Measuring hot electron distributions in intense laser interaction with dense matter

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Abstract. Retrieving the characteristics of hot electrons produced in the interaction between solid targets and ultra-intense (\(I > 10^{18}\ W\ cm^{-2}\)) laser pulses is essential for achieving progress in our understanding of the interaction physics, which is key for optimizing numerous downstream applications. Until now, various methods have been used, direct or indirect, but no correlation and no assessment of their respective merits were performed. Here we compare results retrieved from four different diagnostics, direct or indirect, as well as local or non-local, i.e. spectrometry of electrons, spectrometry of the protons accelerated by the electrons and optical probing of these beams expanding into vacuum from the targets. We show that measurements obtained locally at the

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target rear surface are consistent with those far away from the target and that one can use the diagnostics of the co-moving proton beams to retrieve information about electrons.

Energetic (MeV) electrons generated by irradiation of solids by ultra-intense short laser pulses with intensities of $10^{18} \text{–} 10^{20} \text{W cm}^{-2}$ are directly or indirectly used for a wide variety of applications due to their inherent qualities, namely high brightness, short duration and high energy. These applications range from the generation of secondary sources of particles and radiation (neutrons, ions, x-ray, $\gamma$-rays) that serve as fast and bright probing tools for laboratory astrophysics, material science and plasmas, or even medical diagnostics. It is also envisioned to use them for fast ignition of inertial confinement fusion (ICF) targets [1–3]. That is why measuring the characteristics of these fast electrons (spectrum, mean energy (the so-called temperature), number and density) has been the subject of much effort.

Until now, measurements of electron populations have been made mainly by simple, albeit distant measurement techniques, i.e. using spectrometers [4–7] or nuclear activation diagnostics [8] located a few cm to a few meters behind the target. Another simple technique was to deduce the fast electron characteristics from the spectrum of MeV protons that the electrons electrostatically accelerate during the plasma expansion into vacuum [9]. Protons that stem from the target with this acceleration technique are also measured by diagnostics located at least a few cm away from the target (www.ispcorp.com/products/dosimetry/index.html) [10, 11] (corresponding to a distant, non-local measurement). Hot electron spectra can be deduced from fitting proton spectra [12] since these hot electrons are the source of the proton acceleration. The issue is to clarify whether these distant or indirect measurements are relevant with respect to the characteristics of the electrons located within the dense target and that could be obtained by local measurement. The correspondence of both the distant and the local measurement is not obvious since the electrons reaching the far-distant detectors are the escaping ones, whose characteristics can be altered by the potential built around the target over a Debye length by the hot electrons themselves (http://meetings.aps.org/link/BAPS.2009.DPP.NO5.12; http://meetings.aps.org/link/BAPS.2010.DPP.UO5.9).

To circumvent this issue, other measurement methods have been developed to retrieve information about the electrons locally in the target, e.g. K$\alpha$ [13–16] and optical transition radiation (OTR) [17]; but K$\alpha$ and OTR measurements are not the most suitable technique for measuring MeV electrons since they are most sensitive to lower (keV) and higher (tens of MeV) energy electrons, respectively. Lately, a technique allowing us for the first time to measure directly the electron density and temperature of the relevant MeV-range electrons has been developed [18, 19]. This technique (time- and space-resolved interferometry (TASRI)) exploits time-resolved phase measurements of an optical probe beam reflecting off laser-irradiated solids, so it samples locally the hot electron distribution produced in the laser–solid interaction. Using this measurement technique, it is possible to retrieve the initial parameters of the hot electron population, i.e. its initial density $n_{e0}$ and temperature $T^0$. The diagnostic is able to detect electron densities down to $5 \times 10^{18} \text{cm}^{-3}$, and has a resolution of $\sim 4 \text{ps}$ and $6 \mu \text{m}$ [19]. Thus, we can now compare the measurement performed locally on the target to measurements obtained non-locally, using e.g. spectrometers, and clarify their relation.
In this paper, we compare these various measurements and show that measurements obtained with distant diagnostics, electron and proton spectrometry as well as nuclear activation, yield similar hot electrons characteristics as the local sampling of the distributions at the target surface, which is more difficult to field. Our measurements thus support recent simulations, suggesting that distant measurements could be indeed relevant for local ones. These simulations show that the spatial temperature distribution of the electrons leaving the rear target surface contains at its front a region that retains the initial temperature the electrons had at the target surface at the start of their expansion into vacuum [20]. This part of distribution therefore remains unchanged, although most of the electrons transfer their energy to the co-moving ions, lowering their initial temperature.

The experiments were performed using the 100 TW laser at the Laboratoire pour l’Utilisation des Lasers Intenses (LULI) working in the chirped pulse amplification (CPA) mode. The experimental setup is shown in figure 1. Experiments were performed in two modes: with the wavelength of the laser light, in S-polarization, either at 1.057 or 0.527 µm, the latter allowing us to explore the interaction of the laser with sharp-surface solids since the temporal contrast of the laser is higher when frequency doubled. The experiments were also performed with two laser pulse durations \( \tau \): either 320 fs or 5 ps, as measured after compression and before focusing. Dynamic wavefront correction is performed before every shot using a deformable mirror [21] in order to eliminate cumulative thermal loading in the amplifiers. Focusing of the main interaction laser is achieved using a \( f/3 \) off-axis parabola. Targets positioned at focus are irradiated at normal incidence.

We used four independent diagnostics: the first diagnostic was a calibrated proton and electron spectrometer [7] located 81 cm behind the target and sensitive to protons and electrons of energies \( > 1.3 \) MeV. The second diagnostic was a stack of radiochromic films (RCFs) (www.ispcorp.com/products/dosimetry/index.html), containing RCFs of the type MD-55 and HD-810 commercially produced by Gafchromic. The RCFs are calibrated in dose and were located 3 cm behind the target. The third diagnostic was a stack, located just behind the RCFs, consisting of image plates (IP) of the type BAS SR-2025 from Fuji Photo Film that were interleaved by a 2 mm slab of Al and read using a BAS SR-2025II IP scanner. The IP stack was sensitive only to electrons since protons were stopped by a 2 mm Al slab positioned in front of all films. The last diagnostic was the TASRI diagnostic mentioned above. As shown in figure 1, the image of the target surface illuminated and reflected by the probe beam is collected by a lens and sent to the TASRI. For the TASRI diagnostic, we used a probe beam, a pick-off from the main beam at the wavelength 1.057 µm. It has a diameter of \( \sim 16 \) mm, an energy of \( \sim 100 \) mJ, S-polarization and it is chirped linearly to about 50 ps. The probe beam is incident on the target at \( \theta = 45^\circ \) (see figure 1). With a micrometric timeslide it is possible to change the delay between the main beam and the probe beam with a precision \( <1 \) ps.

We used aluminum targets of thickness 2, 10, 25 and 30 µm with very-high-quality reflectivity as needed for the TASRI diagnostic. Different experimental configurations were explored in order to test the consistency of the various diagnostics in various conditions. Unfortunately, beam time on such a large-scale laser facility is always limited; hence, we limited ourselves to a few but relevant diversified experimental configurations: (A) using the laser beam at the fundamental frequency (\( \omega \)) irradiating a 10 µm Al target at a laser intensity of \( I = 5 \times 10^{19} \) W cm\(^{-2} \) and \( \tau = 320 \) fs; (B) using the frequency-doubled (\( 2\omega \)) laser beam irradiating a 2 µm Au target at \( I = 1 \times 10^{19} \) W cm\(^{-2} \) and \( \tau = 320 \) fs; unfortunately, it was not possible to test the \( 2\omega \) configuration for the previous intensity since the energy loss incurred
in the frequency conversion cannot be compensated for by focal spot size reduction (this is limited by the beam aberrations that maintain the focusing to a few times above the diffraction limit); (C) using a beam at the fundamental frequency irradiating a target 25 µm Al target at $I \sim 3 \times 10^{18}$ W cm$^{-2}$ and $\tau = 5$ ps.

We first concentrate on the determination of the temperature of the electron population ($T_h$), i.e. the slope of the electron energy distribution function. This experiment is performed in configuration A. In this case, as already reported elsewhere, from the TASRI (direct local measurement) we find $0.85 \pm 0.2$ MeV [18], that is obtained by post-processing simulations of the plasma expansion into vacuum induced by the fast electrons. We adjust the initial parameters of the fast electrons population into the code so that the calculated phase of a probe propagating

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**Figure 1.** Experimental setup showing the main beam, the probe beam and the different diagnostics used in the experiments: RCF, IP and electron/proton spectrometer located behind the target; the TASRI uses the probe beam. Inset: (a) measured on-target laser spot focused by an $f = 300$ mm off-axis parabola. The measurement is made after pulse compression and at full energy. Wave front correction is applied. A Strehl ratio of $\sim 0.6$ is measured. (b) Average mean radial profile of the pattern shown in (a). The ordinate is in log-scale to increase readability.
Figure 2. 1D PICLS simulations of plasma expansion into vacuum of a 10 µm thick target irradiated by a laser with intensity $I = 5 \times 10^{19} \text{ W cm}^{-2}$ at the fundamental frequency. (a) Position of the rear surface critical density interface as a function of time for either a pure H target or a CH target. (b) Calculation of $\int ne \, dz$, where $z$ is the space coordinate along the expansion axis, again for the H and CH targets. This parameter is proportional to the phase that is measured by the TASRI diagnostic.

through this plasma, reflecting off the critical density interface and going into the diagnostic, fits the experimental phase recorded by the TASRI. It is this adjustment of the initial parameter that results in the ±0.2 MeV variation quoted above. In our initial analysis of the TASRI data obtained in the experimental configuration A, we considered a pure H target due to code restrictions [33]. We now test the influence of considering a more realistic CH target where the presence of heavier C ions behind the H front could modify the overall plasma expansion. We used here only CH targets, since the only difference with an Al target with CH contaminant layers on the surface would be in the transport within the Al. But since we use for these targets one-dimensional (1D) simulations (see below), the transport effect that could vary from Al to CH is not relevant. Also, since the CH layer is sufficiently thick not to be depleted during the proton acceleration, having or not having an Al substrate in the simulations would not affect the result. For this, we simulated, using the 1D PICLS code [22], the plasma expansion and the phase shift induced on the probe beam by propagating through this plasma, for two targets: a pure H target and a CH target. We used 1D simulations since they are well adapted for the currently considered situation. Indeed the target expansion induced by the hot electrons has been demonstrated to be very laminar [23], i.e. each target radius at the rear surface can be considered as expanding in a 1D fashion. This is justified since the longitudinal dimension (in the range of a Debye length, in our conditions $\sim 1 \mu m$) is much smaller than the considered lateral dimension of the sheath ($> 100 \mu m$). That is why 1D models have been shown to reproduce well the features of such electron-induced target expansion [24]. In this frame, as can be seen in figure 2, the time derivative of the phase shift, from which the hot electron temperature is retrieved [19], differs between the pure H and CH targets only by 16%, which is well within the uncertainty of the derived value. We can thus consider that the previous omission of the heavier ions’ influence on the plasma expansion does not impact significantly the inferred value of the hot electrons temperature.
Figure 3. (a) Two-electron spectra and (b) proton spectrum obtained from a 10 µm Al target irradiated by a laser with an intensity of \( I = 5 \times 10^{19} \text{ W cm}^{-2} \) at the fundamental frequency.

In the same conditions, we recorded electron spectra, using the electron spectrometer, as shown in figure 3(a). These spectra are reproducible as can be inferred by the two shots displayed in figure 3(a). From these spectra, we can measure two hot electron temperatures, one of 0.76±0.1 MeV for the lower energy part of the spectrum and one of 9.9±1.1 MeV for the higher-energy part. The feature of two-temperature spectra has already been reported from many experiments performed at the fundamental frequency of the laser, i.e. when the laser pulse temporal shape includes a significant prepulse [25]. The latter generates a preplasma in which very-high-energy electrons can be generated, albeit in low numbers, corresponding to the 9.9 MeV temperature. However, most of the electrons are generated at a lower temperature [9, 26, 27] at the critical density interface where the laser propagation stops.

Within the experimental uncertainties of each, the first temperature (0.76 MeV) recorded in the electron spectrometer is very consistent with the TASRI measured one. As mentioned above, this is also consistent with simulations [20] showing that during the entire expansion process of the hot electrons, the energetic tail of this population that is at the front of the expansion remains at the initial temperature of the electrons at the beginning of the expansion. The TASRI and the spectrometer both see this energetic tail. However, the TASRI retrieves the initial parameter of the hot electron population (later in time these electrons cool down and indeed the TASRI detects a lowering temperature, but what we can retrieve is the initial hot \( T \), i.e. that of the electrons produced during the interaction). The spectrometer detects the hot electrons directly, but they are of low number because only a fraction can leave the target due to potential build up. The higher-temperature population that is recorded by the spectrometer is however not reflected by the TASRI diagnostic, probably because the electrons involved are of too low a number and below the detection threshold of the TASRI diagnostic indicated previously (\( \sim 5 \times 10^{18} \text{ cm}^{-3} \)).

Additionally, we compare the previous two measurements to another one, obtained in the same laser and target conditions, using spectra of protons accelerated from the solid by the expanding electrons. Applying a fluid model such as that described in [25, 33], we can describe the proton spectrum as follows:

\[
\frac{dN}{dE} = n_0 c_s T_{\text{acc}} S_{\text{sheath}} / (2E T_h)^{1/2} \times \exp\left(-\frac{2E}{T_h}\right)^{1/2},
\]  

(1)
where \( n_{e0} \) is the initial electron density, \( c_s \) the sound speed, \( t_{\text{acc}} \) the acceleration time, in this case taken as 1.3 times the laser pulse duration [25], \( S_{\text{sheath}} \) the electron sheath surface and \( E \) the proton energy.

This model has been shown to yield good results for our laser and target parameters [28], i.e. intensities from \( 10^{18} \) up to \( 5 \times 10^{19} \) W cm\(^{-2} \) and laser pulse duration 60 fs–1 ps. We used Mawellian proton spectra since these were obtained during the experiment (see figures 3(b) and 4(b)) and are those found in similar laser-interaction conditions. We are aware of other models that could be used based on different proton spectral shapes [29]; we, however, preferred to limit our study to the above-mentioned model since it had been experimentally confirmed for the considered applicability range [25].

In equation (1), one can see that the proton spectrum depends on the two electron parameters, \( T_h \) and \( n_{e0} \). Fitting the proton spectra this way yields, as shown in figure 3(b), with the above-mentioned formula, \( T_h = 0.84 \pm 0.3 \) MeV, again well consistent with the TASRI data.

The results reported above show that the distant measurements of either the electron or proton spectra reflect well the initial temperature of the hot electrons that can be measured directly at the target surface using the TASRI diagnostic. This was observed in the experimental configuration A where the laser beam is at the fundamental frequency. We now test if this still holds when the laser is frequency-doubled (configuration B), in which case the electron generation mechanism changes and the electron temperature is lower [30, 31]. In this configuration, two diagnostics are fielded: the IP stack that allows us to retrieve the electron spectrum, and proton spectrometry. From the IP stack, we can retrieve the dose deposited by the electrons in different energy ranges. Then, using the GEANT 4 [32] code and assuming a Maxwellian spectrum distribution for the electrons entering the stack, we fit the dose deposited by the electrons in the different layers of the stack. We assumed a Maxwellian spectrum since this type of spectrum applies very well to the electrons that were generated in our interaction.
Figure 5. Inset: Schematic diagram of the setup for retrieving hot electron density parameters by indirect (proton) measurements. Comparison of the electron density including error bars for an Al 25/30 µm target as retrieved by RCFs calculated analytically using the model explained in the text (blue dashed line) and values detected by the TASRI (red solid lines).

process (see figure 3(a)) and is conventionally assumed in laser–matter interaction [33]. The best fit (i.e. the smallest values of the $\chi^2$, fitting indicator) is found for electron temperatures ranging between 0.1 and 0.3 MeV, as shown in figure 4(a). These values are in good agreement with the values obtained by fitting the proton spectrum, similarly as described above, that indicate $0.24 \pm 0.1$ MeV. We can therefore state that, independently of the electron generation mechanism and of the values of actual electron temperature, one can use distant diagnostics to obtain a measurement of the electron temperature at the target surface, and one can also use an indirect (proton) spectrum to retrieve $T_h$. The comparison of the values obtained with the different methods is illustrated in figure 4(c). One can deduce that, taking into account all error bars, all measurements converge for an electron temperature around 0.28 MeV.

We now compare different methods for retrieving the hot electron density $n_h$ at the target rear surface, i.e. at the initial time before plasma expansion into vacuum occurs. The experiment here was performed using the experimental setup C. The local measurement of $n_h$ is provided by the TASRI diagnostic [18], yielding $n_h$ ranging from $2.5 \pm 1 \times 10^{19}$ cm$^{-3}$ for the central radial position in the target to the detection threshold of $5 \pm 2 \times 10^{18}$ cm$^{-3}$ at $\sim 45$ µm away in radius (see figure 5). The TASRI gives for this shot $T_h = 0.45 \pm 0.2$ MeV.

Another way of accessing $n_h$ is to fit, as for $T_h$, the proton signal collected far away from the target after the protons have been accelerated by the hot electrons from the target surface. The proton signal is here collected by the stack of RCFs. The way $n_h$ can be retrieved from the proton signal has already been reported in [24]. The principle is as follows: the target rear surface is imprinted with periodic grooves. These lead to a spatial modulation of the dose of the proton beam expanding into vacuum. On the RCF detector, one can therefore observe a strongly magnified image of the source, in particular, of the target surface. From there protons were accelerated with a periodic spatial fiducial due to the grooves. Using the correspondence between proton energy and penetration range within the RCF stack (mostly
determined by the Bragg peak), we can determine the specific proton energy corresponding to a particular RCF (in our case 1.2, 3.2, 4.5, 5.6, 6.5 and 8.2 MeV). Thus, through the image of the grooves, we can now deduce the proton source size corresponding to a particular proton energy. The last step is to relate the proton energy to electron density within the sheath. This can be done with the help of proton acceleration models using information about hot electrons [25, 34, 35]. From the model, we obtain that the maximum proton energy depends on the electron density and temperature as follows: \( E_{\text{proton}} = 2k_bT_h(\ln(\theta + (\theta^2 + 1)^{0.5}))^2 \), where \( k_b \) is the Boltzmann constant and \( \theta = \omega_{pi}\tau/2.32 \), \( \tau \) being the laser pulse duration and \( \omega_{pi} \) the plasma frequency \( \omega_{pi} = ((n_e e^2)/(m_p e_0))^{0.5} \), where \( e \) is the electron charge, \( m_p \) the proton mass and \( e_0 \) the relative permeability. \( T_h \) is obtained, as shown in the previous section, by fitting the proton spectrum, yielding \( 0.45 \pm 0.1 \) MeV. We can therefore extract, for each RCF layer, the size over which the protons were accelerated, and to which hot electron density this corresponded. The results are shown in figure 5 (in blue), overlaid with the values measured by the TASRI (in red). As one can see, there is, within the uncertainty of each method, good agreement between both data sets. For the sake of completeness one may add that for these target thickness and laser conditions, a fit of \( T_h \) using the proton spectrometer reveals \( 0.36 \pm 0.2 \) MeV.

As the last step, we can compare the conversion efficiency between the laser, electrons and protons. In the configuration using the 25 \( \mu \)m target and the 5 ps laser pulse, the laser delivers \( \sim 7 \) J on the target, the electron spectrum, when considering electron energies above 3 MeV, indicates \( 0.018 \pm 0.003 \) J, whereas from the proton spectra, we obtain \( 0.022 \pm 0.02 \) J. This gives a laser-to-proton conversion efficiency of 0.3%, consistent with scaling laws indicated in [25], which indicate \( \sim 0.3–0.5\% \). Regarding the hot electrons, for the laser-to-electron conversion efficiency we obtain a value of \( \sim 0.3\% \), less than we would expect using the scaling laws indicated in [36] for the fraction of laser light absorbed into the preplasma as fast electrons, i.e. \( \sim 6\% \). However, this should be not surprising, since the values obtained by [6] have been obtained using a higher-energy, longer-pulse laser (200–400 J, 20 ps), where the absorption efficiency is higher. Moreover, in our calculation we only consider part of the spectrum. On the other hand, this scaling law concerns the efficiency at the front side of the target, whereas the spectra measure the electron energy at the rear target surface. We can therefore deduce that a consistent energy loss is due to the transport of the electrons within the target.

In summary, we have shown that measurements of hot electrons made by the TASRI diagnostic locally on the rear target surface are consistent with those obtained by diagnostics that are placed at a certain distance from the target (e.g. spectrometers). We have also shown that measurements of accelerated protons allow reconstruction of the characteristics of hot electrons present at the target rear surface. Therefore, with those techniques, it is possible to retrieve the number and energy of the electrons produced in the laser–solid interaction. This is of importance to optimize a number of applications, e.g. the production of secondary sources that use these electrons. But this information can also be used to deduce, for example, the subsequent target heating that results from the injection of hot electrons within the target, a topic of importance for the realization of the so-called warm dense matter states by lasers [37].

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