Resonant Control of Electron Bunches and Nonlinear Decoherence of Protons in IOTA

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Resonant control of vertical beam position with minimal loss of beam quality

Higher-intensity hadron rings with ever lower beam losses are required.

Particle injection or extraction can dominate beam losses and subsequent structure activation.

There is a need to develop new approaches for injection and extraction for high-intensity hadron rings.

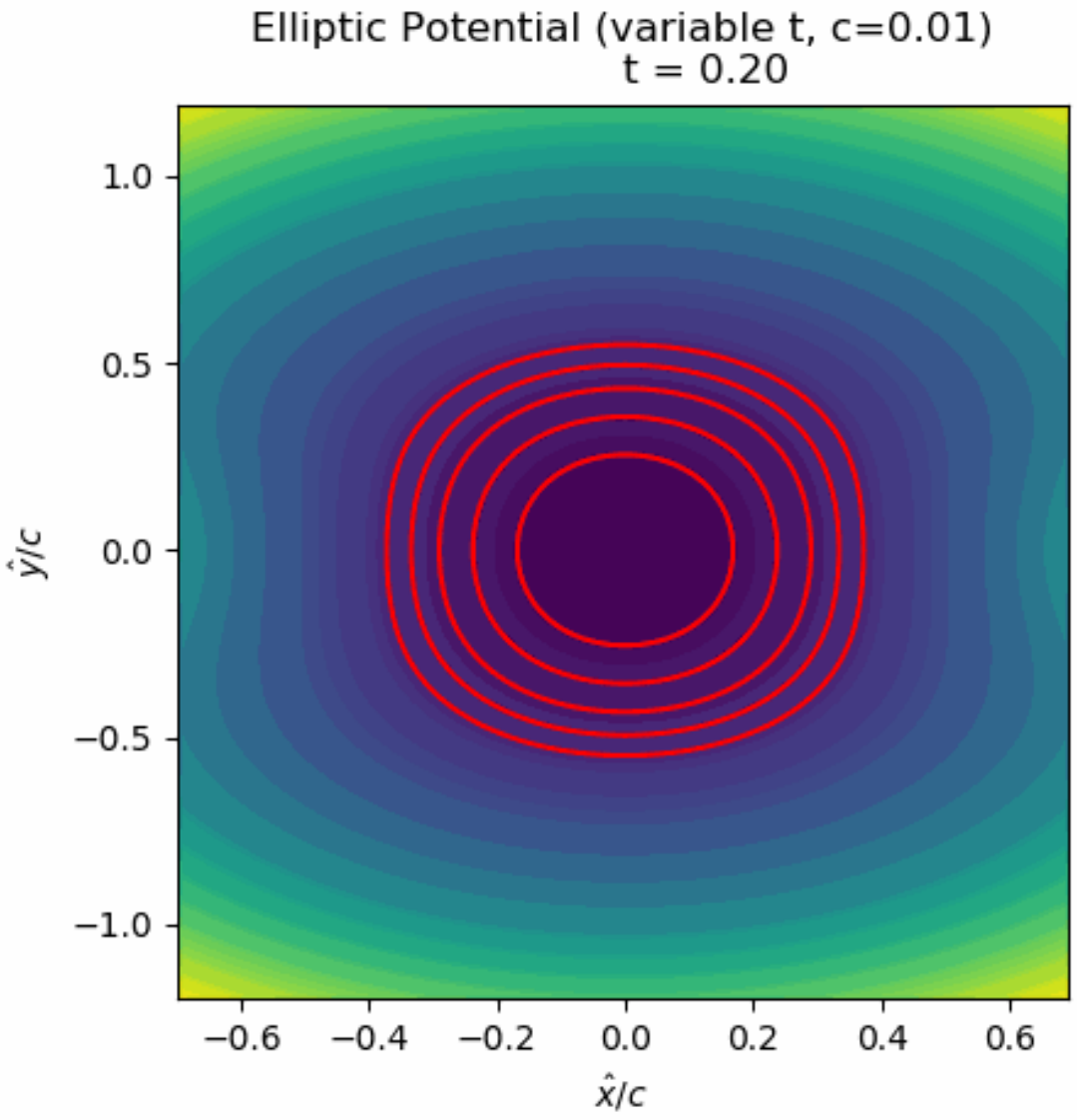
An interesting approach can be explored in IOTA, using electron bunches as a proxy for hadrons.

IOTA's nonlinear insert can manipulate vertical on-axis stability

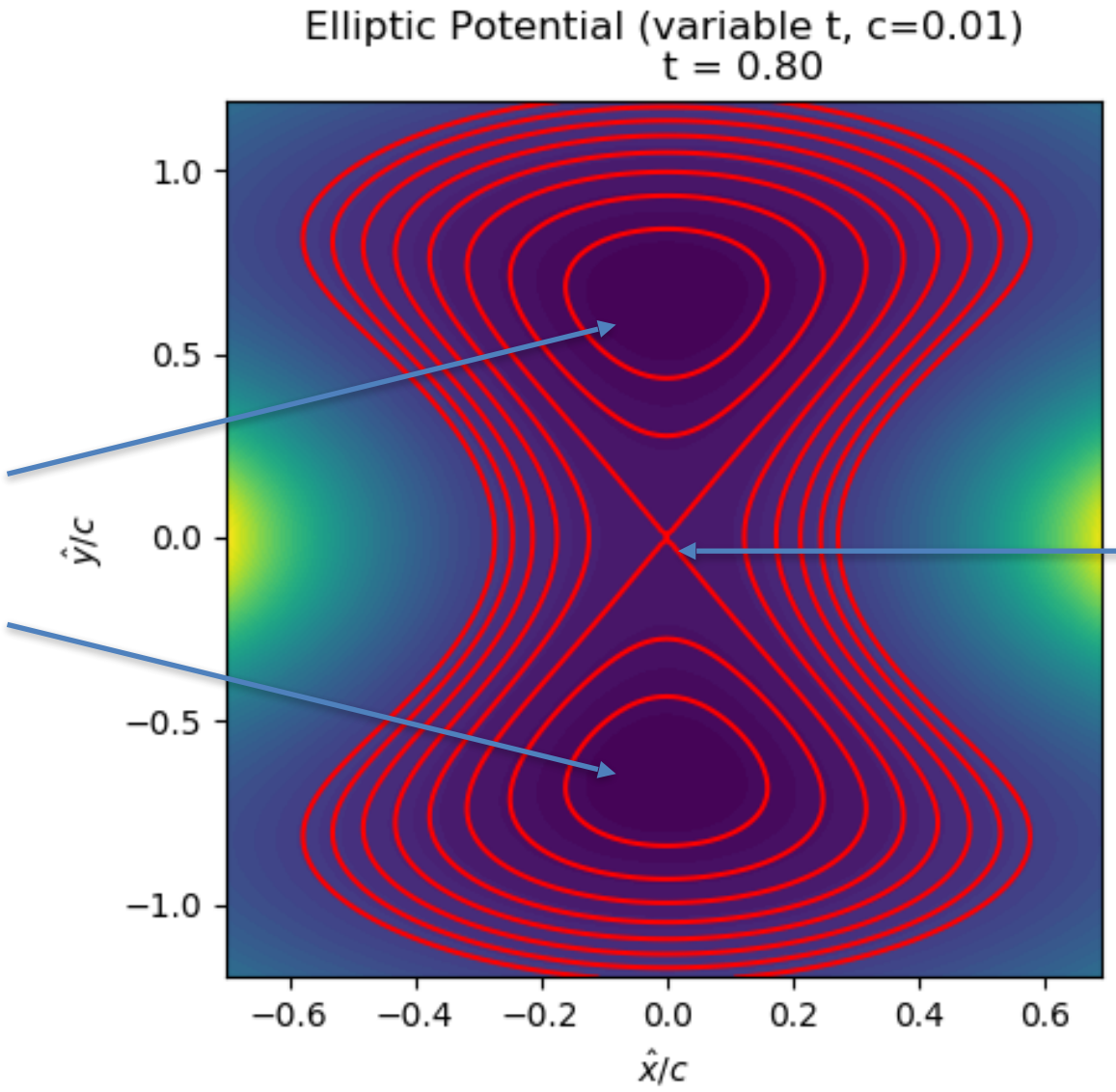
- Elliptic potential has quadrupole term
  - Nagaitsev, Valishev, Danilov, Proc. HB2010:

$$V(\hat{x},\hat{y}) \approx t\mathrm{Re}\left((\hat{x}+i\hat{y})^2 + \frac{2}{3}(\hat{x}+i\hat{y})^4 + \ldots\right)$$

  - *t* increases focusing horizontally, decreases vertically
- *t > 0.5* causes loss of linear focusing at origin
  - quadrupolar focusing in vertical "goes negative", becomes defocusing
  - origin becomes a hyperbolic fixed point
  - C. Mitchell et al., PRAB **23**, 064002 (2020).
- Fixed points rearrange themselves
  - hyperbolic fixed points move from "infinity" to the origin
  - elliptic fixed point at the origin splits into two elliptically stable lobes



“Loss of Linear Focusing” in Integrable Optics



elliptic fixed point, linearly stable

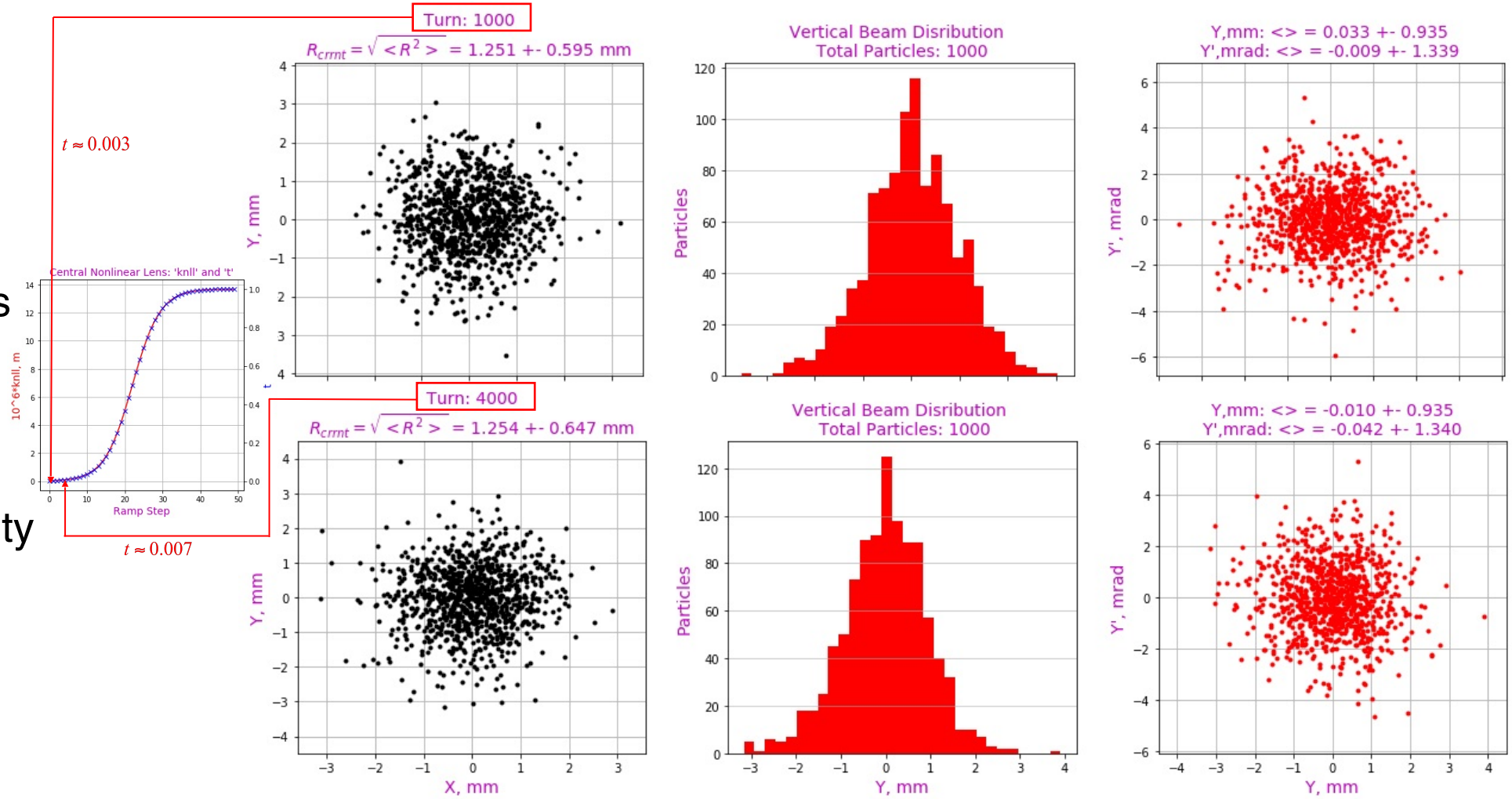
hyperbolic fixed point, linearly unstable

Early simulations indicate ramping *t* preserves beam

Initial gaussian beam, magnet off, t = 0

Switching function starts off slowly

* need to explore the importance of adiabaticity

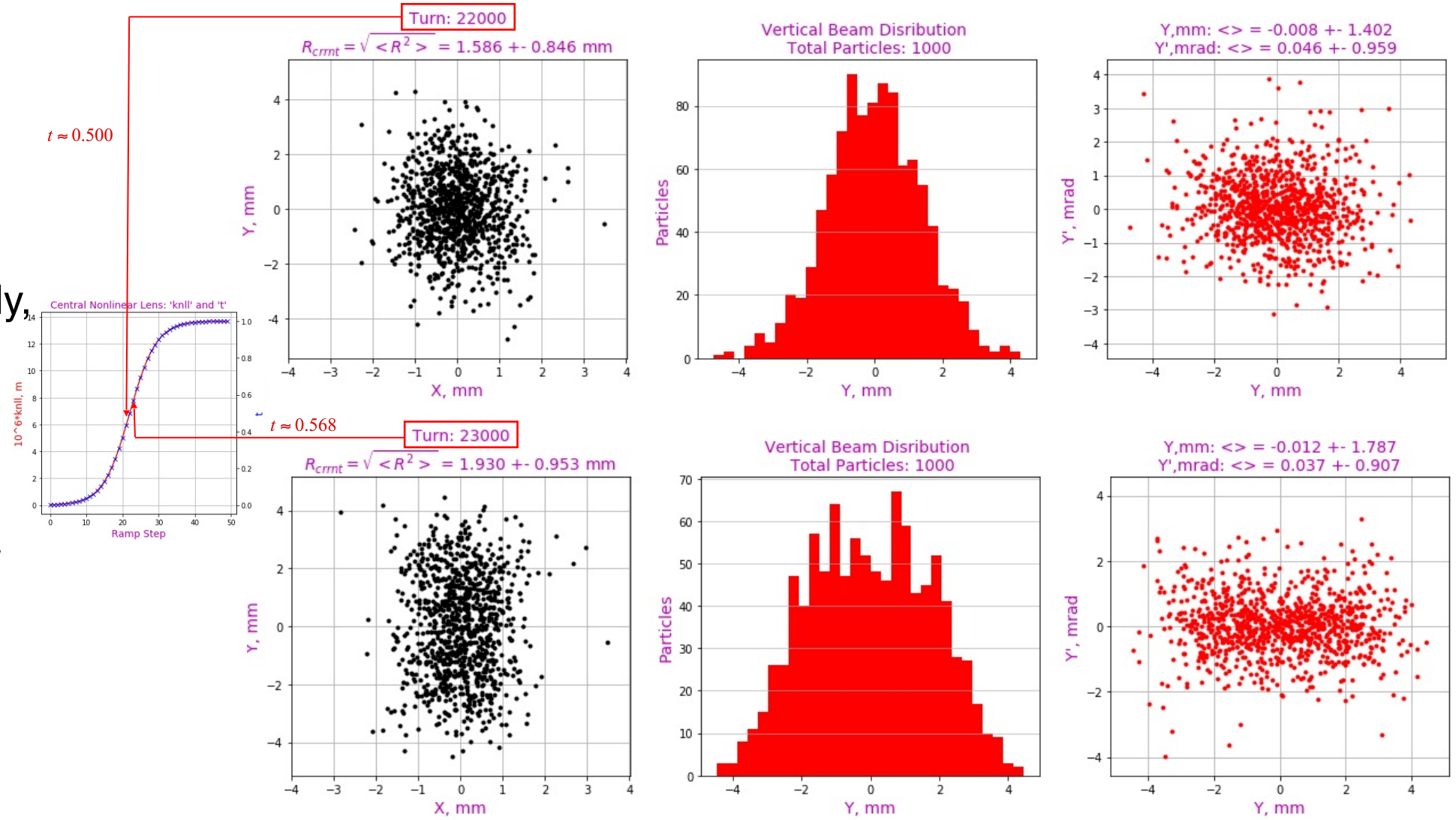


Ramp the nonlinear magnet rapidly through unstable region

Near the loss of linear stability, $t \approx 0.5$

Bunch distends vertically, but no particle losses observed

* importance of fast ramping through *t = 0.5* needs to be explored

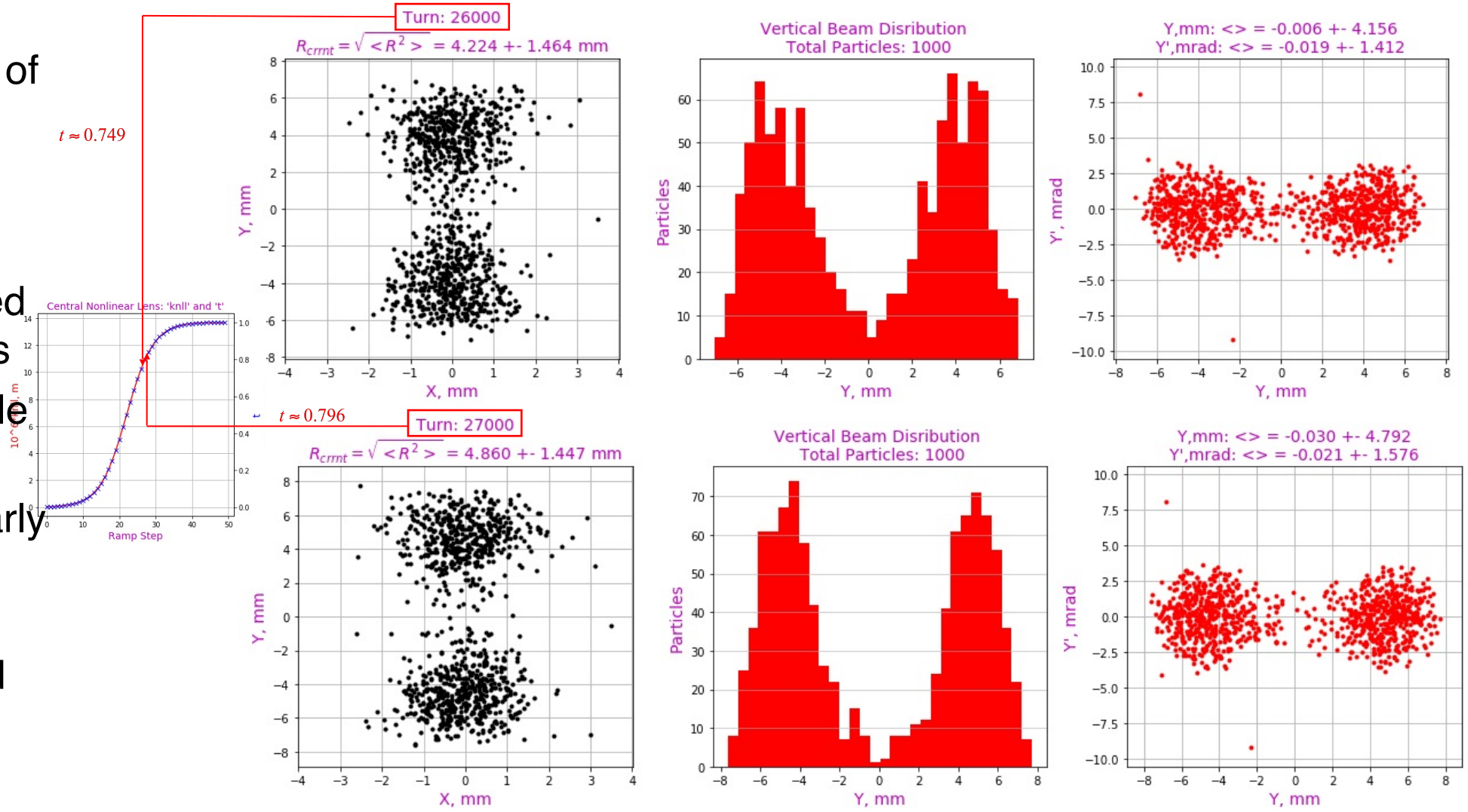


Two vertically-separated beams are observed

At maximum strength of the magnet,

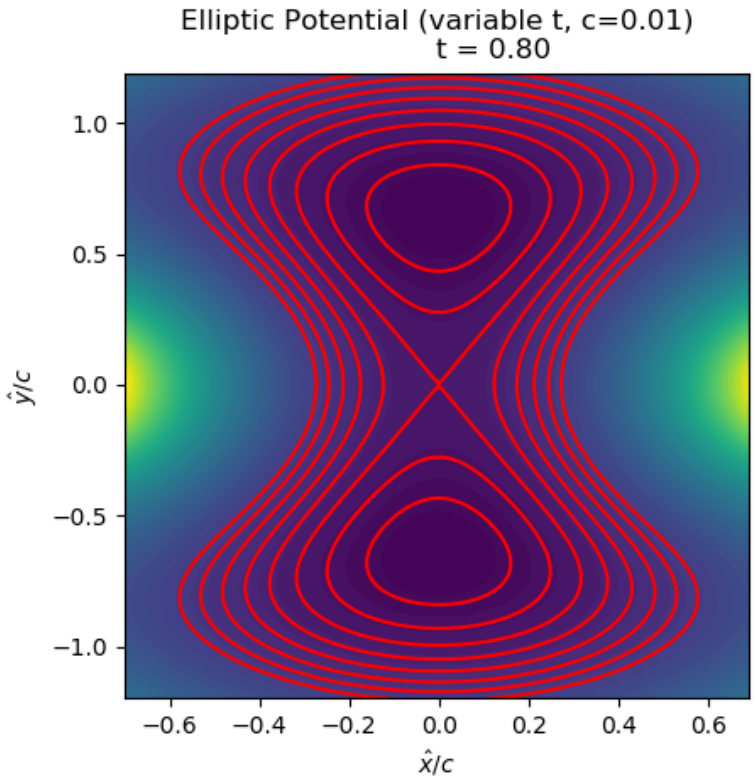
$t \approx 0.8$

- Bunch has separated into two stable lobes
- No significant particle loss observed
- Beam quality is clearly degraded
- More detailed simulations required



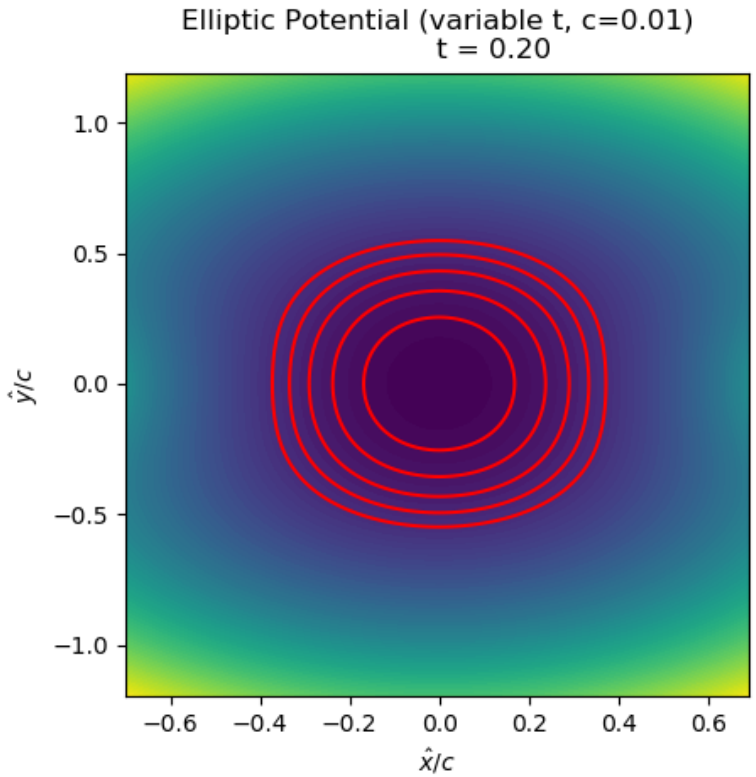
Stable Lobe Injection Concept

Inject a gaussian bunch
off-axis into stable lobe…



… ramp the nonlinear
element below *t=0.5*…

…and store the beam on-
axis with the familiar NIO



Outline of a proposed experiment

- Capture electrons on-axis, $t = 0$, then ramp t up and down
  - measure emittance change after each cycle
  - measure particle losses
  - validate simulations
- Explore the possibility of off-axis injection with electrons
  - start with $t > 0.5$, then ramp down to 0
  - measure beam loss, emittance growth
  - explore different switching functions for t
  - validate simulations

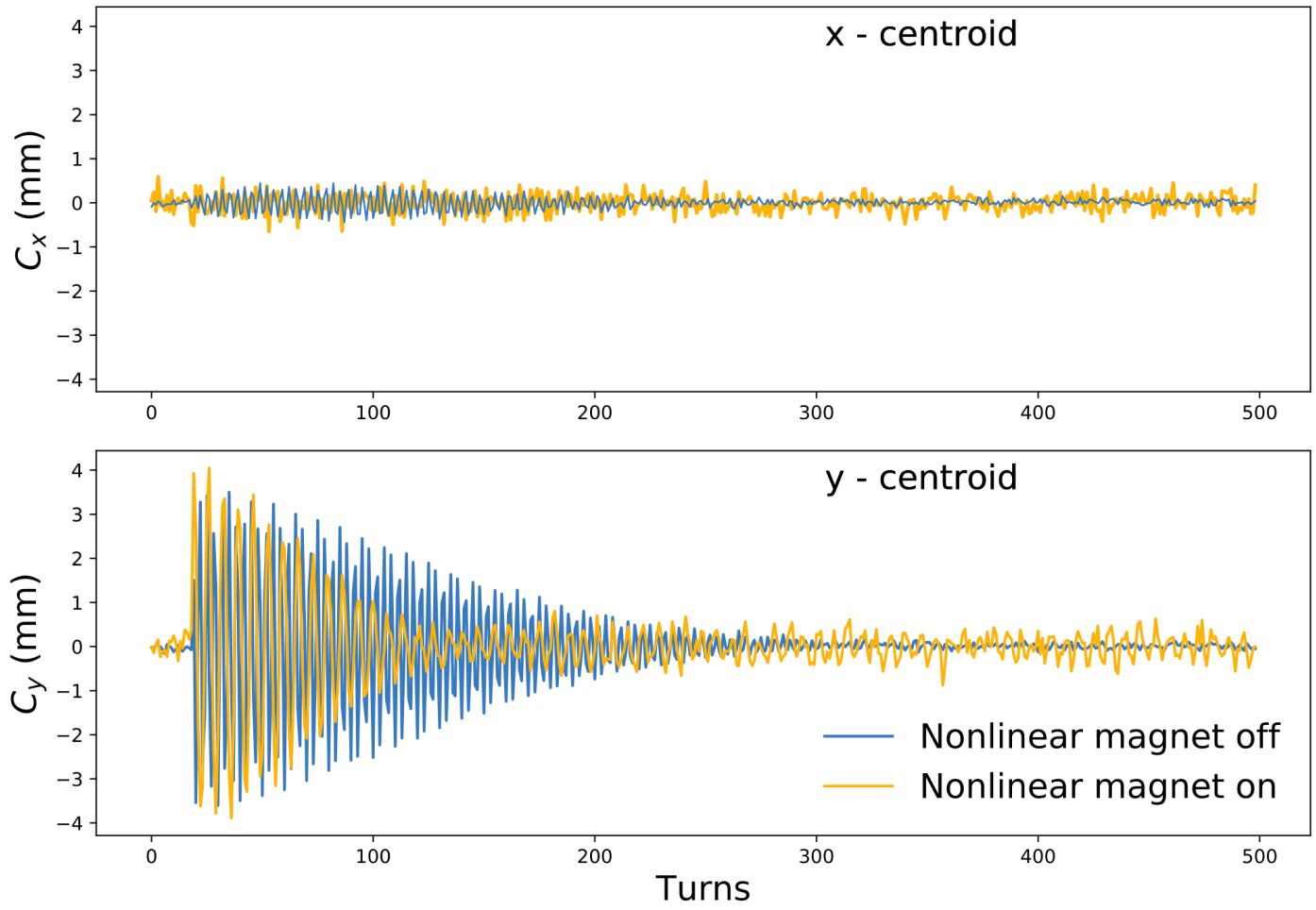
Nonlinear Decoherence Time with Space Charge

Nonlinear decoherence has been studied thoroughly for the single particle limit

Introducing space charge forces has a profound effect on the decoherence time

This can be explored during a proton run at IOTA

Nonlinear decoherence of centroid oscillations has been measured…

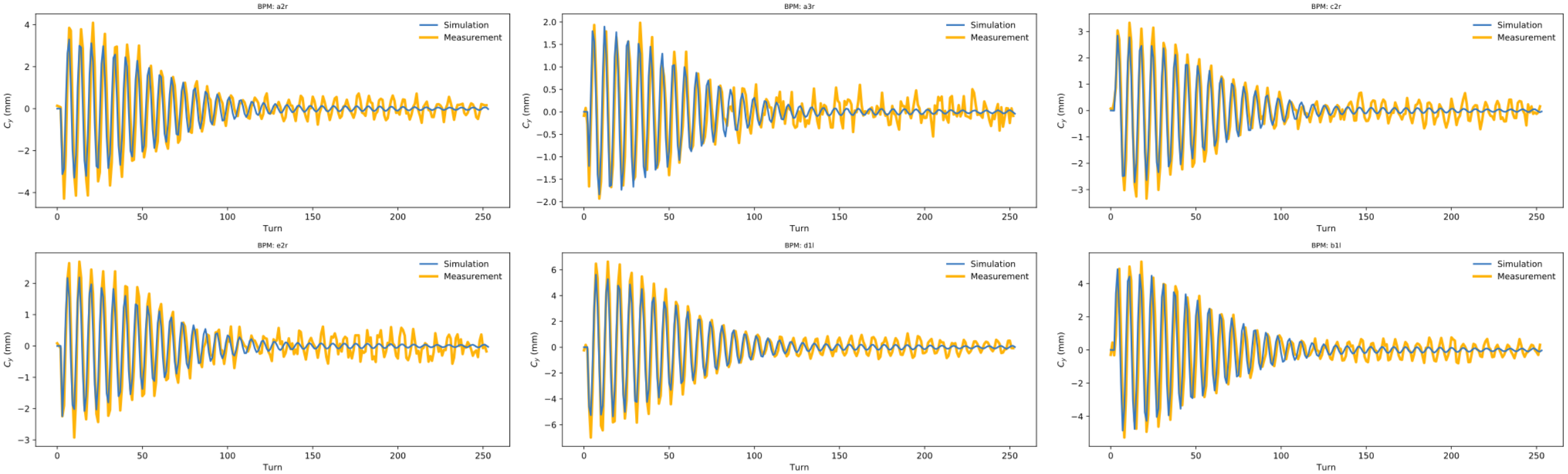


Decoherence in IOTA comes from chromaticity and energy spread, in addition to the nonlinear magnet

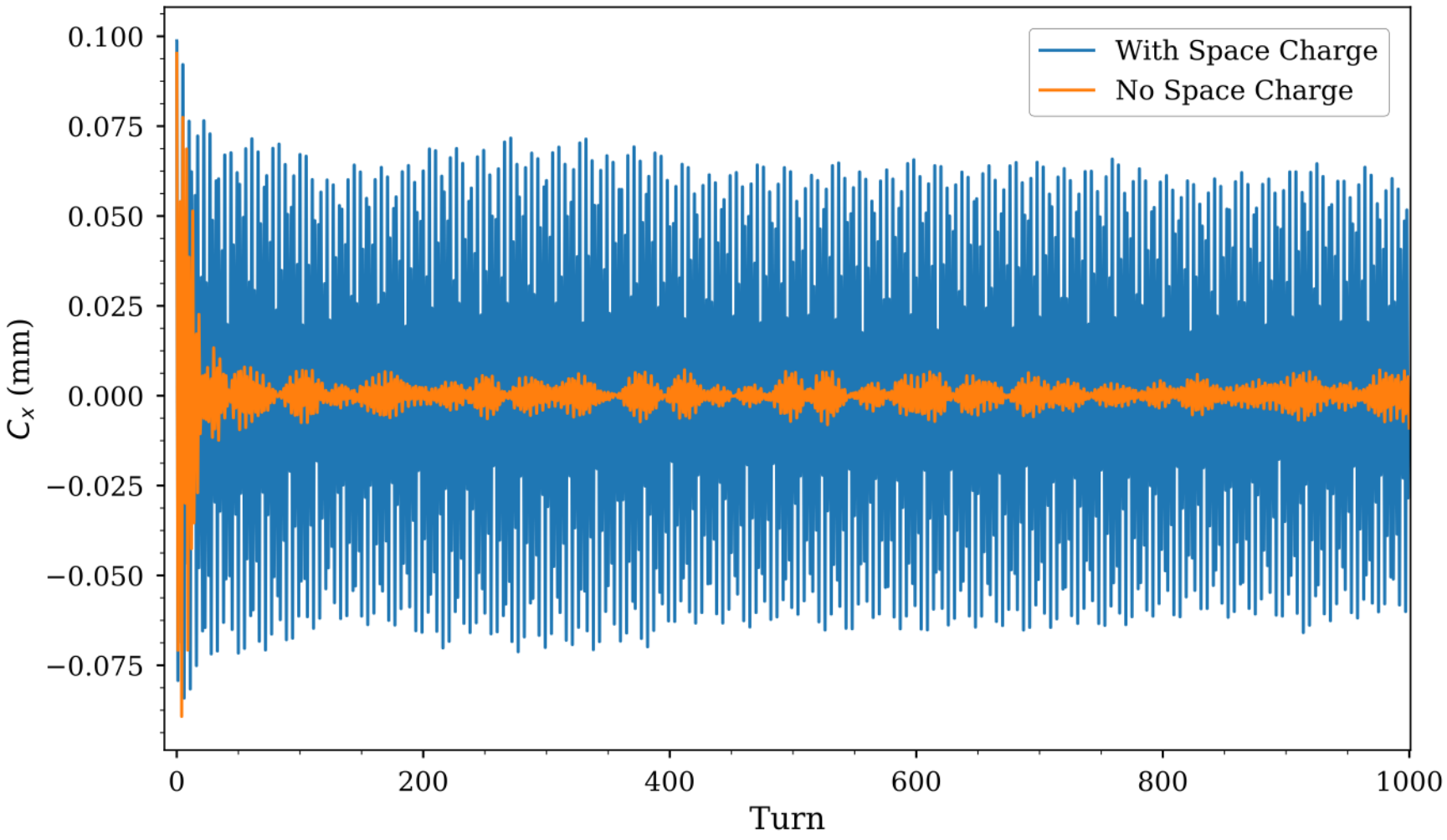
See, e.g., talks by
C. Hall (RadiaSoft),
N. Kuklev (U. Chicago), and
S. Szustkowski from
2019 FAST/IOTA meeting

…and validated against simulations

Including effects of IBS-induced energy spread and chromatic tune spread, measurements of decoherence in IOTA agree very well with tracking code simulations

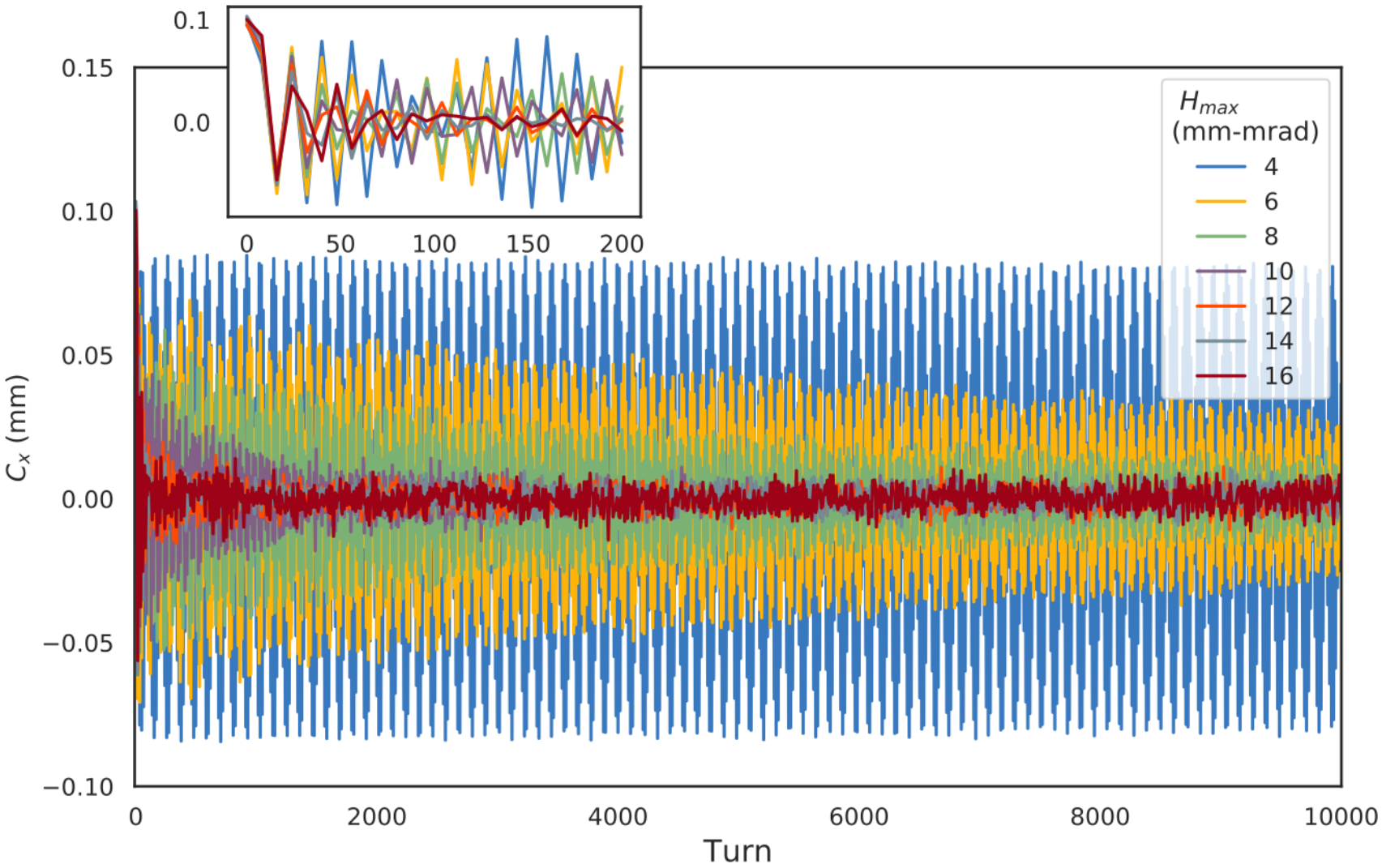


Space charge increases the nonlinear decoherence time



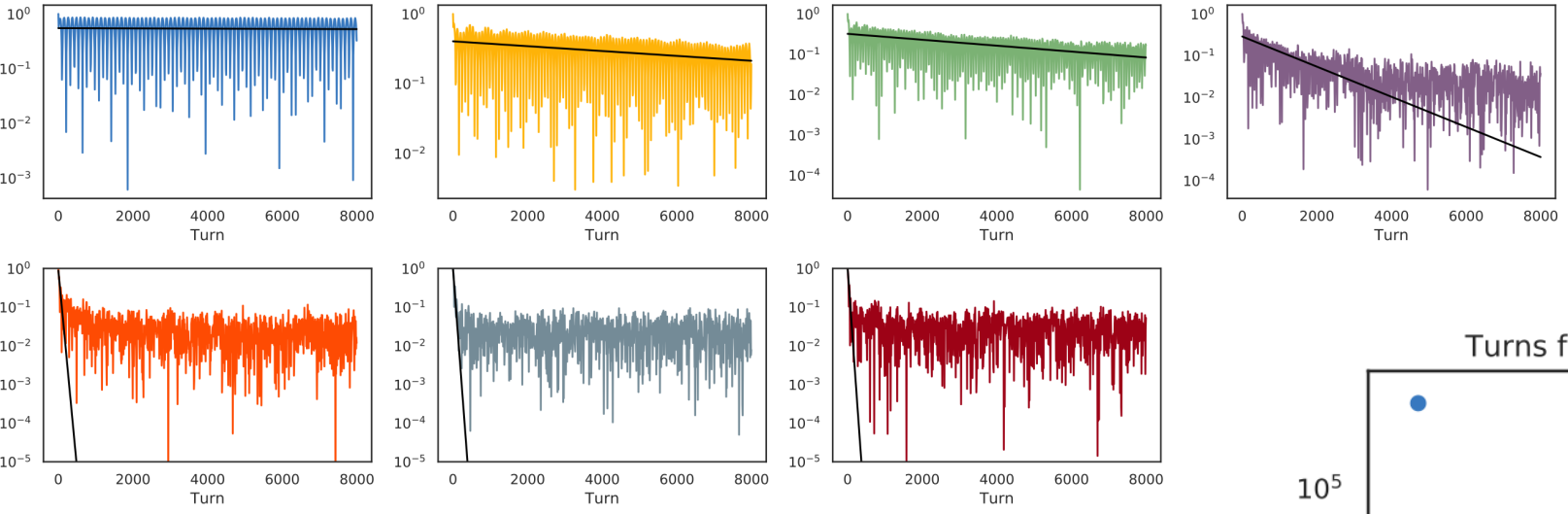
- IOTA lattice, tuned to cancel linear space charge
- waterbag-like distribution
- 8 mm-mrad max. emittance
- $dQ_s = 0.03$
- $t = 0.4$

Strong emittance dependence for the decoherence time w/ space charge



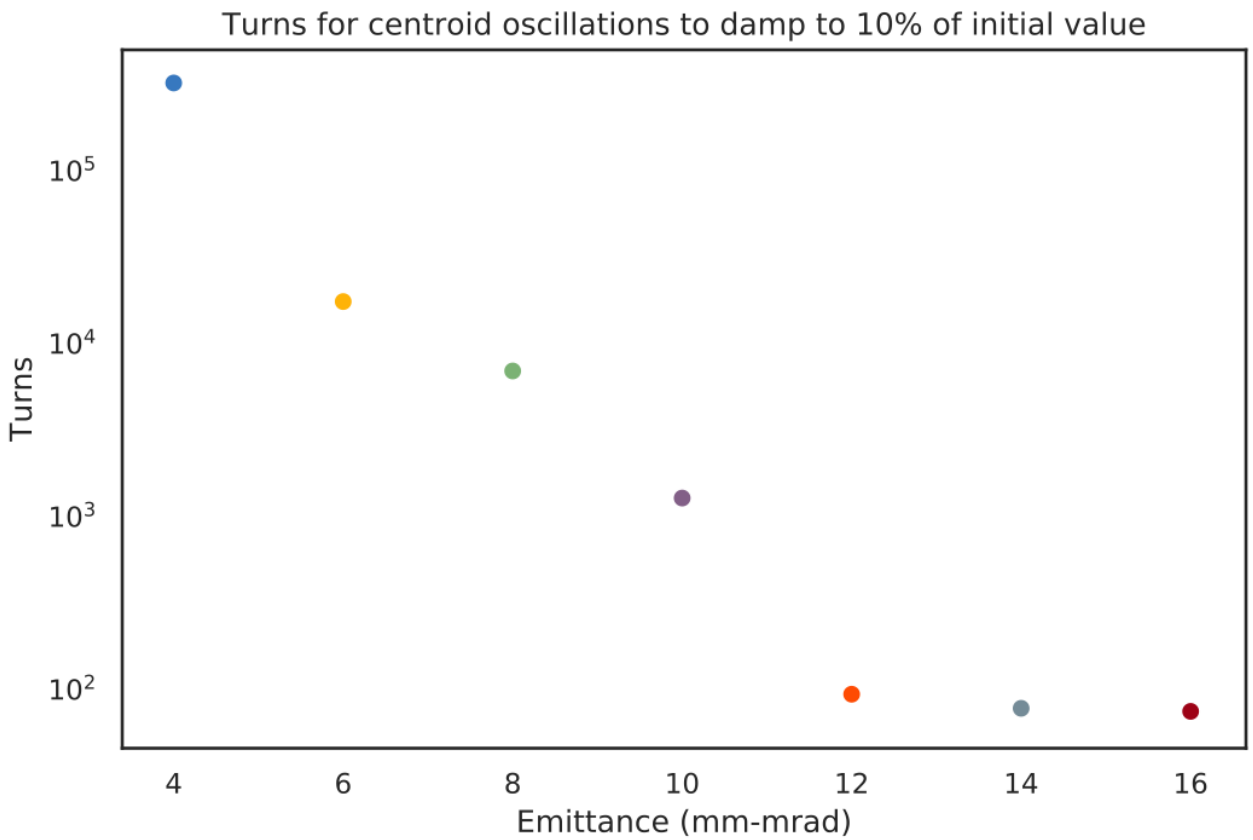
Fixing the tune depression $dQ_s = 0.03$ across all runs, and varying the emittance, we see a strong dependence on decoherence time versus emittance

Strong emittance dependence for the decoherence time



Damping is exponential for small emittances, then flatten into nearly immediate damping at sufficiently large emittance

The damping time τ is a function of emittance and space charge — how do these vary and compare to coherent instability growth times?



Outline of experiment exploring nonlinear decoherence with space charge

- Study centroid decoherence with proton beams
  - fixed beam kick and emittance, sweep current
  - fixed beam kick and current, sweep emittance
  - vary kick with fixed emittance and current
  - explore decoherence versus these parameters, and compare to simulations
- Follow-on experiments considering different mechanisms for tune shift with amplitude
  - elliptic potential
  - electron lenses
  - octupoles
  - etc.

Thank you

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