Plasma hole boring by multiple short-pulse lasers

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Abstract. Channeling of a train of laser pulses into dense plasma is studied using particle-in-cell simulation. When the pulse duration and the interval between the successive laser pulses are appropriately chosen, the laser pulse train can bore into the plasma deeper than a single long-pulse laser of similar peak intensity and total energy, and laser-induced plasma instabilities are greatly suppressed by the intermittent laser-energy cut-offs. The increased penetration distance can be attributed to the repeated application of ponderomotive force, the greatly reduced plasma instabilities, as well as the continuous between-pulse plasma channel expansion due to ion inertia.

1. Introduction
In the conventional approach to inertial fusion, a deuterium-tritium plasma pellet is compressed and heated by the shock waves generated from laser-driven implosion [1]. For energy gain, more than one megajoule of laser energy has to be deposited within nanoseconds. In the fast ignition (FI) scheme [2], the high fuel density is obtained by conventional laser-driven plasma implosion, but the necessary ultrahigh temperature is achieved through fast and intense heating of a small region inside the fuel by a separate ultra-intense laser pulse, thus greatly reducing the total laser energy needed. However, for effective operation the ignition pulse has to be delivered to a sufficiently high-density region of the pre-compressed fuel, which includes underdense as well as overdense outer regions. Successful channeling of laser energy in dense plasmas is thus of crucial importance to FI and many other applications.

The channeling or boring of an intense laser pulse in plasma has been investigated theoretically, computationally, and experimentally by many authors [3-11]. In the relativistic-intensity regime, the laser-plasma interaction is dominated by the ponderomotive force. With the plasma pushed aside by the laser, the laser pulse enters the plasma like a piston. However, the high-intensity laser-plasma interaction also leads to other nonlinear processes such as laser-beam breakup into filaments [5], various scattering and propagation instabilities [6], etc. Except in sufficiently underdense plasmas, efficient channeling of a relativistic laser is found to be rather difficult.

In this paper, instead of a single pulse, we consider the channeling of a train of laser pulses into a dense plasma. Each time when laser pulse acts on plasma, the plasma near by is set into motion, and
the resulting forward-streaming plasma flow in turn leads to the expansion of plasma channel. At the interval between the laser pulses, the channel expansion continues due to ion inertia, until the forward momentum flow totally vanishes. With suitable interval between the pulses and the pulse duration, a train of short laser pulses can bore into the plasma deeper than a single longer pulse of similar peak intensity and total energy. Long timescale laser-driven plasma instabilities are also greatly suppressed by the intermittent laser-energy cut-offs.

2. Simulation result and discussion

We investigated laser propagation in $2n_e$ plasma. We consider the interaction of a train of short, intense laser pulses with a dense plasma using 2D relativistic particle-in-cell (PIC) simulation [12]. Circularly polarized and spatially Gaussian laser pulses are incident along the x axis from the left vacuum region into the plasma layer. The laser wavelength is $\lambda=1.06$ µm, the normalized laser strength parameter is $a_L=4$, and the spot size is $w=10\lambda$. The corresponding laser intensity is of the order of $10^{19} W cm^{-2}$, which is available in many laboratories. A $40\lambda$ long plasma layer of density $n=n_c$, where $n_c$ is the critical density, is located in the middle of the simulation box. The simulation box is $60\lambda$ along the x axis and $30\lambda$ along the y axis. The plasma layer is bounded by two $10\lambda$ wide vacuum regions on both sides. The spatial and time coordinates are normalized by the laser wavelength and period, respectively, the ion density is normalized by $n_c$, the electromagnetic energy density is $E^2+B^2$, where $E$ and $B$ are the electric and magnetic fields normalized by $m_0\omega_0c/e$, where $\omega_0$ is the laser frequency and $c$ is the speed of light in vacuum.

For comparison, we first consider hole boring by a single laser pulse, whose intensity is

$$I/I_c=(a/a_L)^2=\exp[-(t-t_0)^2/\tau^2]$$  \(1\)

where we shall let $t_0=\tau$. Figures 1 (a) - (c) show the distributions of the plasma ion density for the pulse durations $\tau=12.5\tau$, $25\tau$, and $50\tau$, respectively. All the three snapshots were taken at the moment when the corresponding channel extends deepest in the plasma, i.e., well after the laser light has dissipated or reflected. The ponderomotive force first accelerates and pushes the plasma electrons away as the laser pulse propagates into the plasma, the space-charge field thus generated then also expels the ions. As a result, the plasma in front of the laser pulse set into motion. This forward plasma motion continues by ion inertia even after the action of laser light has stopped (due to reflection and/or absorption). The hole boring continues for a while, until the forward momentum flow totally vanishes.

![Fig. 1. Hole boring by a single laser pulse: distributions of the ion density for laser-pulse durations $\tau=12.5\tau$ (a), $25\tau$ (b), and $50\tau$ (c), respectively, showing the maximum distances bored. The case (c) shows that increasing the laser pulse duration does not improve the penetration distance.](image)

For the same peak intensity, a pulse with longer duration has more electromagnetic energy. One can see in Figs. 1(a) and 1(b) that the pulse with duration $\tau=25\tau$ can push into the plasma deeper compared to the $\tau=12.5\tau$ pulse. However, further increase of the pulse length or laser energy fails to further improve the hole boring. Instead, instabilities such as filamentation and laser beam deflection become significant, as shown in Fig. 1(c) for the $\tau=50\tau$ pulse. That is, the additional laser energy is
mainly spent in feeding the instabilities. For the laser and plasma parameters under consideration, the laser pulse of duration $T_{25}=\tau$ is optimum for the purpose of hole boring. It delivers sufficient laser energy for channeling, while avoiding significant development of unfavorable instabilities.

We next examine hole boring by two shorter laser pulses. Instead of a single pulse of $T_{50}=\tau$, we now use two $25T$ pulses, each having the same parameters as that in Fig. 1(b), i.e., $a_{2}=4$ and $w=10\lambda$.

We note that the total energy in two such $25T$ pulses is nearly same as that in the $50T$ pulse in Fig. 1(c). The time delay between the peaks of the two pulses is taken to be $70T$.

Fig. 2. Hole boring by two $\tau=25T$ pulses at $t=69.62T$, when the second pulse is still outside the plasma: distributions of the electromagnetic energy density (a) and ion density (b).

Fig. 3. Hole boring by two $\tau=25T$ pulses at $t=79.56T$: distributions of electromagnetic energy density (a) and ion density (b). Here the light energy of the first laser pulse is almost gone while the second pulse is still outside of the plasma, the plasma channel is still extending due to ion inertia.

Figure 2 shows the distributions of the electromagnetic energy density (a) and ion density (b) at $t=69.62T$. At this instant, the first laser pulse is strongly pushing into the plasma. One can see that the laser beam as well as the induced plasma channel is slightly tilted, showing that instabilities have begun to emerge.

Figure 3 shows the distributions of electromagnetic energy density (a) and ion density (b) at $t=79.56T$. One can see that the light energy of the first pulse has mostly been dissipated or reflected, while the second pulse is still outside the plasma. However, in the absence of laser ponderomotive force the plasma channel keeps on extending forward by ion inertia, while the instabilities have stopped growing since the laser-energy supply is cut off. Thus, properly chosen time interval between the two laser pulses can enhance hole boring by taking advantage of inertial extension of plasma channel and prevention of further instability development.

Figure 4(a) shows the distributions of ion density at $t=248.63T$, when the action of the second laser pulse is over, and the plasma channel has reached the deepest in the plasma. For comparison, in Fig. 4(b) is for maximum hole boring by a single $\tau=50T$ pulse, i.e., the same as Fig. 1(c). The significant difference in the performance of hole boring into the same plasma by a single pulse and two shorter pulses demonstrates the advantage of the multi-pulse scheme, since the total laser energy in the two
cases are comparable. The significant reduction of instabilities in the two-pulse case also justifies the present 2D simulation, since almost all 3D effects are caused by long-timescale instabilities.

![Image of ion density distributions]

Fig. 4. The distributions of ion density in hole boring: (a) by two \( r = 25T \) pulses at \( t = 248.63T \), and (b) by a single \( r = 50T \) pulse at \( t = 139.23T \), i.e., same as Fig.1 (c). In both cases the snapshots were taken a maximum hole length. The two-pulse scheme can clearly bore a deeper hole in the plasma and with less instabilities.

3. Conclusion
In summary, we have investigated multi-pulsed laser channeling in dense plasma using relativistic 2D PIC simulations. Our results show that a number of short, intense laser pulses can penetrate deeper into a dense plasma than a longer pulse of the same peak intensity. In this scheme laser induced plasma instabilities are also greatly suppressed. The results here are useful for controlling the point of ignition in the fast ignition scheme of inertial fusion.

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