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EXPERIMENTAL STUDIES OF SINGLE INVARIANT QUASI-INTEGRABLE NONLINEAR OPTICS AT IOTA*

N. Kuklev†, Y.-K. Kim, University of Chicago, Chicago, IL, USA
S. Nagaitsev, A. Romanov, A. Valishev, Fermilab, Batavia, IL, USA

Abstract

The Integrable Optics Test Accelerator is a research electron and proton storage ring recently commissioned at the Fermilab Accelerator Science and Technology facility. Its research program is focused on testing novel techniques for improving beam stability and quality, notably the concept of non-linear integrable optics. In this paper, we report on run 1 results of experimental studies of a quasi-integrable transverse focusing system with one invariant of motion, a Henon-Heiles type system implemented with octupole magnets. Good agreement with simulations is demonstrated on key parameters of achievable tune spread, dynamic aperture, and invariant conservation. We also outline current simulation and hardware improvement efforts for run 2, planned for fall of 2019.

INTRODUCTION

One of key factors limiting beam intensity in modern circular accelerators are collective instabilities, which can be suppressed by amplitude-dependent tune shift through Laundau damping, or in case of slow instabilities by an external damper. Tune spreads are conventionally produced with standalone octupoles distributed around the ring, as is the case for LHC [1]. The disadvantage of using octupoles, and most other nonlinear elements, is the appearance of resonant behavior, leading to chaotic and unbounded motion, and eventual particle loss [2]. Recently, a new nonlinear focusing system was proposed by Danilov and Nagaitsev (DN) [3] that can achieve significant tune spreads without such detrimental effects. To test this concept, the Integrable Optics Test Accelerator (IOTA) storage ring was constructed at Fermilab, and has recently finished its year 1 commissioning and scientific run [4]. In this paper, we discuss the obtained results as well as plans for run 2, scheduled for fall of 2019.

INTEGRABLE OPTICS

The basis of all strong-focusing lattices is a linear system that has no amplitude-dependent tune shifts and is fully integrable - that is, it has the same number of conserved dynamic quantities (Courant-Snyder invariants) as degrees of freedom, and so particle motion is regular for any initial conditions. Due to misalignments, field errors, and the need to correct chromaticity and induce tune spread, real accelerators have significant nonlinearities which break exact CS invariant conservation. Their set of initial conditions with regular motion is limited to a finite region, called the dynamic aperture (DA) - preserving its size is critical for achieving good accelerator performance. Mathematically, transverse particle dynamics can be 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 any nonlinear terms (in general dependent on time ($\equiv s$) and transverse (x,y) position). DN approach is to seek solutions for V that yield two invariants of motion and also are implementable with conventional magnets. First invariant comes from appropriate time scaling of $V(x,y)$, such that it becomes a time-independent potential $U(x_N,y_N)$ in normalized coordinates, namely

$$z_N = \frac{z}{\sqrt{\beta(s)}} \qquad p_N = p\sqrt{\beta(s)} - \frac{\beta'(s)}{2\sqrt{\beta(s)}}$$

It is furthermore possible to derive a specific form of $U(x_N,y_N)$ (DN solution) that yields another invariant of motion. Such system is both nonlinear and fully integrable, and its experimental demonstration is the ultimate goal of IOTA. However, this is a difficult task due complex field shape, and extremely small tolerances on optics and field errors [5]. Conveniently, the first nonlinear term in the DN potential multipole expansion is that of a spatially varying octupole, which produces tune shift ΔQ_z quadratic with particle oscillation amplitude, 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 component instead of full DN potential gives a system of so-called Henon-Heiles type [6], first studied in the context of galaxy dynamics, and known to have rich dynamical behavior. It has a single invariant of motion, and is hence only quasi-integrable, with finite DA. However, even a single invariant is highly beneficial for particle stability, and unlike the DN potential, this system is easily implementable with conventional magnet designs and predicted to be highly robust to misalignments and other lattice errors [7], making it the perfect first nonlinear optics system to test at IOTA.

EXPERIMENTAL SETUP

IOTA is a research electron and proton storage ring recently commissioned at Fermilab's Accelerator Science and

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[†] nkuklev@uchicago.edu

Technology (FAST) facility. It has a circumference of 40m, and is designed to use either 2.5 MeV protons provided by an RFQ injector, or 150 MeV electrons from FAST linac. The lattice, shown in Fig. 1, has mirror symmetry with two 1.8m nonlinear element-compatible drifts and can be configured to satisfy all the necessary integrability constraints. An extensive suite of beam diagnostic systems is installed, that provides capabilities both for the beam-based alignment at required precision, and the subsequent turn-by-turn dynamics analysis. Two independent single-turn kickers, vertical and horizontal, allow for beam 'pings' to anywhere in the available aperture.

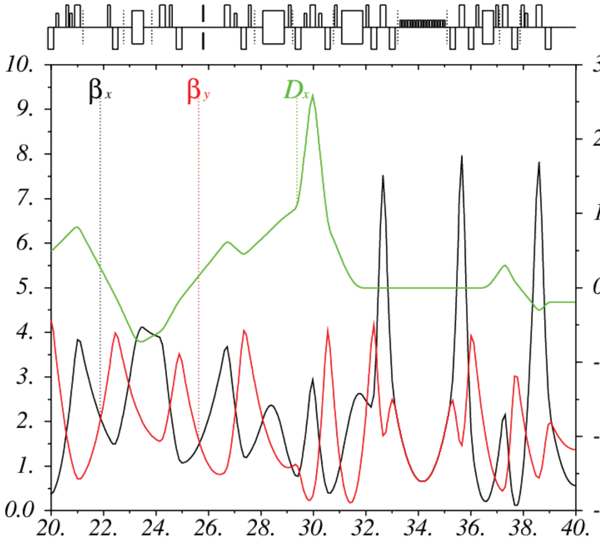

Figure 1: Half of IOTA lattice at working point $Q_{x,y}$=5.3. All units in meters, $\beta_{x,y}$ on the left, D_x on the right. Lattice is mirror symmetric across 20m marker.

The octupole insert is shown in Fig. 2 - it is comprised of 17 equidistant air-cooled iron yoke octupoles with 28mm aperture and 7cm length, that are designed to approximate piecewise the ideal continuous octupole potential. Each magnet is individually powered by a 2A bipolar supply ($K_{3\,max}$ = 1.4kG/cm^3). Alignment was done using manual laser-guided method (with pinhole markers), with subsequent beam-based measurements indicating center-to-center shifts of 200 µm rms transversely, within the design specifications.

Data Collection

The key advantage of integrable systems is improved DA at same tune shift, or alternatively a higher maximum tune shift without beam losses. To measure these figures of merit, we first determined the DA boundary by repeatedly pinging the beam to a certain amplitude with octupole insert on or off, and recording the current. Iteratively, kick strength was maximized until degradation in lifetime relative to control run was observed at very low currents (<0.1mA, to minimize intra-beam scattering). Corresponding amplitude was then taken as a DA limit.

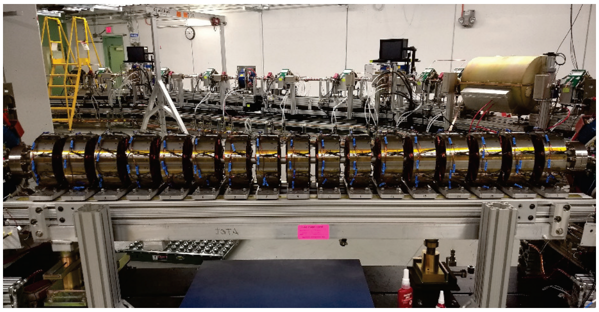

Figure 2: IOTA octupole insert in segment B2L. RF cavity and synchrotron radiation diagnostics in the background.

For above identified points, pings were repeated at high beam currents (>1mA) to obtain accurate and linear turn-by-turn BPM data. Arrays of 2000 turns from 21 BPMs were recorded, of which 17 were used for analysis. Due to large chromaticity and momentum spread, signal decoherence was very fast (150 turns), and extensive data processing techniques were required for sufficient tune resolution ($<10^{-4}$). Core algorithm was implemented in Python 3, based on iterative coupled mode unmixing technique [8] and subsequent NAFF analysis [9] of combined (M BPMs × N turns) hybrid datasets [10]. For all runs, beam was kicked in both planes simultaneously, ensuring sufficient signal regardless of coupling strength. Unfortunately, due to power supply limitations, weak h-plane kick and hence signal prevented invariant reconstruction to the desired precision, and further software development is in progress to combine BPM data for increased signal-to-noise ratio. Reference simulation results were obtained by long-term symplectic particle tracking and frequency map analysis (FMA) [11] with tracking code 'elegant', using complete experimental lattice but with no field errors or misalignments.

RESULTS

Dynamic Aperture

A selection of extinction scans are plotted in Fig. 3, demonstrating different beam loss rates observed for varying combinations of octupole insert strength and kick amplitude. Note how small, 10% changes in either parameter immediately spoiled beam lifetime (green and purple lines), indicating that 1.0A/4.5kV and 1.1A/4.2kV are very close to DA limit and hence good candidates for further kick analysis.

Tune Shift

Points of interest identified above were tested to find the largest tune shifts. Previous simulations have found optimum insert strength to occur with ~1A in the central octupole - experimental data is in agreement, with best tune shift obtained at 1.1A/4.2kV, corresponding to physical amplitude of 3.85mm in the middle of the nonlinear drift. We observed tune shifts of $\Delta Q_x = -0.030 \pm 0.003$ and $\Delta Q_y = +0.013 \pm 0.001$, as shown in Fig. 4, with near -2:1 ΔQ_x:ΔQ_y ratio being consistent with theoretical predictions.

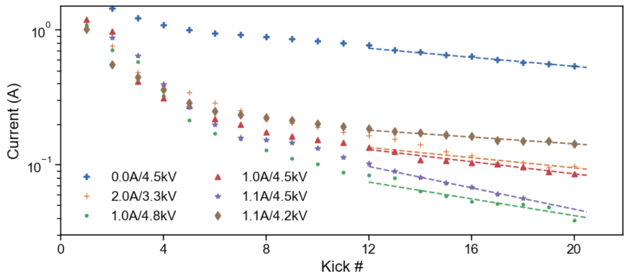

Figure 3: Semilog plot of extinction scan currents. Kicks were performed every 20 seconds. Dotted lines are linear fits to low current data.

As compared to simulations, only ~70% of the expected performance was achieved, which nonetheless significantly exceeded equivalent single octupole results (not shown). We attribute this shortcoming to the lack of chromaticity correction and overall alignment and power supply drift issues that introduced systematic and yet time-dependent lattice errors.

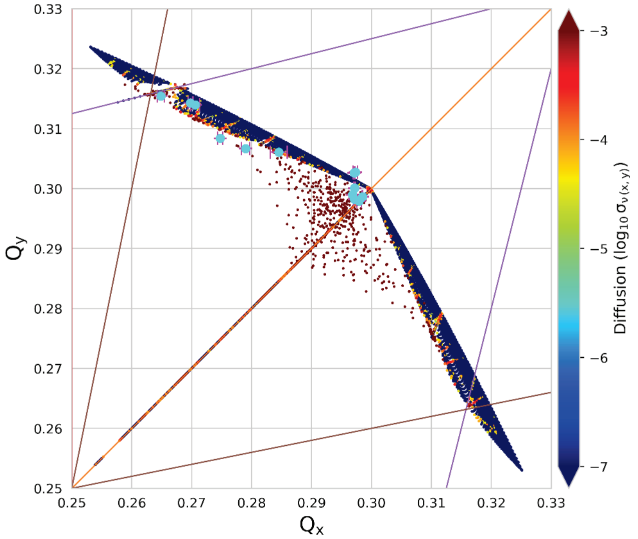

Figure 4: Experimental tune shifts (in cyan, 3σ error bars in magenta) for various kicks overlaid with simulated FMA. Background density denotes amount of tune diffusion, as determined by sliding window NAFF of 8192 turns, with red indicating more chaotic regions and white particle loss. Small tune shift points are offset due to residual coupling.

Effects of optics errors and resonances

Several categories of optics and magnet errors were tested experimentally - 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 (± 10 cm), and the current in individual octupoles ($\pm 10\%$). For each category, we found that performance degradation was below 15%, thus showing high system resiliency.

Furthermore, phase advances within nonlinear drift were moved to $\mu_x/\mu_y = 0.26$ (with adjusted octupole current profile), while keeping integer phase advance within the rest of the lattice. Beam pings then rapidly brought Q_x down to $\sim= 0.24$, across the 1/4 resonance. During subsequent damping, over half the beam survived the reverse resonance crossing. With octupoles off, complete beam loss and generally poor injection efficiency was observed.

FUTURE PLANS

IOTA run 2 is scheduled to start in fall of 2019, with a number of planned upgrades, including full ring realignment, addition of 8 sextupoles, improvements in BPM system sensitivity, and more. These are expected to significantly improve limits on optics accuracy and stability faced during run 1.

In preparation, several efforts were started to better model and optimize performance of nonlinear inserts, such as nonlinear online correction algorithms development with use of machine learning techniques [12] and exploration of newly proposed alternative magnet/optics arrangements [13]. Several ancillary experiments are also planned for run 2, such as continuation anti-damper studies (simulating fast collective instabilities) and reconstruction of resonance crossing dynamics, which will provide supporting experimental evidence for the usefulness and practicality of nonlinear integrable inserts.

Finally, we also hope to apply all the above procedures to the fully integrable DN magnet, which has already been placed into the ring - several proposed accelerators, including the rapid cycling synchrotron for Fermilab proton upgrade program, incorporate nonlinear elements and will rely on this experimental data to guide final design.

SUMMARY

We have presented a successful implementation of the octupole Henon-Heiles quasi-integrable system with single invariant at IOTA. Our results show strong agreement with theoretical predictions, achieving 70% of ideal case performance and significantly exceeding that of an equivalent standalone element. A number of hardware and software upgrades are planned for run 2 that will enable even better system performance and more precise particle dynamics reconstruction.

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