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Focusing of intense laser pulse by a hollow cone

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Abstract

It is shown that an intense laser pulse can be focused by a conical channel. This anomalous light focusing can be attributed to a hitherto ignored effect in nonlinear optics, namely that the boundary response depends on the light intensity: the inner cone surface is ionized and the laser pulse is in turn modified by the resulting boundary plasma. The interaction creates a new self-consistently evolving light-plasma boundary, which greatly reduces reflection and enhances forward propagation of the light pulse. The hollow cone can thus be used for attaining extremely high light intensities for applications in strong-field and high energy-density physics and other areas.

Keywords: Laser-cone interaction; Laser focusing; Particle-in-cell simulation

Strong-field or high-energy-density physics relies much on the very high concentration of laser energy in an extremely small time/space interval. Chirped pulse amplification technology has opened a new era in strong-field physics. By compressing the laser pulse to the femtosecond regime, terawatt, or even petawatt lasers have become available (Perry & Mourou, 1994; Perry *et al.*, 1999; Mourou *et al.*, 1998). Furthermore, considerable effort has been made in concentrating laser energy to a small or tightly focused spot. Recently, powerful lasers have been focused to the 10-wavelength level (Fritzler *et al.*, 2003; Cowan *et al.*, 2004), with peak intensities reaching 10^{21} Wcm^{-2} or higher. However, with conventional methods it is difficult to further reduce the spot radius to, say, one wavelength or less. It is thus of interest to investigate the possibility of focusing to the one-wavelength level.

The nonlinear propagation and self-focusing characteristics of laser pulses with different profiles have been widely investigated (Mori, 1997; Asthana *et al.*, 2000; Sodha *et al.*, 2009). The availability of highly focused laser pulses with small spot sizes and high intensities has opened new areas of applications, such as fast ignition in inertial confinement fusion (Tabak *et al.*, 1994), production of collimated energetic electrons and ions (Esarey *et al.*, 2009; Borghesi *et al.*, 2007; Ruhl *et al.*, 1999; Beg *et al.*, 1997; Willi *et al.*, 2007), and novel high-brightness X-ray and K_α sources (Rajeev *et al.*, 2003; Park *et al.*, 2008).

A hollow metal cone with closed tip was first used by Kodama *et al.* (2001) in connection to fast ignition. An unexpected increase in the thermal fusion-neutron yield was observed. Since then the cone target was intensively examined experimentally and theoretically (Chen *et al.*, 2005; Stephens *et al.*, 2003; Van Woerkom *et al.*, 2008; Mason, 2006; Lei *et al.*, 2006; Sentoku *et al.*, 2004; Nakamura *et al.*, 2007; Pasley & Stephens, 2007; Sakagami *et al.*, 2006; Nagatomo *et al.*, 2007; Key, 2007). Using particle-in-cell (PIC) simulation, Sentoku *et al.* (2004) and Nakamura *et al.* (2007) considered the interaction of a semi-infinite laser with a closing-tip hollow cone and found that the laser is effectively guided and focused by the cone. As a result, laser-plasma interaction at greatly enhanced intensity occurs in the closed cone tip.

We consider here the propagation of an intense short laser pulse in a hollow cone with its tip opening having a radius of just one laser wavelength. The purpose is to see if such a cone can focus, or squeeze, the laser light into a tiny pulse. Our PIC simulation results show that the laser pulse can

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indeed be squeezed, with the modified pulse of light leaving the cone-tip opening at greatly enhanced energy density. The tightly focused and still fairly coherent light pulse can propagate over a distance of several wavelengths before it starts to diffract. That is, the hollow cone acts like an optical device that focuses the laser pulse to a spot at the one-wavelength level.

In general, the characteristics of light propagation depend on the properties of medium and the light-medium interface. Nonlinear optical effects can appear when the response of the medium depends on the light intensity, leading to phenomena such as parametric scattering and self-focusing of light. Similarly, the light-medium interface or boundary can also respond nonlinearly at high light intensities. In fact, our results can be attributed to a focusing effect of the light-intensity dependent laser-plasma boundary at the inner cone surface: as the intense laser pulse propagates in the hollow cone, the inner cone surface is rapidly ionized, and the plasma electrons are pushed inward by the ponderomotive (or light-pressure) force and pile up in a thin high-density layer inside the inner cone surface. That is, the highly nonlinear laser-plasma interaction self-consistently modifies the boundary plasma as well as the light pulse. As a result, light reflection is greatly reduced and forward propagation, and focusing (squeezing) of the laser pulse is enhanced.

We consider the propagation of a short, intense laser pulse in a hollow cone open at both ends. The laser is launched at the left opening into the cone, and exits at the right opening. For the simulation, we use a 2D3V PIC code (Xu *et al.*, 2002; Yu *et al.*, 2009) and consider plasma that is uniform in the z direction. The circularly polarized incident laser pulse has the Gaussian envelope $a = a_0\exp[-(t - t_0)^2/\tau^2]\exp[-(y - y_0)^2/w^2]$ and propagates in the x direction. The laser strength parameter is $a_0 = 4$, the spot radius is $w = 10\lambda$, and the pulse duration is $\tau = t_0 = 25T$, where λ and T are laser wavelength and period, respectively. Hollow cones of different cone angles are considered, but the radii $r_L = 15\lambda$ and $r_R = 1\lambda$ of the left and right openings are fixed. The density of the cone plasma is $n = 10\ n_c$ and its thickness is $d = 2\lambda$, where n_c is the critical density. The simulation box is 80λ along the x axis and 40λ along the y axis. The spatial mesh contains 1024×512 cells, with 2.56×10^7 each of electrons and ions. The initial velocity distributions of the plasma electrons and ions are taken to be Maxwellian, with temperatures of 1 keV for the electrons and 0.3 keV for the ions. The simulation time step is $0.05T$, where $T = 3.5$ fs. The spatial and time coordinates are normalized by the laser wavelength and period, respectively, and the electron and ion densities are normalized by n_c. The electromagnetic (EM) energy density is $E^2 + B^2$, where $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electric and magnetic fields normalized by $m\omega_0 c/e$, and e, m, c, and ω_0 denote the electron charge and rest mass, the speed of light in vacuum, and the laser frequency, respectively.

Figure 1 shows the spatial distribution of the EM energy density at $t = 89.51T$. One can see that the hollow cone acts like a lens: the laser light is reflected, absorbed, guided, and focused by it. As the resulting pulse leaves the tip opening, the light energy is confined to a tiny spot of one-wavelength radius. Moreover, the tightly focused light pulse keeps propagating at high intensity over a distance of several wavelengths (similar to the Rayleigh length in free space) before it eventually diffracts.

When irradiated by intense laser light, the inner cone surface is completely ionized, and the laser-plasma boundary is strongly modified by the ponderomotive force. That is, the boundary condition for laser propagation is intensity dependent, which in turn significantly changes the laser properties. Figure 2 shows the distribution of the electron

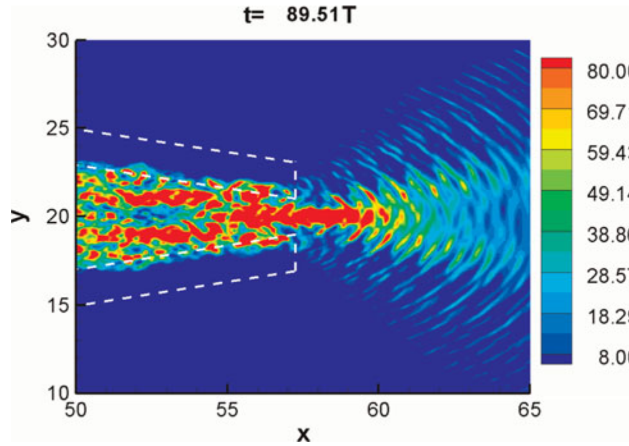

Fig. 1. (Color online) The normalized EM energy density at $t = 89.51T$. The white dashed lines mark the initial hollow cone. The laser parameters are $a_0 = 4$, $w = 10\lambda$, and $\tau = 25T$. The cone parameters are $r_L = 15\lambda$, $r_R = 1\lambda$, $n = 10\ n_c$, and $d = 2\lambda$. The cone angle is 30°. The upper (deep red) and lower (deep blue) ends of the color bar represent energy densities above 80 and below 8, respectively. The peak energy density is about 493 at $x = 57.97$.

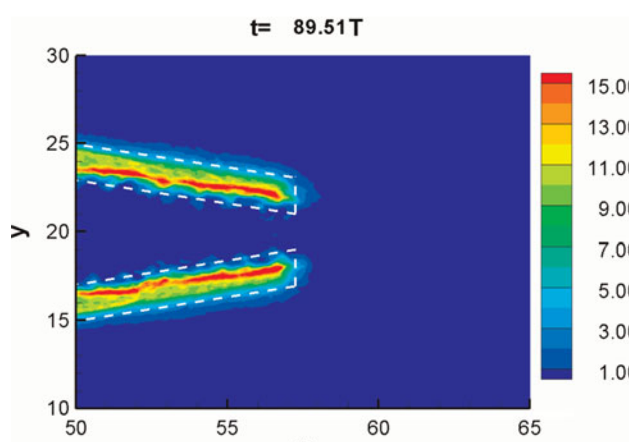

Fig. 2. (Color online) The electron density at $t = 89.51T$. The parameters are the same as Figure 1. Intense light-plasma interaction takes place in the lower-density region of the inner cone surface. The high-density layer (red) is formed by the inward (into the cone wall) propagating electrons driven by the light pressure in the low density region.

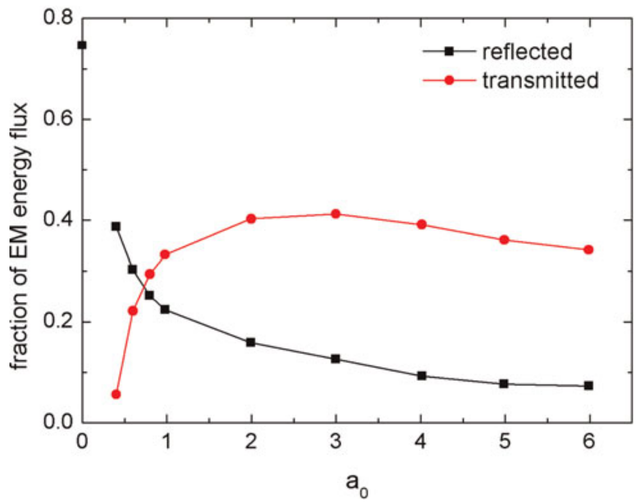

Fig. 3. (Color online) Dependence of the fractions of the reflected (black squares) and absorbed (red circles) EM energy flux on the laser strength from $a_0 = 6$ to $a_0 = 0.4$. The data point on the y axis shows the fraction of reflected light in the linear limit ($a_0 = 0$) as obtained from optical ray tracing. The extrapolation of the PIC result seems to approach this limit.

density at $t = 89.51T$. One can see that as the laser pulse propagates in the hollow cone, the plasma in the inner cone surface is pushed inward and piled up, leaving a lower-density plasma layer that self-consistently interacts with and modulates the propagating light pulse.

In general, the focusing of a light pulse or beam occurs when the refractive index on the propagation axis is larger than the off-axis. As the intense laser light propagates in the hollow cone, the refractive index in the center vacuum region remains $\eta_R = 1$. Near the inner cone wall the periphery of the laser pulse encounters the cone plasma, and the relativistic refractive index becomes $\eta_R = (1 - n/\gamma n_c)^{1/2} < 1$, where n and γ are the local plasma density and the relativistic factor, respectively. As a result, the periphery of the phase front bends toward the propagation axis, and the beam focuses. That is, at the beginning the focusing occurs mainly in the vicinity of the cone walls and the wave field in the center (vacuum) region is less affected, until the cone walls become very close (say a few wave lengths).

The generation and modulation of the cone-surface plasma consume laser energy, but the self-consistent light-plasma interaction at the cone boundary also suppresses back reflection, reduces the pulse waist, enhances the intensity, as well as promotes forward propagation of the resulting light pulse. Figure 3 (color online) shows the dependence of the fractions of reflected (black) and absorbed (red) light energy on the laser strength for the 30° cone. With increasing a_0, the modulation of the plasma boundary becomes more significant and more laser energy is absorbed by the cone. On the other hand, for relativistic laser pulses ($a_0 > 1$), light reflection is greatly reduced, and light transmission remains at the level of 40%. We also note that for $a_0 < 1$, light absorption decreases rapidly with decreasing a_0, while light reflection rapidly increases. That is, the dependence of the absorption and transmission on the laser intensity is highly nonlinear.

One might be tempted to compare the present result with that of the propagation of weaker light through a mirroring hollow cone. It is well known that light cannot be focused by the latter: only a small fraction of light can go through a 30° cone and the transmitted light also does not converge. Furthermore, because of the smallness of the cone opening (on the order of a wave length), traditional geometric-optics methods are not expected to apply.

Figure 4 (color online) shows the dependence of the fractions of the transmitted (red) and reflected (black) EM energy on the cone angle. The conical channels have different lengths for different cone angles such that the radii of the left and right openings are fixed. We can see that with increasing cone angle the reflection increases and the transmission decreases, but the absorption (by the cone plasma) remains at the level of 30–40%. For the 30° cone, about 52% of the initial laser energy leaves the tip opening as a tightly focused light pulse.

In view of the suggested mechanism that modifies the laser pulse, one would expect that, unlike most other focusing methods, imperfections in the initial profile of the laser spot should not significantly affect the focusing. To verify this, we have also simulated cone focusing of a pulse with two less-intense wings ($a_0 = 2$, $w = 5\lambda$), usually considered as a serious fault in the pulse quality, around the central peak ($a_0 = 4$, $w = 5\lambda$). The centers of the two wings are 10λ away from the center spot, and the other parameters are kept the same, so that the initial energy of the pulse is similar to that in Figures 1 and 2. Figure 5 (color online) shows the transverse distributions of the EM energy density when the peak of light pulse passes the left (black curve) and right (red curve) openings of the cone. We see that the laser spot size is reduced to just 10% of its initial value and the peak

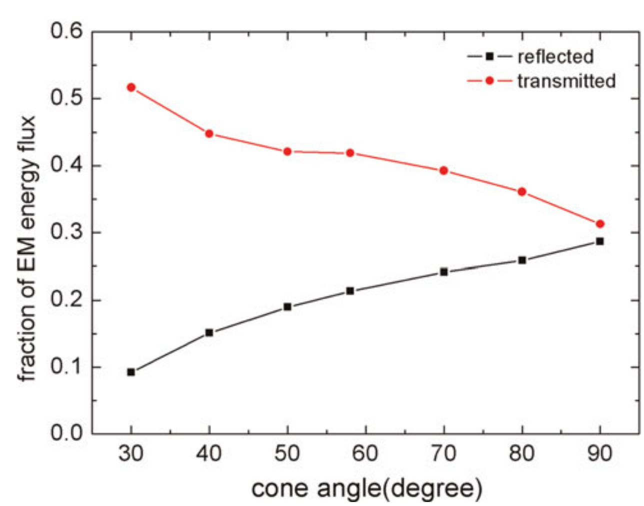

Fig. 4. (Color online) The fractions of the transmitted (red circles) and reflected (black squares) EM energies as a function of the cone angle, for $a_0 = 4$. The other parameters the same as in Figures 1 and 2.

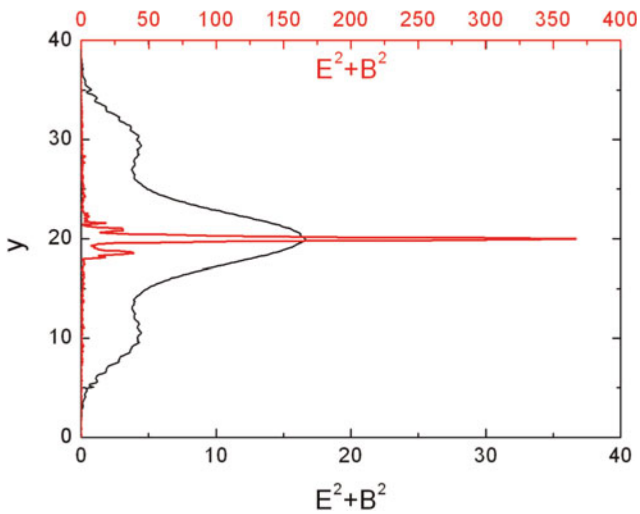

Fig. 5. (Color online) Radial distributions of the EM energy density as the peak of a winged laser pulse passes the left (black curve with wide profile, lower energy scale) and right (red curve with narrow profile, upper energy scale) openings at $x = 5\lambda$ and $x = 57.5\lambda$, respectively, of the hollow cone. The laser-pulse parameters are $a_0 = 4$ and $w = 5\lambda$ for the center peak and $a_0 = 2$ and $w = 5\lambda$ for the two wings. The other parameters are the same as those for Figure 1. Note that the exiting light pulse is of very small spot radius ($\sim 1\lambda$), very high intensity ($\sim 20a_0^2$), and very high contrast.

intensity is increased by more than 20 times. Furthermore, after the squeezing the wings in the original pulse still exist but the magnitude and spatial extent are greatly reduced. This result also shows that there is indeed squeezing of the light pulse. On the other hand, the peak exiting energy density of about 350 is less than that (about 493) of the simple Gaussian pulse case, since the more intense pulse periphery here interacts more strongly with the cone and leads to a higher absorption rate. To see this effect more clearly, we have also carried out simulations for a pulse with two high-intensity wings and no center peak. Such a pulse is almost completely absorbed and reflected by the cone plasma since its high-intensity periphery interacts very strongly with the cone surface, leading to strong absorption and reflection of the laser energy. Nevertheless, what is left of the pulse is also focused and transmitted at the cone tip.

For comparison, in Table 1, the fractions of the reflected, absorbed, and transmitted energy fluxes for a laser pulse with different transverse profiles are summarized. We see that the simple Gaussian laser pulse (case *a*) can be transmitted and focused effectively with little reflection since only the weak periphery of the pulse interacts with the cone surface. As expected, when the same intense pulse has a narrower waist (case *b*), which is difficult to produce in reality, the transmission is somewhat improved since the laser-plasma interaction takes place closer to the cone tip. For the laser pulse with a center peak and two weaker wings (case *c*), about 43% and 12% of the incident laser energy flux is absorbed and reflected, respectively, and about 45% exits the cone-tip opening. However, for the pulse with only the intense wings (case *d*), most of the energy is absorbed and reflected and only about 3% exits the cone-tip opening. Accordingly, the interaction of a laser pulse with the hollow cone is mainly by the pulse edge and thus depends strongly on the profile of the light intensity. Minor imperfections in the laser profile are minimized by the interaction, so that the quality of the original laser pulse is much improved.

In conclusion, we have considered the propagation of a short, intense laser pulse through a hollow cone with a tiny tip opening. It is shown by 2D PIC simulation that the laser pulse can be squeezed and focused into a light pulse with a spot radius of just one wavelength at much enhanced intensity. It can propagate forward for a distance of a few wavelengths before it diffracts. The cone focusing can be attributed to the self-consistent nonlinear laser-plasma interaction between the periphery of the laser pulse and the low-density plasma at the surface of the inner cone wall. The boundary modulation self-consistently restructures the original laser pulse, so that the highly squeezed pulse at the cone-tip remains fairly coherent. Thus, nonlinear focusing by hollow cone is a simple and inexpensive method for achieving intense tiny light pulses at the one-micron level, and should be useful in many modern applications such as charged-particle acceleration (Cao *et al.*, 2008). On the other hand, light squeezing and focusing by cavities of wavelength size, which can involve conversion of the mode structure, deserves further theoretical investigation.

Table 1. *The fractions of the reflected, absorbed, and transmitted light energies for laser pulses with different transverse profiles. Here the subscript* c *stands for* center *and* w *for* wing

Transverse pulse profile	Intensity a_0, spot size w, central position y_0	Fraction of light energy		
		reflected	absorbed	transmitted
(*a*) center spot only	a_{0c}=4, $w_c = 10\lambda$, $y_{0w} = 20\lambda$	0.09	0.39	0.52
(*b*) center spot only	a_{0c}=4, $w_c = 5\lambda$, $y_{0w} = 20\lambda$	0.06	0.32	0.62
(*c*) center spot with two wings	a_{0c}=4, $w_c = 5\lambda$, $y_{0c} = 20\lambda$	0.12	0.43	0.45
	a_{0w}=2, $w_w = 5\lambda$, $y_{0w} = 30\lambda$, 10λ			
(*d*) two wings only	a_{0w}=2, $w_w = 5\lambda$, $y_{0w} = 30\lambda$, 10λ	0.29	0.68	0.03

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