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X and XUV time resolved emission of laser created hot Xe and Kr plasmas

N. Kontogiannopoulos[1], S. Tzortzakis[1], J.-R. Marques[1], S. Bastiani-Ceccotti[1], L. Lecherbourg[1], F. Thais[2], I. Matsushima[3], O. Peyrusse[4], C. Chenais-Popovics[1]

[1]Laboratoire pour l'Utilisation des Lasers Intenses, CNRS UMR7605, Ecole Polytechnique, 91128 Palaiseau, France
[2]CEA/DSM/SPAM, Centre d'Etudes de Saclay, 91191 GIF-sur-Yvette Cedex, France
[3] National Institute of Advanced Industrial Science and Technology, Tsukuba, 3058568, Japan
[4]CELIA, Université Bordeaux 1, 33405 Talence, France

Abstract: X-ray spectra and XUV time-resolved spectra emitted by xenon and krypton laser-produced gas-jet plasmas are reported. Simultaneous measurements of the electron and ion temperatures and densities by Thomson scattering diagnostics will allow direct comparisons with non-local thermodynamic equilibrium model predictions of the highly-ionized plasmas.

1-Introduction

Plasma in non-local thermodynamic equilibrium (NLTE) appears in various research fields like in inertial confinement fusion, in astrophysics plasmas, in X-laser and X-ray plasma sources. The calculations of the ionic dynamics for the NLTE plasma of low or high atomic number Z is under development, giving results that are frequently diverging. In particular the code AVERROES [1] that O. Peyrusse has developed permits the calculation of the spectra of the high-Z elements of plasmas in NLTE using the formalism of the unresolved transition arrays (UTA) and of the Superconfigurations that have proved their efficiency in the case of plasmas in local thermodynamic equilibrium (LTE) [2]. To test this code specific experiments are necessary, where the plasma emission-spectra and the plasma parameters (density, temperature) are measured independently.

The experiment described here has been performed in this perspective. Both time-integrated X-ray spectra and time-resolved XUV-spectra emitted by gas jet plasmas of Xe and Kr have been measured. The temperature and the density of the plasma have been measured with the auto-diffusion Thomson technique. This experiment completes previous studies on the same subject [3-7].

2-Experiment

For the experiment a frequency – doubled neodyme laser beam (λ = 0.53-µm), of the LULI2000 facility was used. At this wavelength the maximum laser energy was 400-J with a doubling efficiency of 50 to 60%. The doubled laser beam was focused on a gas jet with a lens of f = 800-mm coupled to a random phase plate (RPP) to obtain an elliptic focal spot of 1-mm large and 150-µm high. The gas jet was characterized by a Mach-Zender interferometry experiment. The diameter of the gas jet was 1-mm. The width of the laser focal spot was choosen to be equal to the gas jet diameter (1-mm) in order to avoid cold gas around the plasma that would reabsorb the emmision of the plasma.

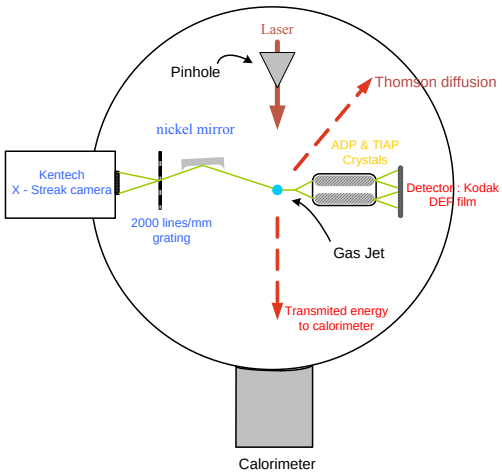


Figure 1 : Experimental scheme (top view).

The X-ray emission has been measured at 90° from the laser axis by a spectrograph composed by two plane Bragg crystals, a TlAP crystal and an ADP. The TlAP crystal was used in the spectral region of 12-16 -Å which correspponds to the 3d-4f transitions of the xenon gas while the ADP crystal was used in the spectral region of 6-8-Å which corresponds to the 2-3 and 2-4 transitions of the krypton gas. The spectral resolution was 38 mÅ and 16mÅ for the Xe and the Kr respectively. Spectral resolution was limited by the height of 150μm of the laser focal spot. The X-ray spectra were recorded on a DEF film with spatial resolution and time integration. On previous experiments [3] it has been demonstrated that the X-ray spectra do not varie in time. This justifies the choice for the time-integrated registration here.

The XUV spectra were measured also at 90° from the laser axis by a spectrograph with a trasmission grating. This spectrograph was placed on the opossite side of the X-ray spectrograph as shown in figure 1. The XUV spectrograph used a Ni spherical mirror for the imaging of the source with curvature radius 5200-mm, and a transmission grating of 2000-l/mm covering the spectral range of 20 – 200-Å. The resolution of the spectrograph was 2.5-Å. The time resolution of the XUV spectra was obtained by a streak camera placed behind the spectrograph. Time resolution was necessary for this spectral region where emit atoms during the recombination of the plasma. This camera was specially protected from the rise of the pressure, due to the gas jet, by a differential pumping system through a slit of 500-μm of width.

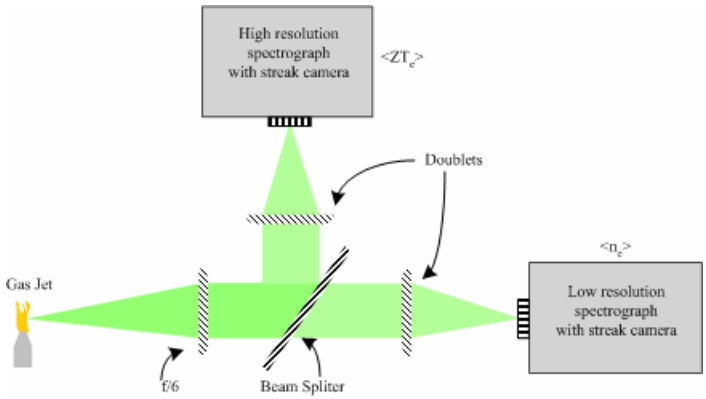


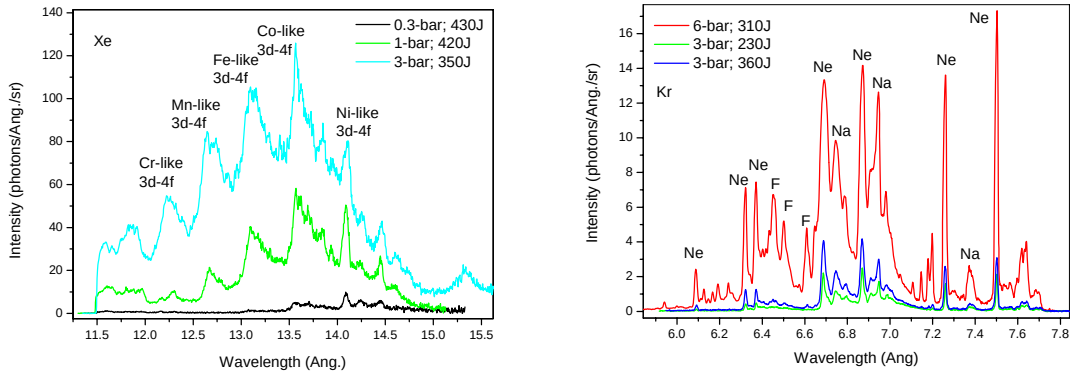
Figure 2: Thomson auto - diffusion experimental disposition.

The plasma electronic density and temperature was measured using the auto – diffusion Thomson technique. This technique uses the scattered radiation of the incident laser beam from the plasma. In particular the scattered radiation presents characteristic maxima which allow for the characterization of the plasma. These maxima occur in two different spectra regions. The one appears near the wavelength of the incident radiation. This part of the scattered radiation is known as "ionic spetra" and allow the determination of the quantity $\langle ZT_e \rangle$, where $\langle Z \rangle$ is the mean ionization number and T_e is the plasma electronic temperature. The other, which is known as "electronic spectra", appears in wavelengths far from the wavelength of the incident radiation and allows the characterization of the electronic density of the plasma. The disposition of the Thomson arrangement is shown in figure 2. The auto – diffused radiation, at 135° from the axis of the laser, is collected with a lens of f/6. The collected radiation is separated by a 50/50 beam spliter. Each branch of the splited radiation is focused at the spectrograph input using a doublet lens. In particular two spectrographs coupled with a streak camera, for the temporal resolution, and with a CCD, for the image recording, were used. The one with high resolution (± 5 nm around the laser wavelength) was used for the measurement of the "ionic" part of the scattered radiation. The other with less resolution covered the spectral region of 400–700 nm. This spectrograph measured the "electronic" part of the scattered radiation. In order to have high signal to noise ratio for this part of the scattered radiation a filter that supressed the wavelengths of the "ionic" spectra was used. The resolution of the "electronic" spectrograph was 6.4 nm and of the "ionic" 0.02 nm.

3 – Experimental results

The emission of the Xe and Kr plasmas were studied as a function of the pressure of the gas (from 0.3 to 6-bars) and of the energy of the laser beam (from 100 to 400-J).

In figure 3(a) are shown the characteristic X-ray spectra of the Xe for different values of the gas pressure and of the laser energy. The spectra are dominated by the 3d-4f transition arrays that correspond to different ionic states of the Xe in the isoelectronic sequence from the nickel to the chrome (Xe^{26+} to Xe^{30+}).



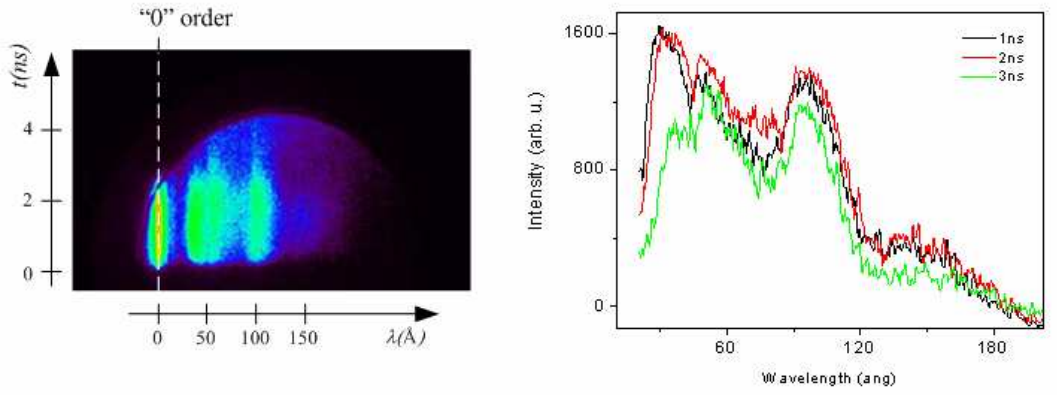
(a) *(b)*

Figure 3 : Time-integrated X-ray spectra for different gas pressures and laser energies.
(a) Xe, (b) Kr

One can observe an evolution of the amplitudes of the spectra with a simultaneous change of the transition arrays ratio due to the variation of the ionization level of the gas. The spectra that have been obtained for 1-bar pressure and 420-J energy are very similar with the results of the previous experiments [3-6].

The measured X-ray spectra of the Kr gas are shown in figure 3(b). The spectra are principaly dominated by the 2-3 and 2-4 transitions of Kr in the isoelectronic sequence from the magnesium to the fluor (Kr^{24+} to Kr^{27+}). As in the case of the Xe an increase of the pressure and the energy results in variation of the intensity ratios of the transition arrays and show an increase of the gas ionization level.

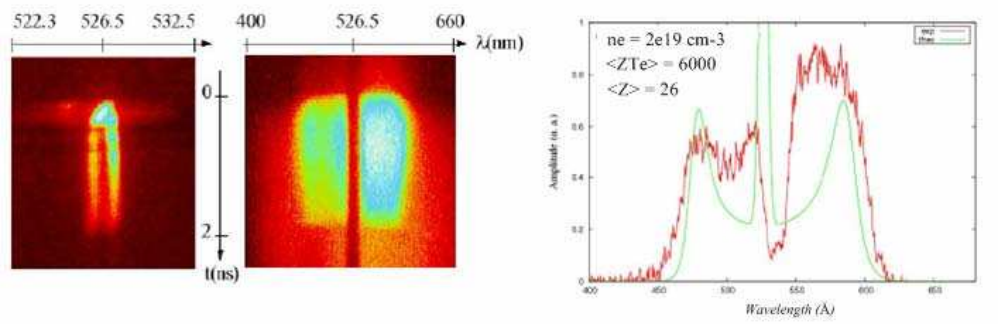
In figure 4(a) is shown a streak image of a time resolved XUV spectrum of the Kr gas, for 0.3-bar of gas pressure and 350-J energy of the laser beam. In figure 5(b) are shown three traces of 5(a) that were taken 1, 2 and 3-ns after the laser pulse. Spectra were integrated over a temporal window of 0.3-ns. As one can see from the temporal evolution of the spectra the structures that correspond to the short wavelengths disappear shortly after the end of the laser pulse while the long wavelength emission persists due to the recombination procedure of the plasma.



(a) *(b)*

Figure 4 : (a) Time – resolved XUV spectra image of Kr (3-bar, 360-J).
(b) Spectra traces at instants 1, 2 and 3-ns after the laser pulse.

Two typical time resolved Thomson "ionic" and "electronic spectra" images are shown in figure 5(a),(b). Thomson diffusion spectra analysis was done by a parametric fitting of the measured spectra with theoretical curves. The fit parameter for the "ionic spectra" was the mean electronic temperature and for the "electronic spectra" the electronic density. In figure 5(c) is shown the fit on a profile of 5(b), at 1ns after the laser pulse, for the determination of the electronic density of the plasma.



(a) *(b)* *(c)*

Figure 5: Thomson spectra of Xe gas (0.3 – bar, 420 -J)

Analysis of the Thomson measurements resulted in values for the electronic density of the two gases liying in the range of $2x10^{19}$ – $1.2x10^{20}$ cm^{-3}. Similarly the mean electronic temperature of the Xe laid in the range 160 – 370 eV. For the Kr gas the mean electronique temperature was 160 ± 25 eV.

All the spectra that have been measured for the two gases will be compared to the spectra that the AVEROES – TRANSPEC [1] code will calculate for the conditions of the temperature and the density given by the Thomson difussion measurements. Also the measured spectra will be analyzed with models that calculate the transitions ion by ion and allow the identification of the transition arrays giving in this way a measure of the plasma ionization level.

4-Conclusion

This experiment completes the previous work on the same subject. Interesting results have been obtained especially on the temporal depedence of the XUV emission but also by the "rich" X-ray spectra of the two gases. The results will contribute on the further development of the codes for the atomic physics of the NLTE behavior of the high – Z elements.

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