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The University of Maryland Electron Ring Program

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ABSTRACT

The University of Maryland Electron Ring (UMER) is a unique machine that uses scaled electron beams at nonrelativistic energies (10 keV) to inexpensively model GeV beams of heavy ions over long path lengths (kilometers of transport distance). The UMER beam parameters correspond to space charge tune depressions, at injection, adjustable in the range of 0.14–0.85. Although a ring, many of the intense beam studies on UMER are applicable to linacs. This paper reviews the UMER program, which contains experimental, computational, and theoretical components. We outline the research areas of interest, recent accomplishments, and future plans, emphasizing the relevance to heavy ion drivers. Specific topics include longitudinal induction focusing and beam manipulations; generation and propagation of space charge waves, including large-amplitude solitons; bunch end interpenetration and observation of a multi-stream instability; beam halo studies; and diagnostic development.

1. Introduction

Space-charge-dominated beams, in which the strength of space charge-induced expansion exceeds that from beam emittance, differ 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 [1–3], limitations of experimental facilities have, until the recent commissioning of UMER, hampered adequate experimental verification.

Prior to UMER, experimental platforms existed that could probe the region of strong space charge, but the transport distances in those machines were inadequate to examine more than the initial transients in beam evolution. The Maryland periodic solenoid channel in the early 1990s was limited to 36 periods and a length of 5 m [4]. Similarly, experiments with induction linacs at LBNL [5], such as the SBTE [6] and the MBE-4 [7], while able to access beams of extreme intensities ($\chi \sim 1$), have been limited to about 50 lattice periods. More recently, NDCX-II has been commissioned as a driver for laboratory high energy density physics experiments [8,9], but again, is limited in transport distance. Rings, on the other hand, have been traditionally designed to limit Laslett tune shifts from space charge to less than 0.25. The construction of a recirculating ion ring at LLNL with parameters similar to UMER was unfortunately never completed [10]. The most intense beam that has been propagated in a ring, in pioneering experiments at Brookhaven, had an incoherent tune shift of 1, corresponding to a space charge intensity parameter $\chi = 0.3$ [11]. UMER has already propagated beams with tune-shifts of >5 and $\chi > 0.9$ for many turns.

In recent years, much progress has been made in experimental modeling of the transverse beam dynamics using Paul traps [12–16]. While Paul trap simulators can access the space-charge-dominated region of parameter space, the longitudinal dynamics in a Paul trap are entirely different from a beam bunch in an accelerator. Furthermore, an accelerator experiment like UMER can be used to test a broader range of phenomena, e.g. skew quadrupole effects, magnetic harmonic errors, and beam control in a realistic environment.

This paper has two purposes. First, we provide a brief description of UMER and an update on its present status and capabilities. Second, we provide a brief review of recent investigations performed on UMER.

In this section we briefly describe UMER; more information about its design and configuration can be found in Refs. [17–21]. Fig. 1 illustrates the layout of UMER. The ring has 72 quadrupoles and 36 dipoles arranged in 36 FODO cells at a period of 32 cm. A 10 keV electron beam is produced from a gridded thermionic gun with a pulse length variable from 25–140 ns. Since the circulation time is 197.0 ns, the typical 100-ns UMER bunch fills approximately half of the ring's 11.52-m circumference. A single long rectangular bunch is typically injected through a pulsed dipole into the ring, at a repetition rate of 60 Hz. The bunch circulates until it is totally lost to the pipe walls when the pulsed elements in the injection section ramp down. Other gun pulsers

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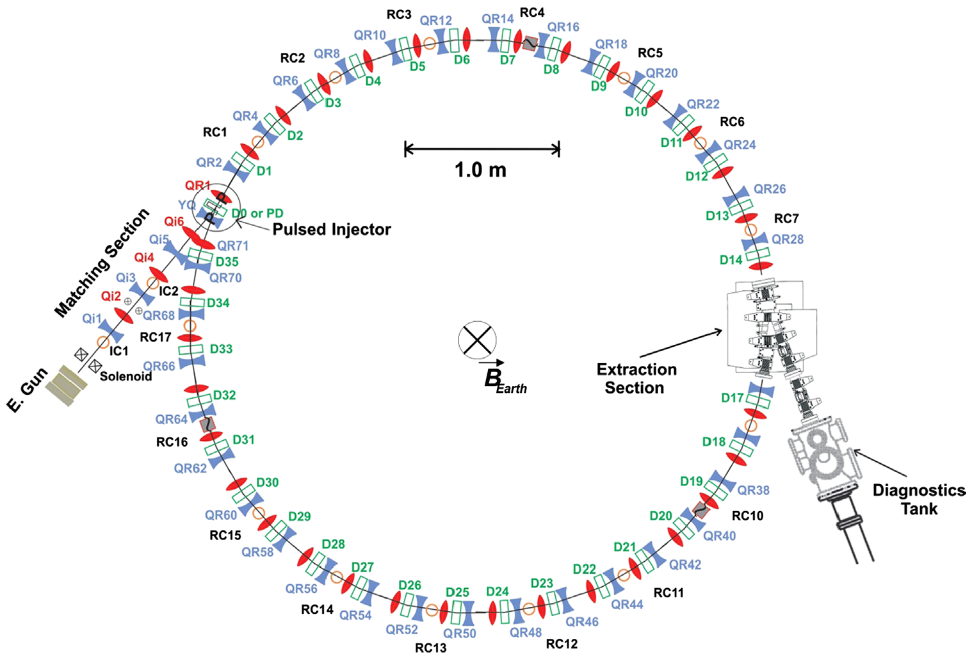

Fig. 1. Schematic layout of UMER, including the planned extraction line.

have been developed to inject a parabolic bunch or multiple bunches, but are infrequently used. 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 (Fig. 2).

The ring 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. Application of longitudinal focusing using an induction cell [22] 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 profile. Typical ear field voltages for confinement range from 50 V to 862 V for beam currents of 0.5 mA and 100 mA, respectively. The higher current beams require a faster repetition rate in the application of ear fields because of the faster beam end erosion. While a repetition rate of 1 MHz (once per 5 turns) suffices for the 0.5 mA beam, three induction cells per turn need to be fired at 5 MHz for the 100 mA beam. Construction of additional induction modules for the higher current beams is in progress. An extraction section [23], currently in the late design/early construction stage, is planned for installation in the summer of 2013.

Due to the low fields required, UMER uses independently-powered printed-circuit quadrupole and dipole magnets [24]. The magnet currents needed are typically in the range of 0.5–3 A, with stronger currents permissible only if the magnet is pulsed to reduce heating, which can damage the printed circuits. Variation of the quadrupole currents enables us to vary the zero-current tunes of the machine, independently in x and y, over the range of 5.5–8.5, corresponding to a phase advance of 55°–85° per alternating-gradient period. The lower limit is of phase advance is constrained by the larger beam size, while the upper limit is constrained by the quadrupole currents. We have shown it possible to conduct experiments at larger phase advances by reconfiguring the nominal lattice to one with fewer magnets and a larger lattice period [25]. For the typical zero-current operating phase advance, σ_o, of 66°, the average beam radius varies from 1.6 mm for the 0.6 mA beam, up to 11.1 mm for the 100 mA beam. The latter's envelope excursion can reach 17 mm, which is a good fraction of the 24.5 mm pipe radius.

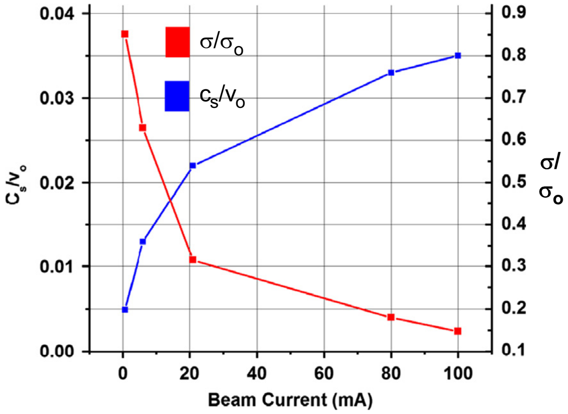

Fig. 2. Variation of space charge tune depression and longitudinal wave speed (normalized to the mean beam velocity, v_o) over the range of beam currents available in UMER.

Table 1
Key parameters for several UMER beams. Normalized rms emittances are measured using tomography in the injection line and on the first turn. Average radii, intensities, and sound speeds are calculated under the smooth approximation for an operating zero-current phase advance of 66° and can be measured turn by turn.

I [mA]	ε_n, rms [mm]	a_{ave} [mm]	σ/σ_o	c_s/v_o
0.6	0.4	1.6	0.85	0.005
6.0	1.3	3.4	0.62	0.013
21	1.5	5.2	0.32	0.022
78	3.0	9.6	0.17	0.033
104	3.2	11.1	0.14	0.035

Table 1 summarizes the beam parameters, while Fig. 2 illustrates how measures of transverse and longitudinal space charge vary with UMER beam current. Here, the tune depression due to