High-current fast electron beam propagation in a gas

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Abstract. Propagation of high-current relativistic electron beam in a gas has been studied experimentally in [1] in connection with the fast ignition concept of the inertial confinement fusion. In this paper, our numerical code based on the Particle-in-Cell method is utilized to simulate the electron beam propagation under the conditions similar to those of the experiment [1]. Our results demonstrate generation of a strong electrostatic field at the surface of the target from which the beam enters into the gas. The strength of this field depends in particular on the density of the gas and the field may reflect a significant part of the beam back into the target and decelerate the propagating beam. Ionization of the gas is provided by the electric field created by a dense bunch of runaway electrons and the ionization front may propagate with the velocity close to the velocity of light until the runaway bunch is depleted.

1. Introduction

High-current fast electron beam is supposed to ignite the precompressed fuel in the fast ignition concept of the inertial confinement fusion. Efficient propagation of such electron beam requires charge and current neutralization provided by free electrons. When free electron density is much higher than the density of the beam (solid conductor) neutralization is relatively easy. Dielectric targets do not contain free charge carriers initially and thus ionization must take place before the neutralization. This results in enhanced beam energy dissipation and slower, density dependent, propagation of the beam [2]. Gas is a very low density dielectric material and as the density of electrons produced by ionization may be comparable to the density of the beam, neutralization is more difficult. High-current relativistic electron beam has to propagate in the material of comparable density in the fast ignition scheme before reaching the compressed core. Neglecting collisional effects, the situation is similar to that in recent experiments [1] concerned with relativistic electron beam propagation in a gas.

Theoretical model of high-current relativistic electron beam propagation in a gas has been developed in [3]. However, this model is stationary and therefore, it can describe neither energy losses of the beam nor the temporal evolution of the beam and the return current distributions. We have developed a kinetic simulation model based on the Particle-in-Cell method to study high-current electron beam propagation in solid density dielectric target in [2]. Our model includes the electric field and the collisional ionization processes as well as the elastic collisions of electrons. This model is adopted for simulations of electron beam propagation in a gas and applied to the situation similar to that in experiment [1].

2. Simulation model

One-dimensional relativistic electrostatic and collisionless PIC code [2] is used to simulate the fast electron beam propagation. The electron beam is initiated in the foil composed of dense
(10^{23} \text{ cm}^{-3}) and relatively cold (100 \text{ eV}) plasma and it propagates into the gas of the density 10^{19} \text{ cm}^{-3} composed of neutral hydrogen, helium, or argon atoms. The beam, the return current and the free electrons in the source layer are treated as separate species with different numerical weights. The computational cell size is 5 nm. Electric field ionization is simulated using Monte Carlo approach with the ADK tunneling ionization rate \cite{4}. Multiple ionization of higher Z atoms is taken into account. Ions are treated as immobile ionization centers.

The simulated electron beam is 30 \mu m long, it has homogeneous density profile and uniform velocity distribution ranging between \( v_{\text{min}} \) and \( v_{\text{max}} \). In the case of propagation in the hydrogen, the beam density, \( n_b \), is 10^{19} \text{ cm}^{-3} and \( v_{\text{min}} \) and \( v_{\text{max}} \) are 0.9c and 0.98c respectively, where \( c \) is the velocity of light. If the gas is composed of helium or argon, the parameters are chosen to roughly correspond to the experiment \cite{1}, i.e. \( n_b = 10^{20} \text{ cm}^{-3} \), \( v_{\text{min}} = 0.95c \) and \( v_{\text{max}} = 0.995c \).

3. Results and discussions

In our simulations, the beam propagates from the dense cold plasma (foil) into the initially neutral gas. A strong charge-separation electric field is formed at the head of the beam in the gas. This field ionizes the gas and accelerates the return current. However, the return current is not able to compensate the space-charge separation due to the propagating electron beam unless the densities of electrons in both counter streaming currents are at least comparable. If the density of the return current is lower, a strong electrostatic field is formed at the surface of the foil, similarly like in the TNSA process \cite{5}. The field is self-consistently adjusted depending on the density of the beam and the return current and it enables propagation of only a part of the electron beam. The rest of the electron beam is reflected back and it enhances the return current. This situation is demonstrated in Fig. 1. The peak in the beam density profile located at \( x = 1.2 \mu m \) corresponds to the point where the slowest beam electrons are stopped and reflected back. The density of the beam on the left of this point \( (x < 1 \mu m) \) is about 1.8 times the initial density of the beam which indicates that a significant part of the beam is reflected.

In our simulations, the electron beam current is constant along the beam and the electrostatic field at the surface of the foil does not change significantly after a short initial period during which the field is being created. This implies that the current density of the total electron flux across the foil surface is approximately zero. We assume that the beam electrons, which are reflected by the electrostatic field, return to the foil with their initial but oppositely directed velocity. This assumption is justified by the phase space distribution plotted in Fig. 2 and it allows us to express the current density at the surface of the foil in the following form

\[
\int_{v_{\text{min}}}^{v_{\text{max}}} vf(v) \, dv - \int_{v_{\text{min}}}^{v_{\text{br}}} vf(v) \, dv - n_v v_r = 0 ,
\]

where \( v_{\text{br}} \) is the velocity of the fastest backreflected beam electrons. The velocity of the return current in Eq. 1 should be in the range \( (v_{\text{br}}, v_{\text{max}}) \). According to the parameters of our simulations, this range is narrow and thus, we may further assume \( v_r = (v_{\text{max}} + v_{\text{br}})/2 \) without significant loss of accuracy. Inserting the velocity distribution used in our simulations, \( f(v) = n_b/(v_{\text{max}} - v_{\text{min}}) \), into Eq. 1, we obtain

\[
v_{\text{br}} = v_{\text{max}} - \frac{n_v}{n_b} (v_{\text{max}} - v_{\text{min}}) .
\]

The beam electrons with velocity \( v < v_{\text{br}} \) are reflected back and the density of the beam which may propagate further is \( n_v \). The average electrostatic field in the sheath at the surface of the foil, \( E \), and the thickness of this sheath, \( \lambda \), can be expressed as

\[
E = \sqrt{\frac{n_b T_{br}}{\varepsilon_0}} , \quad \lambda = \sqrt{\frac{\varepsilon_0 T_{br}}{\varepsilon^2 n_b}} , \quad \text{where} \quad T_{br} = mc^2 \left( (1 - v_{\text{br}}^2/c^2)^{-1/2} - 1 \right) .
\]
The beam electrons with energy higher than $T_{br}$ may propagate further into the gas but they also lose a substantial part of their kinetic energy.

The return current density, $n_r$, in the expressions above is not exactly known. On the first point of view, it can be estimated as $n_r \approx Zn_g$, where $n_g$ is the density of the gas and $Z$ is the average ion charge. However, this is correct only in a narrow region behind the ionization front where the return current is relatively slow. On the contrary, the return current density is significantly lower at the surface of the foil, where its velocity approaches the speed of light. It is in the range of about 30%-40% $Zn_g$ in the simulation with hydrogen as one can see in Fig. 1.

A remarkable peak in the density of the beam observed in Fig. 1 at $x = 10 \ \mu m$ corresponds to a dense bunch of relativistic electrons in Fig. 2. This bunch is due to runaway electrons which escape from the foil before the strong electrostatic field is created. In Fig. 1, ionization of the gas is provided by the electric field created by this runaway bunch. The ionization front thus initially propagates with the velocity of the bunch which is close to the speed of light. However, the runaway bunch is depleted by the field it creates. After some time the bunch is not dense enough to provide complete ionization of the gas and the ionization front velocity decreases.

As the density of the beam decreases behind the runaway electrons and as the return current is collisionless, the electric field in our simulations decreases to zero and changes its sign at this place after some time. This situation is similar to that in which an electron beam propagating in low density plasma creates a wakefield behind himself. The negative electric field decelerates the return current and slightly accelerates the beam. As can be seen in Fig. 3, this results in bunching of the fast electron beam.

The phase space distribution in Fig. 3 demonstrates additional interesting effects. Firstly, the runaway bunch is not able to provide complete ionization of the gas in this time and the ionization is completed in the next bunch of fast electrons. Secondly, the velocity of the return current approaches zero near the foil surface, indicating presence of a strong negative electric field in this region. The propagating electron beam leaves the foil at about the time 110 fs and afterwards, the space-charge of the foil is rapidly neutralized by the return current. Therefore, the return current in the time 137 fs must be stopped behind the beam to neutralize the gas.

Temporal evolution of the size of the ionized region of the gas is presented in Fig. 4. The size is measured from the foil surface to the most distant point where the density of neutral atoms is less than 50% of $n_g$. We remind that the beams propagating in helium and in argon are more dense and more energetic. The propagation velocity of the ionization front is initially close to
Figure 3. Phase space distribution of electrons in the gas taken from simulation with hydrogen in the time 137 fs. The color scale is in logarithmic units.

Figure 4. Temporal evolution of the size of the ionized region of the gas. Propagation of the ionization front with the velocity of light is included for comparison.

the velocity of light but it gradually decreases in time and after the beam energy is largely depleted, the ionization front stops. The beam is stopped in helium on the shortest distance due to a very high ionization potential. On the other hand, it is remarkable that the beam propagating in argon is stopped on a shorter distance than in hydrogen even if both gases have the same density and similar ionization potential of the outermost electron. This behaviour is probably connected with multiple ionization of argon which is observed in our simulations in the region behind the foil surface. It will be analyzed in details in our forthcoming publication.

4. Conclusions
Propagation of a high-current relativistic electron beam from the dense plasma into the neutral gas is simulated using our 1D PIC code which includes electric field ionization. Our results demonstrate generation of a strong electrostatic field at the surface of the target from which the beam enters into the gas. The strength of this field depends in particular on the density of the gas and the field may reflect a significant part of the beam back into the target and decelerate the propagating beam. Ionization of the gas is provided by the field generated by the dense bunch of runaway electrons and the ionization front propagates with the velocity close to the velocity of light until the runaway beam is largely depleted. The gas composed of higher Z atoms like helium or argon may be multiply ionized in the region close to the foil surface. At this moment, our results are not comparable to those obtained in the experiment [1]. Our electron beam has an ad hoc prescribed distribution and it is relatively short for computational reasons. Nevertheless, we demonstrate some important effects which influence the electron beam propagation and which should be taken into account in the theoretical models.

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