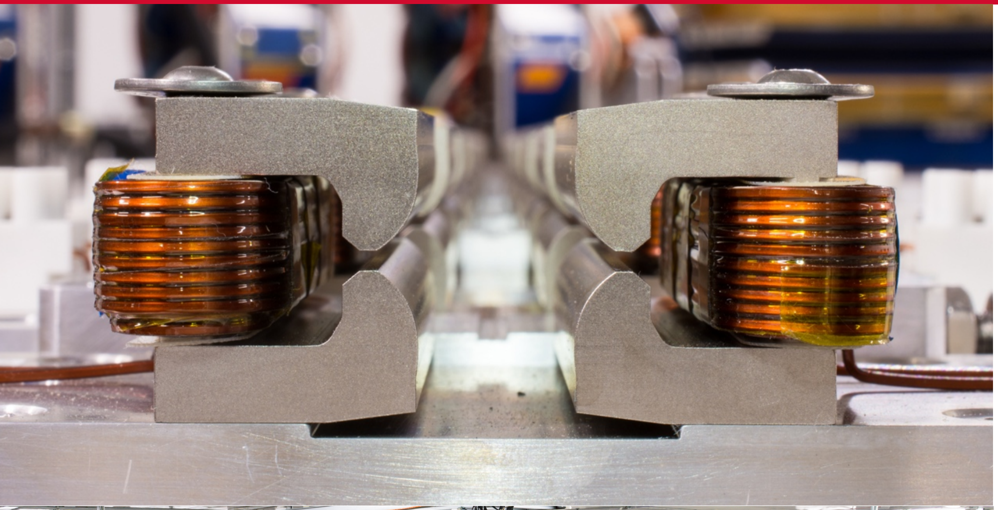
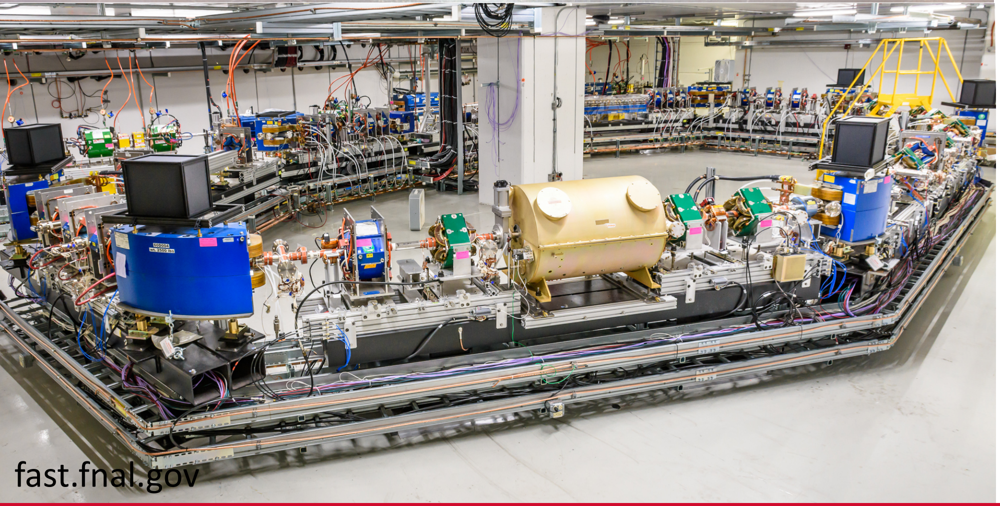




IOTA Nonlinear Integrable Optics Experiment: NL Magnet

Sebastian Szustkowski, Sasha Valishev, Nikita Kuklev, Sasha Romanov

06/10/2019

Research supported by DOE GARD and NIU Accelerator Cluster Funds (NIU: Swapan Chattopadhyay, PI and Bela Erdelyi, Co-PI) & (NIU: Swapan Chattopadhyay, PI)

Northern Illinois University

NIU

Fermilab

Acknowledgments

Northern Illinois University
S. Chattopadhyay

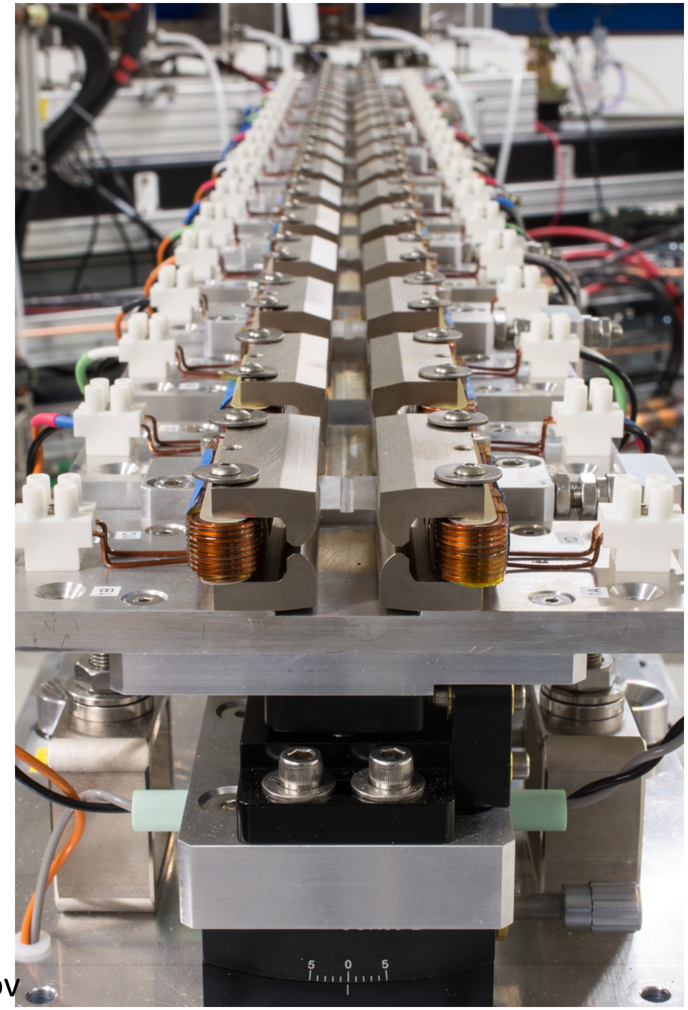
Fermilab
K. Carlson, D. Crawford , N. Eddy, D. Edstrom, J. Eldred, S. Nagaitsev, J. Santucci, A. Romanov, A. Valishev

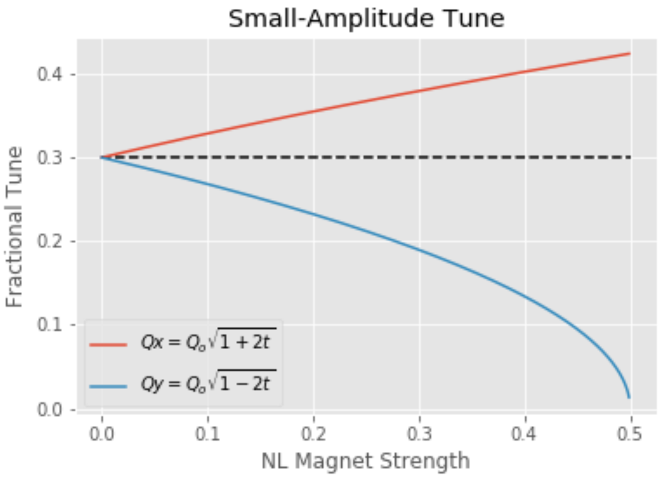
University of Chicago
N. Kuklev

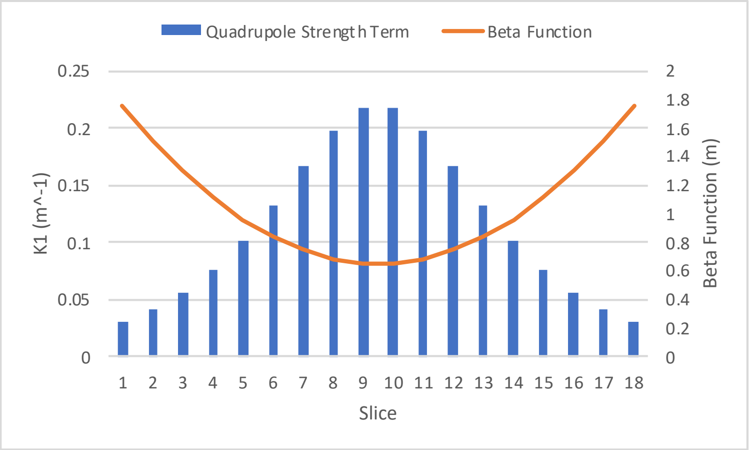
Outline

- Alignment of the Nonlinear Magnet
  - Calibration
- Limiting Factors of IOTA
- Measurements
  - Amplitude Dependent Tune Map

Nonlinear Magnet







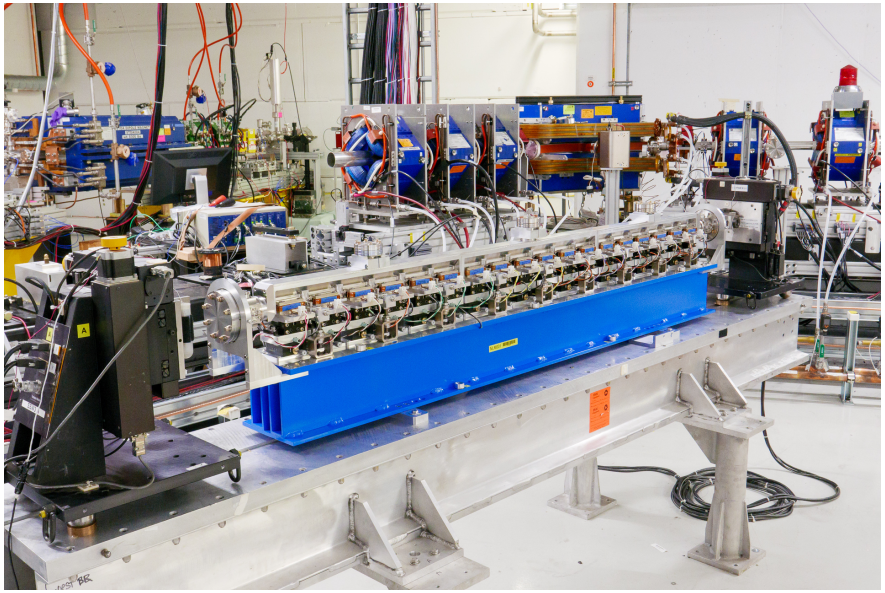
fast.fnal.gov

V. Danilov and S. Nagaitsev, Phys. Rev. ST-AB **13,** 084002 (2010)s

A. Romanov

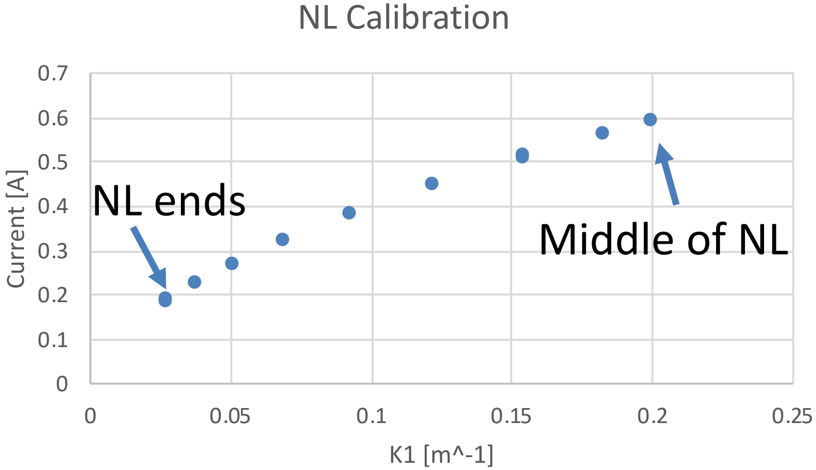
Element Centering

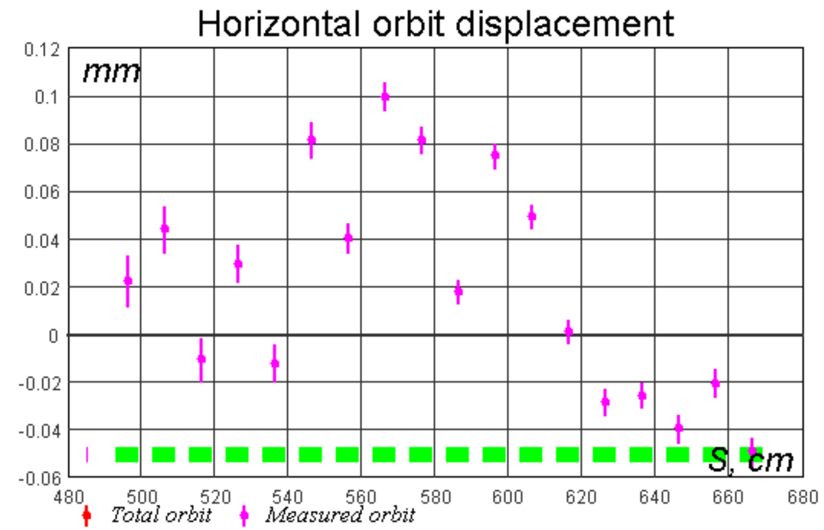
- Alignment experts from AP-STD, Joe DiMarco, measured the center of the 18 magnets individually
- Used stretched wire method
    - copper-beryllium wire
- Magnetic center is to within ±50 um

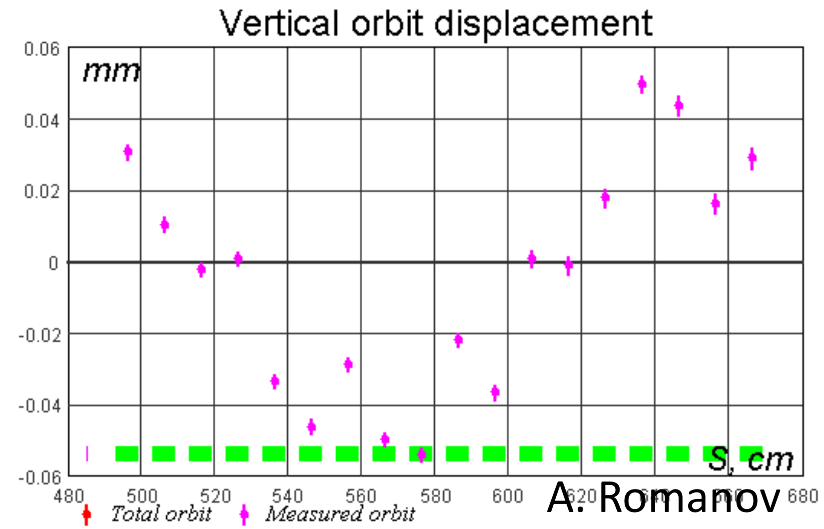


Verification

- Used beam based Orbit Response Measurement
  - Alignment is good up to 100um
- Powered individual magnets for a tune response measurement
  - Fitted calibration strength coef.



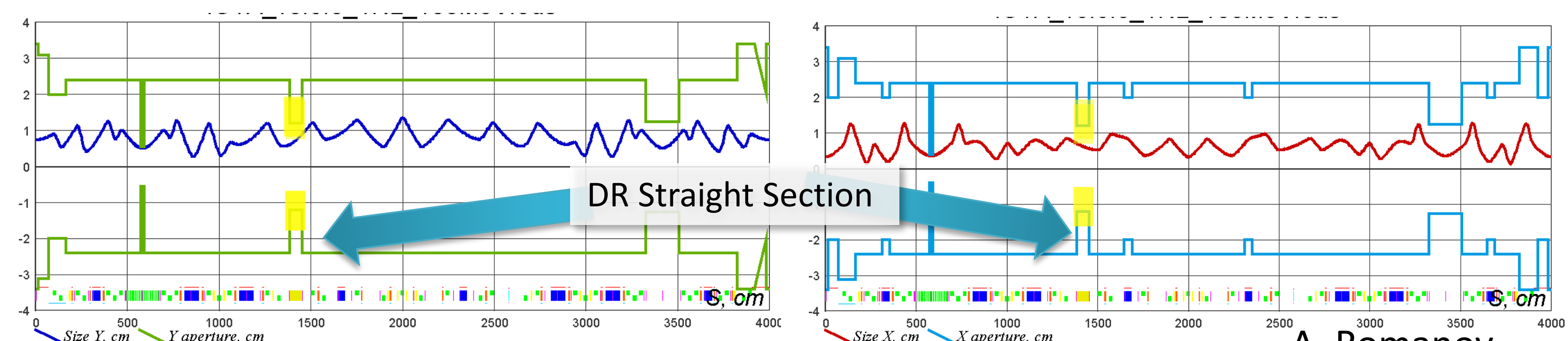




A. Romanov

Limiting Factors

- Mechanical Restrictions
  - DR straight beam pipe has a ~6mm misalignment
    - Planning to fix this during shutdown
  - By design the smallest restriction should be at the middle of nonlinear magnet, 5.5mm vertically
  - Beam measurements indicate an unexpected restriction of 6mm in DR straight section
- T-insert transfer map must be precise, up to 1%
  - During run, lattice tuning up to 10%, will be improved next run



Vertical Mechanical Restriction

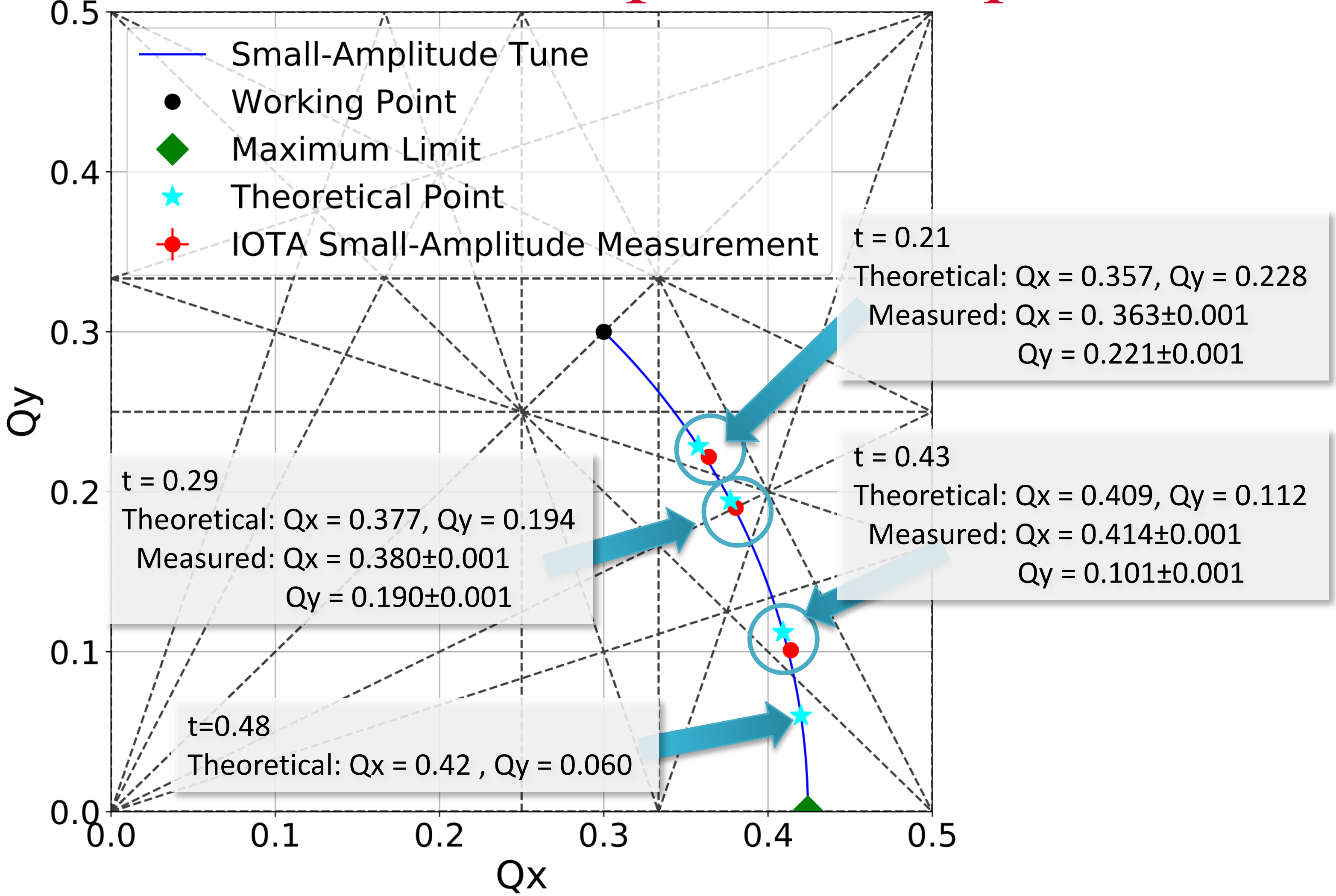
A. Romanov

Horizontal Mechanical Restriction

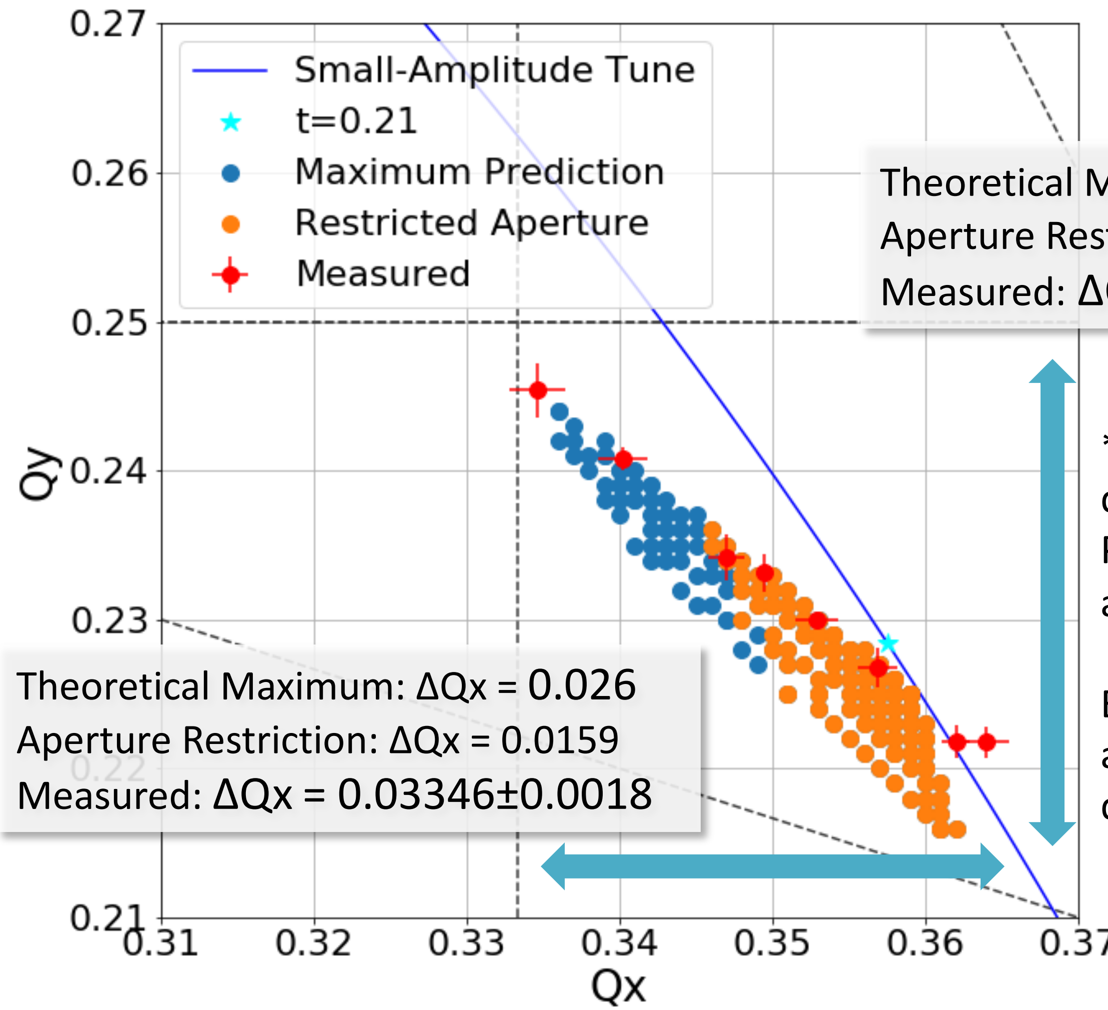
Tune Measurements

- Kicked a 100 MeV electron beam vertically from 0.3kV to 4.8kV
- Changed strength of nonlinear magnet to t = 0.21, 0.29, 0.43
- Calculated tunes via FFT algorithm from data collected via 21 Beam Position Monitors (BPM) around the ring

Small-Amplitude Map



Amplitude Dependent Tune Map, t=0.21



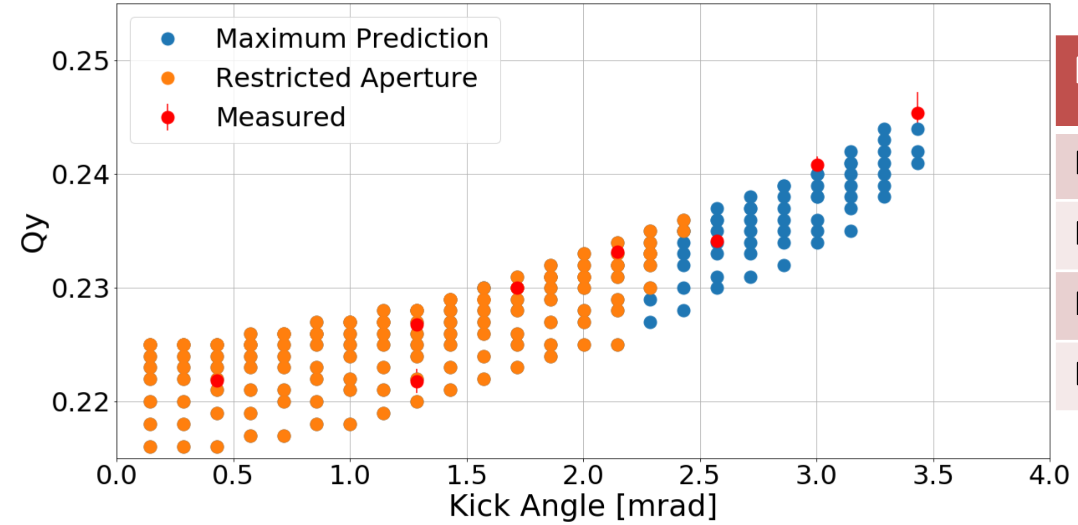
Theoretical Maximum: ΔQy = 0.028
Aperture Restriction: ΔQy = 0.020
Measured: ΔQy = 0.0245±0.0018

Theoretical Maximum: ΔQx = 0.026
Aperture Restriction: ΔQx = 0.0159
Measured: ΔQx = 0.03346±0.0018

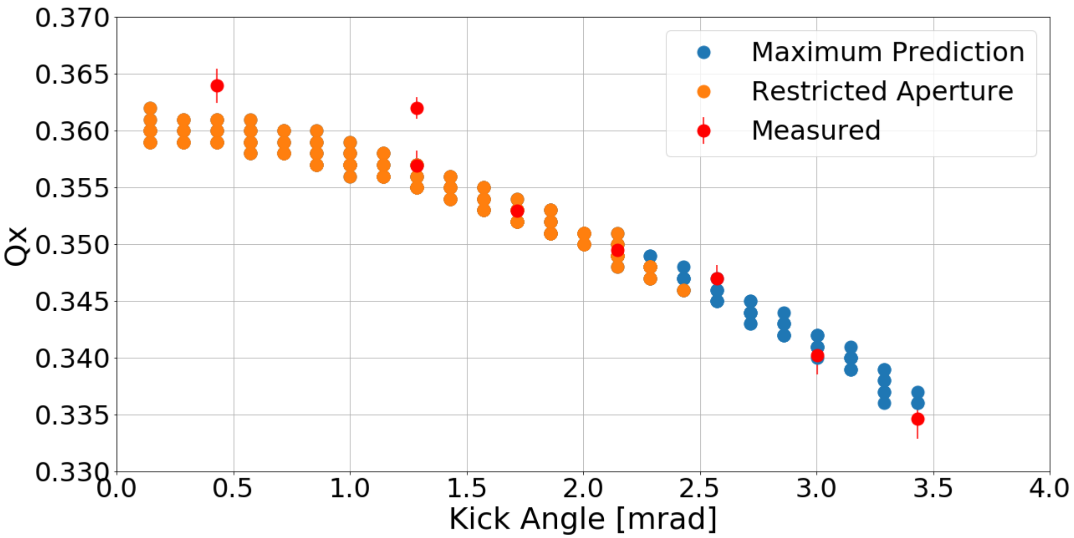
*Restricted Aperture simulation disregards lost particles <1000 turns, Particle loss occurs in 300-500 turns at DR straight section

Experiment had large chromaticity and momentum spread, beam decoheres in ~200 turns

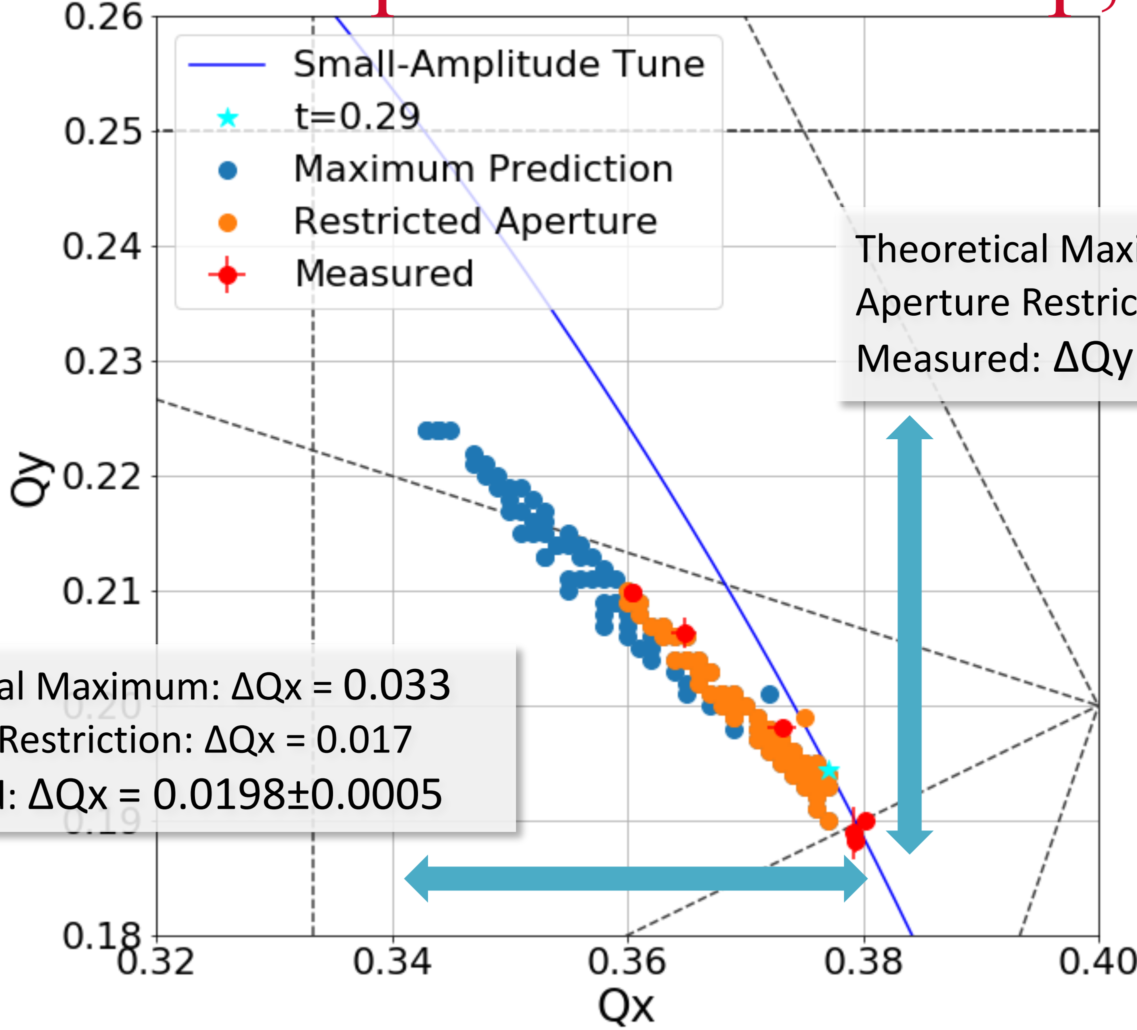
Amplitude Dependent Tune Shift, t = 0.21



Parameter	Meas.	Aperture Restriction	Model
Max Kick [kV]	4.80	3.39	4.80
Max Kick Ang. [mrad]	3.43	2.43	3.43
Max Amp at NL [mm]	4.48	3.18	4.48
DR-Restriction [mm]	6	6	10



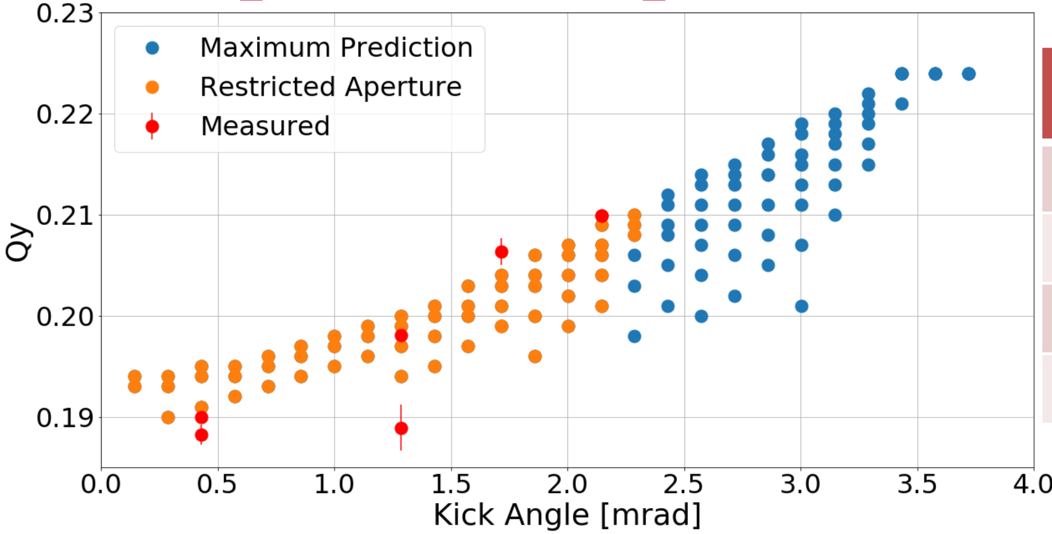
Amplitude Dependent Tune Map, t=0.29

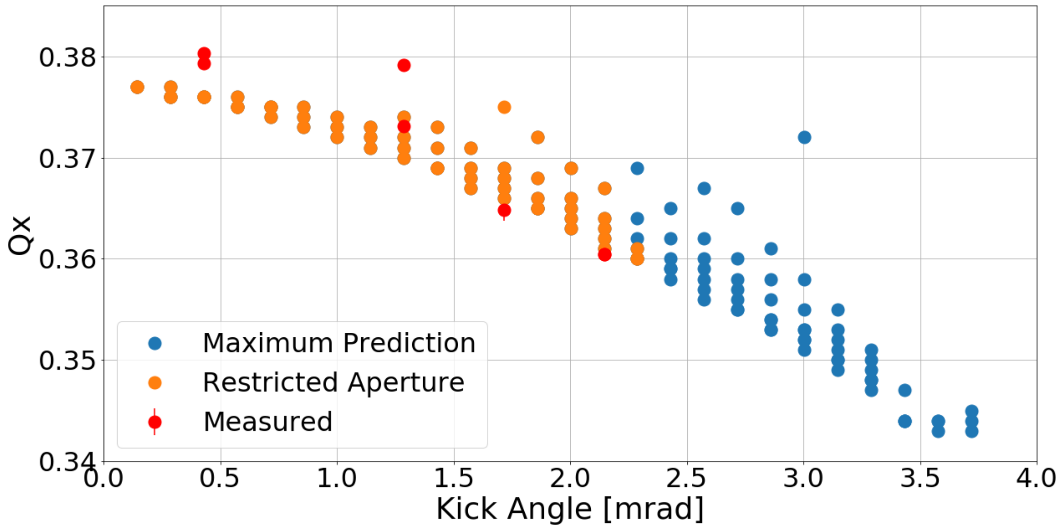


Theoretical Maximum: ΔQy = 0.034
Aperture Restriction: ΔQy = 0.02
Measured: ΔQy = 0.0216±0.0010

Theoretical Maximum: ΔQx = 0.033
Aperture Restriction: ΔQx = 0.017
Measured: ΔQx = 0.0198±0.0005

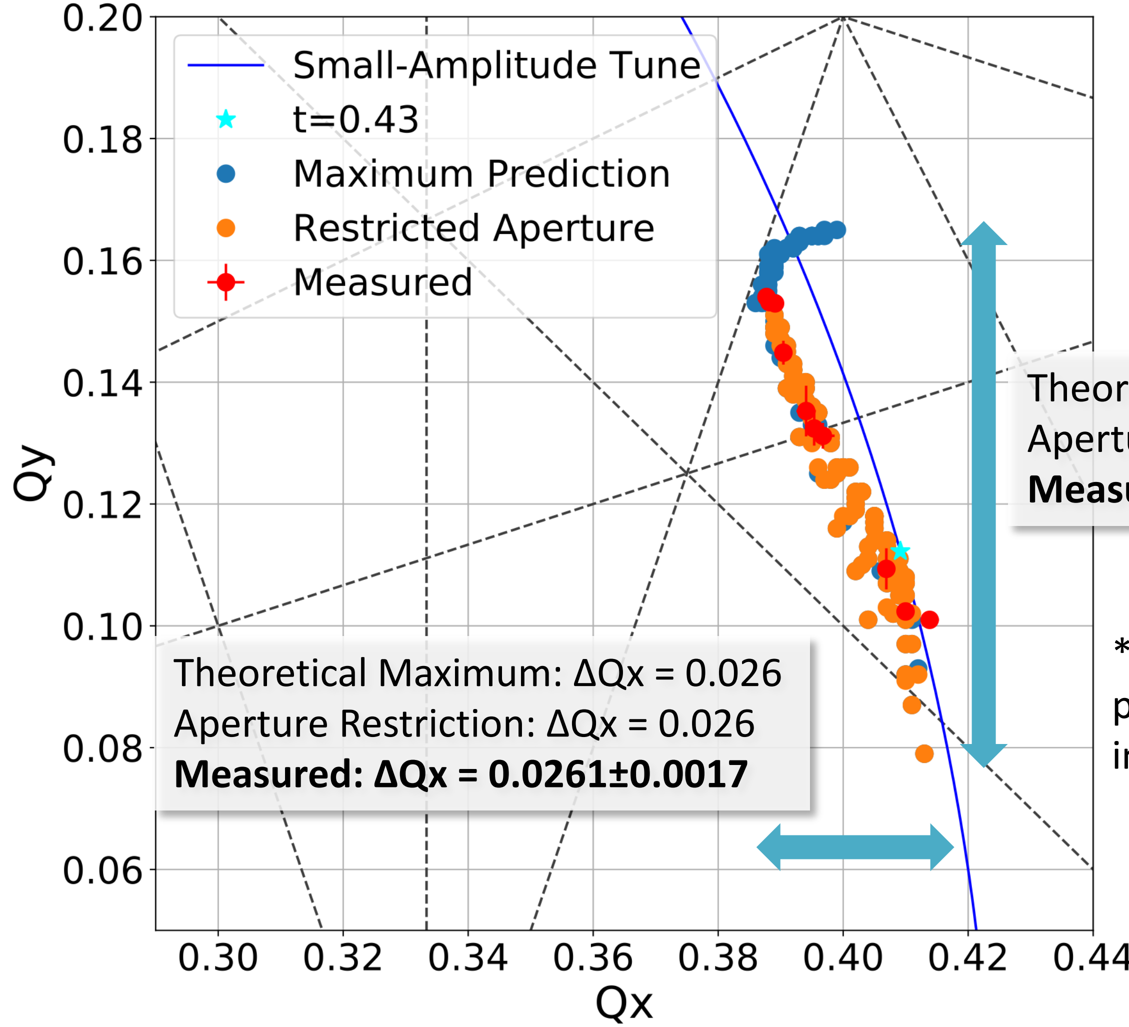
Amplitude Dependent Tune Shift, t = 0.29





Parameter	Meas.	Aperture Restriction	Model
Max Kick [kV]	3.00	4.68	5.18
Max Kick Ang. [mrad]	2.14	2.28	3.71
Max Amp at NL [mm]	5.19	2.73	5.19
DR-Restriction [mm]	6	6	10

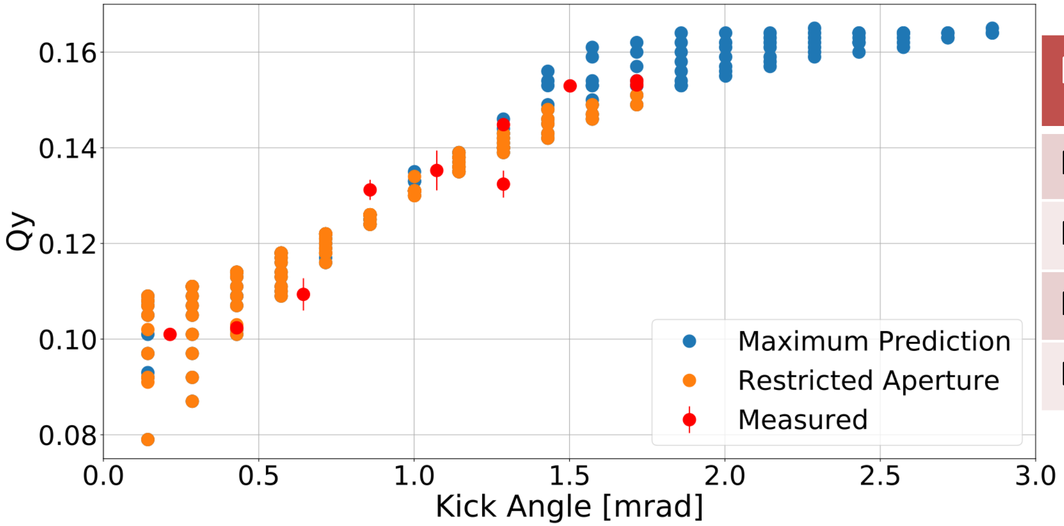
Amplitude Dependent Tune Map, t=0.43



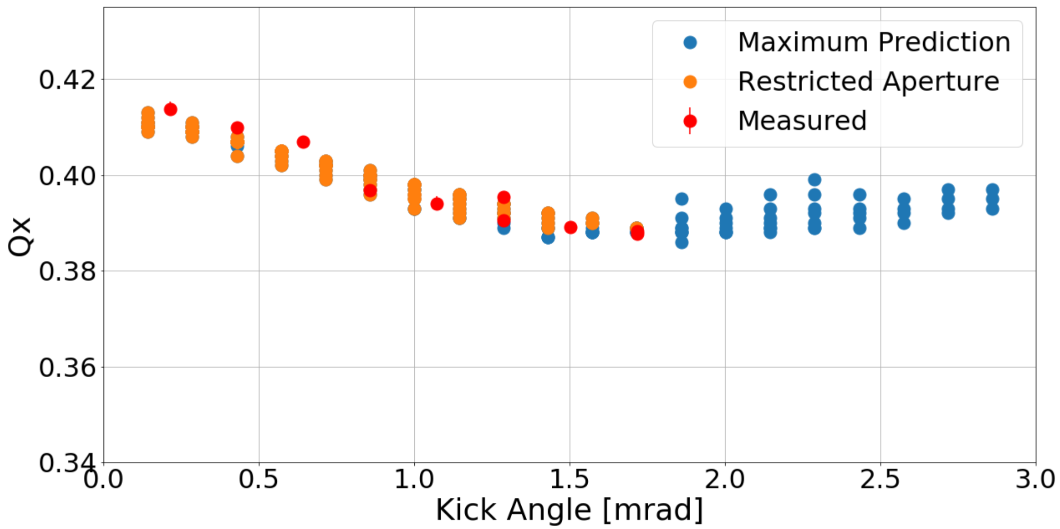
Theoretical Maximum: ΔQy = 0.085
Aperture Restriction: ΔQy = 0.072
Measured: ΔQy = 0.0530 ± 0.0018*

*Beam loss was observed, possible due to IBS. Further investigation needed

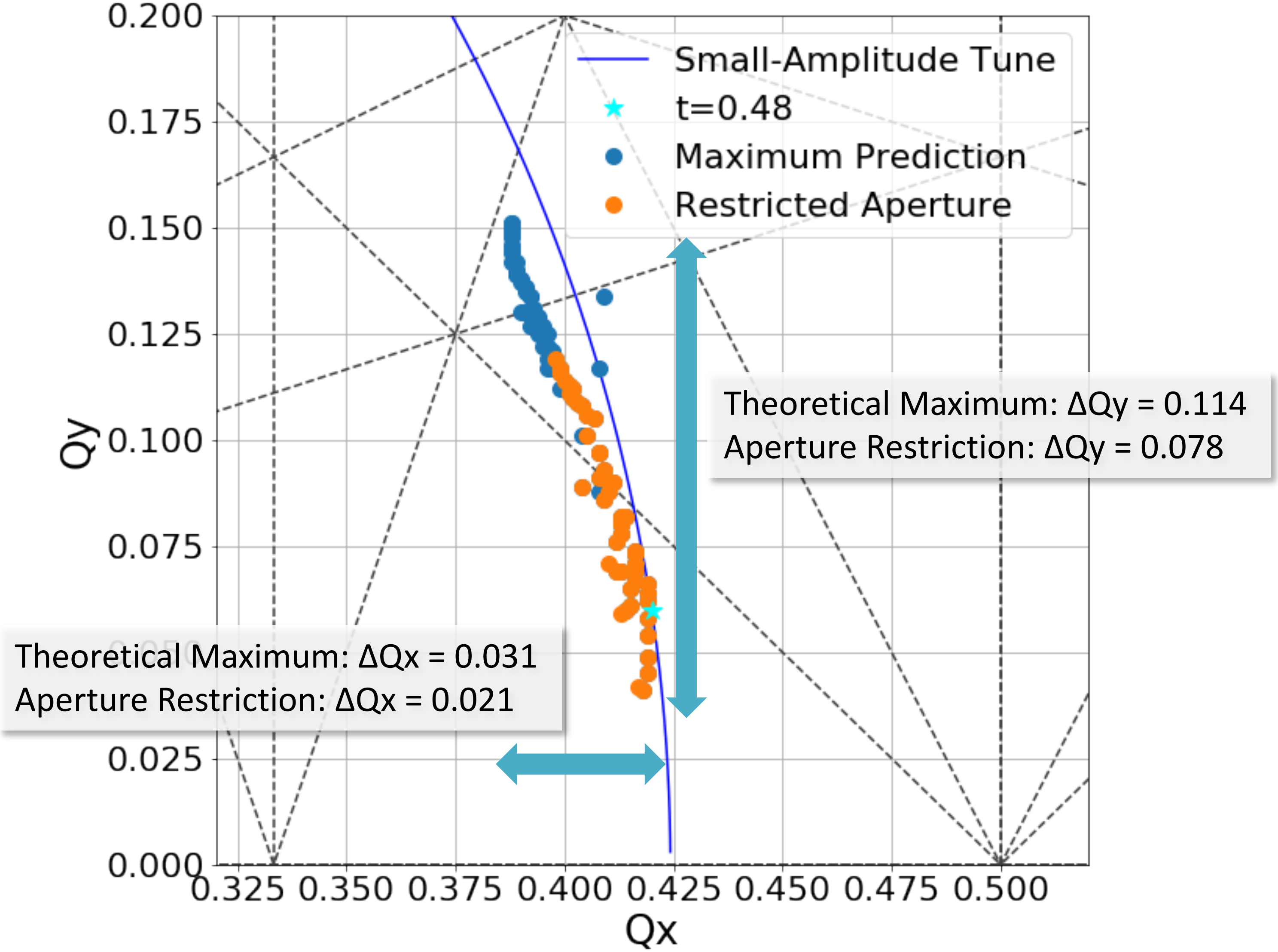
Amplitude Dependent Tune Shift, t = 0.43



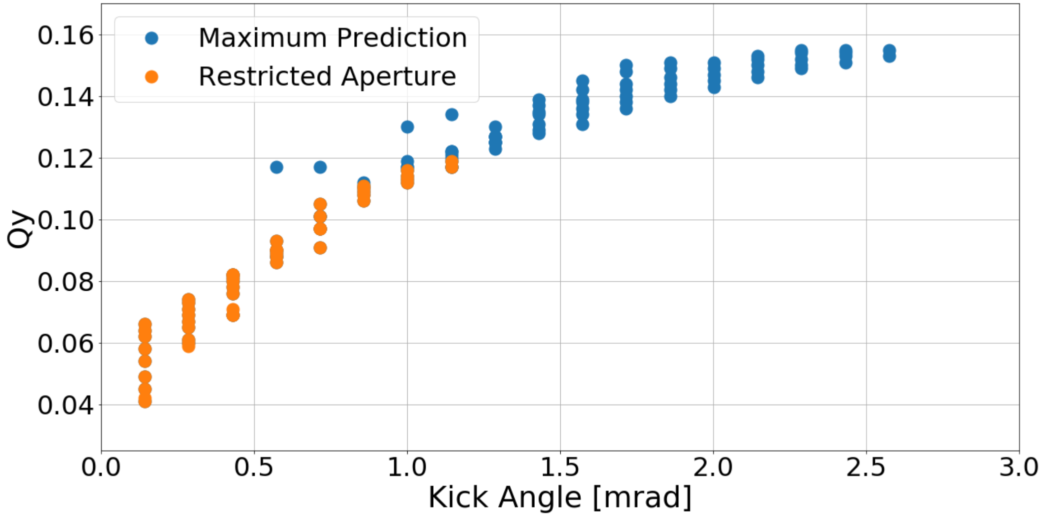
Parameter	Meas.	Aperture Restriction	Model
Max Kick [kV]	2.4	2.4	4.0
Max Kick Ang. [mrad]	1.71	1.71	2.86
Max Amp at NL [mm]	3.65	3.65	5.19
DR-Restriction [mm]	6	6	10

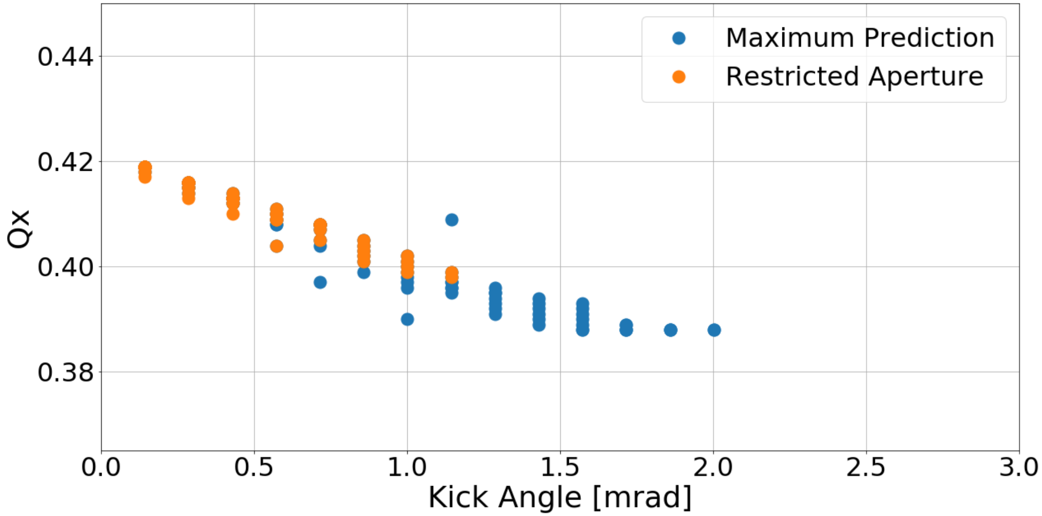


Simulation Amplitude Dependent Tune Map, t=0.48



Simulation of t = 0.48, Amplitude Dependent Tune Shift





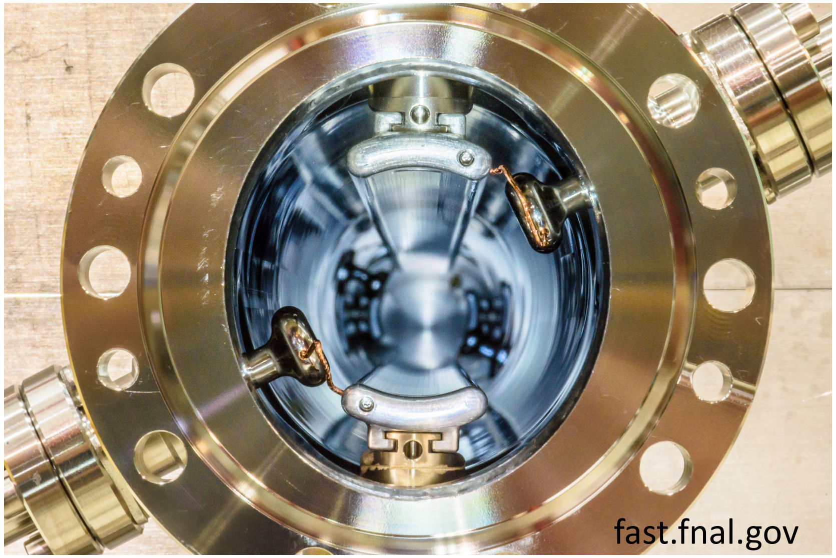
Parameter	Aperture Restriction	Model
Max Kick [kV]	1.60	3.60
Max Kick Ang. [mrad]	1.14	2.57
Max Amp at NL [mm]	3.37	5.10
DR-pipe radius [mm]	6	10

Summary and Outlook

- Measured tunes in good agreement with MAD-X Simulation
- Largest observed tune shift of $\Delta Qx = 0.0261 \pm 0.0017$ and **$\Delta Qy = 0.0530 \pm 0.0018$**
  - At larger strength value of t=0.48, simulation shows a tune shift of **$\Delta Qy \approx 0.11$**
- Next Run will have ring improvements, allowing further exploration of the dynamic aperture
  - Realignment
  - Fix DR beam pipe
  - BPM Improvements
  - Additional sextupoles
  - Working horizontal kicker
- Further studies in understanding beam loss from previous run needs to done

Back up Slides

Stripline Kicker

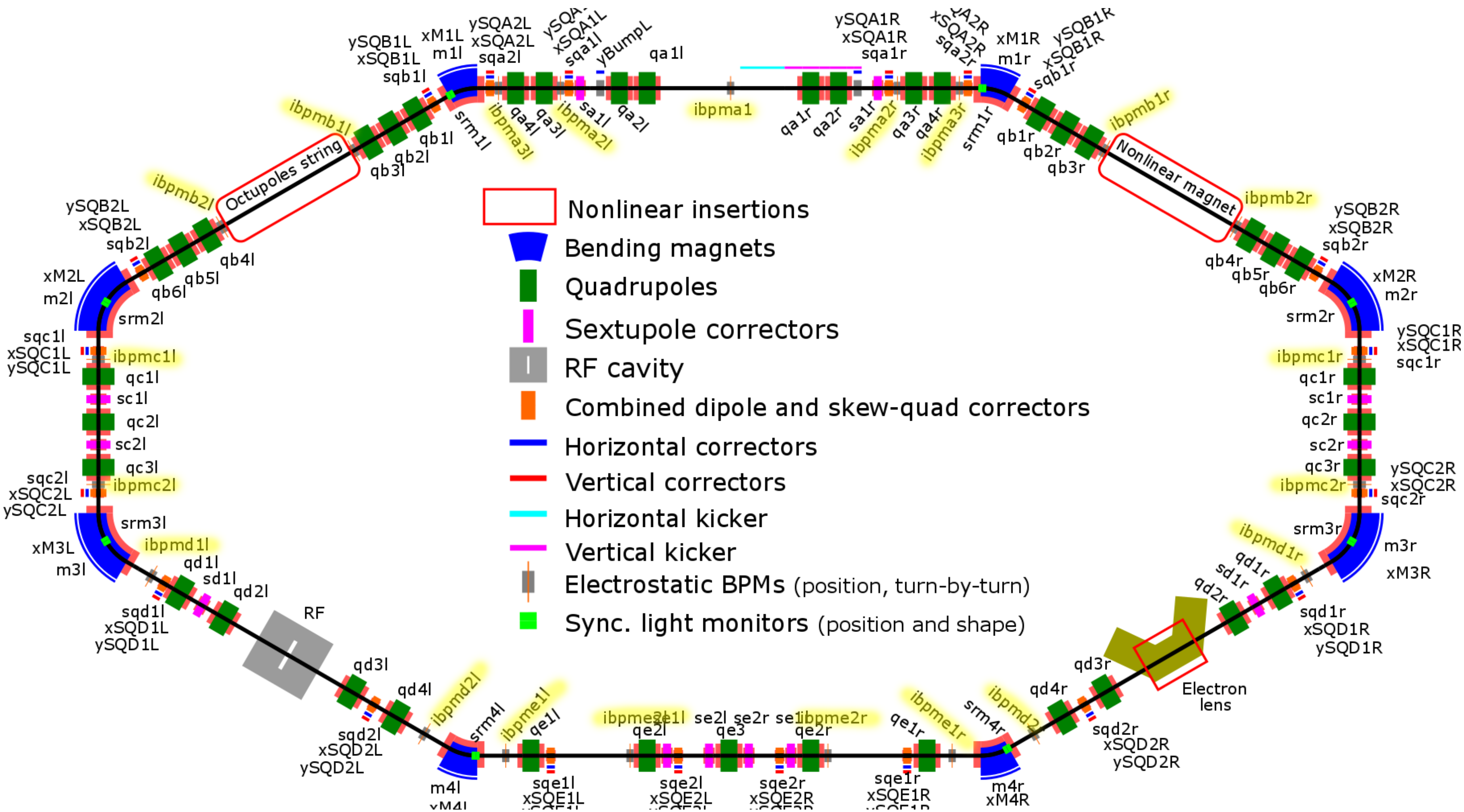


Parameters of vertical (horizontal) kicker	
Plate inner radius	20 mm
Plate thickness	6 mm
Plate opening angle	65 deg
Length of plates	1050 (580) mm
Max plate Voltage	±25kV
Max. kick angle	16 (8) mrad

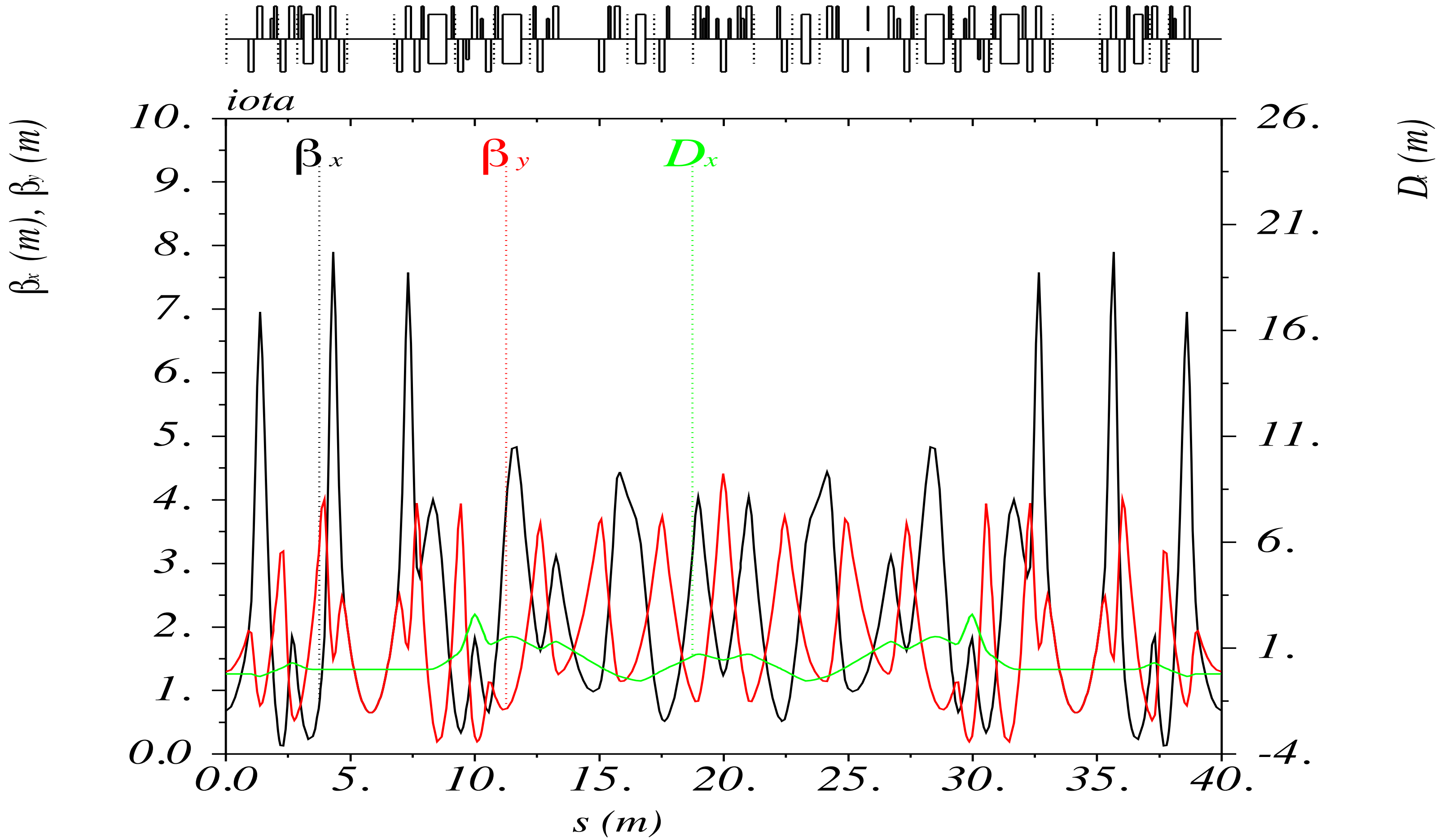
Kicker Strength: $$\alpha = \frac{2VL}{r}\frac{4}{\pi}\sin\frac{\theta}{2}$$

S. Antipov, et.al, arXiv:1607.00023

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)
Octupoles string
Nonlinear magnet
Electron lens
RF
ibpma1
ibpmb1l
ibpmb2l
ibpmb1r
ibpmb2r
ibpmc1l
ibpmc2l
ibpmc1r
ibpmc2r
ibpmd1l
ibpmd2l
ibpmd1r
ibpmd2r
ibpme1l
ibpme1r
ibpme2r

IOTA Lattice

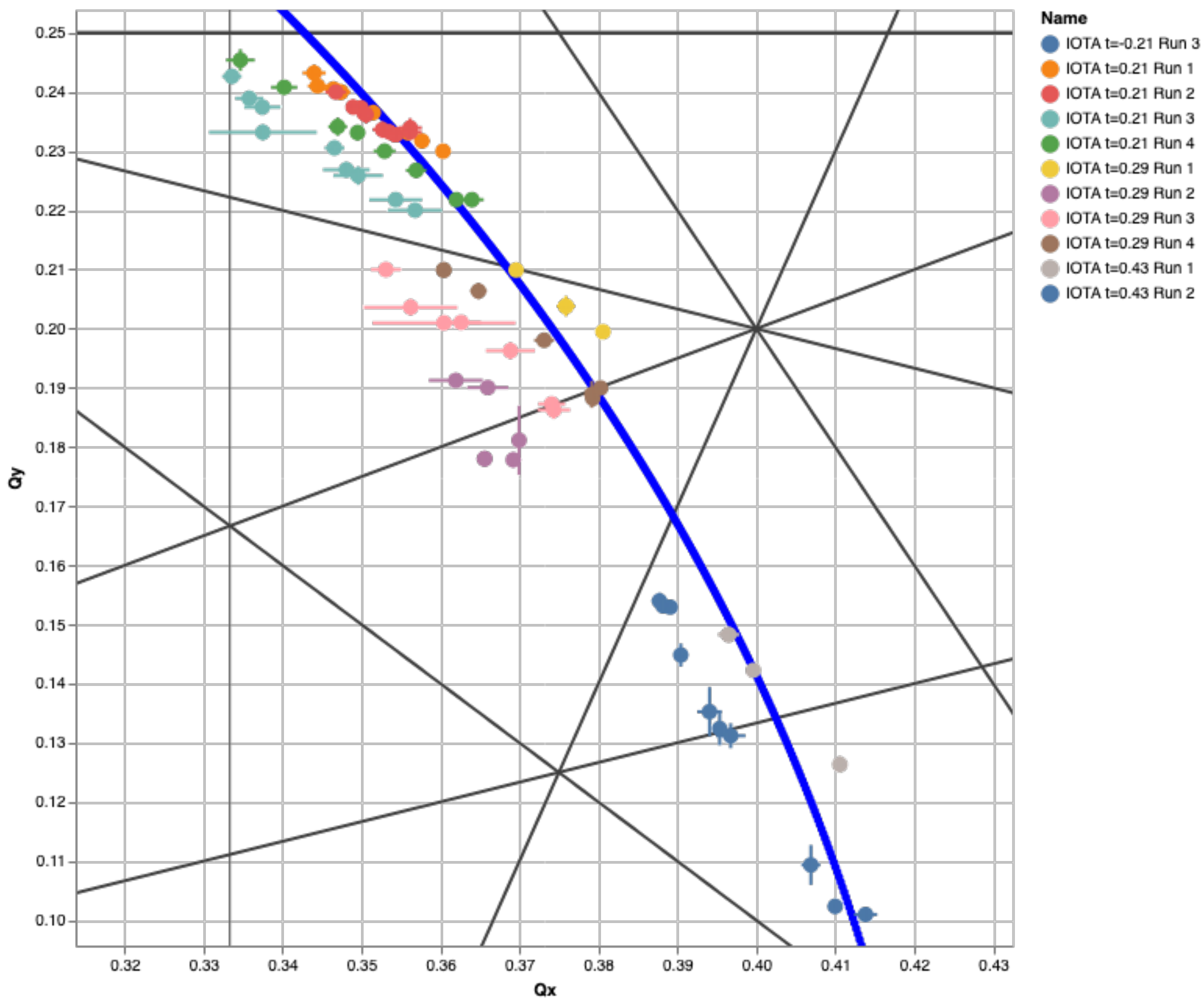


IOTA Parameters

PARAMETER	VALUE
Beam Energy	150 MeV
Circumference, C_0	39.97 m
Revolution period, T_0	133.3 µs
RF voltage, frequency, revolution harmonic	1 kV, 30.0 MHz, 4
Number of particles, beam current	2×10^9, 2.4 mA
Betatron tunes, $Q_{x,y}$	4-6
Synchrotron tunes, Q_s	5.3×10^{-4}
Momentum compaction, α_p	0.067
Radiation damping times $\tau_{x,y}$, τ_z	0.9 s, 0.24 s
Maximum beta-function, β_x, β_y	8.5, 4 m
Equilibrium beam emittance, $\epsilon_{x,y}$	0.04 µm
Beam energy spread, bunch length, σ_E, σ_z	1.35×10^{-4}, 10.8 cm
Vacuum	6×10^{-10} Torr

S. Antipov et al, J. Instrum. **12**, T03002 (2017)

All Measurements



Linear Focusing Accelerator

All present circular accelerators are built around linear focusing optics.

$$H = \frac{(p_x^2 + p_y^2)}{2} + K_x(s)\frac{x^2}{2} + K_y(s)\frac{y^2}{2}$$

The transverse motion, has two degrees of freedoms that the equation of motion is a linear oscillator, leads to two invariants, which are called action or integrable of motion.

$$\left.\begin{array}{ll} z_N(s) = \dfrac{z(s)}{\sqrt{\beta_z(s)}} & p_{zN}(s) = \sqrt{\beta_z(s)}p_z(s) - \dfrac{\beta_z^{'}(s)}{2\beta_z(s)}z(s) \\ \psi_z(s) = \displaystyle\int_0^s \frac{ds^{'}}{\beta_z(s^{'})} & J_z = \dfrac{1}{2\pi}\displaystyle\oint p_{zN}dz_N \end{array}\right\} H = \nu_x J_x + \nu_y J_y$$

Time-Independent Hamiltonian

Start with a Hamiltonian with equal transverse focusing.

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

Have H time-independent in normalized coordinates and introduce a 'new' time, which is the betatron phase

$$z_N(s) = \frac{z(s)}{\sqrt{\beta_z(s)}} \qquad p_{zN}(s) = \sqrt{\beta_z(s)}p_z(s) - \frac{\beta_z'(s)}{2\beta_z(s)}z(s) \qquad \frac{d\psi}{ds} = \frac{1}{\beta(s)}$$

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

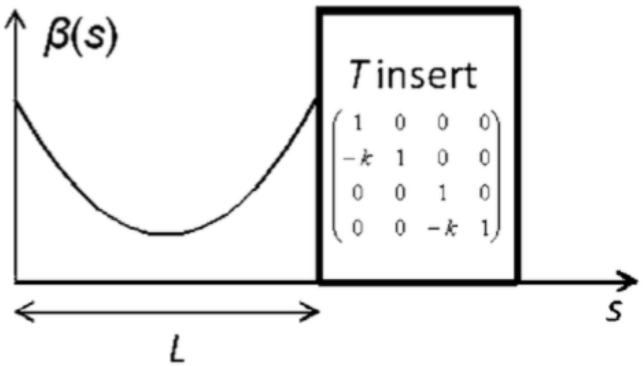
$$H_N = \frac{(p_{xN}^2 + p_{yN}^2)}{2} + \frac{x_N^2 + y_N^2}{2} + U(x_N, y_N, \psi)$$

H is now an integral of motion

Implementation Into An Accelerator

Start with a linear focusing accelerator with equal horizontal and vertical optics.

- The linear optics can be built with standard optics, but must have a n-π phase advance, "T-insert"
- Drift region L, matched beta function (L=1.8m in IOTA)

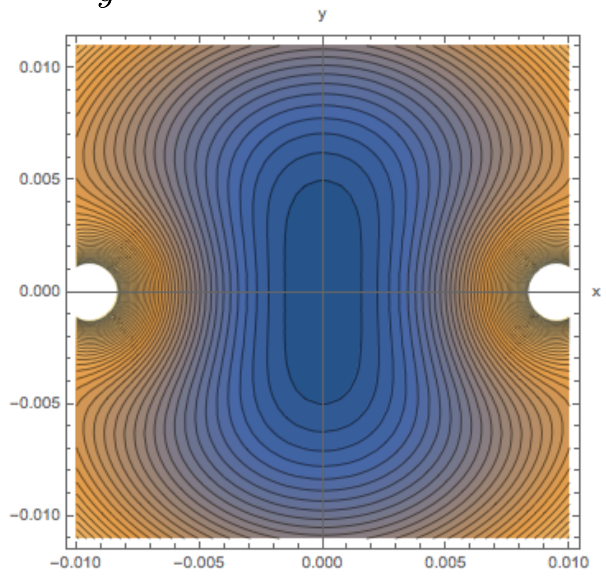


Add a nonlinear potential V(x,y,s) in the drift region

2^{nd} Integral of Motion– Elliptical Potential

- Find a potential that satisfies the Laplace equation, and is separable in some variables and has a second integral of motion that is quadratic in momentum
- First studied by Gaston Darboux in 1901, yielded to the Bertrand-Darboux partial differential equation:

$$xy(U_{xx} - U_{yy}) + (y^2 - x^2 + c^2)U_{xy} + 3y_x - 3xU_y = 0$$



- A general solution satisfying the equation:

$$U(x,y) = \frac{f(\xi) + g(\eta)}{\xi^2 + \eta^2}$$

$$f_2(\xi) = \xi\sqrt{\xi^2 - 1}[d + t\ \text{acosh}(\xi)]$$

$$g_2(\eta) = \eta\sqrt{1 - \eta^2}[b + t\ \text{acos}(\eta)]$$

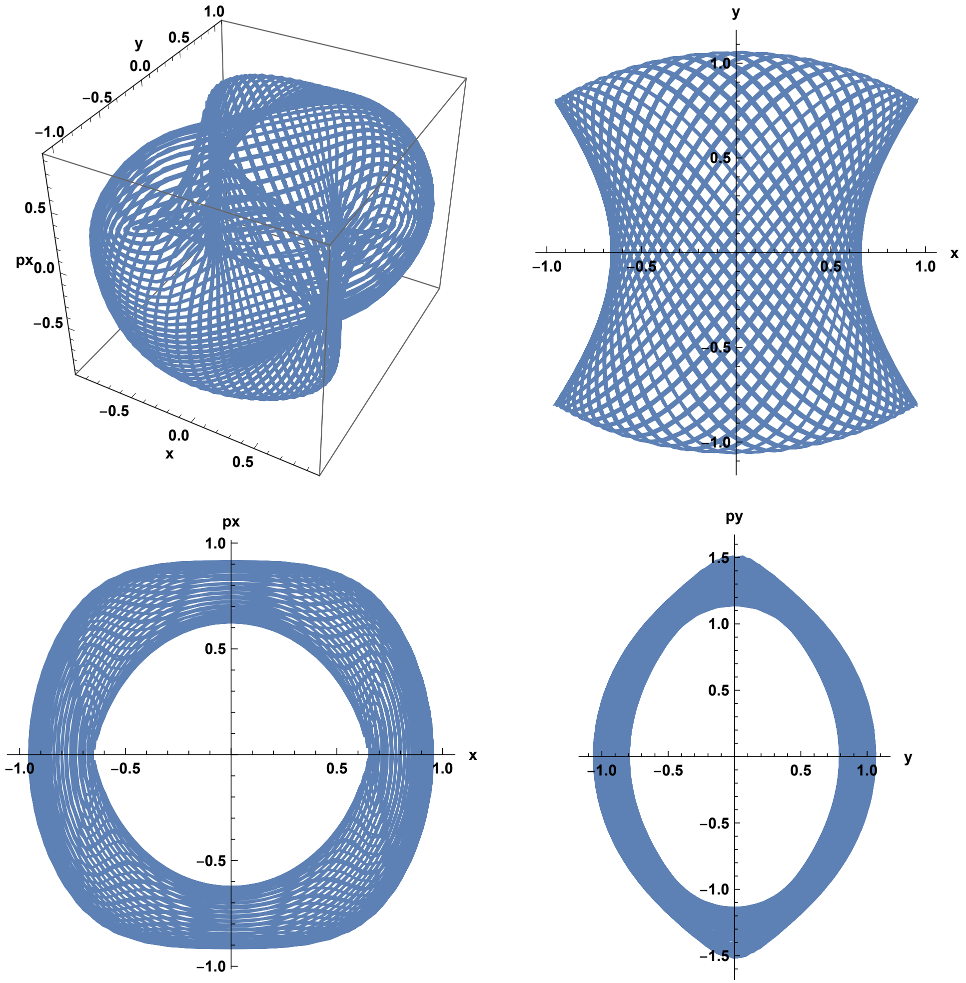
- The second invariant is then:

$$I(x, y, p_x, p_y) = (xp_y - yp_x)^2 + c^2p_x^2 + 2c^2\frac{f(\xi)\eta^2 + g(\eta)\xi^2}{\xi^2 - \eta^2}$$

Which has the form of $f = \frac{f_1}{2} + f_2$ and $g = \frac{g_1}{2} + g_2$, where $f_1(\xi) = c^2\xi^2(\xi^2 - 1)$ and $g_1(\eta) = c^2\eta^2(1 - \eta^2)$.

V. Danilov and S. Nagaitsev, Phys. Rev. ST-AB **13,** 084002 (2010)

Projections



Mathematica Toy Model
c = 1 Dimensional Parameter
t = 0.47 Strength of NL magnet
b = -Pi/2 * t
d = 0

X0= 0.95
Y0= -0.8
Px0=0
Py0=0.1