A simple model for cavity-enhanced laser-driven ion acceleration from thin foil targets

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Abstract. A scenario for the enhanced laser-driven ion acceleration from a thin solid target at high laser intensity is considered, where the target is enclosed in a reflecting cavity. The laser pulse reflected from the target is redirected towards the target by reflection at the inner cavity wall. This scenario is discussed in the context of sub-wavelength foil acceleration in the radiation pressure regime, when plasma dynamics is known to be reasonably well described by the light-sail model. A semi-analytic formula is presented that describes the effect of cavity reflections in one-dimensional geometry. The effect of cavity reflections on sub-wavelength foil acceleration is then evaluated for two concrete examples of ultra-intense laser pulses of picosecond and femtosecond duration.

PACS. 52.38.Kd Laser-plasma acceleration of electrons and ions – 41.75.Jv Laser-driven acceleration

1 Introduction

In the last decade there has been growing interest in laser-driven ion acceleration, where energetic ions are generated by irradiating a thin foil (with thickness in the micrometer range) with an ultra-intense (above $10^{18} \text{ W/cm}^2$) laser beam. The laser-generated proton pulses had been used for example for ultra-fast radiography and radioisotope production, and together with laser-generated beams of heavier ions they are of high interest from the point of hadron tumor therapy and fast ignition of inertial confinement fusion targets [1][2][3]. The use of an ultra-intense laser as an ion driver offers certain advantages over conventional linear or circular accelerators, allowing for construction of very compact devices that produce particle pulses of high intensity and very short duration. Unfortunately, ion energies achieved so far in this approach are not very high (below 100 MeV per nucleon), and the achieved values of the laser-to-ion energy conversion efficiency are generally below 10% [4][5].

It was recently observed that basic parameters of the laser-accelerated ion pulses - the maximum ion energy, the average ion energy, and the laser-to-ion energy conversion efficiency - could be considerably improved if the target foil is enclosed in a cavity that redirects the laser pulse reflected from the foil back into the foil, thus in a sense “recycling” the laser energy [6][7][8]. This mechanism, dubbed the Laser Induced Cavity Pressure Acceleration (LICPA), was found to be very effective at sub-relativistic laser intensities ($\sim 10^{15} \text{ W/cm}^2$), where enhancement in ion acceleration is predominantly due to the buildup of thermal plasma pressure inside the cavity [9][10]. Computer simulations performed at higher laser intensities indicate that the LICPA mechanism would be effective also in the case when the radiation pressure becomes important [11][12][13]. A possible target arrangement realizing the LICPA principle in the radiation pressure regime is shown in Fig. 1. The validity of the cavity-enhancement idea is confirmed by a recent experiment [12], where a target with a half-cavity of spherical shape was used to redirect and refocus the reflected pulse at the intensity of $10^{19} \text{ W/cm}^2$. In this note we consider a realization of the LICPA idea in the radiation pressure regime, but in a narrower context, namely when the plasma dynamics is reasonably well described by the light-sail (LS) model [14][15]. Such a situation occurs for example when a high intensity and high contrast laser pulse is incident on a foil of sub-wavelength thickness. This acceleration regime attracted recently considerable attention [16][17][18][19][20][21][22][23][24], because it may lead to creation of bunches of highly energetic ions with low energy dispersion. We point out that in the LS regime and in a one-dimensional approximation one may obtain a semi-analytic description of the cavity-enhanced ion acceleration by adapting observations on LS dynamics made in [14]. We employ this semi-analytic description to discuss some characteristic features of the cavity-enhanced ion acceleration for realistic ultra-thin foil targets and laser parameters close to the expected capabilities of the big new laser facilities that should become available in the near future [25][26].
2 The light-sail model in one dimension

Let us consider a thin planar foil of areal mass density \( \sigma \), irradiated at normal incidence by an intense laser beam propagating along the \( x \) axis, with the temporal profile of intensity \( I(t) \) in the laboratory reference frame. Let us also assume that the foil is ideally reflective in its instantaneous rest frame. The equation of motion for such a foil driven by the laser beam had been first derived in the context of laser-driven interstellar space travel \[13,14\]. The solution of this equation for the speed of the foil which was at rest at \( t = 0 \) has the following form:

\[
\beta(w) = \frac{1 + e(w))^2 - 1}{(1 + e(w))^2 + 1},
\]

where \( \beta = \frac{dx}{dt} \), \( w = ct - x \) is the retarded relativistic time variable, and \( e(w) \) is the total laser energy per unit area incident on the foil up to the retarded time \( w \), normalized to the half of the relativistic rest energy per unit area of the foil:

\[
e(w) = \frac{2}{c^2} \int_0^w I(w'/c)dw'.
\]

This very simple 1D model was found to be surprisingly useful in interpreting results of 3D and 2D kinetic simulations for laser ion acceleration. The light-sail behaviour was famously identified in a 3D simulation at the laser intensity of \( 1.4 \times 10^{23} \) W/cm\(^2\) \[15\]. It was found that the initially planar foil was deformed into a “cocoon”, in which the laser pulse is confined, and a stable plasma clump is formed from the portion of the foil, that is being then pushed forward by the radiation pressure. In simulation reported in \[15\] a linear polarization was assumed for the laser beam, but it was later observed that circularly polarized beams create more favorable conditions for this mode of plasma acceleration \[27\], and a parametric study in 1D had shown that the LS-type of behavior becomes visible for ultra-thin targets already at \( I \times (\lambda/1\mu m)^2 = 2.8 \times 10^{20} \) W/cm\(^2\) \[23\]. The case of linear polarization is more complex, because generally at less extreme intensities a broad energy spectrum is obtained. In the following we shall assume that the laser beam is circularly polarized. It is interesting that the evolution of targets which are relatively thick compared to the laser wavelength is also found to be consistent with the LS dynamics \[30,31\], although such targets are not accelerated as rigid bodies and undergo internal evolution.

A generalization of the relativistic LS foil dynamics beyond the one-dimensional approximation was outlined in \[16,21\] and applied to the study of instabilities appearing in the acceleration of ultra-thin foils.

3 Cavity-enhanced light-sail acceleration

Let us now consider foil acceleration with cavity enhancement, as illustrated in Fig. 1. When a circularly polarized beam is incident on a target foil that is sufficiently thick to be opaque to the laser light, a substantial part of the beam is reflected from the foil and lost from the system. When the target foil is enclosed in a cavity with a massive rear wall, this reflected light is reflected once again at the rear cavity wall and redirected into the foil. One could imagine that for a properly designed cavity it may be possible for the laser light to circulate back and forth inside the cavity several times. This could result in a significant enhancement of the ion acceleration from the foil in comparison with the standard arrangement.

The interaction of the laser beam with the foil and the cavity is of course a complicated multi-scale phenomenon, which would be studied through detailed numerical simulations elsewhere. In this note we want to discuss a very simple model of this interaction, which nevertheless may be argued to be sufficiently realistic to properly illustrate some essential features of the cavity-enhanced acceleration. The big advantage of this model is that it may be described by a semi-analytic formula, which makes it easy to perform all kinds of parametric studies.

The basic assumptions of the model are as follows: (1) the dynamics is one-dimensional (which may be realized through an optimized choice of the shape of the cavity, but is of course a crude approximation due to the evolution of the foil and the divergence of the laser beam); (2) during the acceleration the foil remains ideally reflective in its instantaneous rest frame (although during the evolution of the target normal incidence could not be preserved on all segments of the foil, so that even for a circularly polarized beam some laser energy would be lost due to the heating of the target); (3) the fraction \( R_c \) of the reflected laser energy being redirected back into the target does not change as a result of evolution (in reality \( R_c \) may be affected by the deteriorating quality of the reflected light, resulting in enhanced heating of the rear cavity wall, as well as interactions with side walls of the cavity and the low-density plasma expanding into the cavity; however, our experience
with cavity-enhanced dynamics shows that only first few reflections are of practical interest.

The parameter $R_c$ is of crucial importance in the cavity-enhanced acceleration. It is difficult to give an a priori estimate for $R_c$, because it is primarily affected by the amount of the laser light being lost through the entrance to the cavity, which in turn is strongly dependent on the 3D geometry of the concrete cavity and the transverse profile of the laser beam. In further calculations we assume that in proper conditions for circular polarization $R_c$ could have values in the range $0.5 \div 0.7$.

The problem of generalization of the 1D LS dynamics to take into account the contribution from a recirculating pulse was considered already in [14] in the context of the interstellar space travel driven by an Earth-based laser. In the following we adapt the reasoning presented in [14] to the case of cavity-enhanced laser-driven acceleration in the microscale: we write down an explicit formula that is valid for arbitrary temporal profile of the driving beam and allows for determination of the foil position at arbitrary time.

Let us assume that the laser pulse enters the cavity at $x = 0$ and is reflected by the foil located at $x(w)$. The pulse returns to the inner cavity wall located at $x = 0$ and then redirected towards the foil. Let us denote by $w_j$, $j = 0, 1, 2, \ldots$, the values of the retarded time for which the leading edge of the laser pulse is redirected towards the foil from the position of the inner cavity wall for the $j$-th time. Assuming that the laser pulse starts at $w_0 = 0$ and the foil is initially at $x(0) = L_c$, where $L_c$ denotes the depth of the cavity, we obviously have $w_1 = 2L_c$. Next, let $x_j(w)$ denote (for $j \geq 1$) the position of the foil for $w$ in the interval $[w_{j-1}, w_j]$. These functions satisfy an obvious continuity relation $x_j(w) = x_j(w_{j-1})$. The values of $w_j$ and $x_j(w_j)$, the value of $w_{j+1}$ is fixed by the formula

$$w_{j+1} = w_j + 2x_j(w_j).$$

Finally, let $e_j(w)$ denote (for $j \geq 1$) the total laser energy per unit area of the foil - expressed in the units of a half of the relativistic rest energy per unit area of the foil - that was incident on the foil for $w$ in the interval $[w_{j-1}, w_j]$, i.e. during the whole acceleration process up to $w_j$. The value of $e_j(w)$ is simply given by Eq. (1). The values of $e_j(w)$ for $j \geq 2$ may be determined iteratively. The expression for $e_{j+1}(w)$ consists of three terms: the first representing the total (normalized) laser energy per unit area incident on the foil up to $w = w_j$, the second representing the energy deposited by the primary laser pulse in the interval $[w_j, w]$, and the third representing the energy per unit area that had been reflected from the foil in the interval $[w_{j-1}, w_j]$ and was then redirected towards the foil. The laser energy per unit area reflected from the foil in an interval $[w_a, w_b]$ is given by the formula

$$\frac{\sigma c^2}{2} \frac{e(w_b) - e(w_a)}{[1 + e(w_a)][1 + e(w_b)]},$$

but only a fraction $R_c$ of this is redirected to the foil by the reflection at the inner cavity wall. Taking into account all contributions we obtain

$$e_{j+1}(w) = e_j(w_j) + e_{j+1}(w_{j+1}) + e_{j+1}(w),$$

where

$$e_{j+1}(w) = \frac{2}{\sigma c^2} \int_{w_j}^{w} I(w^\prime) e(w^\prime) dw^\prime$$

represents the effect of deposition of the laser energy by the primary laser pulse and

$$e_{j+1}(w) = R_c \frac{e_j(w_{j+1}) - e_j(w_{j-1})}{[1 + e_j(w_{j+1})][1 + e_j(w_{j-1})]}$$

represents the effect of recirculated laser energy. The function $w_{j+1}(w)$ appearing above is a solution of an implicit equation

$$w = w_{j+1}(w) + 2x_{j+1}(w).$$

i.e. it represents the value of the retarded time variable from the interval $[w_{j-1}, w_j]$ for which a redirected ray that is incident on the foil at $w \in [w_j, w_{j+1}]$ was for the last time reflected from the foil. Obviously, $w_{j+1}(w_j) = w_{j-1}$. The relativistic speed $\beta_{j+1}(w)$ in the interval $w \in [w_j, w_{j+1}]$ is obtained by substituting $e_{j+1}(w)$ into Eq. (1). The position of the foil is then obtained from the formula

$$x_{j+1}(w) = x_j(w_j) + \int_{w_j}^{w} \frac{\beta_{j+1}(w^\prime)}{1 - \beta_{j+1}(w^\prime)} dw^\prime.$$

The relativistic kinetic energy of the accelerated ions for $w \in [w_0, w_j]$ is given by the formula

$$E_i(w) = m_e c^2 \frac{[e_j(w)]^2}{2[1 + e_j(w)]^2}.$$

If we use Eq. (5), Eq. (6) and Eq. (7) to calculate $e_j(w)$ at $w = w_j$, assuming a rectangular temporal profile of the pulse and $R_c = 1$, we obtain expression given in Eq. (13a) in [14].

Despite its simplicity and highly approximate character this model is useful in providing some concrete numbers for cavity-enhanced ion acceleration at future high-intensity laser facilities.

4 Concrete examples

Let us consider the predictions of the cavity-enhanced LS model in two concrete scenarios characterized by the same total laser fluence, but with distinctly different pulse lengths. The first scenario involves a pulse with the maximum intensity of $10^{21}$ W/cm$^2$ and the full width at half maximum equal to $t_{HW} = 1.3$ ps; such parameters should be in principle available for example at the future PETAL facility [25]. The second scenario involves a laser pulse with the maximum intensity of $10^{22}$ W/cm$^2$ and duration of 130 fs; such parameters should be in principle attainable for example with a slightly defocused kilojoule beam at the...
future ELI Beamlines facility [25]. The temporal profiles of these pulses are taken to be super-Gaussian, and they are assumed to start at the intensity smaller by a factor of 100 relative to the maximum intensity: \( I(t) = I_0 \exp\left[-\left(t - t_p/2\right)^2/\tau^2 \right] \) for \( t \in [0, t_p] \), where \( t_p = t_{lw} (\log 100/\log 2)^{1/6} \) and \( \tau = t_{lw} (\log 2)^{1/6} \). The laser energy fluence on target in both scenarios is equal to 12.81 J/(μm)^2.

Our target is assumed to be an ultra-thin carbon foil, with the density of 2.2 g/cm^3. In 1D the condition for nearly total reflection takes the form [23,24] \( \pi f/l(\lambda) \times (n_e/n_i) > a_0 \), where \( l \) is the foil thickness, \( \lambda \) is the laser wavelength (which is either 800 nm for ELI or 1054 nm for an Nd:glass picosecond laser), \( n_e \) is the electron number density in the ionized target, \( n_i = (4\pi^2c^2/m_e\varepsilon_0/e^2) \times (1/\lambda^2) \) is the critical electron density for a given wavelength (\( m_e \) is the electron mass), and \( a_0 \) is the dimensionless laser field amplitude, related to the intensity \( I \) of a circularly polarized beam by the relation \( I = m_e^3c^8n_ea_0^2 \). The non-transparency condition may be rewritten in the form

\[
l > \frac{2}{c n_e} \frac{\varepsilon_0 f}{e^2}.
\]

For a fully ionized carbon we have \( n_e = 6.62 \times 10^{21} \) cm^3, so for a circularly polarized beam with \( I = 10^{22} \) W/cm^2 we obtain a condition \( l > 32 \) nm. In the following we present concrete predictions for \( l = 200 \) nm, which in our view is a realistic value, leaving some margin for possible prepulse issues which might be important in the case of kilojoule beams. We then discuss how the achieved ion energies would scale with the thickness of the target. As for the cavity parameters, in both cases we choose as a reference value \( L_c = 80 \) μm, which seems to be a technologically achievable value, and we discuss the \( L_c \) dependence separately.

In Fig. 2 we show the evolution of the ion energy per atomic mass unit of ion mass (i.e. \( E_{ion}^\text{kin}/m_i \), where \( m_i \) is the ion mass) as a function of the acceleration distance for the 1.3 ps pulse with \( 10^{21} \) W/cm^2 peak intensity. The evolution in the absence of the cavity reflections is indicated by the solid line: the foil is rapidly accelerated over a distance of 215 μm to the energy of 119 MeV/u, and then “sails away” at a constant speed.

When reflections at the inner cavity wall are taken into account the acceleration of the foil is continuously enhanced by the laser pulse redirected multiple times towards the target by reflection at the inner cavity wall (as indicated by the dash-dotted line). For \( R_c = 0.7 \) the leading edge of the laser pulse hits the accelerating foil for the fourth time when the foil has moved approximately 410 μm from the starting position. The recirculation of laser light results in nearly doubling of the resulting ion energy relative to the case without the cavity reflection. For \( R_c = 0.5 \) (dashed line) the energies to which the ions are accelerated are slightly smaller, but the general pattern is the same.

The result for the ion energy per a.m.u. is easily converted into the laser-to-ion conversion efficiency, which is shown on the right side of the figure. The total ion energy per unit surface area of the target is given by \( \sigma \times E_{ion}^\text{kin}/m_i \), so every 10 MeV of ion energy per a.m.u. corresponds to the ion beam energy fluence of 42.45 MJ/cm², which implies a laser-to-ion energy conversion efficiency of 3.31%. Note that the acceleration efficiency is quite high - around 40% - even without the cavity reflections, which is characteristic of the radiation pressure acceleration in 1D geometry [15,24].

The results for ion energies reported above correspond to the target foil thickness of \( L = 200 \) nm, but due to the simplicity of the LS dynamics it is straightforward to extend them to other values of this parameter. In Fig. 3 we show the ion energy per a.m.u. at the acceleration distance of 300 μm, as a function of thickness of the target foil, with the fraction \( R_c = 0.7 \) of the laser energy being reflected at the inner cavity wall. For thinner targets higher ion energies are achieved, although the relation is far from trivial, since lighter targets are moving faster and may experience smaller number of reflections. However, in practice very thin targets may be used only when the level of contrast in the pulse is high, so that the foil would not damaged by the prepulse. It is interesting that energies of the order of 200 MeV/u - which is considered to be an important threshold for example for the hadron therapy [11] - seem to become accessible in the arrangement considered here.

In calculations shown in Fig. 2 we assumed \( L_c = 80 \) μm. In Fig. 4 we show the ion energy per a.m.u. at the acceleration distance of 300 μm, as a function of the depth \( L_c \) of the cavity, with \( R_c = 0.7 \). Somewhat surprisingly, this dependence turns out to be rather weak.

The evolution of ion energy per a.m.u. for the case of 130 fs pulse with \( 10^{22} \) W/cm² peak intensity is shown in Fig. 5. If there are no cavity reflections, the foil is rapidly accelerated over a very short distance of 22 μm, achieving the same energy as in the case of picosecond pulse, and then “sails away” at a constant speed. If reflections at the
Fig. 3. The ion energy per a.m.u. at the acceleration distance of 300 μm, as a function of the thickness of the target foil, for the 1.3 ps pulse with intensity of $10^{21}$ W/cm$^2$ peak, with the fraction $R_c = 0.7$ of the laser energy being reflected at the inner cavity wall.

Fig. 4. The ion energy per a.m.u. at the acceleration distance of 300 μm, as a function of the depth $L_c$ of the cavity, for the 1.3 ps pulse with intensity of $10^{21}$ W/cm$^2$ peak, with $R_c = 0.7$ of the laser energy being reflected at the inner cavity wall.

Fig. 5. The ion energy per a.m.u., as a function of the acceleration distance, for the 130 fs pulse with peak intensity of $10^{22}$ W/cm$^2$. The solid line indicates acceleration without cavity reflections, while the dash-dotted (dashed) line indicates the acceleration with the fraction $R_c = 0.7$ ($R_c = 0.5$) of the laser energy being reflected at the inner cavity wall. The dotted line corresponds to the case of a shorter cavity with $L_c = 60$ μm.

have small effect on the resulting ion energies when ultrathin target foils are used. This is an important information for the design of cavity targets, because it shows that it is enough for the cavity reflector to survive only few reflections, since the loss of further reflections due to a deteriorating cavity wall would not significantly affect the final result. However, this picture could be different if a more dense target is used, for example a metal foil. Such a foil would accelerate less rapidly, so even for a small acceleration distance many cavity reflections could occur. The ion energy per a.m.u. achieved without cavity reflections would be small in this case, but the enhancement due to presence of the cavity could be much bigger than 100%.

Figure 5 illustrates one possible risk for cavity-enhanced acceleration in the setup discussed above: the accelerated foil performs “free flight” over extended distances, because the spatial extension of the laser pulse is short compared to cavity depth and there is no overlap between the original pulse and redirected reflections. There is risk that during such motion plasma would expand and its density would drop below critical density, making it effectively transparent to the laser light. This could be avoided by reducing the cavity depth, as much as it is allowed by technological constraints. The effect of changing $L_c$ from 80 μm to 60 μm is illustrated in Fig. 5 with a dotted line.

5 Conclusions

Summarizing, we presented a simple implementation of the cavity-enhanced laser-driven ion acceleration - dubbed LICPA - in the light-sail regime. The model accommodates in a general way the additional contribution from pulses reflected from the target foil and redirected towards the target via reflection at the inner cavity wall. We had shown
how the effect of these reflections may be described by a semi-analytic formula. We used this formula to obtain concrete predictions for acceleration of an ultra-thin carbon foil, driven by laser pulses of different duration—a ps range pulse and a fs range pulse—and different intensity, but the same laser fluence, in the parameter range that would become available at forthcoming facilities, providing a convincing illustration of characteristic features of LICPA. The potential for a considerable increase in the ion energy and the laser-to-ion conversion efficiency relative to conventional laser-driven ion acceleration—by a factor of 1.5 or more—was clearly shown. Our results provide additional support for the use of circularly polarized beams for laser-driven acceleration. In addition to the fact that the basic interaction of such beams with solid targets leads to smaller target heating and smaller energy spread of accelerated ions, the fact that a substantial part of the beam is reflected from the target makes it possible to enhance the acceleration by recirculating the reflected pulse.

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