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Time-Resolved Probing of Electron Thermal Transport in Plasma Produced by Femtosecond Laser Pulses

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We present the first direct observation of a supersonic ionization front supported by electron thermal transport in a hot solid density plasma produced by 100fsec-laser-pulse irradiation of a transparent fused quartz target.

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Recent experiments[1] have shown that when a transparent solid target is irradiated with a high intensity ultrashort laser pulse, a high temperature and solid density plasma layer is rapidly formed at the target surface by the leading edge of the laser pulse. As a result, the remainder of the laser pulse is blocked from reaching the bulk region behind the critical density surface where the plasma frequency is greater than the laser frequency. The remainder of the pulse, however, continues to interact with the surface plasma and deposit its energy at and above the critical density. The absorbed energy is then transported supersonically into the bulk region via electron thermal conduction until expansion of the surface plasma becomes important. Detailed understanding of the roles of transport mechanisms in plasma formation and its subsequent expansion is important in the generation of hot solid density plasmas for the development of ultrashort x-ray sources.

We have measured the reflection, transmission and frequency shifts of a 100fsec. probe pulse interacting with a plasma produced by pump laser irradiation of a transparent fused quartz solid. The pump intensity is $5x10^{14}W/cm^2$ at a focal spot of 75µm in diameter. The probe beam at a focal spot of 25µm is $2x10^{10}W/cm^2$; and it is S-polarized, orthogonal to that of the pump, so that the diffusedly scattered light of the pump may be rejected by polarizers before detection. The measurements are recorded as functions of the relative delay between the pump and probe pulses. The frequency shifts of the probe light interacting with the expanding plasma at the front (vacuum-plasma) side determine the plasma ion acoustic velocity and temperature. In contrast, the back (plasma-solid) side probe light, unaffected by plasma expansion, directly interacts with the bulk region behind the surface. Changes in material properties of the bulk region are a result of energy transport phenomena. Front and back side probing provide different but complementary information on the plasma evolution and energy transport mechanisms.

Fig.1a shows imultaneous measurements of the front side probe reflection (solid circles) and transmission (open circles) as functions of time delay between the pump and the probe pulses. The measurements at negative delays correspond to that of cold target where the probe arrives earlier and sees the target undisturbed by the pump. At some later delay when a solid density plasma layer is formed during the onset of the pump pulse, the probe transmission rapidly decreases to zero. Following the increase the probe reflection experiences a slow decay which is atttributed to increasing absorption by the expanding and cooling surface plasma. To quantify the effects of plasma motion, expansion velocity and its spatial extent on the probe reflected signals, calculations based on hydrodynamic equations have been carried out.[2]

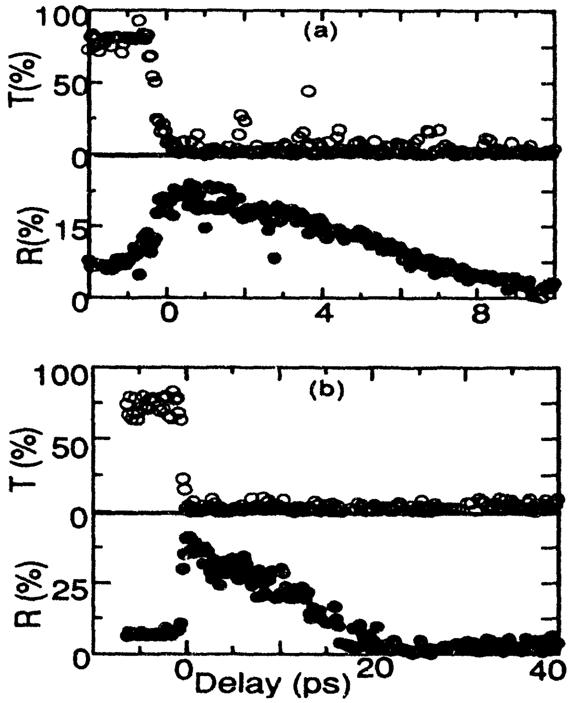

FIG.1: Single-laser-shot measurements of transmission (open circles) and reflection (closed circles) of a) front side probe and b) back side probe pulses as functions of time delay between the pump and probe pulses.

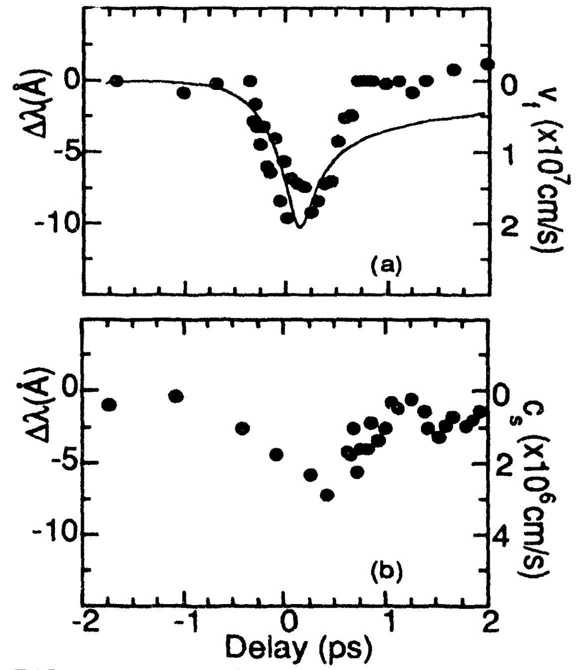

FIG.2: Measured wavelength shifts (closed circles) in the reflected (a) back side and (b) front side probe light. The solid curve is shifts calculated from the nonlinear heat wave model with V_f as the speed of the thermal wave front. The sound speed c_s is obtained from an isothermal plasma model.[3]

Fig.1b displays the reflection and transmission data for the back side probe beam. The data again shows a drop in transmission and increase in the reflection due to rapid formation of a supercritical surface plasma. Moreover, the strong reflection enhancement implies that the plasma, as seen from the rear side in the interior, acts like a mirror, indicating a steep density gradient at supercritical density and elevated temperature. The reflection increase however is followed by a rather prolonged decay of 15ps, 2.5 times slower than that of the front side probe data. It should be noted that during this time laser heating by the pump pulse has ceased and that the back side probe light is not affected by effects of hydrodynamic expansion taking place at the front. For these reasons, the observation of the prolonged reflection decay in the back side probe leads to the realization that diffusion of thermal electrons or thermal transport phenomenon may play a dominant role in creation of the plasma behind the surface.

The dominant role of electron thermal transport is further evidenced by the recent observation of the frequency shifts in the backside probe light.[4] In Fig.2a, the wavelength shifts $\Delta\lambda$ of the center-of-gravity wavelength component in the spectrum of the reflected back side probe are shown (solid circles) as a function of delay. The shifts are assumed to be due to a thermal wave or steep ionization front moving into the transparent target toward the back side probe, and are determined by the Doppler formula,[3] i.e. $\Delta\lambda / \lambda = -2n_s \cos\theta V_f / c$. The factor of 2 accounts for reflection, θ is the incidence angle of the probe, n_s =1.46 is the solid target refractive index, c and V_f are the speed of light and ionization velocity, respectively. The observed maximum shift of nearly -10Å corresponds to a maximum velocity of 1.8x10^{7}cm/s. Fig.2b displays the time history of the wavelength shifts (closed circles) in the reflected front side probe light. These shifts are due to combined effects of the motion of the turning point (N_{TP} $=N_{cr}\cos^2\theta$), and the increase of plasma density in the region below N_{TP}. Estimates of the shifts and the turning point velocity, which are both proportional to the plasma sound velocity c_s, have been derived using an isothermal plasma expansion model.[3] From the maximum shift of ≈ -7Å, we estimate c_s = 3x10^{6}cm/s for the maximum sound velocity and nearly 40eV for the maximum temperature of the carbon plasma with an average ionization of 3. Hence, the ionization front in the bulk region is supersonic; and it is attributed to a thermal wave created by electron thermal transport. Using a nonlinear diffusion equation for electron with a Spitzer-type conductivity, and neglecting plasma expansion,[4] plasma formation in the bulk region due to electron thermal transport is characterized. The time development of the velocity V_f of the ionization front or thermal wave front (solid curve in Fig.2a) is then extracted from the evolution of the density profiles. At early delays, ≤0.7ps, the calculated velocities are in good agreement with the experimental results. The discrepancy in the data at later delays suggests some reduction in the rate, or inhibition, of electron thermal transport.

In summary, we have presented experimental results from both front and back side probing of a plasma produced by 5x10^{14}W/cm^2, 100fs laser pulse irradiation of a transparent target. The plasma, as seen from the interior of the target, has a steep density gradient; and its high specular reflectivity persists for about 15ps. The plasma is formed by a supersonic ionization front as suggested by comparison between the measured front and back side probe frequency shifts. Calculations using a nonlinear electron diffusion equation to describe plasma evolution yield fairly good agreement with the data.

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