Comparative Study of Laser Ion Acceleration with Different Contrast Enhancement Techniques

A. Flacco, T. Ceccotti, H. George, P. Monot, Ph. Martin

Physique à Haute Intensité (PHI/IRAMIS/SPAM), CEA-DSM, 91191 Gif sur Yvette, France

F. Réau, O. Tcherbakoff, P. d’Oliveira

Saclay Laser-matter Interaction Center (SLIC), CEA-DSM, 91191 Gif sur Yvette, France

F. Sylla, M. Veltcheva, F. Burgy, A. Tafzi, V. Malka

Laboratoire d’Optique Appliquée, ENSTA-Ecole Polytechnique-CNRS UMR 7639, Chemin de la Hunière, 91761 Palaiseau CEDEX, France

D. Batani

Università degli Studi di Milano-Bicocca, P.zza della Scienza 1, 20133 Milano, Italy

Abstract

The study of the interaction between ultrashort laser pulses at relativistic intensities and solid matter has promoted, in recent years, a promising way of investigating ultrafast phenomena and has suggested the possibility of efficiently producing accelerated particle beams. As laser technology has been improving and increasing intensities and energies, it has become clear that the temporal contrast of a laser pulse is a key parameter in defining the conditions of interaction and the involved phenomena. In this paper we present the results that have been obtained in laser ion acceleration experiments from recent past to present days, using the most recent temporal cleaning methods. Different technologies have been adopted to improve the temporal contrast: the obtained effect on the proton acceleration is presented and discussed.

The interaction between ultra-intense laser pulses and solid, overdense, targets offers a promising way to gain deeper insight in the physics of relativistic laser-matter interaction, and offers a realisable source of energetic ion. The obtained ion beams are laminar, short and have a good emittance[1, 2].

Most of the experiments have shown that the most energetic protons emerging from the interaction are produced by Target Normal Sheath Acceleration (TNSA)[3, 4] process. When the laser at relativistic intensity ($I > 10^{19}\text{W/cm}^2$) interacts with an overdense target, a part of its energy is transferred to the electrons in the material, which are heated up to energies in the range from several keV to MeV. As the hot electrons fill up part of the target volume, the material is ionized and the created plasma expands in the vacuum. The high temperature reached by the hot electrons increases the charge separation that is set up at the plasma vacuum interface. The electrostatic field here produced ($\sim TV/m$) can in turns extract and accelerate ions from the material bulk and from the contaminants layer on the target surface. Higher proton energies are usually produced on thinner targets, for the reduced dispersion of charge during the electron drift to the non-illuminated surface results in higher accelerating fields.

During the process of energy deposition, a major role is played by the temporal contrast of the laser pulse, i.e. the ratio between the intensity peak of the short pulse and the background light that precedes it. The residual laser energy may influence the state of the illuminated (front) and non-illuminated (back) surfaces when the interaction and the acceleration start[5, 6].

The research activities in the field of laser-particle acceleration have pushed on the developments in laser and material technologies. Nowadays multi-terawatt laser systems are commercially available. Various techniques to increase the temporal contrast have been tested and validated: as available laser energies are being increased, the need of more efficient techniques for temporal contrast cleaning becomes more and more important. Also, the availability of ultra-high contrast pulses is helping to deepen the knowledge of the laser-ion acceleration process, by providing cleaner interaction conditions.

In this paper we discuss the features of the most effective contrast enhancement techniques that are relevant.
to ion acceleration in present systems. The discussion on different techniques is corroborated by recent results in proton acceleration experiments.

1. Ion Acceleration and Contrast Effects

Several mechanisms have been recognised [7, 8, 9] for transferring energy from the laser field to the freed electrons in the material. Depending on the density gradient length of the plasma that is present on the target surface, at the arrival of the intensity peak, the various mechanisms can gain different relative importances, leading to different number and density of the heated electrons, temperature and ratio of absorbed laser energy. Other parameters, like polarization and impinging angle, do play a role in defining their importance.

At the intensities that are commonly reached for proton acceleration, the pedestal of the laser pulse is normally intense enough to trigger an early ionization of the solid target, that may start from several nanoseconds to less than a hundred of picoseconds before the main peak. The plasma expansion on the illuminated surface affects the laser-target interaction and the ion acceleration in different ways. Different roles are played by the intensity of the pedestal depending on the distance in time from the main pulse, from nanoseconds (ns) to picoseconds (ps).

On the illuminated surface, the nanosecond pedestal can initiate the expansion of a low density plasma towards the vacuum, which displaces the surface where the light absorption takes place. The creation of long density gradients, $L_{\text{grad}} \gg \lambda$, reduces the importance of energy absorption by vacuum heating, in favor of other mechanisms ($J \times B$, resonant absorption), thus reducing the hot electron temperature. Importantly, if the plasma length is large enough, i.e. with a length comparable of the Rayleigh laser length, the peak intensity of the laser can be smaller than the vacuum peak intensity.

In addition, the shock wave that is produced by the plasma expansion starts travelling through the target, eventually reaching the back surface before the arrival of the high intensity peak. The reflection of the shock wave onto the non-illuminated surface may trigger the creation of a density gradient on it, which, in most of the cases, is detrimental to the TNSA accelerating field [10]. This effect of the nanosecond scale pedestal is often indicated as the reason for the presence of an optimal target thickness arising in most of the experiments [11], thinner targets developing too important gradients on the accelerating surface.

In some experimental cases, the pedestal may exceed the ionization threshold only starting from some tens of picoseconds before the main pulse. The effects induced on ion acceleration by this condition have not been extensively studied yet. If the interaction happens on an unperturbed target, a short density gradient is produced. This particular aspect may even be beneficial to the acceleration process, as previous theoretical works show that the presence of a very short density gradient on the illuminated surface does increase the efficiency of electron heating [13, 14]. However, hydrodynamic simulations show that increases in pedestal intensity above $10^{11} - 10^{12} \text{W/cm}^2$ from $t = -50 \text{ps}$ do increase the production of energetic photons and hot electrons. In the case of very thin targets, the interaction of these electrons and photons with the rear surface can trigger its early expansion, producing the detrimental effects mentioned above.

In recent years technologies for producing laser pulses at ultra-high contrast have become available, which has triggered new advancements in laser-ion acceleration experiments. The use of ultra-high contrast enables the use of very thin targets (down to several nanometers) which in turns increase the efficiency of the acceleration process and the proton energy [15]. In [16] it is shown that the lack of pedestal in conjunction with the use of thin targets permitted the production of a symmetric expansion of the foil, observing ion beams of the same energy produced during the interaction and propagating on the forward and on the backward direction.

The experimental results presented in this paper have been obtained from two different laser systems. The first (LOA-SJ) is the multiterawatt Ti:Sapphire laser chain that is installed in the Salle Jaune laser room at the Laboratoire d’Optique Appliquée of ENSTA/CNRS. The second (CEA-UHI100) is the multiterawatt commercial system by Amplitude Technologies installed at the Saclay Laser-Matter Interaction Center (SLIC), in CEA-Saclay. The measurements of the temporal contrast in all of the experimental conditions described hereafter have been realized by the same team using the same instrument, a 3x correlator with a dynamic range of $10^{12}$. The proton cutoff energies have been measured by two Thomson Parabolas coupled to Microchannel Plates.

2. Contrast Enhancement

In the CPA amplification strategy the problem of the temporal contrast of the pulse arises mostly in the first stages of amplification, where the seed pulses with energies of nano-joules need to be amplified by several orders of magnitude.

The use of clean seed pulses and the separation between the injection front-end and the high power amplification part of the laser chain has been recognised as an effective way to reduce the level of amplified spontaneous emission (ASE), increasing the final temporal contrast [17, 18].

In fact, the use of a separate preamplifier enables to seed the high energy part of the laser system with higher intensity pulses, which intrinsically reduces the final ASE level. Moreover, several filtering techniques have been proposed to enhance the temporal contrast during the pre-amplification, which allows to further clean the pulse; these techniques include the use of saturable absorbers [17], fast pockels cells, X-Polarized Wave Generation [19]. Other
techniques have been studied to clean the full energy laser pulse before compression (eg. fast Pockels cells) or after compression (Plasma Mirrors[20]).

In this paper we present the results that can be obtained with the X-Polarized Wave Generation (XPW) and with a Saturable Absorber (SA). The first technique has been experimented on the LOA-SJ laser chain. The second (SA) is in use on the UHI100 system of CEA-Saclay. Further contrast enhancement with a Double Plasma Mirror (DPM) is also available on the same chain.

2.1. LOA-SJ and X-Polarized Wave Generation

The XPW technique uses non-linear materials with anisotropic $\chi^{(3)}$ term to produce an output wave with a polarization rotation [19, 21]. The used non-linear process is a degenerate four wave mixing. In the application to contrast enhancement, a polarizer is used to set the input polarization plane. The beam is then focused on one or more crystals. The crossed polarized beam is selected by a second polarizer (analyzer). The contrast enhancement resides on the third order dependency between the amplitudes of input and output waves. The limiting factor on the capability of the XPW to increase the temporal contrast is in the extinction power of the two crossed polarizers ($\sim 10^{-5}$)

The energy that is required to obtain a sufficient output from the XPW is in the order of some millijoules. For this reason the seed pulse from the oscillator needs to be pre-amplified before injecting in the filtering setup.

The multi-terawatt laser system of LOA-SJ is a CPA system composed by three multipass amplification stages, capable of delivering pulses of $E_L = 1.5J$ before compression. The contrast in the front-end (oscillator and pre-amplifier) is filtered by an XPW system composed by two slabs of BaF$_2$ glass[21]. The femtosecond pulses are firstly stretched, pre-amplified and re-compressed, then sent through the XPW system; once stretched again, they are injected in the CPA chain. The final temporal contrast is better than $10^{10}$ on the ns timescale. The $3\omega$ cross-correlator traces are shown in Fig.1 from $t = -150$ps and Fig.3 from $t = -30$ps.

2.2. Saturable Absorber and CEA-UHI100

The laser system UHI100 of SLIC in CEA-Saclay is a commercial multiterawatt CPA chain (Amplitude Pulsar-100). The amplification chain is composed by a regenerative and three multipass amplifiers. In the front-end, the pulses from the oscillator are pre-amplified by a ring femtosecond amplifier and filtered by a saturable absorber. The injection in the CPA chain is done at the $\mu$J level, with a contrast that is better than $10^{10}$ on the ns timescale. The contrast of the amplified pulse is shown in Fig.1 (red line) and in Fig.3 (dashed black line).

On the UHI100 experimental facility, a double plasma mirror setup is used for further increasing of the temporal contrast. The system is installed in the beam transport between the compressor and the experimental chamber.

![Figure 2: Scheme of the insertion of a double plasma mirror on the beampath. 1. focusing/collimating parabolas; 2. Anti-reflection coated dielectric plates.](image_url)

The double plasma mirror setup (Fig.2) is composed by two parabolas, for focusing and collimating back the laser beam, and two parallel, anti-reflection coated, fused silica mirrors. When the flux exceeds the ionization threshold, an overdense plasma is formed on the surface, which reflects the forthcoming part of the beam. In the correct configuration, the intensity increase must trigger the ionization not much before the main intensity peak, letting most of the pedestal pass through the glass plate[20]. The contrast enhancement before the plasma mirrors are triggered is limited to the product of the residual reflectivity of the two A/R coatings, $\sim 10^{-4}$. The measured efficiency of energy transport is $E_{L,\text{out}}/E_{L,\text{in}} \simeq 50\%$.

Fig.3 shows a comparison between the temporal contrast of the pulse filtered by the XPW (LOA) and what is obtained on UHI100 with the plasma mirrors in place (SA+DPM), starting from $t = -30$ps; for comparison the plot obtained with SA is added. The plasma mirror is able to clean the temporal profile up to the picosecond timescale.

3. Ion Acceleration

Experimental campaigns on ion acceleration have been performed in the two laboratories in similar conditions (see
Figure 3: 3ω cross correlator traces showing the temporal contrast up to 30ps before the main pulse (DPM: Double Plasma Mirror, SA: Saturable Absorber, XPW: X-Polarized Wave generation).

Table 1. On the CEA-UHI100 system, the experiment has been carried without (CEA-LC) and with (CEA-HC) the double plasma mirror in place.

<table>
<thead>
<tr>
<th></th>
<th>Energy on Target [J]</th>
<th>2w₀ [μm]</th>
<th>I₀ [10¹⁸W/cm²]</th>
<th>Proton Energy [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOA</td>
<td>0.35</td>
<td>5</td>
<td>40</td>
<td>4.3</td>
</tr>
<tr>
<td>CEA-LC</td>
<td>1.5</td>
<td>8</td>
<td>77</td>
<td>5.1</td>
</tr>
<tr>
<td>CEA-HC</td>
<td>0.85</td>
<td>8</td>
<td>38</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Table 1: Experimental configurations for ion acceleration, including (i) total energy transported on the target, (ii) beam waist, (iii) peak intensity and (iv) proton cutoff energy. The I₀ term is calculated including the ratio of energy in the focal spot envelope, not shown here. The proton energy is the one measured in the best experimental condition, see Fig.4.

The proton beam is obtained by focusing the laser energy on thin aluminum targets of variable thicknesses. On both installations the laser pulse is focused by f/3 off-axis parabolae and impinges p-polarized on the target, with an angle of 45°. In the LOA experiment a deformable mirror is used to improve the beam phase front, increasing its focusability (see Table 1). The total on-target energy is calculated from the laser energy before compression and the total losses due to compression and transport of the beam. The peak intensity is calculated from the total energy contained in the I > (I₀)/e² area of the focal spot. This analysis is performed numerically on high resolution, high dynamic range images of the focal spot.

The proton spectra are measured by Thomson Parabolas coupled to Micro-channel plates. The plotted points show the average value of proton energy obtained from multiple shots. Figure 4 shows the variation of the maximum proton energy divided by the laser peak intensity (expressed in 10¹⁸W/cm²) with the target foil thickness. The duration of the laser pulse, τ_L = 30fs, and the wave-length, λ = 800nm, are the same in the two laser systems. However, the two experiments are carried at different intensities and the difference in shapes and intensities of the pedestal will produce different interaction conditions. Since k_B T_hot ∝ √I, where T_hot is the hot electron temperature[22, 23], this normalization enables us to compare the results from the point of looking for the best interaction conditions. The error bars have not been added in order to enhance the readability of the figure; nevertheless, during the experimental procedure, the rms fluctuation of proton cutoff energy never increased over 5%.

Proton energy in the worse contrast condition (CEA-LC) shows the usual inversion of tendency for targets thinner than an ideal thickness, here at 6μm. This is consistent with what is shown in Fig.1: the pedestal intensity in the CEA-LC case turns out to be I_{ASE,LOA} ∼ 8 × 10¹¹W/cm². For targets thinner than the optimum, the proton energy in the CEA-LC case rapidly decreases.

In the two other cases, XPW and SA+DPM, the intensity of the nanosecond pedestal is well below the ionization threshold, being I_{ASE,LOA} ∼ I_{ASE,HCLC} ∼ 4 × 10⁹W/cm². The behaviour of the proton energies measured in these two cases (Fig.4) is similar. In both of the high contrast conditions, it is observed an optimal thickness of the target, which is 3μm for LOA and 1.5μm for CEA-HC. The decreasing of proton energy after the optimum is, in both of the cases, much slower than what observed in the low contrast case. In the two cases the proton energy loss between the best acceleration condition and the thinnest target case is in the order of ~ 10%.

Looking at the rising front of the laser intensity profile, some tens of picoseconds before the femtosecond peak, the plots of the temporal contrast show that the SA+DPM case is at least two orders of magnitude better than XPW. Since the peak intensity is almost the same in the two
cases, the consequences on LOA experiment are expected to be worse than the CEA-HC case. By taking as an example the pedestal level at $t = -20\,\text{ps}$, in LOA experiment it is $I(t = -20\,\text{ps}) \sim 4 \times 10^{11}\,\text{W/cm}^2$ while in CEA-HC is as low as $I(t = -20\,\text{ps}) \sim 4 \times 10^{9}\,\text{W/cm}^2$.

The presence of an optimum (and the consequent decreasing of proton energy) in the two high contrast cases has to be related to the increase of pedestal intensity in the picosecond range. This is in agreement with the plots in Fig. 4, where LOA and CEA-HC curves are superposed until the optimum on the LOA plot is reached at $d = 3\,\mu\text{m}$.

The presence of an optimum on the CEA-HC might suggest a detrimental effect of the pulse rising front (Fig. 3) that starts at $t = -5\,\text{ps}$.

4. Conclusions

Experiments of proton acceleration with ultrashort laser pulses have been realized in high-contrast and ultra-high contrast, using the techniques that are considered nowadays the most promising ones. The variation of the (normalized) proton cutoff energy versus the thickness of the target indicates that both the techniques are able to successfully lower the nanosecond pedestal and to void its detrimental effect on the acceleration process. The best accelerating conditions are obtained with the double plasma mirror in the CEA-HC experiment. The two systems, however, do reach an optimum thickness, which is $3\,\mu\text{m}$ for LOA and $1.5\,\mu\text{m}$ for CEA. In both these cases the worsening of the acceleration conditions is much slower than what observed on the CEA-LC configuration. This experimental result, analyzed in comparison with the $3\omega$ cross-correlation measures of the temporal contrast, suggests that this detrimental effect on the proton energy should be related to the shape of the intensity rising front, on a timescale of some tens of picoseconds. This fact motivates further studies to better understand the dynamics of energy deposition on such timescale and which constraints should be requested to the laser system. The contrast plots also show that future laser systems will need to accompany the increase in energy with a further improvement of the pulse cleaning technologies, in order to keep the pedestal to acceptable levels.

References


