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IOTA RUN 2 BEAM DYNAMICS STUDIES IN NONLINEAR INTEGRABLE SYSTEMS*

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Abstract

Nonlinear integrable optics is a promising design approach for suppressing fast collective instabilities. To study it experimentally, a new storage ring, the Integrable Optics Test Accelerator (IOTA), was built at Fermilab. IOTA has recently completed its second scientific run, incorporating many hardware and instrumentation improvements. This report presents the results of the two integrable optics experiments - the quasi-integrable Henon-Heiles octupole system and the fully integrable Danilov-Nagaitsev system. We demonstrate tune spread and dynamic aperture in agreement with tracking simulations, and a stable crossing of the integer resonance. Based on recovered single-particle phase space dynamics, we show improved invariant jitter consistent with intended effective Hamiltonian. We conclude by outlining future plans and efforts towards proton studies and larger designs.

INTRODUCTION

One of major factors limiting peak current in circular accelerators are beam losses. Particles are lost through a variety of both coherent and incoherent (single-particle) processes - of special concern for future hadron machine are the high intensity collective effects. The standard approach to stabilize such beams is to use nonlinear elements like octupoles to produce amplitude-dependent betatron tune spread [1]. This suppresses both longitudinal and transverse instabilities by preventing resonant energy coupling to particles, and is known as Landau damping. The disadvantage of this approach is dynamic aperture reduction, again leading to beam losses [2]. Recently, a new nonlinear focusing system was proposed by Danilov and Nagaitsev (DN) [3] that is predicted to achieve significant tune spreads without such negative effects though careful shaping of the magnetic potential and special requirements on lattice optics. To test this concept, the Integrable Optics Test Accelerator (IOTA) storage ring was constructed at Fermilab [4]. In this paper we report results of IOTA run 2 nonlinear optics studies.

INTEGRABLE OPTICS

Modern accelerator designs are based on a strong-focusing linear lattice, which has no tune spread and is fully integrable - it has the same number of conserved dynamic quantities, Courant-Snyder (CS) invariants, as degrees of freedom, and so particle motion is regular everywhere. Due to misalignments, field errors, and the need to correct chromaticity and induce tune spread, real accelerators are slightly nonlinear, and so no longer have CS invariants. Their regular motion is limited to a finite region, called the dynamic aperture (DA) - preserving DA size is critical for achieving good performance. Transverse beam dynamics are described by the Hamiltonian

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

with $K_{z=x,y}$ being the linear focusing strength, and $V(x, y, s)$ containing nonlinear terms (dependent on time ($\equiv s$) and transverse (x, y) position). DN approach is to seek solutions for V that yield two invariants and are also implementable with conventional magnets. First invariant comes from time scaling of $V(x, y)$ to obtain time-independent potential $U(x_N, y_N)$ in normalized CS coordinates. Then, solving for a specific transverse form of $U(x_N, y_N)$ (DN solution) yields another invariant of motion. Such system is both nonlinear and fully integrable. Conveniently, the first nonlinear multipole in the DN solution is an octupole, and has potential of the form

$$V(x, y, s) = \frac{\alpha}{\beta(s)^3}\left(\frac{x^4}{4} + \frac{y^4}{4} - \frac{3x^2y^2}{2}\right),$$

where $\alpha\,(\mathrm{m}^{-1})$ is the strength parameter. Using only this multipole produces a system of so-called Henon-Heiles type [5]. It has a single invariant of motion, and is hence only quasi-integrable (QI), with finite DA. While QI system does not produce as large of a tune spread as DN one, even a single invariant is highly beneficial for particle stability. Moreover, QI is easily implementable with standard octupole magnets and is predicted to be significantly more robust to misalignments and other lattice errors [6]. As such, in IOTA both QI and DN systems are studied.

EXPERIMENTAL SETUP

IOTA is a research electron and proton storage ring recently commissioned at Fermilab FAST facility. It is designed to use either 2.5 MeV protons, or 150 MeV electrons (100 MeV used for run 2). IOTA lattice is shown in Fig. 1. An extensive beam diagnostics suite is available, including electrostatic beam position monitors (BPMs) and independent vertical and horizontal single-turn kickers.

The QI insert is comprised of 17 equidistant air-cooled iron yoke octupoles that approximate piecewise the QI potential. A manual laser-guided alignment method (with pinhole markers) was used for relative alignment, with insert

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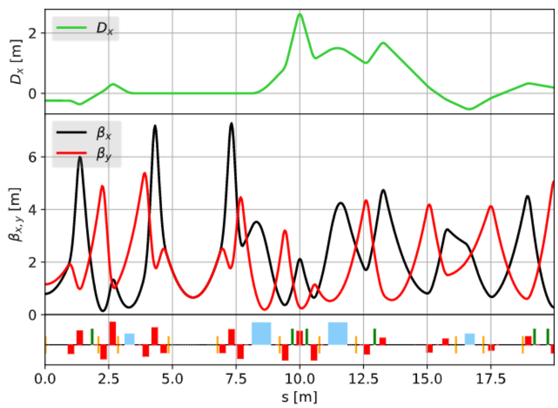

Figure 1: Half of IOTA lattice at working point $Q_{x,y} = 5.3$. All units in meters, bottom - $\beta_{x,y}$, top - D_x.

endpoints laser tracker referenced to the rest of the ring. Beam-based measurements were used to estimate the center-to-center shifts at 200 µm rms transversely (except for 2 outliers).

The DN insert has a similar design with 18 separate magnets, but due to complex pole profile and changing aperture also includes an integrated vacuum chamber. Due to tight tolerance requirements, it was aligned to a higher precision of 50 µm rms using the vibrating wire method. This alignment was also verified with beam-based measurements.

A number of improvements were implemented in IOTA based on run 1 results [7]. Four new chromatic sextupoles were added, enabling chromatic decoherence compensation at the cost of introducing extra nonlinearities. BPM analog frontends were overhauled, improving signal-to-noise ratio and achieving 100 µm rms precision in turn by turn (TBT) mode at currents above 0.8 mA, with linearity deviations below 1%. Edge field correctors were added to main dipoles to address path length discrepancies, and a number of smaller fixes implemented, improving operational uptime.

Data Collection and Analysis

For both QI and DN systems, we collected TBT data after pinging the beam in X/Y parameter space (grid pattern) for several lattice configurations. At each kick with acceptable beam losses and current, arrays of 8000 turns from 21 BPMs were recorded for offline processing. Given the inherently strong nonlinearities and the relatively large beam size due to IBS and lattice optics, signal decoherence was very fast (<150 turns) even with chromaticity compensation. Extensive data processing techniques were developed to achieve sufficient accuracy in such challenging conditions. Our code is publicly available as part of pyIOTA package [8], and only a brief outline is given here.

Data is first preprocessed to remove bad or suspicious signals with veto voting filters, and then cleaned with SVD. Signal regions with sufficient SNR are processed further. Tune algorithm used is modified NAFF [9], but with adaptive windowing and decoherence phase correction. Phase space algorithm uses standard linear optics solution applied to the best available BPM pair, taking into account observed noise levels, signal amplitudes, and phase advances. We present a novel extension of this algorithm to multiple pairs ("N-BPM") in another paper [10], but it was not used for current preliminary analysis. Decoherence compensation was done with MCMC fitting of 1D octupolar and chromatic decoherence envelope [11]. Reference simulation results were obtained with 6D symplectic tracking in elegant.

RESULTS

Tune Footprints

The main figure of merit for NIO systems is tune spread within the available DA. For QI, previous simulations found optimal insert strength at ~1A in the central octupole. Experimentally, this configuration showed tune shifts of $\Delta Q_{x,y} = 0.035 \pm 0.003$ in both planes, for overall tune spread of $\Delta Q = 0.05$, as shown in Fig. 2. Data is in very good agreement with simulations, with slight systematic offset in branch slopes that is attributed to suspected main dipole sextupolar detuning effects. A direct benchmark for QI system is a configuration with flat octupole current profile but same detuning strength. Its observed tune footprint (not shown) was much smaller due earlier beam losses (DA ~ 70% of QI), and significant resonant capture at higher kick amplitudes.

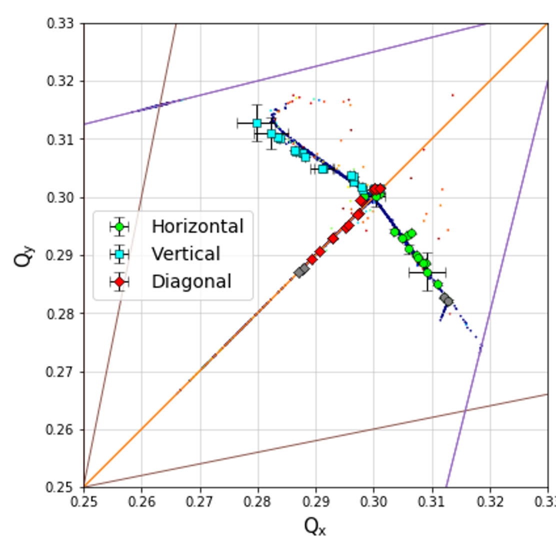

Figure 2: QI tune map at nominal 1.0A current overlaid with FMA simulation (dark blue). Gray markers indicate significant but not total beam losses.

Similarly good performance was observed with DN system, as is shown in Fig. 3. At dimensionless strength of $t = 0.218$, a tune spread of $\Delta Q = 0.06 \pm 0.002$ was achieved.

Note how in Fig. 3, small amplitude tune has shifted from nominal due to quadrupole component of DN potential. By continuing to increase insert strength, it is possible to approach $Q_y = 5.0$ resonance at critical strength value of $t = 0.5$. Experimental scans across $t = 0.5$ (not shown) resulted in only minor beam losses and transition into a new,

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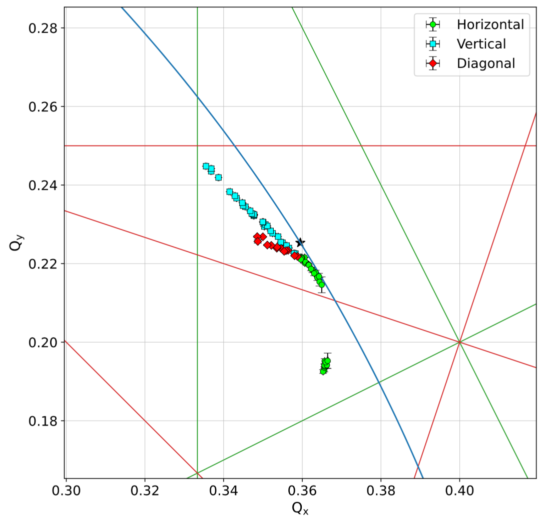

Figure 3: DN tune map at $t = 0.218$. Theoretical small amplitude tune is denoted with a black star.

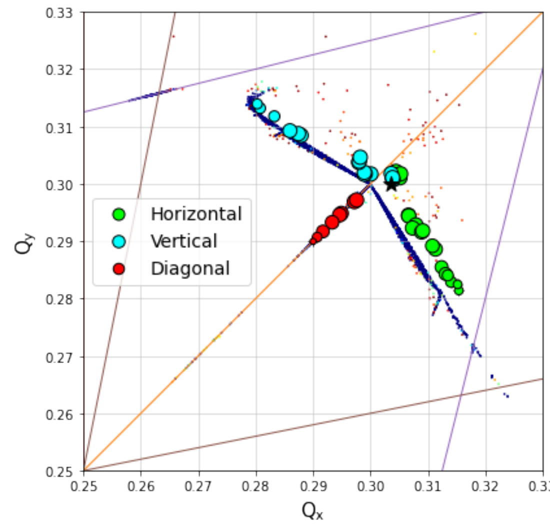

Figure 4: QI tune map at nominal 1.0A current and working point error of $\Delta Q_x = +0.003$, overlaid with nominal FMA simulation. Decreasing marker size denotes beam losses.

two-orbit topology, consistent with theory. This remarkable result is in contradiction with textbook resonance analysis. To our knowledge, it is the first demonstration of slow integer crossing and highlights the strength of DN system in instability suppression.

Error Tolerances

Given the enormous parameter space, only a few general optics and magnet error categories were tested experimentally. We varied the phase advance within the insert $\pm 0.01 Q_x/Q_y$ (equivalent to β^* or current profile mismatch), the longitudinal location of β-function minimum ($\pm$10 cm), dispersion ($\pm$10 cm), the current in individual octupoles ($\pm$10%), and the overall current profile (equivalent of $\pm 0.01 Q$). We focused on QI system due to higher data quality, and for each category found that performance degradation was small, below 15%, showing high system robustness. An example of such a perturbation, $\Delta Q_x = +0.003$, is shown in Fig. 4, and demonstrates that while working point moved as expected, tune spread performance remained comparable to nominal one.

Phase Space and Invariants

Phase space measurements were limited to medium amplitude kicks so as to collect sufficient number of turns before decoherence. A representative result of QI kick is shown in Table 1.

Note that the reported jitter (also referred to as smear in older literature) is a relative quantity defined as $(\sigma_I/\bar{I})$, where I is a linear Courant-Snyder or a DN/QI nonlinear invariant. With this normalization, and ensuring equal detuning with amplitude in both systems, a meaningful comparison can be made. Namely, results in Table 1 indicate significantly better conservation of QI Hamiltonian in the QI system, while the linear CS invariant results are comparable. This suggests QI system is more integrable, and

Table 1: Summary of Octupole QI and Flat Jitter Results for a Kick at Half the Available DA. Number of Turns Indicates Interval after Kick with Sufficient BPM Signal

Invariant	Jitter QI	Turns QI	Jitter flat	Turns flat
CS_x	3.84%	190	3.78%	80
CS_y	6.38%	210	6.11%	100
H_{QI}	4.68%	190	5.91%	80

supports larger observed DA. Qualitatively, these jitter trends are matched by simulations, but in all cases the expected jitter is lower than what was observed. We attribute this to an idealistic BPM model, as well as unaccounted element nonlinearities (outside insert), and are working to tune our model based on experimental results.

SUMMARY AND FUTURE PLANS

We have presented successful implementations of QI and DN nonlinear integrable systems - demonstrated results are in agreement with theoretical and simulation predictions, including large tune spread and improved conservation of invariants. While current studies focused on single-particle dynamics, for the next run IOTA will commission the proton injector, allowing for direct tests of space charge dominated regimes and collective instabilities. Furthermore, incremental upgrades including addition of 8 more sextupoles and new BPM electronics, as well as raising ring energy, will improve TBT signal quality significantly and allow further exploration of lattice and insert parameter spaces. Beyond purely academic interest, NIO is a potential option in several proposed accelerators, notably the rapid cycling synchrotron for Fermilab proton upgrade program (PIP-III) - results of current electron and upcoming proton studies will have a large impact on final design decisions of these projects.

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