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Temporal and spectral behavior of sub-picosecond laser-created X-ray sources

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The rapid development of the high-energy, ultra-short pulse laser technology allowed the development of bright X-ray sources in the picosecond as well as in the sub-picosecond temporal range. Due to their brightness, these sources have potential applications as diagnostic of inertial confinement fusion plasmas, medical imaging, and XUV lithography. Their short duration opens up the route to material structural analysis with temporal resolution as low as the elementary vibration mechanisms duration. The number of experiments dealing with the temporal characterization of the X-ray sources created by a ultra-short laser pulse on a solid material is relatively limited, as ultra-fast streak cameras, required for such studies, have been developed quite recently [1-3].

Several mechanisms play a role in sub-picosecond laser – matter interaction. On one side, a thin plasma region is heated to several eVs electronic temperature, leading to the so-called "thermal" emission, with a duration related to the hydrodynamic evolution, the thermal conduction and the plasma recombination. On the other side, the suprathermal electrons interact with the matter and generate inner-shell vacancies in ions or atoms, leading to Kα line emission. In this contribution, we present the results of a recent experiment devoted to the measurement of the temporal duration of a thermal X-ray source.

We used the LULI 100TW laser facility to irradiate thick Al and thin Se targets. Some of the Al targets were coated with a thin Vanadium layer (0.2 μm), to absorb the laser Amplified Spontaneous Emission (ASE) preceding the main pulse, and allow the main pulse to interact with the still solid Al. In figure 1 we illustrate the experimental set-up. The 1.06 μm wavelength CPA laser was used either at its shortest (300 fs) pulse duration, either stretched up to 33 ps. The laser beam was focalized on the target by an f/3 off-axis parabolic mirror, giving a maximum intensity on target (for the shortest pulse) of $5 \cdot 10^{19}$ W/cm^2. The X-ray emission was spectrally and temporally resolved by coupling a conical Bragg crystal with a fast streak camera, covering the 7.6-8.1 Å spectral window.

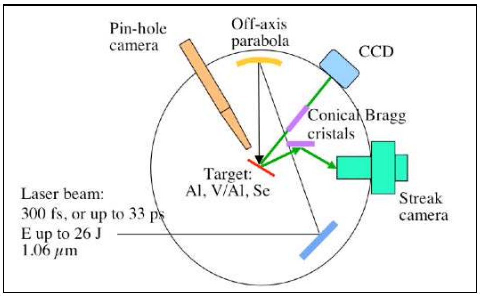

Figure 1: The experimental setup, showing the diagnostics arrangement.

A second conical Bragg crystal spectrometer recorded the time integrated spectra on a slightly larger spectral range (7.5-8.5 Å), and a X-ray pinhole camera was used to monitor the laser-target interaction. Only the streak camera results will be presented in this contribution.

Figure 2 shows time evolution of some Al and V/Al spectra, for two different laser pulse durations. The line identification is shown in fig. 2b. The spectrum in fig. 2a exhibits characteristics of a very high density plasma, close to the solid density: a low Heα emission, due to the strong reabsorption, a missing intercombination (IC) line, and strong spectral broadening, due not only to Stark effect, but also to merging with higher order dielectronic satellites [4,5]. Moreover, the rather stationary temporal evolution indicates very slow variation of the hydrodynamic parameters.

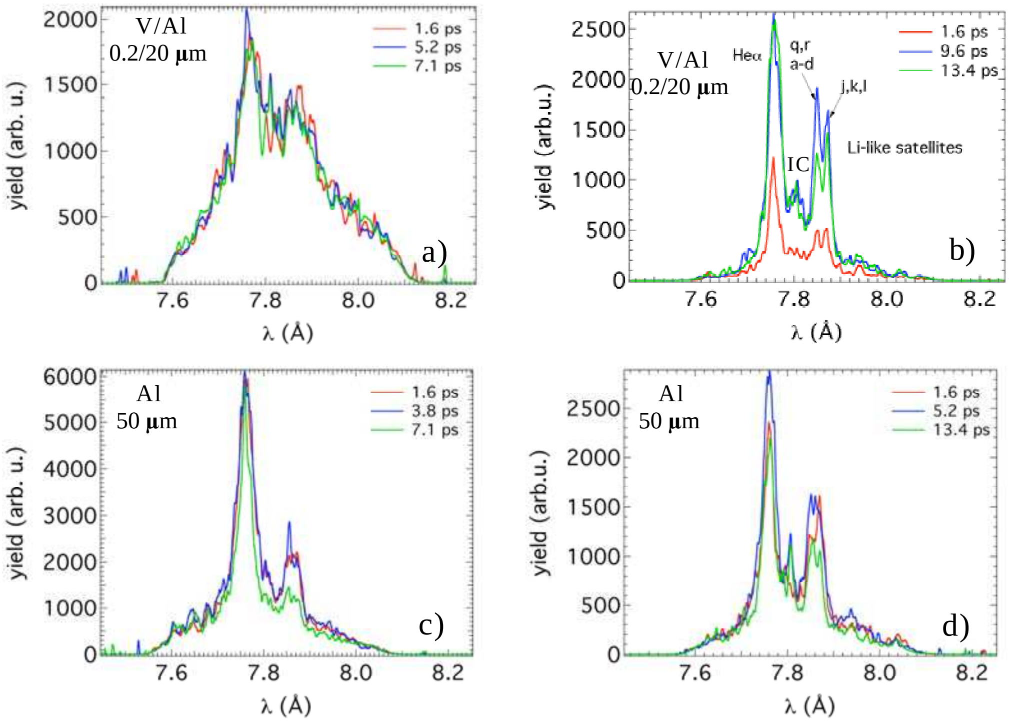

Figure 2: Spectra obtained at different times in various experimental conditions: a) V/Al target, 300 fs laser pulse duration, $I=4.3\cdot10^{19}$ W/cm^2; b) V/Al target, 3 ps laser pulse duration, $I=2.3\cdot10^{18}$ W/cm^2; c) Al target, 300 fs laser pulse duration, $I=4.8\cdot10^{19}$ W/cm^2; d) Al target, 3 ps laser pulse duration, $I=2.7\cdot10^{18}$ W/cm^2.

The V/Al spectra obtained with the 3 ps laser pulse duration (fig. 2b) are, on the contrary, much more similar to those obtained since about two decades in the nanosecond laser pulse regime, even if significant differences can be pointed out. First, the spectrum at earlier time is characterized by the absence of the IC line, and a relatively weak Heα line with respect to the Li-like satellites. Again, this is characteristic of a high density plasma. Second, for the spectrum at 9.6 ps, we can observe that the {j,k,l}/{q,r,a-d} line intensity ratio is inverted with respect to that at a later time, which is typical of a ns-laser produced plasma. This behavior has been shown to be produced by a highly transient regime, with non steady-state population kinetics [6,7].

Finally, the Al spectra (fig. 2c and 2d) are very similar to those obtained in the nanosecond regime, even for the 300 fs laser pulse duration case.

These data show the dramatic impact of the laser ASE on the X-ray spectral characteristics, leading to “ns-type” irradiation, even for sub-ps laser, if no special care is taken to minimize its effect.

Figure 3 show various spectra obtained on thin (240 Å) Se targets, at the maximum of the emission, and for different laser conditions. As no minimization of the ASE effect has been performed, we expect that the spectral shape is similar to that obtained in previous studies performed in the ns regime. In this regime, it has been established that intensity ratios of Ne-like resonance lines and Na-like satellite lines can be used to obtain the plasma parameters (density and temperature) [8]. In particular, the intensity ratio between the Ne-like 3C and 3D lines and the Na-like satellites {e,f,g} (see fig. 3) is mostly sensitive to the electron temperature.

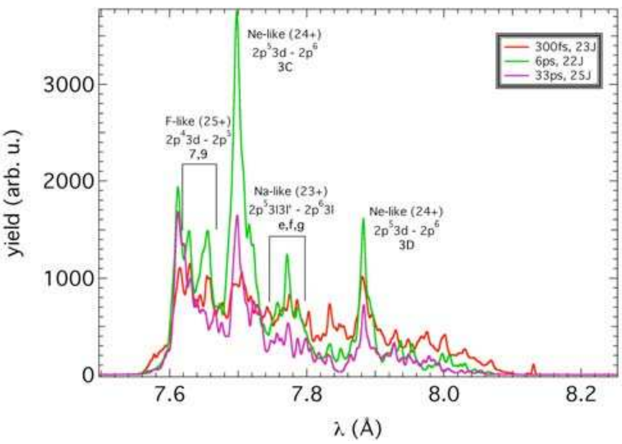

Figure 3: Se spectra obtained at the emission peak, for different laser pulse parameters.

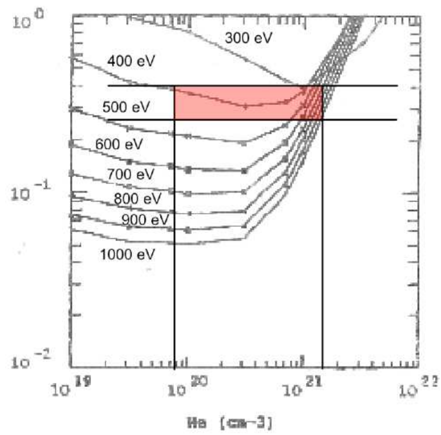

Figure 4: Intensity ratio of the Ne-like lines (3C + 3D) and the Na-like satellites e,f,g} as a function of the electronic density, and for different electronic temperatures.

In figure 4 we plot this ratio, as a function of the electronic density, and for different electronic temperatures. The grayed layer represents the range of variation of the experimental intensity ratio. This allows us to determine a likely range for the plasma parameters, namely from some 10^{19} to about 10^{21} cm^{-3} for n_e and 400-500 eV for T_e. It is important to stress that these values are coherent with the preliminary CHIVAS hydrodynamical simulations, performed on the Al case, which give an ASE-created, coronal plasma with n_e between $5 \cdot 10^{19}$ and $2 \cdot 10^{21}$ cm^{-3} and T_e between 400 and 500 eV.

This work is still in progress. We plan to perform other hydro-simulations, for the three targets used, to infer the plasma parameters. The spectra obtained in the V/Al – 300 fs case will be simulated using a line-shape code, to identify the relative importance of the Stark effect versus the higher order satellites contribution. The spectra obtained on the Al and V/Al targets will also be simulated using a collisional-radiative code, and the plasma parameters obtained will be cross-checked with the hydrocode results. The Se spectra will be simulated using a “hybrid” atomic physics code, merging a statistical treatment of the lines, and a detailed description of some transitions.

The time-integrated spectrometer data obtained with the Al and the V/Al targets will be analyzed to study the behavior of the Kα emission, and to have insight on suprathermal electron production.

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