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X-ray spectroscopy and imaging of a plasma collision

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ABSTRACT

The collision of laser-produced plasmas has been diagnosed by X-ray spectroscopy and imaging. The two colliding plasmas are produced on Al thin foils at a distance of 200 to 900 μm irradiated at $\lambda = 0.53 \mu\text{m}$ with laser intensities of 3×10^{13} to $6 \times 10^{13} \text{ W/cm}^2$. Interpenetration of the plasmas was visualised by replacing one of the foils material by magnesium. The main diagnostics viewing the inter-target space were time-resolved monochromatic imaging of the $1s^2 \rightarrow 1s3p$ aluminum line (He β at $\lambda = 6.635 \text{ \AA}$), Doppler broadening measurement with a vertical Johann very high resolution spectrograph in the range 6.5-6.7 $\text{\AA}$, space-resolved high resolution spectra of the dielectronic satellites of the $1s-2p$ Lyman α line (7.1-7.2 $\text{\AA}$), space-resolved spectra with a flat-crystal spectrograph in the range 5-7 $\text{\AA}$ and in the range of 43-48 $\text{\AA}$ obtained with a new OHM crystal spectrograph and a pinhole camera. A multifluid eulerian monodimensional hydrodynamic code coupled with a radiative-atomic package provided simulations of the experiments. Hydrodynamic 2D simulations calculating the lateral expansion of the plasma enabled a reliable treatment of reabsorption along the line of sight of the spectrographs. The size and the time duration of the collision, the plasma parameters (Te, Ti and ne) in the collision region and interpenetration were measured. The hydrocode simulations give a good understanding of the behavior of the collision in function of intertarget distance and laser intensity.

1. INTRODUCTION

The collision of laser-produced plasmas has not been much studied experimentally, but a number of numerical simulations and theoretical papers have been published. Two main experimental schemes have been explored: the collision of blown plasmas produced at the front of thick laser-irradiated targets¹⁻⁷ and the collision of the plasmas produced at rear sides of two laser-exploded thin

foils⁶. The X-ray imaging and spectroscopic diagnostics have proved to be very powerful tools for the determination of laser-produced plasma parameters. We present here the study of the collision of plasmas produced on the rear of laser-irradiated thin foils, diagnosed by a number of different spectroscopic and imaging X-ray tools. The experiment has been also simulated with hydrodynamic and atomic physic codes. The main insight on the experiment has been obtained by comparing the experimental results with a 1D eulerian multi-fluid code. In the present paper, we emphasize the spectroscopic methods which have led to the measurement of electron density and temperature, ion temperature and plasma dimensions and interpenetration in the collision region.

2. EXPERIMENTAL SET-UP

The experiment has been performed with two frequency-doubled beams of the Nd glass laser of the Laboratoire pour l'Utilisation des Lasers Intenses (LULI) facility at $0.53 \mu\text{m}$ wavelength and with a pulse duration of 600 ps. The energy was focused perpendicularly to the targets through $f=250 \text{ mm}$ lenses and random phase plates to obtain homogeneous $200 \mu\text{m}$ diameter FWHM focal spots. Laser intensity has been varied between 3 and $6 \times 10^{13} \text{ W/cm}^2$. The targets were either two aluminum thin foils ($0.8 \mu\text{m}$ thick) or an aluminum foil in front of a magnesium foil ($1.0 \mu\text{m}$ thick). Inter-target distance has been varied from 450 to 900 μm (see Figure 1d). The main diagnostics were probing X-ray emission perpendicularly to the laser axis. They have been set-up on several experimental campaigns, using sometimes the same viewing axis.

Figure 1 : Experimental setups : (a) mounting of the monochromatic imaging and flat ADP spectrograph ; (b) mounting of the Vertical Johann spectrograph ; (c) mounting of the OHM flat crystal and toroidally bent crystal spectrograph ; (d) target mounting.

Figure 1 shows the experimental set-ups including the different spectrographs and imaging systems :

- two toroidally bent quartz crystal were imaging the $1s^2-1s3p$ ($\text{He}\beta$, $\lambda = 6.635 \text{ \AA}$) emission of aluminum with a space resolution of $35 \mu\text{m}$ onto two cathodes of a 120 ps resolution framing camera open at two different times (Figure 1a);⁹

- two time integrating spectrographs were viewing the intertarget space at 90° from each other:

- (i) a classical flat ADP crystal with a slit of $35 \mu\text{m}$ recording the $5.5-7 \text{ \AA}$ region, i.e. the He-like and H-like lines of aluminum and H-like lines of magnesium (Figure 1a),

- (ii) a high resolution vertical Johann spectrograph was set with a quartz (10.0) crystal bent to 76.8 mm radius of curvature to record the width of the aluminum $\text{He}\beta$ line.¹⁰ The spectral resolving power was limited to 2000-3000 due to the size of the plasma ($200-400 \mu\text{m}$). This high resolution was necessary to measure the ion temperature from the Doppler broadening of this line. The high luminosity of this instrument has made it very efficient to measure the interpenetration distance defined as the distance on which the aluminum $\text{He}\beta$ or the magnesium Lyman δ lines were visible over the threshold of the detector :

- a very high resolution spectrograph using a toroidally bent quartz (10.0) crystal was set on the dielectronic satellites of the Lyman α H-like line in the $7.1 - 7.4 \text{ \AA}$ range (Figure 1c). The radii of curvature were 146 mm in dispersion plane and 149 mm in the perpendicular plane. In the dispersion plane, the spectrograph was in a Johann type geometry, with the film on the Rowland circle and the plasma inside this circle. In the plane perpendicular to the dispersion plane, the radius of curvature determined the distance to the source to ensure imaging with 0.42 magnification and $10 \mu\text{m}$ spatial resolution onto the Rowland circle ;

- the flat crystal spectrograph has been used with an (Octadecyl-Hydrogen-Maleate (OHM) crystal with large inter-reticular distance ($2d = 63.5 \text{ \AA}$) (Figure 1c).¹¹ The spectral range covered was 43 to $48 \text{ \AA}$. The spectrograph has been set with its $38 \mu\text{m}$ wide slit parallel and perpendicular to the inter-target axis in order to measure and compare the longitudinal and lateral spread of Be-like and He-like ions. For the measurement of the lateral spread, the emission from the foils was hidden and only the emission of the collision plasma was reaching the spectrograph. A 512×512 back-thinned CCD camera filtered with $0.3 \mu\text{m}$ thick carbon foil was used as a detector.

- Finally, a pinhole camera filtered with aluminized mylar was imaging the inter-target space.

3. EXPERIMENTAL RESULTS

3.1 Temperature measurements

The data obtained on the vertical Johann and flat ADP crystal spectrographs have been simultaneously analyzed to deduce non-ambiguously the electron and ion temperatures. In Figure 2 is shown such the adjustment of the measured spectra in the case of an intertarget distance d_i of $560 \mu\text{m}$ and a laser intensity I_L of $6 \times 10^{13} \text{ W/cm}^2$. The spectra are simulated with the collisional-radiative code FLY, the time-dependent version of RATION.¹² With a time variation deduced from the time-resolved monochromatic images. This measurement has shown that the $\text{He}\beta$ line is emitted only during 150 ps FWHM. The high resolution spectral profile of the $\text{He}\beta$ line measured with the vertical Johann spectrograph has been fitted varying the ion temperature and the size of the plasma (Figure 2a). The He-like and H-like spectrum measured on the flat crystal spectrograph (Figure 2b) has been fitted using the same plasma size, and varying the electron temperature and density. The plasma size broadens the lines of both spectra through reabsorption. Additionally, it broadens the flat crystal spectrum through instrumental broadening. Only an order of magnitude of electron density was obtained from these spectra which are not very dependent on this parameter.

Figure 2: Spectra obtained at $6 \times 10^{13} \text{ W/cm}^2$ laser irradiance and 560 μm target separation (solid lines), compared with the best fit calculated with the code FLY (dashed lines). (a) vertical Johann spectrometer; (b) flat crystal spectrometer.

Radial gradients, and Doppler shift due to lateral velocity have been neglected. This assumption was not trivial and a Doppler shift in a non-homogeneous plasma could have changed the determination of T_i . The assumptions of homogeneity and small lateral velocities have been justified by Lasnex 2D lagrangian simulations. The results of these simulations can be used here as maxima values as this single fluid lagrangian code overestimates the lateral expansion and velocity.

In LASNEX simulations, the lateral velocity in the high electron temperature region is around $2 \times 10^6 \text{ cm/s}$, inducing Doppler shifts on the order of 0.5 mÅ, i.e. much smaller than the 10 mÅ Doppler width expected for an ion temperature in the range of 10 keV. Short lateral gradients have also been measured with the OHM crystal spectrograph as shown hereunder.

The parameters measured at the center of the inter-target space are grouped in table 1. They show that electron temperatures stay in the range of 0.35 to 1 keV. At high laser intensity, when interpenetration occurs, the measured ion temperature rises to 4 to 10 keV.

$I_l \text{ (W/cm}^2\text{)}$	$d_l \text{ (}\mu\text{m}\text{)}$	Experiment		MULTIF simulation		
		$T_e \text{ (keV)}$	$T_i \text{ (keV)}$	$T_{e \text{ max}}$	$T_{i \text{ max}}$	T_{iD}
3×10^{13}	450	0.35 ± 0.1	0.35 ± 0.2	0.35	0.40	
3×10^{13}	600	0.75 ± 0.2	1.00 ± 0.3	0.50	6	< 2.5
3×10^{13}	900	0.8 ± 0.3	0.8 ± 0.3	0.55	4	< 1.3
6×10^{13}	450	0.8 ± 0.2	10 ± 3	0.98	27	5.9
6×10^{13}	600	0.8 ± 0.2	10 ± 3	1	20	7.1
6×10^{13}	900	0.9 ± 0.3	3 ± 1	0.85	18.5	5.3

Table 1: Plasma parameters measured and calculated at target midplane for different inter-target distances and laser intensities.

3.2 Electron density measurements

Electron density has been measured more accurately from the analysis of the He-like dielectronic satellites of the Lyman α H-like line. The principle of the satellites measurements is a comparison of the measured ratios of different satellites with time-dependent collisional-radiative calculations done with FLY with the time variation described above for temperature measurements. The electron temperature range has been restricted to 600-1000 eV using the previous measurements. From the four measured line ratios, regions in the (n_e, T_e) were determined. The common delimited regions gave a range of densities and temperatures. The ratios depend mostly on density, and the width on ion temperature. The diagnostic is not very dependent on electron temperature. Non stationary effects are important mostly at densities lower than $5 \times 10^{21} \text{ cm}^{-3}$. The uncertainty of the electron temperature gave an uncertainty on the determination of the density. The experimental spectrum can also be directly compared to the simulated one as shown in Figure 3. The data are still under analysis. One shot has been completely analyzed giving a electron density of $(1.5 \pm 0.5) \times 10^{21} \text{ cm}^{-3}$ and a ion temperature of 3.4 keV for a laser intensity of $5 \times 10^{13} \text{ W/cm}^2$ and an inter-target distance of 450 μm .

Figure 3 : Comparison of the calculated and measured H-like Lyman α dielectronic satellite spectrum.

3.3 Dimensions of the collision region

We have measured the size of the collision zone along and across the inter-target axis by different diagnostics: monochromatic images, pinhole images, and the OHM flat crystal spectrograph. All the diagnostics measured X-ray emission at different wavelengths and used different detectors. Pinhole images filtered with aluminized mylar give a lateral expansion much larger than monochromatic images at 6.635 $\text{\AA}$ and crystal spectrographs in the keV range, associated with He-like emission. At 600 and 900 μm inter-target distance the X-ray emission of He-like ions gave 300 μm lateral expansion and the pinhole camera gave 800 μm FWHM profiles at 900 μm intertarget distance as shown in Figure 4a. This difference has been explained by measuring the lateral spread of He, Be and B like emission with the OHM crystal spectrograph as shown in Figure 4b. He-like and Be-like emissions respectively at 46.056 $\text{\AA}$ and 46.391 $\text{\AA}$ extend on a profile of 200-250 μm FWHM, as B-like ions

spread on 970 μm for a shot done at 900 μm intertarget distance. This can be attributed to a temperature profile rather steep for the highest temperature region and a temperature plateau at low temperatures. This measurement supports the hypothesis of homogeneity of the He-like emission region assumed for the Doppler broadening deconvolution. Further numerical analysis will quantify this effect.

Figure 4. (a) Lateral dimension of XUV emission as measured with a pinhole camera as a function of inter-target distance. (b) Lateral profiles of He-, Be- and B-like XUV emission as measured with the OHM crystal spectrograph.

4. NUMERICAL SIMULATIONS AND INTERPRETATION OF THE RESULTS

Numerical simulations have been performed with the multifluid code MULTIF to understand better the interpenetration and the exchange of ion kinetic energy to thermal energy. MULTIF is a multispecies, Eulerian, 1.5-D fluid code in which the lateral expansion is taken into account through a self-similar model.¹³ The code uses the improved flux-corrected transport modules of Boris,¹⁴ and flux-limited Spitzer conductivity. The early laser absorption and foil acceleration stages are modelled by the 1.5-D fluid code FILM.¹⁵ A simple estimate of radiative cooling and ionization is made with a multispecies LTE calculation of ionization states. The output of this code was post-processed by FLY and by the detailed spectroscopy model TRANSPIC¹⁶ to compare the calculated X-ray emission of the plasma directly with the experimental results. Excellent agreement between the interpenetration distance determined from the calculated Al He β axial emission profile and experiment has been obtained.¹⁷ The maximum values of the plasma parameters $T_{e,\text{max}}$ and $T_{i,\text{max}}$ at target midplane as calculated with MULTIF are shown in table 1 and their time variation is shown in Figure 5 for an irradiance of $6 \times 10^{13} \text{ W/cm}^2$ and for the experimental inter-target distances. Electron density is of order 10^{21} cm^{-3} , and ion temperature rises to 20-27 keV (see Figure 5). The electron density measured with the dielectronic satellites is in good agreement with the value shown in Figure 5a. The most striking feature happening when the distance is increased to 900 μm , is that the maximum of T_i occurs much later at target midplane than the maxima of n_e and T_e . This is linked to the interpenetration of the plasmas. The collision region spreads in space and time and the maximum ion temperature occurs later, when the relative velocity of the counterstreaming plasmas cancels. Figure 5 also shows the time variation of the maximum of the He β line profile calculated with MULTIF+FLY. The predicted He β line emission does not follow the variation of the electron density and temperature closely due to non stationarity. It lasts for only 100 to 200 ps, in agreement with the time-resolved monochromatic imaging measurements. Due to this short duration, the He β emission samples the ion temperature over a comparable time scale, at a time close to the maximum of electron density and temperature.

Figure 5: Temporal evolution of the plasma parameters as calculated by MULTIP and of the maximum of the Heβ line emission given by MULTIP+FLY, at target midplane, for a laser irradiance of $6 \times 10^{13} \text{ W/cm}^2$. Inter-target distance of 600 μm (a), and 900 μm (b). Solid line: n_e ; dashed line: T_e ; dotted line: T_i ; thick solid line: Heβ emission.

Secondly, Doppler broadening measurements give an ion temperature very different from the theoretically expected maximum of T_i . This effect is particularly important in the long inter-target separation regime when the maximum of T_i occurs long after the peak of electron density and temperature. The spectral width of the time-integrated Heβ line profile at the center of the inter-target space provides a value of the ion temperature, $T_{i,D}$, which is reported in Table 1. $T_{i,D}$ is very consistent with the experimental data for the high-laser-intensity case and shows the same decrease at high inter-target separation. This effect is particularly important in the wide separation regime when the maximum of T_i occurs long after the peak of electron density and temperature. This decrease is an experimental evidence that the plasmas interpenetrate.

5. CONCLUSION

X-ray diagnostics associated with multifluid simulations have given a good understanding of the collision of counter-streaming plasmas. The development of new spectroscopic and imaging tools of very high temporal, spatial and spectral resolution adapted have permitted the measurement of the parameters of the collision. It is demonstrated that the toroidally bent crystals can be efficiently used for plasma spectroscopy and imaging. The comparison of the experimental data to numerical simulations have evidenced that at high laser irradiances and large inter-target distances, i.e. when density decreases and relative velocity of the counter-streaming plasmas increases, interpenetration occurs in a large region and ion heating occurs later when relative velocities cancel.

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