Numerical study on optimization of cone target and ignition pulse shape for fast ignition

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Abstract. Electron energy characteristics generated by the irradiation of ultra-intense laser pulses onto solid targets are controlled by using cone targets. Two important parameters characterizing the laser-cone interaction are introduced, which are cone angle and the ratio of the laser spot size to cone tip. By changing these parameters, the electron energy characteristics are controlled. They are optimized for fast ignition with the aid of 2D Particle-in-Cell (PIC) simulations.

1. Introduction
In fast ignition, cone targets are used to guide laser pulses close to the core plasma which is surrounded by large-scale corona plasma, and to generate high energy charged particles which heat up the core. Advantages in using cone targets were confirmed in experiments which show huge increase of neutron yield by using cone targets [1]. Numerical simulation also showed that cone targets focus laser energy and high energy electrons at the cone tip that results in higher coupling efficiency from laser to electrons [2]. Since the core heating efficiency strongly depends on the electron energy characteristics [3], it is quite important to understand the electron acceleration processes taking place in cone targets and design the optimum cone shape.

In this paper, we study how the electron energy characteristics are controlled by changing the cone shape by using 2D PIC simulations. Two important parameters characterizing laser-cone interactions are introduced that are the cone angle and the ratio of laser spot size to tip diameter, and are optimized for fast ignition. The optimum parameters on the cone geometry such as cone angle, tip size, and buffer-shell, and laser conditions such as spot diameter and resulting laser intensity are shown.

2. Optimization of cone target shape for fast ignition
It has been shown that electrons are accelerated at both the cone tip and side wall [4]. The electron acceleration which plays a dominant role in the laser-cone interaction is the ponderomotive acceleration at the cone tip [5]. Therefore, controlling the laser intensity at the cone tip becomes important. Electrons are also accelerated at the cone side wall when the cone angle is as small as 30 degree due to the surface field effect [6,7]. To characterize and control those acceleration processes, we introduce two parameters; the cone angle and the ratio of laser spot size to cone tip size. The cone angle affects the laser propagation inside the cone target, which changes the energy absorption rate. In
addition to the cone angle, the ratio of laser spot size to cone tip size changes how much the laser field is intensified at the cone tip, which modifies the effective temperature of electrons.

2.1. Cone angle

Depending on the cone angle, the number of the laser reflection at the cone side wall changes. This results in the differences of energy absorption, which is shown by 2D PIC simulations. The simulation conditions are as follows. The target geometry is shown in Fig.1. The target density is set 100 nc, where $n_c = \frac{m e^2 \omega_0^2}{c^2}$ denotes the critical density. Here, $e$, $m$, $\omega_0$ and $c$ are the electric charge, electron rest mass, dielectric constant in vacuum, and the laser frequency, respectively. The scale lengths of preplasma are 1.0 $\mu$m and 0.25 $\mu$m at the cone tip and side wall, respectively. The initial electron temperature is set to be 1 keV, and ions are kept immobile. The laser pulse irradiates the target from the left boundary whose intensity is $2.0 \times 10^{19}$W/cm$^2$ with 1 $\mu$m wavelength. The laser field is linearly polarized where polarized plane is in the simulation plane. The intensity profile is Gaussian in the y-direction with a spot size of 5.0 $\mu$m (FWHM). The laser ramps up within five laser periods, and maintains this intensity for the duration of 150 fs. The energy absorption rate is plotted in Fig.2 as a function of cone angle. As is seen in the figure, the absorption rate strongly depends on the cone angle, and has larger value for targets with smaller angle, since the laser hits the targets more as the angle becomes smaller. But as the angle becomes as small as 30 degree, the absorption rate does not increase further by reducing the angle. This is because the absorption rate sharply drops as the incident angle goes over 75 degree [8]. The energy spectra are also compared which are shown in Fig.3(a). It is seen that as the cone angle becomes smaller, the effective temperature of high energy electrons increases since the laser field is more intensified at the cone tip for smaller angle case. Since the electrons which are favorable for core heating have energies around 1MeV, too much intensification of laser field is not favored. As is shown in Fig. 3(b), the electrons...
around 1 MeV are more effectively generated for 30 degree cone. As a result, the optimum cone angle for fast ignition is considered to be around 30 degree.

2.2. Cone tip and laser spot size
Since the electron beam radius is roughly equal to the cone tip size, it is better to choose the tip size as comparable to the core size. Thus the laser spot size is another parameter to be optimized. By changing the laser spot size, the effect of interaction at side wall changes. When the laser light is directly focused to the cone tip by using optical lens, the interaction at side wall does not play a role. On the other hand, when laser light is focused larger than the tip diameter, the light is focused to the tip by cone guiding together with generating electrons at the side wall, which are compared by PIC simulation. In Fig. 4 the electron energy flux observed 3 μm behind the cone target are compared for three cases where the intensity (W/cm²) and spot size are (1) 3.3 × 10¹⁸ with 30 μm, (2) 1.0 × 10¹⁹ with 10 μm, and (3) 3.3 × 10¹⁹ with 3 μm. As is seen in the figure, the energy coupling is the highest for the case (2) where the laser spot size is 3.3 times larger than the cone tip size. This is understood by considering that the laser ray irradiated at the cone entrance within the spot region of 3.3 times the tip diameter is focused to the tip by simple ray-trace. Although the dominant electron acceleration takes place at the cone tip, interaction at the side wall enhances the energy coupling by using laser spot size which is 3.3 times the tip size, and roughly 3.8 times the tip size at maximum.

2.3. Double-cone geometry
In above simulations, outside the cone wing are assumed to be vacuum. But in experiments of fast ignition, the cone target is surrounded by a corona plasma generated by the implosion of fuel capsule whose density is well above the critical density, which is observed in the radiation-hydro code PINOCO [9]. In this case, electrons pushed by the laser field at the cone side wall propagate freely into the surrounding plasma. In order to prevent electrons from escaping aside, a double-cone target is introduced where additional cone is placed outside in order to make vacuum buffer region [10]. In Fig. 5 the distribution of electron energy density is compared for single cone and double-cone target. In double-cone target case, MeV electrons are well confined inside the target and propagating forward from the tip of the cone. In single cone case, the electron energy flux is reduced to 55% of the isolated cone case, which is recovered to 93% in double-cone case.
2.4. Pico-second laser pulse duration
In FIREX-I project in Osaka University, the ignition laser pulse is energy of 10 kJ and pulse duration of 1 ps to 10 ps which is much longer than the above simulations. In longer pulse irradiation, plasma profile is considered to be modified which results in modification of electron energy spectra. In order to see the high energy coupling by above optimized cone target work in longer pulse duration, calculation of longer pulse was carried out. The pulse length is 1 ps and intensity is $4.4 \times 10^{19}$ W/cm$^2$ which corresponds to the spot diameter of 120 $\mu$m being 4 times larger than the estimated core size. The density steepening is observed and resulting electron spectra is shifted to lower energy part. Even the energy spectra is modified, the high energy flux is sustained during 1 ps laser irradiation.

2.5. Laser pointing accuracy
For maximizing the cone ability to effectively couple laser energy to high energy electrons, the laser pointing accuracy is also important, since the laser intensity at cone tip depends on the laser. When the laser pointing is deviated about same size of the laser spot size, the energy coupling is sharply drops down to about 50%.

3. Conclusions
Optimization of the shape of the cone target and ignition laser pulse is performed by using 2D PIC simulations. The optimum cone target is 30 degree with double-cone geometry and tip size is comparable to core size. The optimum laser spot size is roughly 3~4 times larger than the cone tip size, which becomes diameter of 120 $\mu$m for experiments in FIREX-1. The high energy coupling by optimized cone target is shown to work for longer pulse irradiation where plasma profile and electron energy spectra are modified.

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