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Thomson scattering measurement of a collimated plasma jet generated by a high-power laser system

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Thomson scattering measurement of a collimated plasma jet generated by a high-power laser system

T. Ishikawa[1], Y. Sakawa[2], T. Morita[2], Y. Yamaura[1], Y. Kuramitsu[3], T. Moritaka[2], T. Sano[2], R. Shimoda[4], K. Tomita[4], K. Uchino[4], S. Matsukiyo[4], A. Mizuta[5], N. Ohnishi[6], R. Crowston[7], N. Woolsey[7], H. Doyle[8], G. Gregori[8], M. Koenig[9], C. Michaut[10], A. Pelka[11], D. Yuan[12], Y. Li[12], K. Zhang[13], J. Zhong[13], F. Wang[13], and H. Takabe[1,2]

[1]Graduate School of Sciences, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka, Japan
[2]Institute of Laser Engineering, Osaka University, Japan
[3]National Central University, Taiwan
[4]Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Japan
[5]RIKEN, Computational Astrophysics Lab., Japan
[6]Department of Aerospace Engineering, Tohoku University, Japan
[7]Department of Physics, University of York, UK
[8]Department of Physics, Oxford University, UK
[9]LULI, Ecole Polytechnique, France
[10]LUTH, Observatoire de Paris, France
[11]Helmholtz-Zentrum Dresden-Rossendorf, Germany
[12]Institute of Physics, Chinese Academy of Sciences, China
[13]Institution National Astrophysical Observatories, CAS, China

E-mail: `ishikawa-t@ile.osaka-u.ac.jp`

Abstract. One of the important and interesting problems in astrophysics and plasma physics is collimation of plasma jets. The collimation mechanism, which causes a plasma flow to propagate a long distance, has not been understood in detail. We have been investigating a model experiment to simulate astrophysical plasma jets with an external magnetic field [Nishio *et al.*, *EPJ. Web of Conferences* **59**, 15005 (2013)]. The experiment was performed by using Gekko XII HIPER laser system at Institute of Laser Engineering, Osaka University. We shot CH plane targets (3 mm × 3 mm × 10 μm) and observed rear-side plasma flows. A collimated plasma flow or plasma jet was generated by separating focal spots of laser beams. In this report, we measured plasma jet structure without an external magnetic field with shadowgraphy, and simultaneously measured the local parameters of the plasma jet, i.e., electron density, electron and ion temperatures, charge state, and drift velocity, with collective Thomson scattering.

1. Introduction

Astrophysical jets are as well-collimated outflows from compact objects generated by the dynamic interactions in an accretion disc. The collimation mechanism, which causes a plasma flow to propagate a long distance, has not been understood in detail. There are three effects to contribute to the collimation of astrophysical jets: radiative cooling, interstellar medium, and magnetic fields. The experiments on plasma jets have been conducted with high-power laser facilities[1-4]. In the previous report from our group, Nishio *et al.*[5] compared the plasma jets with and without an eternal perpendicular magnetic field (0.2 $\sim$ 0.3 T). In this paper we investigate plasma jet formation without an external magnetic field with collective Thomson scattering (CTS) measurements. We shot a plastic (CH) target plane with two high-power laser beams and generated plasma jet structure. We measured the structure with optical diagnostics, and simultaneously measured the local parameters of the plasma jet (electron density n_e, electron and ion temperatures T_e, T_i, charge state $< Z >$, and drift velocity v_d) with CTS. Moreover we evaluated error bars of the obtained plasma parameters.

2. Experiment

The experiments were performed with Gekko XII HIPER laser system at the Institute of Laser Engineering, Osaka University. Figure 1 shows a schematic drawing of the experimental setup. A CH target was irradiated by two beams with the energy of $\sim$120 J/beam at a wavelength of 351 nm with a pulse duration of 500 ps. A plasma flow was observed at the rear side of the plane. To produce a non-uniform plasma flow, the CH plane target was irradiated by laser beams focused at different positions[6]. The distance between two focal spots at the target surface was $\sim$260 μm and the focal spot size was 300 μm. We measured the plasma jet structure with shadowgraphy using an ICCD camera (200 ps gate width), and simultaneously measured the local parameters of the plasma jet. The wavelength and the pulse width of the probe beam were 532 nm and $\sim$10 ns, respectively. Figure 1(c) shows the target chamber and schematics of diagnosis. We used an X-ray pinhole camera to observe the focal spot separations. The Thomson scattering probe (a wavelength of 532 nm and the energy of $\sim$0.3 J in $\sim$8 ns) was focused at $x = 0, y = 0, z = 3.0$ mm. The incident angle of the Thomson probe with respect to the HIPER laser was 45 degrees, and the scattered light was detected at 90 degrees from the probe laser by using a triple-grating spectrometer (TGS)[7] and a 2 ns-gate ICCD camera as shown in Fig. 1(c).

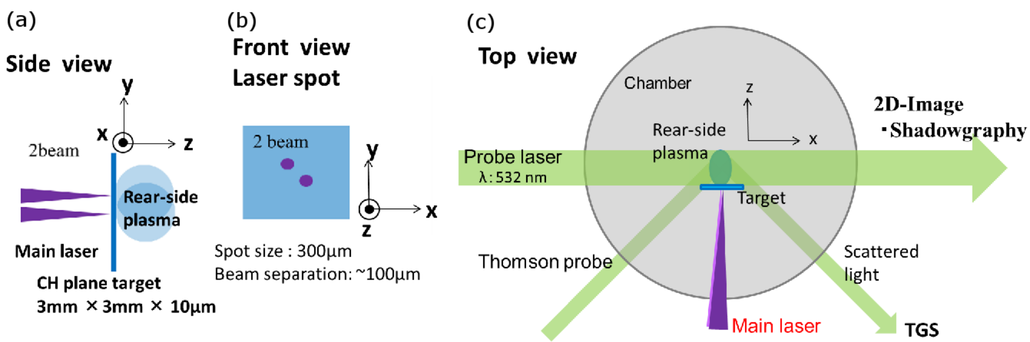

Figure 1. (a) Side and (b) front views showing the configuration of main laser beams and a target. (c) Top view of the target chamber and schematics of the diagnostics.

3. Results

Figure 2(a) shows a shadowgraphy image at 40 ns from the main laser timing. The rear-side plasma expands in the target normal direction, and two plasma jets appear. Figure 2(b) shows the CTS spectrum at the same shot and timing as Fig. 2(a). Figure 2(c) shows the spectra derived from Fig. 2(b) at $z = 3.0$ mm from target rear-surface. The wavelength of the probe laser is blocked at the TGS as shown with a shaded area [Fig. 2(c)]. The Thomson scattering power is expressed by using the spectral density function S(k) with two species i (i = H for hydrogen and i = C for carbon). In Fig. 2(c), the experimental data(dots) are fitted with $S(k)$[8](red line). Here, $T_i = T_H = T_C, v_d = v_H = v_C = v_e, n_H = n_C$ are assumed. Electron density n_e is obtained from the total scattered power calibrated by Rayleigh scattering[9]. The average charge state of carbon $< Z_C > = < Z >$ is derived self-consistently to satisfy the collisional-radiative model[10] with $< Z_H > = 1$. We neglect the scattering from the electron component and consider only the ion-acoustic feature because the electron component is small in the wavelength of $\lambda = 531 - 533$ nm. The plasma parameters, n_e, T_e, T_i, $< Z >$, and v_d are obtained from these spectra at each position[Fig. 3]. The electron densities at $x = 0.3$, $z = 3.3$ and $x = 2.4$, $z = 5.4$ mm are larger than those around them. T_e and T_i at each position are $15 - 25$ eV. They are nearly constant for $x = 0 - 4.1$, $z = 3.0 - 6.1$ mm at 40 ns. The charge state at each position is 4. The drift velocity increases as a function of the distance along z-axis. A typical sensitivity of the fit is estimated by increasing (green lines) and decreasing (blue lines) a single parameter and find a new best-fit result for the spectrum obtained at $x = 0, z = 3.0$ mm [Fig. 2(c)] as shown in Figs. 4(a)-4(d). As a result, the sensitivity for n_e, T_e, T_i, and v_d are $-15 \sim +30\%, \pm 15\%, -35 \sim +45\%$, and $\pm 5\%$, respectively. Moreover we calculated the sensitivity of $< Z >$ from those of n_e and T_e, as a result, it was $\pm 3\%$. We assumed that these sensitivities are independent of the position.

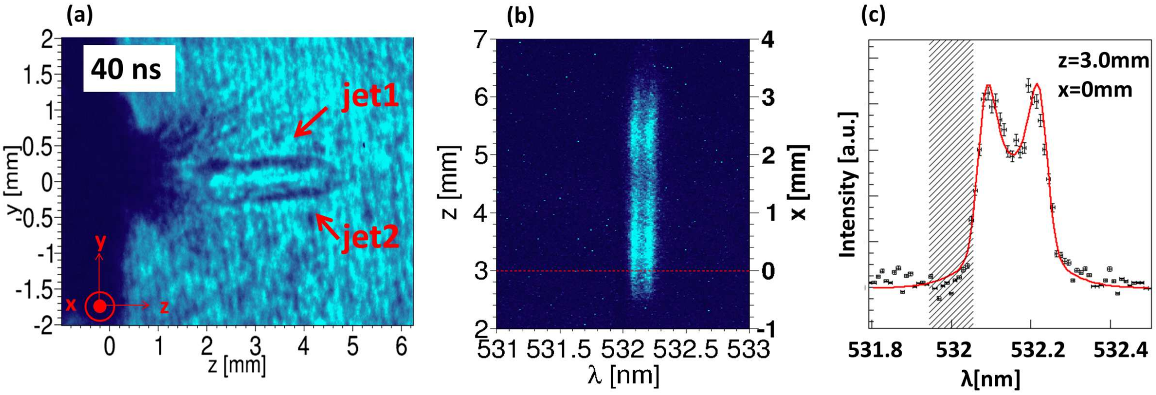

Figure 2. (a) The shadowgraphy image at 40 ns from the main laser. Total laser energy was 248 J. (b) CTS data at the same shot and timing (40 ns) as in (a). (c) A CTS spectrum at $x = 0, z = 3.0$ mm from target (dotted lines in (b)). The experimental data are shown in dots and the best fit for the spectrum is shown in a red line.

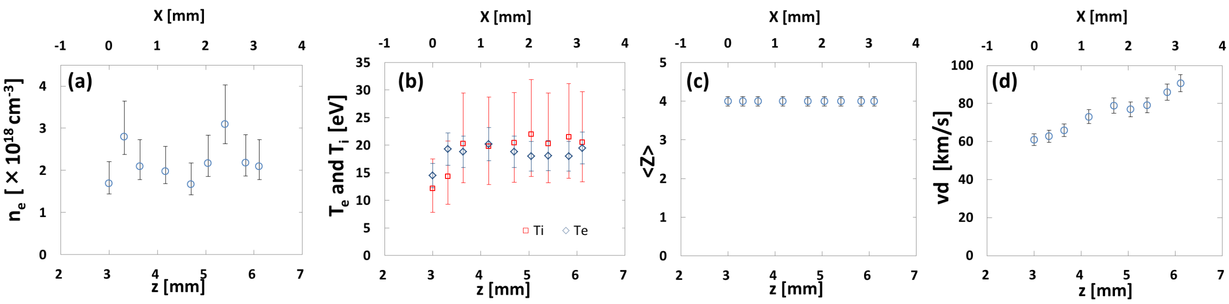

Figure 3. The obtained (a)n_e, (b) T_e and T_i, (c) $< Z >$, and (d) v_d as a function of position z.

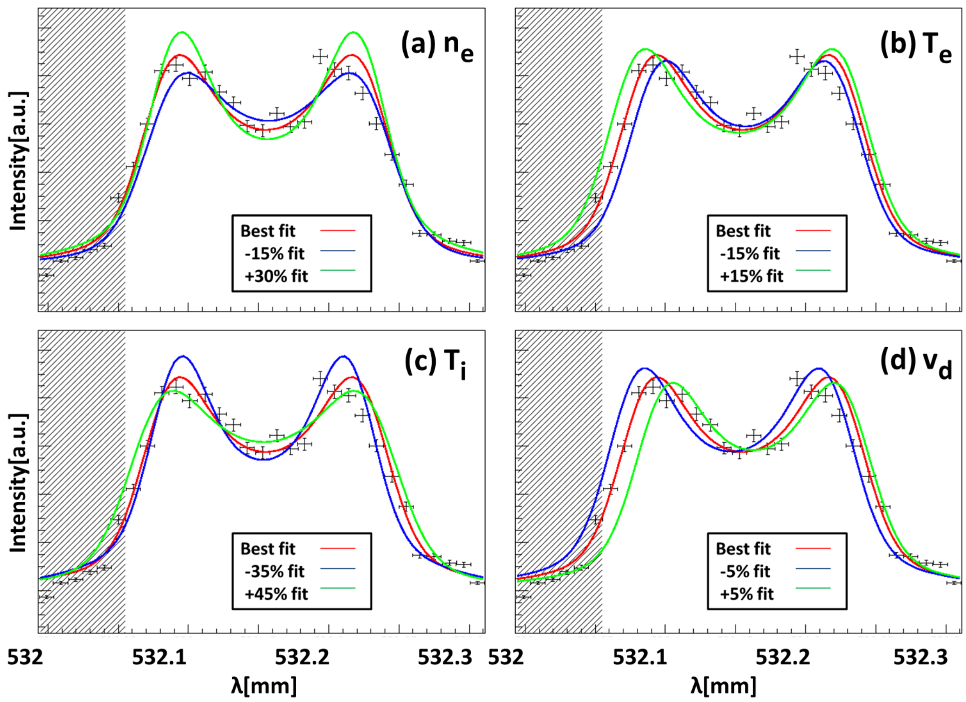

Figure 4. Sensitivities to the fit at $z = 3.0$ mm for (a) n_e, (b) T_e, (c) T_i, and (d) v_d. Red lines are the best-fit results. Green and blue lines are fitting lines when a single parameter is increased and decreased, respectively, by -15 and +30% (n_e), ±15% (T_e), -35 and +45% (T_i), and ±5% (v_d) from the best-fit results.

4. Conclusion

We generated a rear-side plasma jet by irradiating a CH plane target with high-power laser beams. We measured the plasma jet with optical diagnosis and collective Thomson Scattering, simultaneously. The electron densities at $x = 0.3$, $z = 3.3$ and $x = 2.4$, $z = 5.4$ mm are higher than those around them.

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