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# Transmission Degradation of Femtosecond Laser Pulses in Opened Cone Targets\*

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**Abstract** Irradiated by femtosecond laser pulses with different energies, opened cone targets behave very differently in the transmission of incident laser pulses. The targets, each with an opening angle of  $71^\circ$  and an opening of  $5\ \mu\text{m}$ , are fabricated using standard semiconductor technology. When the incident laser energy is low and no pre-plasma is generated on the side walls of the cones, the cone target acts like an optical device to reflect the laser pulse, and 15% of the laser energy can be transmitted through the cones. In contrast, when the incident laser energy is high enough to generate pre-plasmas by the pre-pulse of the main pulse that fills the inner cone, the cone with the plasmas will block the transmission of the laser, which leads to a decrease in laser transmission compared with the low-energy case with no plasma. Simulation results using optical software in the low-energy case, and using the particle-in-cell code in the high-energy case, are primarily in agreement with the experimental results.

**Keywords:** femtosecond laser pulse, cone target, transmission ratio

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## 1 Introduction

Cone targets<sup>[1]</sup> used in a fast ignition scenario<sup>[2]</sup> have attracted a great deal of interest because they can guide the ignition laser pulse to the pre-compressed core surrounded by long-distance corona plasma<sup>[3]</sup>. The ignition pulse laser will avoid absorption and be deflected by the corona plasma, and the efficiency of both the energy of the laser to fast electrons and the energy of the fast electrons to the compressed core will be increased compared with conventional compressed deuterium-tritium pellets<sup>[4]</sup>. In this context, laser-cone interaction physics play an important role in fast ignition research<sup>[5]</sup>. However, most of the incident laser energy will probably not reach the tip of the cone because of **a.** the wing of the laser pulses' interaction with the walls of the cone<sup>[6]</sup>, and **b.** the propagation loss in the pre-plasma generated by the amplified spontaneous emission (ASE) and pre-pulse of the main pulses<sup>[7]</sup>. The interaction of the laser pulses with the walls will generate fast electrons, which will be confined along the wall of the cone and guided to the tip of

the cone. This phenomenon has been studied in recent years<sup>[8]</sup>. On the other hand, the pre-plasma will partially reflect and absorb the main laser pulse, and then decrease the coupling efficiency between the laser and the fast electrons<sup>[9]</sup>. However, how the pre-plasma affects the transmission of the laser pulse is still not well understood.

In this work, we studied the effect of the pre-plasma on laser transmission by changing the incident laser energy. The results clearly show that the transmission is much lower when a higher energy is used compared with the low-energy case. We also performed a 2D particle-in-cell (PIC) simulation for the high-energy irradiation case, which clearly shows that the pre-plasma is the main factor for transmission reduction.

## 2 Experimental setup

The experiment was carried out at the eXtreme Light II (XL II) laser facility<sup>[10]</sup> at the Institute of Physics, Chinese Academy of Sciences. The XL II laser facility

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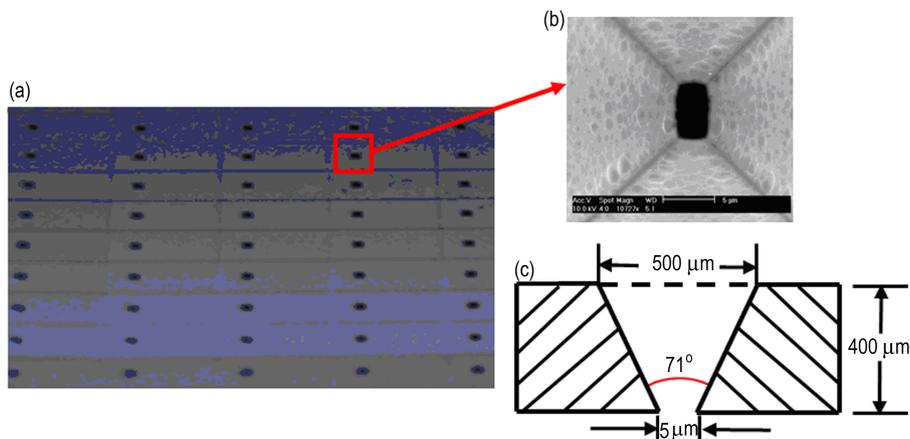
is a Ti:sapphire femtosecond laser system which delivers femtosecond laser pulses centered at 800 nm, with 60 fs in duration and 300 mJ in energy. The pulse laser was focused by a 90° off axis parabolic mirror with an  $f$  number of 3.5. Far-field measurements gave a  $5\ \mu\text{m}$  (full width half maximum) diameter laser spot containing about 20% of the total energy, with a corresponding peak intensity of  $6 \times 10^{18}\ \text{W}/\text{cm}^2$ . Third-order autocorrelation measurements revealed the presence of a short  $10^{-6}$  pre-pulse arriving 10 ps before the main pulse.

The opened cone targets used in this experiment were fabricated with single crystallized silicon etched in KOH, which is a standard process used in semiconductor technology [11]. When the silicon wafer was etched in KOH solution along the  $\langle 111 \rangle$  direction, the etching rate was faster than  $\langle 100 \rangle$ . With suitable masks and etching time, we were able to make opened cone targets with a  $71^\circ$  opening angle and a  $5\ \mu\text{m}$  opening width. The target arrays and the configuration of the target are shown in Fig. 1.

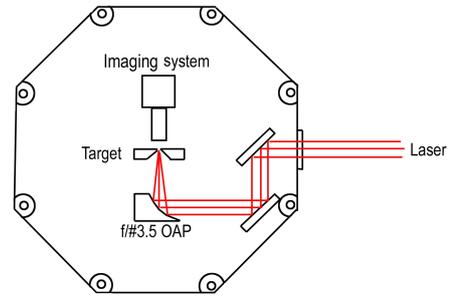
During the experiment we used two kinds of laser pulses. One was low enough in energy and with no plasma produced when the laser pulse was irradiated. The other was high enough in energy with a peak intensity of  $6 \times 10^{18}\ \text{W}/\text{cm}^2$ . The layout of the experiment and the two kinds of laser pulse are illustrated in Fig. 2.

For both cases, the laser pulses were aligned with the symmetric axis of the cone, which was monitored by a microscope imaging system behind the cone, as shown in Fig. 2.

In the high-energy case, we diagnosed the transmission energy by using a laser energy meter directly. In contrast, in the low-energy case, we obtained the ratio of the transmission energy to the incident energy by integrating the digital intensity distribution of the laser spot on the charge coupled device (CCD).



**Fig.1** (a) An image of the re-entrant cone arrays etched in a silicon wafer, (b) An image of an etched cone taken by a scanning electron microscope (top view), (c) A schematic view of the cone configuration. The width of the opening entrance is  $5\ \mu\text{m}$

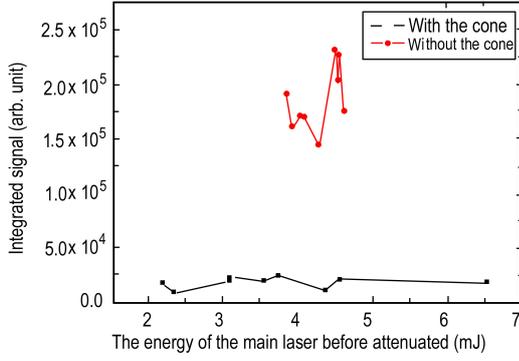


**Fig.2** Schematic view of the experimental setup

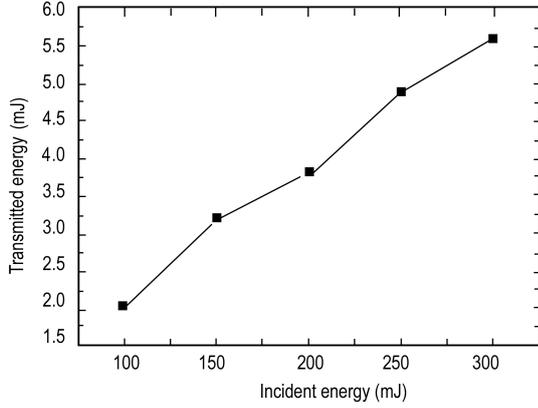
### 3 Experimental results and discussion

The transmission ratios of the laser pulse in the two situations were measured and calculated using the two methods described above. In the low-energy case, we integrated the pattern of the incident laser pulse with no cone target mounted as the incident laser pulse energy, and then integrated the laser pattern out of the cone as the transmitted laser energy, and treated their ratio as the transmission ratio. In this case the laser pulse was highly attenuated ( $10^{-5}$ ) by the neutral filters to make sure the laser energy was low enough. The measured scattered points are shown in Fig. 3. We can obtain a transmission ratio of 15% for the low-energy case, i.e. 15% of the laser pulse energy is leaked out of the cone tip.

In the high-energy case, the CCD cannot image the laser spot directly. Therefore, we had to measure both the incident and transmission energy using the laser energy meter. When measuring the transmission energy, we used a lens to collect the laser pulse out of the tip of the cone. The transmitted energy versus incident laser energy is given in Fig. 4. We can obtain an average transmission ratio of 2%, which is much lower than the low-energy case.



**Fig.3** The transmitted laser signals with and without the cone on the CCD camera for different incident laser energies



**Fig.4** The transmitted energy vs. the incident energy in the high-energy case

The wing of the incident laser pulse would be partly reflected by the wall because there was no plasma in the low-energy case. Meanwhile, since the opening width of the cone was almost the same as the full width half maximum of the laser spots, the main part of the laser energy would be transmitted directly. We can calculate the ratio of the energy of the central part to the total energy of the beam, and taking the energy concentration into account, we can get a 19% transmission ratio as follows. The transverse profile of the laser intensity can be expressed as

$$I(r) = I_0 \exp\left(-2\frac{r^2}{w_0^2}\right), \quad (1)$$

where  $I_0$  is the peak intensity of the transverse profile,  $w_0$  is the waist radius of the laser and  $r$  is the distance to the peak.

Consequently, the total energy of the laser pulse can be expressed as

$$E_{\text{total}} = I_0 \int_{-\infty}^{+\infty} \exp\left(-2\frac{r^2}{w_0^2}\right) dr. \quad (2)$$

The energy contained in the main spot can be expressed as

$$E = I_0 \int_{-w_0}^{w_0} \exp\left(-2\frac{r^2}{w_0^2}\right) dr. \quad (3)$$

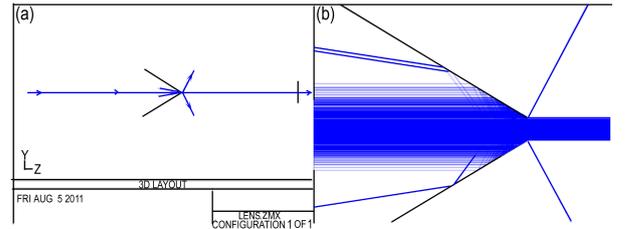
As a result, the energy ratio of the energy in the spot to the total energy can be calculated as

$$\text{ratio} = EC \times \frac{E}{E_{\text{total}}} = 0.2 * \frac{\frac{\sqrt{\pi}}{2\sqrt{2}} w_0 * \text{erf}(\sqrt{2})}{\frac{\sqrt{\pi}}{2\sqrt{2}} w_0}, \quad (4)$$

$$= 0.2 * \text{erf}(\sqrt{2}) = 0.2 * 0.9545 = 19\%, \quad (5)$$

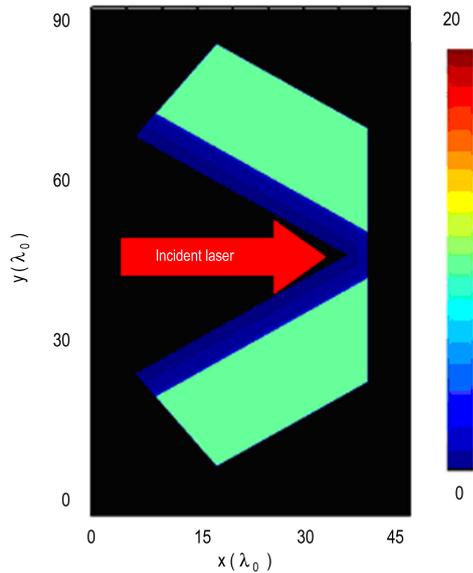
where  $EC=0.2$  is the energy concentration as described in section 2, and  $\text{erf}(\sqrt{2}) = 0.9545$  is a constant. This calculated number is close to but a bit larger than the experimental results in the low-energy case. The small difference is probably induced from the scattering of the laser light and the deflection on the surface of the side wall of the cone.

We also carried out optical ray tracing simulations using the Zemax software, with the same parameters as in the experiment. The simulation results are shown in Fig. 5, which shows that part of the incident laser energy is reflected and the main part of the laser is transmitted through the cone. We obtained a 17% transmission ratio of the incident laser energy, which is close to the experimental findings and the analytical calculation. The analytical and simulation results are both slightly higher than the experimental results because of the idealism of the reflection and energy distribution.

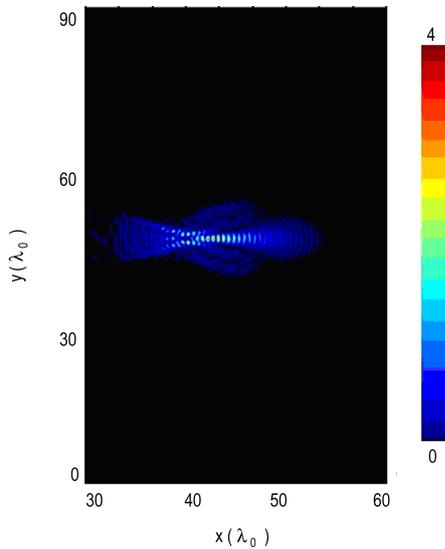


**Fig.5** (a) The layout of the optical simulation using Zemax, (b) The light ray traces at the tip of the simulated cone

In the high-energy case, we carried out PIC simulations with a 2D relativistic fully electromagnetic code [12]. The configuration of the simulations is illustrated in Fig. 6. The simulation box is  $45\lambda_0 \times 90\lambda_0$ , where  $\lambda_0 = 0.8 \mu\text{m}$  is the central wavelength of the incident laser light in vacuum. There are 25 cells per wavelength and 25 particles per cell. The opened cone target is composed of two plasma slabs, each of which is  $35\lambda_0$  long,  $15\lambda_0$  wide, with a density of  $10 n_c$ , where  $n_c$  is the critical density corresponding to the incident laser. The two plasma slabs are separated by a distance of  $5\lambda_0$  to simulate the opened entrance of the cone targets. Each plasma slab is covered by a pre-plasma with a density of  $0.1n_c$  and a scale length of  $2\lambda_0$ . The laser is incident from the left.



**Fig.6** The 2D PIC simulation configuration of the interactions in the high-energy case



**Fig.7** The distribution of the electromagnetic field energy simulated by the 2D PIC code

We diagnosed the electromagnetic energy distribution for a time  $t=906$  fs, and the result is shown in Fig. 7. After integrating the energy of the electromagnetic fields out of the cone tip and that in front of the cone, we obtained a ratio of 3.5%. This is similar to the experimental results in the high-energy case. This result is higher than the experimental results, and we attribute this difference to the simulation's downscale nature. When the pre-plasma is properly adjusted, the transmission ratio gets a high enhancement, even in

the low-energy case, which means that the level of the pre-plasma determines the ratio of the transmission energy to the incident energy. The pre-plasma will reflect and absorb the incident energy, which changes the simple reflection model of the cone as in the low-energy case. This makes the cone with plasmas inefficient to the transmission of the laser.

## 4 Conclusion

Laser energy transmission through opened cone targets with and without a pre-plasma presented inside the cone was investigated. The transmission ratio in the low-energy case is 10 times larger than in the high-energy case. Optical simulation was also made in the low-energy case and PIC simulation in the high-energy case. Both produced similar results to the experimental measurements. This implies that the pre-plasma generated by the ASE and pre-pulse is the main reason for this degradation in transmission.

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