Modeling proton probing of femtosecond laser propagation through underdense plasma

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Introduction

Propagation of ultra short, ultra high intensity ($>10^{19\text{-}20}$ W/cm^2) laser beams in plasmas has recently received much attention particularly in relation to their applications as plasma based accelerators[1]. At such high intensities, the interaction of the laser beam with plasmas is highly relativistic and nonlinear leading to many interesting phenomena such as self-focussing, self-channelling and wake field acceleration. In underdense plasma, an intense laser pulse drills a channel due to radial ponderomotive expulsion of electrons. The electron expulsion is followed by ion acceleration due to the charge separation field or coulomb explosion, depending on the laser and plasma parameters. The length of laser pulse is an important parameter which controls the interaction. For long (~ps) pulses the ions have time to move under the effect of the radial space-charge force related to ponderomotive expulsion of electrons, and this leads to the formation of a plasma channel in the trail of the laser pulse. For an ultrashort pulse, the ions may not have time to acquire sufficient momentum, and electron cavitation may last only as long as the ponderomotive force of the laser is present. The pattern of the excited wakefield differs significantly for laser pulses longer and shorter than the plasma period (λ_p)[2]. An ultra-relativistic intense laser pulse shorter than λ_p breaks the plasma wave after the first oscillation. The so-called bubble regime signifies the formation of a cavity free from cold plasma electrons behind the laser pulse, this regime has been shown to lead to the acceleration of a monoenergetic relativistic electron bunch[3]. Dynamics of these transient and localized interactions have been observed in computer simulations, and indirect measurements from relevant experiments helped to establish the wake field acceleration theory[3]. In this report we present the possibility of recording the interaction employing proton projection imaging (PPI) technique, exploiting a proton's time of flight arrangement.

Proton Projection Imaging (PPI)

The PPI technique is based on the use of laser accelerated multi-MeV protons as a charged probe beam of transient electric/magnetic fields in plasmas, a possibility allowed by the low emittance and high laminarity of the proton source[4] as well as by its ultra-short duration and easy synchronization with an interaction laser pulse. The experimental implementation of the diagnostic takes advantage from the broad energy spectrum of protons, since in a time-of-flight arrangement, protons of different energy will probe the plasma at different times. Therefore,

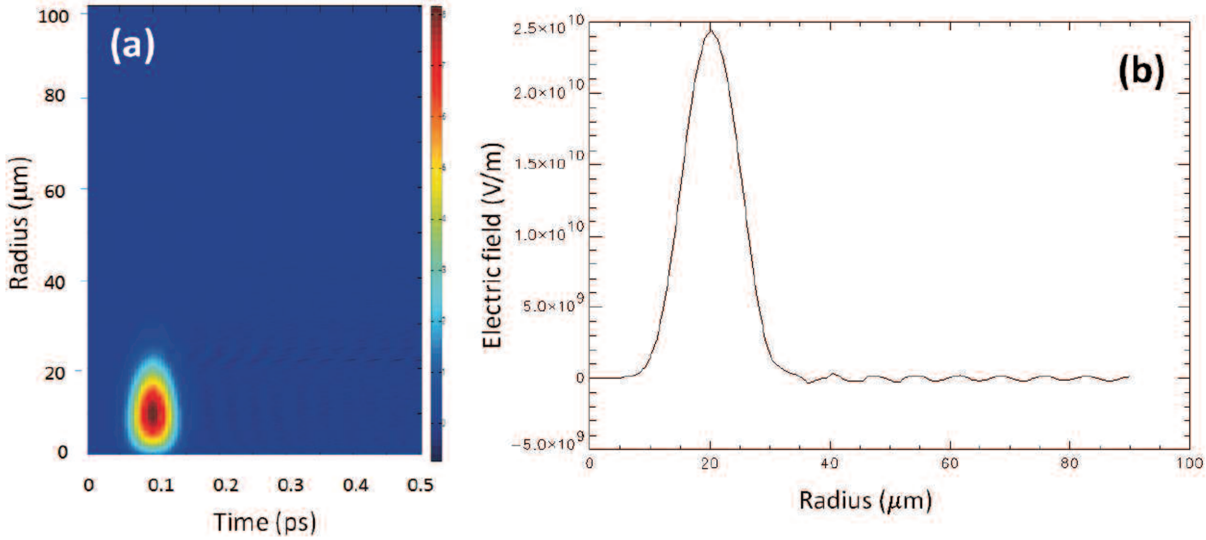

Figure 1a. Simulation profile of electric field obtained from PIC for a laser pulse duration of 50fs. 1b: the line out of the electric field taken across the spatial coordinate r having a peak amplitude of the order of 2.5×10^{19} v/m.

an energy-resolved monitoring (eg. employing stack of radiochromic film/CR39 detectors) of the proton probe profile allows single-shot, multi-frame temporal scans of the interaction to be obtained[5]. Proton imaging and the related 'proton deflectometry' technique permit spatial and temporal maps of the electric fields in the plasma to be gathered, and therefore have proven to be an unique tool to explore the dynamics of laser-plasma phenomena[6] via the associated space-charge fields.

In a recent experiment, the distribution of the electric field generated during the self-channeling process of a relatively long pulse (~ps) was measured with high spatial and temporal resolution using the PPI technique[7]. The proton images were well reproduced numerically by simulating the proton probe deflection by a space and time dependent electric field distribution obtained from one-dimensional electrostatic PIC model. While the above experiments and simulations were done for a picosecond laser interaction with plasma, the above technique could also provide sufficient temporal resolution in order to diagnose ultra-short laser interaction relevant to experiments at the Gemini laser facility. The ultrafast interaction was modeled using 1D PIC simulations to obtain the electric field and incorporated with 3D particle trace codes to obtain the proton images.

PIC code simulation results

The model used in these simulations is described in ref[8]. Figure 1 shows the profile of electric field $E_r(r, t)$ from a PIC simulation with the radius of the laser pulse at its waist $r_0 = 5$ µm, the dimensionless field amplitude $a_0 = 2.9$ and an initial density $0.01n_c$ (where n_c is the critical density and $n_c = 10^{21}$ cm^{-3} for $\lambda = 1$ µm). The pulse duration and intensity corresponds to 50 fs and 10^{19}Wcm^{-2} respectively. The charge-to-mass ratio of ions is $Z/A = 1/2$. The simulation clearly shows the formation of an electron-depleted channel, resulting in an externally directed radial space-charge electric field, which vanishes when the ponderomotive effect of the laser stops. The plasma initial temperature is taken to be zero and no significant self-heating occurs.

Particle tracing results

A 3D particle tracing simulation, employing the PTRACE code[9] was carried out to obtain the proton images for an electric field given by $\mathbf{E}(x, r, t) = \hat{\mathbf{r}}E_r(r, t - x/c)$. The Proton projection simulations in fig 2 are simulated for 12 MeV protons probing the plasma. Simulations for higher energy probe protons (20 MeV) produced similar results. The spatial scale indicated in figure 2 corresponds to the object plane. The white vertical line indicates the center of divergent probe beam.

Each slice of the image corresponds to the probing of the interaction at a different time as labeled, with respect to the time of arrival of the laser pulse at the centre of the probe beam.

The presence of a positively charged channel created by radial electron expulsion as shown in figure 1, in the field of view is detected by proton deflection, which creates a white channel with dark boundaries in the proton images.

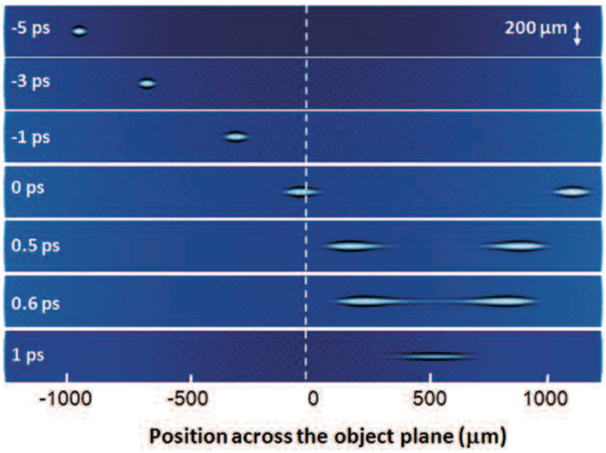

Figure 2. Simulated proton projection images obtained from particle tracing simulations for 12 MeV protons from the electric field pattern obtained from 1D PIC simulations based on ponderomotive model. The white channel stretches towards the right side of the frame (compare -5 ps with 0 ps). The laser pulse in the figure moves from left to right.

At early time, the channel appears in the left side of the image and moves to the right with subsequent probing times. Although the laser moves with the speed of light, the velocity with which the white channel moves appears slightly different from the laser speed. This is due to the protons arrival time across the object plane which is a function of the distance from the axis. In a point projection imaging scheme, as shown in figure 3(a), the arrival time of a given energy protons can be written as $\tau(x,E) = t_0(E) + [L(x)-L_0]/v_p$, where L_0 is the distance between the source and object plane, v_p is the proton velocity, and $t_0(E)$ is the time at which the protons of energy E directed perpendicularly to the object plane cross the latter, relative to the instant at which the laser pulse peak reaches the focal plane ($x = 0$).

In figure 2, one can see that the white channel gets stretched towards the right (considering the leftmost white channel in the snaps of figure 2) and gets constricted towards the left. This effect could be explained with respect to the temporal dispersion of the protons over the object plane, because of their different arrival times at

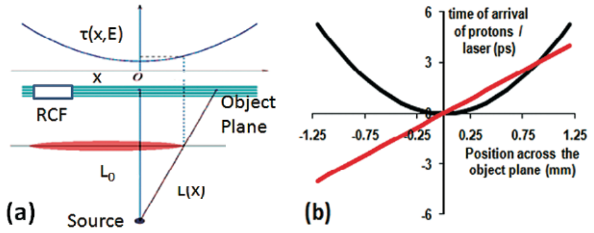

Figure 3a. Schematic diagram depicting proton probing of a propagating channel where L_0 is the distance between the source and object plane. 3b: Graph showing the time of arrival of Probe Protons/laser Vs position across the object plane. The black parabola is the time of flight of protons with respect to the object plane. The red line indicates the time of arrival of the laser pulse.

different points. Since the laser pulse is moving from left to right, the protons will probe the pulse for extended time interval in the right to the proton axis and vice-versa.

The second interesting effect is the appearance of a secondary channel as the pulse crosses the center of probe beam which moves from right to left with the probing time. The two channels finally meet in the proton image at some subsequent probing time and disappear afterwards. The effect again is formed by virtue of proton arrival time at different axial locations as explained below. The arrival time of protons is parabolic in nature with respect to the position over the object plane as shown in figure 3(b). In the same graph one can draw a straight line demonstrating the motion of the laser pulse with a constant velocity. Therefore, the temporally dispersed proton beam will probe the laser beam twice for a given delay time (the time difference between the arrival of the laser and axial proton at the centre of the field of view). As we decrease the delay time (equivalent of increasing the probing time), i.e. as we shift up the parabolic curve of the protons arrival time, the intersection points will move closer and will meet eventually. Afterwards, the proton beam will not be able to probe the pulse. However, the images for the later times have been captured already as the secondary channels.

Conclusion

The dynamics of electric field during the interaction of a femto-second laser pulse with underdense plasma is simulated using 1D PIC simulations and the proton projection images are reconstructed using 3D particle tracing code. Temporally resolved proton images of the laser propagation inferred two peculiar effect of the diagnostic due to the temporal dispersion of a divergent probe beam over the object plane. The effects are stretching of the channel and double probing of the channel in a single frame. These effects helps to detect the ultra-short and transient interaction, hence motivating a possible experiment in Gemini laser facility.

References

1. T. Tajima and J. M. Dawson, *Phys. Rev. Lett.* **43**, 267 (1979).
2. T. M. Antonsen and P. Mora, *Phys. Rev. Lett.*, **69**, 2204 (1992).
3. J. Faure *et al.*, *Nature*, **431**, 541 (2004).
4. M. Borghesi *et al.*, *Phys. Rev. Lett.* **92**, 055003 (2004).
5. J. Fuchs *et al.*, *Nat. Phys*. **2**, 48-54 (2006).
6. M. Borghesi *et al.*, *Phys. Rev. Lett.* **94**, 195003 (2005).
7. S. Kar *et al.*, *New Journal of Physics,* **9**, 402 (2007).
8. A. Macchi *et al.*, arXiv:physics/0701139.
9. A. Schiavi, *PhD thesis*, Imperial College, London, UK (2003).