A MODEL EXPERIMENT OF A DOUBLE-CONE TARGET USING A GAP TARGET

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Abstract. We have conducted preliminary experiments to prove the vacuum-shielding effect using an Al-Cu double-foil (both Al and Cu foils are 1 mm x 1 mm x 10 μm) target with a vacuum-gap. Particle-in-cell simulation results have shown that the double-cone confines the electrons for hundreds of femtoseconds by the sheath electric field inside the vacuum-gap [T. Nakamura, et al., Phys. Plasmas 14, 103105 (2007)]. Cu-Kα intensity decreased with the vacuum-gap, i.e., the number of fast electrons that reached the Cu foil decreased with the gap. In the stack measurement, the number of electrons detected in the target surface direction increased with the gap. These results indicate that when the double-cone target is used, fast electrons created by an ignition laser can be reflected from the vacuum-gap, move along the cone surface, and be transferred towards the cone tip.

1. Introduction
In the Fast Ignition scheme with a re-entrant cone, an efficient heating of a dense core with fast electrons is required. It is known that a cone target is surrounded by coronal plasma generated during the implosion, and electrons created by an ignition laser can escape freely from cone sides to the surrounding coronal plasma. As a result, an energy flux to the core plasma through the cone tip decreases. Nakamura et al. have suggested using a double-cone target to prevent the electrons from escaping aside [1]. Their two-dimensional (2D) Particle-in-cell (PIC) simulation results have shown that the double-cone confines the electrons for hundreds of femtoseconds (fs) by the sheath electric field inside the vacuum-gap [T. Nakamura, et al., Phys. Plasmas 14, 103105 (2007)]. Cu-Kα intensity decreased with the vacuum-gap, i.e., the number of fast electrons that reached the Cu foil decreased with the gap. In the stack measurement, the number of electrons detected in the target surface direction increased with the gap. These results indicate that when the double-cone target is used, fast electrons created by an ignition laser can be reflected from the vacuum-gap, move along the cone surface, and be transferred towards the cone tip.
focused to the compressed core by using the double-cone [2]. In the simulation, a P-polarized laser pulse (1.06 μm in wavelength, 1.2 \( \times 10^{19} \) W/cm\(^2\) in intensity, 67 fs in rise-time, and flat-top pulse shape for 1.5 ps in pulse duration) has been irradiated on a double-cone target, in which the inner-cone wall has been isolated from the background corona plasma due to a vacuum-gap of 3 μm. It has been found that the number of high-energy electrons escaping from the side-walls of the cone is greatly reduced by the vacuum-gap inside the wing of the double-cone. Two mechanisms to confine high-energy electrons have been found; the sheath electric field at the rear-side of the inner-cone wing and the quasistatic magnetic field inside the vacuum-gap. The quasistatic magnetic field has been due to a localized supply of high-energy electrons, originally produced at the inner-cone and the cone tip. In addition to this electron current coming from the cone tip, an opposite-directional surface-current moving along the inner-surface of the outer-cone has given rise to a large quasistatic magnetic field inside the gap. The quasistatic fields have continued to confine the high-energy electrons for longer than a few picoseconds. It has been shown that whereas about 30% of the total input laser energy escapes into the surrounding corona plasma from the side-walls as high-energy electrons in the single-cone case, the escaped energy is reduced to about 11% percent in the double-cone case [2].

We have conducted preliminary experiments with double-foil targets with a vacuum-gap to prove the effect of sheath electric filed using a high-power laser system. In the experiment, since the laser intensity is nearly an order of magnitude lower and pulse duration is by a factor of three lower than those used in PIC simulation [2], generation of quasistatic magnetic field is expected to be small.

2. Experimental
The experiments were performed with Gekko MII laser system (Nd: Glass laser, wavelength = 1.05 μm, pulse duration = 400 - 500 fs, energy = 4 - 13 J on target, laser intensity = \((1 - 4) \times 10^{18}\) W/cm\(^2\), S- or P-polarized) at the Institute of Laser Engineering, Osaka University. In order to clarify the vacuum-shielding effect, an Al-Cu double-foil (both Al and Cu foils are 1 mm x 1 mm x 10 μmt) target with a vacuum-gap was used. The gap width \(\Delta W\) was varied as 0, 10, 20, and 100 μm with four Al spaces (100 μm x 100 μm x \(\Delta W\)) located at four corners of the target. The laser beam was irradiated on an Al foil side with 20 (S-20) or 70 (S-70) degrees from the target normal direction for S-polarized and 60 degrees (P-60) for P-polarized cases. Figure 1 shows schematic diagram of the experimental setup for S-20. An X-ray pinhole camera (XPHC) was used to measure the incident laser spot-size on the Al foil at 38.5 degrees from the axis of the laser direction. Cu K-shell emission was measured from the rear-side of the Cu foil using an x-ray spectrometer located at 48.5 degrees from the laser axis. A stuck of imaging plates (IPs) was placed behind the target, 35 mm and 15 mm from the target for S- and P-polarized cases, respectively, in order to measure the transport of fast electrons. An Al foil was placed in front of the IPs to block the laser light.

![Fig. 1 Schematic diagram of the experimental setup for S-20. Polarization of incident laser beam is perpendicular to the sheet.](image-url)
3. Results and discussion
In the rear-side x-ray spectroscopy, Cu-Kα1, Kα2, and Kβ lines were observed. We focus only on the peak intensity of Cu-Kα1 line. Figure 2(a) shows x-ray intensity from the front-side Al foil measured by XPHC as a function of laser energy $E_L$ for S-20. We see that the x-ray intensity increases monotonically with the laser energy independent of the gap width $\Delta W$. Figure 2(b) represents the rear-side Cu-Kα intensity for S-20. Whereas the Cu-Kα intensity increases by increasing the laser energy, the intensity at a given laser energy is lower with the vacuum-gap. The decrease in Cu-Kα intensity with the vacuum-gap is much clear for S-70 as shown in Fig. 2(c); Cu-Kα intensity for the gap-targets with $E_L > 10$ J is even lower than that for no-gap targets with $E_L < 8$ J. For S-70, because of the location of the XPHC, the front-side emission from Al foil was not measured. The measured reduction of the rear-side Cu-Kα intensity with the vacuum-gap indicates the number of fast electrons that reached the Cu foil decreased with the gap.

Fig. 2 (a) X-ray intensity from the front-side Al foil measured by XPHC for S-20, and rear-side Cu-Kα intensities for (b) S-20 and (c) S-70.

Kα radiation is emitted by inner-shell transition when an L-shell electron fills a vacancy in the K-shell via radiative decay. The lifetime of the K-shell vacancy induced by a fast electron is less than $10^{-12}$ s. Cu K-shell collisional-ionization cross-section as a function of the incoming electron energy has the maximum around 27 keV, and energy range of electrons for the half-maximum is roughly 10 – 270 keV [3]. Therefore, we can estimate the flux of the tens to few hundreds of keV electrons from the Cu-Kα intensity measurements.

Figures 3(a) and 3(b) show two-dimensional (in vertical and horizontal directions) intensity profiles of IP for $\Delta W = 0$ and 20 μm, respectively, for S-70. The vertical angle $\theta_v = 0$ and the horizontal angle $\theta_h = 0$ correspond to the axis of the incident laser beam. The horizontal angle $\theta_h = -20$ and 0 degrees correspond to the directions of specular reflection and the target surface. Figure 3(c) shows signal intensity profiles as a function of horizontal angle $\theta_h$ for $\Delta W = 0$ [Fig. 2(a)] and 20 μm [Fig. 3(b)] at $\theta_v = -10$ degrees. We see that signal intensity profile for $\Delta W = 0$ shows two peaks; in the directions of specular reflection ($\theta_h = -20$ degrees) and axis of the incident laser beam ($\theta_h = 20$ degrees). On the other hand, for $\Delta W = 20$ μm, the signal intensity peaks in the directions of target surface ($\theta_h = 0$). Similar results were obtained for P-60, i.e., the signal intensity shows two peaks in the directions of specular reflection and axis of the incident laser beam for $\Delta W = 0$, and one peak in the direction of target surface for $\Delta W = 20$ μm. Note that the signal intensities in the directions of specular reflection and axis of the incident laser beam for $\Delta W = 20$ μm are nearly identical to those for $\Delta W = 0$. On the other hand, the signal intensity in the directions of target surface increased nearly by a factor of three by adding $\Delta W$ from 0 to 20 μm. Therefore, in the stack measurement, the number of electrons detected in the target surface direction increased with the vacuum-gap.

When Al-Cu no-gap targets are irradiated by the laser beam, a sheath electric field is created in the rear-side of the Cu foil, and low-energy electrons that cannot escape the sheath field are reflected back to the target and may transported towards the target surface direction. When a vacuum-gap is added to
the Al-Cu interface, sheath electric fields are created at the vacuum-gap at the rear-side of Al foil in addition to the rear-side of the Cu foil. Therefore, there are two sheath fields, and the reflection of the electrons at the sheaths are enhanced for the gap-target compared with that for the no-gap target. These results indicate that when the double-cone target is used, fast electrons created by an ignition laser can be reflected from the vacuum-gap, move along the cone surface, and be transferred towards the cone tip.

4. Summary and Conclusions
We have conducted preliminary experiments to prove the vacuum-shielding effect using an Al-Cu double-foil target with a vacuum-gap. Cu-Kα intensity decreased by increasing the vacuum-gap width ΔW, i.e., the number of fast electrons that reached the Cu foil decreased with the gap. In the stack measurement, the number of electrons detected in the target surface direction increased with a vacuum-gap. These results indicate that when the double-cone target is used, fast electrons created by an ignition laser can be reflected from the vacuum-gap, move along the cone surface, and be transferred towards the cone tip.

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Fig. 3 Two-dimensional (in vertical and horizontal directions) intensity profiles of IP for (a) ΔW = 0 and (b) 20 μm, for S-70. The vertical angle θv = 0 and the horizontal angle θh = 0 (indicated by a solid circle) correspond to the axis of the incident laser beam. The horizontal angle θh = -20 and 0 degrees correspond to the directions of specular reflection and the target surface, respectively. Laser energies were (a) 14.8 J and (b) 22.9 J. (c) Signal intensity profiles as a function of horizontal angle θh for ΔW = 0 [Fig. 3(a)] and 20 μm [Fig. 3(b)] at θv = -10 degrees.