*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-4.018 (2004)*

Vlasov-Fokker-Planck Simulations of Fast Electron Transport for studying Proton Acceleration in Laser-Solid Interactions

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Introduction

There is great interest in the production of multi-MeV protons beams in ultraintense laser-solid interactions. It has been suggested that the strong electric field that is set up at the rear surface of targets due to fast electrons is responsible for the acceleration of these protons [1]. It is conventionally argued that, because a quasistatic sheath field reflects most of the fast electrons back into the target, the potential across the sheath must at least equal the fast electron temperature. The sheath must be sustained for at least the laser pulse duration, and possibly well beyond that. We show that although the sheath field approximates to the static model in some respects, time dependence and fast electron density are important in determining the field structure, the available potential drop, and whether the protons can acquire the available energy in a time comparable to the laser pulse duration.

Theory

It has been shown, both experimentally and theoretically [2], that, in laser-solid interactions, the fast electrons have an energy distribution that can be adequately described by a Maxwellian. Recently Passoni et al.[3] have developed a static theory for the sheath field set up at the sharp interface of a two-temperature plasma and vacuum. They showed that close to the interface the key scale length was $\lambda_{D,f} = \sqrt{\frac{\varepsilon_0 T_f}{e^2 n_f}}$, the fast electron debye length, and that the maximum electric field scaled as $\sqrt{n_f T_f}$. As a Maxwellian distribution was used, $\phi(x) \rightarrow -\infty$ as $x \rightarrow \infty$, and the theory gives no time-scale. The theory does point out that the cold electron temperature and density do affect the sheath field.

Numerical Simulation

Simulations have been carried out using a 1d3p version of the Vlasov-Fokker-Planck(VFP) code KALOS. In KALOS the distribution function is expanded in spherical harmonics. The code is fully relativistic, and includes electron-ion and electron-electron collisions. Recently field and collisional ionization have been included in the code. The ion populations are all tracked separately, but there are no excited states, and there is no recombination. Ion motion is neglected, and currently the laser field is not simulated at all (i.e. no absorption). Instead, in a "heating region", cold electrons are energised into fast electrons in a way that gives the correct power input. This code is described (albeit not a version that includes ionization) in [4].

The simulations were set up with a uniform spatial grid 75μm long, with $\Delta x = 0.1\mu$m. The maximum energy on the grid was 1.4MeV. The ionization energies were resolved. Sixteen spherical harmonics were used. The first 3μm was initially fully ionized carbon at diamond density, and at a temperature of 50eV. Beyond that, extending up to 25μm, was unionized carbon at diamond density. From that up to the end of the grid was initially vacuum. The injected fast electron temperature was, $T_f = 280$keV. The total heating power was 1TW, and the heating power per unit volume went as $P = P_0 \cos^2\left(\frac{\pi x}{2x_h}\right)\sin\left(\frac{\pi t}{\tau_h}\right)$, with $x_h = 2.5\mu$m, and $\tau_h = 100$fs. P_0 controlled the fast electron density, and the baseline simulation had $P_0 = 1.78 \times 10^{21}$Wcm^{-3}. This would give an estimated $n_f = 1.3 \times 10^{20}$cm^{-3}. The simulations were run for 250fs.

Results

The evolution of the electric field for the baseline simulation is shown in 1. Up to about 150fs the field structure is dominated by the ionization front in the target, after 150fs it is dominated by the rear surface sheath. The field structure consists of a sharp

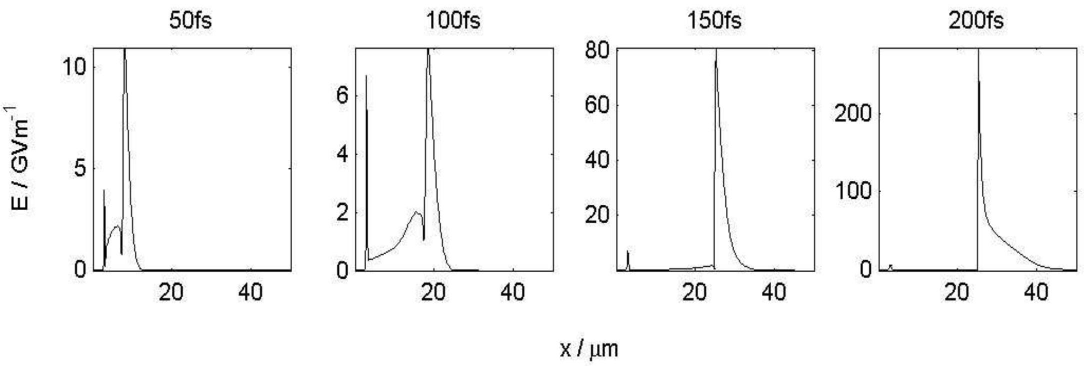

Figure 1: Electric Field evolution in baseline simulation. Interface at 25μm. Peak field does not move after 150fs

spike, and a lower extended region of field. We have found that the peak electric field, and scale length of the spike are described quite well by static theory. The maximum sheath potential observed in any run was always greater than T_f ($13T_f$), and this varied weakly with n_f. On examining the distribution (see fig.2(right)) we find that the fast electrons in the vacuum are either being reflected or are escaping into the vacuum. The spike corresponds to Debye shielding by reflected electrons. Higher energy electrons that cross the interface before the spike reaches full strength give rise to an extended region of electric field, the potential across this region is a large fraction of the total potential across the sheath. As the sheath field can persist for much longer than 150fs after heating is turned off, we can only estimate the acceleration that takes place after 250fs (simulation time). Particle tracking with a fixed field(baseline at 180fs; see fig 2(left)) shows that protons only acquire $\approx T_f$ in 200fs, and do not acquire all the available potential even

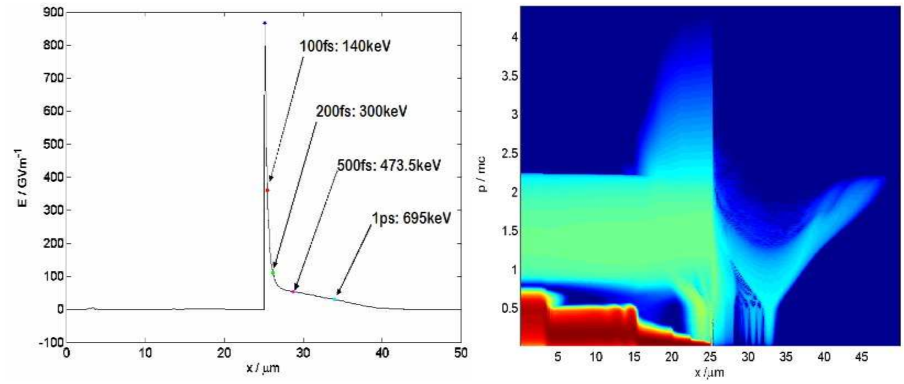

Figure 2: Left:Proton Tracking in a Fixed Field.Right:$p^2 f_0$:Electron Density in Phase Space

after 1ps. Thus further work is required to understand the late time decay of the electric field, and how the experimentally observed energies, which for these parameters would be about 1MeV, are produced.

We have also found that material physics is important. When we repeated the runs with pre-ionized targets (Z=6;T=50eV) we found that the electric field structure was translated further out into the vacuum. This happened because the background electrons had time to relax into the vacuum before the fast electrons arrived. In particle tracking, this results in protons starting at 25μm gaining negligible energy over 1ps.

References

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