Laser and Particle Beams (2008), *26*, 671–675. Printed in the USA.

doi:10.1017/S0263034608000748

Time-dependent neutral-plasma isothermal expansions into a vacuum

Y. HUANG,[1] X. DUAN,[2] X. LAN,[2] Z. TAN,[2] N. WANG,[2] X. TANG,[2] AND Y. HE[3]

[1]Department of Engineering Physics, Tsinghua University, Beijing, China and China Institute of Atomic Energy, Beijing, China
[2]China Institute of Atomic Energy, Beijing, China
[3]Department of Engineering Physics, Tsinghua University, Beijing, China

(RECEIVED 15 April 2008; ACCEPTED 1 August 2008)

Abstract

A time-dependent solution for neutral-plasma isothermal expansions into a vacuum in a special-transformation coordinate system is obtained. In this new coordinate system, the special self-similar solutions of it were given by Huang and co-workers (Appl. Phys. Lett. 92, 031501). Combining the time-dependent solution and the quasi-linear increase of the electron density due to the hot-electron recirculation, an analytic model is proposed to reveal the influence of the hot-electron recirculation on the increase of electric field and on the acceleration of ions of different masses and charges.

Keywords: Hot-electron recirculation; Laser-ion acceleration; Time-dependent

INTRODUCTION

The generation of energetic particles and acceleration mechanisms in the ultra-intense laser pulses interaction with plasmas have become an international research focus nowadays (Chen *et al.*, 2008; Karmakar & Pukhov, 2007; Schwoerer *et al.*, 2006; Flippo *et al.*, 2007; Kaluza *et al.*, 2004; d'Humires *et al.*, 2005; Wilks *et al.*, 2001; Huang *et al.*, 2007, 2008*a*, 2008*b*). Some new schemes with novel targets (Limpouch *et al.*, 2008; Schwoerer *et al.*, 2006; Strangio *et al.*, 2007; Schollmeier *et al.*, 2007) to enhance the ion acceleration and improve the quality of ion beams have been proposed. The progress of them can provide fundamental theory for inertial confined fusion (ICF) (Eliezer *et al.*, 2007) and promote the realization of it effectively. The target normal sheath acceleration (TNSA) (Wilks *et al.*, 2001) is a generally accepted mechanism for the ion acceleration. However, the fundamental theory of TNSA is a special self-similar solution for neutral-plasma isothermal expansions into a vacuum (Mora, 2003; Huang *et al.*, 2008*a*, 2008*b*), which is time-independent in the transformation system. Whatever, the influence of the hot-electron recirculation has not been accounted for in the self-similar solution. Therefore, it is suitable for the target thickness larger than a critical value, L_c. Mackinnon *et al.* (2002) observed enhancement of proton acceleration by hot-electron recirculation in thin foils whose thickness is less than L_c. In addition, Sentoku *et al.* (2003) predicted an equation to conclude the influence of electron recirculation. However, they did not propose a clear description of electron recirculation. Their physical picture is too simple and not clear because n times of electron recirculations cannot happen all at once and the electron density cannot jump to n times of the initial density. Although Huang *et al.* (2007) have proposed the step model to describe the hot-electron recirculation in which the electron density increased step by step, the step model combined the Mora's result and the linear increase of the electron density easily. However, an analytic solution on the bases of the fundamental equations: the equations of continuity and motion of the ions are still needed to reveal the influence of the hot-electron recirculation on maximum ion velocity rationally.

In this paper, a time-dependent solution for neutral-plasma isothermal expansions into a vacuum and a simple model based on the equations of continuity, and motion of the ions are proposed to obtain the time-dependent electron density and maximum ion velocity for the target of arbitrary thickness. The model describes the hot-electron recirculation and the influence of it on the ion acceleration in the laser-foil interactions analytically. The maximum ion velocity given by our model for some target thicknesses have been compared with experiments (Mackinnon *et al.*, 2002; Kaluza *et al.*, 2004). Since the decrease of the laser

Address correspondence and reprint requests to: Yongsheng Huang, Department of Engineering Physics, Tsinghua University, Beijing 100084, China. E-mail: hyc05@mails.tsinghua.edu.cn

absorption efficiency and the three-dimensional (3D) effect on the electron density have been ignored, the results given by our model are larger than the experimental data for thin targets. In order to understand the differences in some degree, the influence of the decrease of the laser absorption efficiency and the 3D effect on the ion acceleration have been discussed.

TIME-DEPENDENT TARGET NORMAL SHEATH ACCELERATION

For convenience, the physical parameters are normalized as follows:

$$\begin{gathered}\hat{t} = \omega_{pi0} t, \quad \hat{l} = l/\lambda_{D0}, \\ u = v/c_s, \quad \hat{E} = E/E_0, \quad \hat{\phi} = e\phi/k_B T_e, \\ \hat{n} = n/n_{e0}, \quad \hat{c} = c/c_s,\end{gathered} \tag{1}$$

where E is the electric field, n (n_i or n_e) is the density (ion or electron), n_{e0} is the reference hot-electron density at the rear of the target, ϕ is the electric potential, $c_s = \sqrt{Zk_B T_e/m_i}$ is the ion acoustic speed, $\omega_{pi0} = \sqrt{Zn_{e0}e^2/m_i\epsilon_0}$ is the initial ion plasma frequency, $\lambda_{D0} = c_s \omega_{pi0}$, c is the light speed and $E_0 = k_B T_e / e\lambda_{D0}$. Here e is the elemental charge.

When a relativistic laser pulse interacts with a solid target, the laser-produced fast electrons with a unique temperature, $k_B T_e$, determined by the laser ponderomotive potential are instantly created in front of the target and propagate through the target collisionlessly, and then form a high energy plasma at the rear of the target. The hot-electrons at the rear of the target can be considered to be reflected by sheath field at the ion front (Santos *et al.*, 2002; Mora, 2003) and come back to the front of the target, because the field there is strongest. No matter, the laser pulse exists or has gone, the hot electrons are assumed to be reflected back and forth between the front of the target and the ion front at the rear of the target. Furthermore, the electron beam is assumed to be in equilibrium with a single temperature $k_B T_e$. Let the zero time be when the hot electrons come to the rear of the target for the first time and $t_0 = 0$. For convenience, the hot-electron speed used is the light speed c. Therefore, the time is $-L/c$ when the laser get to the front target, where L is solid target thickness. The electrons return back from the rear at $t = 0$ and arrive at the front of the target when $t = L/c$. For $t \leq t_l$, assuming the laser intensity is constant, the hot-electron temperature, $k_B T_e = m_e c^2(\gamma - 1)$, is invariant due to the energy supply from the laser pulse. The plasma expansion is an isothermal expansion. Let $\hat{t}_1$ be the time when the hot electrons undergo a circle and reach the ion front again at the first time.

The reference frame used here is $\tau = \hat{t}$, $\xi = \hat{x}/\hat{t}$. With the transformation, the equations of continuity and motion are obtained easily in the new coordinate system.

The fast-electron density is a function of the parameters: the acceleration time, τ, the target thickness, L, laser intensity, I, laser focus radius, r_L, the laser absorption efficiency, η, the incidence angle of the laser pulse, θ_{in}, the half-opening angle of fast electrons, θ_e and amplified spontaneous emission (ASE) duration, τ_{ASE}. The laser absorption mechanisms in the femtosecond laser-plasma interactions determine the generation rate of the hot electrons, f, and then the laser absorption efficiency, η (Cai *et al.*, 2006). Assuming the time-dependent electron density for thin foils is variable-separating, then:

$$n_e(\tau, \xi) = N(\tau) N_e(\xi), \; N(\tau = \tau_L) = 1, \tag{2}$$

where $\tau_L = 2\hat{L}/c/\sqrt{2e}$, $N_e = n_{e0}\exp(-\xi/\beta_1 - 1)$, n_{e0} is the hot-electron density when $t = t_L = 2L/c$, β_1 is a constant and $N(\tau)$ describes the increase of the maximum electron density due to electron recirculation and the electron generation by the laser-plasma interactions at the front of the target. The physical implication of β_1 is the same as that given by Huang *et al.* (2008) and corresponds to $P_k = (Z_k/M_k)(M/Z)$ (where Z and M are the charge number and mass of the reference ion, Z_k and M_k are the charge number and mass of the concerned ion, respectively) in (Gurevich *et al.*, 1979). For different ions, β_1 will be different. Therefore, the acceleration of ions of different masses and charges can be described with our model. If we choose the proton as the reference ion, $\beta_1 \leq 1$ for any other ions. Here, $N_e = n_{e0}\exp(-\xi/\beta_1 - 1)$ corresponds to the special self-similar solution given by Huang *et al.* (2008*a*, 2008*b*) and Gurevich *et al.* (1979) for the impurity ions. $\beta_1 = 1$ corresponds to the classic self-similar solution given by Mora (2003).

Assuming that f is constant in the interval, t_l, the hot-electron total number that propagate through the target when $t = t_l$, $N_t = \eta(L)E_l/(k_B T_e)$ for $t_l \leq t_L$, and $N_t = \eta(L)E_l t_L/(k_B T_e t_l)$ for $t_l \geq t_L$, where E_l is the laser energy. Using Eq. (2) (Kaluza *et al.*, 2004), with N_t, then n_{e0} in Eq. (2) can be estimated by:

$$n_{e0} = \frac{4.077\,\eta(L) I_{10^{18}\mathrm{W/cm^2}}}{(\gamma - 1)(1 + (L^*/r_L)\tan(\theta_e))^2}, \; t_L \leq t_l, \tag{3}$$

where r_L is the laser pulse focus radius, $L^* = L/\cos(\theta_{in})$ is the efficient target thickness, θ_{in} is the incidence angle of the laser pulse, and $\theta_e \approx 17^\circ$ is half-opening angle of the superathermal electrons which was measured by Santos *et al.* (2002). When $r_L \gg L$ and $\tan(\theta_{in}) \ll 1$, $(1 + (L^*/r_L)\tan(\theta_{in}))^2 \approx 1$, the angular effect can be neglected. Therefore, the influence of $\eta(\hat{L})$ and electron recirculation become dominated for thin targets.

As usual, assuming that the hot electrons satisfy uniform distribution in the bulk from the front of the target to the ion front and $f = \bar{f}$ where $\bar{f}$ is the mean value of f, $N(\tau)$ can be roughly described by:

$$N(\tau) = \frac{\tau}{\tau_L}\frac{\hat{L} + \hat{l}(\tau_L)}{\hat{l}(\tau) + \hat{L}}, \; \tau \leq \tau_l. \tag{4}$$

For $\tau_L \leq \tau_l$, the electron density increases continuously until $t = t_l$. With Eq. (4), the maximum value of $N(\tau)$ is larger than 1, which can describe hot-electron recirculation (Mackinnon *et al.*, 2002; Sentoku *et al.*, 2003; Huang *et al.*, 2007). However, for $\tau_L \geq \tau_l$, the maximum value of $N(\tau)$ is smaller than 1. Therefore, it is assumed conveniently that the hot-electron recirculation stop synchronously with laser pulse ending. As pointed by Huang *et al.* (2007), the critical condition for hot-electron recirculation is $\tau_L = \tau_l$ and the critical target thickness is: $L_c = 0.5ct_l$. Therefore, hot-electron recirculation should be considered for $L \leq L_c$.

With the quasi-neutral approximation, $n_i = n_e = Nn_{e0} \exp(-\xi/\beta_1 - 1)$. Solving the equations of continuity and motion of ions, the time-dependent ion velocity and potential are $u_i = \xi + \beta_1 + \beta_1\delta(\tau)$, $\hat{\phi} = -\beta_1\xi - \beta_1^2 + \phi_1(\tau, \xi)$, where $\delta(\tau) = \tau\partial \ln N(\tau)/\partial\tau$, and $\phi_1 = -\beta_1(2\tau\partial \ln N/\partial\tau + \tau^2\partial^2 \ln N/\partial\tau^2)\xi$. With this, neutral condition of the plasma is still satisfied. Therefore, the zero-ion-velocity position should be: $\xi_{u_i=0} = -\beta_1[1 + \tau\partial \ln N(\tau)/\partial\tau]$ or $x_{u_i=0} = -\tau\beta_1[1 + \tau\partial \ln N(\tau)/\partial\tau]$. For $N \equiv 1$, the result is the same as the self-similar solution's result (Huang *et al.*, 2008*a*, 2008*b*). Therefore the dependence of the ion velocity on the time is:

$$u_i = \ln(\tau^{\beta_1} N) + \beta_1\tau\partial \ln N(\tau)/\partial\tau. \tag{5}$$

Eq. (5) shows the influence of the time-dependent electron density on the ion acceleration. Now the first part of Eq. (5) is $\ln(\tau N)$ compared with $\ln(\tau)$ in the classic solution (Mora, 2003). For $N > 1$, the hot-electron recirculation affects the ion acceleration. The second part exists for $\partial \ln N(\tau)/\partial\tau \neq 0$ that means time-dependent. For $N \equiv 1$, Eq. (5) returns to the self-similar solution (Huang *et al.*, 2008*a*, 2008*b*), which is time-independent.

The ion velocity at the ion front is the maximum ion velocity. Beyond the ion front, the ion density is zero and the electron density is still demonstrated by Eq. (2). The field for the ions at $\xi < \xi_{i,f}$, where $\xi_{i,f}$ is the self-similar variable at the ion front, is shielded by the ions beyond them. Therefore, the ion velocity at the ion front is larger than the ion velocity at $\xi < \xi_{i,f}$ and can not be described by Eq. (5), and should be obtained by another way. There are two methods to obtain the ion-front velocity: a mathematical way used by Huang *et al.* (2008*a*, 2008*b*); a physical way given by Mora (2003). For convenience, the physical way will be used here. Similar with Mora's discussion (Mora, 2003), using $\lambda_D = \lambda_{D0}(n_{e0}/n_e)^{1/2} = c_s t$, the ion velocity at the ion front is given by:

$$u_{i,f} = \beta_1 \ln(\tau^2 N) + \beta_1\tau\partial \ln N(\tau)/\partial\tau. \tag{6}$$

Eq. (6) shows that the ion velocity at the ion front is larger than that given by Eq. (5) and $u_{i,f} - u_i = \beta_1 \ln(\tau)$.

Eqs. (4) and (6) are combined to give: $u_{i,f} = C_1(t) \beta_1[\ln(\tau^2 N) + 1]$, where $C_1(t) = (\hat{l}(\tau) + \hat{L})/(\hat{l}(\tau) + \hat{L} + \beta_1\tau)$. For $\hat{l}(\tau) + \hat{L} \gg \tau$ at $\tau \leq \tau_{acc}$, $C_1 \approx 1$. $\hat{l}(\tau)$ is the position of the ion front. With $u_{i,f} = 0$, the beginning time of the ion acceleration is: $\tau_b = [(\tau_L/e)\hat{L}/(\hat{L} + \hat{l}(\tau_L))]^{1/3}$, here $e = 2.71828....$ Therefore, the position of the ion front is decided by:

$$dF/d\tau = (\beta_1 F/(F + \beta_1\tau))[\ln(\tau^3 F_L/\tau_L F) + 1],\ \tau \in [\tau_b, \tau_{acc}]. \tag{7}$$

where $F = \hat{L} + \hat{l}(\tau)$ and $F_L = \hat{L} + \hat{l}(\tau_L)$.

However, for $l_f(\tau_L) \approx l_f(\tau_{acc})$ or $L \gg l_f(\tau_{acc})$, $N(\tau_{acc}, L) \approx (L_c/L)(L + l_f(\tau_L)/(L + l_f(\tau_{acc}))) \approx L_c/L$, $\tau\partial \ln N(\tau)/\partial\tau \approx 1$ at $\tau = \tau_{acc}$, where τ_{acc} is the normalized acceleration time and a little longer than the laser pulse duration. Therefore, $C, L \leq L_c$ $C, L \leq L_c$, where η_s is the saturate laser absorption efficiency for large target thickness and about 30–50% C is a constant and $t_{acc} \approx (1 \sim 2)t_l$ is the physical acceleration time. The self-similar ion velocity at the ion front given by Huang *et al.* (2008*a*, 2008*b*) is $\beta_1 \ln(t_{acc}^2(\eta/\eta_s)) + C$, which is suitable for the target thickness larger than L_c since the hot-electron recirculation has not been accounted for. Sentoku *et al.*'s model (2003) shows that: $u_{i,f} \propto \sqrt{L_c/L}\,\ln(t)$. However, the key physical relation given by Huang *et al.*'s (2007) step model is about $2\sqrt{L_c/L}\,\ln(t_{acc}\sqrt{\eta/\eta_s})$.

With above discussions, the dependence of laser absorption efficiency on the target thickness becomes the most important unknown information. With Eq. (3), for $L \leq r_L$ and $(L^*/r_L)\tan(\theta_e) \ll 1$, the reference electron density $n_{e0} \approx 4.077\eta(L)I_{10^{18}\mathrm{W/cm^2}} t_L/(\gamma - 1)t_l$ and is proportional to laser absorption efficiency and target thickness. When the laser absorption efficiency tends to zero with $L \to 0$, $n_{e0} \to 0$ and the maximum ion velocity tends to zero too. d'Humires *et al.* (2005) have given a curve to describe that, but can it be used for any other target or other parameters of laser pulse? However, the changing law should be similar, the exact relationship have not been obtained. In fact, the dependence of opening angle of electrons on the target thickness and laser parameters is also important for the electron density, and the opening angle of ions to be ascertained, but still a challenge. The angle decides the electron density n_{e0} as shown in Eq. (3) and increases with target thickness. Therefore, for thin target, the opening angle should be smaller than 17° (Santos *et al.*, 2002) and becomes zero when $L \to 0$.

COMPARISON WITH EXPERIMENTS AND DISCUSSION

In fact, to compare our model with the relative experiments exactly, $\eta = \eta(L, I, \lambda, r_L)$ and $\theta_e = \theta_e(L, I, \lambda, r_L)$ should be ascertained first. However, Figure 1 shows a course comparison with the assumptions: laser absorption efficiency and the opening angle of electrons are fixed for different target thicknesses, $\eta = 40\%$, $\theta_e = 17°$, and $\beta_1 = 1$. Other parameters are the same as the compared experiments. With Figure 1a, the results of our model are consistent with the experimental data. In these experiments, Mackinnon *et al.* (2002), the

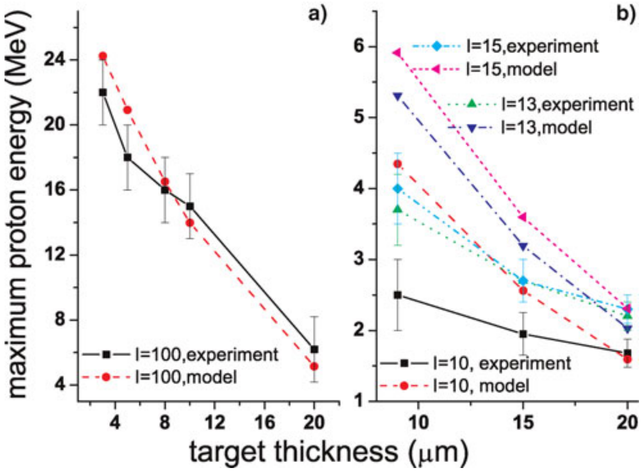

Fig. 1. (Color online) Comparisons with Kaluza *et al.*'s and Mackinnon *et al.*'s experiments, where the unit of I is 10^{18} W/cm^2. Kaluza *et al.*'s experimental parameters are: $\lambda = 790$ nm, $r_L = 2.5$ μm, $t_l = 150$ fs and $t_{ASE} = 2.5$ ns, $I = 1.0 \times 10^{19}$ W/cm^2, $I = 1.3 \times 10^{19}$ W/cm^2 and $I = 1.5 \times 10^{19}$ W/cm^2 with incidence of 30° onto targets, and laser absorption efficiency is about 40%; Mackinnon *et al.*'s experimental parameters are: $\lambda = 0.8$ μm, $r_L = 2.5$ μm, $t_l = 100$ fs, intensity contrast ratio is 10^{10}: 1 with incidence of 22° onto targets, and laser absorption efficiency is 40%. In our model, the half opening angle of electrons is 17°(Santos *et al.*, 2002).

contrast ratio of intensity is large enough that the influence of the prepulse can be neglected. Therefore, for $L \gtrsim 1$ μm, the laser absorption efficiency sustains a constant. However, if the contrast ratio is not large enough and the influence of the prepulse on η can not be ignored, η should not be assumed to be a constant and the results given by our model are larger than experimental data as shown by Figure 1b. It is concluded that for $L \leq L_c$, the influence of the hot-electron recirculation on the ion acceleration is evident: maximum ion energy increases quickly with the decrease of the target thickness and larger than the experimental data.

The reasons for larger results given by our model may be:

(1) the parameters of laser absorption efficiency is taken as constants. In fact, the laser absorption efficiency stays constant for the target of thickness large enough and decreases with the decrease of the target thickness for thin foils and tends to zero as $L \to 0$ shown by Fig. 12 in (d'Humires *et al.*, 2005) with particle-in-cell simulations. In general cases, the analytic function of the dependence of laser absorption efficiency on target thickness, laser intensity, laser pulse duration and ASE duration is still a challenge, although Huang *et al.* has a half-analytic way to obtain it (Huang *et al.*, 2007). Here, the function can also be concluded with the similar method. It is easy to realized and is not repeated here.

(2) the three dimensional effect is not contained. The electron density does decrease with the plasma expansion as the electrons recirculate and spread laterally with a given opening angle. This dilute effect of the electron density is ignored here. In our sequence articles, it will be considered.

CONCLUSION

In conclusion, the time-dependent isothermal expansion for the target normal sheath proton acceleration is briefly proposed. The influence of hot-electron recirculation on the ion acceleration has been shown by Eq. (6) analytically and by Figure 1 obviously. For $L \leq L_c$, the hot-electron recirculation enhances the ability of the ion acceleration for thin foils.

ACKNOWLEDGMENTS

This work was supported by the Key Project of Chinese National Programs for Fundamental Research (973 Program) under contract No. 2006CB806004 and the Chinese National Natural Science Foundation under contract No. 10334110.

REFERENCES

Cai, H.B., Yu, W., Zhu, S.P., Zheng, C.Y., Cao, L.H. & Pei, W.B. (2006). Vacuum heating in the interaction of ultrashort relativistically strong laser pulses with solid targets. *Phys. Plasmas* **13**, 063108–6.

Chen, Z.L., Unick, C., Vafaei-Najafabadi, N., Tsui, Y.Y., Fedosejevs, R., Naseri, N., Masson-Laborde, P.E. & Rozmus, W. (2008). Quasi-monoenergetic electron beams generated from 7 TW laser pulses in N-2 and He gas targets. *Laser Part. Beams* **26**, 147–155.

d'Humires, E., Lefebvre, E., Gremillet, L. & Malka, V. (2005). Proton acceleration mechanisms in high-intensity laser interaction with thin foils. *Phys. Plasmas* **12**, 062704–13.

Eliezer, S., Murakaml, M. & Val, J.M.M. (2007). Equation of state and optimum compression in inertial fusion energy. *Laser Part. Beams* **25**, 585–592.

Flippo, K., Hegelich, B.M., Albright, B.J., Yin, L., Gautier, D.C., Letzring, S., Schollmeier, M., Schreiber, J., Schulze, R. & Fernandez, J.C. (2007). Laser-driven ion accelerators: Spectral control, monoenergetic ions and new acceleration mechanisms. *Laser Part. Beams* **25**, 3–8.

Gurevich, A., Anderson, D. & Wilhelmsson, H. (1979). Ion acceleration in an expanding plasma with non-Maxwellian electrons. *Phys. Rev. Lett.* **42**, 769–764.

Huang, Y.S., Bi, Y.J., Duan, X.J., Lan, X.F., Wang, N.Y., Tang, X.Z. & He, Y.X. (2008). Self-similar neutral-plasma isothermal expansion into a vacuum. *Appl. Phys. Lett.* **92**, 031501–3.

Huang, Y.S., Bi, Y.J., Duan, X.J., Lan, X.F., Wang, N.Y., Tang, X.Z. & He, Y.X. (2008). Energetic ion acceleration with a non-Maxwellian hot-electron tail. *Appl. Phys. Lett.* **92**, 141504–3.

Huang, Y.S., Lan, X.F., Duan, X.J., Tan, Z.X., Wang, N.Y., Shi, Y.J., Tang, X.Z. & Xi, H.Y. (2007). Hot-electron recirculation in ultraintense laser pulse interactions with thin foils. *Phys. Plasmas* **14**, 103106–6.

Kaluza, M., Schreiber, J., Santala, M.I.K., Tsakiris, G.D., Eidmann, K., Meyer-ter-Vehn, J. & Witte, K.J. (2004). Influence of the laser prepulse on proton acceleration in thin-foil experiments. *Phys. Rev. Lett.* **93**, 045003–4.

Karmakar, A. & Pukhov, A. (2007). Collimated attosecond GeV electron bunches from ionization of high-Z material by radially polarized ultra-relativistic laser pulses. *Laser Part. Beams* **25**, 371–377.

Limpouch, J., Psikal, J., Andreev, A.A., Platonov, K.Y. & Kawata, S. (2008). Enhanced laser ion acceleration from mass-limited targets. *Laser Part. Beams* **26**, 225–234.

Mackinnon, A.J., Sentoku, Y., Patel, P.K., Price, D.W., Hatchett, S., Key, M.H., Andersen, C., Snavely, R. & Freeman, R.R. (2002). Enhancement of proton acceleration by hot-electron recirculation in thin foils irradiated by ultraintense laser pulses. *Phys. Rev. Lett*. **88**, 215006–4.

Mora, P. (2003). Plasma expansion into a vacuum. *Phys. Rev. Lett*. **90**, 185002–4.

Murakami, M. & Basko, M.M. (2006). Self-similar expansion of finite-size non-quasi-neutral plasmas into vacuum: Relation to the problem of ion acceleration. *Phys. Plasmas* **13**, 012105–7.

Santos, J.J., Amiranoff, F., Baton, S.D., Gremillet, L., Koenig, M., Martinolli, E., Rabec Le Gloahec, M., Rousseaux, C., Batani, D., Bernardinello, A., Greison, G. & Hall, T. (2002). Fast electron transport in ultraintense laser pulse interaction with solid targets by rear-side self-radiation diagnostics. *Phys. Rev. Lett*. **89**, 025001–4.

Schollmeier, M., Roth, M., Blazevic, A., Brambrink, E., Cobble, J.A., Fernandez, J.C., Flippo, K.A., Gautier, D.C., Habs, D., Harres, K., Hegelich, B.M., Hesslinga, T., Hoffmann, D.H.H., Letzring, S., Nurnberg, F., Schaumann, G., Schreiber, J. & Witte, K. (2007). Laser ion acceleration with micro-grooved targets. *Nucl. Instr. Meth. Phys. Res. A* **577**, 186–190.

Schwoerer, H., Pfotenhauer, S., Jackel, O., Amthor, K.-U., Liesfeld, B., Ziegler, W., Sauerbrey, R., Ledingham, K.W.D. & Esirkepov, T. (2006). Laser-plasma acceleration of quasi-monoenergetic protons from microstructured targets. *Nature* **439**, 445–8;

Sentoku, Y., Cowan, T.E., Kemp, A. & Ruhl, H. (2003). High energy proton acceleration in interaction of short laser pulse with dense plasma target. *Phys. Plasmas* **10**, 2009–2015.

Strangio, C., Caruso, A., Neely, D., Andreoli, P.L., Anzalone, R., Clarke, R., Cristofari, G., Del Prete, E., Di Giorgio, G., Murphy, C., Ricci, C., Stevens, R. & Tolley, M. (2007). Production of multi-MeV per nucleon ions in the controlled amount of matter mode (CAM) by using causally isolated targets. *Laser Part. Beams* **25**, 85–91.

Wilks, S.C., Kruer, W.L., Tabak, M. & Langdon, A.B. (1992). Absorption of ultra-intense laser pulses. *Phys. Rev. Lett*. **69**, 1383–1384.

Wilks, S.C., Langdon, A.B., Cowan, T.E., Roth, M., Singh, M., Hatchett, S., Key, M.H., Pennington, D., MacKinnon, A. & Snavely, R.A. (2001). Energetic proton generation in ultra-intense laser-solid interactions. *Phys. Plasmas* **8**, 542–548.