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Intense local plasma heating by stopping of ultrashort ultraintense laser pulse in dense plasma

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Abstract

Self-trapping, stopping, and absorption of an ultrashort ultraintense linearly polarized laser pulse in a finite plasma slab of near-critical density is investigated by particle-in-cell simulation. As in the underdense plasma, an electron cavity is created by the pressure of the transmitted part of the light pulse and it traps the latter. Since the background plasma is at near-critical density, no wake plasma oscillation is created. The propagating self-trapped light rapidly comes to a stop inside the slab. Subsequent ion Coulomb explosion of the stopped cavity leads to explosive expulsion of its ions and formation of an extended channel having extremely low plasma density. The energetic Coulomb-exploded ions form shock layers of high density and temperature at the channel boundary. In contrast to a propagating pulse in a lower density plasma, here the energy of the trapped light is deposited onto a stationary and highly localized region of the plasma. This highly localized energy-deposition process can be relevant to the fast ignition scheme of inertial fusion.

Keywords: Critical density plasma; Energy absorption; Energetic ions; Ultrashort ultraintense laser

1. INTRODUCTION

Ultrashort ultraintense (USUI) laser pulses of duration less than 10 laser periods and intensity up to 10^{21} Wcm^{-2} have attracted much recent attention (Wilks & Kruer, 1997; Sarkisov *et al.*, 1997; Ditmire *et al.*, 1999; Karsch *et al.*, 1999; Malka *et al.*, 2002, 2004; Roth *et al.*, 2002, 2005; Hegelich *et al.*, 2002, 2005; Mangles *et al.*, 2004, 2006; Geddes *et al.*, 2004; Faure *et al.*, 2004; Kawata *et al.*, 2005; Yu *et al.*, 2005; Xu *et al.*, 2005; Glowacz *et al.*, 2006; Koyama *et al.*, 2006; Lifshitz *et al.*, 2006). In such a pulse, a huge amount of electromagnetic energy is concentrated in such a tiny volume that its interaction with matter involves new space, time, and energy scales (Gibbon, 2005; Mourou *et al.*, 2006). The interaction physics, such as collisionless and collisional scattering and absorption of laser light, of the short pulses can be quite different from that for the longer ($\gtrsim$ 1 ps) pulses containing many light-wave periods (Yu & Shukla, 1978; Kruer, 1988; Lashinsky *et al.*, 1999).

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For USUI laser pulses of only a few wave periods, the pulse envelope, and the wave length are of similar order of magnitude in both space and time (Wilks & Kruer, 1997; Gibbon, 2005; Mourou *et al.*, 2006). The light pressure of such a steep-gradient pulse is extremely strong and is on extremely short time scale, and new phenomena can appear. For example, the ponderomotive or light pressure of an USUI laser pulse can drive away almost all the plasma electrons in the pulse region, leaving behind the massive ions and an intense space-charge force which balances the ponderomotive force (Gibbon, 2005). A positively charged propagating electron cavity co-existing with the self-trapped light is thus created (Yu & Shukla, 1978). If the plasma is underdense, the cavity-pulse system will propagate through the slab without losing much energy. If the plasma is overdense, the laser will be mostly reflected at the vacuum-plasma interface. Between these two limits one can expect a regime where a part of the laser pulse would penetrate into the plasma, be trapped, and eventually stopped inside. In that case, highly localized intensive heating of a very small volume of the plasma can be realized.

In this paper, we investigate by particle-in-cell (PIC) simulation the interaction of an USUI laser pulse in a critical-density plasma by PIC simulation. It is shown that a significant part of the USUI pulse can indeed enter into and propagate a finite distance in the plasma, be trapped and completely stopped, and its energy efficiently deposited in a small plasma region as energetic ions.

In the next section, we present a brief description of the proposed process and a discussion of the differences between this and the related processes. In Section 3, we summarize the PIC simulation configuration and parameters. For the sake of comparison, we present and briefly discuss the results for several different interactions. In Section 4, we analyze the trapping and stopping of the transmitted light pulse for the case of interest, and in Section 5, we discuss the local plasma heating. In Section 6, the validity of our model and a discussion of the results and possible application to fast ignition are given.

2. INTERACTION OF USUI LASER WITH DENSE PLASMA

A laser pulse will propagate in a plasma if the electron density n satisfies $n < \gamma n_c$, where $\gamma = \sqrt{1 + a^2}$ (with $a = eA/m_e c$, where e and m are the electron charge and rest mass, A is the laser-light vector potential, and c is the speed of light) is the relativistic factor. When an USUI pulse impinges on a critical-density ($n \sim \gamma n_c$) plasma, a part of the laser light is reflected, but a significant part can still enter the plasma as a smaller light pulse together with a number of much smaller light fragments originating from the impact. Despite the high density, the plasma electrons in the pulse region can be almost completely expelled by the ultraintense ponderomotive force (Yu & Shukla, 1978; Wilks & Kruer, 1997; Kawata *et al.*, 2005), resulting in an electron cavity with an intense space-charge field. At the cavity boundaries the ponderomotive and space-charge forces on the electrons balance. The propagation of the self-trapped light pulse will slow down when the local electron density at the front of the pulse-cavity system increases due to pile-up of the expelled plasma electrons, as well as decrease of the relativistic factor γ because of light dissipation. Eventually n approaches γn_c and the tiny light and cavity system comes to a stop. Since the pulse is stationary, a longer time scale becomes relevant and processes such as Coulomb explosion (Sarkisov *et al.*, 1997; Ditmire *et al.*, 1999) of the cavity ions, formation of ion channel and shock layers, as well as their subsequent relaxation, occur. The trapped light energy is thus efficiently transferred to the plasma within a highly localized region in the plasma.

Despite several apparent similarities such as plasma channel formation, the process here is physically very different from that of a *long-pulse* ($\gtrsim$ ps) laser in a dense plasma. There the ions can follow the ponderomotively driven electrons when the laser is still acting on the electrons, so that there is little or no generation of charge-separation field. Instead, hole digging (Kodama *et al.*, 1996, 1999; Harbara *et al.*, 2004) of the plasma by the laser occurs. Hole digging by laser is physically similar to self-consistent cavitation of discharge plasma by RF fields (Kim *et al.* 1974; Yu & Shukla, 1978). The process studied here also differs from the interaction of an USUI pulse in a *low-density* plasma for producing monoenergetic particle bunches (Mangles *et al.*, 2004; Geddes *et al.*, 2004; Faure *et al.*, 2004). There a propagating electron cavity and/or wake plasma oscillation are created since $d > \lambda$ and the condition (Wilks & Kruer, 1997; Mourou *et al.*, 2006) $d/\lambda < \sqrt{n_c/n_0}$, where d and λ are the laser pulse width and wavelength, n_0 and n_c are the plasma and critical densities, for wake generation can be satisfied. The laser energy will then be mainly transferred to the wake-field, which can accelerate a small number of electrons almost mono-energetically. Finally, the present problem also differs from that of target-normal acceleration of surface ions in a *solid-density* plasma by an intense laser pulse (Karsch *et al.*, 1999; Hegelich *et al.*, 2002; Roth *et al.*, 2005). In that case, the latter hardly penetrates the

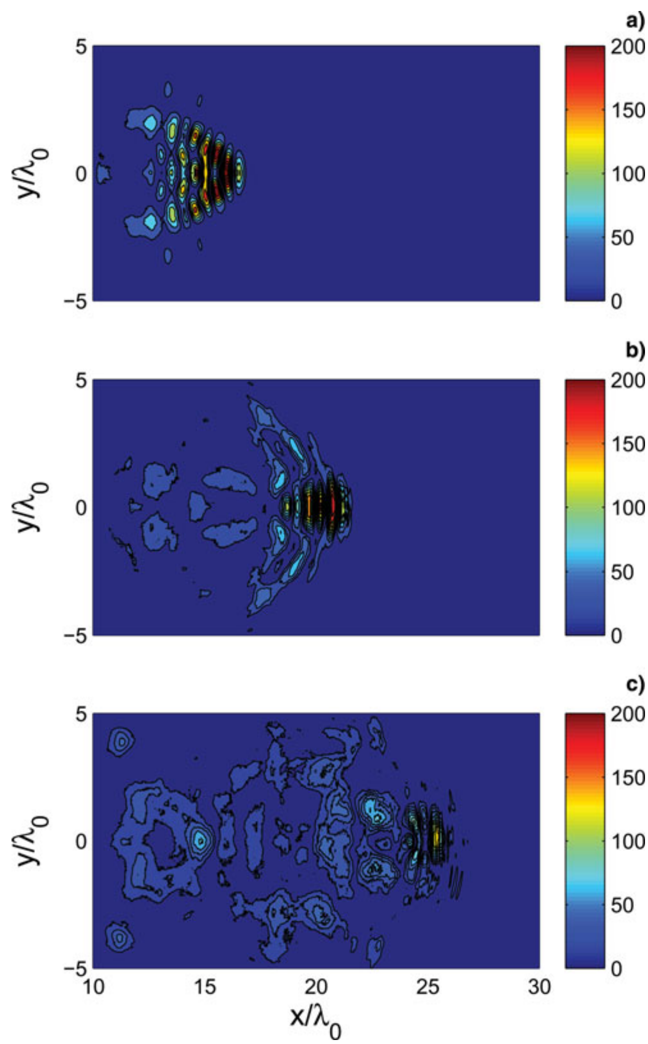

Fig. 1. (Color online) Snapshots of the longitudinal laser electric field $|E_z|$ (arb. units) at $t =$ (**a**) 21 T_0, (**b**) 27 T_0, and (**c**) 33 T_0, for $a = 10$ and $n_0 = 0.5n_c$. The laser pulse can pass through the plasma slab located in $10\lambda_0 < x < 30\lambda_0$.

plasma and ion acceleration is accomplished by the space-charge field created by the laser-expelled electrons.

3. PARTICLE-IN-CELL SIMULATION

In this study, we are interested in the basic physical mechanism of laser pulse stopping. For simplicity we shall use a two-dimensional (2D) configuration for the PIC simulation. For the purpose of comparison, we shall present the results for the interaction of an USUI laser pulse with a plasma at below, near, and above the critical density (Wilks & Kruer, 1997; Xu *et al.*, 2005). The simulation box (x, y) is $40\lambda_0 \times 10\lambda_0$, where $\lambda_0 = 1$ μm is the laser wavelength. Inside the box, a $20\lambda_0$ long plasma slab is placed at the center, with $10\lambda_0$ long vacuum segments on both sides of the slab. A linearly polarized laser pulse with wave electric field $\mathbf{E} = E_z\hat{\mathbf{e}}_z$ enters the box from the left boundary $(x = 0)$ and propagates through the left vacuum region into the plasma slab at $x = 10\lambda$. The pulse, Gaussian in the x and y directions, has a spot size $w_0 = 3\lambda_0$ and FWHM $d = 5\lambda_0$. The simulation grid contains $1200\times$ 600 cells, with 25 particles per cell, and the minimum time step is $0.015\mathrm{T}_0$, where T_0 is the light wave period (Xu *et al.*, 2005). The initial electron temperature is 1 keV, and the electron-ion mass ratio is $1/1836$.

We first consider a laser pulse of strength parameter $a = 10$ and background density $n_0 = 0.5n_c$ (underdense plasma), where $n_c = 10^{21}$ cm^{-3}. Figure 1 shows snapshots of $|E_z|$ at $t = 21$, 27, and 33 T_0. As expected, the pulse suffers very little (about 5%) reflection at the vacuum-plasma boundary and the plasma electrons are

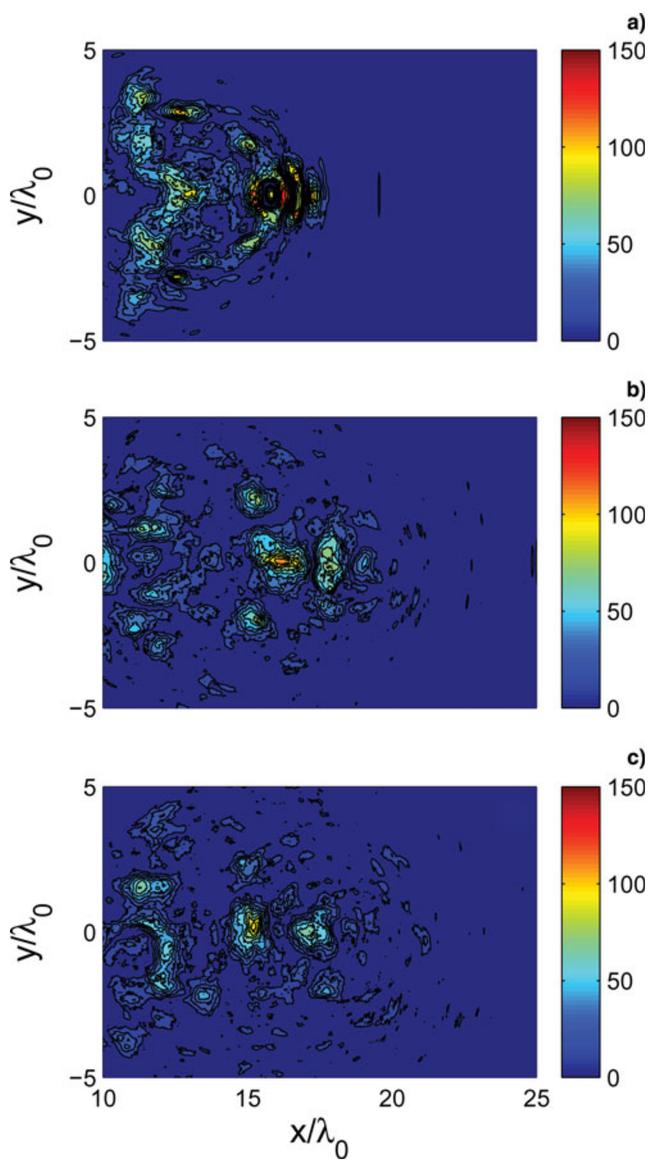

Fig. 2. (Color online) Snapshots of the longitudinal laser electric field $|E_z|$ at $t = $ (**a**) $24T_0$, (**b**) $30T_0$, and (**c**) $36T_0$, for $a = 10$ and $n_0 = n_c$. The laser pulse is trapped inside the plasma slab.

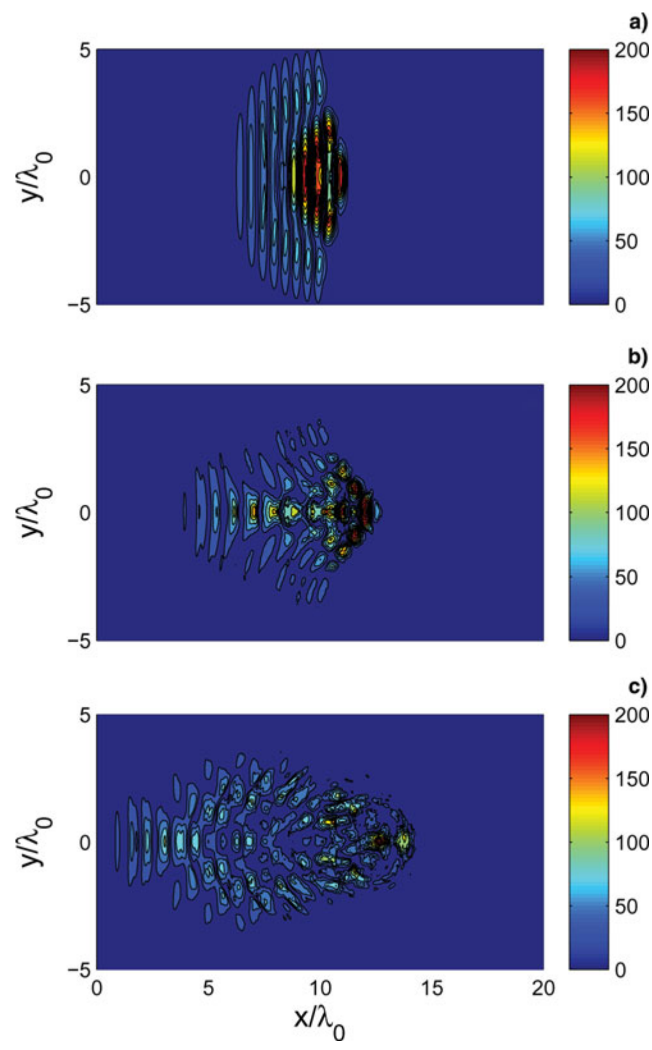

Fig. 3. (Color online) Snapshots of the longitudinal laser electric field $|E_z|$ at $t = $ (**a**) 15 T_0, (**b**) $18T_0$, and (**c**) $21T_0$, for $a = 10$ and $n_0 = 2n_c$. Here the vacuum region on the left is also shown (recall that the vacuum-plasma boundary is at $x = 10\lambda_0$). Thus, here most of the laser pulse is reflected and the remaining part can only penetrate a very short distance into the plasma.

pushed aside by the radiation pressure. An electron cavity is created in the plasma and it moves together with the laser pulse. The self-trapped pulse-cavity system eventually passes through the plasma slab. Next, we consider the interaction of same laser pulse with a plasma at critical density ($n_0 = n_c$). Figure 2 shows snapshots of $|E_z|$ at $t = 24$, 30, and 36 T_0. We see that reflection at the boundary is significant (~25%). As the transmitted pulse propagates in the plasma, it also create a co-moving electron cavity. The pulse also deforms significantly, especially in its tail part. The main pulse still contains much light energy. But before $x = 20\lambda_0$ this self-trapped light pulse comes to a complete stop and remains there until its energy is totally dissipated. At still higher plasma densities, such as $n_0 = 2n_c$ in Figure 3, the same laser pulse is mostly (more than 60%) reflected at the slab boundary. In fact, the laser can only penetrate a short distance into the plasma and no closed electron cavity is formed. However, a sufficiently intense laser pulse can still penetrate into the $n_0 = 2n_c$ plasma and be stopped inside it, as shown in Figure 4 for $a = 20$. In this case, the interaction is similar to that for the $a = 10$, $n_0 = n_c$ interaction shown in Fig. 2), although here much higher energy is involved.

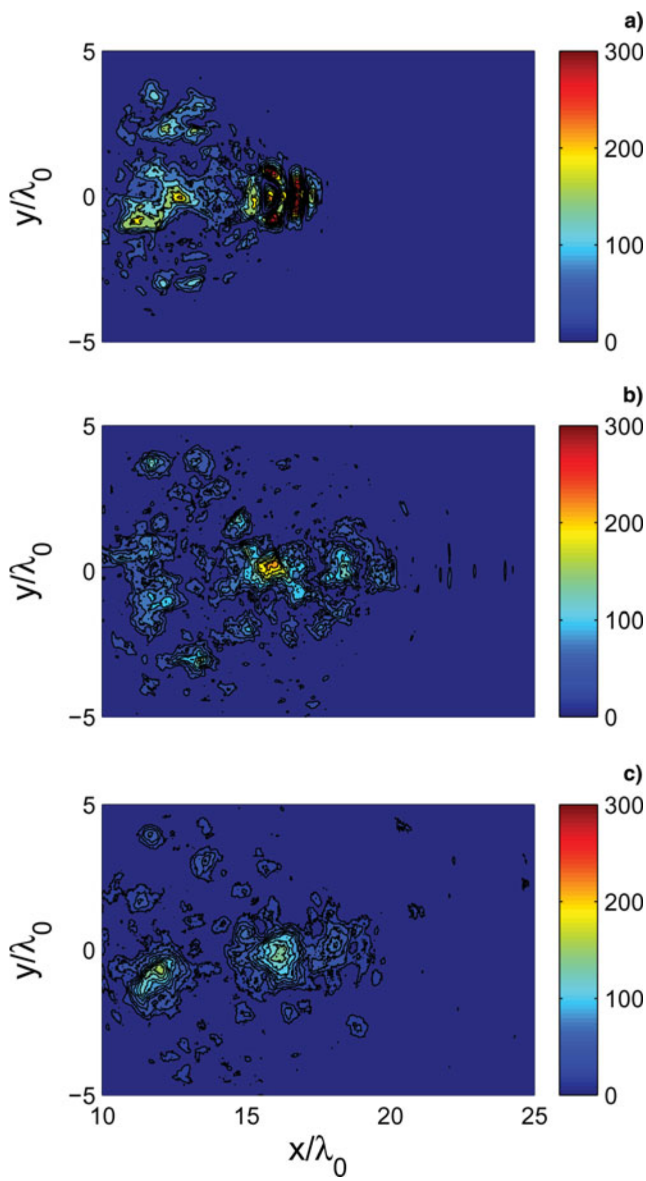

Fig. 4. (Color online) Snapshots of the longitudinal laser electric field $|E_z|$ at $t =$ (**a**) $20T_0$, (**b**) $30T_0$, and (**c**) $36T_0$, for $a = 20$ and $n_0 = 2n_c$. Similar to that in Fig. 2, the laser pulse can penetrate into the plasma slab and be stopped inside. Apparently the system is not more chaotic despite the higher interaction energy.

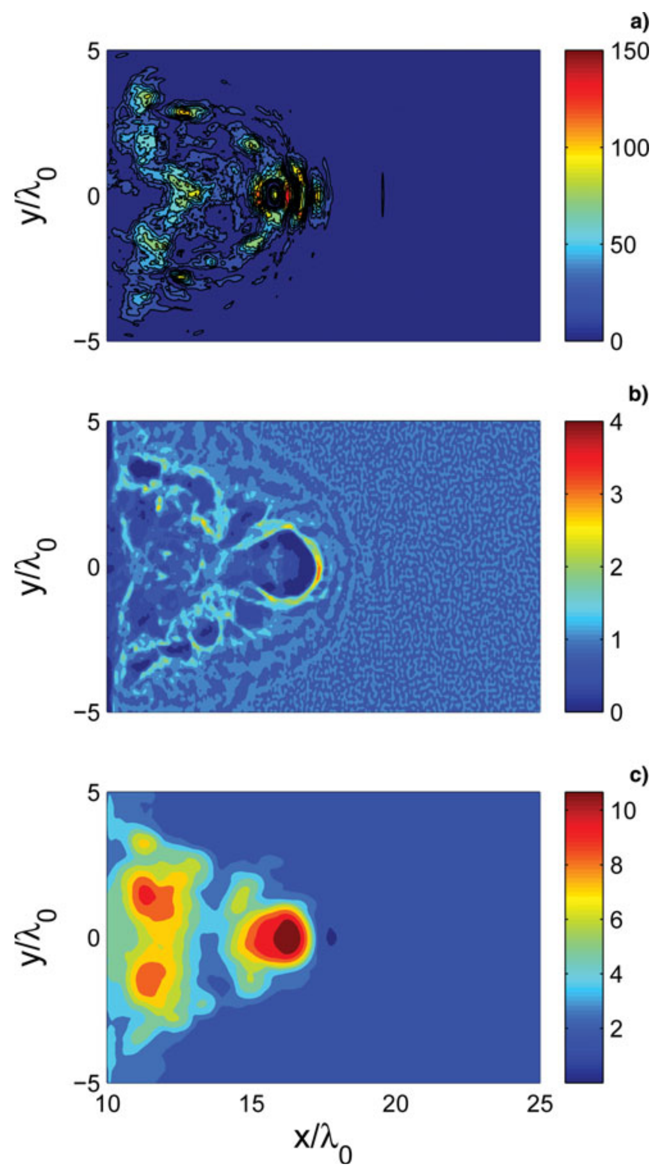

Fig. 5. (Color online) Snapshots of (**a**) $|E_z|$, (**b**) electron density n, and (**c**) space-charge field Φ for the case $n_0 = n_c$ at $t = 24T_0$, which is just before the laser pulse comes to a complete stop.

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4. SELF-TRAPPING AND STOPPING OF LIGHT PULSE

To investigate in more detail the process of laser-light self-trapping, we now concentrate on the case $a = 10$ and $n_0 = n_c$. Figure 5 shows the spatial distributions of (a) $|E_z|$, (b) n, and (c) the scalar potential Φ at $t = 24\ T_0$, which is approximately the time when the self-trapped pulse is stopped. The profiles of $|E_z|$, n, and Φ at the pulse indicate that the light pressure pushes away the electrons, creating an electron-deficient cavity region. The laser light, weakened by energy loss to the electron cavitation process as well as density increase of the boundary plasma, becomes self-trapped and the pulse-cavity system propagates forward self-consistently until it is stopped near $x = 20\lambda_0$, when the electron density in front of the pulse exceeds the effective critical density γn_c. Figure 5b also shows that the electrons at the cavity boundary, and especially in the front of, the cavity are compressed to high density by the light pressure, and the electron density disturbance at the cavity boundary propagates into the unperturbed plasma. The highest density ($\sim 4n_c$, at $x \sim 17\ \lambda_0$) occurs at the pulse front where the compression of the electrons is strongest.

5. ION DYNAMICS AND PLASMA HEATING

Electron cavitation with almost no ion participation can occur because the displacement of the massive ions accelerated by the space-charge and ponderomotive forces is insignificant on the initial short time scale. However, in the wake of the pulse or when the pulse is stopped, longer-time-scale effects such as Coulomb explosion (Sarkisov *et al.*, 1997;

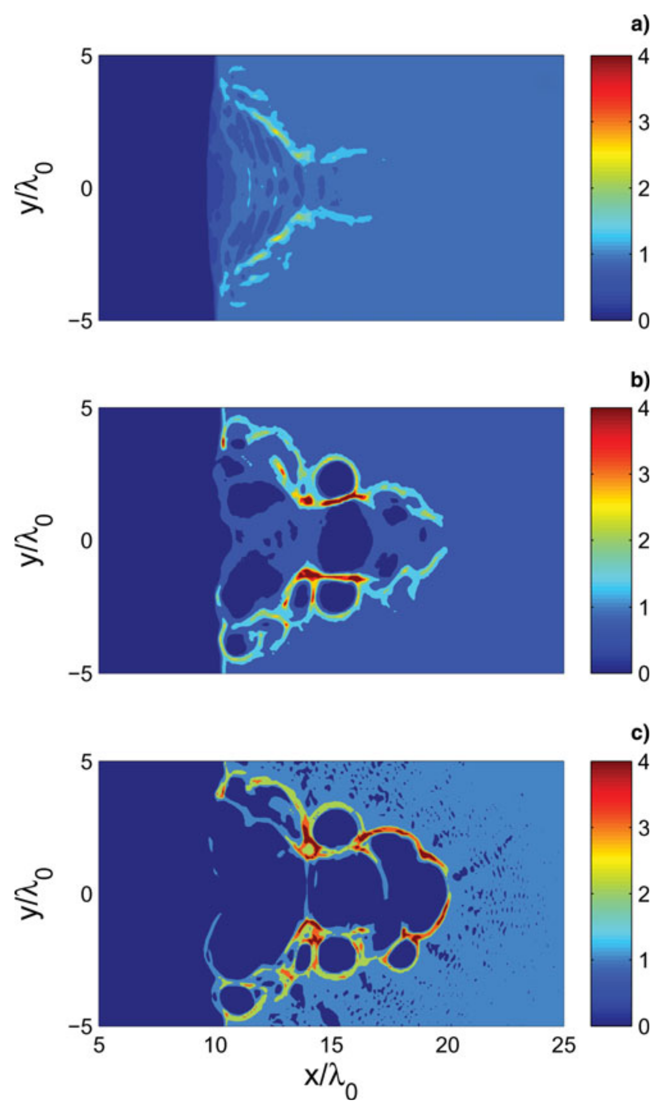

Fig. 6. (Color online) Snapshots of the ion density n_i at (**a**) 25, (**b**) 42, and (**c**) $57T_0$.

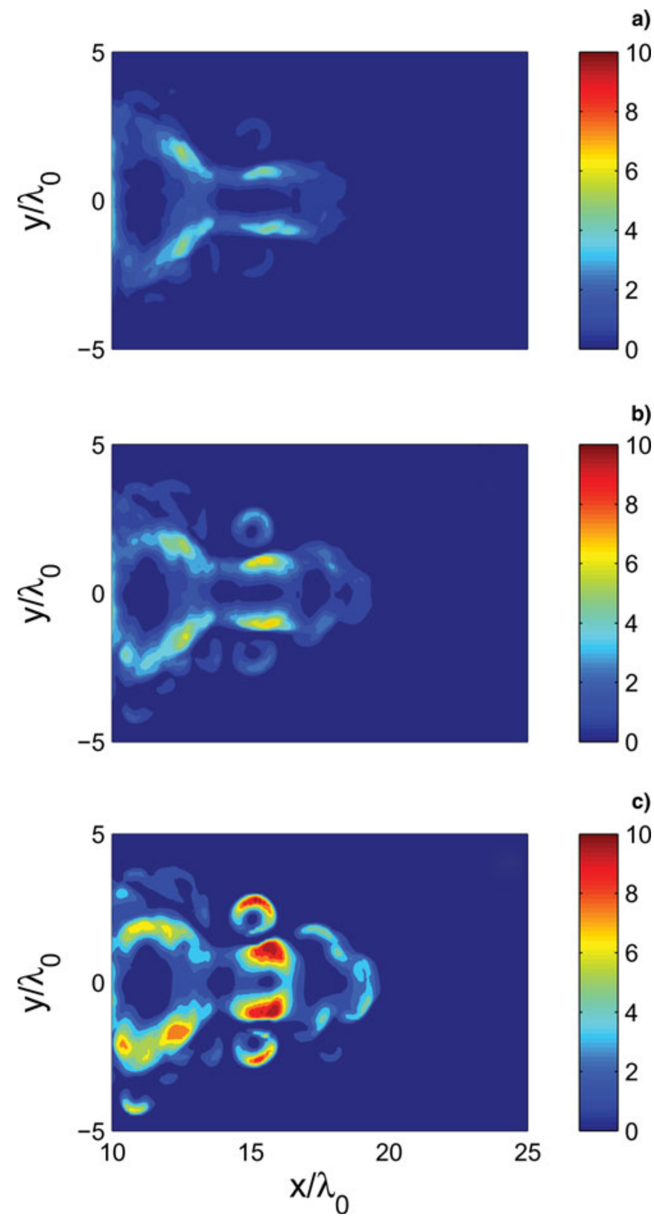

Fig. 7. (Color online) Snapshots of the ion energy ε_i of the ions at (**a**) 25, (**b**) 42, and (**c**) $57T_0$.

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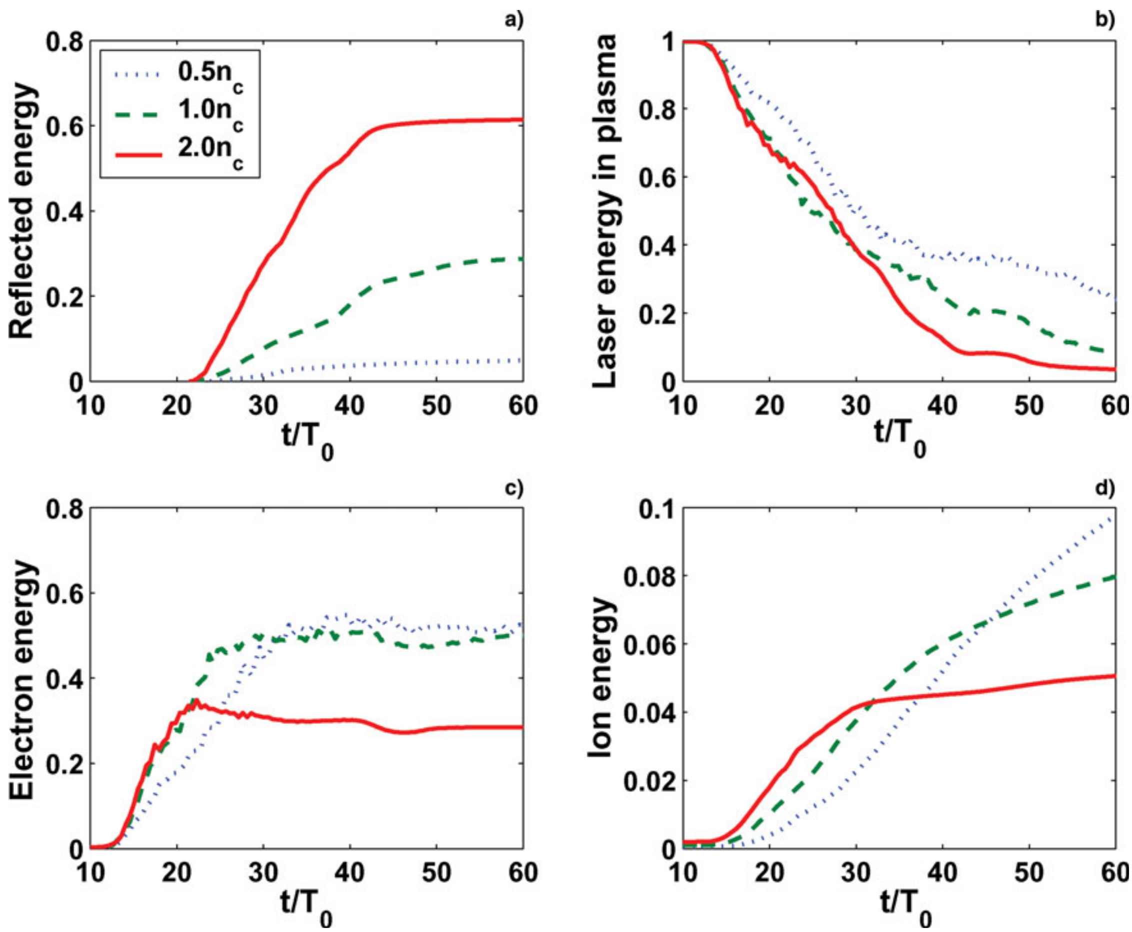

Fig. 8. (Color online) Time evolution of the total (**a**) reflected laser energy, (**b**) laser energy inside the plasma, and energy of the plasma (**c**) electrons and (**d**) ions, all normalized by the total incident laser energy, for $n_0 = 0.5$, 1, and $2.0n_c$, and $a_0 = 10$.

Ditmire *et al.*, 1999) of the ions in the cavity and ion channel formation in the wake plasma can occur.

Figure 6 shows the ion density n_i at (a) $27T_0$ (shortly after the pulse is stopped), (b) $42T_0$, and (c) $57T_0$. In (a) we see that except at the edge of the cavity where the relativistic ponderomotive force is strongest, the ion displacement is still insignificant. Figure 6b shows that Coulomb explosion of ions has started, ion holes and high density layers appear. In Figure 6c, we can see that an ion channel (where $n_i \ll n_0$) extending all the way back to the vacuum region is formed as the cavity ions are driven abruptly into the neighboring plasma, forming high-density shock-like layers at the channel edges. The channel has a rather long life-time since the inertial ions return only by collisional or turbulent diffusion. One can also notice that fine-structured wave-like ion-density patterns appear in the background plasma around and in front of the channel. The origin of these patterns is still unclear and deserves more detailed study. They could be a result of ion waves or wakes excited by the very energetic but small ion bunches that are also produced by the Coulomb explosion.

To confirm that the high-density layers corresponds to shocks (Sarkisov *et al.*, 1997; Ditmire et al., 1999), in Figure 7 we present the ion energy (ion energy density divided by density) ε_i at (a) $27T_0$, (b) $42T_0$, and (c) $57T_0$. One can see that the high-density and high-energy regions nearly overlap and they can thus be considered as shock layers. The ion energy in the latter can reach several tens KeV and density several times n_0.

Figure 8 shows the evolution of the total (a) reflected laser energy (light energy in the left vacuum region minus the total injected laser energy, plus the light energy that has left the left computation boundary), (b) light energy in the plasma slab, and energy of the (c) electrons and (d) ions, all normalized by the incident laser energy. One can see that for $n_0 = 0.5n_c$ a laser pulse of $a = 10$ penetrates into the plasma with very little reflection. But the transmitted pulse can pass through the slab with only little energy. For $n_0 = n_c$ about 20% of the incident energy is reflected, and for $n_0 = 2n_c$ the reflection is more than 60%. The total light energy inside the plasma slab decreases with time, as the main electron cavity and other, smaller, structures are created. We can clearly see the two distinct time scales in the evolution of the laser, electron, and ion energies. One, the fast scale, is associated with the ponderomotively driven electron motion. The laser energy is rapidly spent in accelerating and compressing the electrons. The longer time scale is associated with the Coulomb expulsion of the cavity ions and the subsequent ion dynamics.

6. CONCLUSION

We have considered the 2D interaction of an USUI laser pulse with a dense plasma slab at near the critical density, such that the conditions for exciting wake plasma oscillations are *not* met. Despite the high density, a considerable fraction of an USUI laser pulse can enter the plasma slab, drive out the electrons, and form a cavity which traps the entered laser light. The light pulse-cavity system rapidly comes to a stop inside the plasma. In the resulting stationary cavity, Coulomb explosion of the ions creates a long-living plasma channel. The exploded ions have very high energy and form shock layers at the channel boundary. That is, in this process, the transmitted light energy is deposited within a very small stationary plasma region of shock-compressed density. Besides the main electron cavity and ion channel, the energetic laser impact also creates in the plasma different smaller structures and wave patterns that can be attributed to secondary cavities and electron or ion waves generated at the cavity and channel boundary. Some localized structures still contain light energy, but they do not seem to affect the evolution of the main cavity but can affect the heating and transport properties of the background plasma.

The possibility of laser-pulse trapping and stopping in a plasma indicates that one can focus a number of USUI laser pulses on a dense fuel plasma such that the penetrated light pulses are stopped at a common small plasma region and form either a single super cavity or many closely packed cavities. The location and intensity of the heating can be controlled by managing the laser intensity and the fuel density, as well as laser focusing. The multi-keV ion bunches resulting from the Coulomb explosion can efficiently heat a fuel plasma (Deutsch *et al.*, 1997; Deutsch, 2004; Liftshitz *et al.*, 2006), and may be superior to that from laser-cluster interaction which also depends on Coulomb exploded ions (Sarkisov *et al.*, 1997; Ditmire *et al.*, 1999) since here the energy deposition can be much more local and concentrated. Our 2D simulation precludes certain instabilities (Mourou *et al.*, 2006) and other higher dimensional effects, especially at longer times. Nevertheless, the results here should be useful as a starting point for laboratory experiments as well as more elaborate simulations. Finally, it may be of interest to point out that the interaction considered here is quite similar to that of USUI electron- or positron-bunch interaction with dense plasma (Deutsch *et al.*, 1997; Deutsch, 2004; Lu *et al.*, 2005; Zhou *et al.*, 2006).

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REFERENCES

Deutsch, C., Furukawa, H., Mima, K., Murakami, M. & Nishihara, K. (1997). Interaction physics of the fast ignitor concept. *Laser Part. Beams* **15**, 577–581.

Deutsch, C. (2004). Penetration of intense charged particle beams in the outer layers of precompressed thermonuclear fuels. *Laser Part. Beams* **22**, 115–121.

Ditmire, T., Zweiback, J., Vanovsky, V.P., Cowan, T.E., Hays, G. & Wharton, K.B. (1999). Nuclear fusion from explosions of femtosecond laser-heated deuterium clusters. *Nature* **398**, 489–492.

Faure, J., Glinec, Y., Pukhov, A., Kiselev, S., Gordienko, S., Lefebvre, E., Rousseau, J.-P., Burgy, F. & Malka, V. (2004). A laser-plasma accelerator producing monoenergetic electron beams. *Nature* **431**, 541–544.

Geddes, C.G.R., Toth, C.S., Tilborg, J. Van Esarey, E., Schroeder, C.B., Bruhwiler, D., Nieter, C., Cary, J. & Leemans, W.P. (2004). High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding. *Nature* **431**, 538–541.

Gibbon, P., (2005). *Short Pulse Laser Interactions with Matter: An Introduction*, London: Imperial College Press.

Glowacz, S., Hora, H., Badziak, J., Jablonski, S., Cang, Y. & Osman, F. (2006). Analytical description of rippling effect and ion acceleration in plasma produced by a short laser pulse. *Laser Part. Beams* **24**, 15–22.

Habara, H., Lancaster, K.L., Karsch, S., Murphy, C.D., Norreys, P.A., Evans, R.G., Borghesi, M., Romagnani, L., Zepf, M., King, J.A., Snavely, R., Akli, K., Zhang, B., Freeman, R., Hatchett, S., MacKinnon, A.J., Patel, P., Key, M.H., Stoeckl, C. & Stephens, R.B. (2004). Ion acceleration from the shock front induced by hole boring in ultraintense laser-plasma interactions. *Phys. Rev. E* **70**, 046414.

Hegelich, M., Karsch, S., Pretzler, G., Habs, D., Witte, K., Guenther, W., Allen, M., Blazewic, A., Fuchs, J., Gauthier, J.C., Geissel, M., Audebert, P., Cowan, T. & Roth, M. (2002). MeV ion jets from short pulse-laser-plasma interaction with thin foils, *Phys. Rev. Lett.* **89**, 085002.

Hegelich, B.M., Albright, B., Audebert, P., Blazevic, A., Brambrink, E., Cobble, J., Cowan, T., Fuchs, J., Gauthier, J.C., Gautier, C., Geissel, M., Habs, D., Johnson, R., Karsch, S., Kemp, A., Letzring, S., Roth, M., Schramm, U., Schreiber, J., Witte, K.J. & Fernández, J.C. (2005). Spectral properties of laser-accelerated mid-Z MeV/u ion beams, *Phys. Plasmas* **12**, 056314.

Karsch, S., Habs, D., Schatz, T., Schramm, U., Thirolf, P.G., Meyer-ter-Vehn, J., and Pukhov, A. (1999). Particle physics with petawatt-class lasers, *Laser Part. Beams* **17**, 565–570.

Kawata, S., Kong, Q., Miyazaki, S., Miyauchi, K., Sonobe, R., Sakai, K., Nakajima, K., Masuda, S., Ho, Y.K., Miyanaga, N., Limpouch, J. & Andreev, A.A. (2005). Electron bunch acceleration and trapping by ponderomotive force of an intense short-pulse laser. *Laser Part. Beams* **23**, 61–67.

Kim, H.C., Stenzel, R.L. & Wong, A.Y. (1974). *Phys. Rev. Lett.* **33**, 886–890.

Kodama, R., Takahashi, K., Tanaka, K.A., Tsukamoto, M., Hashimoto, H., Kato, Y. & Mima, K. (1996). Study of laser-hole boring into overdense plasmas. *Phys. Rev. Lett.* **77**, 4906–4909.

Kodama, R., Tanaka, K.A., Yamanaka, T., Kato, Y., Kitagawa, Y., Fujita, H., Kanabe, T., Izumi, N., Takahashi, K., Habar, H., Okada, K., Iwata, M., Matsushita, T. & Mima, K. (1999). Studies of intense laser-plasma interactions for the fast ignitor concept at ILE, Osaka University. *Plasma Phys. Control. Fusion* **41**, 419–425.

Koyama, K., Adachi, M., Miura, E., Kato, S., Masuda, S., Watanabe, T., Ogata, A. & Tanimoto, M. (2006). Monoenergetic electron beam generation from a laser-plasma accelerator. *Laser Part. Beams* **24**, 95–100.

Kruer, W.L. (1988). *Physics of Laser Plasma Interactions* New York: Addison-Wesley.

Lasinski, B.F., Langdon, A.B., Hatchett, S.P., Key, M.H. & Tabak, M. (1999). Particle-in-cell simulations of ultra intense laser pulses propagating through overdense plasma for fast-ignitor and radiography applications. *Phys. Plasmas* **6**, 2041.

Lifschitz, A.F., Faure, J., Glinec, Y., Malka, V. & Mora, P. (2006). Proposed scheme for compact GeV laser-plasma accelerator. *Laser Part. Beams* **24**, 255–259.

Lu, W., Huang, C., Zhou, M.M., Mori, W.B. & Katsouleas, T. (2005). Limits of linear plasma wakefield theory for electron or positron beams. *Phys. Plasmas* **12**, 063101.

Hegelich, M., Karsch, S., Pretzler, G., Habs, D., Witte, K., Guenther, W., Allen, M., Blazewic, A., Fuchs, J., Gauthier, J.C., Geissel, M., Audebert, P., Cowan, T. & Roth, M. (2002). MeV Ion Jets from shortpulse-laser-plasma interaction with thin foils, *Phys. Rev. Lett*. **89**, 085002.

Malka, V. & Fritzler, S. (2004). Electron and proton beams produced by ultra short laser pulses in the relativistic regime. *Laser Part. Beams* **22**, 399–405.

Malka, V., Fritzler, S., Lefebvre, E., Aleonard, M.-M., Burgy, F., Chambaret, J.-P., Chemin, J.-F. Krushelnick, K., Malka, G., Mangles, S.P.D., Najmudin, Z., Pittman, M., Rousseau, J.-P., Scheurer, J.-N., Walton, B. & Dangor, A.E. (2002). Electron acceleration by a wake field forced by an intense ultrashort laser pulse. *Science*. **298**, 1596–1600.

Mangles, S.P.D., Murphy, C.D., Najmudin, Z., Thomas, A.G.R., Collier, J.L., Dangor, A.E., Divall, E.J., Foster, P.S., Gallacher, J.G., Hooker, C.J., Jaroszynski, D.A., Langley, A.J., Mori, W.B., Norreys, P.A., Tsung, F.S., Viskup, R., Walton, B.R. & Krushelnick, K. (2004). Monoenergetic beams of relativistic electrons from intense laser-plasma interactions. *Nature* **431**, 535–539.

Mangles, S.P.D., Walton, B.R., Najmudin, Z., Dangor, A.E., Krushelnick, K., Malka, V., Manclossi, M., Lopes, N., Carias, C., Mendes, G. & Dorchies, F. (2006). Table-top laser-plasma acceleration as an electron radiography source. *Laser Part. Beams* **24**, 185–190.

Mourou, G.A., Tajima, T. & Bulanov, S.V. (2006). Optics in the relativistic regime. *Rev. Mod. Phys.* **78**, 309–371, and the references therein.

Roth, M., Blazevic, A., Geissel, M., Schlegel, T., Cowan, T.E., Allen, M., Gauthier, J.-C., Audebert, P., Fuchs, J., Meyer-ter-Vehn, J., Hegelich, M., Karsch, S. & Pukhov, A. (2002). Energetic ions generated by laser pulses: A detailed study on target properties. *Phys. Rev. ST Accel. Beams* **5**, 061301.

Roth, M., Brambrink, E., Audebert, B., Blazevic, A., Clarke, R., Cobble, J., Geissel, M., Habs, D., Hegelich, M., Karsch, S., Ledingham, K., Neelz, D., Ruhl, H., Schlegel, T., & Schreiber, J. (2005). Laser accelerated ions and electron transport in ultra-intense laser matter interaction. *Laser Part. Beams* **23**, 95–100.

Sarkisov, G.S., Bychenkov, V. Yu., Tikhonchuk, V.T., Maksimchuk, A., Chen, S.Y., Wagner, R., Mourou, G. & Umstadter, D. (1997). Observation of the plasma channel dynamics and Coulomb explosion in the interaction of a high intensity laser pulse with He gas jet. *JETP Lett* **66**, 828–830.

Wilks, S.C. & Kruer, W.L. (1997). Absorption of ultrashort, ultra-intense laser light by solids and overdense plasmas. *IEEE Quantum Electron* **33**, 1954–1961.

Xu, H., Yu, W., Lu, P.X., Senecha, V.K., He, F., Shen, B.F., Qian, L.J., Li, R.X. & Xu, Z.Z. (2005). Electron self-injection and acceleration driven by a tightly focused intense laser beam in an underdense plasma. *Phys. Plasmas* **12**, 013105.

Yu, M.Y. & Shukla, P.K. (1978). *Phys. Fluids* **18**, 1591.

Yu, W., Xu, H., He, F., Yu, M.Y., Ishiguro, S., Zhang, J. & Wong, A.Y. (2005). Direct acceleration of solid-density plasma bunch by ultraintense laser. *Phys. Rev. E* **72**, 046401.

Zhou, C.T., He, X.T. & Yu, M.Y. (2006). A comparison of ultrarelativistic electron- and positron-bunch propagation in plasmas. *Phys. Plasmas* **13**, 092109.