Pellet ignition using ions shock accelerated in the corona

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Fast ignition, using a beam of high energy electrons generated by a short laser pulse and directed into a previously compressed fusion pellet, was suggested some time ago as a means of reducing the total energy needed to achieve ignition [1]. More recently attention has been given to the use of ions rather than electrons. One suggested method is to use a separate target to generate the ions by the familiar target normal surface acceleration process, as described in a recent review by Fernandez et al [2]. Another is to use ions driven by the ponderomotive force of a very intense laser beam [3]. The requirement for this would be for a very tightly focused beam at an intensity of around 10^{22} W/cm^2. Recently we suggested that another possible scheme is to use a collisionless shock generated in the subcritical corona region of a compressed pellet to generate fast ions that would penetrate to the dense core and be absorbed there [4]. In this paper we expand on this idea and show that, while further detailed work is needed, the scheme appears feasible and worth further investigation. We shall first give a brief account of some of the relevant properties of collisionless shocks, then present some calculations of ion stopping power in dense plasmas to ascertain the approximate energy range needed. With the aid of some shock simulations we conclude that shock acceleration of ions from the corona to the required energy does indeed appear feasible.

Turning first to the nature of collisionless shocks in an unmagnetized plasma, a key paper with early simulations was published more than forty years ago by Forslund and Freidberg [5]. They showed that at low Mach numbers there is a smooth structure with a potential ramp followed by downstream potential oscillations. In this regime the potential jump is not sufficient to reflect a large number of the upstream ions. We have recently developed an analytic theory to describe this regime [6] and shown that the structures so formed may be relevant to a number of laser plasma experiments. At higher Mach numbers (above around 1.5) there is a change to a more complicated structure in which a large fraction of the upstream ions are reflected and there is a population of trapped ions in the downstream region. The low Mach number shocks can give rise to a very narrow accelerated ion energy spectrum, since only a small part of the tail of the ion distribution is reflected. We have shown that this effect can well explain some experiments on ion acceleration [7]. In the higher Mach number regime there is a broader energy spectrum, but many more accelerated ions [6,7]. For the purpose of pellet ignition a narrow energy spectrum does not seem necessary, but rather the aim should be to obtain as large an ion flux as possible so that the higher Mach number regime is appropriate. A rough estimate of the ion energy can be obtained by noting that in the laboratory frame the speed of the reflected ions is twice the shock speed. Thus, if we approximate the ion sound speed by $(T_e /m_i)^{1/2}$, the ion energy is around $2M^2T_i$ in a single species plasma.

Turning now to the ion energy needed for fast ignition, we look at the range of ions in a plasma, using a formula for stopping power given by Li and Petrasso [9]. This work takes account of small and large angle scattering from ions and electrons, quantum effects and excitation of collective plasma oscillations. Estimates of the relevant Coulomb logarithms are given. Here we take the value 3 for ion-electron collisions and 10 for ion-ion collisions, typical of the range of values given by Li and Petrasso. To obtain an idea of the ion range we have looked at a range of parameters, looking at the trajectory of an ion in a plasma with a density ramp increasing by one order of magnitude.

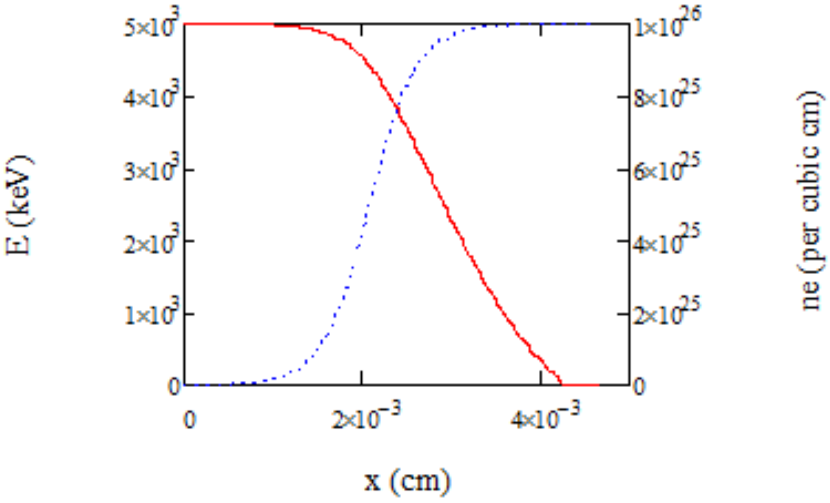

Figure 1. Ion energy (red) in the density ramp shown in blue.

Figure 1 shows the energy loss of a 5MeV hydrogen ion going into a plasma consisting of equal concentrations of deuterium and tritium where the density goes up to 10^{26} cm^{-3} and the temperature is 5keV. At the highest density it can be seen that the ion range becomes of the order of a few tens of µm. A similar plot for a density two orders of magnitude lower is shown in Figure 2.

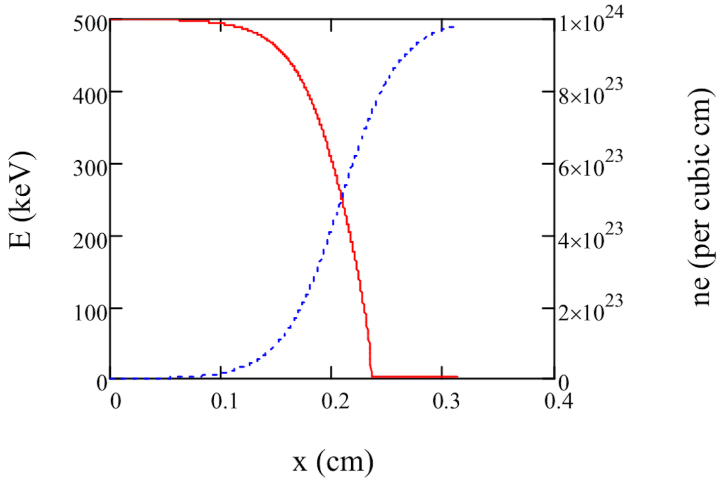

Figure 2. As for Figure 1 but with lower density.

Now the particle range has gone up to be of the order of mm. From calculations like this we estimate that ions of around 5-10 MeV generated in the corona will be able to penetrate to the dense plasma core and be sufficiently rapidly slowed down so as to deposit most of their energy there.

Finally we look at some simulations using OSIRIS [10] of a shock generated in a D-T plasma density ramp by a CO_2 laser pulse of intensity 10^{18} W/cm^2 and duration 14ps.

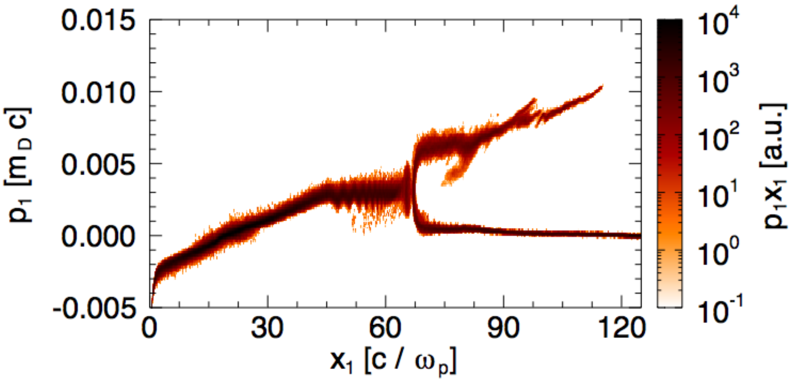

Figure 3. Deuterium phase space.

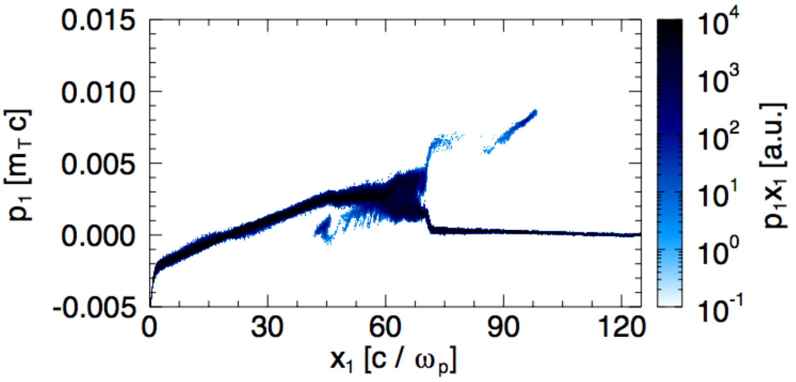

Figure 4. Correponding tritium phase space.

Clearly the lighter ions are preferentially accelerated and it has been shown that energies up to a few 10s of MeV can be obtained. In the corona of a plastic coated target we would have a carbon/hydrogen or possibly carbon/deuterium plasma, but these preliminary simulations indicate that the lighter component can be picked out and very effectively accelerated by a collisionless shock.

In conclusion, our results indicate that collisionless shock launched in the corona of a compressed target by a short intense laser pulse can generate ions of the energy needed to penetrate into the dense core and deposit their energy there.

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