ISBN: 978-3-95450-208-0
doi:10.18429/JACoW-IPAC2019-MOPGW105

PRELIMINARY LATTICE STUDIES FOR THE SINGLE-INVARIANT OPTICS EXPERIMENT AT THE UNIVERSITY OF MARYLAND*

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Abstract

A novel approach to transverse resonance suppression in next generation high-intensity accelerators is the use of nonlinear optical elements to induce large tune spreads which result in reduced responses to resonance driving perturbations [1]. In order to test this theory, we have built and characterized an octupole channel insert for use in the **U**niversity of **M**aryland **E**lectron **R**ing (UMER). This paper presents experimental lattice studies using a low space-charge intensity beam at an energy of 10 keV with a beam current of 150 µA, tune depression < 0.005, and unnormalized RMS emittance of 4.3 mm-mrad. We apply beam based measurement techniques in order to evaluate the quality of our single-invariant lattice and better understand the nonlinearities created by the octupole channel.

INTRODUCTION

In conventional circular accelerators the design goal of a focusing magnet system is to have a restoring force that varies linearly with the distance from the system center. In actuality several resonances will be driven by imperfections in the machine. The resonances excite other degrees of freedom of the beam motion which can cause instabilities, amplitude growth, and ultimately particle loss. Many of these resonances limit the beam intensity and luminosity that can be physically achieved in current machines.

One solution for mitigating the effects of resonances comes from the theory of nonlinear integrable optics [1]. The insertion of strong nonlinear magnets into the transverse focusing system allows for large amplitude dependent tune shifts which act to detune resonant driving perturbations. By also selecting an appropriate nonlinear potential that obeys Laplace's equation and is practical to construct, the invariant of motion for the system can be conserved, guaranteeing long time beam confinement.

An ongoing experimental program at the University of Maryland Electron Ring (UMER) is working on demonstrating the feasibility of nonlinear integrable optics. The experiment uses a long octupole channel insert to establish a single-invariant lattice solution: where one invariant of motion is conserved in the 2-D transverse Hamiltonian system in normalized phase space coordinates.

$$V(x_N, y_N) = \frac{\kappa}{4}(x_N^4 + y_N^4 - 6x_N^2 y_N^2)\,, \quad x_N \equiv \frac{x}{\beta_x(s)} \qquad (1)$$

* Funding for this project provided by DOE-HEP and NSF.
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The octupole potential in Eq. (1) provides the stabilizing tune spreads as well as a bounded, but chaotic, orbit. The fully integrable, two invariant, system will be tested at the newly-built IOTA facility at FNAL [2].

Extensive simulation and design work has been done looking at the acceptable range of tolerances for the experiment at UMER [3]. This paper builds on this by using a model-based approach to designing and experimentally implementing a working lattice on the machine. Beam-based tuning and measurements are used to meet the required lattice conditions.

LATTICE DESIGN

Nonlinear optics theory requires three basic conditions to be met in order to have an integrable lattice solution:

- The beam must be round ($\beta_x(s) = \beta_y(s)$) through the nonlinear octupole channel insert.
- The octupole potential must scale as $\beta_{x=y}^{-3}(s)$ longitudinally through the nonlinear insert.
- The phase advance between each nonlinear insert must be integer-π ($n\pi$).

While these are required properties of the lattice, other factors such as operating tune, lattice functions, dispersion, and chromaticity must also be considered. Initial simulations estimate an average horizontal dispersion of 0.05 m through the nonlinear insert.

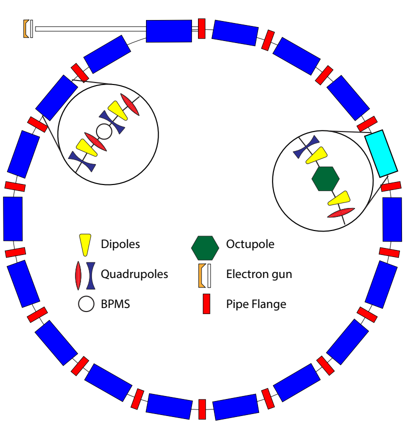

Figure 1: UMER diagram. The ring is designed with an 18 cell symmetry and no straight sections.

Early designs focused on a 3-period symmetric lattice and assumed equal bending angles for all dipoles [3]. Implementation of this lattice turned out to be difficult in the machine due to steering (earth's field) issues. The lower operating tune required focusing magnets to be signficantly

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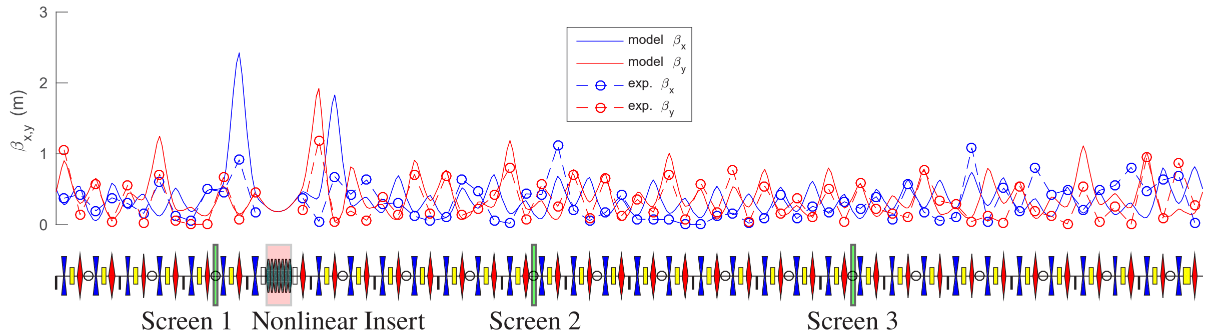

Figure 2: Beta function measurements for the designed lattice. UMER has 72 quadrupoles and 36 ten degree bend dipoles.

weaker than normal; this amplified the effect of the earth's field perturbation in the machine which can not be ignored in UMER's case. Helmholtz coils have since been installed to better compensate for the effect in the vertical directions. Horizontally, we have enough dipoles to correct for the perturbation around the ring, but this means each dipole is set to a slightly different (10-20%) bending angle and thus breaks the vertical cell symmetry in the ring.

Due to not having true symmetry in the machine, the decision was made to use a 1-period lattice. See fig 1 for a diagram of this lattice. The single nonlinear insert will be a matching section while the remainder of the ring is set to near normal operating values. By keeping the magnets near normal operating conditions we can better guarantee stable operation. The nonlinear insert section uses a total of ten quads, five upstream and five downstream, to match the beam through and meet all the required integrability conditions. An effort is also made to optimize to specific integer tune values and minimize betatron oscillation amplitudes as much as possible in order to improve dynamic aperture and orbit control.

MODEL-BASED TUNING

Models of the machine were built in AT [4] (Accelerator Toolbox), a single particle code, and WARP, a particle in cell code. [5]. Because of computational efficiency, the single particle code was used to construct a model and optimize to the required lattice conditions. Afterwards, the model was reconstructed in WARP where space charge effects can be added and simulated. The codes have been benchmarked with each other.

Using response matrix techniques and tune scans [6], AT was able to accurately model UMER under its normal operating conditions by calculating a set of fit parameters for each magnet in the machine. This model was then used as the starting point in designing the nonlinear optics lattice. An optimization routine was created in order to meet all three integrability conditions, fit to a specific tune value, reduce the maximum beta amplitudes, and minimize dispersion along the nonlinear insert. Each of these conditions had weights that were adjusted to get an acceptable solution. The resulting solution was configured on the machine and first turn, beam-based, steering techniques were used to get a circulating beam and acceptable closed orbit.

The first requirement for an integrable solution requires the beam to be round, meaning the beta functions must be equal through the nonlinear insert. Because UMER has individual power supplies for each magnet, we are able to experimentally measure beta functions at the 72 quadrupole locations in the ring and see if this integrability requirement is met. Eq (2) is used for the measurement where Q is the measured tune, K is the quadrupole strength, and l_{eff} is the effective quadrupole length [8]. Results are in fig 2.

$$< \beta_{xy}(s) >= \frac{4\pi\Delta Q_{xy}}{(\Delta K l_{\text{eff}})(s)} \tag{2}$$

The third requirement for an integrable solution requires the phase advance from one nonlinear insert to the next to be $n\pi$, where n is an integer value. In order to test this, phases (Ψ_{xy}), along with tunes (Q_{xy}), were measured with BPMs and compared with the model. Looking at the third row in Table 1, the $n\pi$ requirement is met vertically (y) as there is good agreement between the measurement and model. Horizontally (x) the agreement is off suggesting models of the dipoles are still not perfect and work is being done to improve this. Note the transverse tunes in row one are not equal, but instead are a π phase advance apart. The optimization routine suggested these values in order to best meet the required integrability conditions.

Table 1: Tune and Phase Advances Compared Between the Model and Experiment (phase advance ($\Delta\Psi$) units are in $n\pi$)

Parameter	Model	Experiment
$Q_x \| Q_y$	6.69 | 7.23	6.64 | 7.24
$\Delta\Psi_x \| \Delta\Psi_y$ nonlinear insert	0.38 | 0.38	0.67 | 0.53
$\Delta\Psi_x \| \Delta\Psi_y$ elsewhere	13.00 | 14.07	12.61 | 13.95

BEAM IMAGING

Due to the presence of space charge forces and nonlinear fields, it is important to understand how the transverse

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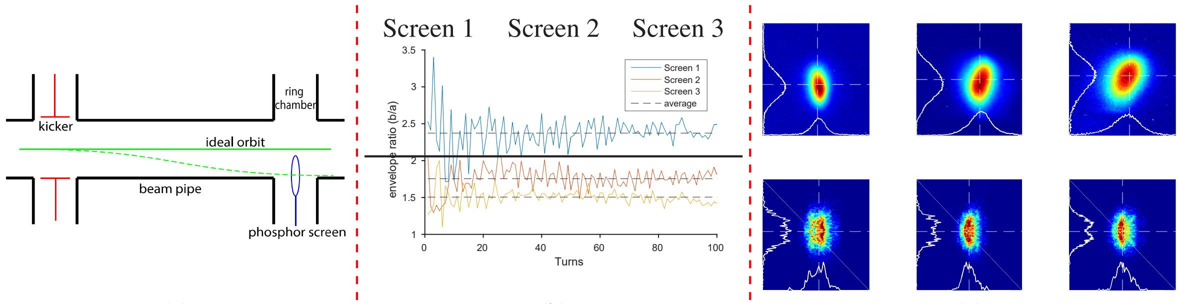

(a) (b) (c)

Figure 3: (a) A schematic diagram of the knockout imaging technique employed at UMER. The length between the kicker and phosphor screen is about a half betatron wavelength. (b) The top row is the beam knocked out and imaged at three different phosphor screen locations around the ring. This is at turn 50. The bottom row is simulation in WARP at the same screen locations using a 512x512 grid with 10000 particles. (c) The ratio of the measured envelopes (b/a) as a function of turns. Beam size is calculated from the images using the full width half max.

profile of the beam evolves in time and verify this with simulations. One way is to extract and image the beam directly on a phosphor screen. This is a challenge because UMER does not have an extraction section. Instead we use a knockout technique to get non-intercepting imaging in the ring. A phosphor screen is inserted partially into the beam pipe allowing a camera outside the ring to image the screen through a viewing port. An upstream electrostatic kicker is used to kick the beam onto the downstream phosphor screen. The setup is integrated into the controls allowing the ability to image the beam on the Nth turn. See fig 3 (a).

The beam is imaged each turn across a 100 turns at three screen locations. Beam sizes are measured at each location and plotted in fig 3 (c). The results give good agreement between the expected beam size based on the simulation at the same locations (See table 2). WARP simulations of the beam density (bottom of fig 3 (b)) also agree reasonably well with the imaged beam (top of fig 3 (b)).

Table 2: Ratio of Beam Envelopes Compared Between Simulation and Experiment at Three Screen Locations

Location	Sim. (b/a)	Exp. (b/a)	Error (%)
Screen 1	2.000	2.056	2.8
Screen 2	2.875	2.922	1.6
Screen 3	2.200	1.707	22.0

NONLINEAR INSERT MEASUREMENT

After verifying the lattice and beam properties in the machine, the nonlinear insert was installed. The closed orbit was re-optimized to get maximum beam transmission with the inserted element.

As a starting point in trying to understand the impact of the octupole channel on the lattice, fractional transverse tunes were measured as a function of the octupole strength using the NAFF algorithm [7]. The measurement in fig 4 shows a slight increase in the horizontal tune and a smaller decrease in the vertical tune as octupole strength is increased.

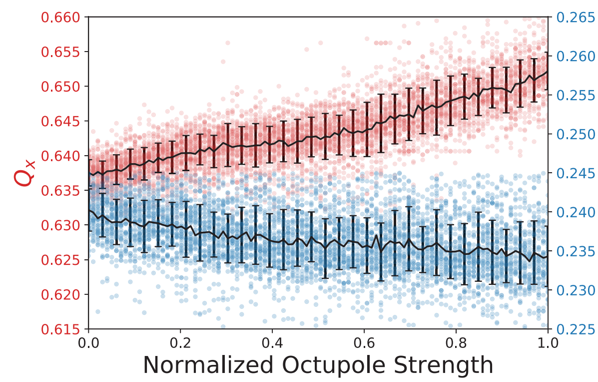

Figure 4: Experimental measurement of the transverse fractional tunes as a function of the octupole channel strength using 14 bpms and many measurements. The error bars represent +/− one standard deviation from the mean.

CONCLUSION

We have developed an accurate model of our ring using beam based methods. This model was then used to design a lattice that meets all the requirements for single-invariant integrability based on nonlinear optics theory. After achieving an acceptable closed orbit, experimental measurements of the beta functions were done and our models updated based on the results. The transverse beam profile was also imaged and compared to WARP simulations.

With the lattice fully characterized, the octupole channel has been installed in the machine. Early measurements of the octupole channel's impact on fractional tunes was measured. Further experiments with the channel are planned for the summer.

ACKNOWLEDGEMENTS

This work was supported by DOE-HEP (DE-SC0010301), and NSF award PHY1414681. Travel to IPAC'19 was supported by the APS Division of Beam Physics and ANSTO. Thanks to the UMER group for their helpful discussions.

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