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Hole-boring RPA with two ion species

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Introduction

In the past few years there has been growing interest in the possibility of accelerating ions to extremely high energies with lasers by means of the Radiation Pressure Acceleration (RPA) mechanism [1-3]. The principle that underpins RPA is relatively simple – it is a regime of ion acceleration where the electrons couple the light pressure to the ions effectively at the irradiated surface so that the ions there experience a force approximately equal to the light pressure.

There are two main modes of RPA that are important to consider: the hole-boring (HB) mode where the light-pulse is driving into a thick mass of plasma, and the light-sail (LS) mode where the light-pulse pushes a finite mass of plasma ahead of itself. In both cases the plasma must be opaque to the driving radiation.

In this article we will report on a recent investigation into HB-RPA, and we will look specifically at how HB-RPA works with multiple ion species. The principal conclusion of this work is that HB-RPA with multiple ion species differs very little from the single species case, with the exception of certain extreme circumstances. This is demonstrated by a set of numerical tests of theory.

Analytic theory

The single species problem can be solved by considering the momentum balance in the frame which is co-moving with the 'piston-head'. The piston is actually a strong spike in the longitudinal electric field that is created by the light-pressure displacing the electrons relative to the ions. If steady state hole-boring is possible then either all ions must approach the piston-head and retreat with the same velocity or some ions will pass through the piston, which may eventually destroy the steady state pistoning. Considering the first possibility we then note that this means that we obtain the same solution as the single species case except that the mass density is now a summation over all ion species (composite density):

$$\frac{2I}{c}\frac{1-\beta}{1+\beta} = 2\gamma_b^2 v_b^2 \sum_i n_i m_i \qquad (1)$$

This yields the same results as obtained in [4]. Defining $\Xi = I/\rho c^3$, as a dimensionless parameter, the HB velocity and ion energies are given by:

$$\beta_b = \frac{\sqrt{\Xi}}{1+\sqrt{\Xi}} \qquad (2)$$

$$\varepsilon = m_i c^2 \frac{2\Xi}{1+2\sqrt{\Xi}} \qquad (3)$$

Now we turn our attention to the second possibility – that of ions passing through the light piston. This can be done by estimating the electrostatic potential of the light piston, and writing down an energy inequality. The end result is that one finds that that reflection will occur provided that the following is satisfied:

$$\frac{Z}{m_i} > \frac{n_e}{4\rho} \qquad (4)$$

Which is generally easy to satisfy. In the following sections we will now carry out numerical tests of this theory using 1D EM PIC simulations.

Numerical test 1

The first aspect of the theory that was tested was its ability to predict the variation of ion energy with HB velocity. A series of simulations were carried out using a several micron thick CH plasma irradiated by a flat-topped pulse of intensity 10^{21} Wcm^{-2} and1 μm wavelength. The plasmas had composite densities in the range of 100-500 kgm^{-3}. When the average energy of the ions was compared to the analytic expressions it was found that there was very good agreement. This is shown in figure 1.

Numerical test 2

The analytic theory clearly indicates that there is no dependence on the charge or charge-to-mass ratio of either ion species. This was tested by carrying out a series of similar simulations where the plasma density was fixed at 500 kgm^{-3}, and the charge state of the carbon ion was varied. It was found that the effect on both the carbon and proton energies was weak until the carbon ion charge was reduced to Z=1, at which point there is a strong deviation from equation 3, as is shown in figures 2 and 3. However at this point, the condition in inequality 4 is close to being violated so this is consistent with the C^+ ions initially passing through the light piston.

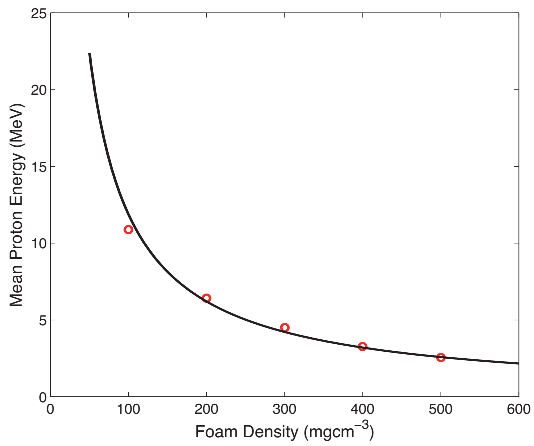

Figure 1. Mean proton energy again foam density: red circles are from PIC simulation, and black line is analytic expression.

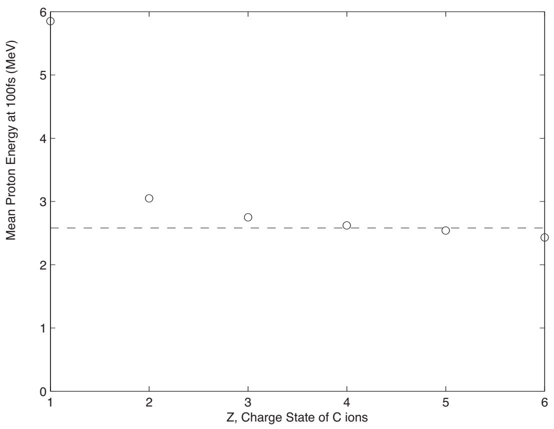

Figure 2. Mean proton energy against carbon ion charge state in PIC simulations where it was varied.

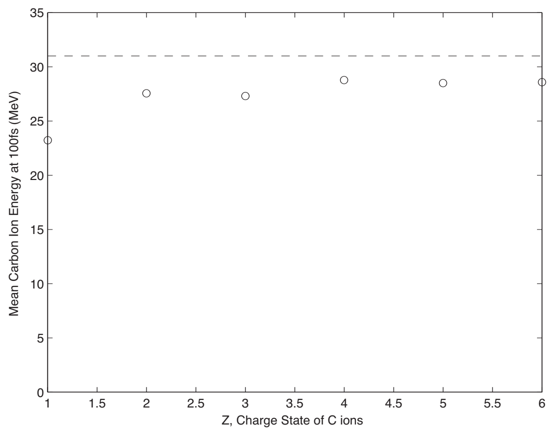

Figure 3. Mean carbon ion energy against carbon ion charge state in PIC simulations where it was varied.

Numerical test 3

As the only relevant target parameter in the analytic theory is the composite mass density, the pure numerical fractions of the ion species should not influence the HB RPA process. This was also tested by running simulations for two targets with identical mass densities (500 kgm^{-3}). Target A consisted of 90% carbon ions and 10% protons by number, and Target B consisted of 10% carbon and 90% protons by number. On running the simulations, at 100 fs, the average carbon energy in the accelerated bunch in Target A was 67.7 MeV and the mean proton energy was 6.37. The mean carbon energy in the accelerated bunch in Target B was 67.1 MeV, and the proton energy was 5.94 MeV. The analytic model predicts 6.2 MeV and 74.4 MeV for the proton and carbon ion energies. Clearly both targets are producing similar energies that are both very close to the analytic model. Therefore this validates the prediction that the numerical proportions of the ion species are not highly relevant to the hole-boring dynamics.

Conclusions

In this work we have studied 'hole-boring' RPA for the case of multiple ion species. An analytic theory was developed that is almost identical to the single species theory. Numerical tests carried out for the two species case showed that this was more than adequate for describing the hole-boring dynamics (HB velocity and ion energies). It is quite likely that this generalizes to an arbitrary number of species.

Acknowledgements

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