LONGITUDINAL DYNAMICS IN THE UNIVERSITY OF MARYLAND ELECTRON RING *

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Abstract

The University of Maryland Electron Ring (UMER) is a low energy electron recirculator for the study of space charge dominated beam transport. The system's pulse length (100 ns) and large number of diagnostics make it ideal for investigating the longitudinal evolution of intense beams. Pulse shape flexibility is provided by the pulser system and the gridded gun, which has the ability to produce thermionic and photoemission beams simultaneously. In this paper, we report on the generation and evolution of novel line charge distributions in UMER.

INTRODUCTION

The University of Maryland Electron Ring (UMER) is a circular quadrupole transport system for the study of intense electron beams [1,2]. Although the UMER beam parameters were originally chosen to be relevant for heavy ion fusion research [3], experiments on UMER are applicable to a wide range of accelerator and non-accelerator applications, including FELs [4], novel light sources, and galactic dynamics [5]. UMER is particularly useful for studying the longitudinal dynamics of intense beams. This is due to the relatively long path length over which the beam can travel; the presence of large numbers of diagnostics, particularly beam position monitors [6]; the relatively long, nanosecond-scale lengths characteristic of longitudinal effects in the UMER beam; and the ability to generate a variety of line charge distributions from the UMER gun. In this paper, we briefly describe our research on longitudinal effects in UMER.

LONGITUDINAL EXPANSION

The most fundamental longitudinal effect in beams is longitudinal expansion, which depends on the beam's initial conditions. The expansion of beams with two types of initial conditions has been studied in UMER. Expansion of a beam with parabolic line charge density is governed by the longitudinal envelope equation [7]. In UMER, such a beam can be generated by laser-driven photoemission from a conventional dispenser cathode operating at reduced temperature [8]. The conventional thermionic beam in UMER has an initially rectangular line charge density. The expansion of such a beam can be calculated from the one-dimensional cold fluid model [9]. Under this model, the beam will expand by erosion at the beam ends, with shock waves propagating into the beam bulk at the sound speed c_0 while the particles at the extreme ends of the beam are launched into the vacuum at the escape velocity $2c_0$. The sound speed is given (for electrons) by

$$c_0 = \sqrt{\frac{qg\lambda_0}{4\pi\varepsilon_0 m\gamma^5}}\,, \tag{1}$$

where q is the fundamental charge, λ_0 is the initial line charge density in the beam, ε_0 is the permittivity of free space, m is the mass of the electron, γ is the relativistic factor and

$$g = \alpha + 2\ln\left(\frac{b}{a}\right) \tag{2}$$

is a geometry factor depending on the beam radius a, the beam pipe radius , and a constant α. The value of α is variously stated as being between zero and one. Note that the geometry factor serves to couple the longitudinal and transverse dynamics. The importance of this coupling has led to the in-house development of image processing software to facilitate transverse beam measurements.

Previous experiments verified these models for well-matched beams propagating in the UMER quadrupole focusing lattice under ideal conditions [10]. However, beams are frequently mismatched, sometimes severely, and it is important to explore the sensitivity of longitudinal expansion to this mismatch. To test this, the 80%-20% rise time and fall time of the beam were measured for beam currents of approximately 5 mA to 100 mA, while the transverse focusing system was kept at its nominal 85 mA settings. The 80%-20% rise time depends on the distance traveled by the beam and the sound speed in the beam, which enables the geometry factor to be determined experimentally for each value of the beam current. This data is shown in Figure 1.

For comparison, it is useful to calculate how the geometry factor changes as a function of beam current. For an intense matched beam, the average radius is given by

$$R_m = \sqrt{\frac{AI_m}{k_0^2}}\,, \tag{3}$$

where I_m is the matched beam current, k_0 is the betatron

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wave number, which is a measure of transverse focusing strength, and A depends on the beam voltage and particle species. If the beam current is varied while the transverse focusing is kept uniform, the beam will undergo mismatch oscillations. However, if we neglect these oscillations, we can take the average beam radius to be

$$R = R_m \sqrt{\frac{I}{I_m}} \tag{4}$$

at the new current I. This gives a geometry factor of

$$g = \alpha + 2\ln\left(\frac{b}{R_m}\sqrt{\frac{I_m}{I}}\right), \tag{5}$$

which can be evaluated provided the average beam radius for a matched beam is known at a given current. For the 85 mA beam in UMER, the matched beam average radius is 9.5 mm [11]. This theoretical geometry factor is shown plotted in Figure 1 for α of zero and one. Good agreement is shown between these values and the experimental values, except for very low currents. This supports the idea that the long-scale longitudinal expansion of intense beams is insensitive to local transverse envelope oscillations due to mismatch, as well as those due to breathing modes in quadrupole focusing channels.

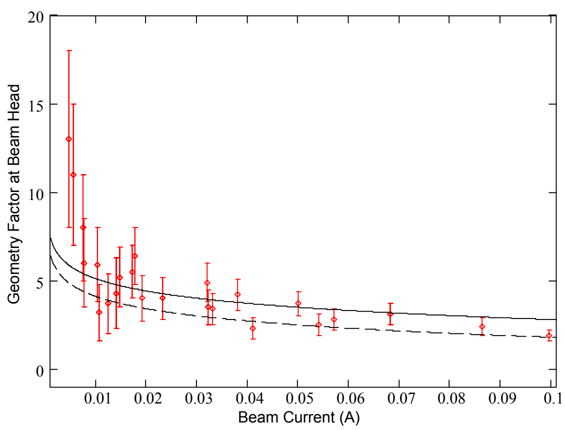

Figure 1: Geometry factor for beam head. Solid line is theoretical value with α of one, dashed line is theoretical value with α of zero.

TRIODE EFFECTS

In addition to studying beam end evolution, we have done experiments in which we modify the beam current profile to generate wave behavior. While this is traditionally done by deliberately modulating the grid-to-cathode voltage in gridded guns [12], we have chosen to use two different methods on UMER.

The first of these relies on the fact that the gridded gun in UMER is essentially a planar triode [13]. By increasing the grid-cathode voltage, emission from the cathode can be suppressed below the space charge limit. In this mode, the UMER gun operates as a triode amplifier. Any ringing, noise, or droop on the cathode pulser voltage will be amplified, and will appear as a current modulation in the beam (Figure 2). In UMER, this results in a sinusoidal modulation at the beam head and a droop across the rest of the beam pulse. This modulation is observed to decay and reappear as the beam travels downstream. This is due to the splitting of the modulation into a forward-traveling and a backward-traveling wave, each traveling at the sound speed in the beam frame, which interfere with each other.

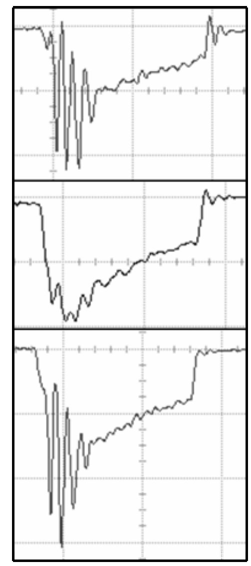

Figure 2: Beam current measured at 0.83 m (top), 3.23 m (middle), and 5.78 m (bottom) downstream from the cathode.

PERTURBATIONS

For many applications, it is desirable to add discrete current perturbations to the beam. These discrete perturbations split into forward-traveling and backward-traveling waves, each traveling at the sound speed in the beam frame. These waves are particularly useful for beam diagnostics [14] and studies of the resistive wall instability [15]. If multiple perturbations of arbitrary strength can be produced with adjustable spacing, this allows the construction of more complicated beam current profiles than is otherwise possible. In addition, the ability to generate very large perturbations allows the study of nonlinear effects in beams [16].

We have recently demonstrated a system to accomplish these objectives [17]. This system makes use of combined thermionic emission and photoelectric emission from our dispenser cathode, and is an extension of ongoing cathode development work at Maryland [8, 18]. By using photoemission to modulate the electron beam, we produce perturbations in particle density only, while modulation of the grid-cathode voltage results in perturbation in both density and velocity. Generating controlled beam modulation by photoemission requires a modulated light source. To accomplish this, we used a Continuum Minilite Nd:YAG laser to generate a 5 ns long pulse of 1064 nm light. This light was then shifted into the ultraviolet and split into four pulses by an arrangement of delay lines and polarized beam splitters (Figure 3). Half wave plates and quarter wave plates were used to rotate the polarization of the laser light to determine how much of the incident light would be reflected or transmitted at each beam splitter, and therefore to

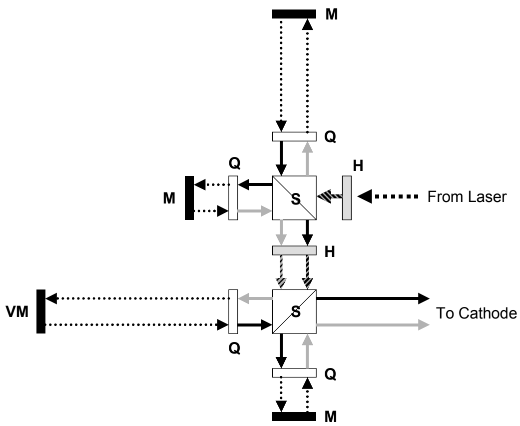

Figure 3: Optical modulation system, showing polarized beam splitters (S), half wave plates (H), quarter wave plates (Q), fixed-distance mirrors (M) and variable-distance mirror (VM). Arrow colors and styles correspond to light polarization states.

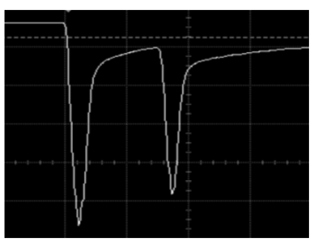

Figure 4: Sample optical pulse train. Up to four pulses could be produced.

determine the relative intensity of the peaks in the optical pulse train (Figure 4). Interpulse spacing was controlled by changing the delay line length. This light was then directed through a viewport in the beam line and onto the cathode by a mirror in vacuum. Timing of the pulse train relative to the thermionic beam pulse was controlled by a modified [17] version of the UMER triggering system [19], and could be adjusted with a Stanford Research Systems DG535 variable delay trigger source. This enabled us to place a beam density perturbation of 5 ns width anywhere in the thermionic beam, including at the beam ends.

The UMER gun was normally operated in the temperature-limited mode during perturbation experiments. In this mode, beam current was enhanced by production of additional electrons from the cathode due to photoemission. However, during the transition from temperature-limited to space-charge-limited operation, injection of additional electrons from the cathode due to photoemission was found to suppress beam current [17]. This is believed to be due to the transverse defocusing effects of adding additional beam current in the UMER gun.

SUMMARY

Longitudinal dynamics research on UMER is currently ongoing, with an emphasis on the generation and evolution of novel current distributions. UMER's capability to address interesting issues in longitudinal dynamics will be enhanced by the recent closure of the ring and the resulting multiturn operation. Lessons learned from these studies will facilitate improved diagnostics, applications, and beam control systems for intense beams.

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