Nonlinear Integrable Optics Experiments in IOTA run 4

A.Valishev, N.Kuklev, A.Romanov, G.Stancari, S.Szustkowski

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Nonlinear Integrable Optics – Overall Goals

- We want to build an optical focusing system that
  a. Is strongly nonlinear = strong dependence of oscillation frequency on amplitude
  b. Is 2D integrable = stable = free from resonances
  c. Can be realized with magnetic fields in vacuum

- Mathematically, that means the system should
  – Possess two integrals of motion
  – Have steep Hamiltonian
- Practical consequences
  – Reduced chaos in single-particle motion
  – Strong immunity to collective instabilities via Landau damping

NIO Research at IOTA

1. Experimentally demonstrate viability of theoretical concepts

- Very strong academic interest – stability of nonlinear systems
- Most importantly, show whether nonlinear focusing lattices offer practical benefits relative to linear lattices

2. Establish limits of applicability

- Are requirements to implementation tolerances supported by present-day technology?

3. Develop practical solutions for circular accelerators pushing the envelope in beam brightness without significant cost increase

Phased Approach

- Phase I – research concentrates on the academic aspect of single-particle motion stability using electron beams
  - Demonstrate large amplitude-dependent detuning with conservation of dynamic aperture
  - Demonstrate practical machine tuning and limits of integrable optics stability in terms of imperfections, other nonlinearities, impact of longitudinal dynamics
  - Practical benefits in terms of improvement of coherent beam stability

- Phase II – intense-beam studies with protons
  - Interplay between NIO and space-charge
  - Effect of NIO on halo formation, emittance growth and losses

Components of IOTA NIO Program

1. System with 1 invariant, aka Quasi-Integrable or Henon-Heiles Type
   - Implemented with Octupole string in BL straight
2. System with 2 invariants, aka Danilov-Nagaitsev or Elliptic potential
   - Implemented with special magnet (RadiaBeam) in BR straight

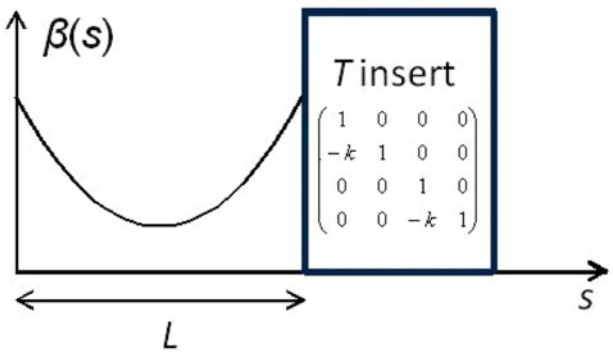
- Effect of nonlinear optics on coherent beam stability (as a separate experiment NIOLD)

Implementation of NIO Systems

1 Start with a round axially-symmetric *linear* lattice (FOFO) with the element of periodicity consisting of

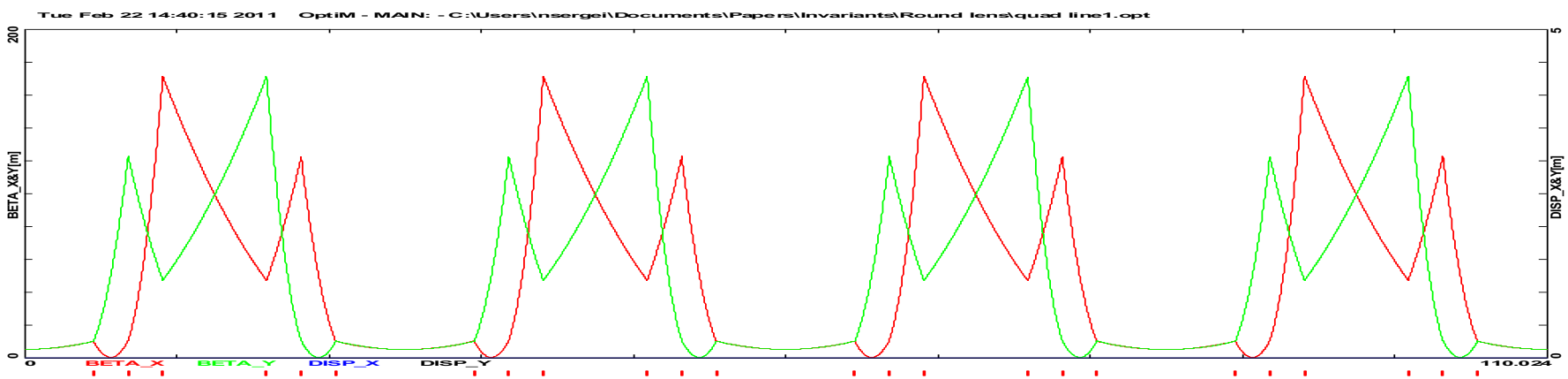
a. Drift L

b. Axially-symmetric focusing block "T-insert" with phase advance n × π



2 Add special nonlinear potential *V(x,y,s)* in the drift

- Results in time-independent Hamiltonian

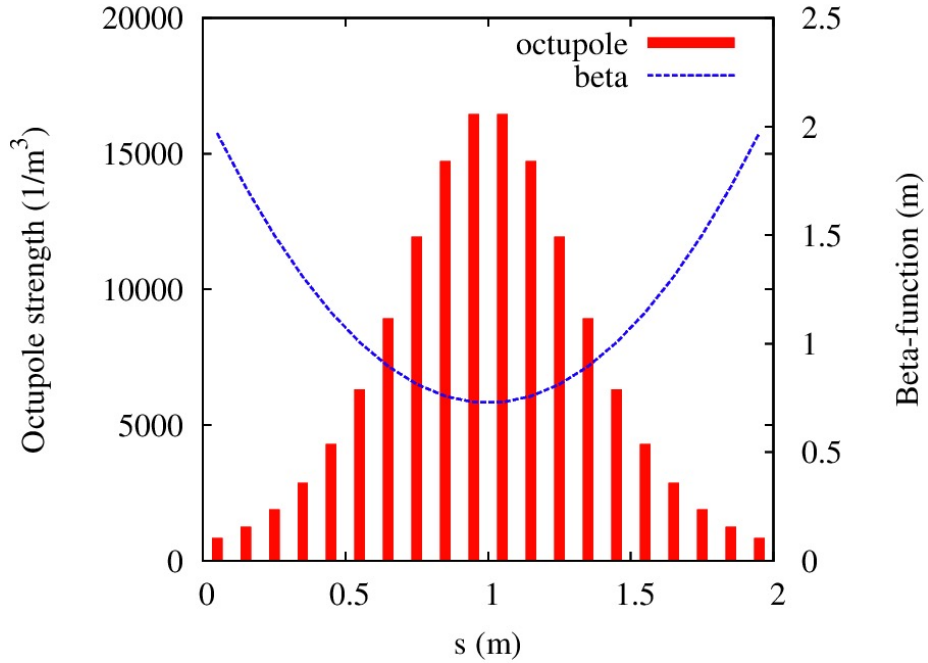


Henon-Heiles Type Systems

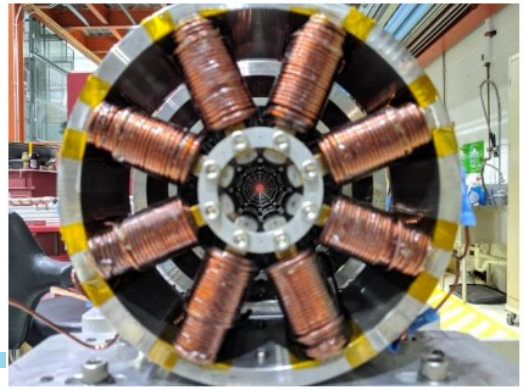
- For example, build *V* with Octupoles

$$V(x,y,s)=\frac{\kappa}{\beta(s)^3}\left(\frac{x^4}{4}+\frac{y^4}{4}-\frac{3x^2y^2}{2}\right)$$

$$U=\kappa\left(\frac{x_N^4}{4}+\frac{y_N^4}{4}-\frac{3y_N^2x_N^2}{2}\right)$$



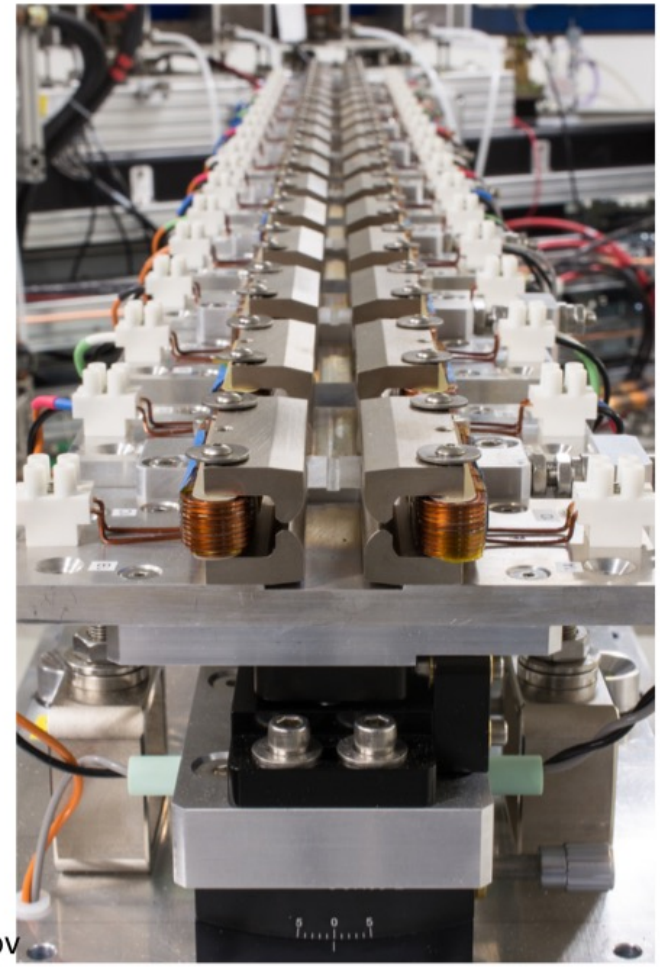
$$H=\frac{1}{2}(p_x^2+p_y^2)+\frac{1}{2}(x^2+y^2)+\frac{k}{4}\left(x^4+y^4-6x^2y^2\right)$$



- Only one integral of motion – *H*
- Tune spread limited to ~12% of Q_0

System with 2 Invariants – Danilov-Nagaitsev

- Shape V to obtain second invariant



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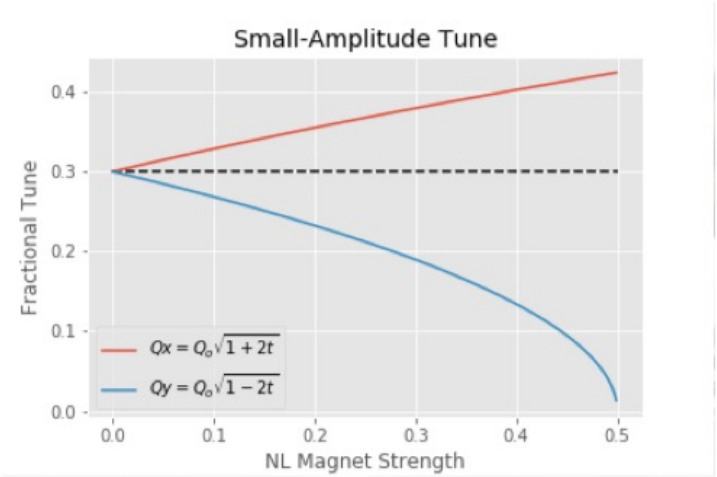
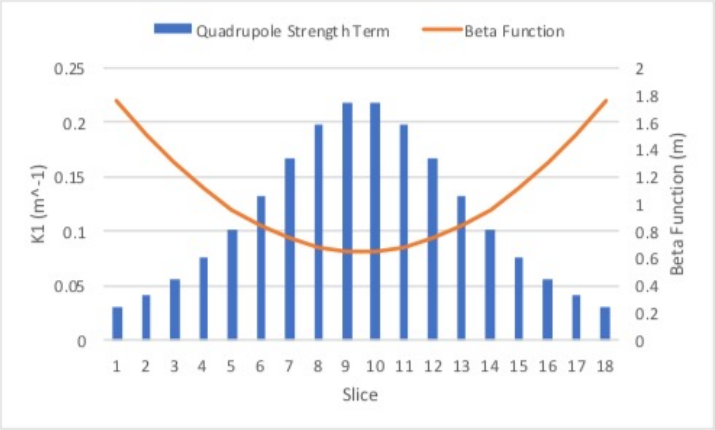
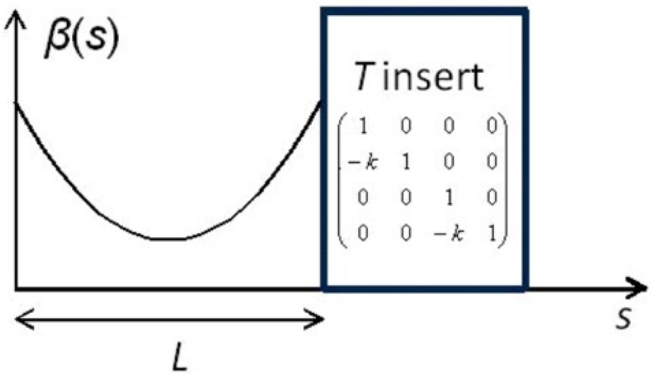
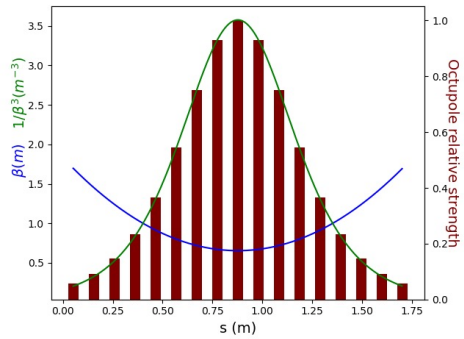




Fermilab

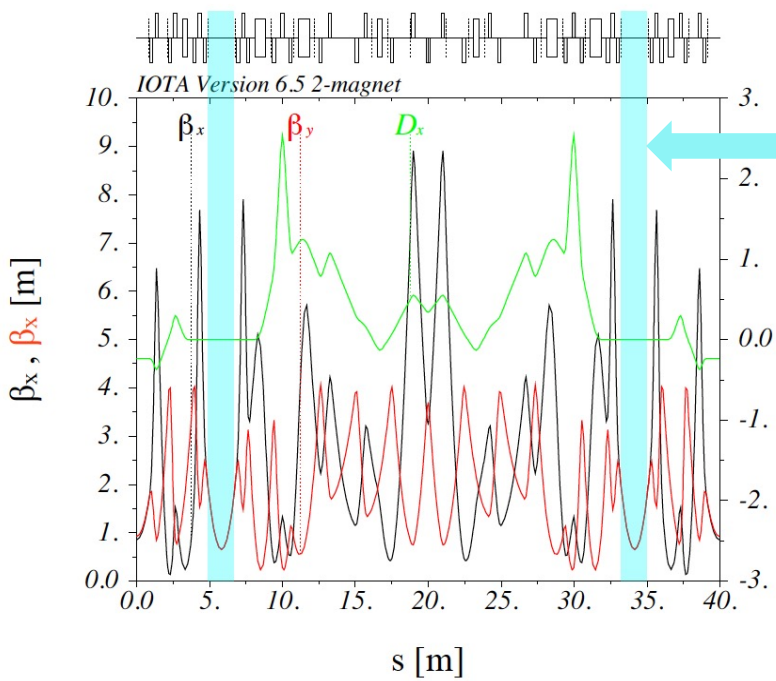
Implementation of NIO in IOTA

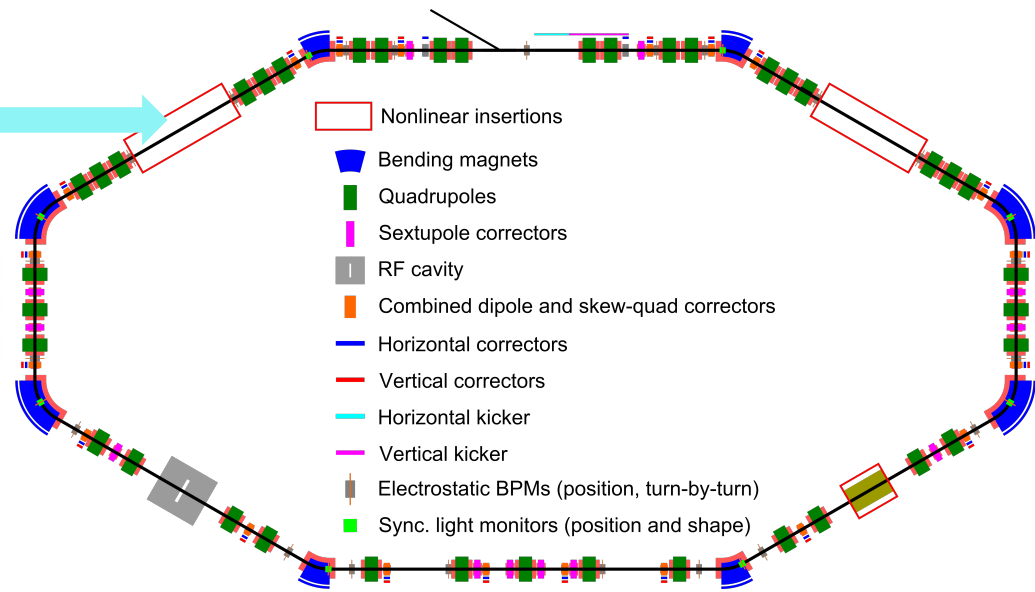




Practical requirements:

- Round axially-symmetric linear lattice (FOFO)
  - 2π x n phase advance
- Drift with $\beta_x=\beta_y$, no dispersion



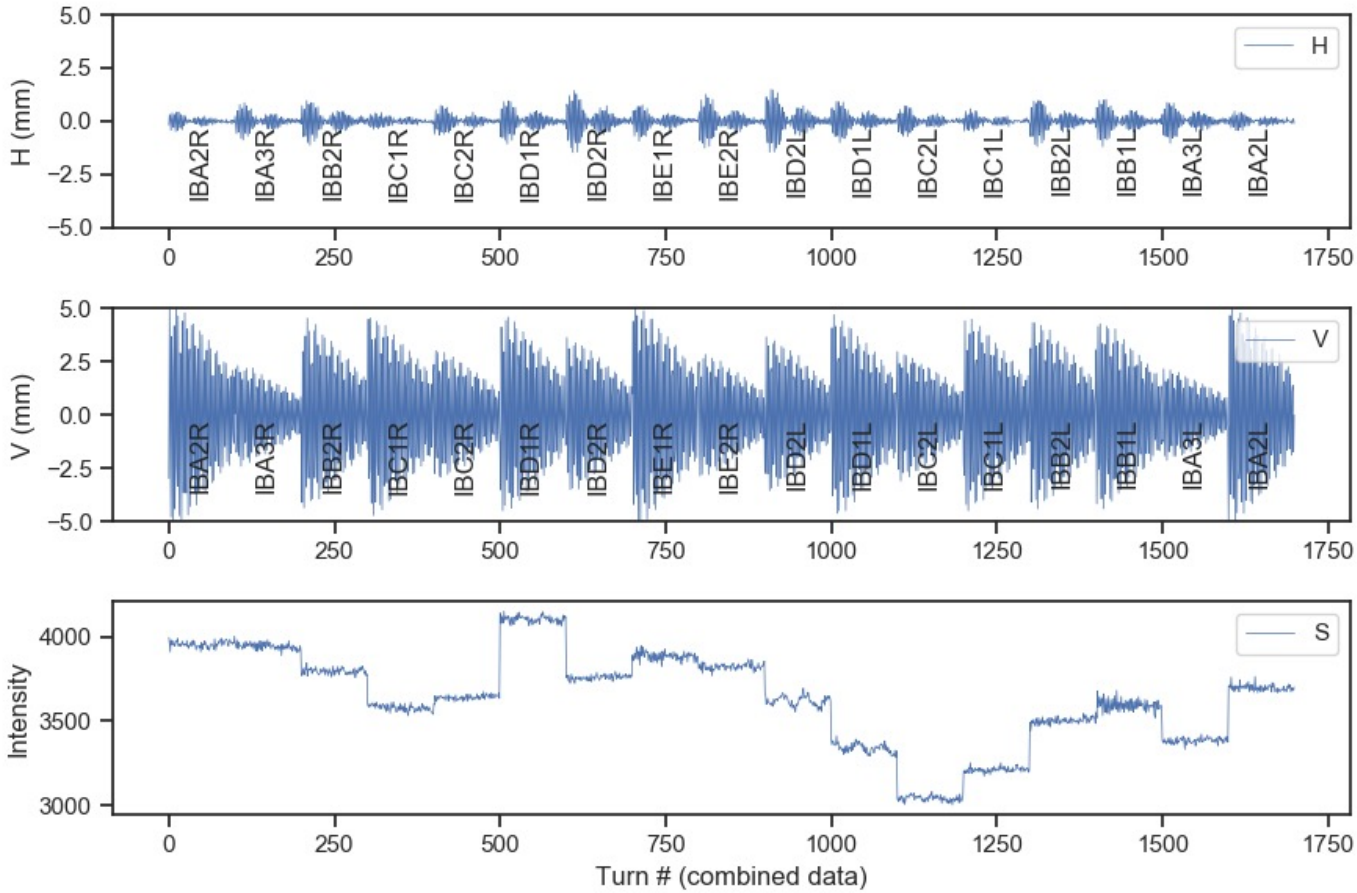


Run-2 Goals and Objectives

1. Demonstrate large (as predicted by modeling) nonlinear amplitude-dependent tune shift without reduction of dynamical aperture
   - For QI system as a function of Q_0 and *strength* = t
   - For DN system as a function of *strength* = t
2. Demonstrate conservation of dynamic invariants
   - Restore p, p_x, y, p_y from TBT data
3. Systematic study of sensitivity of the NIO systems to imperfections
   - T-insert mismatch
   - Intrinsic resonances
     - Effect of sextupoles
     - Q_0=¼ with octupoles
     - Effect of integer resonance for DN system at high t

Experimental Method

- Kick beam with V/H kicker to selected amplitude
- Record BPM turn-by-turn positions and beam intensity

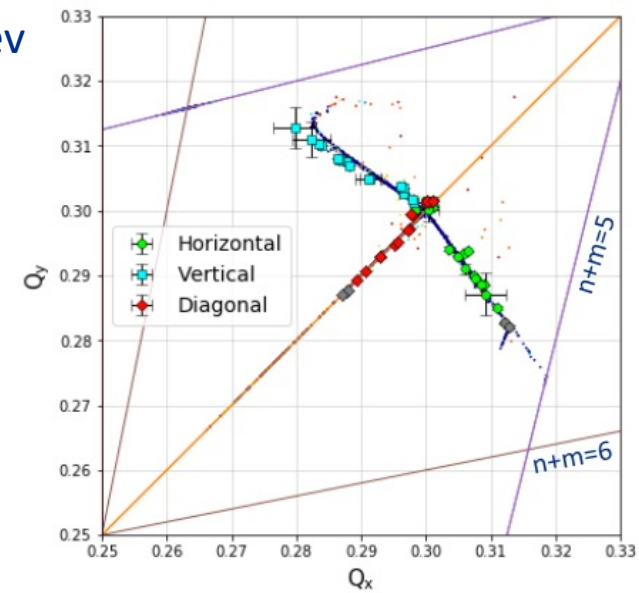


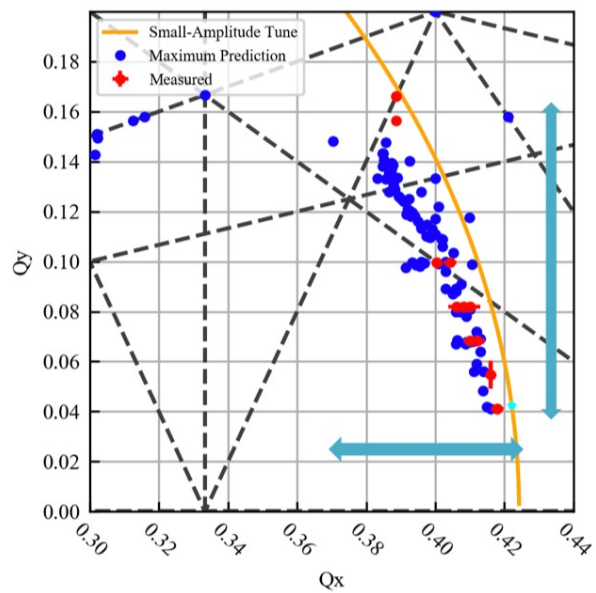
0.6kV Vkick
1A octupoles
100 turns

Run-2 Results

1. Demonstrate large (as predicted by modeling) nonlinear amplitude-dependent tune shift without reduction of dynamical aperture
   - ✓ For QI system as a function of Q_0 and *strength = t*
     - *Good agreement with simulations*
   - ✓ For DN system as a function of *strength = t*
     - *Poor DA at some t or amplitude – need Stage 3 experiments*

N.Kuklev





S.Szustkowski

Run-2 Results

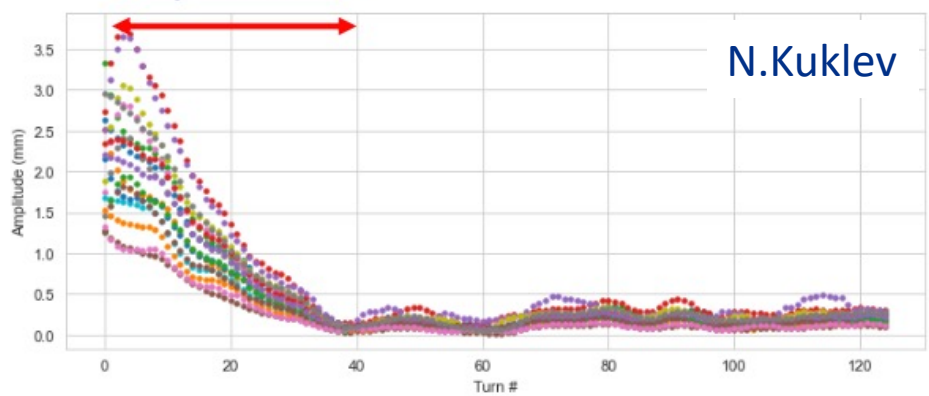
2. Demonstrate conservation of dynamic invariants
   - Restore p, p_x, y, p_y from TBT data
     - Dynamical variable and invariant restoration difficult due to short length of useful dipole moment caused by filamentation (decoherence)
       - Chromaticity
       - Nonlinearity

$$e^{-\alpha^2/2}\frac{1}{1+\theta^2}exp\left[-\frac{A^2}{2\sigma^2}\frac{\theta^2}{1+\theta^2}\right]$$

$$\theta = 4\pi\Delta QN$$

$$\alpha = \frac{2\xi\sigma_E \sin\pi Q_s N}{Q_s}$$

Only 25 turns!



DN t=0.363 diagonal kick (no beam loss)

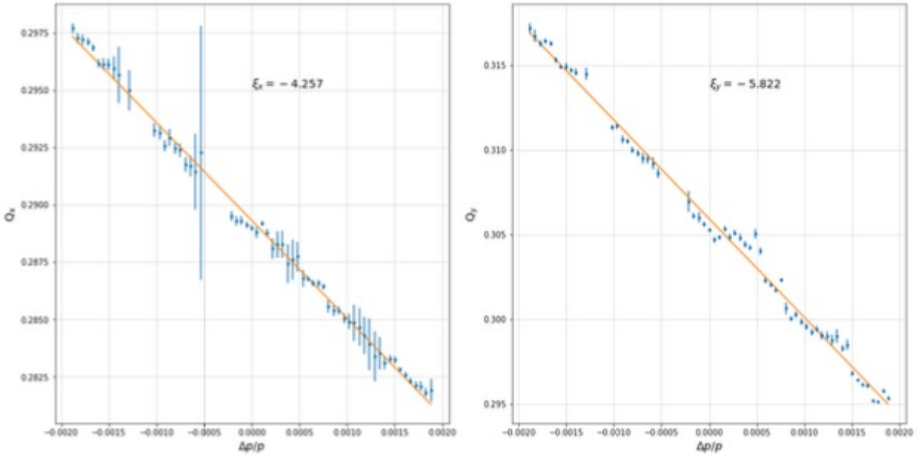
Fermilab

Run-2 Results

3. Systematic study of sensitivity of the NIO systems to imperfections – not started due to run cancellation (covid shutdown)
   - T-insert mismatch
   - Intrinsic resonances
     - Effect of sextupoles
     - Q_0=¼ with octupoles
     - ✓ Effect of integer resonance for DN system at high t

Lessons Learned and Selected Issues

- Nonlinear magnet worked well
- Octupole string (also re-tested in run-3)
  - Numerous problems with alignment
  - Intermittent short
- Machine / beam
  - Good tuning of nominal lattice
    - 1% beta-function, 0.001-0.003 betatron phase, 50um orbit centering
  - Good machine aperture
  - Not well understood sextupole nonlinearity / chromaticity



Lessons Learned and Selected Issues

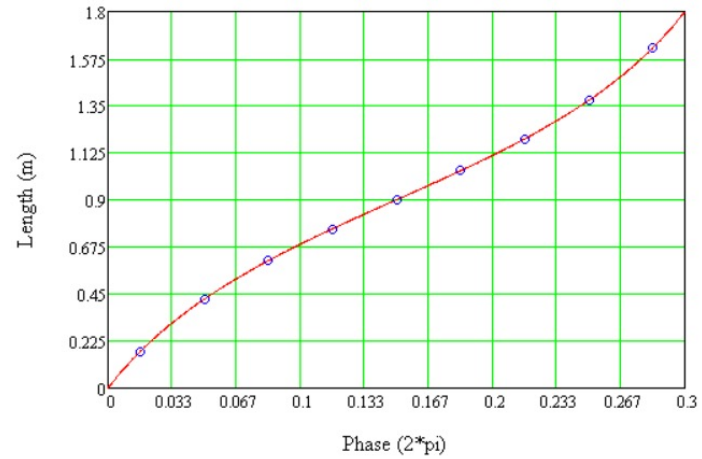
- Instrumentation
  - BPM TBT worked well at currents of >1 mA (100um noise or better).
  - BPM closed orbit mode works well at low currents (extensively used in run-3).
  - Excellent performance of synclight system.
- Software
  - SixDSim – LOCO (machine mode-switching fully implemented in run-3).
  - pyIOTA software by N.Kuklev capable of automated data-taking.

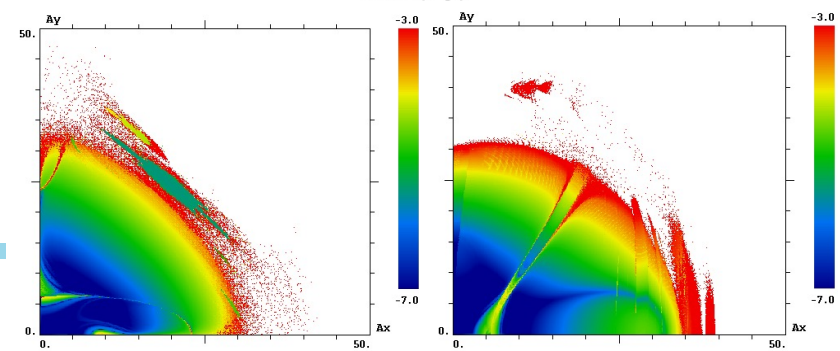
Improvements Since Run-2

- Realigned selected quadrupoles aiming to reduce local coupling in BR → lower skew corrector current
  - Still needs further work
- Commissioned 150MeV operation
  - This will result in much better signal quality due to smaller beam size and momentum spread
- Improved alignment of injection section (better tuning range)
- Improved stability of quadrupole power supplies
- Streamlined operational procedures
- Single-electron tracking shows great promise
  - As tool for detuning measurement
  - Potentially for phase-space reconstruction

Improvement of NIO Implementation

- Presently, both QI and DN systems are implemented with equidistant ‘thin’ kicks (Euler integrator)
- The representation of the nonlinear potential can be improved via element placement equidistant in phase (e.g. Ruth symplectic integrator S.Baturin, arXiv:1908.03520)
- Simulations show that system with ½ the segments can achieve the same preservation of invariants
- Reassembly of octupole string with different spacing would allow for test of such approach





Proposed Goals for NIO in Run-4

Operating IOTA with electron beam at 150MeV

1. Perform systematic study of sensitivity of the NIO systems to imperfections (phase 3)
   - T-insert mismatch
   - Intrinsic resonances
     - Effect of sextupoles
     - Q_0=¼ with octupoles
     - Effect of integer resonance for DN system at high t
2. Implement QI system with small (9) number of octupoles aiming to achieve performance of run-2
3. Collect data for dynamical variable reconstruction and demonstration of invariant preservation

Necessary Actions

- Shutdown
  - Reconfigure IOTA for NIO
    - Remove OSC
    - Reinstall DN magnet
    - Rebuild octupole string

    } Required for proton run
- Operations
  - Commission NIO lattice at 150MeV
  - Improve coupling near BR section
  - Commission sextupole system
  - Understand IOTA chromaticity correction

  } Important for future OSC research

Conclusion

- IOTA run-2 NIO experiments produced exciting results, demonstrating record-high nonlinear amplitude dependent tune shifts
  - System is robust to perturbations, worked well despite limited knowledge of the machine at the time
- However, full scientific potential was not realized. Planned program was not executed
  - Significant progress on IOTA was made during run-3
- New approach to approximation of continuous potential with discrete elements may result in better performance
- NIO program being very demanding to the level of machine development pushes the team to implement improvements
  - Electron run would help OSC, mitigate risk for proton ops.