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Nonlinear interaction of ultraintense laser pulse with relativistic thin plasma foil in the radiation pressure-dominant regime

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Abstract. We present a study of the effect of laser pulse temporal profile on the energy/momentum acquired by the ions as a result of the ultraintense laser pulse focussed on a thin plasma layer in the radiation pressure-dominant (RPD) regime. In the RPD regime, the plasma foil is pushed by ultraintense laser pulse when the radiation cannot propagate through the foil, while the electron and ion layers move together. The nonlinear character of laser–matter interaction is exhibited in the relativistic frequency shift, and also change in the wave amplitude as the EM wave gets reflected by the relativistically moving thin dense plasma layer. Relativistic effects in a high-energy plasma provide matching conditions that make it possible to exchange very effectively ordered kinetic energy and momentum between the EM fields and the plasma. When matter moves at relativistic velocities, the efficiency of the energy transfer from the radiation to thin plasma foil is more than 30% and in ultrarelativistic case it approaches one. The momentum/energy transfer to the ions is found to depend on the temporal profile of the laser pulse. Our numerical results show that for the same laser and plasma parameters, a Lorentzian pulse can accelerate ions upto 0.2 GeV within 10 fs which is 1.5 times larger than that a Gaussian pulse can.

Keywords. High-intensity laser–matter interaction; ion acceleration; radiation pressure-dominant mechanism; plasma mirrors.

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1. Introduction

Today the laser drive of relativistic ions, i.e. ions whose kinetic energy exceeds their rest energy, is an attractive goal of the intense laser–matter interaction physics [1,2]. Higher laser intensities ($I > I_{\text{rad}} = 10^{23}$ W/cm^2 at a wavelength of 1 μm) allow us to use laser pulse particle acceleration in radiation pressure-dominant (RPD) regime. The radiation pressure of the laser acts on the electron component of the plasma layer which is pushed instantly. As a result of the charge separation, an intense electric field is created. Because of this intense electric field, the ions are accelerated and rush towards the electrons with almost the same velocity ($\sim c$) as that of the electrons. Ions, being heavier, acquire more energy. This is the mechanism of ion acceleration in RPD regime [3,4].

Radiation pressure arises from the 'coherent' interaction of the radiation with the particles in the medium. In the RPD regime, the accelerated plasma foil, i.e. a thin dense plasma foil, made of electrons and hydrogen ions (i.e. protons), pushed by ultraintense laser pulse in conditions where the radiation cannot propagate through the foil, while the electron and ion layers move together, can be regarded as forming (perfectly reflecting) relativistic plasma mirror copropagating with the laser pulse. The importance of the plasma mirror lies in the reflection of radiation from the copropagating plasma mirror (i.e. thin dense plasma slab). Relativistic plasma mirrors are being realized in the laboratory [5], and has the potential for efficient generation of hard X-rays/γ-rays [6,7]. As a consequence of the reflection from the copropagating plasma mirror, the frequency of the electromagnetic wave decreases by a factor of $(1-v/c)/(1+v/c) \approx 1/(4\gamma^2)$, where v is the mirror velocity and $\gamma = (1 - v^2/c^2)^{-1/2}$ is the Lorentz factor of the plasma mirror and the same increases by a factor of $4\gamma^2$ in the case of reflection from a counterpropagating plasma mirror [8].

In the RPD regime, the energy transfer from the laser to the ions can be seen by considering the reflection of the laser pulse in the laboratory frame. Before the reflection, the laser pulse has the energy $\varepsilon_L \propto E_L^2 L$, and after the reflection its energy becomes much lower:

$$\varepsilon_{L,\,ref} \propto \tilde{E}_L^2 \tilde{L} = \frac{E_L^2 L}{4\gamma^2},$$

where L is the incident pulse length, E_L is the laser electric field, $\tilde{E}_L$ is the reflected laser electric field and $\tilde{L}$ is the reflected pulse length. The reflected pulse length is longer by a factor of $4\gamma^2$ and the transverse electric field is smaller by a factor of $4\gamma^2$. Hence, the plasma mirror acquires the energy $(1 - (1/4\gamma^2))\varepsilon_L$ from the laser pulse [3]. For reflection from the thin plasma mirror receding at ultrarelativistic velocity radiation energy is almost completely transferred to the energy of ions. Thus, the efficiency of laser energy conversion into ordered kinetic energy of matter tends to unity when matter moves at ultrarelativistic velocities.

This process of ion acceleration is likely to open up a wealth of applications: in particular, radioisotope production [9], proton probing and oncological hadron therapy [10–12], novel high-energy physics applications e.g., production of large fluxes of neutrinos [13,14], high-energy astrophysical phenomena such as the formation of photon bubbles in the laboratory [15,16] etc. The acceleration of ions up to several tens of MeV by the interaction of intense laser beams ($I > 10^{20}$ W/cm^2) with solid targets has been recently reported in [17]. Ultraintense laser beams imply laser electric field that can accelerate ions to relativistic energies in N_L laser cycle. For this to be so the incident laser electric field E_L on thin plasma foil of thickness l must satisfy the condition $E_L > 2\pi e n_e l > m_i \omega c/2\pi e N_L$, where n_e is the electron density and ω is the angular frequency of the laser radiations [3]. Hence, to produce relativistic ions in one laser cycle we need an EM wave with $E_L > 300 m_e \omega c/e = 10^{15}$ V/m which corresponds to ultraintense laser intensity $I_L \sim 10^{23}$ W/cm^2. With a further increase of intensity in the range $I = 10^{23}$–10^{24} W/cm^2, radiation reaction comes into play giving rise to bright hard X-rays and γ-rays.

This paper presents an analytical and numerical study of the effect of the initial momentum of the ion and laser pulse profile on the energy/momentum acquired by the ions as a result of the intense laser–plasma interaction when the radiation pressure is dominant. We present our numerical results of the variation of the normalized energy $\varepsilon_{i,k}/m_i c^2$ of the ions as a function of time t. We also numerically study the dependence of the energy transfer to the ions on the laser pulse temporal profile. The numerical results show that a Lorentzian pulse can accelerate ions upto 0.2 GeV within 10 fs which is ~1.5 times more than that of Gaussian pulse.

The paper is organized as follows: Section 2 of the paper gives the basic equations depicting the equation of motion of a thin plasma foil under the action of the incident radiation pressure. Section 3 gives an upper limit to the ion energy. Results and discussion are given in §4 of the paper. Conclusions are drawn in §5 of the paper.

2. Equation of motion of thin plasma foil

The motion of thin plasma foil, when incident radiation is falling normally on it, is governed by the equation [3]

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{E_L^2[t - x(t)/c]}{2\pi n_e l} |\rho(\omega')|^2 \frac{(m_i^2 c^2 + p^2)^{1/2} - p}{(m_i^2 c^2 + p^2)^{1/2} + p}, \tag{1}$$

where p is the momentum of ions representing the foil. In the simplest case, when $E_L = \text{const.}$ and the reflection coefficient $\rho = 1$, the solution $p(t)$ is an algebraic function of t. Integrating (1), one gets

$$\frac{p}{m_i c} + \frac{2}{3}\left(\frac{p}{m_i c}\right)^3 + \frac{2}{3}\left(1 + \left(\frac{p}{m_i c}\right)^2\right)^{3/2} = \frac{E_L^2}{2\pi n_e l m_i c} t + \frac{k}{m_i c}, \tag{2}$$

where k is the constant of integration. For the initial condition $p = p_0$ at $t = 0$, one obtains

$$\frac{p}{m_i c} + \frac{2}{3}\left(\frac{p}{m_i c}\right)^3 + \frac{2}{3}\left(1 + \left(\frac{p}{m_i c}\right)^2\right)^{3/2} = \frac{E_L^2}{2\pi n_e l m_i c} t + \frac{p_0}{m_i c} + \frac{2}{3}\left(\frac{p_0}{m_i c}\right)^3 + \frac{2}{3}\left(1 + \left(\frac{p_0}{m_i c}\right)^2\right)^{3/2}, \tag{3}$$

or

$$\frac{3}{2}\left[\frac{p}{m_{\mathrm{i}}c}+\left(1+\left(\frac{p}{m_{\mathrm{i}}c}\right)^2\right)^{1/2}\right] + \frac{1}{2}\left[\frac{p}{m_{\mathrm{i}}c}+\left(1+\left(\frac{p}{m_{\mathrm{i}}c}\right)^2\right)^{1/2}\right]^3 = \Omega t + \frac{3}{2}h_0 + \frac{1}{2}h_0^3. \tag{4}$$

It can be written in a compact form as

$$p = m_{\mathrm{i}}c[\sinh(u) - \mathrm{cosech}(u)/4], \tag{5}$$

where

$u = 1/3 \times \mathrm{arcsinh}(\Omega t + h_0^3/2 + 3h_0/2)$,

$\mathrm{cosech}(u) = 1/\sinh(u)$,

$\Omega = 3E_{\mathrm{L}}^2/2\pi n_{\mathrm{e}} l m_{\mathrm{i}} c$

and

$$h_0 = \frac{p_0}{m_{\mathrm{i}}c} + \left(1+\left(\frac{p_0}{m_{\mathrm{i}}c}\right)^2\right)^{1/2}.$$

The ion kinetic energy is given by

$$\varepsilon_{\mathrm{ik}} = c(m_{\mathrm{i}}^2 c^2 + p^2)^{1/2} - m_{\mathrm{i}}c^2. \tag{6}$$

Substitution of p from eq. (5), one gets the following expression for ion kinetic energy:

$$\varepsilon_{\mathrm{ik}} = m_{\mathrm{i}}c^2[\sinh(u) + \mathrm{cosech}(u)/4 - 1]. \tag{7}$$

In the limit $t \to \infty$ it asymptotically tends to

$$\varepsilon_{\mathrm{ik}} \approx m_{\mathrm{i}}c^2(3E_{\mathrm{L}}^2 t/8\pi n_{\mathrm{e}} l m_{\mathrm{i}} c)^{1/3}. \tag{8}$$

3. Upper limit to the ion energy

The laser-accelerated ions have applications in the fast ignition of thermonuclear targets [18], hadron therapy in oncology [10], to generate ultrahigh intense electromagnetic fields [19] etc. Proof-of-principle experiments on the flying relativistic mirror concept are reported in ref. [20], where the generation of soft X-rays with a narrow energy spectrum was observed. In this experiment the frequency upshift factor reached the value from 50 to 114. In this reference it is important to evaluate the upper limit of the ion energy acquired due to the interaction with a laser pulse of finite duration. For this, we must include the dependence of the laser EM field on space and time. Because of the foil motion, the interaction time can be much longer than the laser pulse duration t_{L}. Therefore, it is convenient to consider the dynamics in terms of the dimensionless variable [3]

$$\psi = \int_{-\infty}^{t-x(t)/c} \frac{E_{\mathrm{L}}^2(\xi)}{4\pi n_{\mathrm{e}} l m_{\mathrm{i}} c}\mathrm{d}\xi, \tag{9}$$

which can be interpreted as the normalized energy of the laser pulse portion that has been interacting with the moving foil in time t. Its maximum value is $\max\{\psi\} = \varepsilon_{\mathrm{L}'}/N_{\mathrm{i}} m_{\mathrm{i}} c^2$, where $\varepsilon_{\mathrm{L}'} = E_{\mathrm{L}}^2 sct_{\mathrm{las,int}}/(4\pi)$ is the laser pulse energy, $N_{\mathrm{i}} = n_{\mathrm{e}} l s$ is the number of ions in the region of area s of the foil irradiated by the laser pulse. The solution of eq. (1), rewritten in terms of ψ, gives the ion kinetic energy

$$\varepsilon_{\mathrm{ik}} = m_{\mathrm{i}}c^2 \frac{(2\chi\psi + h_0 - 1)^2}{2(2\chi\psi + h_0)}, \tag{10}$$

where

$$\chi = \frac{1}{\psi}\int_0^{\psi} |\rho(\omega')|^2 \mathrm{d}\psi.$$

The upper limit of the ion kinetic energy and, correspondingly, the laser to ion energy transformation can be found from eq. (10) by substituting $\psi = \max\{\psi\}$:

$$\varepsilon_{\mathrm{ik,\,max}} = m_{\mathrm{i}}c^2 \frac{(2\chi(\varepsilon_{\mathrm{L}}/N_{\mathrm{i}} m_{\mathrm{i}} c^2) + h_0 - 1)^2}{2(2\chi(\varepsilon_{\mathrm{L}}/N_{\mathrm{i}} m_{\mathrm{i}} c^2) + h_0)}, \tag{11}$$

where χ is the reflection coefficient, taken in the co-moving reference frame, averaged over the foil motion path; $0 < \chi \le 1$. For $p_0 = 0$, eq. (11) reduces to

$$\varepsilon_{\mathrm{ik,\,max}} = \frac{2\chi\varepsilon_{\mathrm{L}}}{2\chi\varepsilon_{\mathrm{L}} + N_{\mathrm{i}} m_{\mathrm{i}} c^2}\frac{\chi\varepsilon_{\mathrm{L}}}{N_{\mathrm{i}}}. \tag{12}$$

We see that, within this model, almost all the energy of the laser pulse is transformed into the energy of the ions if $\varepsilon_{\mathrm{L}} \gg N_{\mathrm{i}} m_{\mathrm{i}} c^2/2$. The acceleration length $x_{\mathrm{acc}} \approx ct_{\mathrm{acc}}$ and the acceleration time t_{acc} can be estimated as

$$t_{\mathrm{acc}} \approx (2/3)[\varepsilon_{\mathrm{L}}/N_{\mathrm{i}} m_{\mathrm{i}} c^2]^2 t_{\mathrm{L}}.$$

For obtaining numerical results for ion energy and momentum, we consider the following laser intensity temporal profiles:

$$E_{\mathrm{L}}^2(t) = E_{\mathrm{L}}^2, \quad \text{constant profile,}$$

$$E_{\mathrm{L}}^2(t) = E_{\mathrm{L}}^2 \exp[-(t/\tau)^2], \quad \text{Gaussian profile,}$$

$$E_{\mathrm{L}}^2(t) = E_{\mathrm{L}}^2\left[\frac{1}{1+(t/\tau)^2}\right], \quad \text{Lorentzian profile.}$$

For this we solve eq. (1) numerically using Runga–Kutta method. We present our results in §4.

4. Results and discussion

We give our numerical results for the maximum momentum and energy transfer from laser to foil, assuming the moving foil opacity/transparency. The laser and thin plasma foil parameters chosen are: laser intensity $I = 1.37\times10^{23}$ W/cm^2, laser wavelength $\lambda = 1$ μm and, pulse duration ∼100 fs, laser spot size $= 10^{-6}$ cm^2 , laser energy ∼10 kJ, thin foil thickness $l = 1$ μm and electron density $n_e = 5.5\times10^{22}$/cm^3. We solve numerically the differential equation (1) of the foil accelerated by the radiation pressure. The results show that the maximum energy/momentum transfer to the ions occurs when the laser pulse profile is Lorentzian. With increasing value of initial momentum p_0 of the thin plasma layer, the relativistic factor increases and as a consequence the energy and momentum transfer from the laser to the plasma layer increases. As a result, the laser pulse energy transferred to the mirror is $\sim(1-(1/4\gamma^2))\varepsilon_L$, where ε_L is the energy of the incident laser. Effectively, increasing p_0 enhances the energy/momentum transfer from laser to thin plasma layer.

Figure 1 shows the variation of the normalized ion momentum $p/m_i c$ and ion kinetic energy $\varepsilon_{ik}/m_i c^2$ as a function of absolute time t when the intensity of the incident laser pulse is constant. The curves are shown for initial value of ion momentum $p_0 = 0.0, 0.1, 0.2$ (in the unit $m_i c$). Incident laser intensity is assumed to be constant at $I = 1.37 \times 10^{23}$ W/cm^2. By increasing the initial value of the momentum p_0, the momentum

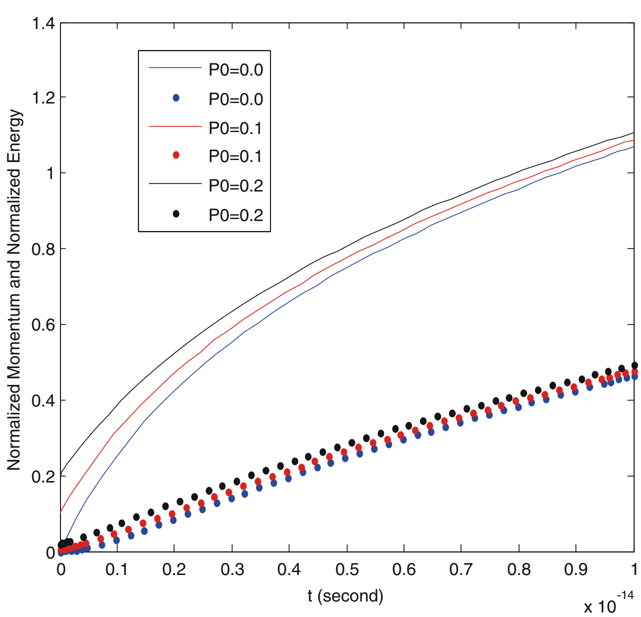

Figure 1. Variation of the normalized ion momentum $p/m_i c$ and ion kinetic energy $\varepsilon_{ik}/m_i c^2$ as a function of the absolute time t when the incident laser pulse is of constant intensity. The curves are shown for initial value of ion momentum. $p_0 = 0.0, 0.1, 0.2$ (in the unit $m_i c$).

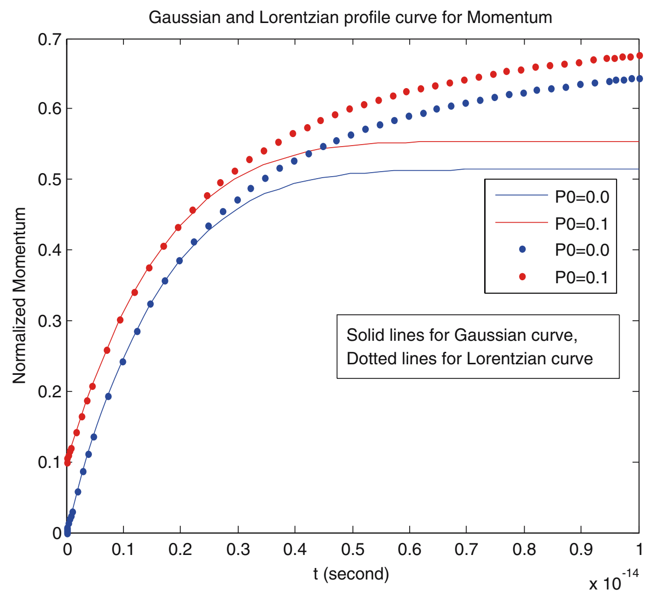

Figure 2. The variation of the normalized ion momentum $p/m_i c$ as a function of the absolute time t, when the incident laser pulses are Gaussian and Lorentzian. Solid lines correspond to Gaussian curve and dotted lines correspond to Lorentzian curve. The curves are shown for initial value of ion momentum. $p_0 = 0.0, 0.1$ (in the unit $m_i c$).

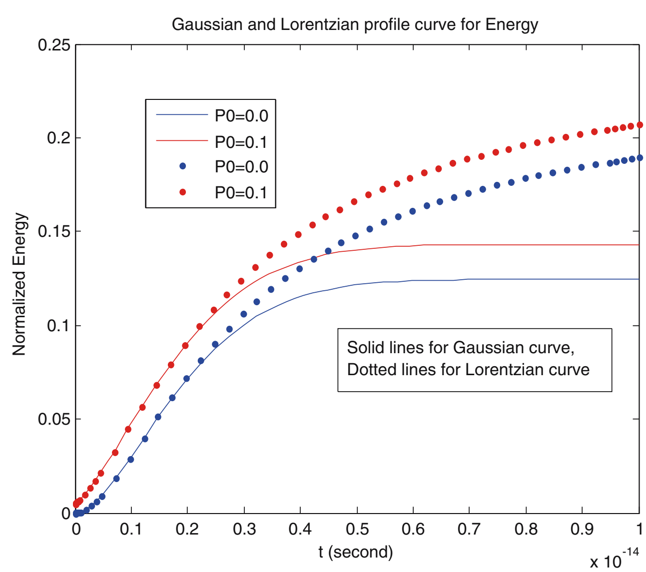

Figure 3. The variation of the normalized ion kinetic energy $\varepsilon_{ik}/m_i c^2$ as a function of the absolute time t, when the incident laser pulses are Gaussian and Lorentzian. Solid lines correspond to Gaussian curve and dotted lines correspond to Lorentzian curve. The curves are shown for initial value of ion momentum. $p_0 = 0.0, 0.1$ (in the unit $m_i c$).

gained by the ions from the incident laser pulse also increases. However as $t \to \infty$, the final momentum approaches a limit which is completely independent of the initial value p_0.

Figure 2 shows the variation of the normalized ion momentum $p/m_i c$ as a function of the absolute time t, when the incident laser pulses are Gaussian and Lorentzian. The curves are shown for initial value of ion momentum $p_0 = 0.0, 0.1$ (in the unit $m_i c$). Incident laser intensity $I = 1.37 \times 10^{23}$ W/cm^2. By increasing the initial value of the momentum p_0, the momentum gained by the ions from the incident laser pulse also increases. However, as $t \to \infty$, the final momentum value takes a steady value which increases with increase in the initial value p_0.

Figure 3 shows the variation of the normalized ion kinetic energy $\varepsilon_{ik}/m_i c^2$ as a function of the absolute time t, when the incident laser pulses are Gaussian and Lorentzian. The laser intensity $I = 1.37 \times 10^{23}$ W/cm^2. By increasing the initial value of the momentum p_0, the energy gained by the ions from the incident laser pulse also increases. However, as $t \to \infty$, the final energy value takes a steady value which increases with increase in the initial value p_0.

Figure 4 shows the variation of the normalized maximum ion energy $\max\{\varepsilon_{ik}\}/m_i c^2$ as a function of the incident normalized laser energy $(\varepsilon_L/(N_i m_i c^2/2))$. We see that in the extreme case $((\varepsilon_L/(N_i m_i c^2/2)) \geq 1)$

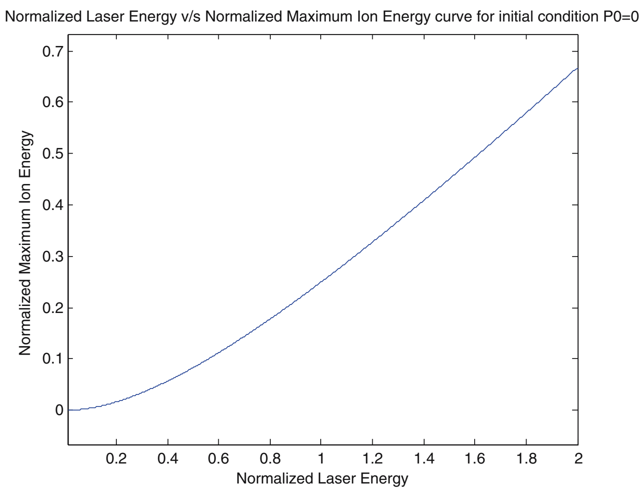

Figure 4. The variation of the normalized maximum ion energy $\max\{\varepsilon_{ik}\}/m_i c^2$ as a function of the incident normalized laser energy $(\varepsilon_L/(N_i m_i c^2/2))$ when ions are initially at rest.

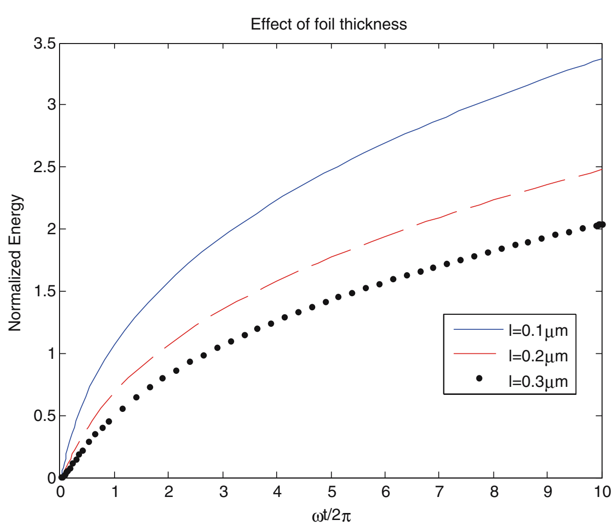

Figure 5. The variation of normalized energy of the ion $\varepsilon_{ik}/m_i c^2$ as a function of normalized time $\omega t/2\pi$ for various values of foil thickness $l = 0.1\ \mu$m, 0.2 μm, 0.3 μm.

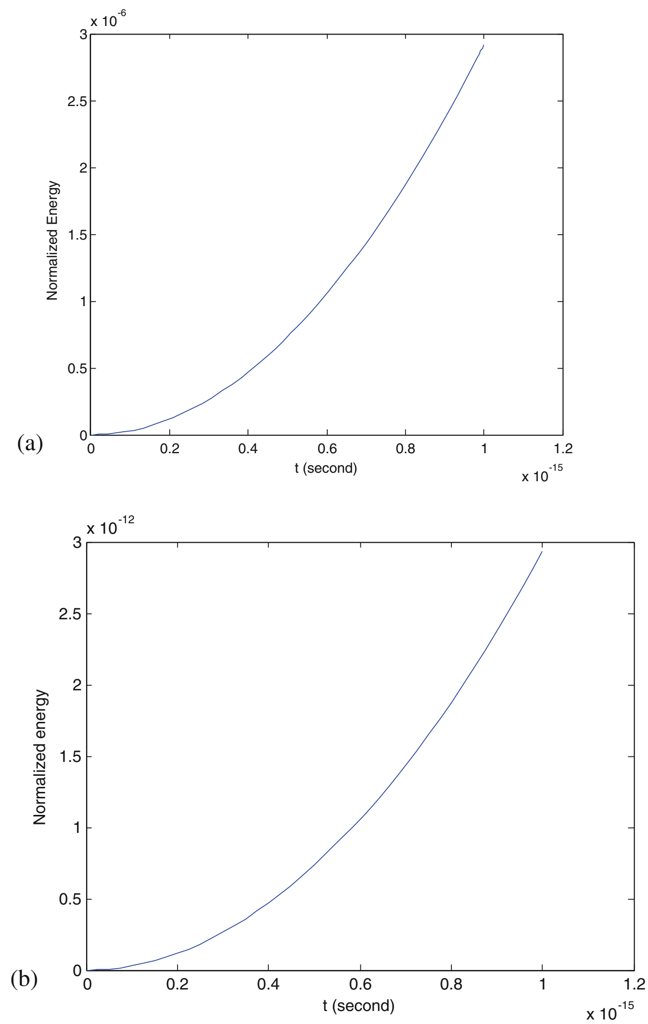

Figure 6. The variation of the normalized ion energy $\varepsilon_{ik}/m_i c^2$ as a function of the absolute time t: (**a**) corresponds to intensity $I \sim 10^{21}$ W/cm^2 and (**b**) corresponds to intensity $I \sim 10^{18}$ W/cm^2.

almost all the laser pulse energy is transformed into the energy of the ion.

Figure 5 shows the variation of normalized energy of the ions $\varepsilon_{\mathrm{ik}}/m_{\mathrm{i}}c^2$ as a function of the normalized time $\omega t/2\pi$ for various values of foil thickness $l = 0.1$ μm, 0.2 μm, 0.3 μm. Incident laser intensity is assumed to be constant at $I = 1.37 \times 10^{23}$ W/cm^2. The kinetic energy of the ion increases with the decrease of the foil thickness.

Figure 6 shows the variation of the normalized ion energy $\varepsilon_{\mathrm{ik}}/m_{\mathrm{i}}c^2$ as a function of the absolute time t. Figure 6a corresponds to $I \sim 10^{21}$ W/cm^2 and figure 6b corresponds to $I \sim 10^{18}$ W/cm^2. In both cases, we see that the kinetic energy of the ion is almost negligible. So, for the smooth ion acceleration in the radiation pressure-dominant regime, the intensity must be between 10^{23} and 10^{24} W/cm^2.

5. Conclusions

The radiation pressure dominant regime of laser ion acceleration requires high-intensity laser pulses to function efficiently. Moreover, the foil should be opaque for the incident radiation during the interaction to ensure maximum momentum transfer from the pulse to the foil, which required proper matching of the target to the laser pulse [21]. A dense ion-electron layer moving at a relativistic speed almost fully reflects the incident electromagnetic pulse. Interaction with such a relativistic mirror reduces the energy of the reflected electromagnetic wave by a factor of $\approx 1/4\gamma^2$. Results show that the momentum acquired by the ions as a result of laser interacting with a thin plasma foil is more when incident laser pulse profile is Lorentzian. Highest value of the momentum gained by the ions by the Lorentzian pulse is $\sim$1.25 times the Gaussian pulse for the same intensity. The numerical results also show that the energy gained by the ions when accelerated by the Lorentzian pulse is $\sim$1.5 times more than when accelerated by the Gaussian pulse. We find that incident laser pulse of the Lorentzian form is reasonable for a compact laser ion accelerator.

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