

# EXPERIMENTAL AND SIMULATION STUDY OF THE LONG-PATH-LENGTH DYNAMICS OF A SPACE-CHARGE-DOMINATED BUNCH\*

I. Haber, B. L. Beaudoin, S. Bernal, R. A. Kishek, T. W. Koeth, Y. C. Mo  
University of Maryland, College Park, MD 20742, USA

## Abstract

The University of Maryland Electron Ring (UMER) is a low-energy (10 KeV) electron facility built to study, on a scaled machine, the long-propagation-length evolution of a space-charge-dominated beam. Though constructed in a ring geometry to achieve a long path length at modest cost, UMER has observed important space-charge physics directly relevant to linear machines. Examples are presented that emphasize studies of the longitudinal dynamics and comparisons to axisymmetric simulations. The detailed agreement obtained between axisymmetric simulation and experiment is presented as evidence that the longitudinal physics observed is not strongly influenced by the ring geometry. Novel phenomena such as soliton formation, unimpeded bunch-end interpenetration, and an instability that occurs after this interpenetration, are discussed.

## BACKGROUND

The University of Maryland has had a long-standing program, inspired and nurtured by the late Prof. Martin Reiser, of using electron beams to conduct research, on a scaled basis, into the fundamental physics of intense charged particle beams when the beam evolution is dominated by the influence of space charge. An important and continuing element of this research has been its emphasis on comparison of theory and simulation to experiment. The early successes achieved are a strong motivation for the current research.

During the early years, the primary experimental facility was a 240 mA, 5 KeV electron beam injected into a transport system that consisted of 38 discrete iron core solenoid magnets, placed 13.6 cm apart [1]. Particle-in-cell (PIC) simulations [2] that carefully modelled the iron core solenoids [3] were successful in reproducing, in detail, experimentally observed behavior. The influence of space charge on beam characteristics such as emittance growth in the presence of misalignments and small errors in the initial match [4] were quantitatively reproduced and explained.

A significant milestone in simulation/experiment benchmarking [5] was achieved in an experiment where a mask was placed immediately downstream of the electron gun to produce a five beamlet pattern. This experiment was performed to test the theory that a nonuniform transverse current profile will relax to the lowest-potential-energy uniform profile. The excess energy would be converted to kinetic energy, causing the beam

emittance to grow [6]. Agreement was obtained on the emittance growth between experiment and simulation and theory.

An unexpected downstream re-emergence of the initial five-beamlet pattern was observed on a series of downstream phosphor screen images. Furthermore, the image evolution was reproduced in striking detail in simulation. The simulations assumed uniform emission from the gun with the intrinsic emittance calculated from the cathode temperature and employed no adjustable free parameters. In addition, evolution of the current cross-section was sufficiently sensitive to the initial emittance that only a few percent variation in the initial emittance assumed in the simulation resulted in a noticeable deviation from the experimentally observed patterns. Comparison between simulation and experiment could therefore be used to deduce beam emittance.

To study conversion of the space charge potential energy in a mismatch to kinetic energy, an additional series of experiments was performed where the beam was purposely mismatched. Theoretical predictions of the energy exchange were verified. However, unlike the matched beamlet case where a final distribution with a uniform cross section was observed, the extra kinetic energy was transferred mostly to a beam halo [7].

Additional experiments were also conducted to test longitudinal beam dynamics. Generally good agreement between theory and experiment was also obtained [8]. In investigating both transverse and longitudinal dynamics, many experiments were conducted that validated both theoretical predictions of the physics of the evolution of space-charge dominated beams, as well as, the ability of simulations to predict the observed behavior. However, because of the limited length of the linear transport line, it was not possible to address many significant questions about the physics of space-charge-dominated beams. For example, what are the characteristic of the equilibrium distribution that is reached after long time relaxation of a space-charge-dominated beam? In addition, many questions concerning the longitudinal dynamics, which have a much slower evolution time than the transverse dynamics are inaccessible in a short linear transport system.

## UNIVERSITY OF MARYLAND ELECTRON RING (UMER)

### Ring Description

In order to address the long pathlength physics of a space charge dominated beam, while remaining within the available space and budgetary limits, the University of Maryland Electron Ring (UMER) was constructed. A

\*Work supported by the United States Department of Energy and the Office of Naval Research.

substantial number of simulation studies was first conducted. From these studies it was determined that emittance growth of the propagating bunch would remain within acceptable limits with achievable construction tolerances [9].

UMER is a 11.52m circumference electron ring with 36 alternating-gradient (A-G) quadrupole periods and an approximate  $60^\circ$  phase advance per period. Immediately downstream of the 10KeV electron gun is an aperture wheel that can selectively insert different apertures without breaking vacuum. The apertures allow injected beam currents to be varied from 0.6mA to 100mA. Normalized beam emittances for the range of injected currents range between  $\sim 0.3\mu\text{m}$  and  $\sim 3\mu\text{m}$ . As a result, the beam space charge phase advance can range from moderately to substantially depressed. Under usual operating conditions, a 100ns constant current bunch is injected covering approximately half of the ring. The injection dipole is then switched to recirculate the bunch. Details of the UMER ring as well as performance measured during conditioning are beyond this discussion, but are documented in detail elsewhere [10-12].

### *Longitudinal Dynamics in UMER*

A consequence of employing a ring is the added complexity of the transverse dynamics compared with a linear machine. For example, there are potential distortions of the transverse equilibrium as the beam is bent and the possibility of resonances that are not present in a linear geometry. This is a complex area of space-charge physics currently under study and is beyond the scope of the current discussion. However, because of the separation of time scales between the transverse and longitudinal evolution, the conventional wisdom expects that the longitudinal evolution will be averaged over the more rapid transverse dynamics and the two will be decoupled. Evidence is presented that this is what actually happens.

### *Bunch-End Expansion and Interpenetration*

Because the injected UMER bunch does not fill the entire ring, unless the bunch ends are contained by an applied bunching force, the space charge forces in the bunch will cause the ends to expand [13]. The front of the bunch will eventually overtake the rear end of the previous turn. Because the bunch length is much greater than the pipe radius, the longitudinal electric field is largely shorted-circuited by the conducting pipe. This results in a longitudinal self-electric field that is proportional to the derivative of the line density. Consequently, at the minimum in current that occurs between overtaking bunch ends, the self-electric field vanishes and the ends freely interpenetrate.

This behavior and the consequent evolution of the longitudinal bunch toward uniformly filling the ring, is illustrated in Fig. 1, which is a plot of the time evolution of the beam current passing a resistive wall current monitor about half way around ring circumference

downstream of the injection. Also plotted on the same axes is a simulation using a straightened-pipe axisymmetric numerical PIC model with a uniform constant applied solenoid focusing force. The simulated curve is corrected for the measured transverse beam loss and also for the characteristics of the measurement circuit, primarily the inductance that is in parallel with the resistance of the current monitor [14].

### *Multi-Stream Instability*

As the bunch ends overtake and interpenetrate more than once, there are eventually several interpenetrating streams with different longitudinal velocities at any location along the bunch. Owing to the multiple streams, development of space-charge-driven instability is predicted by simulation, and is observed experimentally. There are small differences in details of the instability onset time and the details of the current modulation. However, this can be expected, since instability onset is generally sensitive to fine details of the initial distribution. This instability, which occurs at a wavelength several times larger than the pipe diameter, differs from the usual plasma two-stream instability. The usual two-stream instability is observed in simulations but occurs at a much shorter wavelength and saturates at too low a level to be observed experimentally.

### *Solitons*

Another series of experiments where excellent agreement has been obtained between experiment and simulation, is the propagation of a short large-amplitude perturbation in the initial beam current created by laser excitation of the cathode [15]. In this case also, axisymmetric simulations reproduce, in detail, the measured current evolution, including the breakup of the large-amplitude initial pulse into a soliton train. Several parametric tests have been conducted to verify that the observed behavior reproduces what is expected from soliton propagation.

## SUMMARY

Several experiments have been described where the beam evolution is reproduced in detail by “straightened” axisymmetric simulations. These simulations replace the flutter in the alternating-gradient focusing with a constant axisymmetric focusing force. In addition to neglecting the A-G flutter, these simulations also neglect the consequences of beam bending. The major effect that must be included to obtain agreement between simulation and experiment is to account for transverse current loss. This was done by assuming that such loss occurs uniformly along the bunch.

The degree to which agreement is obtained notwithstanding these assumptions argues strongly for the assumption that the transverse and longitudinal dynamics are decoupled. The UMER ring is therefore an excellent vehicle for the general exploration of space-charge-dominated longitudinal beam dynamics, and the results obtained should be directly applicable to linear machines.

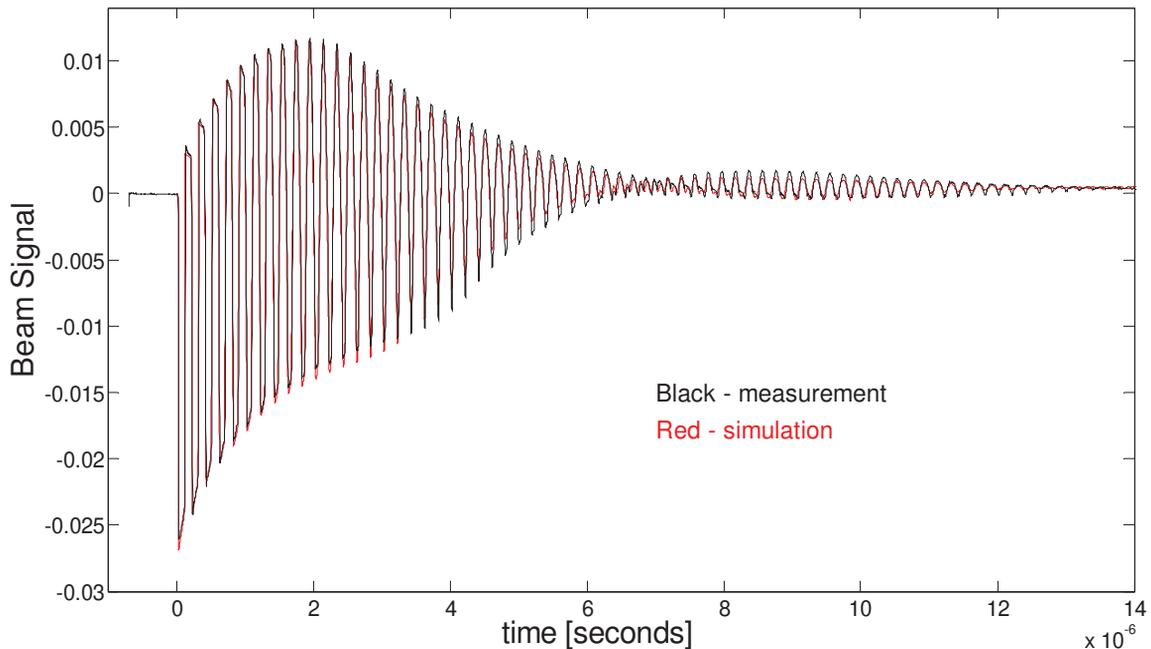


Figure 1: Excellent simulation/experiment agreement is seen in a comparison of the 6 mA wall-current monitor signal with simulated current profile adjusted to include beam loss and the equivalent circuit model of the detector.

## REFERENCES

- [1] D. Kehne, K. Low, M. Reiser, T. Shea, C.R. Chang, Y. Chen "Experimental studies of electron beam transport in the Maryland periodic solenoid channel," Nucl. Instrum. Methods A **278**, 194 (1989).
- [2] David P. Grote, Alex Friedman, Jean-Luc Vay, and Irving Haber, "WARP – A Parallel Framework Combining Features of Plasma (Particle in Cell) and Accelerator Codes," AIP Conf. Proc 749(1) 2005.
- [3] P. Loschialpo, W. Namkung, M. Reiser, J. D. Lawson, "Effects of space charge and lens aberrations in the focusing of an electron beam by a solenoid lens," J. Appl. Phys. **57** 10 (1985).
- [4] H. Rudd, C. R. Chang, D. Kehne, K. Low, M. Reiser, T. Shea, and I. Haber, "Comparison of Simulation Theory & Measurement for the Maryland Transport Experiment," Nucl. Instr. & Methods in Physics Res. A278, 198 (1989).
- [5] I. Haber, D. Kehne, M. Reiser, and H. Rudd "Experimental, Theoretical and Numerical Investigation of the Homogenization of Density Nonuniformities in the Periodic Transport of a Space-Charge Dominated Beam," Phys. Rev. A15, 44, 5194 (Oct. 15, 1991).
- [6] T. P. Wangler, K.R. Crandall, R.S. Mills, and M. Reiser, "Relation Between Field Energy and RMS Emittance in Intense Particle Beams," IEEE Trans. Nucl. Sci. NS-32. 2196, 1985.
- [7] D. Kehne, M. Reiser, H. Rudd, "Experimental Studies of Emittance Growth Due to Initial Mismatch of a Space Charge Dominated Beam in a Solenoidal Focusing Channel," Proc. of the 1991 Particle Accelerator Conf. <http://www.JACoW.org>
- [8] D. X. Wang, J. G. Wang, D. Kehne, M. Reiser, I. Haber, "Experimental Studies of Longitudinal Beam Dynamics of Space-Charge Dominated Beams," Proc. of the 1993 Particle Accel. Conf. <http://www.JACoW.org>
- [9] R.A. Kishek, S. Bernal, M. Reiser, M. Venturini, J.G. Wang, I. Haber, and T. Godlove "Beam Dynamics Simulations of the University of Maryland Electron-Ring Project" Nuclear Instruments and Methods **A415**, 417-421 (1998).
- [10] I. Haber, S. Bernal, B. Beaudoin, M. Cornacchia, D. Feldman, R.B. Feldman, R. Fiorito, K. Fiuzza, T.F. Godlove, R.A. Kishek, P.G. O'Shea, B. Quinn, C. Papadopoulos, M. Reiser, D. Stratakis, D. Sutter, J.C.T. Thangaraj, K. Tian, M. Walter, and C. Wu, "Scaled electron studies at the University of Maryland," Nuclear Instruments and Methods A **606**, 64-68 (2009).
- [11] R.A. Kishek, B.L. Beaudoin, S. Bernal, M. Cornacchia, K. Fiuzza, I. Haber, T. Koeth, P.G. O'Shea, D.F. Sutter, and H. Zhang, "Advances in Modeling the University of Maryland Electron Ring," PAC 2011, New York, (2011). <http://www.JACoW.org>
- [12] <http://www.umer.umd.edu>
- [13] A. Faltens, E.P. Lee, S.S. Rosenblum, "Beam end erosion," J. of Appl. Phys., Vol. **61**, 12, p.5219, (1987).
- [14] T. Koeth, B. Beaudoin, S. Bernal, I. Haber, R.A. Kishek, and P.G. O'Shea, "Longitudinal Relaxation of a Space-Charge Dominated Bunch," Proceedings of the 2011 IEEE Particle Accelerator Conference. <http://www.JACoW.org>
- [15] Y. Mo, B.L. Beaudoin, D. Feldman, I. Haber, R.A. Kishek, P.G. O'Shea, and J.C.T. Thangaraj, "Experimental Observations of Large-amplitude Solitary Waves in Electron Beams," Paper ID TUPPC094, IPAC 2012, New Orleans (2012).