Maintaining stable radiation pressure acceleration of ion beams via cascaded electron replenishment

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Abstract

A method to maintain ion stable radiation pressure acceleration (RPA) from laser-irradiated thin foils is proposed, where a series of high-Z nanofilms are placed behind to successively replenish co-moving electrons into the accelerating foil as electron charging stations (ECSs). Such replenishment of co-moving electrons, on the one hand, helps to keep a dynamic balance between the electrostatic pressure in the accelerating slab and the increasing laser radiation pressure with a Gaussian temporal profile at the rising front, i.e. dynamically matching the optimal condition of RPA; on the other hand, it aids in suppressing the foil Coulomb explosion due to loss of electrons induced by transverse instabilities during RPA. Two-dimensional and three-dimensional particle-in-cell simulations show that a monoenergetic Si¹⁴⁺ beam with a peak energy of 3.7 GeV and particle number 4.8 × 10⁹ (charge 11 nC) can be obtained at an intensity of 7 × 10¹⁷ W cm⁻² and the conversion efficiency from laser to high energy ions is improved significantly by using the ECSs in our scheme.

1. Introduction

Laser-driven ion acceleration has aroused great interest during the past decade [1, 2] due to its many prospective applications, including proton imaging [3], tumor therapy [4], inertial confinement fusion [5] and nuclear physics [6]. Most applications require high-energy ion beams with a monoenergetic spectrum, small divergence and large particle number. Several mechanisms of laser ion acceleration are proposed, including target normal sheath acceleration (TNSA) [7, 8], radiation pressure acceleration (RPA) [9–13], shock acceleration [14–16] and others.

Previous studies have focused on the TNSA mechanism. In TNSA, ions are accelerated by the sheath field at the rear of the foil, created by suprathermal electrons generated from the front side via the oscillating j × B heating of linear polarized (LP) lasers. The produced ion beams are typically characterized with large divergence and broad energy spread. Recently, RPA using circularly polarized (CP) laser pulses has emerged as one of the most promising schemes for obtaining high-energy monoenergetic ion beams. Compared with LP lasers, CP lasers can inhibit the generation of thermal electrons caused by the j × B heating and consequently TNSA is suppressed. The RPA mechanism is composed of two stages: ‘hole-boring’ and ‘light-sail’ RPA. First, electrons are steadily pushed forward by the nonoscillating ponderomotive force, inducing an intense charge separation field that accelerates ions repeatedly until the laser pulse punches through the foil, known as the ‘hole-boring’ stage; then the compressed electron and ion layers constitute a quasineutral plasma slab acting as a reflecting mirror, and the acceleration physics is similar to the ‘light-sail’ concept of space-flight [17, 18], corresponding to the ‘light-sail’ stage.

However, in the multidimensional case, various effects, such as the finite spot [19], transverse expansion [20] and transverse instabilities [21–23], may terminate the acceleration. In particular, during the interaction of the
laser and plasma, the laser acts as a photon fluid pushing against the dense target [21, 22]. Thus, transverse Rayleigh–Taylor-like (RT) instability inevitably sets in and grows, which may eventually deform and dig through the foil [21, 22, 24, 25]. Meanwhile strong electron heating develops as the target surface is deformed and light is obliquely incident, which leads to heavy loss of the co-moving electrons. Resultantly, the accelerating ion beam undergoes Coulomb explosion and RPA breaks [25, 26], which is much more serious for heavy ion acceleration [25].

Furthermore, the classical optimal condition of efficient RPA [11, 13] is based on the assumption of a constant laser amplitude, which is hard to match for a laser with a Gaussian temporal profile, leading to a significant reduction of laser-to-ion conversion efficiency. Recently, the effect of such a laser pulse on the hole-boring RPA has been investigated, and the conditions of efficient ‘hole-boring’ RPA have been formulated for such a laser pulse by Weng et al [27, 28]. However, on the one hand, the discussion is dominant for the ‘hole-boring’ stage of RPA; on the other hand, actually either tailoring a laser pulse or modulating the target density distribution is extremely challenging with the current experimental condition and target fabrication technology.

In this paper, we propose a novel method to maintain and enhance ion stable RPA, especially for the ‘light sail’ stage, from laser-irradiated thin foils, where a series of high-Z nanofilms is placed behind, as shown in the schematic in figure 1 (a). The hole-boring stage is very short for an intense laser irradiating on thin foils. Then the quasineutral plasma slab constituted by electrons and ions is pushed forward. When the accelerating slab passes through the nanofilm (almost ballistically due to the ultrathin thickness of the film), all electrons in the high-Z nanofilm are blown out by the strong laser ponderomotive force, which catch up with the accelerating slab rapidly and become co-moving with the latter, while the high-Z ions undergo Coulomb explosion and lag behind. This replenishment of co-moving electrons can be successively achieved by placing a series of high-Z separate nanofilms with proper distance intervals, like cascaded ‘electron charging stations’ (ECSs) during RPA. The key roles of the ECSs in the stabilization of ion RPA can be summarized as two aspects. On the one hand, by replenishing additional co-moving electrons, they help to achieve a dynamic balance between the electrostatic pressure in the accelerating slab and the increasing laser radiation pressure with a Gaussian temporal profile at its rising front; on the other hand, the cascaded replenishment of co-moving electrons by the ECSs offsets the detrimental effects induced by the RT and other instabilities, suppressing the deformation and Coulomb explosion of the accelerating slab, and eventually maintaining stable RPA.

The positions of the ECSs are given theoretically and verified by two-dimensional (2D) and three-dimensional (3D) particle-in-cell (PIC) simulations. The results show that monoenergetic Si$^{14+}$ beams with a peak energy of 3.7 GeV and particle number $4.8 \times 10^8$ (11 nC) can be obtained at an intensity of $7 \times 10^{23}$ W cm$^{-2}$ with this method. The conversion efficiency from laser to high-energy ions can be improved by 40% compared to that without the ECS case.

2. Theoretical model

Let us start with the ion acceleration equation [11–13] in RPA

$$\frac{dp_t}{dt} = \frac{Z}{A} \frac{2I}{m_p n_e c^2} \frac{\sqrt{1 + p_t^2} - p_t}{\sqrt{1 + p_t^2} + p_t},$$  \hspace{1cm} (1)

where \(I\) is the laser intensity at the foil location \(x(t)\), \(p_t = P/m_t c\) is the normalized momentum of ions, \(A\) and \(Z\) are the mass number and charge state and \(l\) is the foil thickness. Previously, based on the assumption of a constant laser amplitude \(a_0\) (intensity \(I_0\), i.e. a flat-top temporal profile, an optimal condition of the foil
thickness for efficient RPA is given as \( l_0 = (1/\pi)(n_c/n_e)a_0 \lambda \) \([13, 29, 30]\), where \( \lambda \) is the laser wavelength and \( n_c \) is the critical density of the incident laser pulse with \( n_c = \pi m_e c^2/e^2 \lambda^2 \) or \( n_c^{rel} = \gamma \pi m_e c^2/e^2 \lambda^2 \), \( \gamma = \sqrt{1 + a_0^2}/2 \) considering relativistic effects. However, in fact the intense laser pulse generally has a Gaussian temporal profile \( a(t) = a_0 \exp(-t^2/\tau^2) \), so the optimal condition of RPA for a single thin foil actually cannot be satisfied dynamically during the whole RPA. This leads to a significant reduction of the efficiency of RPA, as shown in figure 1(b) by comparing the blue \((l = l_0 \sim a_0)\) and red \([l \sim a(t)]\) lines.

To increase the RPA efficiency, in our scheme, we propose to use a series of ECSs (here we use two as an example in our manuscript) behind the accelerating foil to successively increase the electrostatic pressure in the accelerating foil so that it dynamically matches the optimal condition of RPA with a Gaussian laser in its rising front. Afterwards, we use another cascade of ECSs (also using two in our manuscript) to replenish electrons into the accelerating foil so that the detrimental effects induced by the transverse RT instabilities, such as loss of electrons, can be offset, and a stable RPA can be maintained. The energy acceleration curve of our proposed scheme is represented by the green line in figure 1(b), which clearly shows that the acceleration can be much enhanced compared to the single foil case. To demonstrate that our method is not just applicable for the acceleration of proton or light ions, we will focus on heavy ion acceleration in the following. As an example, we choose barium (Ba) nanoﬁlms behind ultrathin silicon (Si) foil to demonstrate the principle of our method. Using other materials of foil and nanoﬁlms has little effect on the results of our scheme, only if the atomic number of the nanoﬁlms is larger than that of foil, i.e. \( Z_{ECS} > Z_{foil} \) to ensure that electrons can be replenished into the accelerating foil \([29]\).

The position and thickness of each nanoﬁlm can be given theoretically. They should be placed at the positions where the foil will become transparent. Thus the timely replenishment of electrons ensures that the acceleration is efﬁcient and stable. For the ﬁrst two nanoﬁlms, the areal density should satisfy

\[
n_{e,SI}^{SI} + \sum n_{e,Ba}^{ba} \geq a_0 \lambda/\pi. \tag{2}\n\]

Instabilities are not so serious as to consider the electron loss at the beginning \([19, 21]\). Thus if we know the temporal proﬁle of the laser, the positions of the ﬁrst two nanoﬁlms are easily determined. For the last two nanoﬁlms, the areal density should satisfy

\[
n_{e,SI}^{SI} + \sum n_{e,Ba}^{ba} - \sum n_{loss} \geq a_0 \lambda/\pi, \tag{3}\n\]

where \( \sum n_{loss} \) includes the electron loss caused by target expansion in transverse and the escape of hot electrons. The target expansion can be ignored when the acceleration length is much less than the Rayleigh length \( L_R = \pi r_0^2/\lambda \), where \( r_0 \) represents the laser radius \([19, 31]\). It is very difﬁcult to give a self-consistent theory of electron loss with time, but we may propose a heuristic pragmatic approach to obtain qualitative estimations. During the laser–plasma interaction, the target surface is signiﬁcantly modulated by RT instability, and multiple cusps and bubbles form there \([21]\). As a result, the laser no longer normally irradiates on the deformed surface, which leads to serious electron heating via direct laser acceleration \([32]\) and Bruenel heating \([33]\), and a resultant loss of co-moving electrons. The more heavily the RT instability develops, the more seriously the target surface deforms, and more electrons are lost. Therefore, it is obvious that the rate of electron loss depends heavily on the RT growth rate. We suppose that the growth time \( \tau_{RT} = \sqrt{A/Z} \sqrt{m_p n_i \lambda/\omega_{RT}/E_i} \) \([21]\) is an important criterion to describe the electron loss and decide the intervals of nanoﬁlms further. Then the electron loss and intervals can be estimated by

\[
n_{loss} \sim 1/\tau_{RT}, \tag{4}\n\]

\[
d \sim \tau_{RT} \bar{v}, \tag{5}\n\]

where \( \tau_{RT} \) represents the mean growth time during the passage of ions through the intervals and \( \bar{v} \) is the mean velocity.

### 3. Simulation results

In order to verify the new scheme, 2D PIC simulations are carried out with the EPOCH code \([34]\). The simulation box \((x, y) = 12 \lambda \times 16 \lambda \) containing \( 9600 \times 3200 \) cells. A circularly polarized laser propagating from the left boundary at \( x = -2.0 \lambda \) with \( I_0 = 7 \times 10^{21} \) W cm\(^{-2}\) and wavelength \( \lambda = 800 \) nm is incident on the target located at \( x = 0 \). The laser pulse is temporally Gaussian with a duration (FWHM) of \( \tau = 10T_0 \) \((T_0 = \lambda/c)\) and transversely fourth-order Gaussian with spot radius \( r_0 = 4 \lambda \). The solid Si foil has a density of \( 2.33 \) g cm\(^{-2}\), a thickness of \( d_{foil} = 16 \) nm and a charge state of Si\(^{2+}\) (fully ionized with an electron density of 405n\(_e\)) with temperature \( T_s = T_{Si} = 280 \) eV, and the Ba nanoﬁlms have a density of \( 3.51 \) g cm\(^{-3}\), a charge state of Ba\(^{54+}\) (partly ionized with electron density 480n\(_e\)) with the same thickness of \( 4 \) nm for simplicity. The charge states of the ions are estimated using the Ammosov–Delon–Krainov rate \([35]\). The particle number per cell is \( 200 \) for each particle. The positions of the ﬁrst two nanoﬁlms of Ba can be conﬁrmed just from equation (2), and the positions
of the last two nanofilms will be determined by equations (3)–(5). As shown in figure 1(c), the blue line shows the ion velocity evolution with distance and the green line represents the RT instability growth time changes. We can see that the growth time remains almost the same as the ion travels from 0.5 μm–3.0 μm, while the velocity increases about 1.6 times, suggesting that the third interval should be 1.6 times longer than the second. Thus we can give the positions of the four Ba nanofilms as 0.16 μm, 0.64 μm, 1.24 μm and 2.24 μm. To clearly show the roles of the Ba nanofilms, simulations without the Ba nanofilms are also carried out for comparison, where the foil thicknesses are taken as \( l = 16 \text{ nm} \) (the same value of Si in our scheme) and 25 nm (the optimal value corresponding to the peak laser intensity).

In figure 2, the evolutions of the electron (2(a)–(c)), Ba\(^{54+} \) (2(d)–(f)) and Si\(^{14+} \) (2(g)–(i)) ion density maps during the acceleration are shown at \( t = 6T_0, 12T_0 \) and \( 18T_0 \) respectively. Evolutions of the electron (3(a)–(c) and (g)–(i)) and Si\(^{14+} \) ion (3(d)–(f) and (j)–(l)) density maps for the case of 16 nm and 25 nm Si without Ba nanofilms are also plotted for comparison. At \( t = 5.6T_0 \), the ion beam starts to enter the first nanofilm of Ba and then passes through it at \( t = 5.8T_0 \). During this process (less than 0.2\( T_0 \)), ions pass through nearly ballistically because...
the nanofilm is ultrathin and the temperature of the particles is very high. Meanwhile, when the laser irradiates on the nanofilm, all the electrons are pushed forward and catch up with the foil, where they will co-move together with the foil, as shown in figures 4(a)–(c), whereas the Ba ions remain almost immobile (figure 2(d)). This replenishment of electrons ensures that the acceleration almost matches the optimal condition of RPA until the laser intensity increases to $4.4 \times 10^{21}$ W cm$^{-2}$. Then the ion beam enters the second nanofilm of Ba and the cascaded replenishment of electrons repeats. Note that the increase of laser intensity is slower than that of the electrostatic pressure, which leads to the peak accelerating electrostatic field moving back a little (figure 4(d)). This actually helps to lower the energy ions being accelerated by the larger field, which can catch up with the higher energy ions, leading to a concentration of ion phase space and a better monoenergetic spectrum, shown in figure 4(e). The phase space (figure 4(d)) shows a typical RPA ‘rolling up’ structure where the majority of ions in the distinct ‘head’ are concentrated. At the falling edge of a Gaussian laser, the other two nanofilms are used to replenish co-moving electrons to compensate the electron loss caused by instabilities. Such a replenishment of electrons keeps the foil neutral and the accelerating foil opaque to the laser until the laser has finished (figures 2(c) and 5(d)). From the curves in figure 4(c), we see that the replenished electrons from the Ba nanofilms contribute more than 60% of the whole co-moving electrons for acceleration of the Si foil, which leads to an enhanced peak density of electrons two times higher than that without the ECS case. Meanwhile, comparing the insets in figures 2(h) and 3(k), larger cusps appear on the target surface for the case of 25 nm Si, which means that the instabilities are suppressed with the nanofilms considered [21].

If there are no Ba nanofilms as ECSs even satisfying the optimal condition of RPA with the peak laser intensity, the target will become transparent to the laser and the acceleration will be terminated prematurely (figures 3(l) and 5(d)). As the transverse instabilities develop, the significant loss of electrons leads to rapid Coulomb explosion and transparency of the accelerating foil. Comparing figure 5(a) with figure 5(b), we can clearly see that the electron density is much higher when ECSs are considered, which keeps the accelerating foil opaque to the intense laser and helps to stabilize the acceleration of Si$^{4+}$. Meanwhile, the foil travels farther and is still accelerated by a larger longitudinal field when ECSs are considered, which means the acceleration is enhanced. As the green line shows in figure 5(a), the negative gradient $E_x$ still compresses the foil for the case with ECSs, while the foil will be torn up by the electric field without ECSs considered (figure 5(b)). Moreover, for the case of 16 nm Si without ECSs, the effective RPA breaks much earlier (figures 3(c), (f) and figure 5(d)), as the Gaussian laser penetrates through the foil at the rising front.

Figure 5(c) plots the final energy spectra of Si$^{4+}$ at $t = 20T_0$ for different cases when the laser has finished. By using our proposed scheme, a quasi-monoenergetic Si beam with a peak energy of 130 MeV u$^{-1}$ (3.7 GeV) is produced. The maximum energy is about 220 MeV u$^{-1}$, which is about 16% higher than the case of 25 nm Si.
(190 MeV $u^{-1}$), just as our model shows in figure 1(b). The particle number with energy larger than 100 MeV $u^{-1}$ in the beam is about $4.8 \times 10^6$ (charge as 11 nC) and the total beam energy is about 3.2J, which means the conversion efficiency is about 6%. However, for the case of 25 nm Si without Ba nanofilms, the energy spectrum just appears as a plateau, which is much lower than the peak of RPA with ECSs. More importantly, the particle number with energy larger than 100 MeV $u^{-1}$ is 1.3 times larger in the ECS case as compared with the case without ECSs. Meanwhile, the conversion efficiency from laser to high energy ions is improved by 40%. For the case with an initial thickness of 16 nm, the energy spectrum is exponentially decaying, which is much worse than both cases mentioned above. In figure 5(d), we plot the mean ion energy changing with time to represent the acceleration efficiency. As for the cases of 16 nm and 25 nm Si without ECSs considered, the energy spectra are too broad to give the peak energy at the end. We can see that the case with ECSs has a higher acceleration than the case of 25 nm and the acceleration also lasts much longer, which means our method is much more efficient and stable. The divergency angle (HWHM) of the high quality Si$^{14+}$ ion beam with energy larger than 100 MeV $u^{-1}$ is about 7.5°, as shown in the inset of figure 5(c).

In order to confirm that our results are not a 2D artefact, 3D PIC simulations are carried out. To reduce the computational cost, the simulation box $(x, y, z)$ is $12 \lambda \times 14 \lambda \times 14 \lambda$ containing 4800 $\times$ 560 $\times$ 560 cells. The particle number per cell is 32 for particles of the Si target and electrons of nanofilms and 2 for ions of nanofilms. As the transverse instabilities grow faster and more co-moving electrons escape from the foil in the 3D cases, the thickness of the last two nanofilms is increased to 8 nm. Other parameters are the same as those in the 2D simulation above. The density of Si$^{14+}$ at $t = 20 T_0$ with and without nanofilms is shown in figures 6(a) and (b). Figure 6(c) shows the corresponding energy spectra. A quasimonoenergetic Si$^{14+}$ beam with a peak energy of 130 MeV $u^{-1}$ is still obtained, which is similar to the result of the 2D simulation. However, the result of 25 nm Si without nanofilms is much worse than the 2D simulation result with an exponentially decaying energy spectrum. Thus we are confident that the 3D effect does not qualitatively impact our proposed scheme.

4. Discussion

To verify that our scheme is robust and practical for experiment, we perform simulations where the intervals do not satisfy the conditions strictly, with the third and fourth nanofilms placed at 1.04 $\mu$m, 2.24 $\mu$m and 1.64 $\mu$m, 2.24 $\mu$m, while the positions of the first and second nanofilms remain unchanged. The results are not as satisfactory, but still much better than the case without ECSs, and quasi-monoenergetic ion beams can also be
obtained, as the dash-dotted green and cyan lines show in figure 5 (c). Even when the last two nanofilms are removed, the results are still better than the case without ECSs, though much worse than the case satisfying the conditions, shown as the dash-dotted magenta line in figure 5 (c). These simulations verify our theory that the distance intervals depend on the RT instability growth time linearly. Exploring the reason is beyond the scope of this paper. We may identify it in the future.

There are some other practical considerations for our method. A laser contrast in excess of $10^{10}$ is required, which can be achieved by using plasma mirrors [36] or via the deployment of parametric amplification techniques [37], and the laser intensity higher than $1 \times 10^{22}$ W cm$^{-2}$ is within current laser systems [38]. The nanometer foil targets have also been used in the experiment, in which the target was produced by thermal evaporation at $10^{-6}$ mbar followed by a floating process with a deposition rate of 0.2 nm s$^{-1}$ [39]. The contaminants have little effect on the acceleration because the heavy ion species can be accelerated efficiently together with the light ion species in stable RPA [29, 40, 41]. Thus the example used in this paper could be tested experimentally with the existing facilities.

5. Conclusion

In conclusion, we have proposed a novel method to maintain and enhance stable ion RPA from laser-irradiated ultrathin foils, where a series of high-Z nanofilms are placed behind. These nanofilms, acting as ECSs, can not only help to maintain a dynamic balance between the electrostatic pressure in the accelerating foil and the increasing laser radiation pressure with a Gaussian temporal profile at its rising front to achieve more efficient RPA, but also can aid in offsetting the detrimental effects induced by RT and other instabilities, leading to more stable acceleration. The position of each nanofilm is estimated from theory and verified by 2D PIC simulations. 2D and 3D PIC simulations show that a monoenergetic Si$^{14+}$ beam with a peak energy of 3.7 GeV and a higher conversion efficiency (improved by 40%) can be obtained at an intensity of $7 \times 10^{21}$ W cm$^{-2}$ with this novel scheme.

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References

[1] Daido H, Nishizaki M and Pirozhkov A S 2012 Rep. Prog. Phys. 75 056401
[2] Macchi A, Borghesi M and Passoni M 2013 Rev. Mod. Phys. 85 751
[3] Borghesi M, Schiavi A, Campbell D H, Haines M G, Willi O, MacKinnon A J, Gizzi L A, Galimberti M, Clarke R J and Ruhl H 2001 Plasma Phys. Control. Fusion 43 A267
[4] Bulanov S V, Esirkepov T Z, Khoroshkov V S, Kuznetsov A V and Pegoraro F 2002 Phys. Lett. A 299 240
[5] Tabak M, Hammer J, Glinsky M E, Krueer W L, Wilks S C, Woodworth J, Campbell E M, Perry M D and Mason R J 1994 Phys. Plasmas 1 1626
[6] Beg F N et al 2002 Appl. Phys. Lett. 80 3009
[7] Wilks S C, Langdon A B, Cowan T E, Roth M, Singh M, Hatchett S, Key M H, Pennington D, MacKinnon A and Snively R A 2001 Phys. Plasmas 8 542
[8] Schwoerer H, Pfromenhauer S, Jackel O, Amthor K-U, Liesfeld B, Ziegler W, Sauerbrey R, Ledingham K W D and Esirkepov T 2006 Nature 439 445
[9] Esirkepov T, Borghesi M, Bulanov S V, Mourou G and Tajima T 2004 Phys. Rev. Lett. 92 175003
[10] Macchi A, Cattani F, Liseykina T V and Cornolti F 2005 Phys. Rev. Lett. 94 165003
[11] Robinson A P L, Zepf M, Kar S, Evans R G and Béllié C 2008 New J. Phys. 10 013021
[12] Qiao B, Zepf M, Borghesi M and Geissler M 2009 Phys. Rev. Lett. 102 145002
[13] Macchi A, Veghini S and Pegoraro F 2009 Phys. Rev. Lett. 103 085003
[14] Fiuza F, Stockem A, Boella E, Fonseca R A, Silva L O, Haberberger D, Tochitsky S, Gong C, Mori W B and Josthi C 2012 Phys. Rev. Lett. 109 215001
[15] Zhang W L, Qiao B, Huang T W, Shen X F, You W Y, Yan X Q, Wu S Z, Zhou C T and He X T 2016 Phys. Plasmas 23 073118
[16] Zhang W L, Qiao B, Shen X F, You W Y, Huang T W, Yan X Q, Wu S Z, Zhou C T and He X T 2016 New J. Phys. 18 093029
[17] Simmons J F L and Mclennan C R 1993 Am. J. Phys. 61 205
[18] Qi, B, Zepf M, Gibbon P, Zepf M, Kar S, Evans R G and Béllié C 2009 Plasma Phys. Control. Fusion 51 024004
[19] Dollar F et al 2012 Phys. Rev. Lett. 108 175003
[20] Yan X Q, Wu H C, Sheng Z M, Chen J E and Meyer-ter-Vehn J 2009 Phys. Rev. Lett. 103 135001
[21] Pegoraro F and Bulanov S V 2007 Phys. Rev. Lett. 99 065002
[22] Palmer CA J et al 2012 Phys. Rev. Lett. 108 225002
[23] Wan Y et al 2016 Phys. Rev. Lett. 117 234801
[24] Steinke S et al 2013 Phys. Rev. ST Accel. Beams 16 011303
[25] Wu D, Zheng C Y, Qiao B, Zhou C T, Yan X Q, Yu M Y and He X T 2014 Phys. Rev. E 90 023201
[26] Qiao B, Zepf M, Gibbon P, Borghesi M, Dromey B, Kar S, Schreiber J and Geissler M 2011 Phys. Plasmas 18 043102
[27] Qiao B, Geissler M, Kar S, Borghesi M and Zepf M 2011 Plasma Phys. Control. Fusion 53 124009
[28] Qiao B, Kar S, Geissler M, Gibbon P, Zepf M and Borghesi M 2012 Phys. Rev. Lett. 108 115002
[29] Weng S M, Murakami M, Azechi H, Wang J W, Tasokko N, Chen M, Sheng Z M, Mulser P, Yu W and Shen B F 2014 Phys. Plasmas 21 012705
[30] Weng S M, Liu M, Sheng Z M, Murakami M, Chen M, Yu L L and Zhang J 2016 Sci. Rep. 6 22150
[31] Qiao B, Zepf M, Borghesi M, Dromey B, Geissler M, Karmakar A and Gibbon P 2010 Phys. Rev. Lett. 105 155002
[32] Yan X Q, Liu C, Sheng Z M, Guo Z Y, Liu B C, Liu Y R, Fang J X and Chen J E 2008 Phys. Rev. Lett. 100 135003
[33] Bulanov S S, Esarey E, Schroeder C B, Bulanov S V, Esirkepov T Z, Kando M, Pegoraro F and Leemans W P 2015 Phys. Rev. Lett. 114 105003
[34] Gahn C, Tsakiris G D, Pukhov A, Meyer-ter-Vehn J, Pretzler G, Thirolf P, Habs D and Witte K J 1999 Phys. Rev. Lett. 83 4772
[35] Brunel F 1987 Phys. Rev. Lett. 59 52
[36] Arber T D et al 2015 Plasma Phys. Control. Fusion 57 113001
[37] Ammosov M V, Delone N B and Krainov V P 1986 Sov. Phys. JETP 64 1191
[38] Dromey B, Kar S, Zepf M and Foster P 2004 Rev. Sci. Instrum. 75 645
[39] Tavella F, Marcinkevicius A and Krausz F 2006 Opt. Express 14 12822
[40] Yanovsky V et al 2008 Opt. Express 16 2199
[41] Braenzel J, Andreiev A A, Platonov K, Klingspoor M, Ehrentraut L, Sandner W and Schnr M 2013 Phys. Rev. Lett. 114 124801
[42] Ji L, Shen B, Zhang X, Wang F, Jin Z, Li X, Wen M and Cary J R 2008 Phys. Rev. Lett. 101 164802
[43] Kar S et al 2012 Phys. Rev. Lett. 109 185006