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Plasma channeling by multiple short-pulse lasers

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Abstract

Channeling by a train of laser pulses into homogeneous and inhomogeneous plasmas is studied using particle-in-cell simulation. When the pulse duration and the interval between the successive pulses are appropriate, the laser pulse train can channel into the plasma deeper than a single long-pulse laser of similar peak intensity and total energy. The increased penetration distance can be attributed to the repeated actions of the ponderomotive force, the continuous between-pulse channel lengthening by the inertially evacuating ions, and the suppression of laser-driven plasma instabilities by the intermittent laser-energy cut-offs.

Keywords: Instability suppression; Plasma channeling; PIC simulation; Short-pulse laser

INTRODUCTION

The channeling or boring of an intense laser pulse in plasma and ion acceleration have been investigated extensively (Wilks *et al.*, 1992; Borisov *et al.*, 1992; Tabak *et al.*, 1994; Zepf *et al.*, 1996; Pukhov & Meyer-ter-Vehn, 1997; Borghesi *et al.*, 1997, 2002, 2007; Fuchs *et al.*, 1998; Vshivkov *et al.*, 1998; Tanaka *et al.*, 2000; Willi *et al.*, 2001; Kodama *et al.*, 2001; Najmudin *et al.*, 2003; Hoffmann *et al.* 2005; Flippo *et al.* 2007; Laska *et al.* 2007; Lei *et al.*, 2007). In the relativistic-intensity regime, the relativistic ponderomotive force, which is proportional to the gradient of the laser intensity, dominates the laser-plasma interaction ($f_p \propto -\nabla I$). The laser pulse enters the plasma like a piston, pushing and compressing the plasma in front of it. However, the high-intensity laser-plasma interaction also leads to other nonlinear processes such as laser filamentation and breakup (Schifano *et al.*, 1994; Tanaka *et al.*, 2000; Osman *et al.*, 2004), scattering and propagation instabilities (Najmudin *et al.*, 2003; Bret & Deutsch, 2006; Laska *et al.*, 2007; Gupta *et al.*, 2007), etc., which can reduce the quality and length of the channel. Efficient channeling of a relativistic laser in higher density plasmas has been found to be rather difficult.

In this paper, instead of a single pulse, we consider the channeling of two or more laser pulses into homogeneous as well as inhomogeneous plasmas. It is found that with suitably chosen duration and interval of the pulses, a train of short laser pulses can channel into the plasma deeper and more stably than a single longer pulse of similar peak intensity and total energy. The improvement can be attributed to the repeatedly applied ponderomotive force in the forward direction, the suppression of laser-driven plasma instabilities due to the intermittent laser-energy cut-offs, as well as the continuous between-pulse channel lengthening by the still evacuating ions.

THE SIMULATION PARAMETERS

We shall investigate the interaction of a train of short, intense laser pulses with dense plasma using two-dimensional (2D) relativistic particle-in-cell (PIC) simulation (Xu *et al.*, 2002; Yu *et al.*, 2007). Circularly polarized laser pulses with Gaussian envelop $a = a_L \exp[-(t-t_0)^2/\tau^2] \exp[-(y-y_0)^2/w^2]$ in both longitudinal (x) and lateral (y) directions are incident from the left vacuum region along the x axis into the plasma layer, where $a_L = 4$ is the laser strength, τ is the pulse duration,

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and $w = 5$ µm is the spot radius, respectively. The corresponding laser intensity is thus about 10^{19} W/cm^2, now available in many laboratories. The laser wavelength is $\lambda = 1.06$ µm. The simulation box is 60λ along the x-axis and 30λ along the y-axis. The plasma layer is bounded by 10λ wide vacuum regions on both its left and right sides. The spatial mesh contains 1024×512 cells with 12.8 million each of electrons and ions. The initial velocity distributions of the plasma electrons and ions are taken to be Maxwellian, with temperatures of 4 keV for the electrons and 1 keV for the ions. The time step of the simulation is $0.033T$, where $T = 3.5$ fs is the laser period. The spatial and time coordinates are normalized by the laser wavelength and period, respectively, and the ion density is normalized by n_c, where n_c is the plasma critical density. The electromagnetic energy density is $E^2 + B^2$, where $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electric and magnetic fields normalized by $m\omega_0 c/e$, where e, m, c, and, ω_0 denote the electron charge and rest mass, the speed of light in vacuum, and the laser frequency.

SINGLE PULSE PENETRATION

For the purpose of comparison, we shall first consider channeling by a single laser pulse in a 40λ long *uniform* plasma layer of density $n_e = 2n_c$. Figures 1a–1c shows the distributions of the plasma ion density for the pulses with $\tau = 12.5T$, $25T$, and $50T$, respectively. All three snapshots were taken when the corresponding channel extends deepest in the plasma, i.e., after the laser light has dissipated or reflected. As is well known, the laser ponderomotive force pushes away the electrons as it propagates in plasma, and the resulting charge-separation field then expels the massive ions, creating a channel. Here we are mainly interested in the effect of the forward-streaming ions on channel lengthening. We note that even after the laser action vanishes due to reflection and absorption, the still evacuating ions continue to lengthen the channel, until the forward momentum of the ions is totally spent, and the final channel length is reached. Figure 1 also shows that some of the expelled ions pile up in the plasma near the channel boundary, forming shock-like compressed layers.

For the same peak intensity, a pulse with longer duration has more electromagnetic energy. Figures 1a and 1b show that the $\tau = 25T$ pulse can channel deeper into the plasma than the $\tau = 12.5T$ pulse. However, further increase of the pulse length or laser energy does not increase the final channel length. Instead, instability-driven deterioration of the channel quality occurs, as can be seen in Figure 1c for the $\tau = 50T$ pulse. Here the additional laser energy is diverted to deflecting the light energy, creating a branch channel below the original one without lengthening the latter. For the laser and plasma parameters under consideration, we found that the $\tau = 25T$ pulse is optimal for channeling. Here most of the laser energy is spent on the latter, without too much excitation of unfavorable instabilities.

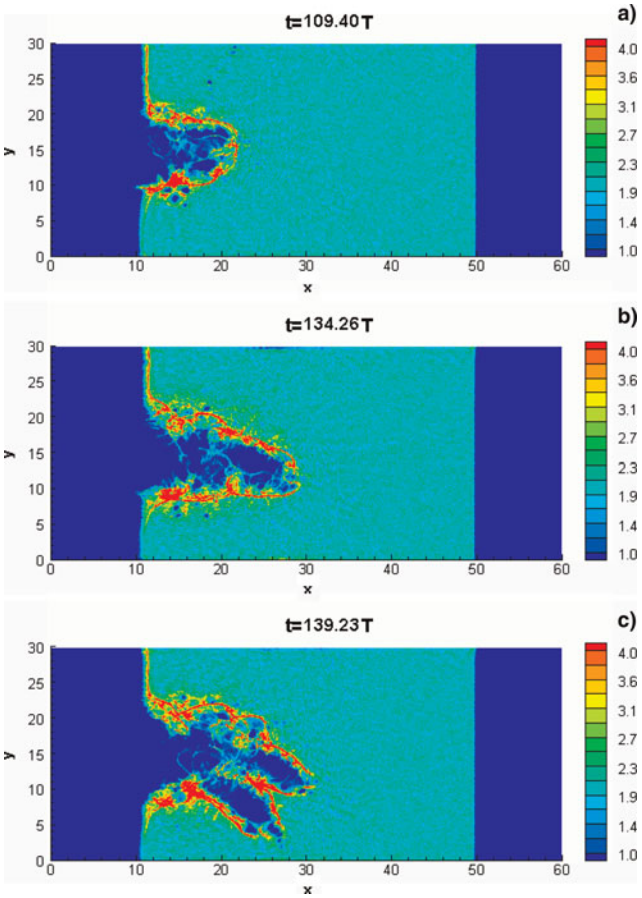

Fig. 1. (Color online) Channeling of a laser pulse into a plasma layer: distributions of the ion density for pulse durations $\tau = 12.5$ T (**a**), 25 T (**b**), and 50 T (**c**), respectively, at the maximum channel lengths. The case (c) shows that a 50 T pulse leads to considerable deterioration of the channel quality without lengthening it, as compared with that of the 25 T pulse.

TWO-PULSE SYSTEM

We next examine plasma channeling by two short laser pulses. Instead of a single pulse of $\tau = 50T$, we now employ two $\tau = 25T$ pulses. The time delay between the peaks of the two pulses is $70T$. The other parameters are the same as those for Figure 1. The total energy in the two-$25T$ pulses is about the same as that in the $50T$ pulse (Fig. 1c). Figure 2 shows the electromagnetic energy and ion densities at $t = 69.62T$, when the first laser pulse is channeling into the plasma and the second pulse is still far away. We see that at this time, the laser has already started to deflect, causing bending of the plasma channel. Deterioration of the pulse and channel quality indicates that unfavorable instabilities have set in.

Figure 3 shows the distributions of the electromagnetic energy and ion densities at $t = 79.56T$, when the action of the first pulse has almost vanished and the second pulse is still outside the plasma. The shock-compressed layers are visible at the sides of the channel but not at its very front, which is still extending because of the inertially evacuating

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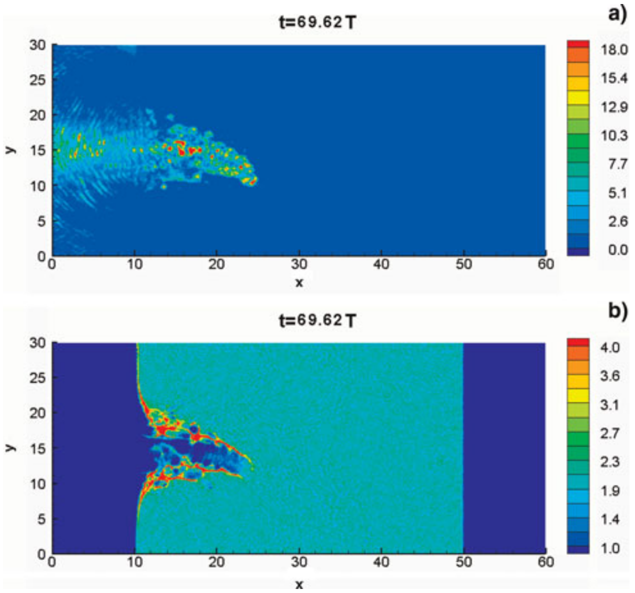

Fig. 2. (Color online) Channeling by two $\tau = 25$ T laser pulses at $t = 69.62$ T. (**a**) The electromagnetic energy density and (**b**) the ion density. Directional instability and channel bending is clearly occurring.

ions. Furthermore, there is no further development of the instabilities because of the cut-off of the laser-energy supply. Figure 4 shows the electromagnetic energy and ion densities at $t = 139.23T$, when the second laser pulse is acting on the plasma at the front of the channel created by the first pulse. The plasma channel is further extended in the laser direction. Finger-like laser and channel branching appears, but on smaller space scales. Figure 5a shows the ion density at $t = 248.63T$, when the action of the second laser pulse is also over. Again, the inertially evacuating

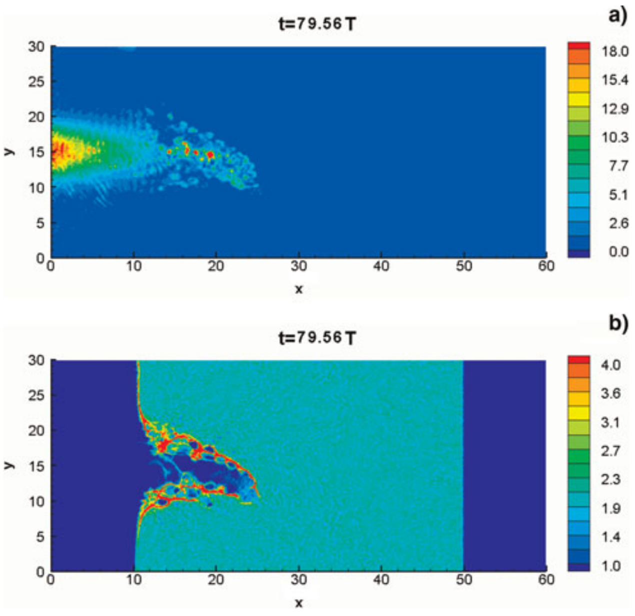

Fig. 3. (Color online) Channeling by two $\tau = 25$ T pulses at $t = 79.56$ T. (**a**) The electromagnetic energy density and (**b**) the ion density. Here the second pulse is still outside the plasma while the light energy of the first pulse has almost vanished. The energy cutoff stops further bending of the channel. Irregular high-density shock-like layers due to ion pile up can be seen at the sides of the channel.

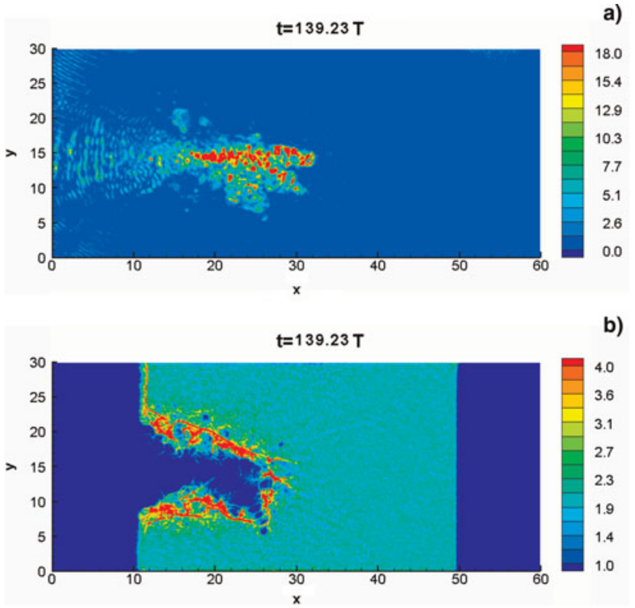

Fig. 4. (Color online) Channeling by two $\tau = 25$ T pulses at $t = 139.23$ T. (**a**) The electromagnetic energy density and (**b**) the ion density. Instabilities and channel branching still occur, but at much smaller scales. The difference in the penetration distance of the light and the plasma channel is due to the much slower speed of the evacuating ions.

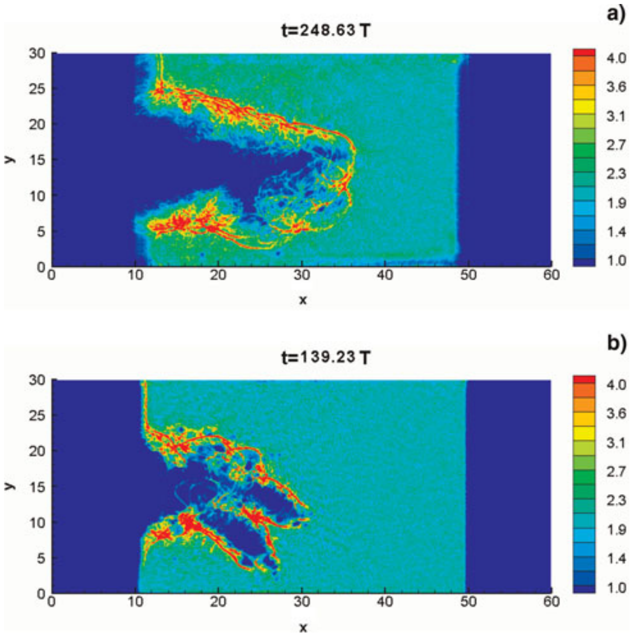

Fig. 5. (Color online) The ion density in channeling (**a**) by two $\tau = 25$ T pulses at $t = 248.63$ T and (**b**) by a single $\tau = 50$ T pulse at $t = 139.23$ T, i.e., same as Figure 1c, with the observation times corresponding to that at maximum channel length. The two-pulse scheme can clearly channel deeper into the plasma. The single longer (50 T) pulse leads to considerable deterioration of the channel quality without lengthening it.

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ions continue to lengthen the channel, until the forward momentum of the ions is totally spent and the plasma channel attains its maximum length. The finger-like branching structure remains small because of the laser-energy cut-off. For comparison, Figure 5b is for maximum channeling by a single pulse with $\tau = 50T$, i.e., the same as Figure 1c. The significant difference in the length and quality of the channels made by a single pulse and two shorter pulses indicates that the multi-pulse scheme is more efficient, since the total laser energy in the two cases is similar. Nevertheless, to justify the multi-pulse scheme, we need to show that the plasma channel can further lengthen if more laser pulses are applied.

MULTIPLE-PULSE SYSTEM

In view of the above results, we now consider the effect of a third $\tau = 25T$ laser pulse. The other parameters are the same as in the two-pulse case, except that the interval between the second and third pulses is (corresponding to the optimum case) $90T$.

Figure 6a shows the electromagnetic energy density at $t = 228.74T$, when the third pulse is inside the plasma channel. Its action is similar to that of the second pulse and it further lengthens the channel. Figure 6b shows the distribution of the light energy later ($t = 248.63T$). We see that the nearly dissipated light pulse has propagated through the plasma slab and exited at its rear surface. Figure 6c shows the ion density at a still later (in order to allow for the inertial evacuation of the ions) time, namely at $t = 288.41T$. One can see that the 40λ plasma layer has been completely bored through by the laser pulse train. For comparison, Figure 6d shows the ion density at $t = 129.29T$ for a single pulse with $\tau = 75T$. The total energy in the single $75T$ pulse is about the same as that in the three-$25T$ pulses. In Figure 6d, one sees bending of the plasma channel. The length of the channel in the laser direction made by the $75T$ single pulse is much shorter than that made by the three-$25T$ pulses.

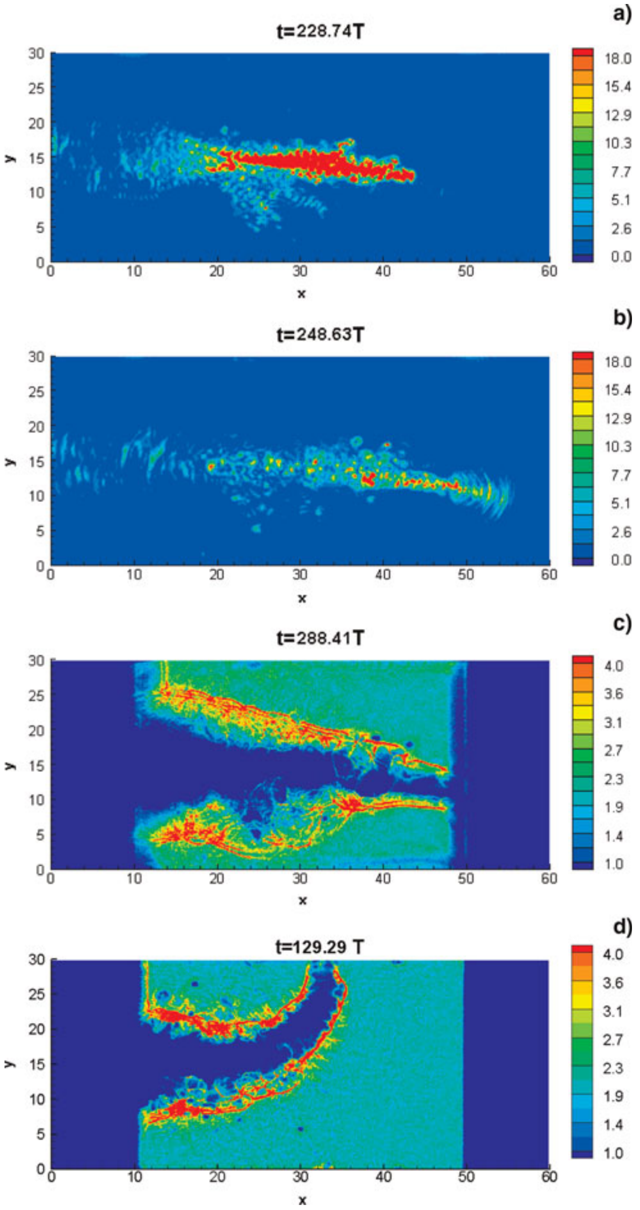

Fig. 6. (Color online) Channeling by three $\tau = 25$ T laser pulses. The electromagnetic energy density at (**a**) $t = 228.74$ T and (**b**) $t = 248.63$ T. The panel (**c**) shows the ion density at a still later time ($t = 288.41$ T), when the 40 λ plasma layer has been bored through. For comparison, the panel (**d**) shows the ion density at $t = 129.29$ T for a single pulse with $\tau = 75$ T.

In order to see the effect of density inhomogeneity on multi-pulse channeling, we next consider a plasma slab whose density increases linearly from 0 to $7n_c$ between $x = 10\lambda$ and $x = 50\lambda$. The laser parameters are the same as that for Figure 2, and the time interval between the two peaks is $70T$. Figure 7a shows the ion density at $t = 198.90T$ (corresponding to maximum channel length in the inhomogeneous plasma) for channeling by two $\tau = 25T$ pulses. For comparison, Figure 7b shows the ion density at $t = 169.07T$ for maximum channeling by a single pulse, as in Figure 5b. Although the total energy in the single $50T$ pulse is similar to that in the two $25T$ pulses, the length and quality of the channel made by the two-pulse laser train is again superior. We note that the single $50T$ pulse can only penetrate to a density of $n_e < 3n_c$, and the resulting channel is severely bent. On the other hand, the two-$25T$ pulses can efficiently penetrate up to a density of $4.5n_c$ without causing deterioration of the channel quality. In order to see if the channel in the inhomogeneous plasma can be further lengthened, we consider the effect of a third $25T$ laser pulse. The time interval between the peaks of the second and third pulses is again $90T$. Figure 8 shows the ion density at (a) $t = 258.57T$ as the third pulse starts to act on the plasma, and (b) $t = 278.47T$ for maximum channeling. One can see the third pulse can indeed extend the channel to a still higher density region, namely to $n_e = 6n_c$, without causing serious deterioration of the channel quality.

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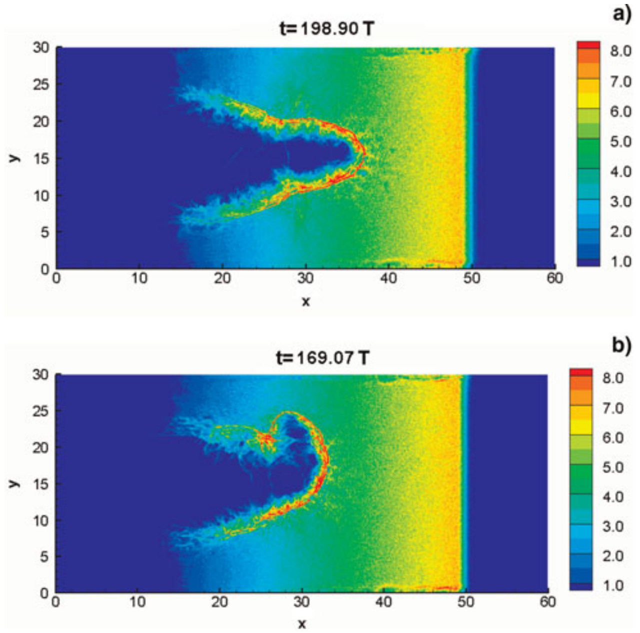

Fig. 7. (Color online) Laser channeling in inhomogeneous plasma with linear density $n_i = 0 \rightarrow 7n_c$ across the slab $x = 10 \rightarrow 50\lambda$. (**a**) The ion density at $t = 198.90$ T, when the channel longest, for two consecutive pulses with the same parameters as in Figure 2. For comparison (**b**) shows channeling into the same plasma by a single $\tau = 50$ T pulse whose parameters are the same as in Figure 5b.

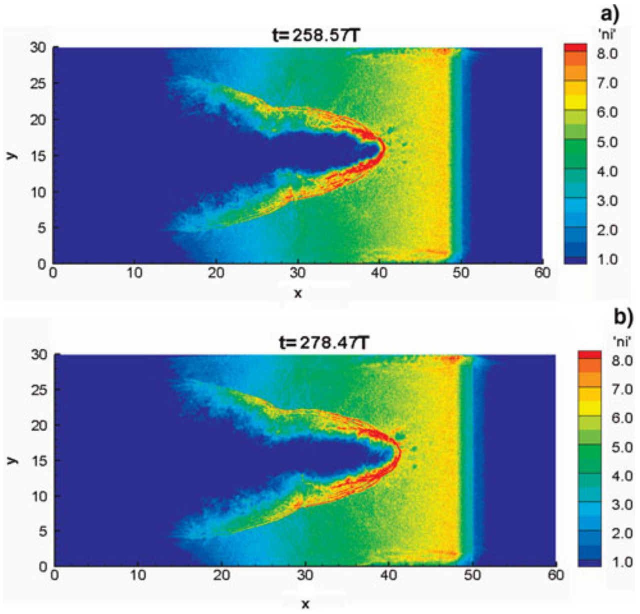

Fig. 8. (Color online) Channeling by three laser pulses into the inhomogeneous plasma layer of Figure 7. The incident lasers are the same as in Figure 6. The ion density at (**a**) 258.57 T and (**b**) 278.47 T.

CONCLUSION

In conclusion, we have investigated multi-pulsed laser channeling in both homogeneous and inhomogeneous plasmas using relativistic 2D PIC simulations. It is found that two shorter laser pulses can penetrate deeper into the plasma than a single long pulse of similar peak intensity and total energy. This is because, in the two-pulse case, the ponderomotive force acts on the plasma twice and the laser-induced plasma instabilities that can severely deteriorate the channel quality and length are greatly suppressed because of the cutoff of their source energy from the laser. A third laser pulse can further lengthen the plasma channel. One can expect that laser channeling into dense plasma can be improved by employing a suitably designed train of laser pulses. The scheme is similar to precision hole boring of solid materials by multiple short-pulse lasers at the 10^{14} w cm^{-2} level (Bogaerts *et al.*, 2003; Zeng *et al.*, 2006; Wolowski *et al.*, 2007), although the physics is somewhat different. There the repeated action of the short pulses allows the material to be photo-ionized and removed layer by layer at the atomic level, without overheating the hole walls and causing uncontrolled particle emission.

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