Time-duration dependence from the simultaneous measurements of iron K- and L-shell radiation from laser produced plasmas

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Abstract. High resolution X-ray spectra of plasmas produced by the interaction of Ti:Sa laser pulses (duration from 60 fs to 1 ps, and energy from 15 mJ to 128 mJ) with a solid Fe target are investigated experimentally and theoretically. Interestingly, both L-shell and K-shell Fe spectra were simultaneously measured while changing the time-duration of the laser experiments. In particular, the L-shell Fe radiation from Fe, Ne, and Na-like ions between ~14-16.3 Å were observed from the first order reflection with a mica crystal. Simultaneously measured alongside the L-shell radiation was the Fe cold Kα lines (~1.94 Å), from 8th order reflection. Two non-LTE Fe kinetic models have been developed to account for the L-shell radiation from the Fe ions and for the K-shell radiation from the low ionization stages emitting the Fe cold Kα lines. Preliminary analysis of the simultaneously measured Fe L- and K-shell radiations from changing the time-duration of the experiments shows varying relative line intensities from different ionization stages. Resulting plasma parameters as well as the opacity of the strongest resonance line, 3C, and their dependence on changing the time-duration will be discussed.

1. Introduction

Studies of different laboratory and astrophysical plasmas, such as tokamaks, astrophysical, and ICF applications, involve the comprehensive investigation of K- and L-shell iron spectra. Previous work was mainly focused on the separate study and measurements of L-shell [1] or K-shell iron spectra [2]. Also, it is very important to measure and analyze them simultaneously, especially for the case of fs-scale interactions with solid targets when fast electrons are produced and ionize solid targets up to the M-shells [3]. In particular, it is interesting to investigate the ionization balance and spectra of iron for
the case of < 100 fs laser pulses interactions with a solid target. In the present paper, we are reporting such investigation for the first time.

2. Experimental Setup
The experiments were performed using a Ti:Sapphire (Ti:Sa) laser system from a national laboratory for ultrafast and ultraintense optical science (ULTRAS-CNRS-INFM, Politecnico di Milano, Italy), which generates 800 nm pulses with 10 Hz repetition rate, maximum energy of 130 mJ, and minimum duration of 60 fs. The duration of laser pulses was varied between 60 fs and 2 ps by changing the distance between gratings in the compressor stage. The laser pulse contrast can be varied between ~ $10^3 - 10^5$ in the nanosecond time scale and ~ $10^2 - 10^4$ in the ps scale. Iron slabs were used as targets.

The laser beam was focused on a target surface at an incidence angle of 15° by an off-axis parabola mirror in a spot between 10–20 µm in diameter (the Rayleigh length of the focusing system in vacuum is about 200 µm). The peak intensity varies in the range $4 \times 10^{15} - 6 \times 10^{17}$ W/cm$^2$ for the pulse duration between 1 ps and 60 fs. The target was continuously shifted in order to shoot on a fresh surface each time. Laser radiation focusing and plasma expansion were controlled by an X-ray pinhole camera with a 15-µm aperture diameter. The 1:1 plasma image was recorded on a RAR-2492 film in the X-ray spectral range with photon energy greater than 0.4 keV. In this experiment, the laser pulse contrast was intentionally reduced to about $10^2$ in the 100-ps scale by inverting a dielectric steering mirror between the regenerative and the high power amplifiers; in this way, a weak prepulse reflected from the substrate surface was generated.

X-ray radiation from the plasma was measured by the focusing spectrometer with spatial resolution (FSSR) spectrometer [4, 5] based on the spherically bent mica crystal (2d = 19.91 Å). The crystal curvature radius is R = 100 mm and the aperture size is 8x26 mm$^2$. The X-ray radiation was registered by a CCD camera (Roper Scientific, 1300 x1300-cells matrix) with the cell size of 20 µm. The CCD-matrix was protected from the visible and vacuum ultraviolet VUV radiation by three layers of the 1µm polypropylene film coated with a 0.2-µm Al layer. The spectrometer was adjusted to the Bragg reflection at the angle $\theta = 49.8^\circ$ to observe the first order reflections in the vicinity 14.1-16.2 Å capturing the 3-2 transitions of L-shell Fe with the spectral resolution $\lambda/\delta\lambda \sim 5000$. Simultaneously measured in 8th order reflections was radiation from the Fe Kα line in the spectral range 1.75 – 2 Å. The spectral measurements were performed with the one-dimensional spatial resolution about 50 µm transverse to the plasma expansion direction.

3. Experimental Results and Modeling of Line Radiation
X-ray spectra from the plasmas were obtained from the interaction of a Ti:Sa laser with a solid Fe target. The obtained spectra, especially for the case of heating by 60 fs laser pulses, were noisy due to the interaction of fast electrons and gamma rays with the CCD. Therefore x-ray spectra were cleaned with a special procedure to remove the noise [6]. The solid line in figure 1 shows an experimental spectrum with the L-shell lines from hotter plasma (1st order reflection) and cold Kα lines from cooler plasma (8th order reflection). The L-shell lines were produced by the prepulse plasma. The laser radiation interacted with the plasma producing hot electrons which heated the solid dense iron target producing the cold Kα lines. A total of nine experiments were analyzed. Each experiment had either best contrast, ps-prepulse, or ns-prepulse with main pulse durations of 60 fs, 600 fs, or 1 ps. All experimental spectra showed increasing intensities of the cold Kα lines with decreasing laser main pulse duration. The L-shell lines also decreased with decreasing main pulse duration, but only slightly with experiments with the best contrast.

In order to model radiation from the experiments, two non-LTE kinetic models were used. The first model accounted for the L-shell radiation from the hotter multiply-charged ions and has been used to model radiation from the implosion of stainless steel x-pinches [7] and wire arrays [8]. An example of a synthetic spectrum accounting for the L-shell radiation is shown in figures 1 and 2. Some L-shell spectral features seen are the F-like lines labels F1, F2, and F3 which are $2p^4 3d \rightarrow 2p^5$ transitions and the Ne-like lines labeled 3C and 3D which are $2p^3 3d \rightarrow 2p^5$ transitions. The relative ratios of lines
from adjacent ionization stages, such as F2 to 3D, were used to constrain the electron temperature. For instance, the ratio of F2 to 3D is lower in figure 1 than in figure 2 and therefore the electron temperature is cooler in figure 1. The unlabeled lines between 3C and 3D are mainly Na-like satellite lines and were helpful to constrain electron density as well as the electron temperature.

**Figure 1.** An experimental spectrum from the interaction of a Ti:Sa laser system with a psz prepulse and 60 fs main pulse and an iron target (solid line). The result of modeling the L\textsubscript{z}shell lines (long dash line) with electron temperature of 170 eV and electron density of $10^{21}$ cm\textsuperscript{-3}. The result of modeling the cold K\textalpha{} lines (short dash line) with electron temperature 20 eV, electron density of $10^{22}$ cm\textsuperscript{-3} and a 0.5% fraction of hot electrons.

The second model was recently developed to account for the cold K\textalpha{} radiation by the excitation of inner shell states from the interaction of hot electrons with the solid dense iron target. An example of a synthetic spectrum accounting for the cold K\textalpha{} lines is shown in figure 1. These lines originate from cooler denser plasma from inner shell excitations with hot electrons in lower ionization stages. It was found in modelling that increasing the fraction of hot electrons not only shifted the ionization balance to higher ionization stages, but also tended to broaden the ionization balance. This tendency constrained the fraction of hot electrons to < 1% to reproduce the experimental spectra.

L-shell modelling of spectra with the best contrast and psz-prepulse showed that the electron temperature increased while the electron density decreased with increasing main pulse duration. However, spectra produced with ns-prepulse showed no appreciable difference in electron density and a small change in electron temperature with the different main pulse durations. In figures 1 and 2, there is a difference in intensity of 3C lines between the synthetic spectrum and experimental spectrum which is due to opacity. The 3C line has the largest radiative decay rate of the Ne-like resonance lines of Fe and therefore the effects of opacity should occur first in this line compared to the other Ne-like lines. In figure 2 there is also a difference in the F1 line intensities between the synthetic spectrum and experimental spectrum. Again, this difference is due to opacity. The F1 line has the largest radiative decay rate of the F-like resonance lines. The difference between the ratio of the theoretical to the experimental 3C line intensity correlates with increasing K\textalpha{} intensity.

4. **Summary**

X-ray spectra were obtained from the interaction of a Ti:Sa laser with a solid iron target. Simultaneous measurements of L-shell emission (1\textsuperscript{st} order reflection) from the hotter plasma and the cold K\textalpha{} (8\textsuperscript{th} order reflection) emission from the cooler plasma were obtained. The L-shell lines were produced by the prepulse plasma. The laser radiation interacted with the plasma producing hot electrons which...
heated the solid dense iron target producing the cold Kα lines. Radiation was modelled from the different regions with two non-LTE kinetic models. The first model accounted for the L-shell radiation from the hotter multiply charged ions, while the second accounted for the cold Kα radiation by the excitation of inner shell states from the interaction of hot electrons with the solid dense iron target. All experimental spectra showed increasing intensities of the cold Kα lines with decreasing laser main pulse duration. The L-shell lines also decreased with decreasing main pulse duration, but only slightly with experiments with the best contrast. L-shell modelling of the experimental spectra with the best contrast and ps-prepulse showed that the electron temperature increased while the electron density decreased with increasing main pulse duration. However, spectra produced with ns-prepulse showed no appreciable difference in electron density and a small change in electron temperature with the different main pulse durations. A difference in the intensity of the 3C line between synthetic spectra and experimental spectra was found and is due to opacity. This difference was found to correlate with strong cold Kα emission.

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