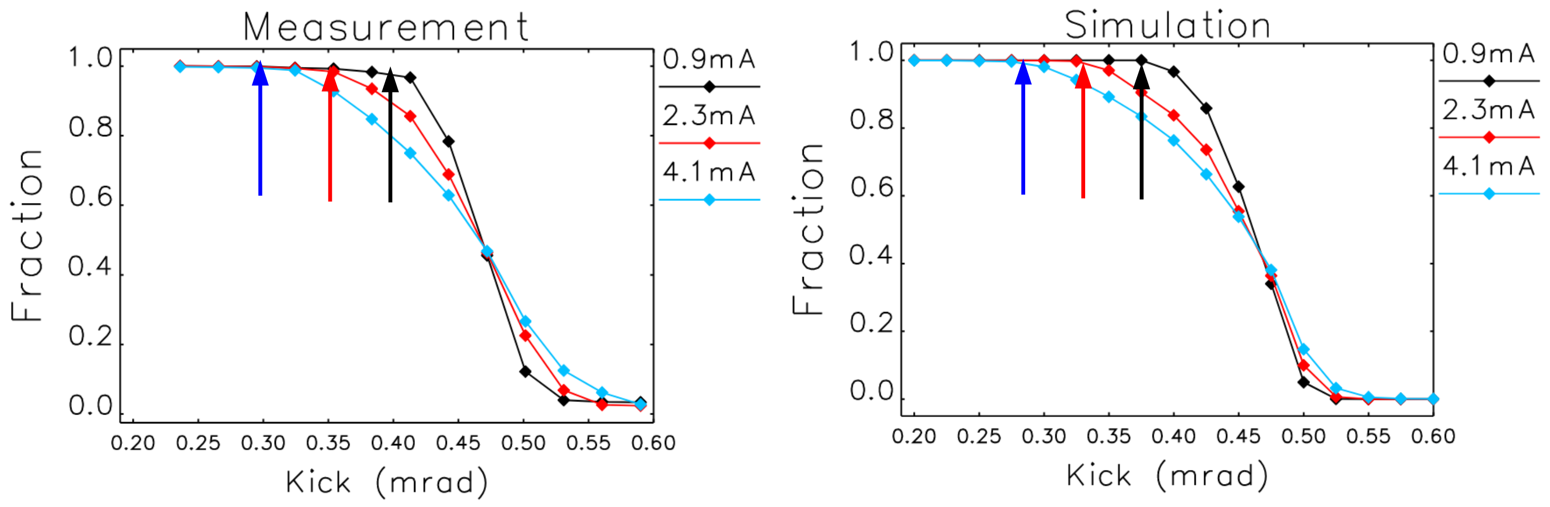
- Consider a test particle driven by the collective force of the oscillating beam:

$$\frac{d^2x_j}{dt^2} + \omega_j^2 x_j = \frac{e^2 N_e}{\gamma m c T_0}\int dz'\, \lambda(z') W_x(z_j - z')\langle x(t)\rangle = \langle x(t)\rangle \mathcal{W}_j$$

- Centroid oscillation "damps" primarily from the tune spread in the bunch, which we model with the simple expression $\langle x(t)\rangle \sim \sin(\omega_\beta t)e^{-t/\tau}$, with τ/T_0 ~ 30 turns; this implies that most particles have $|\omega_j - \omega_\beta| = |\Delta\omega| < 1/\tau$
- The approximate solution to the driven oscillator problem at long times is

$$x_j(t \gg \tau) \approx \frac{cx_0'}{\omega_\beta}\left\{1 - \frac{\tau\mathcal{W}_j(\tau\Delta\omega_j)}{2\omega_\beta[1+(\tau\Delta\omega_j)^2]}\right\} - \frac{cx_0'}{\omega_\beta}\frac{\tau\mathcal{W}_j}{2\omega_\beta[1+(\tau\Delta\omega_j)^2]}\sin(\omega_j t)$$

- Oscillation amplitude depends upon particle frequency and longitudinal location in bunch

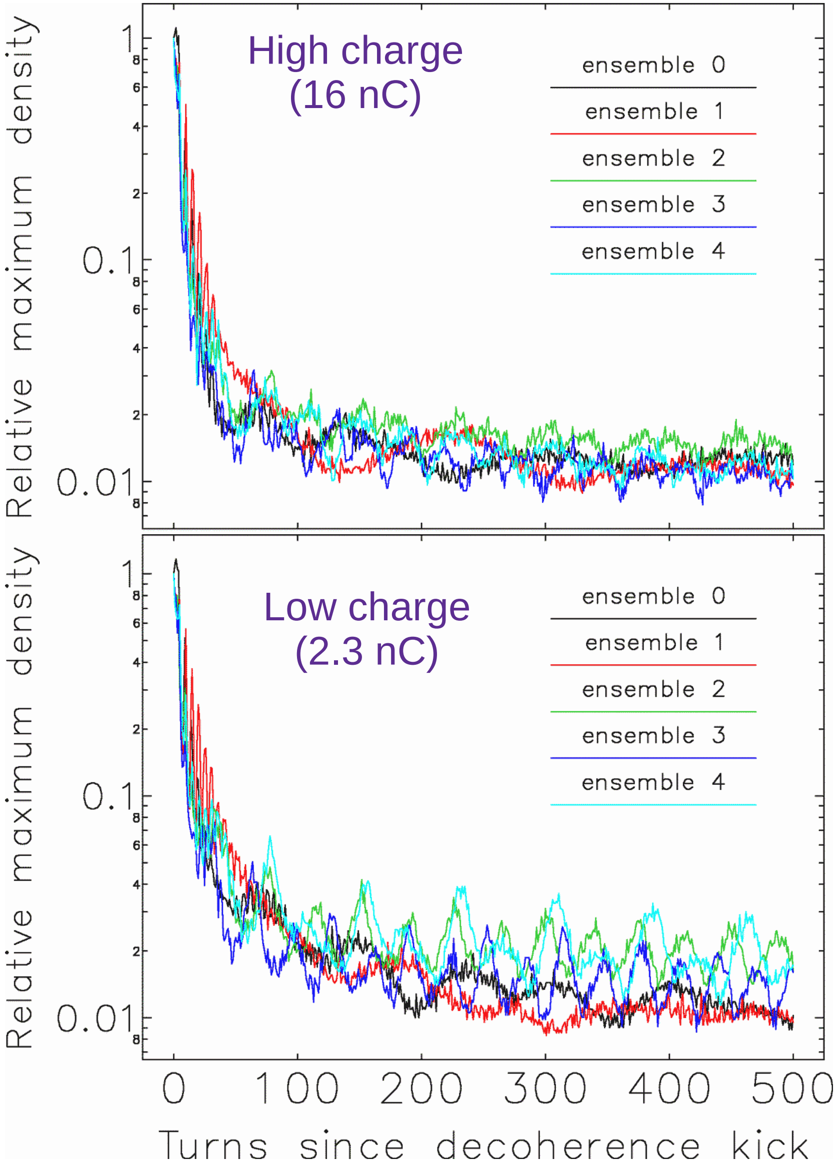


If I = 0.9 mA first loses charge at 0.40 (0.37) mrad

→ I = 2.3 mA first loses charge at 0.22 (0.33) mrad

→ I = 4.1 mA first loses charge at 0.30 (0.28) mrad

Wakefields may affect the extracted bunch during swap-out



- The energy density of an extracted bunch can be significant
- The APS-U plans to minimize damage at the beam dump by using a dedicated decoherence kicker
  - Stored bunch is given a 100 μrad kick prior to extraction
  - Nonlinear decoherence significantly reduces energy density within less than 100 turns
- Element-by element tracking shows that transverse wakefields enhance the decoherence in the high-charge (16nC) bunch
  - Provides additional margin for the most damaging case
- The low-charge (2.3 nC) bunch shows coherent emittance oscillations that somewhat reduce the decoherence
  - Still sufficient for this less problematic case