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Characterization of preformed plasmas using a multi-dimensional hydrodynamic simulation code in the study of high-intensity laser–plasma interactions

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Abstract. We observed a preformed plasma of an aluminum slab target produced by a high-intensity Ti:sapphire laser. The expansion length of the preformed plasma at the electron density of 3×10^{18} cm^{-3}, which was the detection limit, was around 100 μm measured with a laser interferometer. In order to characterize quantitatively and to control the preformed plasmas, we perform a two-dimensional hydrodynamic simulation. The expansion length of the preformed plasma was almost

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the same as the experimental result, if we assumed that the amplified spontaneous emission lasted 3.5 ns before the main pulse arrived.

1. Introduction

Recently, high-energy ions, electrons, and X-rays from high-intensity laser-produced plasmas have been observed. The high-energy protons from a tantalum plasma produced by a high-intensity Ti:sapphire laser was observed in [1]. The ion generation in the preformed plasma slab created by a relatively intense prepulse has been reported. This experimental result indicated that the characterization of a preformed plasma was of essential importance for the interpretation of ultra-short high-intensity laser–plasma interactions. Among the diagnostics for plasma characterization, optical interferometry is a reliable technique for the measurement of an electron density profile [2]. It can provide us with two-dimensional (2D) spatial information of the preformed plasma with temporal resolution comparable to the probe laser pulse width. In this paper we measure the preformed plasmas of an aluminum slab target produced by a high-intensiy Ti:sapphire laser with an interferometric technique [3]. We performed the experiments and simulations in order to characterize the preformed plasmas and tune up the 2D hydrodynamic simulation code [4].

2. Experimental results

A commercial Ti:sapphire laser with a central wavelength of 800 nm was used. The pulse duration of 50 fs (full width at half maximum) was measured by an auto-correlator. However, the temporal shape of the laser pulse was composed of prepulses such as the leakage of the switch out from the regenerative amplifier, the amplified spontaneous emission (ASE), whose duration is in the nanosecond regime, which comes from the main amplifier, and the picosecond pedestal components adjacent to the main pulse. In this laser system, the contrast ratio (defined as the prepulse versus the main pulse intensity ratio) of the prepulse at approximately 12.5 ns before the main pulse was around 10^{-4}. The ASE and pedestal levels of around 10^{-6} and 10^{-3}, respectively, were measured by a high-dynamic-range third-order cross-correlator. The laser beam was divided into pump and probe beams. The pump beam was focused by an off-axis parabolic mirror and the peak laser intensity was approximately 5×10^{16} W cm^{-2} at the target surface. On the other hand, the probe beam was used for an interferometer. The interference fringes were produced by using a Fresnel biprism and detected by a CCD camera. The electron density profile was obtained by using an Abel inversion of the phase shift profile calculated from measured fringe shifts [3]. Figure 1 shows the electron density profile at the time of around 10 ps before the main laser pulse arrives. The upper arrow shows the direction of the main laser pulse propagation and the other shows the position of the target surface. A gray area denotes the region of the interferogram where the fringe shift could not be determined. The front of the preformed plasma is placed at around 100 μm from the original target surface.

3. Two-dimensional hydrodynamic simulation

Figure 2 shows the prepulse condition for simulation. In this case, we assumed the intensities of the prepulse at 12.5 ns before the main pulse and the ASE with the

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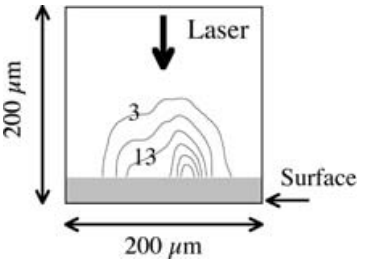


Figure 1. Experimentally observed electron density profile of the aluminum slab target. The contour levels are labeled in units of 10^{18} cm^{-3} and separated by 5×10^{18} cm^{-3}.

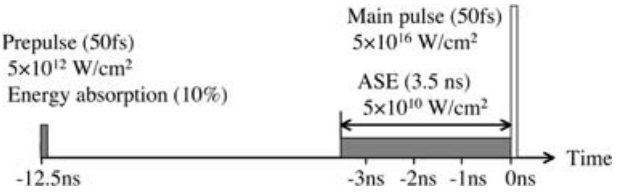


Figure 2. Prepulse condition used for the hydrodynamic simulation.

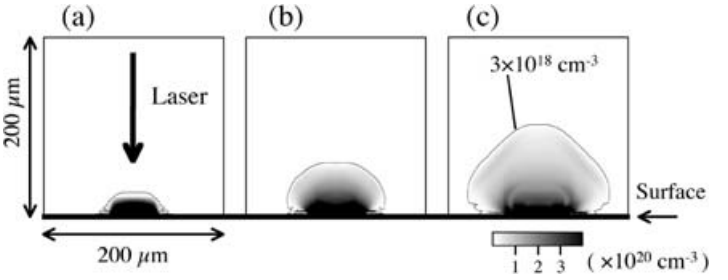


Figure 3. Simulation results for electron density profiles at (a) −2 ns, (b) −1 ns, and (c) 0 ns before the main pulse interaction.

time duration of 3.5 ns before the main pulse were 5×10^{12} and 5×10^{10} W cm^{-2}, respectively. The aluminum target is assumed to absorb 10% of the prepulse energy [5]. The time steps were 0.25 fs during the prepulse illumination and 1 ps after the prepulse illumination. The initial density and temperature of the aluminum slab target were set to be 2.7 g cm^{-3} and 0.026 eV, respectively. Figure 3 shows that the electron density profiles obtained with the 2D hydrodynamic simulation code at the time of (a) −2 ns, (b) −1 ns, and (c) 0 ns before the main pulse interaction [4]. We estimated the electron density from an ionization state as a function of the density and temperature based on the Thomas–Fermi model [6]. The mesh size was 2 μm × 2 μm. We assumed a Gaussian distribution for the spatial profile of the laser with a spot size of 18 μm (full width at half maximum). The outermost contour lines in Fig. 3 show the electron density of 3×10^{18} cm^{-3}. The expansion length of the preformed plasma shown in Fig. 3(c) is nearly consistent with the experimental observation when the ASE duration was 3.5 ns before the main pulse. As a result, the calculation shows that the ASE plays a significant role in producing

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the preformed plasma. Note that the observed electron density is lower than the simulation result in the high-density region. This may come from the refraction and misalignment of the probe beam in the high-density region ($\sim 10^{20}$ cm^{-3}). On the other hand, the simulation does not include the realistic experimental conditions such as spatial laser profile, absorption, and so on. It is necessary to further develop experimental measurements and the simulation code for their mutual comparison.

4. Summary

We observed the preformed plasmas of an aluminum slab target produced by a high-intensity Ti:sapphire laser. The expansion length of the preformed plasma is almost in agreement with that obtained from the 2D hydrodynamic simulation, if we took into account the ASE illumination which should be characterized precisely in an experiment for the tune up of the hydrodynamic code.

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