

Ion acceleration using high-contrast ultra-intense lasers

J. Fuchs¹, P. Antici^{1,2}, E. d'Humières³, E. Brambrink¹, E. Lefebvre³, H. Pépin⁴, P. Audebert¹

¹*Laboratoire pour l'Utilisation des Lasers Intenses, UMR 7605 CNRS-CEA-École Polytechnique-Univ. Paris VI, 91128 Palaiseau, France*

²*Dipartimento di Energetica, Università di Roma « La Sapienza », Via Scarpa 14-16, 00165 Roma, Italy*

³*DPTA, CEA-DIF, Bruyères-le-Châtel, France*

⁴*INRS-ÉMT, 1650 bd. L. Boulet, J3X1S2 Varennes, Québec, Canada*

In the last few years, intense research has been conducted on the topic of laser-accelerated ion sources and their applications [1]. These ultra-bright ion sources [2] are accelerated from the rear-surface of thin foils by irradiating them with ultra-intense short laser pulses. A number of applications, like probing dense matter [3], e.g. the core of fusion targets, or ion therapy of deep-seated tumours [4] require increasing the maximum energy of the accelerated ions. Presently, ~ 20 MeV is achieved on 100 TW class laser facilities and ~ 50 MeV on PW class laser facilities. One way to achieve an increase of the maximum ion energy is to increase the laser on-target power density. This however requires going towards very large, costly, facilities using glass amplifiers since compact high-energy CPA lasers do not yet exist. Another approach would be to decrease the target thickness as it helps mitigating the effect of electron divergence within the target [5]: thicker targets lead to a lower density accelerating electron sheath and thus to lower ion energies. Indeed, the accelerating field scales as $E_{\text{acc}} \propto (n_{\text{hot}} T_{\text{hot}})^{1/2}$ where n_{hot} and T_{hot} are respectively the density and temperature of the hot electrons in the sheath. However, there is a limit in the minimum target thickness that is imposed by the laser contrast [6] in order to avoid target burn-through before the main pulse. Such burn-through perturbs the high-gradient of the rear surface and the acceleration process. Too high a contrast, leading to a negligible preplasma, is also detrimental since it leads to a reduction in laser absorption efficiency. However, using very thin targets and ultra-high contrast pulses could be interesting. There, the laser-target interaction would enter in the relativistically transparency regime [7] where simulations show that proton acceleration should be even more efficient [8]. In this regime, the laser pulse can propagate throughout the

relativistically transparent target; accelerate a large number of electrons within the target volume to high energies which in turn will accelerate ions efficiently. The first requirement to access this regime is to generate very high contrast laser pulses.

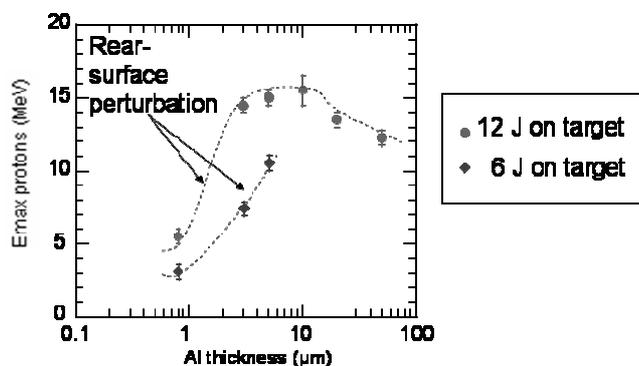


Figure 1 : Evolution of the proton beam maximum energy with the Al foil thickness when a Fast Pockels cell (ASE duration ~ 500 ps) is used. The dashed lines are a guide for the eye.

We have compared the acceleration of high-energy protons from the rear-surface of thin foils for various contrast conditions of the ultra-intense laser pulse irradiating the targets. We concentrate on protons since these are the easier to accelerate using untreated targets where hydrogen-rich contaminants are present. The experiments were performed using the 100 TW laser at the Laboratoire pour l'Utilisation des Lasers Intenses (LULI) working at $1.057 \mu\text{m}$ with 15-20 J energy pulses of $> 10^{19} \text{ W}\cdot\text{cm}^{-2}$ intensity. The focal spot full width at half maximum (FWHM) is $\sim 6 \mu\text{m}$ and the pulse duration is ~ 350 fs [9]. Measurement of the proton beam is performed using radiochromic film (RCF) dosimetry media [10] directly exposed to the beam. We used Al targets of variable thicknesses. The energy pedestal (ASE) ahead of the main pulse is controlled by the rise time of the Pockels cells within the laser chain. Usual ASE duration is ~ 1.5 ns for a contrast ratio of 10^{-7} in intensity (ratio of the ASE intensity to the main pulse intensity). Such ASE induces that the minimum target thickness that can be used for ion acceleration is $\sim 10 \mu\text{m}$, before target burn-through dominates. This minimum thickness can be reduced by reducing the ASE duration (but not the contrast ratio) using a fast Pockels cell [6] with a reduced rise time of ~ 0.5 ns. This is illustrated in Figure 1. However, targets thin enough so that they can be relativistically transparent cannot be used since the ASE would still blow them out before the main pulse.

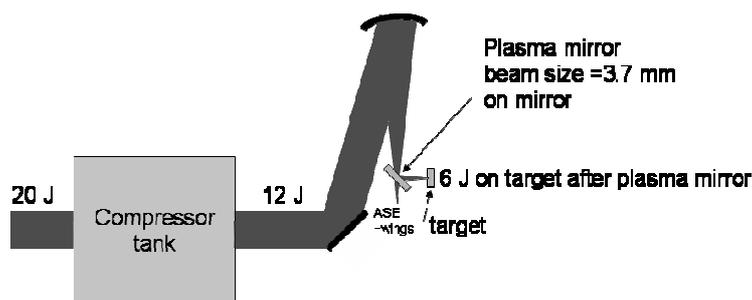


Figure 2 : Experimental set-up of the plasma mirror on the 100 TW LULI laser facility target chamber. The plasma mirror is positioned 14 mm away from focus. The focusing parabola has an aperture of $f/3$ with $f=300$ mm. Laser energy at various stages of beam propagation are indicated.

In order to improve significantly the contrast ratio and prevent explosion of very thin targets before the main pulse, we have implemented a plasma mirror [11] before focus. As illustrated on Figure 2, the latter was installed at an intermediate field position, in between the focusing optics and the target (with a fluence on the mirror of ~ 70 J/cm²), so that its effect was optimized, i.e. phase effects are low enough so that the reflected pulse is not distorted (see Figure 3) and at the same time reflectivity is still high, i.e. ~ 0.5 .

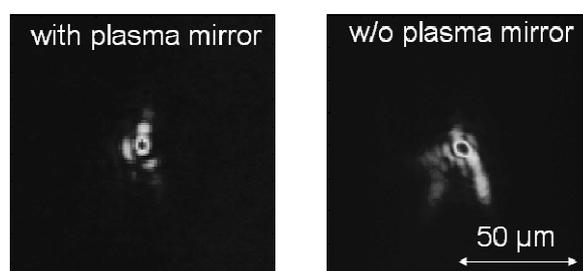


Figure 3 : Focal spots on target at full energy measured with (left) and without (right) plasma mirror before focus. Color scale is linear for both images. The central peak is similar for both but the plasma mirror brings the advantage of suppressing the low-energy wings.

Results are shown on Figure 4. We can distinguish several phases for the evolution of the maximum proton energy with the target thickness. As we reduce progressively the target thickness, we first find an increase of the proton energy due to the electron sheath density increase in thin targets. Then we observe a sudden drop of the maximum proton energy due to rear-surface perturbation since the plasma mirror cannot steepen infinitely the leading edge of the pulse. However this drop takes place for quite thinner targets than in Figure 1. We observe a subsequent re-increase using 50 nm thick targets, followed by a decrease. This peak for 50 nm thick targets could be due to an interaction of the laser

pulse with a partially blown-out plasma that is still dense enough to accelerate a sufficient number of hot electrons. Further experiments will be carried out to test this hypothesis.

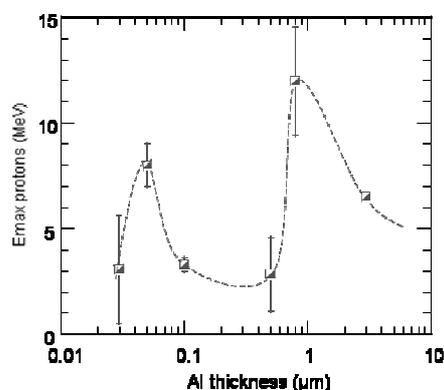


Figure 4 : Evolution of the proton beam maximum energy with the Al foil thickness when the plasma mirror is used before the target. The dashed line is a guide for the eye.

This work was supported by DAAD, and grant E1127 from Région Ile-de-France

References:

- 1 E. Clark et al., Phys. Rev. Lett. **84**, 670 (2000); R. A. Snavely et al., Phys. Rev. Lett. **85**, 2945 (2000); A.J. McKinnon et al., Phys. Rev. Lett. **86**, 1769 (2001); S. Karsch et al., Phys. Rev. Lett. **91**, 015001 (2003); M. Allen et al., Phys. Rev. Lett. **93**, 265004 (2004); J. Fuchs et al., Phys. Rev. Lett. **94**, 045004 (2005).
- 2 T. Cowan et al., Phys. Rev. Lett. **92**, 204801 (2004); M. Borghesi et al., Phys. Rev. Lett. **92**, 055003 (2004).
- 3 A. Mackinnon et al., Rev. Sci. Inst. **75**, 3531 (2004).
- 4 A. Boyer et al., Physics Today, Sept. 02 issue, p. 34.
- 5 R. Stephens et al., Phys. Rev. E **69**, 066414 (2004); J. Fuchs et al., Phys. Rev. Lett. **91**, 255002 (2003).
- 6 M. Kaluza et al., Phys. Rev. Lett. **93**, 045003 (2004).
- 7 J. Fuchs et al., Phys. Rev. Lett. **80**, 2326 (1998).
- 8 E. d'Humières et al., Phys. Plasmas **12**, 062704 (2005).
- 9 B. Wattellier et al., Optics Letters **29**, 2494 (2004)
- 10 N. V. Klassen et al., Med. Phys. **24**, 1924 (1997).
- 11 P. Monot et al., Opt. Lett. **29**, 893 (2004); G. Doumy et al., Phys. Rev. E **69**, 026402 (2004).