THE UNIVERSITY OF MARYLAND ELECTRON RING (UMER)*

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Abstract

A detailed understanding of the physics of space-charge dominated beams is vital for many advanced accelerators that desire to achieve high beam intensity. In that regard, low-energy, high-intensity electron beams provide an excellent model system. The University of Maryland Electron ring (UMER), currently under construction, has been designed to study the physics of space-charge dominated beams with extreme intensity in a strong focusing lattice with dispersion. The tune shift in UMER will be more than an order of magnitude greater than exiting synchrotrons and rings. The 10-keV, 100 mA, UMER beam has a generalized perveance in the range of 0.0015, and a tune shift of 0.9. Though compact (11-m in circumference), UMER is a very complex device, with over 140 focusing and bending magnets. We report on the unique design features of this research facility, the beam physics to be investigated, and early experimental results.

1 INTRODUCTION*

As beam physicists we strive to develop ever more intense, high quality beams. At the University of Maryland, we have a tradition of using low-energy electron beams as model systems for studying space charge phenomena that are of general interest in intense beam systems [1]. The low-cost, modular nature of our experimental systems has allowed us to develop test stands that are adaptable to many problems in beam physics. Previously, all of our research had been done with straight-line systems. Our motivation to develop a ring system is twofold. There are many interesting phenomena in intense beam physics that evolve over longer distances than our 5-m linear solenoid channel. Furthermore, a ring with both strong focusing and dispersion would also allow us to study resonance issues in a realistic setting.

In linear accelerators, there has been an increased interest in space charge effects in recent years. The introduction of beam with ever lower emittance and increased current, had meant that space-charge driven emittance growth and halo formation can be a consideration at energies as high as high as 100 MeV in some electron linacs proposed for fourth generation light sources [2].

Generally, recirculators and rings have been limited to much lower intensities than linear accelerators. One of the most important limitations in circular machines is the space-charge tune shift. Fear of destructive resonances has constrained existing rings to low intensity and relatively modest tune depression. With space charge, the resonances are no longer caused by the interaction between the single particle orbits and the harmonics of the field errors. Instead, a resonance can occur when the frequency of a collective beam mode coincides with one of the harmonics of the error frequency spectrum. Conventional recirculators (i.e. synchrotrons) have been limited in intensity by the necessity for the beam to make a very large number of orbits.

There has never been an opportunity to perform experiments on such recirculating machines in the region of deep tune depression, and extreme beam intensity. Therefore, almost all of our understanding in this region is based on theory, simulation and conjecture. There is a tremendous need to obtain experimental data in the regime of intensity that exceeds the reach of current machines. UMER [3] is an analog computer for the investigation of phenomena at extreme beam intensity.

The experimental and theoretical study of beam dynamics in UMER will have important applications to high-current circular accelerators other than heavy-ion fusion recirculators; examples of such applications include the low energy end of high intensity electron linacs, ion booster synchrotrons, muon colliders, and spallation neutron sources.

In order to put UMER in a proper context, it is important to define what we mean by intensity, and to illustrate how the increased intensity influences the collective beam motion. We use the dimensionless intensity parameter, χ, as the ratio of the space-charge force to the external focusing force at the beam radius $\chi = \dfrac{K}{k_0^2 a^2}$. The space charge term is represented by K/a

where $K = \dfrac{2I}{I_0(\beta\gamma)^3}$ is the generalized perveance, a is the 2x rms beam radius, I is the beam current, and

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$I_0 \approx \dfrac{mc^2}{30q}$ (I_0 = 3.1 x 10^7 (*A*/*Z*) Amps for ions with charge state Z and atomic number *A*, and I_0 = 17 kA for electrons). The external focusing forces are represented by k_0, the zero-current betatron wavenumber. These quantities are related to the 4x rms emittance, ε, through the matched beam envelope equation, in the smooth approximation: $k_0^2 - \dfrac{K}{a^2} = \dfrac{\varepsilon^2}{a^4} = k^2$ (where k is the depressed betatron wavenumber) or $1 - \chi = \dfrac{\varepsilon^2}{k_0^2 a^4} = \dfrac{k^2}{k_0^2}$. The tune depression can then be expressed in terms of χ as $\dfrac{\nu}{\nu_0} = \dfrac{k}{k_0} = \sqrt{1-\chi}$, and the plasma wavenumber k_p as $\dfrac{k_p}{k_0} = \sqrt{2\chi}$. For a zero current, fully emittance dominated beam we have χ = 0, while χ =1 for a fully space charge dominated beam, with zero emittance. At the lowest values of χ, the motion is dominated by single particle effects and emittance. As χ approaches unity, collective plasmas oscillations become increasingly dominant. For χ = 0.5, the space-charge and emittance terms in the envelope equation are equal, Thus, for the range 0 <χ < .5, we can say that the beam radius (hence the beam physics) is emittance-dominated, while for 0.5 < χ <1 the beam radius (physics) is space-charge dominated.

For example, heavy ion fusion drivers will likely operate with 0.89 <χ < 0.98. We see that it is possible to achieve such values of χ with electrons at 10 keV, 100 mA, ε = 50 μm and a =1 cm. Figure 1 shows the range of the intensity parameter for UMER. With χ ranging from 0.2 - 0.98 UMER offers a unique opportunity to study intense beam physics in a completely new regime that begins near the upper intensity range of existing machines. In the space-charge dominated regime of UMER, not only will the tune depression be unprecedented, but also the plasma frequency will exceed the zero-current betatron frequency. This implies that, at the high end of the UMER intensity range, collective effects will have an enormous impact on the beam dynamics.

We should note that a beam in a given machine in places might be either space charge dominated or emittance dominated, depending on the degree of focusing applied. When the beam is large it may be space charge dominated, but when brought to a focus at an interaction point, it may become emittance dominated. Therefore, even in the space charge dominated regime, where the emittance may have only a small influence on the beam envelope evolution, a detailed knowledge of how the emittance is evolving will be necessary in order to understand the behavior of the beam at a final focus [4].

The unknown territory in the extreme space-charge dominated regime will be very challenging and should provide a wealth of new phenomena. The UMER facility will allow us to investigate emittance growth due to conversion of free energy, halo formation, and equipartitioning in a circular machine. So far, these effects have only been studied in linear transport lines. In addition, UMER will permit experimental investigations of longitudinal-transverse coupling and beam profile changes resulting from dispersion; the behavior of bunch ends, resonance traversal; the longitudinal resistive wall instability; and other effects in the space-charge dominated regime that is currently inaccessible.

We are also investigating the possibility of using UMER, and related systems for laboratory studies related to galactic dynamics. Many of the dynamical processes involved in galactic formation and evolution appear to have analogs in the physics of high intensity beams [5].
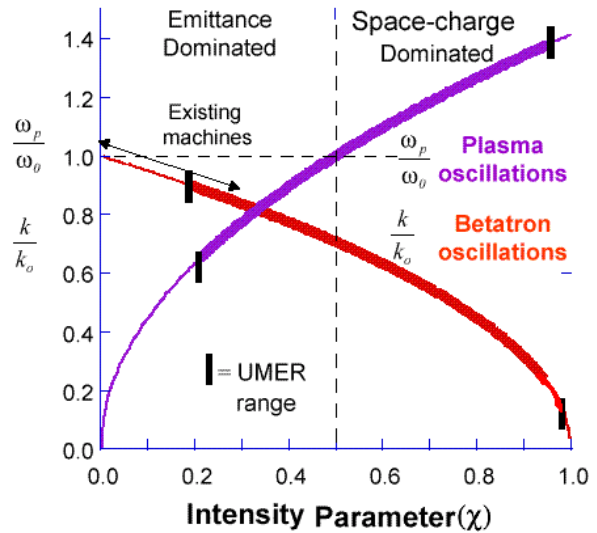
FIGURE 1. Emittance dominated and space-charge dominated regimes, showing the betatron tune depression and plasma tune enhancement with increasing intensity parameter..

2 UMER DESIGN FEATURES

In its initial phase UMER will operate at a fixed energy of 10 keV (β = 0.2). Future upgrades will allow UMER to operate as a fast cycling recirculating accelerator at energies of up to 50 keV (β = 0.4). Table 1 gives the nominal specifications of UMER at 10 keV. The intensity parameter, tune depression or beam current can be varied in UMER over a wide range by changing to different apertures sizes in the beam collimator at the exit of the gun, by changing the anode–cathode spacing, or by changing the beam energy. A complete description of the UMER design features is beyond the scope of this paper.

Further details can be found on the UNER Web site and in literature cited therein [3].

TABLE 1. UMER design specifications

Energy	10 keV
β (= v/c)	0.2
Current	100 mA
Generalized perveance	1.5×10^{-3}
Emittance, 4x rms, norm	10 μm
Pulse Length	40 ns
Circumference	11.52 m
Lap time	197 ns
Pulse repetition. rate	60 Hz
Mean beam radius	< 1 cm
FODO period	0.32 m
Zero-current phase advance, σ_o	76°
Zero-current Betatron tune, ν_o	>7.6
Tune Depression	>0.12

The focusing lattice consists of 36 FODO periods of length 0.32 m and the ring circumference is 11.52 m. Each FODO section contains two printed-circuit quadrupole magnets and one printed-circuit dipole. A detailed mechanical layout of a full lattice period is shown in Figure 3. The zero-current phase advance per period is $\sigma_0 = 76°$, corresponding to a tune of $\nu_0 = 7.6$. The maximum tune depression due to space charge is expected to be between 0.12 and 0.2. There are 13 diagnostic ports, and three induction modules that provide fast-rising "ear fields" to prevent expansion of the bunch ends and permit acceleration to 50-keV in a future extension of the ring operation.

The electron bunch is injected into the ring at a repetition rate of 60 Hz or less from the injector system [6] with the help of two pulsed Panofsky quads and a pulsed dipole (see figs. 2,3). The bunch can be extracted within the first turn or after any number of turns with a system that duplicates the features of the injector line except that the electron gun is replaced by a large diagnostic chamber with phosphor screen, emittance meter and energy analyzer [7, 8].

The operating vacuum is determined by gas-scattering-induced emittance growth. The entire vacuum system is designed to be bakeable. All pumping is by ion pumps, one at each diagnostic station, approximately 70 cm apart; our goal is to reach the low 10^{-9} Torr range after bakeout that will be adequate for the ~100 turns in UMER.

2.1 Magnet System

The design of the UMER magnetic elements presented a particular challenge. The uniform magnetic field required to make a 10 keV electron orbit at the radius of UMER (1.8 m) is 1.5 Gauss – about three to five times the value of the vertical component of the earth's magnetic field in the UMER laboratory. The earth's field in the region of the ring has been mapped with milligauss accuracy using a 3-axis flux-gate magnetometer. The vertical component will be used to assist the bending in the ring. The horizontal component is sufficient to deflect the beam about 1 mm vertically in a half lattice period. Compensation for the horizontal component is implemented with a series of nine segmented Helmholtz coils placed in a toroidal geometry around the ring. Segmentation of the compensation is necessary because of the sinusoidal variation of the magnetic force from the horizontal with angle around the ring, and because of local variations in the field strength.

When complete the ring magnetic lattice will consist of over 140 quadrupoles, dipoles and steering magnets. The typical focusing gradients and bending fields are on the order of 5 Gauss/cm and 10 Gauss, respectively. The use of iron-based magnets is impractical for such low fields. Therefore, the UMER magnets are based on an iron-free printed circuit (PC) design [9]. These printed circuits are fabricated to a very high tolerance, carefully mounted, measured and then installed and aligned on the beamline. The general tolerances on these PC magnets are similar to those of the iron-based magnets of large accelerators.

A new feature that we have introduced recently is a quadrupole with electronically adjustable skewness (roll). The feature allows us to both correct for residual skewness in our system, and also the deliberately introduce skewness at various location in the ring for beam dynamics studies [10]
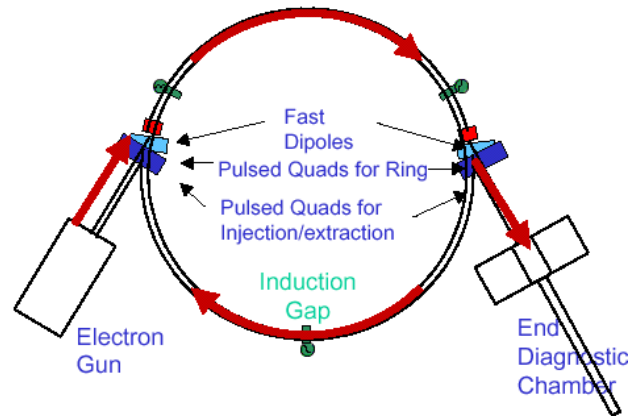
FIGURE 2. **UMER schematic showing injection and systems and induction gaps (green)**
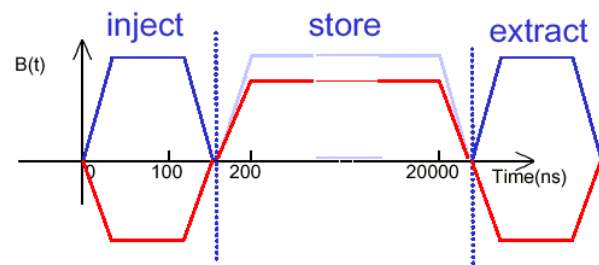
FIGURE 3. **Timing schematic for injection and extraction dipoles (red) and Panofsky quadrupoles (blue)**

2.2 Gun and Injector

The design of the electron gun and simulations of its performance are described elsewhere [11, 12]. It employs a commercial 8-mm diameter dispenser cathode with integral filament and grid. The e-gun includes a micrometer-controlled adjustable A-K gap to vary the beam current, a gate valve and an ion pump. A built-in Rogowski-type current monitor is included, as is a rotatable calibrated aperture plate with six masks. The plate includes a pepperpot and a five-beamlet aperture as well as four round apertures ranging from 0.5% to 100% transmission. Pulses of 50-100 ns with various pulse shapes can be generated.

In addition, we have been investigating the possibility of producing ultra-short (1 ns) current pulses on top of the main pulse. We have achieved this by using a nitrogen laser as a photocathode drive laser on the dispenser cathode [13]. This will allow is to create perturbations on the beam that are well located in time and space. The evolution of such a perturbation will allow us to study dissipative processes, e.g. resistive wall phenomena.

The remainder of the injector consists of the transport channel with a solenoid immediately after the gun followed by 5 quadrupoles that lead to the pulsed injection kicker system (figs.3, 4).

2.2 Diagnostics Controls and Alignment

To allow detailed comparison between theory and experiment, UMER will have a comprehensive set of beam diagnostics. Each of the 13 diagnostic stations around the ring will have a phosphor screen and capacitive beam position monitor [14]. In addition, fast current monitors and resistive beam position monitors will also be installed. A sophisticated diagnostic end-chamber has been fabricated by FM Technologies. The chamber houses emittance meters of the slit-wire and pepper-pot types; a retarding-field energy analyzer with eV resolution for energy and energy spread measurements; a movable phosphor screen with 1.5 meter travel for insertion into the complete transport line; and a Faraday cup for current measurement.

Details of alignment and controls are provide in a companion paper [15]

3 INITIAL EXPERIMENTAL RESULTS

3.1 Emittance

The initial emittance characterization is by the pepper pot method (fig, 4), which has shown that the beam has a 4x normalized emittance of 15 µm. The emittance data has yet to be evaluate in detail; however, fig.4 indicates that the local temperature of the beam varies with radius.
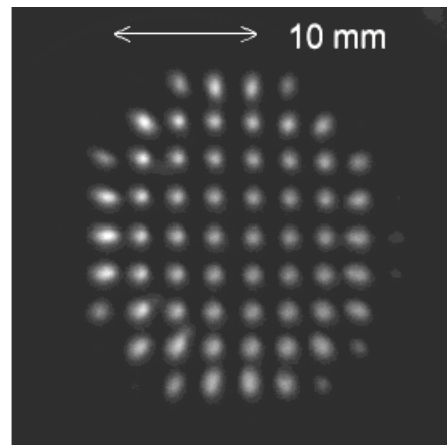

FIGURE 4. Pepperpot image of the beam from the UMER gun

3.2 Energy Spread

We have developed an energy an electrostatic retarding voltage energy analyzer {Valfells, Cui]. Simulations show the resolution of the device is about 8 eV, and the measured values of the energy spread are just slightly greater than this value(fig. 6).
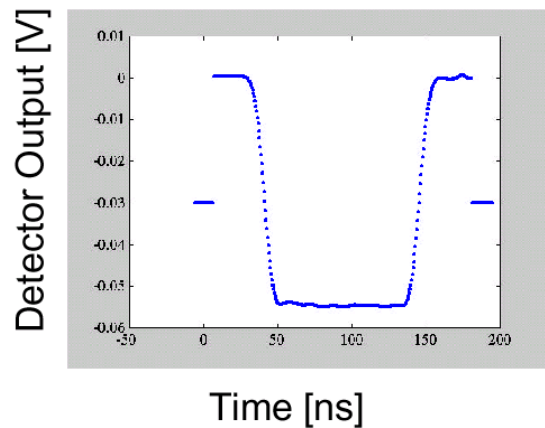

Figure 5 Current pulse on energy analyzer with zero bias voltage
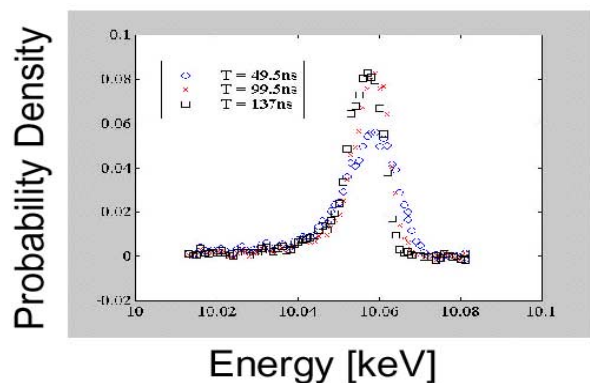

Figure 6 Energy Spread measured at three times with the current pulse in fig 5

While the measured energy spread meets our specification of 20 eV, we are continuing to improve our diagnostic. We have designed an improved energy analyzer with a resolution of 0.5 eV (cui).

3.3 Matching

The beam in the injector has been configures to meet the specifications for matching into the ring (fig. 7)
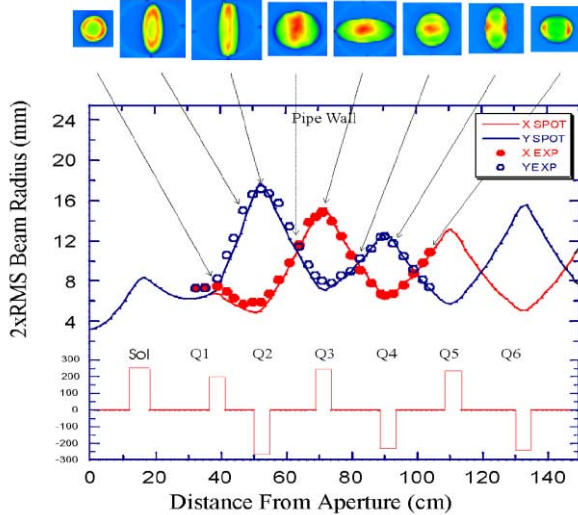
Figure 7 Simulation (solid) and experimental data (points) for the 2x RMS beam radius along the injector

4 PLANS

At present, (June 2000) the UMER injector is going through final testing. Injection into the first turn of the ring will commence shortly.

The remaining phases of the UMER project are as follows:

- Construction/Experimental Phase I
  Sequential installation of injector and ring section beam physics experiments for about 75% of one turn. The phase is just beginning (August 2000) and will take three years.
- Experimental Phase II
  Ring closure and multi-turn operation.
  Low current operation (10 mA) for 100 turns.
  High current operation (100 mA) for at least 10 turns

  with $\dfrac{\Delta\varepsilon}{\varepsilon} \leq 4$

  This phase will begin toward the end of the current grant period
- Upgrade Phase

Upgrade of UMER to a fast cycling synchrotron to accelerate the beam to 50 keV over 50-100 turns to study resonance crossing.

6 REFERENCES

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