Shock wave acceleration with short, high power laser pulses in two-ion-species plasma

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In the previous work [1] we have studied the proton acceleration in a proton plasma, which is basically produced by expanding a thin hydrogen foil initially at solid density. The dynamics of the plasma expansion together with the soliton propagation in this non-uniform medium results in the reflection of protons from the shock-front with relatively low energy spread. This mechanism has been proven for long pulses in near-critical plasma using long (picosecond) laser pulses at moderate intensity [2, 3]. In our study we have demonstrated that it works also with ultrashort high intensity pulses.

In the present work our goal is to investigate the same mechanism in the presence of multiple ion species, which is much easier to produce in real experiments by using CH targets, for instance. Thus the next step was to include a heavier ion beside the proton with density ratio n_i/n_p. The charge state Z of heavy ions is a very important parameter, but we can include it in the parameter $n = Zn_i/n_p$, which gives the ratio of electrons originated from the heavy ion part and protons respectively. Another parameter, which needs to be included in a two-ion-species plasma is the mass ratio: $\alpha = m_i/(m_pZ)$. In the earlier work presented in Ref. [4] it was shown that the electric field acting on the light protons can be $\sqrt{\alpha}$ times greater than in the case of a plasma consisting only of protons (and electrons). Later we show that, in contrast with the results of Ref. [1], here the density scale length (l_n) at the rear side of the expanded plasma slab also becomes an important parameter.

Before we present the simulation results let us discuss theoretically the effect of these parameters: n, α and l_n. It is clear that the ion acoustic speed defines the dominant part in the velocity of reflected protons, which can be calculated from the dispersion relation of the plasma [5]:

$$C_{s,eff} = C_s \left(\frac{1+n/\alpha}{1+n} \right)^{1/2}, \qquad (1)$$

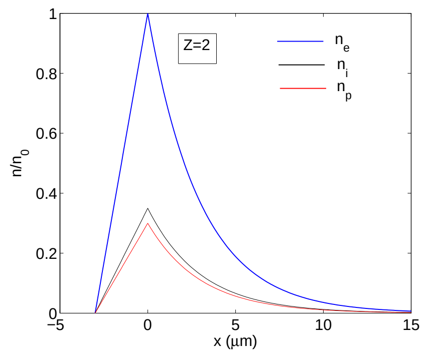

Figure 1: *Initial density distributions. The laser pulse comes from the left.*

where $C_s = \sqrt{T_h/m_p}$ corresponding to the proton plasma, where $n = 0$ and we obtain C_s for the acoustic speed. The relation between the plasma length, density and pulse duration is the same as in [1]: the laser pulse has to be capable of heating all electrons in the target providing a nearly one-temperature hot plasma, which means: $l_f + l_n \approx ct_L$, where l_f is the scale length at the plasma front side and t_L is the laser pulse duration. In the presented simulations the electron and ion density profile is the same as in [1], only the absolute value has to fulfill the charge neutrality: $n_e = Zn_i + n_p$. The initial density distribution of different species is shown in Fig. 1.

The main difference, in comparison with the proton plasma case, is that the expansion of the background plasma is much slower, therefore l_n can be considered constant. The velocity of protons is nearly uniform, because the electric field is also uniform [6]: $E_x = T_h/el_n$, and has the following form: $v_0(t) = F(\alpha)T_h t/(m_p l_n)$. The function $F(\alpha)$ is used to account for the effect of heavy ions [4] and we distinguish two regimes, where this function behaves as:

$$F(\alpha) = \begin{cases} \ln(n\sqrt{2\alpha} + \mathrm{e}), & \text{if } 0 \leq n \approx 1 \\ \sqrt{\alpha}, & \text{if } n \gg 1 \end{cases}$$

In the proton plasma case $n = 0$ has to be used, l_n also depends on v_0 and in Ref. [1] we introduced t_i, which was the time when the reflection starts. In the one-ion-species plasma case we found that $v_0(t_i)$ does not depend significantly on l_n. Here the l_n parameter comes also into play, which we assume to be constant during the acceleration, because the heavy ions can be considered immobile. This approximation is valid for large n values, when the portion of protons in the plasma is small. Depending on n and α parameters the reflection can occur before or after the proton solitary wave reaches the heavy ion front, which influences the energy.

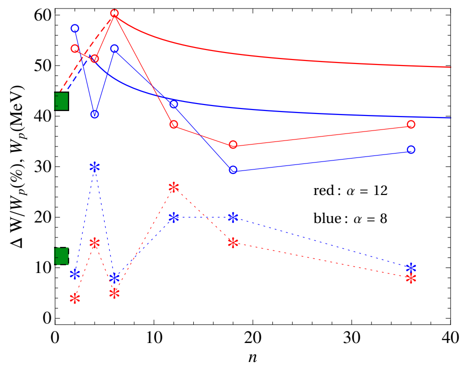

Figure 2: *Proton energy in the peak (W_p, joined circles) and relative energy spread ($\Delta W/W_p$, joined stars) as a function of n and α parameters. The full ($n \gg 1$) and dashed (small n) lines show the results of analytical model described by Eq. (2). The green squares represent the result obtained in the case of proton plasma.*

Numerous simulations have been performed for different l_n, α and n parameters. The laser intensity is always the same, $I_L = 9 \cdot 10^{20}$ W/cm^2, and uniform after 6 fs linear ramp. The pulse duration is 20 fs, the peak plasma density is $8n_{cr}$ and $Z = 2$ or 4 was used. The charge state, as a parameter, is not included explicitly in the modeling, therefore its value is not important: for any Z value one can find mass and density ratios for a given (n, α) parameter-set. In Fig. 2 the results of a parameter-scan using PIC simulations are shown with $l_f = l_n = 3\mu$m. As we expected, the energy increases with α, but for higher n values, the energy is smaller. Another interesting result is that the energy spread is below 20 % in most of the cases.

Based on the knowledge gained from Ref. [1] we can derive an expression for the velocity of reflected protons. First we estimate the velocity of background plasma $v_0 = C_s\tau F(\alpha)$, where we introduce a dimensionless quantity: $\tau = C_s t/l_n$. For our simulation parameters it is easy to prove that τ is on the order of unity. Another parameter is introduced in order to simplify the final expression: $N_\alpha = ((1+n/\alpha)/(1+n))^{1/2}$, thus the velocity of reflected protons in the moving frame [7]: $v_r = 2M_{sh}C_sN_\alpha$, where M_{sh} is the shock Mach number varying between 1 and 3 [8]. Now the final velocity in the laboratory frame reads:

$$\frac{v_f}{c} = \frac{C_s}{c}\frac{\tau F(\alpha) + 2M_{sh}N_\alpha}{1 + 2M_{sh}\tau N_\alpha F(\alpha)(C_s/c)^2}. \tag{2}$$

This equation is the same as the one provided in Ref. [1] because in the limit of proton plasma ($n = 0$), when $F(\alpha) = 1$, $N_\alpha = 1$ and $M_{sh} = 1.6$, we obtain: $v_f = C_s(\tau + 3.2)/(1 + 3.2\tau(C_s/c)^2)$, where $\tau \approx 0.8$ was obtained [1]. By using the electron temperature formula from Ref. [1] we know that for our laser parameters $(C_s/c)^2 \approx 5 \cdot 10^{-3}$, for the Mach number we can take $M_{sh} =$ 1.6 and for the acceleration time $\tau = 1$. In Fig. 2 these parameters are used, which shows qualitatively good agreement with the simulation results. At large n values τ varies also, which makes the mechanism more complicated. This figure shows that the maximum proton energy can be increased by including also heavy ions, which provide a stronger acceleration of the background protons in the downstream plasma.

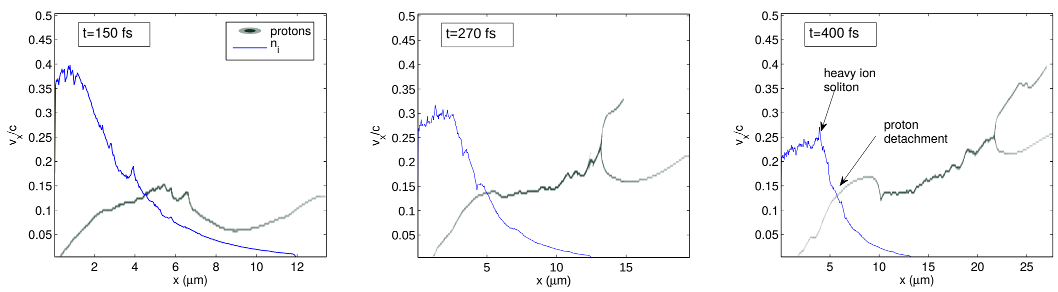

Figure 3: *Proton velocity phase-space (gray color) and heavy ion density profile (blue line) at three time instances for $l_n = 3\,\mu m$, $n = 6$, $\alpha = 12$. The ion density is normalized to 10^{28} m^{-3}.*

In order to get a deeper insight into the acceleration process we show the time evolution of the ion density profile and proton velocity phase-space in Fig. 3. First of all we see that the final velocity of reflected protons is mostly defined by the background velocity of protons, which is $v_0 \approx 0.17c$ at the beginning of reflection. During the whole acceleration process the density of heavy ions does not change significantly, only at the end a small peak appears, which corresponds to a heavy ion soliton. Another observable feature is the detachment of the protons from the plasma: the velocity and density profiles will not be continuous, but it is cut by the electric field associated with the heavy ion soliton (at $x \approx 5\,\mu$m). After the protons are pushed out from the plasma v_0 further increases due to self expansion and the proton reflection continues. Finally the reflected protons are cumulated in a small energy range around 60 MeV, which is about 40 % higher than the energy obtained in Ref. [1] with the same laser pulse.

In reality much higher charge states are present in heavy ion plasmas, which means higher Z value. However, if we consider $Z \gg 1$, then the ions must be much heavier than protons and their density should be much smaller than the proton density in the material in order to obtain the results presented here. We have seen that the energy of proton bunch can be higher if heavier ions are also present, but it requires an optimal parameter-set, which is not trivial to achieve in experiments. The CH (or organic) materials do not seem to be adequate, because they do not meet these conditions, unless the low charge state is somehow maintained during the interaction. Preliminary 2D simulations show that high electron current is maintained by the protons moving relative to the heavy ion bulk, which in turn results in the development of Weibel instability [9, 10] for a time much longer than in the purely proton plasma [1]. This effect should be avoided to ensure the same proton beam quality as in 1D. In conclusion we can say that shock wave acceleration works also in multi-species plasmas with possible improvements.

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