Effects of substrate-ion density gradients on light-ion acceleration from ultraintense laser pulse irradiated thin-foils*

Liu Ming-Wei(刘明伟), Li Ru-Xin(李儒新)†, Xia Chang-Quan(夏长权), Liu Jian-Sheng(刘建胜), and Xu Zhi-Zhan(徐至展)

State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, *China*

(Received 10 August 2009; revised manuscript received 30 November 2009)

A general solution of the electrostatic potential that determines the maximum light-ion energy is derived for the test-particle acceleration model by taking into account the influence of the substrate-ion density gradient. It is shown that the substrate-ion density structure is also dependent on laser pulse duration. In the picosecond or sub-picosecond regime, the decreasing density gradient of the substrate-ions leads to an evident reduction in the acceleration efficiency of the light-ions. However, this kind of influence is negligible in the ultrashort regime.

Keywords: laser–plasma interaction, ion acceleration, substrate-ion density gradient
PACC: 5250J, 5275D, 5240

1. Introduction

Generating energetic ion beams from thin foils irradiated by ultraintense laser pulses has become an area with growing interest because of several present and potential applications, such as radiography,[1] fast ignition,[2,3] introduction of nuclear phenomena,[4,5] cancer therapy,[6] and production of radioactive isotope for positron emission tomography.[7] Laser accelerated ion beams with energies up to multi-MeV were observed in experiments,[7−12] based on the so-called target normal sheath acceleration (TNSA) mechanism.[13] For the purpose of applications, much attention has been paid to the optimization of the interaction conditions so that one can appropriately choose the laser-target parameters and optimize (as well as control) the quality of the ion beams, which requires a well understanding of the effects that affect the ion beam quality.

According to the target composition,[14] there are two typical kinds of analytical models describing the ion acceleration process. In the high light-ion (e.g. proton) density limit, this process is usually described as quasi-neutral or non-quasi-neutral plasma expansion into a vacuum.[15−22] If the light-ion density is sufficiently low, it is convenient to describe the light-ions as 'test particles',[23−25] which will be accelerated by an electrostatic field established by the (heavy) substrate-ions and electrons. And it is usually assumed that (hot as well as cold) electrons follow the Maxwell–Boltzmann distribution,[13−25] although the electron density described by the Maxwell–Boltzmann function is nonzero until $x \to \infty$, indicating an infinite extent of the accelerating field. Therefore, in order to obtain a finite acceleration process, it is commonly assumed that ions are accelerated up to the time of laser pulse duration $\tau_{\rm L}$, although, e.g. in the expansion model, the acceleration time $t_{\rm acc} \sim 1.3\tau_{\rm L}$ matches well with the experimental results.[19] Assuming that the election population can be described with the Maxwell–Boltzmann function, Passoni and Lontano[25] proposed that only those bounded electrons could contribute to the formation of the electron cloud on the target rear surface, while the most energetic electrons were lost from the system, and thus successfully predicted a finite acceleration process for the light ions. However, the substrate-ion density in their model was assumed to be uniform and it is found

*Project supported by the National Natural Science Foundation of China (Grant No. 10734080), the National Basic Research Program of China (Grant No. 2006CB806000), the Chinese Academy of Sciences, the Shanghai Commission of Science and Technology (Grant Nos. 06DZ22015 and 0652nm005), and the Hunan Provincial Natural Science Foundation of China (Grant No. 09JJ3012).
†Corresponding author. E-mail: ruxinli@mail.shcnc.ac.cn
© 2010 Chinese Physical Society and IOP Publishing Ltd

that the relative deviation of their model values from the experimental results depends on laser pulse duration. In the expansion model, it was demonstrated that a finite ion density gradient could reduce the maximum ion energy.[13,16−19] However, to our knowledge, the influence of a substrate-ion density gradient on the light-ion acceleration has not been studied analytically.

In this paper, we study the effect of a finite substrate-ion density gradient on light-ion acceleration by making use of the test-particle model in which only bounded electrons contribute to the formation of the electron cloud. And the dependence of the substrate-ion density gradient on the pulse duration is analysed according to the deviation of the modified model values from the experimental results.

2. Derivation of the maximum light-ion energy

We consider a one-dimensional plasma composed of cold substrate ions with charge state $Z_{\rm I}$ and hot electrons at initial temperature T in the interval $-d \leq x \leq 0$, where d represents a finite extent of the target. At the rear surface, i.e. $x = 0$, a quasi-steady equilibrium is assumed.[25] Moreover, the influence of cold electrons is neglected for simplicity. Instead of a uniform distribution, the substrate-ion density is assumed to have a finite gradient from the position $x = -l_{\rm s}$ in the front, that is, one can write the substrate-ion density in three regions (defined as in Fig. 1) as follows:

$$\mathrm{I}: n_{\rm I} = 0 \quad (x > 0), \tag{1}$$

$$\mathrm{II}: n_{\rm I} = n_{\rm I0} g(\phi) \quad (-l_{\rm s} \leq x \leq 0), \tag{2}$$

$$\mathrm{III}: n_{\rm I} = n_{\rm I0} \quad (x \leq -l_{\rm s}), \tag{3}$$

where $n_{\rm I0}$ is a constant value of the substrate-ion density, and $g(\phi)$ is a function representing the finite substrate-ion density gradient. What should be mentioned is that in region II we describe the substrate-ion density as a function of electrostatic potential ϕ, since the electrons are commonly assumed to follow the Maxwell–Boltzmann distribution, i.e. an explicit function of ϕ. Therefore, in the ultrarelativistic limit, the density of the bound electrons participating in the formation of the quasistationary electron cloud on the target rear surface can be written as[25]

$$n_{\rm e} = \tilde{n}_k \left[\exp\left(\frac{e\phi}{T}\right) - 1 \right], \tag{4}$$

where e is the electron charge and $\tilde{n}_k$ is a constant related to the maximum electron density. According to Eq. (4), it is seen that ϕ is zero only when $x \geq \tilde{x}$ (a distance from $x = 0$ outside the target); otherwise, $\phi > 0$ always holds.

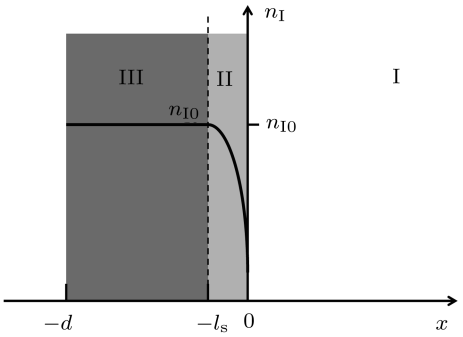


Fig. 1. Sketch of the heavy substrate-ion distribution. To the right of the dash line, an example with a decreasing substrate-ion density gradient is illustrated. Light-ions are accelerated in region I (the sheath) by the E field.

According to the test-particle model, the light-ions are accelerated in region I and their influence on the acceleration field is assumed to be negligible. Moreover, the heavy substrate-ions are assumed to be immobile during the light-ion acceleration. Then, it is not necessary to consider the details of the light-ions motion in determination of their maximum energy after acceleration. Assume that a light-ion is initially located at $x = 0$ with zero velocity and charge state $Z_{\rm i}$, then after acceleration in region I, its maximum kinetic energy will be simply given by

$$\varepsilon_{\rm i,max} = Z_{\rm i} e \phi_0, \tag{5}$$

where ϕ_0 is the quasistationary potential at position $x = 0$. If one further assumes that the (hot) electrons produced by the laser pulse have effective temperature T on the order of the ponderomotive potential of the laser pulse, the maximum energy of the accelerated light-ions then can be written as

$$\varepsilon_{\rm i,max} = Z_{\rm i} \tilde{\varphi}_0 m_{\rm e} c^2 \left(\sqrt{1 + \frac{I_{\rm L} \lambda^2}{1.37 \times 10^{18}}} - 1 \right), \tag{6}$$

where $\tilde{\varphi}_0 = e\phi_0/T$ is the normalised potential at $x = 0$, $m_{\rm e}$ is the rest mass of electrons, c is the light velocity in vacuum, $I_{\rm L}(\mathrm{W \cdot cm^{-2}})$ is the laser pulse intensity, and $\lambda\,(\mu\mathrm{m})$ is the laser wavelength.

To determine $\tilde{\varphi}_0$, one needs to solve the Poisson equation

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}x^2} = 4\pi e(n_{\rm e} - Z_{\rm I} n_{\rm I}), \tag{7}$$

in regions I, II and III. If we define the dimensionless potential $\varphi = e\phi/T$ and distance $\xi = x/\lambda_{\rm D}$, where

$\lambda_{\rm D} = \sqrt{T/4\pi\tilde{n}_k e^2}$ is the Debye length, the Poisson equation in region I simply reads

$$\frac{{\rm d}^2\varphi_1}{{\rm d}\xi^2} = {\rm e}^{\varphi_1} - 1, \tag{8}$$

where φ_1 is the normalised potential outside the target ($\xi \geq 0$) and satisfies the boundary conditions $\varphi_1|_{\xi=\tilde{x}/\lambda_{\rm D}} = 0$ and ${\rm d}\varphi_1/{\rm d}\xi|_{\xi=\tilde{x}/\lambda_{\rm D}} = 0$. Integrating Eq. (8), it is easy to obtain the acceleration field (normalised by $E_0 = \sqrt{4\pi\tilde{n}_k T}$) and the implicit solution between φ_1 and ξ, i.e.

$$-\frac{{\rm d}\varphi_1}{{\rm d}\xi} = \sqrt{2}\left[{\rm e}^{\varphi_1} - 1 - \varphi_1\right]^{1/2}, \tag{9}$$

$$\int_{\tilde{\varphi}_0}^{\varphi_1} \frac{{\rm d}\varphi}{({\rm e}^{\varphi} - 1 - \varphi)^{1/2}} = -\sqrt{2}\xi, \tag{10}$$

respectively. Making use of continuity conditions $\varphi_1|_{\xi=0} = \varphi_2|_{\xi=0} \equiv \tilde{\varphi}_0$, $\varphi_2|_{\xi=\xi_{\rm s}} = \varphi_3|_{\xi=\xi_{\rm s}} \equiv \varphi_{\rm s}$, and ${\rm d}\varphi_1/{\rm d}\xi|_{\xi=0} = {\rm d}\varphi_2/{\rm d}\xi|_{\xi=0}$, integrating the Poisson equations in regions II and III once, yield

$$\frac{{\rm d}\varphi_2}{{\rm d}\xi} = -\sqrt{2}\left[{\rm e}^{\varphi_2} - \varphi_2 - \alpha\int_{\tilde{\varphi}_0}^{\varphi_2} g(\varphi){\rm d}\varphi - 1\right]^{1/2}, \tag{11}$$

$$\frac{{\rm d}\varphi_3}{{\rm d}\xi} = -\sqrt{2}\left[{\rm e}^{\varphi_3} + {\rm e}^{\varphi^*}(\varphi^* - 1 - \varphi_3)\right]^{1/2}, \tag{12}$$

respectively, where $\varphi_{\rm s}$ is the normalised potential at $\xi_{\rm s} = -l_{\rm s}/\lambda_{\rm D}$, φ_2 and φ_3 are the normalised potentials in regions II and III, $\alpha = {\rm e}^{\varphi^*} - 1$, and φ^* is the normalised potential at $\xi_{\rm d} < 0$ inside the target and the plasma becomes locally quasineutral when $\xi \leq \xi_{\rm d}$. The potential φ^* is also associated with the normalised maximum energy of the trapped electrons and can be scaled as[25]

$$\varphi^* \approx 4.8 + 0.8\ln[\varepsilon_{\rm L}({\rm J})], \tag{13}$$

where $\varepsilon_{\rm L}({\rm J})$ is the laser energy. It is easy to see that $\xi_{\rm d} \leq \xi_{\rm s} \leq 0$.

If one further imposes the continuity of the electrostatic field at $\xi = \xi_{\rm s}$, i.e. ${\rm d}\varphi_2/{\rm d}\xi|_{\xi=\xi_{\rm s}} = {\rm d}\varphi_3/{\rm d}\xi|_{\xi=\xi_{\rm s}}$, from Eqs. (11) and (12), a general (implicit) solution of $\tilde{\varphi}_0$ is then given by

$$\int_{\varphi_{\rm s}}^{\tilde{\varphi}_0} g(\varphi){\rm d}\varphi = \frac{{\rm e}^{\varphi^*}(\varphi^* - \varphi_{\rm s} - 1) + \varphi_{\rm s} + 1}{{\rm e}^{\varphi^*} - 1}. \tag{14}$$

Equations (6), (13) and (14) determine the maximum energy of the light-ions in the presence of a finite substrate-ion density gradient. It can be directly seen that Eq. (14) reduces into the expression

$$\tilde{\varphi}_0 = \varphi_0 = \frac{{\rm e}^{\varphi^*}(\varphi^* - 1) + 1}{{\rm e}^{\varphi^*} - 1}, \tag{15}$$

when $\varphi_{\rm s} = \varphi_0$, which is identical to the assumption that substrate-ion density is uniform.[25] Then it is reasonable to write out the relation $\varphi_0 \leq \varphi_{\rm s} \leq \varphi^*$. That is, one can define

$$\varphi_{\rm s} = \varphi_0 + \beta(\varphi^* - \varphi_0), \tag{16}$$

where $\beta \in [0, 1]$ is a parameter related to the strength of the substrate-ion density gradient.

3. Numerical analysis

In the usual test-particle model,[23−25] the assumption that the immobile substrate-ions are uniform indicates that their density has a sharp boundary at the target–vacuum interface. And an exponentially decreasing ion density along the propagation distance can be obtained by considering a quasi-neutral and uniform plasma expanding into a vacuum.[13,15] Therefore, we assume the exponential expression of the substrate-ion density with a finitely sharp boundary in the following calculation. And it will be shown that the substrate-ion density is sufficiently low at the sharp boundary when the gradient strength is large in the decreasing gradient case.

When the target is irradiated by a long (e.g. picosecond or sub-picosecond) laser pulse, the hot electrons produced by the leading edge of the pulse can induce the significant preheating of the target rear surface. And the substrate-ions are more efficient to expand into the vacuum on a large time scale. That is, the substrate-ion density decreases along the propagation distance when the pulse duration is long. This is consistent with the experimental results as listed in Table 1. For example, the value of maximum proton energy $\varepsilon_{\rm p0}$ (MeV), estimated according to Passoni's uniform substrate-ions model,[25] presents a larger (positive) relative deviation [i.e. $\Delta\varepsilon_{\rm r0} = (\varepsilon_{\rm p0} - \varepsilon_{\rm pm})/\varepsilon_{\rm pm}$] from the experimental result $\varepsilon_{\rm pm}$ (MeV) when the pulse duration is longer. This overestimation indicates that substrate-ion expansion hampers light-ion acceleration and is nonnegligible when the foil is irradiated by a relatively long laser pulse.

Table 1. Values of laser energy $\varepsilon_{\rm L}$ (MeV), pulse duration $\tau_{\rm L}$ (fs), pulse intensity $I_{\rm L}$ ($\rm W\cdot cm^{-2}$), maximum proton energy $\varepsilon_{\rm pm}$(MeV) (experiment) and $\varepsilon_{\rm p0}$(MeV) (Passoni's model), relative derivation $\Delta\varepsilon_{\rm r0}$ (Passoni's model) and $\Delta\varepsilon_{\rm r}$ (modified model), and gradient strength parameter β, with laser wavelength $\lambda = 1$ μm.

Ref.	$\varepsilon_{\rm L}$	$\tau_{\rm L}$	$I_{\rm L}$	$\varepsilon_{\rm pm}$	$\varepsilon_{\rm p0}$	$\Delta\varepsilon_{\rm r0}$	β	$\Delta\varepsilon_{\rm r}$
[8]	500	500	3×10^{20}	58	61.7	6.5%	0.7	0.7%
[9]	400	700	2×10^{20}	44	48.6	10%	0.8	0.6%

Since the electric field in the target decreases rapidly, the expansion of the substrate-ions can be considered to start from the effective position $\xi = \xi_{\rm s}$ (correspondingly, $\varphi = \varphi_{\rm s}$). Therefore, we propose an exponentially decreasing density in the form $n_{\rm I} = n_{\rm I0}\exp[\varphi - \varphi_{\rm s}]$ for the substrate-ions in region II. Then one has the gradient function

$$g(\varphi) = \exp[\varphi - \varphi_{\rm s}]. \tag{17}$$

Substituting Eq. (17) into Eq. (14) yields the relation between $\tilde{\varphi}_0$ and φ^*, i.e.

$$\tilde{\varphi}_0 = \varphi_{\rm s} + \ln\left[\frac{\varphi^*}{1-{\rm e}^{-\varphi^*}} - \varphi_{\rm s}\right]. \tag{18}$$

Equations (6), (13) and (18) lead to the relations from which we can modify the maximum light-ion energy by taking into account the influence of a decreasing substrate-ion density gradient. To demonstrate the modification, we define a relative deviation of the modified maximum proton energy [i.e. $\varepsilon_{\rm p} = \varepsilon_{\rm i,max}$ with $Z_{\rm i} = 1$, according to Eqs. (6), (13) and (18)] from the experimental results, i.e. $\Delta\varepsilon_{\rm r} = (\varepsilon_{\rm p} - \varepsilon_{\rm pm})/\varepsilon_{\rm pm}$. As shown in Table 1, a larger modification is required in the longer pulse duration case, since the resulting expansion of the substrate-ions is stronger.

To further illustrate the improvement arising from a decreasing substrate-ion density gradient, the distributions of the (normalised) substrate-ion and electron densities [i.e. $n_{\rm I}$ (represented by solid, dot and dash curves) and $n_{\rm e}$ (represented by solid-circle, dot-delta and dash-square curves)], normalised potential $\varphi = e\phi/T$, and normalised electric field $E = -{\rm d}\varphi/{\rm d}\xi$ along propagation distance $\xi = x/\lambda_{\rm D}$ are plotted in Fig. 2(a), Fig. 2(b) and Fig. 2(c), respectively, in the cases of different gradient strengths, i.e. $\beta = 0$ (solid curves, the results from Passoni's model[25]), $\beta = 0.6$ (dot curves) and $\beta = 0.9$ (dash curves). The laser wavelength is $\lambda = 0.8$ μm and the laser energy is $\varepsilon_{\rm L} = 6$ J. First, we consider the uniform and weak gradient substrate-ion distribution cases. As shown by solid and dot curves in Fig. 2(c), the electric field decreases rapidly in the target. That is, it is reasonable to neglect the expansion after a position $\xi_{\rm s}$ when the expansion time is not too long, as shown, for example, by the dash curves with $\beta = 0.6$, and this corresponds to $\sim 5.8\%$ modification of the maximum light-ion energy with respect to that from Passoni's model. However, the modification becomes very large when $\beta \geq 0.9$, e.g. the modification is about 24% when $\beta = 0.9$. Correspondingly, the electric field extends deeply into the target. And the ion density in the front of the substrate-ions becomes very low, that is, the sharp boundary falls. But the extreme case of this kind should not be reasonable for the test-particle model, since the light-ions should be accelerated before significant (collective) expansion of the substrate-ions.[23–25] We also plot the maximum proton energy $\varepsilon_{\rm p}$ as a function of the laser intensity $I(10^{20}$ W $\cdot$ cm$^{-2})$ in Fig. 2(d), according to Eqs. (6), (13) and (18). It is shown that the modification increases with gradient strength parameter increasing and the modified maximum proton energy rises more slowly in comparison with that in the uniform case when the laser intensity increases.

However, if the target is irradiated by an ultrashort laser pulse with a pulse duration of tens of femtoseconds, a reduction in substrate-ion density, due to the collective expansion and the preheating by the pulse leading edge, is negligible in this short time regime. What should be mentioned is that a significant fraction of the hot electrons produced from the front of the target can escape from the target only when the target is sufficiently charged due to the target capacitance.[17] Moreover, the maximum substrate-ion density should be somewhat larger than that of the bounded electrons, considering the contribution of those (lost) most energetic electrons. That is, an increasing substrate-ion density should be suitable for modifying the assumption of uniform density when the foil is irradiated by an ultrashort laser pulse. And this is really indicated by the values of $\Delta\varepsilon_{\rm r0}$ listed in Table 2. From this point of view, we simply assume an exponentially increasing substrate-ion density in region II, i.e. $n_{\rm I} = n_{\rm I0}\exp[\varphi_{\rm s} - \varphi]$, to improve

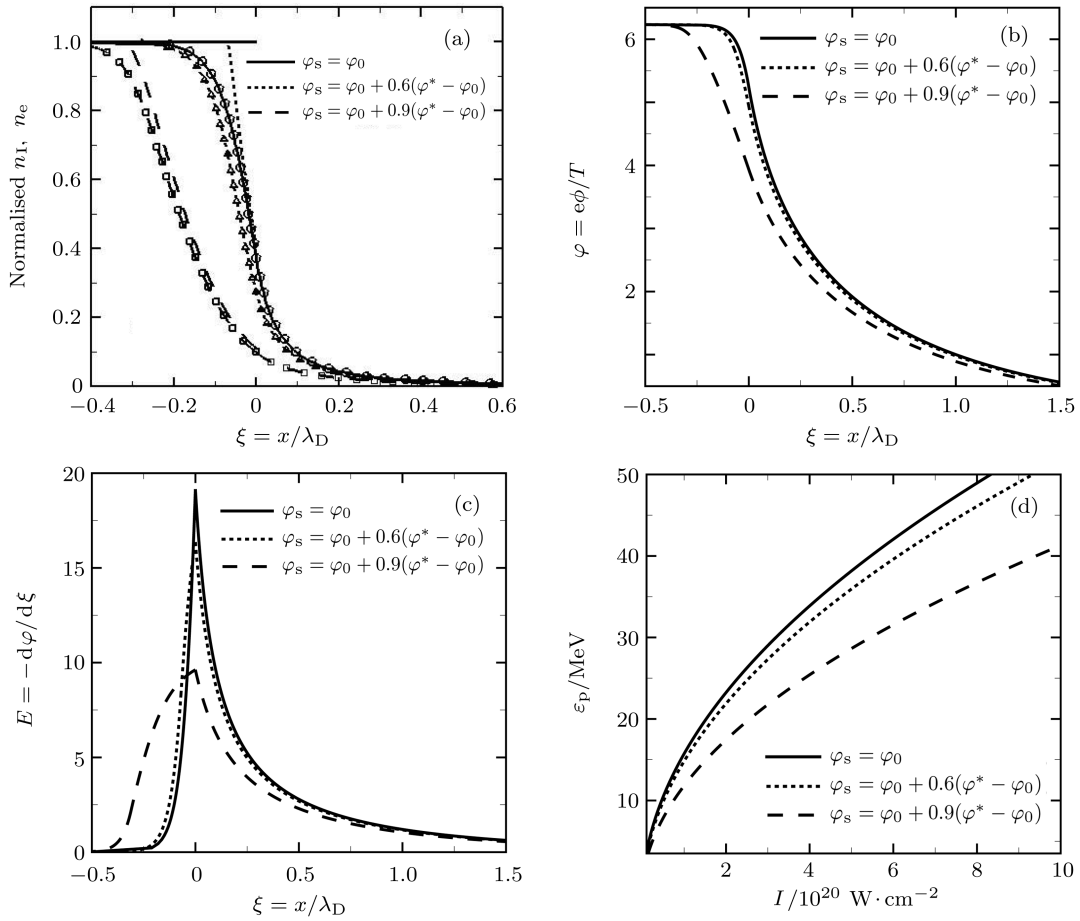


Fig. 2. Spatial distributions of normalised substrate-ion density $n_{\rm I}$ (represented by solid, dot and dash curves) and corresponding electron density $n_{\rm e}$ (represented by solid-circle, dot-delta and dash-square curves) (a), corresponding distributions of potential φ (b) and electric field $E = -{\rm d}\varphi/{\rm d}\xi$ (c), and maximum proton energy $\varepsilon_{\rm p}$ (MeV) derived from Eqs. (6), (13) and (18) versus laser intensity (d), in the different gradient strength cases.

the underestimation of the maximum light-ion energy by Passoni's model.[25] The gradient function is then given by

$$g(\varphi) = \exp\left[\varphi_{\rm s} - \varphi\right]. \tag{19}$$

Making use of Eq. (19), it is easy to derive the expression of $\tilde{\varphi}_0$ from Eq. (14), i.e.

$$\tilde{\varphi}_0 = \varphi_{\rm s} - \ln\left[\varphi_{\rm s} + 2 - \frac{\varphi^*}{1 - {\rm e}^{-\varphi^*}}\right]. \tag{20}$$

Correspondingly, the modified maximum light-ion energy is determined by Eqs. (6), (13) and (20).

Table 2. Values of laser energy $\varepsilon_{\rm L}$ (MeV), pulse duration $\tau_{\rm L}$ (fs), laser intensity $I_{\rm L}$ (W·cm^{-2}), maximum proton energy $\varepsilon_{\rm pm}$(MeV) (experiment) and $\varepsilon_{\rm p0}$ (MeV) (Passoni's model), relative deviation $\Delta\varepsilon_{\rm r0}$ (Passoni's model) and $\Delta\varepsilon_{\rm r}$ (modified model), and gradient strength parameter β, with laser wavelength $\lambda = 0.8$ μm.

Ref.	$\varepsilon_{\rm L}$	$\tau_{\rm L}$	$I_{\rm L}$	$\varepsilon_{\rm pm}$	$\varepsilon_{\rm p0}$	$\Delta\varepsilon_{\rm r0}$	β	$\Delta\varepsilon_{\rm r}$
[7]	0.84	40	6×10^{19}	9.5	8.5	–10%	1	–6.3%
[10]	0.2	60	7×10^{18}	1.5	1.39	–7.3%	0.7	0.3%
[11]	0.1	60	6.8×10^{18}	1.2	1.12	–6.6%	0.7	–0.2%
[12]	0.6	150	1×10^{19}	2.5	2.4	–4.8%	0.5	0.3%

According to the values of β and $\Delta\varepsilon_{\rm r}$ in Table 2, it seems that a larger modification is needed when the laser pulse duration is shorter in the ultrashort regime. Correspondingly, when the laser pulse duration increases towards the sub-picosecond regime, the effects leading to an increasing density gradient should weaken while those decreasing the substrate-ion density become dominant. Therefore, the maximum light-ion energy estimated from Passoni's model[25] will be in excellent agreement with the experimental results in the relatively moderate short pulse duration regime. But what should be mentioned is that an increasing substrate-ion density gradient has never been considered before, and the ion expansion is commonly assumed to occur from a uniform density distribution.[13,15] Preformed decreasing plasma density gradients at the target rear surface were demonstrated experimentally to show that decreasing ion density gradients could hamper the ion acceleration,[17,18] also as suggested by the simulation results of the expansion model[16]. However, it may not be easy to truly diagnose the density structure of the substrate-ions produced by field ionisation in the target within an extent less than the Debye length before obvious (collective) expansion as displayed in Figs. 2(a) and 3(a). Moreover, the expansion model and the test-particle model are applicable for different conditions.[14]

Taking into account the influence of an increasing substrate-ion density gradient with different values of the strength parameter, i.e. $\beta = 0$ (represented by solid curves, the results of Passoni's model[25]), $\beta = 0.6$ (represented by dot curves) and $\beta = 0.9$ (represented by dash curves), the distributions of $n_{\rm I}$ and $n_{\rm e}$, $\varphi = e\phi/T$ and $E = -{\rm d}\varphi/{\rm d}\xi$ in the ultrashort pulse case are also plotted in Fig. 3(a), Fig. 3(b) and Fig. 3(c), respectively. And the evolution of

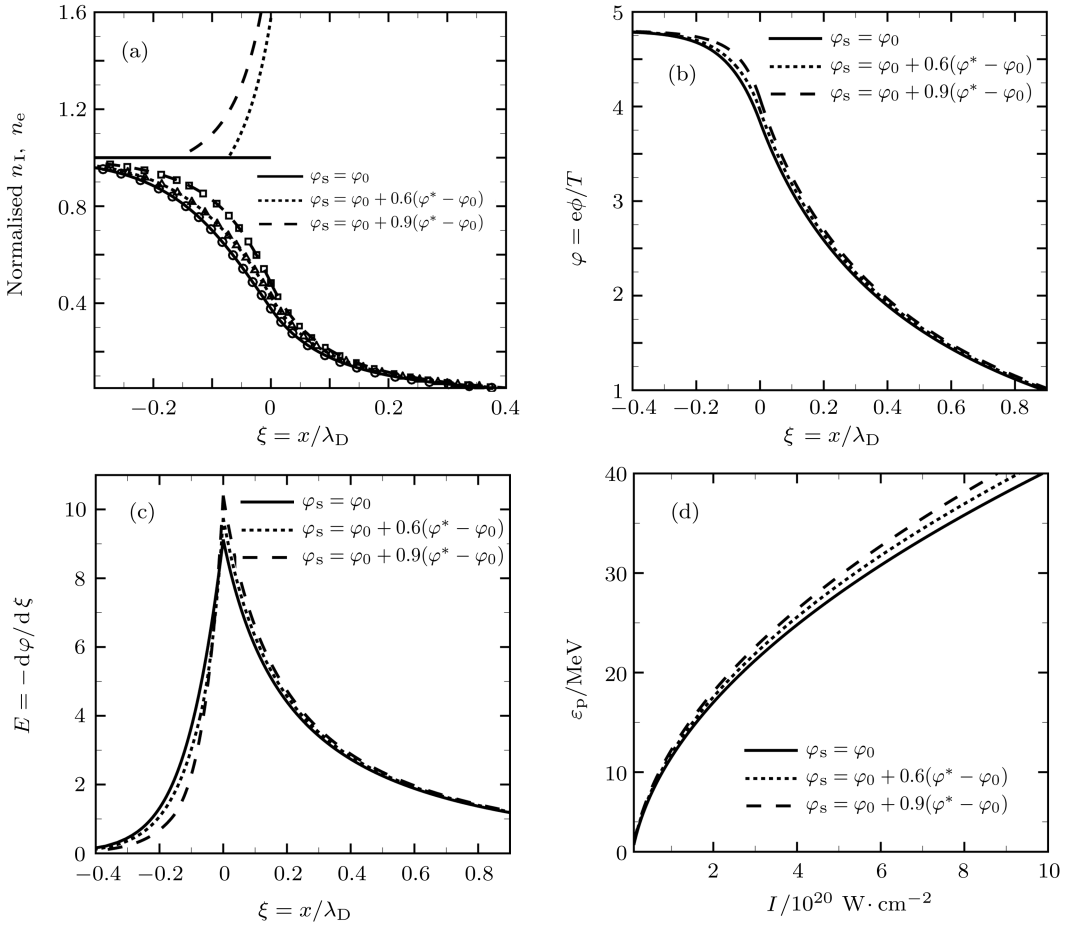


Fig. 3. Spatial distributions of normalised substrate-ion density $n_{\rm I}$ (represented by solid, dot and dash curves) and corresponding electron density $n_{\rm e}$ (represented by solid-circle, dot-delta and dash-square curves) (a), corresponding distributions of potential φ (b) and electric field $E = -{\rm d}\varphi/{\rm d}\xi$ (c), and maximum proton energy $\varepsilon_{\rm p}$ (MeV) derived from Eqs. (6), (13) and (20) versus laser intensity (d), in the different gradient strength cases.

the corresponding maximum proton energy is plotted in Fig. 3(d) as a function of the laser intensity I (10^{20} W $\cdot$ cm^{-2}). The laser energy is $\varepsilon_{\rm L} = 1$ J and the laser wavelength is $\lambda = 0.8$ μm. However, the modification for Passoni's model from this kind of increasing substrate-ion density gradient is not so efficient as that in the decreasing gradient case, although the substrate-ions are assumed to highly accumulate in the front. For example, this modification is $\sim 6.3\%$ even the strength parameter $\beta = 0.9$. This may come from the fact that the hot electrons produced by ultraintense laser–solid interactions do not entirely satisfy the Maxwellian distribution in a quite short period.[26]

4. Conclusion

The light-ion acceleration in the quasistationary electronic field at the foil rear surface is studied by taking into account the influence of finite substrate-ion density gradients. It is qualitatively shown that the laser pulse duration determines the substrate-ion density structure, which further affects the light-ion acceleration. In the picosecond and the sub-picosecond time regimes, due to the expansion and the preheating by the laser pulse leading edge, the substrate-ion density has a decreasing gradient along the propagation distance and hampers the light-ion acceleration. This characteristic is similar to that occurring in the expansion model. In the ultrashort time regime, the increasing substrate-ion density gradient is demonstrated to be able to improve the model results estimated on the assumption that the substrate-ion density is uniform. However, the improvement is not so efficient as that in the decreasing gradient case. The non-Maxwellian distribution of the hot electrons may also make a significant contribution in this ultrashort period.[26]

References

[1] Borghesi M, Cecchetti C A, Toncian T, Fuchs J, Romagnani L, Kar S, Wilson P A, Antici P, Audebert P, Brambrink E, Pipahl A, Amin M, Jung R, Osterholz J, Willi O, Nazarov W, Clarke R J, Notley M, Neely D, Mora P, Grismayer T, Schurtz G, Schiavi A, Sentoku Y and d' Humieres E 2008 *IEEE Trans. Plasma Sci.* **36** 1833

[2] Roth M, Cowan T E, Key M H, Hatchett S P, Brown C, Fountain W, Johnson J, Pennington D M, Snavely R A, Wilks S C, Yasuike K, Ruhl H, Pegoraro F, Bulanov S V, Campbell E M, Perry M D and Powell H 2001 *Phys. Rev. Lett.* **86** 436

[3] Li S W, Yi R Q, Jiang X H, He X A, Chui Y L, Liu Y G, Ding Y K, Liu S Y, Lan K, Li Y S, Wu C S, Gu P J, Pie W B and He X T 2009 *Acta Phys. Sin.* **58** 3255 (in Chinese)

[4] Ledingham K W D, McKenna P and Singhal R P 2003 *Science* **300** 1107

[5] Lu H Y, Wang C, Chen G L, Kim C J, Liu J S, Ni G Q, Li R X and Xu Z Z 2009 *Chin. Phys.* B **18** 537

[6] Khoroshkov V S and Minakova E I 1998 *Eur. J. Phys.* **19** 523

[7] Fritzler S, Malka V, Grillon G, Rousseau J P, Burgy F, Lefebvre E, d'Hunières E, McKenna P and Ledingham K W D 2003 *Appl. Phys. Lett.* **83** 3039

[8] Snavely R A, Key M H, Hatchett S P, Cowan T E, Roth M, Phillips T W, Stoyer M A, Henry E A, Sangster T C, Singh M S, Wilks S C, MacKinnon A, Offenberger A, Pennington D M, Yasuike K, Langdon A B, Lasinski B F, Johnson J, Perry M D and Campbell E M 2000 *Phys. Rev. Lett.* **85** 2945

[9] McKenna P, Ledingham K W D, Yang J M, Robson L, McCanny T, Shimizu S, Clarke R J, Neely D, Spohr K, Chapman R, Singhal R P, Krushelnick K, Wei M S and Norreys P A 2004 *Phys. Rev.* E **70** 036405

[10] Spencer I, Ledingham K W D, McKenna P, McCanny T, Singhal R P, Foster P S, Neely D, Langley A J, Divall E J, Hooker C J, Clarke R J, Norreys P A, Clark E L, Krushelnick K and Davies J R 2003 *Phys. Rev.* E **67** 046402

[11] Fujii T, Oishi Y, Nayuki T, Takizawa Y, Nemoto K, Kayoiji T, Horioka K, Okano Y, Hironaka Y, Nakamura K G and Kondo K 2003 *Appl. Phys. Lett.* **83** 1524

[12] Kaluza M, Schreiber J, Santala M I K, Tsakiris G D, Eidmann K, Meyer-ter-Vehn J and Witte K J 2004 *Phys. Rev. Lett.* **93** 045003

[13] Wilks S C, Langdon A B, Cowan T E, Roth M, Singh M, Hatchett S, Key M H, Pennington D, MacKinnon A and Snavely R A 2001 *Phys. Plasmas* **8** 542

[14] Robinson A P L, Bell A R and Kingham R J 2006 *Phys. Rev. Lett.* **96** 035005

[15] Mora P 2003 *Phys. Rev. Lett.* **90** 185002

[16] Grismayer T and Mori P 2006 *Phys. Plasmas* **13** 032103

[17] Mackinnon A J, Borghesi M, Hatchett S, Key M H, Patel P K, Campbell H, Schiavi A, Snavely R, Wilks S C and Willi O 2001 *Phys. Rev. Lett.* **86** 1769

[18] Fuchs J, Cecchetti C A, Borghesi M, Grismayer T, d' Humières E, Antici P, Atzeni S, Mora P, Pipahl A, Romagnani L, Schiavi A, Sentoku Y, Toncian T, Audebert P and Willi O 2007 *Phys. Rev. Lett.* **99** 015002

[19] Fuchs J, Antici P, d' Humières E, Lefebvre E, Borghesi M, Brambrink E, Cecchetti C A, Kaluza M, Malka V, Manclossi M, Meyroneinc S, Mora P, Schreiber J, Toncian T, Pépin H and Audebert P 2006 *Nature Phys.* **2** 48

[20] Huang Y S, Bi Y J, Shi Y J, Wang N Y, Tang X Z and Gao Z 2009 *Phys. Rev.* E **79** 036406

[21] Huang Y S, Shi Y J, Bi Y J, Duan X J, Wang N Y, Tang X Z and Gao Z 2009 *Phys. Rev.* E **80** 056403

[22] Murakamia M and Basko M M 2006 *Phys. Plasmas* **13** 012105

[23] Schreiber J, Bell F, Grüner F, Schramm U, Geissler M, Schnürer M, Ter-Avetisyan S, Hegelich B M, Cobble J, Brambrink E, Fuchs J, Audebert P and Habs D 2006 *Phys. Rev. Lett.* **97** 045005

[24] Albright B J, Yin L, Hegelich B M, Bowers K J, Kwan T J T and Fernández J C 2006 *Phys. Rev. Lett.* **97** 115002

[25] Passoni M and Lontano M 2008 *Phys. Rev. Lett.* **101** 115001

[26] Huang Y S, Bi Y J, Duan X J, Lan X F, Wang N Y, Tang X Z and He Y X 2008 *Appl. Phys. Lett.* **92** 141504