Integrated double-plasma-mirror targets for contrast enhancement in laser ion acceleration

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Abstract. We introduce a target concept for laser-driven ion acceleration with ultrashort, highly-intense laser pulses that includes an integrated double plasma mirror for contrast enhancement. It comprises three nanometer thin plastic foils, embedded in a small metal structure, which ensures precise mounting. The geometry allows to apply a double plasma mirror directly in front of a target foil within the converging beam, enabling moderate-energy (~1 J) laser systems to reach the required fluence of several hundred J/cm² on the plasma mirrors.

During an experimental campaign, performed at the Laboratory for Extreme Photonics in Munich, we observed proton energies increased by a factor of three using this new target, which is attributed to an enhanced laser contrast after the integrated double plasma mirrors.

1. Introduction

In the upcoming Petawatt era, laser facilities all over the world are targeting to reach peak intensities up to 10²² W/cm² in a focal spot of a few micrometers diameter [1]. At such extreme conditions, the target’s ionization threshold (~10¹³ W/cm²) is exceeded by many orders of magnitude and precise knowledge and control of the temporal laser profile (laser contrast) is often crucial for experimental performance. Pre-pulses, that originate from the amplification process of the laser, precede the main pulse on ns- to fs-timescales. This can cause a pre-expansion of the target and can alter the often desired sharp vacuum-solid boundary, therefore strongly influencing experimental results [2–4].

Several contrast-cleaning techniques have been developed over the last years to suppress such pre-pulses. The ASE-level can be lowered by optical parametric chirped pulse amplification (OPCPA) [5,6], saturable absorbers [7] or cross-polarized wave generation (XPW) [8], whereas single pre-pulses can be removed to some extent by fast Pockels cells and the avoidance of transmissive optics in the laser. All these components can improve the laser contrast but also partially require major reconstructions in the laser setup.

A self-triggering plasma mirror (PM), which usually consists of a fused silica substrate with an anti-reflection coating [9–13], provides a simple means of contrast improvement by orders of magnitude and is usually implemented after the compression of the amplified laser. To adjust its ignition, the PM is placed along the converging laser, usually before focus, such that the intensity of any pre-pulse remains below the ionization threshold of the substrate, whereas the rising part of the main pulse generates a reflective plasma. With a reflectivity of ~10⁻²-10⁻³ for the pre-pulse and 0.6 – 0.8 for the main pulse, a single
PM enables significant contrast enhancement of two to three orders of magnitude, at the expense of laser energy on target.

A larger number of plasma mirrors can be employed to further improve contrast. The use of a double plasma mirror (DPM) has in fact several motivations. In a re-collimating setup, the ideal fluence for triggering the plasma mirror is available before and after focus, offering twice the contrast enhancement in a single telescope setup. The angle of incidence, however, is around 45° then and this has detrimental effects on the main pulse reflectivity [14]. Nevertheless, the use of such DPMs after the final focusing parabola has proven very useful, because it avoids reflecting the laser over yet more optics that potentially contribute to contrast deterioration and, more pragmatically, does not require re-arranging the complete experiment.

Proper reflection requires a certain fluence (several 10s to 100s J/cm²) [15], hence in a DPM used in a converging beam the main pulse reflectivity can never be as optimal as in two independently operated single PMs (or a telescope setup). So far, the use of DPMs as described had been limited to large scale systems with kJ energy and large beam diameters [16]. Such pulses can trigger the PM centimeters before focus, thus providing sufficient space for their implementation prior to target. For laser systems in the low-J range, the distance to target reduces to some millimeters, which has so far hindered the use of this generally simple concept at such systems.

We present a new compact target design, consisting of three nanometer-thin plastic foils, embedded in a metal structure, where two of these foils function as a DPM and the third as the target for laser-ion acceleration. Using this approach, the DPM can be placed as close as 2.9 mm and 0.9 mm to the target. Therefore, the new design provides a small, cost-efficient setup for significant contrast enhancement, which allows implementation in particularly tight experimental setups.

2. Concept and production

Our DPM target was designed for an f/2 off-axis parabolic mirror and 2 J laser energy on target with horizontal polarization (p-polarized in the PM-case). A sketch of the DPM geometry and the incident laser is shown in figure 1a, where α = 14° is the convergence angle of the focused beam. The design was optimized for achieving the required fluence on the first mirror, minimizing the path to the second and preventing clipping at the metal structure that supports the thin foils (parameters x and m).

Feasible values for all geometric parameters were determined by numerical analysis and yielded an optimum incidence angle of β = 30°, resulting in fluences of 100 J/cm² on the first and 800 J/cm² on the second PM. Those fluences lead to intensities of 4·10¹⁵ W/cm² and 3.2·10¹⁶ W/cm² on PM1 and PM2, respectively. We therefore estimate a total reflection of $R_{\text{calc,high}} = 0.675 \cdot 0.68 = 0.46$ for a laser pulse with 25 fs duration [9].

![Figure 1. a) This sketch shows the geometry of the DPM target. The path of the laser is illustrated in blue. The design parameters are the opening angle β and distances x and m in order to prevent clipping at the metal structure. b) Image of the final target holder containing 18 DPM targets.](image-url)
Optimization of the PM performance (i.e. contrast enhancement) can be achieved by minimizing the reflectivity for pre-pulses. This is done by matching the PM foil thickness to the destructive interference criterion for the central laser wavelength of $\lambda = 800$ nm: $d_{\text{pm}} = \lambda / (2 \cdot \cos \delta \cdot n_{\text{pm}}) = 295$ nm, where $\delta = 20^\circ$ is the light angle in the PM foil and $n_{\text{pm}} = 1.445$ the refractive index of the PM material. The foils used for the PM had a thickness of $(270 \pm 30)$ nm. The reflectivity for a single PM can be calculated using the formula for thin film etalons: $R = 1 - 1 / (1 + F \sin^2 (2 \pi n_{\text{pm}} d \cdot \cos (\delta) / \lambda))$, where $F = 4 \cdot R_p / (1 - R_p)^2$ and $R_p$ is the reflectivity on the foil frontside for p-polarized light. For a thickness $d = 270$ nm, one obtains $R = 0.0057$. But the reflectivity is also influenced by the fact that the laser is strongly convergent ($\Delta \beta = 14^\circ$) and broad band ($\Delta \lambda = 50$ nm). Therefore, $R_{\text{min}} = [(\partial R/\partial \lambda) \cdot \Delta \lambda]^2 + [(\partial R/\partial \beta) \cdot \Delta \beta]^2]^{1/2} = 0.011$ will represent a lower limit in reflectivity of a single pass. The DPM reflectivity therefore is $R_{\text{calc,low}} = (R + R_{\text{min}})^2 = 0.279 \cdot 10^{-3}$ and we hence estimate a contrast enhancement of $R_{\text{calc,high}} / R_{\text{calc,low}} = 1648$.

The PM foils are produced in a quick and cost-efficient way using the droplet method [17], for which Formvar serves as the PM material due to its high reproducibility. The third foil, in our study functioning as the target for laser ion acceleration, can be chosen as demanded by experimental requirements, for example regarding its thickness or material. The foils are applied on several metal plates, which are then patched to achieve the geometry described above. The angular mounting accuracy minimizes the deviation of beam pointing (final focus) within a square of $200 \mu m \times 200 \mu m$, i.e. within the field of view of the focus diagnostic microscope. As a final result, a metal frame offers a compact setup with a total number of 18 DPM targets (see figure 1b).

3. Experimental implementation and results
The DPM system was implemented at the ATLAS 300 laser at the Laboratory for Extreme (LEX) Photonics at LMU Munich in Garching. An attenuated beam was used to determine the reflectivity of the DPM setup without target foil. Comparing the intensity of transmitted light with and without PM yielded $R_{\text{meas,low}} = 0.0032 \pm 0.001$, which is 10 times larger than estimated above. It is most likely that this high reflectivity is a result of insufficiently well controlled PM thickness, for example a foil with $d = 240$ nm would theoretically have a similar reflectivity. The same procedure with full power resulted in $R_{\text{meas,high}} = 0.49$, which is in good agreement with the theoretical value. The measured contrast enhancement for our DPM system is therefore $R_{\text{meas,high}} / R_{\text{meas,low}} = 153$.

Figure 2. Schematic of the experimental setup: a 90° off-axis parabola focuses the laser onto the DPM target. After passing a dipole magnet, the accelerated protons are recorded by a RadEye detector. The functionality of the DPM and an exemplary laser contrast curve of the incident laser is pictured in the inset.
The schematic of the experiment used for laser ion acceleration with the described DPM target is shown in figure 2. The incident laser is focused onto the target by an f/2, 90° off-axis parabola. The pulses contain 2 J of energy within a pulse duration of 25 fs. An exemplary contrast curve shows two short pre-pulses at 670 and 500 ps prior to the main pulse with a contrast ratio of almost $10^6$. Considering a peak intensity of $10^{20}$ W/cm², both pre-pulses exceed the damage threshold of the target material. Although such pre-pulses can be suppressed in principle in the laser, this situation serves well for our demonstration study. The DPM reduces the pre-pulses by more than a factor of 100, sufficient to suppress their intensity to below the damage threshold of typical target materials. The target frame was constructed compatible to and mounted onto the inhouse-built nano-foil target positioning system [18] (not shown in figure 2). The emitted protons are deflected by a dipole magnet and recorded by online RadEye detectors. The detector is covered with different layers of aluminum (45 μm on the left side, 75 μm on the right) in order to define energies at 2.1 and 2.9 MeV for subsequent calibration and evaluation of the detected protons energy distribution [19].

Figure 3 shows experimental results, with quantitative differential spectral amplitudes of the protons plotted against the kinetic energy. The red curve represents a typical shot on a single plastic foil of 500 nm thickness (without PM, i.e. no contrast enhancement), whereas blue, yellow and green mark shots on DPM-targets with 20 nm thick plastic foils. The noise level of each shot is shown by the dashed lines in the corresponding color. The maximum proton energies are defined as the intersection point of signal and noise for every shot. Looking at these representative shots we can already see an increase of the kinetic energy up to 11 MeV and differential spectral amplitudes by up to two orders of magnitude if we compare the DPM target with a single plastic foil. For the following we extract only the maximum proton energy for the evaluation of the acceleration performance with and without plasma mirrors.

![Figure 3](image-url)  
**Figure 3.** Exemplary proton spectra, i.e. differential spectral amplitudes of the protons are plotted against kinetic energy for four exemplary shots.

Figure 4 summarizes maximum proton energies for different target materials and thicknesses. Circles mark energies which were acquired using the DPM target, whereas triangles symbolize shots without contrast enhancement. Shots with plastic targets (Formvar and polystyrene) were evaluated for two experimental days in order to provide information on reproducibility of the results. On one of the days,
diamond-like carbon (DLC) was used as target material as well. The DPM foils were exclusively 270 nm thick Formvar for all shots.

When using single plastic foils, the minimum target thickness for detectable ions above 2.1 MeV appeared to be 200 nm, for DLC it was 100 nm. The highest proton energy of 4.2 MeV was observed for 700 nm thick targets. With 2 J on target, those numbers are clearly insufficient. Exemplary snapshots of the laser light transmitted through 20 nm and 200 nm thin targets shot without PM (Fig 5a and b) suggest that the collapse of proton acceleration from 20 nm foils is accompanied by target transparency. This is likely due to pre-expansion induced by short pre-pulses that arrive long before the main pulse [20]. Although the pulse energy is reduced to ~1 J when inserting the DPM, proton energies increase to values between 6 - 11 MeV at foils of 20 nm thickness. In this case, the target remains largely opaque (Fig 5c).

**Figure 4.** The plot shows the maximum proton energies for different target materials and thicknesses. Circles mark shots with DPM targets, whereas triangles symbolize single foil targets without DPM. Vertical error-bars resemble the detector resolution, horizontal error-bars cover a thickness fluctuation of ± 10 nm for DPM targets and ± 20 % for single foils.

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**Figure 5.** Exemplary images of a transmission screen behind the target, where a) shows a shot on a single 20 nm thick plastic foil without PM (96.8% transmission), b) a shot on a single 200 nm thick plastic foil without PM (11.3% transmission) and c) a shot with DPM and a 20 nm target foil (14.9% transmission)
4. Summary and discussion

We have demonstrated a new target concept that enables accommodating a DPM for laser ion acceleration close to the focus. This integrative design is particularly beneficial for laser systems with energies in the low-J regime. The demonstrated solution enables precise positioning via implementation in existing target systems [18]. Foils can be fabricated cost-efficient with high reproducibility in advance to experimental campaigns. A contrast enhancement of more than two orders of magnitude is viable, in line with successful proton acceleration from targets as thin as 20 nm. Future improvement must concentrate on better control of the PM thickness and homogeneity as well as an on-shot/single shot diagnostic for intensity distribution measurements to reduce the currently observed large shot-to-shot variation. Although based on non-optimal contrast, our concept may provide a quick solution to increase the proton energy by more than a factor of two and the proton numbers by more than a factor of 100 without having to intervene into the laser system, despite the reduced energy on target of 0.98 J.

Remaining challenges comprise mainly the improvement of mounting accuracy. We are currently operating the system in shot-on-demand mode as the limited angular accuracy of the mounting leads to fluctuations of the focus position inside a 200 μm × 200 μm square which requires realignment for every shot. Although this fact limits our repetition rate up to now, target mass production prior to experiment is already possible which would favor a high-repetition system if the positioning accuracy is improved. Due to the fast production and good reproducibility we choose the droplet method for the foil fabrication. Recent measurements have shown though that a better foil quality can be achieved by using spin-coated foils which would not only improve the beam quality but also reduce the reflectance of the low intensity part as thickness fluctuations would decrease. As a last point it has to be mentioned that, in the current setup, foils close to the primary focus are frequently destroyed. In the worst case, only 4-8 of the 18 targets could be used in our experiment. Mitigating this effect will be essential to benefit from the full capacity in future studies.

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Author contributions
D. H., C. K., F. H. L., T. O. and P. H. built the experimental infrastructure in LEX-Photonics and designed the experiment setup. M. A. O. H., D. H., P. H. and J. S. designed and developed the DPM system. M. S., D. H., J. H. B., T. O., Y. G., R. Y., F. H. L., T. F. R. and C. K. performed the experiment at LEX-Photonics. M. S., J. H. B., D. H. and J. S. analyzed the data, discussed and interpreted the results and prepared the manuscript.

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