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COLLECTIVE ION ACCELERATION BY MEANS OF VIRTUAL CATHODES

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1. Introduction

Experiments on collective ion acceleration by means of the formation of a virtual cathode have been carried out for a number of years in the Soviet Union and in the United States. Recently, there has been renewed interest in the subject as a possible means of accelerating ions to very high energies. By understanding the physics underlying the acceleration process it may be possible to determine the feasibility of virtual cathode staging for very high energy ion production.

For this reason, a theoretical and computational effort is underway at Los Alamos in order to clarify the basic issues of collective ion acceleration by means of virtual cathodes. To support the theoretical effort, simulations were done with the fully electromagnetic and relativistic particle-in-cell code ISIS (in a one-dimensional mode) and the electrostatic one-dimensional code BIGON¹. In the simulations, an electron beam of density $6 \times 10^{11} \text{ cm}^{-3}$ is injected into a one-dimensional box of length L . To supply the necessary ions for collective acceleration, a plasma source containing both ions and electrons was initialized near the emitting boundary (Fig. 1).

Of prime interest in this study was to understand the dynamics of virtual cathode formation and the dynamics of the acceleration process for the ions. In particular, the question of whether the ions are accelerated by a moving potential well¹ or hydrodynamic pressure due to ambipolar expansion² is of primary interest.

2. Virtual Cathode Formation

Consider a relativistic electron beam injected into a box of length L such that $\varphi(x=0)=0$ and $\varphi(x=L)=0$. A time-dependent analysis of the problem up to the first electron turning point was presented by Poukey and Rostoker¹ for the one-dimensional problem, but with the boundary conditions $\varphi(x=0)=0$ and $E(x=\infty)=0$. Even so, their results should describe the problem at hand if $x_m/L \rightarrow 0$, where x_m is the position of the virtual cathode.

To study the formation and dynamics of the formation of a virtual cathode, simulations were done in order to verify a simple one-dimensional steady-state model, and to provide a benchmark for understanding the general time-dependent problem. In the simulations, electrons are injected into a drift-tube consisting of two grounded end plates. Plots of the electric potential, electric field, and virtual cathode position were obtained for different values of the injection velocity.

According to the time-dependent theory, a virtual cathode should form at a distance on the order of an electron beam skin depth c/ω_b from the emitter. The earliest electrons should propagate across the box at the injection velocity v_0 . This effect could be easily seen in the simulations. After the beam front leaves the box, the gross features of the phase space are constant, though the simulations definitely show virtual cathode oscillations. The oscillations for low beam $\gamma_0 = \sqrt{1 + v_0^2/c^2}$ show both higher frequency and amplitude than the corresponding simulations for large γ_0 .

The position of the virtual cathode was also measured as a function of the beam γ_0 for different values of the beam injection velocity. To minimize the effects of the oscillations in the virtual cathode position, these runs were done for large values of γ_0 . As Fig. 2 shows, the agreement between the simulations and the Poukey-Rostoker theoretical scaling (x_m proportional to $\gamma_0^{1/2}$) is quite good.

For late times in the simulations, a "steady state" was reached. By this we mean all physical quantities averaged over the virtual cathode oscillations were essentially unchanged for all time. A simple, steady-state model was then formulated which assumes a priori that a virtual cathode forms at the point $x=x_m$. Assuming the beam makes up three species (the injected particles, the reflected

particles, and the transmitted particles), Poisson's equation, the equation of continuity, and the conservation of energy equation $(\gamma - \gamma_0) mc^2 = e\varphi$ for each species can be used. The solutions cannot be integrated exactly in the general case, but in the non-relativistic regime they can be obtained exactly. The result for the potential $\bar{\varphi}(\equiv e\varphi/(\gamma - 1)mc^2)$ can be written:

$$\bar{\varphi}(\bar{x}) = \left[1 - 3 \bar{x} \sqrt{(1-T/2)} \right]^{1/3} - 1 \quad (2a)$$

for $x < x_m$, and

$$\bar{\varphi}(\bar{x}) = \left[-(\bar{L} - \bar{x}) \sqrt{(9T/2)} \right]^{1/3} - 1 \quad (2b)$$

for $x > x_m$. In Eqs. (2) the dimensionless lengths are overstruck by bars and are normalized to the beam skin depth $\delta = v_0/\omega_i$. The quantity T (which is a function of $\bar{x}_m$ only) is the transmission coefficient of the beam; that is, the ratio of the transmitted current to the injected current. In Fig. 3, Eq.(2) is plotted in comparison with a typical potential plot from the one-dimensional simulations. The agreement is surprisingly good.

The steady-state solutions above impose a requirement on the virtual cathode position as a function of the initial beam density n_0 , the initial beam velocity v_0 , and the length L of the gap spacing. In terms of dimensionless quantities, this equation can be written:

$$\bar{L} = \bar{x}_m + (9 - 1/\bar{x}_m^2)^{-1/2} \quad (3)$$

In Fig. 4 we plot the theoretical curve for Eq.(3) with the corresponding simulation data points. The simulations were made with values of L ranging from 0.1cm to 2.0cm. Identical values for the initial beam density n_0 and velocity v_0 were used in these runs. Because of the variation in virtual cathode position due to the virtual cathode oscillations in this nonrelativistic case ($\gamma_0 = 1.01$), the data points correspond to a simple average of the maximum and minimum amplitudes.

3. Collective Acceleration

When a plasma is introduced into the box, the beam space charge can be neutralized by this plasma. The beam then propagates a distance equal to c/ω_p beyond the plasma boundary, until a virtual cathode forms. In the "moving virtual cathode theory", the resulting electron space charge in the thin sheath beyond the plasma pulls the ions ahead in a bootstrap process. The motion of the potential well with respect to time can be derived in a simple fashion from Eq.(2), and will be discussed in a later study.

In the one-dimensional runs with an ion-to-electron mass ratio of 1836, no virtual cathode motion was seen. Typically, these runs had a rich source of ions in the form of a localized plasma of density 50 times the injected electron beam density. When the electron-to-ion mass ratio was reduced to 20, as in the work of Mako and Tajima³, there was virtual cathode motion observed. Whether or not the virtual cathode movement is simply a result of the artificially low mass ratio or a real physical effect has not yet been determined.

The one-dimensional simulations with equipotential boundary conditions ($\varphi=0$) show that the measured maximum ion energy is a little over three times the initial beam energy (Fig. 4). This agrees with the results of Ref. 3. In the simulations using the Poukey and Rostoker boundary conditions, the measured maximum ion energy increases up to twenty times the initial beam energy. In the two-dimensional simulations the maximum ion energy scaled as $(I/I_{SCL})^{1/2}$, where I_{SCL} is the space-charge limit current in the drift tube.

In conclusion, we have presented a simple calculation for the electric potential and electric field in a one-dimensional virtual cathode formed by the injection of a relativistic electron beam into a drift tube region. The theoretical predictions seem to agree in a time-averaged sense with a simple steady-state model. The maximum energy given to the ions is a little over three times the initial electron beam energy, in agreement with the results of previous authors. Further work is needed to extend the simple analytic model to relativistic, and perhaps time-dependent, regimes. Finally, it is planned to use the results of this study to design future accelerators with significantly higher values of ion energy.

Acknowledgments

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References.

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Figure captions.

Fig. 1. Schematic drawing of a relativistic electron beam injected into a drift region containing a localized source of plasma. The collector plate, which is at a distance of L cm away from the emitter, is not shown.

Fig. 2. Virtual cathode position x_m as a function of initial beam energy γ_0 . The solid curve shows $\gamma_0^{1/2}$ scaling.

Fig. 3. Potential plots.

Fig. 4. Variation of virtual cathode position x_m/δ as an implicit function of the gap spacing L/δ from Eq. (3). The data points are from one-dimensional simulations.

Fig. 5. Ratio of maximum ion energy to initial beam energy as a function of ν/γ .

PHI VS. X

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PHI VS. X