LINEAR RESONANCE ANALYSIS OF BEAMS WITH INTENSE SPACE CHARGE IN THE UNIVERSITY OF MARYLAND ELECTRON RING (UMER)

Chao Wu [*], E.H. Abed,
Institute for Systems Research, University of Maryland, College Park, MD, 20742, USA.
S.Bernal, B. Beaudoin, R.A. Kishek, P.G. O'Shea, M. Reiser, D. Sutter
IREAP, University of Maryland, College Park, MD 20742, USA

Abstract

Space charge can significantly affect the resonant properties of rings. The University of Maryland Electron Ring is a scaled experiment in which we have circulated beams with unprecedented intensities. Here we discuss the resonance analysis performed using the electrostatic particle-in-cell code WARP, to understand the effect of space charge on the ring resonances. Beams with varying degrees of space charge in both the emittance-dominated and space-charge-dominated regimes are attempted. The operating point is scanned to map the tune diagram under various lattice and injection errors. The results of the simulation study are compared to experimental measurements.

INTRODUCTION

The importance of understanding and predicting beam loss, in order to improve the machine performance, cannot be underestimated for high intensity synchrotron or storage rings. There are many causes for beam loss. Examples include injection errors, mechanical misalignments, errors in beam steering, and unstable operating points. To correctly identify the cause is a challenge. Moreover, when the operating point is close to the integer or half integer tune operating point, the multi-turn beam quality will deteriorate quickly. Space charge introduces a shift in the tune that complicates the analysis. The tune shift has both an incoherent component as well as a coherent component experiences by the beam as a whole due to the image forces. This shift affects the beam quality and shifts the resonance point [2].

This paper will use the University of Maryland Electron Ring(UMER) as a platform to study beams with varying degrees of space charge force. We use both experiment and computer simulation to explore how space charge forces and lattice errors affect the resonant property. This study is focused on the integer and half integer resonances.

The University of Maryland Electron Ring (UMER) is a low-energy, high-current machine designed to carry out beam physics research with space charge [6, 7, 8]. It models the transport physics of intense space-charge-dominated beams. Its current varies from 0.6mA to 100mA, as in Table (1), which covers a wide region from emittance dominated beams to space-charged dominated beams.

For UMER, the design goal is to circulate low current beam for 100 turns and high current beam for 10 turns without beam loss, and the emittance growth is less than a factor of 4. At the same time, this is a good opportunity to benchmark our simulation code in WARP [3], WinAgile, and ELEGANT.

Table 1: Typical UMER Beam Parameters

Beam current	Radius	Emittance	Tune depression
0.7 mA	1.5 mm	7.6 μm	0.82
7.0 mA	3.0 mm	25.5 μm	0.56
23.0 mA	5.0 mm	39.0 μm	0.34

Traditionally, there is a stability requirement that incoherent Laslett tune shift limit be $\delta\nu < 0.25$ to avoid integer and half-integer resonance. However, from Table (2) of UMER, it can be seen that the tune shift for these three different beams is much greater than 0.25. Nevertheless, we have a good multi-turn circulation with appropriate lattice settings.

Table 2: Tune shift for three beams

	0.7mA	7mA	23mA
Nominal tune	6.17	6.17	6.17
Incoherent tune spread	1.1	2.7	4.1
Coherent tune shift	0.02	0.08	0.20

First, define a parameter r to quantify the beam loss in the ring. Without loss of generality, we use the beam position monitor (BPM) signals:

$$r = \frac{\text{total BPM current at turn 4}}{\text{total BPM current at turn 1}} = \frac{I_4}{I_1} \qquad (1)$$

where the BPM location, in general, does not matter. r defines the beam loss, or the ratio of transmitted current. Larger r indicates better quality of multi-turn operation.

Figure (1) is the experimental result for two beams with different degrees of space charge. The 7mA beam has less space charge and the 23mA beam has intense space charge. The top plot is for the 7mA beam, where we see a significant beam loss in three regions. The first region is 1.85-1.95A, the widest one. The second region is 2.03A-2.07A. The third region is around 2.17A with only a dip. The bottom plot is for the 23mA beam, where we see a significant beam loss in three regions. However, this time, there is a shift for the beam loss region and the width of the region differs from that of the 7mA beam. The first region is 1.94-1.96A. The second region is 2.06-2.08A. The third region is 2.12-2.2.

---

[*] wuchao@umd.edu

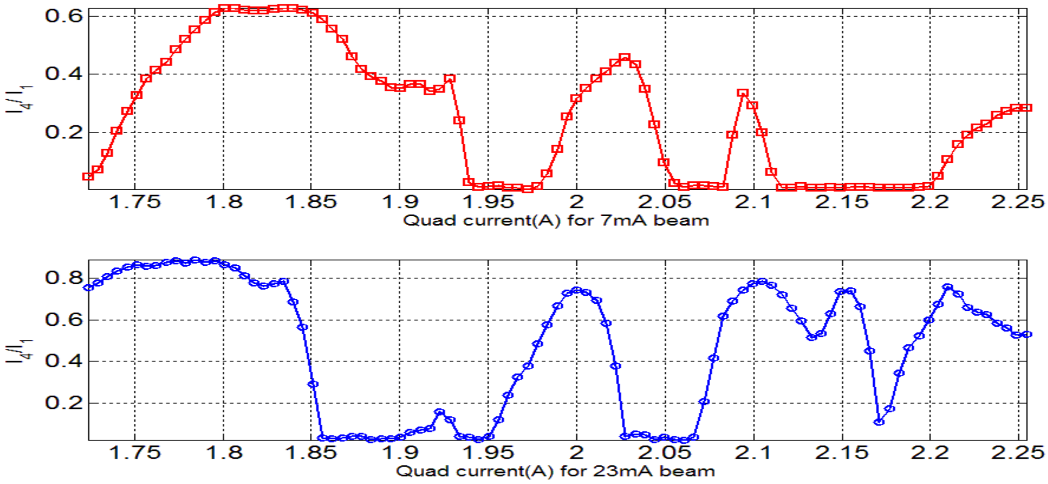

Figure 1: Experimental result: quadrupole scan versus transmitted total current. The upper plot is for 7mA beam and the bottom plot is for 23mA beam. Beam loss is observed at different operating points.

To better understand why and how this beam loss happens in these regions, we simulated the ring under various circumstances as described in the next section.

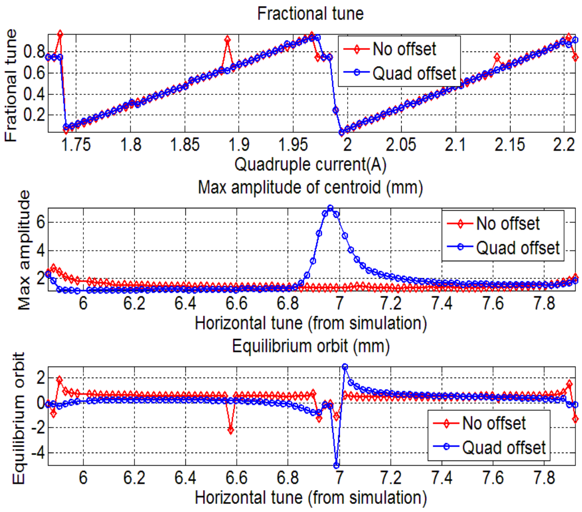

Figure 2: Simulations for 0.7mA beam. The red ”diamond” line refers to the case without quadrupole error. The blue ”circle” line refers to the case with quadrupole error. The top plot is the fraction tune versus quadrupole current. The middle plot is the maximum centroid amplitude versus calculated tune. The bottom plot is the equilibrium orbit versus calculated tune.

For the simulation, we choose Particle-in-cell code WARP([3]), which has been developed at Lawrence Livermore National Laboratory for heavy ion fusion applications. One important feature of WARP is its ability to deal with space-charge dominated beams.

The simulations were set up as following:

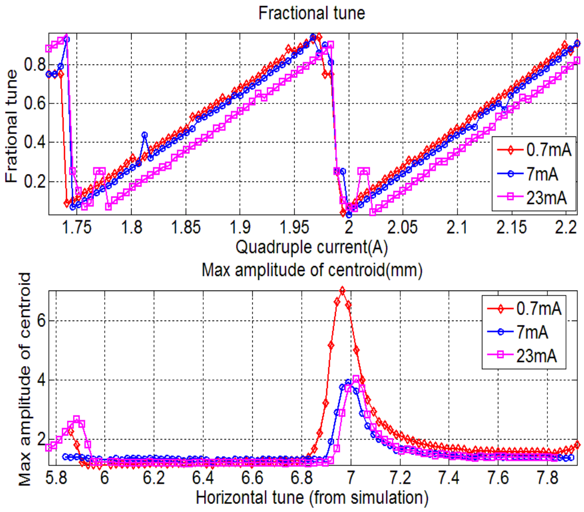

Figure 3: Simulation for 0.7mA, 7mA and 23mA beams with random quadrupole alignment error. The red ”diamond” line refers to 0.7mA beam. The blue ”circle” line refers to 7mA beam. The purple ”squared” line refers to 23mA beam. The top plot is about the fractional tune and the bottom plot is about the maximum centroid amplitude.

1. The initial beam has a semi-Gaussian distribution,
2. Constant earth field, By=0.4 Gauss,
3. Ignore the injection,
4. Magnets include full fringe fields and nonlinearities,
5. Particle number np=20,000, grid nx=ny=256, ds=0.002m,
6. Use 4-turn measurement approach as described in

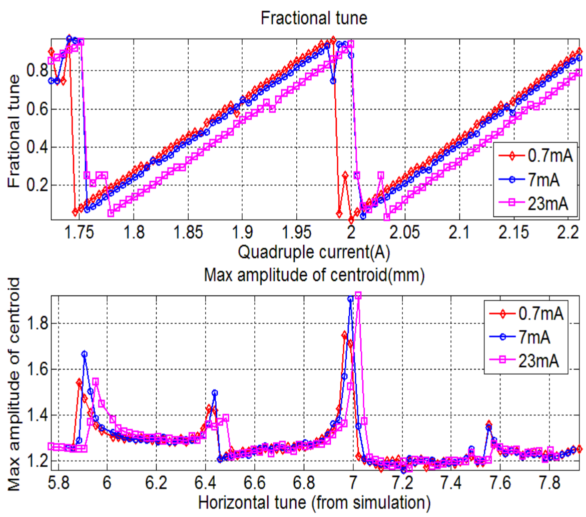

Figure 4: Simulation with quadrupole random strength error for 0.7mA, 7mA and 23mA beams. The red ”diamond” line refers to 0.7mA beam. The blue ”circle” line refers to 7mA beam. The purple ”square” line refers to 23mA beam. The top plot is about the fractional tune and the bottom plot is about the maximum centroid amplitude.

next subsection to obtain fractional tune and equilibrium orbit.

In the simulation, we considered three different situations: (1)no error, (2)quadrupole alignment error, (3)quadrupole strength error. We assume the errors are uniformly distributed along the ring.

We take the approach from Koutchouk ([5]) by using consecutive beam position monitor signals to calculate the fractional tune and equilibrium orbit.

The simulation results are plotted in Figures (2), (3), and (4).

In Figure (2), it can be seen that the maximum amplitude of beam centroid (in X plan) grows significantly around the integer tune point when there exists quadrupole misalignment error. The equilibrium orbit is greatly distorted around the integer tune point when there is quadrupole misalignment error. However, there are no centroid growth and no equilibrium distortion when there is no quadrupole alignment error.

In Figure (3), it can be seen that the maximum amplitude of the beam centroid is distorted for all three beams around integer tune operating point. However, the bandwidth of the resonance for these three different beams, from emittance-dominated to space-charge-dominated, is almost the same. The tune shift agrees well with Table (2) for three beams. The integer resonance for the low current beam appears to be much stronger than for high current, where space charge plays a detuning effect.

In Figure (4), unlike the pure random quadrupole alignment error, it can be seen that there exist both integer resonance and half integer resonance when there exists a quadrupole strength error, which agrees that the quadrupole strength error introduces first order and second order resonance ([8]).

In this paper, we applied simulation to explore the resonant properties, and compared them with experimental results. The simulation has provided a valuable tool for us to understand some intricate physical phenomena which are difficult to explain analytically. Future work will include analysis on higher harmonic errors, injection/recirculation, beam losses, detailed RMS envelope matching, and incoherent space charge effects.

This work is sponsored by the U.S. Department of Energy Offices of High Energy Physics and High Energy Density Physics, and the US Dept. of Defense Office of Naval Research and Joint Technology Office.

REFERENCES

[1] C. Wu., et. al, “Error and resonance analysis of beams with intense space charge in the University of Maryland Electron Ring,” *13th Advanced Accelerator Concepts Workshop,* Santa Cruz, CA, July 2008.

[2] R. Baartman, “Betatron resonances with space charge,” *Workshop on space charge physics in high intensity hadron rings,* Shelter Island, NY, May 1998.

[3] D.P. Grote, A. Friedman, I. Haber, W. Fawley and J.L. Vay, “New developments in WARP: Progress toward end-to-end simulation,” *Nuclear Instruments and Methods in Physical Research A*, 415, p.428, 1998.

[4] R.A. Kishek et. al., “HIF research on the University of Maryland Electron Ring(UMER),” *Nuclear Instruments and Methods A* 544, 179-186, 2005.

[5] J. Koutchouk, “Frontiers of Particle Beams: Observation, Diagnosis and Correction,” *Proceedings, Anacapri, Isola di Capri, Italy, (Lectures Notes in Physics 343, M. Month, S. Turner CEds-),* p 46, 1988.

[6] P.G. O’Shea, M. Reiser, R.A. Kishek, et. al., “The University of Maryland Electron Ring (UMER),” *Nuclear Instruments and Methods A 464,* 646-652, 2001.

[7] M. Reiser, P.G. O’Shea, R.A. Kishek, et. al, “The Maryland Electron Ring for Investigating Space-Charge Dominated Beams in a Circular FODO System,” *Proceedings of the 1999 IEEE Particle Accelerator Conference,* New York City, NY, 234, 1999.

[8] M. Reiser, *Theory and Design of Charged Particle Beams,* WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2004.