Influence of target geometry on the ion temperature of laser-produced plasmas

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Abstract. Thomson scattering measurements of laser-produced plasmas have been performed with a 4\omega probe beam in Shenguang II laser facility. Three kinds of the targets are irradiated with 3\omega laser beams: disc target, curved target, and void hohlraum. Thomson scattering spectra are quite different with the different targets. The two ion-acoustic resonance peaks become much broader when a curved target or a hohlraum is irradiated. The experimental results show that the target geometry has a strong influence on the ion temperature of the laser-produced plasmas. The ion temperature could be about several ten keV in the plasma produced with curved target or hohlraum.

1. Introduction
Thomson scattering (TS) is a powerful plasma diagnostic technique [1] and has been extensively utilized to characterize laser-produced plasmas relevant to inertial confinement fusion (ICF) in the past decade. After many years of development, TS evolves into a standard plasma diagnostics in the field of ICF because it can provide reliable time- and space-resolved plasma parameters that are fundamental in understanding of laser-produced plasmas. With TS as a key diagnostic tool, laser-produced plasmas are extensively investigated, such as two-ion species plasmas [2], high-Z Au plasmas generated with disc target [3, 4], and low-Z plasmas in a gas-filled hohlraum [5], etc. Plasmas in x-ray conversion layer are also be addressed with 4\omega laser probe [6], and electron thermal transport in plasmas is studied [7] with a short pulse (100 ps) probe beam.

In this article, we report our experimental results of the effect of target geometry on the ion temperature of laser-produced plasmas by using TS as a key diagnostic tool. We irradiate three types of targets with 3\omega laser: Au disc, Au curved target and void hohlraum. The TS spectra off the plasmas show that ion temperature can be greatly enhanced due to the target geometry.
2. Experimental Setup
The experiments are performed in the Shenguang-II (SG-II) laser facility [8]. SG-II consists of eight Nd: glass beams operating at 1.053 $\mu$m, which can be frequency converted into $2\omega$, $3\omega$, and $4\omega$ and be focused to target independently. Eight $f/3$ focusing lenses stand at the vertexes of a cuboid with the ratio of its three sides of 1 : 1 : $\sqrt{2}$. In the experiments, targets are positioned at the center of the cuboid. The eighth beam, which is frequency quadrupled, is switched to the probe beam [6]. The probe beam focused with a $f/12$ focusing lens is irradiated into laser-produced plasmas with a spot size of about 100 $\mu$m in diameter. Typically, the probe beam is operated with the energy of about 20 J at $4\omega$ and the duration of 1 ns in full width at half maximum (FWHM). The other beams, which are frequency tripled, are used as the heater beams. The energy of the heater beam on the target is about 260 J and the pulse duration of the heater beams is about 1 ns (FWHM). No beam smoothing technique is utilized in the experiment. An $f/10$ imaging optics with a magnification of 1.5 is used to collect the scattered light. The scattering direction is parallel to the target surface and the scattering angle is 90°. With this setup, the stray light coming from the target is minimized. The scattered light is then imaged onto the entrance slit of a 75 cm Czerny—Turner spectrometer equipped with a 2400 l/mm grating. The scattered spectrum is detected with a streak camera and recorded with a charge-coupled device (CCD). The scattering volume is $70 \times 50 \times 100$ $\mu$m$^3$, which is determined by the spot size of the probe beam and the slit widths of the spectrometer and the streak camera. The spatial resolution along the target normal is 50 $\mu$m. The spectral and temporal resolutions of the detection system are about 0.6 Å and 50 ps, respectively. In the experiments, the polarization of the probe beam is carefully adjusted to be perpendicular to the scattering plane. By moving the target, scattered light from different positions of the plasmas is measured.

3. Experimental Results and Discussions
In our experiment, TS is operated in the regime of collective scattering. In this regime, the TS spectrum is governed by the collective motions in the plasma. In the low frequency region, the TS spectrum usually presents two resonance peaks at the frequencies corresponding to the two counter-propagating ion-acoustic waves, i.e., at $\omega = \omega_0 \pm \omega_{ia}$, where $\omega_{ia}$ is the frequency of ion-acoustic waves, $\omega_0$ is the frequency of the probe beam. In the long wavelength limit, $\omega_{ia} = kc_i$, where $k$ is the differential wave vector determined by the scattering geometry [1], and $c_i$ is the isothermal sound speed of the plasma. Theoretically, the widths of the resonance peaks are determined by the damping rate of the waves. For a high-Z plasma like Au plasma, the electron Landau damping is usually much greater than the ion Landau damping because the ratio $ZT_e/T_i$ is usually much larger than one, except for the case of $T_e \gg T_i$, where $T_{ei}$ are the electron (ion) temperatures. In experiment, the spectral width due to the electron Landau damping is usually much narrower than that determined by the spectral resolution of the diagnostic system. Hence the TS spectrum should present two sharp spikes in the case of $ZT_e/T_i \gg 1$. However, the ion Landau damping increases very quickly with the decrease of the ratio $ZT_e/T_i$. In the case of $ZT_e/T_i = 1$, the damping rate of a ion-acoustic wave becomes very heavy, $\gamma/\omega_{ia} = 0.42$ [9] where $\gamma$ is the damping rate of the wave. In this case, two ion-acoustic resonance peaks may merge into a broad band spectrum centered at $\omega = \omega_0$, which width is proportional to the square root of the plasma temperature. If this phenomenon occurs, it can be inferred that the ion temperature of the plasma is the same order of $ZT_e$. Since $Z \gg 1$, ion temperature could be much higher than electron temperature for a high-Z plasma.

In our experiments, we irradiate three types of targets: plate disc, curved target and void hohlraum. All these targets are made of gold. The configurations of the targets and the laser beams are shown in Fig. 1. The curved target is made with a hohlraum cut into two halves along the cylinder axis, seen in Fig. 1. The diameter of the hohlraum is 800 $\mu$m and the length is
1450 µm. For a curved target, four heater beams are irradiated onto the inner wall of the target. The probe beam is irradiated into the plasma produced with the heater beam indicated with green. For a hohlraum, the laser entrance hole is removed from the side where the scattered light is collected, and six heater beams are fired. The probe beam is irradiated into the hohlraum through a square hole (400 × 400 µm$^2$) at the wall of the hohlraum.

Figure 2. From left to right is the streak images of Thomson spectrum from the plate disc, curved target and hohlraum, respectively.

Typical TS spectra from the three types of the targets are shown in Fig. 2. The spectral lines scattered from two ion-acoustic waves can be clearly seen in the Thomson spectrum from the disc target, as we already reported [6]. However, the spectral lines of the Thomson spectra from the curved target and the hohlraum are significantly broadened. In fact, the two spectral lines are nearly inseparable. In order to see the spectra more clearly, we present in Fig. 3 the line profiles of the TS spectra from the three types of the targets. We also presented in Fig. 3 the fitting curves to the experimental data. For the disc target, the two ion-acoustic peaks are well separated, and the spectrum can be well fitted with the inclusion of the plasma gradients although the total spectral width is only about 4 Å. As seen in Fig. 3, however, it is difficult to separate two ion-acoustic resonance peaks scattered from the plasmas generated with the curved target and the hohlraum. The only possible explanation to the phenomena is that the ion temperatures of the plasmas are so high and hence the ion-acoustic waves become so heavily damped that the two ion-acoustic peaks merge together. In this case, the agreement between the experimental data and the fitting curves is reluctant. We can just estimate that the ion temperature is about 33 keV for the plasma produced with the curved target and about 46 keV for the plasma produced with the hohlraum.

Effect of target geometry on the ion temperature is very impressive in our experiment. For a disc target, we cannot infer the ion temperature because the damping rate of the wave is so small that the spectral width of TS spectrum is essentially determined by the instrument spectral resolution [6]. When the curved target and hohlraum are irradiated, the ion-acoustic spectral lines are significantly broadened, from which we can just deduce that the ion temperature is the order of $ZT_e$. It is the geometry of the target that makes the ion
temperature so different: kinetic energy of a plasma in a curve target or a hohlraum can be converted into ion thermal energy at the cylinder axis due to strong ion viscosity. Since the flow velocity of the laser-produced plasma can be higher than the sound speed, it can be deduced from the energy balance equation that ion temperature could be the same order of $ZT_e$ with the assumption that the plasma is stopped at the axis of the cylinder.

4. Summary

We report the experimental results of the effect of target geometry on the ion temperature of laser-produced plasmas. Three types of targets are irradiated: Au disc, Au curved and Au hohlraum. Thomson scattering is performed to measure the plasmas with a probe beam of 4eV. The experimental data show that the plasmas produced with avoid hohlraums have the highest ion temperature of about 50 keV.

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