Nonlinear Integrable Optics studies at IOTA

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In partnership with:

The team

Accelerator science is collaborative - a lot of credit for making this research happen is shared with whole NL team

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+

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THE UNIVERSITY OF CHICAGO

Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center

Northern Illinois University

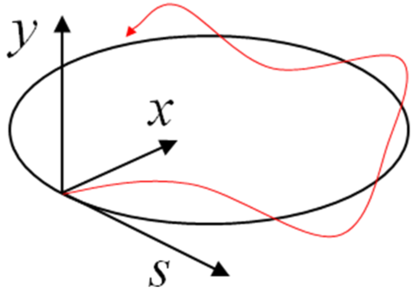
Outline

- **Integrable optics**
- Implementation and IOTA ring
- IOTA NIO program
- NIO research
  - Hardware – beam diagnostics
  - Hardware – nonlinear inserts
  - Simulations
  - Commissioning
  - Data collection
  - Analysis and results
- Software and ML
- Conclusion

Background – single particle dynamics

- Key principle of accelerator design: linear transverse focusing

$$H = \frac{p_x^2}{2} + \frac{p_y^2}{2} + \frac{K_x(s)\, x^2}{2} + \frac{K_y(s)\, y^2}{2} + O(z^3)$$

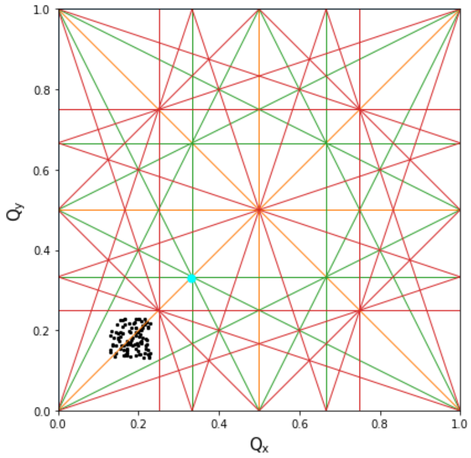


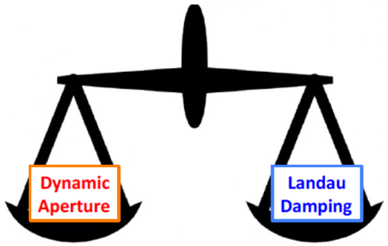
- Also have higher order 'nonlinear' terms
  - Some unavoidable (misalignments, beam-beam)
  - Others intentionally introduced (e.g. sextupoles)
  - Can cause chaotic motion → beam losses
  - Drive critical parameters – **DA**, **MA**, lifetime, injection efficiency, etc.

Background – collective effects

On top of single particle dynamics, have collective instabilities

- Coherent collective instabilities
  - Occur in intense beams
  - Some can be dampened with external feedback
  - Others too fast – have to use **Landau damping**
    - Natural instability suppression through betatron tune spread
  - However, by creating tune spread **lose DA – a careful tradeoff**





Background – collective effects

Landau damping has been used in many accelerators

Princeton-Stanford CBX (1965)

- First mention of an 8-pole magnet – increased beam current from ~5 to 500 mA

CERN PS (1968)

- At 10^12 protons/pulse observed (1st time) head-tail instability – octupoles helped

LHC

- 336 octupoles @ 500A to create 0.001 tune spread

FCC-hh

- Will require >500 superconducting octupoles to retain stability

Background – integrable optics

Fundamental question – is there a **stable nonlinear accelerator**? (“**Nonlinear Integrable Optics” – NIO**)

Many attempts over the years:

- McMillan (1967) – 1D solution
- Perevedentsev, Danilov (1990) – generalization of McMillan case to 2D, round colliding beams
- Danilov, Shiltsev (1998) – non-linear low energy electron lenses suggested to fight beam-beam
- **Danilov, Nagaitsev (2010) – lattice with 2 invariants that can be implemented with magnets**

Background – integrable optics

Linear case:

$$H \to H_N = \frac{p_{xN}^2}{2} + \frac{p_{yN}^2}{2} + \frac{x_N^2}{2} + \frac{y_N^2}{2} = Q_x \boxed{J_x} + Q_y \boxed{J_y}$$

Motion integrable, have 2 Courant-Snyder invariants

Nonlinear case:

$$H = \frac{1}{2}\left(p_x^2 + p_y^2 + K_x(s)\,x^2 + K_y(s)\,y^2\right) + V(x,\ y,\ s)$$

Want to find V that:

- Gives **2** invariants
- Obeys Laplace equation **ΔV=0**

Background – integrable optics

1st invariant: impose longitudinal constraint (time-independent normalized potential) – get invariant **H**

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

V = continuously varying octupole

2nd invariant: impose transverse constraint – get second invariant **I**

$$H(x, y, p_x, p_y) = \frac{p_x^2}{2} + \frac{p_y^2}{2} + \frac{x^2}{2} + \frac{y^2}{2} + \frac{f_2(\xi) + g_2(\eta)}{\xi^2 - \eta^2}$$

$$I(x, y, p_x, p_y) = (xp_y - yp_x)^2 + c^2 p_x^2$$

$$f_2(\xi) = \xi\sqrt{\xi^2 - 1}\left(d + t\,\mathrm{acosh}(\xi)\right)$$

$$g_2(\eta) = \eta\sqrt{1 - \eta^2}\left(b + t\,\mathrm{acos}(\eta)\right)$$

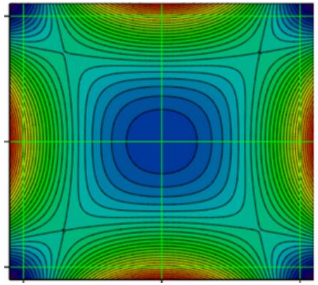
$$\xi = \frac{\sqrt{(x+c)^2 + y^2} + \sqrt{(x-c)^2 + y^2}}{2c}$$

$$\eta = \frac{\sqrt{(x+c)^2 + y^2} - \sqrt{(x-c)^2 + y^2}}{2c}$$

Hénon, M.; Heiles, C. (1964). "The applicability of the third integral of motion: Some numerical experiments".
Phys. Rev. ST Accel. Beams 13, 084002 (2010)

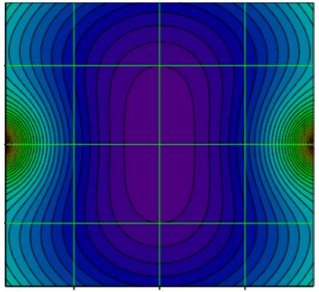
Background - integrable optics

Derived 2 (idealistic) special arrangements of lattice optics and magnets



“QI”

Octupole system
1 invariant (**H**)



“DN”

Danilov-Nagaitsev system
2 invariants (**H** and **I**)

Integrable systems can produce strong Landau damping with few elements and little DA loss!

Useful in:

- Rapid cycling synchrotrons (SC losses, ultra-fast coherent instabilities)
- Circular colliders (coherent instabilities)

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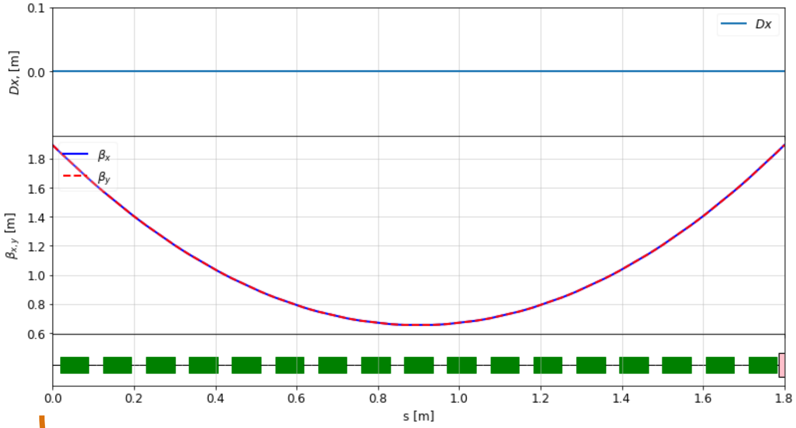
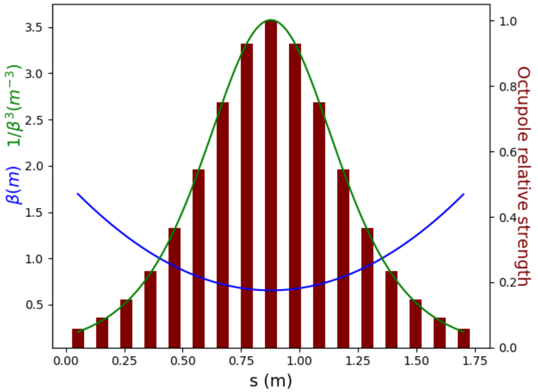
Implementation - lattice

Goal – ring with the desired effective Hamiltonian

- Linear optics satisfied by a "**T-insert + drift**"
- Continuous potential approximated by discrete elements





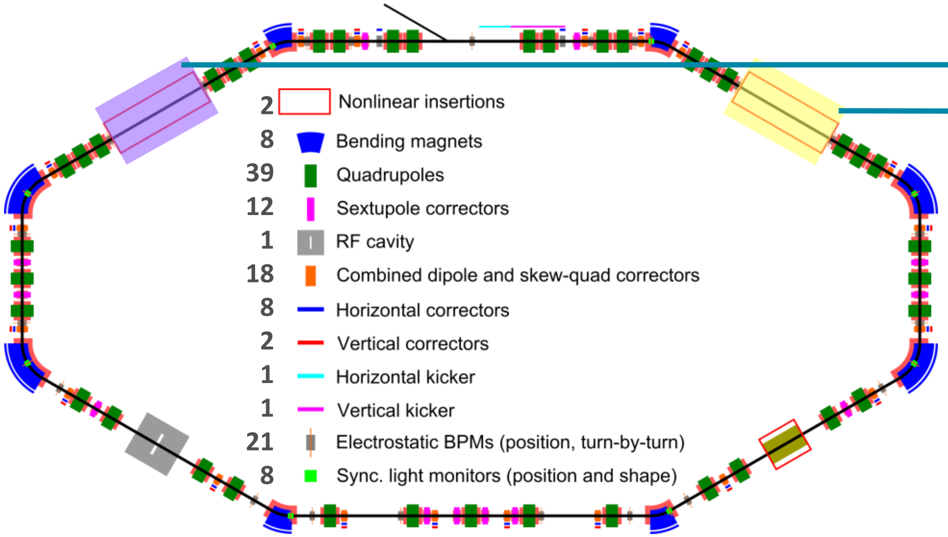
Drift with U(x,y)=V(x,y,s) discretized

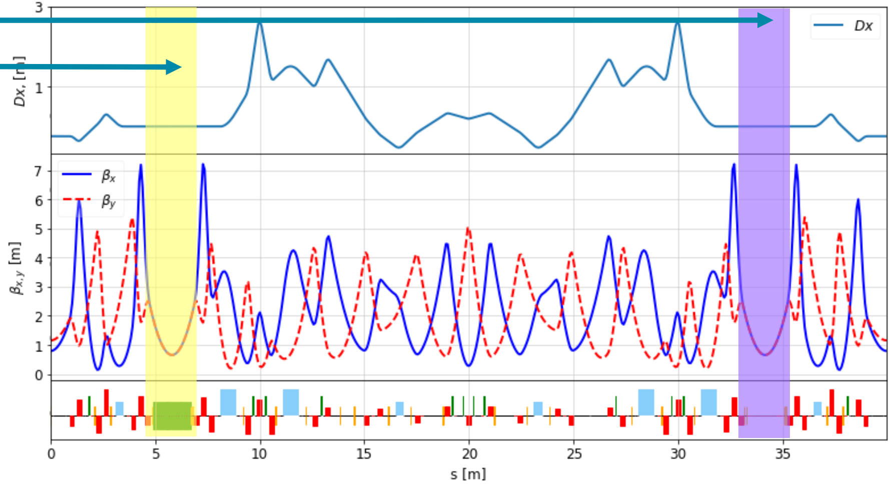
+

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ -k & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -k & 1 \end{pmatrix}$$

Axially symmetric lens
2π x n phase advance
(rest of the ring)

Implementation - IOTA

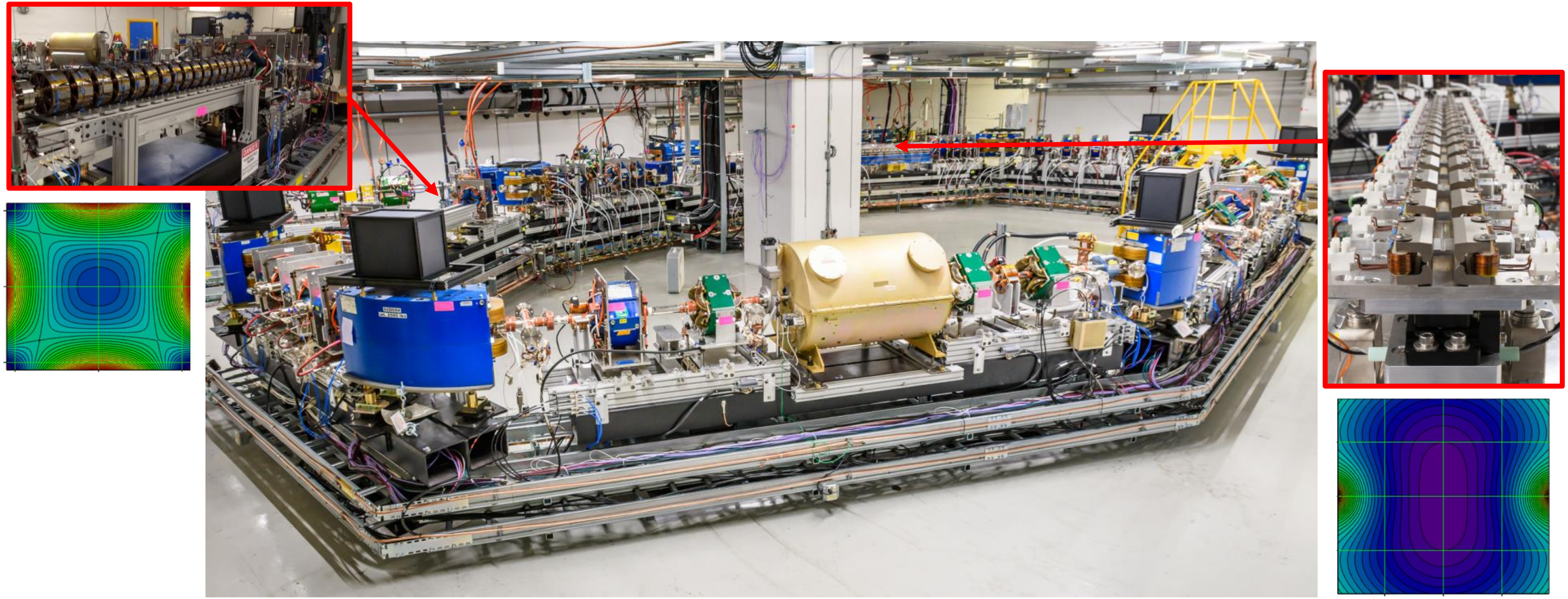




IOTA satisfies all NIO constraints, and has:

- User-selectable energy and inserts, independent power supplies, ample instrumentation
- Electron or (soon) proton species selection

Implementation - IOTA



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IOTA NIO

IOTA NIO program has both fundamental physics and practical use goals:

Demonstrate viability

- Academic interest in stability of nonlinear systems
- Show whether nonlinear focusing lattices offer practical benefits

Establish limits of applicability

- Are required tolerances supported by present-day technology?

Develop practical solutions without significant cost increases

- i.e. RCS for booster replacement at FNAL

Phase I – e- beam (2018–2021)

- Demonstrate large detuning, DA conservation, successful machine tuning and limits of stability
- Show improvements in coherent beam stability

Phase II – p beam (2021–2023)

- Space-charge effects, halo formation, losses, etc.

IOTA NIO

My focus: experimental/simulation studies of NIO phase 1 nonlinear beam dynamics

Major projects:

- Synchrotron radiation beam diagnostics
- Octupole (‘QI’) insert assembly and commissioning
- QI and NL simulations
- Data collection and analysis over 2 experimental runs
- Software development for accelerator control and ML-aided optimization

Many happened simultaneously - for clarity, will present by topic

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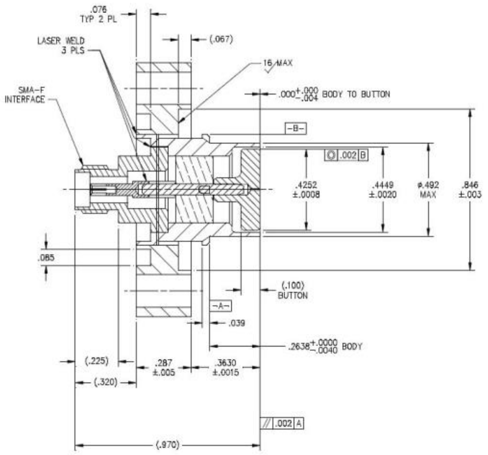
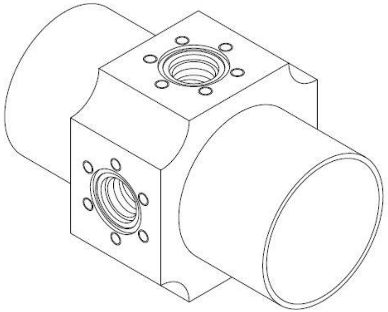
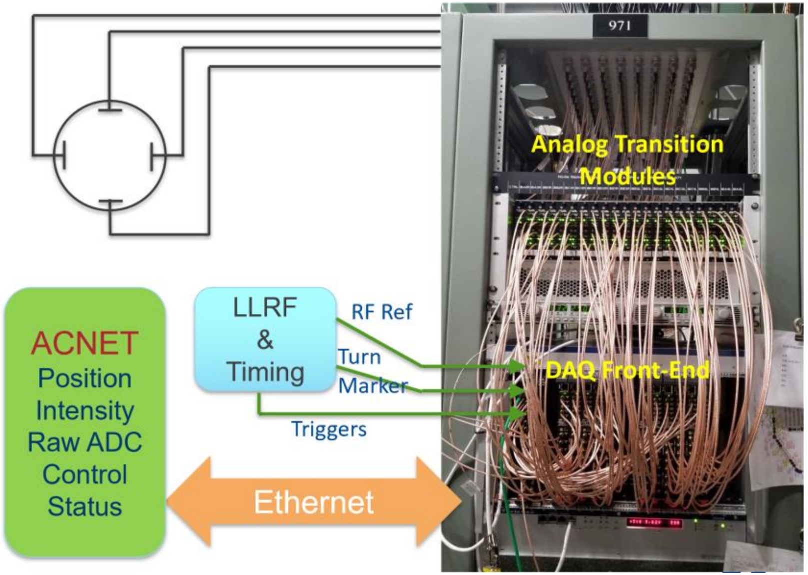
Research – beam diagnostics

IOTA BPMs are designed to work with electron **and** proton bunches

- Brand new design, prototype for other FNAL facilities
- Developed by AD instrumentation group





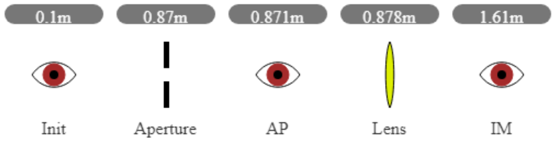


Images courtesy of N. Eddy, "IOTA BPM System Overview"

Research – beam diagnostics

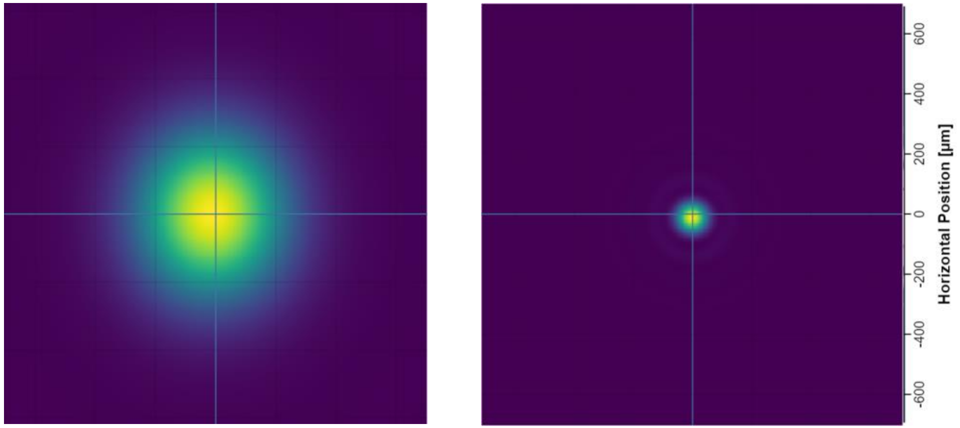
IOTA bending radiation has near-visible critical wavelength

- Can measure with simple CCD sensors
- Very accurate orbit BPM, profile, intensity data source
- Designed in-house



Worked on:

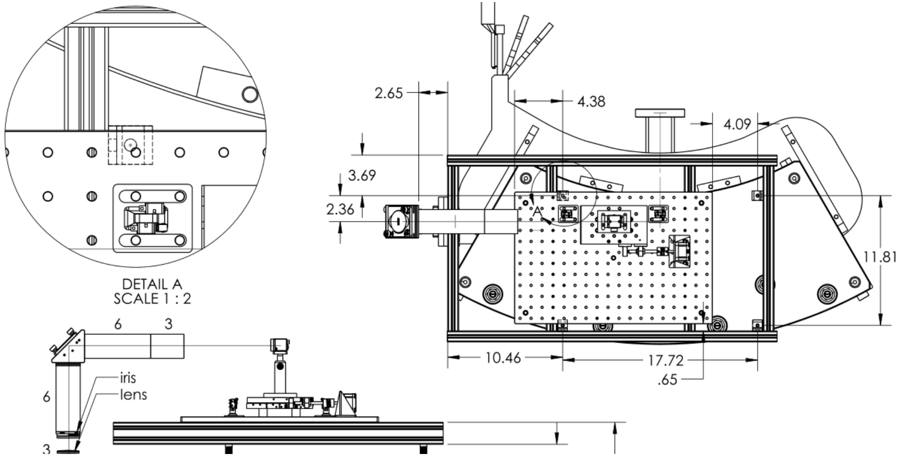
- **Simulation**
- Mechanical CAD
- Control electronics
- Testing and assembly
- Operational use

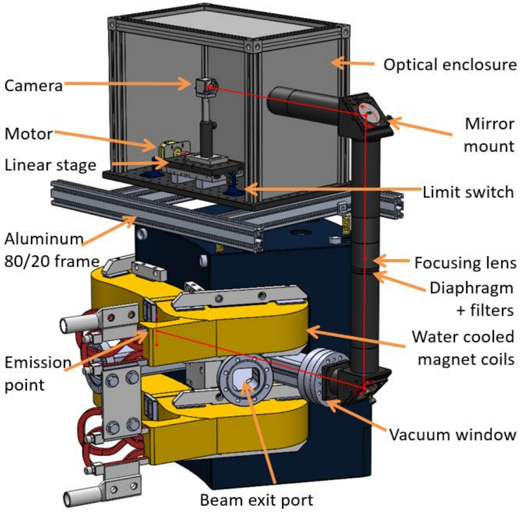


Research – beam diagnostics

Worked on:

- Simulation
- **Solidworks/NX mechanical CAD**
- Control electronics
- Testing and assembly
- Operational use





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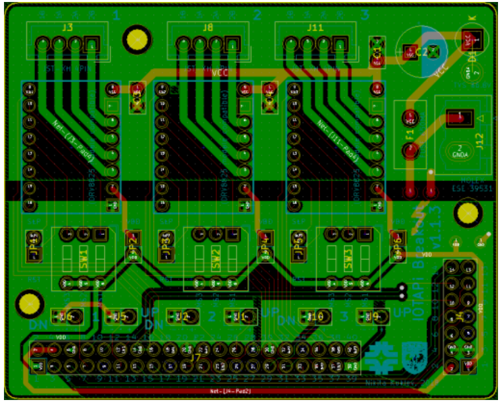

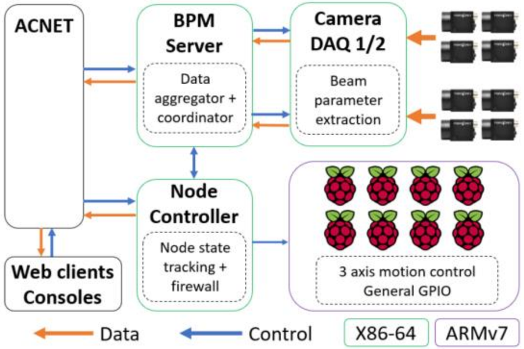

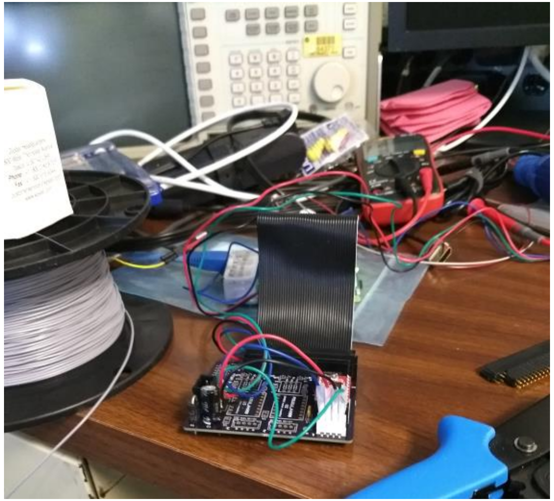

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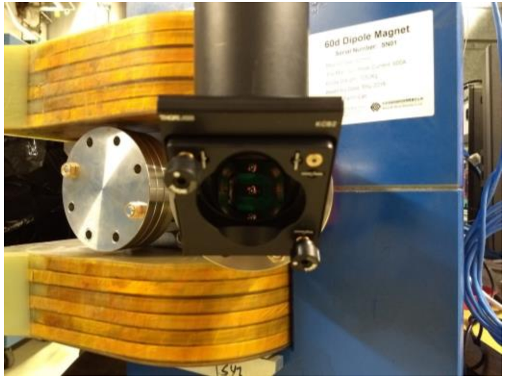

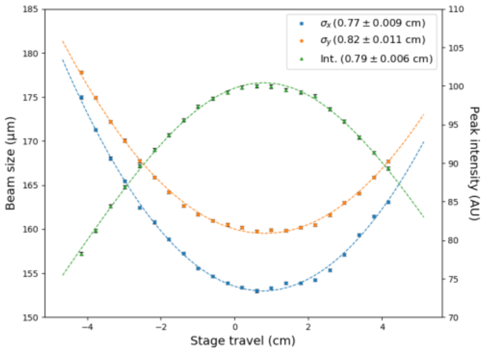

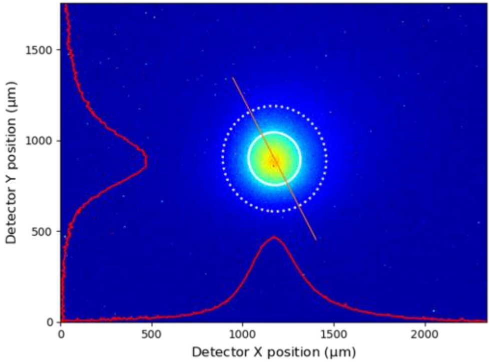

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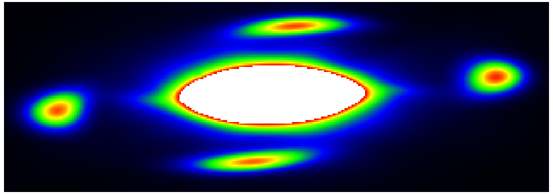

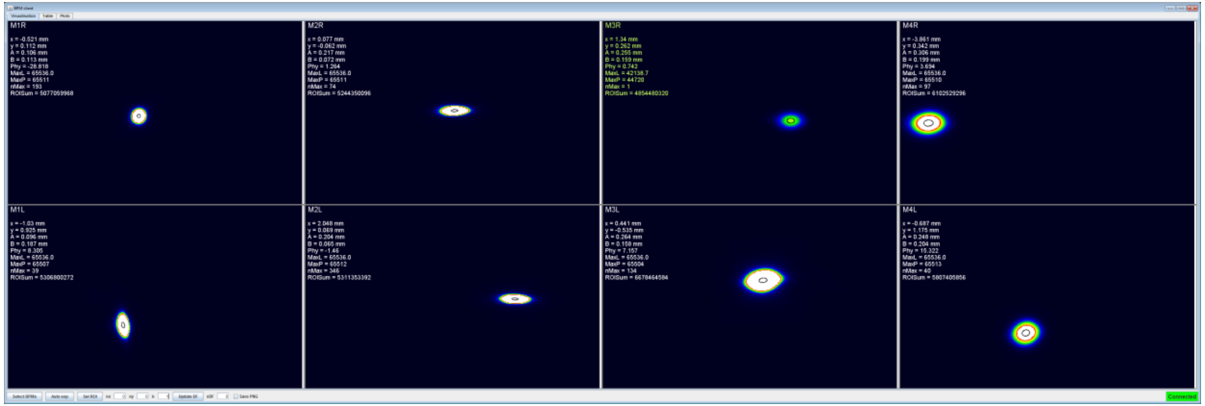

SW by A. Romanov

Achieved **50nm** resolution, **20 FPS** rate, sensitivity down to **single electron**

N. Kuklev, Y. K. Kim, and A. L. Romanov, “Synchrotron Radiation Beam Diagnostics for the Integrable Optics Test Accelerator”, in Proc. 9th Int. Particle Accelerator Conf. (IPAC’18)
N. Kuklev et al., “Synchrotron Radiation Beam Diagnostics at IOTA - Commissioning Performance and Upgrade Efforts”, in Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)
N. Kuklev and Y. K. Kim, “Turn-by-Turn Synchrotron Radiation Transverse Profile Monitor for IOTA”, presented at the 8th Int. Beam Instrumentation Conf. (IBIC’19)

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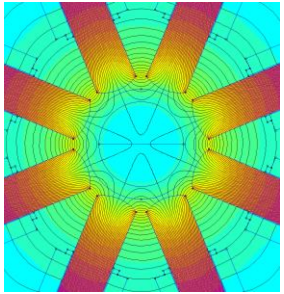
NIO – inserts

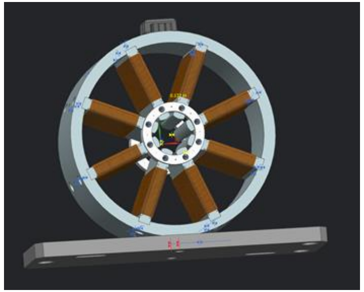
DN:

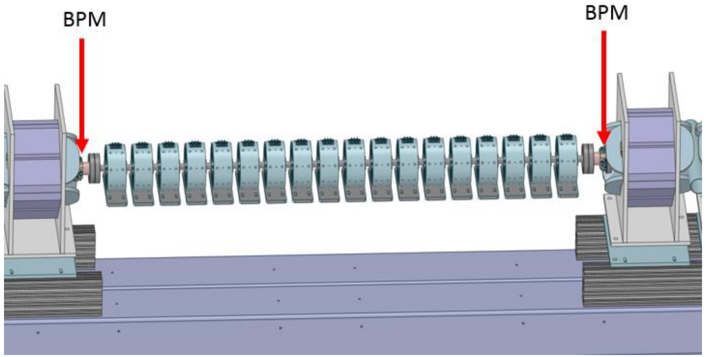
- Pre-assembled, no work needed

QI:

- Initial design error! Had to modify pole design and redo simulations…
- Tested, assembled, and aligned the insert



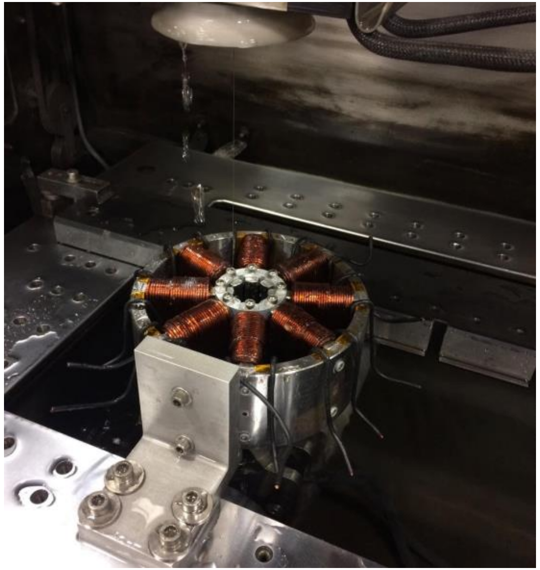




NIO – inserts

Machining and testing

Re-epoxy and assembly

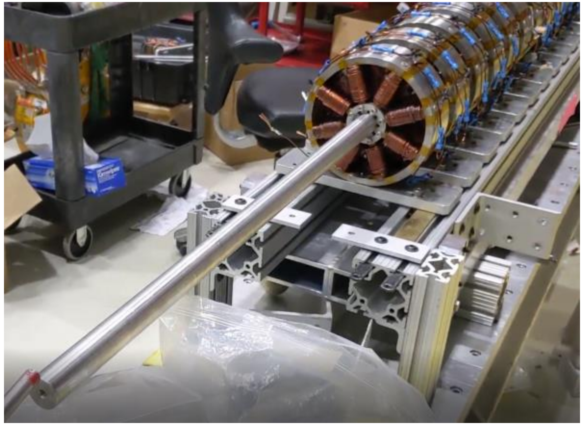


Wire EDM

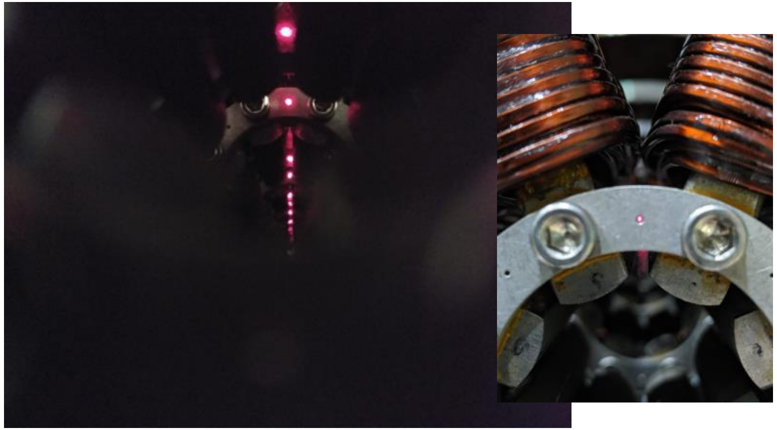
Harmonic measurement

NIO – inserts

Cheap and effective insert alignment with rod + “pinhole” crown



‘Precision soviet stick’ alignment

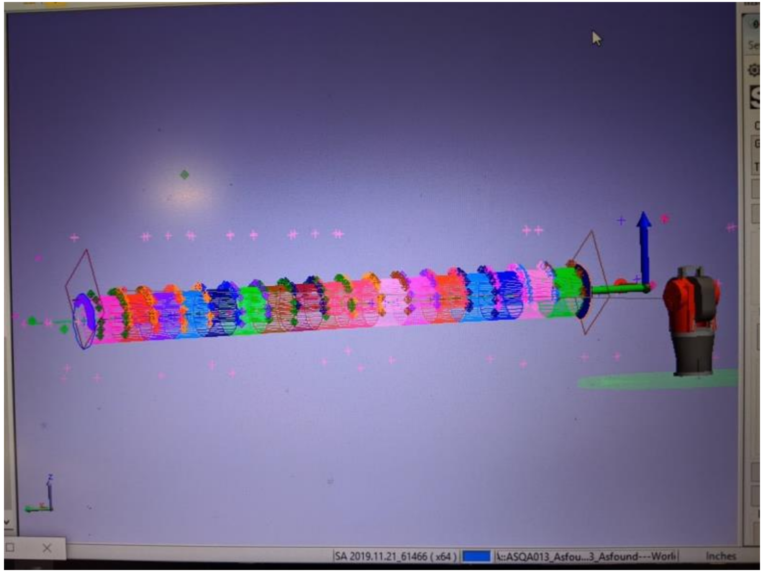


Laser alignment

NIO – inserts

Final ring installation and verification

Tracker measurements



Generated model

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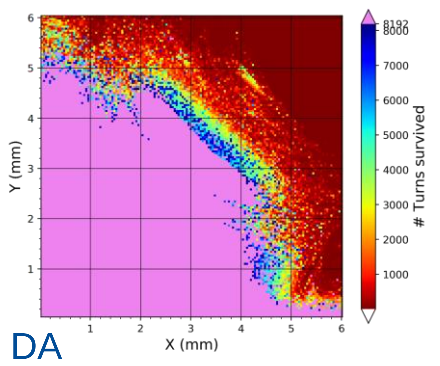
NIO – simulations

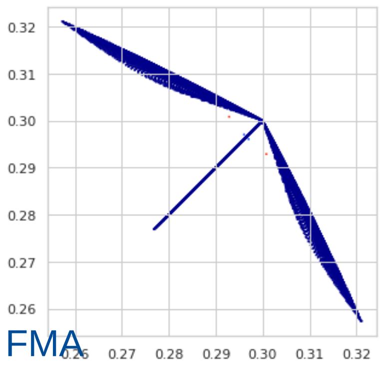
Lattice design and optimization is a common task, but NIO has unique constraints

- Performance metrics:
  - Dynamic aperture (DA)
  - Tune spread (FMA)
  - **Integrability** (jitter of dynamic invariants)

- Knobs: optics, sextupoles, insert properties



DA

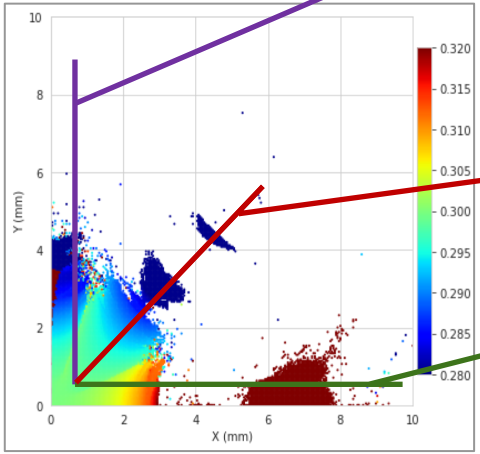


FMA

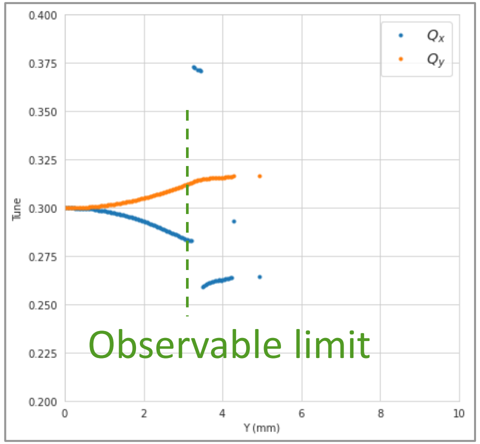
- Used many codes: MAD-X, Lifetrac, Elegant, OCELOT
  - Each has advantages – speed vs thick/thin vs symplecticity
  - Added new elements/integrators
  - Connected to optimizers, benchmarked, etc.

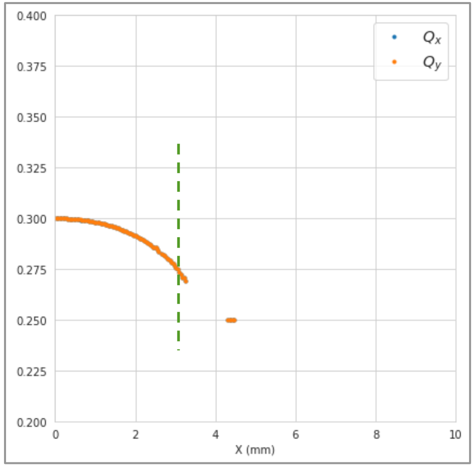
NIO – simulations

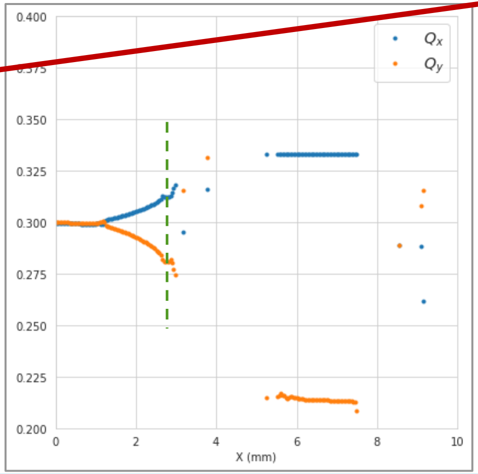
- Prediction of experimental tune measurement scans



QI frequency map



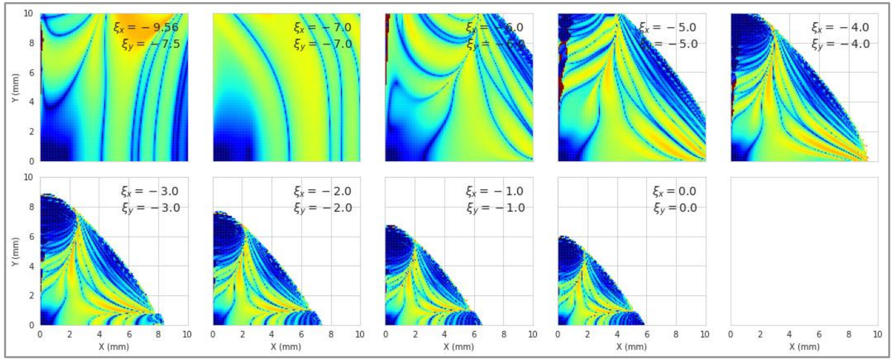




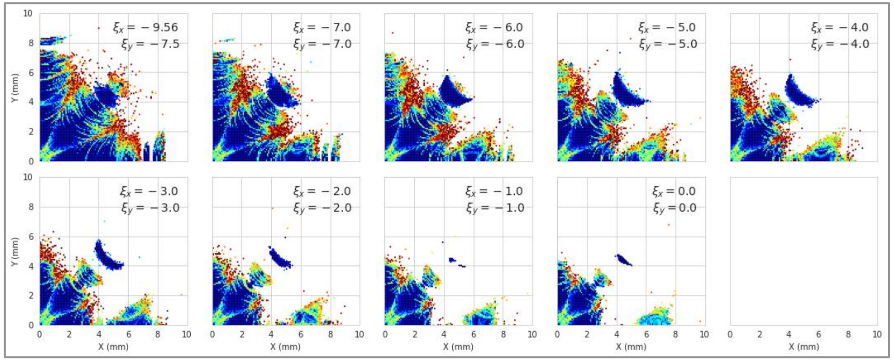
NIO – simulations

- Strong impact of chromaticity correction
  - Need low chromaticity to get more data and lower beta-function chromaticity
  - But only had 2 families of sextupoles (not properly π-phased) out of 6
  - Resulting nonlinearities hurt dynamics

Sextupoles only



Sextupoles + octupoles



Dynamic aperture plots - color scale is diffusion (how chaotic)

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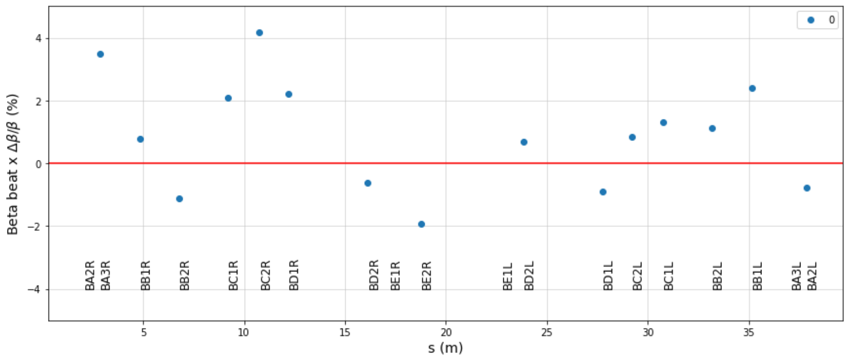
NIO - commissioning

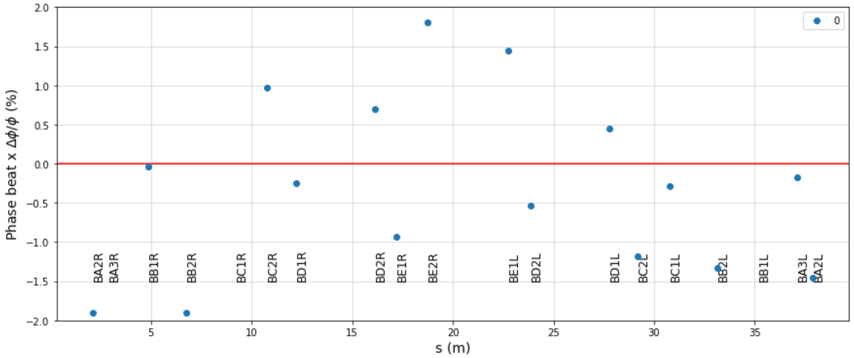
NIO experiments require calibration of lattice, kickers, BPMs, insert

Lattice: LOCO tuning (A. Romanov) provided good results

- β within a few %, but with some drift + hysteresis
- Verified with TBT data analysis

Requirements
QI: 10% beta-beat
DN: 1% beta-beat

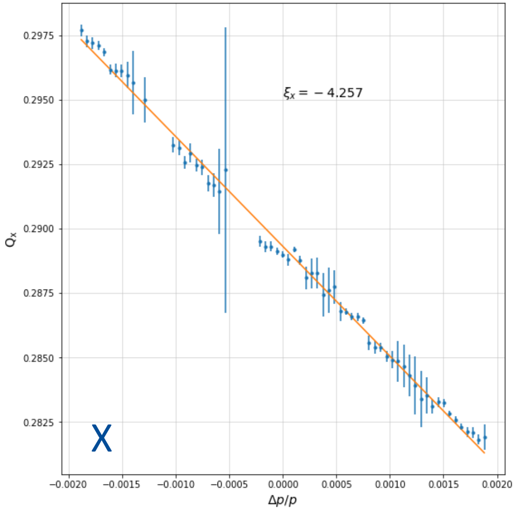


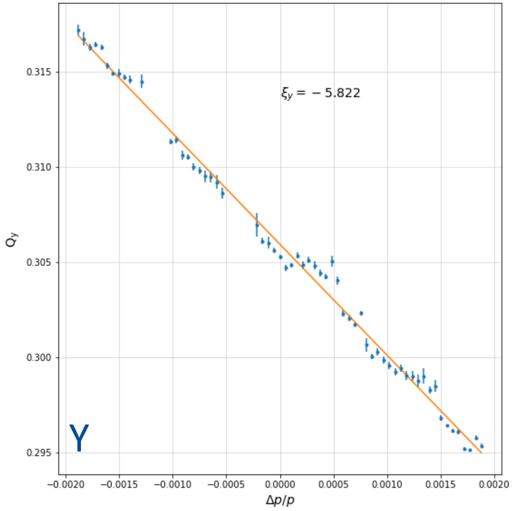


NIO - commissioning

Lattice: Found anomalously low X chromaticity

- Suspect due to dipole fringe fields





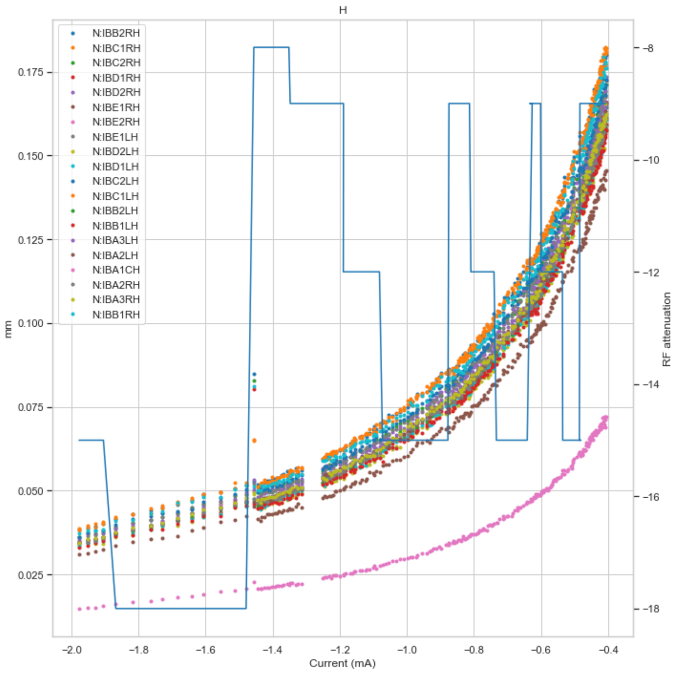
Kickers: analyzed amplitude of repeated triggers

- Jitter and linearity within 5%

NIO - commissioning

BPMs: Measured signal noise and response to orbit bumps

- TBT noise:
  - 100um @ 0.8mA - met specs
- Orbit linearity and noise:
  - <1% linear within 4 mm of center
  - ~1um @ 0.3mA



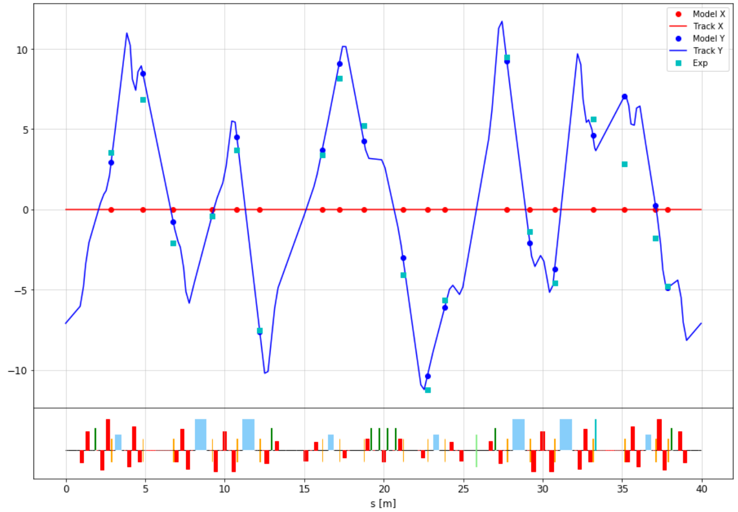
Position rms noise vs current (and RF=bunch length)

NIO - commissioning

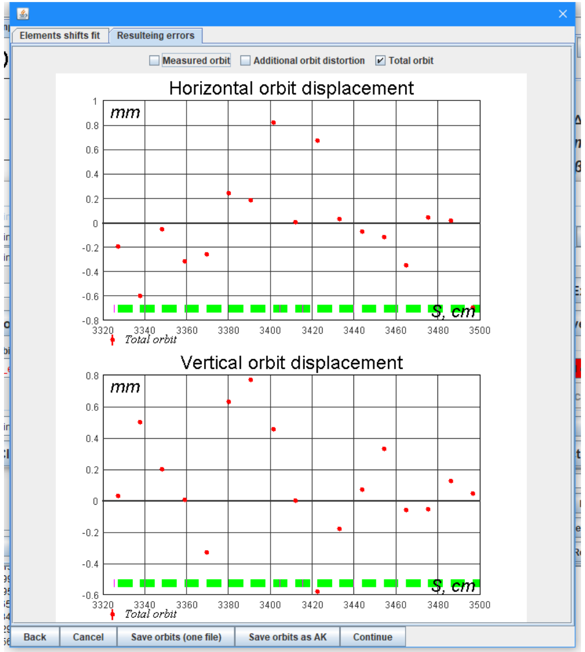
Requirements
QI: 200um
DN: 50um

Insert alignment: measured using closed orbit responses

- Most magnets OK, but some large displacements



Closed orbit distortion model/measurement from BPM orbit data



Magnet offsets from LOCO (A. Romanov)

Outline

- Integrable optics
- Implementation and IOTA ring
- IOTA NIO program
- **NIO research**
  - Hardware – beam diagnostics
  - Hardware – nonlinear inserts
  - Simulations
  - Commissioning
  - **Data collection**
  - Analysis and results
- Software and ML
- Conclusion

NIO – data collection

Aim to **measure single particle dynamics**

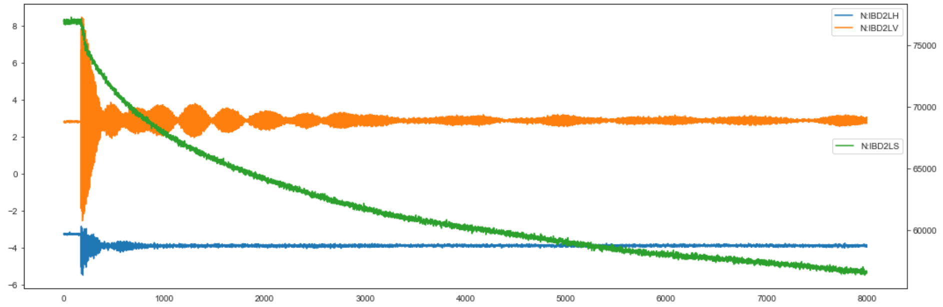
- Use 'pencil'-like electron beams and kick to desired X/Y amplitudes (i.e. actions)
- Collect turn-by-turn (TBT) position at multiple points

Can extract:

- Tune
- Dynamic invariants
- Beam losses (= DA)
- Resonant driving terms

Complications:

- IBS and natural emittance
- Nonlinear decoherence
- Physical aperture
- BPM noise and systematics

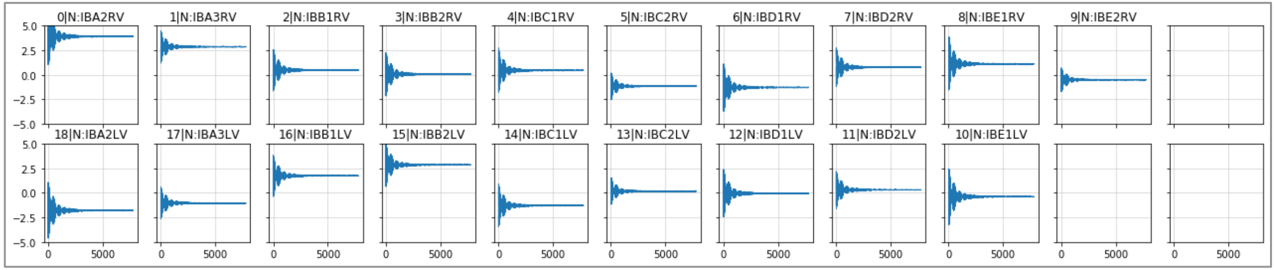


Example of signal from 1 BPM for 8000 turns
H/V/Sum

NIO - data details

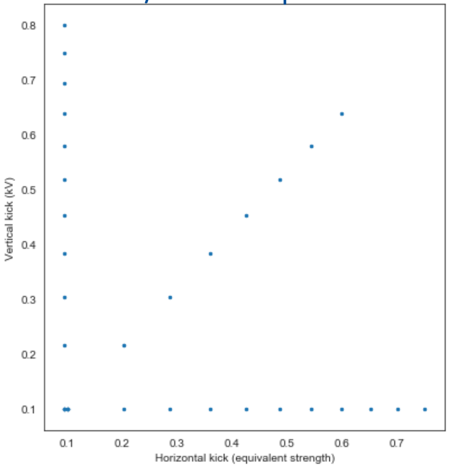
- **Devices**:
  - **19** BPMs x **8k** turns
  - Ring state (300+ ch.)

All BPM data from single 'kick'

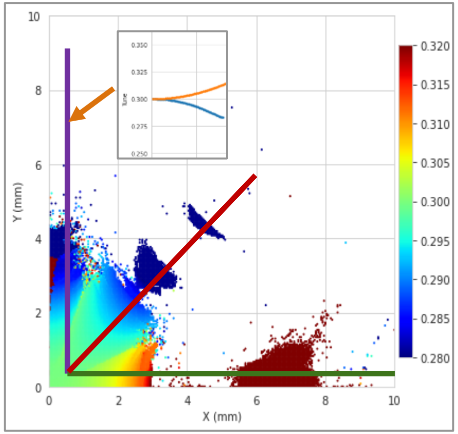


- **Typical dataset**:
  - ~60 nonlinear kicks in 3 lines
  - ~5-10 calibration kicks (nonlinearities off)
    - Used for optics recovery/verification

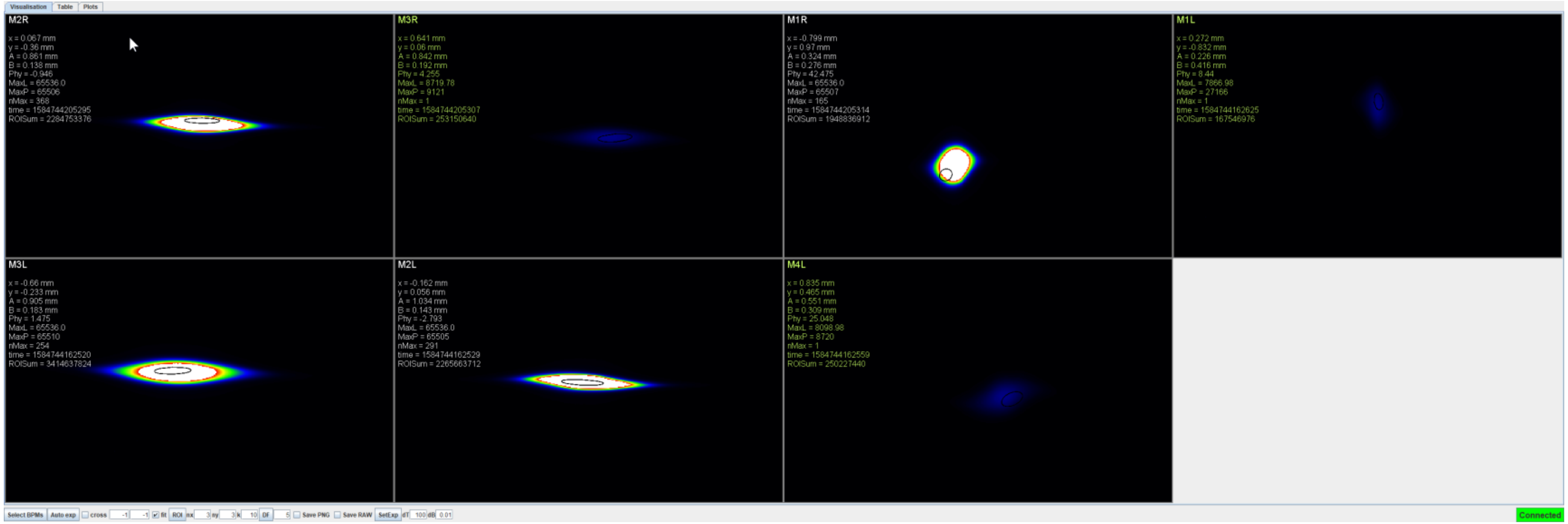
H/V kick amplitudes



FMA from simulation



NIO - how a kick looks like in real-time



Bending magnet SR cameras

Outline

- Integrable optics
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  - Commissioning
  - Data collection
  - **Analysis and results**
- Software and ML
- Conclusion

NIO – available data

Data:

- QI: **2600** kicks / 37 configs
- DN: **1100** kicks / 36 configs
- Calibrations: **1000**
- 1-2k for other studies (RDTs, …)

Stage 1 + 2 done

- Commission, measure nominal configuration
- Perturb (tune/dispersion/field errors/etc.) and measure resiliency to errors

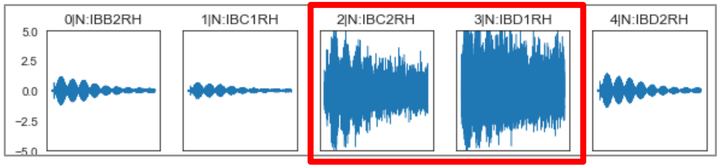
Stage 3 – lab shutdown

- Different working points, exotic conditions

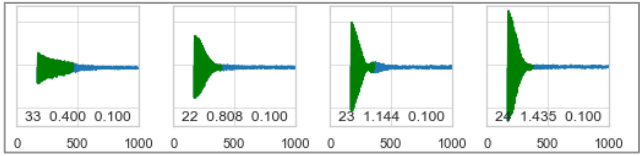
NIO - analysis overview

Pipeline:

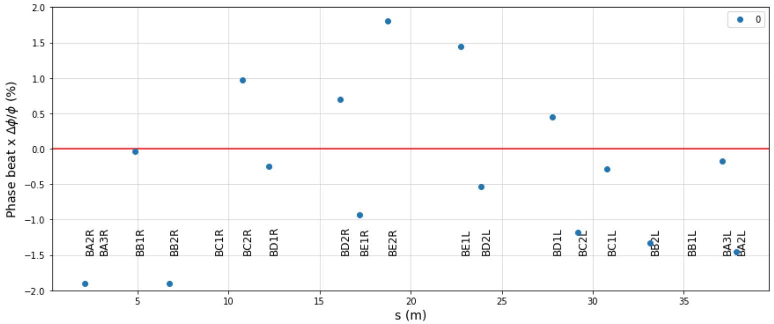
- Preprocessing
  - Anomaly veto voting/rejection
  - SVD cleaning, ROI cut based on SNR
- Tunes
  - Modified adaptive NAFF + clustering
- Linear optics
  - Model-independent
  - 2-BPM, 3-BPM, N-BPM
- Phase space
  - Mode decomposition
  - Envelope function – chromatic + octupolar decoherence fit with annealing/bin hopping



Bad signal

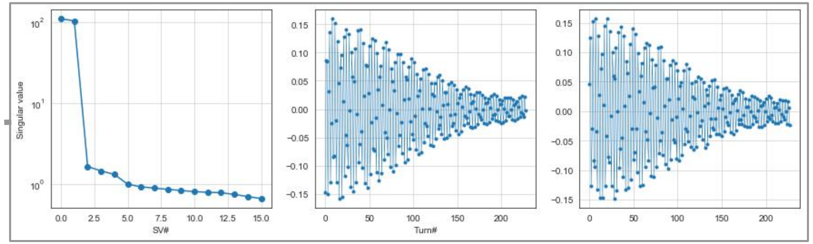


ROI



Phase error

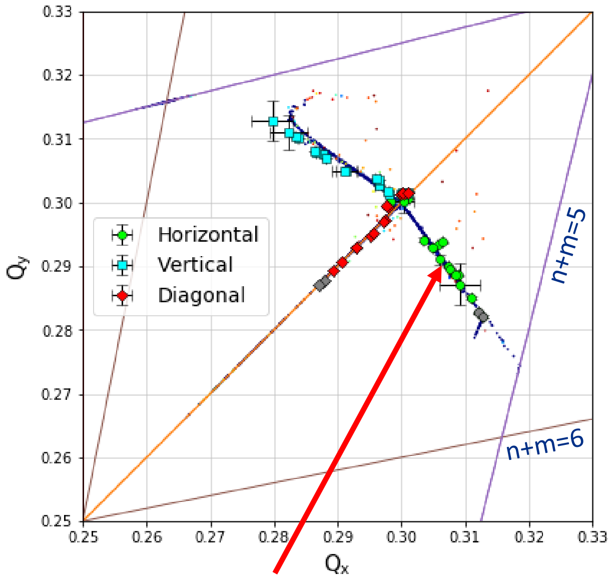
SVD



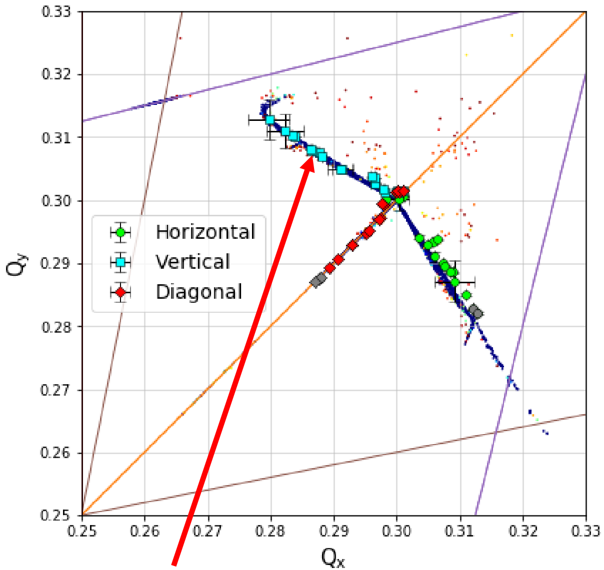
A. Petrenko, A. Valishev and V. A. Lebedev, "Model-independent analysis of the Fermilab Tevatron turn-by-turn beam position monitor measurements"
P. Zisopoulos, Y. Papaphilippou, and J. Laskar, "Refined betatron tune measurements by mixing beam position data"

NIO – nominal results

- Nominal config – 1.0A QI (central octupole)
  - Good match with FMA simulations, **0.05** tune spread
  - Discrepancy in H/V slope due to different (sextupolar) detuning – result of mystery chromaticity!



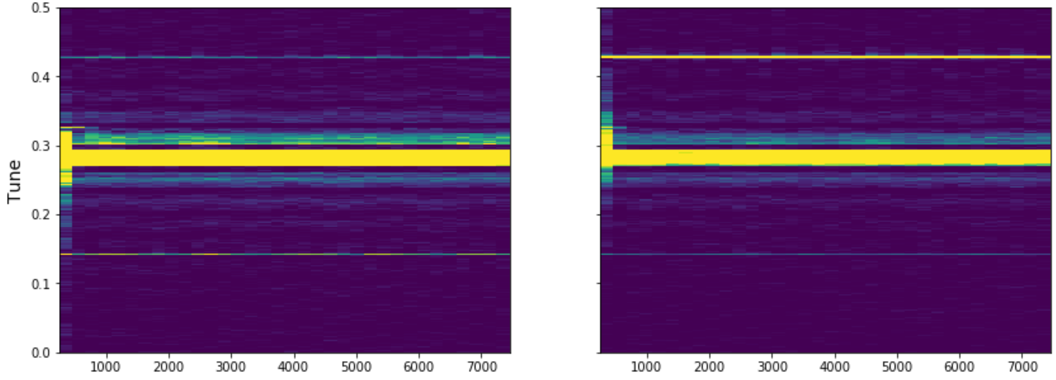
ξ=0 matches H branch



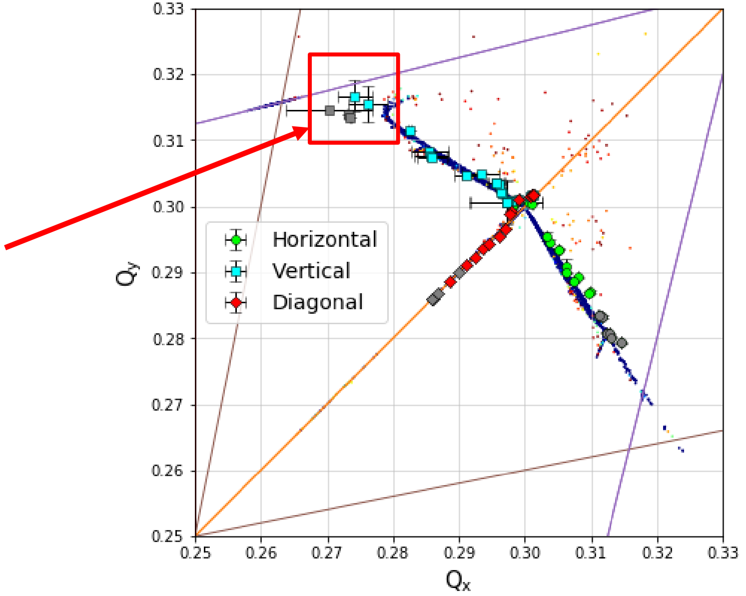
ξ=-2 matches V branch

NIO – nominal results

- Comparison with 0.25A flat distribution ('conventional octupole')
  - Has same detuning with amplitude
  - Loses more beam at same amplitude (= lower DA)
  - Resonant excitations overwhelm signal



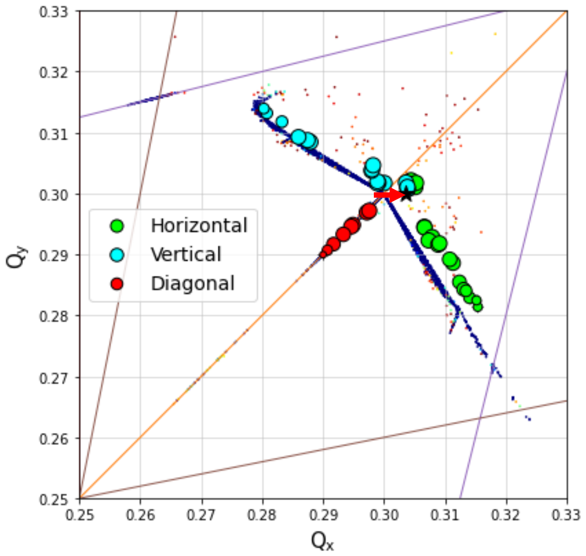
Signal spectrogram



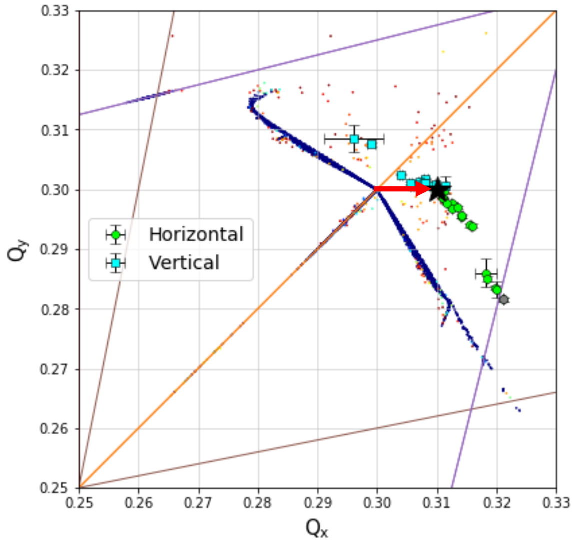
Ideal lattice FMA + flat data

NIO – perturbation results

- Example of 'perturbation': tune inside insert
  - Small shifts – little impact
  - Large shifts – different behavior, DA reduction



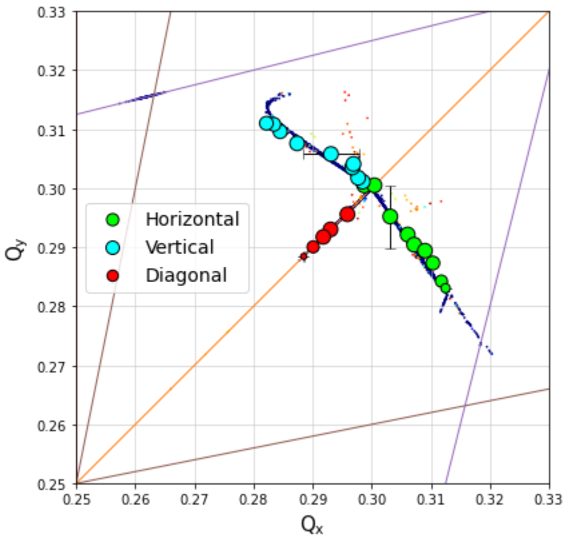
Qx+0.003 shift



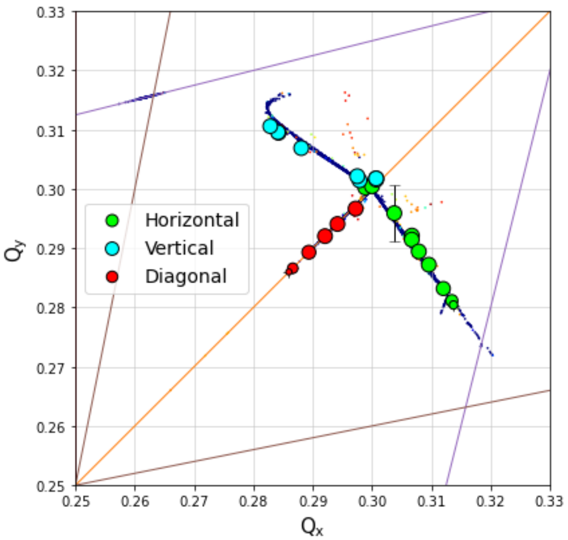
Qx+0.01 shift

NIO – perturbation results

- Other perturbations less impactful
  - i.e. magnet strength distribution mismatch



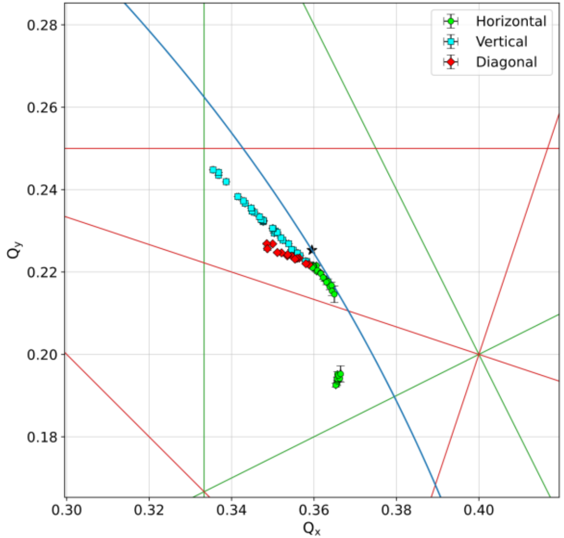
QI powered for 0.31 tune advance



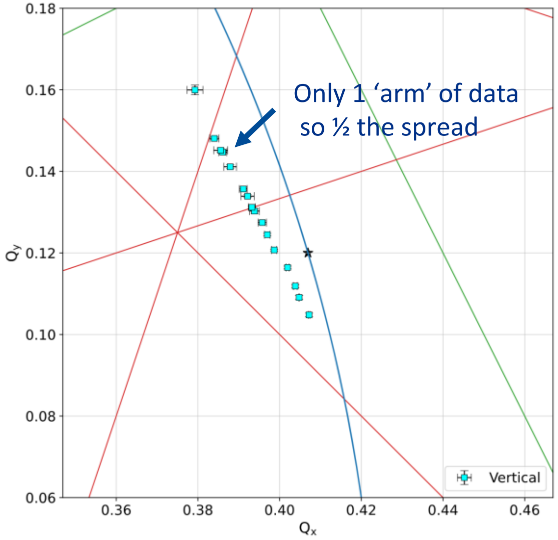
QI powered for 0.29 tune advance

NIO – DN results

- DN magnet affects tune, so scan starts from 'small amplitude' value
  - Significantly stronger detuning vs QI at cost of tighter tolerances

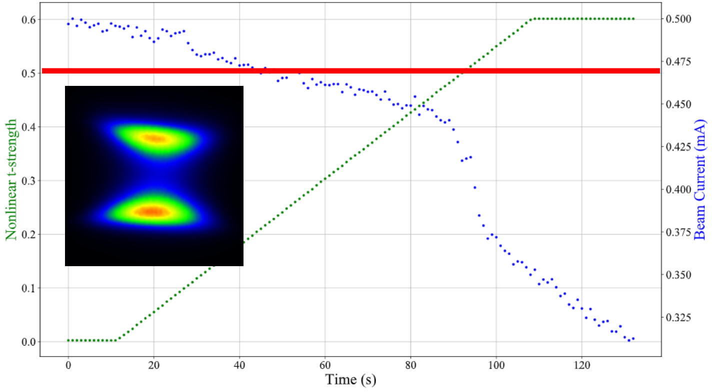


t=0.218 -> **0.06**



t=0.42 -> **0.12**

S. Szustkowski

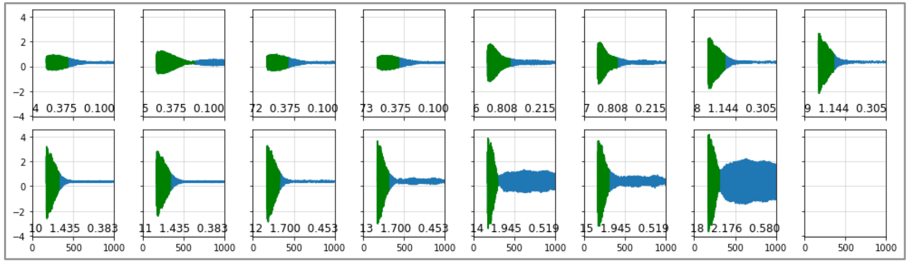


t=0.5 -> **integer tune crossing**

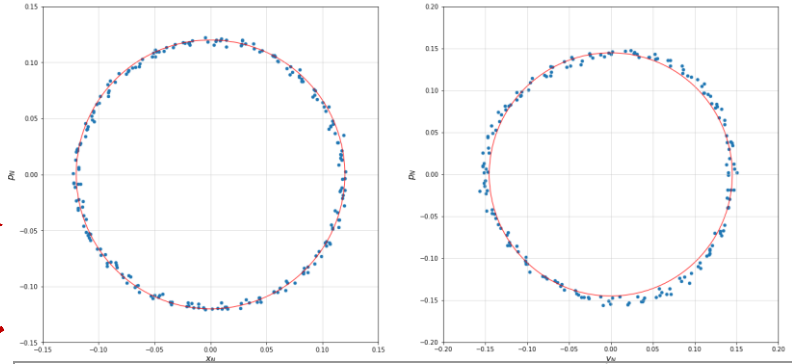
(into new 2-orbit topology)

NIO – invariants

- Want to show invariant existence



Kick data + optics model



Normalized phase space after decoherence compensation

New invariants
(hopefully better than CS)

QI

$$H_N = \frac{1}{2}(P_{xN}^2 + P_{yN}^2 + X_N^2 + Y_N^2) + \alpha\left(\frac{x_N^4}{4} + \frac{y_N^4}{4} - \frac{3x_N^2 y_N^2}{2}\right)$$

CS linear part — Strength parameter

DN

$$H_N = \frac{1}{2}(P_{xN}^2 + P_{yN}^2 + X_N^2 + Y_N^2) - \tau U(X_N, Y_N) \quad U = \mathcal{R}e\left(\frac{z}{\sqrt{1-z^2}}\arcsin(z)\right)$$

CS linear part

$$I_N = (X_N P_{yN} - Y_N P_{xN})^2 + P_{xN}^2 + X_N^2 - \tau W(X_N, Y_N) \quad W = \mathcal{R}e\left(\frac{z+z^*}{\sqrt{1-z^2}}\arcsin(z)\right)$$

‘Angular momentum’ — Strength parameter

NIO – invariants

Decoherence model critical:

- **Linear chromaticity** - oscillatory term (not as important due to compensation)

$$F_\delta = \exp\left(-\frac{\alpha^2}{2}\right); \quad \alpha = \frac{2\xi\sigma_\delta \sin \pi\nu_s n}{\nu_s}$$

$$\langle x(n)\rangle = x_0 F_\delta \cos(2\pi\nu_\beta n + \phi_\beta)$$

- **1D quadratic nonlinearity** – gaussian envelope initially, transitions into exponential
  - Critical parameter: kick amplitude vs rms beam size

$$F_x = \frac{1}{1+\theta^2} \exp\left(-\frac{x_k^2}{2\sigma_x^2}\frac{\theta^2}{(1+\theta^2)}\right)$$

$$x_k = \beta_x \Delta x'; \quad \theta = 4\pi\Delta\nu_x n; \quad \phi_x = 2\arctan\theta;$$

$$\langle x(n)\rangle = -x_k F_x \sin\left(2\pi\nu_x n + \phi_x + \frac{x_k^2}{2\sigma_x^2}\frac{\theta}{(1+\theta^2)}\right)$$

- **2D quadratic nonlinearity** – adds cross-terms
  - Fitting becomes very unstable

$$F_{xx} = \frac{1}{1+\theta_{xx}^2} \exp\left(-\frac{x_k^2}{2\sigma_x^2}\frac{\theta_{xx}^2}{1+\theta_{xx}^2}\right); \quad F_{xz} = \frac{1}{1+\theta_{xz}^2} \exp\left(-\frac{z_k^2}{2\sigma_z^2}\frac{\theta_{xz}^2}{1+\theta_{xz}^2}\right)$$

$$F_{zx} = \frac{1}{1+\theta_{zx}^2} \exp\left(-\frac{x_k^2}{2\sigma_x^2}\frac{\theta_{zx}^2}{1+\theta_{zx}^2}\right); \quad F_{zz} = \frac{1}{1+\theta_{zz}^2} \exp\left(-\frac{z_k^2}{2\sigma_z^2}\frac{\theta_{zz}^2}{1+\theta_{zz}^2}\right)$$

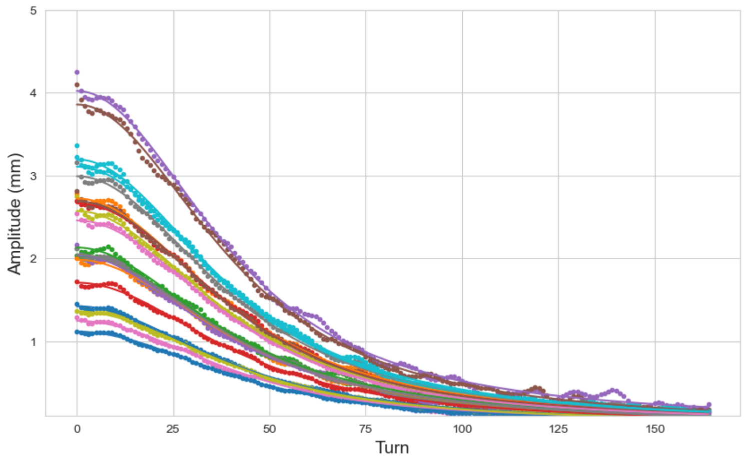
$$\theta_{xx} = 4\pi k_{xx}\sigma_x^2 n; \quad \theta_{xz} = 4\pi k_{xz}\sigma_z^2 n; \quad \theta_{zx} = 4\pi k_{zx}\sigma_x^2 n; \quad \theta_{zz} = 4\pi k_{zz}\sigma_z^2 n.$$

$$\langle x(n)\rangle = -x_k F_{xx} F_{xz} \sin\left(2\pi\nu_x n + \phi_{xx} + \phi_{xz} + \frac{x_k^2}{2\sigma_x^2}\frac{\theta_{xx}}{1+\theta_{xx}^2} + \frac{z_k^2}{2\sigma_z^2}\frac{\theta_{xz}}{1+\theta_{xz}^2}\right)$$

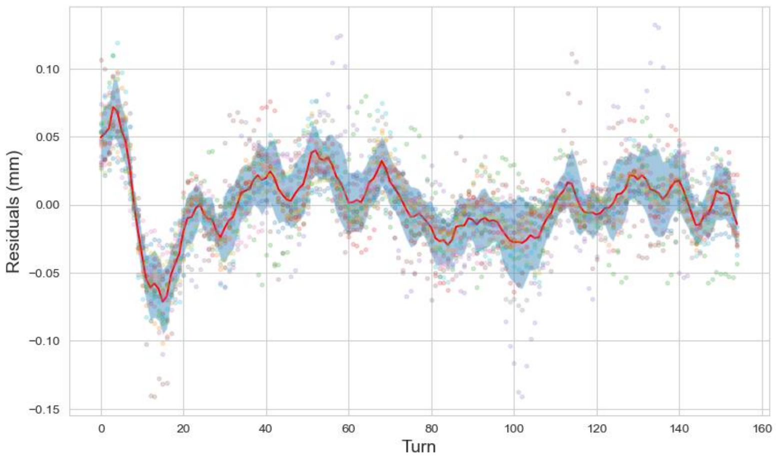
S.Y.Lee, Decoherence of the Kicked Beams II, report SSC-N-749

NIO – invariants

- Simpler models more general at the cost of possible systematics
  - For now, use 1D nonlinearity + empirical corrections
  - Good agreement over ~100 turns, residuals at noise level
  - Better ring model would help constrain parameters, especially coupling - WIP



Smoothed envelope fit

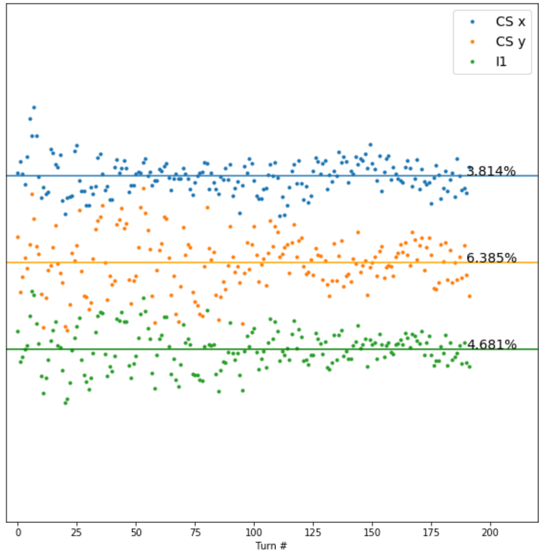


Fit residuals

NIO – invariants

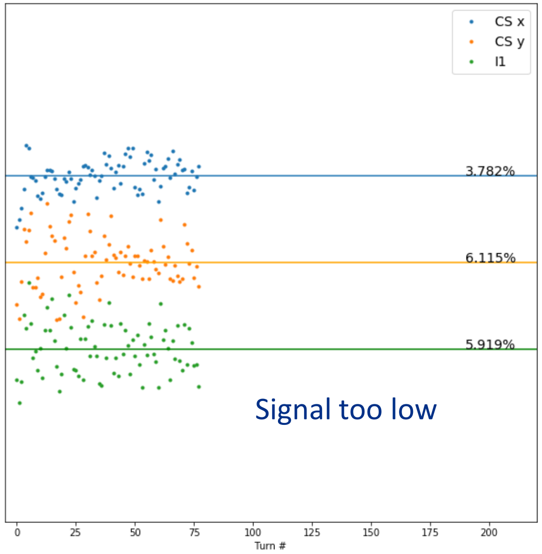
- For QI, can benchmark directly
  - Flat configuration H-invariant jitter worse while CS invariants ~ same
  - Both higher than in simulations (sensitive to bunch parameters)

I1



1.0A nominal

=
=
<

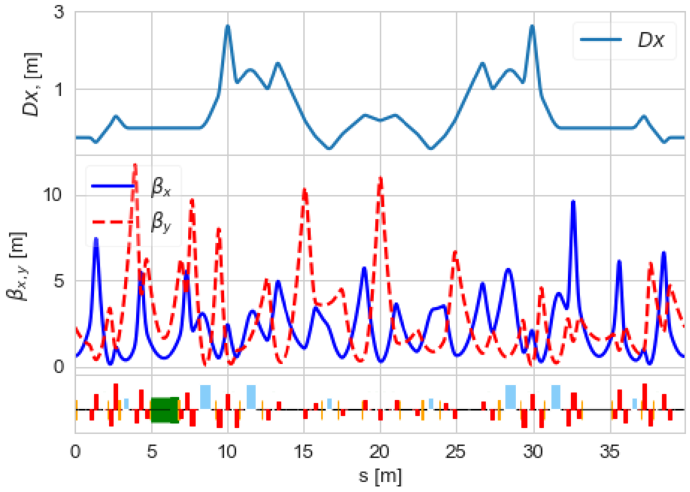


I1

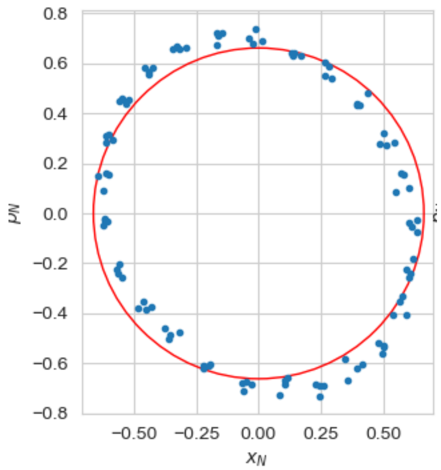
0.25A flat

NIO – invariants

- For DN, things more complicated
  - No direct benchmarks
  - Lattice optics gets distorted, hard to do 'small amplitude' calibration



Lattice @ t=0.42

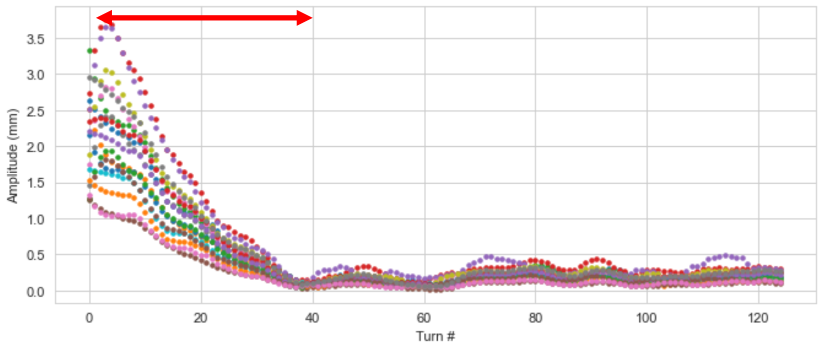


Optics model mismatch (should be a circle)

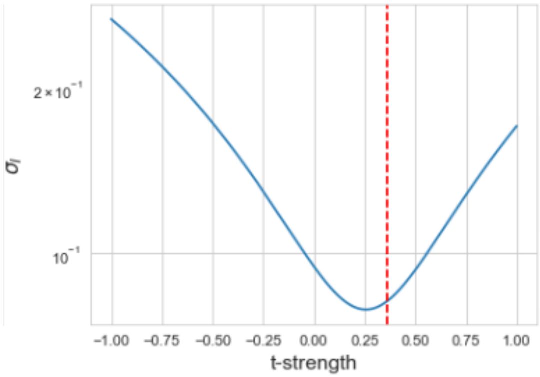
NIO – invariants

- For DN, things more complicated
  - Biggest problem – fast nonlinear decoherence
  - Qualitatively, minimum invariant jitter near expected strength
  - Quantitative recovery algorithms WIP

Only 25 turns!



t=0.363 diagonal kick
(no beam loss)

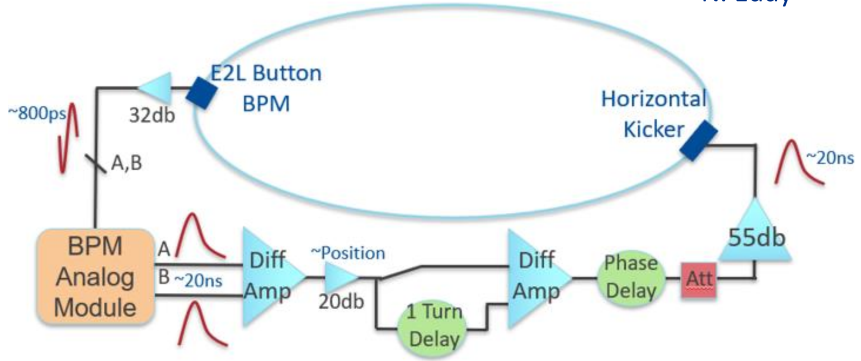


NIO – anti-damper instabilities

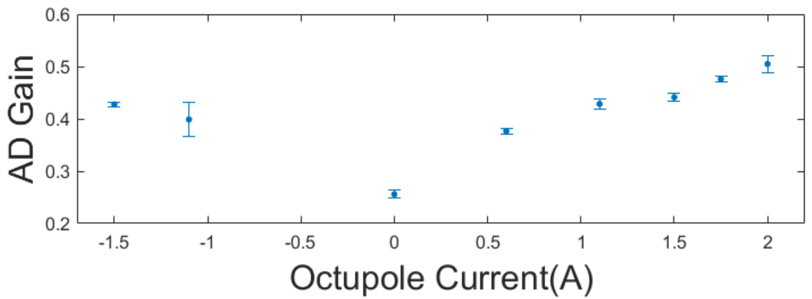
Checked instability suppression with anti-damper (NIOLD study, N. Eddy)

- Showed increased stability (higher feedback gain) with octupoles on vs off

N. Eddy



N. Eddy



Research – NIO summary

NIO studies have:

- Demonstrated significant detuning, consistent with simulations
  - High tune spread, invariant conservation
  - Superior performance vs flat arrangement
- Further work
  - Finding sources of ring nonlinearities
  - Wider parameter space coverage
  - Hardware improvements

N. Kuklev et al., "Experimental Demonstration of the Henon-Heiles Quasi-Integrable System at IOTA", in Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)
N. Kuklev et al., "Experimental Studies of Single Invariant Quasi-Integrable Nonlinear Optics at IOTA", presented at the North American Particle Accelerator Conf. (NAPAC'19)
A.L. Romanov, [and 19 others, including N. Kuklev], "Recent Results and Opportunities at the IOTA Facility", presented at the North American Particle Accelerator Conf. (NAPAC'19)
N. Kuklev, A. Valishev, A. L. Romanov, Y. K. Kim and S. Nagaitsev, "Experimental demonstration of single invariant nonlinear integrable system", in preparation for PRSTAB.
A. Valishev, N. Kuklev, S. Szustkowski, A. L. Romanov, G. Stancari and S. Nagaitsev, "Nonlinear beam focusing in a storage ring operating at an integer resonance", in preparation for PRL.

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  - Analysis and results
- **Software and ML**
- Conclusion

Software and ML

A lot of above research was enabled by continuous tooling and software development

Started as a mess of separate scripts, evolved into a full framework - ‘**pyIOTA**’

- Open-source: github.com/nikitakuklev/pyIOTA
  - 8k lines of code
  - 2.5k lines of comments

pyIOTA

Accelerator control, modelling, and data analysis framework

Features

pyIOTA is a mix everything I found useful in experimental beam dynamics studies - glue I/O and logic to talk with various accelerator codes, algorithms for optics and TBT data analysis, adapters for controlling accelerators and storing experimental data, and other small things.

Software and ML

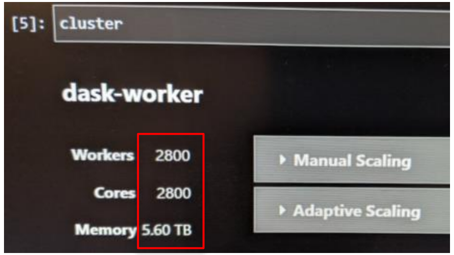
Philosophy: 'Don't reinvent the wheel'

- Write new code when necessary, wrap existing tools if sufficient
- Designed to speed up research and tinkering

Features:

Script generation and cluster job management

- i.e. parametric elegant taskfile generation via Python
- Job queuing and post-processing with SLURM, Dask

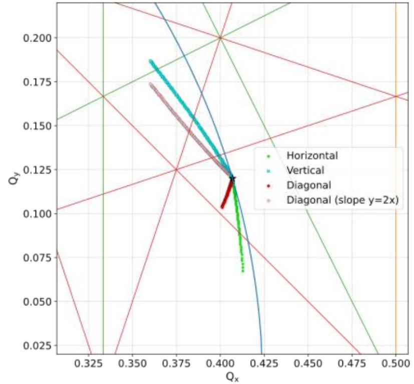


Wrappers for data and lattice formats

- MAD-X TFS, Elegant SDDS, 6DSim .6ds, openPMD, etc.

Integration with OCELOT core

- Linear/nonlinear optics and tracking in pure Python

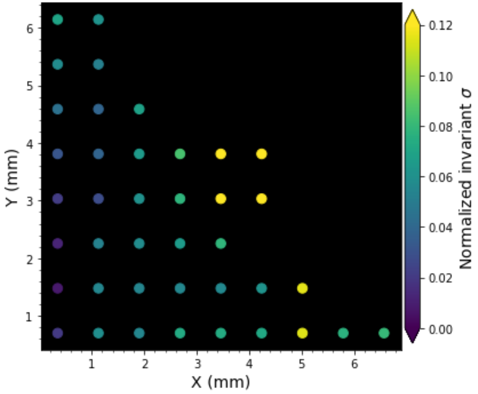


Convenience functions for advanced optimization and machine learning

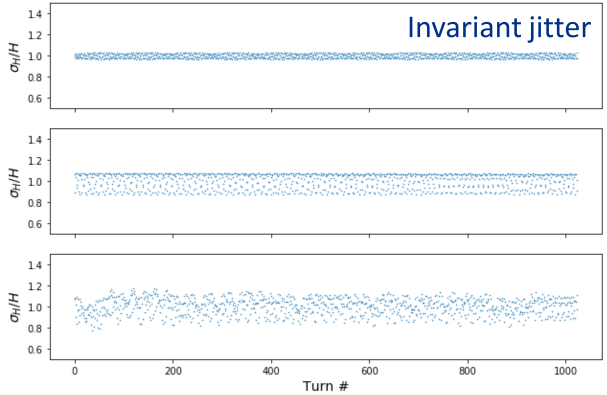
Well documented and referenced

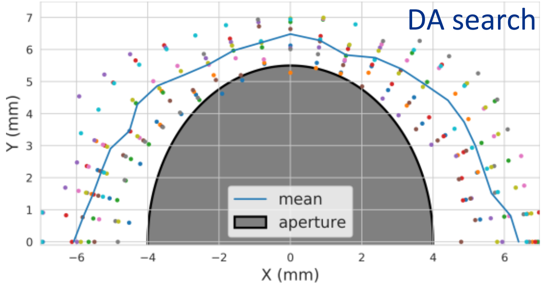
Software and ML

Surrogate modelling and GP optimization for simulation speedup



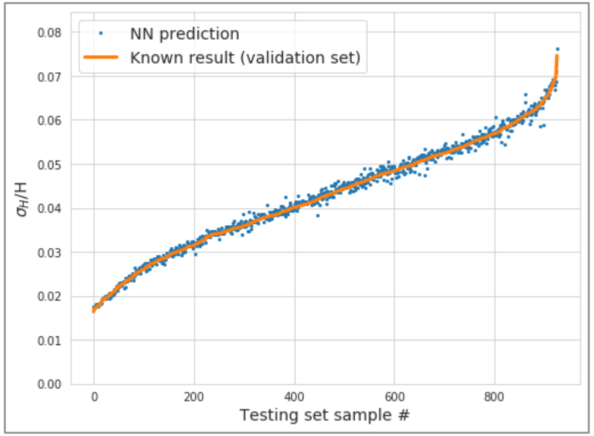
Particle tracking



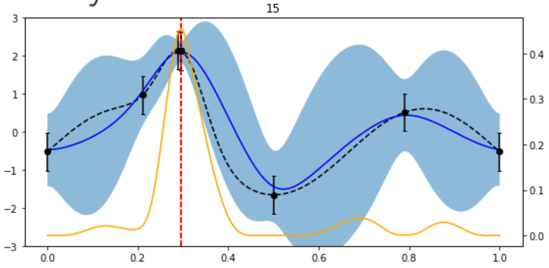


Surrogate model

TensorFlow



PyTorch BoTorch

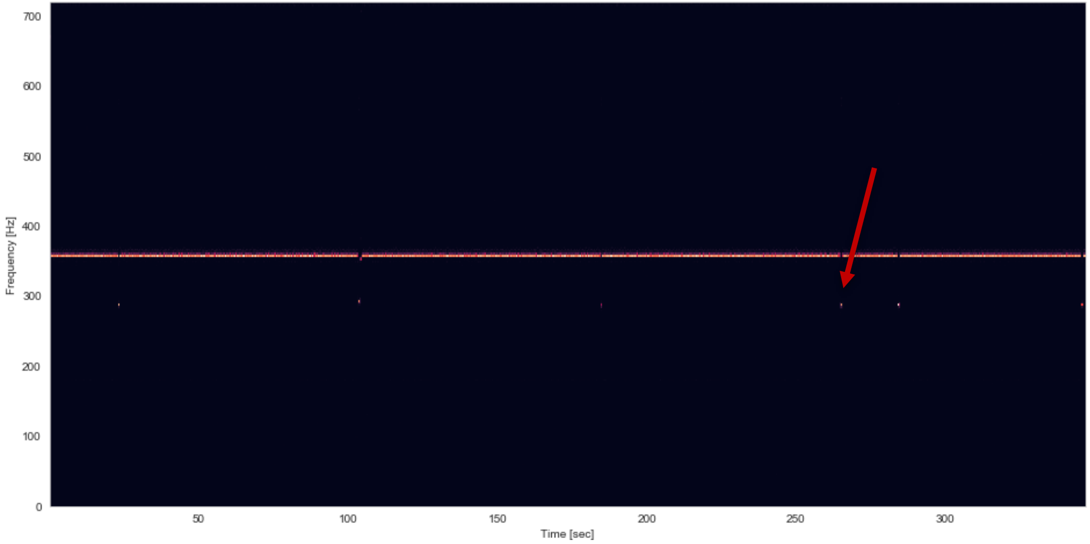


Parallel Bayesian optimization

N. Kuklev et al., "Online Modelling and Optimization of Nonlinear Integrable Systems" (NAPAC'19 contributed talk TUYBB4)

Software and ML

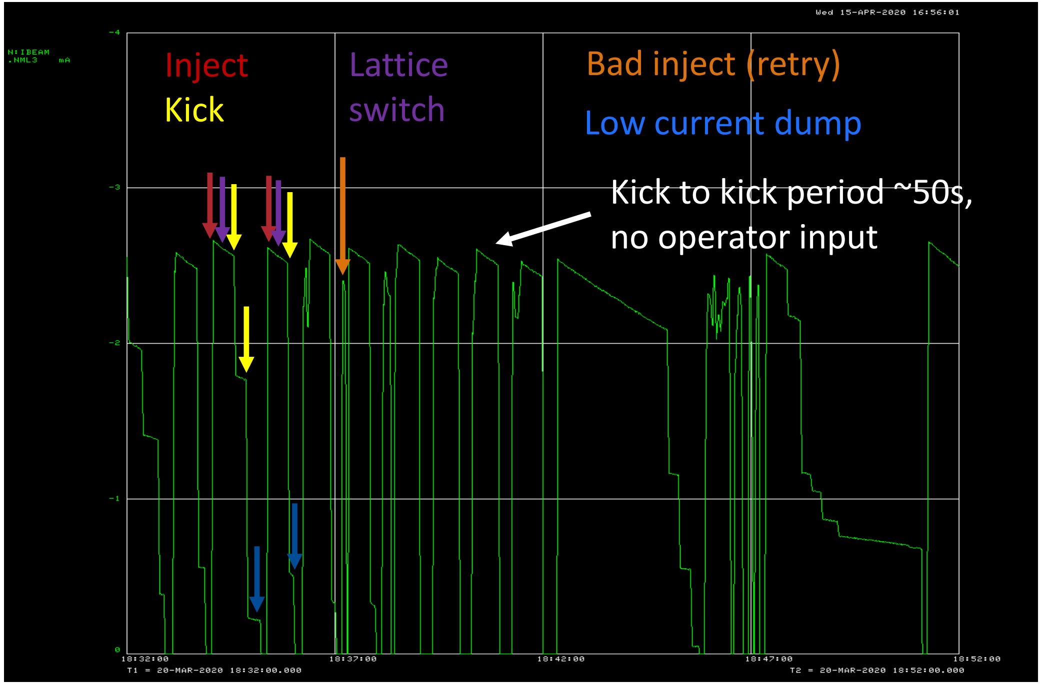
Clustering + classification of readbacks to detect anomalies and alert operator



Power supply readback anomaly

Software and ML

Automated kick data collection (allowed for thousands of reinjections)



Beam current vs time
(20 min span)

Outline

- Integrable optics
- Implementation and IOTA ring
- IOTA NIO program
- NIO research
  - Hardware – beam diagnostics
  - Hardware – nonlinear inserts
  - Simulations
  - Commissioning
  - Data collection
  - Analysis and results
- Software and ML
- **Conclusion**

Conclusion

NIO research involved many interesting experimental and simulation tasks!

- Design and implementation of SR beam diagnostics
- Development of multi-purpose control, modelling, and analysis framework
- Simulation, assembly, commissioning, data collection, and analysis of NIO systems
  - Tune spread in agreement with simulations
  - Improved conservation of invariants
  - **Accomplishment of stages 1 and 2 of phase 1 NIO program**
- Many interesting experiments remain – proton beams, electron lenses, etc…

Thanks!
Questions?