Re-entrant Cone Angle Dependence of the Energetic Electron Slope Temperature in High-Intensity Laser-Plasma Interactions

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INTRODUCTION

The rapid development of high-intense laser systems, both in terms of the available energy and the power that can be focused onto target, provides many new opportunities for studies in high energy density science. These include the fast ignition approach (FI) to inertial confinement fusion (ICF) [i]. The FI scheme allows the compression of the deuterium-tritium fuel to be separated from the heating phase. The heating is then caused by the stopping of large numbers of fast electrons or ions that are generated during an ultra-intense laser-plasma interaction. The crucial issue of this concept is the transfer of energy from the laser pulse to the compressed plasma. The reentrant-cone concept, where a hollow gold cone is inserted into a spherical shell, has been proposed as a method of avoiding plasma instability growth in the coronal plasma [iii]. A significant increase in the yield of thermal fusion neutrons was observed with this configuration [iii]. A recent study with three-dimensional particle-in-cell (PIC) simulations has shown that the laser pulse at the cone tip can be up to 20 times more intense compared to that at the inlet plane, in addition, the surface electron flow is also confined in a plasma skin layer by self-generated quasi-static magnetic fields that are coupled with the electrostatic sheath field [iv]. The energetic electron and proton production from hollow-cone target was also investigated experimentally, shows higher fast electron number as well as accelerated proton cutoff energy was obtained with an opening angle of 30 deg compare to 60 deg [v]. However, no systematic studies have been yet made to optimize the cone shape such as the opening angle of the cone.

In this report, hollow cone geometry (opening angle, tip size) dependence of relativistic electron production is described and discusses the optimum cone geometry to achieve high energy concentration at the cone tip.

EXPERIMENT AND RESULTS

The experiment was performed at GMII laser facility at the Institute of Laser Engineering in Osaka University operating in the optical parametric chirped pulse amplification system (OPCPA). An s-polarized pulse was focused with an F/3.8 off-axis parabola at an incidence angle of 4 deg onto the target with a focal spot size of 20-30 µm Full Width at Half Maximum (FWHM). This 1.053 µm, 700 fs FWHM duration laser pulse had an average intensity in excess of 10^{18} W cm^{-2}. A schematic layout of the experimental arrangement is shown in Fig. 1. The targets consisted of a hollow-glass cone attached to a plane solid Al slab. The Al slab had a thickness of 10 µm and size of 500 µm × 500 µm. It was attached to the cone via a glue joint with 4 deg to the cone axis normal. The focusing laser axis was same as the cone axis. The hollow diameter at the cone tip was 15 µm. The opening full angles of the cones are varied from 8 deg to 60 deg. An electron spectrometer (ESM) [vi] was deployed directly along the laser axis to detect the fast electron energy spectra generated by the laser-plasma interaction.

Figure 2 shows the obtained electron slope temperature as a function of cone angle. The circles are data points with the cone tip size of 15 µm, whereas the square is of 40 µm. The temperature obtained with the open geometry target (Al plane without cone) is shown as the horizontal line. The solid and the dotted lines are calculations, which are described in the next section. The electron temperature clearly depends on the cone angle and reaches a maximum around 25 deg. In addition, significant decreasing of the temperature was shown with increasing the cone tip size from 15 µm to 40 µm.

The results presented here clearly show that the temperature of the fast electrons is dependent on the opening angle of the cone. If one makes the reasonable assumption that the electron temperature is proportional to the square root of the focused laser pulse intensity [vii], the results suggest that the laser light is optically guided by a plasma mirror generated on the inner walls of the cone and the resultant light intensity became higher than the intensity of the incident pulse. When a sufficiently intense laser is incident inside the cone, ionization takes place on the leading edge of the pulse and the rest of the laser pulse then interacts with the plasma formed there. The very rapid increase in the reflectivity at the cone wall as the plasma mirror is formed there then acts to reflect most remaining energy to the tip of the cone [viii].

The intensity at the cone tip was calculated using a ray-tracing model, in which the incident rays were specularly reflected at the cone wall by the plasma mirror and had straight trajectories between reflections. The reflectivity was calculated by dividing the laser fraction into s- and p-polarization interactions. For the p-polarized component, the reflectivity depends on the
incidence angle to the cone wall. This was taken from the calculations of collisionless absorption in sharp-edges plasmas of Gibbon and Bell [ix]. For the s-polarized component, the reflectivity of light was assumed to be 70% at all angles of incidence. In addition, concerning the optical path length, the phase of each ray was also included in this model. The local intensities of each small region at the cone tip were calculated by superposition of each ray's intensity including their phase. The resultant light intensity at the cone tip was defined as the average of these local intensities. The intensity distribution of the incident beam was defined to have an Airy pattern and the FWHM at the focus point was 30 µm. Since the focus spot was measured to have a non-negligible energy spread out over many times the ideal spot size in this experiment, the Airy pattern was superimposed onto a background level such that only 30% of the incident laser energy was contained within the FWHM of the first central maximum. Outside of the 5 times of the FWHM (=150 µm), light energy was put 0.

The cone angle of the focusing rays was 15 deg (F/3.8) which was the same as the experiment. Temporal evolution was not included in this calculation.

The calculated results are shown in Fig. 2, where the fast electron temperatures are given by the square root of the focused light intensity at the cone tip. The solid line is a result with the tip size of 15 µm and the broken line is of 40 µm. The fluctuations of the results come from the phase effect. The experimental results were reproduced using the model. The calculation suggests that an optimum angle of the cone for efficient optical guiding exists. The calculations confirm that it was between 10 – 25 deg. At the same time, the experimental results show the slope temperature decreases more rapidly with lower opening angle cones compared with the calculations. One possibility is that more absorption or scattering than estimated value were occurred due to pre-plasma formation (which can be generated by the pedestal of the laser pulse and arises from amplified spontaneous emission (ASE)) and refraction of the laser light by density gradients in the coronal plasma. Another is the ponderomotive-induced denting of the critical density surface. Since the interaction between the light and the cone wall plasma can increase with decreasing cone angle, more energy loss can occur in lower angle under low specular reflectivity from the cone wall plasma.

CONCLUSIONS

In conclusions, the energy spectra of fast electrons produced by the hollow cone attached targets have been experimentally investigated. The results show that the fast electron slope temperature is strongly dependent on the opening angle and the tip size of the cone. This cone geometry dependence can be described by intensity enhancement at the cone tip which was confirmed by ray-tracing calculations. Both experiment and modeling indicate that the optimization of the opening angle and the tip size of the cone are very important to enhance the intensity or energy density of the light at the cone tip. For the cone-guided FI application the re-entrant cone geometry should be chosen carefully which needs large number of high energy electrons to ignite the compressed core.

ACKNOWLEGEMENTS

The authors are thankful to K. Sawai, K. Suzuki, Y. Miyazaki, K. Okabe, and T. Sera of the GMII operating group, and Y. Kimura and T. Sudo of the target fabrication group. This research is supported by the project of “high energy density plasma photonics” under the CREST, Japan Society and Technology Agency.

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