Radiation pressure acceleration by ultraintense laser pulses

Tatiana V Liseykina\textsuperscript{1,2}, Marco Borghesi\textsuperscript{3}, Andrea Macchi\textsuperscript{3,4,5} and Sara Tuveri\textsuperscript{5}

\textsuperscript{1} Max Planck Institute for Nuclear Physics, Heidelberg, Germany
\textsuperscript{2} Institute of Computational Technologies SD RAS, Novosibirsk, Russia
\textsuperscript{3} School of Mathematics and Physics, the Queen’s University of Belfast, Belfast, UK
\textsuperscript{4} polyLab, CNR-INFM, Pisa, Italy
\textsuperscript{5} Dipartimento di Fisica ‘Enrico Fermi’, Università di Pisa, Pisa, Italy

E-mail: Tatyana.Liseykina@mpi-hd.mpg.de

Received 2 June 2008, in final form 15 July 2008
Published 5 November 2008
Online at stacks.iop.org/PPCF/50/124033

Abstract

The future applications of the short-duration, multi-MeV ion beams produced in the interaction of high-intensity laser pulses with solid targets will require improvements in the conversion efficiency, peak ion energy, beam monochromaticity and collimation. Regimes based on radiation pressure acceleration (RPA) might be the dominant ones at ultrahigh intensities and most suitable for specific applications. This regime may be reached with present-day intensities using circularly polarized (CP) pulses thanks to the suppression of fast electron generation, so that RPA dominates over sheath acceleration at any intensity. We present a brief review of a previous work on RPA with CP pulses and a few recent results. Parametric studies in one dimension were performed to identify the optimal thickness of foil targets for RPA and to study the effect of a short-scalelength preplasma. Three-dimensional simulations show the importance of ‘flat-top’ radial intensity profiles to minimize the rarefaction of thin targets and address the issue of angular momentum conservation and absorption.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In 1962, Forward considered the possibility of interstellar travel by a rocket propelled by an Earth-based laser beam (see [1] and references therein). The concept is as simple as follows: the rocket’s engine and fuel are replaced by a light sail, i.e. a mirror, and the force exerted on the sail due to the radiation pressure of the laser light boosts the rocket. In 1966, Marx [2] found that the efficiency of the system, i.e. the ratio between the mechanical energy of the object accelerated by the laser beam and the energy contained in the laser beam itself, would
approach unity as the velocity of the object approaches the speed of light. An heuristic (though incomplete) argument might be given in terms of light quanta, i.e. photons, although the system can be described as entirely classical: let us consider a ‘perfect’ mirror irradiated by a monochromatic light wave of frequency $\omega$, which contains a certain number $N$ of photons and thus has a total energy $N h \omega$. The mirror reflects photons conserving their number in any reference frame. If the mirror has an (instantaneous) velocity $V = \beta c$ in the laboratory frame, the frequency of the reflected photons is $\omega' = \omega(1 - \beta)/(1 + \beta)$. Thus, since $N$ is invariant, the energy of the reflected pulse tends to zero if $V \rightarrow c$, so that a mirror moving at a speed close to $c$ absorbs almost all the energy of the incident pulse.

Marx paper’s conclusions turned out to be right although its approach needed a critical revision, as can be found in the rigorous and pedagogical description of [3]. According to the formulas in [3] it would take three years for a 10 TW laser to accelerate a $10^3$ kg rocket to $V = (4/5)c$. Scaling this result to the typical parameters of superintense laser pulses and micro-targets, we obtain that about $5 \times 10^{10}$ carbon ions might be accelerated to the same speed in 1 ps by a 1 PW laser, which is within the capabilities of the present technology. Note that the required acceleration length would be of the order of 100 $\mu$m, which is a suitable value for the Rayleigh length, so that laser pulse diffraction should not be a strong limiting factor on the achievable energies. This makes the perspective of radiation pressure acceleration (RPA) attractive for applications requiring large numbers of relativistic ions.

Nearly all of the experiments reported in the last decade on the acceleration of ions (mainly protons) by superintense laser pulses (see e.g. [4, 5] and references therein) are not based on RPA but instead on the target normal sheath acceleration (TNSA) mechanism, in which ions are accelerated by space-charge fields created by multi-MeV electrons escaping into vacuum. The dominance of RPA over TNSA in thin solid targets irradiated at intensities higher than those of present-day experiments has been claimed by Esirkepov and coworkers [6, 7], on the basis of simulations showing a transition occurring at some intensity value above $10^{21} \text{W cm}^{-2}$, with a strong dominance leading to the so-called ‘piston’ regime over $10^{23} \text{W cm}^{-2}$. Such an intensity may be available only in several years from now thanks to the development of advanced laser facilities. Experimentally, a preliminary indication of RPA effects in thin targets at intensities approaching $10^{20} \text{W cm}^{-2}$ has been published recently [8] (some experimental results on ion acceleration at intensities $\leq 10^{19} \text{W cm}^{-2}$ were also interpreted in terms of purely ponderomotive, i.e. radiation pressure effects [9]).

The question then arises whether it is possible to achieve an RPA-dominated regime already at lower intensity; this corresponds in practice to quenching the generation of high-energy electrons which drive TNSA but do not contribute to RPA. This may be possible using circularly polarized (CP) laser pulses at normal incidence because the oscillating components of the Lorentz force in the direction perpendicular to the sharp density gradient vanish (for a plane wave) or are relatively small (for a finite laser spot size); as a consequence, the motion of electrons at the interaction surface is predominantly adiabatic and electron heating is strongly reduced, while the space-charge field created to balance the local radiation pressure (i.e. the ponderomotive force) accelerates ions.

The strong differences between the cases of linearly polarized (LP) and CP pulses have been evidenced in some papers by our group [10, 11], mostly for the case of ‘thick’ targets, i.e. thicker than the skin layer. These studies showed that for CP the interaction accelerates all the ions in the skin layer and the fastest ones produce a very dense ‘bunch’ with a narrow energy spectrum, directed in the forward direction.

Recently, the experimental availability of ultrathin targets (i.e. with thickness down to a few nanometers) and high contrast laser pulses (see, e.g. [12–14]) has called for studies of CP-RPA
with such pulses and targets. The simulations performed independently by several groups [15–19] suggest that indeed the whole target may be accelerated, leading to efficient generation of large numbers of ions with monoenergetic spectra in the near-GeV range. Presently, no experiment using CP pulses at normal incidence has been reported in publications yet, but several related proposals have been made, so that the CP-RPA concept is expected to be explored soon.

This paper reviews the main issues of CP-RPA and reports novel numerical results on parametric studies in one spatial dimension (1D), showing the role of the target thickness and the case of RPA in short-scalelength preformed plasmas, as well as first results in fully 3D geometry where, in particular, the issue of angular momentum conservation can be addressed.

2. Theory and earlier work

Firstly we shall provide a brief description of the interaction in the case of a thick target. The ponderomotive force of the laser pulse causes the electrons to pile up in the skin layer until it is balanced by the charge separation field that accelerates the ions. The ions produce a sharp density spike at the end of the skin layer where hydrodynamical breaking occurs, with the faster ions creating a dense bunch (with a narrow spectrum) that moves ballistically into the plasma (a rather similar dynamics has been noted in the case of radial ponderomotive acceleration of ions in an underdense plasma [20]). A detailed physical description and a simple model of RPA in thick targets (assuming \textit{a priori} non-relativistic ions) have been given in previous works [10, 21]. The model provides the following scaling, valid for sub-relativistic ion velocities, for the maximum ion velocity (which almost corresponds to the bunch velocity) and the corresponding energy:

\begin{equation}
\frac{v_{\text{im}}}{c} = 2 \sqrt{\frac{Z}{A}} \frac{m_e n_e}{m_p n_p} a_L, \quad \varepsilon_{\text{im}} = \frac{m_i}{2} v_{\text{im}}^2 = 2 m_e c^2 Z \frac{n_e}{n_p} a_L^2,
\end{equation}

where \( n_e = m_e \omega^2/4\pi e^2 \) is the cut-off density for the laser wavelength \( \lambda = 2\pi c/\omega \), \( n_e \) is the background electron density, \( a_L = e E_L/m_e c \omega = 0.85 (I \lambda^2 /10^{18} \text{W cm}^{-2}) \) is the dimensionless amplitude of the laser pulse with electric field \( E_L \) and intensity \( I \) and other symbols are standard. Actually, this result has been derived in the limit of a relatively low intensity, but this scaling has been found to hold up to a much higher intensity in parametric 1D simulations [21].

The ion bunch is formed in a time of the order of \( \sim c/\omega_p v_{\text{im}} \) (where \( \omega_p \) is the plasma frequency) after which it exits the skin layer accompanied by neutralizing electrons, and the laser pulse may accelerate a new layer. If energies higher than the above estimate must be reached, it is necessary to repeat the acceleration stage on the same ions, i.e. the target must be thin enough in order to bunch and accelerate all ions via several cycles. Simulation results on the acceleration of ultrathin targets have been interpreted with the model of the accelerating mirror [17] (where the mirror is assumed to be a ‘rigid’ object, neglecting any internal dynamics).

Although a few authors have proposed the RPA of a thin foil as a way to generate high-energy protons, this approach seems to be most interesting for the acceleration of higher-Z ions. In fact, while it seems technologically unfeasible to have an ultrathin target made of hydrogen only, in a target made of multiple species all the ions will be accelerated to the same velocity, resulting in higher energies for the heavier species. If a lighter species (e.g. hydrogen) is present, these ions will be first accelerated overtaking the heavier ones. This will cause them to decouple from the laser pulse, which is screened by the heavier ion layer. The
heavier ions will be accelerated until they reach the lighter ions, allowing the laser to reach them and accelerate them further. In the end all species will have the same velocity. Due to this effect, for an ultrathin target of a single material (e.g. carbon) a monoenergetic ion spectrum is expected.

The above picture of the acceleration dynamics should change when the ions finally reach a speed close to $c$, as they will no longer be separated from the electrons. The ‘laser-piston’ regime investigated by Esirkepov et al [6] corresponds to conditions in which the ions are promptly accelerated to relativistic velocities and stick to the electrons, which may not be assumed to be in a mechanical quasi-equilibrium anymore. In this paper we restrict our analysis to the regime of non-relativistic ions because near-term experiments on RPA are unlikely to have the potential to accelerate ions up to strongly relativistic energies.

The theoretical picture and the predicted scalings have been supported by 1D simulations. So far multi-dimensional effects have been addressed at most by 2D simulations for both thick [10,11,21] and thin [17–19] targets. In the thick target cases, the energy spectrum is basically determined by the convolution of the 1D scaling law with the intensity profile of the pulse. The angle of emission of ions is energy dependent, but a good collimation is already obtained for a Gaussian pulse profile [11]. For thin targets, the use of a flat-top profile increases the monoenergeticity and collimation and quenches the heating of electrons, as expected [17, 18].

The issue of target stability during RPA has been addressed in thin foil 2D simulations for CP [18] and also for linear polarization in the ultraintense regime [22], showing a bending instability which has been interpreted to be of the Rayleigh–Taylor type and hence can be described in terms of the radiation pressure only. Simulations for thick targets, however, have shown that surface instabilities are weaker for CP pulses than for the LP ones. The quality of the ion beam is expected to be lower for linear polarization [21].

3. 1D simulations

3.1. The role of the target thickness

We performed a parametric study to determine the optimal values of target thickness $d$ to obtain a higher efficiency and/or ion energy for given laser parameters. In order to be able to cover a quite wide range of parameters and to simulate ‘realistic’ target densities we used 1D simulations, which in the CP-RPA regime have so far proved to yield efficiency and ion energy values close to those from 2D or 3D simulations for those cases where a comparison is possible (i.e. for moderate density values). Results are shown in figure 1. The electron density of the target and the pulse duration were kept constant for all runs and corresponded, for a laser wavelength $\lambda = 0.8 \mu m$, to $n_e = 4.3 \times 10^{23} \text{ cm}^{-3}$ and $\tau_L = 24 \text{ fs}$. The three values of the dimensionless amplitude that were studied ($a = 2.9, 9.2$ and 29) corresponded to intensities $I = 1.8 \times 10^{19} \text{ W cm}^{-2}, 1.8 \times 10^{20} \text{ W cm}^{-2}$ and $1.8 \times 10^{21} \text{ W cm}^{-2}$, respectively.

The values of $d$ for which efficiency and ion energy have their maximum are close to each other and, as expected, they correspond to ultrathin, sub-micrometer targets. The strong decrease in efficiency and energy for smaller values of $d$ may be explained with the onset of relativistically induced transparency in the thin foil when $d \approx \lambda a (n_e/n_c)$ [23], so that the total radiation pressure on the target decreases. This point will be further discussed below when three-dimensional effects are addressed (section 4).

The energy per nucleon reported in figure 1 can be scaled to all species with $Z/A = 1/2$. For carbon ($A = 12$) the highest energy of 0.96 GeV is obtained for $a = 29$ and $d = 0.025 \lambda$. Note that these are ‘peak’ energies which correspond to a distinct maximum in the ion
Figure 1. Energy conversion efficiency into ions (red filled diamonds) and the ‘peak’ energy per nucleon (blue empty diamonds) as a function of the target thickness, investigated by parametric 1D PIC simulations. The top, middle and bottom plots are for a pulse amplitude $a = 29, 9.2$ and $2.9$, respectively. In all the runs, the laser pulse had a duration of 9 cycles (FWHM), the electrons density was $n_e = 250n_c$ and the charge-to-mass ratio was $Z/A = 1/2$.

spectra. However, depending on the interaction parameters some tail of higher energy ions appears. Moreover, the width of the ion energy peak also varies throughout the simulations and does not remain constant in time, as some broadening is observed after the laser pulse is over. This broadening appears to be related to electron heating which occurs at the end of the acceleration stage, creating ‘warm’ electrons which are much less energetic than those produced for LP interaction but may already drive the expansion of the thin plasma foil. Hence, monoenergeticity of ions appears to be a non-trivial issue already in 1D.

In higher dimensionality it is known that the intensity distribution in the laser spot gives rise to an energy spread correlated with the direction of laser-accelerated ions [11], so that a ‘flat-top’ distribution, whenever feasible, may improve monoenergeticity as well as beam collimation (see e.g. 2D simulations in [17]). Additional effects of the pulse profile are also discussed in section 4.

3.2. RPA in preformed plasmas

The use of ultrathin targets in experiments will require the use of systems with an extremely high contrast ratio, otherwise the prepulse preceding the main interaction pulse will destroy the target completely. Interaction experiments in such a regime appear to be presently possible [12, 14], thanks, for example, to the use of plasma mirrors to improve the contrast [13]. Such conditions are optimal to test the CP-RPA of ultrathin targets, provided that the strategies implemented to improve the pulse contrast are compatible with preserving the circular polarization of the pulse. It is also worth stressing that the need for normal pulse incidence might also be non-trivial to be experimentally satisfied due to the danger of back-reflection from the overdense plasma.

It is interesting in any case to consider the possibility of the interaction of the CP pulse with a non-uniform preplasma, as this may be present in experiments where the contrast ratio
Figure 2. Interaction with preformed plasmas. Left: snapshots of the profiles of $E_2 = E^2_1 + E^2_2$ (dashed blue line), $n_i$ (thick black line) and $n_e$ (thin red line) soon after the formation of the ‘fast’ ion bunch (evidenced by the arrow). The pulse intensity was $a = 3$ corresponding to $1.2 \times 10^{20} \text{ W cm}^{-2}$ for $\lambda = 1 \mu\text{m}$, the density profile was rising with a $\sim (x - x_0)^3$ law up to a peak density $n_0 = 40n_c$. Right: conversion efficiency (red filled diamonds, solid line) and peak energy (blue empty diamonds, dashed line) of ions as a function of the density scalelength $L$, for three values of the laser amplitude $a$. In all the simulations the laser pulse had a duration of 9 cycles (FWHM) and the density profile was rising with a $\sim (x - x_0)^4$ law up to a peak density $n_0 = 16n_c$ and then remained constant.

is modest. Moreover, the expected scaling of the ion energy with the inverse of the plasma density suggests that, in a preformed plasma, a given laser pulse may produce a lower total number of ions but with higher energy, as the interaction occurs with the layer at the cut-off density $n_c$. We performed a set of parametric 1D simulations assuming initial density profiles of the power-law type (i.e. $n_0(x) \sim (x - x_0)^k$ for $x > x_0$) and different values of the density scalelength at the cut-off layer, $L = n_c/|\partial_x n_0|_{n_0 = n_c}$. The snapshot of the ion density $n_i$ in figure 2 shows that $n_i$ undergoes spiking and ‘breaking’ and that a ‘fast’ bunch forms near the cut-off density layer, with features very similar to the case of a sharply rising density (no preplasma) [10]. The bunch density is several times $n_c$. As a function of $L$, both the maximum ion energy and the conversion efficiency have their maxima for a very short scalelength $L \approx 0.5\lambda$, as also shown in figure 2 where $L = 0$ corresponds to the case of no preplasma, i.e. a step-like profile. When compared with the energy scaling (1), the observed ion energy would correspond to a density value intermediate between $n_c$ and the peak density ($16n_c$) of the profile. The decrease in energy and efficiency for larger values of $L$ might be related to the weaker coupling of the laser pulse to the cut-off layer; a relevant part of the pulse energy is found to be absorbed in the underdense plasma, e.g. by excitation of plasma waves, causing the absorption degree into electrons to be higher than into ions and consequently decreasing the total radiation pressure. The stronger heating of electrons may account for the broad energy spectrum that is observed for non-optimal values of $L$; figure 2 reports the maximum or cut-off energy, but several and broad ‘peaks’ may appear in the spectrum under such conditions, while the spectrum is narrow for the case of absolute maximum energy. These preliminary results suggest that RPA may be strongly affected by prepulse effects. However this may allow one to achieve dense bunches of multi-MeV ions using ultrashort pulses with controlled contrast. For longer pulses (hundreds of femtoseconds), this approach may become ineffective because of strong steepening effects during the rise of the pulse, decreasing the value of $L_c$. The width of the target layer that remains undamaged by the prepulse may also play a
role because the ions may undergo relevant collisional losses while crossing the solid-density region (see, e.g. the discussion in [8]).

4. 3D simulations

As is always the case for computational plasma physics, 3D simulations would be required for a ‘realistic’ description, but the limits of computing power force the restriction to a narrow set of ‘feasible’ parameters. This is the case for CP-RPA where, furthermore, the resolution must be high enough to resolve effects such as the strong spiking of the density observed in 1D and 2D. Thus, only a few 3D runs could be performed and for plasma densities much less than solid-density values, though well above \( n_c \).

The comparison with 1D and 2D results is also important because a CP pulse carries a net angular momentum whose conservation law appears as an additional constraint in 3D. Note that, despite the strong absorption of pulse energy, no absorption of angular momentum is expected, at least as long as the acceleration is adiabatic (as is assumed in the ‘perfect mirror’ model). In fact, coming back to the heuristic argument of the introduction, if the number of photons is conserved and the reflected beam conserves helicity (which can be shown to hold), no angular momentum is left in the target because the ‘spin’ of any photon is \( \hbar \), independent of the frequency.

In order to study these issues in detail, we performed several 3D simulations. In all the runs discussed here the normally incident laser pulse was CP with a peak intensity of \( 3.4 \times 10^{19} \text{ W cm}^{-2} \) and \( \sim 60 \text{ fs} \) duration and the target consisted of electrons and protons. Figure 3 presents the results of the interaction of a laser pulse with a ‘flat-top’ intensity profile of \( 6 \mu \text{m} \) width with a target of density \( n_e = 16n_{cr} = 1.7 \times 10^{22} \text{ cm}^{-3} \) and \( 0.3 \mu \text{m} \) thick. Figure 3(a) shows the projected 2D distributions of ion density at \( t = 75, 100 \) and \( 130 \text{ fs} \) and (b) the 3D plot of the ion density when the laser pulse is over. The density of the ‘bunch’ is approximately 0.7 of the initial density of the target, the peak energy of ions in this bunch is \( \sim 4 \text{ MeV} \) the number of accelerated ions is \( \sim 4 \times 10^{10} \). When the laser pulse is over most of the absorbed angular momentum (\( \sim 4\% \)) is transferred to the ions (the energy absorption in this case was \( \sim 7\% \)). To prove that a torque on the plasma ions exists, we plot in figure 3(c) the integral (over \((y, z)\)) of the poloidal current \( J_{\phi} \) of the ions. We thus see that on average there

![Figure 3.](image-url)
is a net ‘rotation’ of the ions, while the same plot for the electron current shows that the latter averages over $x$ almost to zero. The poloidal ion current is concentrated near the edge of the laser spot where the angular momentum density has a maximum.

Angular momentum absorption in laser–plasma interactions has been mostly studied so far in underdense plasmas as a problem closely related to the generation of a steady magnetic field (inverse Faraday effect). Haines [24] reported a short critical review of a previous work and discussed the effects leading to a torque on the plasma ions. The issue of angular momentum absorption in overdense plasmas has received much less attention so far. In the present context, the observation of some degree of angular momentum absorption is a signature of non-adiabatic or ‘dissipative’ effects (which are an interesting issue in collisionless systems) not included in the ‘perfect mirror’ model of RPA. They may be related to the onset of hydrodynamical breaking during the acceleration process [10], violating the adiabaticity condition.

In figure 4 the results of the interaction of a tightly focused ($3 \mu m$ width) Gaussian laser pulse with a target of density $n_e = 9n_{cr} = 1 \times 10^{24} \text{cm}^{-3}$ and thickness of $0.4 \mu m$ are shown. In this case the pulse focusing was tight enough to contribute dramatically to the induced transparency of the target.

In both cases presented here the density and the width of the targets were chosen in a way to ensure their opacity on the basis of the 1D analysis. However, 3D effects decrease the transparency threshold because the foil tends to expand in the perpendicular direction. For the tightly focused Gaussian laser pulse this effect is very pronounced so that the foil becomes transparent even if initially it was opaque. Since the use of a target with densities not very far from the transparency threshold is more suitable to achieve an efficient acceleration rate, the shape of the laser pulse becomes a critical issue and the use of ‘flat-top’ laser pulses, whenever possible, may help.

**Acknowledgments**

This work was supported by CNR-INFM and CINECA (Italy) through the super-computing initiative and by CNR via a RSTL project. Some of the simulations were performed on the Linux Cluster of MPI-K, Heidelberg. A part of the work was performed during a stay of two of the authors at Queen’s University, Belfast, UK, supported by a Visiting Research Fellowship (AM) and by COST-P14 (ST). TVL also acknowledges the support from RFBR (via 08-02-08244 grant). The authors are grateful to D Bauer, F Cornolti and F Pegoraro for a critical reading and comments.
References

[1] Forward R L 1964 Roundtrip interstellar travel using laser-pushed lightsails J. Spacecraft and Rockets 21 187
[2] Marx G 1966 Interstellar vehicle propelled by terrestrial laser beam Nature 211 22–3
[3] Simmons J F L and McInnes C R 1993 Was Marx right? or How efficient are laser driven interstellar spacecraft? Am. J. Phys. 61 205–7
[4] Borghesi M, Fuchs J, Bulanov S V, MacKinnon A J, Patel P K and Roth M 2006 Fast ion generation by high-intensity laser irradiation of solid targets and applications Fusion Sci. Technol. 49 412
[5] McKenna P et al 2007 Low- and medium-mass ion acceleration driven by petawatt laser plasma interactions Plasma Phys. Control. Fusion 49 B223–31
[6] Esirkepov T, Borghesi M, Bulanov S V, Mourou G and Tajima T 2004 Highly efficient relativistic-ion generation in the laser-piston regime Phys. Rev. Lett. 92 175003
[7] Esirkepov T, Yamagiwa M and Tajima T 2006 Laser ion-acceleration scaling laws seen in multiparametric particle-in-cell simulations Phys. Rev. Lett. 96 105001
[8] Kar S et al 2008 Plasma jets driven by ultra-intense laser interaction with thin foils Phys. Rev. Lett. 100 225004
[9] Badziak J, Glowacz S, Jablonski S, Parys P, Wolowsky J, Hora H, Krása J, Laska L and Rohlena K 2004 Production of ultrahigh ion current densities at skin-layer subrelativistic laser–plasma interaction Plasma Phys. Control. Fusion 46 B541–55
[10] Macchi A, Cattani F, Liseykina T V and Cornolti F 2005 Laser acceleration of ion bunches at the front surface of overdense plasmas Phys. Rev. Lett. 94 165003
[11] Liseykina T V and Macchi A 2007 Features of ion acceleration by circularly polarized laser pulses Appl. Phys. Lett. 91 171502
[12] Neely D, Foster P, Robinson A, Lindau F, Landh O, Persson A, Wahlstrom C-G and McKenna P 2006 Enhanced proton beams from ultrathin targets driven by high contrast laser pulses Appl. Phys. Lett. 89 021502
[13] Thaury C et al 2007 Plasma mirrors for ultrahigh-intensity optics Nature Phys. 3 424–9
[14] Cuccotti T, Levy A, Popescu H, Reau F, D’Oliveira P, Monot P, Geindre J P, Lefebvre E and Martin Ph 2007 Proton acceleration with high-intensity ultrahigh-contrast laser pulses Phys. Rev. Lett. 99 185002
[15] Zhang X, Shen B, Li X, Jin Z and Wang F 2007 Multistaged acceleration of ions by circularly polarized laser pulse: Monoenergetic ion beam generation Phys. Plasmas 14 073101
[16] Zhang X, Shen B, Li X, Jin Z, Wang F and Wen M 2007 Efficient GeV ion generation by ultraintense circularly polarized laser pulse Phys. Plasmas 14 123108
[17] Robinson A P L, Zepl M, Kar S, Evans R G and Bellei C 2008 Radiation pressure acceleration of thin foils with circularly polarized laser pulses New J. Phys. 10 013021
[18] Klimo O, Psikal J, Limpouch J and Tikhonchuk VT 2008 Monoenergetic ion beams from ultrathin foils irradiated by ultrahigh-contrast circularly polarized laser pulses Phys. Rev. ST Accel. Beams 11 031301
[19] Yan X Q, Lin C, Sheng Z M, Guo Z Y, Liu B C, Lu Y R, Fang J X and Chen J E 2008 Generating high-current monoenergetic proton beams by a circularly polarized laser pulse in the phase-stable acceleration regime Phys. Rev. Lett. 100 135003
[20] Macchi A, Ceccherini F, Cornolti F, Kar S and Borghesi M 2009 Electric field dynamics and ion acceleration in the self-channeling of a superintense laser pulse Plasma Phys. Control. Fusion 50 at press (arXiv:physics/0701139)
[21] Liseykina T V, Prellino D, Cornolti F and Macchi A 2008 Ponderomotive acceleration of ions: circular versus linear polarization IEEE Trans. Plasma Sci. at press
[22] Pegoraro F and Bulanov S V 2007 Photon bubbles and ion acceleration in a plasma dominated by the radiation pressure of an electromagnetic pulse Phys. Rev. Lett. 99 065002
[23] Vshivkov V A, Naumova N M, Pegoraro F and Bulanov S V 1998 Nonlinear electrodynamics of the interaction of ultra-intense laser pulses with a thin foil Phys. Plasmas 5 2727–41
[24] Haines M G 2001 Generation of an axial magnetic field from photon spin Phys. Rev. Lett. 87 135005