ION BEAM PROPAGATION SIMULATIONS

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INTRODUCTION

A series of numerical particle-in-cell simulations of ion beam propagation have been performed with the LASL two-dimensional electromagnetic code, CCUBE.[1] A few results for each of two different simulations are presented. They are intended to illustrate plasma effects relevant to 1) ion propagation in a relatively dense plasma background, and 2) ion vacuum propagation with co-moving electrons.

PROPAGATION IN PLASMA BACKGROUND

Ion propagation through a background gas sufficiently dense to result in plasma production necessary to charge and current neutralize the beam but tenuous enough to avoid serious degradation of beam quality is a possible propagation mode for inertial confinement. In this mode ballistic ion beam propagation and focusing is a possibility provided the beam ion-background electron two-stream instability remains harmless. This issue along with the effects of incomplete current neutralization is investigated in the first simulation.

The simulation was performed in r,z cylindrical spatial coordinates which were divided respectively into 50 and 150 grid points. Spatial dimensions of the simulation grid and the unperturbed ion beam envelope are shown in Fig. 1(a).

The ion beam is injected at $t = 0$, from the LHS of the simulation grid. Beam ion speed is given by $\beta = 0.548$, beam ion to electron mass by $m_b/m_e = 50$, and beam-to-background plasma density by $n_b/n_e = 10^{-1}$. These and other dimensionless simulation parameters are listed in the Fig. 1 caption where V_{th} denotes thermal speed, and the subscripts "b", "i", and "e" denote beam ion, background ion, and background electron parameters.

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The beam rises to full strength and propagates across the simulation in about 200 plasma periods, ω_{pe}^{-1}. During this time the beam first becomes charge and current neutralized (0-10 ω_{pe}^{-1}), begins to lose current neutralization and, consequently, magnetically pinch (~ 100 ω_{pe}^{-1}), and develop axial modulations in the beam density and velocity, a result of the nonlinear development of the ion-electron two-stream instability (100 ~ 150 ω_{pe}^{-1}).

Figures 1(a)-1(b) are respectively $r - z$ and $v_z - z$ phase plots of the beam ions after the beam has propagated across the simulation grid, the two stream instability has saturated and magnetic pinching is active. Spatial dimensions are in units of c/ω_{pe}, time in units of ω_{pe}^{-1}, and velocity in terms of $\beta_z\gamma$ where $\beta_z = V_z/c$ and $\gamma = (1 - \beta_z^2)^{-\frac{1}{2}}$.

For the initial beam and background plasma parameters, the ion electron two-stream growth rate (ω_I) and group velocity (V_{gr}) are given by $\omega_I = 0.0695\ \omega_{pe}$ and $V_{gr} = 0.643\ \beta C$. These parameters correspond to a factor of 10 growth in wave amplitude at the point 10 V_{gr}/ω_I or 50.6 c/ω_{pe}, a distance which according to Figs. 1a-1b is associated with large one-dimensional beam density and velocity modulations. Wave saturation by trapping of the beam ions occurs at about this point. After saturation the background plasma is observed to heat at a rate consistent with a transfer of beam energy to plasma energy of 17%. This transfer is in line with the prediction of a single wave two-stream heating model,[2]

$$2\left(\frac{n_b}{2n_p}\ \frac{m_e}{m_i}\right)^{1/3} ,$$

which given the present simulation parameters is 20%. No instability produced deflection of beam particles in the radial direction is observed.

Magnetic pinching of the beam occurs in part because the neutralizing background electron stream depletes the electron population in the region of beam injection and electrons initially outside the beam cannot efficiently current neutralize the beam. This boundary effect was not anticipated but nonetheless results in a gross distortion of the beam. The resulting beam envelope is in general consistent with the ion beam envelope equations derived by Wright.[3]

VACUUM PROPAGATION WITH CO-MOVING ELECTRONS

Vacuum or near vacuum ion beam propagation is also an attractive mode since uncertainties involved in beam plasma production and instabilities are avoided. In this case, active current and charge neutralization are necessary for ballistic propagation. This may be achieved either by beam electron pickup or the injection of comoving electrons as proposed in TRW's light ion driver.[4] The ion electron charge separation at injection which is a feature of the latter scheme provides considerable electrostatic energy which initially goes into the electrons. How and whether this energy is transferred to the ions in amounts which can inhibit ballistic focusing is a subject of continuing investigation.

It is, however, easy to estimate the electrostatic energy involved for a typical parameter. Assume an infinite sheet of ions and an infinite sheet of electrons both with thickness δ and density n separated by a distance Δ. The electrostatic energy per electron (W) due to the charge separation is then given by $W = 2\pi e^2 n\delta(\Delta + 2/3\ \delta)$. For $n = 10^{10}/\text{cm}^3$, $\delta = 5$ mm and $\Delta = 3$ mm, $W = 2.86$ keV, a significant amount of transverse energy is equally partitioned with the ions.

Electron motion within self-electrostatic fields is illustrated by the numerical simulation of the simultaneous injection into a vacuum of three pairs of cylindrical concentric hollow ion and electron beamlets. The simulation was performed in r,z coordinates on a grid of 80 by 100 grid points. Figures 2(a) and 2(b) are respectively ion and electron r,z phase plots 24.5 ω_{pe}^{-1} after injection. Spatial dimensions are in units of c/ω_{pe}. Initial beam velocities are given by $\beta = 0.0728$, $m_b/m_e = 3670$, and beamlet charge densities were initialized to provide for zero net charge within each beamlet pair. Other parameters are listed in the Fig. 2(a)-2(b) caption.

The ion time scale, ω_{pi}^{-1}, is too long in this simulation to observe ion motion. In contrast, the electrons are propelled into large excursions from the ions both axially and radially by electrostatic forces. The heads of the electron beamlets remain intact because beam charge densities are initially zero and rise exponentially to their full value in about 20 ω_{pe}^{-1}.

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REFERENCES

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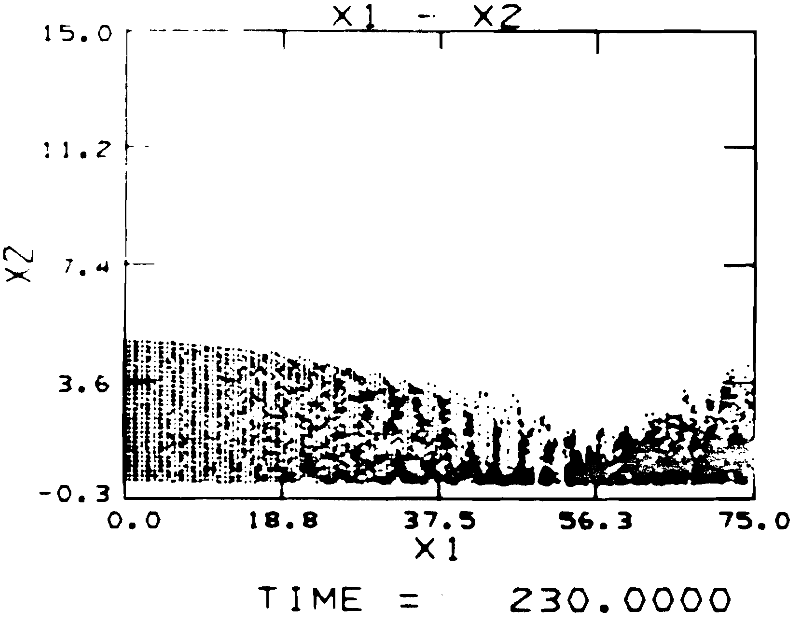

Fig. 1(a)

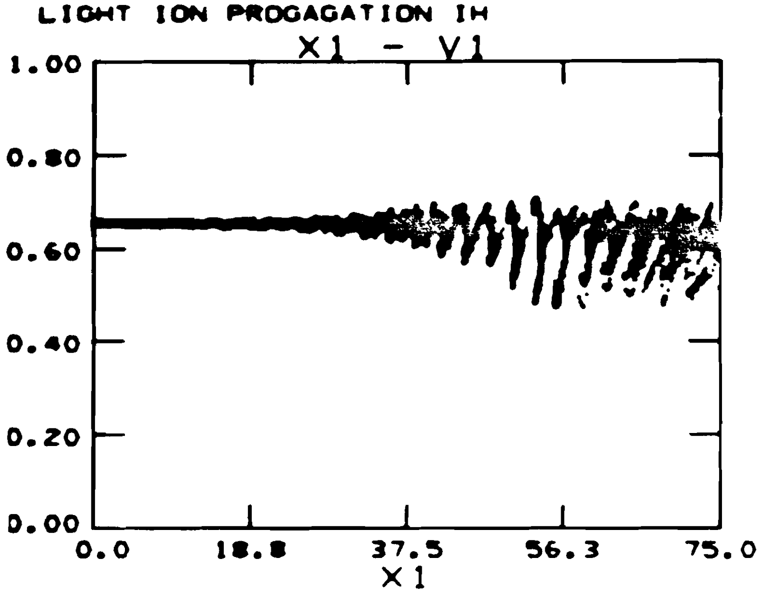

Fig. 1(b)

Figs. 1(a)-1(b). Ion beam particle plots in X2-X1 (i.e., r-z) space 1(a) and V1-X1 (i.e., V_z-z) space 1(b). Simulation parameters are $\beta = 0.548$, $m_b/m_e = 50$, $m_i/m_e = 100$, $n_b/n_e = 10^{-1}$, $V_{thb}/c = 10^{-3}$, $V_{thi}/c = 10^{-4}$, and $V_{the}/c = 10^{-2}$. Distances and times are in units of c/ω_{pe} and ω_{pe}^{-1} respectively.

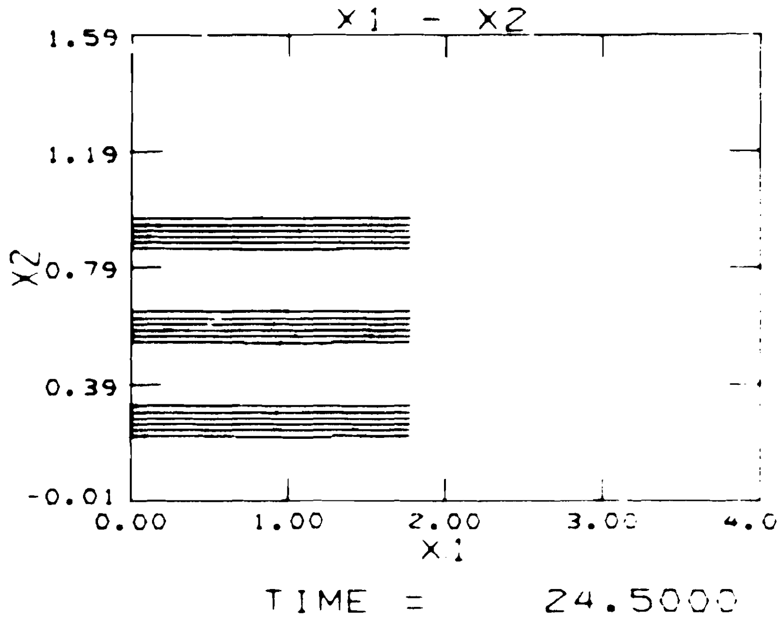

Fig. 2(a)

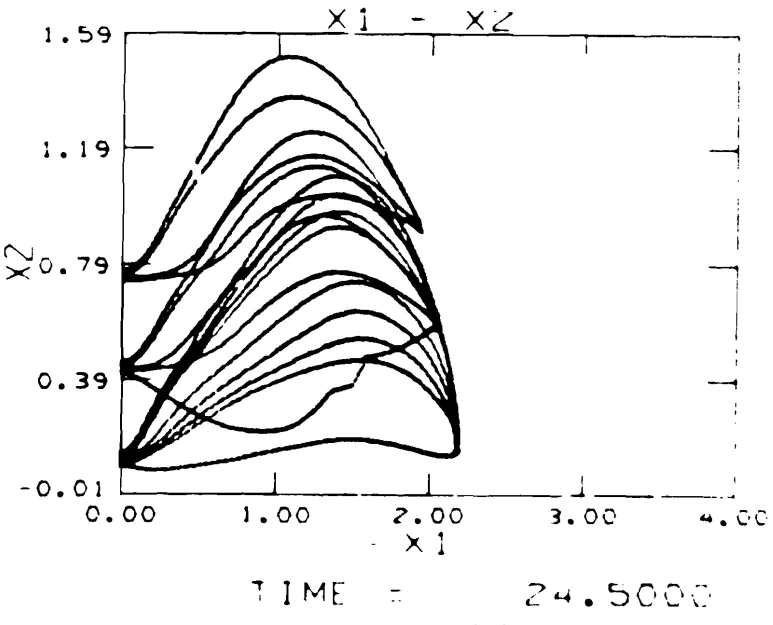

Fig. 2(b)

Figs. 2(a)-2(b). Ion beam 2(a) and co-moving electron 2(b) particle plots in X2-X1 (i.e., r-z) space. Simulation parameters are $\beta = 0.0728$ and $m_b/m_e = 3670.5$. Particles are completely cold. Distances and times are in units of c/ω_{pe} and ω_{pe}^{-1} respectively.