EXPERIMENTAL PLANS FOR SINGLE-CHANNEL STRONG OCTUPOLE FIELDS AT THE UNIVERSITY OF MARYLAND ELECTRON RING *

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Abstract

Nonlinear quasi-integrable optics is a promising development on the horizon of high-intensity ring design. Large amplitude-dependent tune spreads, driven by strong nonlinear magnet inserts, lead to decoupling from incoherent tune resonances. This reduces intensity-driven beam loss while quasi-integrability ensures a well-contained beam. In this paper we discuss on-going work to install and interrogate a long-octupole channel at the University of Maryland Electron Ring (UMER). This is a discrete insert that occupies 20 degrees of the ring, consisting of independently powered printed circuit octupole magnets. Transverse confinement is obtained with quadrupoles external to this insert. Operating UMER as a non-FODO lattice, in order to meet the beam-envelope requirements of the quasi-integrable lattice, is a challenge. We discuss efforts to match the beam and optimize steering solutions. We also discuss our experiences operating a distributed strong octupole lattice.

INTRODUCTION

Beam resonances that drive particle losses and beam halo present a significant challenge for high intensity accelerators, limiting beam current due to risk of damage and/or activation. While Landau damping can control resonant effects, the addition of weak nonlinearities to a linear lattice can introduce resonant islands and chaotic phase space orbits, which reduce dynamic aperture and lead to destructive particle loss. Theory predicts that lattices with one or two invariants and sufficiently strong nonlinear elements should suppress tune and envelope resonances without loss of stable phase space area [1].

The small-angle Hamiltonian for transverse particle motion in the normalized frame is given by

$$H_N = \frac{1}{2}\left(p_{x,N}^2 + p_{y,N}^2 + x_N^2 + y_N^2\right) + \kappa U(x_N, y_N, s)$$

with general nonlinear contribution U. (Normalized coordinates are $x_N = \frac{x}{\sqrt{\beta(s)}}$ and $p_N = p\sqrt{\beta(s)} - \frac{\alpha x}{\sqrt{\beta(s)}}$)

In order for U to be an invariant quantity and for H_N to be conserved, $\beta_x = \beta_y$ inside the nonlinear element and the nonlinear element strength parameter $\kappa(s)$ depends on $\beta(s)$. In particular, for an octupole element $\kappa \propto \frac{1}{\beta(s)^3}$. External focusing is provided by a linear lattice, which should reduce to an integer π phase advance between nonlinear inserts, as depicted in Fig. 1.

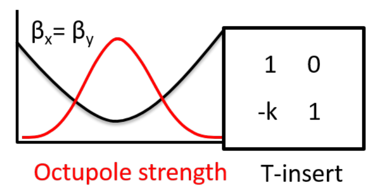

Figure 1: Simple quasi-integrable system: FOFO focusing with nonlinear insert.

Parallel work at the IOTA ring [2] will test a fully integrable nonlinear solution. The focus of the UMER nonlinear optics program is on the quasi-integrable case of the octupole lattice (with 1 invariant of motion), with the goal of experimentally observing transverse stability and halo mitigation.

EXPERIMENT

UMER is an 11.52 m circumference ring with a dense FODO lattice of printed circuit magnets (72 quads, with cell length 32 cm). The arrangement of quadrupoles in the standard UMER lattice can be seen in Fig. 2. All UMER magnets are flexible printed circuit boards (PCBs). The first generation of PCB octupoles for nonlinear optics experiments have been manufactured and characterized [3].

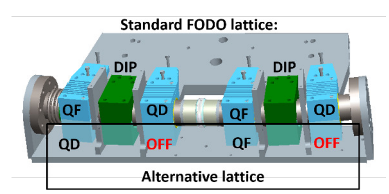

Figure 2: 20° of UMER, consisting of 2 dipoles and 4 quadrupoles in a FODO arrangement. A custom section is being designed to accomodate a single long octupole mount.

To meet the requirements of a quasi-integrable lattice as described above, UMER must operate as a non-FODO lattice. The nonlinear insert will occupy a single 20° section of the ring, with quadrupole strengths modified to obtain envelope and tune requirements. Previous flexibility of the UMER lattice has been demonstrated in the alternative lattice, which uses a lengthened FODO cell of 64 cm [4]. The UMER quadrupoles are each individually powered with unique polarity switches, allowing for any imaginable combination of families and lattice functions.

Characterization of the "single-channel" octupole lattice will be made monitoring beam loss and profile evolution of

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0.6 mA and 60 µA beams, with respective space charge tune depressions of 0.83 and 0.95 (estimated for standard FODO lattice, see [5]). We expect externally induced tune spreads up to $\delta\nu = 0.2$.

STEERING

In earlier work, loss data was recorded for 50 turns through a distributed octupole lattice in a FODO lattice [6]. Integer and half-integer stop bands are observed (see Fig. 3), although fine structure is obscured both by low scan resolution and by overall large beam loss at all operating points. The only observable effect of the octupole tune shift is a broadening of the resonance bands.

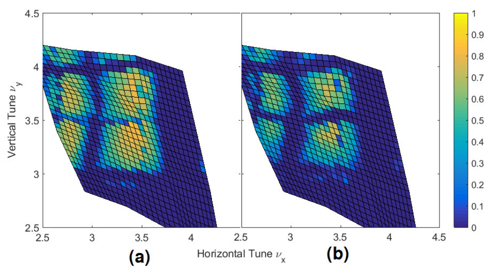


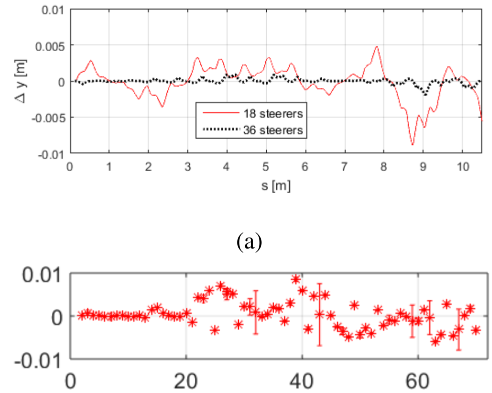
Figure 3: Tune scan for distributed octupole lattice, beam survival at 25th turn, normalized to 10th turn. (a) no octupoles, linear FODO lattice (b) Octupoles powered at 0.5 A (37 T/m^3 peak).

The distributed octupole lattice uses the long 64 cm FODO cell, with weaker focusing (ring tune is decreased from 6.7 in both planes to roughly half that). The resulting larger beam is therefore more susceptible to scraping losses from orbit oscillations and deviations of the closed orbit, and the steering tolerances are much tighter when compared to "as-designed" operation in the dense FODO lattice.

Vertical control is maintained through 18 printed circuit vertical steerers at 20° separation, with an integrated field strength of 3.886 G-cm/A. For 10 keV beam, each steerer offers maximum of 1.3° of orbit correction (limited by maximum DC current that can safely be maintained without over-heating). Although the average background radial field is < 1 mG , the field is locally high in some azimuthal locations, up to $200mG$. Over 20° of the ring, this corresponds to 2.2° of bending, greater than the available correction.

In practice, this means that orbit deviations cannot be locally minimized, but rather that there is a global solution which maximizes current throughput. Excellent recirculation has been found using response matrix tuning, for a vertical closed orbit with large deviations from the pipe center. However, this closed orbit is not robust to changes in lattice function nor easily correctable. Larger beams are more susceptible to scraping losses. This is a crucial path for nonlinear optics experiments, which rely on modified (and tunable) lattice functions and must accommodate predicted RMS emittance growth into an equilibrium state [7].

The most straightforward upgrade is to replace the 18 weak correctors with 36 weak correctors, capable of 1.2°



(a)

(b)

Figure 4: (a) Simulated 1st turn vertical orbit control for two steering systems (18 vs. 36 weak correctors). Best case RMS deviation from pipe center is 2.6 and 0.7 mm, respectively. (b) Measured vertical orbit for standard lattice operation on first turn, showing excursions of ±1 cm.

of correction, but at twice the density, so the accumulated residual field error is at maximum 1.1°. From there, the usual steering algorithms may be applied. An example of orbit improvement can be seen in Fig. 4a.

MATCHING

The requirements for quasi-integrable transport in a strong octupole lattice (that is, transport preserving one invariant of transverse motion) is that (1) the beam envelope comes to a waist through the nonlinear insert and (2) the phase advance between nonlinear inserts is a multiple of π.

To restate, the UMER lattice consists of 72 independently powered quadrupoles. Two of these are large-bore magnets which accommodate injection, including one (YQ) with a yaw rotation and transverse offset from the beam pipe. Matching into the ring is done with 6 quadrupoles and a solenoid in the injection line.

This represents a very large parameter space (72 variables) that can be used to meet size requirements $(\beta_x, \beta_y, \alpha_x, \alpha_y, \nu_x, \nu_y)$. Reduction of the problem into a smaller number of variables is necessary to direct the search, as well as make small, predictable adjustments.

Most recently, matching calculations have been done in the WARP code, using both the envelope integrator and 2D PIC simulation [8]. Fast iteration is done with envelope integration, with small adjustments needed to achieve a matched beam in the PIC code. The search for solutions is reduced to a 4D problem, in which predictable adjustments can be made to the lattice tunes while maintaining a matched solution.

Parametrization of Lattice Solutions

The problem of matching 72 quadrupoles to meet 6 requirements $(\beta_x, \beta_y, \alpha_x, \alpha_y, \nu_x, \nu_y)$ is an over-constrained problem in an unnecessarily huge space. To reduce the

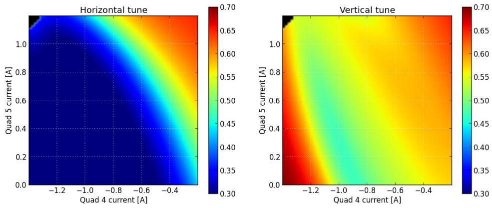


Figure 5: Matching conditions and sector tunes as a function of quad strengths.

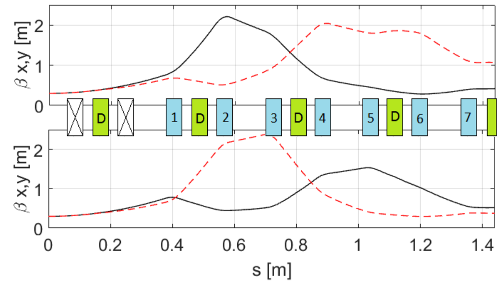


Figure 6: Two matching solutions for octupole channel experiment. Quads are numbered as they are identified for matching.

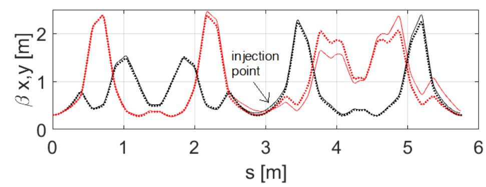


Figure 7: Half-ring lattice solution, for settings shown in 6. Dotted line is integrated envelope calculation, solid line is RMS envelope from 2D PIC propogation. Agreement is incomplete, and small errors are amplified even over this short length.

problem, we assume symmetry of the solution and divide the ring into eight segments that are mirrored and repeated around the ring, with symmetric-beam waists at four locations around the ring.

Generally, up to 7 free parameters may be used to satisfy the above 6 requirements. However, optimization over all six conditions simultaneously was unproductive. More precisely, finding solutions with an exact tune requirement while maintaining matched envelope functions was difficult, as most optimization methods did not efficiently explore tune space, even with weighted conditions.

The strategy that resulted in the most straightforward path to a solution was a brute force method in which the problem is parametrized without regard for tune optimization, a wide space is scanned and potential solutions cherry picked from the resulting tune landscape. This requires good agreement of beam envelope evolution between the envelope integrator, which can be used for fast iteration, and the PIC solver, which will be used to interrogate beam dynamics. Of the 7 independent variables characterizing a ring sector (subtending 90° of the ring), 3 quadrupole strengths are held fixed, 2 are systematically varied along a grid, and 2 are used to match the beam envelope in the sector.

Figure 5 shows the resulting 2D scan from a search parameterizing the 4th and 5th quads in the sector (1st, 2nd and 3rd are held to fixed values, 6th and 7th are used to complete the match, if one exists). The partial tunes for the sector ($\Delta\nu$ over $\frac{1}{8}$ of the ring) are mapped to the 2D space, as well as the corresponding strengths of the 6th and 7th quadrupoles. A number of quantities can be parametrized in this manner, including corrections for octupole perturbation of RMS envelope, adjustment of β^* in the drift, tuning the phase advance of the ring, and correcting for inconsistencies in the ring "as-modeled" and "as-exists."

The full ring solution was found to be more stable to single quadrupole strength perturbations and initial condition mismatch when implementing two sets of matched solutions, alternating large/steep envelope excursions between the horizontal and vertical planes. Two 2D parameter scans are completed, then a simple search identifies combinations that meet the desired tune condition $\nu_{ring} - \nu_{channel} = \frac{n}{2}$. Due to the imperfect agreement between the PIC and envelope calculations, slight adjustment of quadrupole strengths is required to keep the optimal tune for PIC simulations. The 2D tune landscape (Fig. 5) guides this adjustment. A pair of satisfactory solutions can be seen in Figs. 6 and 7, with calculated tunes in Table 1. It seems beneficial to align the position of the beam waist with injection, as the large bore injection magnets will be unpowered in the non-FODO lattice, and coupling of steering to YQ strength may be neglected. This places the octupole channel at the 5th ring section (RC5) at the 80° point, where radial field is quite low and vertical closed orbit is typically well-contained (Fig. 4b).

Table 1: Tune Estimates for Single Lattice Solution, Based on Different Calculation Methods

solver	$\Delta\nu_x$	$\Delta\nu_y$
Envelope	2.982	2.766
PIC (particle fft)	2.974	2.733

SUMMARY AND FUTURE WORK

Increased control of vertical orbit is necessary to implement non-FODO focusing schemes for a single-channel quasi-integrable octupole lattice. Finding lattice solutions that meet the experimental requirements is challenging, but the search can be made efficient through parameterization and fast iteration. Higher order effects not yet considered are sector-focusing due to steering correctors and earth field variations [9] as well as dispersion. Ongoing work includes finding injection line match and testing non-FODO lattice solutions on UMER.

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