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Probing ultrafast dynamics in a solid-density plasma created by an intense femtosecond laser

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Abstract. We report a study on the dynamics of a near-solid density plasma using an ultraviolet (266 nm) femtosecond probe laser pulse, which can penetrate to densities of $\sim 10^{22}$ cm^{-3}, nearly an order of magnitude higher than the critical density of the 800 nm, femtosecond pump laser. Time-resolved probe-reflectivity from the plasma shows a rapid decay (picosecond-timescale) while the time-resolved reflected probe spectra show red shifts at early temporal delays and blue shifts at longer delays. This spectral behaviour of the reflected probe can be explained by a laser-driven shock moving inward and a subsequent hydrodynamic free expansion in the outward direction.

1. Introduction

Ultra-intense lasers can create extremely hot, high-density plasma while interacting with a solid. Extreme states of matter, achieved on a laboratory table-top by such interactions are very interesting to study, the measurement of the equation of state similar to that of an astrophysical object being a striking example[1]. Relativistic energy electron beams produced at the plasma critical surface in such interactions are crucial to the success of fast ignition[2] of the fusion pellet in inertial confinement fusion(ICF). A lot of experimental and theoretical studies have been performed in recent decades for the basic understanding of intense short-pulse-laser matter interaction[3] and for applications like particle acceleration[4, 5]. The hot dense plasma created via various laser absorption mechanisms[6] evolves very rapidly (on femtosecond and picosecond time-scales) and these dynamics can be monitored using the pump-probe technique[7, 8, 9].

In this paper, we investigate the temporal dynamics of a highly dense electron layer($n_e = 10^{22}$ cm^{-3}) inside a plasma created on an aluminium-coated BK7 glass target by a laser at relativistic light intensities. Doppler spectrometry of the reflected probe enables the observation of the ultrafast motion of its critical surface (high density layer) inside the hot dense plasma. A numerical simulation is performed which reproduces the results of the experiment.

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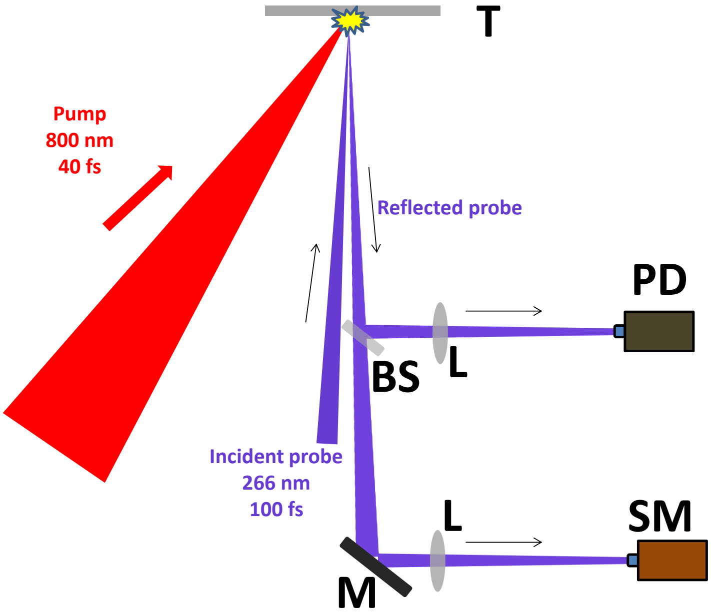

Figure 1. Experimental setup: T-target, BS-Beamsplitter, M-mirror, L-lens, SM-spectrometer, PD- Photo diode.

2. Experiment

The experiment (Fig. 1) was carried out with a chirped-pulse-amplification-based 20 TW laser system (800 nm, 40 fs, 10 Hz) at Tata Institute of Fundamental Research. An extra Pockels' cell was used to obtain a 10^{-6} nanosecond intensity contrast. The pump pulse was focussed on a solid slab at 45^0 angle of incidence to a focal spot of 17 μm (FWHM) to obtain intensities of $\sim 10^{18}$ W/cm^2. A small portion of the laser pulse (5 %) was extracted using a beam-splitter, up-converted to 266 nm, and focussed to a spot of 60 μm at the interaction point at near-normal incidence using a fused-silica lens. The reflected probe pulse was then split into two parts and fed to a photodiode and a high-resolution ultraviolet spectrometer. A delay line was introduced in the path of the probe to change the relative temporal delay between the pump and the probe. The focussed probe intensity was $\sim 10^{11}$ W/cm^2. Spatial and temporal overlap was achieved by looking at the reflected probe intensity from a plasma created on a dielectric slab at relatively lower pump intensity (10^{17}W/cm^2). We define the temporal zero where the reflectivity shows a sudden spike. In this experiment we observed the probe reflectivity and spectrum from a solid-density plasma on aluminium-coated BK-7 target.

3. Results & Discussions

Figure 2(a) shows reflection of the probe as a function of probe delay with respect to the pump from a super critical layer (n_e=10^{22} cm^{-3}) in the plasma. Target: Al-coated 5 mm BK-7 glass target. The probe reflection shows an exponential decay ($\tau = 5$ ps) as the plasma eveolves after excitation by pump. The reflectivity of the normally incident probe can be written as [10]

$$R \propto \exp\left(-\frac{8\nu_{ei}^{*}L}{3c}\right) \tag{1}$$

where ν_{ei}^{*} is the effective electron ion collision frequency. L is the spatial scale length of plasma over which the probe gets absorbed. The collision frequency is a function of electron density

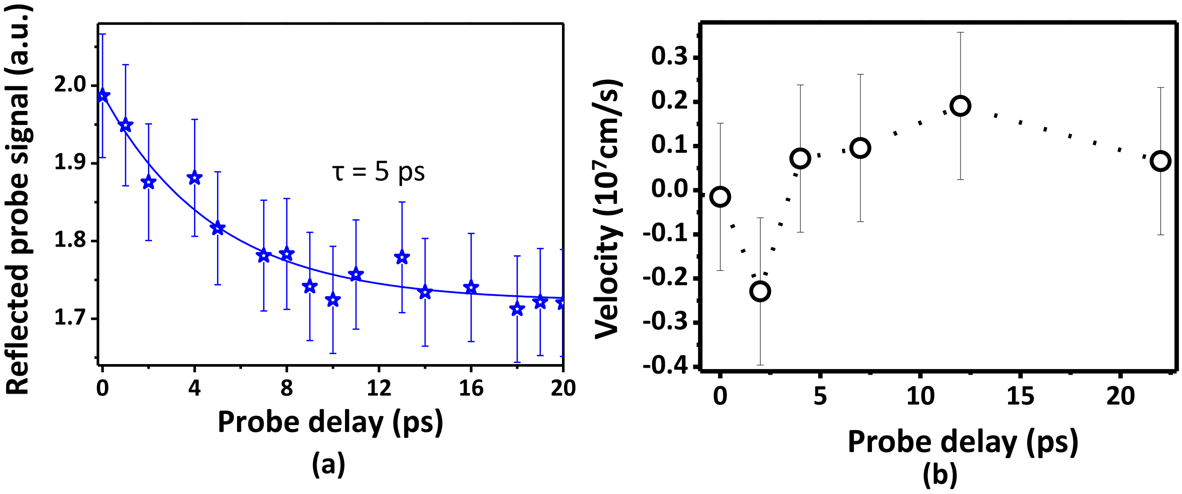

Figure 2. (a) Reflected probe intensity as a function of probe delay. The blue line is the exponential fit to the experimental data (blue asterisks). The decay time is measured to be 5 ps from the fit. (b) A similar plot for the velocity of the probe-critical-layer is shown. These velocities (black open circles) are calculated from the Doppler shifts of the ultraviolet probe measured from pump-probe Doppler spectrometry.

and temperature. In this context of fast time scale (few picosecond) probe reflectivity is mainly dependent on L, if we assume quasi-static values of density and temperature.

The velocity of the supercritical layer was measured by pump-probe Doppler spectrometry[8]. The velocity can be expressed as,

$$v_{exp} = -0.5c\frac{\Delta\lambda}{\lambda} \tag{2}$$

Where $\Delta\lambda$ is the Doppler shift from the experiment and $\lambda = 266$ nm in our case. Figure 2(b) shows the velocity of the probe-critical-layer, calculated from the Doppler shift at various probe delays. At initial few picoseconds, the probe critical-surface moves deeper into the plasma (negative velocity) riding on a non-relativistic shock. At subsequent times, the critical surface moves towards vacuum with the freely expanding plasma (positive velocity).

4. Simulation

Figure 3 shows the velocity of the probe critical-layer results from 1-D hybrid simulations. First, the HYADES code was run on a 500 μm silicate target. The output form this (ion, mass and electron density) was then interpolated onto a regular grid for use in an 1-D PIC code (ELPS) to find the hotspot formed by the pump laser. The code was run with 800 nm, 30 fs, 2×10^{18}W/cm^2 laser pulse. A density spike was observed and its motion was simulated by a Lagrangian hydro code. These 1-D simulations calculate a slightly higher velocity of the critical-layer of the 266 nm probe beam than the experimental observation. The sign reversal of the velocity is around 6 ps, which is close to the experimental result.

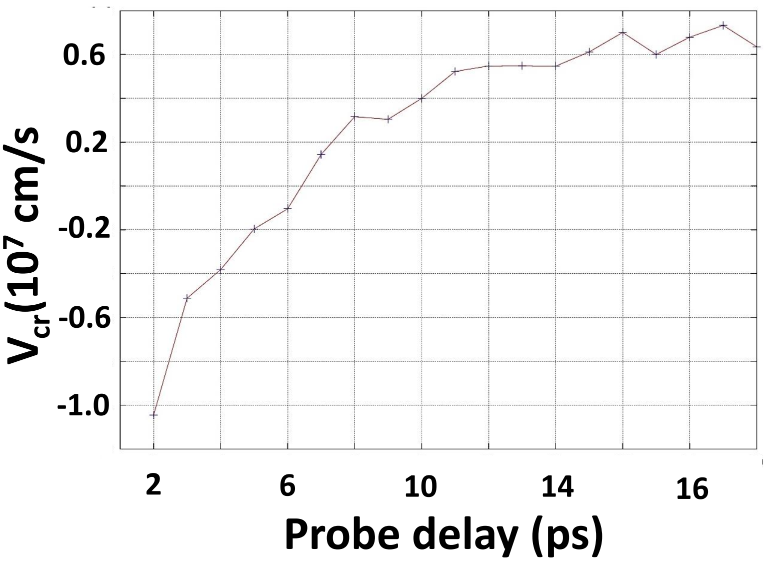

Figure 3. The simulated velocity of the probe-critical-layer as a function of the probe delay. The sign convention: outward motion corresponds to positive velocity.

5. Conclusions

In this study, we observe ultrafast motion of a supercritical (10^{22} cm^{-3}) electron layer in a plasma created by a high-intensity, femtosecond laser pulse on a solid target. We see laser-driven density pile-up and propagation of a non-relativistic shock inside the solid. 1-D hybrid HYADES-PIC-HYDRO simulations support the experiment results.

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