Characterization of laser excited shock waves in tenuous plasma

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The observation and characterization of collisionless shock waves generated in laser plasma interactions is presented. The shock waves are generated by long pulse ∼1ns, intense ($10^{15} W/cm^2$) laser irradiation of solid targets and are observed to propagate in a tenuous ($10^{13} - 10^{16} cm^{-3}$), non magnetized background plasma. These nonlinear entities are detected and characterized by employing a proton imaging technique, which allows the simultaneous detection of propagation velocity, width of the shock front and electrostatic field associated with the shock, with high spatial and temporal resolution. Ion Acoustic Solitons (IAS) were observed under certain conditions and as inferred from the reconstructed associated electric field profile. The variation of IAS velocity and width as a function of the ambient parameters was characterized. The data show an increase in velocity and decrease in width as the density of the background plasma (generated via photo ionization of controlled, low density gas in a gas cell) is increased. The experimental results are interpreted in the frame work of Korteweg-de Vries nonlinear wave description and in agreement with theoretical predications.

Collisionless shocks are one of the most interesting phenomena in plasma physics and play a fundamental role in many astrophysical phenomena such as supernova remnants and cosmic ray brusts [1, 2]. There are two possibilities of collisionless shock formation in unmagnetized plasma; electrostatic shocks [3, 4] and weibel mediated shocks [5]; both types have not been explored completely in laboratory yet in astrophysical context. As a result of progress in laser technology, now it is possible to replicate the astrophysical conditions in laboratory and the study of these phenomena has received great importance in last decade [2]. Their relation with other non linear entities (like Ion acoustic Solitons (IAS) [4], Ion acoustic waves [6], Phase space electron-hole [7],etc) also plays a vital role for many astrophysical phenomena [1]. In a laser plasma context, electrostatic shocks have been observed by optical probe, which could not resolve the shock front and distinguish different typologies of shocks [3]. Recently, the collisionless shock had been observed by employing proton projection imaging (PPI) techniques, which resolve the front with simultaneous measurement of propagation velocity, associated electric field with high temporal and spatial resolution [4].

In this paper, we present the experimental observation of propagation of laser driven electrostatic shocks in tenuous plasma. These shocks are generated by the expansion of warm plasma into rarefied ionized background [8] and characterized by laser accelerated protons as a charged particle probe [9].

The experiment was carried out using the VULCAN laser system at RAL. The schematic of experimental setup is shown in figure 1(a). The CPA pulse of pulse duration ∼ 1ps focused by off axis (f/3) parabola to an intensity $\sim 5 \times 10^{19} W/cm^2$, onto $20\mu m$ Au target(proton target), is used to proton probe beam. The long pulse of duration ∼ 1ns was focused onto a Au stripe target (inferred as shock target) of thickness $50\mu m$ and width $70\mu m$ at an angle of 45^o with an intensity $\sim 5 \times 10^{15} W/cm^2$. The setup was enclosed in a gas cell filled by nitrogen at pressure between $10^{-1} mbar - 10^{-4} mbar$. The proton imaging technique was the main diagnostic employed to detect and characterize the shock waves propagating in low density plasma, Interferometry was employed as well to characterize the laser ablated plasma. The distance between the proton target and the shock target was 4 mm and the distance

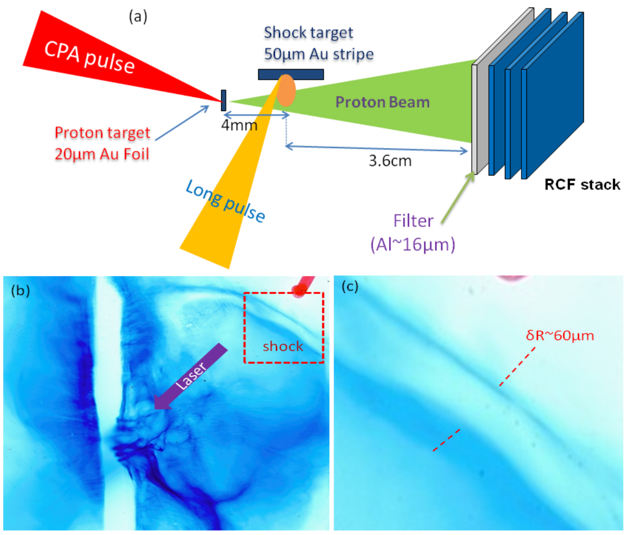

Fig. 1: (a) The schematic of experimental setup, time of flight arrangement of proton probing (b) Proton Image of the interaction of nanosecond pulse with 50μm Au stripe, showing shock waves in laser ablating plasma, arrow shows the direction of laser (c) zoom of observed structure.

between the shock target and the proton detector was $L = 3.6$cm, giving a projection magnification $M = (l + L)/l \simeq 10$. The proton beam, after having probed the plasma, was recorded on a stack of several layers of dosimetrically calibrated radio chromic Films (RCF). The multilayer arrangement of the RCF detector and the broad spectral content of the proton beam provided temporal multi-frame capabilities for the proton probing within a single laser shot. In the time of flight arrangement, the probing time can be calculated by $\tau = \tau_o + \left(\frac{l}{c} \times \left(\frac{2\epsilon_p}{m_p c^2}\right)^{-1/2}\right)$ where $v_p = (\frac{2\epsilon_p}{m_p c^2})^{-1/2} c$ and $m_p c^2 \simeq 940 MeV$ and τ_o is the optical delay between lasers, ϵ_p and m_p is the energy of protons and mass of proton respectively.

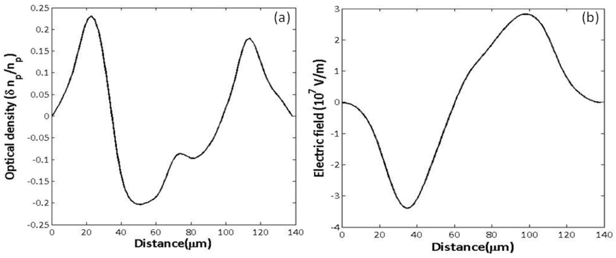

Fig. 2: (a)Proton density line out across the shock front(b) reconstructed electric field E, resembles with theoretically predicted electric field profile of the IAS [4].

Data exemplifying the features observed by PPI is shown in figure 1(b) and (c). As a rule of thumb the electric fields are directed from the regions of a lighter blue color compared to the background (zones of reduced probe proton flux) towards the regions of darker blue color (increased flux). A pronounced modulation in the probe proton density, revealing a strongly modulated field distribution is observed at $\sim$ 1mm from the target. This modulation is interpreted as a shock structure propagating in tenuous plasma (created via photo-ionization, mainly by radiation form laser plasma [8]). The shock has average radius of curvature $\sim$ 700um and thickness $\sim 60\mu m$ and which expands an approximately spherically symmetry from the target. The observed proton density modulation reveals an electric field which changes sign across the shock [4]. The proton density modulation can be related to deflecting transverse electric field by

$$\frac{\delta n_p}{n_p} \simeq \frac{-eL}{2\epsilon_p M} \nabla_{\perp 0} . \int_b E_\perp dz \qquad (1)$$

Where $\delta n_p = n_p - n_{pu}$,with n_p and n_{pu} are perturbed and unperturbed density, ϵ_p is the proton energy, M is magnification, L is the distance between interaction region and detector;and b is the region of non zero charge density crossed by protons given by $b = 2\sqrt{(R + \delta R/2)^2 - R^2}$ with radius of structure R and thickness δR. Proton density modulation profile is shown in figure 2, which qualitatively agrees with theoretical the expected pattern of IAS [4]. The numerical integration of equation (1) leads to electric field profile at shock front is shown in figure 2,having a amplitude $3 \times 10^7 V/m$.

The propagation velocity of shock can be measured in single laser shot, because different shock front position in RCF layers corresponding to different probing times. The shock structure is moving with $8 \times 10^5 m/sec$ at 0.3mbar, but velocity varies for different pressure of background gas (i.e different plasma density when ionnized). The variation of velocity versus the background plasma density, is shown in 3(a). It shows that the velocity of shock decreases with increase of the background plasma pressure. As the PPI technique resolves the shock front,the width of

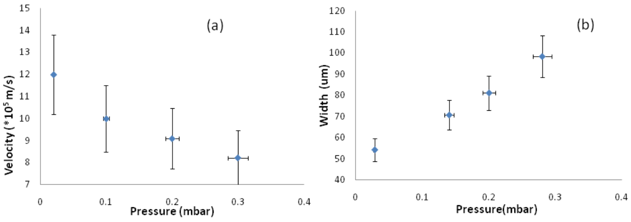

Fig. 3: (a) Variation of the shock velocity and (b) the shock width versus the tenuous plasma pressure.

shock structure can be measured. The width of the shock as well varies with background plasma pressure as shown in figure3 (b).

The electrostatic shock launched by the expansion of dense plasma into tenuous plasma, has been observed and characterized by means of Proton projection imaging technique. Thanks to a high temporal and spatial resolution, of the order of few picoseconds and few micrometers, respectively, proton density modulation and electric field,the propagation velocity and width of shock have been simultaneously measured.

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