THE UNIVERSITY OF MARYLAND ELECTRON RING (UMER) ENTERS A NEW REGIME OF HIGH-TUNE-SHIFT RINGS *

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Abstract

Beams with a high phase space density are useful for many modern applications such as free electron lasers, pulsed neutron sources, high-energy-density physics, and high-luminosity colliders. Production of such beams requires understanding the complex space charge dynamics at the low-energy end of the accelerator. The University of Maryland Electron Ring (UMER) has been designed and built with the purpose of investigating space charge effects using scaled low-energy electron experiments. We have recently circulated the highest-space-charge beam in a ring to date, achieving a breakthrough both in the number of turns and in the amount of current propagated. We have propagated a beam with an integer tune shift for over 100 turns, and other, even higher-current beams, for 5-50 turns albeit with some beam loss. One beam had a tune shift at injection of 5.0, which is several factors higher than anything propagated in the past. We report here as well on other interesting aspects of the UMER work.

INTRODUCTION

Modern accelerator applications require high-quality beams that have a high phase space density. Traditional applications such as high-energy colliders [1-2] can benefit from increased luminosity that allows detection of rare particles. Another class of accelerators at medium energies requires beams with a high brightness to accurately image matter at the molecular and atomic scales. Examples are accelerator-driven neutron sources [3] and high-power free-electron-lasers and light sources [4-7]. Dense beams of heavy ions [8] can also be used to produce exotic states of matter for high-energy density studies, and eventually can be used to drive inertial fusion reactions for energy production.

Production of the high-quality beams needed for such applications represents a major scientific challenge due to the complex dynamics of charged particle collections with high phase-space densities. Particularly at the low-energy end of these accelerators, space charge forces lead to collective behavior that is difficult to analyze self-consistently and is often destructive to the beam. In practical terms, space charge interactions often result in emittance growth and halo formation, i.e., the dilution of the beam phase space and reduction of quality. Beam losses in high-power accelerators due to halos also increase the costs of the accelerator due to the radiation and health issues involved.

The key to increasing beam brightness is to understand space charge dynamics sufficiently to be able to accurately predict beam evolution. In this paper we report on the University of Maryland Electron Ring (UMER) [9], a model accelerator with low-energy electrons designed to enhance space charge forces and study their interactions over relatively long time scales. The parameters of the UMER beam are adjustable over a wide range of intensities, and are scalable to other machines. The UMER effort is further supported by a theoretical and computational modeling effort that is coordinated closely with experiments in order to reveal useful physical insights.

UMER is currently in the multi-turn commissioning phase. Due to the intense space charge in even the lowest-current UMER beams, our commissioning goals have been limited to achieving 100 turns at low-current and 10 turns at the highest beam currents. We are well on our way towards achieving these goals, thus demonstrating the possibility of operating a ring with extreme tune shifts, and in the process learning much about the dynamics of beams with space charge. Of interest are processes leading to emittance growth, halo formation, increase in energy spread, and instability.

This paper serves to summarize the latest developments in the UMER project, including the results of the multi-turn commissioning effort.

SPACE CHARGE INTENSITY

In order to put the UMER effort in context, we will quantify what we mean by space charge intensity. Beam brightness is a commonly used measure of phase-space density and is a good measure of the inherent quality of the beam at the source or target. From the point of view of beam transport, however, what matters is the relative strength of the space charge force to other forces in the system, such as the applied external force or the thermal pressure due to emittance. By normalizing the rms envelope equation, several related dimensionless parameters can be derived that describe this relationship. An example is the tune depression, defined as the ratio of

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* Work supported by US Dept. of Energy grant numbers DE-FG02-94ER40855 and DE-FG02-92ER54178, and by US DOD Office of Naval Research and JTO.

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a particle's (incoherent) tune to the zero-current tune (ν/ν_o), where the tune is the number of betatron oscillations a particle experiences per turn. In this paper we use the intensity parameter, χ, defined as the ratio of the transverse space charge force at the rms edge of the beam to the external focusing force [9-10]. In terms of beam parameters for a matched beam in a uniform focusing channel, the intensity parameter translates to:

$$\chi = \frac{1}{1+\frac{2\beta\gamma I_o}{I}\left(\frac{\varepsilon_n}{a}\right)^2} = 1-\left(\frac{\nu}{\nu_o}\right)^2 \quad \textbf{(1)}$$

where I is the beam current, ε_n is the rms normalized emittance, a the rms beam radius, β the particle velocity normalized to the speed of light, and γ the relativistic mass factor. Here, I_o is the characteristic current, a constant depending on the type of particle, equal to the classical particle radius times the particle charge times the speed of light (~ 17.0 kA for electrons).

By this definition, the intensity parameter χ is a dimensionless number between zero (for zero current) and one (for zero emittance or cold beams at the space charge limit). Naturally, not all the properties of a beam can be described by a single number. In fact, for beams with intense space charge much of the dynamics depends critically on the details of the distribution. This in turn is one of the principal underlying justifications for experimental efforts such as UMER that is aimed at distinguishing distribution-dependent effects.

Figure 1 below displays several existing and planned accelerators as a function of space charge intensity and (normalized) relativistic momentum $\beta\gamma$. The endpoints and the direction of the arrow in each case point to the parameters from the output of the injector to the final target state, with the exception of the LHC and the ILC, for which the starting point is taken as the input to the main ring or the damping rings, respectively. In general, a beam proceeds from a most intense state near the source to a less intense state near the target as space charge forces are reduced by emittance growth and acceleration, unless the beam is actively cooled or longitudinally compressed.

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The reach of UMER is marked in red on Fig. 1, and a list of operating parameters is provided in Table 1. Note that we normally inject one beam at a time with a repetition rate of 10-60 Hz and let it circulate until it is lost. The beam pulse duration is adjustable from 5-100 ns, and is typically 50 or 100 ns. The circulation time of a 10 keV electron beam around a ring of circumference 11.52 m is 197 ns, so the beam is relatively long. We can vary the operating point in parameter space by adjusting the current, radius, and emittance of the injected beam, as well as the applied focusing in the ring. Thus the injected UMER beam can have a large range of intensities spanning numbers of relevance to heavy ion machines, neutron sources, and free electron lasers.

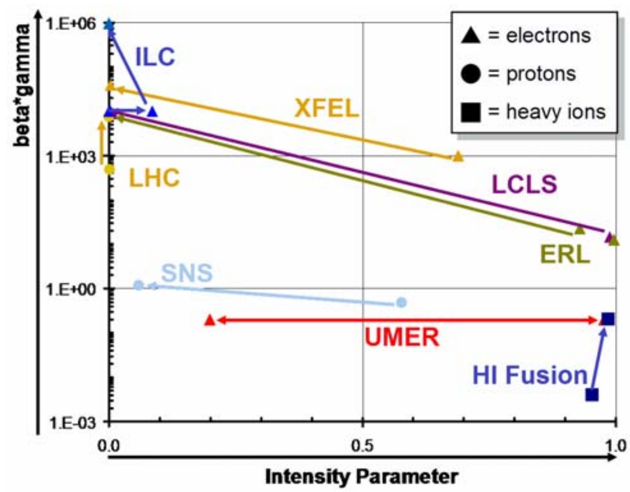

Figure 1: Location of representative modern accelerators in intensity and momentum parameter space.

Table 1: Typical parameters of the UMER beam.

Energy	10 keV ± 0.2 %
Current Range	0.6-100 mA
rms Emittance (ε_n)	0.2-3 mm
Circulation time	197 ns
Pulse length	5-100 ns
Nominal Tune	7.6
Depressed Tune	1.5 ñ 6.5

The UMER lattice consists of 36 FODO cells using a pair of printed circuit quadrupoles to focus the beam and a printed circuit dipole atop a 10° bend. The magnetic fields involved are quite modest ñ of the order of 10 Gauss. In view of the short effective length of the magnets (less than 4 cm), the earth's magnetic field, which has a strength of about 0.5 Gauss, significantly affects the beam orbit and must be included in any analysis. To this end we employ a number of single-particle codes as well as the self-consistent particle-in-cell code WARP [11]. The latter code is useful for predicting higher-order effects such as response and sensitivity of a space-charge-dominated beam to errors, resonances, or choice of initial distribution.

UMER operates in a largely unknown regime where there is little existing experimental data. For example we have found that we need to carefully control the positioning of large objects in the vicinity of the ring, even several feet away from the beamline, due to their effect on the ambient magnetic field.

Another difficulty caused specifically by space charge is the need for close spacing of the magnets to keep the beam size well-constrained. This leaves less room for placement of beam position monitors (BPMs) than we need for accurate beam control. To address this issue, we rely upon systematized quadrupole-scan techniques such that every quadrupole in the ring doubles as a beam position monitor during the first turn [12-14]. We have also studied the possibility of operating the lower-current beams with a sparser lattice and hence longer betatron periods relative to the BPM spacing [15].

Space charge forces have been known to result in exotic beam distributions that contain considerable internal structures [16-17]. Recently, we have discovered that slight imperfections in the cathode positioning inside the gun can lead to even more exotic distributions with a large halo [18]. We are therefore devoting substantial attention to gun simulation, including exploration of ideas for eliminating this halo [18], as well as studies of halo evolution and benchmarking code results against experiments [19].

MULTI-TURN RESULTS

Despite these difficulties, we have been able to circulate beams with unprecedented intensities for many turns. The following figures illustrate some recent results for three different injected beam currents. The first figure shows the signal on each of the four beam position monitor (BPM) plates, while the next two figures show the total beam current measured by summing the four signals from the BPM. The signal or current is shown as a function of time at one location around the ring, each bump corresponding to the beam passing through one additional turn. The data in all three figures is taken at BPM 2 which is located 1.12 m downstream of the injection point.

The commissioning of UMER is still ongoing, so we believe we have not yet encountered any fundamental limit. We are continually optimizing the transported beam by means of more refined orbit control [13-14], tuning of the operating parameters [15], and general debugging of the lab equipment (magnets, power supplies, drivers, software issues, etc.). Indeed, WARP simulations during the design phase have indicated the possibility of operating such a ring with reasonable sets of harmonic errors for over 25 turns, even for the highest-current beam.

Naturally the lowest current beam, being the smallest and the least intense, was the easiest to transport for a long period. The beam current profile remains largely unchanged from turns 3 through 125, which corresponds to a distance of well over 1 km. We have designed UMER with an operations goal of 100 turns, so the beam stops due to the shutting down of the pulsed injection magnet after about 25 μs. There is no fundamental reason for why its propagation should not continue beyond 125 turns.

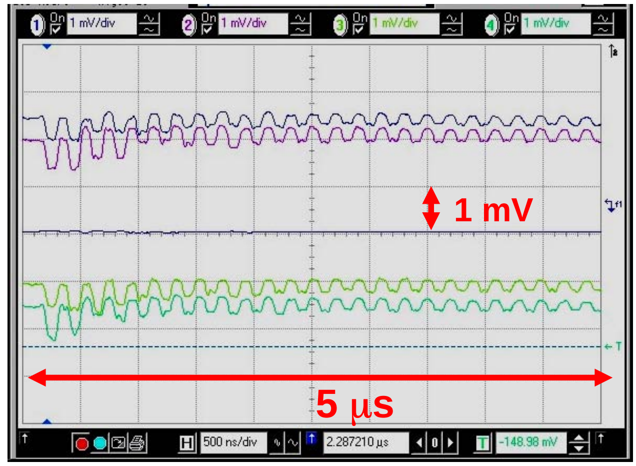

Figure 2: Signals from each of four plates of BPM 2 as a function of time for the *lowest-current* UMER beam [20]. The injected beam current of 0.65 mA corresponds to an intensity parameter χ = 0.37 or a tune shift of 1.5. Only the first 25 turns are shown.

It is worth pointing out that even this lowest current beam represents a significant space charge tune shift of 1.5, as described in Table 2. Here, χ at injection is calculated using Equation 1 and the experimentally measured values of current, emittance, and average beam radius. From that, the incoherent space charge tune shift, $\Delta\nu = \nu_o - \nu$, can be calculated using the calculated zero-current tune, ν_o, and the following formula:

$$\Delta\nu = \nu_o\left(1-\frac{\nu}{\nu_o}\right) = \nu_o\left(1-\sqrt{1-\chi}\right) \quad \textbf{(2)}$$

The zero-current tune is calculated from the magnet settings to be 7.3 for the cases in Figs. 2 and 4, and 7.08 for the case in Fig. 3. Due to the difficulty of measuring the tune when we have beam losses, the calculated value has been verified experimentally only for the lowest-current case for which we have achieved over 100 turns.

The intensities and tune shifts after circulation by n turns are estimated somewhat differently, due to the present incapability of accurately measuring emittance and beam radius beyond the first turn. This will be remedied after building the extraction section which will allow beam characterization on a turn-by-turn basis [22]. In the meantime, we estimate the intensity bounds in two ways. Assuming that the beam loss occurs mostly due to centroid oscillations, as an upper bound we assume that the beam radius and emittance are reduced commensurate with the reduction in beam current. As a lower bound, we assume that they stay the same to account for additional emittance growth.

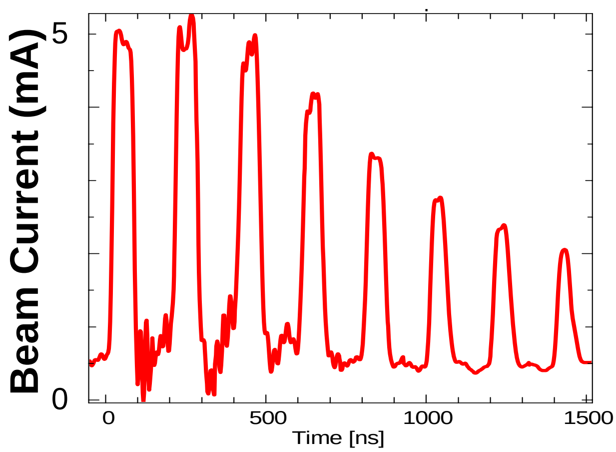

Figure 3: Measured beam current as a function of time for *intermediate* UMER beam at BPM 2. The injected beam current of 5 mA corresponds to an intensity parameter χ = 0.66 or a tune shift of 3.0. Only the first 8 turns are shown.

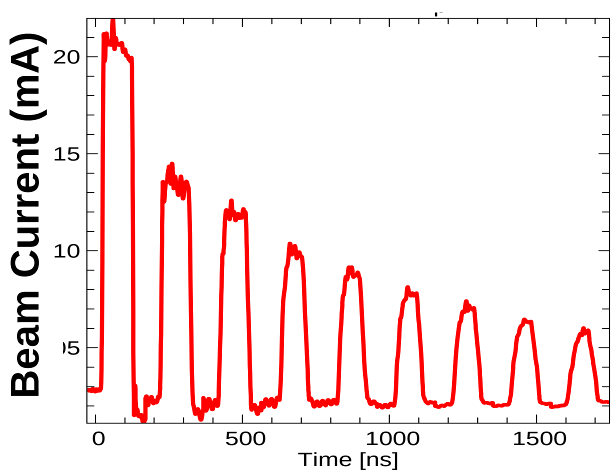

Figure 4: Measured beam current as a function of time for *intense* UMER beam at BPM 2 [21]. The injected beam current of 20 mA corresponds to an intensity parameter χ = 0.9 or a tune shift of 5.0. Only the first 9 turns are shown, but the beam persists for up to 60 turns.

Table 2: Intensity parameters and tune shifts for the three beams in Figs. 2-4 at injection and at the end of each figure.

Beam	Injected		At end (estimated)	
	χ	$\Delta\nu$	χ	$\Delta\nu$
0.65 mA	0.37	1.5	0.18-0.26	0.7-1.0
5 mA	0.66	3.0	0.26-0.48	1.1-2.0
20 mA	0.90	5.0	0.41-0.73	1.7-3.5

We note again that, even for the lowest-current UMER beam, the space charge induced tune shift at the end is estimated to be of the order of 1 integer. In other words, the UMER tune spread spans several low-order resonances and yet we get good circulation for over 100 turns. While this may appear as a mystery, the following facts need to be kept in mind:

- Most studies of ring resonances introduce space charge as a perturbation to an essentially single-particle analysis. For UMER, space charge is far from being a perturbation.
- The location and spacing of resonances can change considerably with the proper introduction of space charge [23-24].
- Use of a realistic particle distribution with a spread of tunes can act to damp any resonant effect [25].

In fact, while wisdom going back to Laslett has restricted rings to tune shifts under 0.25, it has long been postulated that it is quite possible to operate rings with fairly large tune shifts under certain conditions [26-27]. Some pioneering experiments have been performed at the AGS [28] which gave credence to this assertion. Up until these experiments with UMER, however, there has been no systematic experimental study, likely due to cost of modifying an existing high-energy ring for the purpose.

The case in Fig. 3 is interesting since if we increase the strength of all the ring quadrupoles by a mere 1%, corresponding to a zero-current tune of 7.15, the entire beam is lost during or after the second turn. This is not yet completely understood, but note that we paradoxically get better results closer to an integer tune.

For the results with the 5 mA and 20 mA beams, note that the longitudinal pulse shape changes over the first few turns. Due to the longitudinal space charge forces, the beam ends erode creating a broader and more triangular pulse. Currently we have successfully tested a prototype induction module to be used for longitudinal confinement of the beam, which should help in preserving the pulse shape for a longer number of turns. Details of that are discussed in ref. [29]. A related issue that needs to be addressed is pulsed injection. We have a 100 ns window in which to switch a pulsed dipole from injection mode to recirculation mode. However, a small ripple after the switching leads to time-dependent oscillations along the beam during the second turn. For the higher-current beams in Figs. 3 and 4, this results in the loss of the first third of the beam by the end of the second turn.

During installation of the ring we have achieved much better control over steering and matching using DC injection [30]. We anticipate being able to further improve the number of turns propagated by better steering and beam control, better injection and matching techniques, and more accurate measurement of the tune.

OTHER UMER WORK

The primary goal of UMER is to understand the dynamics of beams with space charge. We have therefore invested significant effort in developing new precision diagnostics to map longitudinal and transverse phase space. We have also developed new techniques to manipulate the initial beam distribution so as to

1-4244-0917-9/07/$25.00

experimentally monitor the distribution dependence of various phenomena.

For mapping longitudinal phase space we have developed a compact, high-resolution energy analyzer [31]. By modifying a standard retarding-potential analyzer, we have demonstrated an energy resolution better than 1 part in 10^4, coupled with a time resolution of about 5 ns and a sub-mm spatial resolution. For mapping transverse phase space, we have experimented with slit-wire and with pepper-pot techniques, and now commonly use high-fidelity tomographic techniques that are simple to implement using our existing wealth of view screens and quadrupoles [12]. Due to the uniqueness of the UMER beam, we needed to develop a new tomographic reconstruction algorithm which accounts for space charge forces in the beam [32-33]. The technique has been tested on simulations with WARP, and the latest phase-space reconstructions of experimental data have added to our understanding of the dynamics of beam halo and evolution of nonlinear beam distributions.

In order to decouple the transverse and longitudinal measurements, we have recently implemented means for fast imaging of the beam using an intensified gated camera. We have experimented with two kinds of fast imaging: prompt optical transition radiation [34], and fast phosphor-coated screens with a 1-2 ns time resolution [35].

We have also introduced several methods for manipulating the beam distribution longitudinally and transversely. Noteworthy is the ability to produce pure energy and/or density modulations on the beam and to measure their evolution downstream. We can produce pure *density* modulations using photoemission from a laser beam of much shorter pulse length (~ 5 ns) than the thermionically-emitted main beam [36]. We have also produced pure *energy* modulations of length ~10 ns using the prototype induction module [29]. These new techniques augment the method we have used in the past, namely by applying a perturbation to the cathode grid pulse inside the gun, which suffers from the complexity of the beam dynamics inside the gun. Experiments to date, reported in refs [36-37, and 29], demonstrate the conversion of density modulations to energy modulations and vice-versa, as expected from 1-D theoretical models and as verified by self-consistent WARP simulation.

CONCLUSION

Our experiments on UMER have demonstrated the circulation of beams with unprecedented intensities for relatively long periods of time. We are learning much about operating in this relatively uncharted region of space charge intensity, which presents unique difficulties and different challenges than normal accelerators. Optimization of the UMER beam continues and at this time there is no apparent fundamental limit to the number of turns we can transport. We have further developed a sophisticated suite of experimental tools for manipulating and measuring the beam distribution. Additional details on these topics can be found in some of the references below.

ACKNOWLEDGEMENTS

We are indebted to all our former colleagues for making this possible: P. Chin, Y. Cui, J.J. Deng, H. Li, Y. Li, J. Harris, Y.J. Huo, J. Neumann, M. Pruessner, J.G. Wang, M. Wilson, A. Valfells, M. Venturini, M. Virgo, V. Yun, W.W. Zhang, and Y. Zou. We are also indebted to our former and current collaborators: J.J. Barnard, R. Davidson, G. Franchetti, A. Friedman, D.P. Grote, P. Haldemann, I. Hofmann, D. Kehne, S.M. Lund, F. Mako, H. Nishimura, T. Shea, I. Sideris, T. Wangler, X.Y. Wu, L. Vorobiev, and R. York. We are also deeply saddened at the loss of our former collaborator Courtlandt Bohn, whose enduring contributions and support for our work will not be forgotten.

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