*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-4.052 (2004)*

Simulations of fast electron transport experiments at MPQ

J.J. HONRUBIA[1], M. KALUZA[2], G.D. TSAKIRIS[2] AND J. MEYER-TER-VEHN[2]

1. ETSII, Universidad Politécnica, José Gutiérrez Abascal 2, Madrid, Spain
2. Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, Garching, Germany

Most of the experiments and simulations of electron transport carried out in last years deal with electron propagation in solid targets. Only a few experiments of transport in compressed targets or low density foams have been reported until now.[1] However, fast electron propagation in media with increasing density is found in many applications, such as the fast ignitor scheme and experiments with ns-long prepulses due to amplified spontaneous emission (ASE). Recent experiments of electron transport and proton acceleration carried out with the ATLAS-10 laser system at Max-Planck-Institut für Quantenoptik (MPQ)[2] used ASE prepulses of varying duration. Those prepulses heat and expand the target before the arrival of the main high-intensity pulse, in such a manner that electrons propagate through non-uniform plasmas. We have performed hybrid PIC simulations[3] of fast electron propagation in those plasmas and analysed the role played by the self-generated electric fields from the viewpoint of proton acceleration.

The targets analysed consist of an aluminium layer with initial thickness in the range of 1.5 - 30 μm illuminated by an ASE prepulse with an irradiance of 8×10^{11} W/cm^2, a duration of 2.5 ns and a wavelength of 0.79 μm. This prepulse precedes the high intensity pulse, which delivers a total energy of 0.44 J into a focal spot having a diameter of 4.9 μm (fwhm) in 150 fs (fwhm). It corresponds to a mean intensity of 1.5×10^{19} W/cm^2. The laser-to-electron conversion efficiency has been taken as 25%. A Gaussian distribution of fast electrons in space and time, and an exponential distribution in energy have been assumed. The temperature of this last distribution is obtained as a function of the local laser intensity, also assumed Gaussian, by means of the ponderomotive acceleration law, $kT_f = m_e c^2(\gamma-1)$. The kinetic energy of electrons averaged over the fwhm in space and time is 830 keV, with a peak energy of 950 keV. Electrons with so high kinetic energy interact weakly via collisions with the thin targets considered. Plasma resistivities have been calculated by the model of Lee and More,[4] which allows to calculate transport properties of partially degenerate plasmas.

1. Propagation in exponential profiles

We first consider '*ideal*' targets with exponential density profiles and thicknesses from 10 to 80 μm. The minimum and maximum densities of the profile are fixed and equal to $\rho_0/10$ and

ρ_0, where ρ_0 is the density of solid aluminium. The initial temperature is 5 eV. Solid targets with the same areal density as the '*ideal*' targets have also been considered for comparison. Simulations show higher temperatures in expanded targets than in solid targets due to the enhancement of the resistive heating at low densities. This is consistent with the temperature scaling $T \propto n_b^{-2/5}$, where n_b is the background electron density.[5] Moreover, the energy transferred to the plasma by the resistive heating due to the return current is enhanced in expanded targets, as can be seen in Fig. 1a. Field amplitudes, however, are lower in the expanded targets, as expected from the higher temperatures reached. This is again consistent with the scaling E_z, $B_\theta \propto n_b^{3/5}$ and results in a lower beam collimation in expanded targets, as depicted in Fig. 1b.

It is worth noticing the large dependence of beam collimation and resistive heating with the electron injection half-angle shown in Figs. 1.

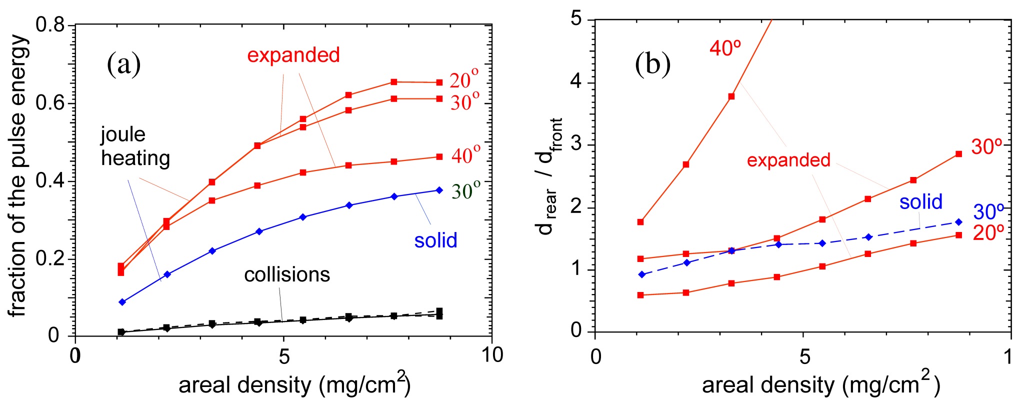

Figure 1. (a) energy loss of fast electrons and (b) beam collimation in expanded and solid targets with the electron injection half-angle as a parameter. d_{rear}= diameter of the electron beam (fwhm) at the rear surface and d_{front}= diameter at the front surface.

2. Application to proton acceleration in thin targets

We have performed simulations with the density and temperature profiles obtained from one-dimensional radiation-hydrodynamic codes.[6,7] The profiles are mapped onto the r-z or x-y-z meshes of the electron transport code assuming uniform densities and temperatures in the radial coordinate. The density profiles for targets thicker than 5 µm are depicted in Fig. 2. The minimum ion density considered in the calculations has been 0.1 g/cm^3 in order to have a ratio between fast and background electron densities less than 0.1.

Simulations show a clear correlation between the density of the background and the beam collimation. The beam starts expanding at the beginning of the propagation. Beam hollowing can then be observed. However, when electron enter in the higher density regions, the beam is pinched by an increasing azimuthal magnetic field. The more expanded the target, the bigger the spot diameter at the rear side.

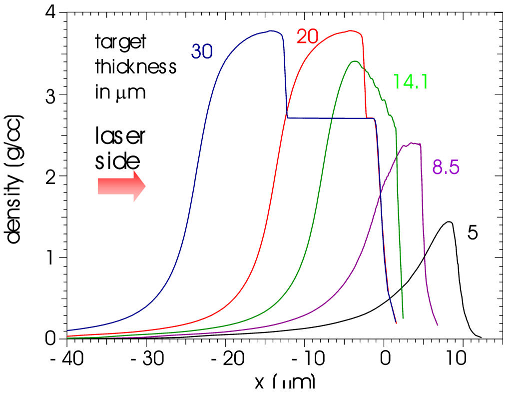

Figure 2. Density profiles at the beginning of the high intensity pulse for different target thicknesses.[6,7]

The results of the electron transport code have been post-processed to obtain the number of electrons (N_e) passing through the spot at the rear side (d_{rear}), their kinetic energy ($\langle E_e \rangle$) and the pulse length (τ_{pulse}). Data are shown in Table I. However, to estimate the proton cutoff energy, one has to take into account the scale length (L_{ion}) of the ion density profile at the rear side. A one-dimensional code has been developed to describe the acceleration of protons including the scale length. It assumes that the acceleration is driven by the electric fields set up by the fast electrons exiting the target rear surface. The effect of the scale length is important for thin targets, which are quite expanded by the ASE prepulse (see Fig. 2) with L_{ion} of the order or greater than 1 μm, as shown in Table I.

Table I. Parameters used to estimate the proton cutoff energy

d_{target} (μm)	d_{rear} (μm)	N_e $\times 10^{11}$	τ_{pulse} (fs)	$\langle E_e \rangle$ (MeV)	L_{ion} (μm)	E_{proton} (MeV)
1.5	4.6	7.30	185	0.65	2.0	0.93
2	4.3	6.42	190	0.67	1.6	1.02
3	3.8	5.38	190	0.69	1.5	1.15
5	4.8	4.93	175	0.75	0.6	2.66
8.5	5.0	5.35	180	0.75	<0.2	3.87
14.1	6.2	5.81	180	0.75	<0.2	3.13
20	7.4	5.15	205	0.73	<0.2	2.46
30	7.6	3.00	220	0.72	<0.2	1.68

The comparison with experiments is depicted in Fig. 3. An electron injection angle of 30º has been used in the FET simulations shown in the figure. For targets thicker than 5 μm, the numerical predictions for the rear-side proton-acceleration process are in good agreement with the experimental results obtained with the ATLAS-10 laser system. For thinner targets, the predicted cutoff energies are too low by at least a factor of 2. However, they can be explained when the front side acceleration process[8] is taken into account.[2]

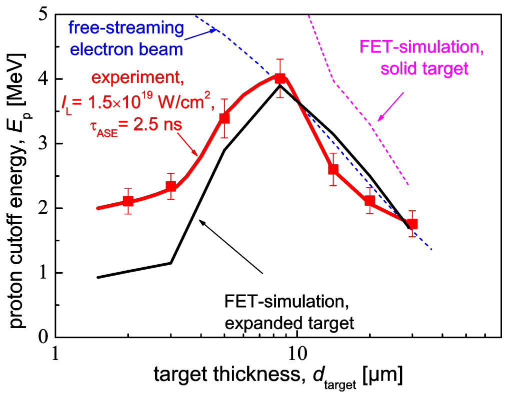

Figure 3. Proton cutoff energy obtained in experiments[2] and from fast electron transport (FET) calculations. The results assuming free streaming electron beam are also shown for comparison.

Surprinsingly, a good agreement is found between electron transport simulations and the fitting carried out in reference 2 assuming that electrons propagate on a straight path with an angular divergence of 8-10º and without energy loss. This can be explained by the balance between the energy loss of electrons and the beam collimation in a certain range of target thicknesses. The effect of the target expansion due to the preheating by the ASE prepulse on the proton cutoff energy is also shown in Fig. 3. If electrons propagate in a solid target, the beam is more collimated and transfers less energy to the background plasma. Then, the peak proton energy would be higher, clearly over the experimental measurements

3. Conclusions

We have shown a significant enhancement of the energy deposited to the plasma by resistive heating when electrons propagate in a density profile. This enhancement is not, however, accompanied by an increase in the beam collimation. Hence, simulations of proton acceleration experiments with ns-long ASE prepulses have to take into account the expansion of the targets before the arrival of the main laser pulse. The density and temperature profiles were estimated by 1-D radiation-hydrodynamics simulations and mapped into the 2-D/3-D mesh of a hybrid PIC code. We found a good agreement with experiments for targets thicker than 5 µm. For thinner targets, however, the cutoff energies predicted by rear-side acceleration are too low. In these cases, the proton are dominantly accelerated at the target front side. If electrons propagate in solid targets, the proton cutoff energy is higher than in the experiments. This gives an idea of the importance of the ASE prepulse on proton acceleration.

References

[1] D. Batani et al., *Phys. Rev. E* **65**, 066409 (2002).
[2] M. Kaluza at al., accepted for publication in *Phys. Rev. Lett.* (2004).
[3] J.J. Honrubia et al., *Laser and Particle Beams* 22, 137 (2004).
[4] Y.T. Lee and R.M. More, *Phys. Fluids* **25**, 1273 (1984)
[5] A.R. Bell and R.J. Kingham, *Phys. Rev. Lett.* **91**, 035003 (2003).
[6] K. Eidmann et al., *Phys. Rev. E* **62**, 1202 (2000).
[7] J.J. Honrubia, *J. Quant. Spectrosc. Radiat. Transfer* **49**, 491 (1993).
[8] Y. Sentoku et al., *Phys. of Plasmas* **10**, 2009 (2003).