The effect of target composition on proton acceleration

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Introduction

Multi-MeV proton beams are observed from the rear of solid targets when they are irradiated by an ultraintense laser. There is both experimental and theoretical evidence to support the notion that electrostatic acceleration due to fast electrons is very important in producing these proton beams. Since laser-produced proton beams may find important technological applications (already they are used as plasma diagnostics), it is important to understand how targets can be constructed to control the proton beam properties.

In this report we consider the effect of varying the ratio of protons to heavy ions in a homogeneous planar target. We firstly present theoretical arguments as to how proton acceleration should occur in the limits of very high and very low proton density. We then present the results of 1D1P two/three species relativistic Vlasov simulations of these two cases, and we compare our results to our hypothesis.

Theoretical Arguments

There are two important limits when considering the effect of target composition. A target could, theoretically, consist entirely of protons. CH targets are 66% protons, so such targets are close to this limit. At the other extreme a target could consist almost entirely of heavy ions with only a low density of protons. The simplest model of ion acceleration is the 1D hybrid model of Gurevich[1)], given below in the two-temperature, multi-species form.

$$\begin{aligned}
&\frac{\partial n_\alpha}{\partial t}+\frac{\partial(n_\alpha u_\alpha)}{\partial x}=0\\
&\frac{\partial u_\alpha}{\partial t}+u_\alpha\frac{\partial u_\alpha}{\partial x}=-\frac{Z_\alpha e}{m_\alpha}\frac{\partial\phi}{\partial x} \qquad\qquad (1\text{-}3)\\
&\frac{\partial^2\phi}{\partial x^2}=\frac{e}{\varepsilon_0}\left(n_{c,0}e^{\frac{e\phi}{k_BT_c}}+n_{f,0}e^{\frac{e\phi}{k_BT_f}}-\sum_\alpha Z_\alpha n_\alpha\right)
\end{aligned}$$

In equations (1-3), the subscript alpha refers to the ion species. The plasma is taken to be semi-infinite with a fast electron density, $n_{f,0}$, and cold electron density, $n_{c,0}$, in the undisturbed plasma. Working from this model, one can obtain estimates of the maximum proton energy. In the limit of a 100% proton target, the target will undergo a two temperature, one species plasma expansion. However one could conjecture that the highest energy protons will undergo essentially a single (fast) temperature expansion. The self-similar solutions that can be derived for the (one temperature, one species) Gurevich model do not give the maximum ion energy, for this we must consult the work of Mora[2)]. Mora solved the one temperature, one species Gurevich model numerically, and found analytic expressions that fitted the numerical results superbly (and with the correct theoretical limits). Mora's result for the maximum ion energy ($\varepsilon_{\max}$) is given by equation (4).

$$\varepsilon_{\max}=2Zk_BT_e\left[\ln\left(\frac{\omega_{pi}t}{\sqrt{2e}}+\sqrt{\frac{\omega_{pi}^2t^2}{2e}+1}\right)\right]^2 \qquad (4)$$

In the limit of very low proton density, the heavy ion front will dominate the electric field structure. The electric field structure will be very close to that of a single species, two temperature plasma expansion. The energy that highest energy protons reach will then be determined by the sheath field around the heavy ion front, and the protons with the maximum energy will originate close to the initial plasma-vacuum interface. In the case of static ions (i.e. zero Z/m heavy ions) the sheath field will be well described by the Passoni[3)] solution. In the limit of low $n_{f,0}/n_{c,0}$ and low T_c this becomes equation (5).

$$E(x)=\frac{\left(k_BT_f\sqrt{2}/\lambda_{D,f}\right)}{1+\dfrac{x}{\lambda_{D,f}\sqrt{2}}} \qquad (5)$$

The proton equation of motion can be integrated to obtain the maximum proton energy for the static sheath. For mobile ions, we can estimate the maximum proton energy by assuming that equation (5) applies at the ion front which moves at the front velocity given by Mora, and that the electric field scales in time as $(1+\omega_{pi}^2t^2)^{-1/2}$ (again using a result of Mora). The proton equation of motion for this moving sheath was integrated for the case where heavy ions had a charge to mass ratio of $e/2m_p$. In both cases the proton started with zero velocity at the heavy ion front. The maximum energy versus time for all three cases are plotted (in dimensionless form) in Figure 1 (note that: $\omega_{pp,f}^2 = n_{f,0}e^2/m_p\varepsilon_0$).

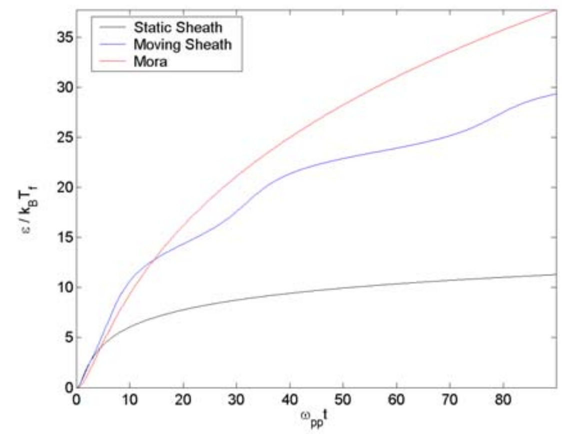

Figure 1. Theoretical maximum proton energy versus time for three cases (see text).

In an actual experiment, the expansion will only correspond to the Gurevich model as long as the laser pulse maintains the fast electron density in the target. For a system such as Target Area West on Vulcan this may correspond to as much as $\omega_{pp,f}t = 80$. On the basis of the theoretical considerations discussed here, we can not only make predictions concerning the maximum proton energy. The proton spectra for the two extremes will differ as well. In a high proton density target the spectrum will be like that of the self-similar solution, i.e. a broad spectrum. However at low density we can expect the protons that are accelerated by the sheath field to form a distinct peak in the spectrum at the maximum energy.

Three Species Relativistic Vlasov Solver

The code used for the numerical simulations is a 1d1p, three species relativistic Vlasov solver. The distribution function is represented explicitly, and the relativistic Vlasov equation is solved by upwind methods. A discussion of these methods can be found in the work of Arber and Vann[4)], and Sircombe[5)]. The spatial grid is non-uniform so that the cold Debye length is resolved over a few microns close to the initial plasma-vacuum interface, and so that sufficiently large vacuum and reservoir regions can be included with relatively few grid points. Overall the plasma region is 85.8µm in length, and the vacuum region is 304µm in length. The plasma is initialized as a uniform, relativistic bi-Maxwellian. The fast electron temperature and density is 1.5MeV and 3.5 x 10^{27}m^{-3}, and the cold electron temperature and density is 10keV and 3.97x10^{29}m^{-3}. The heavy ion species used was C^{4+} , and both protons and C^{4+} are initially cold. Although the cold electron temperature is high it still corresponds to $\lambda_{D,c} \sim$ 1nm, and the fast electron energy density still exceeds that of the cold electrons.

TSRV Simulations of 100% Proton Target

In the case of the pure proton target, the expansion quickly evolves into two self-similar expansions which are connected by a sharp transition region. This is shown by Figure 2, a plot of proton phase space at 200fs. Unlike the one temperature expansion, the two-temperature expansion has a double-peaked electric field structure. The peak that corresponds to the proton front decays quickly, as was found in Mora's work. The peak that corresponds to the transition region, and the transition region itself, is an area that still being studied. The fastest protons seem to undergo a Gurevich-Mora expansion, and this can be seen by comparing the proton spectrum at 760fs to the Gurevich spectrum (using T_f and $n_{f,0}$). This is shown in Figure 3. The maximum proton energy (despite the proton front in the simulation being smoothed by numerical diffusion) compares very well to equation (4). This is shown in Figure 6.

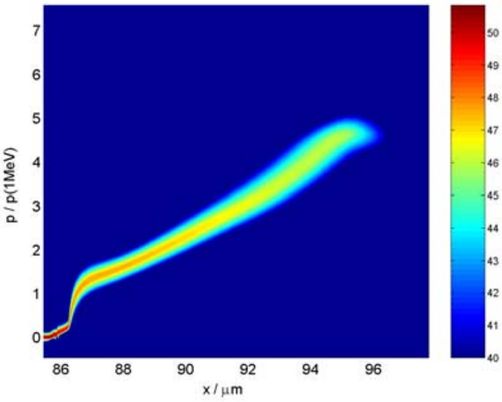

Figure 2. Proton phase space ($\log_{10}$(f)) at 200fs in 100% proton target simulation.

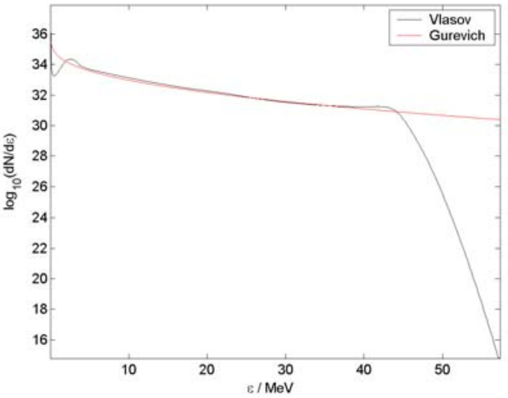

Figure 3. Proton spectrum ($\log_{10}$) at 760fs in 100% proton target simulation. Gurevich spectrum also shown ($n_0 = n_{f,0}$, $T_e = T_f$). Values close to 0 MeV not plotted.

TSRV Simulation of a 0.1% Proton Target

In the case of the target composed mainly of C^{4+}, the expansion was very much like the 100% proton target, except that the C^{4+} ions took the role of the protons. In this simulation, the protons did not affect the electric field structure, as predicted. The highest energy protons are accelerated by the sheath at the C^{4+} front and this forms a peak in the proton spectrum. As the target expands, a significant number of protons are accelerated by the rest of the electric field structure. However these are accelerated to lower energies. This leads to a broad spectrum at lower energies. This is shown in Figure 4, proton phase space at 800fs, and Figure 5, the proton spectrum at 800fs. If the protons were confined to a thin layer at the target interface, then the proton spectrum would exhibit only an isolated peak with a relatively small energy spread.

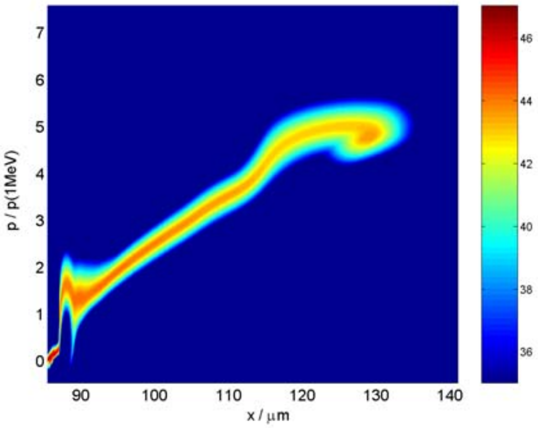

Figure 4. Proton phase space ($\log_{10}$(f)) at 800fs in 0.1% proton target simulation.

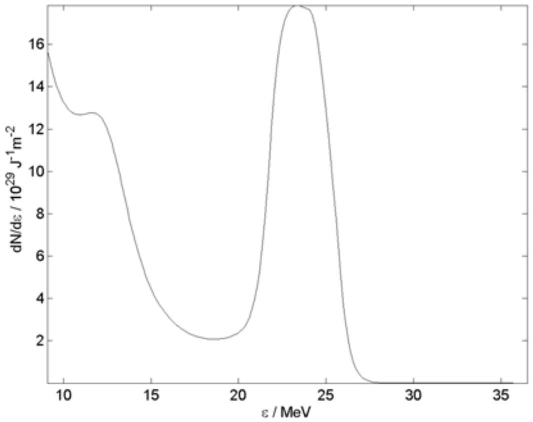

Figure 5. Proton spectrum at 800fs in 0.1% proton target simulation. Low energy points emitted to show peak.

Conclusions

One can compare the results for the maximum proton energy to our hypothesis. This is done in Figure 6. The hypothetical curve for the moving sheath model has been recalculated from Figure 1, for an ion charge to mass ratio of e/3m_p (i.e. as was used in the simulation). As can be seen the 100% proton target compares very well to the Mora formula, and the 0.1% proton target compares very well to the moving sheath model. Additionally we have also found that the proton spectra are very similar to what was expected on theoretical grounds. It seems that our theoretical framework provides a good explanation of these two limits, at least for the high energy protons. On the other hand we do not understand the transition region very well, particularly at late times. The transition region is almost certainly where quasi-neutrality breaks down as described by Wickens-Allen theory[6]. Furthermore, given that the transition region is a sharp change in ion density and velocity, it is possible that the transition region is akin to the rarefaction shock described by Bezzerides[7]. We are continuing to study the transition region.

Our work suggests that there is a conflict between attaining high proton energy and a quasi-monoenergetic spectrum. Additionally it also suggests that to obtain a quasi-monoenergetic spectrum requires a very low proton density, which would lead to considerably fewer protons.

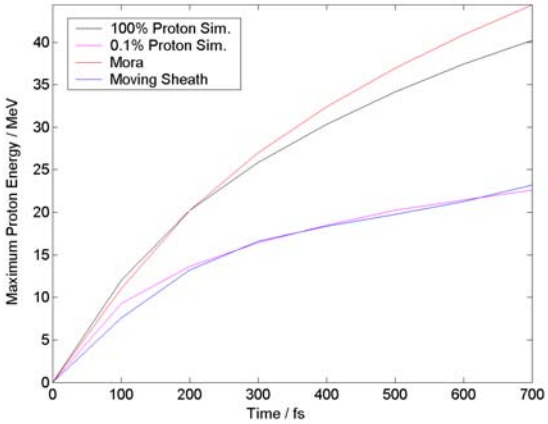

Figure 6. Comparison of Simulation results to our hypothesis.

In the future we will study how proton acceleration varies between these two extremes using this code. Another aspect of our future work will be combining our ion Vlasov solvers with a KALOS code[8] (to solve for the electron distribution). As ionization routines have been included in KALOS codes [9], which may be useful as the charge to mass ratio of the heavy ions can be an important issue in proton acceleration.

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