Laser driven ion acceleration from ultra thin foils in the ultra relativistic intensity regime

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The measurements reported here provide scaling laws for the acceleration process in the ultra-short regime and access ion acceleration conditions never investigated before. The scaling of accelerated ion energies was studied by varying a number of parameters such as target thickness (down to 10 nm), target material (C and Al) and laser light polarization (circular and linear) at normal laser incidence. A pronounced increase in the C^{6+} ion energy up to ~238 MeV has been observed for ultrathin (10-100 nm) carbon targets. Furthermore, it is seen that measured peak proton energies of about 20 MeV are observed almost independently from the target thickness over a wide range (10 nm-10 µm), and the target material (insulator and conductor) and laser polarisation doesn't play a significant role on the maximum proton energy for target thicknesses < 50 nm. The results can be explained by the specific electron dynamics at ultra-high contrast and ultra-intense laser target irradiation. 2D PIC simulations are in good agreement with the experimental findings.

Rapidly growing interest in laser driven ion sources has been stimulated by their potential applications such as high resolution charged-particle radiography [1], production of high energy density matter of interest for astrophysics [2], high brightness injectors for accelerators [3], sources for proton therapy (requisite energy>200 MeV) [4] and ignition of controlled thermonuclear fusion. However, challenges remain for these potential applications in further improvement of the beam specifications and the development of high repetition-rate bright sources. In these contexts, the main trend of current research concerns the increase of maximum ion energy.

Recent advances in laser technology have led to laser systems with high contrast and extreme intensity values, which have opened up new perspectives in the field of laser-matter interactions. The laser acceleration of ions to multi-MeV energies from thin foils has been investigated extensively during the last decade using intense laser pulses (10^{18}–10^{20} W/cm^2) [5 and references there in]. Ions are mainly accelerated in space-charge fields created by laser generated relativistic electrons which penetrate through the target and create the electrostatic sheath field up to several MV/μm at the target rear (Target Normal Sheath Acceleration – TNSA mechanism [6]). These accelerated ion beams have unique properties e.g. small angular divergence and high laminarity but also have large energy spread, slow energy scaling with the laser intensity and low laser to ion energy conversion efficiency. Currently the highest proton energies (~60 MeV) and conversion efficiencies (CE) (~10%) have been obtained using Nd:Glass PW laser systems providing 100s of Joules in ~ps (or several 100s fs) pulses. These systems are large-scale, costly and have very low repetition rate. Obviously, for any application the use of smaller scale high-repetition rate Ti:Sa systems is preferable, which now enable access to intensities above 10^{20} W/cm^2. In view of source development and potential applications, determining energy scaling laws or the efficiency of the acceleration process in these conditions is very important. The scaling of proton energy using ~50 fs laser pulses at intensities ranging 10^{18}–10^{19} W/cm^2 has been reviewed in [7, 8] and CE of about 1 % have been inferred.

In this paper we discuss the dependence of protons energy and ion flux on target thickness measured along several directions: rear surface target normal-RSTN, 10^0 to RSTN and front surface target normal-FSTN under 35° laser irradiance on the target with linearly polarised light. The proton energy dependence on target thickness at normal incidence has also been investigated.

Our experiment has been carried out on ASTRA-Gemini laser at Rutherford Appleton Laboratory, which delivers 12 J ultra-short (~50 fs) pulses at central wavelength 800 nm. The intrinsic intensity contrast of 10^7 at 20 ps prior to the pulse peak was enhanced to the level of ~10^{10} employing a "double plasma mirror" system, which preserves the spatial focal spot qualities although the throughput laser energy is reduced to ~6J. An f/2 off axis parabola was used to focus the laser pulses to a spot size of diameter ~2.5 μm containing 35% of laser energy. Thus, unprecedented intensities of about 5×10^{20} W/cm^2 could be reached. Al targets with the thicknesses varying from 10 nm up to 10 μm were irradiated to this intensity. Absolutely calibrated micro-channel-plate (MCP) detectors coupled to phosphor screen were used to registered ion emission [9].

Fig.2 shows, the maximum proton energies detected along the different lines for a laser incidence angle on target of 35° are plotted versus the target thickness. These maximum values of proton energies are out of at least 4-5 shots at the same thickness. In the RSTN direction, the data show a slow increase in proton energies, which stay almost constant below 100nm thickness. This slow increase has been well estimated by A Andreev's [10] model with a modification taken into account for quasi-neutrality in case of thick targets. The maximal proton energy can then be estimated as:

$$\varepsilon_{p\,max} \approx \left(\frac{3}{4}T_{eh}f + T_{eh}f^{3/2}\frac{2\sqrt{2}}{3^{3/4}} + \frac{3}{4}T_{eh}f\frac{n_p l_p}{Zn_i l_i} + f^{1/2}\sqrt{4\pi e^2 T_{eh}}\frac{n_p l_p}{\sqrt{Zn_i}}\right)\frac{1}{\sqrt{1+(r_{De}/l_i)^2}} \qquad (1)$$

where $n_{p,i}$, $l_{p,i}$ are proton, ion (charge Z) density and layer thickness, $r_{De} = \sqrt{T_{eh}/4\pi e^2 n_{eh}}$ is the Debye radius, T_{eh}, n_{eh} are temperature and energy density of hot electrons, $f \propto 1$. The first and second terms in (1) are the proton energies accelerated in the electrostatic sheath field, and the third and fourth terms describe the energy gained by Coulomb explosion of proton layer. The hot electrons are cooled down adiabatically: $T_{eh} \approx T_{e0}/(1 + (l_i/d_L)^2)$, where $T_{e0} = mc^2\sqrt{1 + a^2}$ is the initial temperature and d_L is the laser spot size. The calculated solid black line in Fig.1 describes well the experimental findings. Similar trend is observed along the 10° direction.

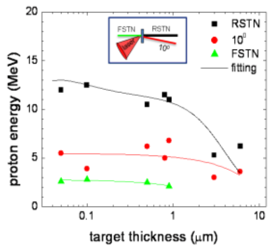

Fig.1 Maximum proton energy variation with target thickness along the measured directions: rear surface target normal (RSTN), 10^0 to RSTN and front surface target normal (FSTN). The solid line is fit calculated from the model. Other two dashed lines are guide for the eye. Aluminums targets were irradiated under 35^0 laser incidence

The effect of target thickness on number of ions emitted in 9 nsr solid angle (hereafter is called as ion flux) under 35° incidence is shown in fig2. Along the RSTN direction both proton and carbon ion flux (see fig 2a) increases with the decrease in target thickness and about an order of magnitude gain in flux is observed going from 6µm thickness down to 100nm. A relatively slow increase in proton flux along 10° is shown in fig.2(b). However, carbon ion flux was detectable only below 100nm thickness.

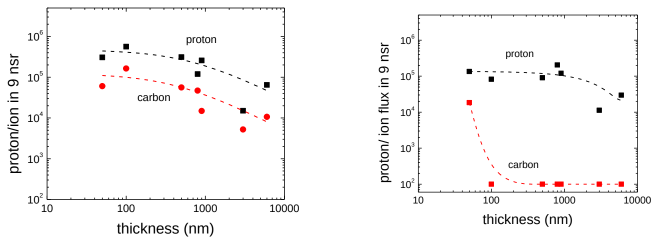

Fig.2 Proton and carbon ion flux variation with target thickness along the measured directions: rear surface target normal (RSTN) and 10^0 to RSTN. The solid lines are guide for the eye. Aluminums targets were irradiated under 35^0 laser incidence.

The effect on proton energy was also investigated for normal laser incidence on the target. In fig.3 proton energy as a function of target (Al) thickness with linearly polarised light has been plotted. Surprisingly, over a vast range of thickness (from 10 μm down to 50 nm) it was found that the maximum proton energies were almost similar. This is still being investigated looking at detailed electron dynamics.

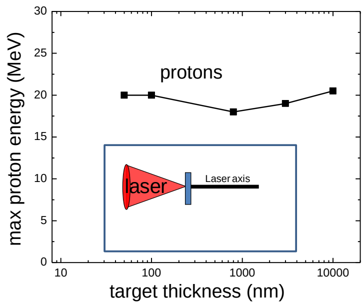

Fig.3 Maximum proton energy variation with target thickness along forward laser axis direction at normal incidence. Solid line is only guide for eyes. The experimental sketch is briefly shown in inset figure.

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