Proton scaling measurements using the Vulcan Petawatt laser

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Introduction

Laser-driven plasma accelerators offer the prospect of compact sources of high energy particles and radiation. Recent international efforts have led to a number of key advances in the development of laser-driven sources of high energy electrons and ions, including the generation of quasi-monoenergetic beams[1,2,3,4,5]. In the interaction of intense laser pulses with thin target foils, protons, arising from thin hydrogenated layers on the target surfaces, are accelerated to tens of MeV energies and with low transverse and longitudinal emittance. Due to unique spatial and temporal properties there is great interest in controlling the production of these multi-MeV proton beams for a number of possible applications including medical isotope production[6,7,8], proton therapy[9,10], proton imaging[11], injection into large accelerators[12], and as a fast ignitor beam for laser-driven fusion[13]. Fundamental to the development of laser-based sources for these applications are investigations of the scaling of proton acceleration as a function of laser pulse parameters.

Although several experimental[14] and theoretical[15] results are reported in the literature on the scaling of proton energy with laser pulse parameters, due to the variety of pulse and target conditions it is difficult to develop a clear picture of the scaling laws. Recent work by Oishi *et al.*[16] reports proton scaling using ultrashort (55 to 400 fs) lasers at intensities up to 1.1×10^{19} Wcm^{-2} and a paper by Fuchs *et al.*[17] addresses laser driven proton scaling for pulse energies in the range 0.2 to 10 J, with corresponding intensity up to 6×10^{19} Wcm^{-2}. Both groups report experimental results which compare well with proton energies calculated using the plasma expansion model described by Mora[18].

In this article we present measurements from an investigation of proton energy and laser-to-proton energy conversion efficiency scaling for laser pulse durations in the range 1 to 20 ps and for pulse energies up to 400 J and intensities up to 6×10^{20} Wcm^{-2}. We discuss our findings in the light of previous results and predictions of a revised plasma expansion model.

Experimental

The petawatt arm of the Vulcan laser was used in this study. It delivered 1.054 µm pulses, *p*-polarised and at an angle of 45° onto Al target foils of thickness 10 µm and 25 µm. The pulse energy delivered to target was varied between 20 and 400 J. For a spot size of 6 µm diameter at FWHM, intensities in the range 4×10^{19} to 6×10^{20} Wcm^{-2} were achieved. The pulse duration was varied from 1 to 20 ps by altering the grating separation in the stretcher. The level of the ASE pedestal intensity was measured to be 10^{-7} at a few ns prior to the peak of the main pulse, and 10^{-6} of the peak pulse intensity at a few ps. These measurements were made with a fast photodiode and oscilloscope, and a 3rd order autocorrelator, respectively.

The experimental arrangement is shown in figure 1. The main diagnostic of multi-MeV proton acceleration was proton-activation of stacks of Cu pieces (ranging in thickness from 25 µm to 1 mm), positioned 5 cm from the rear of the laser-irradiated target. This diagnostic technique has a lower energy threshold of ~4 MeV, as defined by the threshold of the ^{63}Cu(p,n)^{63}Zn nuclear reaction and an upper energy threshold exceeding 80 MeV, as defined by the thickness of the Cu stack. By convoluting the measured activity with the stopping power of protons in Cu and the energy dependant cross section, a proton energy spectrum, integrated over 1 sr solid angle, is extracted. The activity in each Cu foil is determined by measurement of the positron emission decay of the ^{63}Zn isotope[6] (half-life 38.1 minutes).

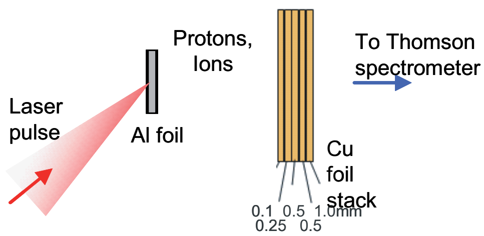

Figure 1. Experimental arrangement. Vulcan petawatt laser pulses are focused onto 10 and 25 µm Al foil targets. The accelerated proton energy spectra are measured by proton activation of Cu foils.

Results and Discussion

Figure 2 shows a typical proton energy spectrum. We discuss measurements of two parameters of interest, the maximum proton energy and the laser-to-proton energy conversion efficiency, as a function of various laser parameters. We define the maximum proton energy as the energy corresponding to the lower detection threshold of the diagnostic technique (10^6 protons/MeV/sr). The conversion efficiency is calculated by integrating the total energy in the proton beam from the diagnostic lower energy threshold limit to the maximum proton energy, and dividing by the laser pulse energy.

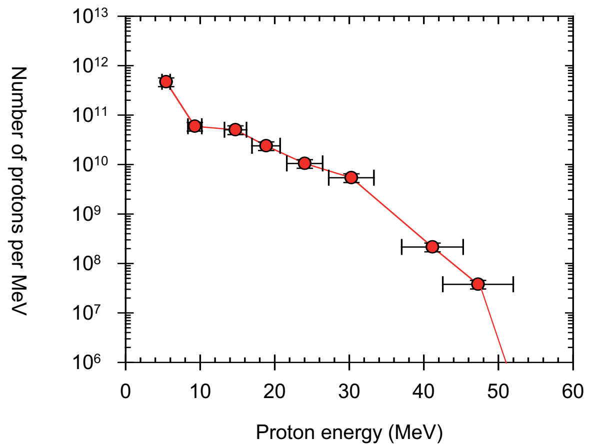

Figure 2. Typical proton energy spectrum, as measured by proton activation of Cu foils.

The scaling of the maximum proton energy as a function of laser intensity from 4×10^{19} Wcm^{-2} to 6×10^{20} Wcm^{-2} is shown in figure 3. For these measurements the pulse duration is held constant at 1 ps, and the laser energy and therefore intensity are varied. The maximum proton energy is observed to increase with a simple power scaling with an exponent of 0.5 ± 0.1, up to a maximum value of ~55 MeV at 6×10^{20} Wcm^{-2}. This scaling relation is in very good agreement to measurements reported by Clark *et al.*[19], for intensities between 10^{18} Wcm^{-2} and 10^{20} Wcm^{-2} for protons measured at the front of laser-irradiated foil targets.

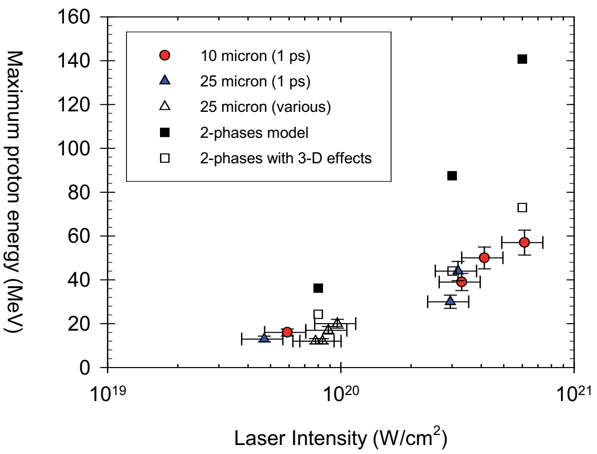

Figure 3. Maximum proton energy detected as a function of laser intensity, by variation of laser energy with constant pulse duration of 1 ps (except unfilled triangles, for which the energy and pulse duration are varied). The squares are results of a 1-D two-phases model, with (unfilled) and without (filled) 3-D effects mimicked (details in the main text).

The energy conversion efficiency as a function of laser energy, and therefore intensity, for a constant pulse duration of 1ps is shown in figure 4. Efficiencies of up to 6% are observed and compare well with values previously reported in the literature [20,21]. We measure a linear dependence of the conversion efficiency on the laser energy for both target thicknesses (the thinner target exhibits higher conversion efficiencies at all laser energies).

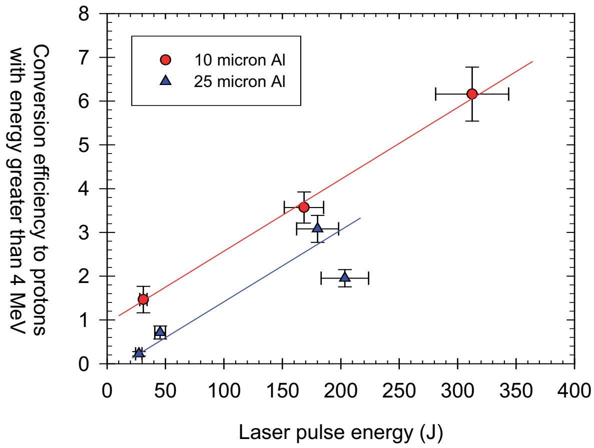

Figure 4. Energy conversion efficiency (as a percentage) from laser pulse to protons with energies greater than 4 MeV, as a function of laser energy, for constant pulse duration of 1 ps.

The variations of the maximum proton energy and the energy conversion efficiency with laser pulse duration from 1 to 8 ps is shown in figure 5. The pulse energy is varied such that the intensity is held constant at ~$(8\pm1)\times10^{19}$ Wcm^{-2}. A relatively weak dependence of both the maximum proton energy and the conversion efficiency with the laser pulse length is observed – from 19 MeV and 0.7% at 1 ps to 24 MeV and 1.5% at 8 ps. Two further laser shots (not shown in the figures) at 12 ps, 5×10^{19} Wcm^{-2} and 20 ps, 3×10^{19} Wcm^{-2} yielded a considerable reduction in proton flux (with energies above the 4 MeV threshold) at these lower laser intensities.

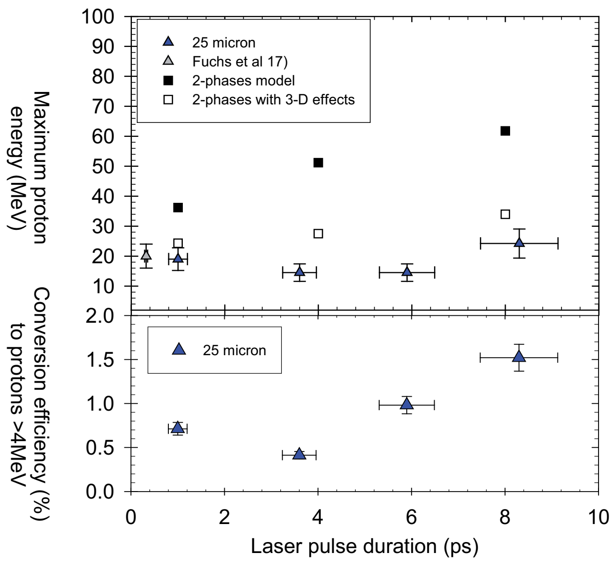

Figure 5. Maximum proton energy and conversion efficiency (as a percentage) as a function of laser pulse duration, by variation of laser energy to maintain a given intensity of 8×10^{19} Wcm^{-2}. Model results same as figure 3 legend.

We note that even though at the lower end of our intensity range our measurements are in good agreement with measurements reported by Fuchs *et al.*[17] (figure 5), we find different scaling relations for the higher intensity regime of the present measurements. Furthermore, although the measurements reported by Fuchs *et al.*[17] compare favourably with calculations using an isothermal plasma expansion model described by Mora[18], we find that the model, when applied in the same way to our laser pulse conditions, greatly overestimates the maximum proton energies observed.

We also used a revised form of this one-dimensional model, for which a more realistic temporal variation of the hot electron temperature driving the ion acceleration replaced the isothermal assumption. The model involves two phases. First the electron temperature rising linearly and then decreases adiabatically as described by Mora (2005)[22]. In addition, to mimic the three-dimensional effects (not normally included in the model), the acceleration in the second phase was stopped when the plasma longitudinal expansion becomes a factor of two larger than the initial extension of the electron cloud at the rear of the target. The details of this work will be presented at a later date. As shown in figures 3 and 5, the maximum protons energies obtained compare favorably with the experimental results.

Summary

The fundamental scaling of the transfer of laser energy to proton acceleration, via electron transport in thin foils, has been addressed in this work. Experimental data in a new laser energy and intensity regime is obtained and has helped to benchmark and develop a plasma expansion model.

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