# RECENT RESULTS ON ACCELERATION MECHANISMS AND BEAM OPTIMIZATION OF LASER-DRIVEN PROTON BEAMS

S. Buffechoux[1,2], M. Nakatsutsumi[1], A. Kon[3], R. Kodama[3], P. Audebert[1], J. Fuchs[1]
S. Fourmaux[2], H. Pépin[2], J.C. Kieffer[2].

[1] LULI, École Polytechnique, CNRS, CEA, UPMC, route de Saclay, 91128 Palaiseau, *France*
[2] INRS-EMT, Varennes, Québec, Canada
[3] Graduate School of Engineering, Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan

*Abstract*

Beam optimization of laser-accelerated protons is a crucial point for the development of applications in various areas. Several directions need to be pursued, namely (i) optimization of the high-energy end of the spectrum e.g. for dense plasma radiography, (ii) enhancement of laser-to-protons conversion efficiency and (iii) reduction of divergence e.g. for fast ignition of inertial confinement fusion targets. We will present recent experimental results on these topics. We will show that high-energy protons in the Target Normal Sheath Acceleration (TNSA) regime could be enhanced using spherical plasma mirror or reduced mass solid targets [1]. The laser-to-protons conversion efficiency is equally sensitive to laser and target parameters and can be increased using ultra-thin targets [2] or reduced mass solid targets [1].

## INTRODUCTION

The development of high intensity lasers created a large range of applications thanks to the opened relativistic interaction regimes. Among the domains of such strong field science, proton beams acceleration is an attractive topic. The high spectral cut-off, high directionality and laminarity, and the short bunch duration opened applications such as proton radiography [3] of fields in plasma, warm dense matter generation [4] or compact ions accelerators. However, even if these beams characteristics are already sufficient for the applications mentioned above, beam divergence, conversion efficiency, monochromaticity and spectral cut-off have to be increased in order to increase the range of applications of these beams. Different paths have been explored such as increasing the laser intensity, which is limited by the capabilities of laser facilities, or reducing target thickness [2] but a high laser temporal contrast is needed in this case. Recently, some experiments have been done at LULI using spherical plasma mirror with short focal length (f/0,5) in order to increase laser intensity on the target. Reduced size targets were also used in order to confine electron with the accelerating sheath and improve the characteristics of laser-driven protons beams [1].

## MECHANISM

Proton beams acceleration occurs when an ultra-intense (>$10^{18}$W.cm$^2$) short duration laser pulse is focused on a thin solid foil (few microns thick). Several mechanisms have been observed in experiments and simulations but Target Normal Acceleration (TNSA) seems to be predominant in the interaction regime accessible presently (Figure 1).

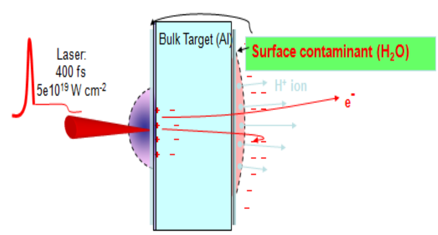


Figure 1: Schematic of proton acceleration in the TNSA regime [5].

In this mechanism, electrons are accelerated from the front target surface by the laser electric field and cross the target toward the rear surface with a 30 degrees divergence angle [6,7]. At the target rear, these electrons form a bell shaped sheath [8] which creates a strong electric field of a few TV/m that can accelerate protons towards the vacuum perpendicularly to the iso-potential. Thus, most of those proton beam characteristics are linked to this electron sheath. One can easily understand that good quality beams can only be accelerated from unperturbed surfaces in order that high separation charges and smooth acceleration occurs. To increase the separation charges and thereby the Debye length, we can also increase electron temperatures by increasing laser intensity or trying to favour re-acceleration. Another way to get a better acceleration is to increase the electron sheath density by increasing the absorbed energy or by confining electrons into the acceleration region.

## INCREASING LASER INTENSITY BY REDUCING THE LASER FOCAL SPOT

One path toward increasing proton beam cut off energy is to increase laser intensity on the target. For this purpose, one can reduce the laser focal spot by using an spherical plasma mirror (SPM) with a very short focal length (f/0,5). This experiment has been done at LULI (at Ecole Polytechnique in France) by using the 100TW laser facility. A 350fs, 10J, frequency doubled laser pulse is focused at the first focal point of an spherical mirror, and is then refocused, once a critical density plasma is created on the surface of the ellipse by the high-intensity laser pulse [9], on the second focal point, see figure 2.

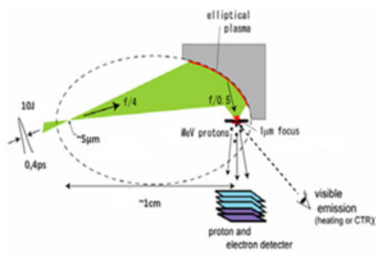


Figure 2: Experimental set-up for using an spherical plasma mirror.

By using such a plasma mirror it is possible to reduce the FWHM by a factor of 5 and so, to significantly increase the laser intensity on the target (Figure 3). Taking into account of the reflectivity efficiency of the SPM, which is about 50%, we can reach up to an intensity of $8.10^{19}$ W/cm$^2$, whereas only $1.10^{19}$ W/cm$^2$ can be reached without SPM.

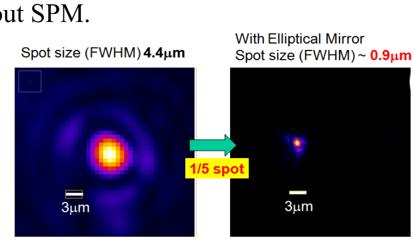


Figure 3: Focal spot obtained after a f/4 parabola (left) and through the spherical plasma mirror (right) at 10Hz (i.e. this does not correspond to a full energy shot).

When we plot proton cut-off energies versus energy on target (here the 30% reflection on the EPM is taken into account), we can clearly see an improvement in proton beam acceleration (Figure 4) when tightly focusing the laser.

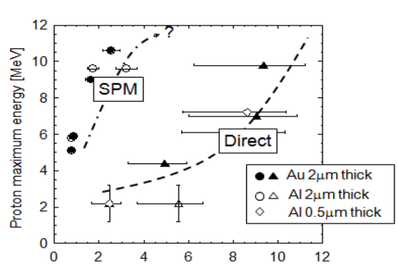


Figure 4: Energy cut-off as a function of laser energy on target.

When we look at the energy cut-off with SPM, it seems to saturate when laser energy is increased on target. That can be explained by the fact that the fluence on SPM grows with the laser energy and so the reflecting plasma surface become more and more perturbed, hence reducing the focal spot quality. By considering focal spot size and energy on target we can compare proton energy cut-off with the same laser intensity on target but with different spot size. Note that in this case, we can observe that acceleration mechanism is more efficient for a large spot size. This is likely due to enhanced lateral spreading of the electrons within the target in the tight focus (associated with a large laser opening angle at the target front) conditions.

## USING LIMITED MASS TARGET IN ORDER TO CONFINE ELECTRONS WITHIN THE SHEATH

Usually larges targets (few millimetres larges) are used for proton acceleration and it was shown that the lateral electronic sheath expansion is about 100 µm for a 9.4 µm thick target [10]. Thus, using small targets (i.e. below ~100 µm can help concentrating electrons within the proton acceleration region by reducing the dilution volume over which they spread within large targets [1]. It was shown that a high contrast laser is needed to avoid rear side perturbation linked to the front side pre-plasma, created before the main pulse that can flow around the target. The experiment was performed with the 100TW laser facility in LULI using a frequency doubled beam (see previous paragraph for laser characteristics) in order to get a better contrast ratio between pedestal and peak intensity. With a magnetic spectrometer and RCF stack diagnostics, we measured proton spectra, transferred laser energy towards protons and beam divergence for Au 2µm thick targets of various lateral sizes. We observe simultaneous increase in proton spectrum cut-off energy and conversion rates (Figure 5) and also a decrease of the beam divergence when the target lateral size is reduced [1].

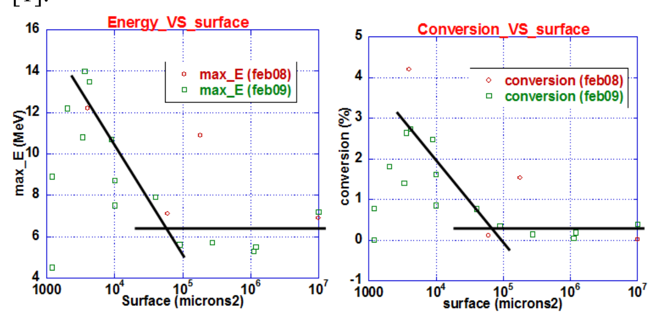


Figure 5: Proton cut off energy and conversion rate for a 2µm thick target.

These trends show a better coupling between laser and plasma which is confirmed by Figure 6: the hot electron number and hot temperature, which contribute to the proton acceleration, increase.

$$\frac{dN}{dE} = \frac{1.3Nhot.cs}{\sqrt{c(2EThot)}} e^{-\sqrt{2E/Thot}} \quad (1)$$

These curves were obtained by fitting the proton spectra (i.e. the number of accelerated protons per unit energy E) using (1) [9], where $c_s=(k_B T_{hot}/m_p)^{1/2}$ with $k_B$

the Boltzmann constant and $m_p$ the proton mass. This has also been confirmed by simulations [1].

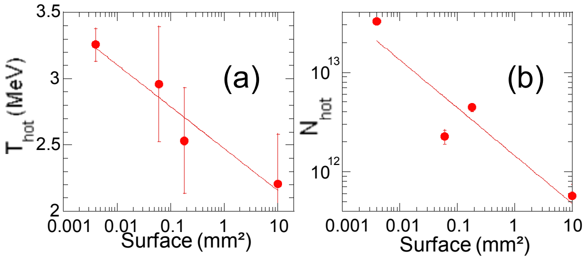


Figure 6: Inferred (a) hot electron temperature $T_{hot}$ and (b) number of laser-accelerated hot electrons $N_{hot}$ for Au 2 µm thick targets. Lines are guides to the eye.

## NEW ACCELERATION REGIMES

Another path towards enhanced laser produced proton beam is to improve laser parameters in order to access new interaction regimes. Recently, new laser facilities allow decreasing laser pulses under 30fs with several joules of energy and a high repetition rate (10 Hz) which permits accessing intensity higher than $10^{20}$W/cm$^2$ on target with relatively small facilities. With this kind of laser, it is interesting to investigate the laser Brunel absorption [12] which differs from ponderomotive electron accelerations, usually prevailing with longer pulses at low contrast. Brunel absorption dominates only if a P polarisation pulse, with an oblique incidence hits a sharp edge and therefore, if the contrast ratio is sufficient to avoid any perturbation of the interaction surface. In this mechanism, electrons are directly accelerated by the P component of the e field through the target; then the separation charge accelerates the proton beam.

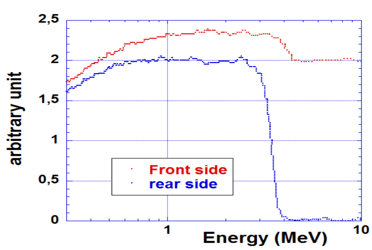


Figure 7: Proton spectra measured with a Time of flight diagnostic.

Some experiments have been done with the 200TW facility at INRS-EMT (Montreal, Quebec) with a 50fs laser pulse, and using a plasma mirror in order to increase the contrast ratio. (Figure 7). With 216mJ (not full power) on target (I=4.10$^{18}$W.cm$^2$), and more than $10^{10}$ contrast ratio 20ps before the main pulse [13], we can obtain 4,2MeV protons, with a 6.5 µm thick target, that proves the interest to study such a regime when compared with others world facilities (Figure 8).

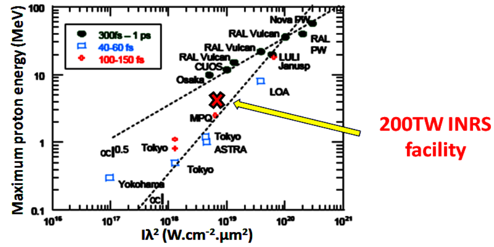


Figure 8: Overview of existing proton parameters as found on different laser facilities.

Thanks to the high contrast, the next interesting step will be to investigate proton acceleration using very thin target, less than 1µm thick which have already proved to be of interest [14].

Alternatives can also be envisioned using more efficient mechanisms as the Radiation Pressure Acceleration (RPA) mechanism at extremely high intensities [15]. Although still untested, it could have the advantage of not requiring larger facilities while allowing producing ion beams with interesting characteristics (e.g. monochromaticity). In this regime, electrons with a circular motion are adiabatically pushed inside the target and thanks to the charge separation can directly accelerate protons.

## SUMMARY

Different paths toward proton beam optimisation have been presented and demonstrate feasible optimization paths for proton beams acceleration. Others are also relevant, such as using a foam target in order to increase laser absorption, or a concave target which can reduce the beam divergence. Using two laser beams or more could also be investigated in order to modify electron injections and propagations in the target [16]. Thanks to the constant comprehension progress and laser facilities development, such ion sources become increasingly interesting for several fields and allow more conceivable compact ion sources.

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