Target ionization by a high current relativistic mono-energetic electron beam

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Introduction

The interaction of ultra intense laser pulses ($I > 10^{18}\,\mathrm{W/cm^2}$) with a solid matter or a gas is a new way of relativistic electron beam production. Many applications can be found such as x-ray generation, ion beam production, and energy transport through a solid matter. Thus, the high current electron beam propagation through a solid target has to be understood. In the case of metals, it is known that the free electron return current neutralizes the fast electron beam and prevents its destruction by the self–consistent electric and magnetic fields. The insulator case is more difficult to describe since the ionization of the material by the fast beam is required to create a return electron current.

We have developed a one-dimensional model based on the previous publications [1, 2] that describes the propagation of a mono–energetic fast electron beam in a dielectric target. The target ionization provides the charge and current neutralization and enables the beam propagation. The ionization process consists of two stages: (i) the self–consistent electric field ionization of atoms in the beam front and (ii) the collisional ionization of atoms by the return current in the beam body. The ionization in the beam front defines the propagation velocity. The charge neutralization quickly suppresses the electric field behind the beam front and the plasma heating by the return current supports the collisional ionization in the beam body. This collisional ionization constitutes the main mechanism of the energy loss for high beam densities.

The beam propagation model

The model assumes weak energy losses during the beam propagation. The process is stationary, that is, all equations can be written in the front reference which evolves at a constant velocity v_f. The fast electrons are described by a collisionless Vlasov kinetic equation. For a quasi-stationary propagation of a mono-energetic electron beam, it reduces to the current density conservation, $j'_b = -en'_b v'_b = -en'_{b0} v'_{b0}$, and the energy conservation, $\varepsilon'_{b0} = \varepsilon'_b + e\varphi'$, where prime denotes the front reference frame. It is supposed that the fast electrons population has a much higher energy than the cold electron population n'_e of the target and they do not mix up. The electric potential φ' follows from the Poisson equation:

$$-\varepsilon_0 \partial^2_{x'} \varphi' = e\,(n'_i - n'_e - n'_b) - \partial_{x'} P'_x \,. \qquad (1)$$

The charge densities are given by the ion n_i' and the cold electron density conservation equations in the stationary front reference frame:

$$-v_f \partial_{x'} n_e' + \partial_{x'}(n_e' v_e') = -v_f \partial_{x'} n_i' = \nu_E (n_a - n_i) + \nu_{ea}(n_a - n_i) - \nu_{rec} n_i \ . \qquad (2)$$

Three source terms appear in these equations. They are presented by the electric field ionization rate, ν_E, the collisional ionization rate between a cold electron and an atom, ν_{ea} and the three body recombination rate, ν_{rec} (electron-electron-atom). The cold electron inertia is neglected, thus their current is described by the Ohm's law in the laboratory reference frame with a constant elastic collision rate: $j_e = e^2 n_e E_x / m\nu_e$, where $E_x = E_x' = -\partial_{x'}\varphi'$. The ion motion is neglected. The cold electron temperature is described by the energy equation in the laboratory reference frame.

$$\frac{3}{2}\partial_t (n_e T_e) = j_e E_x - \alpha J_a \partial_t n_i \ . \qquad (3)$$

The heating is mainly caused by the elastic collisions between the return cold electrons and the atoms/ions: $j_e \cdot E$. We neglect the direct heating by the fast-cold electron collisions. The energy lost by the collisional ionization and the electric field ionization is taken into account in the electron energy equation (3) (with the second term in the right hand side) and in the Poisson equation (1) (with the polarization term), respectively. The study of beam transport is separated in two parts: (i) the beam head where the fast electrons propagate through a neutral material n_a. (ii) the beam body where fast electrons propagate though a plasma.

The beam head: Electric field ionization

As the relativistic electron density is relatively low ($n_b \sim 0.001 n_a$), the direct collisional ionization is not sufficient to ionize the target and to provide a return electron current. The ionization in the beam head is supported by the self–consistent electric field. Indeed, simple estimates show that the charge accumulation is sufficient to provide an electric field comparable to the atomic's one ($E_{max} \sim 10^{10}$ V/m). Thus, the fast electrons are decelerated by the self–consistent electric field and their energy is converted into the atom ionization and the backward acceleration of the new born electrons. Due to the charge separation between these cold electrons and the ions, the electric field drops down, the beam is neutralized and the ionization associated with the electric field, stops. The ionization front velocity v_f, deduced from the ionization process, is lower than the initial fast electron velocity v_b. It increases with the beam current density and the electron energy, see Fig. 1 (right). Other characteristics have been also found: such as the ionization level, the electric field maximum strength, and the thickness of the beam front, where the electric charge is accumulated. The dependence of the normalized electric field maximum

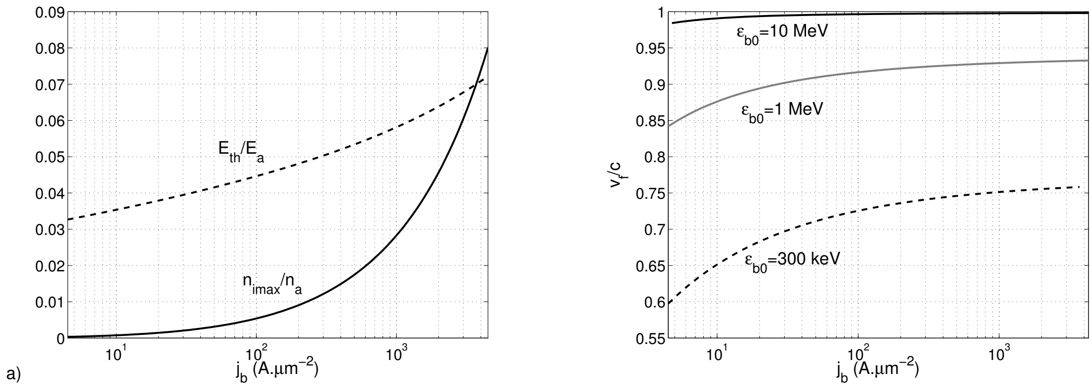

Figure 1: On the left: Dependence of the electric field maximum (dashed line) and ion density (solid line) on the beam current at the end of the electric field ionization. The beam energy is 1 MeV. On the right: Dependence of the ionization front velocity on the electron beam current density j_b and on the electron energy.

E_{th}/E_a and the ionization level $n_{i\max}/n_a$ on the beam current density are presented in Fig. 1 (left). The ionization grows with the beam density. However, the field ionization is incomplete. The electric field maximum is logarithmically increasing with the beam current density due to the sharp dependence of the tunnel ionization rate on the electric field. The front velocity, presented in Fig. 1 (right), also increases with the beam density and energy.

The beam body: Collisional ionization

The electric field ionization is localized in a narrow region in the beam head. Farther, the ionization continues due to the cold electron-atom collisions. It is controlled by a competition between the Ohmic heating by the cold electron current and the three body recombination process. The latter is negligible if the initial cold electron density provided by the electric field ionization in the beam head is weak. Thus, the collisional ionization proceeds steadily, while the electron temperature is stabilized below the ionization potential. The cold electron temperature and the ion density profiles are shown in Fig. 2. The non–monotonic behavior of the temperature is a characteristic feature of the relaxation process. The decrease of T_e is caused by the energy loss into the collisional ionization. Then, since the electron density is increasing, the recombination comes into play and reduces the energy loss. Consequently, the Ohmic heating rises the temperature, the thermodynamic equilibrium is reached.

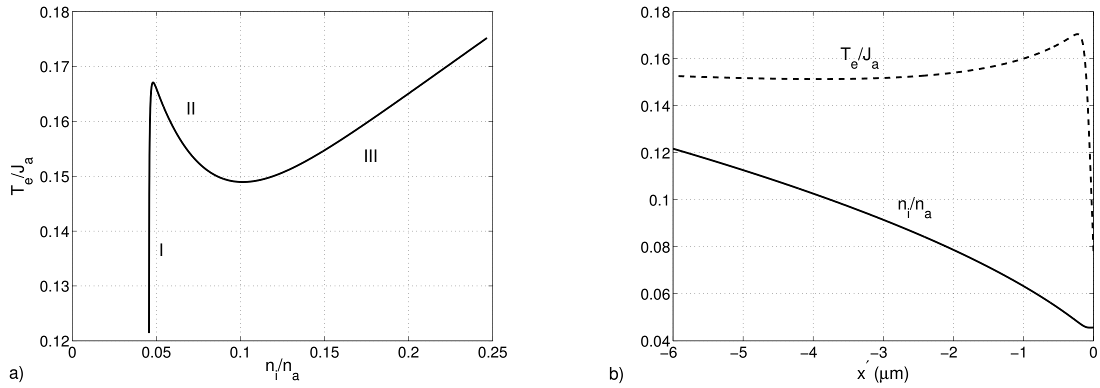

Figure 2: One the left: Dependence of the electron temperature on the plasma density for an electron beam with a current 4.5 kA/μm^2 and an electron energy of 1 MeV. On the right: Ion density $n_i(x')$ normalized to the atom density n_a (solid line) and the plasma electron temperature $T_e(x')$ normalized to the ionization potential J_a (dashed line).

Conclusion

The propagation of a fast mono–energetic electron beam through a dielectric target has been investigated in a one-dimensional model. Compared to previous publications [2, 3], our analysis describes more accurately the ionization processes all along the beam length and shows explicitly the limits of validity of the ionization model and their dependence on the target parameters. The incomplete ionization level by the self–consistent electric field restricts the beam current to $j_b \ll 30\,\mathrm{kA}/\mu\mathrm{m}^2$. Such current magnitudes are generated in laser–matter interactions with intensities of $I \sim 10^{19}\,\mathrm{W/cm}^2$. Moreover, the beam propagation cannot be described with a quasi–stationary collisional ionization model if $\tau_b j_b < 10\,\mathrm{pC}/\mu\mathrm{m}^2$, that is, for low beam densities or short beam pulse durations. From the point of view of the energy balance, the fast electron energy losses are divided between the electric field ionization, the Ohmic heating and the collisional ionization. For high current densities, the beam energy loss mainly occurs in the beam body and is about $2\,\mathrm{keV}/\mu\mathrm{m}$. For low current densities ($j_b \sim 1\,\mathrm{A}/\mu\mathrm{m}^2$), the charge accumulation distance in the beam head attains several μm. This leads to a significant increase of energy losses caused by the electric field ionization, $\Delta\varepsilon_b \sim 0.1\varepsilon_b$, and a shorter beam stopping length.

References

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