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Excitation of ionization wave induced by an electron beam
電子ビームによって駆動された電離波の励起過程

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The interaction of an intense electron beam with a neutral background material is studied. The neutral material is ionized by the electrostatic field generated by the intense electron beam and electron collisional ionization. The structure of ionization wave is analyzed using a simple one-dimensional model.

1. Introduction

High current electron beam can be efficiently generated by intense short laser pulses. One particular application is energetic ion sources using thin foils [1,2]. The understanding of the dynamics of the electron beam in matter is crucial. The propagation of the electron beam through gases or material has been studied for a long time [3,4]. However, relatively few studies have been reported on ionization dynamics in neutral material [5–10].

The high current density of electron beam propagated through a neutral material can generate a large electrostatic field due to the charge nonneutrality. The large electrostatic field can directly ionize the neutral material. It's called field ionization. However, when a plasma is created once by the electrostatic field ionization, the electrostatic field is strongly screened by the charge separation. In addition, the material is also ionized by the electron collision with atoms.

In this paper, we analyze the structure of ionization wave using a simple one-dimensional model.

2. Basic model

In order to describe the ionization dynamics excited by high current electron beam we assumed that the background electron motion is described by electron fluid equations and the atom only changes the charge state. Then the evolution of the densities of background electron and ion charge state z , n_e and n_z, are described by

$$\frac{\partial n_z}{\partial t} = I^{z-1} n_{z-1} + R^{z+1} n_{z+1} - (I^z - R^z)\, n_z, \quad (1)$$

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{v}) = \sum_{z=0}^{Z-1} I^z n_z - \sum_{z=1}^{Z} R^z n_z, \quad (2)$$

where I^z and R^z are ionization and recombination rate from the charge state z, $z = 0$ and Z show the neutral and full ionized atom, $n_N = \sum_{z=0}^{Z} n_z(t)$ is the initial atom density, and $\mathbf{v}$ is the electron fluid velocity. The ionization rate I^z consists of three processes

$$I^z = \nu^z_{FI}(|\mathbf{E}|) + \nu^z_C + \nu^z_B$$

where $\nu^z_{FI}(|\mathbf{E}|)$ is the electric field ionization rate [11], ν^z_B, and ν^z_C are the collisional ionization rate by the high energy electron beam n_b and low energy electron n_e. ν_B and ν_C depend on the electron energy distribution functions. The electrostatic field E assumed to be given by the Poisson equation:

$$\nabla \cdot \mathbf{E} = -4\pi e \left(n_e + n_b - \sum_{z=1}^{Z} n_z \right) \quad (3)$$

where n_b is the electron beam density. The ionization dynamics could be determined by solving the equations (1) - (3), the evolution of the electron beam density $n_b(\mathbf{r}, \mathbf{v}_b, t)$ and the electron fluid velocity $\mathbf{v}$.

3. Results

We consider the one-dimensional structure of ionization wave in the initial electron beam propagation

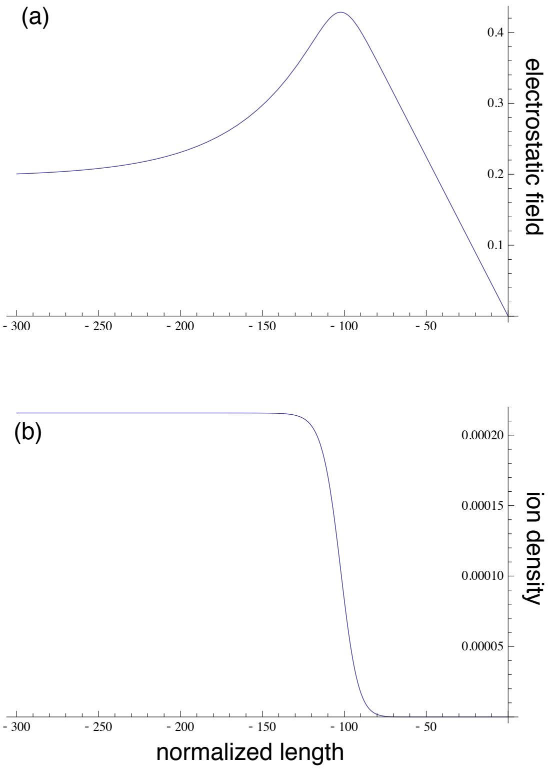

Fig. 1 The profiles of the electrostatic field (a) and ion density (b). The front of the electron beam is origin and propagates to the right. The ion density are normalized by the neutral atom density n_N and the normalized length and electrostatic field is 5×10^8 V/cm and $2.4 \times 10^{-2} \mu$m, respectively.

direction. For simplicity, we assume as follows: the atom has only two charge state of neutral and single ionized atom, the electron fluid velocity $|\mathbf{v}| = -eE/m_e \nu_e$, where e and m_e are the electron charge and mass and ν_e is the electron collision frequency, the electron beam propagates the initial velocity v_b and the energy and density profile of electron beam does not change.

Assuming that the profile of the ionization structure is stationary in the reference frame of the electron beam [5]. Figure 1 shows typical profiles of the electrostatic field and the ion density in the frame. The initial atom density $n_N = 5 \times 10^{22}$ cm^{-3}, $\nu_e/\omega_N = 10^{-2}$ (ω_N is the plasma frequency of n_N), and the first ionization energy of the atom is 13.6 eV. The electron beam density and energy are $n_b/n_N = 10^{-5}$ and $v_b/c = 0.8$ (340 keV). The effects of the collisional ionization are neglected. Figure 2 shows the maximum ion density

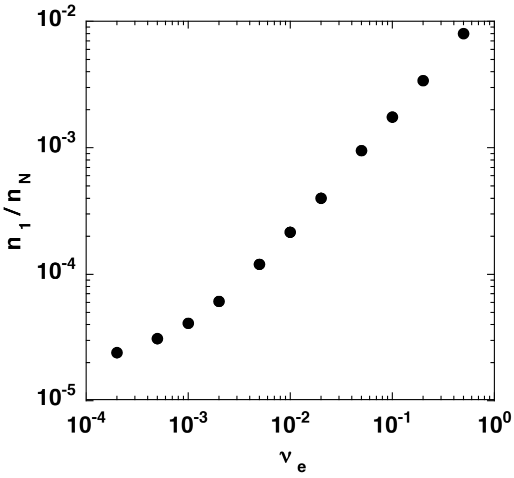

Fig. 2 the maximum ion density as a function of the electron collision frequency ν_e.

as a function of the electron collision frequency. The maximum ion density is strongly depend on the electron collision frequency ν_e. On the other hand, the maximum electrostatic field and width of the ionization front are nearly independent of ν_e. The width ℓ of the ionization front is strongly depend on electron beam density, ℓ ~0.4, 1, and 9 μm for n_b/n_N = 10^{-4}, 10^{-5}, and 10^{-6}, respectively.

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