Auger electron heating of solid aluminium induced by FLASH

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In this work, we have reconstructed the time dependent evolution of near solid density Al foils when irradiated with micro-focused XUV pulses of FLASH. We have highlighted the important Auger electron heating contribution via the detailed analysis of high resolution XUV-emission spectra of Al samples for the first time.

The experiment was carried out at Beam Line 3 where we focused the FLASH beam down to a focal spot size of ~ 2.3 μm using an off-axis parabola [1]. With a pulse duration of about 20 fs and 30 μJ energy, we reached an intensity on target in excess of 10^{16} W.cm^{-2}. We moved the 10 μm thick Al foils to match the 10 Hz repetition rate of the beam in order to hit a fresh sample area. The subsequent emissions have been dispersed using a variable line spacing flat-field grating covering the 10-30 nm spectral range with 1200 lines/mm coupled to a CCD. The black curve in Fig. 1 corresponds to the time integrated XUV emission of the Al foils at best intensity.

Comparison with detailed Hartree-Fock calculations [2] allows us to distinguish three different types of transitions in the Al IV ionization degree. First, we observed the line emissions corresponding to the strong resonant transitions [Be]2p^{5}3s $\rightarrow$ [Be]2p^6 arround 16 nm, and also the [Be]2p^{5}3d $\rightarrow$ [Be]2p^6 arround 13 nm. Second, we also resolved the corresponding satellite transitions belonging to screened resonant transitions $\mathrm{K^2L^7M^X} \rightarrow \mathrm{K^2L^8M^{X-1}} + h\nu$, with X equal to 2 or 3. Finally, the spectra show intra-shell transitions arround 26 nm that correspond to $\mathrm{1s^22s^12p^6M^X} \rightarrow \mathrm{1s^22s^22p^5M^X} + h\nu_{2s-2p}$. The emission originating from these 3 different configurations can be related to different phases in the solid-to-plasma transition. Theoreticaly we decomposed the spectra in three different levels of screening, noted by CI, CII and CIII for one, two and three electrons in the M shell, as shown in Fig. 1. These three configurations are then mixed together in a genetic algorithm to fit the experimental data. The result corresponds to the red curve in Fig. 1.

The overall good agreement allows extracting a scheme for the XUV laser-matter interaction evolution. The 91.8 eV ($\lambda = 13.5$ nm) photons photo-ionize a single electron in the 2p shell of almost every Al atom (experimentally verified due to saturated absorption [3]). After the pulse, this exotic

state of matter stabilizes by Auger decay. As no macroscopic motion takes place on few 10 fs, the matter consists in Al atoms which are still located on their lattice nodes and Auger electrons with about 70 eV of kinetic energy in the conduction band. The equilibration of these electrons then heats the material and leads within few ps to the destruction of the crystalline structure. At this point, the band structure becomes atomic like. In this high density plasma state, dielectronic recombination and collisionnal ionization can occur producing also the screened configurations CII and CIII. The analysis, by means of the genetic algorithm, delivers the respective populations densities of the hole state configurations, which gives the temperature and density (assuming local thermodynamic equilibrium being justified as collisions are larger than relevant Autoionizing rates) of T_e = 25 eV and $n_e \approx 5 \times 10^{22}$ cm^{-3}. The recombination regime then evolves for several ns thereby producing resonant line transitions (as those observed in the CI configuration) at T_e = 8 eV and $n_e \approx 3 \times 10^{21}$ cm^{-3}, respectively [4].
To conclude, we have performed detailed high resolution spectroscopic analysis of the self-emission of an Al foil irradiated at high intensities by the XUV FLASH beam. The Auger effect has been identified to be the principal heating mechanism. The inverse Auger process allowed us to follow the transition between the solid to the WDM and then to the plasma state even using time integrated spectrocopy. Consequently, the use of hollow ion emission as intrinsic X-ray switches, already proposed in [5], might then be of great importance since no X-ray streak cameras on a 10 fs time scale is available yet. The successful experiments and analysis at FLASH encourage the use of the newly emerging hard X-ray free electron laser facilities like the LCLS and the XFEL to probe the exotic matter *in situ* via the hollow ion emission.

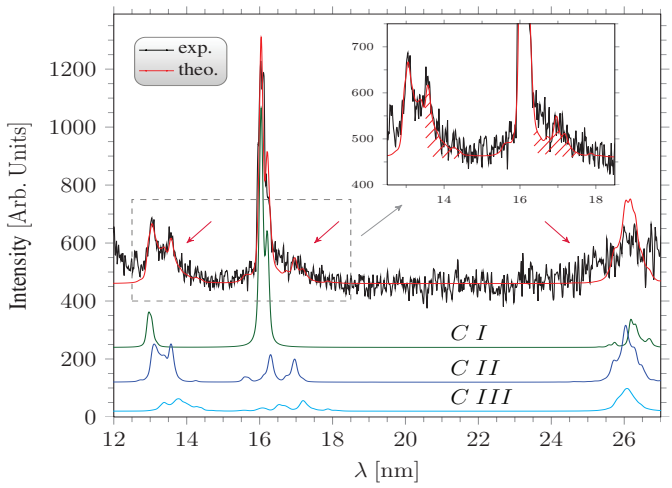

Figure 1: Emission spectra (black line) taken at best focus. The arrows indicate the discrepancy between the data and simulation of the Al IV emission (CI). The red curve is the best fit obtained including also the emission from the L-hole states (CII and CIII).

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