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SCALING OF TNSA-ACCELERATED PROTON BEAMS WITH LASER ENERGY AND FOCAL SPOT SIZE

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Abstract

By focusing an ultra-short high-intensity laser pulse on a solid target, pulses of protons and other positively charged ions with energies of several 10 MeV per nucleon are generated. The properties of these particle beams such as their energy and absolute number are highly dependent on experimental conditions like laser and target parameters. In order to achieve principal comparability between different experimental campaigns at the Draco laser system at the Helmholtz-Zentrum Dresden-Rossendorf, a reference setup for the laser ion acceleration experiment was established. A configuration is sought in which proton beams of reproducible characteristics are generated. To ensure a high stability of the proton spectra, the application of longer focal length parabolas (f ~ 1000 mm) will be tested for this setup, according preparatory studies being presented in this paper.

INTRODUCTION

Laser-based proton acceleration at the ultra-short pulse Draco laser is performed in the regime of target normal sheath acceleration (TNSA) [1]. Due to the intense irradiation of the target's front side, a plasma is created in which relativistic electrons are generated. They propagate through the target and form an electron sheath at its rear side. This effective charge separation leads to a strong quasi-static electric field in which protons and other positively charged ions, stemming from a contaminant layer on the target's rear side, are accelerated. Using light intensities exceeding 10^{20} W cm^{-2} and micrometer thick foils as interaction targets, the accelerated proton beams feature exponential energy spectra. The acceleration performance depends on the laser properties such as contrast (temporal and spatial), pulse length and pulse energy [2, 3], which can be subject to fluctuations. In order to gain comparability between experimental days and campaigns conducted at Draco, reference data of the proton beam properties in a constant experimental configuration (concerning target geometry, irradiation angle and nominal laser energy) need to be collected. Until recently, this was achieved by modifying the experimental setup to the reference configuration, which in the course of experiments proved impractical. This issue was overcome by establishing a separate target area specifically designed as a reference proton source, including independent laser- and particle diagnostics that can be operated in parallel mode to the established laser-proton acceleration experiment.

High stability and low sensitivity concerning the experimental alignment are desirable for a reference setup. This can be achieved by applying an off-axis parabolic mirror (OAP) of relatively long focal length, producing a focus on target with a long Rayleigh length (which quantifies the length of the focus region). The influence of target positioning was quantified in experiments at Draco, where a $f/2.5$ (i.e. a focal length of 250 mm at a laser beam diameter of 100 mm) parabolic mirror was applied to focus the laser beam on the target. In that case, the correct positioning of the target within this region sensitively influenced the value of the highest proton energy (cut-off energy) detected. Moving the target few 10 µm with respect to the optimal focus position resulted in a decrease of the proton cut-off energy by a factor of ≈ 2 [4]. In order to investigate the influence of a longer focal length on the proton beam properties, a scaling experiment under the application of various OAP with different focal lengths is envisaged. An important aspect of this study will be the scaling of the proton cut-off energy with laser spot size, because apart from stability, applications of the proton beam also require high proton energies. Experiments on this matter have been conducted by defocussing the laser beam on target [5] and thus increasing the irradiated area. In this case, due to the absence of a real far field with a well-defined wavefront, the intensity distribution can become highly irregular, thus impeding a reliable statement concerning the ionized region at the target surface. Our concept guarantees a real focus at any time and hence a well-known intensity distribution on the target.

EXPERIMENTAL SETUP

Draco (**Dr**esden **La**ser **Ac**celeration S**o**urce) is one of the most energetic laser systems in Germany with a peak power of 150 TW. The Ti:sapphire-based table top laser produces ultra-short pulses with a temporal duration of 30 fs (full-width at half-maximum (FWHM)) at a repetition rate of 10 Hz. After the current upgrade to a dual-beam system, Draco will provide an additional laser beam with a peak power exceeding 500 TW. Experiments within the reference setup are conducted with the 150 TW-beam.

After temporal compression the 150 TW-beam undergoes wave-front correction performed by a deformable mirror (DM) which is to result in optimal beam focussability onto the target (see Fig. 1). The wave-front corrected beam enters the experimental chamber where it can either be transferred into the 150 TW-target area or propagate into the 500 TW-target area or the reference setup, where it enters the reference setup (encircled region in Fig. 1) and is focussed by a $f/2.5$ OAP onto a 2-µm-thick titanium foil target. Positively charged ions and protons are accelerated and detected with stacks of radiochromic films (RCF) and a Thomson parabola spectrometer [6]. Before irradiating the target, the intensity distribution of the attenuated laser focus can be analysed by imaging the focal spot onto a CCD-camera with a high-definition and aberration-corrected objective lens,

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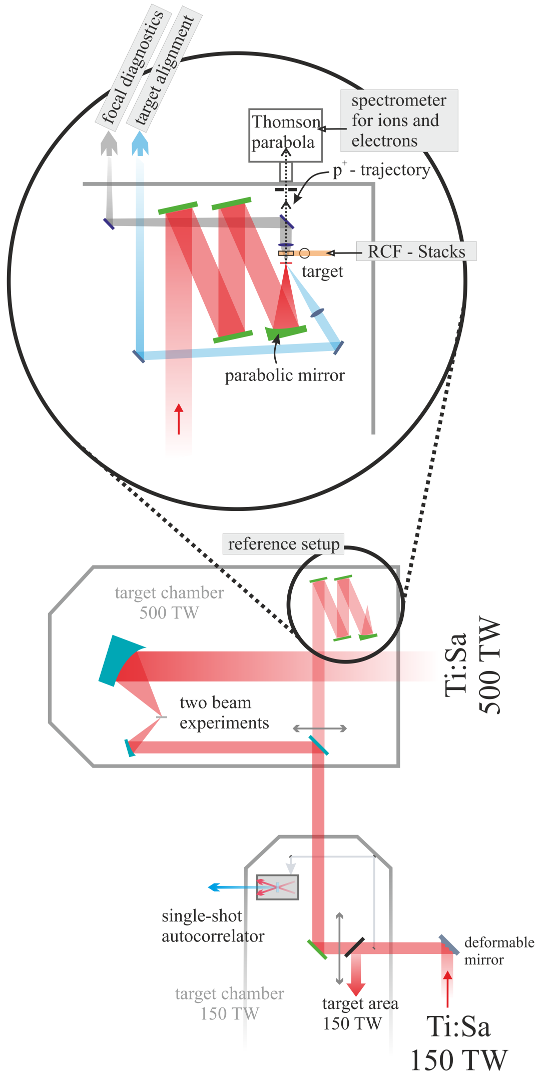

Figure 1: Experimental setup for laser-based proton acceleration at Draco.

imaging the focus under a magnification of 34 to a CCD-camera. A vacuum compatible single-shot autocorrelator is situated in the 150 TW-target chamber and enables shot-to-shot analysis of the laser pulse length. By monitoring both laser and particle beam charasteristics i.e. input and output of the acceleration process, a complete analysis of the latter is possible.

EXPERIMENTAL RESULTS

Preparatory studies of the laser intensity distribution in the focal spot were performed. They were conducted at an attenuated laser pulse energy in the order of few mJ to avoid damage of the focus diagnostic's objective lens.

Wavefront Correction

The first measurements were performed without the DM in place of which a plane mirror was situated. The obtained images of the focus could be compared to the focal spot geometry after the implementation and adjustment of the DM. An analogous measurement was performed at the focus diagnostics in the laser laboratory where the laser beam is focussed by a lens with a focal length of 1.5 m shortly after the DM and then imaged to a CCD-camera under a magnification by a factor 4. This allows for a comparison between the focussability of the laser beam for a long (focus in target chamber) and a short (focus in laser laboratory) propagation length after wavefront correction. Figure 2 shows the focus in the target chamber (upper two images) and in the laser lab (lower two images) with the plane mirror instead of the DM (left side) and with the DM (right side). From Figure 2 it is clear that the wavefront correction is

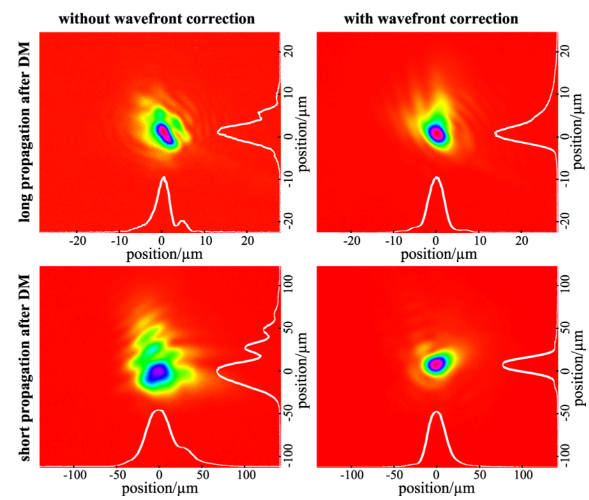

Figure 2: Draco focus in target chamber (upper two images) and in the laser laboratory (lower two images) without (left two images) and with (right two images) wavefront correction by a deformable mirror. Intensity profiles featuring the peak intensity are indicated by normalised white graphs.

more effective for a short propagation length after the DM, resulting in a considerable enhancement of the focal intensity profile concerning its size and symmetry. Assuming optimal wavefront correction in the target chamber, a focal spot size between 3 µm and 4 µm is achievable. The longer free propagation and additional beam guiding optics between DM and OAP in the chamber results in a renewed deformation of the wavefront resulting in diminished focussability. This can be overcome by performing wavefront correction with respect to the plane of the OAP in the experimental chamber.

Spatial Contrast

The laser-proton acceleration process is sensitive to the size and shape of the ionized area on the target front side, given by the intensity profile of the laser focus [7]. Thus a high dynamic range image (HDR) of the focus in the target chamber was generated to resolve intensity structures over the range of five magnitudes (see Fig. 3). Calibrated neutral density filters in front of the CCD-Chip were applied to aquire images of the focus with saturated areas of different size respectively. The images were cleared of background

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noise signal, corrected for the according transmission coefficient and overlayed.

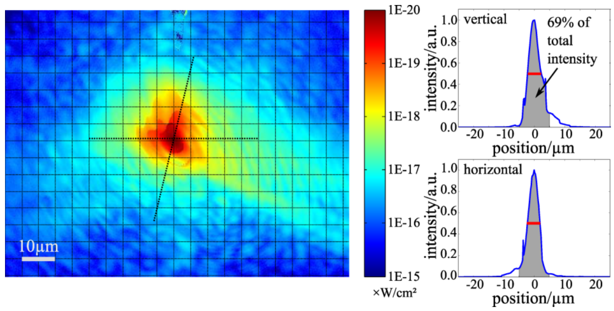

Figure 3: HDR-image of Draco focus at target interaction point, scaled to the peak intensity of 10^{20} W cm^{-2}. Right: normalised intensity profiles along intercepted lines on color map.

In Figure 3 a dynamic range of five magnitudes is covered between peak intensity (red) and outer areas (blue). In regions with intensities higher than 10^{18} W cm^{-2}, relativistic electrons that play a vital role in the acceleration process would be generated in the plasma. On the right side of Figure 3, profiles along cuts through the peak intensity (intercepted lines in HDR-image) are displayed. A Gaussian fit over the profile resulted in a spot size of 4.8 µm (FWHM). 69 % of the beam intensity is accumulated within $\approx 2 \cdot$ FWHM around the peak intensity, indicated by gray regions unter the profile graphs. This value can be further enhanced by improving the wavefront correction as mentioned above.

Focus Stability

In order to perform studies with varying spot size on the target by conduction series of measurements with different OAP, a high shot-to-shot stability of the focus profile while applying each of the parabolic mirrors is mandatory. Thus stability measurements of the focal spot size and the focal pointing, i.e. the position of the focus on the target surface over the course of several seconds, were performed. Figure 4 displays the FWHM of a Gaussian fit performed along a vertical profile through the intensity maximum of the focus (gray markers). Green markers indicate the angle of the laser axis with respect to a mean focus position, representing the focal pointing. The vertical focus FWHM varies between 7.5 µm and 10.2 µm over time. This corresponds to a factor of almost two in the size of the irradiated area on the target. Mean focal pointing augments to (3.5 ± 1.7) µrad which is well within the specified limits of 10 µrad for the entire laser system.

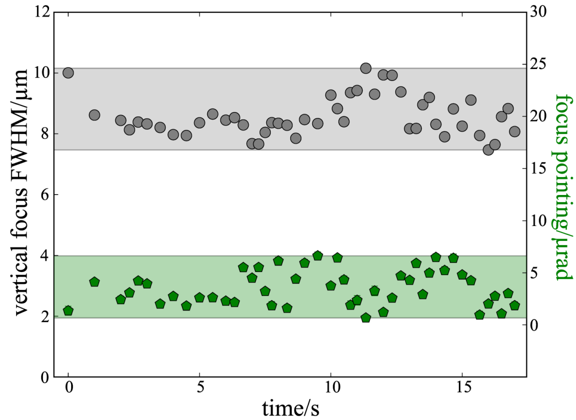

Figure 4: Stability of focal spot size (gray markers) and pointing (green markers) over the course of 18 seconds. Shaded areas indicate the regions between minimum and maximum values.

CONCLUSION

We presented the newly implemented setup that will acquire reference data of TNSA-accelerated protons parallel to the established proton acceleration experiment at Draco. In order to provide an especially stable proton source for this and other applications, e.g. experiments investigating proton beam guiding, a study concerning the scaling of proton energies with laser intensity on target was outlined. This study will be conducted under the application of various off-axis parabolic mirrors of different focal lengths. Preparative studies of the laser intensity distribution in the focus were performed and their results presented.

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