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TUNING LOW-CURRENT BEAM FOR NONLINEAR QUASI-INTEGRABLE OPTICS EXPERIMENTS AT THE UNIVERSITY OF MARYLAND ELECTRON RING*

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Abstract

Design of accelerator lattices with nonlinear integrable optics is a novel approach to suppress transverse resonances and may be crucial for enabling low-loss high-intensity beam transport. Lattices with large amplitude-dependent tune spreads, driven by strong nonlinear magnet inserts, have reduced response to resonant driving perturbations [1]. This paper describes preparations for tests of a quasi-integrable octupole lattice at the University of Maryland Electron Ring (UMER). The planned tests employ a low-current high-emittance beam with low space charge tune shift (~ 0.005) to probe the dynamics of a lattice with large external tune spread (~ 0.26).

INTRODUCTION

At present, one of several aspects limiting transportable beam intensity in high energy accelerators is uncontrolled beam loss. Even low fractional losses in a sufficiently intense beam will result in large amounts of power being deposited on the surrounding environment, presenting a hazard to personnel safety and the integrity of accelerator components as well as compromising beam quality. Known loss mechanisms include both incoherent and coherent resonances that drive particles to large amplitudes. The linear-optics underpinning modern accelerator design is particularly prone to resonant instability. [2]

A solution for mitigating resonant losses has been proposed in the theory of nonlinear integrable optics [1]. Strong nonlinear terms are included in the transverse focusing force in a manner which preserves invariants of particle motion (integrability). In the presence of strong nonlinearity, regular driving terms cannot resonantly couple energy into the beam, as changes in particle amplitudes will act to decohere motion from the resonant condition.

An experiment has been designed at the University of Maryland Electron Ring (UMER) to demonstrate the feasibility of nonlinear integrable optics. UMER is a low-energy, low-cost testbed for beam dynamics relevant to higher energy machines. The planned experiment uses a quasi-integrable octupole (QIO) lattice, in which octupole potentials are used to provide the external, stabilizing tune spread. Transverse motion in this lattice conserves one invariant, the two-dimensional Hamiltonian, resulting in chaotic but bounded motion. Tests of the fully integrable solution found in [1] will take place at the newly-constructed IOTA facility at FNAL. [3]

This paper describes the design and implementation of linear focusing optics for the QIO experiments. In particular, tune and envelope measurements are discussed. Also in these proceedings, Ref. [4] describes the design of the long octupole insert generating external tune shift and preliminary measurements with octupole fields. Reference [5] describes orbit optimization in UMER, including orbit measurements for the QIO linear optics design.

DESIGN OF QUASI-INTEGRABLE OCTUPOLE LATTICE AT UMER

There are unique requirements for the QIO lattice. In the simplest model, the lattice consists of two components: octupole inserts for tune spread and sections of linear (quadrupole) transport which provide transverse confinement. The conditions for quasi-integrability are [1, 3]:

- The beam is round through the insert.
- The longitudinal dependence of the octupole potential scales as $\beta^{-3}(s)$.
- The phase advance between inserts is integer-π.

Linear-Focusing Lattice for QIO Experiments

The UMER lattice was designed for flexibility of focusing optics. Due to the low beam energy, lightweight air-core printed circuit board (PCB) magnets are used for most magnetic elements. The ring lattice consists of 72 PCB quadrupoles and 36 PCB dipoles. Each magnet is independently powered through a programmable power supply, allowing wide flexibility in the choice of lattice focusing function. The only constraint on lattice function are the fixed magnet locations.

The matched solution in the UMER lattice for a QIO experiment operating at tune $\nu_x = \nu_y = 3.26$ is shown in Fig. 1. This solution was found using a hard-edged model of the ring with in-house Matlab-based envelope integrator code MENV for hard edged magnet models described in [6]. The design approach, as described in more detail in [7], assumes a 3-fold symmetry in the ring solution to reduce problem dimension. Of the 72 available quadrupoles, 12 are turned off to allow room for 3 long drifts and the lattice focusing is defined by 10 independent quadrupole current, given in Table 1. The design assumes a low-current, large-emittance beam (40μA, 100 mm-mrad) for weak space charge tune spread during initial experiments. Note the lower current

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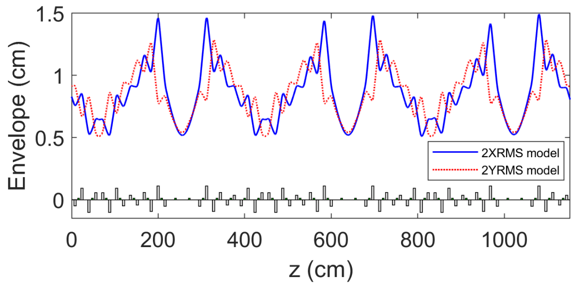


Figure 1: Periodic KV envelope solution for 100 mm-mrad, 40 μA beam.

Table 1: Quadrupole Currents Used Here for Tests of UMER QIO Lattice, in Amps

Q1	Q2	Q3	Q4	Q5
-0.538	1.161	-0.973	0.616	-0.434
Q6	Q7	Q8	Q9	Q10
0.410	-0.458	0.925	-1.109	0.650

range compared to the nominal 1.826 A setting for FODO operation ($\nu_x = 6.675$, $\nu_y = 6.686$). The weaker focusing allows for long (64 cm) drift sections (over which an insertion can be made) while avoiding unacceptably large excursions in beam envelope.

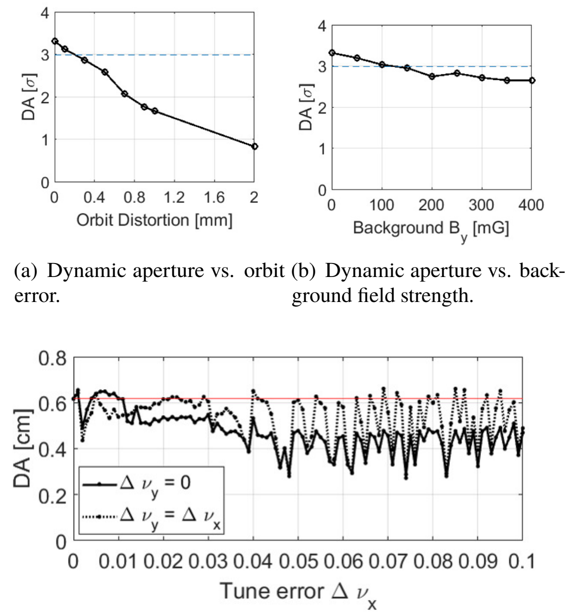
Tolerances for QIO Lattice

A simple model of a QIO lattice consisting of a long octupole channel and thin lens focusing kick was used to explore the dependence of dynamic aperture and tune spread on errors in closed orbit and the linear lattice transfer function. A unique aspect of UMER is that the ambient background fields (dominated by the Earth field) are a significant fraction of the total bending in the ring ($\sim$ 20% in the horizontal plane). Therefore, we consider closed orbit distortions for both shielded (straight) and unshielded (flat background field) cases. For 90% of the dynamic aperture to be preserved, orbit distortions < 0.2 mm and background fields $< 100mG$ (in one plane) are required, as shown in Fig. 2(a) and 2(b).

The effect of tune errors on dynamic aperture was less strong. In general, lattice tunes within < 0.02 of the optimal value resulted in $< 10\%$ loss of dynamic aperture, and errors out to 0.1 resulted in no more than 50% loss but without a strong dependence on the error magnitude as shown in Fig. 2(c). However, the error is desired to be as low as possible as the invariant conservation depends more strongly, with variations $> 20\%$ for single-plane tune errors > 0.01.

TUNING LOW-CURRENT BEAMS IN LINEAR QIO LATTICE

Initial tests of the QIO linear lattice design are done with a 0.6 mA "pencil" beam, with expected emittance of 7.6 mm-mrad (unnorm., 4×RMS) near the source. [8]. This beam is generating by aperturing the cathode output current



(a) Dynamic aperture vs. orbit error. (b) Dynamic aperture vs. background field strength.

(c) Dynamic aperture vs. tune error.

Figure 2: Simulation results from steering/focusing errors on QIO lattice stability.

to 0.25 mm radius near the source. The 0.6 mA beam, traditionally the UMER beam with the weakest space charge effect, has estimated incoherent tune spread 0.94. This beam is *not* a good candidate for initial tests of QIO, which we intend to run with a space charge tune shift significantly less than the predicted maximum 0.26 octupole-induced tune spread. However, due to the low emittance, this beam is useful as a probe beam for lattice dynamics. A large-emittance, low-current beam (mentioned above) is proposed for proof-of-principle experiments with many-turn transport and small space charge contribution ($\delta\nu \sim -0.005$). Finally, a 60μA, 2.5 mm-mrad "mini-pencil" beam is being prepared (as proposed in Ref. [9]) but is not discussed here.

Model-Based Optimization of Lattice Tune

As stated above, the quasi-integrable condition is met when the phase advance between octupole inserts is integer-π. The UMER QIO lattice is designed for a 0.26 tune advance across the insertion region, therefore the fractional ring should be as close as possible to 0.26. As the model is not a perfect representation of the ring, it is assumed that the experimental lattice will need to be "tuned" towards the desired operating point based on measured tunes. Indeed, implementation of the quadrupole solution in Table 1 yielded measured fractional tunes of $\nu_{x,0} = 0.36 \pm 0.07$ and $\nu_{y,0} = 0.32 \pm 0.06$. This is an approximate tune error of $\Delta\nu_{x,0} = 0.10$ and $\Delta\nu_{y,0} = 0.06$ from the desired operating point. Tune measurements were done with the four-turn formula approach described in Ref. [10].

Using a model-based approach, we search for nearby matched solutions as a function of perturbed quadrupole

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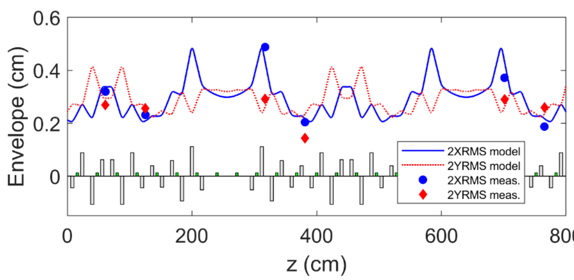

Figure 3: Measured 2×RMS beam profiles compared to periodic KV envelope solution for 7.6 mm-mrad, 0.6 mA beam over 2/3 of ring.

strengths (while maintaining $\beta_* = 0.3$ in the insertion region). It is found that, although the tune of this landscape is a nonlinear function of quadrupole strengths, the dependence is “slow" enough that linear fits are usually sufficient to achieve a tune correction up to $\sim$ 0.2. Applying this method to the UMER lattice, a small change in quadrupole currents ($\Delta I < 0.3A$) shifts the tune to $\nu_{x,0} = 0.32 \pm 0.07$ and $\nu_{y,0} = 0.28 \pm 0.08$, with errors $\Delta\nu_{x,0} = 0.06$ and $\Delta\nu_{y,0} = 0.02$. Presumably more accuracy can be obtained with better tune statistics and multiple iterations.

0.6 mA Probe Beam

The 0.6 mA beam was injected into the proposed QIO lattice. Figure 3 compares the resulting first-turn transverse beam-size measurements against the model prediction. Reasonable agreement is found if the beam emittance is assumed to be 50% larger than the last measured value (11.4 mm-mrad as oposed to 7.6 mm-mrad). This may not be unreasonable, as a new cathode has recently been installed and not yet fully characterized. Under this assumption, a mismatch $\leq 15\%$ in the horizontal and $\leq 40\%$ in the vertical is observed. This is expected to improve with empirical adjustment of the match, as well as re-measurement of the 0.6 mA beam emittance.

Low Current, High Emittance Beam

As mentioned above, a low-current, high emittance beam is proposed for QIO experiments with low space-charge tune spread. Generation of this beam by operating the UMER triode electron gun in voltage amplification mode is described in Ref. [9], including reported emittance (using the quadrupole scan technique) at $40\mu A$ output current to be $\epsilon_x = 300$ mm-mrad, $\epsilon_y = 100$ mm-mrad (unnorm., $4\times$RMS). The large measured asymmetry suggests sufficient scraping losses prior to measurement 3.25 meters downstream of the source.

Initial tests of the $40\mu A$ beam in the QIO linear lattice show poor agreement with model predictions shown in Fig. 1. First, due to large orbit distortion, there is certainly scraping along the first turn that affects the profile measurement. Second, the initial conditions near the source are not well known, as this beam is not apertured.

CONCLUSION AND FUTURE WORK

A design for a test of quasi-integrable optics with applications for high-intensity beam transport at UMER has been described. The approach to optimizing the linear (quadrupole) focusing to provide the required transfer function for QIO experiments is developed. Initial measurements of the model-optimized lattice with a 0.6 mA “pencil" beam show that the ring tune is within $\sim$ 0.1 of the desired tune. A model-based optimization routine lowers this error to 0.06. Comparison of measured 0.6 mA beam envelope with model predictions for first turn transport shows fairly good agreement. No agreement is found for the 40μA beam, which requires more careful characterization.

Future work will focus on optimizing lattice tune towards the desired value and measuring multi-turn beam envelope. More precise control of the beam orbit is required to increase the precision of measured tune, which is currently limited by scraping losses. For the measurements presented here, the horizontal closed orbit was constrained within 3 mm of element centers (as measured at BPMs), while the vertical experienced distortion of almost 9 mm. Current measures to increase orbit control, particularly in the vertical plane. A partial correction to the vertical orbit is included in these results, in the form of field-canceling Helmholtz coils covering 30% of the ring. Further installation of these correctors is expected to improve transmission and reduce orbit errors.

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