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Charge dynamics and proton acceleration in ultrashort laser-solid interactions

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INTRODUCTION

The acceleration of multi-MeV ion beams following the interaction of short (t_l ~ ps or less) and intense ($I > 10^{17}$ W/cm^2) laser pulses with thin solid foils has been one of the most active areas of research in high field science in the last few years [1]. The high brightness, multi-MeV high energy spectral cut-off and the excellent degree of collimation and laminarity [2] distinguish these ion beams from those observed in earlier works, making them suitable for a range of applications like proton radiography, radioisotope generators, high energy density matter production or proton driven fast ignition [3-4].

At the irradiation regimes currently accessible experimentally the most relevant mechanism for ion acceleration is the so-called Target Normal Sheath Acceleration (TNSA) [5]. During the interaction with the front surface plasma, the laser pulse transfers its energy, via a number of processes, to a population of fast electrons. The fast electrons propagate to the rear surface of the target, where they form a dense electron plasma sheath. The electric field associated with the plasma sheath, which can be of the order of a few TW/m, ionizes the back of the target and starts accelerating the ions normal to the target surface. After this initial phase the

acceleration proceeds as a plasma expansion into a vacuum, and a well defined expanding ion front is formed. At this stage the accelerating electric field peaks at the ion front, due to the co-moving plasma sheath. As the beam expands the initially fast electrons progressively transfer their energy to the ions and the field decreases until the acceleration ceases.

We report here on the first direct experimental measurement of the electric fields responsible for the acceleration of high energy protons from a thin foil irradiated by an intense ($I \sim 3.5 \times 10^{18}$ W/cm^2) and short ($t_l \sim 1.5$ ps) laser pulse [6]. The measurement was performed employing an auxiliary laser-accelerated proton beam as a transverse charged particle probe in the Proton Projection Imaging and Proton Mesh Deflectometry arrangements [3].

EXPERIMENTAL RESULTS

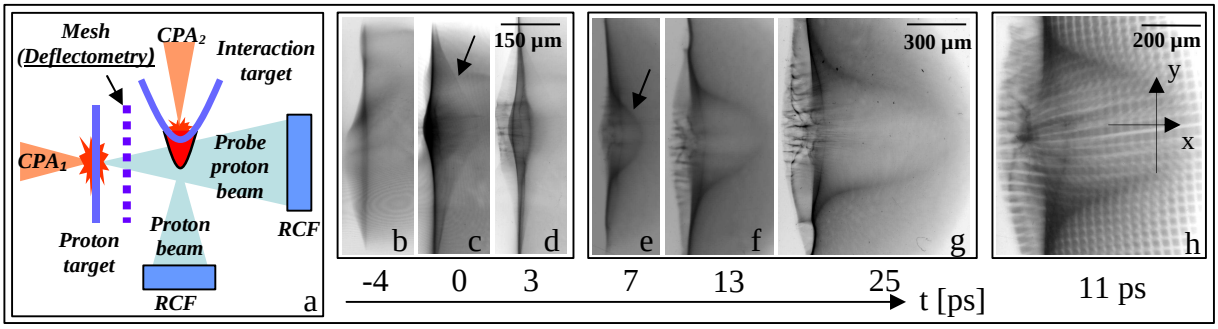

Fig. 1: (a) *Proton Imaging and Deflectometry experimental set-ups.* (b-g) *Proton Imaging and* (h) *Deflectometry typical experimental data.*

The experiment was carried out employing the LULI 100 TW system operating in the Chirped Pulse Amplification mode (CPA). Two laser pulses (CPA_1 and CPA_2) were focused onto two separate targets leading to the acceleration of a proton beam from each target (Fig. 1a). CPA_1 was focused onto 10 to 40 µm thick aluminium and gold foils (*interaction target*) at an intensity of $\sim 3.5 \times 10^{18}$ W/cm^2. CPA_2 was focused onto a ~10 µm thick gold foil (*proton target*) at an intensity of $\sim 2 \times 10^{19}$ W/cm^2. The proton beam from the proton target was employed as a transverse charged particle probe for the accelerating electric fields at the back of the interaction target. The interaction targets were bent in order to minimize the effect of global target charge-up [3], which would have prevented from probing close to the target surface. The time delay between CPA_1 and CPA_2, and therefore the proton probing time, could be optically adjusted with ps precision. The proton beams were detected employing stacks of several layers of Radiochromic films (RCFs). The multi-layer arrangement of the detector provided a spectral multi-frame capability. Thanks to the time of flight arrangement,

this resulted into a temporal multi-frame capability within a single laser shot for the proton probing line [3].

Two qualitatively different structures are observed in Proton Imaging data. Around the peak of the interaction of CPA_1 with the interaction target a transient (t = 0), pronounced deflection of the probe protons is observed (Fig. 2c, indicated by the arrow). The deflection vanishes after a few ps, as can be seen by comparing Fig. 2c-d, and can be attributed to the strong electric field associated with the initial dense and hot electron sheath. At later times (t > 0) a front expanding from the back of the interaction target is observed (Fig. 2d-g), which can be related to the electric field driving the proton beam expansion after the initial phase [5]. The experimentally measured final velocity of the expanding front is 3-4 × 10^7 m/s, which is consistent with the detected high energy spectral cut-off of ~ 6-7 MeV of the proton beam emitted from the interaction target. The front gains about 70 % of the final velocity in the first 2-3 ps after the interaction, while only 30 % of the final velocity is acquired at later times, indicating that the proton beam emitted from the interaction target gains most of its final energy during the initial phase of the acceleration process.

A more quantitative information on the electric field driving the late times acceleration of proton beam was provided by Proton Deflectometry data. The deflection pattern observed in the proton deflectograms (Fig. 1h) reveals an electric field which peaks at the expanding front. The time and spatially integrated electric field value can be estimated by measuring the mesh lines shift in the deflectograms. Referring to Fig. 1h the peak electric field at the expanding front can be estimated to be of the order of a few 10^9 V/m.

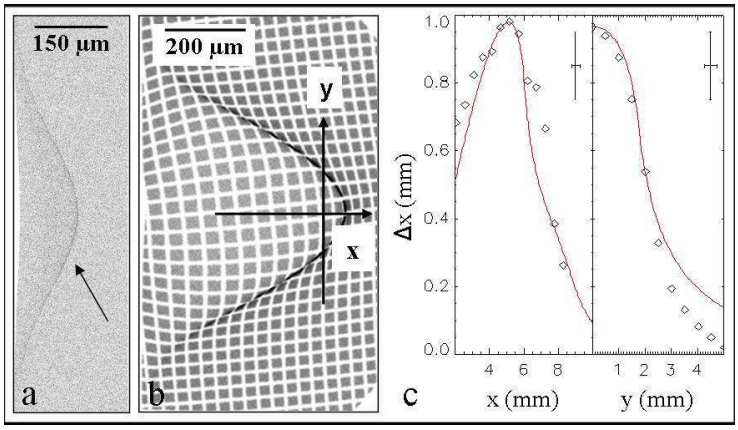

Fig. 2: (a) *Particle tracing simulations of Fig. 1c and* (b) *of Fig 1h experimental data.*
(c) *Comparison of the deflection in the x direction measured along the x and y axes in the experiment (scatter graph) and in the particle tracing simulations (line).*

A more detailed characterization of the accelerating fields was obtained by comparison of experimental results with numerical simulations of the propagation of a probe proton beam through a given time-dependent electric field structure (*particle tracing simulations*). We first simulated the deflection in the transient field corresponding to the case of Fig. 1c. The experimental results could be best reproduced (Fig. 2a) by assuming a field with peak intensity of the order of 4-5 × 10^{11} V/m at the target rear surface and with a finite extension of ~ 20 μm. A finite extension for the electron plasma sheath, resulting in a finite extension for the accelerating fields, was also suggested in [7]. We then simulated the field associated with the expanding ion front, corresponding to the case of Fig. 1d-h. The simulation confirmed that an electric field with the expected peaked structure is required in order to best reproduce the experimentally observed probe proton deflection (Fig. 2b-c). The peak field value of 2 × 10^{9} V/m inferred from particle tracings is in good agreement with the estimation previously given. Experimental results were compared with 1-D fluid and Particle In Cell (PIC) simulations of the expansion of a thin plasma into a vacuum. The simulations take into account that the amount of energy initially stored in the hot electron population is finite, leading to a finite high energy cut-off in the proton spectrum. The initial electron sheath field and the peaked structure of the field at the ion front were observed in the simulations, with a peak field intensity in good agreement with the experimental findings. Excellent agreement with the experiment was also found concerning the evolution in time of the expanding front position and velocity as well as the final proton spectrum.

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