Role of Field and Electron Impact Ionization in Ionization Front Generated by an Intense Electron Beam

Susumu KATO, Yasuaki KISHIMOTO[1)], Eiichi TAKAHASHI and Akira SASAKI[2)]

National Institute of Advanced Industrial Science and Technology (AIST), Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

[1)]*Graduate School of Energy Science, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan*

[2)]*Japan Atomic Energy Agency (JAEA), 8-1-7 Umemidai, Kizu, Kyoto 619-0215, Japan*

(Received 6 February 2012 / Accepted 5 March 2012)

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 impact ionization. The structure of the ionization front is analyzed using a one-dimensional model. The structure is determined primarily by electron impact ionization of the ionized background electrons. In addition, the field ionization contributes to the generation of the ionization front by increasing the density of the electron beam.

Keywords: ionization front, intense electron beam, field ionization, electron impact ionization

DOI: 10.1585/pfr.7.1204038

An intense electron beam can be efficiently generated by intense short laser pulses. One particular application for this is energetic ion sources using thin foils [1, 2]. In this regard, the understanding of the dynamics of the electron beam is crucial. Propagation of the electron beam through fully ionized plasmas has been studied for several decades [3]. However, relatively few studies investigating the ionization dynamics of neutral materials have been reported [4–8].

A high current density electron beam propagated through a neutral material can generate a large electrostatic field owing to the effect of charge nonneutrality. The large electrostatic field can directly ionize the neutral material, a process referred to as field ionization [9]. Furthermore, the field enhances impact ionization by the background electrons. However, once a plasma is created, it strongly screens the electrostatic field. The ionization processes and electrostatic field screening significantly affect the properties of the plasma.

In this paper, the structure of the ionization front in the direction of the initial electron beam propagation is studied using a one-dimensional stationary model, and the role of the ionization processes is clarified. We assumed that the electron motion is separated by the components of the ionized background and input high-energy beam electrons. The density of the background electrons is usually much higher than that of the high-energy electron beam. We assumed that the background electron motion is described by electron fluid equations and that the atom only changes the charge states. The density profile of an electron beam does not change, and its energy ϵ_b is constant; that is, the beam only propagates under the same initial density n_b and velocity u_b. Thus, the evolution of the density of a background electron n_e and that of an ion n_i are described by

$$\frac{\partial n_i}{\partial t} = \nu_I (N - n_i), \tag{1}$$

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \boldsymbol{u}_d) = \nu_I (N - n_i), \tag{2}$$

where N and ν_I are density and ionization rate of the atom, respectively, and $\boldsymbol{u}_d$ is the electron fluid velocity, which is determined by $\boldsymbol{u}_d = -e\boldsymbol{E}/m_e\nu_e$, where $\boldsymbol{E}$ is the electrostatic field, e and m_e are the electron charge and mass, respectively, and ν_e is the electron collision frequency of a background electron. The electron collision frequency and ionization rate are dependent on the type of material and the density and strength of the electric field.

In this model, the ionization rate ν_I is assumed to consist of contributions from the electric field and electron impact ionization,

$$\nu_I = \nu_F(E) + R n_e + \sigma_I(\epsilon_b) u_b n_b, \tag{3}$$

where $\nu_F(E)$ and $\sigma_I(\epsilon_b)$ are the electric field ionization rate and electron impact ionization cross section of the atom, respectively; R is the electron impact ionization rate coefficient from the low energy background electron. The coefficient depends on the energy distribution function of the background electron. These coefficients are determined as follows. It is assumed that the electric field ionization rate can be determined using the Landau model [9]. For a background electron, the electron impact ionization rate coefficient R and electron collision frequency ν_e in the electric field are calculated from collision

author's e-mail: s.kato@aist.go.jp

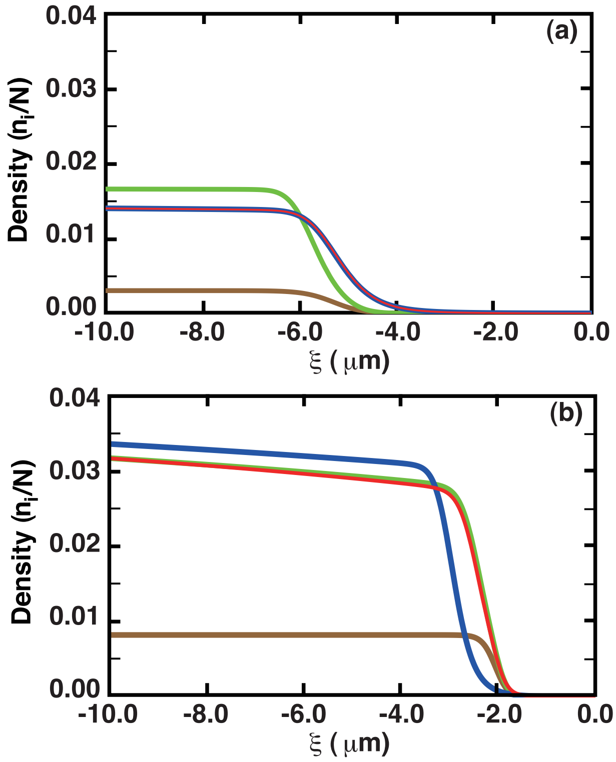

Fig. 1 Ion density profiles for (a) $n_\mathrm{b}/N = 1 \times 10^{-5}$ and (b) $n_\mathrm{b}/N = 3 \times 10^{-5}$. The electron beam in the reference frame ξ is located within the region $\xi \leq 0$. The red line includes all three ionization processes in Eq. (3). The blue line includes the electron impact ionization by the background and beam electrons; that is, it does not include the field ionization. The green line includes the field ionization and electron impact ionization by the background electrons. The brown line includes only the field ionization.

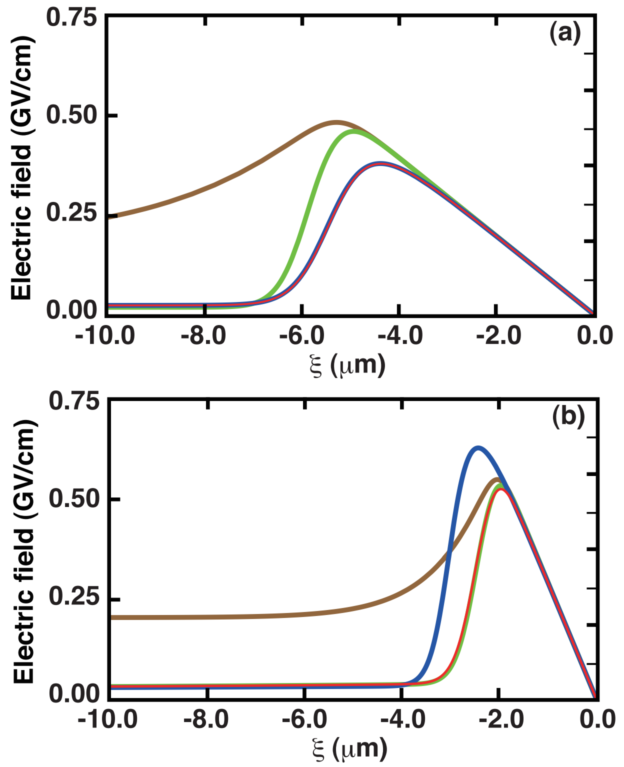

Fig. 2 Electrostatic field profiles for (a) $n_\mathrm{b}/N = 1 \times 10^{-5}$ and (b) $n_\mathrm{b}/N = 3 \times 10^{-5}$, respectively. The colors of the lines represent the same features outlined in Fig. 1.

cross-section data by solving the electron Boltzmann equation [10]. This model is a good approximation in weakly ionized and highly collisional plasma. The ionization cross section of a high-energy electron uses the fitting formula ($\sigma_\mathrm{I}(\epsilon) \sim a(\ln \epsilon + b)/\epsilon$), where a and b depend on the atom.

The electrostatic field E is given by the Poisson equation:

$$\frac{\partial E}{\partial x} = -4\pi e \left(n_\mathrm{b} + n_\mathrm{e} - n_\mathrm{i}\right), \tag{4}$$

where n_b is the electron beam density.

Assuming that the profile of the ionization structure is stationary in the reference frame of the electron beam ($\xi = x - u_\mathrm{b} t$) [5], the following equations are derived from Eqs. (1-3):

$$\frac{\partial n_\mathrm{i}(\xi)}{\partial \xi} = -\frac{\nu_\mathrm{I}(\xi)}{u_\mathrm{b}} \left(N - n_\mathrm{i}(\xi)\right), \tag{5}$$

$$\frac{\partial E(\xi)}{\partial \xi} = -4\pi e \left[n_\mathrm{b}(\xi) - \frac{n_\mathrm{i}(\xi) e E(\xi)/m}{\nu_\mathrm{e}(\xi) u_\mathrm{b} + e E(\xi)/m} \right], \tag{6}$$

and $n_\mathrm{b}(\xi) = n_\mathrm{b} H(-\xi)$, where $H(x)$ is the Heaviside step function $H(x) = 0$ for $x < 0$ and $H(x) = 1$ for $x \geq 0$.

Figures 1 and 2 show typical profiles of the ion density and electrostatic field, respectively, in the frame. We use a dense neon gas and the initial atom density $N = 5 \times 10^{22}\,\mathrm{cm}^{-3}$. The electron beam densities are $n_\mathrm{b}/N = 1 \times 10^{-5}$ (Fig. 1 (a)) and $n_\mathrm{b}/N = 3 \times 10^{-5}$ (Fig. 1 (b)) and the energy ϵ_b is 340 keV ($u_\mathrm{b}/c = 0.8$). The energy flux is of the order of $10^{15}\,\mathrm{W/cm^2}$. In this case, the electron collision frequency ν_e is of the order of $5 \times 10^{15}\ \mathrm{s}^{-1}$ and the ionization time scale τ is a few femtoseconds in this parameter range. The model for the background electron [10] is valid because $\tau \nu_\mathrm{e} \gtrsim 10$. To clarify the contribution of each ionization process, we show four lines of different colors in the figures. The red line includes all three ionization processes in Eq. (3). The details explaining the processes depicted by each line color are shown in the figure caption. For $n_\mathrm{b}/N = 1 \times 10^{-5}$, the blue line overlaps with the red one; that is, the ionization front structure is determined by the electron impact ionization. On the other hand, for $n_\mathrm{b}/N = 3 \times 10^{-5}$, the green line overlaps with the red one; that is, the electron impact ionization following the electric field ionization determines the structure. The density that includes all three ionization processes is approximately three times larger than the one including only the field ionization for the electron beam densities shown in both Figs. 1 (a) and (b). Also, the electric field amplitude is approximately five times smaller than the latter one. The results show that the contribution of electron impact ionization is important to the development of the ionization front.

In this paper, the role of the low energy background electrons ionized by the electrostatic field is clarified using a simple ionization model. Since the properties of the low energy background electrons are strongly dependent on the material, a more detailed investigation of each material is needed. The evaluation of the role of the ionization processes using this model may provide a useful guide for the construction of an integrated simulation code.

This work was supported by JSPS KAKENHI (22540512).

[1] S.C. Wilks, A.B. Langdon, T.E. Cowan, M. Roth, M. Singh, S. Hatchett, M.H. Key, D. Pennington, A. MacKinnon and R.A. Snavely, Phys. Plasmas **8**, 542 (2001).
[2] E. Takahashi, S. Kato, Y. Matsumoto and I. Okuda, Plasma Fusion Res. **3**, 024 (2008).
[3] S. Humphries, Jr., *Charged Particle Beams*, (Wiley-Interscience, 1990).
[4] S. Strasburg, D.D. Hinshelwood, J.W. Schumer, D. Mosher, P.F. Ottinger, R.F. Fernsler and S.P. Slinker, Phys. Plasmas **10**, 3758 (2003).
[5] V.T. Tikhonchuk, Phys. Plasmas **9**, 1416 (2002).
[6] A.J. Kemp, R.E.W. Pfund and J. Meyer ter Vehn, Phys. Plasmas **11**, 5648 (2004).
[7] T. Masaki and Y. Kishimoto, J. Plasma Fusion Res. **81**, 643 (2005).
[8] S.I. Krasheninnikov, A.V. Kim, B.K. Frolov and R. Stephens, Phys. Plasmas **12**, 073105 (2005).
[9] L.D. Landau and E.M. Lifshitz, *Quantum Mechanics, 3rd ed.* (Pergamon, London, 1978).
[10] G.J.M. Hagelaar and L.C. Pitchford, Plasma Sources Sci. Technol. **14**, 722 (2005).