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Laser ion acceleration with micro-grooved targets

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Abstract

This paper reports on recent results of a series of experiments on laser-generated ion beams. The experiments were done at the 30 TW 'Trident' laser system at the Los Alamos National Laboratories in New Mexico, USA, and we demonstrated the first accelerated ions at the 10 TW beamline of the PHELIX laser system at Gesellschaft für Schwerionenforschung, Darmstadt, Germany. The experiments show the dependence of the Target Normal Sheath Acceleration Process (TNSA) on laser imprint and target parameters. The results are compared to a simple model for the ion propagation. It shows that TNSA-driven protons form an ion beam with superior beam quality, following the versatile spatial beam-shaping approaches.

1. Introduction

Charged particles accelerated up to energies of several mega electron volts (MeV) have been observed from laser plasma interaction for more than 20 years. Early experiments with long pulse (several nanoseconds) lasers incident on thin foils and wires observed protons and multiply charged ions up to velocities of 10^9 cm/s (e.g. 0.5 MeV for protons). It was shown that these protons and carbon ions were present regardless of the target material due to hydrocarbon contaminants inside the vacuum system [1].

The irradiation of thin foils with modern, ultra-intense, short laser pulses leads to the generation of MeV ion beams from the non-irradiated target rear side [2]. The accelerating mechanism was identified to be the build-up of a dense sheath of energetic electrons at the non-irradiated, rear surface of the target resulting in an electric field strength exceeding 10^{12} V/m. The acceleration was found to take place within a few picoseconds only. The beam is always directed normal to the local rear surface of the target with an emittance being superior compared to conventional accelerator beams [3,4].

The mechanism is known as Target Normal Sheath Acceleration (TNSA) and explained in detail in Refs. [5,6]. Briefly, relativistic electrons generated by the laser plasma interaction, having an average temperature of several MeV, envelope the target foil and form an electron plasma sheath on the rear surface. The electric field in the sheath scales as $E_{\text{stat}} \sim kT_{\text{hot}}/e\lambda_D$, $\lambda_{\text{D}} = (\varepsilon_0 kT_{\text{hot}}/e^2 n_{\text{e,hot}})^{1/2}$. A few monolayers of atoms at the rear surface are field ionized and accelerated normal to the surface with the most energetic electrons always extending further out into the vacuum, maintaining the accelerating field as long as the electron temperature is high. Because of the accompanying electrons, the ion beam is space charged and current neutralized. The conversion efficiency from laser energy to ion beam energy can be quite high and efficiencies of 10% have already been measured [2]. As will be shown below, the extreme strong, transient acceleration that takes place from a cold, unperturbed surface, results in the low beam transverse emittance of $\varepsilon < 10^{-4}\,\pi$ mm mrad that may be limited only by collisions with the co-moving electrons during the acceleration. Because of the initial thickness of

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the sheath of the order of the Debye length (a few micrometers), the local target orientation can result in density fluctuations, which will be preserved during the subsequent ion beam propagation [2].

Compared to the acceleration gradients achieved in conventional accelerator technology, this gradient turns out to be about six orders of magnitude larger.

2. Experiments

For further investigation of the accelerating mechanism of the ions, the virtual institute VIPBUL was formed, including Gesellschaft für Schwerionenforschung mbH (GSI) as the participating Helmholtz center [7]. The experiments presented in this paper were focused on the problem of laser beam imprint on the ion acceleration and furthermore on first experiments at the GSI PHELIX laser system. In all the experiments, laser intensities of more than 10^{18} W/cm^2 were achieved by focusing several Joules of laser energy of sub picosecond pulse duration onto thin target foils.

A new quality of experiments had become possible after it was demonstrated that patterns on the target surface can cause an imprint in the transverse ion-beam density distribution leading to a one-to-one image of the target on the detector plane. At the University Darmstadt, we have therefore established a target laboratory to precisely design and construct target foils of various thickness and material, all having a well known rear target structure available for acceleration experiments. Thus we could directly determine, in a single shot, the most important beam properties like real source size, divergence angle, emittance and, by reconstructing the shape of the accelerating electron sheath, distortions in the electron transport through the target. An example of a structured target rear surface is given in Fig. 1.

The electron transport is strongly dependent on the target material, e.g. conductivity, and also on the laser parameters. It was found in earlier experiments that the transverse shape of the laser beam strongly influences the transverse shape of the proton beam, see Ref. [8] for details. In [8] the source size of the protons had to be estimated by the angular broadening of the electrons, transported through the target. It was fitted to 25°, a value that roughly fits the angle resulting from multiple Coulomb scattering. We have done experiments at the Trident laser facility at LANL, Los Alamos, to investigate the influence of the laser beam profile on the proton beam, this time with the knowledge of the rear source size at the rear surface.

The targets were thin (10–50 μm) gold foils, which had a micro-structured rear side with equally spaced grooves of 5 or 10 μm distance and less than 1 μm depth. The microstructuring of the rear surface leads to a micro-focusing of the protons following the local surface normal in the initial phase of the acceleration process. While in former experiments by our group the laser was focused to a nearly diffraction-limited spot with a radially symmetric beam profile, we have changed the laser to form a line focus (see Fig. 2). The target was a 13-μm-thick Au-foil with 10-μm-spaced lines at the rear side.

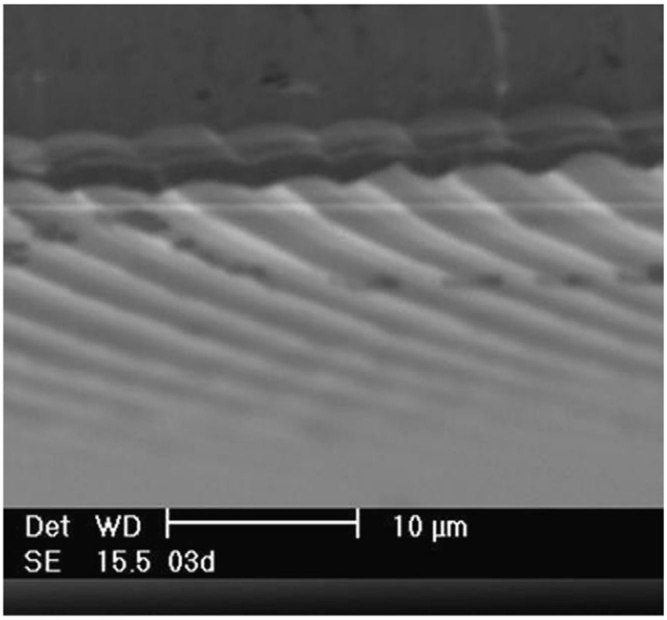

Fig. 1. SEM image of the target rear surface. Whereas the front surface is flat, the rear target surface is corrugated with lines, spacing between 3 and 10 μm and sub-micrometer groove depth.

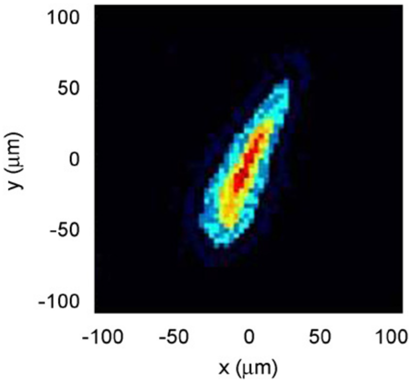

Fig. 2. Astigmatic laser focus, directly measured with a high-resolution CMOS-sensor with 3.5 μm pixel size.

The laser was focused to an intensity of 2.5×10^{18} W/cm^2. The left image in Fig. 3 shows the energy deposition of 5 MeV protons, recorded with a radiochromic film (RCF). In RCF, the deposition of ionizing radiation in an organic dye causes polymerization and a subsequent change in color from transparent to dark blue according to the amount of deposited energy. Due to the pronounced energy deposition of the ions at the end of their range (Bragg peak), stacking of RCF results in images of the transverse beam profiles at distinct energies. Originally designed for medical purpose and X-ray detection, we have absolutely calibrated the RCF for protons using the tandem linear accelerator at Max Planck Institut für Kernphysik, Heidelberg. The micro-structured

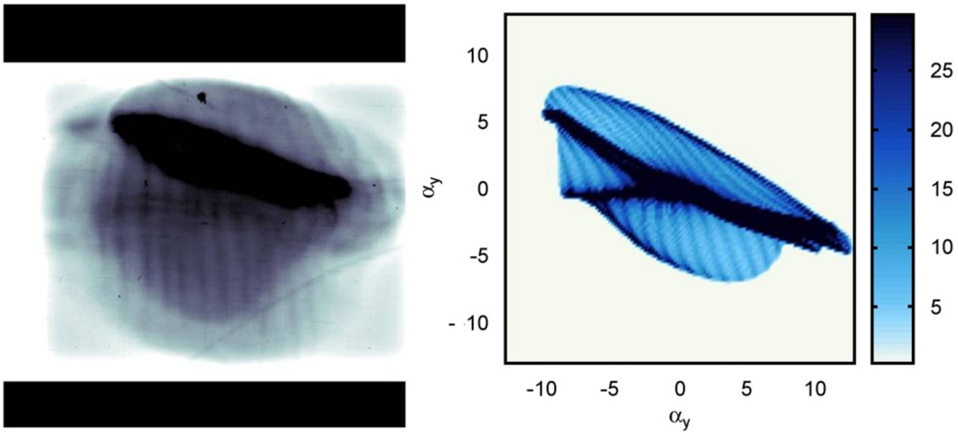

Fig. 3. Left: 5 MeV proton beam from the experiment with laser focus of Fig. 2; right: model including the line imprint reconstruction.

lines of the target rear side lead to the vertical lines in the lower part of the left image in Fig. 3.

The most intense feature shows an ellipse rotated by 90° with respect to the laser ellipse. This can be understood as an effect of the electron-sheath gradient. By simple line counting we determine the source size to be 130 μm for 5 MeV protons. This would correspond to an 150° FWHM angular broadening of the electron distribution while crossing the target. Applying a similar procedure as described in Ref. [8], and assuming only multiple Coulomb scattering for the broadening, we cannot reproduce the image in the RCF. The angular broadening of the electrons is calculated with Molières theory of multiple scattering by Bethe [9]. For the current laser parameters the hot electron energy is ≈0.7 MeV [10], this would result in a broadening of 21°, therefore the large angle is not due to scattering only.

Interpolating the laser focus image to the measured source size, a reasonable agreement with the RCF image can be simulated; see the right side of Fig. 3. While for thick targets ($>50\,\mu$m) the main contribution to the broadening of the electrons forming the accelerating sheath is from multiple scattering [8], this effect seems to be of minor importance for thin targets. Additionally for thin targets the assumption of a pure electrostatic acceleration seems to be wrong. Reasons for the observed source size could be recirculating electrons that travel back and forth on both sides of the target [11] or a transverse broadening of the sheath during the acceleration [4]. Nevertheless, the divergence of the protons in the vertical direction seems to be reduced compared to shot with round foci.

It is interesting to note that the experiments at the LANL Trident laser facility resulted in absolute proton spectra that well match the scaling law by Fuchs [12] and, concerning the maximum proton energy, Schreiber et al., [13]. The experiment shown in Fig. 4 was done at a total laser energy of 27 J on target in a pulse of 790 fs with a focus diameter of 20 μm. The target was a 10 μm palladium foil. Within the observed energy band, the absolute numbers as well as the slope of the spectrum, representing a Maxwellian of about 3 MeV, match the predicted values very well.

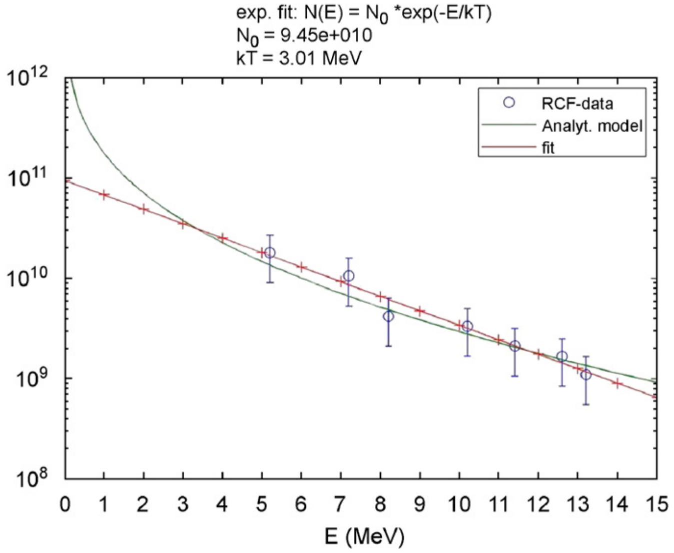

Fig. 4. Absolute proton spectra compared to the predictions in Ref. [8]. Absolute numbers as well as slope match very well. Details are given in the text.

Our recent experiments at different laser systems nicely show the robustness of the ion acceleration mechanism. While we have changed the laser energy, the target thickness as well as pulse length and focused intensity up to orders of magnitude the basic ion beam parameters scale very similar if normalized to the maximum proton energy. E.g. Fig. 5 shows the divergence of the proton beams for the different laser systems. Although the laser energy differed by a factor of 10 and the target thickness by a factor of 5, the divergence always follows a parabolic behavior, as indicated for one example by the red line.

In most of the experiments the beam patterns caused by the micro-structured targets and observed in the detector have straight lines or only minor deformations. Assuming axial symmetry, it is possible to show that these straight lines can be directly traced back to a parabolic ion front

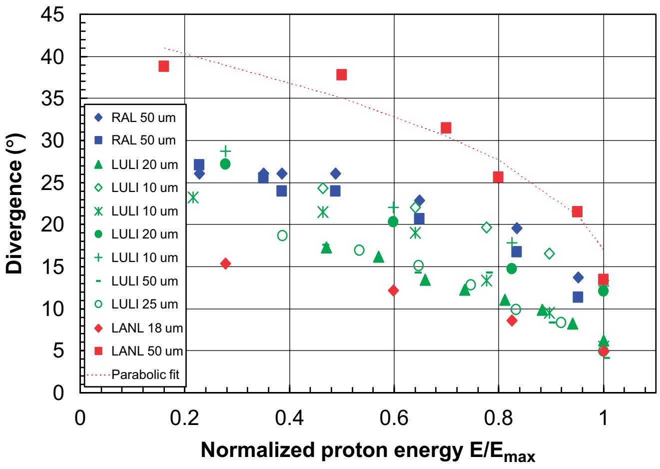

Fig. 5. Divergence of laser-accelerated protons versus normalized proton beam energy. Note that the laser systems differ in energy by a factor of ten and in target thickness by a factor of five.

[14]. Moreover, a parabolic ion front results in equidistant lines, which is in agreement with the experiment. The parabolic ion front seems to be a common feature in laser ion acceleration, as the beam pattern with nearly straight lines has been observed in all experiments using structured targets independently of laser and target parameters.

Till date there is no theoretical model predicting a parabolic ion front. Comparison between proton and light ions indicate a temporal effect responsible for this shape. There is a delay between the acceleration of the protons in the center of the beam and the edge, resulting in a curved ion front [4].

During the commissioning of the PHELIX laser system at GSI Darmstadt we started the first experiments on ion acceleration. While still being commissioned, we already got up to 5 J in less than 700 fs on target. Focused by a short f-number off-axis parabola, we could successfully demonstrate proton acceleration. We used CR-39 solid state nuclear track detectors. CR-39 is sensitive to the impact of single ions, but rather insensitive to electromagnetic radiation and electrons. An ion striking the CR-39 plate destroys the polymer matrix along its path and thereby causes nanometer scale damage. This damage track is transformed into cone- or bowl-shaped craters, when the CR-39 is etched in NaOH solution. We analyze each individual track on the detector plane by optical microscopy with custom pattern recognition software.

During this first experimental campaign, we observed proton emission clearly related to the TNSA process. The laser was focused down to 6 μm FWHM at 45° incident angle. The target was a free-standing gold foil of 30 μm thickness of millimeter size. A few centimeters behind the target, normal CR-39 detectors were placed. The detectors had a hole to allow a free line of sight for a Thomson parabola. The results of two experiments are shown in Figs. 6 and 7. In both images, the beam structure caused by the structured rear surface can be seen clearly. This proves that the ions originate from the rear surface, because any ions from the front would not be affected by a thickness variation of sub micrometer scale. Moreover, the real source size of the protons can be derived directly, by simply counting the number of lines.

The main feature visible in both figures is a large void area without the line structure in the center of the beam. A more detailed analysis shows that the void is in fact filled with protons, showing no line structure and presumably not coming from the rear surface. The main difference of the experiments shown in the figures is that for Fig. 7 the prepulse of the laser had been reduced significantly. In both images the real source size of the TNSA protons was about 60 μm. The void in the center changed from 27 μm in Fig. 6 down to 18 μm in Fig. 7.

The data are still being analyzed. One drawback of the experiments was an insufficient plasma diagnostics that could have answered the presence of a preformed plasma. However, the use of the target-structuring technique shows that the part of the accelerated proton beam has an

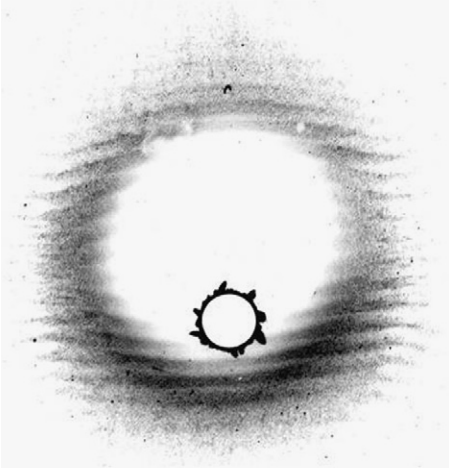

Fig. 6. Beam imprint in the CR39 detector. The line structure originates from the structured rear surface of the 30 μm Au target. The sharp circle in both figures is a hole to allow for a free line of sight to an ion spectrometer.

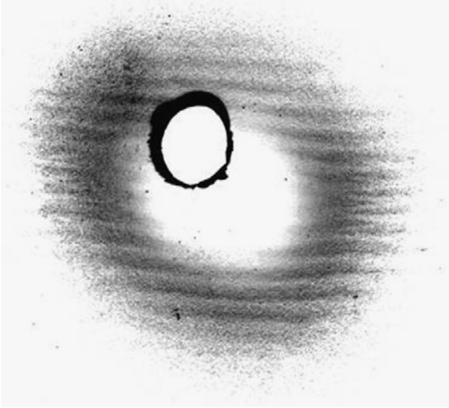

Fig. 7. Beam imprint of the same laser and target characteristics. The only difference was a reduced ASE/prepulse level.

excellent emittance ($<10^{-4}\,\pi$ mm mrad), which allows for the observation of structures down to 250 nm on the target rear surface.

3. Conclusion

We have reported about the first ion acceleration experiments at the PHELIX laser facility. The presence of protons accelerated by the TNSA mechanism has been shown clearly. Details in the ion transverse beam pattern still have to be analyzed, but the TNSA part shows the expected high beam quality.

The experiments at the LANL Trident laser were focused on the imprint of the laser beam spot onto the accelerated ions. In extension to earlier experiments we could show the warp of the ion trajectories. However, even though we could simulate the transverse beam pattern, more detailed understanding in the beam propagation is required. Whereas for thick targets prior assumptions seem to be valid, this does not apply for the thin targets we also used in these experiments. Generally, for the ion beam spectrum, good agreement with the existing scaling laws was found.

Overall we conclude that both the shape of the laser focus as well as the target thickness have strong influence on the ion beam profile. We plan to further investigate these results with additional experiments and 3D-PIC simulations in 2006.

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