Electron Velocity Distribution Evolution During Collisionless Plasma Expansion Into Vacuum

M. Cercek¹, T. Gyergyek¹,², M. Tarana³

¹J. Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia
²Faculty of Electrical Engineering, University of Ljubljana, Tržaška 25, 1000 Ljubljana, Slovenia
³Faculty of Mathematics and Physics, Comenius University, Mlynská dolina F 2, Bratislava, Slovakia

1. Introduction

Considerable attention has been given in the past to the problem of plasma expansion into vacuum. In theoretical [1 - 4] and experimental [5] investigations it was observed that ions are accelerated to supersonic velocities and that the process depends significantly on the form of the electron distribution function in the plasma. In this contribution we present results of a computer simulation experiment on plasma expansion and especially on the investigation of electron velocity distribution development during early stages of the process.

2. Simulation

In the simulations we use Berkeley XPDP1 computer code [6] which allows us to simulate the plasma expansion from a planar plasma source into an initially empty system. The system is 1m to several meters long. The plasma in the source consists of warm hydrogen ions or ions with a smaller simulation mass and electrons with a Maxwellian distribution function. In accordance with many experiments and theoretical works we add to the cool electron population a hot group with a full-Maxwellian or truncated Maxwellian velocity distribution. Equal fluxes of positive and negative particles are injected from the inexhaustible source into the system. The potential of the source is defined to be zero and all particles which are reflected to the source are refluxed with the characteristics of the source plasma. At the opposite side a floating collector bounds the system. The expansion process is collision-less and there is no magnetic field in the system. The evolution of various plasma parameters is investigated through built-in diagnostics.
3. Results and conclusions

Special attention was given to early times of expansion in which ions gain a considerable amount of their energy and in which transient electron distributions are formed in the expansion region. In Fig. 1 the evolution of the hot electron distribution in v-x phase space is shown. Half-Maxwellian electrons streaming from the source form a beam with increasing streaming velocity along the axis of the system. A sharp cut-off edge is formed at the low velocity side of the distribution. Since most of the electrons expand in front of ions, a negative potential profile is formed in which the expanding electrons are decelerated and also reflected. In this way a backstreaming population of electrons is formed with a sharp cut-off edge at high negative velocities. At $\omega_p t = 240$ the fastest electrons reach the collector. At this moment the system is filled up to $x/L = 0.3$ with hot electrons with full-Maxwellian decelerated velocity distribution and truncated on the negative velocity side. From $x/L = 0.03$ on the electron beam is flowing toward the collector. Due to deceleration process the $V_c = v_{c/vehth} = 0$ point moves toward the collector. At $\omega_p t = 722$ the system is in this way filled with full-Maxwellian decelerated and truncated distribution function. The maximum negative velocity value spans from $V_c = 0$ at the collector to $V_c \approx 4$ at the source. Later, at $\omega_p t = 900 \sim 1200$, the collector potential reaches maximum negative value and almost all electrons are repelled from the collector. A full-Maxwellian hot electron distribution develops in the system at $\omega_p t \sim 1900$ and the electron conditions are from this time on similar to those assumed in theoretical works. It should be noticed that the expansion is not isothermal. The thermal velocity is gradually decreasing in the system, as already described by Denavit [2]. In order to determine the electron drift velocity a more precise analysis is required. In Fig 3 a) the cool electron v-x phase space is shown for two expansion times $\omega_p t = 56$ and 240. The velocity distribution is developing similarly as the hot electron distribution but the full-Maxwellian state is formed much earlier. The evolution of the hot electron phase space during the expansion process with truncated full-Maxwellian source distribution function is presented in Fig.3. In this case an electron beam with a very narrow velocity spread is formed. At the moment when the beam hits the collector ($\omega_p t = 378$) three different regions can be identified in the system, regarding the hot electron population. Close to the source, $0 < x/L < 0.08$, electrons with a truncated full-Maxwellian velocity distribution and an almost detached back streaming electron beam can be observed. The temperature of the thermal distribution is decreasing along the axis of the system. In the middle region, $0.08 < x/L < 0.4$, only a backstreaming electron beam is identified. For $x/L > 0.4$ only an electron
beam is directed toward the collector. As in the former case the stagnation point moves to the collector and at $\omega_{b} = 964$ all electrons are reflected from the collector. The backstreaming accelerated electron beam is almost monoenergetic. Near the source it is additionally strongly accelerated so that electrons arrive at the source with much higher energy than the truncation energy given by $m v_{tr}^2/2$. Later all the beam electrons are absorbed in the source and a cloud of thermal hot electrons fills partially the system.

**Fig. 1.** Evolution of the hot electron phase space in early times of the expansion. The source distribution function is a full-Maxwellian with $T_{eh} = 30$ eV. The electron velocity is normalized with respect to the source hot electron thermal velocity $v_{ehth}$.

**Fig. 2.** Evolution of the cool electron phase space in early times of the expansion in case of a) full Maxwellian and, b) truncated hot electron distribution. The source distribution function is a full-Maxwellian with $T_e = 2$ eV. The electron velocity is normalized with respect to the source cool electron thermal velocity $v_{ech}$.
It slowly expands toward the collector, the value of the drift velocity can be determined by a careful analysis. The cool electron population develops into a thermal decelerated Maxwellian distribution much sooner, as can be observed on plot b) in Fig.2. In both cases they are well confined by an internal double layer potential structure. The observed evolution processes are incompletely described in earlier work and are unsatisfactorily taken into account in the investigations of the ion acceleration process. The boundary conditions assumed in theoretical investigations are met at much later times after the beginning of the expansion process.

4. References