Highly Efficient Heavy Ion Acceleration from Laser Interaction with Dusty Plasma

Debin Zou, Mingyang Yu, Xiangrui Jiang, Na Zhao, Tongpu Yu, Hongbin Zhuo, Alexander Pukhov, Yanyun Ma, Fuqiu Shao, Cangtao Zhou,* and Shuangchen Ruan*

Energetic heavy ions with short duration can be generated in the interaction of ultrashort ultraintense (USUI) laser pulse with solid matter. However, the energy conversion efficiency from laser to heavy ions is usually very low. Herein, a novel scheme for efficient transfer of USUI laser energy to the heavy ions of microscopic dust grains in dusty plasma is proposed. Due to the resulting ultraintense space-charge field, the heavy ions expand isotropically together with the laser heated and expelled grain electrons as a plasma cloud on roughly the ion acoustic timescale. It is found that with $3.1 \times 10^{20}$ W cm$^{-2}$ USUI laser, one can produce hundreds-megaelectronvolt C$^{6+}$ ions with $\approx 60\%$ energy transfer efficiency. In fact, up to 300 GeV Au$^{79+}$ ions with $\approx 30\%$ energy transfer efficiency can be obtained by using $8.8 \times 10^{22}$ W cm$^{-2}$ laser. This result suggests the possibility of using hundreds-petawatt laser facility to investigate heavy-ion collisions for nuclear state detection and quantum cardiodynamics phase transition.

1. Introduction

Energetic heavy ions have the properties of high stopping power, accurate control of dosage and range, good direction, and concentrated energy release at the end of their ranges. These features make them suitable for heavy-ion-driven inertial fusion, as well as experiments in nuclear physics, quark-gluon plasmas (QGPs), and quantum chromodynamics (QCDs). Traditionally, generation of heavy ions is mainly by huge particle accelerators, such as the Large Hadron Collider and heavy ion accelerator FAIR. Over the past two decades, laser-based ion accelerators have gained much attention because of their small size, short duration, high beam density, high acceleration gradient, etc. Several mechanisms of ion acceleration have been proposed, including target normal sheath acceleration (TNSA), radiation pressure acceleration (RPA), breakout afterburner acceleration, shock acceleration, and others. However, these mechanisms are mainly for protons or other light ions of high charge-to-mass ratio. Moreover, the laser-to-ion energy conversion efficiency in the experiments is typically only a few percent, which is even lower with ultrashort ultraintense (USUI) laser pulses. Although there are many proposals for enhancing heavy ion acceleration, the achievable energy conversion efficiency still remains rather low and the required laser parameters are difficult to realize in current laboratories. A more efficient and presently realizable heavy ion acceleration scheme is therefore highly demanding.

Many laser-based ion acceleration methods invoke laser irradiation of solid-density targets, and strong light reflection is the main reason for the low energy transfer efficiency. RPA using ultrathin foils is one way to achieve higher efficiency. However, transverse instabilities can lead to destruction of the foil and leakage of the laser energy. Microstructuring or near-critical-density plasma of the target front surface can improve laser light absorption, but energy transfer to the ions is still limited to about 15% for USUI laser pulses.

In this article, we propose to use dusty plasma for achieving efficient heavy ion acceleration by USUI laser pulse. A dusty plasma is a plasma with tiny solid grains suspended in them in a fairly uniform manner. The grains are usually heavily charged because of inelastic collisions with the background plasma electrons, which have much higher mobility than the ions. When the grains interact with ultraintense laser light, they will be field ionized immediately and become the high-density grain plasmas, similar to that in microcluster or droplet targets. Since the original grain atoms are of high density and high charge number, the number of electrons produced via the field ionization is much larger than that of the electrons.
on the pristine grain surface. Accordingly, in our particle-in-cell (PIC) simulations we consider a dusty plasma slab consisting of underdense hydrogen and randomly distributed solid-density neutral microspheres of high-Z heavy-ions. The underdense background plasma can be produced from a gas jet. The desired dust grains can be produced by several methods including the electro浮选 method, and dissociation of suitable gases. The gas slab as well as the suspended grains is ionized by the prepulse or leading edge of the laser pulse. Our 2D PIC simulations show that the laser expels most of the electrons in the background hydrogen plasma, and the protons are accelerated as usual by TNSA. The laser light also heats and expels the electrons in the tiny but dense electron-rich grain plasma spheres, and the resulting intense electrostatic space-charge field in the grains leads to isotropic expansion of the grain ions. For laser pulse of intensity $3.1 \times 10^{20} \text{ W cm}^{-2}$, duration 50 fs, and energy 12 J, we found that the Ce$^{6+}$ ion and proton energies can reach 350 and 46 MeV, with energy transfer efficiency $\eta_i = 60\%$ and 5\%, respectively. The high efficiency for energy transfer to the heavy ions occurs for a wide parametric range, and the maximum heavy-ion energy $E_{\text{max}}$ is linearly proportional to the normalized laser intensity and grain-ion charge number $Z$. For example, with the same laser parameters, $E_{\text{max}}$ and $\eta_i$ of Au ions can be as high as 5 GeV and 54\%, respectively. For higher laser intensity, say $8.8 \times 10^{20} \text{ W cm}^{-2}$ expected from Extreme Light Infrastructure (ELI) or Shanghai Extreme Light Science (SEL), one can even obtain about 300 GeV ($\approx 1.52 \text{ GeV/nucleon}$) Au$^{29+}$ ions with $\eta_i \approx 30\%$.

2. Results

2.1. Numerical Modeling, Results, and Analysis

The 2D PIC simulations presented in this work were conducted with the well-known PIC code EPOCH (a plasma physics simulation code which uses the Particle in Cell method). A sketch of the simulation setup is shown in Figure 1a. A $p$-polarized (in $y$ direction) laser pulse is normally incident on the dusty plasma along the $x$-axis. The laser intensity is $3.1 \times 10^{20} \text{ W cm}^{-2}$, corresponding to the normalized electric field amplitude $a_0 = eE_0/m_e\omega_0c = 15$, where $-e$ and $m_e$ are the electron charge and rest mass, $c$ is the vacuum light speed, $\omega_0$ and $E_0$ are the frequency and the peak electric field of the laser light, respectively. The laser pulse has a Gaussian profile $\exp(-y^2/\sigma_0^2)$ with spot size $r_0 = 5\lambda_0$, where $\lambda_0 = 1 \mu\text{m}$ is the laser wavelength. Its temporal profile is $\sin^2(\pi t/\tau_0)$ with pulse length $\tau_0 = 15\tau_0$, where $\tau_0 = 3.3 \text{ fs}$ is the laser wave period. The simulation box is of size $x \times y = 100\lambda_0 \times 100\lambda_0$, with a spatial resolution up to 50 cells per wavelength. Each cell contains 50 macroparticles. For both the particles and fields, we use the open boundary condition at the right box boundary ($x = 100\lambda_0$) and the periodic boundary conditions at the transverse boundaries ($y = \pm 50\lambda_0$). The target slab is a cold dusty plasma of line width $d_0 = 10\lambda_0$ and height $h_0 = 20\lambda_0$ (the phenomenon is similar for longer heights), and located between $45 < x/\lambda_0 < 55$. The grains are modeled by fully ionized spherical carbon plasmas of density $n_i = Zn_e = 60n_c$, where $n_i = m_i\alpha_0^2/4\pi\epsilon_0$ is the critical plasma density and $Z = 6$. Fifty ($N_0 = 50$) grains of radius $r_0 = 0.4\lambda_0$ are randomly distributed in the slab and the remaining space contains $n_i = 0.1n_c$ hydrogen plasma. The ratio of the total surface area of the dust grains to that of the dusty plasma can thus be given by $\alpha = N_0\pi r_0^2/d_0h_0 = 12.6\%$. For the randomly distributed spherical plasma grains, the first grain is placed on the bottom left corner of the simulation box, with its center at ($x_1 + r_0$, $y_1 + r_0$). The second grain is randomly placed under the condition that the distance between the grain centers is larger than $2r_0$. The other grains are placed in the same manner up to the Nth grain. To see the effect, if any, of the grain distribution in space, we have considered three cases with different, but all roughly homogeneous, grain distributions. The electrons from the grains and the background plasma are separately tagged, so that the source of electrons in the plasma at the later stages can be tracked in the simulations. For the simulation including field ionization, the ionization degree of the carbon ions is initially set to unity to imitate the effect of a laser prepulse. For the high laser intensity (namely, $10^{22} - 10^{24} \text{ W cm}^{-2}$), the laser–plasma interaction enters the radiation dominating near-quantum electrodynamics (QED) regime. The EPOCH-code modules for $\gamma$ photon emission and positron generation are thus turned on. The physics invoked in these modules have been tested in earlier simulations for laser

![Figure 1](https://www.adpr-journal.com)
intensities up to $10^{24}$ W cm$^{-2}$.[48,49] In the 3D simulation, to save computation resource, the simulation box is $x \times y \times z = 60\lambda_0 \times 60\lambda_0 \times 60\lambda_0$, with a spatial resolution of $\lambda_0/16 \times \lambda_0/16 \times \lambda_0/16$, and there are 16 macroparticles in each cell. The dusty plasma is cylindrical in shape, with radius $r_c = 5\lambda_0$, height $d_0 = 10\lambda_0$, and the volume ratio of dust grains $a = N_0(4\pi/3)r_c^3/(\pi d_0^2 h_0/4) = 12.6\%$.

Figure 1b shows the efficiency $\eta$ of energy conversion from the laser to the electrons, carbon ions, and protons. We can see that different simulations for three different initial grain distributions lead to basically the same result. In fact, the same conclusion can be drawn for the results in Figure 2a,b. Nearly 80% of the laser energy is absorbed by the plasma and grain particles ($\eta_{\text{abs}} \approx 77\%$), which is far beyond that from laser interaction with the standard solid-density planar target.[5,6] It should be mentioned that all of the laser energy is actually injected into the dusty plasma if we take into account the energy of the internal electromagnetic fields. At $t = 727 T_0$, the efficiency $\eta_{\text{e}}$ of energy conversion to the electrons is up to 50%: most of the plasma and grain electrons are heated, accelerated, and expelled, leaving behind large charge separation fields that accelerate the protons by TNSA and C$^{6+}$ ions directly. In this process, the hot-electron energy is gradually transferred to two-species ions. Accordingly, both $\eta_{\text{H}^+}$ and $\eta_{\text{C}^{6+}}$ increase with time until saturation occurs. As they expand, the ions, especially for the heavy grain ions, carry most of the laser energy because of the huge mass difference. Note that $\eta_{\text{C}^{6+}}$ can even be as high as 60% and $\eta_{\text{H}^+}$ approaches 5%. The ratio $\eta_{\text{C}^{6+}}/\eta_{\text{H}^+} = 12$ corresponds to that of their mass of two-species ions $m_{\text{C}^{6+}}/m_{\text{H}^+} = 12$ since they have almost the same expanding velocities. The total energy conversion efficiency $\eta_{\text{e}} = \eta_{\text{C}^{6+}} + \eta_{\text{H}^+}$ is close to 65%. Except for the ideal 1D RPA case, this efficiency appears to be the highest among all the laser-based ion acceleration mechanisms. The slight decrease in the energy conversion efficiency from the laser to all particles in Figure 1b is can be attributed to escape of the very fast electrons from the simulation box.

The energy spectra of the C$^{6+}$ ions and protons at $t = 240 T_0$ are shown in Figure 1c. We see that $E_{\text{max}}$ reaches $\approx 348$ MeV ($\approx 30$ MeV/nucleon) for the C$^{6+}$ ions and is about 46 MeV for protons. Due to modulation of the heavy C$^{6+}$ ions,[50] there is a small peak at 30 MeV in the proton spectrum. The ion motion and distribution are mainly determined by the charge separation fields and thus also the electron temperatures. Figure 2a shows the temporal evolution of the temperature $kT_i$ of the grain electrons and the underdense background-plasma electrons for three cases, where $k$ is the Boltzmann constant. One can see that $kT_i$ of the grain electrons is larger than that in the background plasma and is highest at $t = 65 T_0$. Then, it begins to decrease due to efficient energy transfer from the electrons to the two species of ions during the electron adiabatic expansion. The spectra of electrons from the hydrogen plasma and the grain plasmas at $t = 65 T_0$ are shown in Figure 2b. The number of energetic electrons from the high-density carbon grains is almost two orders of magnitude higher than that of (the same energy) from the background hydrogen plasma. That is, the energetic grain electrons contribute most to the space-charge field for C$^{6+}$ ion acceleration.

Since the three different initial grain distributions lead to almost identical energy spectra and energy conversion

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**Figure 2.** a) Temperatures of the grain electrons (solid curves) and underdense background plasma electrons (dashed curves) versus time. b) Spectra of the two types of electrons at $t = 65 T_0$. One can see in panels (a,b) that the three cases (numbered 1–3) with different random and roughly homogeneous initial grain distributions yield almost identical results. c) Energy density distribution of the grain electrons. d) Normalized net charge density distribution $(Z_n - n_n)/n_e$; e) distribution of the electric field component $E_x$, and f) energy density distribution of the C$^{6+}$ ions (left) and protons (right) at $t = 65 T_0$. The color bars in (c,f) represent $n_e E_x/m_e c^2 n_e$ and $n_e E_i/m_i c^2 n_i$, where $E_x$ and $E_i$ are the kinetic energy of electrons and two-species ions, respectively. The white dashed line in (e) marks the boundaries of the dusty plasma target, and the field $E_x$ is averaged over a laser period and in units of $m_e c^2/e \approx 3.2 \times 10^2$ V m$^{-1}$. Note that even at this stage of the interaction, the energetic protons are already significantly separated (they have been accelerated forward by the charge separation field created by the laser-expelled background plasma electrons) from the energetic C$^{6+}$ ions.
efficiencies for all particle species, in the following we shall concentrate on the results from one case. Figure 2c is for the energy density of the grain electrons at $t = 65T_0$, when the main part of the laser pulse has been reflected, absorbed, or penetrated through the grains in the background plasma. We see that a large number of electrons have been heated and accelerated. Such a scenario resembles that of laser interaction with microchannels, droplets, or cluster targets. Since a large fraction of the grain electrons are expelled by the laser (see also Figure S1a and Note 1, Supporting Information, they show irregular and messy distribution), the grains become highly positively charged, as shown in Figure 2d. Figure 2e is for the distribution of the electric field component $E_x$, including that of the explosive fields in the grains, the charge-separation field in the hydrogen plasma, as well as the transverse electric field of the laser light. One can see that huge positive electrostatic fields are built up in the grains. Figure 2f shows that the protons are mainly driven forward by the charge-separation field created by the laser-expelled background plasma electrons (see Figure S1b and Note 1, Supporting Information). We can also see that the $C^{6+}$ grain ions are expanding outward together with the electrons, roughly isotropically. In fact, with higher laser intensity, all the electrons can be expelled in some grains. This can be expected since the grain size is less than the laser wavelength, so that the laser field experienced by the grain electrons is relatively static. Note that along the laser axis, $E_x$ of the reflected light is weaker since the incident light is $y$ polarized, so that exact head-on reflection would not have any $E_x$ component.

**Figure 3** shows several ion trajectories from three spheres near the center of the plasma slab at the early time $t = 120T_0$, as well as the late-stage energy density distributions at $t = 240T_0$. (The temporal evolutions of both the background and grain ions can be found in Figure S1c and S1d, Supporting Information.) In Figure 3a-c, we can see that the heavy $C^{6+}$ ions are roughly isotropic and expand like a plasma cloud together with the hot electrons. The proton energy distribution is less isotropic, with the most energetic and/or fastest protons roughly in the forward and backward directions, which is expected since they are driven by the charge separation field created by the laser-expelled $H^+$-plasma electrons, as shown in Figure 3b-d.

To check the validity of the assumption of preionized dust grains in our simulations, we have also performed a simulation including the ionization process of the dust grains (see Figure S2 and Note 2, Supporting Information). The results show that the spatial and spectral distributions of the protons and the heavy ions are similar to those given earlier because the energy loss of the laser pulse resulting from the ionization of the dust grains $\varepsilon_1$ is very small. For given $d_0 = 10\lambda_0$, $h_0 = 20\lambda_0$, $r_0 = 0.4\lambda_0$, and $\alpha = 12.6\%$, the corresponding grain number in real 3D geometry is $N_0 \approx 738$. The laser energy required to fully ionize all the grains can be approximated to $\varepsilon_1 = (4\pi/3)\rho_0^3 \times N_0 \times 10n_e \times \varepsilon_0 = 1.7 \times 10^{-5}$ J, where $\varepsilon_0 = 489.993198$ eV is the ionization energy for a carbon atom ionized into a $C^{6+}$ ion. $\varepsilon_1$ is far below 12 J of the incident laser energy and is therefore negligible. We note that the values of $\eta$ and $\varepsilon_{\text{max}}$ are slightly larger. The reason is attributed to the preionized electrons and heavy ions are already relatively hot and are also continuously heated by the residual laser fields inside the dusty plasma, leading to an enhancement of the accelerating electric field intensity after $t = 65T_0$ (see Figure S3 and Note 3, Supporting Information).

![Figure 3. Trajectories of the a) $C^{6+}$ ions and b) protons from three spheres in the center region of the target at the early time $t = 120T_0$. The black dots and rows represent the current ion positions and their directions. The length of the rows is the magnitude of the ionic momentum, normalized by $m_{\text{ion}}c$ and $m_{\text{ion}}c$ for $C^{6+}$ ions and protons, respectively. Energy density distribution of the c) $C^{6+}$ grain ions and d) background plasma protons at $t = 240T_0$. Note that the $C^{6+}$ ions are distributed isotropically in both energy and space, as expected of the multibody grain explosion. However, the most energetic protons are in the forward and backward directions, as expected of TNSA.](image-url)
Similar phenomenon can also be found in the study by Braenzel et al.\cite{101}

\[ \eta \propto \frac{a}{a_0} \]

2.2. Scaling Laws

We consider the influence of the laser amplitude \( a_0 \) on \( \eta \) and \( \varepsilon_{\text{max}} \). Actually, the difference 1 – \( \alpha \) represents roughly how much energy the dust plasma can hold in all the absorbed laser energy, which can also be used to measure the highest absorption ratio \( \eta_{\text{abs}} \) of the laser energy since \( \alpha \) should be comparable to the maximum reflectivity of the front surface of dusty plasma.

\eta \text{ for two-species ions can thus be expressed as } \eta_{\text{C}^+} = \eta_{\text{abs}}(1 + \alpha)m_{\text{C}^+}/(m_{\text{C}^+} + m_{\text{H}^+}) \text{ and } \eta_{\text{H}^+} = \eta_{\text{abs}}(1 - \alpha)m_{\text{H}^+}/(m_{\text{C}^+} + m_{\text{H}^+}), \text{ respectively. Taking } \eta_{\text{abs}} = 77\% \text{ and } \alpha = 12.6\% (\text{corresponding to the initial parameters of dusty plasma}), \text{ this gives } \eta_{\text{C}^+} \approx 62\% \text{ and } \eta_{\text{H}^+} \approx 5.2\%. \text{ Figure 4a shows that } \eta_{\text{C}^+} \text{ increases slowly and reaches saturation at } a_0 > 20, \text{ with } \eta_{\text{C}^+} \approx 61.3\%. \text{ The efficiency is consistent with the aforementioned estimated value. For the protons (} Z = 1\text{), } \eta_{\text{H}^+} = 5\% \text{ remains almost unchanged (in fact, it decreases slightly with } a_0 \text{ due to the buffer effect of the high-Z carbon ions.}

In the space-charge-driven ion expansion acceleration, the ion speed is roughly given by the ion-acoustic speed\cite{51,52}

\[ v_\text{max} = \frac{Z k T_e}{m_i^{1/2}} \]

where \( k = 12.5 \) is a constant coefficient, depending on the initial dusty plasma distribution. The mass independence of \( \varepsilon_{\text{max}} \), is similar to that in laser-driven Coulomb explosion of gas clusters.\cite{11,52} Our simulation results suggest that the hot electron temperature (green curve and stars) scales roughly as \( k T_e/m_e c^2 \approx 0.6 a_0 \). This leads to linear dependence of \( \varepsilon_{\text{max}} \) for both ion species on \( a_0 \), which is in good agreement with that (blue curves and triangles) in Figure 4a. The electron temperature scaling found here is somewhat weaker than the Wilks ponderomotive energy scaling\cite{53}

\[ k T_e/m_e c^2 = (1/2 a_0)^{1/2} - 1 \]

and the Beg experimental result\cite{54}

\[ k T_e/m_e c^2 = 0.47 a_0^{1/2} \]

Figure 4b shows that \( k T_e, \eta_{\text{H}^+} \approx 5\%, \text{ and } \eta_{\text{C}^+} \approx 60\% \text{ are almost independent of the charge number } Z \text{ of the heavy grain ions. This can be attributed to the fact that the number of hot electrons depends strongly on the laser amplitude } a_0. \text{ We see that } \varepsilon_{\text{max}} \text{ increases linearly with } Z, \text{ consistent with Equation (1). Dusty plasmas are therefore suitable for USUI laser-driven heavy ion acceleration. For example, Figure 4b shows that with laser of intensity 3.1., 10^{26} \text{ W cm}^{-2}, \text{ duration 50 fs, and energy 12 J, one can obtain } \approx 54\% \text{ energy conversion efficiency and up to 5 GeV (} = 25.4 \text{ MeV/nucleon) maximum energy for Au (} Z = 79\text{). For the comparable laser conditions, earlier work}\cite{15} \text{ has shown that } \eta \text{ and } \varepsilon_{\text{max}} \text{ for Au ions are only } 5\% \text{ and } 1–2 \text{ MeV/nucleon. It should be mentioned that it is necessary to consider the effect of ionization on the laser energy loss for heavier ions since the ionization energy is relatively high and it is impossible for ions to be fully ionized for } \approx 10^{20} \text{ W cm}^{-2} \text{ modest laser intensity. Further simulation including the ionization process shows that the Au ions of different charge state } Z_i \text{ are appeared with the maximum } Z_i \text{ is } 51, \text{ which is in good accordance with the studies by Shen et al. and Braenzel et al.}\cite{13,35} \text{ We find that the laser energy is effectively transferred to Au ions with } \eta_{\text{H}^+} = 23\% \text{ and } \varepsilon_{\text{max}} = 3.2 \text{ GeV (} = 16.2 \text{ MeV/nucleon) (see Figure S4 and Note 4, Supporting Information). The total efficiency of laser to all charge states of gold ions is } \approx 66\% \text{ high. The ionization effect on ion acceleration for different } Z \text{ has also been shown in Figure 4b. One can see that } \eta_i \text{ is slightly increased because the ionization process induces the enhancement of } E_x \text{ at a later time. However, we note that } \varepsilon_{\text{max}} \text{ becomes lower with increasing } Z \text{. This is due to that the ionization effect also leads to the reduction of } Z_{i_{\text{max}}} \text{ and } \varepsilon_{\text{max}} \text{ is thus rather limited since } \varepsilon_{\text{max}} = Z_{i_{\text{max}}}^2 \text{, where } (E_x) \text{ is the averaged accelerating electric field and } t_a \text{ is the acceleration time.}

We have also repeated the simulation to include QED effects with the much higher laser intensity 8.8 \times 10^{23} \text{ W cm}^{-2}, \text{ which is expected from the ELI or SEL facilities. Here, these grains of } Z_i = 99/2 \text{ are composed of fully ionized Au plasmas with the densities of } n_e = 79 n_{i_e} = 2646.5 n_{i_e}. \text{ It is found that much of the laser energy is lost to } \gamma \text{-ray photons. Furthermore, the radiation-reaction trapping of electrons}\cite{49} \text{ significantly weakens electron expulsion by the laser and thus the charge separation}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{The laser-to-ion energy conversion efficiency \( \eta \) for the protons (black curves and circles) and C^+ ions (red curves and squares), the maximum ion energies \( E_{\text{max}} \) (ions: blue curves and lower triangles; protons: pink curves and upper triangles) at \( t = 240T_0 \), and the highest hot-electron temperature (green curves and stars) versus a) laser amplitude \( a_0 \) and b) charge number \( Z \) of the heavy ions. The green solid curves (Fit) are the fitting PIC results. For comparison, several existing scalings of the hot-electron temperature for the laser-planar target interaction are given in (a), including the Wilks ponderomotive energy scaling\cite{57} (green dotted curve, Wilks), Haines relativistic scaling\cite{53} (green dashed curve, Haines), and Beg experimental result\cite{54} (green dash-dot curve, Beg), respectively. In (b), the solid symbols and dashed curves represent the simulation results with the ionization process.}
\end{figure}
field for grain-ion acceleration. Even so, $\mathcal{E}_{\text{max}}$ and $\eta$ can still be as high as 300 GeV ($\approx$1.5 GeV/nucleon) and 30% for Au ions (see Figure S5 and Note 5, Supporting Information). Note that $\approx$50% of laser energy is transferred to gamma photons) due to the multibody grain-explosion and hole-boring acceleration.\(^{[55]}\) The latter originates from the ponderomotive force of the laser and plays a role only at extremely high laser intensities. To our knowledge, the maximum energy of $\approx$300 GeV here is the highest laser-accelerated heavy-ion energy reported in the literature. In addition for medical applications, high heavy-ion energy is relevant to nuclear state detection by intermediate-energy ($\approx$1.5 GeV/nucleon) heavy-ion collisions,\(^{[56]}\) as well as for investigating QCD phase transition process to QGP. For example, to generate the QGP, the energy threshold of heavy ions in the laboratory frame for Au+Au collision is $\mathcal{E}_{\text{max}} = \sqrt{S_{\text{NN}}}/2 \geq 3\pi R_{\text{QGP}}^3/2AR^4$, where $\sqrt{S_{\text{NN}}}$ is the energy per nucleon in the mass-centered frame, $R_{\text{QGP}}$ is the initial radius of QGP, $A$ is the nucleon number, and $R = 0.8$ fm is the Fermi radius.\(^{[57]}\) $\mathcal{E}_{\text{max}}$ is only 1.6 GeV/nucleon for $R_{\text{QGP}} = 5$ fm. Such heavy-ion energy is or close to the typical energy window for the aforementioned applications. More importantly, compared to that of the heavy-ion beams from conventional accelerators, such high energy conversion efficiency and beam number density can lead to several orders of magnitude enhancement of the event numbers in experiments, so that the final-state of the observables can be measured more accurately. The approach is thus ideal for investigating de-confinement QCD phase transitions\(^{[58]}\) and collective effects in the strongly interacting QCD processes by using hundreds-petawatt laser-driven energetic heavy ions.

2.3. Parametric Study

We next consider the effects of the interaction parameters on the energy transfer efficiency, as well as the maximum energy of the ion species. For efficient ion acceleration, the energy of the incident laser pulse should be utilized as much as possible in expelling the grain electrons. Since the laser amplitude $a_0 = 15$ is much larger than unity, the electron oscillation energy scales like $\gamma \approx a_0\sqrt{2}$, and the effective skin depth of the grain plasma is $s_0 = c/\omega_{pe} \propto a_0$, where $\omega_{pe} = (4\pi n_e e^2/m_e)^{1/2}$ is the relativistic grain-plasma frequency. Thus, for effective laser-grain plasma interaction, the grain radius should satisfy $r_0 \geq 2s_0$, or $r_0 \geq \sqrt{a_0 n_0/\eta_0 A_0/2\pi} \approx 0.16a_0$. Figure 5F shows the dependence of the energy conversion efficiencies from the laser to the protons and heavy ions, as well as the corresponding maximum energies, on the interaction parameters. Except in the panels b and c for the effect of the parameters on $a$, we set $a = 12.6\%$. Panel a shows that the suitable grain radius for efficient energy transfer to the C$^+$ ions is around $r_0 \approx 0.2A_0$, which is consistent with the aforementioned estimation. Figure 5B shows the effect of $N_0$ (or $d$) on $r_0$ and $\mathcal{E}_{\text{max}}$ for $r_0 = 0.4A_0$. In general, larger $N_0$ means more hot grain electrons for heavy ion acceleration can be generated, but it also means more laser energy will be reflected by the grains. The combined result therefore depends on competition between these effects and can be the cause of the dip of $\mathcal{E}_{\text{C}^+_{\text{max}}}$ in the region $25 \leq N_0 \leq 150$. Note that there is no dip for $\mathcal{E}_{\text{H}^+_{\text{max}}}$ since the energetic protons are mainly accelerated by the laser expelled background plasma electrons.

3. Discussion

Our simulation results show that, in USUI laser interaction with dusty plasma consisting of undercritical density hydrogen plasma with high-density high-Z heavy ions, the laser-to-heavy ion energy conversion efficiency can be as high as 60% and the maximum energy of the heavy ions can reach the gigaelectronvolt level. Such high levels are much beyond that from existing schemes of laser-accelerated heavy ions.\(^{[9,29–35]}\) The plasma grains used in our scheme resemble that of clusters for producing megaelectronvolt ions.\(^{[31,52,59]}\) However, there the cluster size and density are low, and the energy conversion efficiency for the energetic ions is low since in the cluster explosion process the maximum electric field generated in the cluster scales like $E_c \approx \pi Ze_n r_0$. Note also that the interaction of laser with an isolated overdense spherical microcluster\(^{[41,52]}\) or droplet\(^{[42,43]}\) of size less than the laser spot has been investigated earlier. It is found that the laser light can wrap around the cluster and most of the laser energy is unused. Our results indicate that the presence of a large number of dust grains should also enhance laser energy absorption in such single-cluster interactions. It should, however, be emphasized that the accelerated heavy ions from the present scheme are not monoenergetic and have a relatively isotropic angular distribution, making them unsuitable for applications where precise large heavy-ion doses are required. Several postprocessing methods can be employed to mitigate the large divergence and broad spectrum. For example, ultrafast...
laser-driven microlens,\cite{60} synchronous radio frequency field,\cite{61} and solenoid magnet lens\cite{62,63} are suitable for energy selection and collimation of energetic heavy ions. Permanent magnet miniature quadrupole lenses\cite{64} and conical or hemispheric surface structures\cite{65,66} have also been proposed for focusing and guiding heavy ions.

To ensure that the heavy ion acceleration process considered here is not a 2D artifact, we have also performed full 3D simulation with the same $\alpha (=12.6\%)$. To save computation resources, a lower-energy laser pulse ($\omega_0 = 5, \sigma_0 = 2.5 \lambda_0$, and $\tau_0 = 10T_0$) is used and the simulation box is also smaller. We find that $\varepsilon_{\text{max}}$ and $\eta$ for both ion species are only slightly lower than that from the 2D simulations if $\alpha = \alpha^*$ (see Figure S6c,d and Note 6, Supporting Information). The very small difference can be attributed to the fact that in the 3D case, the laser light is less effectively blocked/reflected by the frontal dust grains, so that more light can reach the grains behind them. In contrast, the most energetic electrons can escape from the smaller simulation box earlier, resulting in reduction of the hot-electron temperature $kT_e$, thereby weakens the ion acceleration.

Because of their importance to basic and space physics, as well as the semiconductor industry, dusty plasmas have gain much interest in the past few decades. Dusty gases containing grains of various composition and sizes can easily be produced.\cite{40,47} For example, the electrofloat\cite{45} or the dissociation of hydrocarbon material\cite{47} can be used to generate dust nanoparticles with a certain volume ratio in Figure 5b. Actually, the density range of $30n_c \leq n_e \leq 270n_c$ in Figure 5d, also covers the actual electron density of the dissociated acetylene or methane. USUI laser pulses are now available in many laser facilities, so that the proposed heavy ion acceleration scheme can be readily tested in the laboratory. A demonstrative experimental design for the

Figure 5. Dependence of the energy conversion efficiencies $\eta$ from the laser to the C$^{6+}$ and H$^+$ ions and the maximum energies of the latter at $t=240T_0$ on: a) and c) the grain radius $r_0$, b) the total grain number $N_0$, d) the electron density $n_e$ of grain plasma, e) the background plasma density $n_{H^+}$, and f) the slab width $d_0$ of the dusty plasma, for $\alpha = 12.6\%$ except in (b,c). In (a), $N_0$ is varied to keep $\alpha$ constant.
As they pass through the CR39 plates, the energetic values are robust for a (10 MeV to hundreds MeV) energy range. Although the ions with 2012 1997 30%. This provides the possibility of 200181 (8 of 10) \textit{Nat. Phys.} © 2021 The Authors. Advanced Photonics Research published by Wiley-VCH GmbH pulse of intensity 3.1. to near-isotropic outward acceleration of their ions. With a laser 12 J interacting with carbon grains, the maximum energy of C 12 ions can reach 350 MeV at 60% laser-to-ions energy conversion efficiency. The protons in the background plasma are also accelerated, but they take up only 5% of the laser energy, with the cutoff energy at 46 MeV. In such heavy ion acceleration, the maximum ion energy increases linearly with the laser intensity and the ion charge number. With the same laser, up to 5 GeV Au ions at \( \eta \approx 54\% \) can be obtained. The high \( \eta \) values are robust for a wide parameter range. Finally, we note that the proposed scheme for heavy ion acceleration can readily be tested experimentally and should be useful in many applications. Moreover, with a laser of intensity 8.8 \( \times 10^{24} \) W cm\(^{-2}\), one can even obtain 300 GeV Au\(^{99+}\) ions with \( \eta \approx 30\% \). This provides the possibility of experimental investigation of heavy-ion collision for nuclear state detection and probing QCD phase transition in the upcoming hundreds-petawatt laser facilities.

4. Conclusion

In summary, we have investigated acceleration of heavy ions from USUI laser interaction with rarefied hydrogen plasma containing microscopic high-density high-Z grains of heavy atoms. It is found that the laser energy is efficiently transferred to the grain electrons, which are expelled and expand adiabatically outward. The grains thus become heavily positively charged, leading to near-isotropic outward acceleration of their ions. With a laser pulse of intensity 3.1. \( \times 10^{20} \) W cm\(^{-2}\), duration 50 fs, and energy 12 J interacting with carbon grains, the maximum energy of C\(^{6+}\) ions can reach 350 MeV at 60% laser-to-ions energy conversion efficiency. The protons in the background plasma are also accelerated, but they take up only 5% of the laser energy, with the cutoff energy at 46 MeV. In such heavy ion acceleration, the maximum ion energy increases linearly with the laser intensity and the ion charge number. With the same laser, up to 5 GeV Au ions at \( \eta \approx 54\% \) can be obtained. The high \( \eta \) values are robust for a wide parameter range. Finally, we note that the proposed scheme for heavy ion acceleration can readily be tested experimentally and should be useful in many applications. Moreover, with a laser of intensity 8.8 \( \times 10^{24} \) W cm\(^{-2}\), one can even obtain 300 GeV Au\(^{99+}\) ions with \( \eta \approx 30\% \). This provides the possibility of experimental investigation of heavy-ion collision for nuclear state detection and probing QCD phase transition in the upcoming hundreds-petawatt laser facilities.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

dusty plasma, heavy ion acceleration, highly efficient, plasma physics

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