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Proton imaging of an electrostatic field structure formed in laser–produced counter–streaming plasmas

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Abstract. We report the measurements of electrostatic field structures associated with an electrostatic shock formed in laser–produced counter–streaming plasmas with proton imaging. The thickness of the electrostatic structure is estimated from proton images with different proton kinetic energies from 4.7 MeV to 10.7 MeV. The width of the transition region is characterized by electron scale length in the laser–produced plasma, suggesting that the field structure is formed due to a collisionless electrostatic shock.

1. Introduction

Shock waves are commonly observed in the universe, space plasmas, and laboratory plasmas. In particular, collisionless shocks play significant roles in particle acceleration, for example, in Earth's bow shock and supernova remnant shocks. In collisionless shocks, collisions between particles do not account for the formation mechanism and particle–field interactions are essential.

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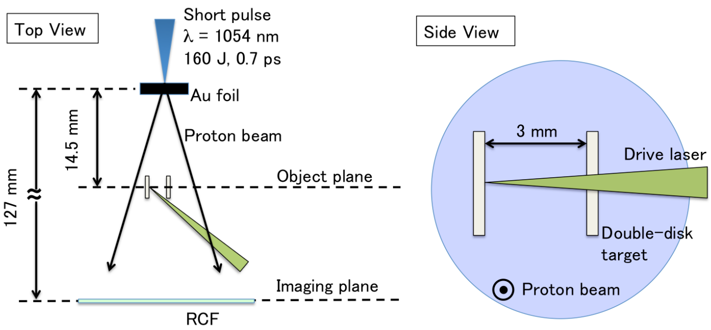

Figure 1. The target design and geometry of diagnostics for proton imaging. Two Mylar (CHO) disks were located in parallel separated by 3 mm, and one side of the target was irradiated by the drive laser. The laser–produced plasmas were diagnosed by a proton beam generated by focusing a short–pulse laser on an Au disk placed at 14.5 mm away from the plasma. The protons were detected by the stack of radiochromic films (RCFs) located at 127 mm from the proton source.

Therefore, the shock thickness is much smaller than ion–ion mean–free–path and a large electromagnetic field exists at the shock front. These shocks have been studied by observing emissions from astrophysical objects[1], and by in–situ measurements using satellites in space plasmas[2].

Laboratory experiments with high–power laser systems can be an alternative to observations or in–situ measurements by satellites[3]. Collisionless shocks have been produced and investigated in counter–streaming laser–produced plasmas[4]. They have been measured by optical diagnostics such as interferometry, shadowgraphy, optical pyrometry, and Thomson scattering to obtain the fundamental plasma parameters: density, temperature, charge state, and flow velocity[5]. However, the measurement of an electromagnetic field is indispensable for collisionless shock experiments.

Proton imaging is one of the methods to measure the field structures[6]; it is widely used for measuring the electric and magnetic fields in inertial confinement fusion experiments[7] and the field in laser–produced plasmas[8].

In this paper, we present the measurement of electric field structures formed at a shock with a proton beam generated by irradiating a thin solid foil by a short–pulse laser beam.

2. Experiment

The experiment was performed with the Jupiter laser facility at Lawrence Livermore National Laboratory. Double–disk Mylar (CHO) targets are used to produce counter–streaming plasmas as shown in Fig. 1. Each disk measures 2×2 mm and 0.5 mm in thickness, and two disks are separated by 3 mm. One of the disks (drive disk) was illuminated by a laser beam (drive laser), delivering 120 J on average in a 1.5 ns square pulse at a wavelength of 527 nm, with a focal spot of 500 μm in diameter. The other disk (second disk) was ablated by the radiation from the laser–produced plasma early in time, and by the plasma arriving later in time as described in the Refs. [4].

A laser pulse (160 J in 0.7 ps, wavelength of 1057 nm) was focused on an Au disk with a thickness of 25 μm to produce high–energy protons for radiography. The distance between the disk and the object plane, where the target was located, was $l = 14.5$ mm. The proton beam images electric and magnetic fields formed in the laser–produced plasmas on radiochromic films located at an imaging plane with a distance $L + l = 127$ mm from the Au disk, where L is the distance between the object and the radiochromic films. The radiochromic films were stacked to detect protons in different energy ranges: 4.7, 7.0, 8.8, and 10.7 MeV with 10% energy width for each film.

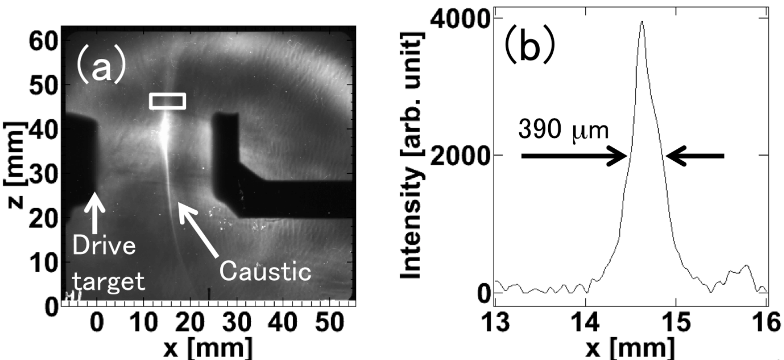

Figure 2. (a) The proton image taken at $t = 20$ ns at the proton energy of 4.7 MeV. (b) The line–out at $x \sim 15$ mm [square in (a)].

3. Result

Figure 2(a) shows the proton image at $t = 20$ ns at the proton energy of 4.7 MeV. A caustic structure is observed at $x \sim 15$ mm in front of the second disk. In general, this sudden change in proton intensity indicates a large electromagnetic field[6]. The line–out of the caustic for Fig. 2(a) is shown in Fig. 2(b). The widths of the caustics depend on the proton energy, i.e., high–energy protons make a thinner structure as shown in Fig. 3.

4. Discussion

The observed caustic structure corresponds to a shock front as discussed in previous works[4], and the left– and right–hand sides of this structure are upstream and downstream of a shock, respectively. Here, we assume that the protons are deflected by an electric field not by a magnetic field. If the shock is formed by a self-generated magnetic field due to electromagnetic Weibel instability, the shock thickness should be much larger ($c/\omega_{\rm pi} > 10$ mm [9]) than experimental observation. Also, a spherically symmetric flat–top potential is assumed in the downstream region at the vicinity of a shock.

The position x on the imaging plane is expressed using the position x_0 on the object plane and the deflection angle $\alpha(x_0)$ as $x = L\,(x_0/l + \alpha(x_0))$[6]. The deflection angle α of the proton beam by a spherically symmetric flat–top potential is expressed as $\alpha(x_0) = (e\phi_0 x_0/2W\sqrt{a\delta})F(\tilde{\xi}) = (e\phi_0(\tilde{\xi}\delta + a)2W\sqrt{a\delta})F(\tilde{\xi})$[6], where $\tilde{\xi} = (x_0 - a)/\delta$, δ is the transition thickness, a is the curvature radius of the potential structure, W is the proton energy, $e\phi$ is the potential energy, and $F(\tilde{\xi}) = (2/\pi)\int_{-\infty}^{\infty} d\eta/((\eta^2 + \tilde{\xi})^2 + 1)$. In case of caustic formation on the imaging plane, $\partial x/\partial x_0 = 0$ is satisfied. Therefore, $1/l + (e\phi_0/2W\delta\sqrt{a\delta})[\delta F(\tilde{\xi}) + (\tilde{\xi}\delta + a)F'(\tilde{\xi})] = 0$. Generally, this equation has two solutions ($\tilde{\xi_1}$ and $\tilde{\xi_2}$), however, the caustic positions $x(\tilde{\xi_1})$ and $x(\tilde{\xi_2})$ can not be resolved in this experiment because of small separation between them, and these two caustics are observed as a single peak in the proton intensity. Therefore, the thickness of an electric field at the shock front (δ) is comparable to

$$\delta \approx |x(\tilde{\xi_2}) - x(\tilde{\xi_1})|. \tag{1}$$

The thicknesses of the caustics in different energy bins are shown in Fig. 3 obtained as full widths at half maximums of the caustics for the energies of 4.7, 7.0, 8.8, and 10.7 MeV. The experimental data are fitted with Eq. (1) for various thicknesses. If this caustic is formed due to an electrostatic shock, the thickness is characterized by electron inertial length $c/\omega_{pe} \sim 2\ \mu$m [$n_e \sim 5 \times 10^{18}$ cm^{-3} evaluated from the interferometry (not shown)][9]. The solid and dotted lines show the fitted results with $\delta = 0.01\ \mu$m $\sim \lambda_D$, where λ_D is the Debye length, and 0.2 μm $\sim c/\omega_{pe}$, respectively. The fitted result with larger thickness of $\delta = 10\ \mu$m (dotted line) shows

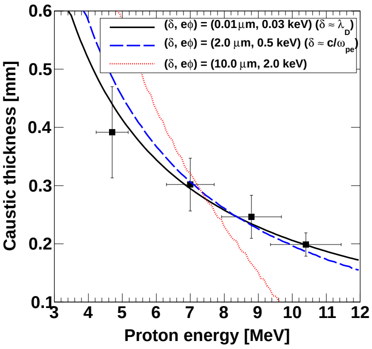

Figure 3. Caustic thicknesses as a function of proton energy. The thickness is evaluated as a full width at half maximum of each line–out as shown in Fig. 2. The best–fit results using various thickness δ are shown with solid ($\delta = 10$ nm $\sim \lambda_D$), dashed ($\delta = 2.0$ μm $\sim c/\omega_{pe}$), and dotted ($\delta = 10$ μm) lines.

large deviation from the experimental data, while the results from small thickness $\delta < c/\omega_{pe}$ shows good agreement with the experimental data, indicating that the structure is defined in an electron scale. Note that the ion inertial length is over hundreds of micron and is much larger than the thickness estimated here. Moreover, the ion–ion mean–free-path of counter–streaming plasmas is $\sim$200 μm[4] using the velocity of $v = 3\,\text{mm}/20\,\text{ns} = 150$ km/s. This small thickness of the electric field structure suggests that the caustic is formed by an electrostatic shock in collisionless counter–streaming plasmas.

5. Summary

We measured an electrostatic field structure formed in counter–streaming laser–produced plasmas with proton imaging technique. The thickness of the electrostatic structure is estimated from proton images with different proton kinetic energies from 4.7 MeV to 10.7 MeV. The width of the transition region is comparable to or less than the electron inertial length of laser–produced plasmas, suggesting that the field structure is formed due to a collisionless electrostatic shock.

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