Fighting Nonlinear Dynamics with Nonlinear Elements: Nonlinear Integrable Optics Experiments at IOTA

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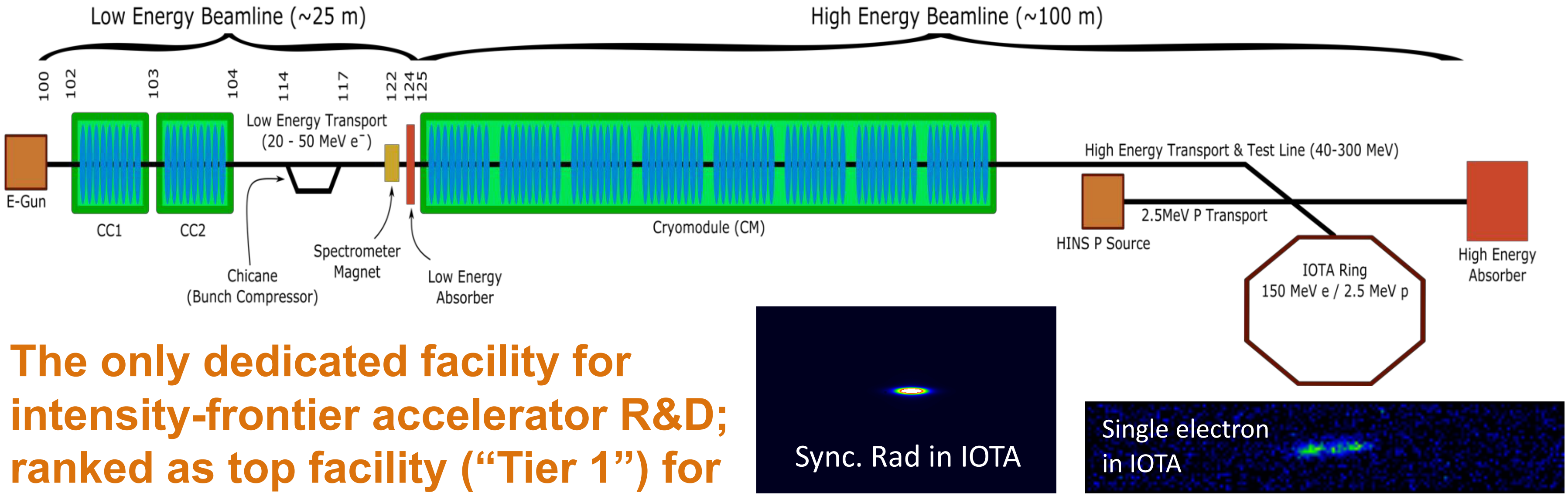
Workshop on Mitigation Approaches for Hadron Storage Rings and Synchrotrons

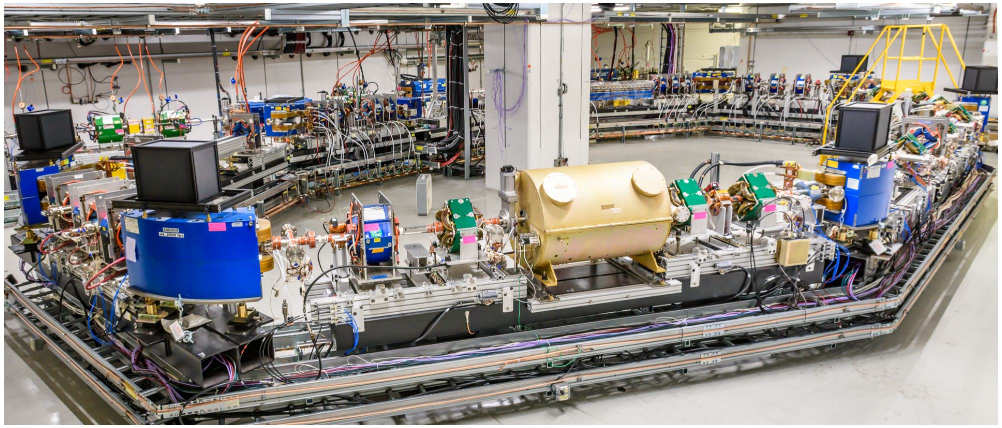
22 June 2020

IOTA/FAST Facility: a center for Acc. and Beam Physics

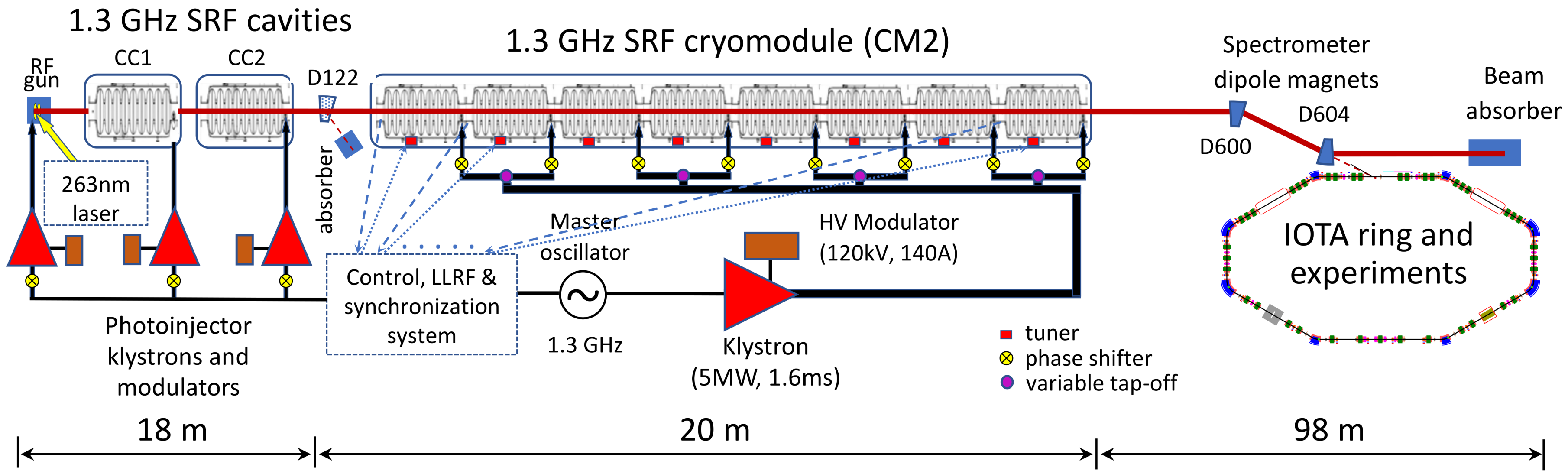
- **IOTA/FAST establishes a capability at FNAL, unique in the world, to address frontier topics in Accelerator and Beam Physics**



- **The only dedicated facility for intensity-frontier accelerator R&D; ranked as top facility ("Tier 1") for acc. & beam physics thrust by recent GARD review**
- ~30 Collaborating institutions
- Nat. Lab Partnerships: ANL, BNL, LANL, LBNL, ORNL, SLAC, TJNAF
- Many opportunities for R&D with cross-office benefit in DOE/SC



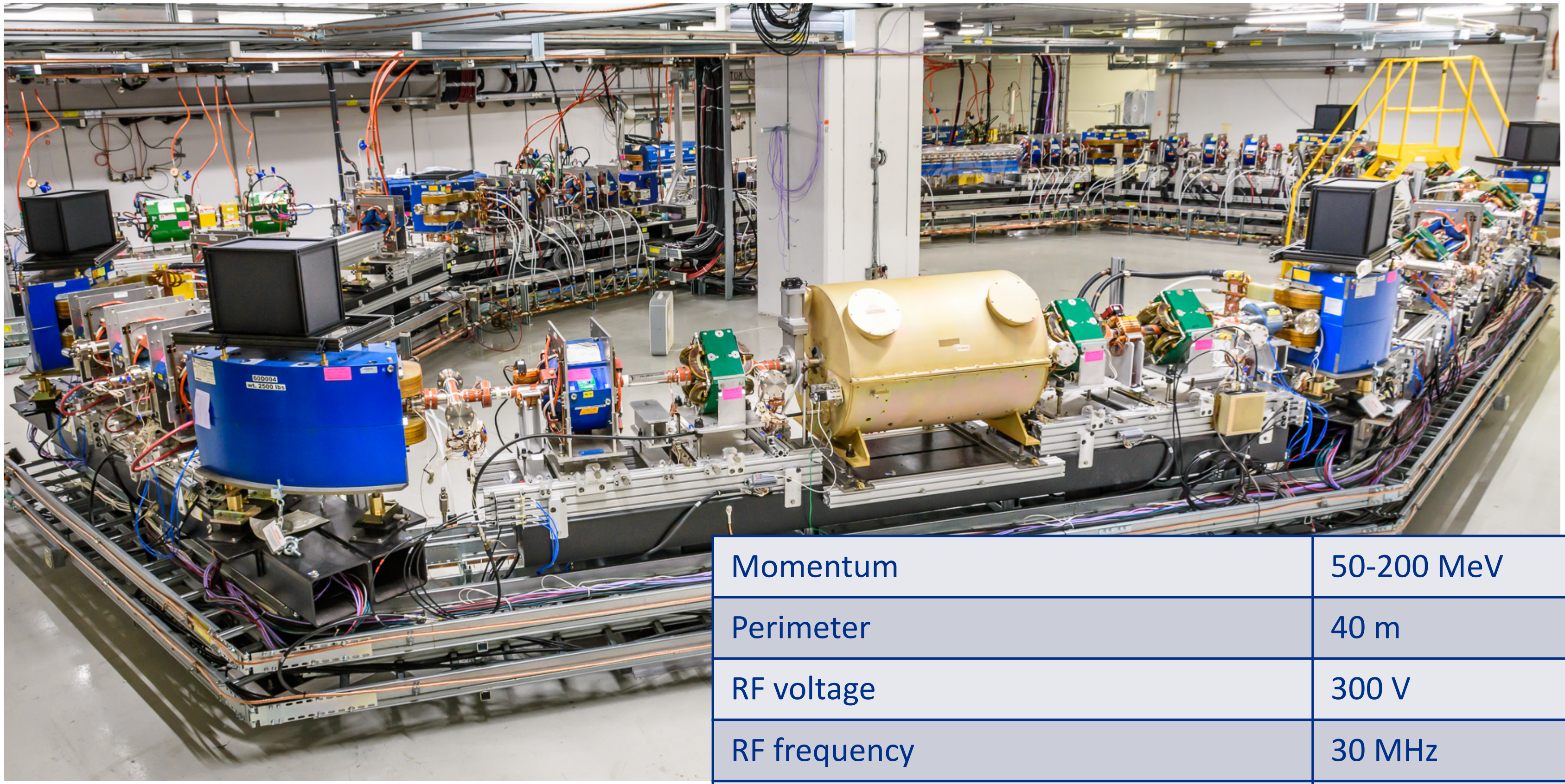
IOTA/FAST Accelerators



Electron beams are supplied to IOTA from FAST, 1.3 GHz Superconducting RF electron linear accelerator

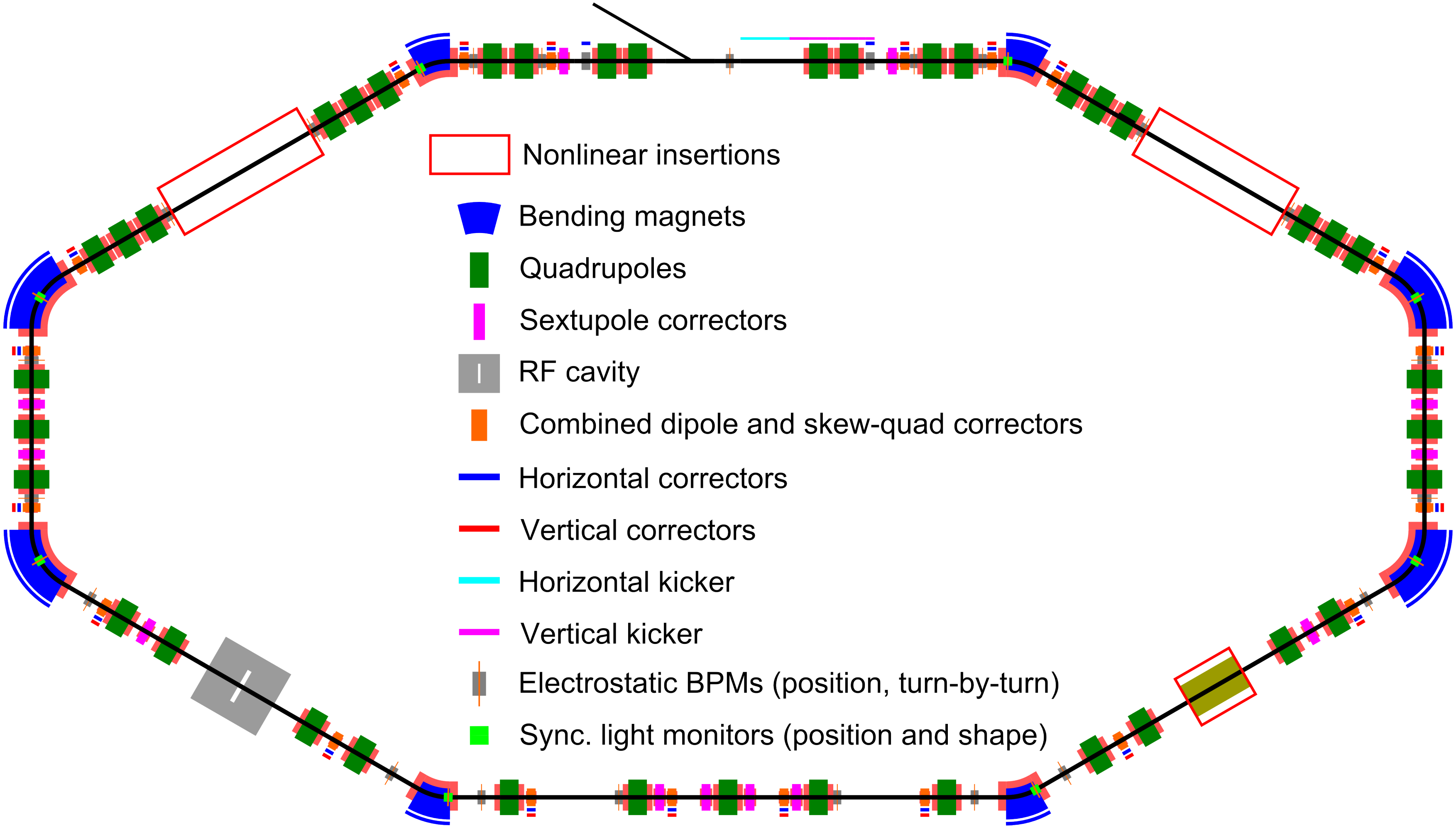
- Beam energy to IOTA: 40-200 MeV
- Bunch charge: 1e- to 3 nC (160 pC nominal)
- Injection frequency: up to 5 Hz

IOTA With Electrons



Momentum	50-200 MeV
Perimeter	40 m
RF voltage	300 V
RF frequency	30 MHz
3 Experimental sections	2x180 cm, 1x150 cm
Main vacuum chamber aperture (R)	25 mm
Lambertson and kickers aperture (R)	20 mm
Electrons bunch	10^9 e, 160 pC, 1.2 mA

IOTA Layout

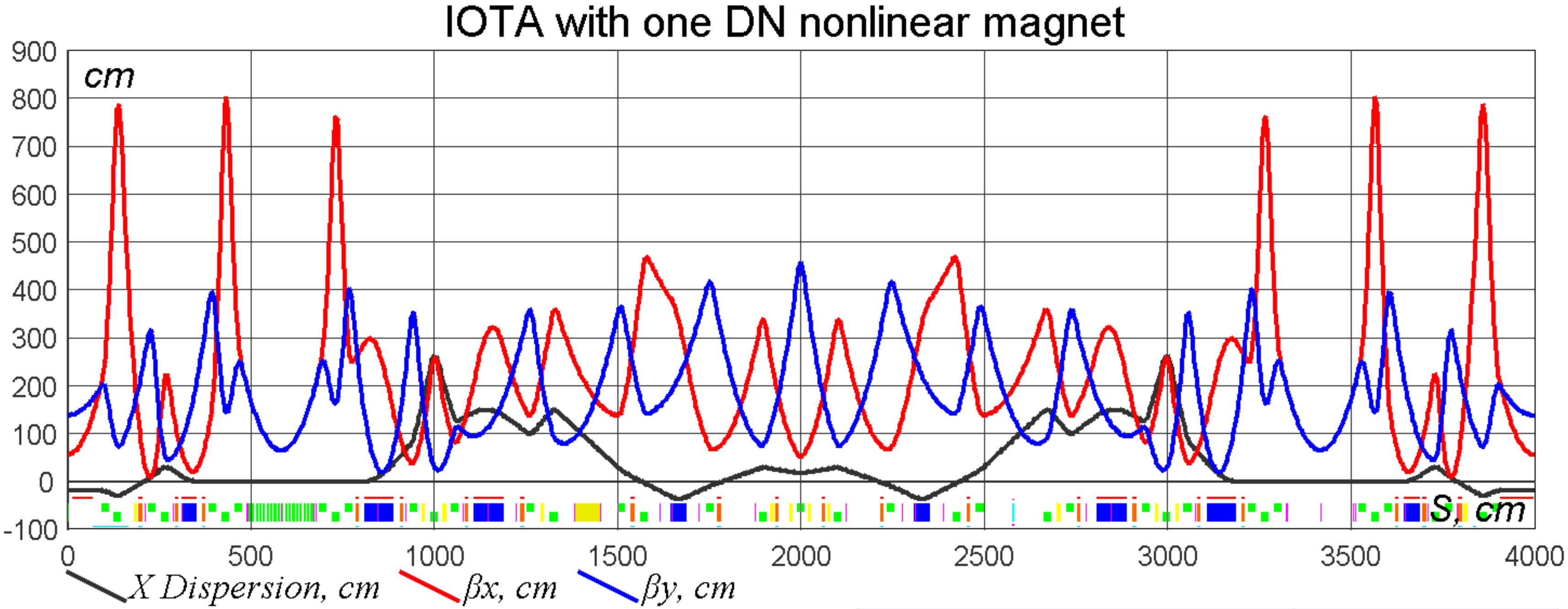


- ▭ Nonlinear insertions
- Bending magnets
- 🟩 Quadrupoles
- ▮ Sextupole correctors
- ▮ RF cavity
- 🟧 Combined dipole and skew-quad correctors
- — Horizontal correctors
- — Vertical correctors
- — Horizontal kicker
- — Vertical kicker
- Electrostatic BPMs (position, turn-by-turn)
- 🟩 Sync. light monitors (position and shape)

IOTA Main Components

Lambertson magnet		1	Horizontal, injection in vertical plane
Kickers		1 hor. & 1 vert.	Horizontal for studies only
Main dipoles		4x60 deg & 4x30 deg	Powered in series with Lambertson
Quads		39	Powered in pairs with individual shunts
Trims	Hor.	8	In main dipoles
	Vert.	2	For injection bump
	Hor.	20	Combined correctors
	Vert.	20	
Skew-quads		20	
Pickups		21	Turn-by turn position
Sync. light monitors		8	Shape and position
RF		1	Dual frequency
Solenoid		1	For electron and McMillan lenses
Sextupoles		12	In six families
DCCT		1	Precision calibrated DC beam current
Wall current monitor		1	Bunch currents and longitudinal shape

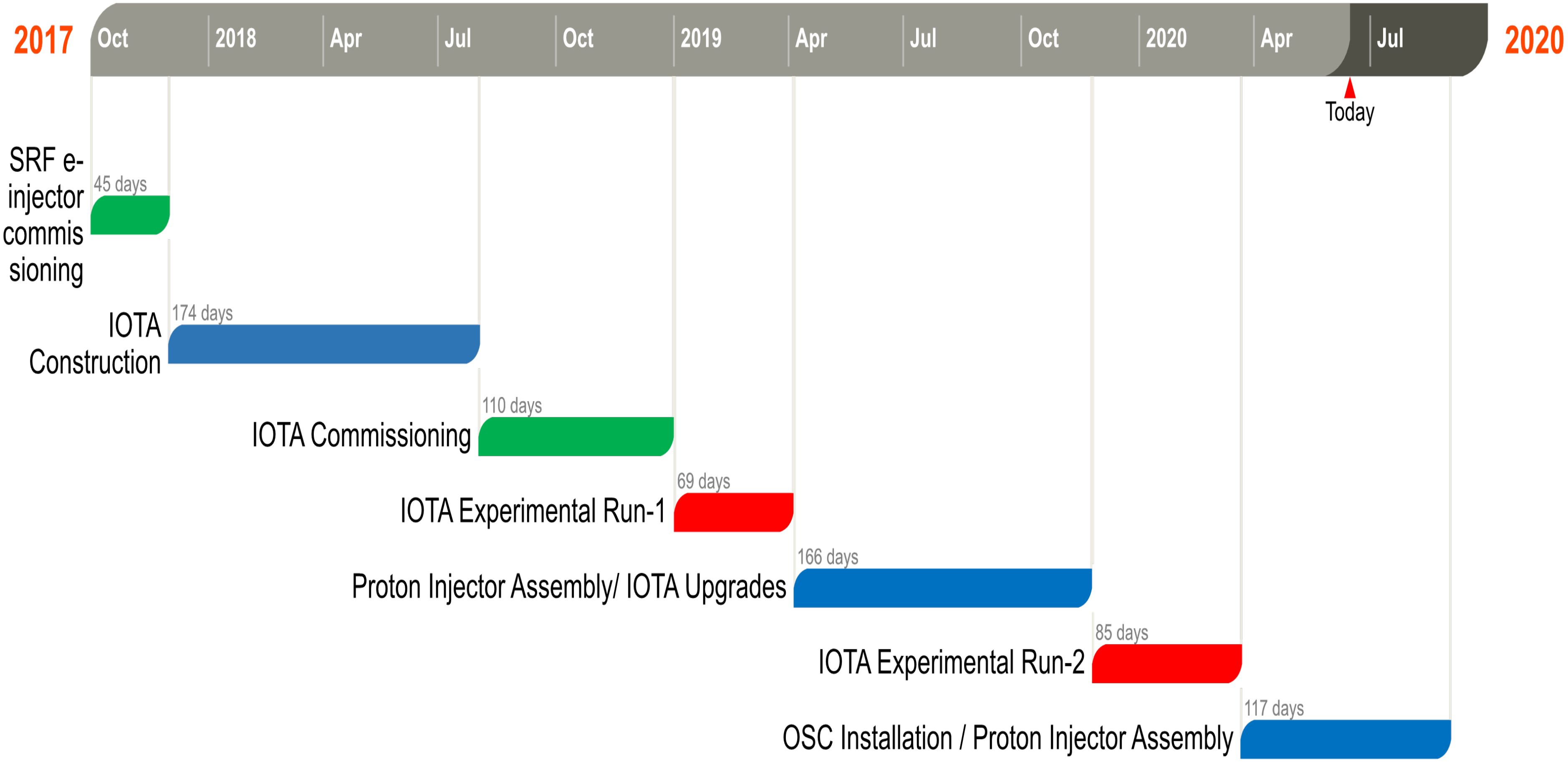
IOTA Lattice Configuration



Parameter	Max error
Betas at the insertion	1%
Beta beating	3%
Dispersion	1 cm
Closed orbit at insertion	0.05 mm
Phase advance between insertions	0.001

Momentum	100 MeV
Tunes, x,y	5.3, 5.3
Mom. comp.	0.0756
RMS emit. (x, x&y-coupled)	(42.8, 11.2) nm
Damp. times (x,y,x&y-coupled,s)	(6.7,2.4,3.5,0.90) s
Energy spread	8.4 E-5
Bunch length @300V	10.6 cm
Sync. Tune @300V	3.8 E-4

IOTA/FAST Recent Timeline



Research in IOTA/FAST Experimental Run 2

Broad program: in all 9 experiments took data over 60 shifts and produced relevant results. Engagement of outside collaborators (CERN, SLAC, Jlab, Uchicago, NIU) and 6 graduate students.

1. Nonlinear Optics Measurements and Correction in the IOTA Ring	PI M.Hofer (R.Tomas), CERN
2. Study of Intrabeam Scattering	V.Lebedev, FNAL
3. Nonlinear Integrable Optics in Run 2	A.Valishev, FNAL
4. Angular Measurement of Photons from Undulator Radiation in IOTA's Single Electron Mode	E.Angelico (H. Frisch/S. Nagaisev), UChicago
5. Measurement of Spontaneous Undulator Radiation Statistics Generated by a Single Electron	S.Nagaitsev, I. Lobach, FNAL/UChicago
6. Fluctuations in undulator radiation	I.Lobach (S. Nagaitsev/G. Stancari), UChicago
7. Instability thresholds and integrable optics	N.Eddy, FNAL
8. Investigations of Long-range and Short-range Wakefield Effects on Beam Dynamics in TESLA-type Superconducting Cavities	A.Lumpkin, FNAL
9. Generation, Transport and Diagnostics of High-charge Magnetized Beams	P.Piot, NIU/ANL

Nonlinear Integrable Optics - Motivation

- All present machines are built around concept of linear focusing
  - Nonlinear aberrations ruin beam quality and particle stability
  - Nonlinear aberrations are intrinsic to charged particle beams and scale with beam brightness
  - Nonlinearities must be introduced to maintain beam's own immunity to coherent instabilities through Landau damping
- Can we attempt a major paradigm change to leave the linear focusing?
  - Let us build machines that are nonlinear by design but stable (like Solar system)
  - We have a novel approach…

History of Search for Stable Nonlinear Solutions

- Orlov (1963)
- McMillan (1967) – **1D solution**
- Perevedentsev, Danilov (1990) – generalization of McMillan case to 2D, round colliding beams. **Require non-Laplacian potentials to realize**
  - Implemented at VEPP-2000 collider at BINP (Novosibirsk, Russia) commissioned in 2006. Record-high beam-beam tune spread 0.25 attained in 2013
- Danilov, Shiltsev (1998) – Non-linear low energy electron lenses suggested to fight beam-beam
  - Proof-of-principle in Tevatron in 2003; Full success in RHIC in 2015/16. Beam-beam tune spread 0.01→0.02. Luminosity improved by 50-100%
- Danilov, Nagaitsev (2010) – Solution for nonlinear lattice with 2 invariants of motion that **can be implemented with Laplacian potential**, i.e. with special magnets – *Phys. Rev. ST Accel. Beams 13, 084002 (2010)*

Nonlinear Integrable Optics - Criteria

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

- Mathematically, that means the system should
  - Possess two integrals of motion
  - Have a steep Hamiltonian
  - Field potential satisfies the Laplace equation

- Practical benefits relevant to future HEP machines
  - Reduced chaos in single-particle motion
  - Strong immunity to collective instabilities via Landau damping

Danilov-Nagaitsev Solution (2010)

1. Remove time dependence from Hamiltonian thus making it an integral of the motion
   - One integral already gives a better degree of regularity in the motion
     - Demonstrated with round colliding beams (BINP, 2013), 1/2-integer working point in colliders (KEK, 2004)
     - Crab-crossing at DAFNE (INFN/LNF, 2008)

2. Shape the nonlinear potential to find a second integral

Time-Independent Hamiltonian

- Start with a Hamiltonian

$$H = \frac{p_x^2}{2} + \frac{p_y^2}{2} + K(s)\left(\frac{x^2}{2} + \frac{y^2}{2}\right) + V(x, y, s)$$

- Choose s-dependence of nonlinear potential V such that *H* is time-independent in normalized variables

$$z_N = \frac{z}{\sqrt{\beta(s)}},$$

$$p_N = p\sqrt{\beta(s)} - \frac{\beta'(s)z}{2\sqrt{\beta(s)}},$$

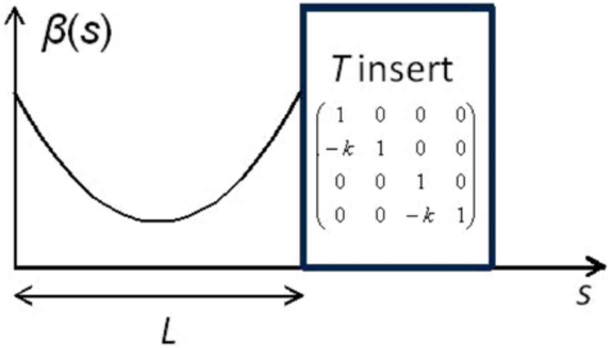
$$H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_N^2 + y_N^2}{2} + \beta(\psi)V\left(x_N\sqrt{\beta(\psi)}, y_N\sqrt{\beta(\psi)}, s(\psi)\right)$$

$$H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_N^2 + y_N^2}{2} + U(x_N, y_N, \psi)$$

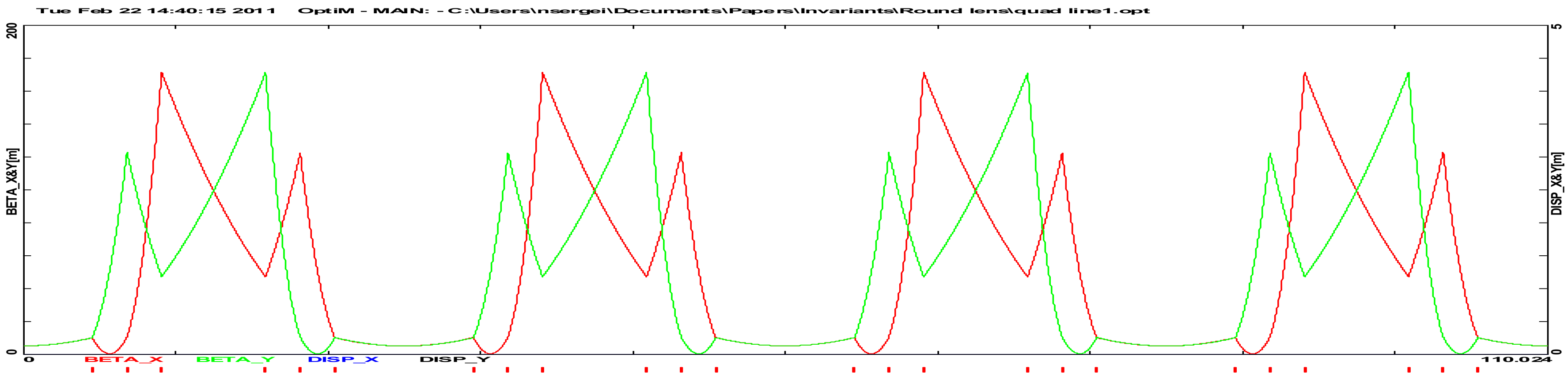
- This results in *H* being the integral of motion
- Note there was no requirement on *V* – can be made with any conventional magnets, i.e. octupoles

Implementation of Time-Independent Hamiltonian

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

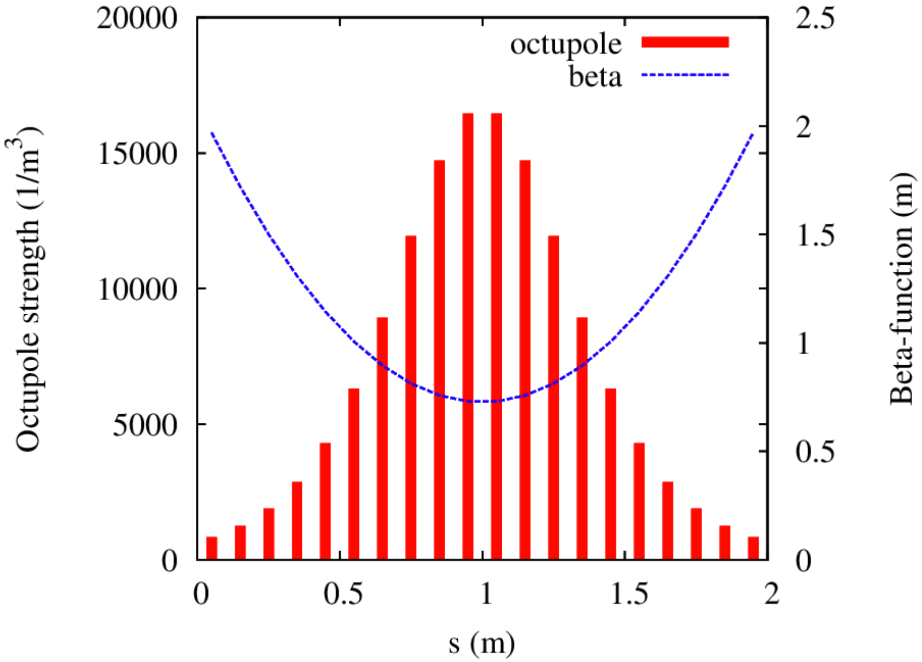


Henon-Heiles Type Systems

- For example, build *V* with Octupoles

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

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

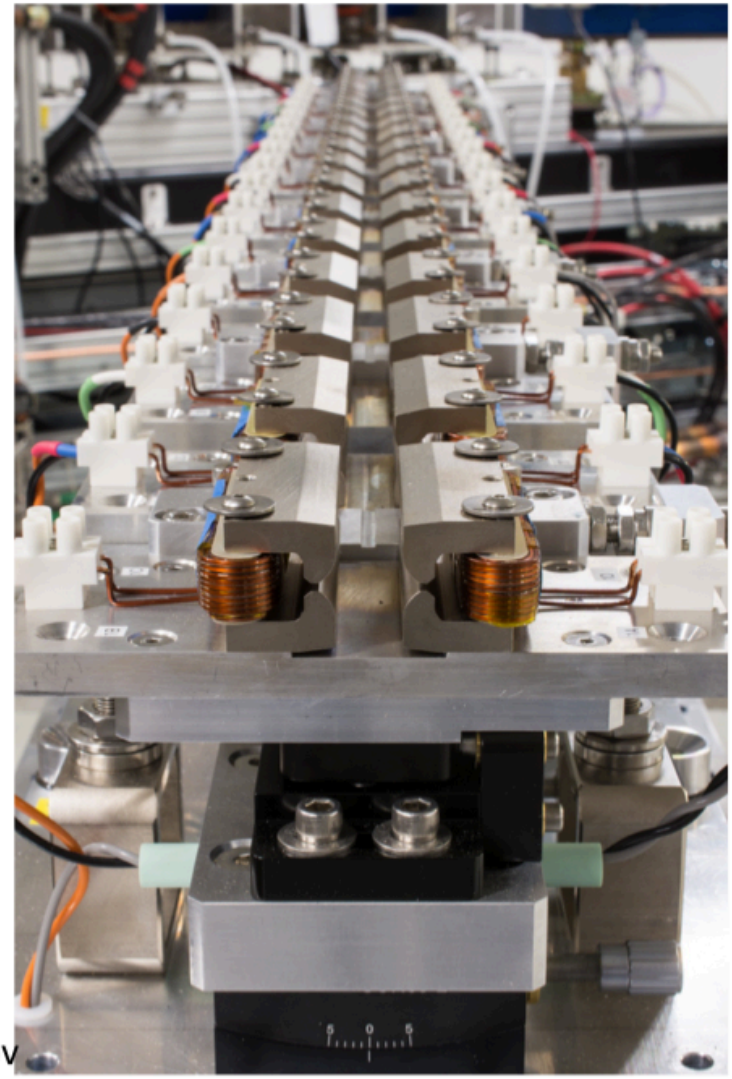


$$H = \frac{1}{2}(p_x^2 + p_y^2) + \frac{1}{2}(x^2 + y^2) + \frac{k}{4}\left(x^4 + y^4 - 6x^2y^2\right)$$

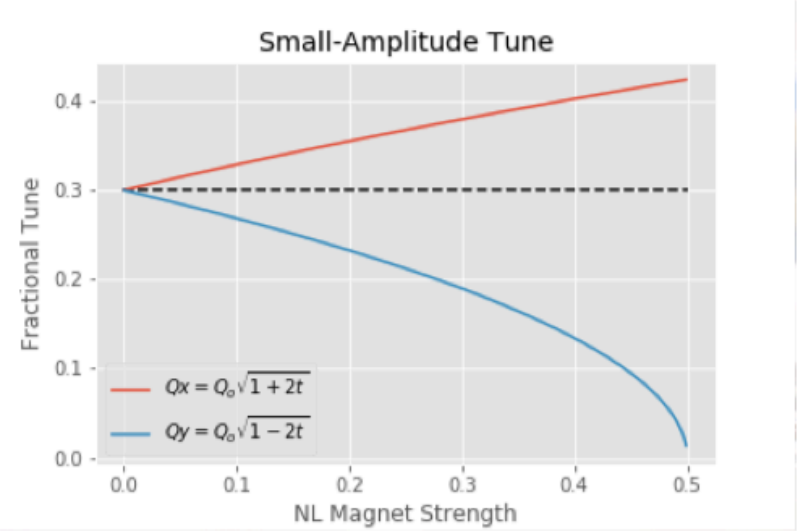
- Only one integral of motion – *H*
- Tune spread limited to ~12% of Q_0

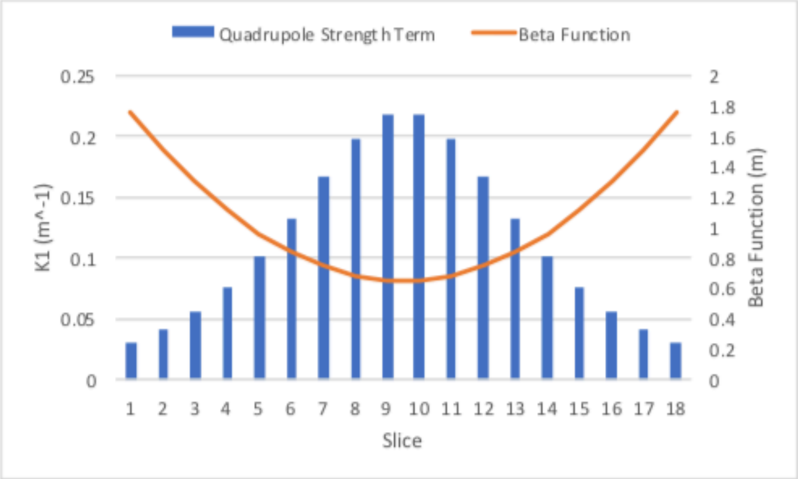
S. Antipov, S. Nagaitsev, A. Valishev, JINST 12 (2017) no.04, P04008

NIO with 2 Invariants of Motion – Special Magnet



fast.fnal.gov





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

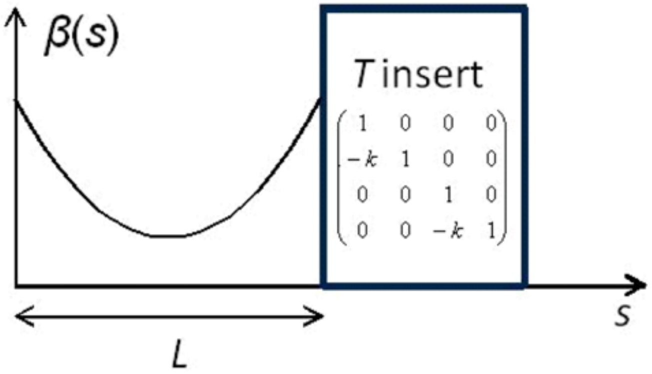
- Phase I – research concentrates on the academic aspect of single-particle motion stability using electron beams
  - Demonstrate large amplitude-dependent detuning with conservation of dynamic aperture
  - Demonstrate practical machine tuning and limits of integrable optics stability in terms of imperfections,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

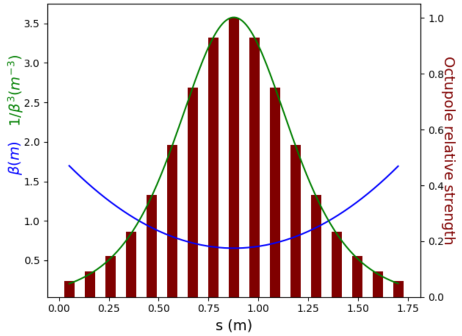
- Phase II – intense-beam studies with protons
  - Interplay between NIO and space-charge
  - Effect of NIO on halo formation, emittance growth and losses

Current Components of IOTA NIO Program

1. System with 1 invariant, aka Quasi-Integrable or Henon-Heiles Type. **Further referred to as QI.**
   - Implemented with Octupole string in BL straight
2. System with 2 invariants, aka Danilov-Nagaitsev or Elliptic potential. **Further referred to as DN.**
   - Implemented with special magnet (RadiaBeam) in BR straight
3. Effect of nonlinear optics on coherent beam stability

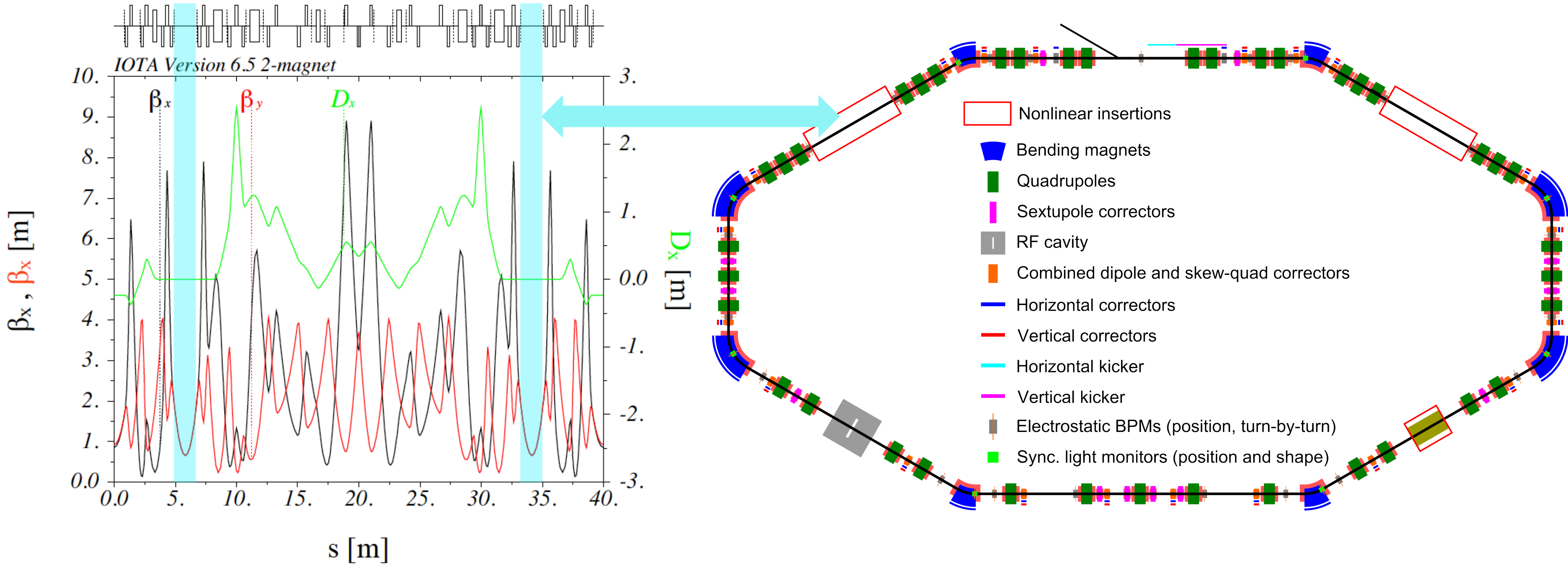
Implementation of NIO in IOTA





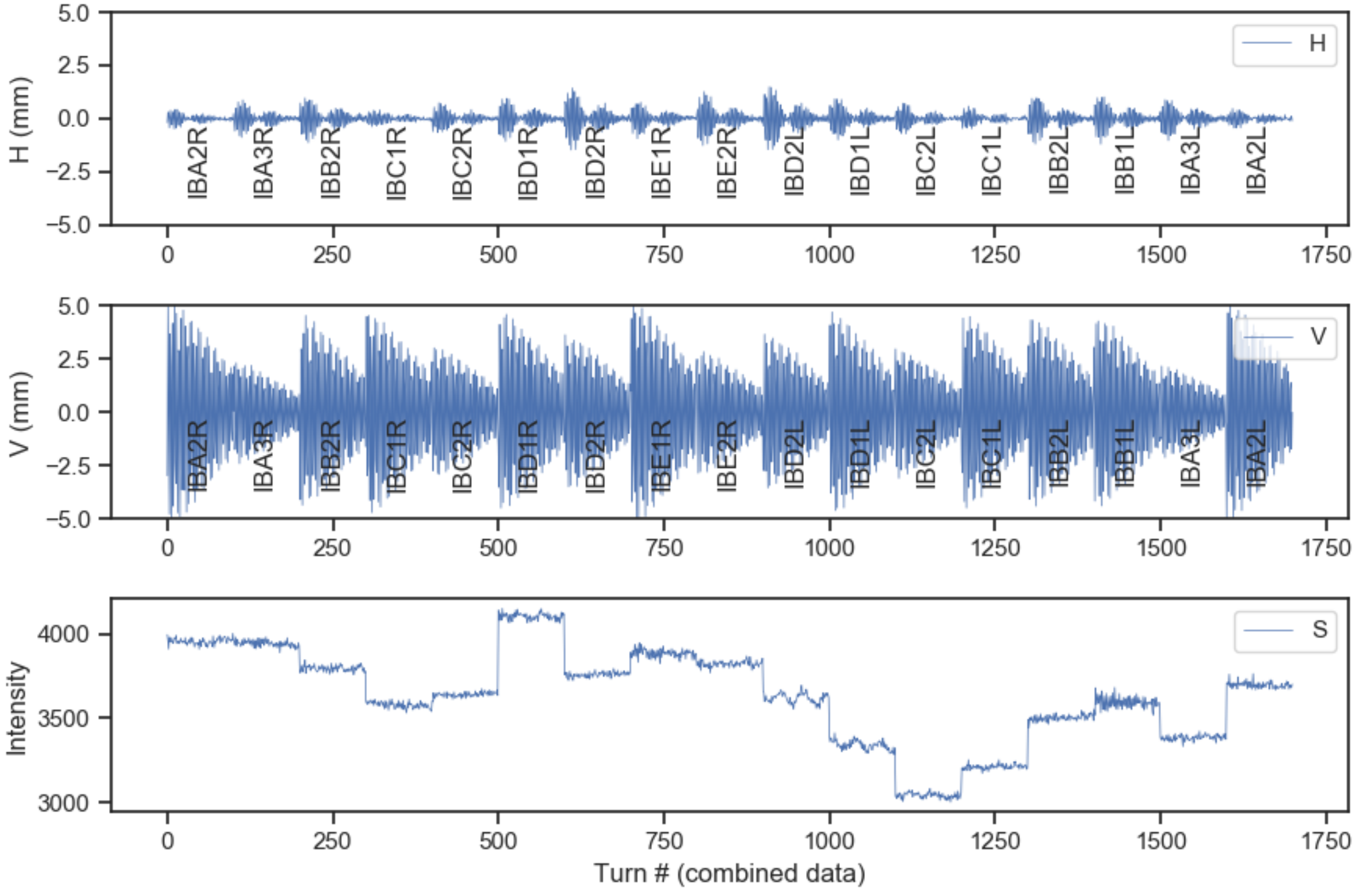
Practical requirements:

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



Experimental Method

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



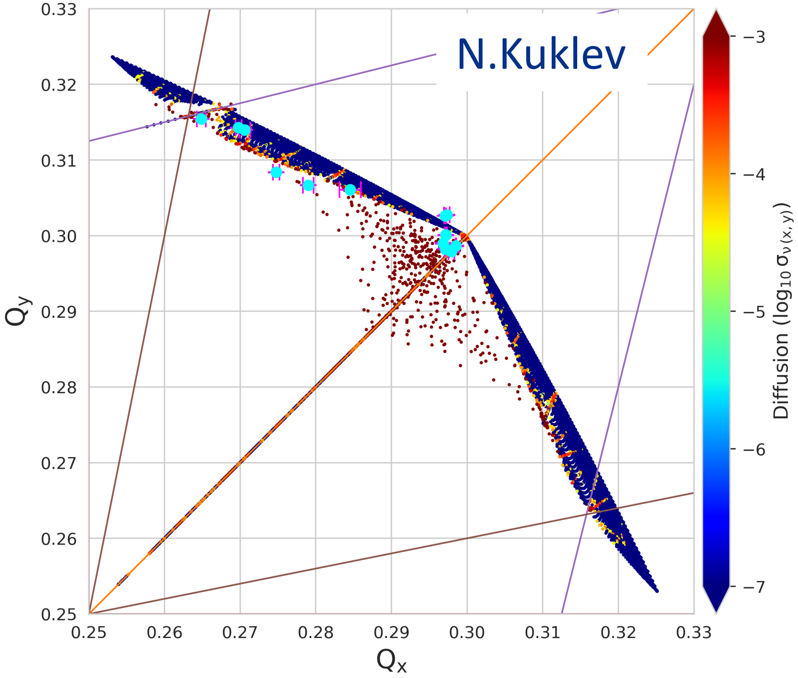
0.6kV Vkick

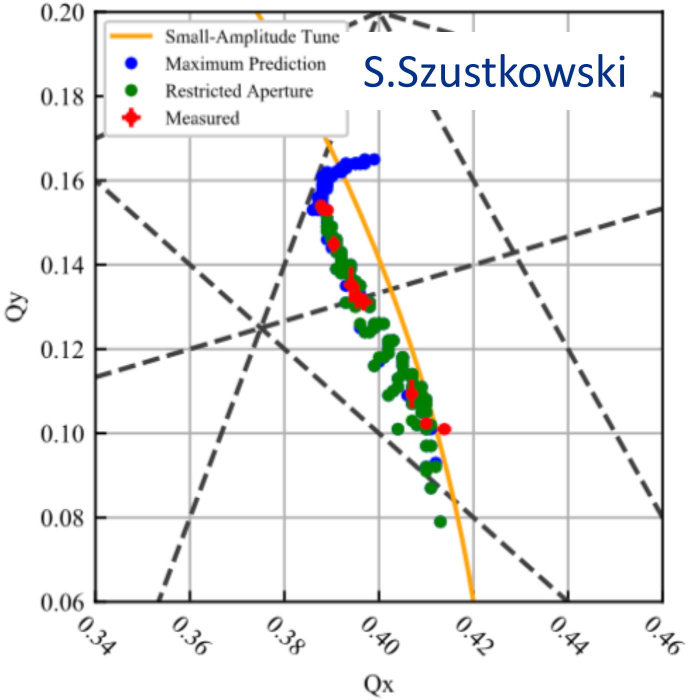
1A octupoles

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





Run-2 Goals and Objectives, Staging

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*

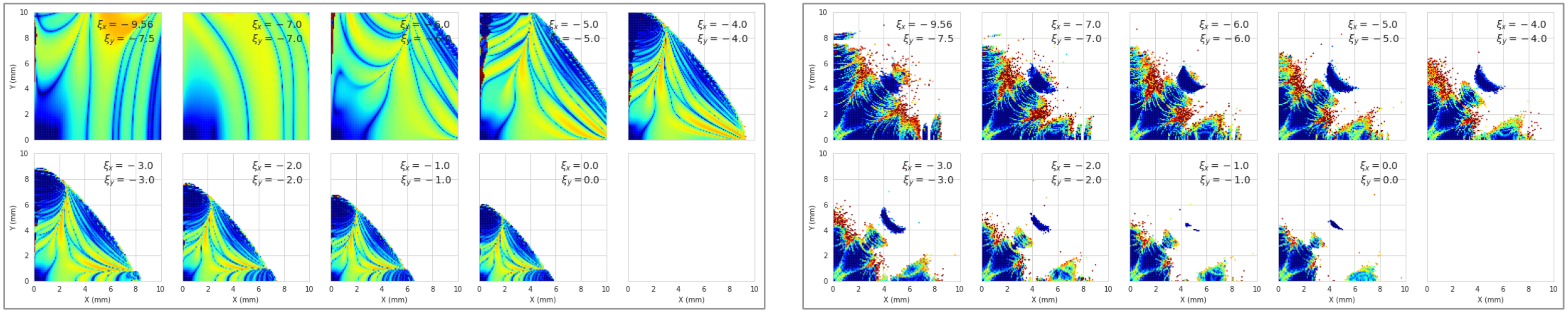
Commissioning Summary

Goal for Run-2: achieve beam parameters, machine tuning and system performance necessary for the NIO experiments

- Octupoles: 10% beta-function accuracy, ~0.01 betatron phase accuracy, 100um orbit centering
- NL magnet: 1% beta-function, 0.001-0.003 betatron phase, 50um orbit centering
- Variable single-turn kick, H/V
- Turn-by-turn BPM system, 100um resolution

Simulations for the QI (Henon-Heiles Type) Octupole System

- Heavy simulations with elegant, via pyIOTA wrapper
  - Thick symplectic tracking - fringe fields + errors + SR
- (Non)linear optics - OCELOT + MADX + custom code
- Predicted strong impact of chromaticity
  - Need to reduce chroma to get more turns (more data)
  - But only have 2 families / 4 sextupoles (not properly π-phased) out of 12 possible
  - Nonlinearities hurt dynamics

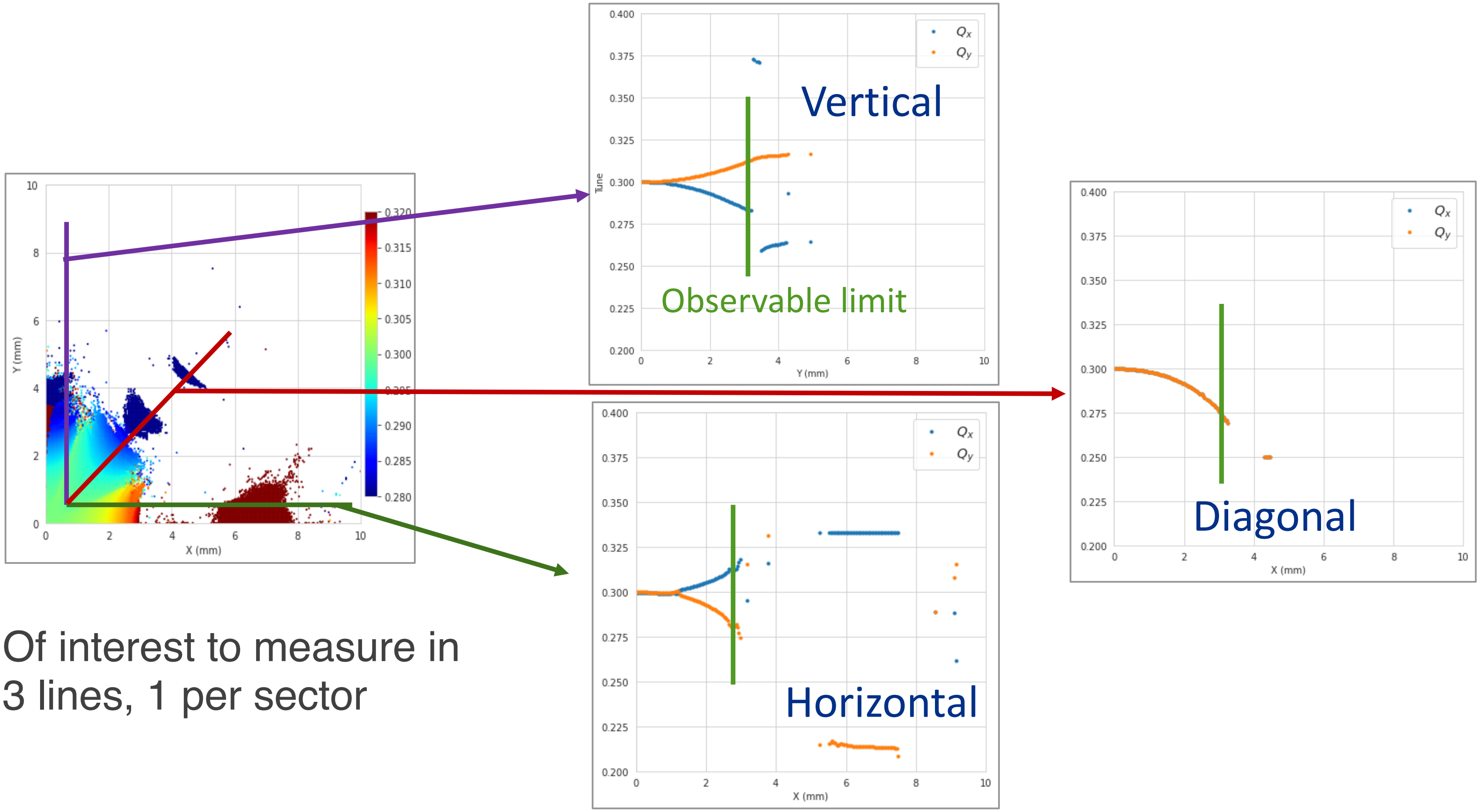


Sextupoles only

Sextupoles + octupoles

Color scale – tune diffusion

Simulation Predictions for QI System

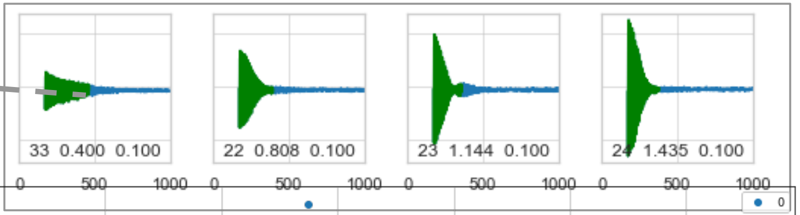


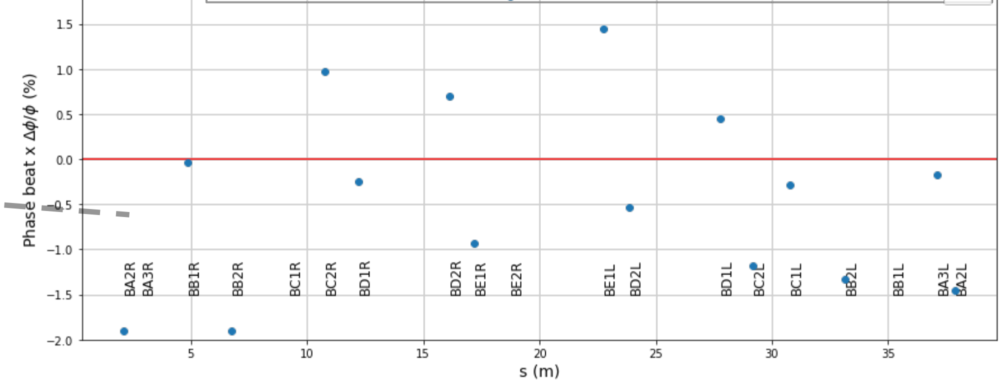
- Of interest to measure in 3 lines, 1 per sector

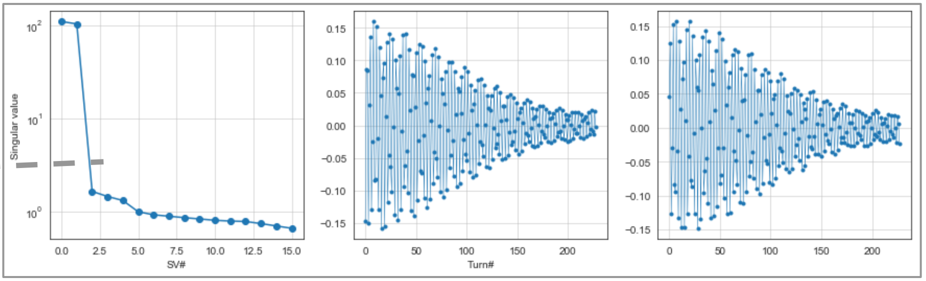
BPM Data Analysis Methods

Methods (briefly)

- Preprocessing
  - SVD cleaning, ROI cut based on SNR
- Tunes
  - Modified adaptive NAFF
- Linear optics
  - Model-independent methods
- Phase space
  - SVD/ICA decomposition
  - Envelope function – chromatic + octupolar decoherence fit with annealing/bin hopping
  - Parameter optimization for smallest invariant



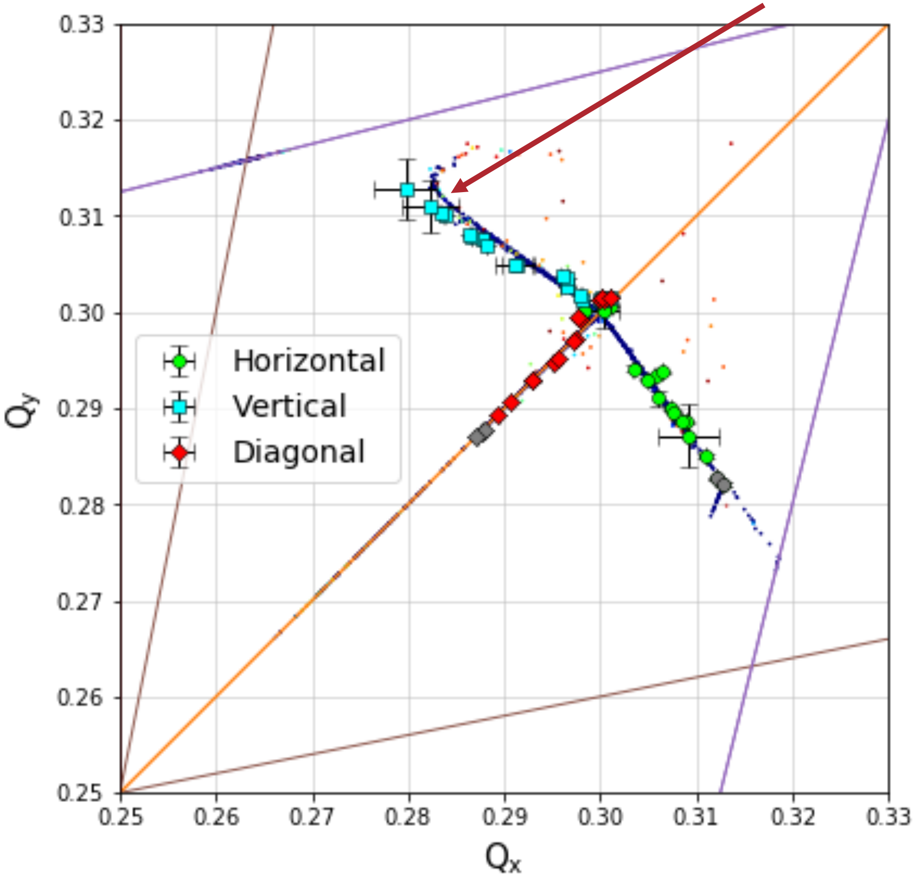




QI Experimental Results (Stage 1 – tune shift)

Nominal config – 1.0A QI (central octupole)

- No aperture scans – estimate from BPM sum
- Good match with FMA simulations
- Similar results at 0.75A/1.25A



Note discrepancy

QI Results (Stage 1)

Looking at invariants

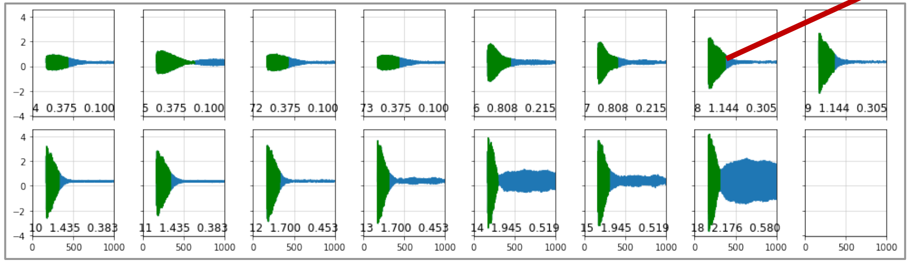
- Analysis ongoing – signal zoo, a lot of manual tweaking, complicated coupling
- Preliminary data using SVD modes
- No quantitative simulation comparison yet (beam size matters, need good bunch estimate)

Strength parameter

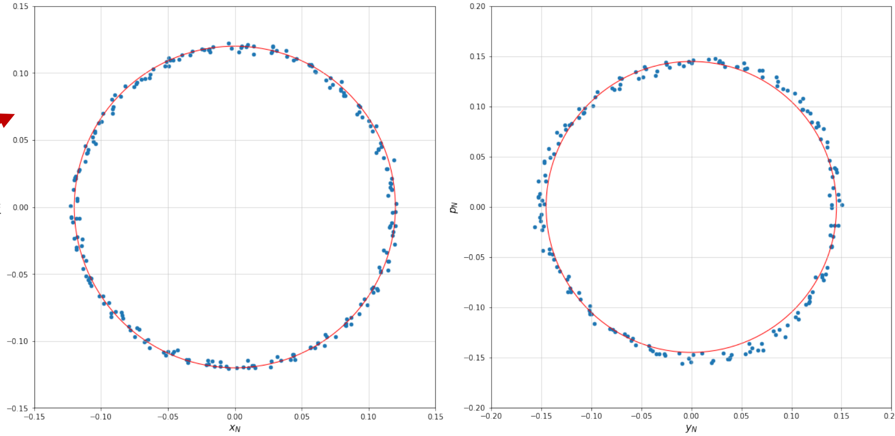
$$H = H_0 + U = \frac{1}{2}\left(P_x^2 + P_y^2 + x_N^2 + y_N^2\right) + \alpha\left(\frac{x_N^4}{4} + \frac{y_N^4}{4} - \frac{3x_N^2 y_N^2}{2}\right)$$

CS linear part

QI



Diagonal kick data

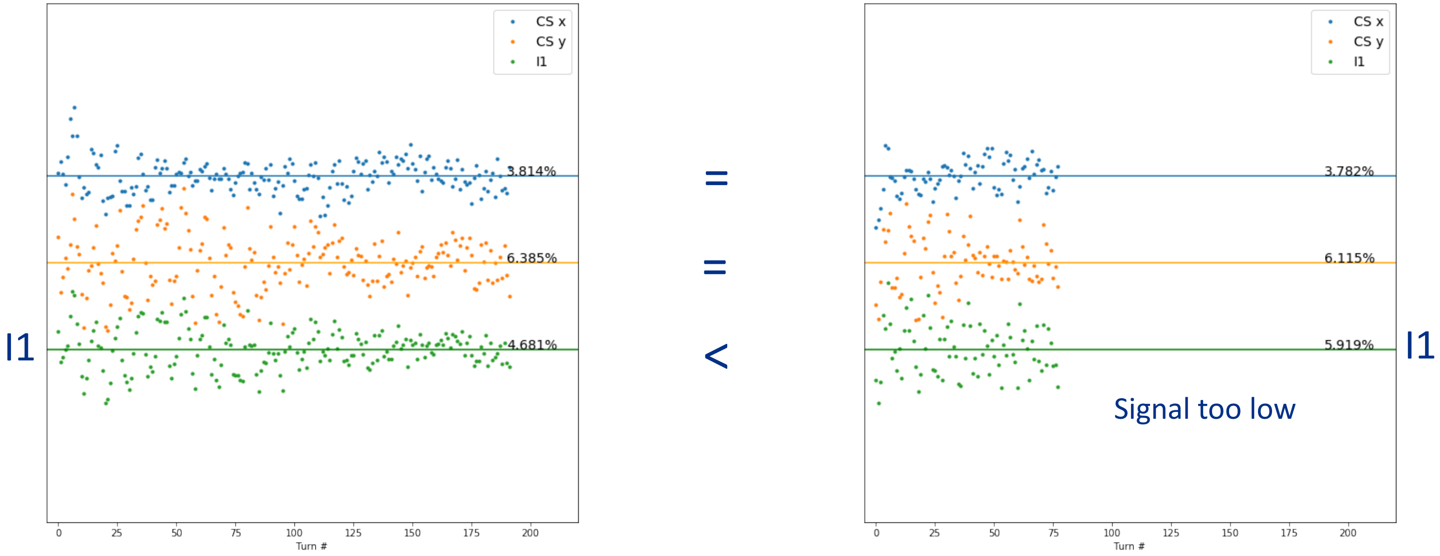


Normalized phase space after decoherence compensation

QI Results (Stage 1)

Looking at invariants

- Flat configuration H-invariant jitter worse while CS invariants ~ same
- Simulation work in progress to verify results and estimate sensitivity



I1 =

=

< I1

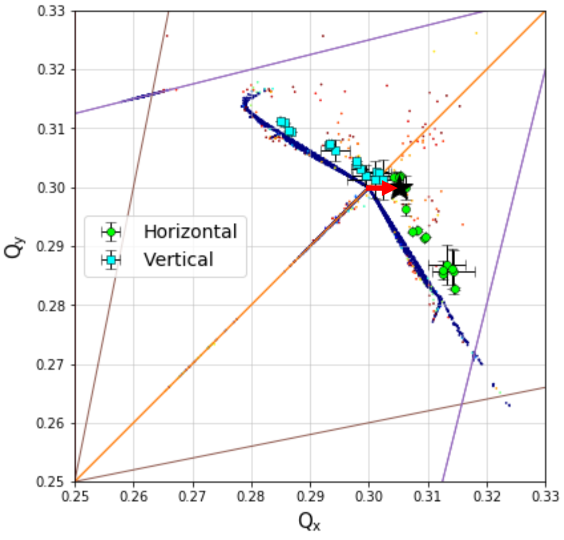
Signal too low

1.0A nominal

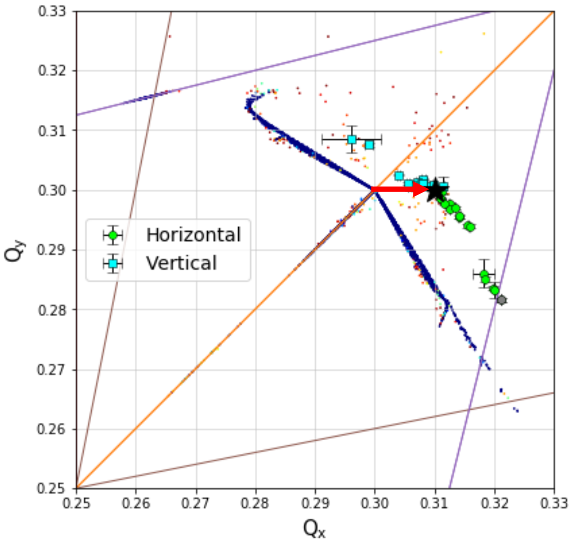
QI Results (Stage 2 – impact of imperfections)

Example: tune inside insert

- Small shifts – little impact
- Large shifts – different behavior, DA reduction, signal anomalies – need stage 3

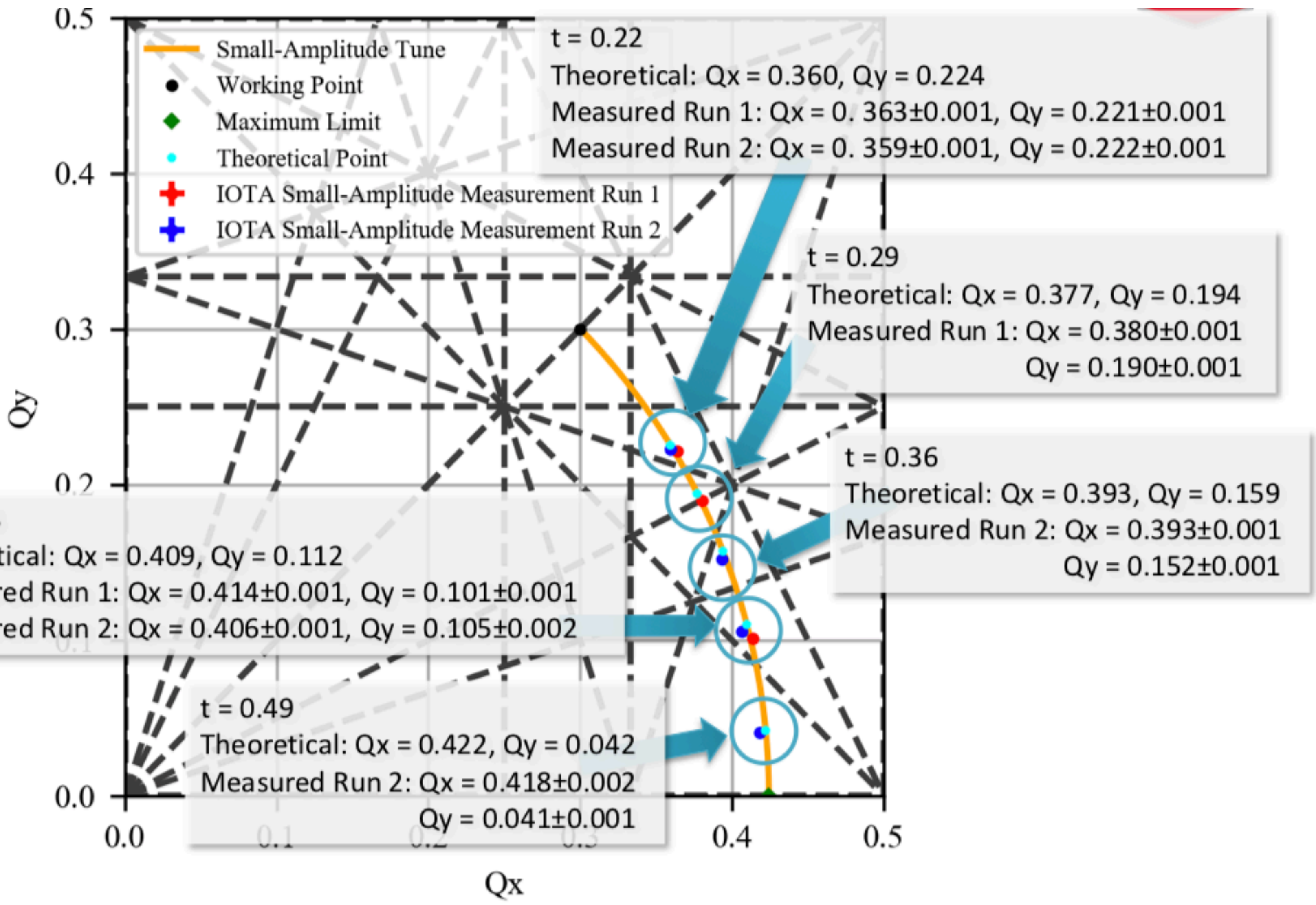


Qx+0.003 shift



Qx+0.01 shift

DN Results – Small-Amplitude Tune



t = 0.22
Theoretical: Qx = 0.360, Qy = 0.224
Measured Run 1: Qx = 0. 363±0.001, Qy = 0.221±0.001
Measured Run 2: Qx = 0. 359±0.001, Qy = 0.222±0.001

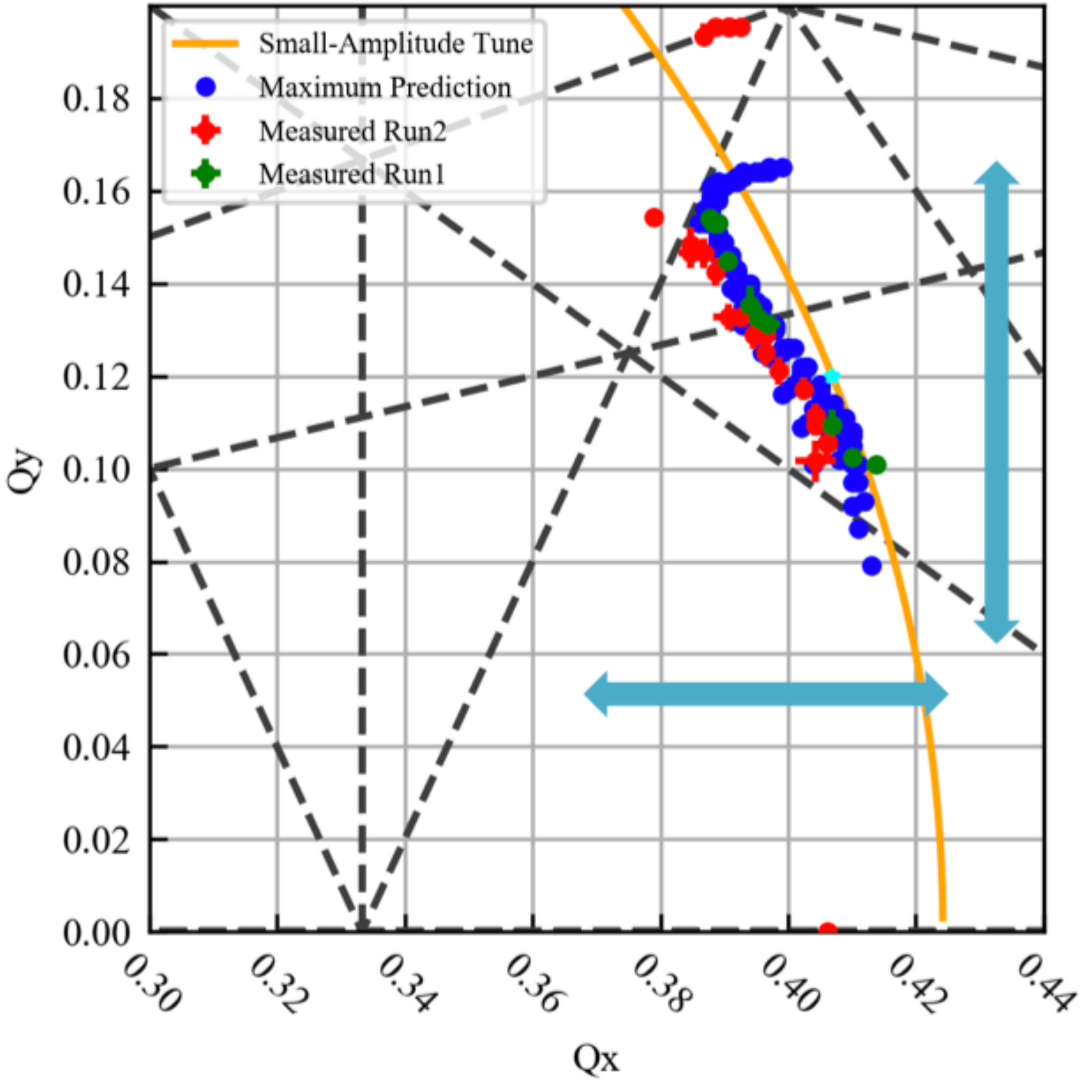
t = 0.29
Theoretical: Qx = 0.377, Qy = 0.194
Measured Run 1: Qx = 0.380±0.001
Qy = 0.190±0.001

t = 0.36
Theoretical: Qx = 0.393, Qy = 0.159
Measured Run 2: Qx = 0.393±0.001
Qy = 0.152±0.001

t = 0.43
Theoretical: Qx = 0.409, Qy = 0.112
Measured Run 1: Qx = 0.414±0.001, Qy = 0.101±0.001
Measured Run 2: Qx = 0.406±0.001, Qy = 0.105±0.002

t = 0.49
Theoretical: Qx = 0.422, Qy = 0.042
Measured Run 2: Qx = 0.418±0.002
Qy = 0.041±0.001

DN Results (Stage 1 – tune shift) t=0.43



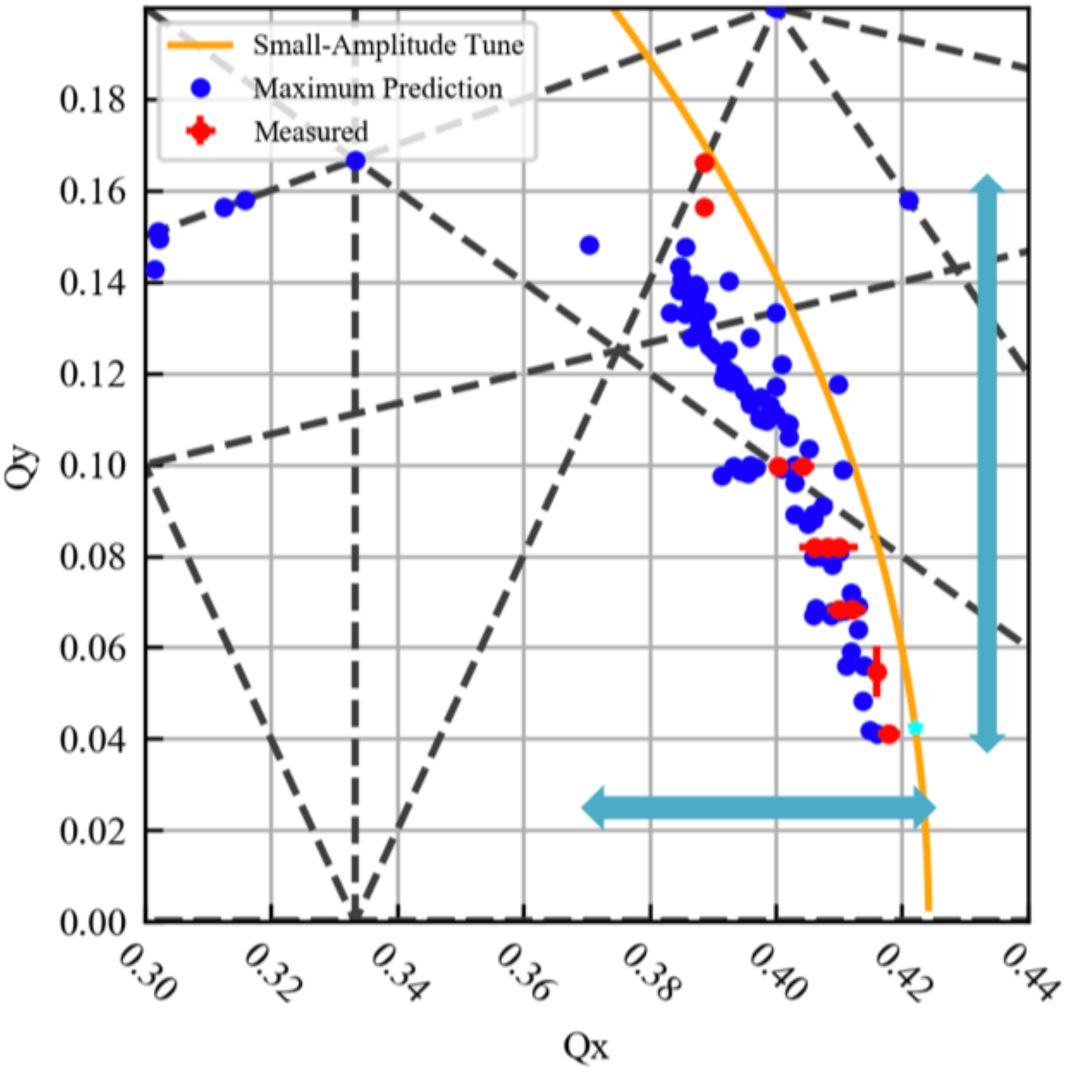
S.Szustkowski

Vertical:
Small Amplitude: Qy=0.12
Theoretical Maximum: ΔQy = 0.085
Measured Run 1: ΔQy = 0.0530 ± 0.0018
Measured Run 2: ΔQy = 0.0524 ± 0.0013

Horizontal:
Small Amplitude: Qx =0.406
Theoretical Maximum: ΔQx = 0.026
Measured Run 1: ΔQx = 0.0261 ± 0.0017
Measured Run 2: ΔQx = 0.0300 ± 0.0016

DN Results (Stage 1 – tune shift) t=0.49

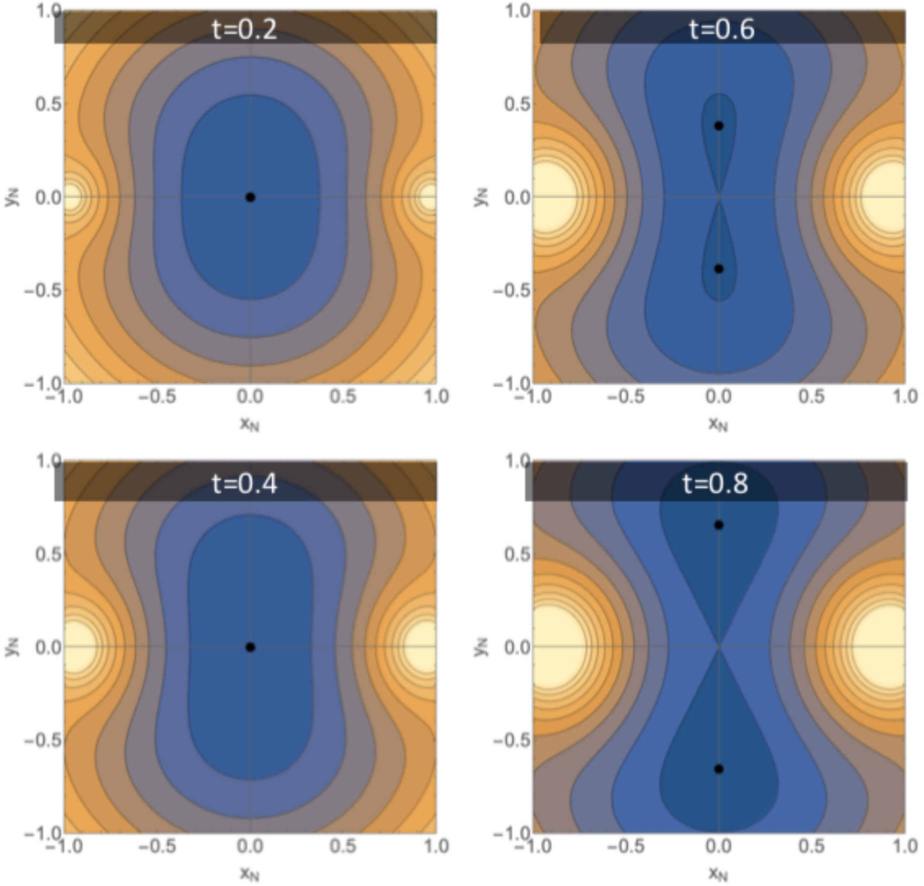
S.Szustkowski

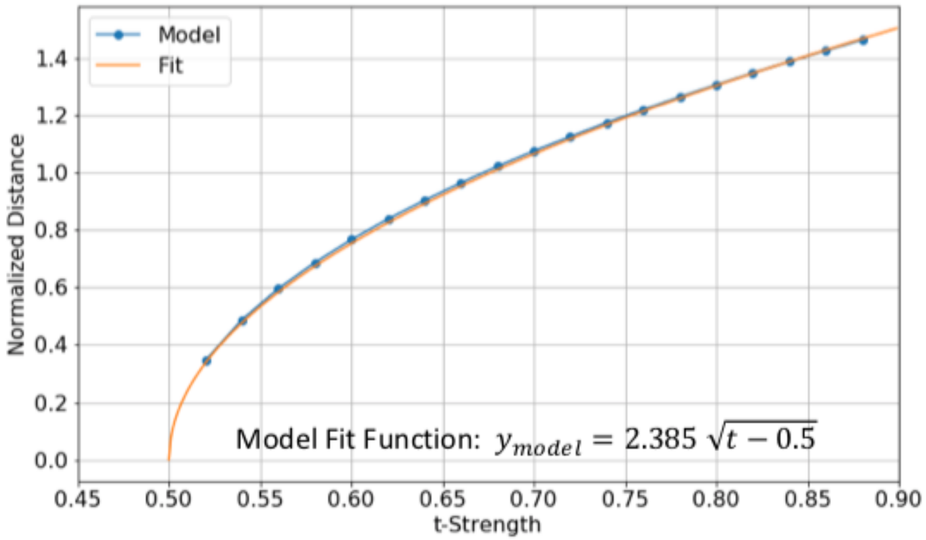


Vertical:
Small Amplitude: Qy= 0.042
Theoretical Maximum: ΔQy = 0.108
Measured Run 2: ΔQy = 0.125 ± 0.0016

Horizontal:
Small Amplitude: Qx = 0.422
Theoretical Maximum: ΔQx = 0.036
Measured Run 2: ΔQx = 0.028 ± 0.0021

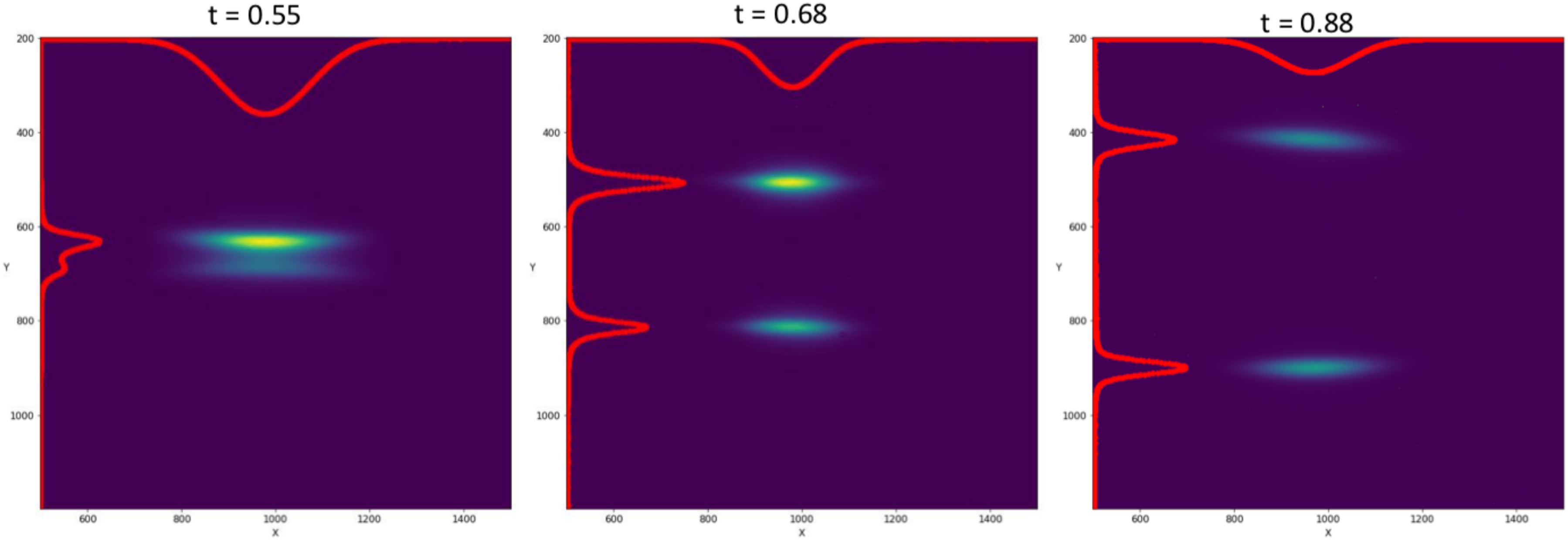
DN System – Phase Space Topology



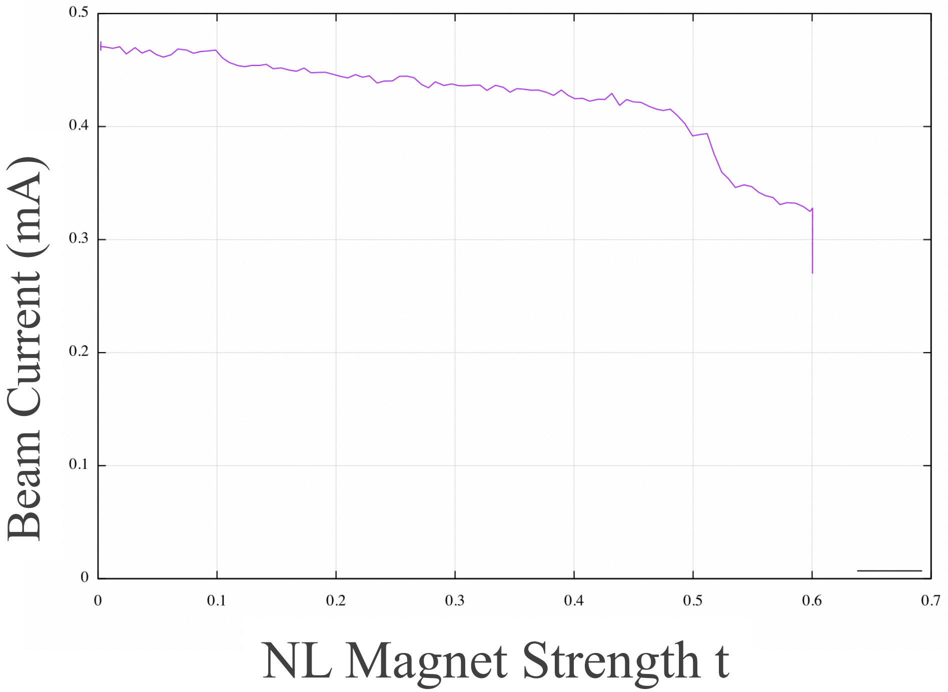


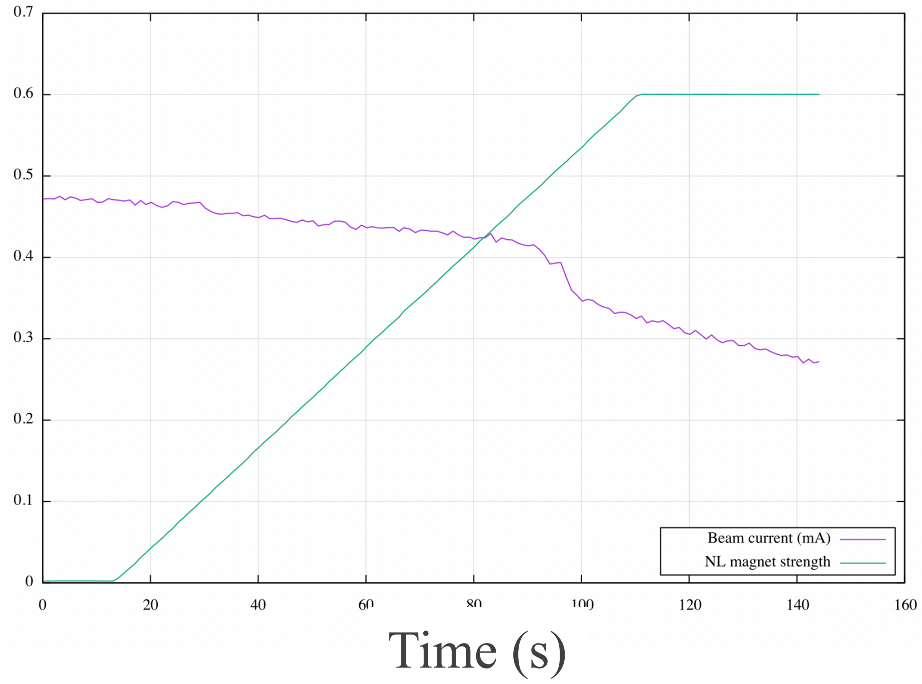
DN Results – Phase Space Topology

- Recorded images with 1-second exposure from synchrotron light diagnostics
- Distance between the two fiexd points increases with nonlinear magnet t-strength
- At t=0.9 reached the mechanical aperture, one of the beamlets dies

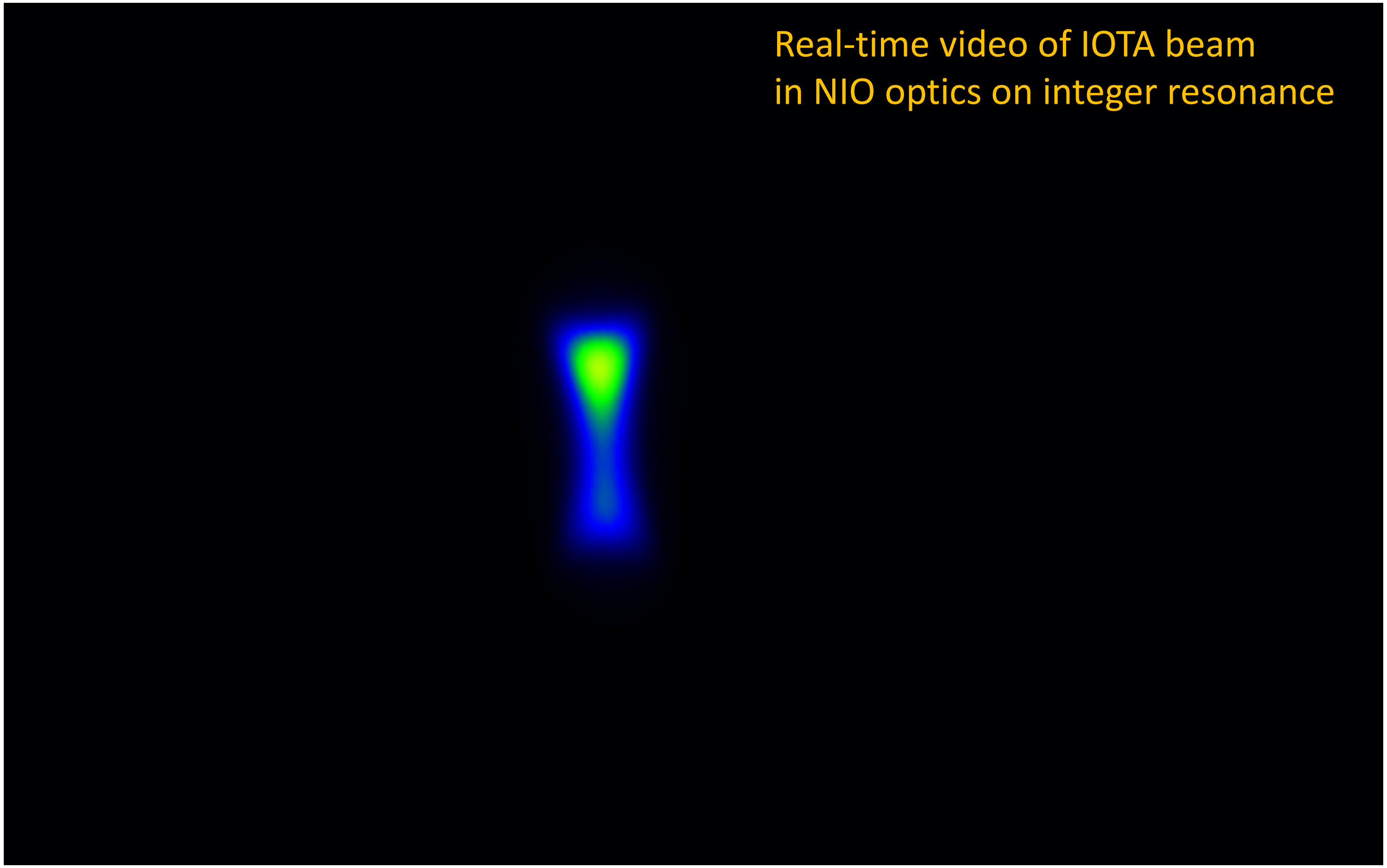


DN Results – Crossing Integer with Beam





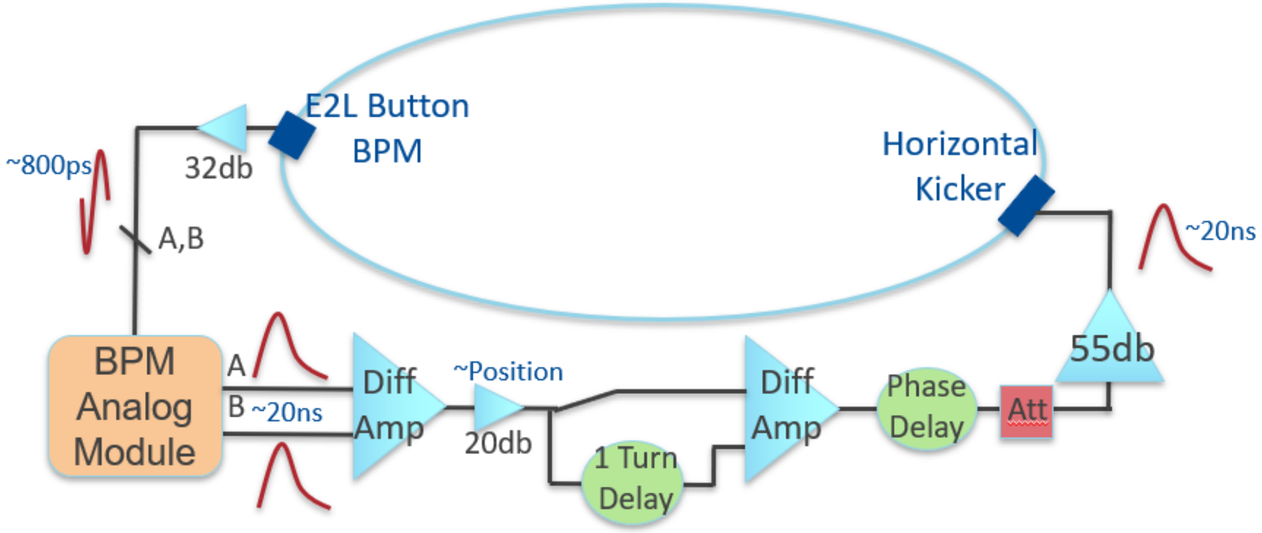
DN Results – Beam on Integer



Real-time video of IOTA beam
in NIO optics on integer resonance

Feedback System Overview

- Use horizontal button electrodes on E2L bpm with 32db RF pre-amplifier on each button
- BPM analog module based upon RF envelope detector conditions fast doublet into longer pulse – provides 32db of programmable gain control
- Implement 1 turn notch filter delay and phase delay with cable



Instability Threshold Study

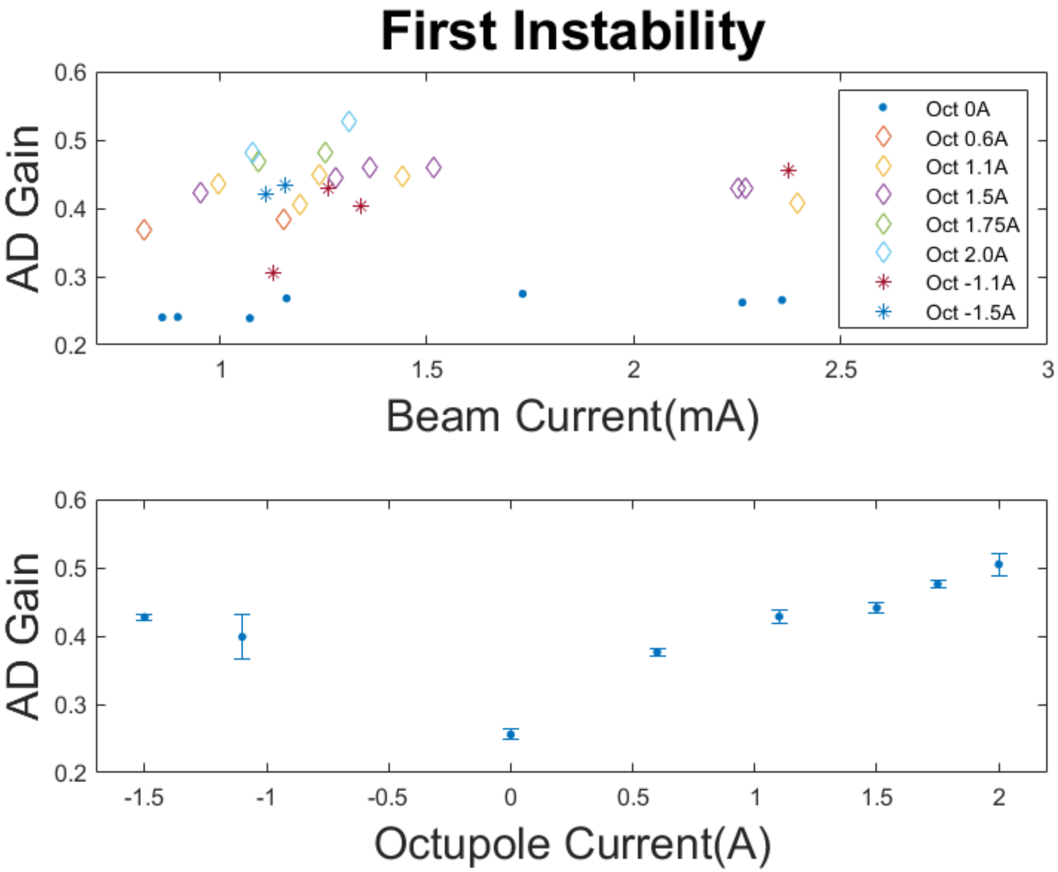
- Study the gain threshold for fast instability as a function of beam current and octupole current
- With nominal emittance (~160-170um), step the feedback gain until a fast instability occurs (>10% beam loss)

$$AD\ Gain = \frac{10^{-\frac{att_{db}}{20}} * Ibe_{am}}{\sigma_b\sqrt{2\pi}}$$

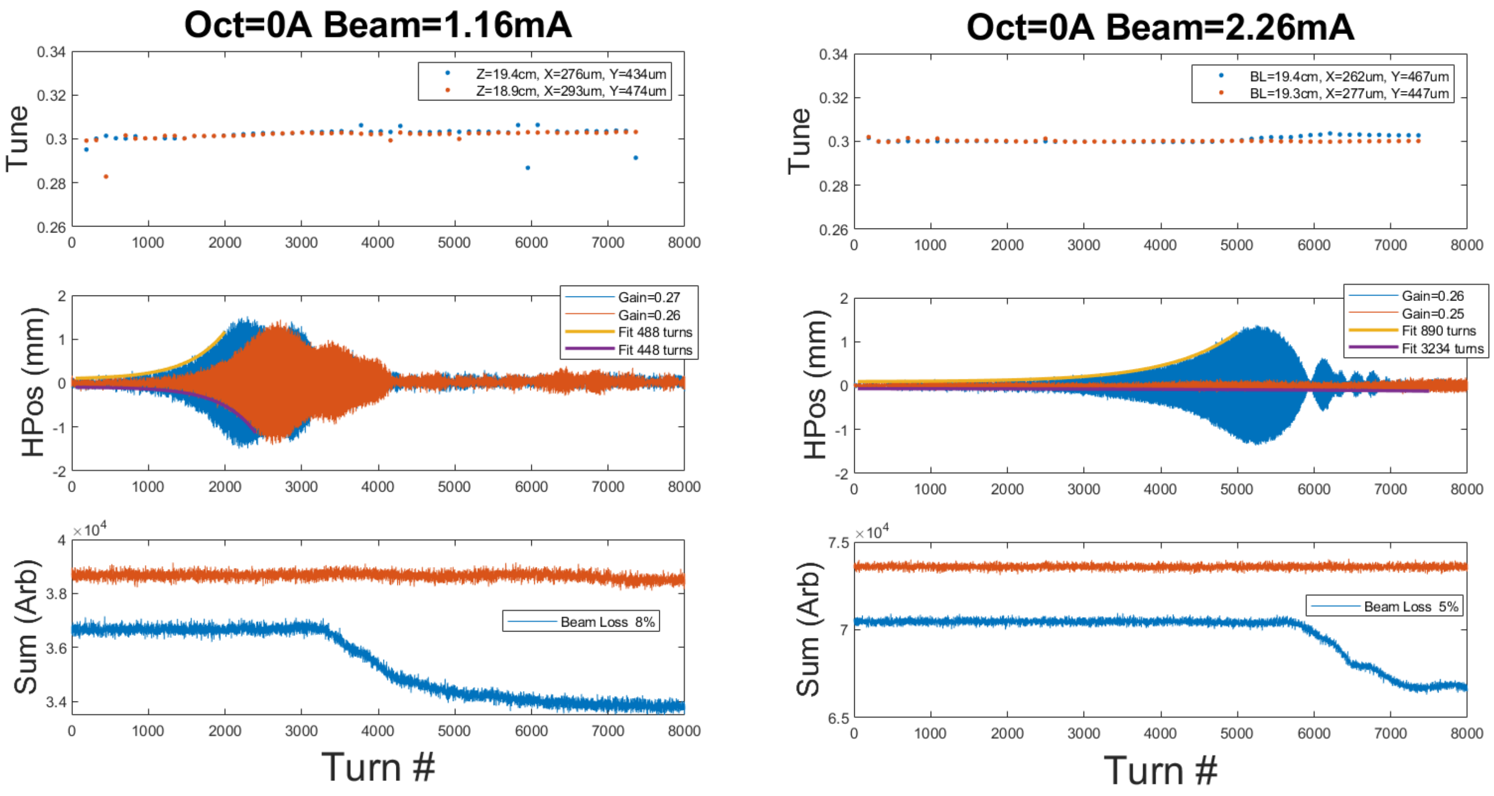
- The analog module attenuators were stepped in 1-2db steps until a fast instability occurred
- After each instability, wait for synchrotron radiation damping to restore beam to nominal emittance

Instability Threshold vs Octupole Current

- Landau damping is sensitive to tails in the beam distribution which are scraped away during an instability with beam loss
- For threshold instability, just the first loss event per store is used
- Observe increase in the threshold with octupole
- At 2A see factor of 2 increase in agreement with Run I

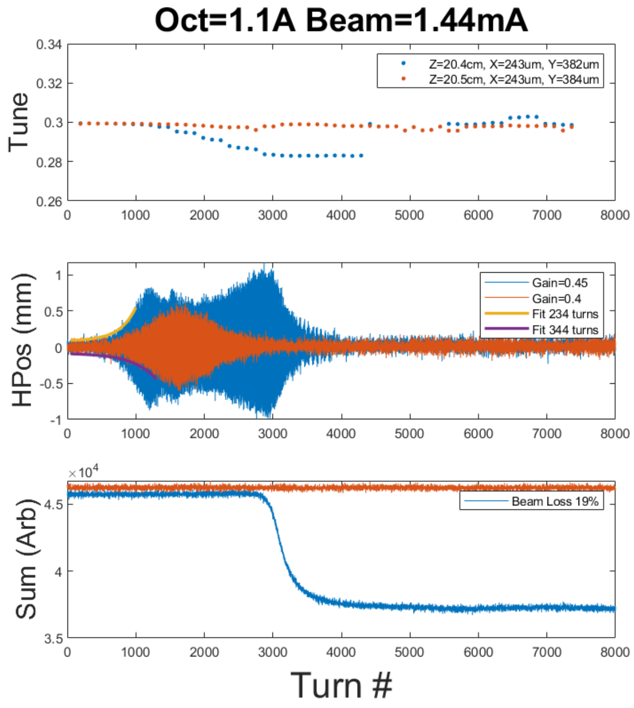


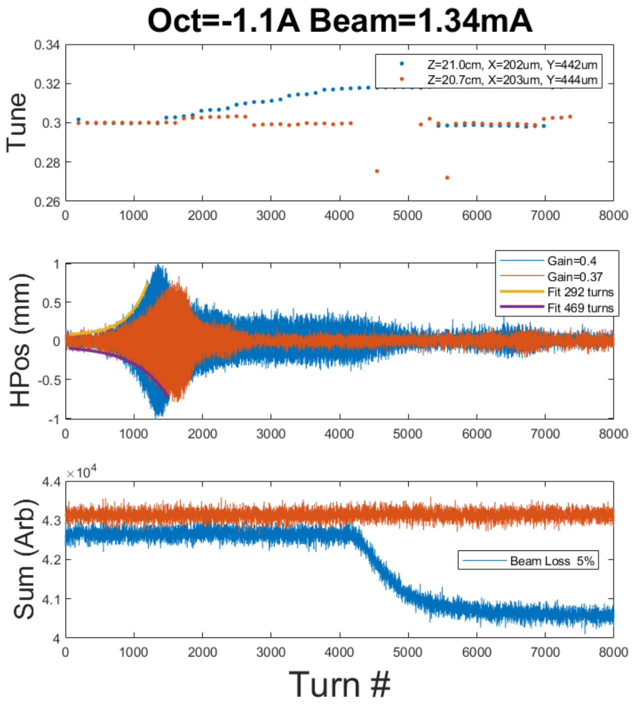
TBT Data Analysis – Octupoles Off



- Measure tune, gain, growth rate, and loss

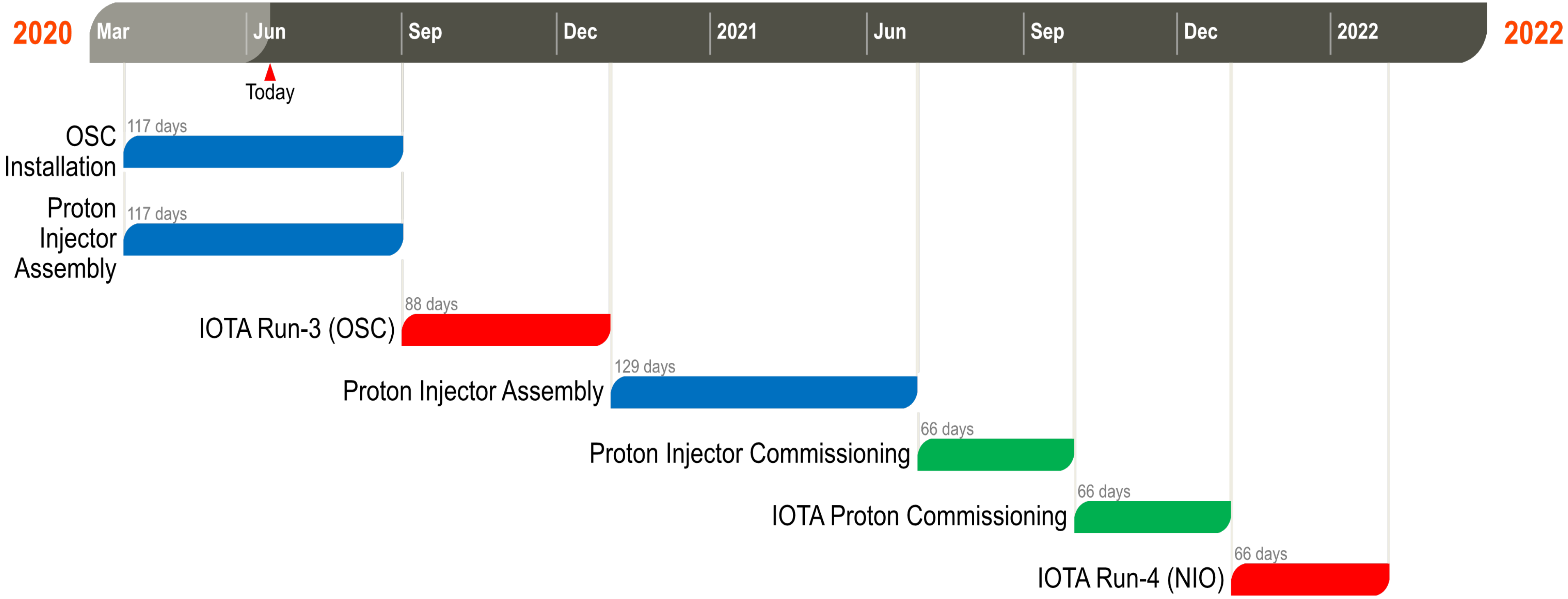
TBT Data Analysis – QI Octupoles On


Oct=1.1A Beam=1.44mA


Oct=-1.1A Beam=1.34mA

- Tune shift direction dependent on octupole sign
- Only see beam loss when tune shifts (always at 0.02 change)

Future Vision

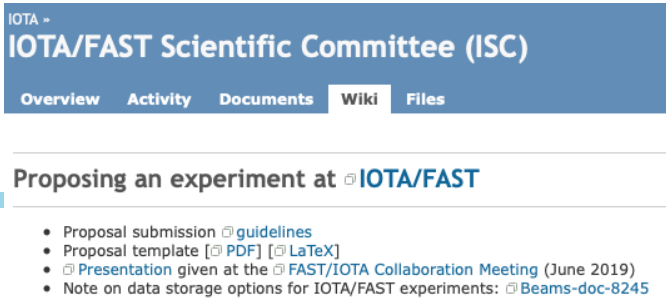


IOTA/FAST schedule was and continues to be impacted by covid-19

- Run-2 was cut short on March 21, 2020 due to Illinois stay-at-home order
- OSC installation and Proton Injector work was stalled until June
- Slow recovery

We Invite Collaboration – Proposals are Welcome!

- The IOTA/FAST Scientific Committee (ISC) evaluates experimental proposals and, together with the Fermilab Directorate, establishes research priorities for the facility.
- Experiments are proposed by Fermilab researchers or by external collaborators. If neither the Spokesperson or the Deputy Spokesperson is a Fermilab employee, a Fermilab Liaison is identified. Before starting experimental work, external members of all experiments register as Fermilab users in the FAST/IOTA Collaboration, which serves as a general umbrella organization for administrative purposes.
- Proposals can be submitted any time. The ISC meets about once a month to discuss and evaluate the proposals.
- Three stages
  - Preliminary Discussions and Letter of Intent
  - Proposal Preparation and Submission
  - Scientific and Technical Reviews



IOTA/FAST Scientific Committee (ISC)

Proposing an experiment at IOTA/FAST

- Proposal submission guidelines
- Proposal template [PDF] [LaTeX]
- Presentation given at the FAST/IOTA Collaboration Meeting (June 2019)
- Note on data storage options for IOTA/FAST experiments: Beams-doc-8245

Reference Material

- FAST Website https://fast.fnal.gov
- FAST Indico https://indico.fnal.gov/category/373/
- 2019 Collaboration Meeting https://indico.fnal.gov/event/20279/
- IOTA E-Lens wiki https://cdcvs.fnal.gov/redmine/projects/iota-e-lens/wiki
- IOTA Fluctuations in Synchrotron Radiation wiki https://cdcvs.fnal.gov/redmine/projects/fur/wiki
- IOTA/FAST Scientific Committee wiki https://cdcvs.fnal.gov/redmine/projects/ifsc/wiki