One-Dimensional Simulation of an Ion Beam Generated by a Current-Free Double-Layer

Albert Meige, Rod W. Boswell, Christine Charles, Jean-Pierre Boeuf, Gerjan Hagelaar, and Miles M. Turner

***Abstract*—A current-free electric double-layer is created in a one-dimensional hybrid (particle ions and fluid electrons) plasma computer code by inserting a loss process along the axis of the simulation to mimic an expanding plasma. The image presented here shows a supersonic ion beam which has been accelerated downstream of the double-layer.**

***Index Terms*—Current-free double-layer, expanding plasma, hybrid simulation, ion acceleration, supersonic ion beam.**

AN ELECTRIC double-layer (DL) is a narrow local region within a plasma, not attached to a wall which can sustain a large potential difference. Particle acceleration by DLs has been studied in a variety of space plasmas and terrestrial plasmas [1]. It has been recently shown that a current-free DL can be generated in a plasma expansion in a magnetic field for pressures less than about 1 mtorr [2]. A supersonic ion beam has been measured downstream of this DL both for argon [3] and hydrogen [4] discharges and to date there has been no satisfactory theoretical analysis.

DLs have been studied by computer simulation since the early 1970s [5], [6], however, our simulation is the first attempt in simulating a current-free DL in an expanding plasma. The hybrid plasma simulation describes the ions as particles (as in a classical particle in cell simulation), whereas the electrons are fluid and supposed to be in Boltzmann equilibrium, so the electron density is written as

$$n_e(x,t) = n_0(t)\exp\frac{\phi(x,t)}{T_e} \quad (1)$$

where n_e is the electron density, n_0 the electron density reference, ϕ the potential and T_e the electron temperature (in eV). Considering (1), Poisson's equation becomes

$$\begin{aligned}\frac{\partial^2\phi(x,t)}{\partial x^2} &= -\frac{e}{\epsilon_0}[n_i(x,t) - n_e(x,t)] \\ &= -\frac{e}{\epsilon_0}\left[n_i(x,t) - n_0(t)\exp\frac{\phi(x,t)}{T_e}\right]. \quad (2)\end{aligned}$$

Manuscript received March 14, 2004.

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Digital Object Identifier 10.1109/TPS.2005.844956

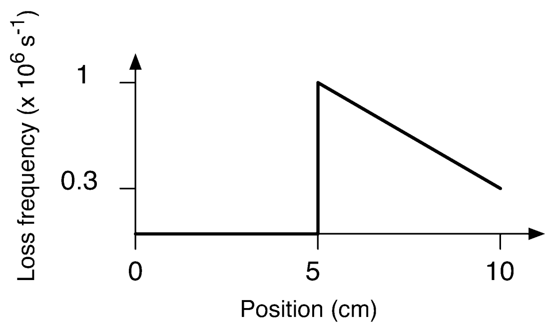

Fig. 1. Loss frequency on axis.

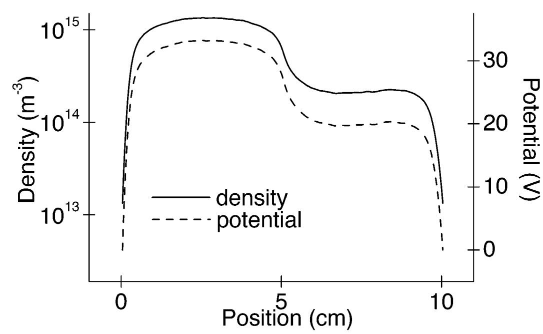

Fig. 2. Density and potential across the system. Drop of 14 V over a few Debye lengths is observed in the potential.

The potential is determined for each time step by solving (2). The reference density (n_0) introduced in (1) is determined by assuming the equality between the ion and electron fluxes on the walls. Ion-neutral collisions (charge exchange and elastic) are handled by a classical Monte Carlo collision process. Since the electrons are fluid, an ion creation process has been implemented to replace ionizing collisions: ions are uniformly loaded in the simulation from a 0.026 eV Maxwellian distribution, at a certain rate which is adjusted depending on the desired final density.

The expansion of the plasma on axis can be seen as a process which removes particles from the system at a given frequency which depends on their position. The loss frequency is a probability to remove a particle from a cell per unit of time. The loss process creates a sharp drop in the density over a narrow distance, and thus in the potential, which is interpreted as a DL. Fig. 1 shows the loss process profile which has been used: the particles are removed suddenly with a given frequency from the middle of the simulation (sudden expansion due to the magnetic field and/or the geometry of the plasma source/diffusion chamber system), and then having a decreasing frequency when moving in the direction of the right wall (equivalent to a constant volume and a less divergent magnetic field). Although DLs were

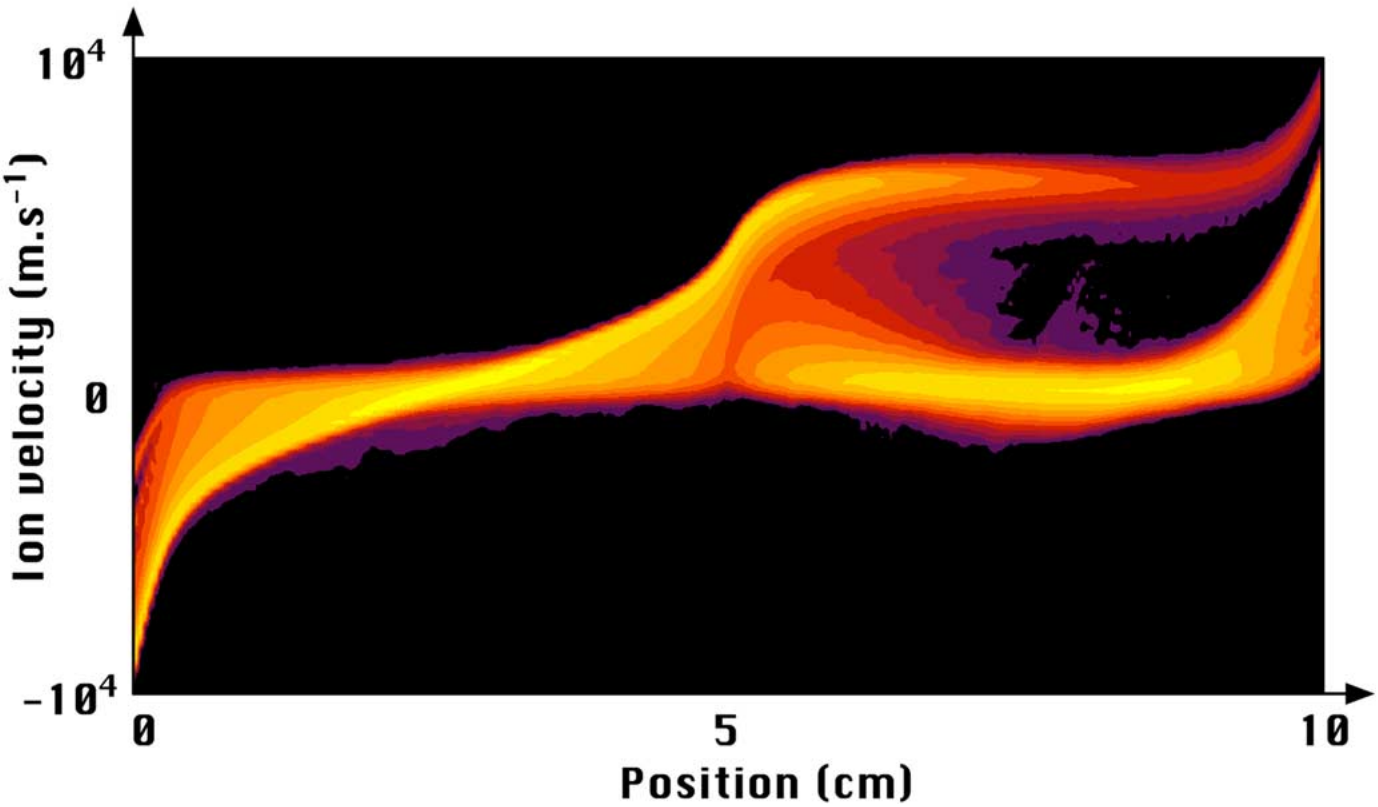

Fig. 3. The ion velocity distribution shows the supersonic ion beam generated by the current-free double-layer.

observed with smoother loss functions, the narrowest DLs were obtained with this sudden loss process (the loss profile and the loss frequency effects are discussed in [77]).

The results which are presented below have been obtained for argon at a pressure of 0.5 mtorr, with an electron density of $6.5 \times 10^{14}\ \mathrm{m}^{-3}$, a temperature of 7.2 eV, and a loss frequency of $10^{-6}\ \mathrm{s}^{-1}$. Such a low plasma density was chosen in order to compare this model with a particle-in-cell (PIC) simulation which has been developed in the same time. To be tractable, the PIC simulation had to represent a low density plasma. However, hybrid simulations were run at higher densities, closer from the experimental context $(10^{16}\ \mathrm{m}^{-3})$ and similar results were found. Fig. 2 shows the density and the corresponding potential across the system: a DL of around 14 V over a few Debye lengths is observed. Fig. 3 shows the ion velocity distribution in phase space with the Y axis representing the velocities of the ions and the X axis their positions. Increased brightness indicates increased density. High velocities on the left and the right boundaries are due to ions accelerated through the wall sheaths. Throughout the simulation length, a low-energy population of ions is observed which corresponds to the ions which are created in this region. Downstream of the DL, a high-energy population can be seen which corresponds to the ions accelerated while traversing the potential drop. The Bohm velocity or the sound speed in argon for an electron temperature of 7.2 eV is

$$c_s = \sqrt{\frac{eT_e}{m_i}} = 4170\ \mathrm{ms}^{-1}. \tag{3}$$

The average velocity of the ion beam is 8500 ms^{-1}, which is twice the sound speed. The density of this ion beam decreases away from the DL as a result of ion-neutral collisions (the mean free path for these conditions is about 15 cm) and of the loss process which removes fast particles as well as slow particles (the mean free path for an ion before being removed by the loss process is about 1 cm).

Although the model is quite simple, the gross behavior of the ions qualitatively agrees with the experiment carried out by the Space Plasma and Plasma Processing group [2]–[4].

ACKNOWLEDGMENT

The authors acknowledge Dr. D. Kwok for his useful discussions on Boltzmann electrons.

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