IOTA run 2 NIO implementation and first results

Nikita Kuklev and IOTA NL team
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Outline

• Previous results and run 2 goals
  • Run 2 configuration
  • Run 2 commissioning
  • Data collection
  • Simulations
  • Analysis
Run 1 – partial success

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

- In run 1, measured significant tune spread, $\sim 0.6x$ of simulated performance

- Did not get invariants to sufficient accuracy

- Limitations:
  - Insufficient BPM resolution
  - Bent pipe aperture restriction
  - Only V-kicker control
Run 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

Needs new lattice design/tuning

Uses same base, nominal lattice
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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)
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Commissioning

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

• Lattice: LOCO provided best precision
  – $\beta$ 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 \((x,y) = (0,0) < \text{model}\)
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/timeout
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
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](image1)

![Magnet offsets (A. Romanov)](image2)
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
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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 pylOTA: 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
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Simulations

• Heavy simulations with elegant, via pylOTA 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
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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
Results – stage 1

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

\[ \xi = 0 \] matches H branch

\[ \xi = -2 \] 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
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)

\[
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\]
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

1.0A nominal

0.25A flat
Results – stage 2

• Available perturbations - a mixed bag, sparse sampling
  – $\Delta \nu$ inside insert
  – $\Delta \nu$ ring (outside insert)
  – $\beta^*$
  – Insert currents (i.e. $\nu=5.31$ 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
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?