# COMPUTER SIMULATION STUDIES OF ELECTRON BEAM PROPAGATION AND COLLECTIVE ION ACCELERATION IN VACUUM*

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## Abstract

The propagation of a relativistic electron beam through plasma into vacuum via collective ion acceleration from the plasma is investigated with a numerical simulation code. Results show dynamic details of virtual cathode formation and the high-energy tail in the ion distribution not noticed previously.

## Introduction

Collective ion acceleration by intense relativistic electron beams passing through a plasma region or an ion-emitting foil into a vacuum drift space has been the subject of several recent experimental and theoretical investigations.[1-9] There is general agreement that the positive ions facilitate the propagation of the electron beam in the vacuum drift region and that the bulk of the ions has a mean kinetic energy comparable to that of the beam electrons. In addition, there is a high-energy tail in the ion distribution with a maximium kinetic energy of typically about two to three times higher than the mean energy depending on the operating conditions. The high-energy tail is of particular interest for the development of collective acceleration methods, and in special experiments energies up to over 20 times the electron beam energy have been observed.[10] While most theoretical analyses of this beam propagation problem conclude that the positive ion acceleration is in some way connected to virtual cathode formation and electron reflection, the mechanisms responsible for the high-energy ion tail and many important details of the beam dynamics have so far not been fully understood.

In our previous paper[9] we proposed an analytical momentum-balance model which describes the average behavior of the beam electrons and of the accelerated ions in the vacuum region when an intense electron beam is injected through plasma or a foil into vacuum. This model leaves two important questions unanswered. First, what mechanism is responsible for the high-energy tail in the ion distribution observed in the experiment, and second, what happens to the virtual cathode when positive ions are accelerated from the plasma surface?

In this paper, we describe the results obtained with a two-dimensional electrostatic code in which a cylindrical beam, simulated by small disks, propagates through an ion emitting planar surface with zero potential at $z = 0$ into free space ($z > 0$) with no boundaries. Since our main interest is to obtain an understanding of longitudinal motion (in beam direction) during the initial phase of beam propagation, we imply that an infinite magnetic field exists which prevents radial motion of the particles.

## Description of the Model

In our model, a cylindrical electron beam with an initial velocity $v_{eo}$ and constant current density $J_{eo}$ is injected through the dense plasma or foil into the vacuum region ($z > 0$). The plasma (or foil) is a source of positive ions that are accelerated into the vacuum region by the space-charge field of the electrons. Each electron disk will enter the region of interest from the injection plane at velocity $v_{eo}$ and with charge density $\rho_e = J_{eo}/v_{eo}$. Ion disks with zero initial velocity, on the other hand, are accelerated into the system by the electric field near the injection plane. The charge density of each ion disk is proportional to the positive electric field at the plasma surface at the time this disk is emitted into the system. The time step $\Delta t$ must be small compared to the beam electron plasma period $T_p = 2\pi/\omega_p$. On the other hand, if $\Delta t$ is very short, computer time becomes excessively large. We chose $\Delta t \approx T_p/31$ as a satisfactory compromise between the two requirements.

## Simulation Results

For the actual simulation runs, we used parameters comparable to the experiments at the University of Maryland,[1,4] namely injected electron current $I_{eo} = 3 \times 10^4$ A, relativistic electron mass factor at injection $\gamma_{eo} = 4$, beam radius $r_o = 1$ cm. The positive ions are taken to be protons in all runs.

The major results of our studies are shown in Figs. 1 through 6 and can be summarized as follows:

(1) At the start of beam injection, some of the early electrons can escape into free space as shown in Fig. 1. But most electrons emitted after about 80 ps are reflected to the injection plane. When electron reflection occurs, a virtual cathode is formed at a very short distance from the injection plane (5-6 mm). This virtual cathode is found to oscillate with approximately the plasma frequency of the beam electrons.

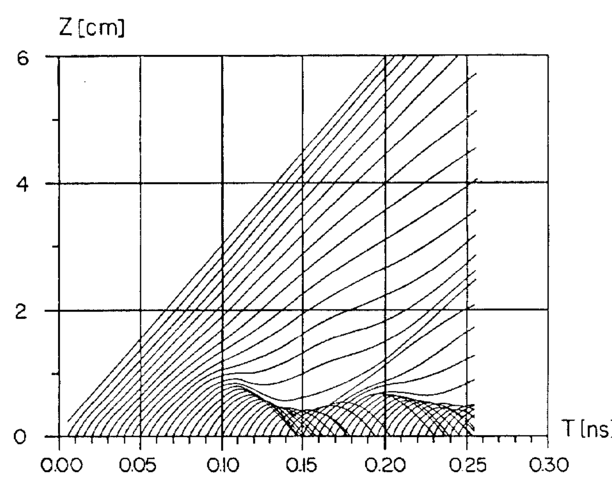


FIG. 1. Electron trajectories vs time in the interval 0.0 ns $\leq t <$ 0.3 ns at the start of beam injection.

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(2) When ions are entering into the system, the virtual cathode moves forward by several millimeters to a new position (8-11 mm) of the beam electrons (see Fig. 2). The potential well at the virtual cathode oscillates about a mean value of - 1.5 MV which corresponds to the electron injection energy. Near the virtual cathode the electron density increases to a value that is about three to five times larger than the injection density $n_{eo}$, and the corresponding plasma period $T_b$ is approximately 0.05-0.10 ns depending on $n_e$. Similar phenomena were observed in the nonrelatavistic studies by Dunn and Ho.[11]

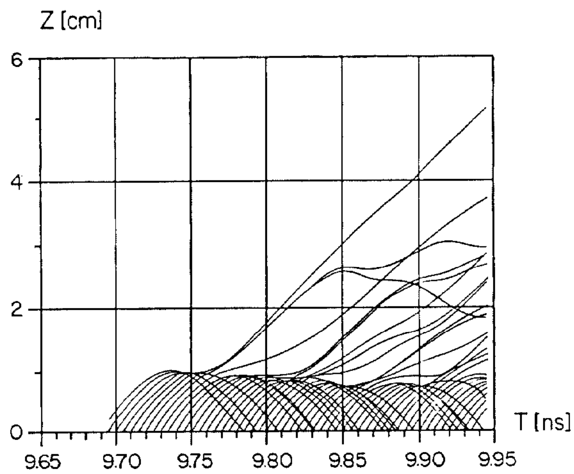


FIG. 2. Electron trajectories vs. time in the later time interval 9.65 ns < t < 9.95 ns with ions in the sytem.

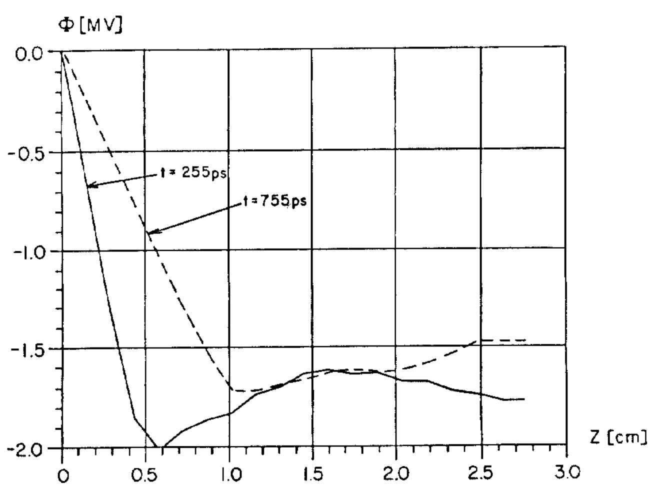


FIG. 3. Potential distribution vs. distance at t = 0.255 ns and t = 0.755 ns.

(3) A deep potential well is formed at the virtual cathode and as the positive ions are accelerated from the plasma surface, the potential minimum moves a small distance further downstream. This behavior is illustrated in Fig. 3 which shows snapshots of the potential distribution vs. distance at time t = 0.255 ns when ions have not yet advanced much into the system (≲ 1 mm) and at t = 0.755 ns where the fastest ions have reached a distance of about 11 mm. Note that the potential minimum (virtual cathode position) has moved from 6 mm to approximately 11 mm in this time interval. Figure 4 shows the potential distribution at the time t = 8.70 ns when the ions have propagated considerably beyond the virtual cathode near the injection plane. As can be seen, a second virtual cathode forms at z ~ 15 cm which is near the ion beam front indicated by the second arrow. This second virtual cathode at the moving beam front is seen consistently in our runs though it does show signs of erosion as the beam propagates further downstream.

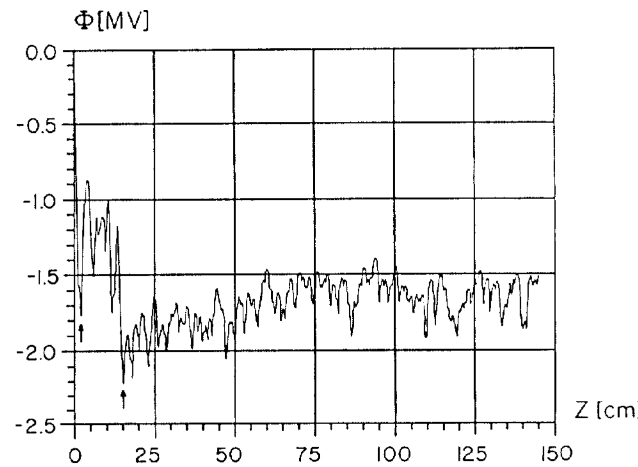


FIG. 4. Potential vs distance at t = 8.70 ns. The two arrows indicate the location of the virtual cathode near the plasma surface and the second potential well near the ion beam front.

(4) Most of the ions gain their energy between the injection plane and the first virtual cathode. After passing through this region, they are basically drifting with a constant velocity of about 1.7 cm/ns through the free space downstream, as is evident in Fig. 5 which shows the velocity distribution vs. distance at the time t = 9.95 ns. As can be seen, beyond the beam front (at about 16 cm) a tail of fast ions with a peak velocity of 3 cm/ns spreads out to a distance of about 30 cm.

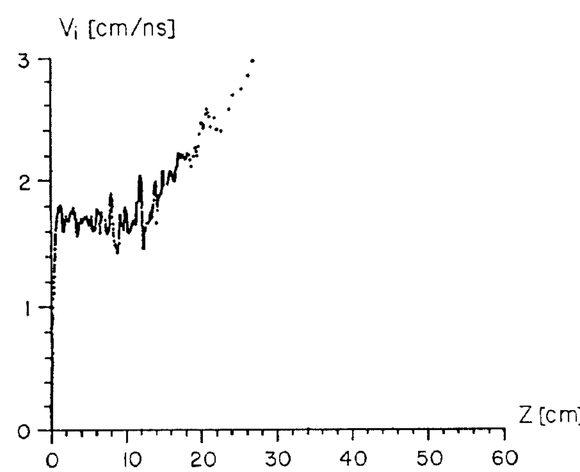


FIG. 5. Ion velocities vs. distance at t = 9.95 ns.

(5) The mean kinetic energy of the bulk of the ions is equal to the mean depth of the potential well at the virtual cathode, which in turn, corresponds to the kinetic energy of the beam electrons at injection (1.5 MeV). The kinetic energy of the fast ions in the high-energy tail, on the other hand, is up to 3 times higher than the mean ion energy. We attribute most of this high energy to the initial acceleration when the potential well moves from its position without ions (5-6 mm) to the new position with ions (8-11 mm), i.e., $T_i = qV_o + qE_e \Delta z$, where $V_o$ corresponds to the initial potential and $E_e$ is the average electrical field associated with the moving virtual cathode. From Fig. 3, the average electric field is 300 MV/m and $\Delta z = 0.5$ cm. Thus, an ion moving in synchronism with the virtual cathode displacement, has gained an additional kinetic energy of $\Delta T_i = qE_o \Delta z = 1.5$ MeV giving it a total energy of 3 MeV. Some further energy gain occurs due to the formation of a second potential well near the ion beam front (shown in Fig. 4). The highest ion velocity is about 0.1 c, which is in good agreement with the experimental observations.[1]

(6) The net charge density is approximately zero except near the injection plane where it is positive, at the virtual cathode where it is always negative, and beyond the ion beam front where it is also negative. A similar result was observed by Taylor[2] even though his model was different from ours.

(7) The energy transfer rate defined as the ratio of total ion energy in the system at a given time to total electron energy that has been injected by this time is estimated to be about 6%. The velocity distribution of the positive ions in the system at time t = 9.95 ns is shown in Fig. 6. It has a strong peak near $v_i = 1.7$ cm/ns which corresponds to a kinetic energy of 1.5 MeV. The high-energy tail beyond the main beam has several small peaks and extends to a velocity of about 3 cm/ns (or 4.7 MeV).

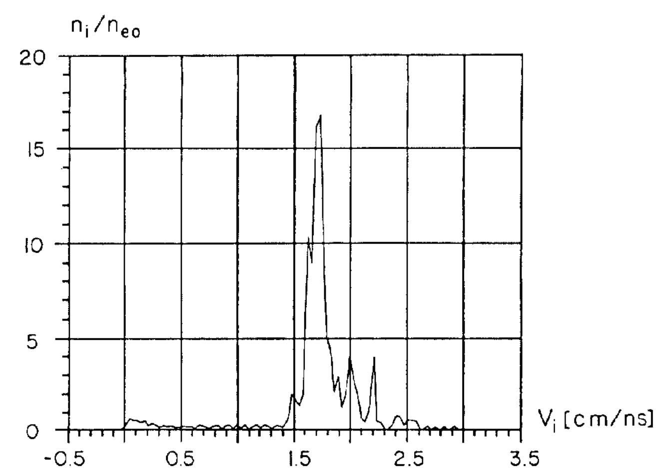


FIG. 6. Ion velocity distribution at t = 9.95 ns. The distribution has a well defined, strong peak near 1.7 cm/ns corresponding to approximately 1.5 MeV energy.

## Conclusion

The picture that emerges from our simulation studies of electron beam propagation through plasma (or a foil) into free-space vacuum and the associated effects of collective ion acceleration is as follows. The electron beam establishes a negative potential well (virtual cathode) near the plasma surface with a mean depth corresponding to the electron beam energy, $eV_o$. Positive ions from the plasma are accelerated by this potential well to a mean kinetic energy equal to the electron energy, $eV_o$. After this acceleration, the bulk of the ions drifts downstream with constant velocity $v_i = (2eV_o/m_i)^{1/2}$.

In addition to the main ion beam, we see in our computer runs a small tail of fast ions whose kinetic energies extent to a maximum of about three times the mean energy. The additional kinetic energy of these fast ions could be attributed to the motion of the virtual cathode near the injection plane early in time and to the formation of a second virtual cathode near the ion beam front. Virtual cathode motion producing a high-energy ion tail was also seen in numerical simulation studies of electron beam propagation through a neutral gas cloud by C. D. Striffler and his students.[12] In this case, however, the virtual cathode motion was due the gas ionization which is different from our model.

Of major interest is the question of whether the positive ions can be further accelerated to higher energies by providing a controlled motion of the virtual cathode. Recent experiments with a laser-produced plasma channel by Destler and collaborators at the University of Maryland have shown that this is indeed possible.[13] Theoretical studies relating to these experiments and describing the radial force balance that must be provided by the positive ions are presented in a paper by Zhang and Striffler.[14] A more detailed account of our own work reported here is published in J. Appl. Phys.[15]

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