Introduction to Nonlinear Integrable Optics Experiments

Alexander Valishev

2020 IOTA/FAST Collaboration Meeting

16 June 2020

Relevance to Fermilab and HEP Mission

Potential applications of strongly nonlinear focusing rings

- Intensity frontier – high-intensity and high-brightness rapid cycling synchrotrons.
  - Mitigation of ultra-fast coherent instabilities via Landau damping
  - Mitigation of space-charge related losses
- Energy frontier – circular colliders (e.g. FCC)
  - Cost-effective mitigation of coherent instabilities via Landau damping

There are strong synergies with other SC offices

- Nonlinear systems can find application in EIC, Ion traps, Light sources

Goals of Nonlinear Integrable Optics Research

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

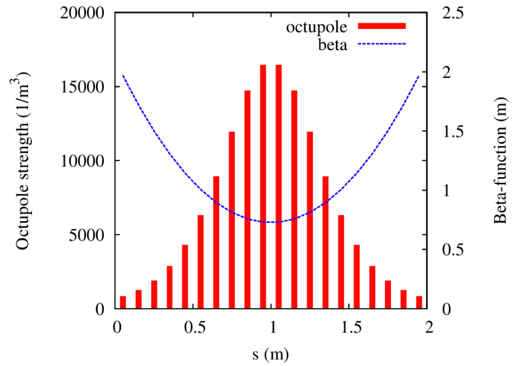
- Phase II – intense-beam studies with protons
  - Interplay between NIO and space-charge
  - Effect of NIO on halo formation, emittance growth and losses

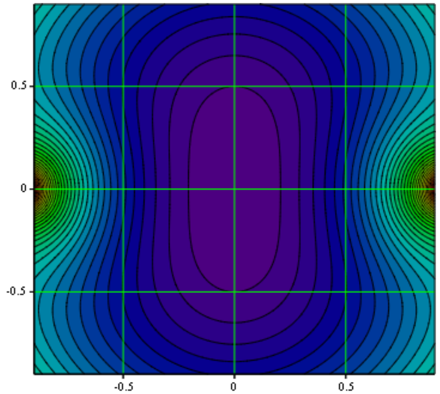
Components of IOTA NIO Program

1. System with 1 invariant, aka Quasi-Integrable or Henon-Heiles Type (talk by N.Kuklev)
   – Implemented with Octupole string in BL straight
2. System with 2 invariants, aka Danilov-Nagaitsev or Elliptic potential (covered by N.Kuklev and S.Szustkowski)
   – Implemented with special magnet (RadiaBeam) in BR straight
3. Effect of nonlinear optics on coherent beam stability (talk by N.Eddy)

Implementations of Nonlinear Integrable Optics

1. Remove time dependence from Hamiltonian thus making it an integral of the motion
   - Can be done with any nonlinear potential, for example octupoles (QI)
2. Shape the nonlinear potential to find a second integral (DN)
   - General solution was found, which satisfies the Laplace equation (*Phys. Rev. ST Accel. Beams 13, 084002, 2010*)

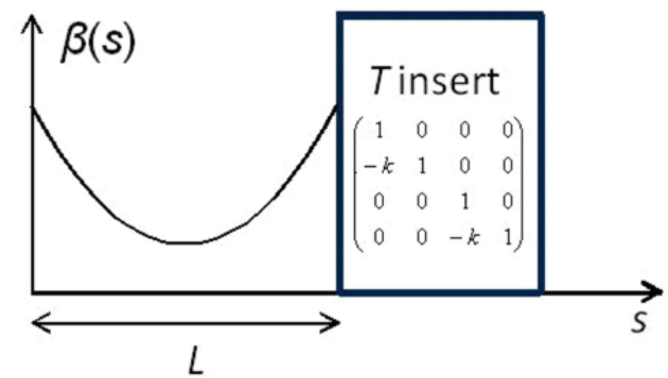


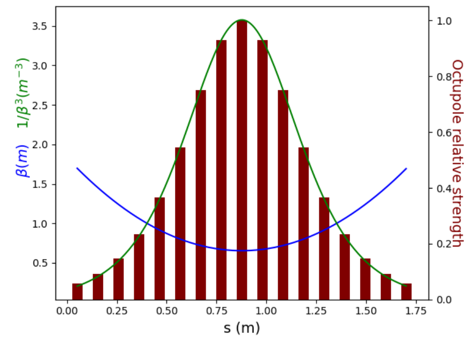


Future: 2D Expansion of McMillan mapping

- Two invariants of the motion
- Implementation with electron lens
- The steepest Hamiltonian

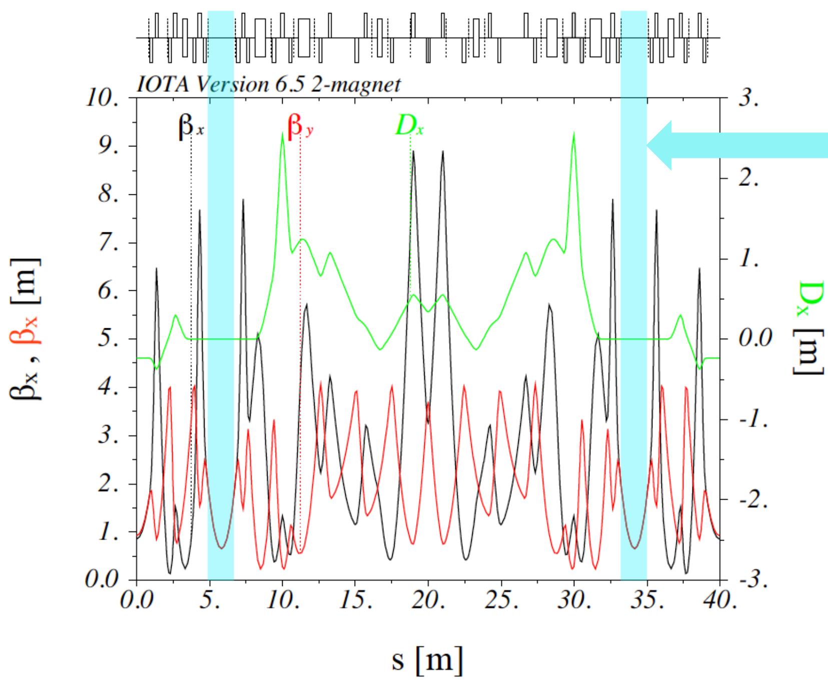
Implementation of NIO in IOTA

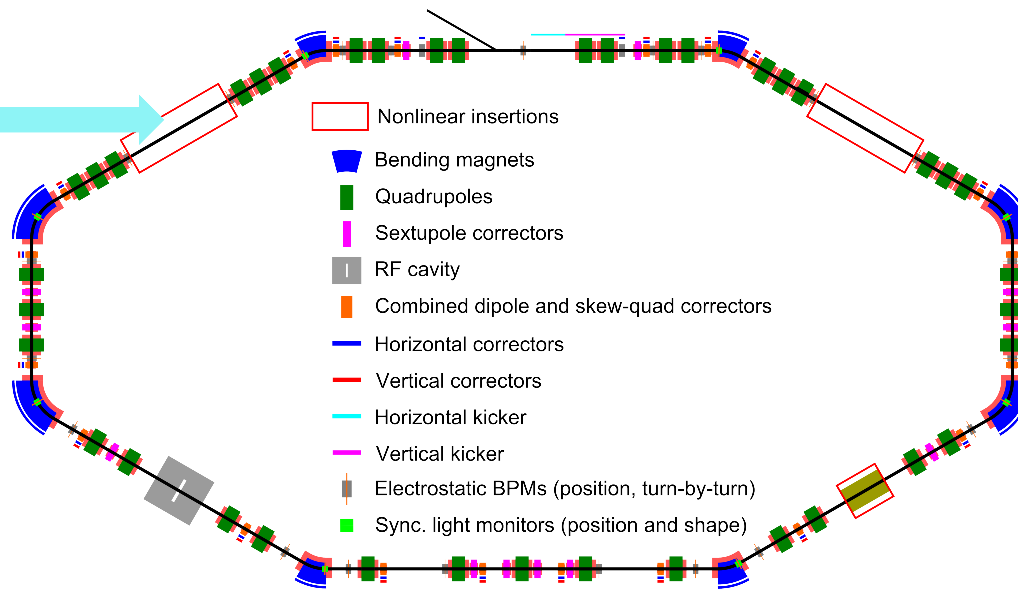




Practical requirements:

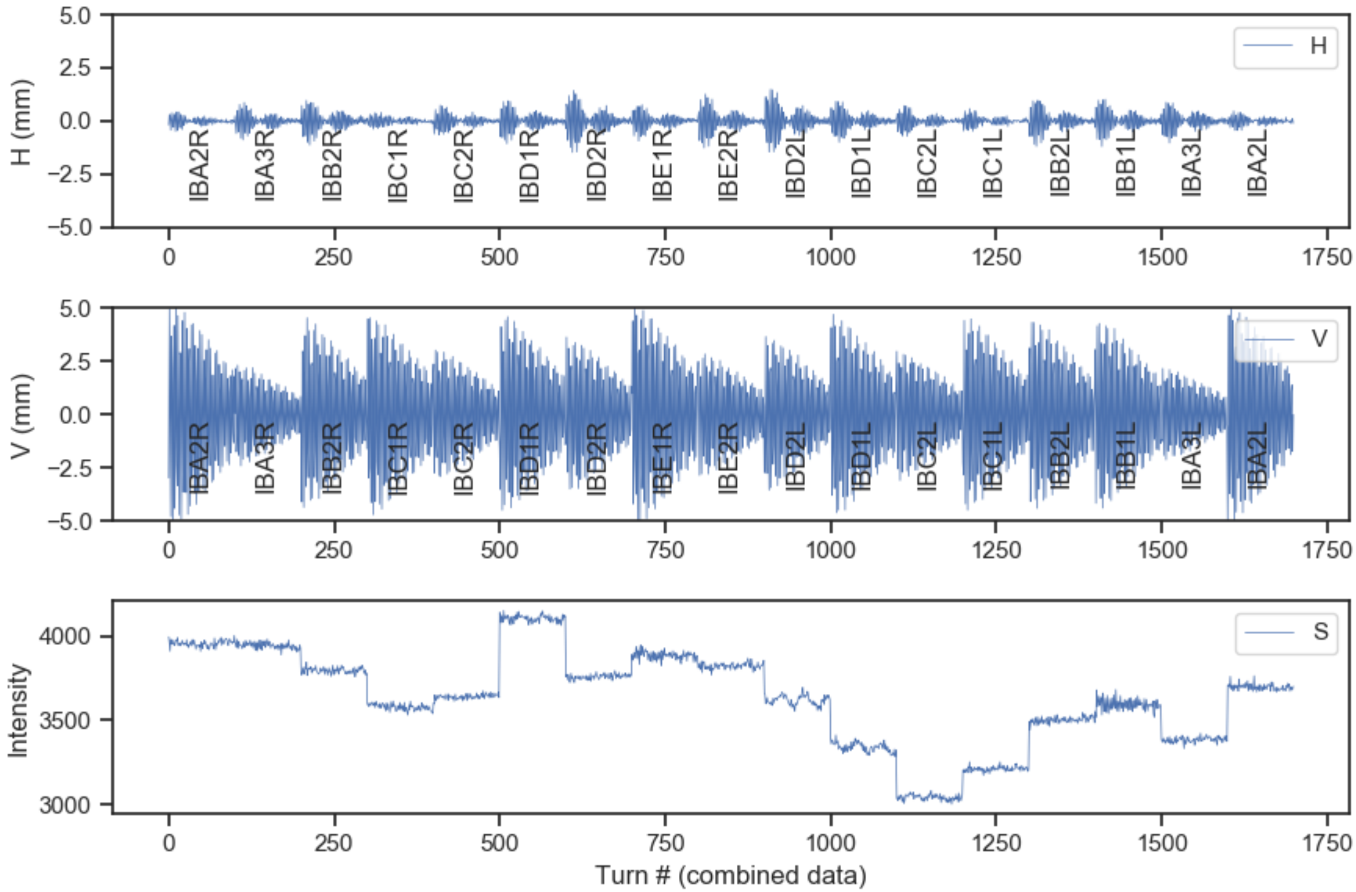
- Round axially-symmetric linear lattice (FOFO)
  - $2\pi \times n$ phase advance
- Drift with $\beta_x = \beta_y$, no dispersion





Experimental Method

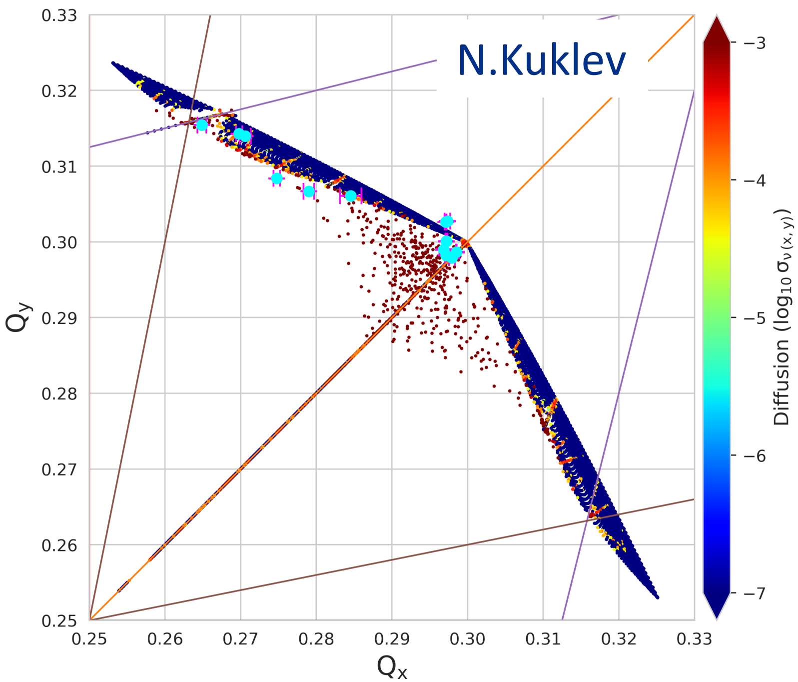
- Kick beam with V/H kicker to selected amplitude
- Record BPM turn-by-turn positions and beam intensity

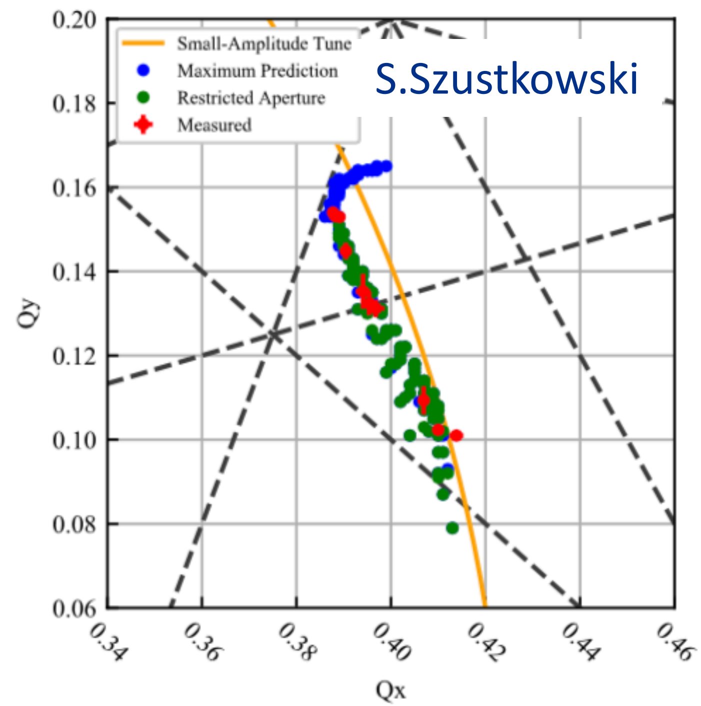


0.6kV Vkick
1A octupoles
100 turns

Run-1 Results – Amplitude-Dependent Tune Shift

- ~60-70% of ideal performance for both types of NIO
- Clear improvement vs single octupole
- Beam loss attributed to aperture restriction in DR
- Limited machine tuning precision
- Too fast decoherence for invariant reconstruction





Fermilab

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*

Improvements/Requirements from Run-1

- Reassemble and Install Octupole string

1. Beam parameters
   a. Smallest momentum spread for long decoherence time without sextupoles → E=150 MeV, low beam current
   b. Smallest transverse emittance → low (<0.5mA) beam current to avoid IBS
2. Lattice tuning and stability
   a. All synclight cameras
   b. Closed-orbit BPM with high resolution (<10μm)
   c. beta-function accuracy, betatron phase accuracy, orbit centering
3. Kicker control
   a. H and V controlled independently 0-1kV
4. Turn-by-turn coordinate measurement
   a. Needs high beam current for best resolution, compromise with 1-b

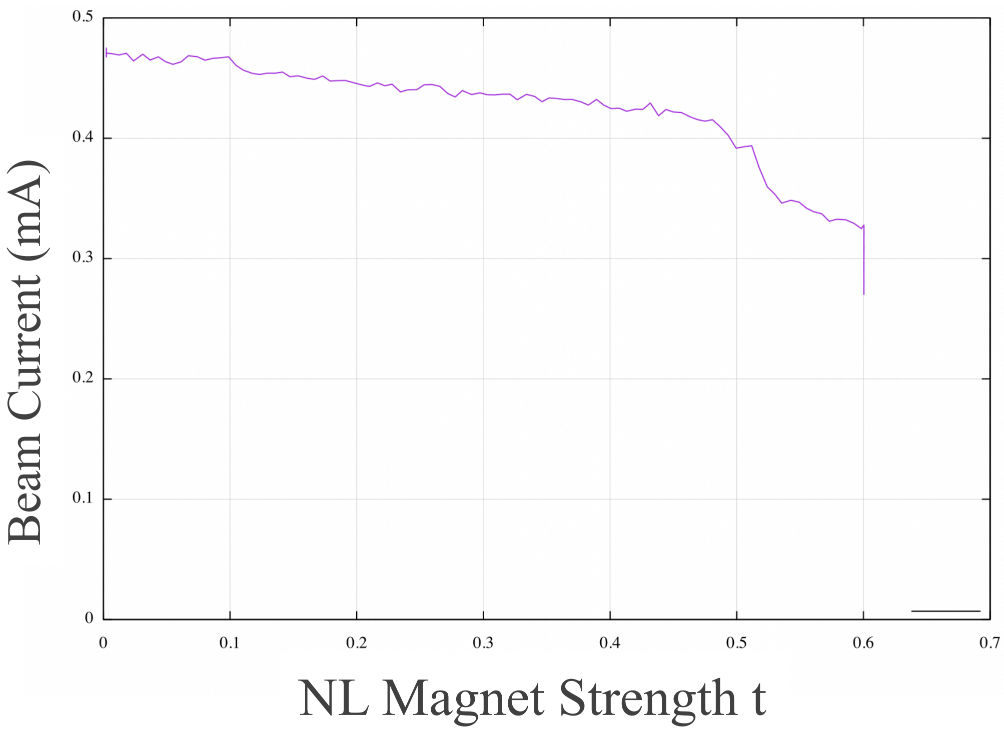
Run-2 Plan

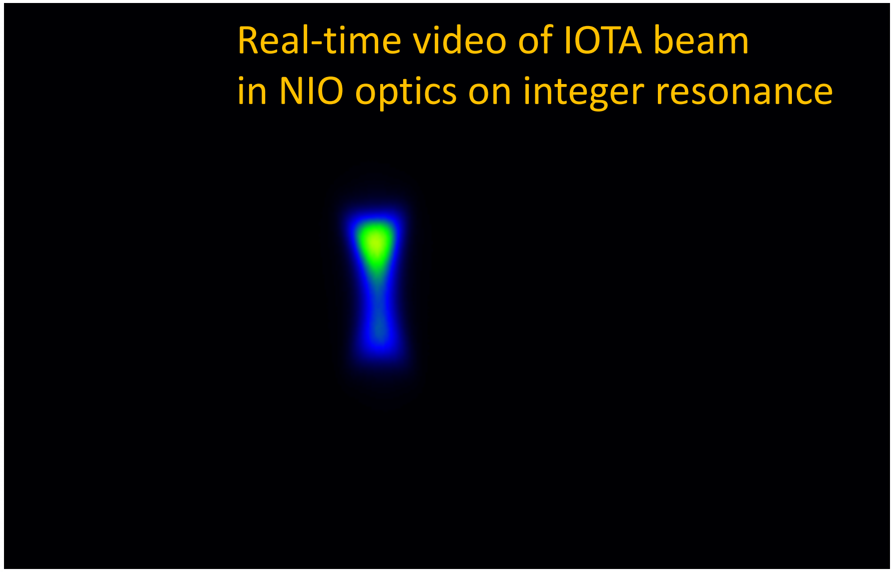
- NIO Experiment consisted of 3 phases
  – Phases 1 and 2 in baseline NIO lattice
  – For Phase 3, several lattice configurations needed
  – Originally planned 12 shifts
    - Phase 1+2 – 6, Phase 3 – 6.
    - RunCo schedule contains 19 shifts
  – Phases 1+2 – data mostly collected
  – Phase 3 was not completed due to run being cut short because of covid-19 lab shutdown
- NIOLD Experiment planned 2 shifts

Key Elements and Selected Issues

- Nonlinear magnet
  - No change since Run-1, worked well
- Octupole string
  - Significant rebuild
- Machine / beam
  - Good tuning of nominal lattice (although LOCO model can be improved)
  - Aperture much improved from Run-1
  - Not well understood sextupole nonlinearity / chromaticity
  - Beam in other buckets
- Instrumentation / software
  - BPM TBT worked well
  - pyIOTA software implemented by N.Kuklev late in run

Run-2 Highlight – Beam on Integer !!!





Run-2 Highlight - Improvement of beam stability