ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS070

FIRST MEASUREMENTS OF NONLINEAR DECOHERENCE IN THE IOTA RING

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Abstract

The Integrable Optics Test Accelerator (IOTA), at Fermi National Laboratory is aimed at testing nonlinear optics for the next generation of high intensity rings. Through use of a special magnetic element the ring is designed to induce a large tune spread with amplitude while maintaining integrable motion. This will allow for the suppression of instabilities in high-intensity beams without significant reduction in dynamic aperture. One important aspect of this is the nonlinear decoherence that occurs when a beam is injected off axis or receives a transverse kick while circulating in the ring. This decoherence has been studied in detail, with simulations, for protons in IOTA both with and without space-charge. However, it has yet to be demonstrated experimentally. During the first phase of the IOTA experimental program, the ring is operated with 100 MeV electrons, allowing for the study of nonlinear optics without the complications introduced by space charge. Here we present measurements taken during the IOTA commissioning, and an analysis of the results.

INTRODUCTION

In many particle accelerators octupole magnets are used to introduce tune-dependence with amplitude and minimize collective effects. Introduction of nonlinear elements is necessary to avoid resonances that might be driven in a mostly linear lattice, however, the price for this damping effect is a reduction of dynamic aperture and loss of integrable motion. The Integrable Optics Test Accelerator (IOTA) [1] was constructed at Fermi National Laboratory to study methods of introducing nonlinearity to the accelerator lattice while retaining integrability. One method is to employ a special 'elliptic' potential [2] that allows for retention of integrability and may provide larger tune spreads and better dynamic aperture than could be achieved with a pure octupole.

Here we show results of an initial experiment to measure the rate of nonlinear decoherence provided by the nonlinear element. Measurements of the centroid damping rate for a kicked beam are shown with both the nonlinear magnet off and on. With the nonlinear element in place, the damping rate is significantly increased. Comparison of the experiment to calculations of the expected decoherence for the base lattice shows excellent agreement.

Elliptic Element

The nonlinear magnet constructed for IOTA uses the 'elliptic' potential described in [2]. This potential may be characterized in terms of a unitless strength parameter t and geometric scale factor c, with units of $m^{\frac{1}{2}}$, that describes the location of two singularities in the x-plane. The first few terms of the multipole expansion for the elliptic potential in normalized coordinates $\hat{x}, \hat{y} = x/\sqrt{\beta}, y/\sqrt{\beta}$ are given by [3]

$$U(\hat{x},\hat{y}) = \frac{-t}{c^2}\, Im\left\{(\hat{x}+i\hat{y})^2 + \frac{2}{3c^2}(\hat{x}+i\hat{y})^4 + \frac{8}{15c^4}(\hat{x}+i\hat{y})^6 + \ldots\right\}. \quad (1)$$

Though this expansion is only valid in the region $\sqrt{\hat{x}^2+\hat{y}^2} < c$ it does allow for approximation of the lowest order amplitude dependence in tune. This will be shown to yield reasonable agreement to simulations using the exact potential, as long as the emittance is sufficiently small.

IOTA

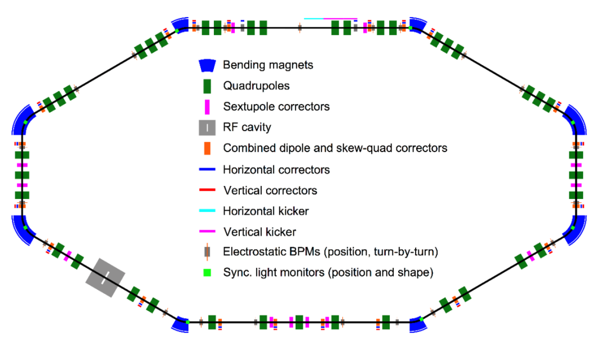

Figure 1: Schematic of IOTA showing position of major elements. The beam is injected in the center of section located at 12 o'clock and passes clockwise through the ring. The nonlinear magnet was placed in the empty section of the first quadrant.

IOTA is 40 m circumference ring (see the schematic in Fig. 1), built to accommodate 100 MeV to 150 MeV electrons injected from the FAST linac. Synchrotron light monitors are available in each dipole and twenty one BPMs are placed around the ring, twenty of which were available for the measurements shown here. Due to limitations in the injection system, electrons were injected into IOTA at 100 MeV for this experiment. The primary consequence of this is that the energy spread appears to be larger than what would otherwise be predicted at equilibrium, 2.5×10^{-4} versus 1×10^{-4}. The increased energy spread is believed to be

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due to intra-beam scattering. The injected beam current was normally started at 1.6 mA, with a nominal beam lifetime of thirty minutes. However, during measurement collection beam current could often dramatically drop as the lattice configuration was changed, particularly, when the nonlinear magnet was turned on.

Table 1: Nominal parameters for IOTA, relevant to the experiment. Values in parenthesis denote observed value that significantly differed from nominal settings.

Parameter	Value
ξ_x, ξ_y	-10.98, -6.48
ν_x, ν_y	0.3, 0.3
ν_s	5.3×10^{-4}
E	100 MeV
$\varepsilon_x, \varepsilon_y$	15 nm, 15 nm
σ_δ	1×10^{-4} (2.5×10^{-4})
I_e	0.3 mA to 1.6 mA

MEASUREMENTS

For this study, vertical and horizontal kickers were used to kick the beam. The vertical kicker is 120 cm long and the horizontal 60 cm. While the horizontal kicker is capable of kicks up to 2 kV, and the vertical kicker up to 25 kV there are physical aperture restrictions that prevent either kicker from being operated at maximum. In total there were twenty turn-by-turn beam position monitors (BPMs) used to measure the resulting centroid oscillations. The BPMs had a nominal resolution of about 100 µm RMS. Though resolution was significantly dependent on current in 0.3 mA to 1.6 mA range used for this experiment. For reliable measurements current above 0.3 mA was necessary or the BPM response became too nonlinear. All measurements shown here were taken from the BPM immediately downstream of the kickers.

Baseline Results

A series of measurements were taken without the nonlinear magnet powered to provide a baseline for the natural decoherence rate of the lattice. Several of these measurements are shown in Fig. 2. All centroid measurements have been shifted to place the average centroid at zero. For these measurements a range of vertical (y) kicks was used and the horizontal (x) kicker was kept at 2 kV. However, the fact the horizontal centroid offset does not peak until ~75 turns after the kick suggests the much of these oscillations may be due to some weak coupling transferring motion from the vertical plane.

With the nonlinear magnet turned off the decoherence observed may arise from two sources. The primary source is due to the natural energy spread of beam giving rise to a spread in tunes via coupling through the lattice's chromaticity. The second is from any other nonlinearities present in the lattice. These two effects are described by the following

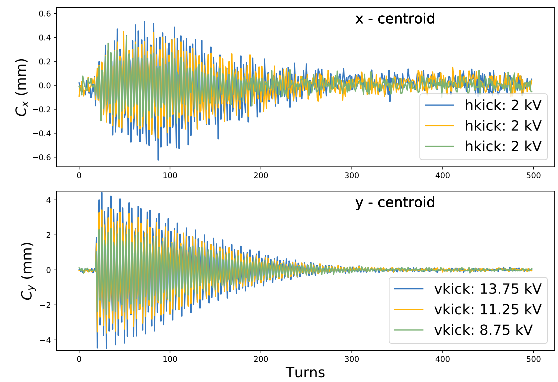

Figure 2: Centroid data for vertical and horizontal (top and bottom) taken from a BPM immediately after the kickers. The nonlinear element was powered down for this measurement.

equation for the centroid motion, C, of a kicked beam as a function of the turn number N from Meller et al. [4].

$$C(N) = \frac{1}{1+\theta^2} e^{-\frac{Z^2}{2}\frac{\theta^2}{1+\theta^2}} e^{-2\left(\frac{\xi_y \sigma_\delta}{\nu_s}\right)^2 \sin^2(\pi \nu_s N)}. \quad (2)$$

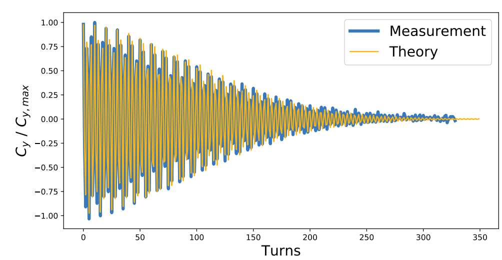

Figure 3: Vertical centroid motion, normalized to peak centroid offset, is shown for measurement with a vertical kick of 11.25 kV. The theoretical line is the plot of Eq. 2

The normalized kick strength is $Z = \beta_y \Delta y' / \sigma_y$ for an angular kick of $\Delta y'$ and $\theta = 4\pi a \varepsilon N$, where a is the coefficient for the quadratic tune dependence with amplitude. Using σ_δ and a as free parameters definitively shows that the expected, equilibrium energy spread of 1×10^{-4} is not sufficient to explain the rate and shape of the centroid decoherence. The presence of some octupole-based amplitude-dependent tune shift is less conclusive. Including a small factor of $a = 8 \times 10^{-3}\ \mathrm{m}^{-1}$ does improve the fit. This amounts to a maximum tune shift of about 0.5 % of the nominal tune. A comparison of Eq. 2 with these parameters to one of the measurements of vertical centroid oscillations is shown in Fig. 3 and gives excellent agreement.

Analysis of the baseline results though is complicated by the lower beam energy and higher current leading to current-dependent energy spread. Determining how much the energy spread might be changing from the measurements shown here is difficult, however, due to the inclusion of residual nonlinearity, both from small circumference of the ring and suspected orbit errors during the measurements.

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Nonlinear Magnet Turned On

Several measurements were taken with the nonlinear magnet powered on. It was found that switching on the nonlinear magnet often led to large drops in the beam current, making accurate measurements more difficult. However, several successful measurements were still collected. Shown in Fig. 4 are the centroid motion for two different kick strengths with the nonlinear magnet powered on.

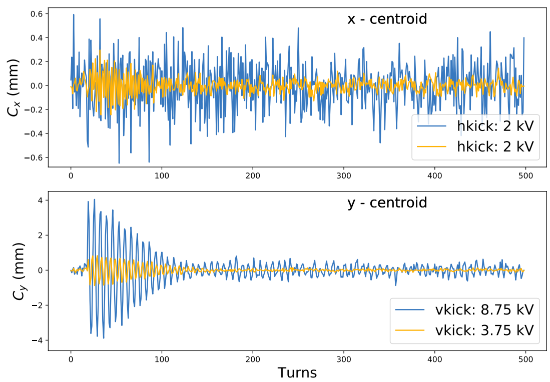

Figure 4: Horizontal and vertical (top and bottom) centroids taken from a BPM immediately after the kickers. The nonlineaer element was turned on for this measurement.

A comparison is made between measurements with the nonlinear magnet on and off in Fig. 5. The vertical centroid clearly shows a faster initial damping rate with the nonlinear magnet turned on, though the jitter in centroid motion remains much higher in the on case. The horizontal centroid shows no evidence of the kick it received. Comparing horizontal centroid motion between Fig. 4 and Fig. 2 does suggest that for an equivalent kick strength significantly less horizontal centroid motion develops. This may be due to the rapid vertical damping not allowing sufficient time for the weak coupling to transfer centroid motion into the horizontal plane.

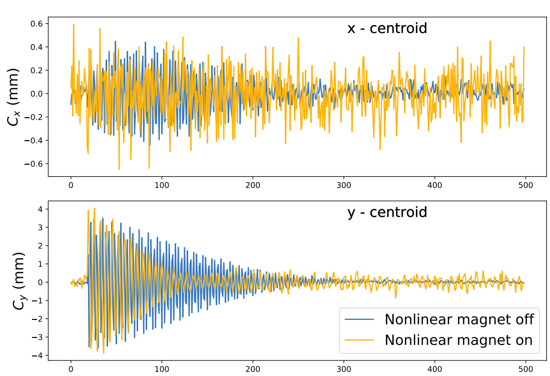

Figure 5: Horizontal and vertical (top and bottom) centroid data, comparing between the nonlinear magnet turned off (blue) and on (yellow).

CONCLUSION

An initial set of measurements has been performed in IOTA to test the capability of a special nonlinear magnet to provide nonlinear decoherence and stabilize against collective effects. Measurements show that it is possible to substantially improve damping times in the case of a kicked beam due to nonlinear decoherence provided by the nonlinear magnet. In the future, resolving orbit errors and minimizing current loss will be necessary for longer term tracking studies. While the decoherence behavior of the lattice without the nonlinear magnet is well understood, modeling of beam behavior with the nonlinear magnet has not shown good agreement to experiment thus far. Work is ongoing to see if this can be improved and develop some insight into the machine performance from simulations.

ACKNOWLEDGMENTS

This work has been supported by the U.S. Department of Energy Office of Science, Office of High Energy Physics under Award No. DE-SC00111340.

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