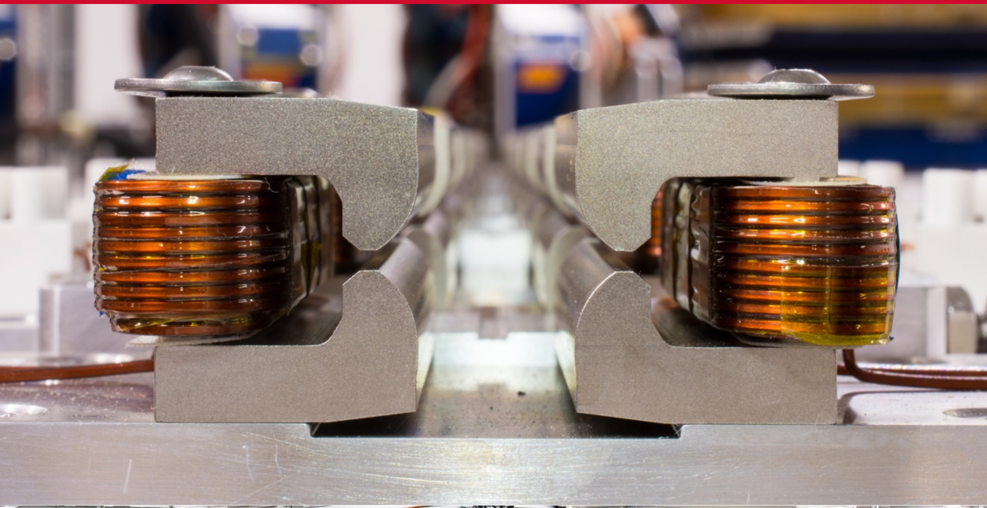

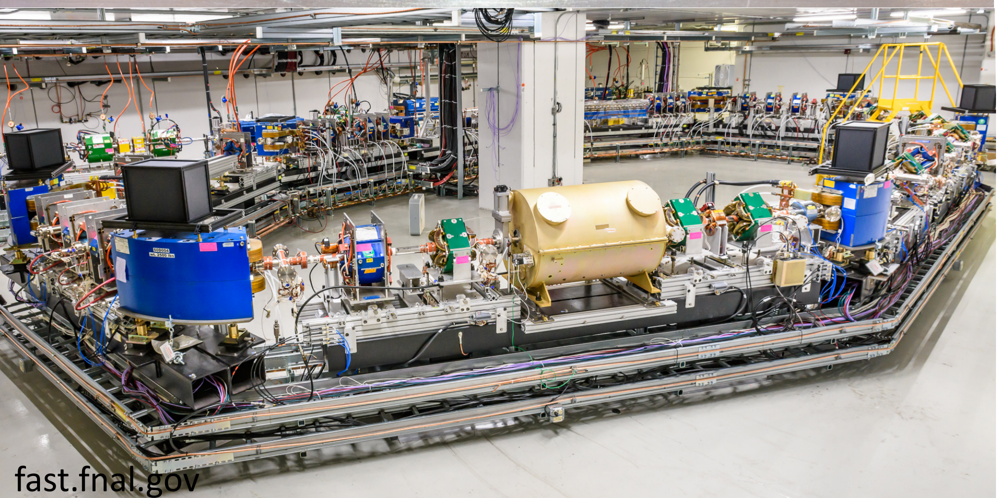

NAPAC2019

NORTH AMERICAN PARTICLE ACCELERATOR CONFERENCE

Nonlinear Tune-Shift Measurements in the Integrable Optics Test Accelerator

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Outline

- Integrable Optics Test Accelerator (IOTA) Overview
- Special Elliptic-Potential Magnet
  - Calibration
- Measurements
  - Small Amplitude Tunes
  - Amplitude Dependent Tune Map
- Run 2 Outlook and Conclusion

Integrable Optics Test Accelerator

- IOTA is currently the only testbed for NL Integrable Optics using electron and proton beams
  - Nonlinear Elliptic Magnet from Danilov-Nagaitsev
  - Octupole String for Quasi-Integrable Henon-Heiles System
  - Electron Lens for Integrable Optics
- Other IOTA Experiments**:
  - Single-Electron Storage, understanding quantum effects
  - Electron Lens for space-charge compensation
  - Optical Stochastic Cooling for bright electron beams
- Over 20 University and Industry Collaborators

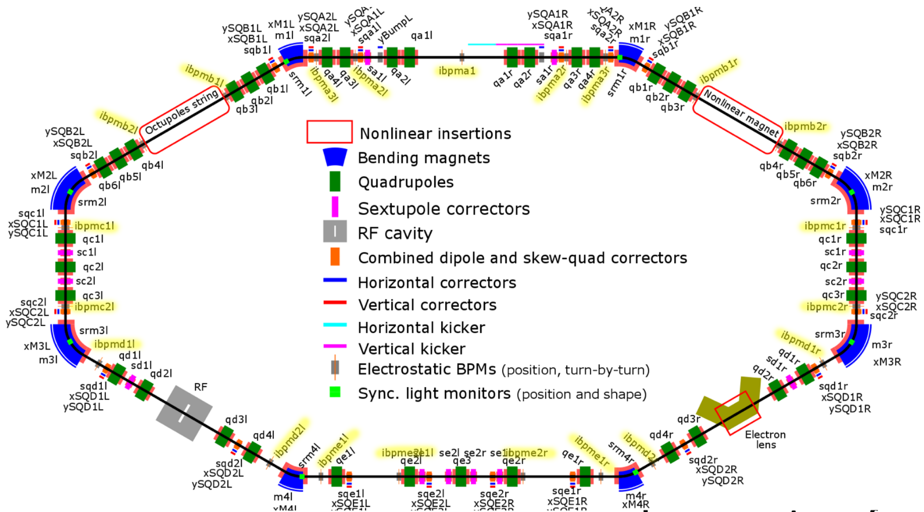
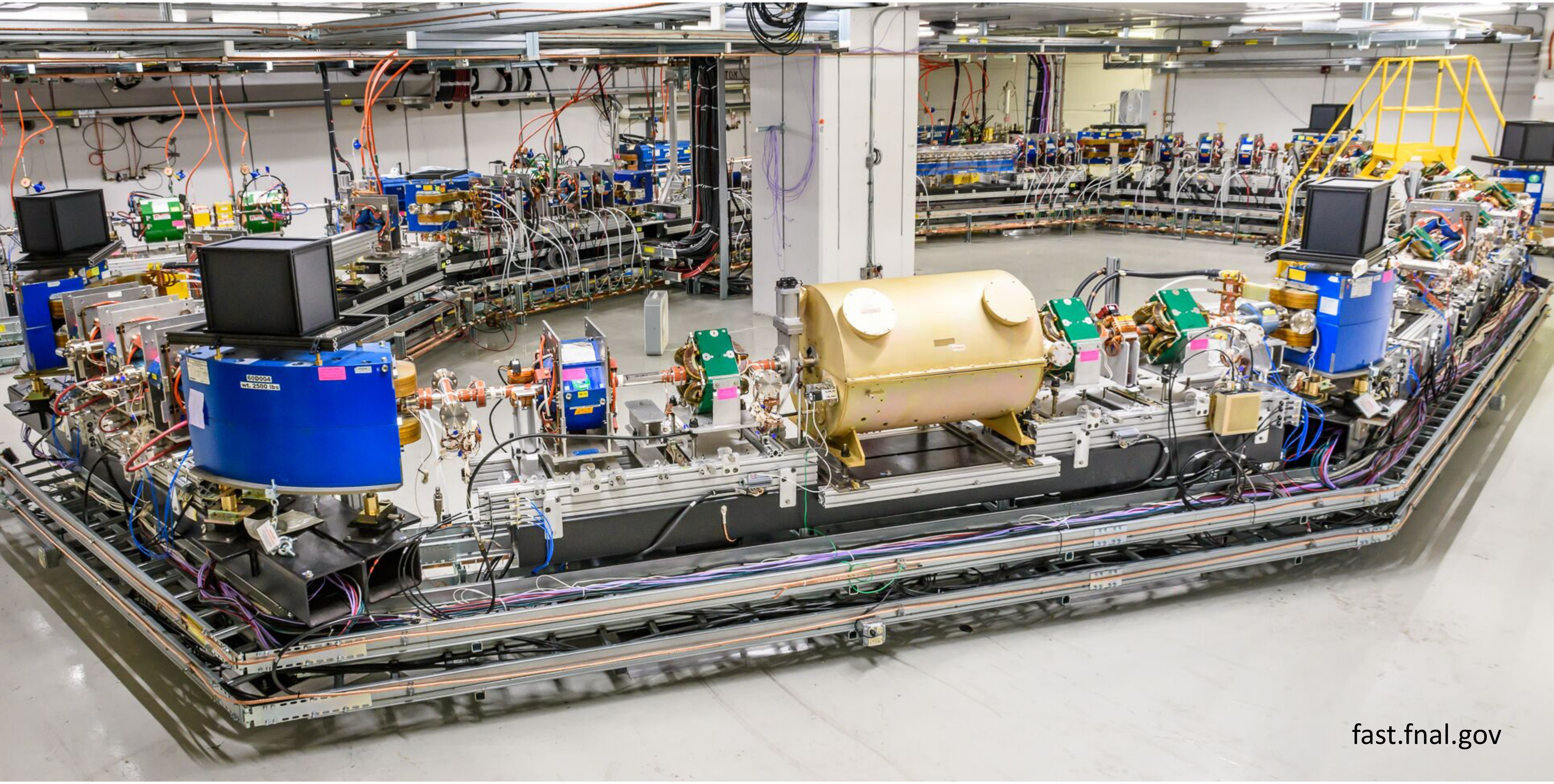


Image courtesy of A. Romanov

Parameter	Value
Perimeter	39.97 m
Momenta	50-200 MeV/c
p_{e-beam}, design	150 MeV/c
p_{p-beam}, design	70 MeV/c
Electron current	1.2 mA
Proton current	10 mA
RF frequency	30 MHz
RF voltage	1 kV
ν_x, ν_y, ν_s	$(0.3, 0.3, 5.7 \times 10^{-4})$
τ_x, τ_y, τ_s	(2.0, 0.7, 0.3) s
$\epsilon_x, \epsilon_{x,ycoupled}$, RMS	(96.3, 25.3) nm
$\Delta p/p$, RMS	1.26×10^{-4}

** See A. Romanov talk tomorrow **WEXBA2**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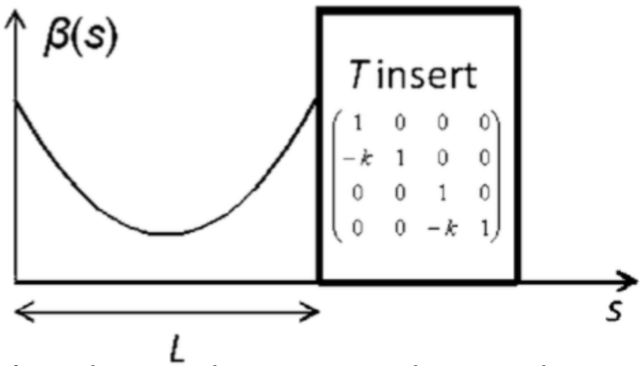
Implementation Into An Accelerator

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)



Hamiltonian should be time-independent in normalized coordinates and introduce a 'new' time, which is the betatron phase

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

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

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:

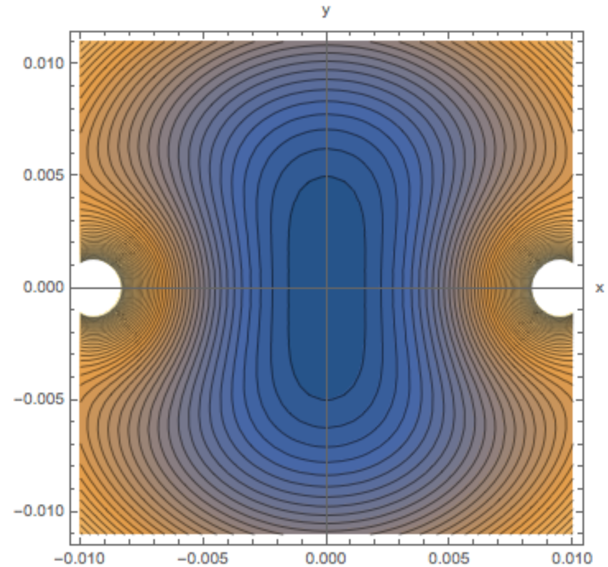
$$xy(U_{xx} - U_{yy}) + (y^2 - x^2 + c^2)U_{xy} + 3y_x - 3xU_y = 0$$

- A general solution satisfying the equation:

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

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

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



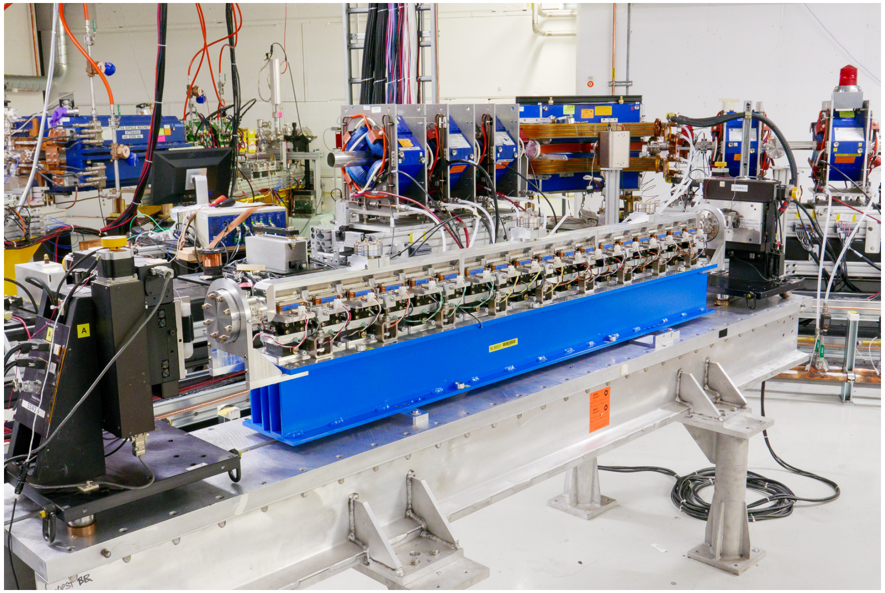
To have lowest multipole expansion term to be a quadrapole: d=0, b = $\frac{\pi}{2}$ t

t is then the nonlinear potential strength

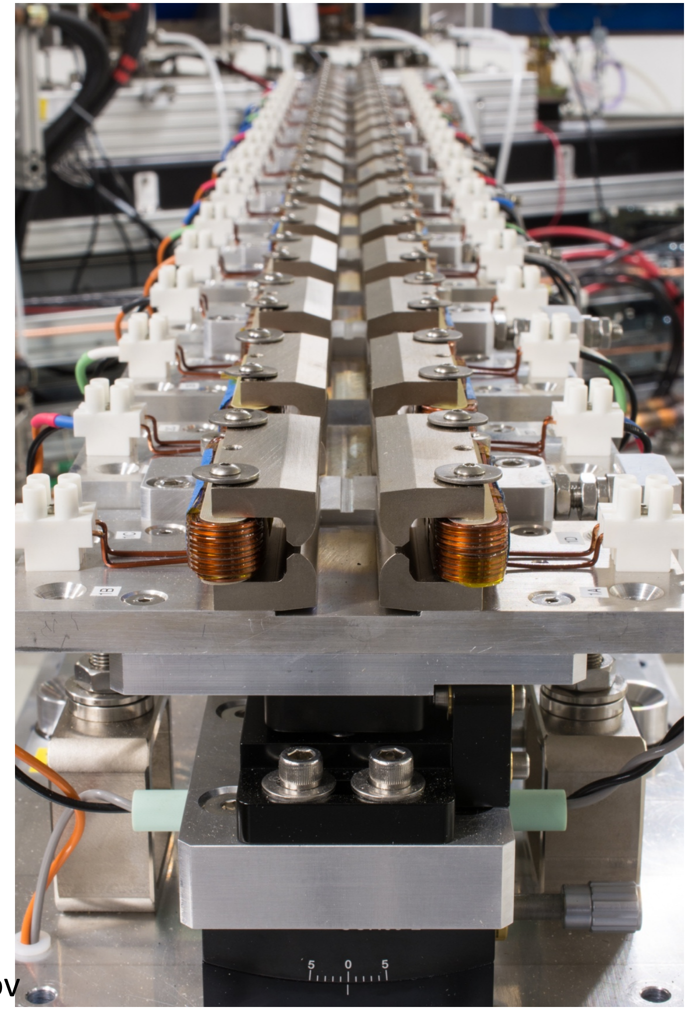
V. Danilov and S. Nagaitsev, Phys. Rev. ST-AB **13,** 084002 (2010)

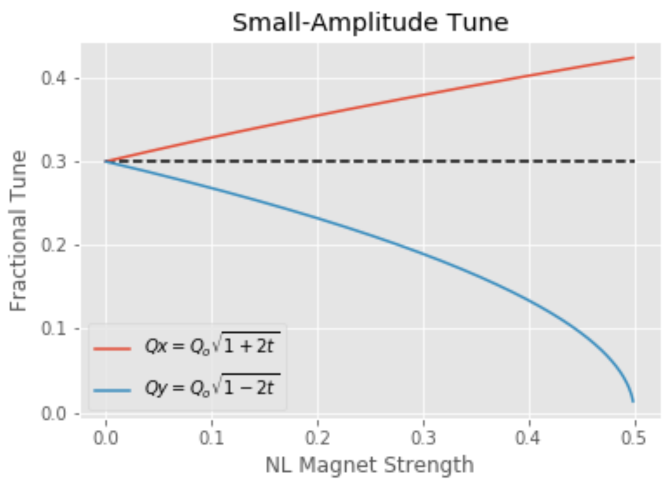
Nonlinear Magnet

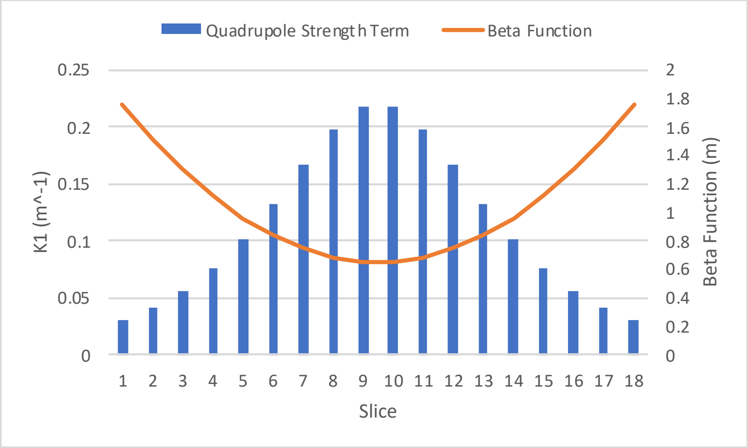
- Magnet and Vacuum chamber designed and manufactured by RadiaBeam Technologies
- Used stretched wire method to measure and align the center of the 18 magnets individually
- Magnetic center is to within ±50 um



Nonlinear Magnet







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

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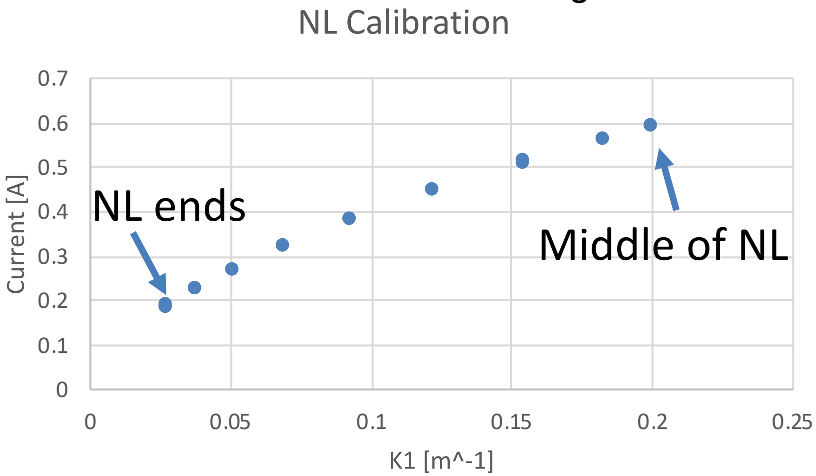
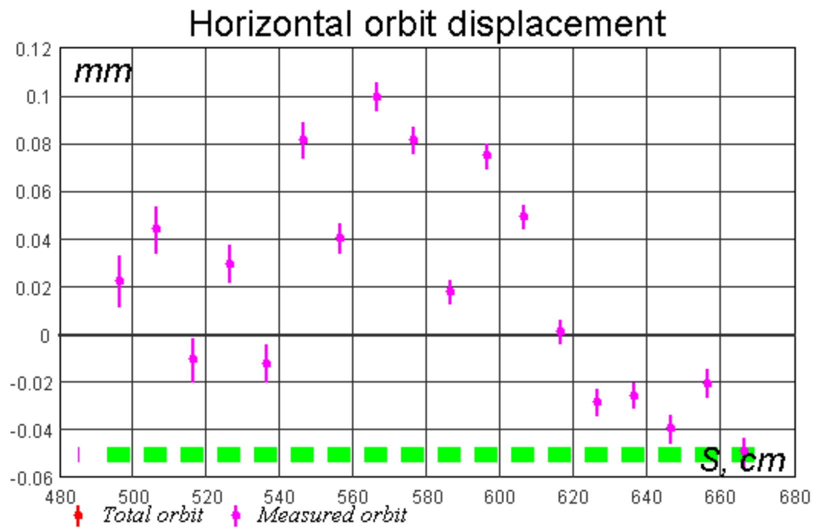
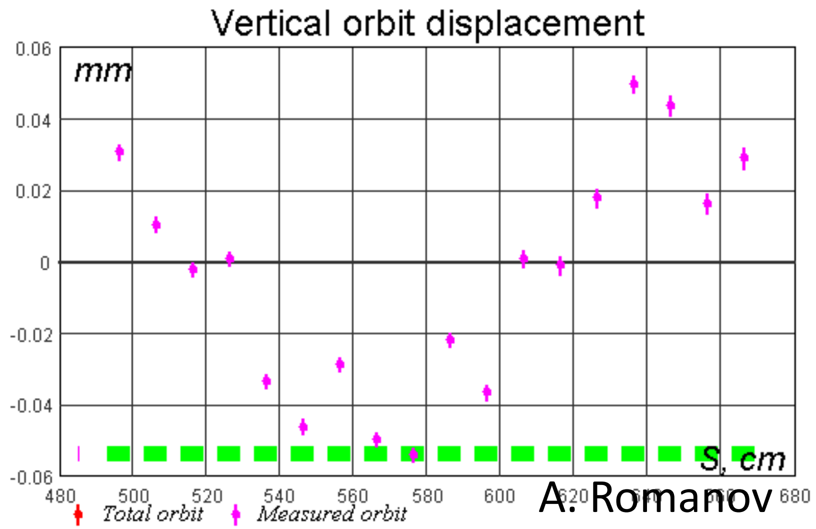
Verification

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







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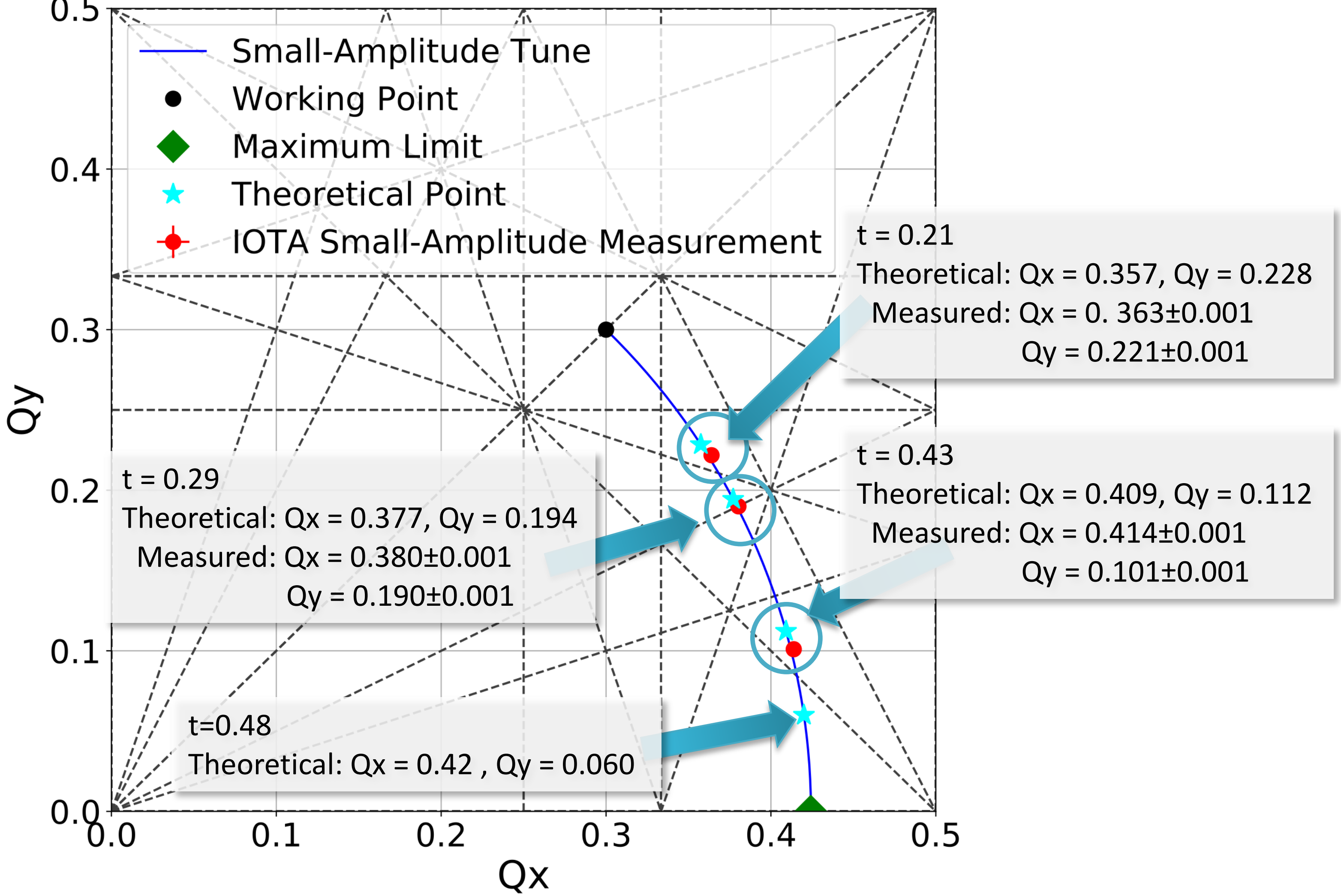
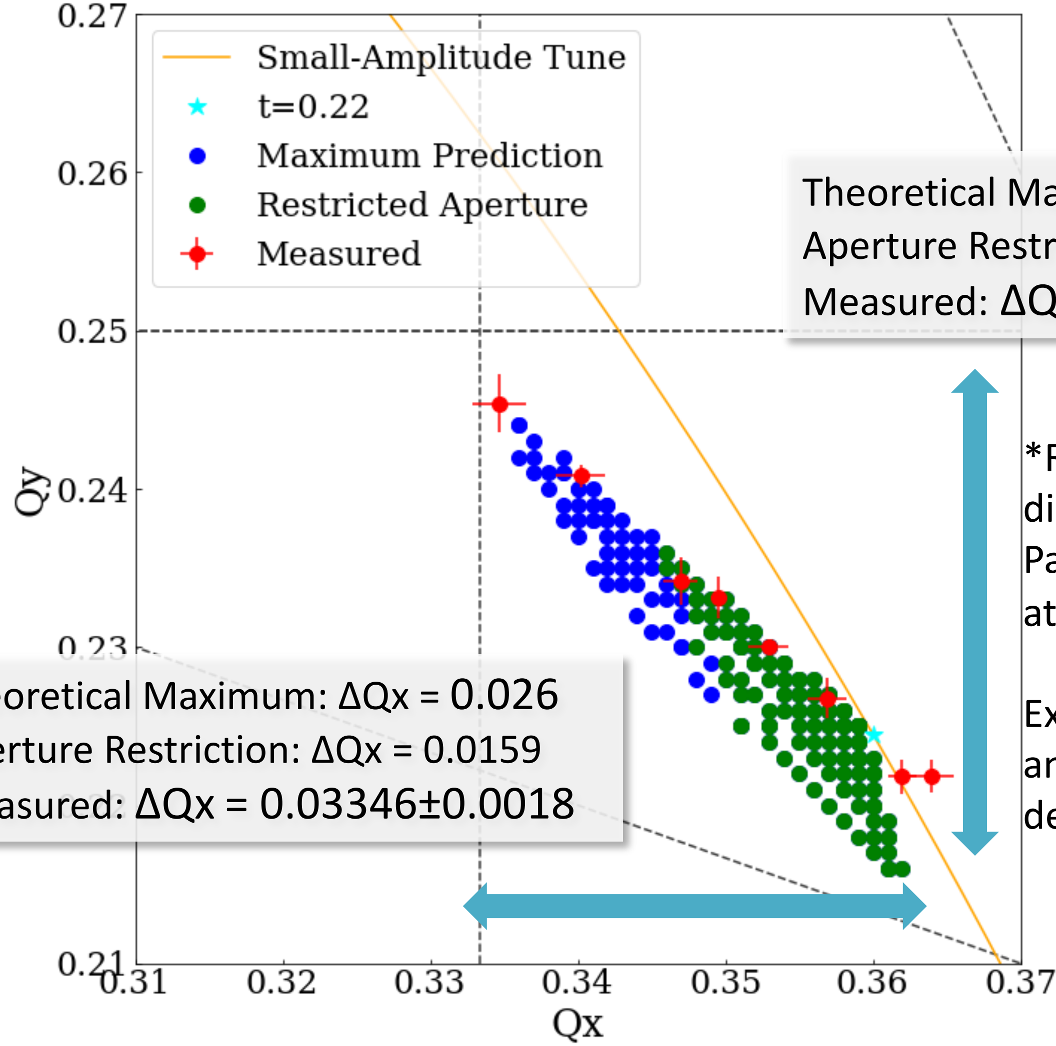
Tune Measurements

- 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=0.22



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

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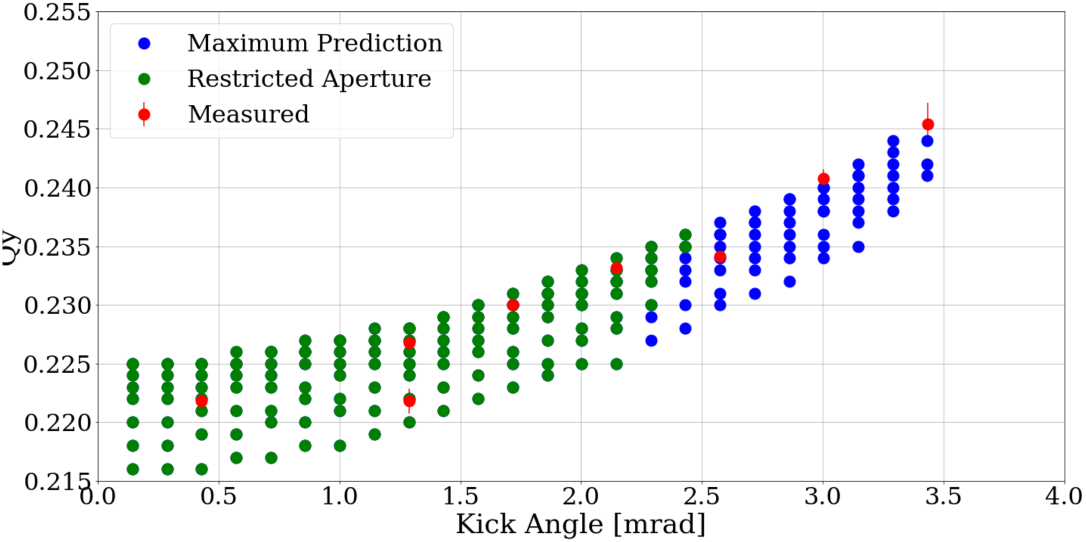
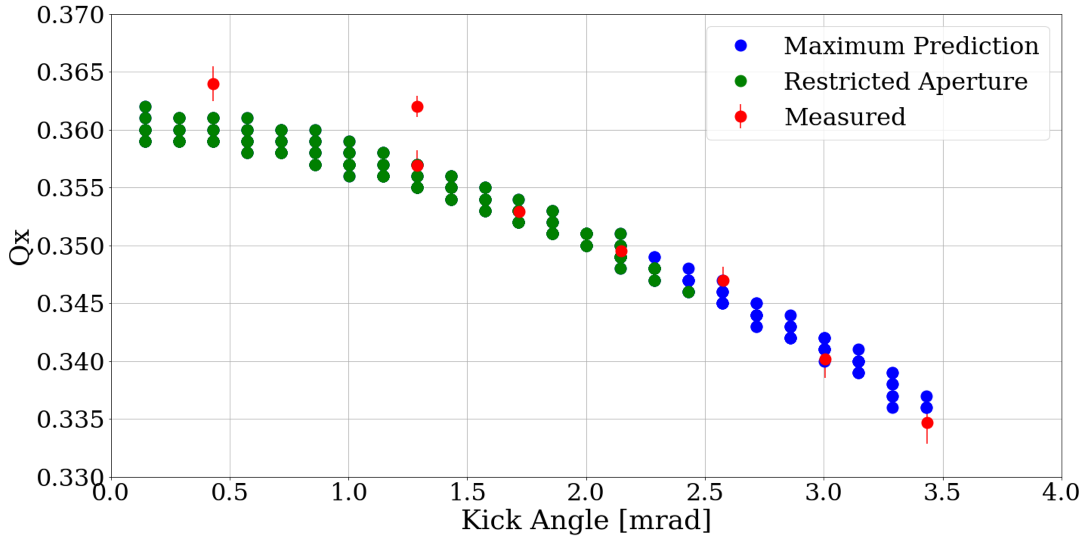
Amplitude Dependent Tune Shift, t = 0.22



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



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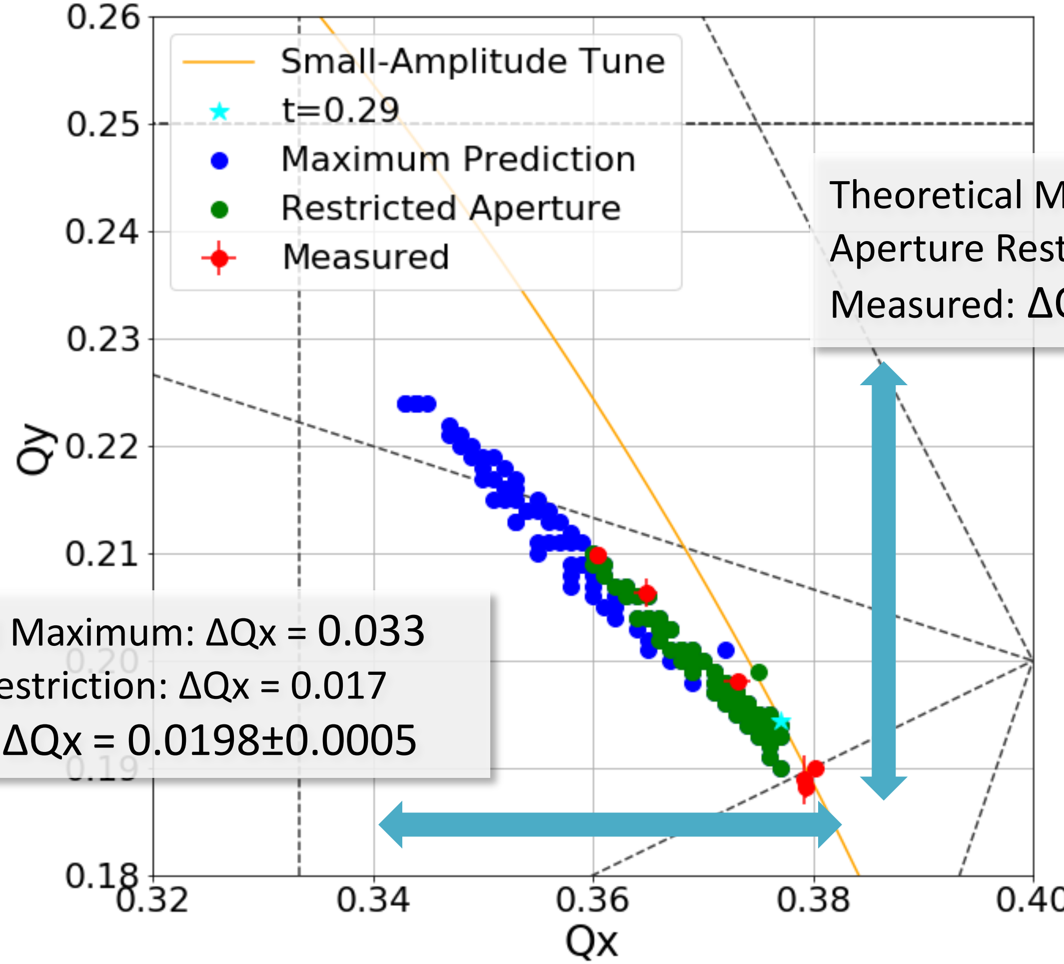
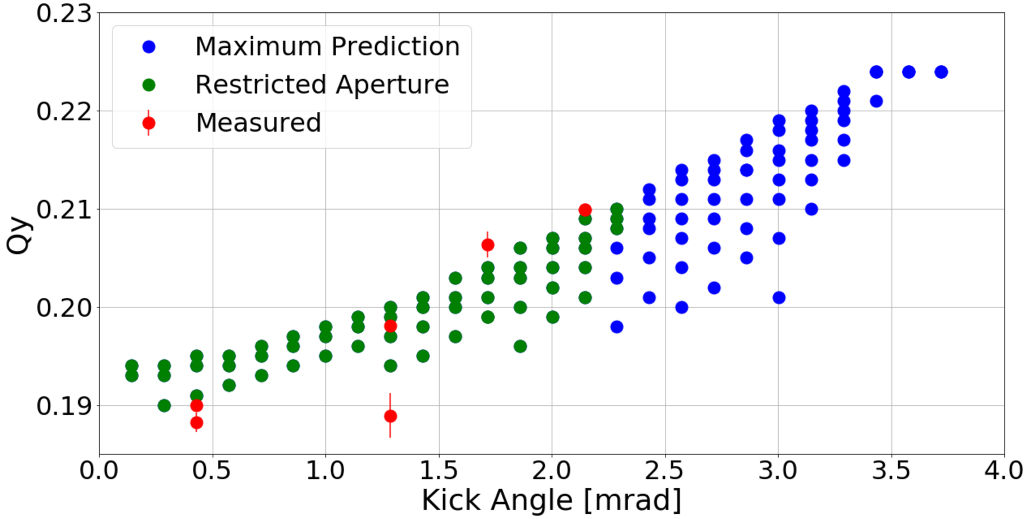
Amplitude Dependent Tune Map, t=0.29



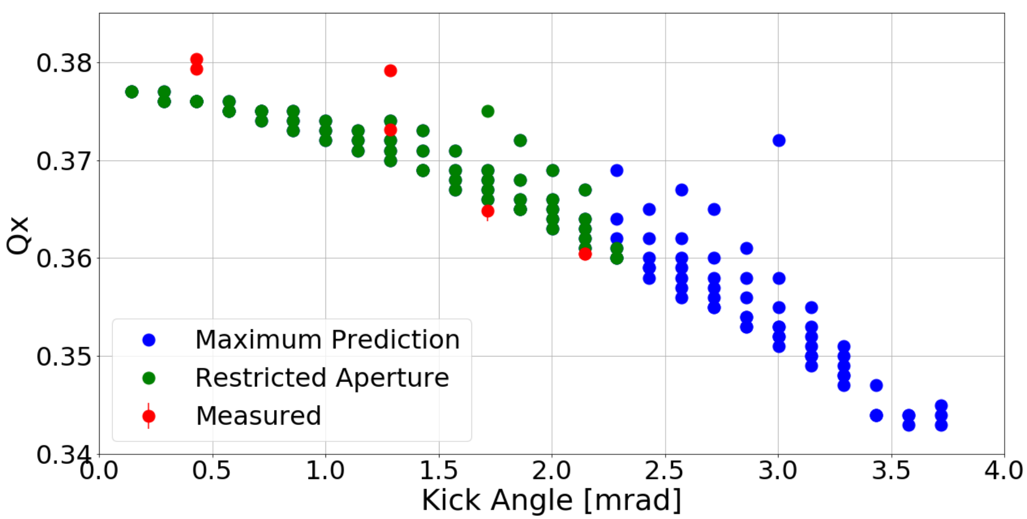
Theoretical Maximum: ΔQy = 0.034
Aperture Restriction: ΔQy = 0.02
Measured: ΔQy = 0.0216±0.0010

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]	2.98	2.73	5.19
DR-Restriction [mm]	6	6	10



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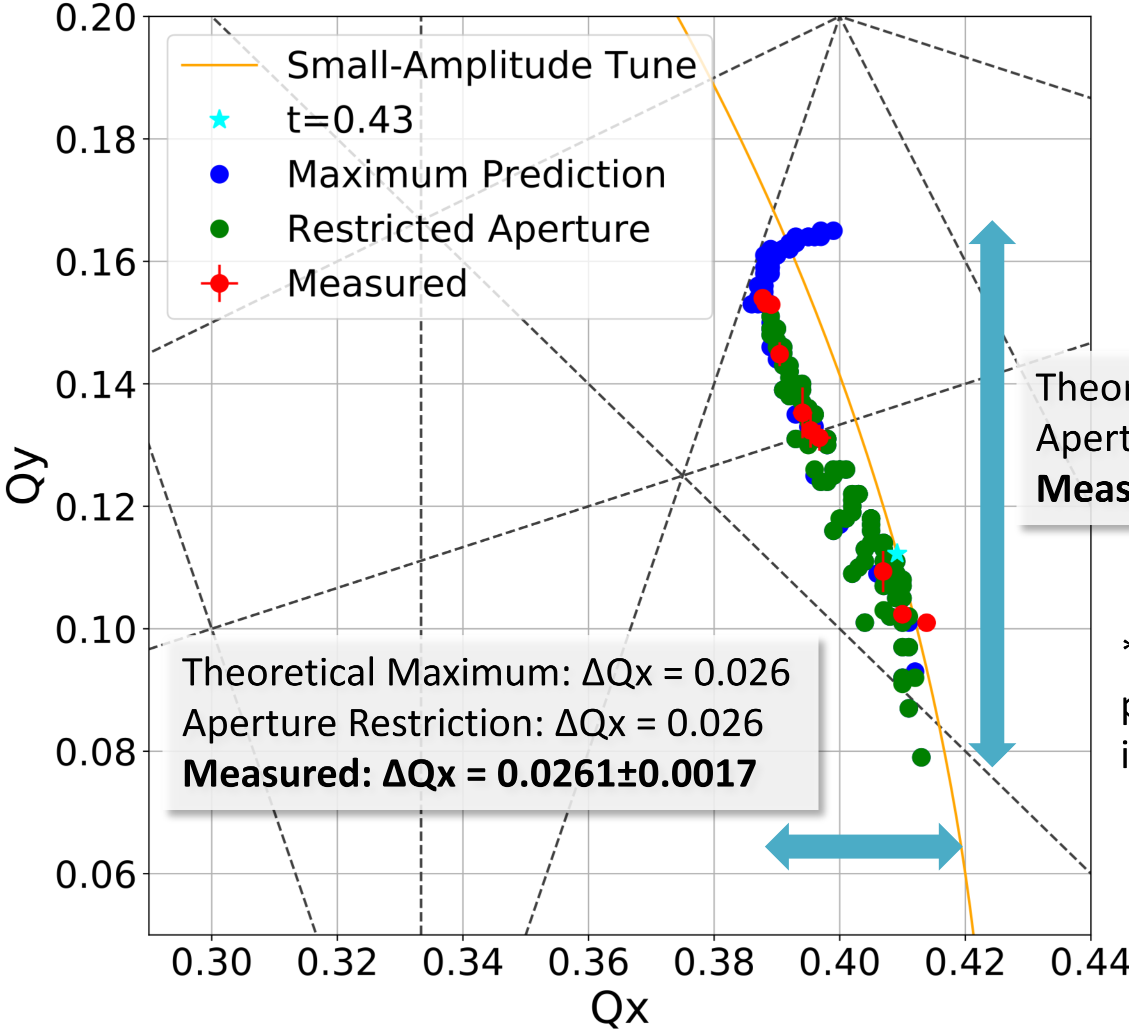
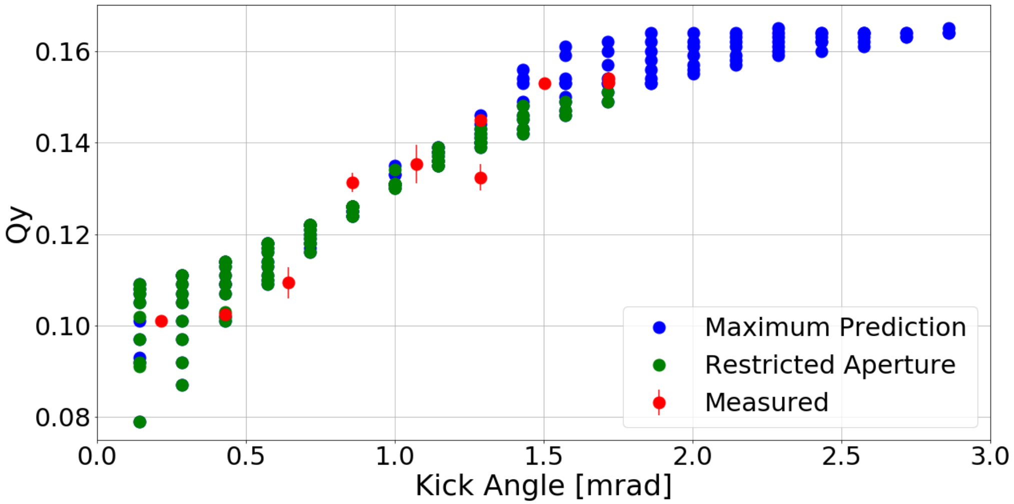
Amplitude Dependent Tune Map, t=0.43

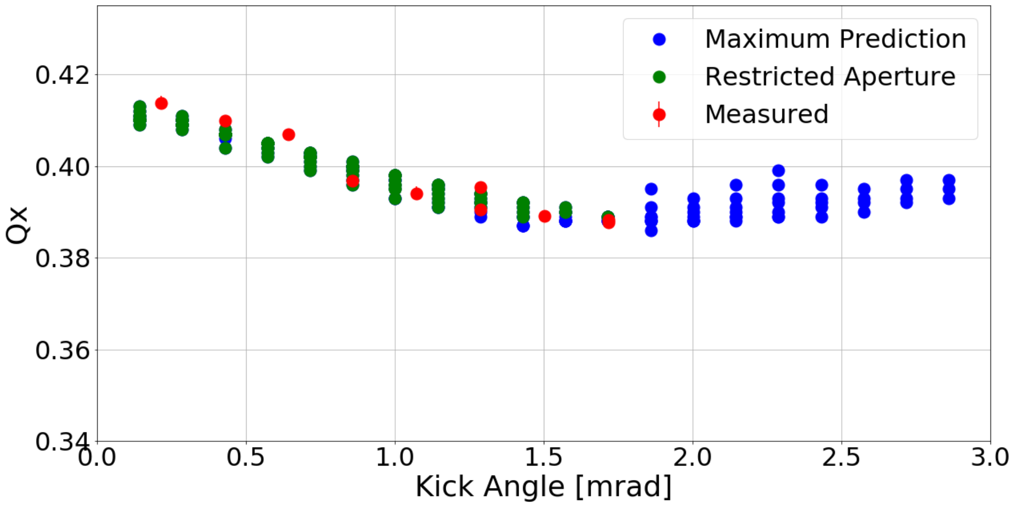


Theoretical Maximum: ΔQy = 0.085
Aperture Restriction: ΔQy = 0.072
Measured: ΔQy = 0.0530 ± 0.0018*

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

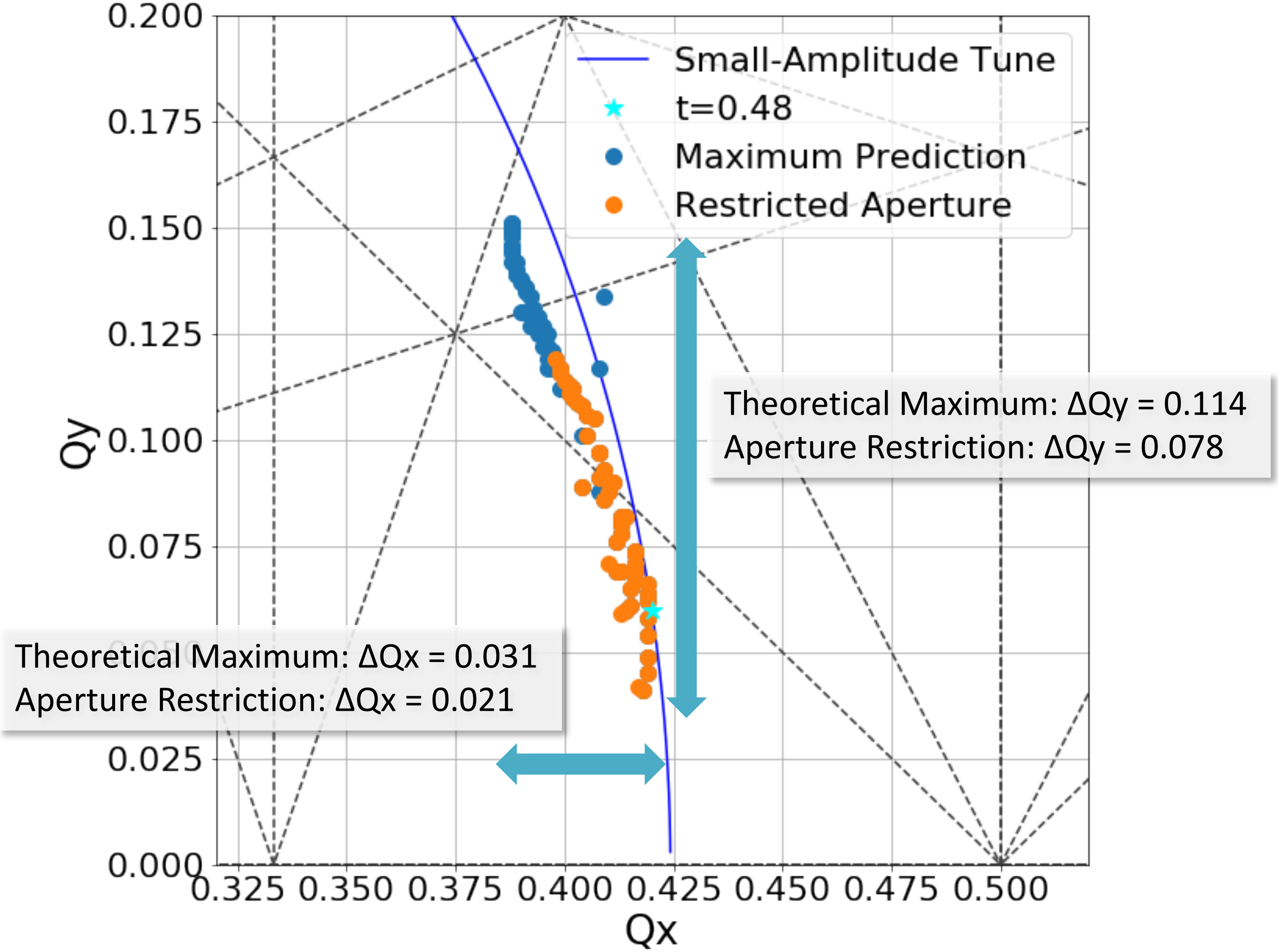
Amplitude Dependent Tune Shift, t = 0.43





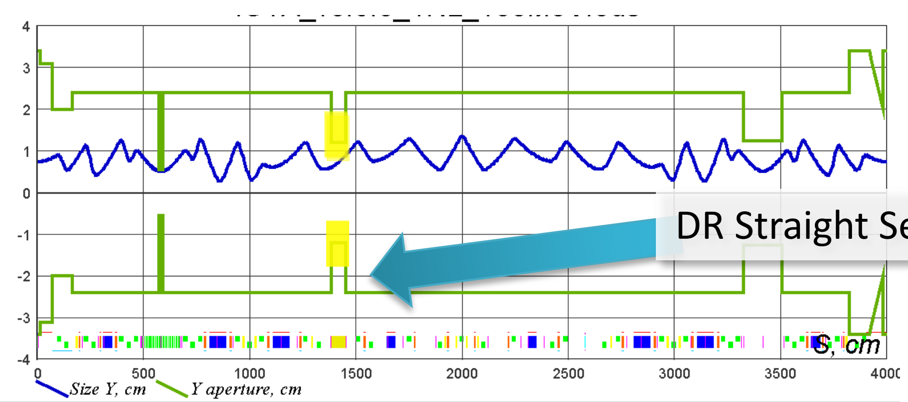
Parameter	Meas.	Aperture Restriction	Model
Max Kick [kV]	2.4	2.4	4.0
Max Kick Ang. [mrad]	1.71	1.71	2.86
Max Amp at NL [mm]	3.65	3.65	5.19
DR-Restriction [mm]	6	6	10

Simulation Amplitude Dependent Tune Map, t=0.48

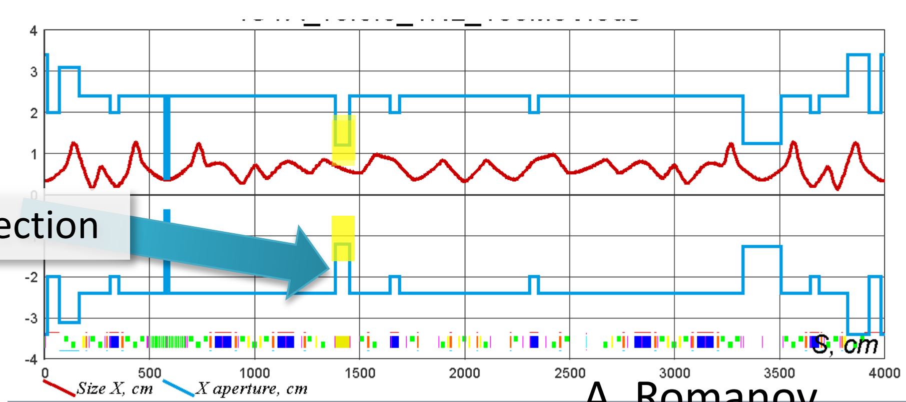


Road Bumps

- 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



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Horizontal Mechanical Restriction

Summary and Outlook

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

Thank you

Please check out other contributions

- A. Romanov, “Recent Results and Opportunities at the IOTA Facility”. **WEXBA2**
- I. Lobach, “Study of Fluctuations in Undulator Radiation in the IOTA Ring at Fermilab” **THYBA5**
- J. Eldred, “Physics Studies for High Intensity Proton Beams at the Fermilab Booster” **THZBA1**
- S. Nagaitsev, “ Review of Recent Advances in Cooling Techniques” **FRXBA1**
- J. Jarvis, “Optical Stochastic Cooling Program at Fermilab's Integrable Optics Test Accelerator” **TUPLM21**
- N. Kuklev, “Experimental Studies of Single Invariant Quasi-Integrable Nonlinear Optics at IOTA”. **TUPLM08**