LATTICE REFINEMENTS FOR NONLINEAR INTEGRABLE OPTICS IN IOTA *

J. Wieland[†,1], A. Romanov, Fermilab, Batavia, IL, USA
[1]also at Michigan State University, East Lansing, MI

Abstract

Nonlinear integrable optics of the type proposed by Danilov and Nagaitsev place strict constraints on the lattice parameters in the matching section outside of the nonlinear insert. In particular, the effects of energy spread in the beam have significant effects on the stability of the system. Typical chromatic compensation using sextupoles has significant perturbative effects on the dynamics but is operationally necessary to suppress fast losses. Fast decoherence of kicked beam measurements limits the available signal for studies. Refinements to the IOTA lattice parameters based on this experience with electron beam operation are presented.

INTRODUCTION

The Integrable Optics Test Accelerator (IOTA) is a research and development storage ring dedicated to beam dynamics studies [1]. The namesake experiment at IOTA is an implementation of nonlinear integrable optics (NIO) of the type proposed by Danilov and Nagaitsev [2]. The NIO Hamiltonian combines strong amplitude dependent tune shift with bounded single particle trajectories, and is a promising system for intense beams. The NIO in IOTA consists of a unique string of magnets as a 1.8 m, 18 magnet insert into a 40 m typical linear storage ring, referred to as the matching lattice. The previous experiments in IOTA have been conducted with a 150 MeV electron beam [3, 4]. This beam has a short damping time and low emittance from synchrotron radiation and is used as a probe of the phase space of the system. In particular, turn-by-turn measurements of kicked beam are used for studies of the underlying dynamics. Some lattice related experimental shortcomings experienced and a series of simulation studies addressing them are presented.

EXPERIMENTAL SHORTCOMINGS

Operational experience with IOTA operations during the last runs has indicated a few deficiencies with the current matching lattice. The NIO system is designed around the matching lattice as an effective thin lens. With nonzero energy spread, this suggests zero dispersion and zero chromaticity through the NIO insert. Further studies [5] indicated that zeroing dispersion in the insert and matching chromaticities in the matching lattice was a sufficient condition. During previous experiments, the chromaticity was fully compensated with sextupoles for this condition, and to increase the

coherence time of kicked bunch measurements in the lattice without NIO excitation.

Additionally, without chromatic correction, significant losses were encountered while ramping the nonlinear insert. Figure 1 shows the comparison of circulating current as the nonlinear insert strength (t parameter) is ramped before and after compensation. Practically, this made the chromatic correction necessary to access higher nonlinear insert strengths.
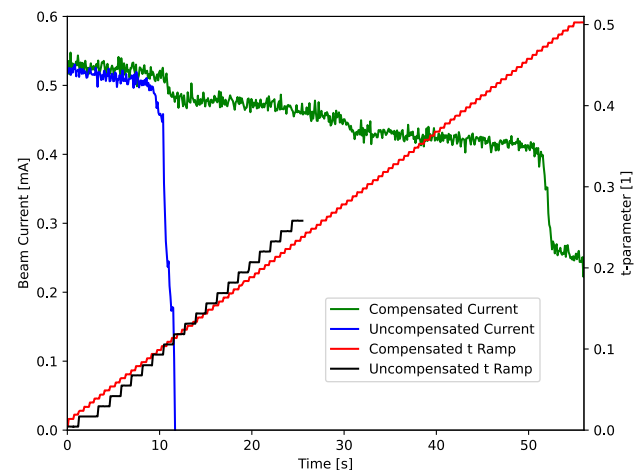

Figure 1: Experimental beam loss with and without chromatic compensation.

Kicked bunch measurements with the NIO insert exhibited fast decoherence, limiting the available signal for tune measurements and momentum reconstruction for studies. This stems from the tune footprint of the bunch at equilibrium emittance.

The basic transverse lattice requirements of the NIO system require 6 degrees of freedom to fully match. With the addition of dispersion suppression, this brings us to 7 degrees of freedom (assuming no coupling). IOTA is usually tuned to be mirror symmetric for convenience, which gives 20 quadrupole knobs, so there is available flexibility in the lattice for significant adjustments. The above shortcomings and available flexibility motivated considering adjustments to the IOTA linear lattice design for future experiments.

CHROMATICITY IMPACT ON INVARIANTS

As the chromaticity has demonstrated impacts on the integrability of the system, this was directly compared to a few different lattice configurations. Select configurations that were considered are presented in Fig. 2 as ImpactX [6] tracking simulations of tune dependence on energy offset. In two
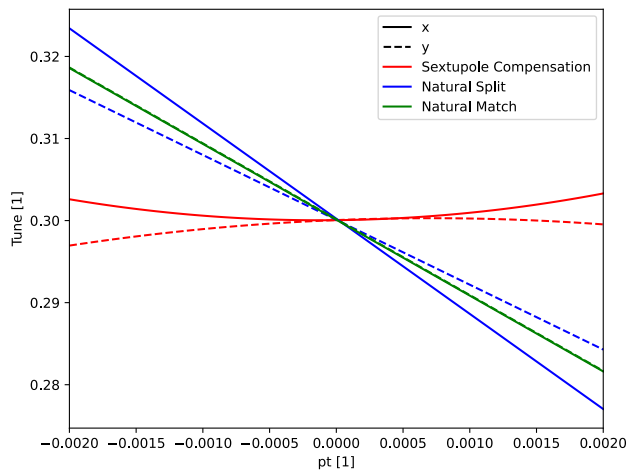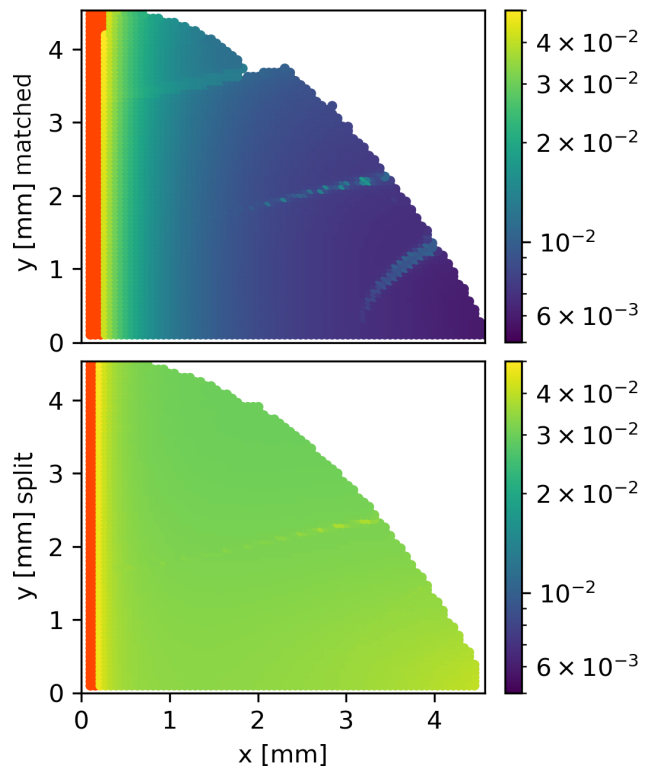
Figure 2: Chromaticity of different IOTA lattices.

configurations, the lattice was optimized for the natural chromaticity from the quadrupoles to either be split or matched. This was optimized in SixDSimulation [7] using available degrees of freedom. Typical chromatic compensation using sextupoles was also considered, note the higher order chromaticity visible in that case where the linear effects are compensated.

To evaluate the impact of the chromatic compensation approaches on the NIO system, the direct conservation of the analytically predicted invariants is compared. These quantities are directly calculated from turn-by-turn position and momentum coordinates and the varience can be be evaluated. Of course, by definition, this value is zero for the perfect analytical case but, the NIO condition is not perfectly matched in a realistic machine in two important ways. The most important effect is that the NIO insert potential is approximately integrated with 18 piecewise steps instead of a continuously longitudinally varying potential. Without energy spread effects and a perfect matching lattice, this approximation yields a fractional standard deviation on the order of 10^{-4} for the two predicted invariants in simulation. The second impact is imperfect matching to the thin lens condition. In a real machine, this stems from the granularity of control over all parameters in the matching lattice. In the simulation studies discussed in this proceeding it stems from differences in the details between the strictly linear design code SixDSimulation and the tracking code ImpactX. This has the clear effect of adjusting the location of the working point and the according locations of parametric resonances, but is difficult to quantify, due to the numerous potential sources.

To compare conservation in simulation, flat planes of input particles in x-y space were placed at a range of initial pt values and tracked through the lattice. The analytic invariants deviation could then be calculated and compared between different energy offsets.

Figure 3 shows the quality of invariant conservation for a single energy offset with split and matched natural chromaticities. The second predicted invariant (usually called I in publication) is plotted as it is more sensitive to the non-

Figure 3: Invariant conservation comparison for pt=-0.001.

linearities in the system. The orange points are amplitudes with fractional invariant deviation of >5e-2. We see that the matched chromaticity case shows improved conservation compared to the split lattice. Full sextupole compensation of the chromaticity demonstrated poor conservation of the invariants (all above 5e-2 threshold), and is not plotted. This suggests that linear element tuning is sufficient to satisfy the energy spread requirements of the NIO system. Simulation studies were unable to replicate the observed fast losses with an uncompensated nonlinear lattice. However, simulations were constructed for maximum clarity in comparison of nonlinear invariant conservation against energy, and may not be sensitive to the full dynamics.

EMITTANCE OPTIMIZATION FOR DECOHERENCE SUPPRESSION

The amplitude dependent tune shift of the NIO system drives strong tune spread within the bunch. The result is very fast decoherence of the beam centroid. This is especially noticeable due to the strong dependence of the vertical tune on the horizontal amplitude. As the horizontal emittance is comparatively large, the vertical coherent oscillation times are quite short, as little as 30 turns for some amplitudes. As the strong tune shift is a desired quality of the NIO system, the remaining option for increasing coherence time is to decrease the emittance of the probe beam by adjusting the lattice. The cyclic IOTA structure is defined by eight dipoles, half 30 degree and half 60 degree dipoles. The 60 degree dipoles dominate the contributions to the equilibrium horizontal emittance. They also border the NIO insert region
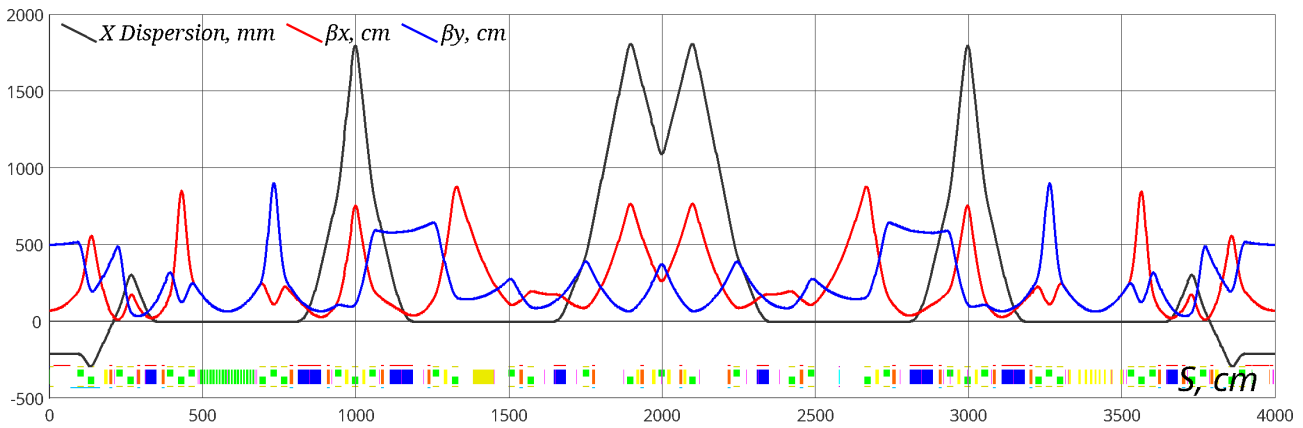
Figure 4: IOTA NIO lattice adjusted for low emittance.

which motivates turning the arc defined by these dipoles into an emittance minimized achromat.

Figure 4 shows the resulting lattice functions for an IOTA lattice with 60 degree dipole achromats. Compared to the previous IOTA lattice used for experiments, this lattice has an order of magnitude reduction in horizontal emittance. To evaluate the impact of thin emittance reduction on coherence time, kicked bunch simulations were performed using ImpactX. A six dimensional gaussian bunch of the emittance predicted with a realistic initial offset is tracked through the IOTA lattice. The centroid position is calculated turn-by-turn as the mean of the macroparticle locations. Figure 5 shows the result of the emittance reduction on the coherence time. Both planes show improvement, with a twofold improvement in the vertical plane for the compared initial amplitude.
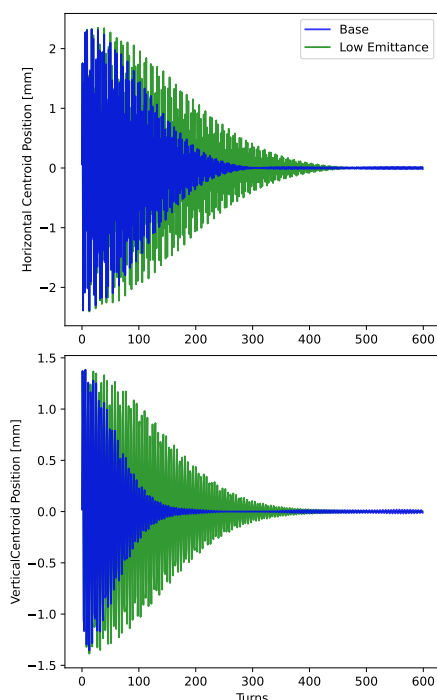
CONCLUSION

Simulation studies demonstrated improved invariant conservation with energy offset for matched chromaticity lattices using only quadrupole tuning. Emittance minimization showed positive impacts on coherent centroid oscillation times with realistic IOTA configurations. Further studies combining these approaches for implementation in future IOTA runs are ongoing.

ACKNOWLEDGMENTS

REFERENCES

[1] S. Antipov *et al.*, "IOTA (Integrable Optics Test Accelerator): Facility and experimental beam physics program," en, *J. Instrum.*, vol. 12, no. 03, T03002, 2017.
`doi:10.1088/1748-0221/12/03/T03002`

[2] V. Danilov and S. Nagaitsev, "Nonlinear accelerator lattices with one and two analytic invariants," en, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 13, no. 8, p. 084 002, 2010.
`doi:10.1103/PhysRevSTAB.13.084002`

[3] N. Kuklev, Y. K. Kim, S. Nagaitsev, A. L. Romanov, and A. Valishev, "IOTA Run 2 Beam Dynamics Studies in Nonlinear Integrable Systems," in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 1964–1967.
`doi:10.18429/JACoW-IPAC2021-TUPAB228`

[4] J. Wieland, A. Romanov, A. Valishev, and N. Kuklev, "Experimental measurements for extracting nonlinear invariants," in *Proc. IPAC'24*, Nashville, TN, USA, 2024, pp. 3015–3018.
`doi:10.18429/JACoW-IPAC2024-THPC20`

[5] S. D. Webb, D. L. Bruhwiler, A. Valishev, S. N. Nagaitsev, and V. V. Danilov, *Chromatic and Dispersive Effects in Nonlinear Integrable Optics*, arXiv:1504.05981 [nlin, physics:physics], 2015. `doi:10.48550/arXiv.1504.05981`

[6] A. Huebl *et al.*, "Next Generation Computational Tools for the Modeling and Design of Particle Accelerators at Exascale," in *Proc. NAPAC'22*, Albuquerque, NM, USA, 2022, pp. 302–306.
`doi:10.18429/JACoW-NAPAC2022-TUYE2`

[7] A. L. Romanov, G. T. Kafka, S. Nagaitsev, and A. Valishev, "Lattice Correction Modeling for Fermilab IOTA Ring," in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 1165–1167.
`doi:10.18429/JACoW-IPAC2014-TUPRO058`

Figure 5: Coherence time improvement for reduced emittance.