Differential Dynamics of Protons and Deuterons in Laser Plasmas

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Introduction

Most plasmas contain a variety of positively charged ions either because of the presence of different chemical elements or through the variation of charge state of ions heavier than hydrogen. Some of the kinetic effects of mixed ion species are well known eg the Landau damping of ion sound waves by protons in a higher Z background plasma but usually the plasma composition is considered to be uniform in space and time. The very large electric fields set up in some laser plasma experiments can however result in a pronounced separation of ion species in a collisionless system and this note considers two such examples: transient proton acceleration in targets with differing fractions of protons relative to heavier ions (henceforth all lumped together as deuterons) and separation of species over longer time scales in the presence of laser filamentation and Stimulated Brillouin Scattering.

Proton Acceleration in an Expanding Plasma Sheath

In any plasma the dynamics of different ion species are determined by their charge to mass ratio Ze/Am_p where Z is the charge state, A the mass number and m_p is the proton charge. Protons have the largest value of $(Z/A) = 1$, deuterons and fully ionised light atoms have $(Z/A) = 1/2$ and other ions have $(Z/A) < 1/2$. In a fixed time interval and a fixed electric field protons will accelerate faster, travel farther and have more energy than other ion species. On the other hand in traveling through the same distance in a fixed electric field ions will simply acquire an energy equal to the potential drop $Z \Delta\Phi$.

Since the early ICF experiments with CO_2 lasers it has been known that at $I\lambda^2 > 10^{16} Wcm^{-2}\mu m^2$ there is a flux of energetic ions leaving solid targets and that protons constitute the fastest component of the ion emission[1]. The protons are observed even from non-hydrogenous targets and are attributed to thin layers of surface contamination containing water and hydrocarbons. The acceleration is believed to occur in an electrostatic field created by the energetic electrons which leave the target and maintain a non-neutral layer as long as the hot electron Debye length $\lambda_{D-hot} = v_{hot}/\omega_{p-hot}$ is greater than the density scale length. Protons have the highest velocity since they remain in the expanding Debye sheath longer than heavier ions which tend to experience a smaller field due to the screening effect of other lighter ions. The same mechanism is observed on the front and particularly the rear surfaces of thin targets irradiated by CPA lasers where it is known as target normal sheath acceleration or TNSA[2].

We have performed simulations with the OSIRIS Particle in Cell (PIC) code[3] in 2-1/2 spatial dimensions of a laser with normalised intensity $a_0 = 8$ (10^{20} Wcm^{-2}) incident on a thin foil with peak density $10n_c$ and thickness $30c/\omega_p$. The ions are divided into a fraction f of protons and (1-f) of deuterons. Simulations have been carried out for f = 0.01, 0.1 and 0.5.

The proton spatial distribution at $t = 401$ ω_p^{-1} for f = 0.1 is shown in the left portion of Figure 1. The figure shows the protons accelerated away from the rear surface of the target and the interior of the foil almost void of protons as they are accelerated through the foil by the shock generated by the laser at the front surface absorption region.
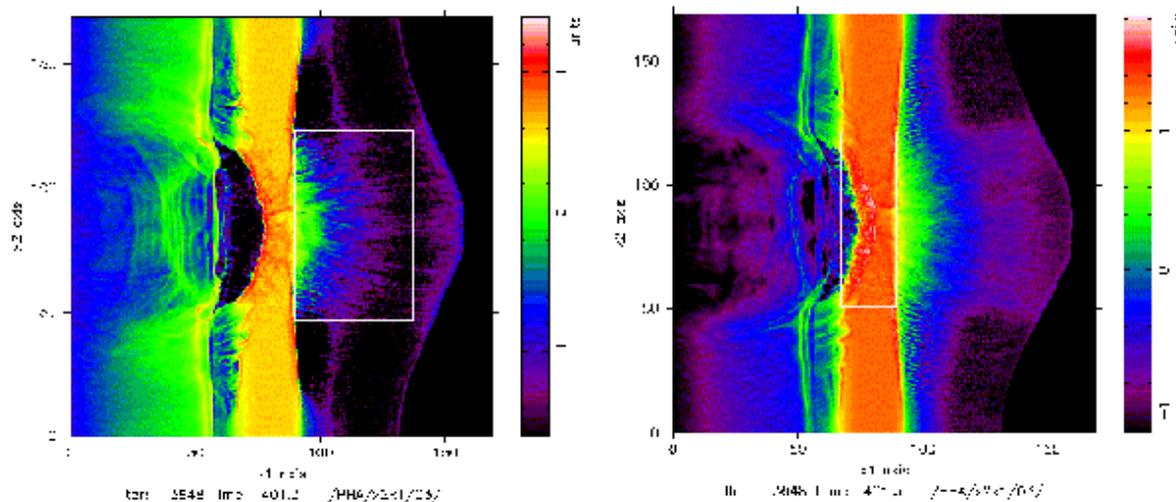
Figure 1 Spatial distribution ofprotons at time 401 ω_p^{-1} in an OSIRIS simulation with 10% protons (left) and 50% protons (right)

As the fraction of protons is increased we observe the maximum proton energy to decrease.

Proton Fraction	f = 0.01	f = 0.1	f = 0.5
Maximum proton energy	30MeV	25MeV	15MeV

This is to be expected since the larger numbers of accelerated protons that go with the higher concentrations also give more shielding of the space charge of the electrons.

A similar effect is observed in the ions which are accelerated by the ponderomotive pressure of the laser at the front side of the target. Where the protons are a minority species the lighter ions can respond without significantly perturbing the charge balance of the plasma, ie they do not affect the screening of the potential in the wake of the shock front. As shown in the left half of Figure 1 the interior of the foil is almost devoid of protons at t = 401 ω_p^{-1}.

The right hand half of Figure 1is for a proton fraction f = 0.5 and is dramatically different with the protons largely remaining in situ in the foil. For each of these cases we calculate the two dimensional p2p1 momentum distribution of the protons within the white rectangles and show these distributions in Figure 2.
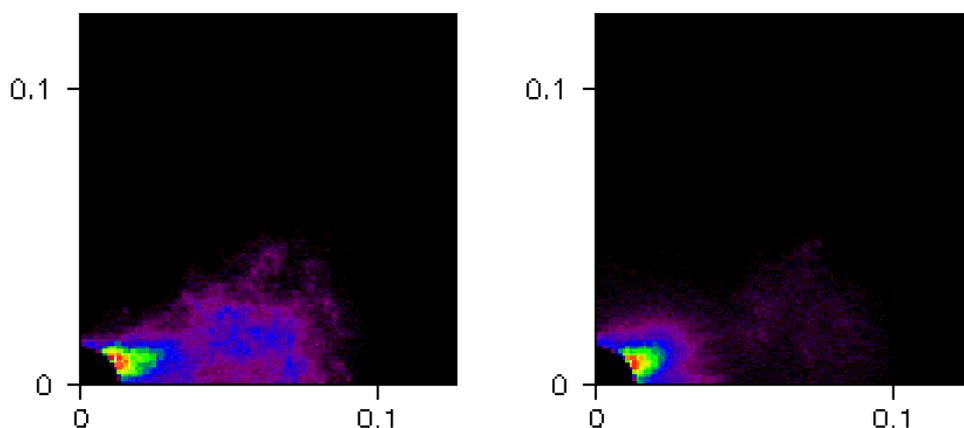

Figure 2   p2p1 momentum distribution for the protons in the 'solid' part of the target (left f = 0.1 right f = 0.5)

Comparison of the two parts of Figure 2 shows a large increase in the numbers of protons with p > 0.05 (E > 1MeV) when protons are a minority species.

These results are significant if the aim of an experiment is to create protons above some threshold energy or if CH and CD targets are compared for the creation of neutrons. The CD target with a small percentage of protons present will produce significantly more energetic protons both internally and via the TNSA mechanism and these energetic protons may produce (p,n) reactions with other materials.

Ion Separation by Filamentation and SBS

In an equilibrium configuration where there are slowly varying potentials (either electrostatic or ponderomotive) there will also be a separation of the ion species of different Z since they have slightly different equilibrium Boltzmann distributions $n = n_0 \exp-((\varepsilon+Ze\Phi)/kT)$. Ions of different charge state of the same chemical species should not be included in this argument since the charge state of any individual ion will fluctuate in time due to ionisation and recombination processes. Ions of different chemical species may tend to separate since their distributions of Z will be different.

In long pulse laser experiments, when the laser pulse duration greatly exceeds the ion plasma period there is time for SBS and ponderomotively driven filamentation to occur. The time scale for the ion distribution across a filament to reach a steady state is given by the ion transit time which for a 2.5keV ion across a 20 micron filament is 60 psec and for times less than this the transient behaviour described in the introduction will also give rise to a separation of species. In practice the filaments will probably move due to deliberate laser beam control through ISI or SSD or uncontrolled changes in the laser beam profile.

To model this longer term behaviour we have carried out an OSIRIS simulation with $a_0 = 0.1$ (10^{16}Wcm^{-2} for a 1μm laser) and $n_e/n_c = 0.3$ so that SBS may occur but not SRS. The ions in the simulation are 50% protons and 50% deuterons by number. Figure 3 shows the density distribution of each species as ponderomotively driven filamentation is beginning to grow.
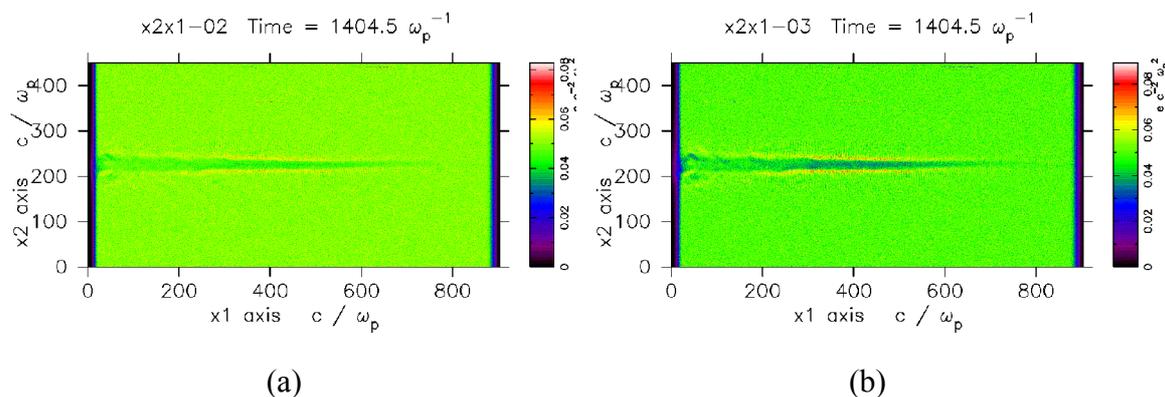

(a)　　　　　　　　　　　　　　　　(b)

Figure 3　Density distribution of deuterons (t) and protons (b) at a time of 1404 ω_p^{-1} (670 fsec) showing the density depression in the light filament.

It is clear that the lighter protons are more effectively driven out of the filament than are the deuterons. Figure 4 shows the difference of the proton and deuteron densities together with the magnetic field of the electromagnetic wave which shows evidence of both forward and backward scattering.
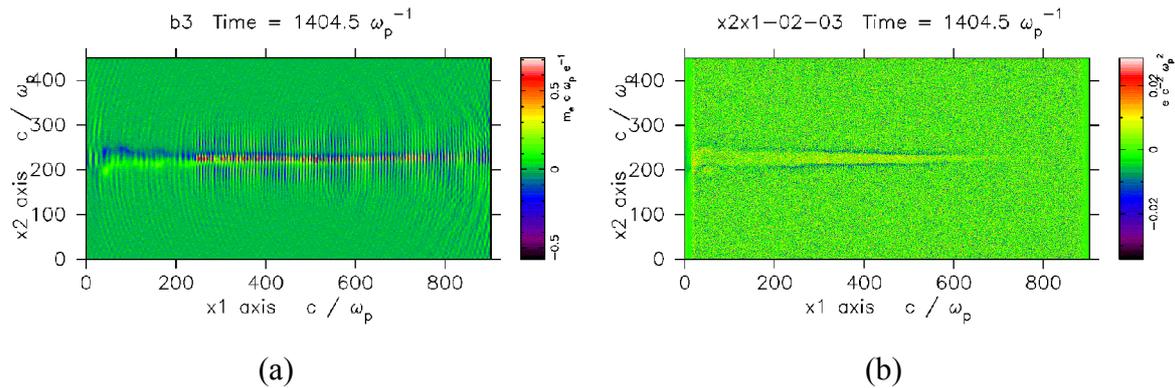
(a)   (b)

Figure 4 (a) Magnetic field of the electromagnetic waves showing scattering from within the filament and (b) the difference of proton and deuteron densities n_d - n_p showing an excess of deuterons inside the filament and an excess of protons just outside the filament.

The significance of the separation of deuterons and protons is that the dispersion relation for ion acoustic waves $\omega_{ia}^2 = k^2(ZT_e/\langle m_i \rangle)$ is no longer uniform in space due to the variation of the average ion mass $\langle m_i \rangle$. This gives rise to a phase mismatch for any waves propagating at an angle to the filament and is a potential mechanism to reduce the amount of SBS generated in plasmas with mixed ion species. Given that the present laser plasma interaction codes generally overestimate the amount of SBS backscatter[4] this ion mass induced phase mismatch should be included in the variety of non-linear frequency shifts and damping mechanisms that are invoked to explain the discrepancy.

Conclusions

The different ion species in a laser produced plasma can be significantly separated by the low frequency electric fields in the sheath regions around light filaments or at the surface of the target. The effects can be significant for proton acceleration and for the suppression of SBS in mixed Z plasmas.

References

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