Effect of ion composition on the expansion of a finite-sized plasma

A. P. L. Robinson
Central Laser Facility, CCLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., OX11 0QX, UK

P. Gibbon
John von Neumann Institute of Computing, ZAM, Forschungzentrum Jülich, Germany

Main contact email address A.P.L.Robinson@rl.ac.uk

Introduction

The generation of multi-MeV protons and ions from targets irradiated by ultra-intense lasers is a matter of great interest to the laser-plasma community. In broad terms there are two reasons for this, apart from pure scientific interest. Firstly, a laser accelerated multi-MeV proton beam may be able to heat compressed fusion fuel to ignition in a variant of the Fast Ignition ICF scheme. The proton/ion energies required all already easily achieved, but there are a number of other issues that need to be addressed. Secondly, it is hoped that laser-accelerated proton beams could be used for the clinical treatment of tumours. This would require protons in excess of 200MeV. In *both* cases an issue that is not fully resolved is the *control of the energy spectrum*. In the case of a cancer therapy beam, a highly monoenergetic beam is required. In the Fast Ignition scenario, a highly monoenergetic beam may not be optimal, but an engineered energy spectrum certainly is[1]. In this article we report on part of our investigation into the production of proton beams with quasi-monoenergetic features in the energy spectrum due to the expansion of a two-ion-species finite-sized plasma. Importantly we show that a 1D calculation can reproduce the important features seen in a 'microdot target' experiment.

Theory

The canonical reduced model for the laser acceleration of protons is the 1D plasma expansion model. This can only account with acceleration away from the target surface normals. The model is dealt with extensively in the literature, however we note that previous work on the role of target composition was confined to the isothermal case. The general case where the total energy is finite has been studied by Mora for the case of a single ion species[2]. In the isothermal expansion of a one temperature plasma with one ion species the electric field in the rarefaction wave, E_{RW}, and the electric field at the ion front, E_{IF}, are given by

$$E_{RW} = \frac{k_B T}{e c_s t}; E_{IF} = \frac{2 k_B T}{e c_s t} \qquad (1)$$

for $\omega_{pi} t \gg 1$. Mora found that E_{RW} goes like t^{-3} and that EIF goes like t^{-2} for the case where the fast electrons are not too strongly relativistic. In the case of a two ion species system this therefore opens up the question of how the generation of spectral peaks is affected. The spectral peaks are due to the perturbation of the proton expansion by the electrostatic shock associated with the termination of the heavy ion density. So how does the electric field of this electrostatic shock vary in time, and how does the electric field in the heavy ion rarefaction wave depend on time? One may be tempted, on the basis of Mora's findings, to hypothesize that the electric field in both rarefaction waves diminishes much faster than the field at the two ion fronts. One would therefore conclude that the spectral peaks would be enhanced, and that noticeable peaks might be produced even for high proton concentrations. A recent 'microdot target' experiment used PMMA rather than PE as the proton source, i.e. 50% H rather than 66% H composition. Is this sufficient to explain the Jena groups observation of a small spectral peak from PMMA but not from a normal contamination layer?

Numerical Simulation

The numerical calculations performed were finite-difference solves of the 1D1P Vlasov-Ampére system. This code is the same as that used in[3]. Only two calculations are reported here.

The computational domain was initialized with a 0.5µm plasma flush with the LH boundary. This is equivalent to a symmetric 1µm target. The targets had an electron density of 10^{29}m^{-3}. The target also consisted of a mixture of two ion species: H^+ and C^{4+}. The percentage of H^+ was set to 66%, and 50%. The cold electron temperature was set to 10keV and also present was a fast population with a density of 10^{27}m^{-3} with a temperature of 1.5MeV. The fast electron parameters are relevant to the conditions generated in interactions around 10^{19}Wcm^{-2}.

Firstly we shall consider the changes to the expansion dynamics by examining the electric field. The electric field in the 50% H^+ run is shown below, in figure 1.

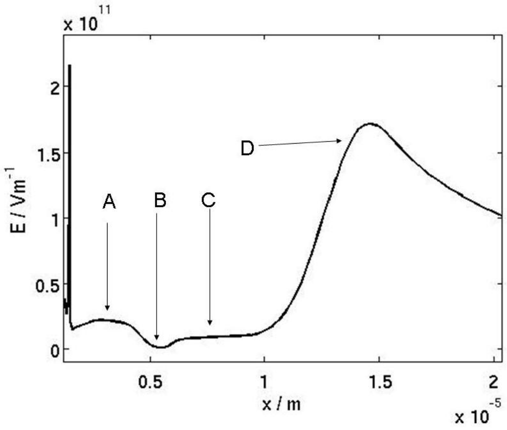

Figure 1. Electric field in 50% simulation at 500fs.

In figure 1 we indicate features A-D. Feature A is the heavy ion rarefaction wave, and B is a region of quasi-ballistic flow just beyond the heavy ion front. A small group of quasi-monoenergetic protons has accumulated in region B. Region C is the proton rarefaction wave, and D is the sheath field associated with the proton front.

At the time of writing we have not yet determined the time dependence of A-D. However in the case of D it is clear that E_{IF} / E_{RW} › 2, in agreement with Mora's result. However the same does not apply to the heavy ion front (A) where a strong shock appears to be completely absent. The consequence of this, as can be seen from the spectrum in figure 2, is that the quasi-monoenergetic feature is no stronger than in the case of an isothermal expansion. The strong peak in the electric field at the far left of figure 1 is a feature like the rarefaction shock, i.e. it is due to the separation of fast and cold electrons. However there is no strong discontinuity in the ion density or rapid acceleration of the ions, thus there is no corresponding peak in then energy spectrum, unlike the isothermal expansion. This is another point in which we agree with Mora's results.

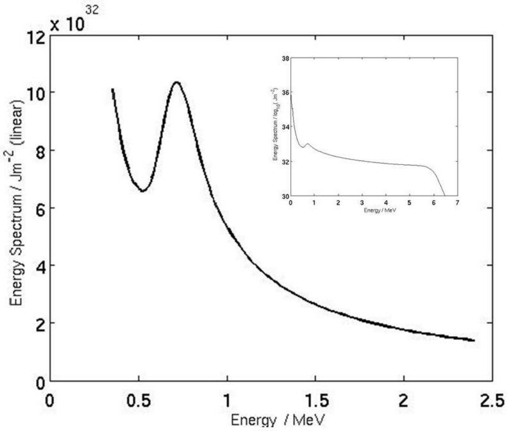

Figure 2. Proton energy spectrum (linear) of 50% run at 500fs. Inset shows the full spectrum on a logarithmic scale.

The generation of this small quasi-monoenergetic feature, as shown in figure 2, is illustrated clearly in figure 3 which shows both the phase space of the protons and the heavy ions at 500fs. It is clear from figure 3, and comparison with figure 1, that the protons associated with the spectral peak are the accumulation just beyond the heavy ion front in the region of very weak electric field marked as region B in figure 1.

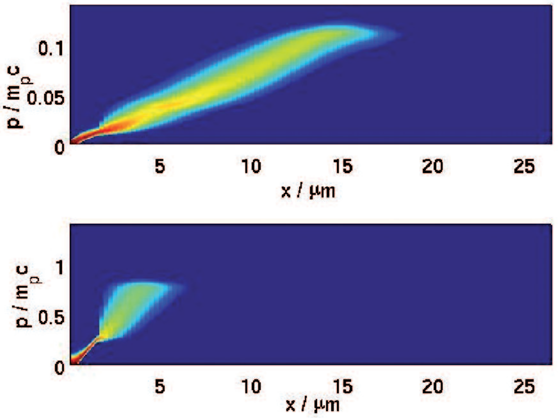

Figure 3. Proton (Top) and C^{4+} (Bottom) phase space at 500fs in the 50% run.

When we examine the 66% run, however we find a significant departure from the isothermal results. A quasi-monoenergetic feature is now completely absent, and this is entirely due to one-dimensional physics. In a previously study of the isothermal case, a spectral peak was present in the 66% simulation. In this run the higher proton density seems to have eliminated region B. The authors have yet to determine the conditions for region B, and hence the quasi-monoenergetic feature to exist. It is very interesting that the physics is so sensitive to such a change in the target composition.

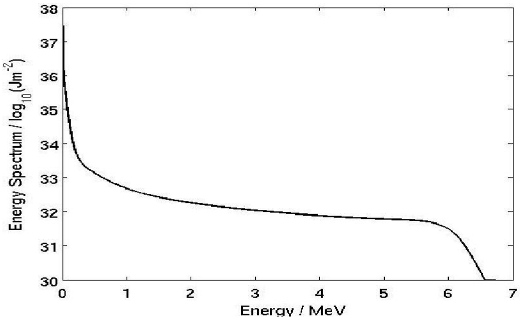

Figure 4. Proton energy spectrum (log) of 66% run at 500fs.

Conclusions

We have carried out some preliminary numerical calculations to investigate the role of ion composition in the plasma expansion of a finite sized plasma. We agree with the findings of Mora concerning the proton expansion and the rarefaction shock. The adiabatic nature of the expansion does not seem to significantly enhance quasi-monoenergetic features, despite what one may initially think.

The most salient result is the *sensitivity* to the proton content of the target. This may explain why CH_2 targets and 'natural' contaminant layers do not produce spectra with peaks, but why cleaned PMMA does. The Jena group observed a spectral peak containing about 10^8 protons at an energy of 1.2 MeV and with an energy spread of 300keV. Here we observe a spectral peak at 730keV, with an energy spread of about 400keV.

The next stage in our investigation is determine the conditions required for the existence of this feature, and how it may be enhanced. In future we also plan to carry out a set of 3D calculations to study the sensitivity to geometry.

References

1. M. Temporal *et al.*, *Phys. Plasmas,* **9**, 3098 (2002)
2. P. Mora, *Phys. Rev. E,* **72**, 056401 (2005)
3. A. P. L. Robinson *et al.*, *Phys. Rev. Lett.,* **96**, 035005 (2006)