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Investigations of ultrafast charge dynamics in laser-irradiated targets by a self probing technique employing laser driven protons

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ABSTRACT

The divergent and broadband proton beams produced by the target normal sheath acceleration mechanism provide the unique opportunity to probe, in a point-projection imaging scheme, the dynamics of the transient electric and magnetic fields produced during laser-plasma interactions. Commonly such experimental setup entails two intense laser beams, where the interaction produced by one beam is probed with the protons produced by the second. We present here experimental studies of the ultra-fast charge dynamics along a wire connected to laser irradiated target carried out by employing a 'self' proton probing arrangement – i.e. by connecting the wire to the target generating the probe protons. The experimental data shows that an electromagnetic pulse carrying a significant amount of charge is launched along the wire, which travels as a unified pulse of 10s of ps duration with a velocity close to speed of light. The experimental capabilities and the analysis procedure of this specific type of proton probing technique are discussed.

1. Introduction

Amongst different laser-driven ion acceleration mechanisms currently under development/optimisation, Target Normal Sheath Acceleration (TNSA) mechanism is the most robust and widely studied process [1]. Although the broad energy spectrum and inherent beam divergence of the TNSA protons pose significant scientific and design challenges towards many of its potential applications (for example cancer therapy [2,3], warm dense matter creation [4–6], production of neutrons [7]), these properties are well suited to radiographic applications [8]. Where the point-like source of the quasi-laminar and divergent beams of TNSA protons produces radiographs with high spatial resolution (of the order of μm), its broad energy spectrum provides a single shot multi-frame capability with high temporal resolution (of the order of ps). The proton probing technique has been extensively used for studying transient electric and magnetic fields associated with intense laser plasma interactions [9–12]. A typical setup for these studies employs two temporally synchronised intense laser pulses. One of the pulses is used to generate the probe protons from a thin metallic foil, while the second pulse with an appropriate target is used to generate the field dynamics, or the physical process, to be investigated.

Here we present investigations of the ultrafast dynamics associated to transient charging of laser-irradiated targets, initiated by an intense laser interaction, using a single laser pulse – in an arrangement we refer to as self proton probing (SPP). Transient charging and discharging of laser irradiated targets have been the object of several previous studies employing the standard proton probing technique (using two laser pulses) [11–14]. These studies revealed positive target charge-up to MV potential following intense irradiation, due to the escape of relativistic electrons from the laser-irradiated region [11,12,15]. The targets were then observed to discharge to ground on timescales of 10s of ps [11,14]. The strong and sudden charge separation caused by the hot electron escape was also seen to lead launch of a unipolar surface electromagnetic (EM) wave along the target, expanding out from the interaction point at nearly the speed of light [13,12]. This surface wave contributes to the target neutralisation process by carrying positive charge away from the interaction region. In this paper we show how an appropriate arrangement allowed us to follow this surface wave along a cm-long wire connected to the laser irradiated target, and to reveal its pulsed nature. The pulse propagated along the wire at a velocity close to the speed of light, while retaining its pulse shape over centimetres of propagation.

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2. Experimental setup

The experiment was performed using the TARANIS laser at QUB [16], employing a CPA pulse of ~600 fs pulse duration with an energy ~5 J on target. The short pulse was focused by a f/3 off axis parabola onto ~10 µm thick and a few mm^2 gold foil at an intensity ~2×10^{19} W/cm^2. Following this interaction protons are accelerated from the rear surface of the foil via the TNSA process and are used as a charged particle probe for a separate portion of the target. A schematic of the experimental setup is shown in Fig. 1 (a). A stack of multilayer Radiochromic films (RCF) of type HD810 [17] was used as a proton detector. Due to the Bragg peak energy deposition profile of protons in matter, the proton image produced in a given layer of RCF corresponds primarily to a narrow range of proton energy, defined by the position of the RCF layer in the stack.

A particular target design (shown in Fig. 1(a)) was used for studying the charge dynamics far away (≥cm) from the interaction region. A thin (~75 µm diameter) and several centimeters long Copper wire was connected to the proton-generating gold foil. In order to maximise the length of wire that could be observed within the field of view of the probe beam, the Cu wire was folded into a square wave pattern (SWP) in front of and parallel to the interaction foil, as shown in Fig. 1(b). There were 8 segments in the SWP, as shown in Fig. 1(b), where the length of each horizontal wire segment was ~2.5 mm and the vertical spacing between two segments was ~600 µm. The distance between the proton source and the centre of the SWP was ~2.4 mm, whereas the RCF stack detector was placed at ~20 mm from the proton generating foil, providing a magnification of ~8.3 in the point-projection arrangement. The length of the Cu wire from the Au foil to the top of the winding in the SWP was approximately 12 mm, so that a EM wave launched by the interaction and travelling along the wire at a velocity close to the speed of light would be intercepted by the probe proton beam.

3. Time resolved detection of EM pulse propagation

Fig. 2 shows the data obtained in three consecutive layers of RCF in the stack detector, which show the propagation of the EM pulse in different segments of the SWP at different probing times. The darkness in the RCF images is proportional to the incident flux of protons of the given energy arriving at the RCF. For an electrically neutral metal wire, a proton radiograph would show a shadow (proton depleted region) of the wire due to multiple-small angle scatterings of the probe protons in the wire. In this case, the width of the shadow on the RCF will be equal to the product of the diameter of the probed wire and the geometrical magnification ($M=L/l$, where l and L represent the distance from the proton source to the probed wire and the RCF respectively). If the wire is positively charged, the probe protons will experience a strong Coulomb deflection. The width of the proton depleted region on the RCF will in this case be related to the strength of the electric field around the wire and the energy of the probe protons.

As can be seen in Fig. 2(a), the segment S2 appears to be charged to some positive potential, while the next wire segment, S3, remains electrically neutral. The conical shape of the proton deflected region around the segment S2, as highlighted by the red dashed line, indicates the rise of the electric field as the charge front moves along the wire from its left hand side, the side which is connected to the laser irradiated target. At a later probing time, as shown in Fig. 2(b), the segment S3 has become positively charged as evident from the increase of the width of the proton depleted region around S3. This suggests that the charge front associated to the surface wave has flown from S2 to S3 during the time elapsed between the snapshots shown in Fig. 2(a) and (b). In the following time frame (Fig. 2(c)), as expected, the charge appears to have entered into the line segment S4. However, it is interesting to observe that the line segment S1 and half of the line segment S2 are back to being electrically neutral at this time. The proton deflected region around S2 takes the form of a reverse conical shape, with the narrower side towards the laser irradiated target. The data therefore are consistent with the propagation of a localised pulse, with a finite temporal width and carrying positive charge. The propagation of this pulse is consistent with the previous observation of a surface EM wave generation and propagation discussed in [12] and [18]. In response to the sudden, positive charge-up of the laser-irradiated area of the target, the propagation of EM pulses away from the interaction regions contributes to lowering the target potential towards neutrality by carrying excess positive charge to remote regions of the target assembly or to ground.

4. Characterisation of the charge pulse profile

Quantitative information about the charge pulse temporal profile can be obtained from the data shown in Fig. 2. The energy (E_{proton}) with which each of the RCF layers shown in Fig. 2 is labelled refers to protons reaching their Bragg peak in the layer, as obtained from SRIM [19] simulations. The probing times labelled at the top right hand corner of the RCF images shown in Fig. 2 correspond to the time of arrival of protons with this energy at the centre of their field of view (see Fig. 3 for a schematic of the

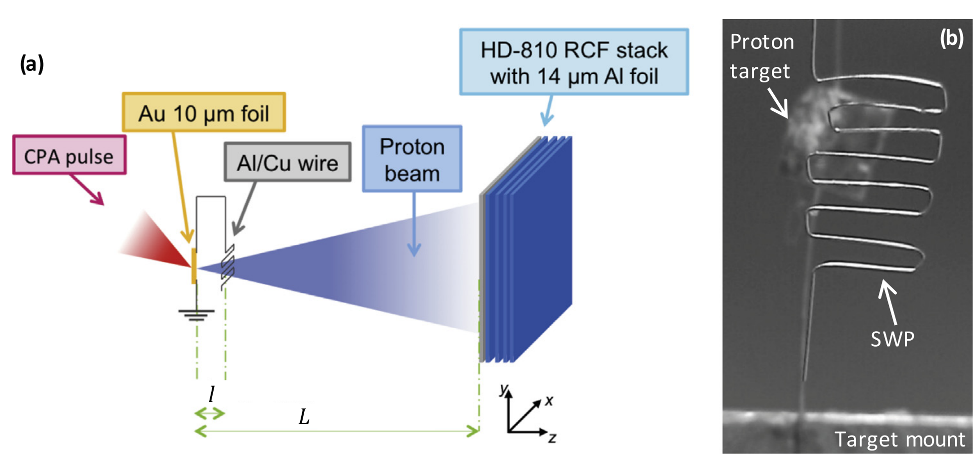

Fig. 1. (a) shows a schematic of the experimental setup used for probing the flow of the discharging current in a wire connected to a laser irradiated target in a self proton probing (SPP) arrangement. (b) Image of the square wave pattern (SWP) target used in the experiment, taken by a 8 bit CCD camera.

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