High Energy Density Physics 16 (2015) 12–17

Contents lists available at ScienceDirect

High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp

Characterization of near-LTE, high-temperature and high-density aluminum plasmas produced by ultra-high intensity lasers

V. Dervieux [a, b, c], B. Loupias [a, *], S. Baton [c], L. Lecherbourg [a], K. Glize [a, c], C. Rousseaux [a], C. Reverdin [a], L. Gremillet [a], C. Blancard [a], V. Silvert [a], J.-C. Pain [a], C.R.D. Brown [d], P. Allan [d], M.P. Hill [d], D.J. Hoarty [d], P. Renaudin [a, e]

[a] *CEA, DAM, DIF, F-91297, Arpajon, France*
[b] *DGA, Bagneux, France*
[c] *Laboratoire pour l'Utilisation des Lasers Intenses – LULI, École Polytechnique, CNRS, CEA, UPMC, 91128, Palaiseau Cedex, France*
[d] *Plasma Physics Group, AWE plc, Reading, RG7 4PR, UK*
[e] *LUTH UMR8102, Observatoire de Paris, CNRS, Université Paris Diderot, 92195, Meudon, France*

ARTICLE INFO

Article history:
Received 30 April 2015
Accepted 30 April 2015
Available online 11 May 2015

Keywords:
UHI
HED
Dense plasmas
Isochoric heating
Plasma spectroscopy
K-shell spectra

ABSTRACT

Ultra-high-intensity lasers have opened up a new avenue for the creation and detailed spectral measurements of dense plasmas in extreme thermodynamic conditions. In this paper, we demonstrate the possibility of heating a dense plasma ($\rho > 1$ gcm^{-3}) to a maximum temperature of 560 ± 40 *eV* using a few-Joule, relativistic-intensity laser pulse. Particle-in-cell, radiation-hydrodynamic and atomic physics simulation tools are used together for a full description of the plasma dynamics, from laser interaction to late-time expansion and x-ray emission, yielding overall good agreement with the spectral measurements. We discuss the sensitivity of our analysis to space-time gradients, non-equilibrium ionization processes and hot electron effects.

1. Introduction

Ultra-high-intensity (UHI) laser pulses are efficient tools to generate hot plasmas at near-solid density. These novel states of matter are promising platforms to address problems associated with stellar opacities [1] and atomic physics in general [2,3]. The mechanisms whereby the laser-accelerated electrons propagate and deposit their energy through dense materials have been extensively investigated over the past years, mainly in the framework of the fast ignition approach to inertial confinement fusion [4–7] and, more recently, to address atomic physics phenomena arising in dense plasmas [8–11]. The non-thermal high energy electron density is usually high enough so that, in addition to the direct collisions with the target particles, the dominant heating process is the ohmic dissipation of the inductive return current formed by collisional background electrons [12–14]. As early as 1996, it has been demonstrated that dense targets can be heated in excess of 100 eV before any significant hydrodynamic motion takes place [15–17]. To achieve this goal high-intensity-contrast pulses are required to prevent the sample from expanding before the peak of the laser pulse, which may be achieved using frequency doubling or plasma mirrors [9,18]. In these experiments, the plasma conditions are commonly inferred from spectroscopic measurements, the interpretation of which implies accurate modeling not only of the radiative properties of the heated sample but also of the early-time heating dynamics. In this paper, we present a detailed analysis of K-shell spectra obtained from laser-driven plastic buried Al samples at the ELFIE facility. In order to produce synthetic spectra to compare to the experiment, we have employed a suite of simulation tools describing the major physical processes arising during the fast electron generation and relaxation phases, as well as the subsequent radiative-hydrodynamic evolution of the target. Our results highlight the great potential of high-contrast UHI lasers to create and explore high energy density (HED) states in the laboratory.

2. Experimental setup and results

Fig. 1 shows a schematic set-up of the experiment performed with the ELFIE laser at LULI. Frequency-doubled pulses

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* Corresponding author.
E-mail address: berenice.loupias@cea.fr (B. Loupias).

http://dx.doi.org/10.1016/j.hedp.2015.04.009
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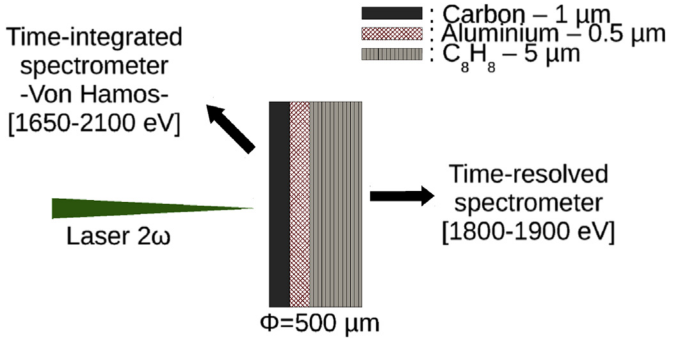

Fig. 1. Schematic experimental setup.

($\lambda = 0.527$ μm) were used to increase the laser intensity contrast to be greater than 10^7. This served to improve the laser-solid coupling efficiency by minimizing the plasma formation before the arrival of the main pulse [9]. Despite frequency-doubling, however, a residual prepulse of intensity $10^{12} - 10^{13}$ Wcm^{-2} was observed 60 ps before the laser peak. Consequently, a preplasma of scale-length <1 μm is produced. The laser beam was focused to a 5 μm FWHM spot size with an *f*/3 off-axis parabolic mirror. The 350 fs FWHM duration pulse delivered a maximum energy of 3 J, yielding an on-target intensity of ~4 × 10^{18} Wcm^{-2}. According to Beg's law [19], fast electrons with energies of ~200 keV are expected at these intensities. The targets, irradiated at normal incidence, were 500 μm-wide, square-shaped three-layer foils glued on a glass stalk, and composed of 1 μm C/0.5 μm Al/5 μm C_8H_8. The main diagnostic was a space- and time-integrated Von Hamos x-ray spectrometer [20] placed at ~40° from the front surface normal. It consisted of a PET cylindrically bent crystal designed to record the Al Ly$_\alpha$, He$_\beta$ and Ly$_\beta$ lines onto an image plate (IP) detector with a 3 eV spectral resolution. This crystal was calibrated using a 25 kV x-ray tube at CEA, whereas the IP calibration was taken from Ref. [21]. In addition, a time-resolved x-ray spectrometer measured the emission along the rear front normal. It comprised a PET toroidal crystal coupled with a picosecond streak camera to produce time-resolved spectra of Al He$_\beta$ line in a spectral range of 1800 – 1900 eV with a time resolution of 1 ps.

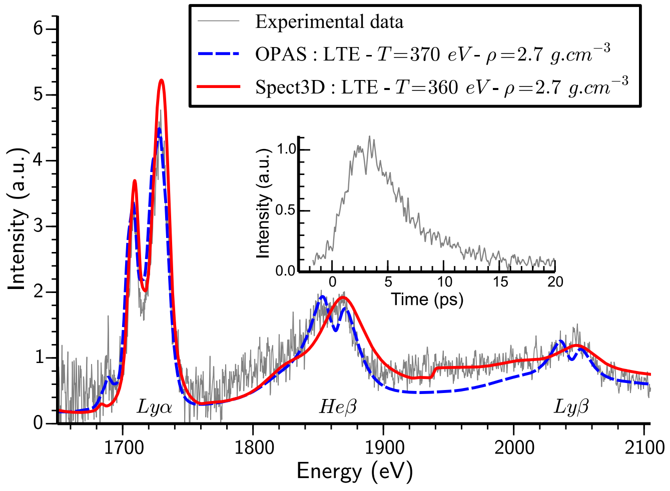

Fig. 2. Best fits of a typical space- and time-integrated experimental K-shell spectrum using two different atomic physics models in the LTE approximation and with a single pair of input parameters (ρ,T). Blue dashed line: OPAS with (ρ,T) = (2.7 gcm^{-3},370 eV). Red solid line: SPECT3D with (ρ,T) = (2.7 gcm^{-3},360 eV). The inset graph shows the time-resolved x-ray emission measured in the range 1800 – 1900 eV. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2 shows a typical K-shell spectrum obtained through averaging over three reproducible shots. The effective plasma density and temperature (ρ,T) are inferred by comparing the line ratios and widths with theoretical spectra obtained using the SPECT3D [22] and OPAS [23] atomic physics codes. Assuming local thermodynamic (LTE) conditions, both codes give similar best-fitting plasma conditions, namely, $\rho = 2.7 \pm 0.6$ gcm^{-3} and $T = 360 \pm 20$ eV. It should be stressed that sophisticated physics must be included for good reproduction of the experimental spectra. For instance, computing Li-like lines is required to capture the red wing of the He$_\beta$ line. Also, to match the measured line widths, one needs to describe the impact broadening and the influence of the plasma microfields on each atomic state. Moreover, the plasma screening model implemented in OPAS enables reproduction of the observed 6 eV shift of the He$_\beta$ line caused the high target density. A similar shift was measured by Saemann et al. [24] in a similar experiment.

The effective density and temperature inferred from the above calculations should be considered as mean values, resulting from the space-time averaging performed by the Von Hamos spectrometer. Yet, the He$_\beta$ emission shown in the inset graph of Fig. 2 is seen to evolve on a picosecond time scale, which suggests the importance of taking the heating and cooling dynamics into account. In the following sections, we combine a variety of simulation tools in order to produce self-consistent synthetic spectra.

3. Interpretations

3.1. Step 1- kinetic simulation of the laser-solid interaction

To simulate the UHI laser-solid interaction and the heating processes during the first picosecond, we make use of the two-dimensional (2-D) Cartesian particle-in-cell (PIC) code CALDER [25]. A three-layer target composed of 1 μm C^{1+}/0.5 μm Al^{3+}/5 μm CH^{1+} is considered in the simulation. The initial electron and ion temperatures are set to $T_e = T_i = 10$ eV. An exponential density profile of 0.4 μm scale-length is added on the front carbon layer to mimic the effect of the laser prepulse. The other layers have a uniform solid density. The laser pulse is injected along the $x > 0$ axis. It has a Gaussian profile with an FWHM spot size of 5 μm and an FWHM duration of 330 fs. A maximum intensity of 4.4 × 10^{18} Wcm^{-2} is reached at $t_{\max} = 475$ fs. The simulation box has dimensions of 384 × 768 μm. The mesh size is $\Delta x = \Delta y = 6.4$ nm and the time step is $\Delta t = 0.016$ fs. In addition to kinetic effects, the code describes field ionization, as well as elastic and inelastic collisions [26,27]. To mitigate the numerical heating intrinsic to high-density PIC simulations, fourth-order weight factors are employed along with the alternating-order interpolation scheme of Sokolov [28]. The total simulation time is 975 fs.

Fig. 3 shows the mass density (left), hot electron fraction (center) and background electron temperature (right) 500 fs after the laser peak, at which time the laser intensity has dropped to 2 × 10^{15} Wcm^{-2}. The hot electrons are defined as those with energies >10 keV, while the background (thermal) electron temperature is computed from the mean energy of the low-energy (<10 keV) electrons. The Al layer is still at solid density (~2.7 gcm^{-3}) although it has been heated to a maximum temperature of ~650 eV around the laser axis. We have checked that this strong isochoric heating is mainly caused by the return current. Owing to the small laser spot size, the temperature profile in the target proves strongly non-uniform: in the Al layer, we measure variations of $\Delta T_e = 70$ eV over 0.5 μm in the longitudinal direction and $\Delta T_e = 350$ eV over 3 μm in the transverse direction.

The hot electron fraction, f_h, is defined as the density of the hot electron density normalized to the background electron density. At the time of Fig. 3, f_h is below 0.5% everywhere in the dense plasma.