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 (ECS's). 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, 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 Si^{14+} beam with peak energy 3.7GeV and particle number 4.8×10^9 (charge 11nC) can be obtained at intensity 7×10^{21}W/cm^2 and the conversion efficiency from laser to high energy ions is improved significantly by using the ECS's in our scheme.

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1. INTRODUCTION

Laser-driven ion acceleration has aroused great interest during the past decade [?, ?] due to its many prospective applications including proton imaging [?], tumor therapy [?], inertial confinement fusion [?] and nuclear physics [?]. Most applications require high-energy ion beams with monoenergetic spectrum, small divergence and large particle number. Several mechanisms of laser ion acceleration are proposed, including target normal sheath acceleration (TNSA) [?, ?], radiation pressure acceleration (RPA) [?, ?, ?, ?, ?], shock acceleration [?, ?, ?] 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 $\mathbf{j} \times \mathbf{B}$ 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 scheme for obtaining high-energy monoenergetic ion beams. Comparing with LP lasers, CP lasers can inhibit the generation of thermal electrons causing by the $\mathbf{j} \times \mathbf{B}$ heating and consequently TNSA is suppressed. 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-light [?, ?], corresponding to "light-sail" stage.

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

Furthermore, the classical optimal condition of efficient RPA [?, ?] is based on the assumption of a constant laser amplitude, which is hard to be matched for a laser with Gaussian temporal profile, leading to significant reduction of laser-to-ion conversion efficiency. Recently, the effect of such laser pulse on the hole-boring RPA has been investigated, and the conditions of efficient "hole-boring" RPA have been formulated for such laser pulse by Weng *et al.* [?, ?]. However, on the one hand, the discussion is dominant for the "hole-boring" stage of RPA; on the other hand, actually either tailoring laser pulse or modulating target density distribution is extremely challenging with 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 are placed behind, as shown in schematic figure **??**(a). The hole-boring stage is very short for 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" (ECS's) during RPA. The key roles of the ECS's in stabilization of ion RPA can be summerized 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 ECS's offsets the detrimental effects induced by the Rayleigh-Taylor and other instabilities, suppressing the deformation and Coulomb explosion of the accelerating slab and eventually maintaining stable RPA. The positions of the ECS's 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 peak energy 3.7 GeV and particle number 4.8×10^9 (11nC) can be obtained at intensity of 7×10^{21} W/cm^2 with this method. The conversion efficiency from laser to high-energy ions can be improved by 40% comparing to that without the ECS case.

2. Theoretical model

Let's start with the ion acceleration equation [**?**, **?**, **?**] in RPA

$$\frac{dp_i}{dt} = \frac{Z}{A}\frac{2I}{m_p n_e l c^2}\frac{\sqrt{1+p_i^2}-p_i}{\sqrt{1+p_i^2}+p_i}, \tag{1}$$

where I is the laser intensity at the foil location $x(t)$, $p_i = P/m_i c$ is the normalized momentum of ions, A and Z are 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 $l_0 = (1/\pi)(n_c/n_e)a_0\lambda$ [**?**, **?**, **?**], where λ 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 $n_c^{(r)} = \gamma\pi m_e c^2/e^2\lambda^2$, $\gamma = \sqrt{1+a_0^2/2}$ 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 significant reduction of the efficiency of RPA, as shown in Fig. **??**(b) by comparing the blue ($l = l_0 \sim a_0$) and red [$l \sim a(t)$] lines.

Figure 1. (color online) (a) Schematic of our proposed scheme, where a series of high-Z nanofilms are placed behind the laser-irradiated thin foils as ECS's. (b) The maximum ion energy per nucleon versus time for the RPA with foil thickness $l = l_0 \sim a_0$(blue), $l \sim a(t)$ (red) and $l = l_{foil} + l_{ECS's}$ (green) in our proposed scheme, where a Gaussian laser pulse with $a_0 = 40$, $\tau = 10T_0$ is assumed to irradiate on Si target with density 2.33g/cm^3 and charge 14+. (c) Ion velocity (blue) and RT instability growth time (green) evolution with distance.

To increase the RPA efficiency, in our scheme, we propose to use a series of ECS's (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 ECS's (also using two in our manuscript) to replenish electrons into the accelerating foil so that the detrimental effects induced by the transverse Rayleigh-Taylor instabilities such as loss of electrons can be offset and stable RPA can be maintained. The energy acceleration curve of our proposed scheme is represented by the green line in Fig. **??**(b), which clearly shows the acceleration can be much enhanced comparing to the single foil case. To demonstrate 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 an ultrathin silicon (Si) foil to demonstrate the principle of our method. Using other materials of foil and nanofilms has little effects 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 [**?**].

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 electrons ensures that the acceleration is efficient and stable. For the first two nanofilms, the areal density should satisfy

$$n_{e,Si} l_{Si} + \sum n_{e,Ba} l_{Ba} \geq a n_c \lambda / \pi. \tag{2}$$

Instabilities are not so serious to consider the electron loss at the beginning [**?**, **?**]. 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

$$n_{e,Si} l_{Si} + \sum n_{e,Ba} l_{Ba} - \sum n_{loss} \geq a n_c \lambda / \pi, \tag{3}$$

where $\sum n_{loss}$ includes the electron loss caused by target expansion in transverse and hot electrons escaping. 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 [**?**, **?**]. It is very difficult to give a self-consistent theory of electrons loss with time, but we may propose a heuristic pragmatic approach to get qualitative estimations. During the laser-plasma interaction, the target surface is significantly modulated by RT instability and multiple cusps and bubbles form there [**?**]. As a result, the laser is

no more normally irradiating on the deformed surface, which leads to serious electron heating via direct laser acceleration [**?**] and Brunel heating [**?**] and resultantly loss of co-moving electrons. More heavily the RT instability develops, more seriously the target surface deforms, and more electrons lost. Therefore, it is obvious that the rate of electron loss depends heavily on the RT growth rate. We suppose that the growth time, $\tau_{RT} = \sqrt{A/Z}\sqrt{m_p n_e l_0 \lambda_{\rm RT}}/E_L$ [**?**] 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

$$n_{loss} \sim 1/\overline{\tau}_{RT}, \tag{4}$$

$$d \sim \overline{\tau}_{RT}\overline{v}_i, \tag{5}$$

where $\overline{\tau}_{RT}$ represents the mean growth time during ions pass through the intervals and $\overline{v}_i$ is the mean velocity.

3. Simulation Results

In order to verify the new scheme, 2D PIC simulations are carried out with the EPOCH code [**?**]. The simulation box (x, y) is $12\lambda\times16\lambda$ containing 9600×3200 cells. A circularly polarized laser propagating from the left boundary at $x = -2.0\lambda$ with $I_0 = 7\times10^{21}$ W/cm^2 and wavelength $\lambda = 800$nm is incident on the target located at $x = 0$. The laser pulse is temporally Gaussian with duration (FWHM) $\tau = 10T_0$ ($T_0 = \lambda/c$) and transversely fourth-order Gaussian with spot radius $r_0 = 4\lambda$. The solid Si foil has density 2.33g/cm^3, thickness $l_{foil} = 16$nm and charge state Si^{14+} (fully ionized with electron density $405n_c$) with temperature $T_e = T_{\rm Si} = 280$eV, and the Ba nanofilms have density 3.51g/cm^3, charge state Ba^{54+} (partly ionized with electron density $480n_c$) with the same thickness of 4nm for simplicity. The charge states of ions are estimated using the Ammosov-Delon-Krainov (ADK) rate [**?**]. The particle number per cell is 200 for each particle. The positions of the first two nanofilms of Ba can be confirmed just from Eq. (2). And the positions of the last two nanofilms will be determined by Eq. (3), (4) and (5). As shown in Fig. **??**(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 keeps almost the same during ion traveling from 0.5μm to 3.0μm, 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 positions of the four Ba nanofilms as 0.16μm, 0.64μm, 1.24μm and 2.24μm. 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 $l = 16$nm (the same value of Si in our scheme) and 25nm (the optimal value corresponding to the peak laser intensity).

In Fig. **??**, the evolutions of electron [**??**(a)-**??**(c)], Ba^{54+} [**??**(d)-**??**(f)] and Si^{14+} [**??**(g)-**??**(i)] ion density maps during the acceleration are shown at $t = 6$, 12 and $18T_0$ respectively. Evolutions of electron [**??**(a)-**??**(c) and **??**(g)-**??**(i)] and Si^{14+} ion [**??**(d)-**??**(f) and **??**(j)-**??**(l)] density maps for the case of 16nm and 25nm Si without

Figure 2. (color online) 2D simulation results: Electron density $\ln(n_e/n_c)$ (a-c), Ba ion density $\ln(n_{Ba}/n_c)$ (d-f) and Si ion density $\ln(n_{\rm Si}/n_c)$ (g-i) at $t = 6T_0$, $12T_0$ and $18T_0$ in the acceleration of a Si foil irradiated by a CP laser pulse at $I_0 = 7\times10^{21}{\rm W/cm^2}$, where four nanofilms of 4nm Ba are used behind the foil. Other parameters are shown in the text. Inset shows zoomed density map in the dot-dashed box, which indicates the seriousness of the RT instability.

Figure 3. (color online) 2D simulation results of the cases for comparison: Electron density $\ln(n_e/n_c)$ (a-c) and Si ion density $\ln(n_{\rm Si}/n_c)$ (d-f) at $t = 6T_0$, $12T_0$ and $18T_0$ for the case of 16nm Si foil irradiated by a CP laser pulse at $I_0 = 7\times10^{21}{\rm W/cm^2}$. The electron and Si ion density maps of the case with 25nm Si foil are shown in (g-i) and (j-l), respectively. Other parameters are the same as the case in Fig. 2. Insets show zoomed density maps in the dot-dashed boxes, which indicates the seriousness of the RT instability.

Figure 4. (color online) The corresponding longitudinal profiles distributions of electrons density $\ln(n_e/n_c)$ of the first (red), second (blue), third (green) and fourth (magenta) nanofilm of Ba around $y = 0$ and at $t = 6T_0$ (a), $t = 12T_0$ (b) and $t = 18T_0$ (c) in the simulation of Fig. **??** for the case with ECS's. The dashed black lines show the distributions of Si^{14+} correspondingly. (d) The dotted lines show the phase space of Si ions at $5.6T_0$ (blue) and $5.8T_0$ (black). The solid lines correspond to the longitudinal electric field at $5.6T_0$ (green) and $5.8T_0$ (red). (e) Energy spectra of Si^{14+} at $5.6T_0$ (blue) and $5.8T_0$ (red).

Figure 5. (color online) The corresponding longitudinal profiles of electron density N_e/n_c (black) and electric field E_x (green) at $t = 12T_0$ for the cases with ECS's (a) and 25nm Si without ECS's (b). (c) Energy spectra of Si^{14+} in our scheme (red), 16nm Si (blue) and 25nm Si (black) without ECS's at $t = 20T_0$. The dash-dotted green and cyan lines correspond to the cases with four nanofilms of Ba but not placed at the optimal positions, while the dash-dotted magenta line represents the case without the last two nanofilms. Inset shows the divergence distribution of Si^{14+} ion energy, where the color represents the relative ion number. (d) The mean ion energy per nucleon of the obtained Si^{14+} beam changing with time for the cases with ECS's (red), 16nm Si (blue) and 25nm Si (black) without ECS's.

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 $0.2T_0$), ions pass through nearly ballistically because the nanofilm is ultrathin and the temperature of particles is very high. Meanwhile, when laser irradiates on the nanofilm, all electrons of it are pushed forward and catch up with the foil, where they will co-move together with the foil, as shown in Fig. **??**(a)-(c), whereas the Ba ions keep almost immobile [Fig. **??**(d)]. This replenishment of electrons ensures that the acceleration almost matches the optimal condition of RPA until the laser intensity increases to $4.4\times10^{21}{\rm W/cm^2}$. 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 [Fig. **??**(d)]. This actually helps to the lower energy ions being accelerated by larger field, which can catch up with the higher energy ions, leading to concentration of ion phase space and better monoenergetic spectrum, shown in Fig. **??**(e). The phase space [Fig. **??**(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 causing by instabilities. Such replenishment of electrons keeps the foil neutral and the accelerating foil opaque to the laser until the laser is over [Fig. **??**(c) and Fig. **??**(d)]. From the curves in Fig. **??**(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 by 2 times higher than that without the ECS's case. Meanwhile, comparing the insets in Fig. **??**(h) and Fig. **??**(k), larger cusps appear on the target surface for the case of 25nm Si, which means the instabilities are suppressed with nanofilms considered [**?**].

If there are no Ba nanofilms as ECS's, 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 [Fig. **??**(l) and Fig. **??**(d)]. As the transverse instabilities develop, significant loss of electrons leads to rapid Coulomb explosion and transparency of the accelerating foil. Comparing Fig. **??**(a) with Fig. **??**(b), we can clearly see that the electron density is much higher with ECS's considered, which keeps the accelerating foil opaque to intense laser and helps to stabilize the acceleration of Si^{14+}. Meanwhile, the foil travels farther and is still accelerated by larger longitudinal field with ECS's considered, which means the acceleration is enhanced. As the green line shows in Fig. **??**(a), the negative gradient E_x still compresses the foil for the case with ECS's, while the foil will be teared up by the electric field without ECS's considered [Fig. **??**(b)]. Moreover, for the case of 16nm Si without ECS's, the effective RPA breaks much earlier [Fig. **??**(c), **??**(f) and Fig. **??**(d)], as the Gaussian laser penetrates through the foil at the rising front.

Figure **??**(c) plots the final energy spectra of Si^{14+} at $t = 20T_0$ for different cases when the laser is over. By using our proposed scheme, a quasi-monoenergetic Si beam with peak energy 130 MeV/u (3.7GeV) is produced. The maximum energy is about 220 MeV/u, which is about 16% higher than the case of 25nm Si (190 MeV/u), just as our model shows in Fig. **??**(b). The particle number with energy larger than 100 MeV/u in the beam is about 4.8×10^9 (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 25nm Si without Ba nanofilms, the energy spectrum just appears a plateau, which is much lower than the peak of RPA with ECS's. More importantly, the particle number with energy larger than 100 MeV/u is 1.3 times larger in the ECS's case as compared with the case without ECS's. Meanwhile, the conversion efficiency from laser to high

Figure 6. (color online) 3D PIC simulation results: the Si^{14+} density isosurface for $n = 2n_c$ with (a) and without (b) the films at $t = 20T_0$. (c) Energy spectra of Si^{14+} with (red) and without (black) the films.

Intensity	Energy	Polarization	FWHM	Duration	Contrast	Lambda	Facility	Target	Thickness	Energy
5×10^{19}	0.7	Circular	$3.6\mu m$	45fs	10^{-11}	810nm	Max Born	DLC	5.3nm	2.5 (3.5) C^{6+}
2×10^{21}	0.8	Circular	$1.2\mu m$	40fs	10^{-15}	800nm	HERCULES	SiN	30nm	7 (12) C^{6+}
1.25×10^{20}	200	Linear	$5.0\mu m$	700fs	10^{-9}	$1\mu m$	VULCAN	Cu	50nm	6 (9) C^{6+}
3.3×10^{20}	8.3	Linear	$5.8\mu m$	30fs	10^{-11}	800nm	PULSER I	F8BT	10nm	10 (13.7) C^{6+}
2×10^{20}	4.5	Circular	$3.5\mu m$	50fs	10^{-9}	800nm	Gemini	DLC	nm	14 (20) C^{6+}
6.1×10^{20}	7.4	Circular	$3.5\mu m$	30fs	10^{-11}	800nm	PULSER I	F8BT	15nm	(93) H

Intensity	Energy	Polarization	Angle	FWHM	Duration	Lambda	Facility	Target	Thickness	Energy
5×10^{19}	50	Linear	45		1ps	$1\mu m$	VULCAN	Pb	2mm	(2) Pb^{46+}
10^{19}	20	Linear	22.5	10	600fs	$1\mu m$	Trident	Pt	$20\mu m$	3(3.5) C^{6+*}
7×10^{17}	0.15	Linear	0	30	40fs	$1\mu m$	JLITE-X	CO_2	0.4mm	15(20) He^{2+}
5×10^{19}	30J	Linear	0	–	300fs	$1\mu m$	LULI	Al(W)	$50\mu m$	(5) F^{7+}
1.25×10^{20}	200	Linear	–	$5.0\mu m$	700fs	$1\mu m$	VULCAN	Cu	50nm	6 (9) C^{6+}
8×10^{19}	1.3	Linear	–	4	30fs	$1\mu m$	Max Born	Au	14nm	(1)Au^{50+} (12)C^{6}+ (4.2)O^{8+}
10^{21}	8J	Linear	45	3	35fs	800nm	J-KAREN	Al	800nm	(16)Fe^{26+}
10^{20}	200J	Linear	0	6	700fs	$1\mu m$	VULCAN	Au	$10\mu m$	14 D^{1+}

energy ions is improved by 40%. For the case with initial thickness 16nm, the energy spectrum is exponentially decaying, which is much worse than both cases mentioned above. In Fig. **??**(d), we plot the mean ion energy changing with time to represent the acceleration efficiency. As for the cases of 16nm and 25nm Si without ECS's considered, the energy spectra are too broad to give the peak energy at the end. We can see that the case with ECS's has a higher acceleration than the case of 25nm 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 100MeV/u is about 7.5°, shown as the inset of Fig. **??**(c).

In order to identify 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 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 3D cases, the thickness of the last two nanofilms is increased to 8nm. Other parameters are the same as those in the 2D simulation above. The density of Si^{14+} at $t = 20T_0$ with and without nanofilms are shown in Fig. **??**(a) and Fig. **??**(b). Fig. **??**(c) shows the corresponding energy spectra. A quasimonoenergetic Si^{14+} beam with peak energy 130MeV/u is still obtained, which is similar to the result of 2D simulation. However, the result of 25nm Si without nanofilms is even much worse than the 2D simulation result with an exponentially decaying energy spectrum. Thus we are confident that 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 that the intervals do not satisfy the conditions strictly, with the third and fourth

nanofilms placed at 1.04μm, 2.24μm and 1.64μm, 2.24μm, while the positions of the first and second nanofilms keep unchanged. The results are not such well, but still much better than the case without ECS's and quasi-monoenergetic ion beams can also be obtained, as the dash-dotted green and cyan lines show in Fig. **??**(c). Even the last two nanofilms are removed, the results are still better than the case without ECS's, though much worse than the case satisfying the conditions, shown as the dash-dotted magenta line in Fig. **??**(c). These simulations verify our theory about 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. Laser contrast in excess of 10^{10} is required, which can be achieved by using plasma mirrors [**?**] or via the deployment of parametric amplification techniques [**?**]. And the laser intensity higher than 1×10^{22} W/cm^2 is within current laser systems [**?**]. The nanometer foil targets have also been used in experiment, in which the target was produced by thermal evaporation at 10^{-6}mbar followed by a floating process with deposition rate 0.2nm/s [**?**]. The contaminants have little effects on the acceleration, because the heavy ion species can be accelerated efficiently together with the light ion species in stable RPA [**?**, **?**, **?**]. 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 electron charging stations, 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 aids in offsetting the detrimental effects induced by the Rayleigh-Taylor 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 peak energy 3.7GeV and higher conversion efficiency (improved by 40%) can be obtained at intensity of 7×10^{21} W/cm^2 with this novel scheme.

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References

[1] H. Daido, M. Nishiuchi and A. S. Pirozhkov, Rep. Prog. Phys. **75**, 056401 (2012).
[2] A. Macchi, M. Borghesi, and M. Passoni, Rev. Mod. Phys. **85**, 751 (2013).
[3] M. Borghesi, A. Schiavi, D. H. Campbell, M. G. Haines, O. Willi, A. J. MacKinnon, L. A. Gizzi, M. Galimberti, R. J. Clarke, and H. Ruhl, Plasma Phys. Controlled Fusion **43**, A267 (2001).
[4] S. V. Bulanov, T. Z. Esirkepov, V. S. Khoroshkov, A. V. Kuznetsov, and F. Pegoraro, Phys. Lett. A **299**, 240 (2002).
[5] M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilks, J. Woodworth, E. M. Campbell, M. D. Perry, and R. J. Mason, Phys. Plasmas **1**, 1626 (1994).
[6] F. N. Beg, K. Krushelnick, C. Gower, S. Torn, A. E. Dangor, A. Howard, T. Sumner, A. Bewick, V. Lebedenko, J. Dawson, D. Davidge, M. Joshi, and J. R. Gillespie, Appl. Phys. Lett. **80**, 3009 (2002).
[7] S. C. Wilks, A. B. Langdon, T. E. Cowan, M. Roth, M. Singh, S. Hatchett, M. H. Key, D. Pennington, A. MacKinnon, and R. A. Snavely, Phys. Plasmas **8**, 542 (2001).
[8] H. Schwoerer, S. Pfotenhauer, O. Jäckel, K.-U. Amthor, B. Liesfeld, W. Ziegler, R. Sauerbrey, K. W. D. Ledingham, and T. Esirkepov, Nature (London) **439**, 445 (2006).
[9] T. Esirkepov, M. Borghesi, S. V. Bulanov, G. Mourou, and T. Tajima, Phys. Rev. Lett. **92**, 175003 (2004).
[10] A. Macchi, F. Cattani, T. V. Liseykina, and F. Cornolti, Phys. Rev. Lett. **94**, 165003 (2005).
[11] A. P. L. Robinson, M. Zepf, S. Kar, R. G. Evans, and C. Bellei, New J. Phys. **10**, 013021 (2008).
[12] B. Qiao, M. Zepf, M. Borghesi, and M. Geissler, Phys. Rev. Lett. **102**, 145002 (2009).
[13] A. Macchi, S. Veghini, and F. Pegoraro, Phys. Rev. Lett. **103**, 085003 (2009).
[14] F. Fiuza, A. Stockem, E. Boella, R. A. Fonseca, L. O. Silva, D. Haberberger, S. Tochitsky, C. Gong, W. B. Mori, and C. Joshi, Phys. Rev. Lett. **109**, 215001 (2012).
[15] W. L. Zhang, B. Qiao, T. W. Huang, X. F. Shen, W. Y. You, X. Q. Yan, S. Z. Wu, C. T. Zhou and X. T. He, Phys. Plasmas **23**, 073118 (2016).
[16] W. L. Zhang, B. Qiao, X. F. Shen, W. Y. You, T. W. Huang, X. Q. Yan, S. Z. Wu, C. T. Zhou and X. T. He, New J. Phys. **18**, 093029 (2016).
[17] J. F. L. Simmons and C. R. McInnes, Am. J. Phys., **61**, 205 (1993).
[18] A. P. L. Robinson, P. Gibbon, M. Zepf, S. Kar, R. G. Evans and C. Bellei, Plasma Phys. and Control. Fus., **51**, 024004 (2009).
[19] F. Dollar, C. Zulick, A. G. R. Thomas, V. Chvykov, J. Davis, G. Kalinchenko, T. Matsuoka, C. McGuffey, G. M. Petrov, L. Willingale, V. Yanovsky, A. Maksimchuk, and K. Krushelnick, Phys. Rev. Lett. **108**, 175005 (2012)
[20] X. Q. Yan, H. C. Wu, Z. M. Sheng, J. E. Chen, and J. Meyer-ter-Vehn, Phys. Rev. Lett. **103**, 135001 (2009).
[21] F. Pegoraro and S. V. Bulanov, Phys. Rev. Lett. **99**, 065002 (2007).
[22] C. A. J. Palmer, J. Schreiber, S. R. Nagel, N. P. Dover, C. Bellei, F. N. Beg, S. Bott, R. J. Clarke, A. E. Dangor, S. M. Hassan, P. Hilz, D. Jung, S. Kneip, S. P. D. Mangles, K. L. Lancaster, A. Rehman, A. P. L. Robinson, C. Spindloe, J. Szerypo, M. Tatarakis, M. Yeung, M. Zepf, and Z. Najmudin, Phys. Rev. Lett. **108**, 225002 (2012).
[23] Y. Wan, C.-H. Pai, C. J. Zhang, F. Li, Y. P. Wu, J. F. Hua, W. Lu, Y. Q. Gu, L. O. Silva, C. Joshi, and W. B. Mori, Phys. Rev. Lett. **117**, 234801 (2016).
[24] S. Steinke, P. Hilz, M. Schnürer, G. Priebe, J. Bränzel, F. Abicht, D. Kiefer, C. Kreuzer, T.

Ostermayr, J. Schreiber, A. A. Andreev, T. P. Yu, A. Pukhov, and W. Sandner, Phys. Rev. ST Accel. Beams **16**, 011303 (2013).

[25] D. Wu, C. Y. Zheng, B. Qiao, C. T. Zhou, X. Q. Yan, M. Y. Yu, and X. T. He, Phys. Rev. E **90**, 023101 (2014).

[26] B. Qiao, M. Zepf, P. Gibbon, M. Borghesi, B. Dromey, S. Kar, J. Schreiber, and M. Geissler, Phys. Plasmas **18**, 043102 (2011);B Qiao, M Geissler, S Kar, M Borghesi and M Zepf, Plasma Phys. and Control. Fus., **53**, 124009 (2011);B. Qiao, S. Kar, M. Geissler, P. Gibbon, M. Zepf, and M. Borghesi, Phys. Rev. Lett. **108**, 115002 (2012).

[27] S. M. Weng, M. Murakami, H. Azechi, J. W. Wang, N. Tasoko, M. Chen, Z. M. Sheng, P. Mulser, W. Yu, and B. F. Shen, Phys. Plasmas **21**, 012705 (2014).

[28] S. M. Weng, M. Liu, Z. M. Sheng, M. Murakami, M. Chen, L. L. Yu and J. Zhang, Sci. Rep. **6**, 22150 (2016).

[29] B. Qiao, M. Zepf, M. Borghesi, B. Dromey, M. Geissler, A. Karmakar and P. Gibbon, Phys. Rev. Lett. **105**, 155002 (2010).

[30] X. Q. Yan, C. Lin, Z. M. Sheng, Z. Y. Guo, B. C. Liu, Y. R. Lu, J. X. Fang and J. E. Chen, Phys. Rev. Lett. **100**, 135003 (2008).

[31] S. S. Bulanov, E. Esarey, C. B. Schroeder, S. V. Bulanov, T. Zh. Esirkepov, M. Kando, F. Pegoraro, and W. P. Leemans, Phys. Rev. Lett. **114**, 105003 (2015).

[32] C. Gahn, G. D. Tsakiris, A. Pukhov, J. Meyer-ter-Vehn, G. Pretzler, P. Thirolf, D. Habs, and K. J. Witte,Phys. Rev. Lett. **83**, 4772 (1999).

[33] F. Brunel, Phys. Rev. Lett. **59**, 52 (1987).

[34] T. D. Arber *et al.*, Plasma Phys. Control. Fus. **57**, 113001 (2015).

[35] M. V. Ammosov, N. B. Delone, and V. P. Krainov, Sov. Phys. JETP **64**, 1191 (1986)

[36] B. Dromey, S. Kar, M. Zepf and P. Foster, Rev. Sci. Instrum. **75**, 645 (2004).

[37] F. Tavella, A. Marcinkevičius and F. Krausz, Opt. Express **14**, 12822 (2006).

[38] V. Yanovsky, V. Chvykov, G. Kalinchenko, P. Rousseau, T. Planchon, T. Matsuoka, A. Maksimchuk, J. Nees, G. Cheriaux, G. Mourou, and K. Krushelnick, Opt. Express **16**, 2109 (2008).

[39] J. Braenzel, A. A. Andreev, K. Platonov, M. Klingsporn, L. Ehrentraut, W. Sandner, and M. Schnrer, Phys. Rev. Lett. **114**, 124801 (2015).

[40] Liangliang Ji, Baifei Shen, Xiaomei Zhang, Fengchao Wang, Zhangyin Jin, Xuemei Li, Meng Wen, and John R. Cary, Phys. Rev. Lett. **101**, 164802 (2008).

[41] S. Kar, K. F. Kakolee, B. Qiao, A. Macchi, M. Cerchez, D. Doria, M. Geissler, P. McKenna, D. Neely, J. Osterholz, R. Prasad, K. Quinn, B. Ramakrishna, G. Sarri, O. Willi, X. Y. Yuan, M. Zepf, and M. Borghesi, Phys. Rev. Lett. **109**, 185006 (2012).