LONGITUDINAL SPACE CHARGE PHENOMENA IN AN INTENSE BEAM IN A RING *

R.A. Kishek#, B. Beaudoin, I. Haber, D. Feldman, T. Koeth, and Y.C. Mo, Institute for Research in Electronics & Applied Physics, University of Maryland, College Park, MD 20742, USA

Abstract

The University of Maryland Electron Ring (UMER) [1] uses nonrelativistic, high-current electron beams to access space charge phenomena observable in high-intensity hadron beams. The UMER beam parameters correspond to space charge incoherent tune shifts, at injection, in the range of 1-5.5 integers. Longitudinal induction focusing is used to counteract the space charge force at the edges of a long rectangular bunch, confining the beam for 100s of turns. We report on two recent findings: (1) Observation of a space-charge-induced longitudinal multi-streaming instability formed from overlapping bunch ends in a ring. An analytical theory successfully predicts the onset of the instability over a wide range of beam currents and initial pulse lengths. (2) Experimental observations of the formation and propagation of soliton wave trains arising from large-amplitude longitudinal perturbations. Both phenomena are reproduced in WARP [2] simulations.

INTRODUCTION

Space-charge-dominated beams, in which the strength of space charge-induced expansion exceeds that from beam emittance, differ fundamentally from beams where space charge is merely a perturbation. The former can support a variety of collective modes and longitudinal space charge waves that can result in exotic structures on the beam, such as high-density rings, solitary waves, or beam halo. While some of this physics has had a long history of theoretical study [3-5], limitations of experimental facilities have, until the recent commissioning of UMER, prevented adequate experimental verification. Prior experimental studies of deep space charge suffered from inadequate transport distances, thus constraining them to measuring the initial transients in beam evolution. UMER, by contrast, accesses deep space charge over long transport distances (tune-shifts > 5 for many turns).

This paper reviews two recent studies concerned with the evolution of noisy, or non-smooth, initial distributions. First we discuss the evolution of a space-charge-induced longitudinal multi-streaming instability [6] relevant to multi-bunch injection in a ring. Second, we discuss the formation and propagation of solitons [7] from large amplitude longitudinal perturbations, observed experimentally and reproduced in simulations.

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

ramiak@umd.edu

EXPERIMENTAL SETUP

Figure 1 illustrates UMER. The UMER ring has 72 quadrupoles and 36 dipoles arranged in 36 FODO cells of period 32 cm. The ring also has three glass gaps for applying longitudinal focusing and acceleration via induction cells. Currently the glass gap at RC4 is used as an induction cell for longitudinal focusing, RC16 for acceleration, and RC10 is used as a wall-current monitor. A 10 keV electron beam is produced from a gridded thermionic gun with a pulse length variable from 25-140 ns. The beam current (0.5-100 mA) and normalized rms emittance (0.3-3.0 μm) are varied by means of an aperture wheel downstream of the anode. The different beam currents enable varying the strength of space charge from the emittance-dominated to the extremely space-charge-dominated.

A single long rectangular bunch is injected through a pulsed dipole into the ring, at a repetition rate of 60 Hz. The bunch circulates until it is totally lost. Application of longitudinal focusing using an induction cell [8] has extended the containment of the bunch to hundreds of turns for the lower-current UMER beams. The pulsed induction “ear fields” keep the beam ends from expanding and indefinitely maintain a rectangular bunch with a flat-top. Development of additional induction modules for the higher current beams is in progress. An extraction section currently in the late design / early construction stage is planned for installation by summer 2013.

MULTI-STREAM INSTABILITY

Without longitudinal focusing, a bunch freely expands under its space charge self-fields. The expanding bunch ends fill the ring, interpenetrate, and wrap repeatedly [9], leading to a “DC” beam on the peak-to-peak current signal. The striated longitudinal phase space, however, drives a multi-stream instability different from the unbounded volumetric two-stream plasma instability. The same effect can occur in multi-bunch injection schemes in a ring, as predicted theoretically [10].

We have observed this instability experimentally (Fig. 2), and systematically studied it over a wide range of beam parameters. Figure 2 illustrates a typical signature of the instability on the wall-current monitor signal. The peak-to-peak signal dwindles as the beam expands and becomes “DC” at about 7 μs, followed by a damped lower-amplitude re-bunching of the beam. The instability appears at about 16.5 μs as a sharper and more random re-bunching, with higher-frequency content.

We have derived a simple theoretical model that accurately predicts the onset of the instability. The model

ISBN 978-3-95450-118-2

assumes that the maximum energy gain for a space charge wave occurs when the separation between the streams is equal to the longitudinal wave speed, at which point the wave is synchronous with particles from the two neighboring streams. This is illustrated in Fig. 3, which shows a phase space picture from simulation. In the simulation, the instability is seeded from numerical noise, whereas in the experiment, the instability grows from small initial modulations in the line charge density and velocity profiles.

The theoretical model is in excellent agreement with RZ WARP simulations that use a conducting boundary, over a wide range of beam currents (0.5-100 mA) and initial bunch lengths (25-125 ns). The experimental results are also in good agreement, but show a small but consistent delay in the onset of the instability. This delay can be explained by the small but observable loss of charge in the experiment, which slows down the beam end expansion rate. When this charge loss is modeled in the simulation (by adjusting the particle weight), the simulation predictions approach the experiments.

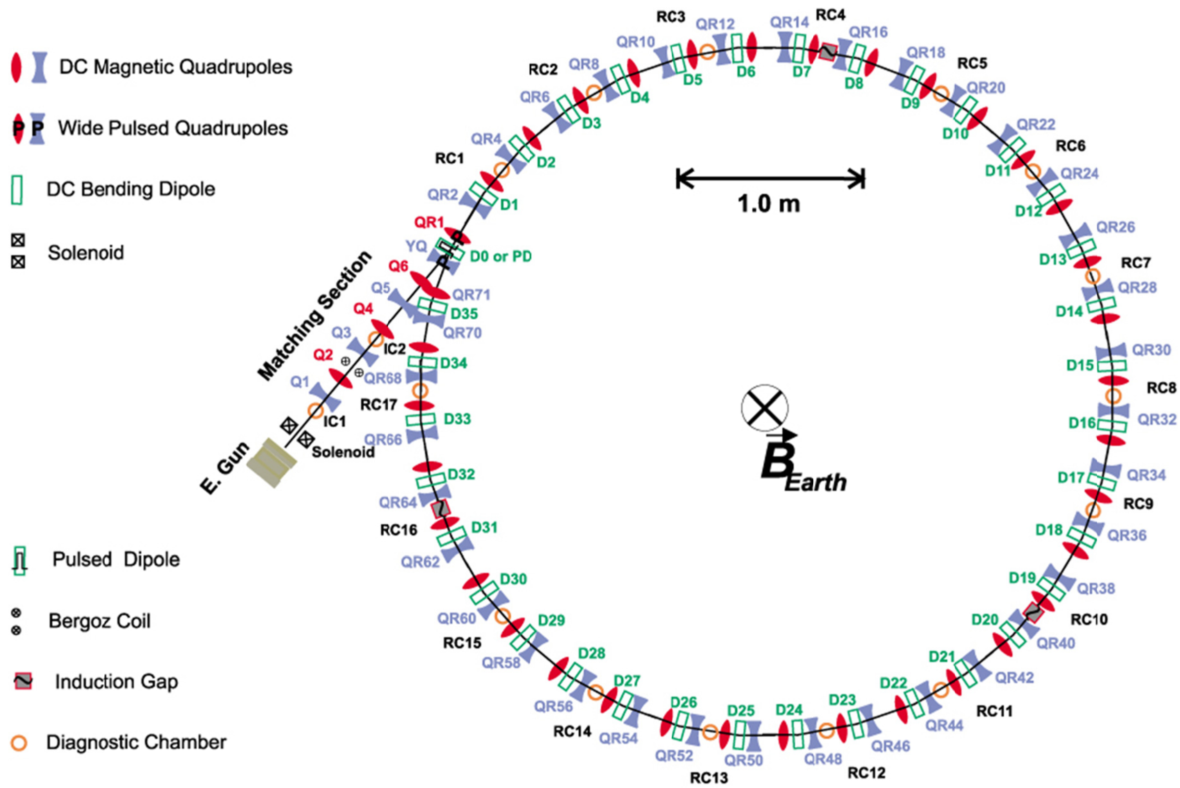

Figure 1: Schematic layout of UMER.

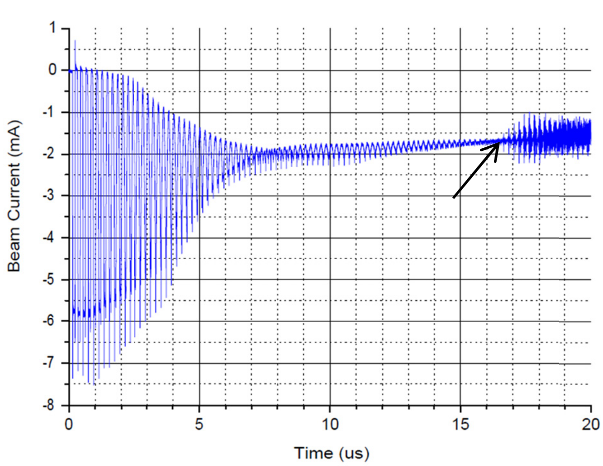

Figure 2: Measured current profile using the RC10 wall current monitor, for the 6 mA 100 ns bunch. Arrow details the onset of the instability at 16.5 μs [11].

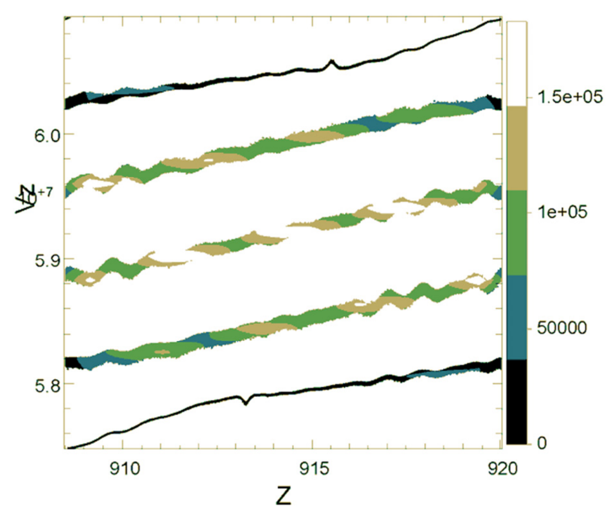

Figure 3: Longitudinal z-v_z phase space from WARP simulation at the time of instability onset [9]

ISBN 978-3-95450-118-2

SOLITON FORMATION AND EVOLUTION

Space charge waves can easily develop in intense beams, e.g., from imperfections in the electron gun pulse, or from mismatch of the induction focusing ear fields. We have developed several techniques to purposely induce such waves and observe their long-term evolution. We perturb the beam density using photoemission on top of thermionic emission, perturb the velocity by triggering the induction module within the bunch, or perturb both by modulating the cathode grid.

For beams with strong space charge, we have observed the nonlinear steepening of large-amplitude density or velocity perturbations, and the formation of solitary waves as the steepening cancels the dispersive term [7,11,12]. In Fig. 4, for example, a 25% perturbation to the beam density is induced near the tail of a 20 mA beam (with photoemission). The fast wave propagates across the beam and steepens, forming multiple sub-pulses that eventually maintain their shape.

While solitons in particle beams have been predicted theoretically for years [13-15], we were the first to observe a soliton wave train on an electron beam [16], as opposed to a single soliton. We have since studied the phenomenon over a range of parameters, clearly observing the interaction of two solitons, and obtaining reasonable agreement with WARP simulations.

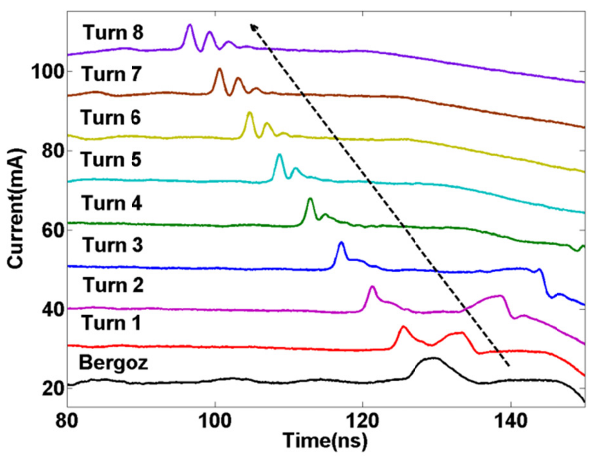

Figure 4: Nonlinear steepening of perturbation and formation of a soliton wave train, for 20mA beam with a 25% initial density perturbation. The beam ends are trimmed and zero suppressed so only the flat top is displayed. Each subsequent turn is offset vertically by 10 mA for clarity [12].

CONCLUSION

In summary, we presented two recent experimental studies in longitudinal space charge physics, conducted on the University of Maryland Electron Ring. A multi-stream instability was observed and studied over a wide range of parameters. Soliton wave trains were observed experimentally for the first time in charged particle beams. More detailed results of these studies can be found in the references below. A major inference from this work is the persistence of longitudinal space charge phenomena over long transport distances. Even if the amplitude of perturbations near the source is insufficient to produce solitons, we have shown that they can seed instabilities far downstream.

ACKNOWLEDGMENT

We thank the other members of the UMER team, especially Dave Sutter, Kamal Poor Rezaei, Hao Zhang, Max Cornacchia, and Santiago Bernal, who contributed much to improve the beam orbit and matching.

REFERENCES

[1] R.A. Kishek, B. Beaudoin, S. Bernal, et al., *"The University of Maryland Electron Ring Program,"* Nuclear Instruments and Methods In Physics Research – A, submitted (2012).

[2] D.P. Grote, A. Friedman, I. Haber, S. Yu, Fus. Eng. & Des. 32-33, 193-200 (1996).

[3] M. Reiser, Theory and Design of Charged Particle Beams, 2nd Ed. (Wiley-VCH Inc., Weinheim Germany, 2008).

[4] Ronald C. Davidson and Hong Qin, Physics of Intense Charged Particle Beams in High Energy Accelerators (Singapore: World Scientific, 2001).

[5] S.Y. Lee, Accelerator Physics, 2nd ed., (World Scientific, 2004).

[6] B. Beaudoin, R.A. Kishek, I. Haber, and T. Koeth, *"Experimental Observations of a Two-Stream Instability in a Single Long Electron Bunch,"* Physical Review Letters, submitted (2012).

[7] Y. Mo, R.A. Kishek, D. Feldman, I. Haber, B. Beaudoin, P.G. O'Shea, and J.C.T. Thangaraj, *"Experimental Observations of Soliton Wave Train in Electron Beams,"* Physical Review Letters, submitted (2012).

[8] B. Beaudoin, I. Haber, R.A. Kishek, S. Bernal, T. Koeth, D. Sutter, P.G. O'Shea, and M. Reiser, Physics of Plasmas 18, 013104 (2011).

[9] T. Koeth, B. Beaudoin, S. Bernal, I. Haber, R.A. Kishek, and P.G. O'Shea, Proc. 2011 IEEE Particle Accelerator Conference, New York, NY, 22 (2011).

[10] I. Hofmann, *"Filamentation of Phase Space and Coherent Noise for Beams Injected into Storage Rings,"* Part. Acc. 34, 211 (1990).

[11] B. Beaudoin, S. Bernal, C. Blanco, I. Haber, R.A. Kishek, T. Koeth and Y. Mo, *"Modeling HIF Relevant Longitudinal Dynamics in UMER,"* Nuclear Instruments and Methods In Physics Research – A, submitted (2012).

[12] Y. Mo, B.L. Beaudoin, D. Feldman, I. Haber, R.A. Kishek, P.G. O'Shea, and J.C.T. Thangaraj, Proc. 2012 International Particle Accelerator Conference, New Orleans, LA, USA, May 2012, TUPPC101 (2012).

ISBN 978-3-95450-118-2

[13] J. Bisognano, I. Haber, L. Smith, and A. Sternlieb, IEEE Trans. on Nucl. Sci. 28, 2513 (1981).
[14] H. Suk, J. G. Wang, and M. Reiser, Phys. Plasmas **3** (2), 669 (1995).
[15] R. Davidson, Phys. Rev. ST-AB, **7**, 054402 (2004).
[16] J. Charles T. Thangaraj, *"Study of Longitudinal Space Charge Waves in Space-Charge Dominated Beams",* Ph.D. Dissertation, University of Maryland, College Park (2009).

ISBN 978-3-95450-118-2