INITIAL TESTS OF NONLINEAR QUASI-INTEGRABLE OPTICS AT THE UNIVERSITY OF MARYLAND ELECTRON RING

H. Baumgartner[†], B. Beaudoin, I. Haber, T. Koeth, D. Matthew, K. Ruisard,
University of Maryland, College Park, USA

Abstract

An octupole channel has been inserted into the University of Maryland Electron Ring (UMER), in order to investigate the mitigation of destructive resonances as a novel approach in high-intensity beam transport. The individual octupole magnets have been characterized using our in-house 3-dimensional magnet mapping stage, with a measured gradient of 51.6 ± 1.5 T/m3/A. A single section (20º) of an 18-cell FODO lattice has been replaced by a longitudinally-varying octupole channel constructed from seven flexible printed circuits (PCBs). We present the design of the channel and preliminary beam based measurements on the ring.

INTRODUCTION

The University of Maryland Electron Ring (UMER) is a small (11.53m), low-energy (10keV) electron ring for the study of intense beam dynamics. UMER has begun an effort to investigate the theory of integrable nonlinear optics, which is a promising area of research in high-intensity ring design [1]. To this end, a quasi-integrable octupole lattice has been incorporated into the existing FODO ring structure.

Integrability is the existence of conserved invariants in particle motion, which results in confined particle motion over long time scales. The theory of nonlinear optics strives to realize integrable potentials which obey Laplace's equation and can be physically constructed. While a fully integrable solution would have two invariants of motion, a quasi-integrable solution has only a single invariant of transverse motion. A quasi-integrable potential is achieved using an octupole channel insert installed in a section of UMER, as shown in Figure 1 below.
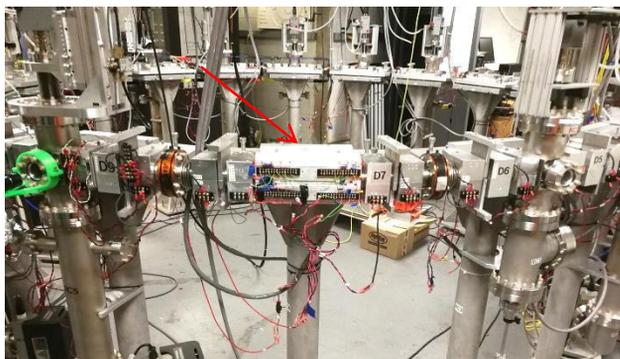
Figure 1: The octupole channel is installed in a section of UMER.

OCTUPOLE CHANNEL DESIGN

Multipole Magnet Flex PCB Generator Script
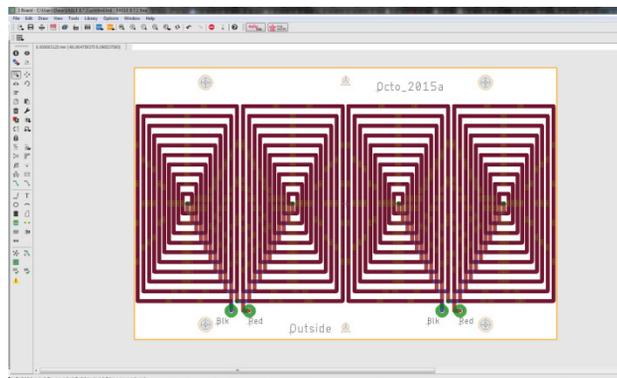
Figure 2: Octupole Flex PCB programmatically generated in Eagle CAD using our open-source script, available for download from the UMER GitHub[§].

Cosine-theta magnets made from flexible printed circuit boards (PCBs) are relatively inexpensive when compared with conventionally wound magnets, and can be manufactured with a quick turnaround time. When wrapped around the beam pipe, the flex PCB creates a multipole field. Due to the their thin width, flex PCBs have the additional advantage that they can be easily stacked or overlapped. For this reason, flex PCBs were ideal for the construction of an octupole channel for nonlinear optics studies.

We have written an open-source script to generate custom Gerber files for flex PCBs of any size and number of poles. The script calculates conductor positions and then approximates rectangular loops of current with a spiral using the method of [2]. The spiral traces, shown in Figure 2, vary in their spacing, to create an azimuthally varying current density that produces a multipole field in the magnet bore. The quality of the fields has been analyzed [3], and the desired multipole components have been shown to be approximately 100 times stronger than undesired components. The script uses MATLAB to generate a script that Autodesk EAGLE then uses to render the PCB and make Gerber files that can be sent directly to a manufacturer. It can generate multipole magnets of any size and any number of poles.

Optimized Magnet Mounts
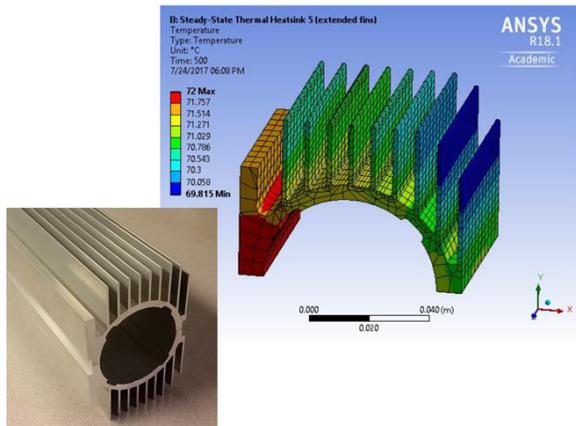
Figure 3: Magnet mount and heat sink for the octupole channel.

To mount and cool the flex PCB magnets, an extruded aluminum heat sink shown in Figure 3 was designed. Using ANSYS workbench, a fin spacing of about 7.5mm was found to be optimal for passive cooling. Fins were made as long as was practicable to manufacture using an extrusion method. A channel allows for a ¼" copper pipe to be installed for water cooling if necessary. Designing the channel to be extruded allowed for it to be manufactured at relatively low cost when compared to CNC machining. PCBs were affixed using a thermally conductive adhesive transfer tape, which allowed for the magnets to be reconfigured if necessary.

Multi-Octupole Channel

While a single large octupole would be ideal, we use seven equally spaced PCB-based octupole magnets at different currents to fill in the desired profile, as can be seen in Figure 4. The gradient of each magnet is 51.6 ± 1.5 T/m3/A, and currents were calculated to minimize the RMS error from the desired shape. The resulting channel is shown in Figure 5.
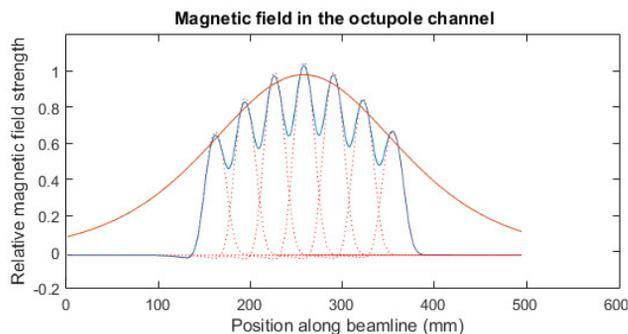
Figure 4: Simulation of magnetic field profile of a channel. The seven octupole PCBs are overlapped to fill in the desired field shape.
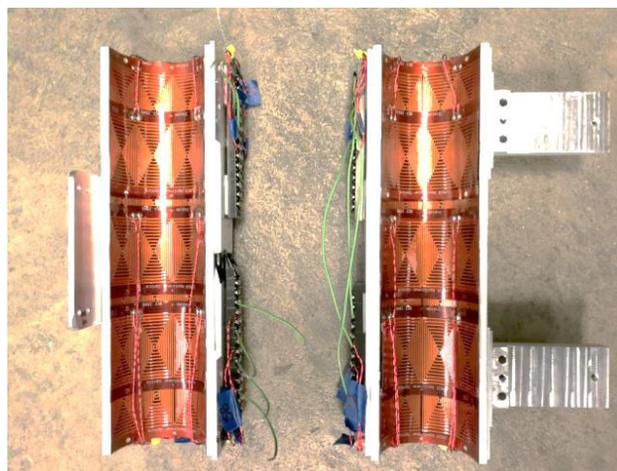
Figure 5: Top and bottom halves of the octupole channel shown side by side. The seven PCBs are equally spaced in the channel in two layers.

EXPERIMENTAL RESULTS

Simulation Results

Experimental setup was informed by key simulation results. Figure 6 displays a frequency map generated from a WARP simulation, in which particles originated in a quadrant of the beam pipe, in the center of an octupole channel, were tracked over thousands of turns [4]. One method of experimentally exploring this space would be to keep the octupole strength fixed and vary particle amplitude, which is what was done in simulation. Another method is to keep particle amplitude constant and vary the octupole strength, proportionally shrinking or enlarging the area in Figure 6. This is the method we used in experiment.
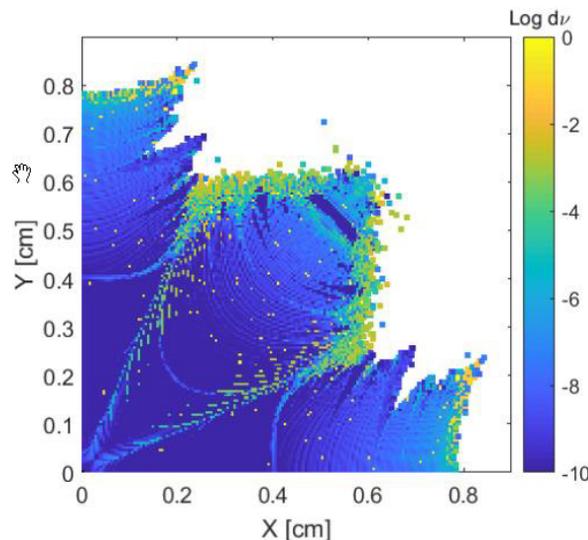
Figure 6: Frequency map showing particle survival and tune shift in one quadrant of the beam pipe. White space indicated particles did not survive, while colors correspond to the magnitude of tune shift of the particle originated at that location. [4]
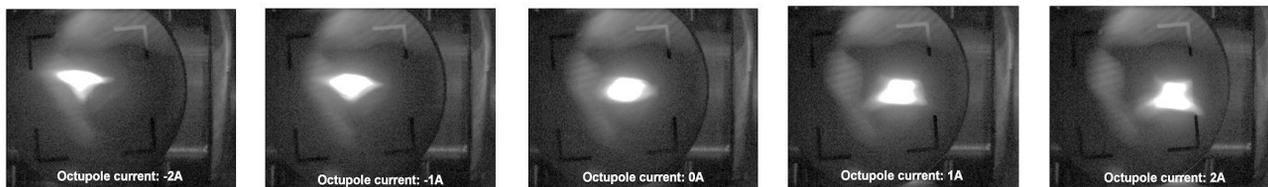
Figure 7: Phosphor screen pictures of a beam passing through the octupole channel as current in the channel is varied from -2A (left) to 2A (right).
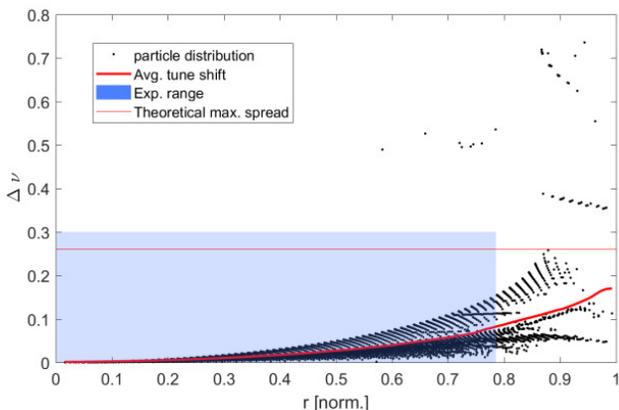
Figure 8: Constructed from data taken using the elegant code, particle tune shifts are shown as a function of normalized initial radius in the center of the octupole channel over many turns. [4,5].

A second important simulation is shown in Figure 8, which plots tune shifts as a function of starting radius in the octupole channel, in normalized units. It indicates that the maximum achievable tune shift is 0.26.

Beam Experiments
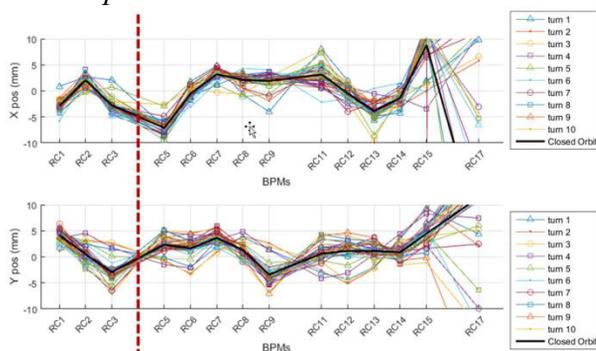
Figure 9: Beam positions in horizontal (top) and vertical (bottom) directions. The dashed line indicates the location of the octupole channel.

A lattice appropriate for nonlinear optics studies was designed by [6], with steering optimization done by [7]. A 10keV, 0.6mA electron beam was passed through the channel as octupole current was varied. As can be seen in Figure 7, the squaring off of the beam shows the effect of the octupole's eight lobes of alternating polarity on the beam's shape in configuration space. Steering for this experiment is shown in Figure 9.
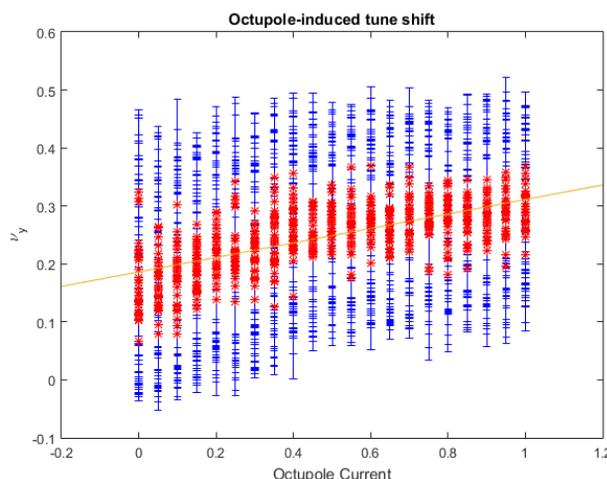
Figure 10: Scatter plot showing octupole-induced tune shift. Data points are red and error bars for each data point are in blue.

As octupole current was varied from 0A to 1A, data in Figure 10 show that average particle tune shifts by about 0.126. The tune was calculated using an FFT of beam position monitor data over 32 turns, with error bars defined by the disagreement between BPMs. Beam current was seen to be lost when the octupole was above 1A due to scraping. This octupole-induced tune shift is within the maximum predicted value.

CONCLUSION

Design of an octupole channel for quasi-integrable nonlinear optics studies was presented. An open-source multipole magnet generator script is available for download. Initial experimental data passing an 0.6mA 10keV electron beam through the octupole channel indicates a tune shift of about half of the maximum theoretically predicted value.

ACKNOWLEDGMENT

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