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Trapping of intense light in hollow shell

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A small hollow shell for trapping laser light is proposed. Two-dimensional particle-in-cell simulation shows that under appropriate laser and plasma conditions a part of the radiation fields of an intense short laser pulse can enter the cavity of a small shell through an over-critical density plasma in an adjacent guide channel and become trapped. The trapped light evolves into a circulating radial wave pattern until its energy is dissipated. © 2015 AIP Publishing LLC.

I. INTRODUCTION

The interaction of laser pulses1,2 with gaseous3–8 and solid-density9–12 as well as near-critical density (NCD)13–17 plasmas has been widely investigated. NCD plasmas can be realized by using low-density foam targets.13,14 A short laser pulse can propagate a considerable distance in low-density \((n_0 < n_c)\), where \(n_c\) is the critical density) plasmas, but can penetrate only about a skin depth in over-critical-density plasmas \((n_0 \gg n_c)\). Its propagation in the NCD plasmas depends strongly on the strength of the laser-plasma interaction.

Two-dimensional (2D) particle-in-cell (PIC) simulations have shown that a laser pulse is partially reflected as well as transmitted when it impinges on a plasma of near- but sub-critical-density \((n_0 ≤ 0.7n_c)\).18 The laser ponderomotive force creates in the plasma a vacuum cavity bounded by a thin over-critical-density layer of compressed electrons. The laser light is self-consistently trapped as a half-cycle electromagnetic (EM) wave in the form of an oscillon-caviton structure. When the sub-critical density plasma has a pre-formed cavity, the trapped laser light can also appear as a quasi-standing wave.18

In this paper, we propose a scheme for trapping laser light. The target consists of a small hollow solid-density shell preceded by a guide channel filled with the NCD plasma. A short intense laser pulse can self-focus and channel19–22 through the NCD plasma and enter the hollow shell by pushing aside the electrons in the former, creating around it an electron wake channel where the light pressure balances the space-charge field. Two-dimensional PIC simulation shows that as the laser pulse enters shell, the space charge field pulls back the expelled electrons in the wake channel, thereby closing it. The trapped radiation in the shell cavity is redistributed: its mode structure is changed according to the size and geometry of the cavity wall as well as the wave-plasma interaction there. That is, the NCD plasma in the guide channel acts as a one-way trap door for the laser light. The trapped radiation has a roughly radial-polarized wave structure that rotates in the cavity. It also dissipates due to interaction of its skirt region with the shell-wall plasma, but can still survive for more than 150 laser periods.

II. LASER SELF-CHANNELING

We have performed 2D3V (two-dimensional in space and three dimensional in velocity) PIC simulations for laser interaction with the NCD guide-channel plasma and the solid-density wall plasma of the hollow shell. As illustrated

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FIG. 1. Schematic of the proposed scheme. A guide channel containing H plasma is attached to the C\(^{6+}\) plasma shell.
in Fig. 1, the latter is made of an $n_0 = 36n_e$ carbon ($\text{C}^{6+}$) plasma shell centered at $(y, z) = (0, 23)$, where $y$ and $z$ are in units of the laser wavelength $\lambda$. Its inner and outer diameters are $10\lambda$ and $16\lambda$, respectively. The attached guide channel $(-6 < y < 6, 5 < z < 15)$ is along the $z$ axis and contains homogeneous hydrogen (H) plasma of density $n_0 = 2n_e$. A circularly polarized Gaussian laser pulse is incident from the left vacuum region on the H plasma in the guide channel. It is of laser parameter $a_{L0} = 3$, spot size $b = 2.5\lambda$, and pulse duration $\tau = 60T_0$, where $T_0$ is the light-wave period. The dimensions of the guide channel and shell cavity are thus of the same order as the laser spot size. The simulation box is $40\lambda \times 50\lambda$, and the space mesh contains $2000 \times 2500$ cells, with 36 ions and 36 electrons per cell.

Figure 2(a) shows the EM energy density distribution $E^2 + B^2$ (the electric and magnetic fields $E$ and $B$ have been normalized by $m_0c\omega_0/e$ and $\omega_0$ is the light wave frequency) and the electron density (normalized by $n_e$) $n$ inside the guide channel at $t = 50T_0$, when the peak of the incident laser pulse is at the left edge of the guide channel. One can see that the front of the laser pulse has penetrated a short distance (about a relativistic skin depth) into the plasma and is self-focused. Fig. 2(b) shows that it is blocked and reflected by a thin ponderomotively compressed and dented electron layer of enhanced density. Figure 2(c) for the EM energy density at $t = 66T_0$ shows that most of the laser light has light until a nearly stationary high-density electron layer is formed in front of the laser pulse by the nonlinear electron response to the light pressure.

We now reduce the density of the guiding-channel H plasma to $n_0 = 1.5n_e$, keeping the other parameters the same as that in Fig. 2. Figure 3 shows that at $t = 50T_0$ the same laser pulse can propagate through the H plasma. In (a) and (b), the core of the laser pulse is compressed and pushed aside the electrons in its path, creating a positively charged wake channel, where the light-pressure and charge-separation forces on the compressed electrons balance on the (moving) front and lateral boundaries. That is, self-channeling by the high-intensity core of the laser pulse in the NCD plasma occurs. One can see that the weaker skirt of the laser pulse can also propagate in the $n_0 = 1.5n_e$ guide channel H plasma without significantly disrupting the local electrons. Fig. 3(b) indicates that the laser pulse in the channel stands from the so-called hosing instability. As a result, the affected plasma becomes turbulent and the front of the laser pulse deviates from the original propagating direction in an irregular oscillatory manner, so that when it enters the shell cavity it may not be exactly (here it is at about $-30^\circ$) in the original laser propagation direction. Figures 3(c) and 3(d) show that at $t = 66T_0$ a considerable fraction of the EM energy in the guide channel has entered the shell cavity, but the plasma electrons of the shell wall is only slightly affected. It is of interest to note that the structure of the radiation in the cavity is considerably more regular than that in the channel. This is because here the wave-plasma interaction takes place only in a thin layer near the shell wall, and is much less intense than that in the guide channel.

### III. LIGHT TRAPPING IN SHELL CAVITY

We now follow the evolution of the light trapped in the shell cavity. Figure 4 shows the same parameters as in Fig. 3, but at $t = 80T_0$. In Fig. 4(a), the radiation in the shell cavity is trapped, and the radiation remaining in the wake channel is still interacting with the channel electrons, whose
density is now higher since the laser expelled electrons are being pulled back by the space-charge field. The trapped radiation is in the form of an EM field with inhomogeneous radial structure that rotates in the cavity. In the guide channel, one can also find on the axis of the turbulent H plasma a tiny self-organized slow-moving caviton\textsuperscript{25} or postsoliton\textsuperscript{26}, which self-consistently traps intense radiation on the laser-wavelength (instead of the laser pulse-width) scale. Near the outer boundaries of the guide channel and the shell, as well as at the front of the H channel and along the cavity wall, one finds highly localized but relatively weak EM (including the ES charge-separation) fields and relatively low-density electrons. These phenomena are results of interaction of the laser-pulse skirt (that did not enter the channel but is still intense) with the external surfaces of the channel and the shell.

Figure 5 shows the trapped EM energy density at still later times. One can see that there is a still-evolving, mostly radially polarized but highly inhomogeneous light wave pattern propagating azimuthally in the cavity. The direction of the circulation depends on the angle (here about $-30^\circ$) of the hosing-unstable radiation pulse at the entrance of the cavity. Because of the interaction with the cavity-wall plasma, the trapped radiation dissipates, but relatively slowly such that it can survive for $>150T_0$. During the process, the inner shell wall remains almost unaffected (not shown, but can be inferred from Fig. 5) by noting that the EM energy distribution near the cavity wall remains quite homogeneous and smooth. It is also of interest to note that the tiny stationary caviton-postsoliton in the wake channel found in Fig. 4(a) still exists at $t = 94T_0$, albeit much weakened by dissipation.

**IV. OPTO-GEOMETRICAL EFFECTS**

In order to see the non-plasma (i.e., optical and/or geometrical) effects on the trapping process, we have independently simulated the stage of wave injection into the cavity using the software COMSOL\textsuperscript{27} that employs the finite-element method for the numerical solution of the wave equations. To model the corresponding scenario in our PIC simulation, we inject a circularly polarized EM wave pulse into a shell cavity via a breach (entrance hole) in the shell wall, with all the parameters similar to that in the PIC simulation. Accordingly, the injected EM wave pulse is of wavelength $1\mu$m, spot radius $3\mu$m, and pulse width 20fs, the diameter of the one-way breach of the shell cavity is also $3\mu$m. There is no plasma in the COMSOL simulation, so that wave-plasma interaction near the cavity wall is precluded. Instead, the total-reflection boundary condition is applied at the inner shell wall.

Fig. 6 shows the COMSOL simulation result for a light pulse with an injection angle of $-30^\circ$, similar to that found in Fig. 3(c). We see that the circularly polarized EM wave field enters the cavity and is reflected along the cavity wall, and an irregular rotating wave structure of partially radial polarization is formed as a result of phase interference of the
reflected wave fronts. We can see that the main features of the trapped field in the cavity, such as the irregular radial wave pattern and the rotation, agree qualitatively with that from the PIC simulation. The difference in the details, such as the EM field distribution near the cavity wall and the prolonged trapping time in the PIC simulation, can be attributed to the self-organizing wave-plasma interaction. The latter is consistent with the tiny self-generated radiation-trapping caviton and postsoliton investigated earlier, and can also be seen in the guide channel here. That is, the self-consistent wave-plasma interaction appears to have a positive effect on the trapping process. Additional COMSOL simulations (not shown) also verify the PIC result that the direction of circulation of the trapped light depends on the injection angle of the injected light pulse.

V. SUMMARY

In this paper, we have investigated trapping of laser radiation inside a small hollow shell of solid density after it has propagated (by relativistic self-channeling) through an NCD plasma in an attached guide channel. The trapped light has a complex inhomogeneous radial wave structure that rotates in the cavity, and it can survive for more than 150 laser periods before it is fully dissipated. However, no well-defined eigenmode structure analogous to that in microwave
resonators\cite{29,30} is found. This scheme of light trapping is characterized by the small sizes of the shell cavity and guide channel. If the cavity is too large, multiple inelastic scattering of the intense laser light by the curved cavity wall plasma and the resulting phase interference would quickly destroy its structure. It differs from the EM caviton\cite{23} or postsoliton\cite{24} that is self-consistently generated through self organization and can have size of the order of or less than the laser wavelength. It also differs from the hohlraum for inertial confinement fusion,\cite{31,32} where the cavity is much larger than the laser pulses and the resulting x-ray radiation is fully incoherent. Aside from the general interest to light confinement,\cite{33,34} the present results may also be useful for interpreting phenomena such as localized light flashes,\cite{35,36} designing new optical materials and structures,\cite{37} optical information control,\cite{38} light interaction with hollow nanostructures, etc.\cite{39}

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