

Analysis of plasma channels in mm-scale plasmas formed by high intensity laser beams

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Abstract. A plasma channel created by a high intensity infrared laser beam was observed in a long scale-length plasma ($L \sim 240 \mu\text{m}$) with the angular filter refractometry technique, which indicated a stable channel formation up to the critical density. We analyzed the observed plasma channel using a rigorous ray-tracing technique, which provides a deep understanding of the evolution of the channel formation.

1. Introduction

For fast ignition of inertial confinement fusion, the effective conversion of Petawatt laser power into $\sim\text{MeV}$ electrons is required to heat a high-density fuel core to ignition temperatures. We use a scheme making use of relativistic laser self-focusing to penetrate through the surrounding plasma corona to the core. However, during the laser propagation in the underdense plasma, the beam loses energy through several laser-plasma instabilities. Therefore, a pre-formed low-density plasma channel may be a good choice for efficient energy transport to the core. In previous experiments [1] with the Omega EP laser at the Laboratory for Laser Energetics at the University of Rochester, we observed the plasma channel formation using the angular filter refractometry (AFR) technique [2]. In this paper, we provide a quantitative characterization of the plasma channel created inside near-critical-density ($\sim 10^{21}/\text{cm}^3$), mm-size plasmas by ray-trace calculation of the short-pulse, ultraviolet probe beam.

2. Experiment

Figure 1 shows the experimental setup. High-density plasma plume is created from a CH flat target ($3 \text{ mm} \times 3 \text{ mm} \times 0.125 \text{ mm}$) irradiated by two ultraviolet (UV) beams ($\lambda_{\text{UV}} = 0.351 \mu\text{m}$) with a total energy of 1 kJ. After the UV beam irradiation, an infrared (IR) channeling laser ($\lambda = 1.054 \mu\text{m}$, pulse length = 10 ps or 100 ps, pulse energy = 1 kJ or 2.6 kJ, peak intensity = $4 \times 10^{19} \text{ W/cm}^2$ or $1 \times 10^{19} \text{ W/cm}^2$, respectively) was injected into the plasma and focused to $n_c/4$. The AFR diagnostic utilized a fourth-harmonic probe pulse ($\lambda = 0.263 \mu\text{m}$, 10 ps, 10 mJ), which observes the plasma density profile by measuring the refraction angle of the probe rays. The refracted probe beam was collected through a lens. On the way to the image plane, an angular filter is inserted in order to measure the refraction angles. At the image plane, contours of constant refraction angle can be observed. The angular filter consists of 2-mm-wide opaque rings blocking the light and 2-mm-wide transparent rings and a 500-



μm -diameter central opaque dot. The spatial resolution of the diagnostic is $\sim 4 \mu\text{m}$, and the field of view extends over 4 mm.

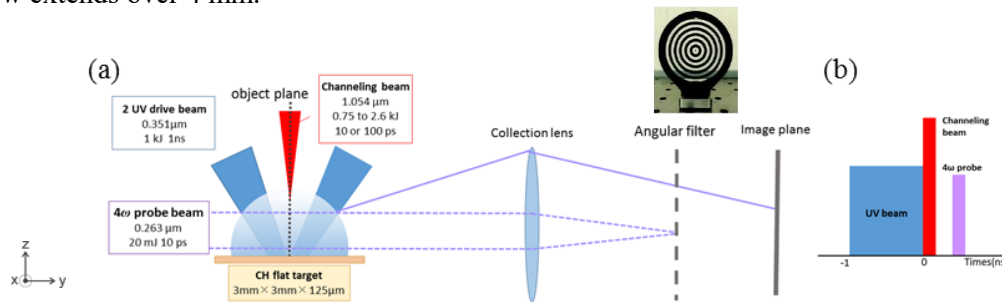


FIG. 1(a) The experimental setup and the model of the AFR diagnostic. The dotted lines represent the unrefracted probe beam and the solid line represents the refracted probe beam. (b) Shot timing diagram.

The delay time of 0 ps of the probe beam is defined as the channelling laser injection timing. The ring collapse at the center of the image (Figs. 2(a) and 3(a)) shows the IR laser propagation and the resultant plasma channel formation. The 100 ps pulse laser propagated deeper into the plasma to higher density region than the 10 ps pulse laser. In the case of the 100 ps pulse, a strong 4ω self-emission generated at the critical density was observed at the second ring from the bottom (Fig. 3(a)). For the 10 ps laser, a filament structure was observed at early probe times that extended from the tip of the plasma channel into the dense plasma. The width of the filament structure was $\sim 200 - 300 \mu\text{m}$. Details of the experimental results are presented in Ref. 1.

3. Analysis

3.1 Ray tracing calculation

The plasma density profiles are analysed by ray trace calculations for various plasma parameters such as plasma scale length or channel diameter. In the calculations, the plasma density profile is given as

$$n_e = n_0 \exp \left[-\frac{x^2 + y^2}{L_g^2} \right] \exp \left[-\frac{z}{L_n} \right] \quad (1)$$

where L_n is the longitudinal plasma scale length along the propagation direction of the IR beam and L_g is a transversal plasma scale length. The low-density plasma channel and the high-density channel wall are approximated by a quadratic function and are then additionally applied inside the profile. The refraction angle of probe rays is related to the spatial gradient of phase shifts.

$$\delta\theta_\alpha = \frac{\lambda_p}{2\pi} \frac{\partial\phi}{\partial\alpha} \quad (2)$$

where λ_p is the wave length of the probe ray, ϕ is the phase shift of the probe ray passing through the plasma, y is the propagation direction of the probe, and α denotes x or z . The summation of the phase shift is calculated along the optical path for spatially divided rays in the calculation.

$$\delta\phi(x, z) = \frac{2\pi}{\lambda_p} \int_{-L/2}^{L/2} \left[1 - \left(1 - \frac{n_e(x, z)}{2n_c} \right) \right] dy \quad (3)$$

In the calculation, each ray propagates in one step for a distance that is equal to λ_p and the refraction angles are updated by Eq. (3). The density gradient in Eq. (3) is calculated by central difference method ($\Delta\alpha = \lambda$).

3.2 Calculation results

Figures 2 and 3 show the experimental and calculation results for the 10 ps and 100 ps pulses. The calculated images agree very well with the experimental AFR images. Figs. 2(c) and 3(c) render the inferred plasma profiles producing the calculated AFR images in Figs. 2(b) and 3(b). The scale length of background plasma can be estimated by the width and separation of the rings, and was $L_n = 240 \mu\text{m}$ in this experiment. The 10 ps and 100 ps pulses reach an electron density of $0.8 n_c$ and $>1.5 n_c$, respectively. The critical density corresponds to the second band from the bottom of the experimental or calculated AFR images, where the strong self-emission signal is observed for 100 ps pulse shot (Fig. 3(a)). Under current plasma conditions, the AFR images exhibit the near actual size of plasma channel at TCC. However, if the channel diameter becomes large ($300 \mu\text{m} \sim$), the size may have an error.

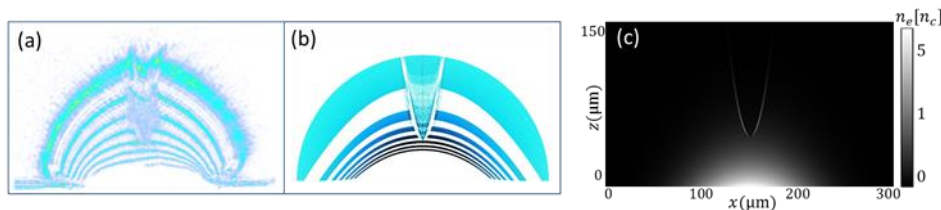


FIG. 2 (a) AFR image of 10 ps (1 kJ) channeling pulse. ($t = 15$ ps) (b) Well-fitted calculated image. (c) A cross section of the plasma density profile used in the calculation.

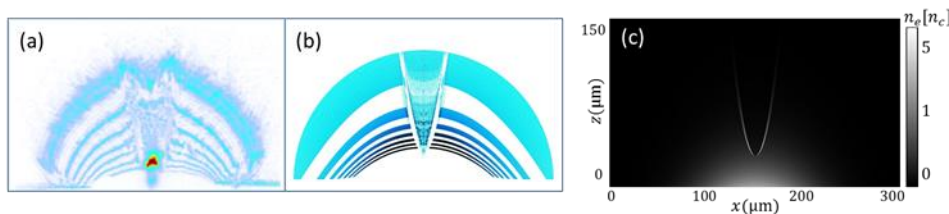


FIG. 3 (a) AFR image of 100 ps (2.6 kJ) channeling pulse. ($t = 65$ ps) (b) Well-fitted calculated image. (c) A cross section of the plasma density profile used in the calculation.

3.3 The effect of the channel profile on the AFR image

Here, we conducted more detailed analysis of the channel by changing the channel parameters. We found (a) that the density inside the plasma channel affects the ring curvature, (b) the high density plasma wall collapses the ring pattern inside the channel, and (c) filamented patterns are reproduced by very small density gap.

Figures 4 (a) and (b) show the magnified experimental and calculated images for the 10 ps pulse. In the calculation, the density inside the plasma channel significantly changes the ring curvature inside the channel. From the comparison of both images, the channel density is estimated to be 0.2 of its background density. In the case of the 100 ps pulse (Fig. 4(c,d)) the channel density is estimated to be 0.5 of its background density. This result indicates that the higher intensity laser pulse forms a lower density plasma channel as predicted by PIC simulations.

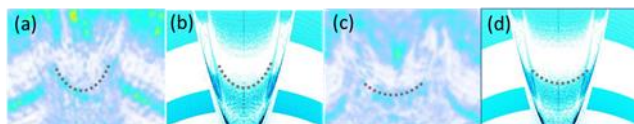


FIG. 4 Experimental images for (a) 10 ps pulse shot ($t = 15$ ps) and (c) 100 ps pulse shot ($t = 65$ ps). (b), (d) Calculation results. Channel density is (b) 0.2 times background and (d) 0.5 times background.

The effect of the plasma channel wall density on the AFR image was also studied. Figures 5(a) and 5(b,c) show experimental and calculated images for wall densities of 10 times and 2 times of the background density, respectively. The ring pattern inside the channel disappears when the wall density becomes higher, which is independent of the inner density of the plasma channel. Therefore, a loss of the ring pattern does not necessarily mean the collapse of the plasma channel structure.

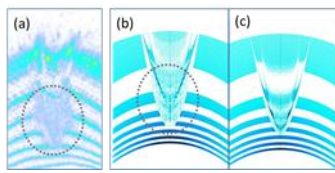


FIG. 5 (a) Experimental image for the 10 ps pulse shot ($t = 15$ ps). Calculation results of (b) high-density ($10\times$) wall and (c) low-density ($2\times$) wall.

Figure 6 indicates (a) filamented structures in the experimental image, and the ray trace images for two different cases of filament structure, (b) micro plasma channel (0.1 times background density) and (c) fast electron filaments (10 times background density). We fixed the diameters of filaments to $5\text{ }\mu\text{m}$, which is about the spatial resolution of the diagnostic. In both cases the filament structure is clearly observed and there is no difference between both. We will conduct a further analysis using a large-scale PIC code to identify the origin of the filamented structure.

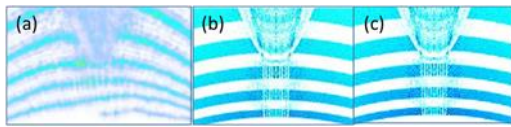


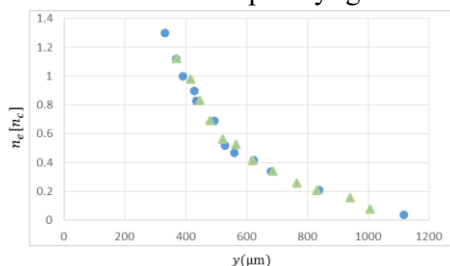
FIG. 6 (a) Filament structure in the experimental image and calculated images of (b) micro plasma channel and (c) electron filaments.

3.4 Error evaluating

The plasma density corresponding to each ring can be obtained by Abel inversion [3]

$$n_e(R = \sqrt{x^2 + y^2}) = -\frac{\lambda_p n_c}{\pi^2} \int_{-\infty}^{\infty} \frac{\partial \phi}{\partial x} \frac{ds}{\sqrt{s^2 + R^2}} \quad (4)$$

where $s = \sqrt{x^2 - R^2}$ is substituted to eliminate the singularity at $x = R$. However in Eq. (4), the ray refractions are completely ignored. Therefore, in the case of large-scale plasma, Abel inversion might



give large errors because the refracted ray passes through a lower density region than along its original direction. Figure 8 indicates the plasma density corresponding to each of the rings obtained by Abel inversion (green triangles) and ray tracing (blue dots). From the comparison, the maximum error of the plasma density between Abel inversion and ray trace calculation is less than $0.2n_c$.

FIG. 7 Plasma densities calculated by the ring positions. The blue dots and green triangles are from the ray trace analysis and the Abel inversion, respectively.

4. Summary

The effect of the plasma channel profile on AFR images was studied with detailed ray trace calculations. The analysis indicates that the plasma channel front propagated up to a background electron density of $0.8 n_c$ for the 10 ps, 125 TW laser pulse and $>1.5 n_c$ for the 100 ps, 20 TW laser pulse, respectively. The residual density inside the channel was found to be $\sim 20\%$ and $\sim 50\%$ of the background density for the 10 ps and 100 ps pulses, respectively.

References

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