J. Astron. Space Sci., Vol. 5, No. 1, 1988

Electron Beam Propagation in a Plasma

Kyoung W. Min
Korea Institute of Technology, Taejon 301-338
and
Wook-Hee Koh
Korea Advanced Institute of Science and Technology, Seoul 130-650
(Received May 5, 1988; Accepted June 10, 1988)

Abstract

Electron beam propagation in a fully ionized plasma has been studied using a one-dimensional particle simulation model. We compare the results of electrostatic simulations to those of electromagnetic simulations. The electrostatic results show the essential features of beam-plasma interactions. It is found that the return currents are enhanced by the beam-plasma instability which accelerates ambient plasmas. The results also show the heating of ambient plasmas and the trapping of plasmas due to the locally generated electric field. The electromagnetic simulations show much the same results as the electrostatic simulations do. The level of the radiation generated by the same non-relativistic beam is slightly higher than the noise level. We discuss the results in context of the heating of coronal plasma during solar flares.

I. Introduction

It is well known that the impulsive X-ray bursts during the solar flare are produced by high-energy electrons streaming from the corona to the chromosphere(Hoyng *et al.*, 1978). The currents associated with these streams are so high that they are soon neutralized by the reverse currents. Analytic theory shows that, in some circumstances, the electric field developed in the ambient corona could prevent the primary beam from reaching the chromosphere(Knight and Sturrock, 1977). The electric field acts as an energy exchange mechanism, extracting kinetic energy from the primary beam and using it to heat the ambient plasma.

In the last decade, a number of artificial particle beam experiments have been carried out in space using both sounding rockets and satellites in order to study ionosphere and magnetosphere plasma properties(Grandel, 1982). More recently, particle beams have been used to actively modify the ambient space plasmas using energetic high-density particle beams. One such example is the SEPAC experiment carried out on board the Spacelab 1 in which an intense electron beam was injected into the ionosphere in an attempt to produce artificial auroral discharges(Obayashi *et al.*, 1984).

In this paper, we present results obtained from a one-dimensional plasma simulation model on the interaction of an electron beam with a fully ionized ambient plasma. The results are compared with the observations and the previous simulation results. Following the introduction, the simulation results are presented in Sec. II. Discussions of the results and conclusions are given in Sec. III.

II. Results

The simulation code used for this paper is a one-dimensional electromagnetic code(Lin *et al.*, 1975). The transverse field components are not calculated for electrostatic simulations. The ambient plasma is located at $256 \leqslant x \leqslant 768$, where the length is normalized by the thermal electron Debye length. The ions are assumed immobile because of their heavy masses, while electrons can respond to the locally generated electric field. The plasma is assumed overall charge neutral for $x \leqslant 768$. Thus, the electric field at x=768 is always set to zero as a boundary condition. The ambient electrons are reflected back when they move out of the boundary at x=768. This corresponds to the flux from the right balancing with the flux from the left of the boundary at x=768, which is a reasonable assumption for the thermal ambient electrons. When the beam electrons reach x=768, the simulation is stopped. At x=256, beam electrons are injected into the ambient plasma at a fixed velocity $v_0=10v_{th}$, where v_{th} is the thermal velocity of the ambient electrons. The beam density is chosen such that the total number of beam electrons injected during the whole simulation is one-eighth of the number of the ambient electrons. When electrons move out of the boundary at x=256, they are considered lost.

Figure 1 shows the instantaneous plots for (a)the beam electron density (b)the ambient electron density (c)the total electron density (d)the beam electron phase space (e)the ambient electron phase space, and (f)the electric field profile at t=20, where time t is normalized by the ambient electron plasma frequency. The ambient electron density gradually decreases as the beam electrons move in, maintaining the charge neutrality more or less, except for the several localized peaks. These peaks come from the trapped particles. Such a particle trapping can also be seen in the phase space plots of beam electrons and the ambient electrons. Both the beam electrons and

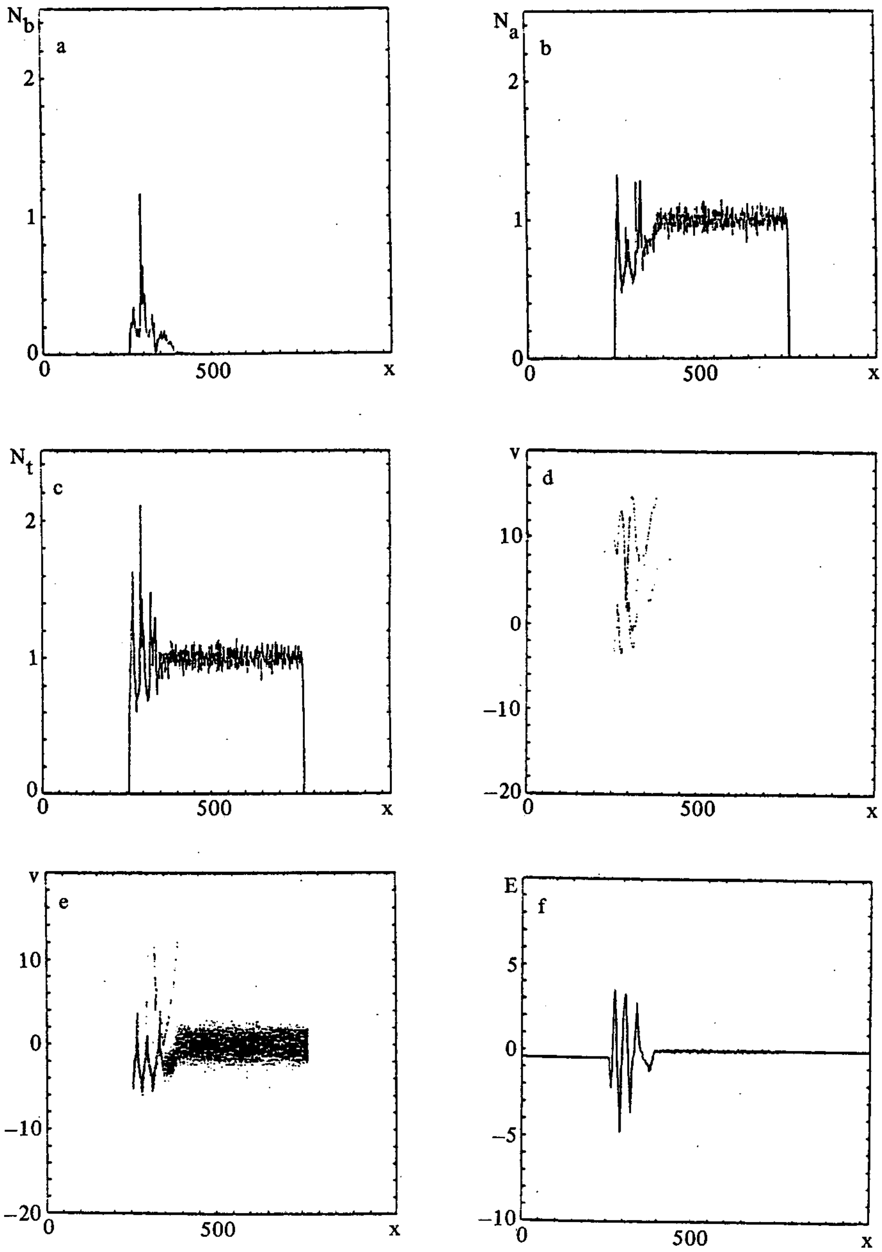

Fig. 1. The electrostatic results at t=20. (a) the beam electron density; (b) the ambient electron density; (c) the total electron density; (d) the beam electron phase space; (e) the ambient electron phase space; (f) the electric field profile.

the ambient electrons suffer accelerations and decelerations depending on the phase of the electric field.

Figure 2 shows the results at t=50. Although the beam electrons are injected at the constant rate, the beam electron density gradually decreases as x increases, which implies that the beam propagation is inhibited. Ambient electron density shows more decrease now than at t=20 near the left boundary, because more beam electrons are present now. The beam and the ambient electron phase space plots show familiar holes and vortices. Although the electric field at the left boundary is below zero as seen in Figure 2(f), it oscillates in time. Thus, the net charge in the simulation region does not change considerably during the whole simulation, except for the oscillation at the plasma frequency.

Figure 3 shows the plots for (a)the perpendicular velocity distributions and (b)the parallel velocity distributions at t=10 and t=50. It is clear that the parallel velocity distribution changes considerably, while the perpendicular velocity distribution does not change much. The parallel velocity distribution becomes broad, as a result of the heating of ambient plasmas. The energy source of the heating is clearly a beam kinetic energy. The average velocity is also seen negative, which represents the return current.

To study the electromagnetic effects of beam-plasma interactions, the transverse field components are calculated. Electromagnetic waves generated in plasmas propagate through the vacuum, and are reflected at the boundaries at x=0 and x=1024. Thus, attenuation zones are introduced at $0 < x < 256$ and at $768 < x < 1024$ to reduce the effects of these reflected waves on the plasmas in the simulation region.

Figure 4 shows the plots at t=50 for (a)the beam electron phase space (b)the ambient electron phase space (c)the longitudinal electric field profile (d)the transverse electric field profile (e)the transverse magnetic field profile, and (f)the parallel-velocity distribution compared with that of t=10. It is easy to see that the phase space plots are very similar to those of the electrostatic simulation, showing holes and vortices. The longitudinal electric field shows the similar oscillating behavior as in the electrostatic case. The transverse fields which are intrinsic only in the electromagnetic case are much smaller than the longitudinal electric field. The level of the transverse fields is about twice the noise level which is obtained without beam-plasma interactions. The parallel velocity distribution shows about the same amount of heating is involved in the electromagnetic simulation. These results lead us to the following conclusions. With the parameters given in this paper, the beam-plasma interaction is mainly electrostatic and the radiation is not important. However, the situation may become different when the beam is highly relativistic.

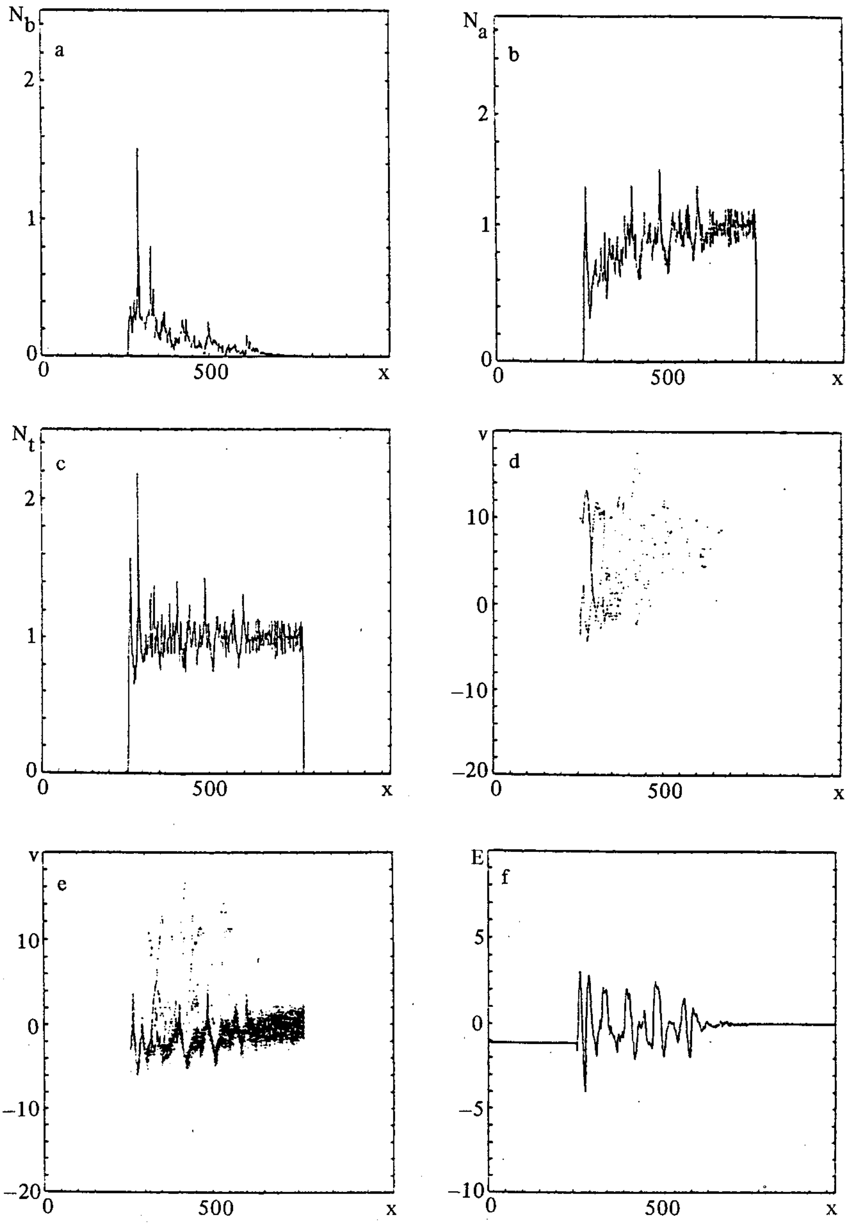

Fig. 2. The electrostatic results at t=50. (a) the beam electron density; (b) the ambient electron density; (c) the total electron density; (d) the beam electron phase space; (e) the ambient electron phase space; (f) the electric field profile.

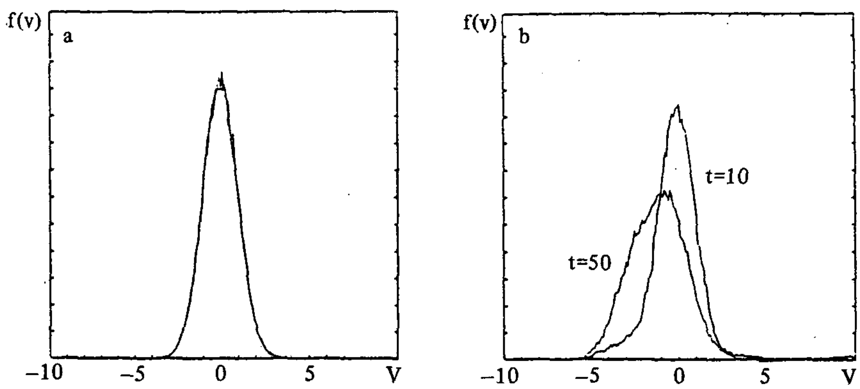

Fig. 3. The velocity distributions obtained from the electrostatic simulation at t=10 and t=50. (a) the perpendicular velocity distributions; (b) the parallel velocity distributions.

III. Discussions

As we can see from the simulation results, the return currents are enhanced and the ambient plasmas are heated when an electron beam penetrates into the plasma. We would like to discuss these aspects of the beam-plasma interaction in connection with the solar flare.

Usual models regarding to the two-ribbon flares involve the reconnection of magnetic fields in the corona region. The onset of the magnetic reconnection may be related with the impulsive phase of the solar flare, and the stream of fast particles then produce microwave bursts and impulsive hard X-ray bursts. When these fast particles hit the chromosphere, we may see famous two-ribbon flares. However, it is not always possible for the beam electrons to reach the chromosphere. As seen in the simulations, strong electric fields are generated locally and these electric fields prevent the beam from propagating through the corona. As also seen in the simulations, the ambient plasmas are heated, and the soft X-rays produced during the main phase of the flare may come from these thermal plasmas. In our simulation the heating is not so high. The temperature at t=50 is about twice of the initial temperature. However, it is obvious that the degree of heating should depend on the parameters chosen. It is known that electron beams with faster velocities propagate better(Okuda and Kan, 1987). When the beams with higher density are studied, it is found that the net number of beam electrons propagating into the ambient plasma does not increase as much. The effects of beam density or the beam velocity on the heating of ambient

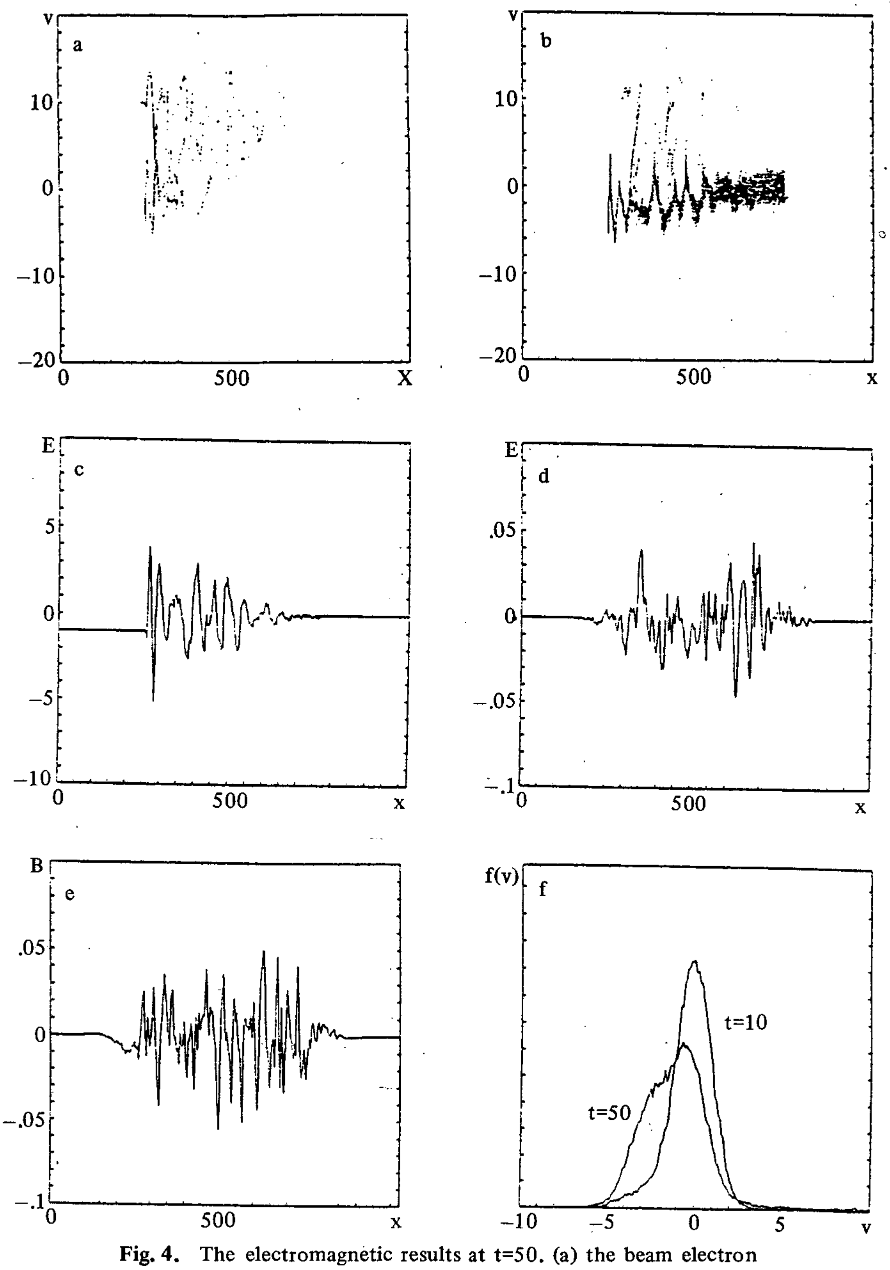

Fig. 4. The electromagnetic results at t=50. (a) the beam electron phase space; (b) the ambient electron phase space; (c) the longitudinal electric field profile; (d) the transverse electric field profile; (e) the transverse magnetic field profile; (f) the parallel velocity distribution compared to that of t=10.

plasmas are not fully explored yet. We are currently concentrating on those aspects, and will report the results in the future communications.

References

Grandel, B. 1982, *Artificial Particle Beams in Space Plasma Studies* (Plenum: New York).

Hoyng, P., Knight, J. W., and Spicer, D. S. 1978, *Solar Phys.,* **58**, 139.

Knight, J. W. and Sturrock, P. A. 1977, *Ap. J.,* **218**, 306.

Lin, A. T., Dawson, J. M., and Okuda, H. 1975, *Phys. Fluids,* **17**, 1995.

Obayashi, T., Kawashima, K., Kuriki, M., Nagatomo, K., Ninomiya, S., Sasaki, S., Yanagisawa, M., Kudo, I., Ejiri, M., Roberts, W. T., Chappell, C. R., Reasoner, P. L., Burch, J. L., Taylor, W. L., Banks, P. L., Williamson, P. R., and Garriott, O. K. 1984, *Science,* **225**, 195.

Okuda, H. and Kan, J. R. 1987, *Phys. Fluids,* **30**, 209.