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Detailed studies of the transverse beam characteristics of laser produced ion beams

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Introduction

The acceleration of ions with intense lasers is, also due to the possible applications like fast ignition [1] or isotope production for medical issues [2], an actual field of research. Since the discovery of intense ion beam emitted from thin foils irradiated by ultra-intense lasers various experiments have shown these beams at different laser systems with similar properties. The ion beams are collimated, very intense and reach energies up to 50 MeV [3].

Under the conditions of the experiments described in this article the ions are accelerated from the non irradiated rear surface of the target [4]. The underlying accelerating mechanism is called Target Normal Sheath Accerleration (TNSA) [5], where energetic electrons created in the laser focus propagate through the target and build up an electrostatic field on the rear side of the target. This field, which reaches typically 10^{12} V/m, confines the electrons and forces them back into the target.

The electrostatic field also ionizes the rear surface and accelerates these ions afterwards. Due to the vacuum conditions there are normally contaminants on the surface of the target, which also contain hydrogen (water, hydrocarbons). These contaminants are the cause for the existence of protons, which are also accelerated by the electric field. As the protons gain energy due to their charger over mass ratio faster speed than the other ion species, they are running in front of the other species, shielding the field and therefore inhibit their acceleration. Thus, as long as there are contaminants on the target, there are mainly protons accelerated.

The ions emitted from the surface are accompanied by electrons, which neutralize the high space charge and currents, which is a necessary condition to prevent the blow up of the beam.

The described acceleration mechanism provides ion beams with unique properties. Besides a high single bunch charge (1 µC), high currents (50 MA), and a short emission time (<10 ps), also the spatial quality of the beam is superior. As the protons are extracted from the cold rear surface of the target, the intrinsic motion of these particles is very low. Experiments have shown, that the emittance is smaller than 0.002 mm mrad [6], theoretical assumptions predict even a smaller value. This opens the possibility to image objects with the proton beam with a high resolution [7].

Another feature of this acceleration is the imaging of surface structures of the target into the proton beam. Small grooves on the target lead to a focusing of the beam at an early state of acceleration, which finally ends up in a spatial intensity modulation of the beam. Due to the high beam quality these modulations are transferred with a thousand fold magnification to the ion detector, which gives an enlarged picture of the target surface. This allows to study the proton beam characteristics at the beginning of the acceleration.

Experimental Setup

The experiments were performed at the 100 TW LULI laser, the Vulcan Petawatt and the Trident laser in Los Alamos. These systems deliver sub-picosecond laser pulses with energies between 10 and 300 J reaching in the focus intensities between 5×10^{18} and 5×10^{20} W/cm^2. The laser systems have typically a prepulse due to ASE pedestal and leakages in the regenerative amplifiers with a contrast in intensity of approximately 10^{-6}.

The targets used in the experiments were 10 to 50 µm thick foils of gold, aluminium and tungsten. On the rear side of the target small structures were engraved to produce intensity modulations in the proton beam. Due to the prepulse the main pulse is interacting with preformed plasma of a typical scale length of several µm.

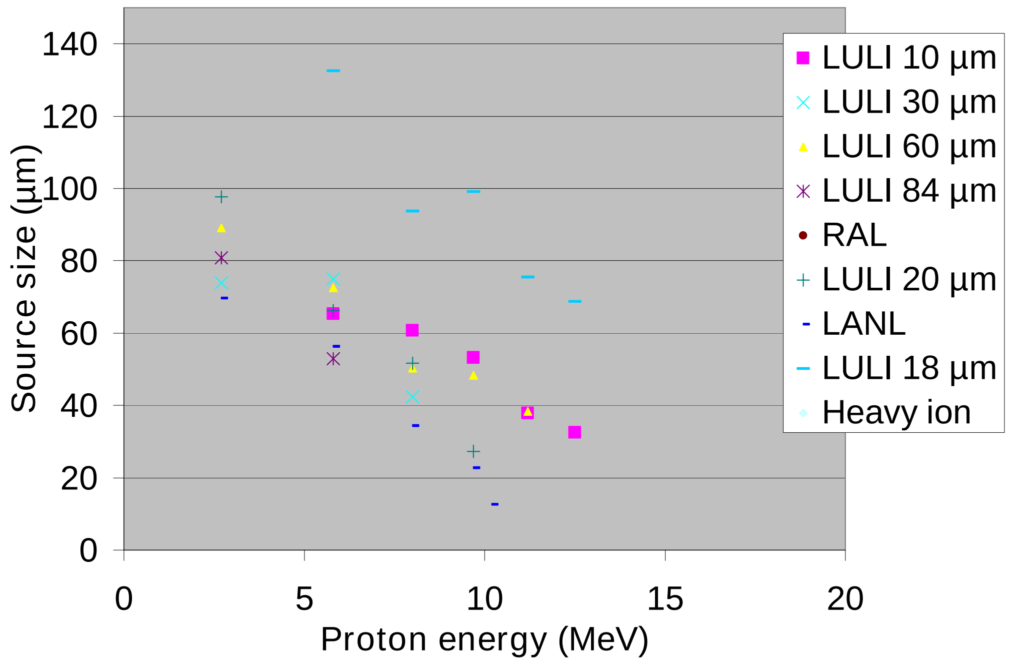
The protons, emitted form the target, are detected with “Radio Chromic film” (RCF) [8], a polymer which is sensitive to ionizing radiation, to obtain a spatial profile of the beam. In addition, as the energy deposition of the protons in the film is the highest at the end of the penetration depth, the film is most sensitive to the protons which are stopped in this layer. Usually in the experiments a stack of RCFs is used to obtain the spatial profile of the proton beam for several energies.

Results

The first part of the analysis is the shape of the structure. Besides of small deformations on the edge of the proton beam, the lines are straight and equidistant. A local emission angle of the protons, which is proportional to the distance to the centre of the beam, will lead to equally spaced lines. As the local emission angle is proportional to the gradient of the electron distribution [9] this predicts a quadratic electron sheath.

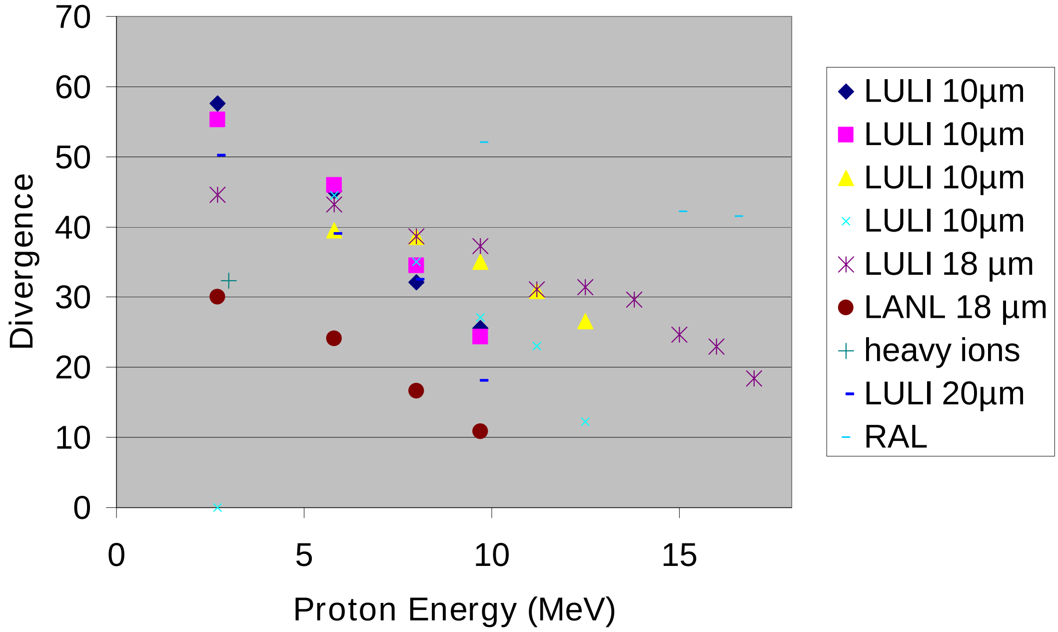
Assuming an axial symmetry of the electron sheath, we can deduce the shape of the electron sheath from the deformations of the pattern of the proton beam. Also here we find that only a parabolic sheath produces the observed straight lines [10].

Analysing the source size of the proton beam in dependence of the proton energy, as shown in the figure below, indicates, that this dependence has a similarity which seems to be only characterized by the maximum energy E_{max} and the source size at E=0, d_{max}.



It's remarkable, that the d_{max} doesn't depend significantly on the target thickness but on the laser intenstiy.

Plotting the divergence over the proton energy shows a similar behaviour. Also here we have similar curves, which have the maximum energy and the maximum divergence as a free parameter. The linearity between the distance from the centre of the beam and the divergence angle implies that we have here the same similarity as for the source size as seen in the figure below. The divergence plotted here is the full opening angle of the beam.



Summary

We present the first systematic measurement of the transverse parameters of laser produced proton beam. We find a similarity for the shape of the accelerating sheath, which is always close to a parabola. We find also a similarity for the relation between source size and proton energy with the maximum source size and proton energy as a free parameter, which is confirming the similarity we already found for the sheath shape.

This is of particular interest for the application of laser produced proton beams as it shows the scalability of the transverse beam parameter.

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