EXPERIMENTAL DETECTION OF ENVELOPE RESONANCE IN A SPACE-CHARGE-DOMINATED ELECTRON RING*

W.D. Stem, T.W. Koeth, I. Haber, B. Beaudoin, IREAP, University of Maryand, College Park, MD 20742, USA

Abstract

Linear perturbation analysis of the RMS envelope equations predicts a frequency splitting of the transverse envelope modes with the onset of space charge. The resulting resonances are a potential source of beam degradation for circular particle accelerators and storage rings encountering space charge. Following WARP simulations that predict measurable consequences of these resonances, an experiment has been designed for their direct detection. This paper provides a detailed description and preliminary results of an experiment to study envelope resonances in the beam at the University of Maryland Electron Ring (UMER), a scalable high intensity electron storage ring.

INTRODUCTION

In a particle beam, the set of particles that make up the transverse extremes of the beam at any given time is called the envelope. Because each particle oscillates sinusoidally in and out of the bulk, the envelope make-up changes in time. Independently of these particle oscillations, the envelope itself oscillates as described by the K-V equations [1,2,3]. These oscillations can be two different types as shown in Figure 1. The first type is called the breathing or even mode, in which the envelope oscillates in an azimuthally symmetric sense. The second is called the quadrupole or odd mode, in which the oscillations of the envelope are 90 degrees out of phase.

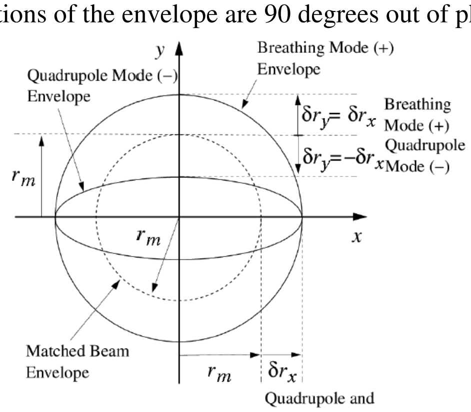

Figure 1: Transverse picture of the envelope modes [4].

At high energies, these envelope oscillations have the same frequency. This frequency occurs at a half-integer resonance, naturally determined from the geometry of the accelerator ring. At the onset of space charge a frequency splitting occurs and we can observe each of these oscillations independently. This frequency splitting is shown for UMER operating parameters in Figure 2.

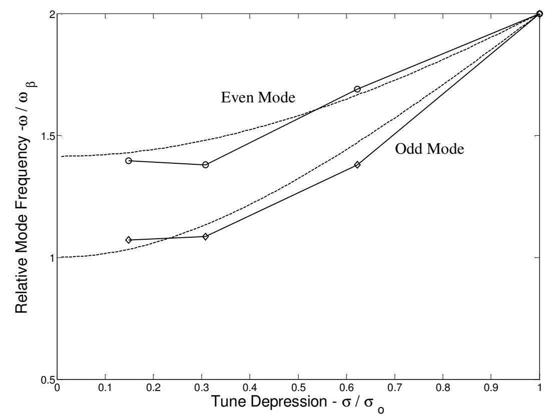

Figure 2: Relative envelope mode frequencies as a function of the tune depression for UMER operating parameters, plotted next to a calculation for the smooth approximation (dashed lines).

If we apply the appropriate perturbation to the envelope in phase with the mode we are trying to identify, the envelope will magnify in amplitude. This amplitude magnification results in the formation of a beam halo as shown in WARP simulation results [5]. After applying the perturbation, we can image the beam halo using a phosphor screen. Sweeping across frequencies, we can identify the resonant frequency of the oscillation as it will be proportional to the formation of beam halo. Applying the breathing mode perturbation may be possible with UMER's existing beam position monitors (BPMs), but the quadrupole mode requires the addition of an electrostatic quadrupole. This paper details the design, fabrication, and bench testing of the electrostatic quadrupole.

QUADRUPOLE DESIGN

In order to apply a quadrupole perturbation to the beam envelope, it is necessary to create a time-varying quadrupole field to match the oscillation frequency of the mode. To accomplish this, we create a resonant LC circuit using the quadrupole as a capacitor. The circuit design is shown in Figure 3.

*Work supported by US Dept. of Energy Offices of High Energy Physics and Fusion Energy Sciences, and by the Office of Naval Research and Joint Technology Office.

ISBN 978-3-95450-138-0

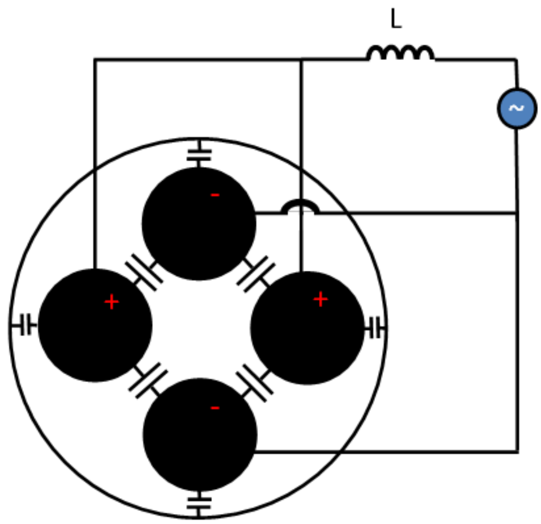

Figure 3: Circuit design for the electrostatic quadrupole. There is an undesired parasitic capacitance as the quadrupole interacts with the beam pipe wall.

Ideally, electrodes for a quadrupole field should have a hyperbolic cross section. However, fixing the ratio between the radius of the aperture and the radius of the electrode at 1:1.1468, a circular cross section approximates a hyperbolic cross section [6].

The quadrupole will replace an existing BPM in a BPM chamber. Due to the close proximity of the beam pipe wall, there exists a parasitic capacitance between the electrodes and the beam wall. To reduce this parasitic capacitance, the quadrupole's electrodes were designed to be half cylinders. The electric fields were simulated using a program developed by the Los Alamos Accelerator Code group called Poisson/Superfish [7]. The simulation is shown in Figure 4.

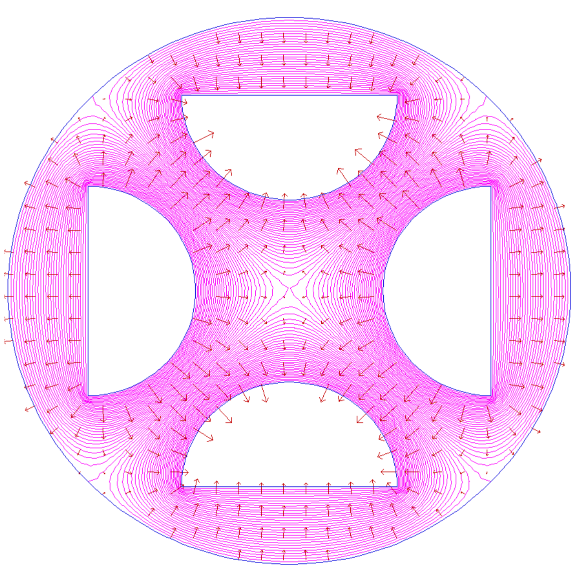

Figure 4: Poisson/Superfish electrostatic quadrupole simulation.

Since the opposing electrodes need to carry an identical, symmetrical voltage, the quadrupole was designed so that each group of opposing electrodes is in electrical contact through the base. Then the electrode pairs are attached by an insulating material. The CAD design for the quadrupole is shown in Figure 5.

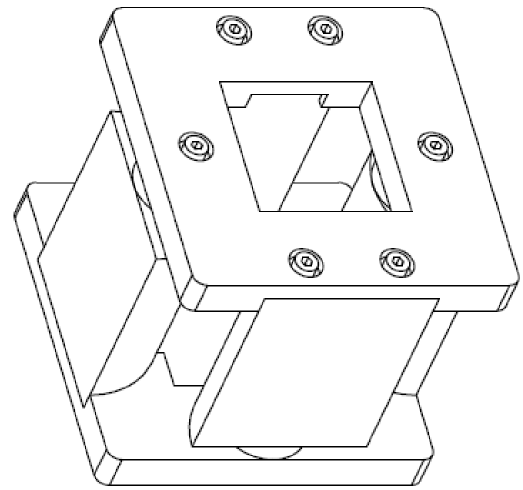

Figure 5: Pro/E diagram of machined quadrupole. Material is aluminum except for the insulating washers and insulating screws.

BENCH TESTS

Having machined the quadrupole to the CAD design in Figure 5, we proceeded to take measurements. By connecting a variable inductor to the bases of the quadrupole using the circuit design shown in Figure 3, a resonant circuit was formed. Using an MFJ-259B SWR Analyzer, the resonant frequency of the resonant circuit was measured. By finding the resonances for several values of inductance, we could plot the resonant frequency versus inductance and extract the capacitance according to the following equation:

$$C = \frac{1}{L(2\pi f_0)^2} \quad (1)$$

where f_0 is the resonant frequency of the circuit. This value was checked against a direct measurement of the capacitance using an SR715 LCR Meter. Initially, we used a stack of Mylar washers an inch in diameter for the insulating standoff. However, with a large area and a dielectric constant of 3.1, the capacitance between the electrodes and the base across the insulating gap was too great and it dominated the capacitance value between the electrodes. Instead, we opted for thinner, hollow plastic tubes to be used in place of the washers. Also, the base was unnecessarily large, so we fabricated new bases in the second bench model design shown in Figure 6.

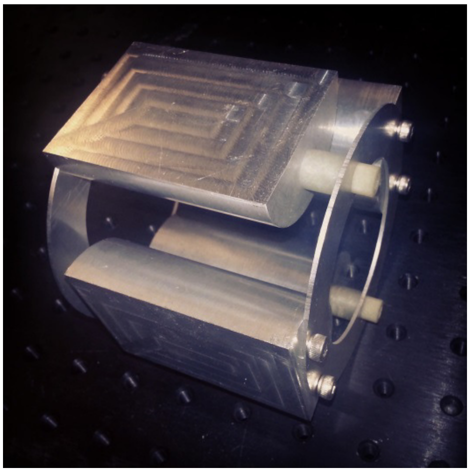

Figure 6: Finished bench model design using updated bases and insulating standoffs.

After completing a workable model of the quadrupole, we placed the quadrupole inside three sheets of wrapped sheet metal with a 6.9" inner diameter to simulate the parasitic capacitance from the beam pipe. Taking an S11 measurement with a network analyzer, the frequency spectrum for the resonant circuit was determined as shown in Figure 7. By perturbing the resonance in different ways, we have determined that the resonant peak for this circuit is just above 60 MHz. This of course can be varied by changing the value of the inductance in the LC circuit.

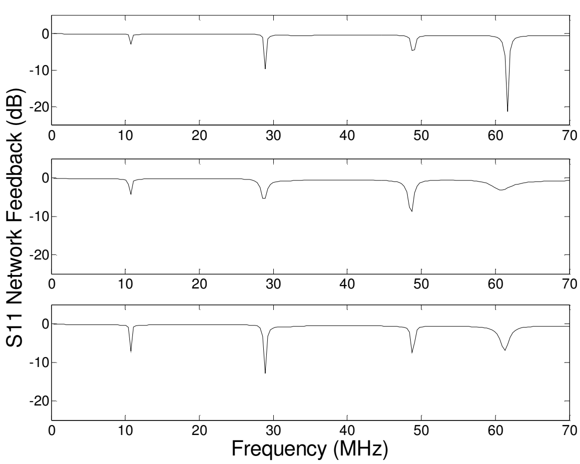

Figure 7: Frequency spectrum of the quadrupole from the network analyzer untouched (top) and touching each electrode (middle and bottom, respectively).

Using Matlab, the resonant peak was analyzed. The following formula was used to determine a Q of 444 for our resonant peak:

$$Q = \frac{f_0}{(f_{3dB} - f_{-3dB})} \qquad (2)$$

where f_{-3db} and f_{3db} represent the 3 dB bandwidth points. Using this analysis, we can verify that the parasitic capacitances from the beam pipe do not interfere with the capacitance of the quadrupole.

CONCLUSIONS

Envelope perturbations arising from resonant modes are present in space-charge-dominated particle accelerators and storage rings. It is important to understand these resonances when building and operating a high intensity accelerator to avoid emittance growth and beam loss. These modes can be observed experimentally using perturbative electric fields generated by an electrostatic quadrupole. After building a prototype and performing bench tests, we are certain that we can produce the fields necessary to induce envelope resonance in the beam. In the future, we plan to install a vacuum-ready electrostatic quadrupole into UMER and experimentally observe and manipulate high intensity envelope modes.

ACKNOWLEDGMENT

Thanks to John Pyle and Nolan Ballew of IREAP for their assistance in the fabrication of the electrostatic quadrupole. Also thanks to Timothy Ayo-Ajayi who assisted in the Pro/E CAD designs. Finally, we thank Alex Friedman, Dave Grote, and Jean-Luc-Vay for their support of the WARP code.

REFERENCES

[1] Kapchinsky, I.M. and Vladimirsky, V.V., *Proc. Int. Conference on High Energy Accelerators and Instrumentation*, CERN 1959, p. 274-288.

[2] Lapostolle, P.M., *IEEE Trans. Nucl. Sci.* **NS-18**, 1101 (1971).

[3] Sacherer, F.J., *IEEE Trans. Nucl. Sci.* **NS-18**, 1105 (1971).

[4] Lund, S.M. and Bukh, B. *Physical Review Special Topics: Accelerators and Beams*, 7 (2004), p. 024801-14.

[5] Stem, W.D. et al. *Envelope Perturbations in a Space-Charge-Dominated Electron Beam.* IPAC 2013 Proceedings, TUPME064, Shanghai, China.

[6] Hawkes, P.W. *Quadrupoles in Electron Lens Design.* Supplement 7. Academic Press. New York, 1970.

[7] Krawczyk, Frank. "Download Area for Poisson Superfish." *Los Alamos Accelerator Code Group*. 6 July 2012. 25 Sept. 2013.