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Particle Simulation of High Current Electron Beam Propagation in Dielectrics

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1. INTRODUCTION

Recent experiments demonstrate an efficient transformation of a high intensity laser pulse into a relativistic electron beam with very high current density. Such electron beams are important in particular for the Fast Ignition of Inertial Fusion targets [1]. The propagation of an electron beam with a high current density inside the target is possible if its current is neutralized [2]. This phenomenon is not well understood, especially in dielectric targets. In this paper, we study the propagation of a high current density ($4-400$ GA/cm^2) electron beam produced by a 40 fs laser pulse in a plastic target using Particle-in-Cell simulations. Our simulation code includes both, ionization of neutral atoms (C and H) and collisions of newborn electrons. The results are compared with a relatively simple analytical model of the ionization front and a reasonable agreement is found. The temporal evolution of the beam velocity distribution and the propagation velocity of the ionization front are analyzed and their dependence on the beam density is discussed. The beam energy losses are mainly due to the target ionization induced by the self-generated electric field and the heating by return current. For the highest beam density, a two-stream instability is observed in the plasma behind the ionization front.

2. NUMERICAL AND ANALYTICAL MODEL

To simulate electron beam propagation in dielectric target, we use a 1D3V relativistic electrostatic PIC code [3]. In this code, fast electrons are treated as a separate species and ions are treated as immobile. The simulation box consists of two spatial regions of solid density materials. The region, in which the beam is initiated, is composed of triply ionized Al plasma, while the region, in which the beam propagates, is composed of neutral plastic (polyethylene, CH_2). Initial velocity distribution of the beam electrons is uniform between 0.7 and 0.9 speed of light in the propagation direction. The density of fast electrons is uniform along the beam and it is in the range $10^{18}-10^{20}$ cm^{-3}. The electric field ionization and both elastic and ionizing collisions of the return current electrons are included in the code in a similar way like in [4].

The analytical model describes the dominant physical processes in the head of the beam in the 1D geometry. It assumes a stationary situation and neglects the energy losses of the beam. Fast electrons are described by the Vlasov kinetic equation and the electric field is calculated using the Poisson equation. The continuity equation with a source term describing the electric field ionization is used to calculate density of ions and newborn electrons. Velocity of the return current is described by the electron mobility equation with a constant collisional frequency. Resolving these equations in the reference frame moving with the ionization front similarly to [5], we find the maximum electric field and the plasma density in the ionization front, the thickness of the front and the front propagation velocity.

3. RESULTS AND DISCUSSIONS

When the head of the beam enters the plastic target, the electric field grows rapidly in consequence of the electron charge accumulation and it starts to ionize atoms. In the maximum of the field, which does not exceed 10% of the atomic field, the density of newborn electrons is two orders of magnitude higher than the beam density, which is sufficient for the current neutralization. Cold electrons are accelerated by the field and heated, until they acquire enough energy for an efficient collisional ionization. Then, the avalanche ionization starts and the further increase of the cold electron density reduces plasma resistivity and the current in the tail of the electron beam is neutralized relatively easily. The electric field inside the beam is an order of magnitude lower than in the ionization front and it drops to zero behind the beam. The ionization processes and the self-consistent electric field are demonstrated in Fig. 1.

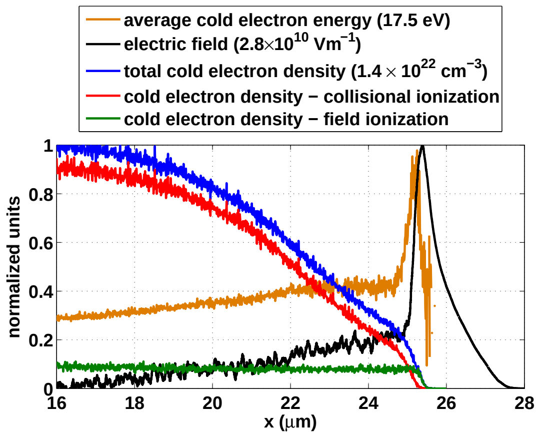

Figure 1: Demonstration of the ionization process in simulation. The 8 μm long electron beam with the density 10^{19} cm^{-3} propagates (from the left) inside the plastic target, which begins at 8 μm. Curves are normalized to the maximum values (see legend). The green and the red curves demonstate the fraction of electrons produced by the field and the collisional ionizations respectively.

Amplitude of the electric field decreases in the ionization front as the beam density decreases, while the thickness of the front increases. A lower amplitude of the field implies a lower ionization rate and the field must be maintained in a larger region to give space for production of a sufficient number of cold electrons. This can be seen in the results of our analytical model shown in

Fig. 2. The same was observed also in simulations. In simulations, it was observed that the lower the beam density the more fast electrons contribute to the field formation in the ionization front. Therefore, the velocity distribution in the front contains more slower electrons. This implies that the ionization front velocity, which can be regarded as the beam propagation velocity or the mean velocity of fast electrons in the ionization front, decreases with the beam density. The dependence of the front velocity on the beam density is very important, as it may provoke a development of the ionization instability [5]. This instability is responsible for filamentation of fast electron beam as it propagates in a dielectric target in recent experiments [6].

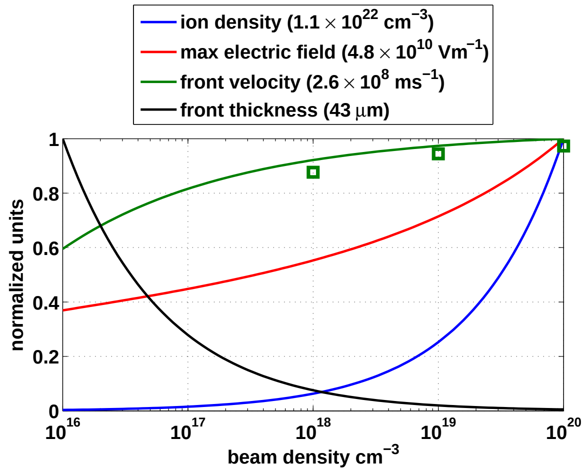

Figure 2: Dependence of the front velocity, maximum electric field, front thickness and ion density on the density of the electron beam calculated using the analytical model (markers represent the front velocity in simulation). Units normalized to maximum values (see legend).

In the simulation, we observed that the beam distribution function evolves temporally. The velocity of the ionization front decreases with time as energy of the beam is dissipated. This is due to the finite length of the beam. As time goes on, all fastest electrons cross the ionization front and then its velocity must decrease in order to accumulate the necessary space charge. Moreover the density of the electron beam behind the ionization front increases as fast electrons are decelerated by the electric field below the average beam velocity and are caught up by the rest of the beam. However on a longer temporal scale, the ballistic evolution of the beam predominates and causes the overall decrease of the beam density.

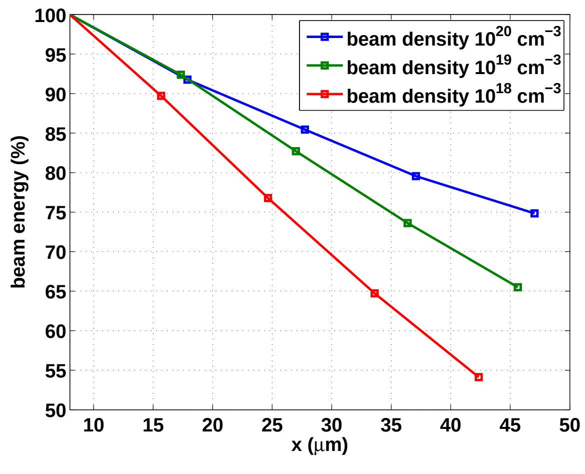

Figure 3: Energy losses of the beam in our simulations in % of initial energy versus the propagation distance. At 8 μm beam enters the plastic target.

The dissipation of energy is demonstrated in our simulation results in Fig. 3. It is the strongest for the lowest density beam for two reasons, the highest electric potential in the ionization front and the lowest front velocity, which implies the longer time needed for an electron to cross the front. Beam energy is transferred into the thermal energy of cold electrons and is spent for an additional ionization through inelastic collisions. The average stopping power acting on electrons in the beam is an order of magnitude higher than the collisional one and for the beam with density 10^{18} cm^{-3} about 50% of energy is lost on the propagation distance of 40 μm. Finally, for the highest beam density, the two-stream instability develops behind the ionization front in the simulations and causes additional beam energy losses.

4. CONCLUSIONS

Propagation of a high current density relativistic electron beam in a dielectric target was demonstrated using the numerical and analytical models, which take into account the ionization and the collisional processes. The current neutralization is established in the ionization front, where initial population of plasma electrons is produced and accelerated toward the beam. Through collisional ionization, the density of plasma electrons behind the beam head and the conductivity are increased several times. The self-consistent electric field in the beam head, which depends on the beam current density, plays an important role in the fast electron transport, as it defines the beam propagation velocity. The dependence of the propagation velocity on the beam density results in filamentation instability in the ionization front as predicted in [5] and already observed in experiments [6]. On a longer distance, the propagation of a relatively short electron beam is significantly influenced by the beam energy dissipation. For higher beam densities, the dissipation is enhanced by the two-stream instability in the beam tail.

Acknowledgments

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