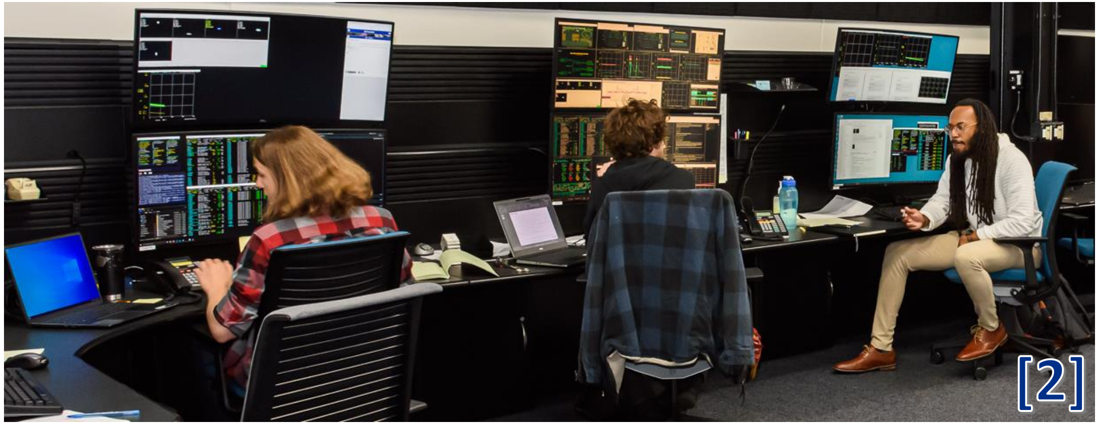
Nonlinear Integrable Optics (NIO) in IOTA Run 4

John Wieland on behalf of NIO collaboration
IOTA/FAST Collaboration Meeting
March 12, 2024

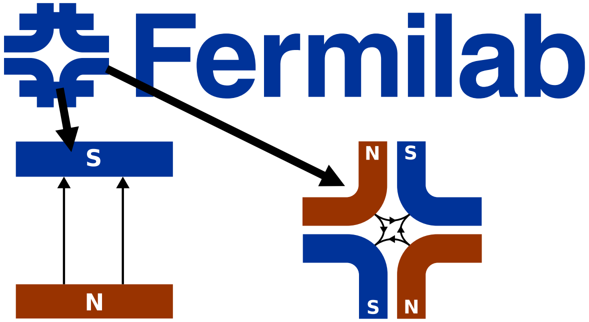
Overview

- NIO Motivation
- Run 4 Experimental Goals
- Turn-By-Turn Measurements
  - Detuning
  - Invariant Conservation
- Dynamic Aperture Measurements
  - Sextupole optimization
- Large-t Beam Profiles


[1]


[2]

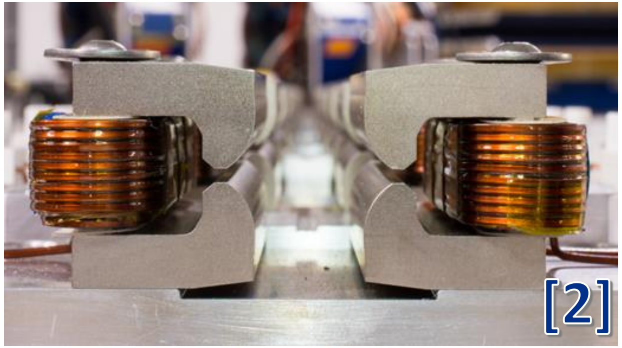
Nonlinear Integrable Optics Motivation

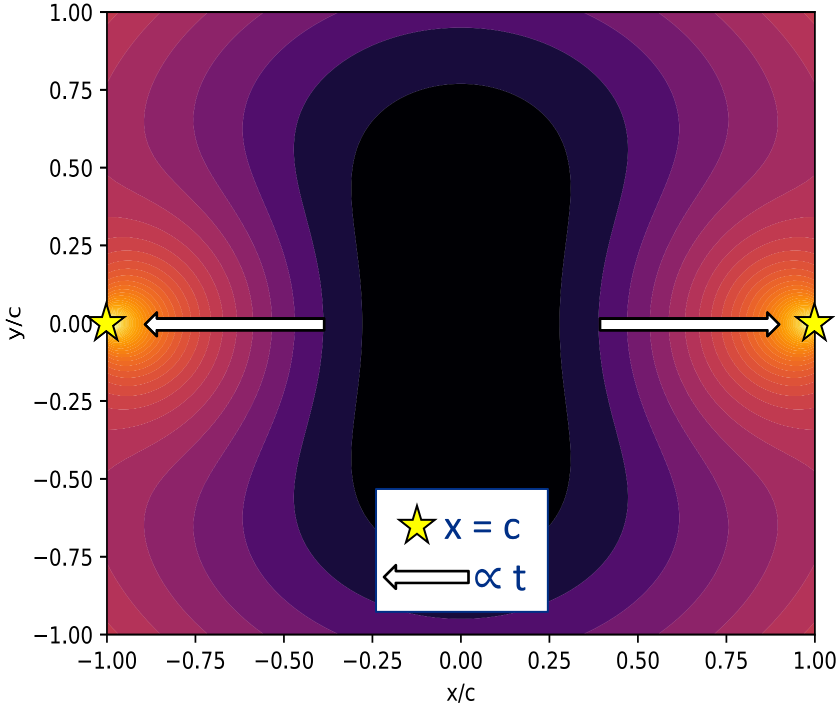


- Contemporary lattices are mostly linear elements
- Real world extra nonlinearities shrink area of stable motion
  - Magnet Imperfections
  - Chromaticity
  - Higher order multipoles
- To ensure stability, we rely on external damping or bunch Landau Damping
- Motivates search for nonlinear integrable potential realizable as magnetic optics
  - All phase space trajectories bounded
  - Amplitude dependent detuning, a condition for Landau Damping of the bunch
- IOTA constructed to evaluate practicality of NIO implementation

IOTA NIO System

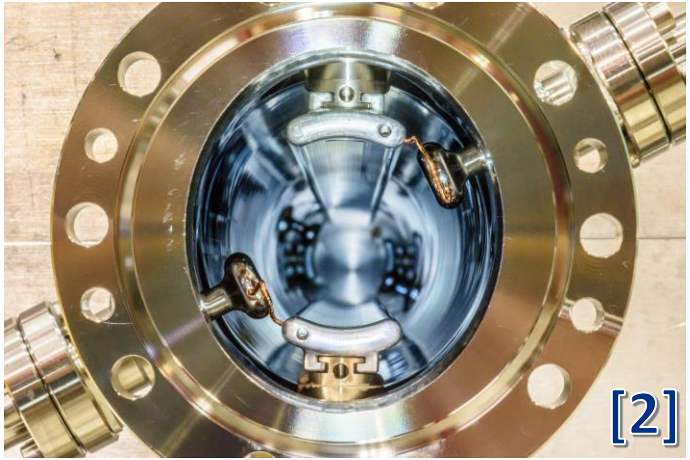
- V. Danilov and S. Nagaitsev (**DN**) discovered three integrable potentials IOTA implements the elliptic potential [1]
- Two important parameters
  - **t**, nonlinear strength parameter, t = 0.5 corresponds to vertical integer resonance
  - **c**, nonlinear geometric parameter, corresponds to analytic discontinuities in potential

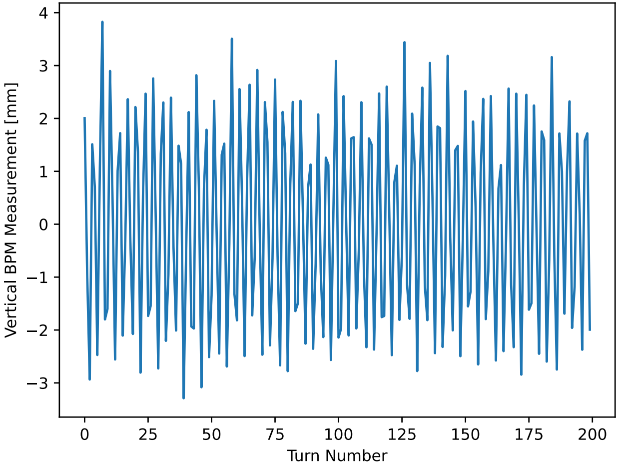




IOTA NIO Electron Program

- Using 150 MeV electrons from FAST superconducting linac with low emmitance we can approximate single particle dynamics
- Two stripline kickers, one horizontal, one vertical can be used to excite coherent transverse oscillations with tunable amplitudes
- Instrumented with 21 button BPMs for turn-by-turn beam centroid information





Preceding NIO Runs

- Run 1: August 2018 - April 2019
  - 100 MeV operation
  - Dominated by commissioning and its associated challenges
- Run 2: November 2019 - March 2020
  - 100 MeV operation
  - Early Shutdown March 20, 2020
- Run 4: April - October 2023
  - IOTA as designed : 150 MeV operation, full complement of sextupoles and diagnostics

Experimental Goals

1. Demonstrate large amplitude dependent tune shifts without degrading dynamic aperture
2. Measure theoretically predicted invariants of motion
3. Determine robustness of NIO systems against perturbations and imperfections
4. Verify the transverse profiles near and beyond the integer resonance agrees with the predicted phase space topology

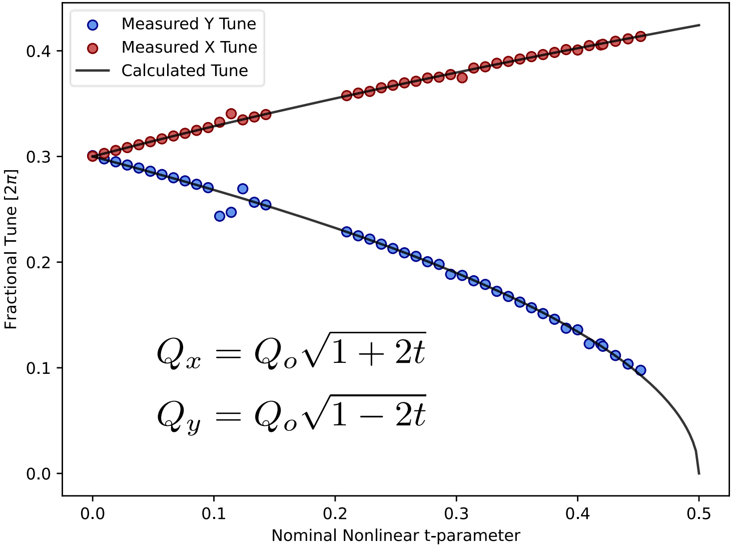
NIO Lattice Requirements

- Danilov-Nagaitsev NIO system places strict requirements on the lattice
  - Integer phase advance across the matching section, 0.3 across nonlinear insert
  - Centered orbit, zero dispersion and correct beta function in nonlinear insert
  - Minimal transverse coupling and small matched chromaticity
- Tune adjusted manually to nominal condition day-by-day

Lattice Parameter	Design Target	Run 4 Calibration
Phase Advance Errors	0.001	0.001(5)
Dispersion	1 [cm]	0.5(2) [cm]
Closed Orbit in Insert	50 [μm]	40(5) [μm]
Beta Function at Insert	1%	2%
Beta Beating	3%	2%

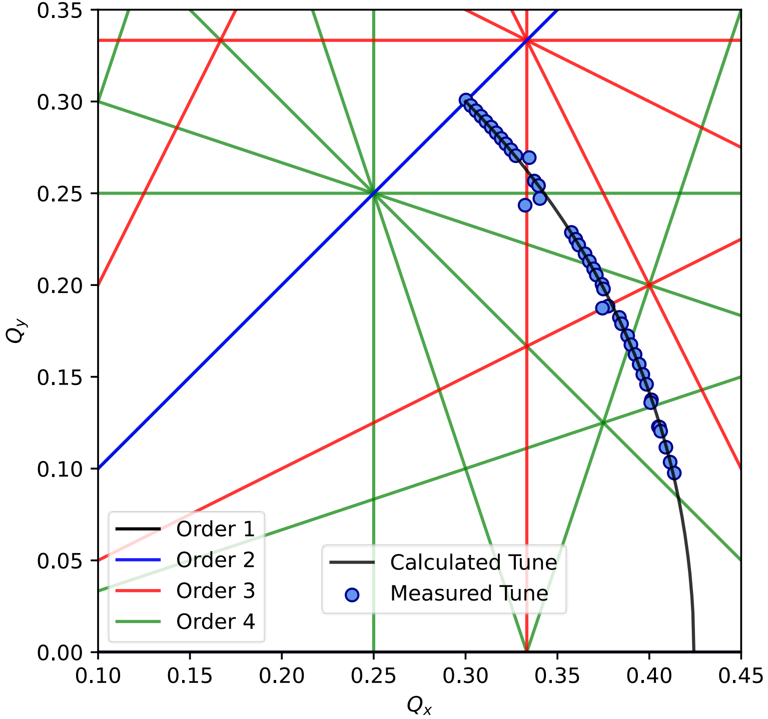
DN Detuning Calibration

- Calibrate nonlinear element t-scaling by measuring small amplitude tunes
- Used minimal resolvable amplitude kicks for tune measurements



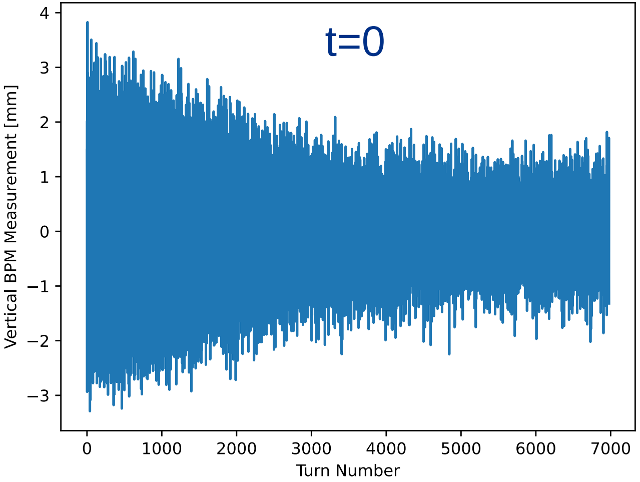
$$Q_x = Q_o\sqrt{1+2t}$$

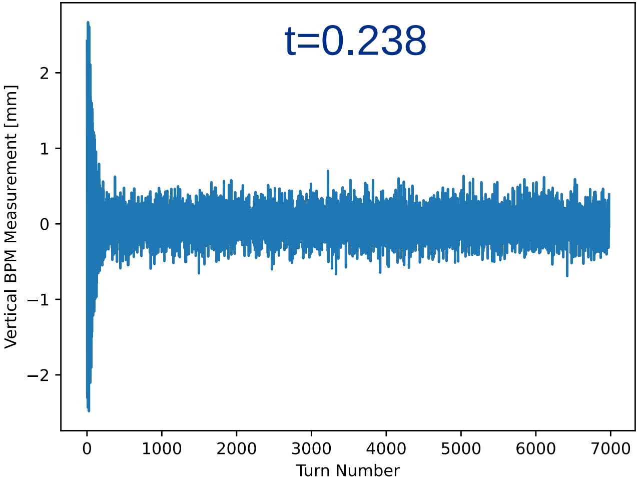
$$Q_y = Q_o\sqrt{1-2t}$$



DN Amplitude Dependent Detuning

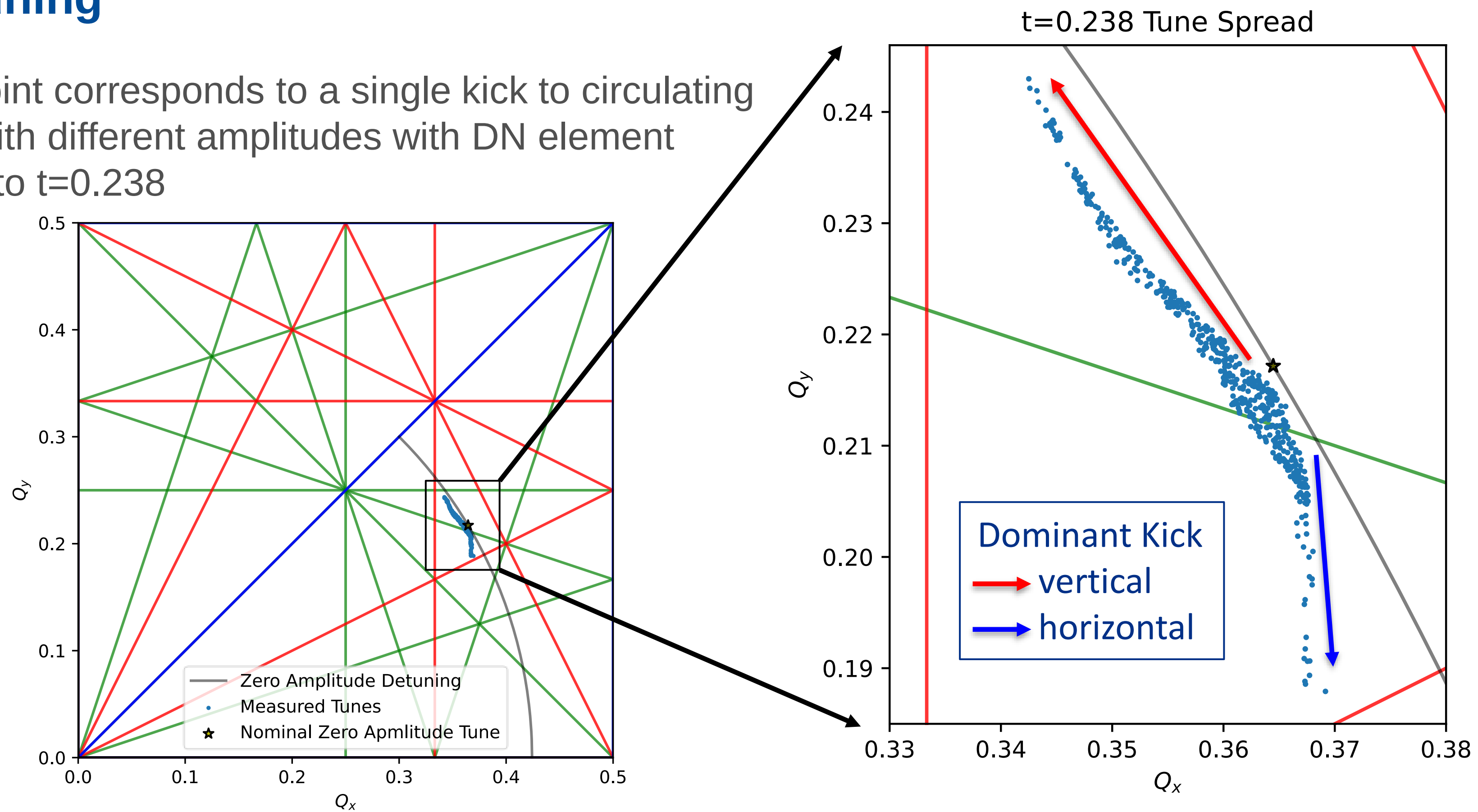
- Singular Value Decomposition applied to turn by turn data for all 21 BPMs
- Apply NAFF algorithm to principle SVD modes to measure fractional tune
- Constrained by nonlinear decoherence





DN Detuning

- Each point corresponds to a single kick to circulating beam with different amplitudes with DN element excited to t=0.238



Invariant Reconstruction

- Simple in principle – Substitute into theoretical expressions for invariants

$$H = \frac{1}{2}\left[p_x^2 + p_y^2 + x^2 + y^2\right] - t\mathrm{Re}\left(\frac{z}{\sqrt{1-z^2}}\arcsin(z)\right)$$

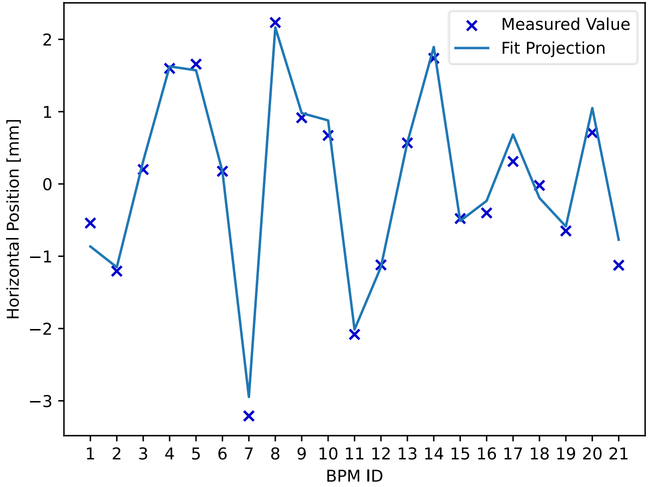
$$I = (xp_y - yp_x)^2 + p_x^2 + x^2 - t\mathrm{Re}\left(\frac{x}{\sqrt{1-z^2}}\arcsin(z)\right)$$

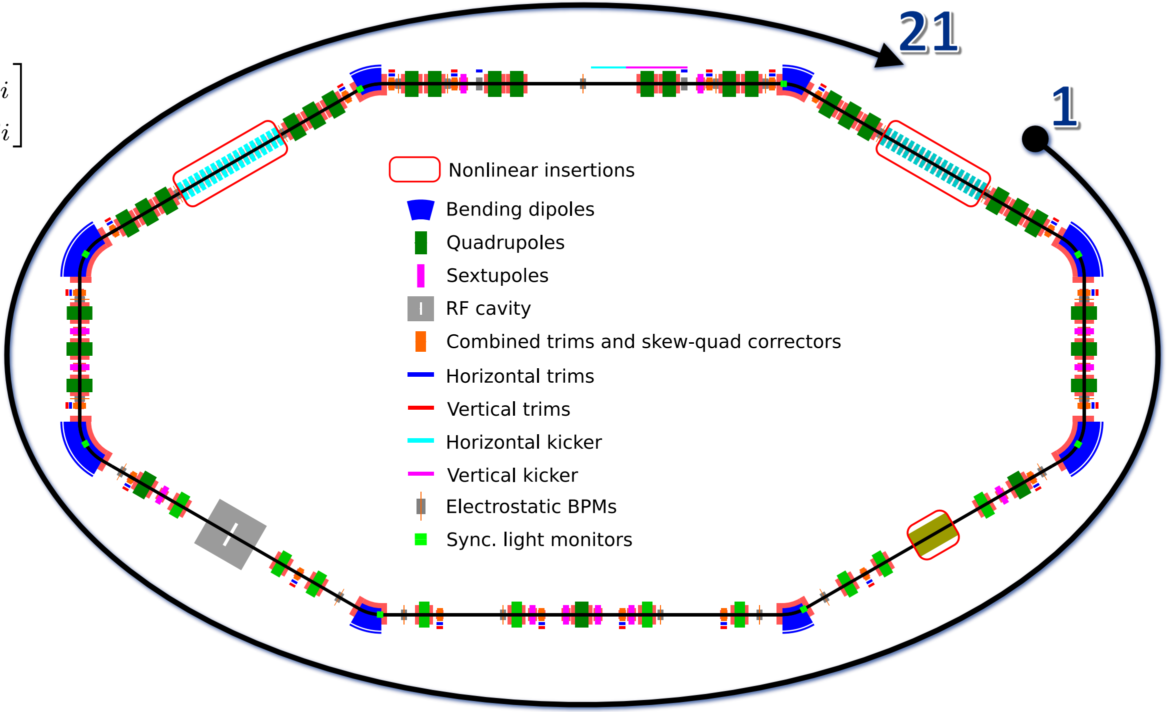
- Need to extract 4-D position from turn by turn data
- Complicated by Decoherence – apparent reduction in coordinate

4-D Position Reconstruction

- Use linear transfer maps to reconstruct 4-D position at a virtual BPM location turn by turn

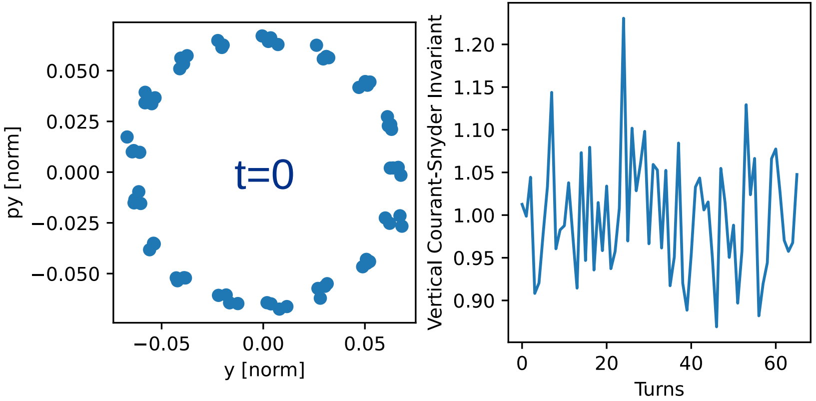
$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ \vdots \\ q_n \end{bmatrix} = \begin{bmatrix} M_{11}(i \rightarrow 1) & M_{12}(i \rightarrow 1) \\ M_{11}(i \rightarrow 2) & M_{12}(i \rightarrow 2) \\ M_{11}(i \rightarrow 3) & M_{12}(i \rightarrow 3) \\ \vdots & \vdots \\ M_{11}(i \rightarrow n) & M_{12}(i \rightarrow n) \end{bmatrix} \begin{bmatrix} q_i \\ p_i \end{bmatrix}$$

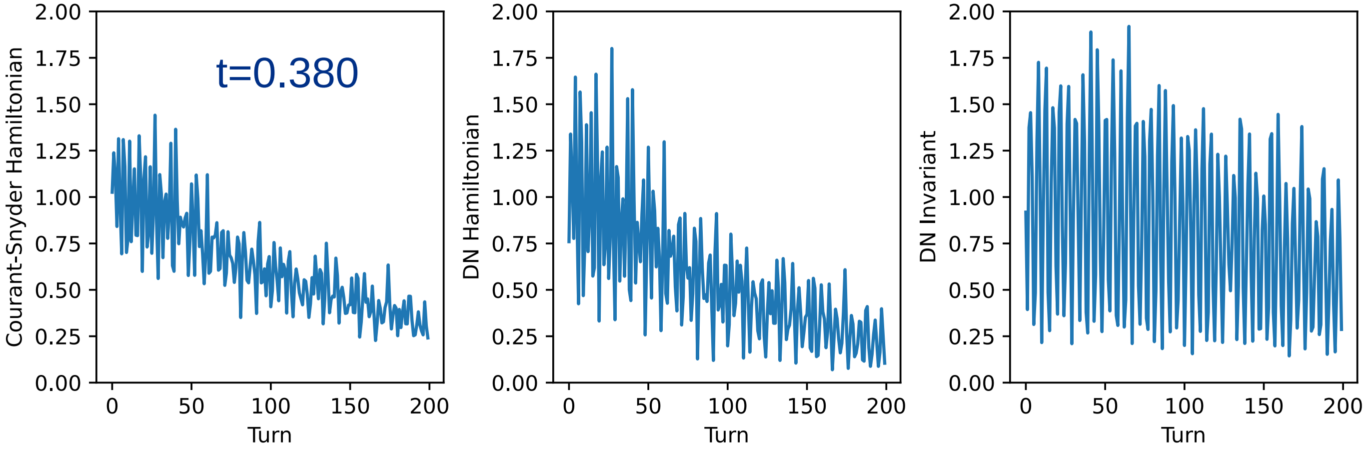




Invariant Conservation

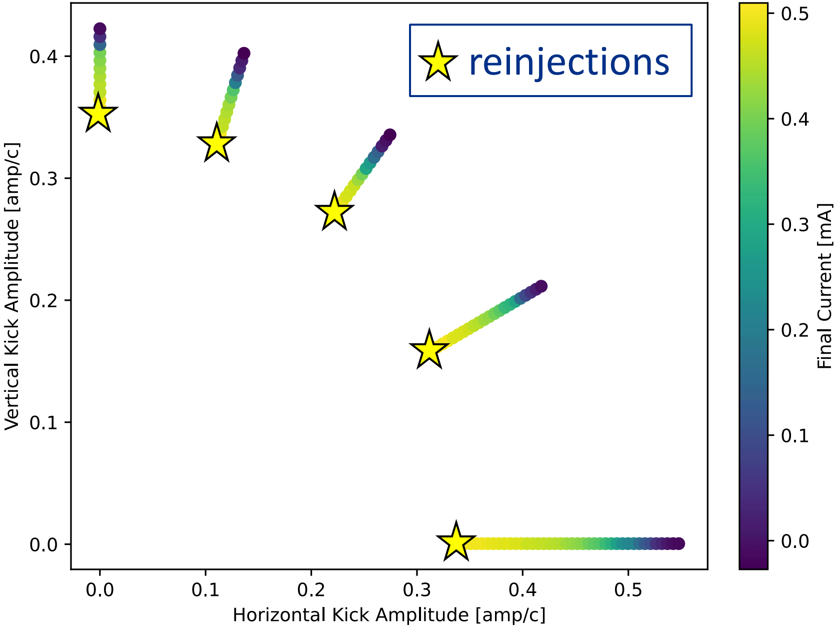
- Look at variance before decoherence
- No indication of superior nonlinear invariant conservation to the Courant-Snyder invariant for identical reconstructed coordinates yet

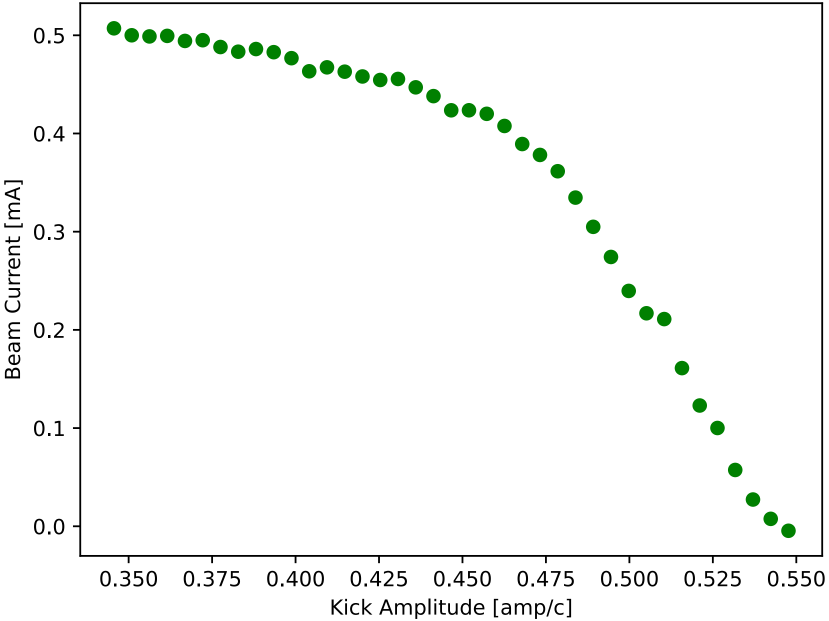




Dynamic Aperture

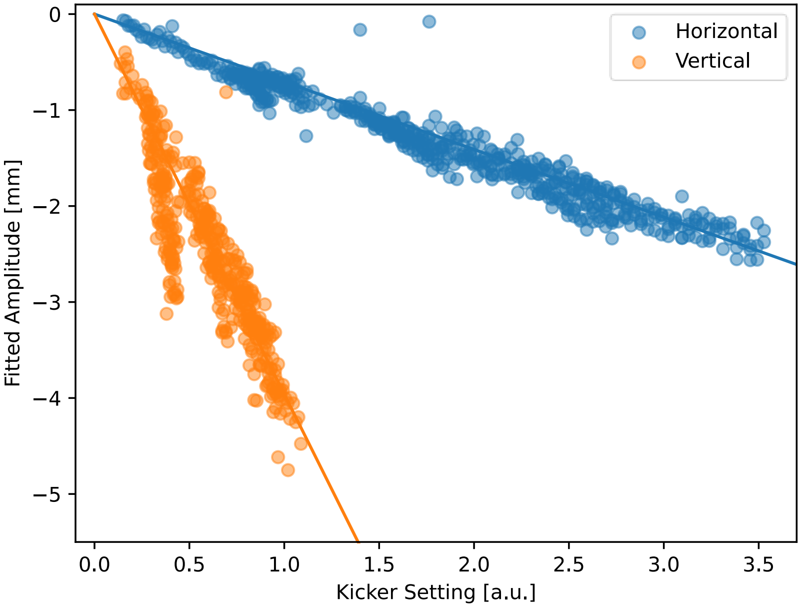
- Performed spoke scans to efficiently probe dynamic aperture
- Kicked to increasing amplitudes while monitoring beam current via DCCT

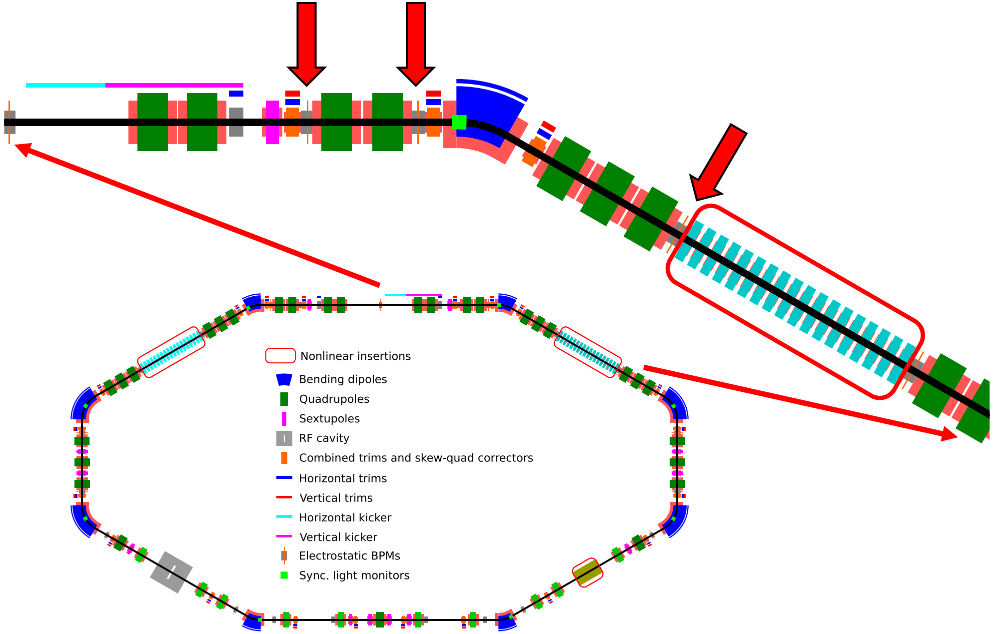




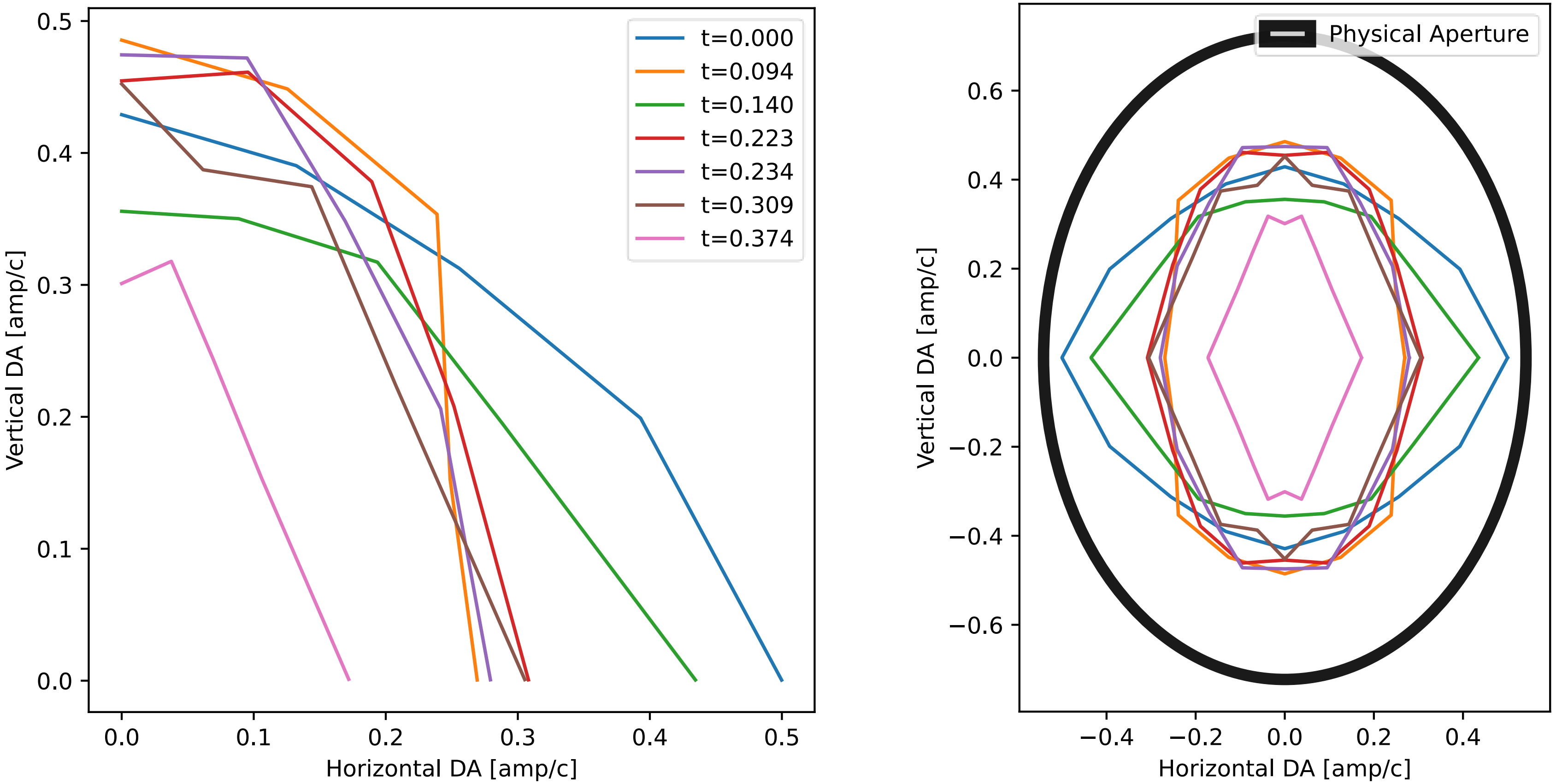
Kicker-Amplitude Calibration

- Correspond kicker amplitude with physical amplitude of beam
- Fitted directly from experimental BPM data in the same manner as momentum reconstruction





DA vs t



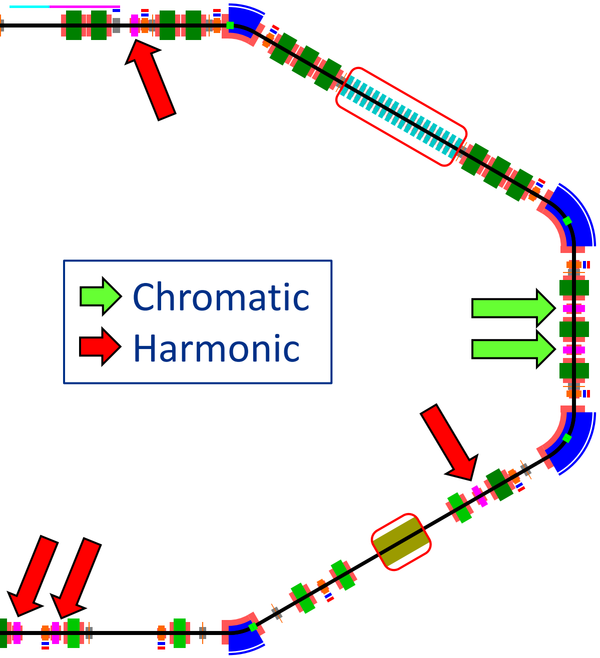
Fermilab

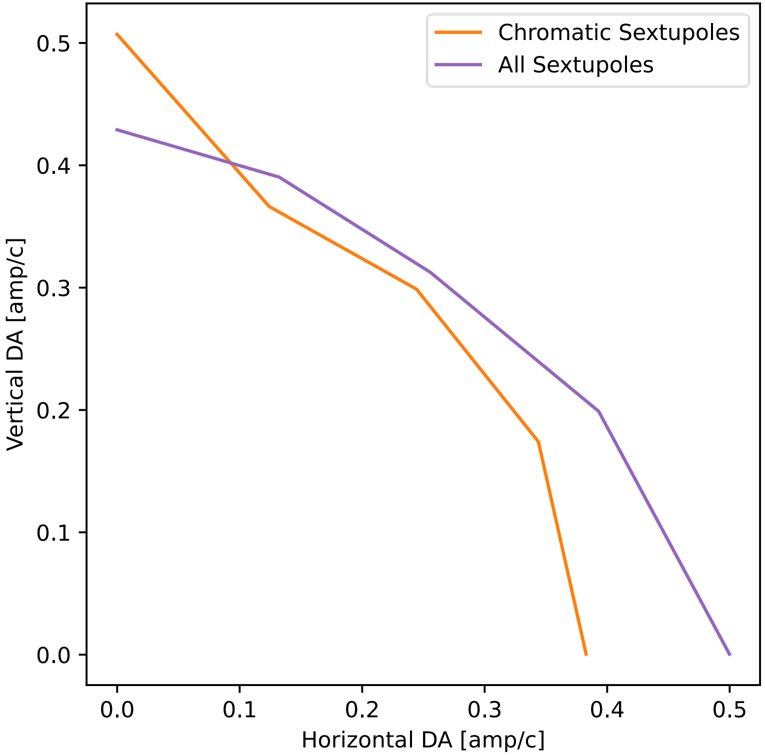
NIO System Perturbations

- Sextupole Configurations
  - No Sextupoles, i.e. uncorrected natural chromaticity
  - Corrected chromaticity, minimum sextupole families
  - Bayesian optimized sextupole configuration
- Linear Lattice Configurations
  - Phase advance in the nonlinear insert
  - Beta star position in the nonlinear insert
  - Dispersion in the nonlinear insert
  - Overall lattice tune

Sextupole Optimization

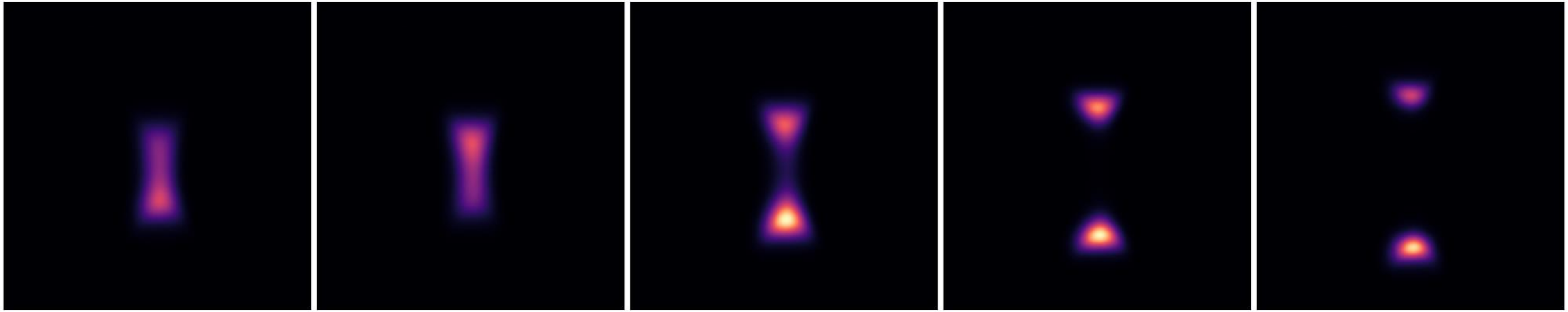
- Using all 6 families of sextupoles, found the chromatic null space (4 symmetric knobs) and implemented Bayesian optimization





Beam Profiles

- Synchrotron radiation measurements of the beam profile for varying the t-parameter of the DN insert beyond t=0.5
- Corresponds to zero amplitude detuning beyond the vertical integer resonance



Next Steps

- Continued Electron Data Analysis
  - Refine invariant conservation measurements, consider alternative methods
  - Beam profile analysis with nonlinear potential
  - Publication this year on NIO electron studies in Run 04
- Proton Studies in NIO
  - IOTA proton commissioning
  - NIO studies with intense proton beam

Thank You

- NIO Collaborators: Sasha Valishev, Sergei Nagaitsev, Sasha Romanov, Nikita Kuklev, Sebastian Stuzkowski, Giulio Stancari, Jonathan Jarvis
- Fermilab Support: Dan Brommelsiek, Chip Edstrom, Kermit Carlson, Steve Daley, Jinhao Ruan, Daniel Maclean, Trey Thompson, Jamie Santucci, Dave Franck, Nathan Eddy, Bobby Santucci, and many more

Citations

[1] Danilov, V., and S. Nagaitsev. “Nonlinear Accelerator Lattices with One and Two Analytic Invariants.” Physical Review Special Topics - Accelerators and Beams 13, no. 8 (August 25, 2010): 084002. https://doi.org/10.1103/PhysRevSTAB.13.084002.

[2] Photo Credit: Giulio Stancari

[3] Photo Credit: Aleksandr Romanov