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# New setups to improve proton acceleration with high intensity lasers

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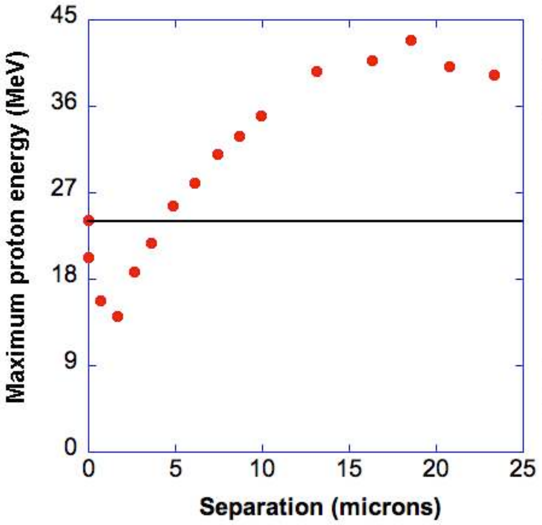
The possibility of producing a low emittance energetic proton beam by means of a high intensity laser interacting with a solid target has been demonstrated experimentally and extensively investigated theoretically over the past years. These proton beams are very promising for applications related to inertial confinement fusion, plasma diagnostics, isochoric heating of matter or medical applications. There is now an increasing need to work out new setups capable of improving the proton beam properties. Configurations coupling two targets, two lasers, or both, look particularly encouraging in this respect. We have performed 2D PIC simulations with the code Calder [1] to study new setups and determine favorable parameters.

The main proton acceleration mechanism at work with nowadays lasers is Target Normal Sheath Acceleration [2]. The lasers heats electrons at the irradiated surface and these hot electrons cross the target and create a strong electrostatic field when they exit the target. This field then accelerates protons from the back surface. There are different ways to improve proton acceleration with this mechanism. All targets used in this study are 1 μm thick and at a density of 10 times the critical density ($n_c$). For cases with one laser, the pulse has a duration of 36 fs and an intensity of $10^{20}$ W/cm$^2$. When two pulses are used, they have the same intensity but a duration of 18 fs. By combining two lasers with one target it is possible to increase the duration of the acceleration phase. This setup only presents a sharp increase of the maximum proton energy for small delays between the two pulses. For a delay of 15 fs, this increase reaches 36.2%. The evolution with time of the maximum proton energy is not very different from the one with only one laser. It is also possible to combine one laser with two targets. By placing a secondary target behind the first one, hot electrons leaving the primary target can create a second accelerating field behind the secondary target. By synchronizing the birth of this field with the arrival of accelerated protons coming from the first target, an additional boost can be achieved. This idea was first tested by Mima et al. [3]. For small separations, this setup is not efficient as the secondary target disturbs the electrostatic field created by the primary target. But for a separation greater than 5 μm, for the parameters of this study, the electrostatic field arising at the back of the secondary target provides a second acceleration phase clearly visible both on the evolution with time of the maximum proton energy and on the proton phase space. The optimum separation measured gives an increase of the maximum proton energy of 77.9% (Figure 1).



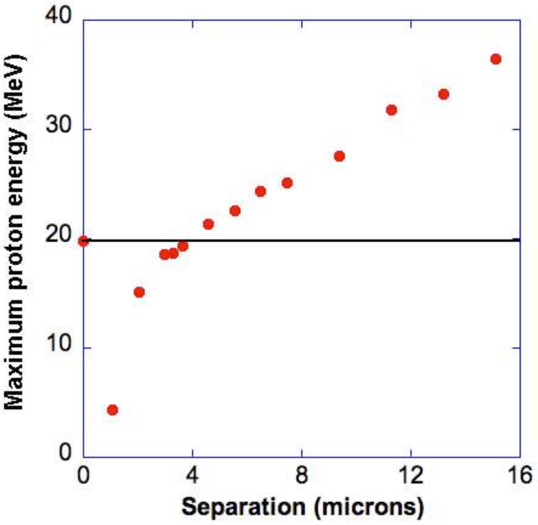


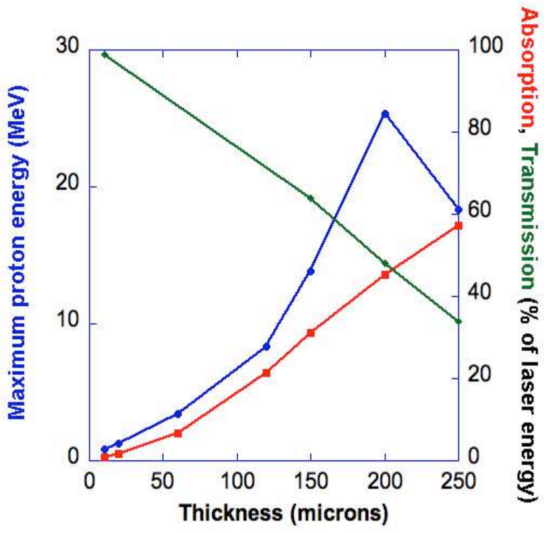
**Figure 1 (left): Evolution of the maximum proton energy with the separation between two targets composed of protons and electrons at 10 $n_c$ and with a thickness of 1 μm. The laser interacting with the primary target has an intensity of $10^{20}$ W/cm$^2$ and a pulse duration of 36 fs.**

**Figure 2 (right): Evolution of the maximum proton energy with the separation between two targets at composed of protons and electrons at 10 $n_c$ and with a thickness of 1 μm. The laser interacting with the primary target is divided in two pulses with an intensity of $10^{20}$ W/cm$^2$ and a pulse duration of 18 fs.**

These new setups can be combined. For now, only the separation between both targets has been changed, leading to an increase of 96.2% of the maximum proton energy at best. The delay between the two pulses can also be changed (Figure 2).

Another possibility is to use the mechanism of stochastic heating [4] to improve proton acceleration. This mechanism needs the use of two or more pulses interacting on an underdense plasma. When parameters such as the angle between the propagation axis of the pulses, the target density, the duration and intensity of the two pulses are chosen correctly, electrons can acquire chaotic trajectories and the coupling between the lasers and the plasma is increased. This can lead to very high electron temperatures, which in turn could be used to improve proton acceleration. Previous studies have shown that stochastic heating is best when the two pulses are counterpropagating. We have therefore tried to use the transparency regime of proton acceleration [5] with a secondary pulse at $5.5\times10^{16}$ W/cm$^2$ and lasting 460 fs interacting with the rear of the target. The goal was to produce stochastic heating at the back surface after the main pulse ($5.5\times10^{18}$ W/cm$^2$, 460 fs) had crossed the target to increase the electron temperature. The target was composed of a 60 nm 10 $n_c$ main target and a 15 μm 0.1 $n_c$ preplasma placed in front of it. Synchronizing the two pulses was therefore the main difficulty. With a variation of the delay between the two pulses, we obtained an increase of 9.1% of the maximum proton energy.

Nowadays lasers can produce very intense pulses but they also launch a nanosecond prepulse, which interacts with the target and creates a preplasma. This preplasma can increase the laser absorption and therefore the electron temperature. But it also explodes very thin targets before the main pulse can interact with them. Numerical simulations show that very thin targets could lead to very high proton energies so a compromise has to be found. One possibility is to use an underdense target in front of an overdense one. A laser pulse propagating through an underdense target heats a cloud of electrons that remains in its wake. When the laser exits the plasma, a strong electrostatic field is created and protons can be accelerated to high energies (Figure 3). Experimentally, it is difficult to use only an underdense target because the surface of the plasma is not well defined. But coupling the underdense target with an overdense target combines the advantages of both target (Figure 4) with a better control of the setup. Foam or gasbags in front of a solid target can be used.



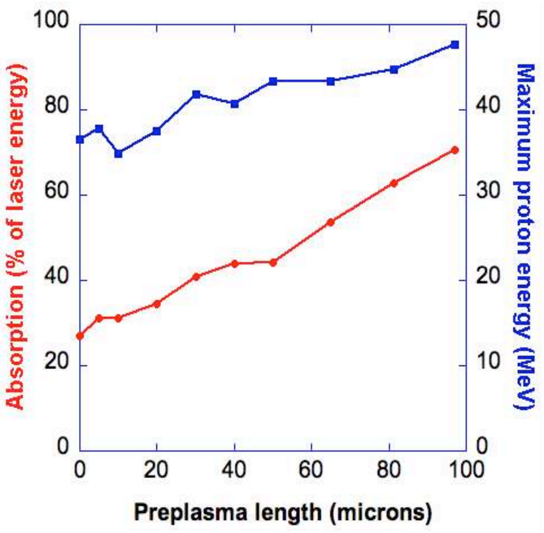


**Figure 3 (left): maximum proton energy, absorption and transmission versus thickness for a $10^{20}$ W/cm$^2$, 36 fs laser pulse interacting on a 0.05 $n_c$ target composed of protons and electrons.**

**Figure 4 (right): Maximum proton energy and absorption versus the thickness of a 0.1 $n_c$ preplasma placed in front of a 5 $n_c$, 1 µm plasma irradiated by a 36 fs, $10^{20}$ W/cm$^2$ laser pulse.**

Significant increases in the maximum proton energy can be achieved by using new setups consisting of two or more lasers, two or more targets or underdense and overdense targets. These setups should now be tested experimentally with the help of numerical simulations to determine the most favorable parameters.

## References

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