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Quasi monoenergetic proton beams from a laser plasma accelerator using microstructured, polymer coated targets

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Abstract

A laser plasma accelerator based on the mechanism of Target Normal Sheath Acceleration (TNSA) was used to generate a quasi monoenergetic proton beam. The protons were accelerated from polymer dots on the backside of a thin Titanium foil. The proton spectra exhibit peaks around $E = 1.2\,\mathrm{MeV}$, with energy spread of $\Delta E/E = 25\,\%$. Our experimental results are well reproduced by 2D-PIC-simulations, which also show that for intensities around $10^{21}\,\mathrm{W/cm^2}$ low-emittance monoenergetic proton beams with an energy of nearly $200\,\mathrm{MeV}$ may be produced using microstructured targets.

Particle acceleration based on high intensity laser systems has lately received considerable attention because of its large potential for applications in science and technology. The interaction of an ultrashort laser pulse with a thin foil leads to the generation of a relativistic plasma and the subsequent, forward-directed acceleration of electrons through the foil [1–3]. The expelled electrons leave behind a strongly ionized target and constitute a quasi-static, target normal electric field, which accelerates protons and ions from the back surface until they compensate the space charge separation - a process known as *target normal sheath acceleration* (TNSA) [4].

The properties and quality of the proton beams are very sensitive to target conditions. Because the origin of the accelerated protons is a hydrocarbon contamination layer on the backside of the foil, it has been proposed to control and increase the proton yield by applying a proton rich layer, e.g. a polymer, to the target [5, 6]. A target design for the generation of monoenergetic protons from TNSA was proposed in [7]. For plain targets the source size for protons is larger than the laser's focal spot and the accelerating electric field will be inhomogeneous resulting in broad exponential proton spectra [2, 8–10]. By using micro structured double-layer targets, where the target backside carries proton rich dots, the source size may be reduced to the focal spot size. The protons accelerated from this dot will experience a homogeneous electric field yielding a

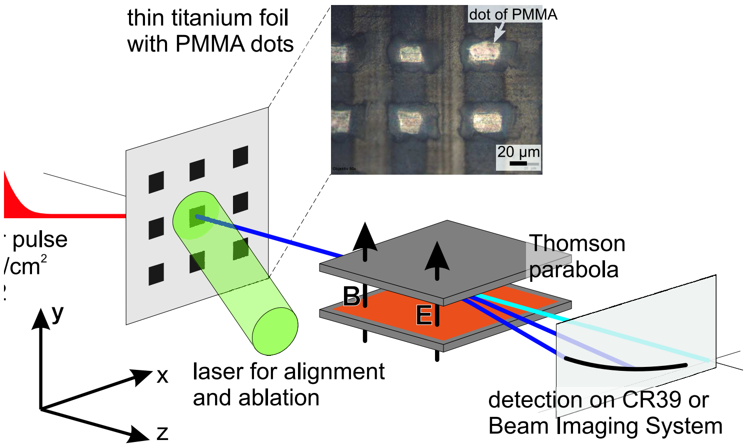

Figure 1: Experimental setup for proton acceleration. The laser was focused onto a thin metal foil. Target details will be discussed in the text. The protons and ions accelerated from the target are dispersed with respect to energy and charge-mass ratio in a Thomson parabola and then detected by either a beam imaging system, comprising a micro-channel plate (MCP) with phosphor screen and CCD camera, or on nuclear track detector plastics (CR39).

monoenergetic proton bunch. The experimental proof of this principle was demonstrated in Jena and is described in [11]. The surge of interest in adapting the spectra of laser accelerated ions to be suitable for further applications is indicated by a number of other papers published earlier this year [12, 13].

Here we present the experimental advancement of laser accelerated proton beams from microstructured targets. A schematic of the experimental setup is given in Fig. 1. The backside of a 5 µm thick Titanium foil was coated with a 0.5 µm thick layer of PMMA. Part of this layer was then processed by fs-laser ablation to provide a microstructured area with dots of approximately 20 µm by 20 µm. The frontside of the foil was irradiated by high intensity pulses from the Jena Ti:Sa laser (JETI). This multi TW laser provided pulses of about 80 fs duration with an energy of 600 mJ on target. The laser pulses were focused by a 45° off-axis parabolic mirror to a focal spot area of 6 μm^2 yielding an intensity of about $4 \times 10^{19}\,W/cm^2$. The protons and ions were accelerated normally to the target surface entering a Thomson parabola through a 3 mm pinhole. The particles were detected by a beam imaging system (BIS) behind the Thomson parabola. The BIS comprises a chevron micro channel plate (MCP) with a phosphor screen that was imaged by fiber optics and an objective onto a CCD. The CCD readout was calibrated against nuclear track detectors (CR39) to infer the proton number from the CCD images. Accurate positioning of the dot in the laser focus was achieved with the help of an alignment laser. The same laser was also used for controlled ablation in the vicinity of the dot in order to reduce the impact of parasitic protons [14].

Fig. 2 presents the result of the irradiation of the microstructured target foil at the position of

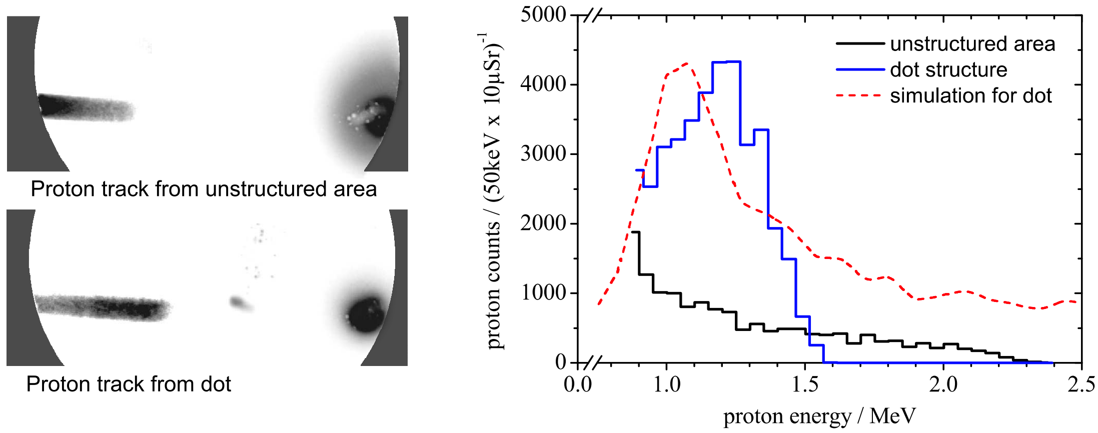

Figure 2: Reduced bandwidth for proton acceleration. On the right two raw images from the MCP show the proton tracks from an unstructured part, and a dot, respectively. Corresponding spectra are displayed in the graph on the right. Acceleration from a dot clearly results in a peaked spectrum (blue curve) in excess of an exponential background (black curve, average over 6 shots). The red curve is the spectrum from the corresponding simulation.

a dot in contrast to unstructured material. The images on the left show representative raw data on the MCP for the two cases. Analysis yields the respective spectra. The blue curve resulting from dot irradiation exhibits a distinct narrow band feature, peaked around $E_{\max} = 1.2\,\text{MeV}$ on top of a broad exponential background. For comparison, the black data represent an average over several proton spectra recorded if the laser hits a blank position, where protons can only originate from an unstructured hydrogen contamination layer. No narrow band feature appears and the exponential shape of the spectrum can be approximated by a temperature of about 0.5 MeV. The width of the peak amounts to $\Delta E_{\text{FWHM}} = 300\,\text{keV}$ or $25\,\%$ of its absolute value. The position of the peak as well as its width vary from shot to shot by about 20%.

The occurence of peaked spectra proved to be a very reliable and reproducible phenomenon. Both the MCP and CR39 detection confirm that a maximum in the proton spectrum is reproduced consistently, if a microstructure on the rear of the target is irradiated. We ascribe the observed narrow band spectra to the homogeneous acceleration of the dot protons within the center of the quasi-static electric field, set up by the laser accelerated electrons beyond the thin target as described above. If the scale of the inhomogeneity of the electric field is larger than the proton rich spot, these protons all experience the same potential.

Our analysis is supported by 2D–PIC simulations based on a code presented in [15]: The red curve in Fig. 2 plots the numerically calculated proton spectrum resulting from experimental parameters. It is dominated by a narrow band structure around $1.2\,\text{MeV}$. Simulation and experiment are in excellent agreement with respect to both the existence of the narrow structure as well as its position and width. In order to investigate the scalability of our results and their feasibility for future application, the parameters for the simulation have been changed to smaller dot sizes ($5\ \mu\mathrm{m}^2 \times 0.1\ \mu\mathrm{m}$), and higher intensities ($10^{21}\,\mathrm{W/cm}^2$). A high repetition rate table-top laser system with such characteristics will be available within the next years [16]. Simulations performed with these parameters result in a peak proton energy at 173 MeV and relative width $\Delta E/E \sim 1\%$. Such proton beams may be suitable for medical proton therapy [7, 17].

We have demonstrated the feasibility of laser-plasma accelerators for producing monoenergetic proton beams utilizing microstructured targets. In the longer term, future laser accelerators may become of more importance as a new generation of particle injectors for accelerators, and source of proton and ion beams, that may be even suitable for medical radiation therapy.

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