Effect of a nanometer scale plasma on laser-accelerated ion beams

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Abstract. Energies of laser-accelerated ions from thin foils in the so-called ‘ultra-high-contrast’ regime have been measured for various preformed plasma sizes on the non-irradiated foil surface. Whereas energies of protons accelerated in the laser counter-propagating direction remain almost constant for plasma scale length up to 300 nm, we found that plasmas as short as a few tens of nanometers reduce the maximum energy of ions accelerated in the laser direction. These experimental measurements are numerically confirmed with two-dimensional particle-in-cell simulations coupled to hydrodynamic calculation. Moreover, our experimental results, supported by simulations, provide evidence for the occurrence of ion wave breaking, and demonstrate its ability to mitigate the ion energy reduction due to the plasma gradient. This wave breaking is observed and characterized for both proton and carbon ion components.

High-energy ions produced by irradiation of thin foils with relativistic laser beams ($I_0 > 10^{18}$ W cm$^{-2}$) draw increasing interest from the scientific community [1]–[3], owing to their remarkable beam properties, such as high laminarity, low divergence and short duration, making them appropriate for a number of applications. Among them, we can mention proton radiography [4], isochoric heating [5] and proton therapy [6]. The main ion acceleration mechanism, target normal sheath acceleration (TNSA) [7], is now well understood: a hot electron beam, generated by the interaction between a relativistic laser pulse and a solid foil, propagates through the target and creates a dense electron sheath on its cold non-irradiated

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surface. There, the resulting intense electrostatic field (few TV m\(^{-1}\)) ionizes and accelerates hydrocarbon pollutants.

In this framework, a number of published works have dealt with the impact on ion acceleration of an inhomogeneous plasma present on the target back surface [8]–[12]. Indeed, due to the presence of a laser pulse pedestal, the generation of a plasma on the thin foil rear surface is an intrinsic drawback for most laser–plasma interaction experiments using chirped-pulse-amplification (CPA) pulses [13, 14]. Using an isothermal model, Grismayer and Mora [12, 15] showed that such a plasma reduces the peak amplitude of the electrostatic field, which reads as:

\[
E_0 \times K/[1 + (K \ell_{ss}/\lambda_{D0})^{3/2}]^{2/3},
\]

where \(K = \sqrt{2/\epsilon_N} (\epsilon_N = 2.7183 \ldots)\), \(\lambda_{D0}\) is the initial electron Debye length, \(E_0 = \sqrt{n_e k_B T_{e,h}/\epsilon_0}\) with \(T_{e,h}\) the hot electron temperature, \(n_e\) the hot electron density, \(\epsilon_0\) is the vacuum permittivity, \(k_B\) the Boltzmann constant and \(\ell_{ss}\) is the rear plasma scale length. Numerical simulations [10] as well as experimental works [9, 11] reported that \(\mu\)m-scale plasmas reduce the maximum proton energy, or even suppress the ion signal. Another mechanism may come into play due to the presence of a plasma on the back surface. Grismayer et al [12] have indeed shown that the rear plasma ions experience an accelerating field, which is decreasing along the plasma gradient direction. Consequently, the highest energy ions are preceded by lower energy ones, which will then be caught up by the former during the acceleration phase. This feature, called ion wave breaking (IWB) in [12], results in a slight increase of the accelerating field. Recently, Fuchs et al [9] speculated that IWB could explain why no decrease of the proton cut-off energy was observed in their experiments for \(\ell_{ss}\) lower than 3 \(\mu\)m. However, no ion energy measurement with nanometer-scale plasma on the back surface has been performed up to now. In particular, we can wonder whether such a short rear plasma will impact the ion acceleration, and how sensitive to IWB this mechanism will be for \(\ell_{ss}\) values in the range of \(\lambda_{D0}\).

In this paper, we report on experimental and numerical investigations of laser-accelerated ions from Mylar foils, initialized with a plasma scale length ranging from 10 to 300 nm on their rear surface. Thanks to the ultra-high contrast ratio of our laser beam [16], our measurements do not suffer from any laser pedestal effect, such as the generation of a preplasma on both target surfaces. We were therefore able to measure a significant reduction of the rear proton cut-off energy even for gradients as short as 100 nm. This energy decrease does not affect protons accelerated in the backward direction. Moreover, we demonstrate the systematic occurrence of IWB, over a large range of rear surface density scale lengths, and characterize its features and impact on the final ion energies.

The experiment was performed at the Saclay Laser Interaction Center Facility, using the UHI10 laser that delivers 10 TW ultrashort pulses (65 fs) at 10 Hz repetition rate. This Ti:sapphire laser, operating at a central wavelength of 790 nm and based on the CPA technique, was split into a low and a high-energy beam (figure 1). First, the low-energy one was defocused to a spot size of 50 \(\mu\)m (FWHM) under 22\(^\circ\) incidence and s polarization, on the rear surface of a 6 \(\mu\)m thick Mylar foil. Frequency doubling (\(\lambda = 395\) nm) by means of a nonlinear crystal and two dichroic mirrors allowed a temporal contrast up to \(10^8\), yielding an intensity of \(10^{15}\) W cm\(^{-2}\) on the foil. Then, with a variable time delay \(\Delta t\), the high-contrast high-energy beam was focused to a spot size of 8 \(\mu\)m (FWHM) using an off-axis \(f = 300\) mm parabola, under 45\(^\circ\) incidence and p polarization, on the Mylar front surface. The laser intensity was \(4 \times 10^{18}\) W cm\(^{-2}\), and the contrast was better than \(10^{10}\) [16], ruling out the presence of any kind of uncontrolled preplasma. Some measurements were also realized at a lower laser intensity (\(1.5 \times 10^{18}\) W cm\(^{-2}\)) by introducing a 40 mm aperture, 10\(^\circ\)-rotated half-wave plate on the optical
Figure 1. Experimental setup. $\Delta t$ is the time delay between the low and the high-energy beams.

path before the focusing parabola [17]. Using an optical delay line, $\Delta t$ was tuned up to 20 ps with a 150 fs accuracy. By collecting the low-energy beam transmitted through the foil with an imaging relay system, we set the temporal origin ($\Delta t = 0$) as the time at which the bulk becomes opaque due to ionization by the high-energy beam. This temporal origin was measured with a 400 fs accuracy. Ion spectra were recorded with the same diagnostics (Thomson parabola) as those used in [17].

The experimental results were interpreted using two simulation codes. First, the plasma generated by the low-energy beam and expanding into vacuum was modeled with the Lagrangian code Esther [18], a one-dimensional (1D) hydrodynamic code specifically designed to describe laser ablation of solid targets. The 1D geometry is well suited to the present setup because the low-energy beam focal spot is much larger than the spot sizes of both the high-energy beam and the high-energy proton source [19], so that laser-accelerated ions originate from a transversely uniform plasma. The Sesame Mylar equations of state, carbon plasma transport coefficients and the Keldysh photo-ionization theory were used in Esther to model the Mylar target. From the simulated evolution of the plasma density profile, we extracted the gradient scale length, $\ell_{ss}$ (in the high-density region) on the Mylar rear surface as a function of $\Delta t$. These results, plotted in figure 2, were fitted with a linear interpolation yielding the average Mylar sound velocity for our parameters, $c_s = 1.8 \times 10^4$ m s$^{-1}$.

The 2D particle-in-cell (PIC) simulations were then performed with the code Calder [20] to study the influence of such a rear-preformed plasma on ion acceleration. Due to numerical constraints, the target thickness was fixed to $L = 500 \text{ nm}$. In a first series of simulations, the target was only composed of protons and electrons, whose initial temperatures ($T_e$, $T_i$) and densities ($n_e$, $n_i$) were set to 1 eV and $180 n_c$ ($n_c = 1.74 \times 10^{21}$ cm$^{-3}$ for $\lambda_0 = 790 \text{ nm}$), respectively. The mesh sizes, $\Delta x = 5 \text{ nm}$ and $\Delta y = 10 \text{ nm}$, ensured a numerical heating lower than 5% of the laser energy. The transverse box size was as large as $60 \mu\text{m}$, whereas the longitudinal one ranged from 38 to $65 \mu\text{m}$ depending on the initial plasma gradient length. Instead of initializing the rear plasma profiles with the Esther results, they were initialized as $n_{e,i}(x) = 180 n_c$ for $0 \leq x \leq L - \ell_{ss}$ and $n_{e,i}(x) = 180 n_c \times e^{-\frac{(x-L-\ell_{ss})}{\ell_{ss}}}$ for $x > L - \ell_{ss}$, and their
density was lower bounded with $n_c/100$, in order to keep the target mass constant over all simulations. The temporal and spatial profiles of the laser beam were Gaussian with FWHM equal to 65 fs and 8 µm, respectively. The peak normalized vector potential $a_0$ was set to 1.17, yielding a peak intensity of $I_0 = 3 \times 10^{18}$ W cm$^{-2}$, reaching the front target surface at $t = 183.5$ fs.

First, we analyze the impact of the plasma gradient on protons accelerated in the laser backward direction. The experimental cut-off energies of such protons are reported in figure 3, where each point represents an average value over ten shots and the error bars correspond to the standard deviation. These measurements display a slight energy decrease with the plasma scale length. This energy lowering, confirmed with numerical simulations, is limited to less than 10% for plasmas as large as 300 nm. It results from the hot electron dilution in target for which the thickness increases with the plasma gradient scale length. So, backward-accelerated protons are
barely sensitive to the rear plasma gradient. We will now focus our attention only on protons accelerated in the forward direction.

The experimental proton cut-off energies are shown in figure 4 as a function of the time delay $\Delta t$ and the plasma scale length $\ell_{ss}$. These data are reported for two different high-energy beam intensities ($\approx 1.5$ and $4 \times 10^{18}$ W cm$^{-2}$). Energies are normalized to their maximum value (respectively, 1.67 and 2.33 MeV) and each point represents an average value over ten shots. We observed that, even for plasma scale lengths of a few tens of nanometers, the proton cut-off energy decreases when $\ell_{ss}$ increases. Moreover, in contrast with results presented in [9], where the maximum proton energy is halved for a gradient scale length near 10 $\mu$m, figure 4 clearly exhibits the same energy decrease over much smaller gradient scale lengths ($\sim 250$ nm). This difference will be further discussed below. In addition, both data sets display the same behavior: the sharp decrease of the cut-off proton energy over small gradient lengths ($\ell_{ss} \lesssim 75$ nm) is followed by a smoother trend for larger $\ell_{ss}$ ($\gg 100$ nm). We report on the same figure the simulation results evaluated at $t = 850$ fs (near the saturation time) and normalized to 5.72 MeV, the value obtained at $\ell_{ss} = 0$. Owing to the thinner foil considered in the numerical study, the absolute values of proton cut-off energies are actually higher than the measured ones. It is worth noting that all PIC simulations give an absorbed laser energy equal to 46.5 $\pm$ 0.6%, so that protons experience a similar hot electron source whatever the scale length is. Numerical data reproduce quite well the measured proton energy trend and display a similar slope break for $\ell_{ss} \sim 100$ nm.

Numerical simulations highlight that this slope change originates in the proton energy gained upon IWB [12]. Due to the presence of an initial plasma on the target rear surface, ions from low-density regions experience lower accelerating fields than ions from higher density regions, leading to a bell-shaped ($x$, $p_x$) phase space early in the acceleration (see figure 5(a)). Later on in the acceleration phase, the more energetic protons catch up with the less energetic ones, yielding a proton wave breaking highlighted in figure 5(b). IWB gives rise to a local peak in ion density, slightly increasing the accelerating field and the proton cut-off energy. This

Figure 4. Normalized maximum energy of forward-accelerated protons versus $\ell_{ss}$ and $\Delta t$. Black triangles represent numerical data ($I_0 = 3 \times 10^{18}$ W cm$^{-2}$) normalized to 5.72 MeV, while experimental measurements plotted with green squares ($I_0 = 4 \times 10^{18}$ W cm$^{-2}$) and blue circles ($I_0 = 1.5 \times 10^{18}$ W cm$^{-2}$) are normalized to 2.33 and 1.67 MeV, respectively.
IWB-induced energy gain is apparent in figure 5(c) as a change in the slope of the proton energy temporal evolution at the wave-breaking time, \( t_d = 340 \) fs. This phenomenon is observed for off-axis ions too, over a transverse size close to the focal spot dimension.

IWB is observed in our simulations as soon as an initial plasma gradient is present on the target rear surface. As shown in [12] and in figure 6(a), the time \( t_d \) at which it occurs depends on the plasma gradient scale length. Within the isothermal model, Grismayer et al [12] have analytically obtained \( t_d = 4 \ell_{ss}/c_{so} \), where \( c_{so} = \sqrt{Zk_BT_{e,h}/m_i} \) is the acoustic velocity, with \( Z \) and \( m_i \) the ion charge and mass, respectively. In our simulations, electrons are heated up to \( T_{e,h} \sim 300 \) keV, so that \( c_{so} \sim 5.5 \times 10^6 \) m s\(^{-1}\). The analytical formula for \( t_d \) is plotted in figure 6(a), with the time origin shifted to \( t_0 = 183.5 \) fs, i.e. the time at which the peak intensity reaches the target in our simulations. It fits the numerical results well up to 100 nm, suggesting that for these \( \ell_{ss} \) the isothermal hypothesis for the electron population is well-founded. Figure 6(b), plotting the temporal evolution of the normalized electron energy, confirms that for these cases, wave breaking occurs when the electron kinetic energy is still larger than 90\% of its peak value. However, for larger gradient scale lengths (>100 nm), \( t_d \) deviates from the analytical formula, reflecting that the proton beam breaks when electrons have already cooled down. For \( \ell_{ss} = 300 \) nm, for instance, the electron kinetic energy is almost halved when proton IWB occurs (figure 6(b)).
The IWB-induced electrostatic field increase enables accelerated protons to gain additional energy (figure 5(c)). Figures 4 and 6 demonstrate that when the ion wave breaks early in the acceleration phase ($\ell_{ss} < 50$ nm), this extra energy is negligible because the acceleration process is almost similar to the standard one. It becomes more and more important as the initial plasma scale length increases ($\ell_{ss} > 50$ nm), and results in a mitigation of the proton energy decrease with $\ell_{ss}$. However, this energy gain is saturated by the electron cooling, leading to an energy decrease with plasma scale length for $\ell_{ss} > 150$ nm, as illustrated in figure 4. In this case, the ion wave breaks as the electron population has lost 30% of its kinetic energy. By considering that electrons start to really cool down when the laser interaction turns off, this feature explains the differences observed between our measurements and those reported in [9]. In this experiment, protons were driven by a 5 ps laser pulse, which is about 70 times longer than our beam. Moreover, electrons were heated up to a temperature almost four times higher than in our experiment, so that wave breaking was two times faster for a given $\ell_{ss}$. A factor of 140 is then expected in the $\ell_{ss}$ scaling between the two experiments, which is in the range of the 15 $\mu$m/250 nm ratio.

A non-negligible signal was also measured for laser-accelerated C$^{3+}$, C$^{4+}$ and C$^{5+}$ ions. To study the influence of such highly charged ions on the proton dynamics, we have also simulated a plasma composed of protons, electrons and C$^{4+}$ ions, the latter being the largest recorded ion population besides protons. The numerical parameters were identical to those from previous simulations, except that the particle densities were chosen to be $n_e = 180n_c$, $n_p = 60n_c$, $n_{C^{4+}} = 30n_c$ to keep the plasma globally neutral.

Figure 7 compares the normalized proton and C$^{4+}$ cut-off energies experimentally measured with those obtained by numerical simulations at $t = 1.5$ ps. We note that the presence of carbon ions significantly modifies the proton cut-off energy in the calculation. We still see a reduction in the energy decrease with $\ell_{ss}$, resulting from wave breaking, but with a slight climb as in experimental measurements. Experimental measurements for C$^{4+}$ ions, plotted in figure 7(b), exhibit the same trend as that observed for protons. It is not so well reproduced with numerical simulations, which however showed IWB for carbon ions. Figure 8, plotting the wave-breaking time for these two species, clearly displays that due to their lower $Z/m_i$ ratio, the carbon ion beam breaks later than the proton one. By comparing these results with the
Figure 7. Normalized cut-off energy versus $\ell_{ss}$ and $\Delta t$ for protons (a) and C$^{4+}$ ions (b): numerical data ($I_0 = 3 \times 10^{18}$ W cm$^{-2}$) normalized to 7.95 MeV for proton and 7.33 MeV for C$^{4+}$ ion (black circles), experimental measurements ($I_0 = 4 \times 10^{18}$ W cm$^{-2}$) normalized to 0.94 MeV for C$^{4+}$ ion (green squares).

Figure 8. Wave breaking time versus the plasma gradient scale length for proton (black) and C$^{4+}$ ion (red). The dotted lines display the analytical formula for $t_d$, with $c_{so} = 3.1 \times 10^6$ m s$^{-1}$ for C$^{4+}$.

analytical formula for $t_d$, we observe that the carbon wave-breaking times are much higher than those predicted by the isothermal model. This discrepancy may originate in the electrostatic field screening by the laser-accelerated protons, which is not described within the isothermal model. These two-species results reveal that the ion cut-off energy is sensitive to the species considered in simulations and their relative densities [21, 22]. The discrepancy between numerical and experimental results certainly originates from the somewhat arbitrary choice of the C$^{4+}$ density and the frozen carbon ionization level. More quantitative simulations require accounting for field ionization, which will be the subject of a future study.

Using ultrahigh-contrast laser pulses, we were able to study in this paper the detailed consequences of a rear plasma gradient scale length on ion acceleration. Whereas backward accelerated protons are barely affected by the rear plasma, we observe in our experimental
conditions that plasma gradient scale lengths as short as 250 nm reduce the maximum proton energy by a factor of 2. Moreover, supported by numerical simulations, we have evidenced the occurrence of IWB during acceleration of both proton and C\textsuperscript{4+} components, and have elucidated its impact on the final forward accelerated ion peak energy. Particularly, we have highlighted that the electrostatic field increase due to this process is able to boost the maximum proton energy, thereby mitigating the field decrease induced by a smoother density profile.

The numerical simulations were performed using the CCRT supercomputer at CEA/DIF.

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