*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, O-2.23 (2004)*

Time and space-resolved X-ray absorption spectroscopy of aluminum irradiated by a subpicosecond high-power laser

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Abstract – Point projection K-shell absorption spectra of transient aluminum plasmas have been measured using two femtosecond beams of the 100-TW laser at the LULI facility. One beam was used to produce an absorbing plasma on a thin aluminum foil (830 or 500 Å), and the other made an X-ray back-lighter source on a thick samarium foil. The spectra have been recorded for different delays between the back-lighter source and the aluminum plasma. Hydrodynamic simulations of average ionization as a function of time show a good agreement with the experimental results.

1. INTRODUCTION

The study of warm dense plasmas produced by the interaction of an ultra-short laser pulse with thin foils is now possible with the development of high energy subpicosecond lasers. When short-pulse, < 1 ps, lasers with intensities in the range of 10^{15}-10^{16} W/cm^2 are used to illuminate thin foils, impulse heating followed by rapid heat conduction produces a high density, high temperature plasma with little hydrodynamic expansion[1]. Recent experiments have used ultra-short pulse lasers for point-projection spectroscopy of expanding plasmas[2] or moderate to strongly coupled plasmas[3], providing space- and time-resolved information on the average ionization. Here, we present an experimental technique in which an ultra-short laser pulse is used to create a thin, high-density plasma slab fairly uniform in density and temperature. A temporally ultra-short X-ray pulse is used to back-light the slab and the space-resolved absorption spectra is gathered with a charge-coupled device (CCD) coupled to a conical crystal. The plasma characteristics were inferred from Frequency Domain Interferometry (FDI) measurements of the hydrodynamic expansion of the plasma as a function of time. The main advantage of this technique is the determination of the initial temperature independently of the space-resolved absorption spectra.

2. EXPERIMENTAL SETUP

The experiment was performed at LULI using two 300 fs beams. The experimental layout is shown in Fig. 1. A small portion of the beam was extracted to provide a laser probe pulse for the FDI. The remaining beam was split into two beams, a 5.0 J frequency doubled beam recompressed to 300 fs for the back-lighter, and a 0.3 J beam recompressed to 300 fs and used to heat the target. The back-lighter beam was focused onto a massive samarium target with an off-axis parabola to a spot size of 100 μm, producing a peak focused intensity

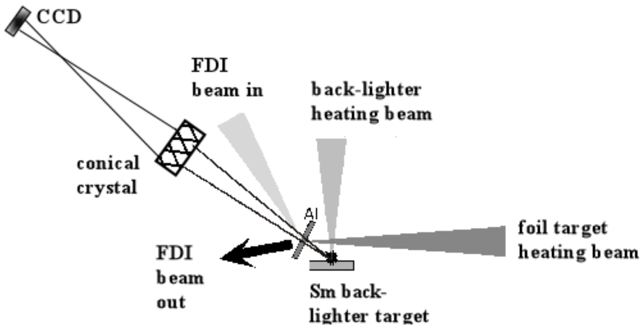

Fig. 1. Layout of the experiment.

of 2×10^{17} W/cm^2. The heating beam was focused onto an aluminum layer, thickness 500 and 830 Å, built on a self-standing 250 Å silicon nitride (Si_3N_4) substrate. This membrane supported a 300 µm diameter gold pinhole made in a 0.5 µm Au deposit. Finally, the aluminum layer was deposited on the rear surface, and the diagnostics are set on the thin foil side[4]. The focal spot was elliptic, 180 µm in the direction of the spectrograph and 60 µm in the direction of the spatial resolution.

The FDI consists in measuring the phase of a chirped laser beam, 15 ps duration, reflected on the rear critical surface of the plasma[5]. The probe beam was at 1.06 µm wavelength, with an energy of 100 mJ, with a 47° incidence angle on the rear surface of the target (see Fig. 1). The light was analyzed through a Mach-Zehnder interferometer coupled to a 1.0 m Czerny-Turner spectrograph with a magnification of 4. The heating pulse was synchronized such that target heating occured during the probe pulse reflection on the target surface.

The X-ray transmission data were recorded in the range 7.7 – 8.5 Å, using a conical potassium-hydrogen-phthalate (KAP) crystal spectrometer coupled to a cooled 1024×1024 16 bits CCD. The 7.7 – 8.5 Å spectral region covers the inner shell n=1 to 2 and n=1 to 3 transitions belonging to Al^{4+} to Al^{11+}. In this spectral region and at the obtained laser intensity, Sm plasma emits a quasi-continuum X-ray spectrum and provides a well adapted back-lighter with a 4 ps duration[2,4]. The CCD setting can be modified to change the focusing of the crystal. By putting the CCD at the focal plane of the crystal, the width of the focal line can be varied from 10 to 100 µm, without changing the wavelength range. Point projection absorption spectra were obtained by moving back the CCD to 9.0 cm from this position. The distance from the back-light source to the plasma was 3.0 mm, which gives a magnification of 30. The spectral resolution was estimated to be 8 mÅ providing a resolving power of $E/\Delta E = 1000$.

3. X-RAY ABSORPTION DATA

Fig. 2 shows space-resolved absorption spectra at different times after the heating laser in the case of the 500 Å (on the right) and 830 Å foil (on the left) irradiated at a laser intensity of 3.10^{15} W/cm^2. For the 500 Å case, at 7 ps, the cold K-edge of aluminum foil is measured on the side of the focal spot of the heating laser. At lower wavelengths, 1s-3p absorption lines can be seen on the edge of the focal spot. For the 830 Å case, the spectra show that the plasma recombination is fast, with a stagnation phase between 7 and 15 ps. The 500 Å thick foil allows to observe higher ionic stages compared to the 830 Å thick foil. The low charge state (Al^{4+} and Al^{5+}) disappear in the middle of the focal spot, where the laser intensity is larger and the plasma hotter.

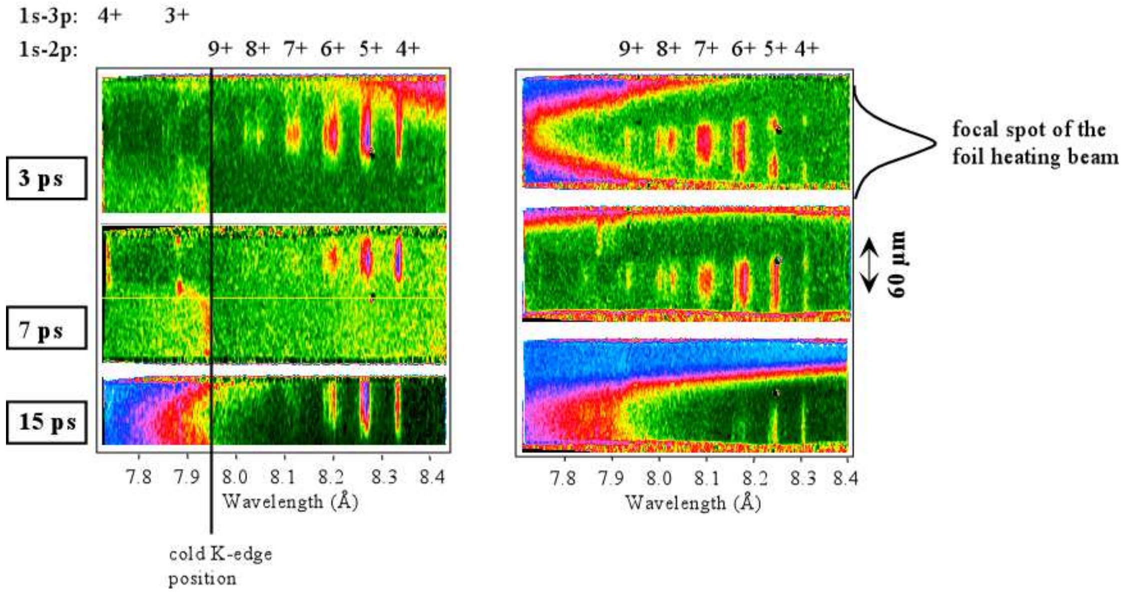

Fig. 2. Space-resolved spectra obtained at three different times labeled on the left of the figure for two different thickness of aluminum: 500 Å (right) and 830 Å (left) irradiated at a laser intensity of 3.10^{15} W/cm^2. The circle seen on some central part of the spectra is the shadow of the 300 µm diameter gold pinhole obtained when the targets are a bit out of alignment. The vertical lines corresponds to absorption and are labeled by the charge of the absorbing ion.

4. FOURIER DOMAIN INTERFEROMETRY DATA

The phase shift of the reflected beam depends mainly on the speed of the critical surface, which is related to the electron temperature[4]. The time-dependent phase of the reflected light was simulated using a self-similar expansion 1D hydrodynamic isothermal model[6]. The isothermal assumption was justified by hydrodynamic simulations run with the code MULTI-fs[7] demonstrating that the temperature is spatially uniform in the expanding plasma. In our model, we assume a uniform initial density equal to solid density, a Thomas-Fermi ionization, and an initial peak temperature, which is therefore the only unknown parameter[4]. The best fit of the phase obtained for a laser intensity of 5.10^{15} W/cm^2 is obtained for an initial temperature of 50 eV. This value is the uniform temperature achieved at the peak of the foil heating pulse.

5. DATA ANALYSIS

Each absorption spectrum obtained for a specific time at the center of the focal spot was analyzed using the HULLAC code[8]. One result obtained is shown in Fig. 3 in the case of a 500 Å foil with the best HULLAC fit obtained for an average ionization of 7.0. All the spectra were analyzed using the same method, providing the time evolution of the average ionization.

We used 1-D hydrodynamic simulations performed with the MULTI-fs code coupled to the time-dependent, non-LTE atomic collisional-radiative AVERROES/ TRANSPEC code[9] to interpret the data. For the 830 Å foil deposited on 250 Å Si_3N_4, the temporal evolution of the average ionization is shown on Fig. 4. Despite the rapid temporal evolution of the temperature, the ionization state given by TRANSPEC is following the experimental data with an overall agreement, suggesting that the plasma is in a non-equilibrium state, even if

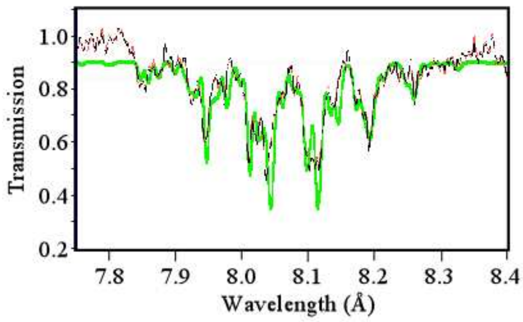

Fig. 3. Transmission of a 500 Å Al foil heated at a laser intensity of 3.10^{15} W/cm^2 7 ps after the heating pulse (in red). The best HULLAC fit obtained for an average ionization of 7.0 is also shown (green curve).

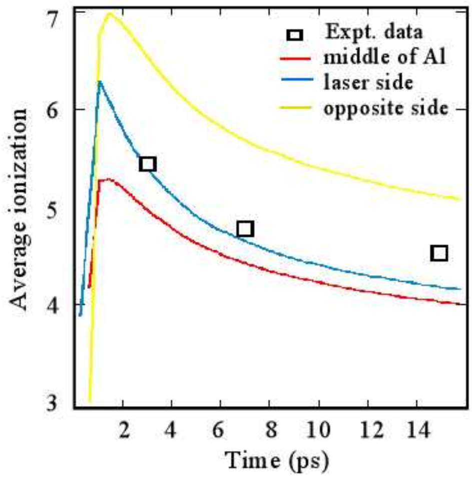

Fig. 4. Time evolution of the measured average ionization of a 830 Å Al foil compared to the numerical simulations at three positions inside the foil.

the density is high. While the electron temperature is quite uniform across the foil thickness, the electron density varies, resulting in a small dispersion of the average ionization.

The picosecond recombination dynamic of thin Al foil heated with a high-intensity ultra-short pulse laser was measured using point projection absorption spectroscopy. A cross-check between FDI inferred temperature and density and transmission spectra from opacity codes results will be done in a near future. The experiment demonstrates the ability to measure absorption spectra on a well characterized warm dense plasmas.

We gratefully acknowledge O. Peyrusse for the use of the AVERROES code.

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