Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

IOTA run 2 NIO implementation and first results

Nikita Kuklev and IOTA NL team

IOTA collaboration meeting

June 15, 2020

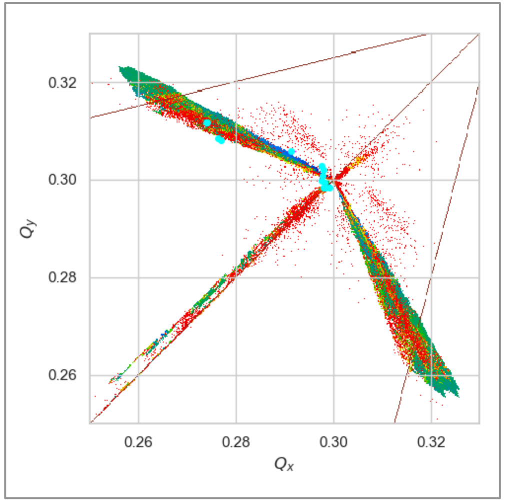
In partnership with:

Outline

- Previous results and run 2 goals
- Run 2 configuration
- Run 2 commissioning
- Data collection
- Simulations
- Analysis

Run 1 – partial success

- Reminder: QI = $$H = H_0 + U = \frac{1}{2}\left(P_x^2 + P_y^2 + x_N^2 + y_N^2\right) + \alpha\left(\frac{x_N^4}{4} + \frac{y_N^4}{4} - \frac{3x_N^2 y_N^2}{2}\right)$$
- In run 1, measured significant tune spread, ~0.6x of simulated performance
- Did not get invariants to sufficient accuracy
- Limitations:
  - Insufficient BPM resolution
  - Bent pipe aperture restriction
  - Only V-kicker control



Run 1 FMA

Run 2 plans

- Improve and fix HW/SW

- 3 experimental phases
  - Stage 1
    - Commission, measure nominal configuration
    - Demonstrate predicted performance
  - Stage 2
    - Perturbed systems (tune/dispersion/field errors/etc.)
    - Demonstrate resiliency to errors
  - Stage 3
    - Different working points, close to resonances, etc.
    - Explore exotic conditions

Uses same base, nominal lattice

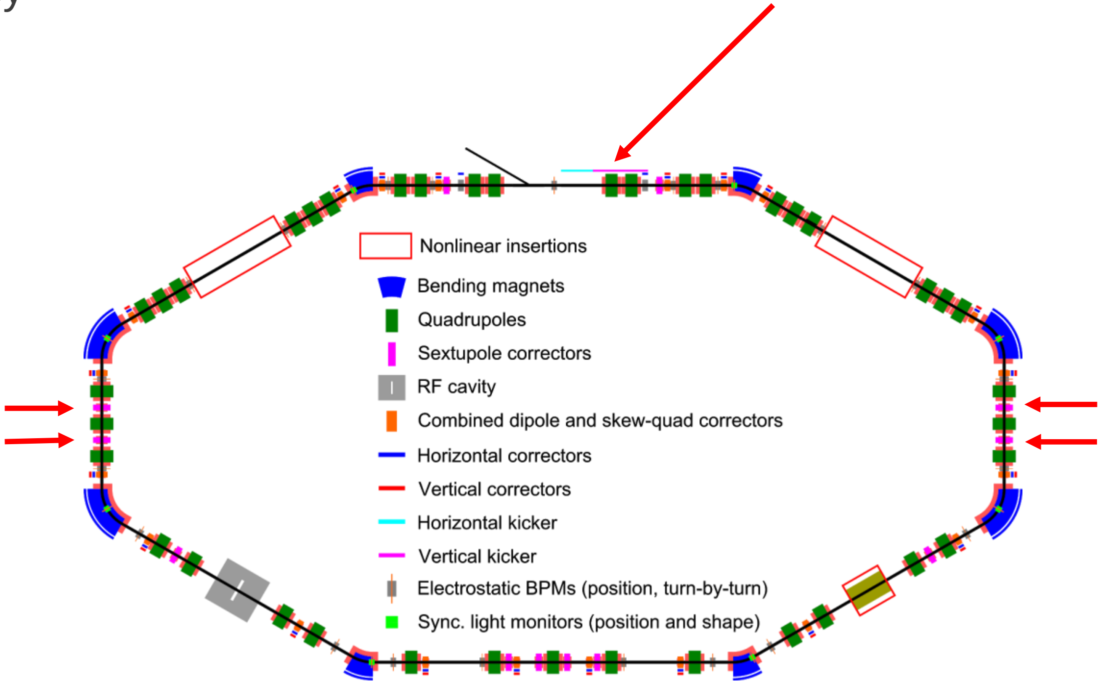
Needs new lattice design/tuning

Outline

- Previous results and run 2 goals
- Run 2 configuration
- Run 2 commissioning
- Data collection
- Simulations
- Analysis

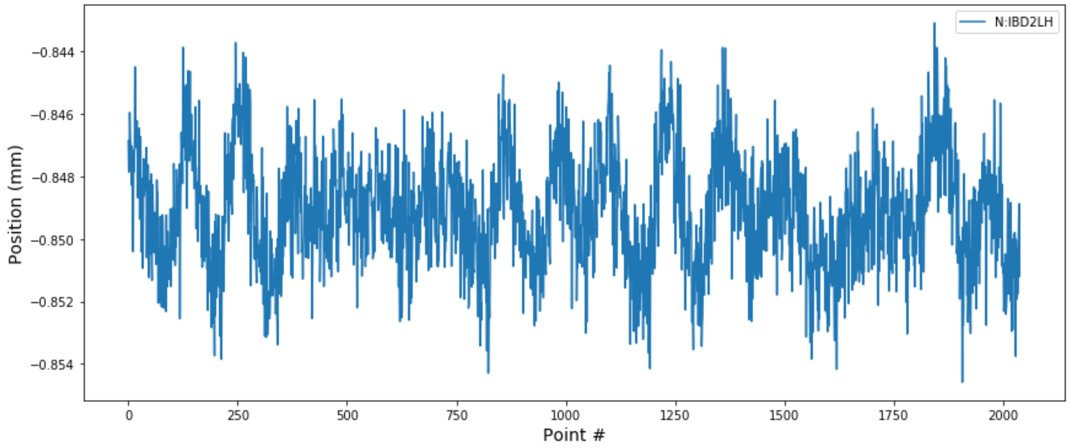
Main upgrades

- Added flux compensators to change dipole edge field
  - Improved path length discrepancy
- Added 4 sextupoles (2 families)
- Added tunable H-kicker
- BPM hardware improvements
- SW/timing improvements



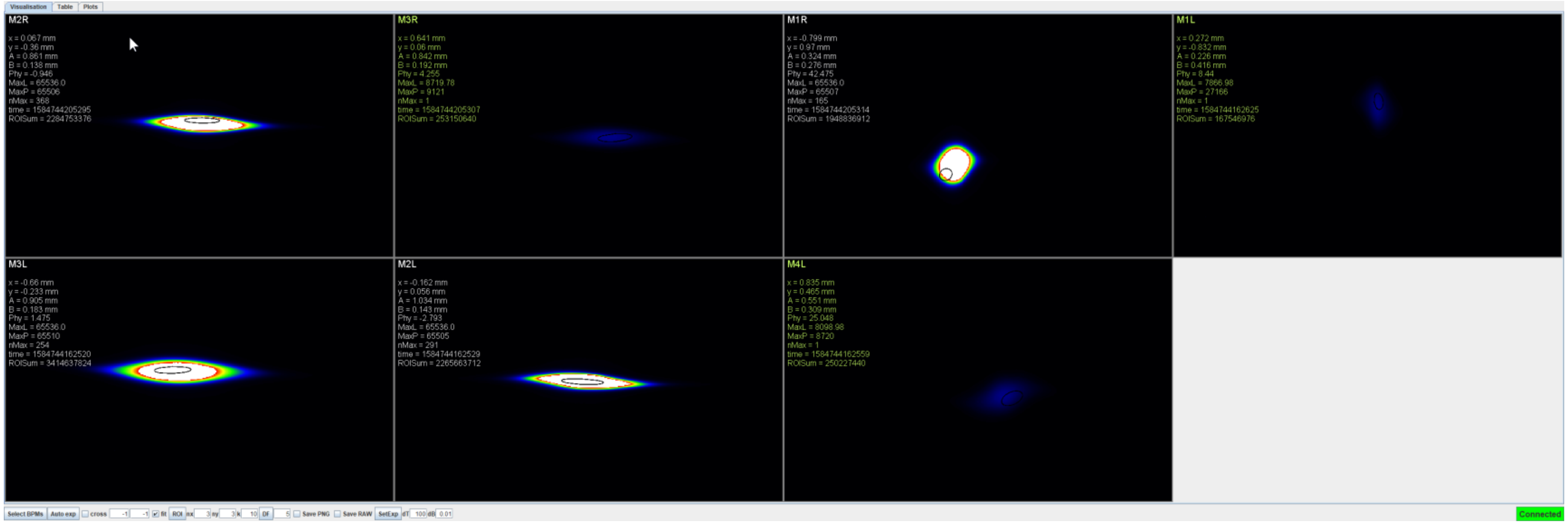
Remaining issues

- Significant optics breathing
- Operational issues – drifts, trips, etc. (minor)



Remaining issues

- Significant optics breathing
- Operational issues – drifts, trips, etc. (minor)



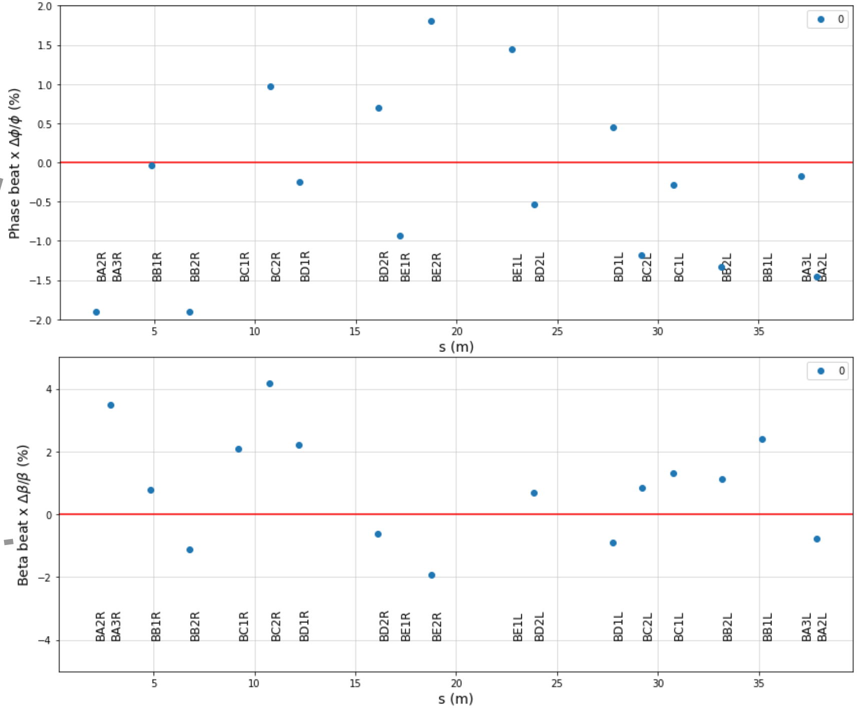
Outline

- Previous results and run 2 goals
- Run 2 configuration
- Run 2 commissioning
- Data collection
- Simulations
- Analysis

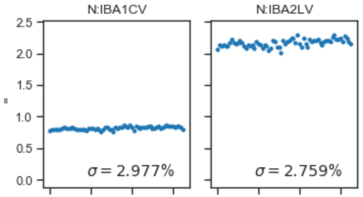
Commissioning

- 4 main categories:
  - Lattice
  - Knobs/kickers/etc.
  - BPMs
  - Insert

- Lattice: LOCO provided best precision
  - β within a few %, but drift + hysteresis problematic
  - Verified with TBT data from each sequence

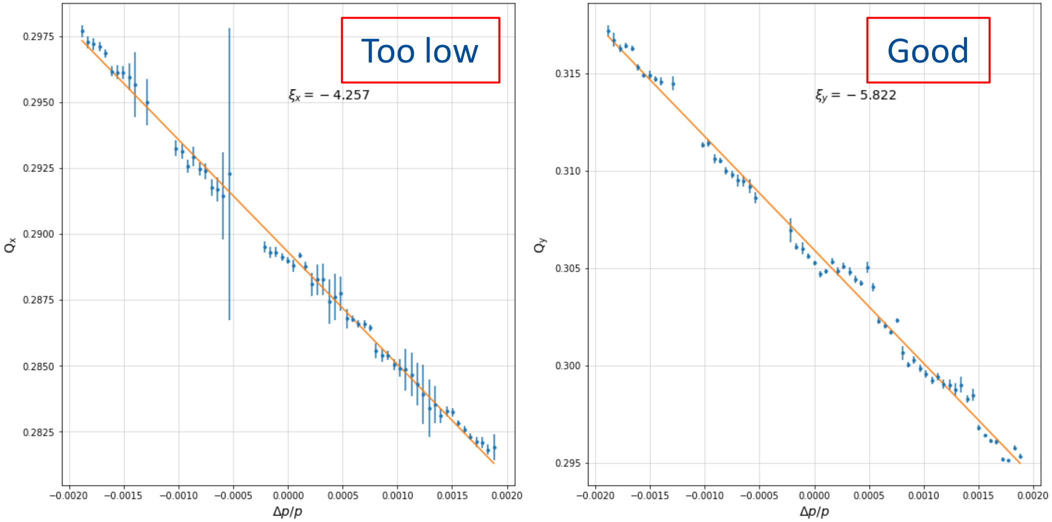


- Kickers: analyzed repeated triggers
  - Jitter - <5% rms
  - Linearity within 5-8%



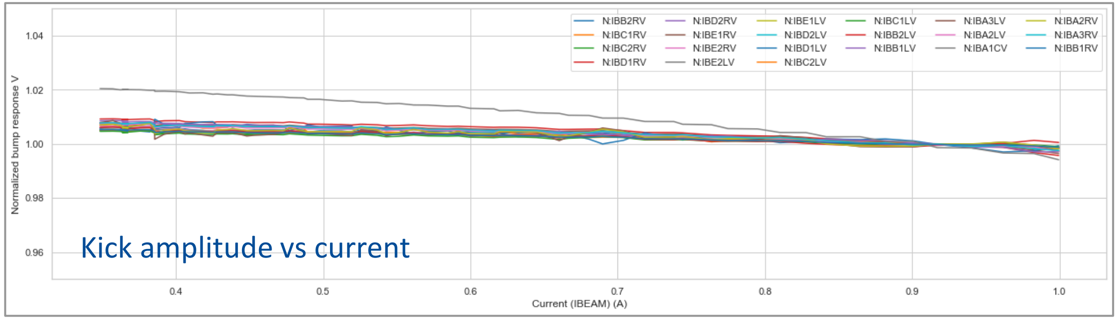
Commissioning

- Lattice: Unknown reduction in x chromaticity
  - Suspect due to dipole effects
  - Means sextupole strength required for (x,y)=(0,0) < model

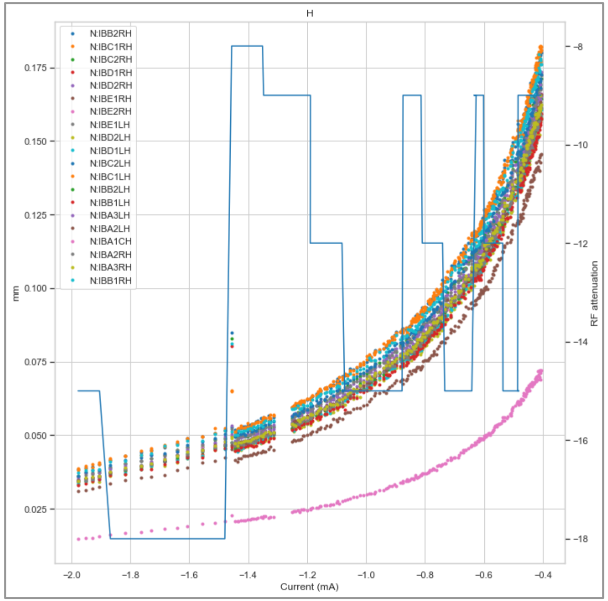


Commissioning – BPMs

- Orbit linearity and noise:
  - <1% linear within 4 mm of center
  - ~1um @ 0.3mA
- TBT noise:
  - 100um @ 0.8mA
  - Meets specs!
- Overall, improved significantly from run 1
- A few issues remained:
  - Dynamic saturation
  - Timing/ADC desync
  - Errors/timeouts



Position rms vs current
(and RF=bunch length)

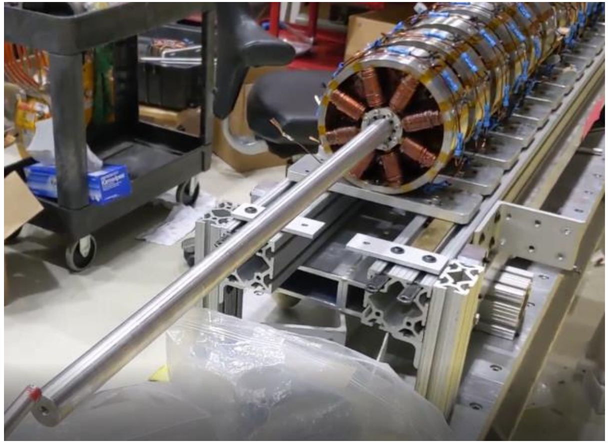


Commissioning – QI

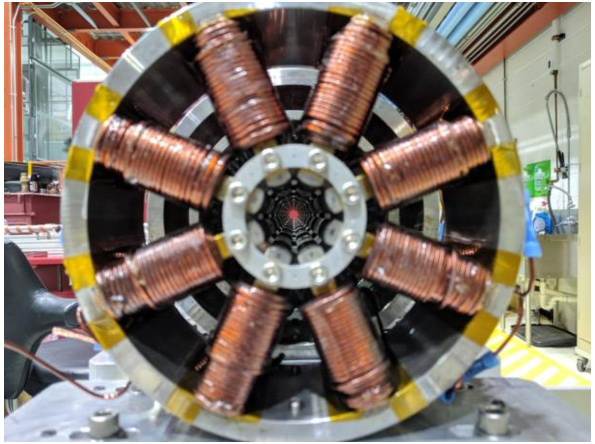
- Insert was taken apart and each magnet tested at TD (rotating coil)
  - Rebuilt with best ones in the middle

- Alignment done with precision mechanical rod and laser
  - Both indicated < 150um mechanical

Testing @ TD VTS



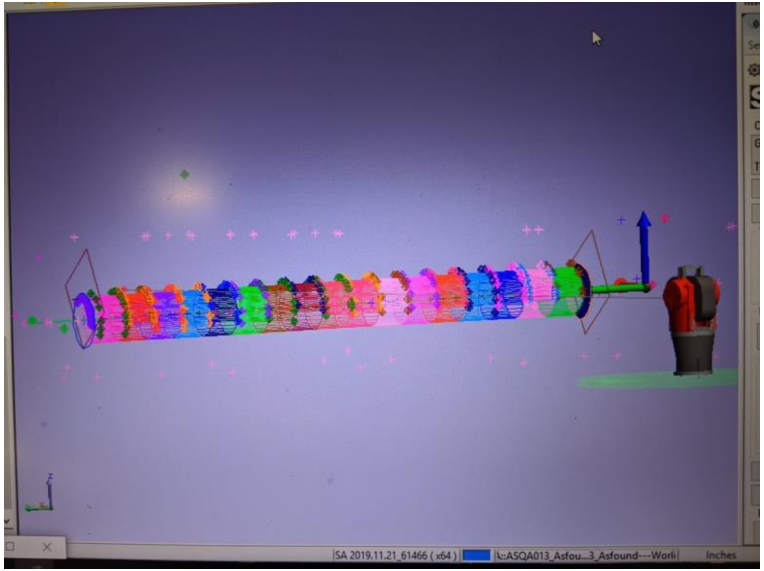
Precision soviet stick alignment



Final assembly

Commissioning – QI

- Laser tracker aligned into the ring

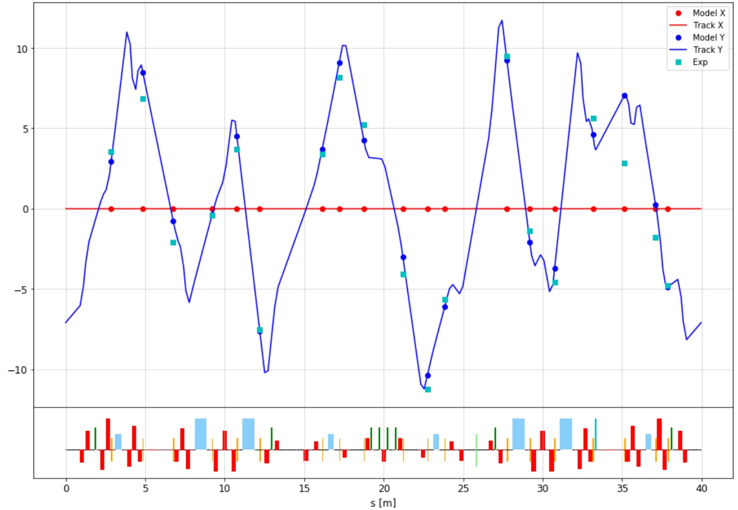


Measured tracker model

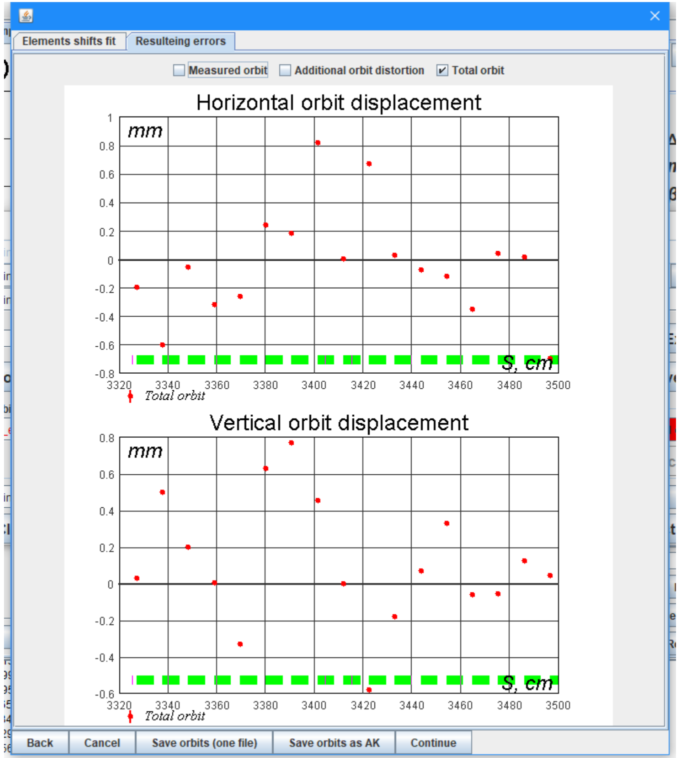
Manual edge checks

Commissioning – QI

- Alignment tested with close orbit responses
- Found very large displacements in some magnets
  - Some not physical (almost 1 mm)!



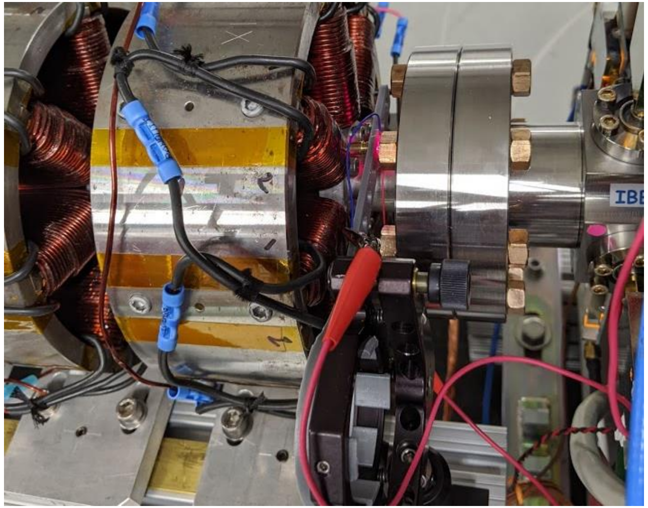
Closed orbit distortion model/measurement



Magnet offsets (A. Romanov)

Commissioning – QI

- Tried to slide around, demagnetize, test inductance
- Realigned in place with laser and left as is
- Root cause still unclear



Laser inserted using 3d-printed holder

Sanity checking/moving with indicators

Commissioning summary

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

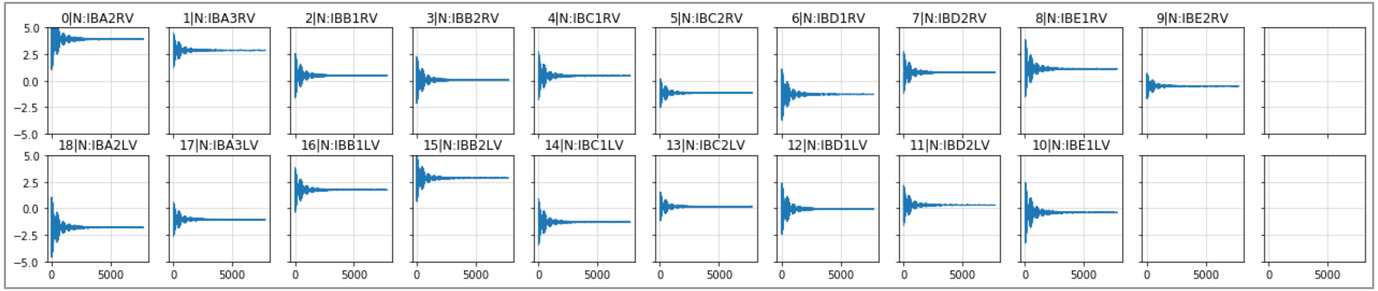
- Octupoles: 10% beta-function accuracy, ~0.01 betatron phase accuracy, 100um orbit centering
- NL magnet: 1% beta-function, 0.001-0.003 betatron phase, 50um orbit centering
- Variable single-turn kick, H/V
- Turn-by-turn BPM system, 100um resolution

Outline

- Previous results and run 2 goals
- Run 2 configuration
- Run 2 commissioning
- Data collection
- Simulations
- Analysis

Data channels

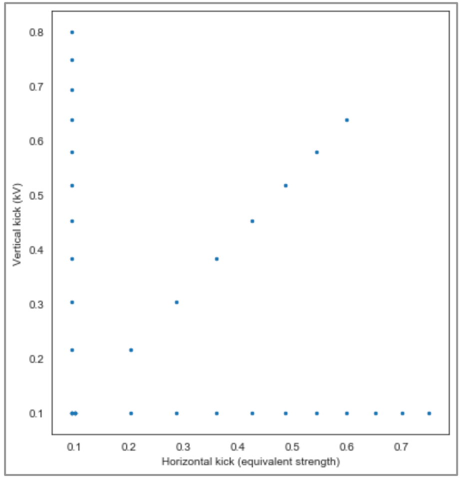
- Nominally, 21 BPMs – 19 useful
  - -1 special pickup, different size/calibration
  - -1 for anti-damper

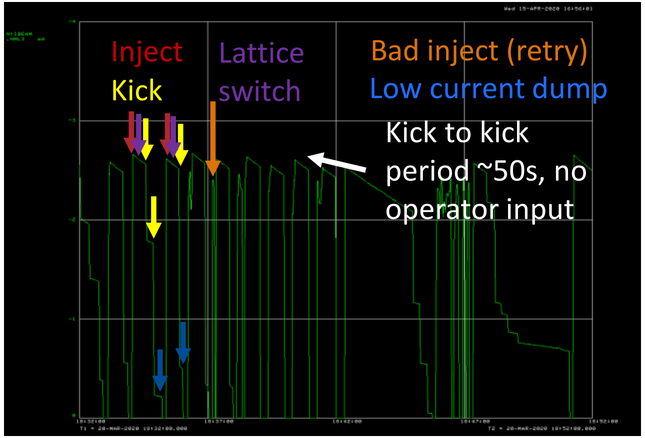


- Data:
  - 8k turns, triggered at -172 from kick ('pilot' signal)
  - Ring state afterwards saved
    - 284 channels – magnets, beam currents, etc.
  - Other data available via ACNET

Collection

- Typical sequence:
  - 58 nonlinear kicks (2/point)
    - In 3 lines, slightly nonlinear spacing
  - ~5-10 calibration kicks (insert off)
    - At start/end + after reinjection – used for optics recovery
  - Automated collection/injection
    - Current > 0.8mA
    - With pyIOTA: github.com/nikitakuklev/pyIOTA "unified modelling/control environment"
- This grid was repeated for many configurations
  - Nominal
  - Tune/dispersion/etc. errors
  - QI/NL current errors





Dataset breakdown

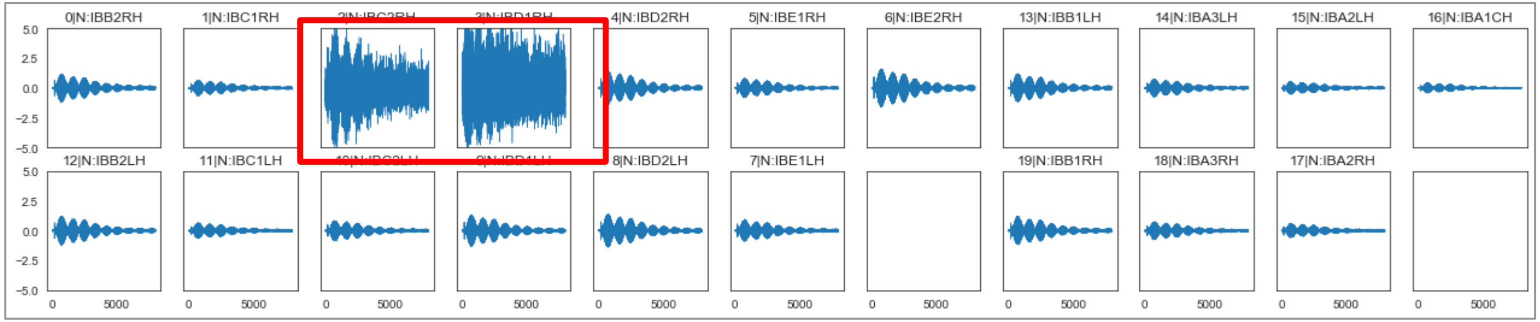
- Two main collection periods
  - ‘doomsday’: March 15/16 + ‘actual doomsday’: March 20/21

- In total:
  - QI: **2600** kicks / 37 configs
  - NL: **1100** kicks / 36 configs
  - ~**1000** on blank lattice for various calibrations
  - Around 1-2k other kicks for various studies (RDTs, …)

- Stage 1+2 – data mostly collected
- Stage 3 was not completed due to covid-19 lab shutdown

Outlier rejection

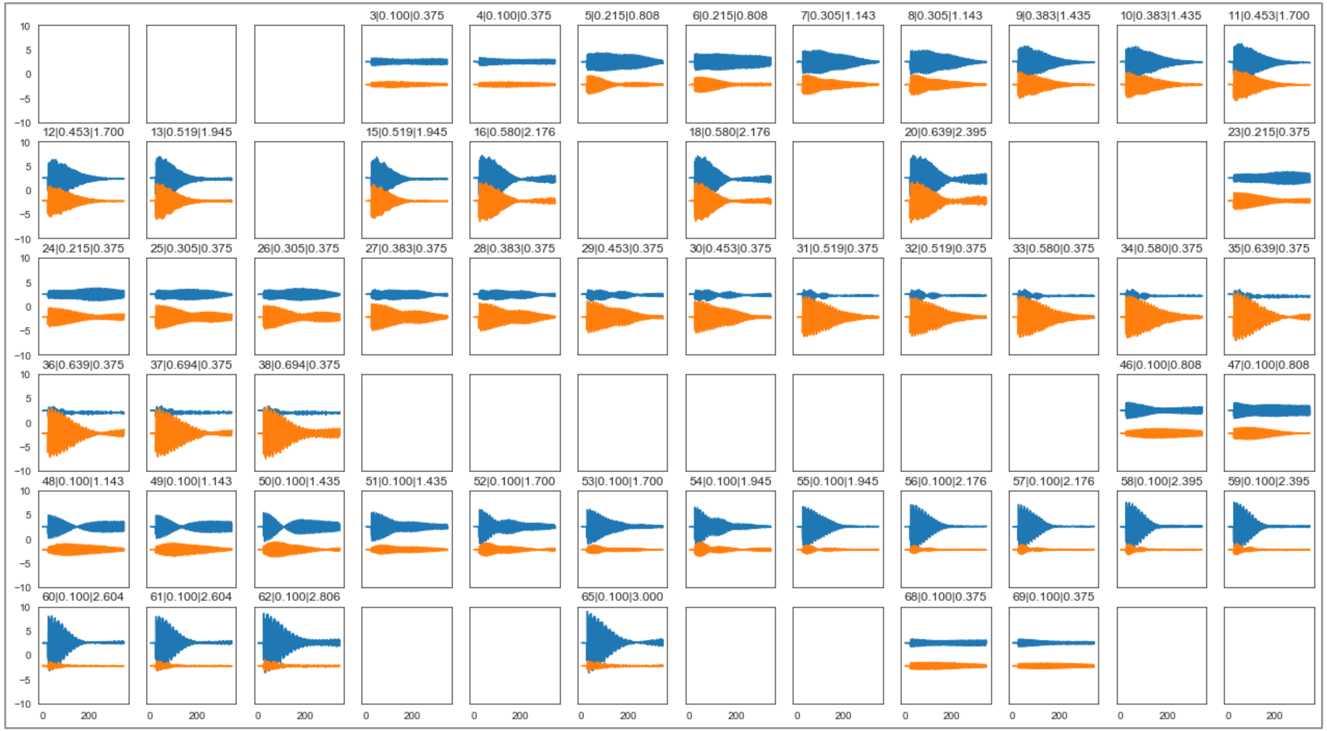
- Observed a variety of anomalies
  - Example: *timing/ADC desync*



- Solution – veto voting by filters + manual curation
  - Absolute value threshold
  - SNR/symmetry
  - Mean/variance outliers

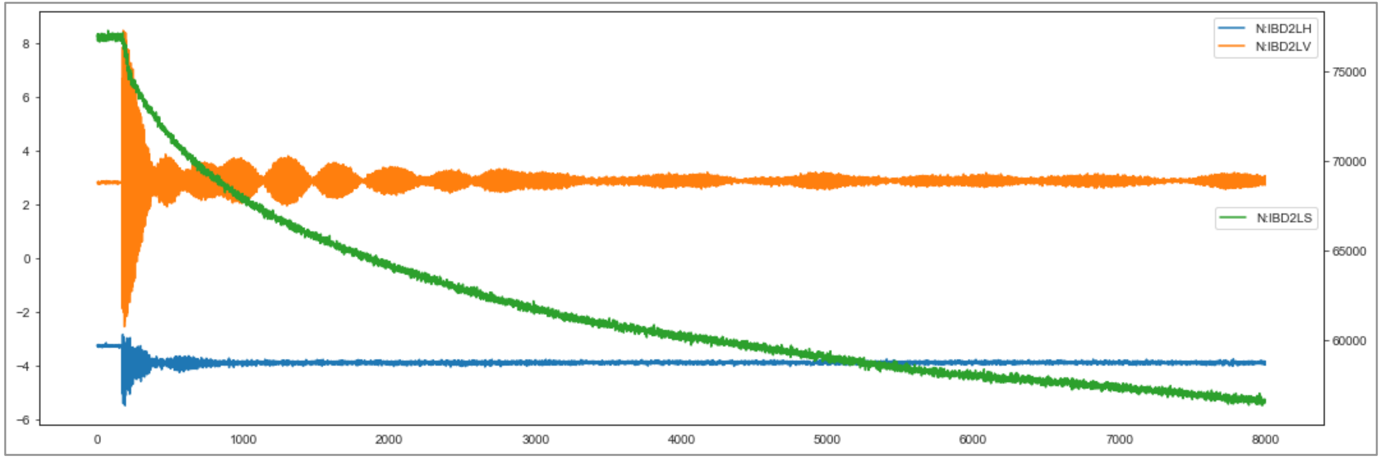
Sample dataset

- Example of data remaining after cleaning



Sample dataset

- Example of single kick data



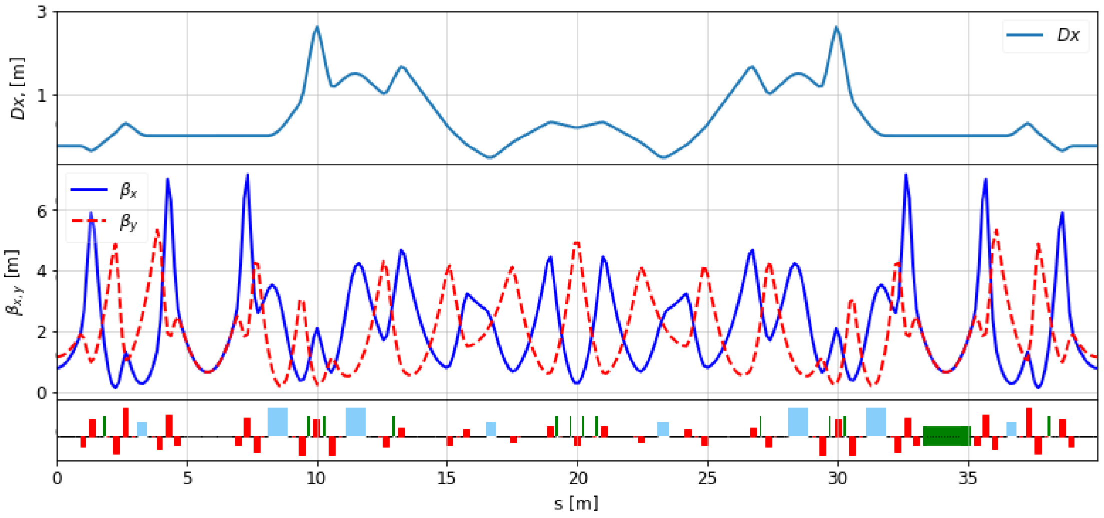
Outline

- Previous results and run 2 goals
- Run 2 configuration
- Run 2 commissioning
- Data collection
- Simulations
- Analysis

Simulations

- Heavy simulations with elegant, via pyIOTA wrapper
  - Thick symplectic tracking - fringe fields + errors + SR

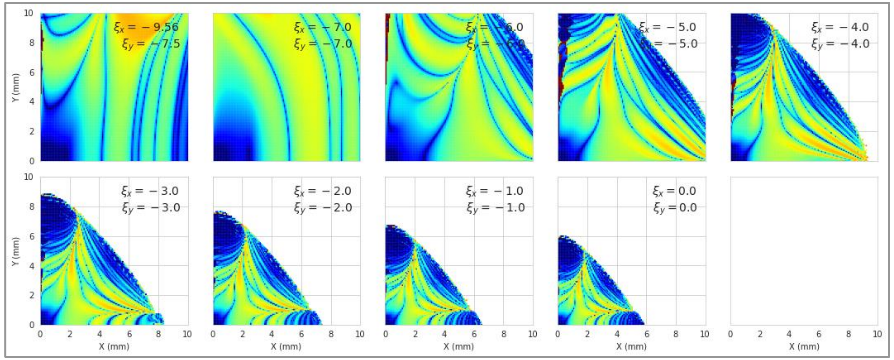
- (Non)linear optics - OCELOT + MADX + custom code



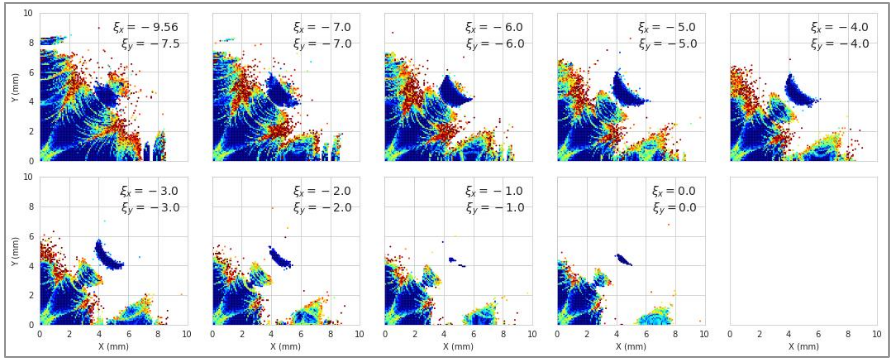
Simulation predictions

- Updated simulations to latest v8.6 lattice run 2 config
- 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

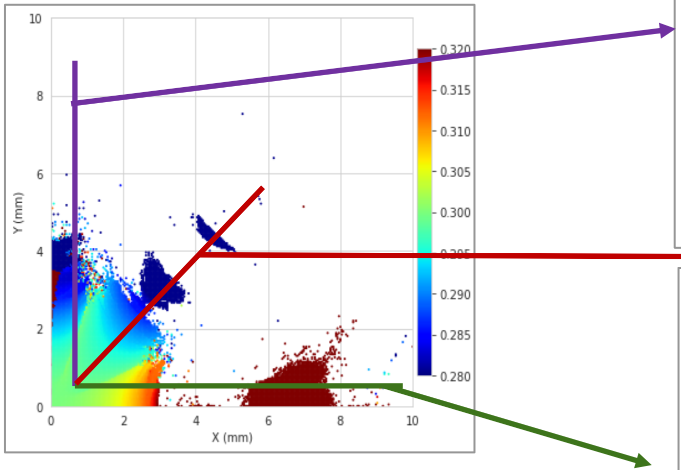


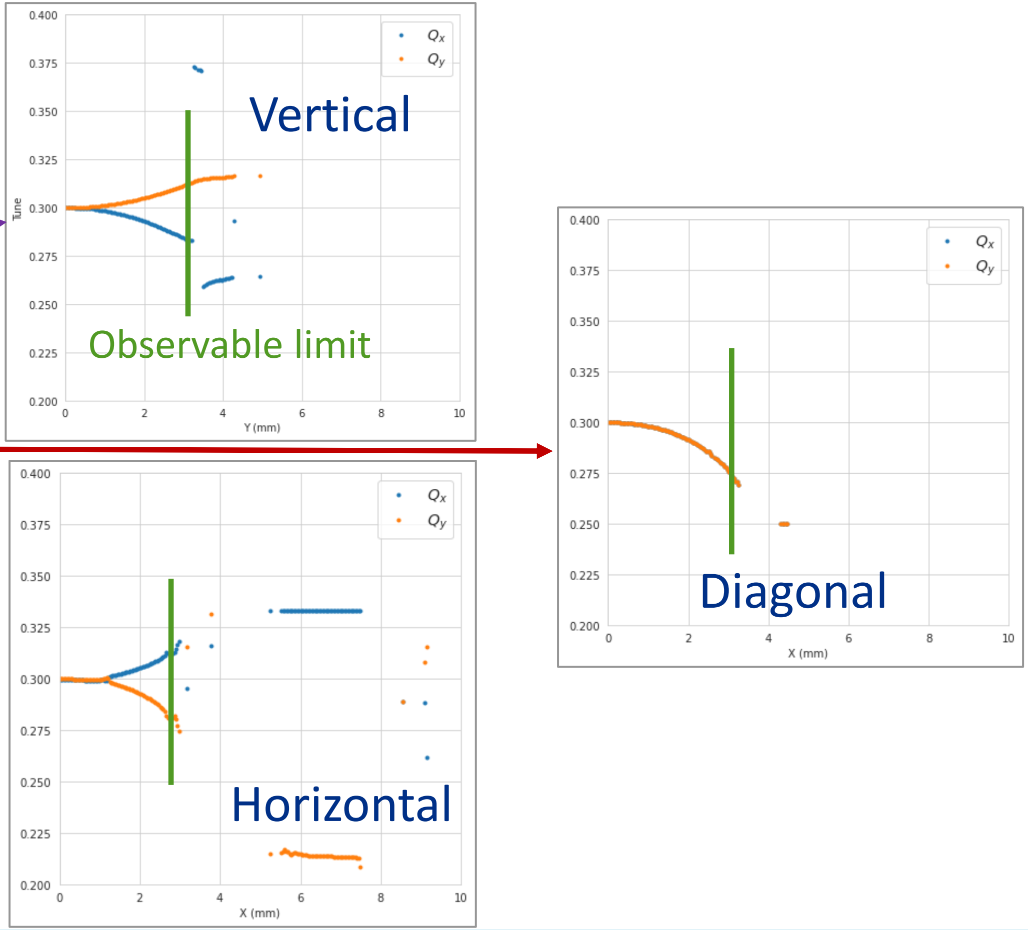
Sextupoles + octupoles



Color scale – diffusion (how chaotic)

Simulation predictions





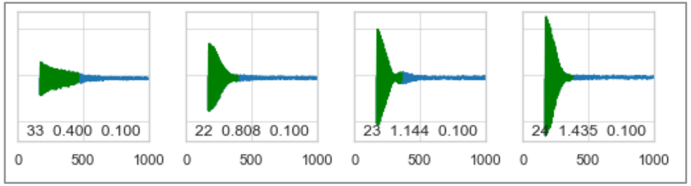
- Of interest to measure in 3 lines, 1 per sector

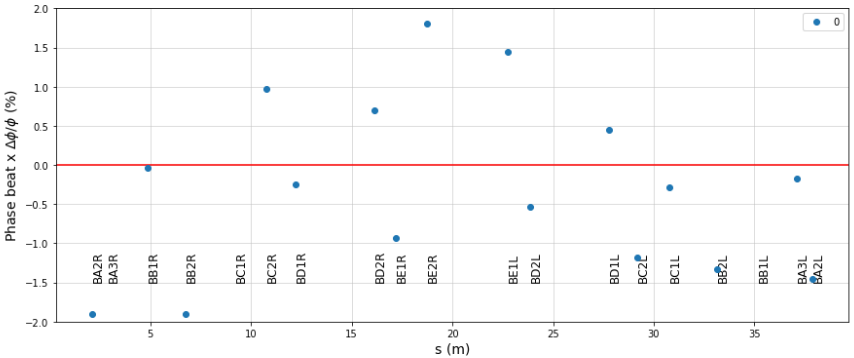
Outline

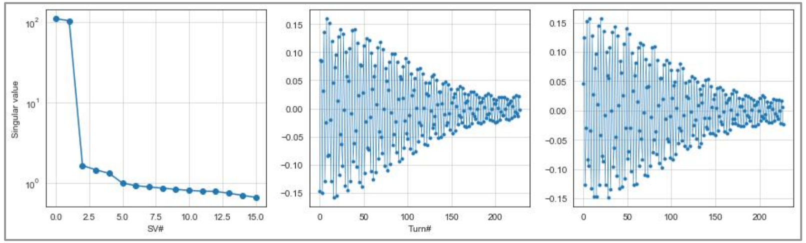
- Previous results and run 2 goals
- Run 2 configuration
- Run 2 commissioning
- Data collection
- Simulations
- Analysis

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 jitter



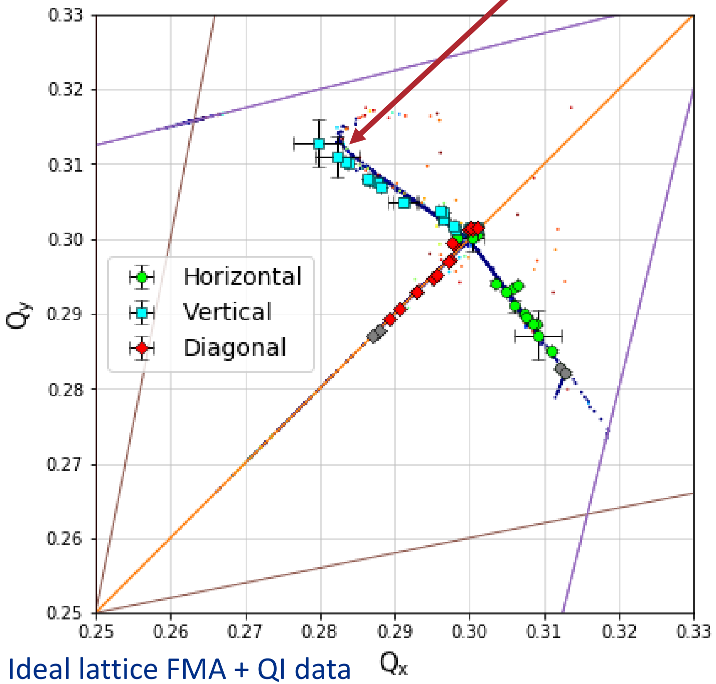




Results – stage 1

- Nominal config – 1.0A QI (central octupole)
  - No time for aperture scans – estimate from BPM sum
  - Good match with FMA simulations
  - Similar results at 0.75A/1.25A

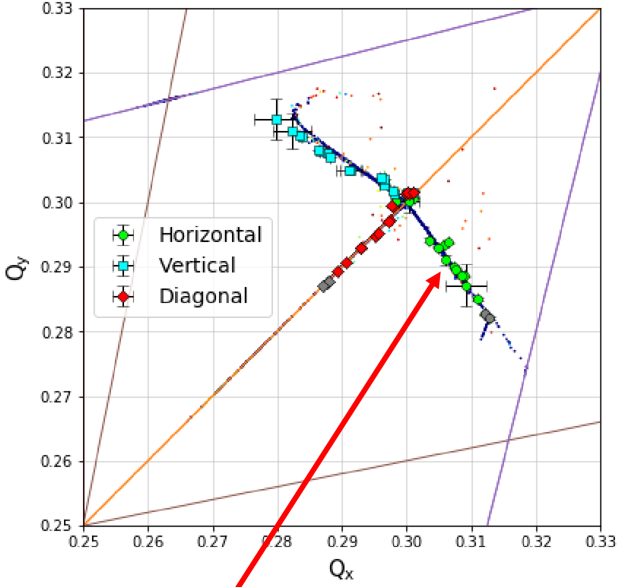
Note discrepancy



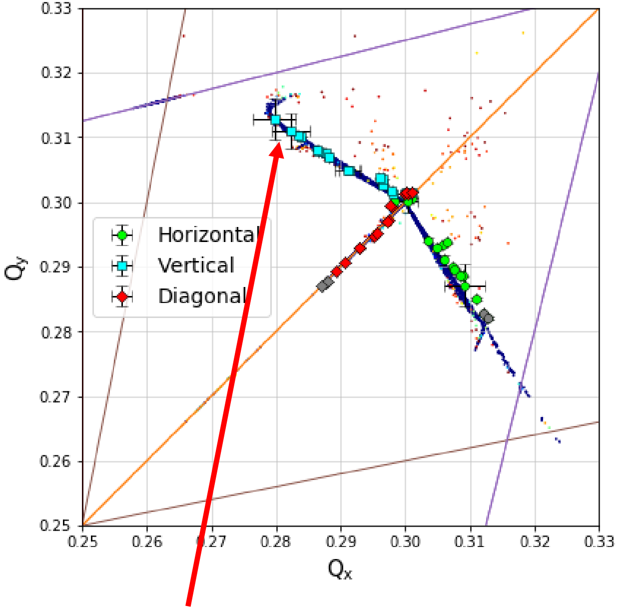
Ideal lattice FMA + QI data

Results – stage 1

- Nominal config – 1.0A QI (central octupole)
  - Discrepancy in H/V due to different (sextupolar) detuning – result of mystery chromaticity



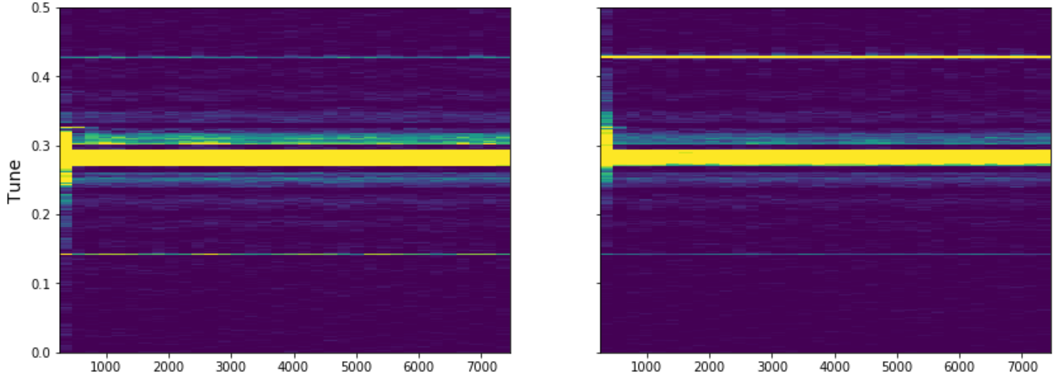
ξ=0 matches H branch



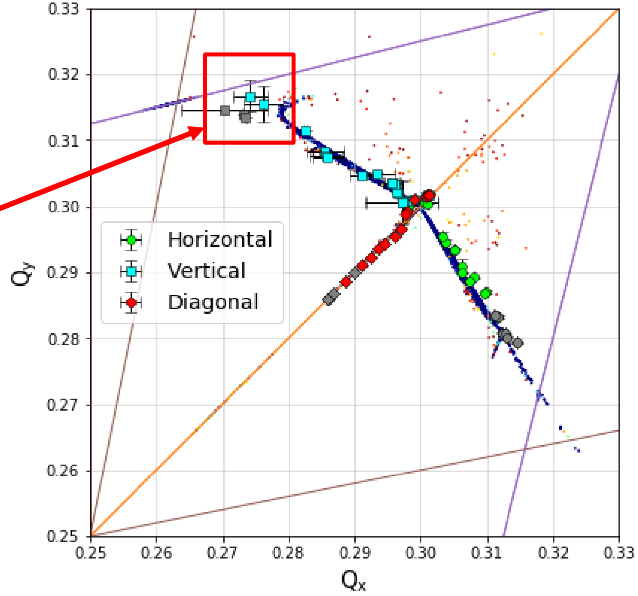
ξ=-2 matches V branch

Results – stage 1

- Comparison with 0.25A flat distribution ('conventional octupole')
  - Has ~ same detuning strength
  - But loses more beam at same amplitude
  - Weird resonant excitations overwhelm signal



Signal spectrogram



Ideal lattice FMA + flat data

Results – stage 1

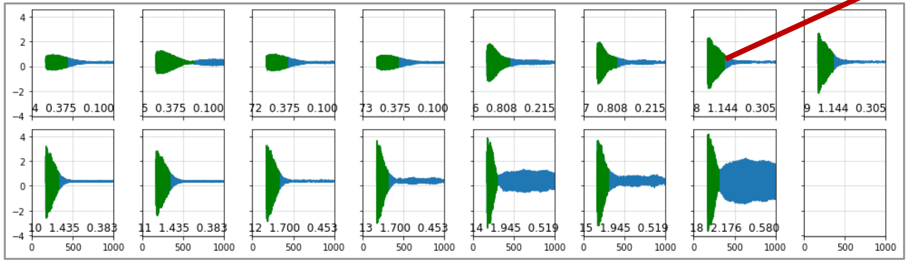
- Looking at invariants
  - Analysis ongoing – signal zoo, a lot of manual tweaking, complicated coupling
  - Preliminary data using SVD modes
  - Can't compare to simulations quantitatively yet (beam size matters, need good bunch estimate)

Strength parameter

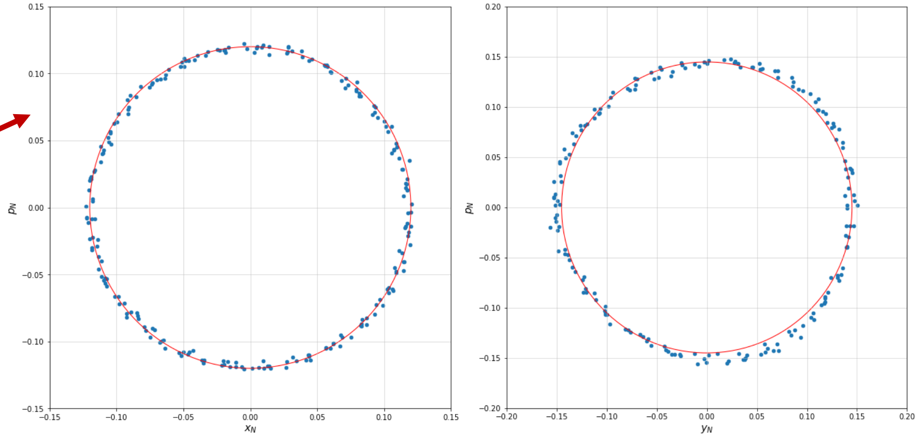
$$H = H_0 + U = \frac{1}{2}\left(P_x^2 + P_y^2 + x_N^2 + y_N^2\right) + \alpha\left(\frac{x_N^4}{4} + \frac{y_N^4}{4} - \frac{3x_N^2 y_N^2}{2}\right)$$

CS linear part

QI



Diagonal kick data

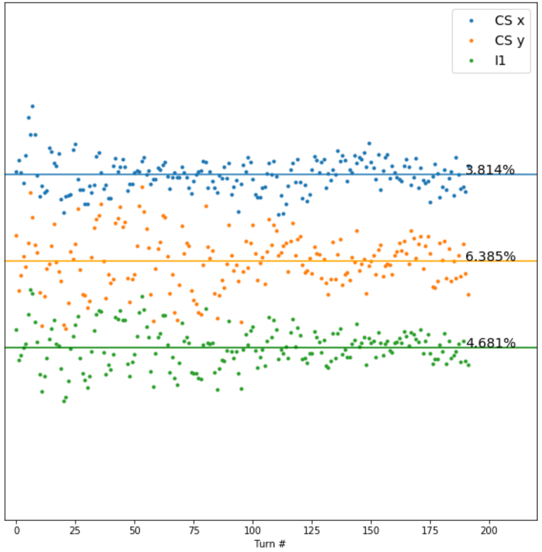


Normalized phase space after decoherence compensation

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

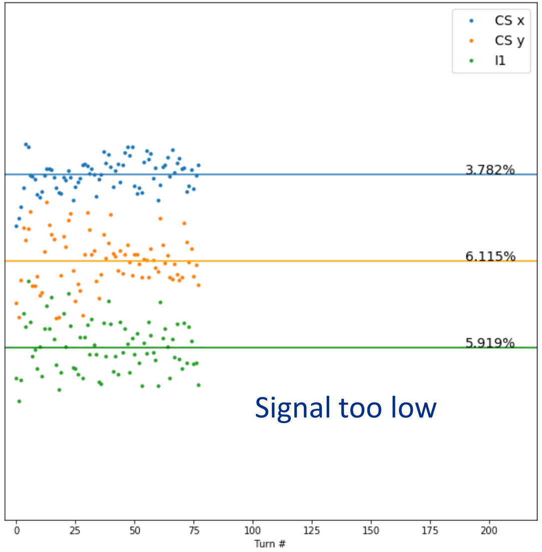


1.0A nominal

=

=

<



I1

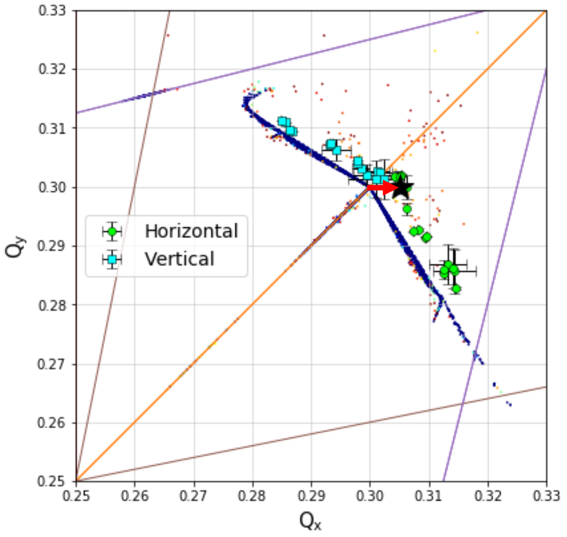
0.25A flat

Results – stage 2

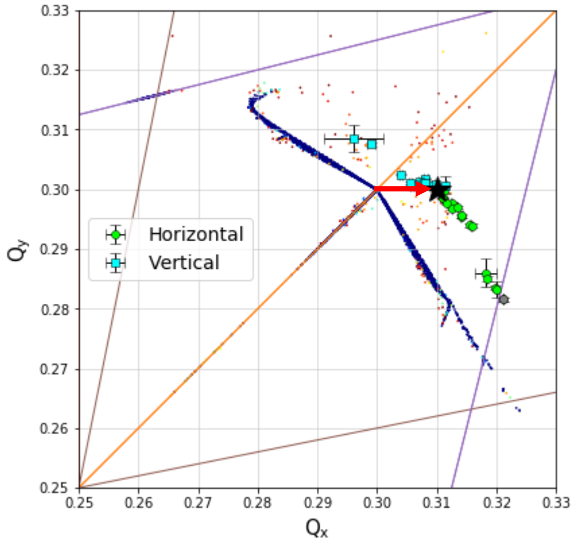
- Available perturbations - a mixed bag, sparse sampling
  - Δν inside insert
  - Δν ring (outside insert)
  - β*
  - Insert currents (i.e. ν=5.31 curve)
  - D_x

Results – stage 2

- 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

Conclusion

- Run 2 has produced significant improvements in data quality

- We demonstrated performance consistent with simulations
  - High tune spread
  - Invariant conservation
  - Superior performance vs flat arrangement
  - Stage 2 perturbation analysis ongoing

- Further required work
  - Characterization of ring nonlinearities
  - Resolving misalignment mysteries
  - Hardware - optics fluctuations fix + full 12 sextupoles (major DA boost!)

Thanks!
Questions?