SPACE-CHARGE-DOMINATED PHENOMENA IN THE UMER SOURCE REGION*

I. Haber, S. Bernal, R. A. Kishek, P. G. O'Shea, B. Quinn, M. Reiser, Y. Zou
University of Maryland, College Park, MD 20742-3511 USA

A. Friedman[1, 2], D. P. Grote[1, 2], J. -L. Vay[1, 3]
[1]HIF-VNL; [2]LLNL,Livermore, CA; [3]LBNL Berkeley, CA

Abstract

For space-charge-dominated beams, details of the beam distribution as it emerges from the source region can strongly influence beam evolution well downstream. This occurs because collective space-charge modes, excited as the beam is born, can remain undamped for many focusing periods. Nevertheless, traditional studies of the source region in particle beam systems have emphasized the behavior of averaged beam characteristics such as total current, rms beam size, or emittance, rather than the details of the full beam distribution function that are necessary to predict the excitation of any collective space-charge modes. Simulations of the source region using the particle-in-cell WARP code along with detailed comparisons to experimental measurements of the beam in the University of Maryland Electron Ring (UMER) are therefore being employed to understand the complex behavior that has been observed in the source region, including a surprising sensitivity of the beam evolution to details of the transverse velocity distribution.

INTRODUCTION

In many accelerator systems space-charge-dominated behavior, including the excitation of space-charge collective modes, can be significant in the source region even when the downstream characteristics are not space-charge-dominated. Furthermore, if the transverse evolution is viewed in a frame moving with the beam, it can be seen that these modes can remain relevant as the beam is accelerated, and it has been observed in simulations that they remain undamped for many focusing periods. Traditional studies of the source region in particle beam systems have emphasized the behavior of averaged beam characteristics, such as total current, rms beam size, or emittance, rather than the details of the full beam distribution function that are necessary to predict the excitation of collective modes. Because of the comprehensive diagnostics on the University of Maryland Electron Ring (UMER) experiment, extensive detailed observations of the evolution of these modes have been possible.

A primary tool for understanding the detailed evolution of a space-charge-dominated beam in the source region in general, and the UMER ring in particular, has been the use of simulation in concert with detailed experimental measurement. However, "first principle" simulations beginning from the emitter surface have often displayed sensitivity to details in the numerical model that appear to reflect similar sensitivities to details of the actual gun geometry. Since accurate prediction of the beam evolution in the UMER ring requires comparable accuracy in specifying the injected beam distribution, a systematic program is underway to compare particle-in-cell WARP code simulations of the beam with experimental measurement in the source region. The sections below will describe some of the complexity in beam evolution that has been observed as a result, including the surprising sensitivity of the evolution of the beam profile to details of the transverse velocity distribution

THE UMER SOURCE

The UMER source is a variable perveance Pierce geometry electron gun modified by a gridded cathode used to control the current pulse, and an anode grid used to impose a uniform potential at the anode plane. The perveance can be varied by changing the cathode-to-anode spacing. The gun is normally operated to provide approximately 118 mA in the anode-to-cathode region, so that the nominal ring injection current of 100 mA current is obtained after interception by the anode grid.

Unlike the anode grid, which appears to have a relatively minor influence on the exiting distribution function, the cathode grid that is used to rapidly switch the current has been observed to strongly influence the beam characteristics. While study of the effect of the cathode grid in a triode has an extensive history, the work that was done has generally concentrated on the parameter regime appropriate to using the beam as an amplifier tube rather than the as a beam switch. In addition, emphasis in early studies was primarily on the behavior of the total current at the anode, and not on the detailed characterization of the beam distribution function important to UMER ring operation. As will be discussed below, examination of the beam distribution that emerges from the cathode has uncovered a degree of complexity not previously appreciated.

EXPERIMENTAL DIAGNOSTICS

The primary experimental diagnostic tool employed here is a phosphor screen mounted on a plunger-like apparatus so the screen can be translated along the injector transport line to measure the variation of the beam profile as it propagates. An additional feature of the apparatus used to measure characteristics of the beam distribution function is the capability to insert various beam masks approximately 1 cm downstream from the anode grid location. One of these masks is a "pepper pot" consisting of an array of small holes that can be used to sample the beam velocity distribution.

A less straightforward use of the masks is to split the beam into five beamlets in a pattern resembling the five face of a die. It has previously been determined that the beam evolution after traversing such a mask depends on the temperature of the beam emerging from the mask. This evolution therefore provides an independent estimate of the beam emittance without relying on the fairly complex slit-slit measurements that were not operational in the early stages of the beam experiments. Two additional measurements which were performed that provide a consistency check on the beam characteristics are the degradation of the shadow of the anode grid with distance and the evolution of the Bernal[1] ring patterns as a single beam propagates.

GUN SIMULATION

Many of the observed UMER gun characteristics described below appear to result from details of the beam evolution in the region between the cathode and the cathode grid. However, with available computer resources it is difficult to resolve the grid region in the same calculation that represents the entire gun structure. This is because the grid wire diameter is 0.0254 mm and the distance from cathode to grid, as well as is the spacing between grid wires, are 0.15 mm. These distance are much less than the 3 mm cathode radius and the approximately 25 mm separation between the cathode grid and the anode grid. In addition, unlike the gun structure itself, the grid geometry is not axisymmetric, so that modeling the grid structure requires full three-dimensional simulation.

The first WARP code simulations were therefore performed assuming axisymmetry. Sensitivities to various experimental and simulation parameters were examined, and comparisons between available measurements and the code predictions were used to infer information about the beam distribution function. More recently high-resolution simulations have been undertaken to examine the influence of the cathode grid on the gun characteristics. These simulations examine only a small transverse central portion of the beam.

COMPARISON TO EXPERIMENT

The set of gun operating parameters used for the UMER injector were determined by experimentally adjusting the anode-cathode spacing and the grid voltage to achieve an output current of 100 mA, which is the value desired for nominal ring operation. The cathode-to-grid potential during the pulse is set by varying a bias voltage added to the voltage pulse applied across the cathode-to-grid gap, so that the negative bias voltage prevents any current from being drawn except during the approximately 100 ns beam pulse. It should be noted that the actual pulse voltage applied to the cathode-to-grid gap is difficult to measure in the existing apparatus and is difficult to calculate because the loading on the pulser as a function of bias voltage is not known. Many of the beam characteristics must therefore be inferred from a combination of simulation and other measurements of the beam characteristics.

Simulation of the gun geometry that assumes self-consistent Child-Langmuir emission from a cathode placed at the location of the cathode grid predicts a current of 125mA. This is close to the actually obtained current of approximately 118mA, as inferred from the 100mA measured downstream of the approximately 87% transparent anode grid. The prediction by this simulation of a current approximating actual observation appears to be evidence that the current enhancement expected from injection into gun with a substantial initial energy approximately counteracts the 66% transparency of the cathode grid.

The Child-Langmuir simulation predicts a hollowed beam with current density at the outer edge of approximately 1.5 times the central value. Because of the difficulty of realistically modeling the emission characteristic of the gridded cathode, a simulation assuming transversely uniform emission from the grid surface was used to test the importance of self-consistently modeling the transverse variation of the emission. The transverse characteristics at the anode plane were very close to those obtained from the self-consistent calculation. On the other hand, sensitivity of the profile to total current was observed, since a reduction of the injected current by approximately 10% resulted in a substantial modification of the profile at the anode plane.

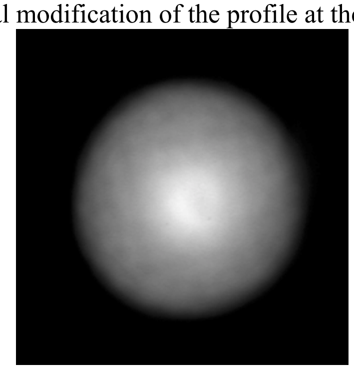

Fig. 1. Phosphor screen image of the beam approximately 60 mm from the anode plane. A weak shadow of the anode grid is observable.

Direct measurements of the beam profile were obtained using a phosphor screen placed approximately 60 mm downstream of the anode grid. Figure 1 is a typical phosphor screen image of the beam. Note that the grid bias voltage is set at a low enough value that the cathode-to-grid potential is into the "saturation" region where the current is weakly dependent on this voltage, in contrast to the rapid variation in current with bias voltage observed in the region near current cut-off by the bias potential.

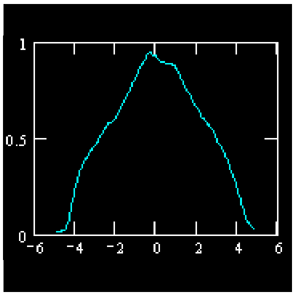

Fig. 2. Current density plotted along a diameter of phosphor image in Fig. 1.

Figure 2 is a plot the light intensity along a diameter cut through the plot in Fig. 1. Unlike the hollowed simulation profiles, it is peaked at the beam center. Furthermore, only when the transverse temperature of the injected distribution is increased by something between a factor of 25 and 100 times the intrinsic value of the 0.1 eV emitter temperature, does the simulated profile begin to match the peaked behavior observed. Such a large assumed transverse injection temperature is inconsistent with the five-beamlet patterns observed[2] as well as to the measured degradation of the anode mask shadow.

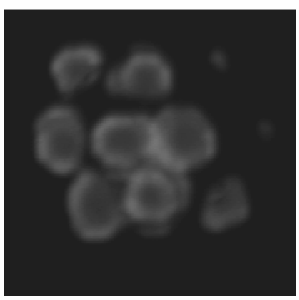

Fig. 3. Phosphor screen image downstream of the pepper pot showing a hollowed velocity space distribution.

The discrepancy between the observed radial variation in current density and that predicted by simulation can be resolved by injecting an initial hollowed transverse velocity distribution such as shown in Fig. 3, which is the image formed by passing the beam through the pepper pot mask. The peaked distribution shown in Fig. 2, including the small depression in beam density at the beam center that can be seen in Fig. 1, are then observed in the simulation. The total transverse energy contained in the hollowed velocity distribution is also consistent with the beam downstream evolution of the beam passed through the five-beamlet mask. The hollowed inital velocity distribution also improves agreement between simulation and phosphor screen measurements of the evolution of the shadow of the anode grid, as well as the downstream evolution of the full beam density patterns.

Because of the uniformity across the beam profile of the hollowed distribution observed in Fig. 3, it is likely that this hollowing is caused by the influence of the cathode grid. Since the grid physics is seen to be important to prediction of the downstream evolution, simulations are underway to examine the influence of the cathode grid on the gun beam characteristics for parameters in the range of interest to the UMER gun.

In order to perform simulations with resolution sufficient to examine the physics of the very small region between the cathode and the cathode grid, only a small transverse region, corresponding to a single cell of the cathode grid is examined. The transverse boundary conditions are assumed periodic, and the computational requirements are further reduced by assuming fourfold transverse symmetry. A typical simulation of such a long thin region, as might be appropriate to examining the beam behavior near the gun center employs 16 by 16 transverse grid cells and 1024 cells in the longitudinal direction.

Analytic calculations of the cathode grid region [3] predict that under typical operating conditions a virtual cathode will form downstream of the cathode grid at a distance somewhat greater than the cathode-to-grid spacing. It is therefore necessary to perform the simulation for a distance much greater than the 0.15 mm cathode-to-grid spacing. It was, in fact, observed that simulating a longitudinal region much shorter than the full gun length would result in sufficient ambiguity in specifying the downstream potential that it was simpler to include the entire 25 mm region.

The simulations were performed with a potential between cathode grid in the range around 20V independently measured by the energy analyzer.[4] Preliminary observation of the parametric behavior, which includes complex current rise waveforms, including virtual cathode oscillations for sufficiently large cathode-to-grid potential is too complex to describe here, however many of the features observed experimentally are reproduced in the model.

CONCLUSIONS

A combination of simulation and measurement has revealed considerable complexity in the behavior of the UMER gridded gun. Furthermore, understanding this complexity appears to be important to predicting the injected beam characteristics for injection into the UMER ring. A continuing program that combines simulation and measurement is therefore underway to develop the level of predicative capability desired for interpretation of the detailed beam characteristics in the ring.

REFERENCES

[1] S. Bernal, R. A. Kishek, M. Reiser and I. Haber, Phys. Rev. Lett. Vol. 82, (May, 1999).

[2] I. Haber, S. Bernal, C. M. Celata, A. Friedman, D. P. Grote, R. A. Kishek, B. Quinn, P. G. O'Shea, M. Reiser, submitted to Nucl. Instr & Methods A

[3] Y. Zou, H. Li, M. Reiser, P. G. O'Shea, submitted to Nucl. Instr & Methods A

[4] Y. Cui, Y. Zou, A. Valfells, I. Haber, R. A. Kishek, M. Reiser, P. G. O'Shea, Proc of 2003 PAC.