CONSIDERATIONS ON COLLECTIVE ION ACCELERATION AS AN INTENSE ION INJECTOR

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Abstract

A virtual cathode collective acceleration configuration is examined for use as a pulsed, intense ion injector. Numerical calculations of the collective acceleration have shown peak ion energies of several times that of the electron beam energy. This is consistent with a variety of experiments. The late time behavior is to accelerate ions to lower energies but at a higher current. This is characteristic of a reflex ion triode, which produces an ion beam largely charge but not current neutralized. Dynamic neutralization must be achieved if accelerator applications, requiring transport and focusing, are to be realized. Representative applications have been simulated and are discussed.

Introduction

Intense ion beam generation has been demonstrated in a variety of diode and triode configurations.[1,2,3] The mode in which an intense electron beam is used to form a virtual cathode downstream of the anode is referred to either as a reflex triode or as a collective ion accelerator, depending on whether one is interested in bulk operating characteristics or peak ion energies. We consider some of the factors involved with use of such an ion generator as an injector for conventional acceleration configurations. The broader subject of intense ion beam generation has been very adequately covered in recent review papers[1,2,3] and will not be detailed further here.

In this paper, we will first review simulation results we have obtained on the acceleration process. These are compared with a model for both the transport and high peak energies. Finally the results of a scaled calculation are discussed in which the self-consistent ion beam is injected into an induction accelerator model.

Theory

The simulation model for the drift region consists of a dense plasma cylinder through which a cold relativistic electron beam is injected. The particle-in-cell code ISIS was used for all calculations. ISIS is a fully electromagnetic, two-dimensional plasma code, capable of treating all particle trajectories and the complete space charge fields. Injection of the electron beam occurred at a grounded surface, which may be regarded as an anode foil. Anode-cathode dynamics, including the electron beam generation, were explicitly neglected in these studies so that the collective dynamics could be isolated. Reflexing through the anode foil was also omitted, though this may play an important role in certain parameter regimes (c.f. Creedon, Smith, and Provo[5,6]). As reflexing tends to enhance the ion generation process the present results may be regarded as a lower bound on generator performance.

The source of ions in our calculations is well localized, similar to the experimental configuration of Destler et al.[4] Extraction of ions depends to some extent on the nature of this source, but the maximum current which can be drawn in the absence of reflexing is the space-charge limited emission. We can have no higher current density than $j_i = \frac{eV_0}{M_i c^2} j_e$.

If all the initial electron current were reflected this would effectively double j_e. The virtual cathode can oscillate at high frequencies but if we assume that ion inertia averages this rapid fluctuation to zero, then the net ion motion will experience a steady potential drop. Under these conditions, the quantity nv_z is approximately conserved as a function of z. Since v_z is initially on the order of its thermal value within the plasma, acceleration to MeV energies will increase this by a significant factor. In turn, this will reduce the ion density. Thus with $j_i \ll j_e$, it is virtually impossible for the ions to neutralize the virtual cathode in this configuration. In other words, for $n_i \gtrsim n_e$ at the virtual cathode, we would need $j_i \gg j_e$. The important result here is: we should <u>not</u> expect ion acceleration to cause the virtual cathode to move downstream.

Once accelerated through the virtual cathode, the dynamics become much more complicated. Since we are interested in accelerator applications, it is useful to consider the asymptotic state in which we are interested and estimate the problems in accessing it from the virtual cathode ion beam state.

The desired asymptotic state for ions is one of zero temperature, or alternatively zero emittance. We assume a nonrotating state. If one imposes the condition that it transports without focusing or divergence, the momentum transfer equation leads to a unique relation between the self electric and magnetic fields,

$$E_r = \beta_i B_\theta \qquad (1)$$

in cylindrical coordinates and $\beta_i = v_z/c$ for the ions. It is easily shown that no such field configuration can be established by a single species beam, if β_i is constant. By introducing a co-flowing electron beam, not necessarily with $\beta_e = \beta_i$, a force balanced state is possible. One finds the ansatz, β_e and β_i uniform, leads to the result from Eq. (1),

$$Zn_i = n_e \frac{1-\beta_i\beta_e}{1-\beta_i^2} \qquad (2)$$

where n_i and n_e are the ion and electron densities, functions of r, and Z is the ionic charge state. The density profiles are still arbitrary at this point but they are directly proportional to each other.

To close the formulation of the state, note that we imposed the condition that the ion state be nonexpanding. Since $n_i \propto n_e$, the electrons must satisfy the same condition. We find that an equation similar to (1) can not be satisfied by the electrons

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unless $\beta_e = \beta_i$. This charge and current neutralized state is well known but is quite restrictive for intense beam generation. If electron pressure is included, another well known but less restrictive state is recovered, the pinched beam state. The equation of state for the electrons depends on the physical configuration but a particularly simple solution is obtained if it is isotropic. Then $P_e = n_e kT_e$, leads to

$$n_e = \frac{n_0}{[1 + (r/a)^2]^2} \tag{3}$$

when the electron temperature, kT_e, is uniform, and

$$n_0 = \frac{2kT_e}{\pi e^2 a^2} \frac{1-\beta_i^2}{(\beta_e-\beta_i)^2} \quad . \tag{4}$$

The scaling parameter a is related to n_0 once the total current is specified. From these, one can evaluate the total ion current I_i if the outer wall radius R_0>>a,

$$I_i = \frac{2\beta^2 \beta_i(1-\beta_i\beta_e)}{(\beta_e-\beta_i)^2} \cdot \frac{m_e c^3}{e} \tag{5}$$

where $\beta^2 = kT_e/m_e c^2$ and $mc^3/e = 17.$ kA. Note that this current diverges when $\beta_e \to \beta_i$, implying no current restrictions.

A series of PIC simulations were conducted with ISIS to check these assertions. The numerical configuration was that a cylindrical pillbox shaped plasma, 2 cm wide and 10 cm diameter, was initialized adjacent to a grounded, conducting plane. The outer wall had a radius of 10 cm, and the total length was 10 cm. An intense relativistic electron beam of radius 4 cm was injected through this plasma, starting at time t = 0. (Code units scale time to $\omega_p = (4\pi e^2 n_0/m)^{1/2}$ and distance to c/ω_p.) A virtual cathode formed outside the plasma and drew out an ion beam. This beam then propagated downstream, carrying electron current with it. To minimize calculational times an unrealistically energetic electron beam was chosen, but the ion/electron mass ratio was kept at 1836, that is protons.

Figs. (1a) and (1b) show the early ($\omega_p t = 20$) phase space $p_z - z$ of the electron and ion "beams" and Figs. (2a) and (2b), their late time ($\omega_p t = 80$) counterparts. We note that the initial reflection point of the electrons in Fig. 1a is at z = 4.2, while it has moved only to z = 3.0 - 4.0 in Fig. 2a. This lack of motion corresponds to times for which the ion beam has propagated through the box. Extensive simulations over a wide range of energy and current have confirmed this behavior. The ion beam energy and density profile are monitored at the far downstream edge of the simulation. Fig. 3 shows this time integrated density profile compared to a crudely fitted distribution of the type in Eq. (3). The agreement is quite good despite the fact that (3) assumed an asymptotic state and the profile in Fig. 3 had only a short distance to equilibrate. Since the initial plasma profile was uniform out to a radius of 5.0 cm and the measured distribution of ions has already pinched to a state with a = 1.0, it is plausible to assert that there is no problem with accessing the state derived above. The chief problem with the calculated state is that a large amount of transverse emittance is also measured. This is presumably due to lack of care in matching the initial ion beam generation to the final desired state.

A final point about the ion beam is important. The time dependent front edge of the ion beam/electron clouds can lead to additional acceleration which imposes a velocity gradient on the ion beam. Simulations show this clearly. Models which lead to this characteristic have been proposed by Reiser, et al.[7], Mako and Tajima,[8] Ryutov and Stupakov,[9] and us.[10] Our recent calculations suggest an interesting scaling of the ratio of peak energy to diode voltage as a function of beam current, ν/Υ, where $\nu = \pi e^2 n_b R_b^2/mc^2$, R_b is the electron beam radius, n_b its density and Υ its relativistic factor. Fig. 4 shows that this ratio scales as roughly $(\nu/\Upsilon)^{0.4}$ when the current exceeds the space charge limit, $\nu_L/\Upsilon = 0.16$ for these conditions. Although the reason for this apparent scaling is unknown, it could be very useful in explaining the large variation in peak ion energy reported for collective ion acceleration experiments in the literature.

Injection Into an Accelerating Structure

There are many issues which must be addressed before the ion generators discussed here will be fully satisfactory as pulsed injectors. The primary characteristic is that self-consistent collective effects dominate all aspects of the process, including extraction from a dense plasma, acceleration through the virtual cathode and subsequent propagation and acceleration downstream. Space limitations prohibit a more complete discussion of these interesting topics, but they cannot be ignored. They lead to a characteristic profile for the ion beam, characteristic energy distributions, and dynamics which are dominated by the self-fields of the ensemble. These may be exploited, as in electrostatic and Robertson lenses, but any serious applications require a full treatment of them.

We conclude with a simple, illustrative example employing a four gap induction accelerator. The parameters and dimensions are purely generic. Further, no external fields were used for transport or pulse shaping. The intrinsic characteristics of this configuration were probed by injecting a low current proton beam into it. The configurational and phase space character can be seen in Fig. 5, a snapshot taken at $\omega_p t = 500$. Next, an intense ion beam was generated in the manner described earlier and allowed to propagate into the accelerator. The injected ion energy for both high and low current cases with 2.0 MeV. Fig. 6 illustrates some of the features of the transport of the intense ion beam through the induction accelerator structure. Collective focusing and secondary virtual cathodes are evident, especially in the first gap. Comparison of Figs. 5 and 6 shows the dominance of collective effects in intense beam acceleration.

Based on these preliminary numerical studies, the primary conclusions are that much more needs to be done before the collective dynamics can be sufficiently understood to be evaluated. Continued analysis and simulation is planned.

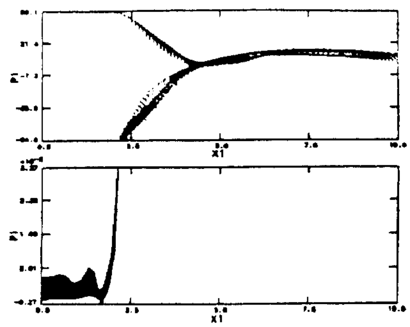

Fig. 1 Electron and ion phase space shortly after virtual cathode formation ($\omega_p t = 20$), $m_i/m_b = 1836$, $I_b/I_L = 5.0$; (a) electron z-p_z space, (b) ion z-p_z space.

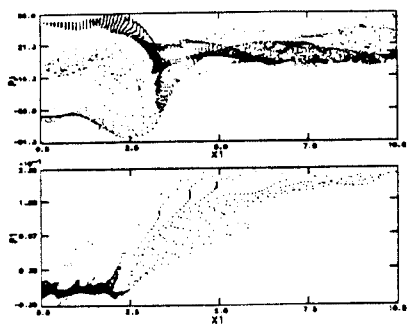

Fig 2. Electron and ion phase space after ion flow is well established ($\omega_p t = 80$), same parameters as

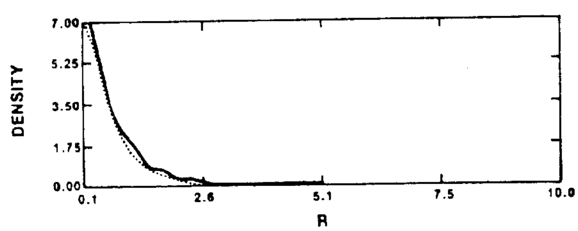

Fig. 3 Radial profile of ion beam at a distance 8 cm from the initial plasma source; dashed line shows Eq. (3) with a=1.0; same parameters as Fig. 1.

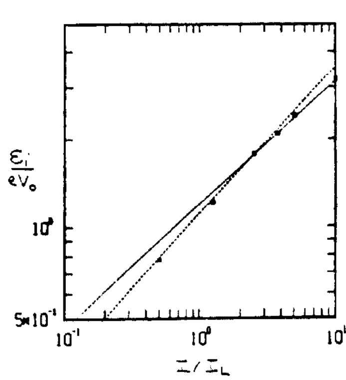

Fig. 4 Ratio of peak ion energy to electron beam energy as a function of injected electron current to the space charge limiting current. Dashed lines are scaling as $(I/I_L)^\alpha$, $\alpha = 0.5$, $\alpha = 0.4.19$.

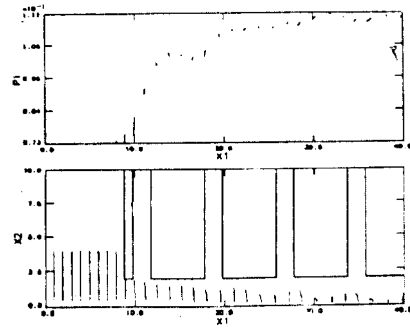

Fig. 5 Ion r-z and z-p_z phase space for low current ion acceleration in an inductin accelerator configuration; I_i = 1. mA, E_i = 2.0 MeV, E_f = 6.4 MeV.

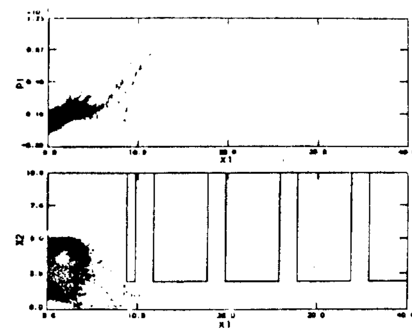

Fig. 6 Ion r-z and z-p_z phase for high current injection into same structure as in Fig. 5.

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