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Study of ultrashort, high intensity laser matter interaction via proton imaging

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Abstract :

The interaction of 30 fs laser pulse at intensity of 10^{19} W/cm^2 with preformed underdense plasma was studied in an EU-funded experiment at the Laboratoire d'Optique Appliquee (LOA), Palaiseau (France) by means of the recently developed proton imaging diagnostics. Proton images of the electric field distribution around the irradiated target were collected, with extremely high spatial and temporal resolution, using nuclear track detectors (CR39). The images indicate the development of some periodic electric field structures in the wake of the laser pulse, irrespective of the target material, likely due to the development of a two-stream instability initiated by wakefield oscillations. Filamentary structures and expanding spherical bubbles are also observed in the proximity of the target. 2D Particle-In-Cell simulations are used to interpret and model the phenomena observed.

Introduction :

A high intensity electromagnetic (EM) wave propagating in underdense plasma excites nonlinear plasma processes that affect its propagation in different ways depending on both the wave and plasma parameters. Recently emerged novel diagnostic, proton imaging [1], provides a unique possibility of detecting slowly varying field entities formed during the nonlinear interactions of powerful short laser pulses with plasmas due to high temporal and spatial resolution. The proton beam produces the image on the detector via. modulation in density distribution due to deflection of protons by the quasi-static electro-magnetic field in the plasma.

This paper presents three striking features observed during experimental investigations of the interaction of an ultrashort (~ 35 fs), intense (~ 10^{19} W/cm^2) laser pulse with preformed plasma using the proton imaging technique. A pattern with surprisingly regular modulations is found inside a long channel in the wake of the laser pulse. The physical process responsible for the formation of this pattern has been investigated with extensive Particle In Cell (PIC) simulations of the long time plasma evolution. Secondly, a spherically expanding bubble-like structure is observed in the low density coronal plasma produced due to the interaction of long prepulse ahead of the short chirped pulse amplified (CPA) pulse. Finally, long filamentary structures were found over very long time duration starting before the interaction of main CPA pulse. The preliminary investigations presented in this report explain the complexity of the situation.

Experimental Setup :

The experiment was carried out at the LOA Laboratory, employing the Salle Jaune laser [2] operating in the CPA mode. The laser pulse was split in two separate pulses (CPA1 and CPA2), each of 35 fs duration, delivering peak intensities of 5 x 10^{19} W/cm^2 and 1 x 10^{19} W/cm^2 respectively on two different targets. The CPA1 pulse was used to accelerate a beam of MeV protons from a thin (6-10 µm) Al foil. The pulsed proton beam was used as a transverse particle probe to diagnose the interaction of the CPA2 pulse with a secondary target or preformed plasma. The spatial resolution of the diagnostic is typically a few µm and the temporal resolution is typically of a few ps, is given by the transit time of the protons across the region where the fields are present. For a schematic of the experimental arrangement see Fig.1 of Ref. [1]. The delay between the two CPA pulses was controlled with ps precision. The LOA high intensity pulse is preceded by an Amplified Spontaneous Emission (ASE) pedestal starting about 10 ns before the pulse peak, with a main-to-prepulse contrast ratio better than 10^6. The point projection magnification of the interaction region was M ~ 14. The experiment was performed in a vacuum chamber evacuated down to a pressure of about 0.05 mbar. The imaging was done by selecting the protons of energy more than 3 MeV, using a 75 µm Al foil before the CR39 nuclear track detector. Due to large flux of protons, CR39 were etched for a short time (~ 15 minutes) in the solution of NaOH at 80^0 C in order to avoid the overlapping of the etched proton tracks. After etching, the detector surface was scanned by Atomic Force Microscopy (AFM) in order to facilitate the precise measurement of the track density, yielding the proton density distribution across the beam crosssection and the spectrum of protons contributing for the image formed in CR39 [3]. The CPA2 beam was focused onto the surface of Al or CH foils of variable thickness. The interaction region was probed with the proton beam at different times before and after the arrival of CPA2 on target, with the aim of identifying various mechanisms via associated electromagnetic (EM) fields of plasma structures induced by the high-intensity interactions. Among several structures observed in the data, we concentrate our attention on three striking features as discussed below.

Results :

The image of the interaction of CPA2 with thin Al foil obtained by the proton radiography consists of three interesting features. A circular structure (probably the projection of a spherical structure) was observed expanding on the side of the interaction with long and straight filament-like structures, seems to be originating from the point of interaction as shown in fig. 1A (a) and (c). Both of them were observed much before and after the arrival of main pulse onto the target. The density and temperature of the coronal plasma, estimated by the 2D hydrodynamic simulation, POLLUX [4], were found favourable for non-collisonal phenomena to take place. The boundaries of the circular structures are different at different time of interaction and drive attention towards the collisionless ion acoustic shock waves or solitons. The period of the multiple peaks is of the order of 25 µm which is approximately six times of the local plasma wavelength, invented from the hydro simulation. The physics of filaments is not yet understood completely. The most striking feature observed is the long periodic structures in the wake of the laser pulse as shown in Fig.1. The phenomena behind all the three type of structures, probably, are not concerned about the type of target as the same effects, at the same places, has been observed for the foils of Al and CH of different thicknesses. All the structures were observed at both sides of thinner CH targets which can be expected to be blow-off by the prepulse, as verified by POLLUX. The periodic structure was observed from a few ps to 40-50 ps after the interaction with very slowly varying period in time and space, which is of the order of 25 – 30 µm. The images and the proton density variation along the structures are shown in fig. 1A (b).

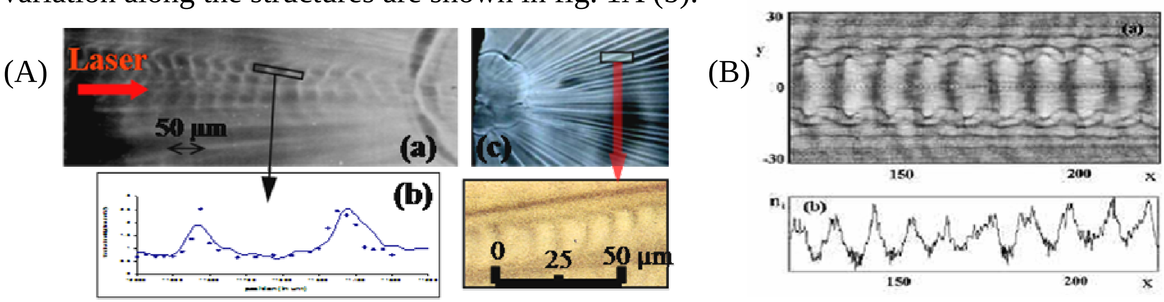

Fig. 1: A: experimentally observed proton radiographs, B: 2D PIC results for ion density.

POLLUX tells that plasma of density higher than 10^{17} el/cc is confined within a region with radius smaller than 300 µm on both side of the thin CH foils (for which we have observed the structures on both sides) and only on the side of the interaction for other targets used in the experiment. However, the tenuous air gas present inside the interaction chamber will be ionized via tunnel ionization by the rising edge of the pulse. We estimate the laser intensity in the region where the periodic structures appeared was in the range from 10^{17} to 10^{18} W/cm^2. This can produce plasma of density in the range 10^{16} to 10^{17} el/cc in the tenuous air medium.

The electric field associated with the periodic structures, along the axis of it, is approximately equal to 3 x 10^8 V/m. Two-dimensional PIC simulations (REMP code [5]) shows the development of a periodic ion pattern from a sequence of plasma phenomena in the wake of the pulse. In the initial stage, the laser pulse excites a Langmuir wake wave accompanied by the formation of a quasistatic magnetic field [6]. The transverse modulations that are clearly visible in fig. 1B develop in two steps. First transverse modulations appear in the electron density and current due to the Lorentz force which, inside an EM wave packet with finite longitudinal and transverse size, acquires a transverse component with scale length of the order of laser wavelength. Later, the charge separation creates electric field that leads to the ion redistribution and to the formation of the longitudinal stripes that last for approximately 6 ps before they dissolve due to ion trajectory intersection and multi-stream motion. We see quasi-periodic structures in the pulse wake with longitudinal spacescale of the order of approximately ten times larger than the laser pulse wavelength but three times smaller than the wakefield wavelength. From the simulation we find the electric field of the order of 3×10^9 V/m. The time of all plasma phenomenon scales with the plasma density as $\sim n_o^{-1/2}$, can explain why under the conditions of the experiment, where the plasma density is substantially lower, the ion wake pattern survives much longer.

Conclusion :

We observed three different types of striking features during the interaction of ultrashort, high intensity laser pulse with preformed plasma. PIC simulation explains the physics of late time periodic ion structure in the wake of the laser pulse.

References:

1. M. Borghesi *et. al.*, Phys. Plasmas, **9**, 2214 (2002)
2. M. Pittman *et. al.*, Appl. Phys. B, **74**, 529 (2002)
3. S. Kar *et. al.*, Rev. Sci. Instrum., submitted (2004)
4. G. J. Pert, J. Comput. Phys., **43**, 111 (1981)
5. E. Zh. Esirkepov, Comput. Phys. Comm., **135**, 144 (2001)
6. B. M. Bolotovskii *et. al.*, Phys. Uspekhi, **173**, 667 (2003)