Quantitative Kα line spectroscopy for energy transport in ultra-intense laser plasma interaction

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Abstract. Absolute Kα line spectroscopy is proposed for studying laser-plasma interactions taking place in the cone-guided fast ignition targets. X-ray spectra ranging from 20 to 100 keV were quantitatively measured with a Laue spectrometer. The absolute sensitivities of the Laue spectrometer system were calibrated using pre-characterized laser-produced x-ray sources and radioisotopes. The integrated reflectivity for the crystal is in good agreement with predictions by an open code for x-ray diffraction. The energy transfer efficiency from incident laser beams to hot electrons, as the energy transfer agency, is derived as a consequence of this work. The absolute yield of Au and Ta Kα lines were measured in the fast ignition experimental campaign performed at Institute of Laser Engineering, Osaka University. Applying the hot electron spectrum information from the electron spectrometer, an energy transfer efficiency of the incident LFEX [1], a kJ-class PW laser, to hot electrons was derived for a planar and cone-guided geometry.

1. Introduction

Fast ignition is recognized as a promising pathway to efficient thermonuclear fusion in laser-driven inertial confinement fusion. A cone-guided CD-shell has been used as a base-line target for the fast ignition experiment [1, 2]. It has long been expected to provide more quantitative information about the hot electron generation and transport in the cone than those derived only with x-ray imaging and neutron detection. In this research, we propose an absolute Kα line spectroscopy dedicated for quantitative measurement of hot electron generation and transportation in high-Z targets. This diagnostic provides local information about the hot electrons propagating through specific materials composing the cone-guided target.

In this study, Au and Ta were chosen as tracers since they are representative higher-Z materials which are available for the guide cone, which provide stronger stopping for the MeV-hot electrons and the ratio of the number of hot electrons to the number of Kα photons produced are better matching with MeV-hot electrons than lower-Z tracers such as Cu.
2. High energy Kα x-ray spectrometer

A Laue spectrometer was developed to cover the high energy Kα lines from Mo (Kα1: 17.48 keV, Kα2: 17.37 keV) to Au (Kα1: 68.80 keV, Kα2: 66.99 keV)[3]. As shown in Fig. 1, the spectrometer consists of a cylindrically curved quartz (10-11) plate and a detector. The detector can either be an imaging plate (IP) from Fujifilm Inc. or a charge coupled device (CCD: Andor Model DH420-FO) with a fiber-optic plate coated with a CsI phosphor of 100 μm thickness. The quartz plate is bent such that the diffracted x-rays are focused at an intermediate slit. X-ray components propagating in a straightforward manner are shielded from the detector directly with a lead pinhole plate located in front of the crystal and a pair of lead shields located at the intermediate x-ray focus. To avoid influence of hard x-rays from plasma on output signal, whole body of the spectrometer and the detector are covered with lead shielding. This Cauchois geometry effectively discriminates 0th order component, stray x-rays and fluorescence from spectrometer components such as filters [4, 5]. By varying the distances from the crystal to the source and detector, this spectrometer can cover the energy range of either 10-60 keV or 22-100 keV.

3. Hot electron trajectory

The hot electron trajectory inside the solid target is tracked with Monte-Carlo simulation. A 3-dimensional code PHITS was applied. The code uses the continuous slowing down approximation (CSDA), which means that the electrons change their direction of motion due to elastic scattering, and lose their energy between two scattering points continuously. An example is shown in Fig. 2. The black square in the center indicates a 1 mm Ta cube, which is surrounded by low density air with a pressure of 10⁻⁵ Torr. The hot electron beam was irradiated on the Ta cube from the left side. An initial divergence of 45° and a Gaussian spatial profile were assumed. The energy spectrum was set based on the electron spectrometer (ESM) measurement in experiments. From Fig. 2, it is clearly seen that most of the electrons with energy less than 0.1 MeV were reflected at the front surface. The penetration depth increased along with electron energy; and only part of the electrons with energy higher than 1 MeV can propagate through the Ta cube and escape from the back surface.

4. Laser transfer efficiency

The laser transfer efficiency, \( \eta_{TE} \), is defined as the fraction of energy deposited into hot electrons. The number of Kα photons \( N_{Kα} \) generated from hot electron with number \( N_h \) and temperature \( T_h \) can be estimated by the following model:

\[
N_{Kα} = N_h \frac{n_A \omega_{Kα}}{4 \pi T_h} \int_0^\infty dE \sigma_{Kα}(E) \times \int_0^d dx f_h(E_0, x) \exp\left(-\frac{x}{\lambda_{mfp} \cos(θ)}\right), \tag{1}
\]
Figure 2. Electron trajectory in the Ta cube: (a) all electrons, (b) electron with energy less than 0.1 MeV, (c) electron with energy from 0.1 to 1 MeV, (d) electron with energy more than 1 MeV. In this simulation, an initial hot electron temperature of 5 MeV is assumed, as $f_h = \exp\left(-\frac{E}{5}\right)$.

where $\sigma_{K\alpha}$, $\omega_{K\alpha}$, and $n_A$ are, respectively, the cross section for K-shell ionization, the K\(\alpha\) fluorescence yield, and the atomic number density. The term $\exp\left(-\frac{x}{\lambda_{mfp} \cos(\theta)}\right)$ describes the reabsorption of K\(\alpha\) photons during the propagation through the target material, where $\theta$ is the angle between the spectrometer and target normal. $f_h(E_0, x)$ describes the energy spectrum for the hot electron propagating inside the Ta cube with a depth $x$, where the information was achieved with PHITS simulations. Considering the absolute K\(\alpha\) photon number $N_{K\alpha}$ measured by the Laue spectrometer, the transfer efficiency $\eta_{TE}$ can be estimated by comparing the experimental measurement and simulation results.

The transfer efficiency from LFEX laser to target has been estimated in the cases of planar and cone-guided geometry. In the case of planar target, an Au plate was placed at the target chamber center and the LFEX laser with maximum energy of 1.8 kJ was focused on the front surface with an incident angle of 10°. The K\(\alpha\) from Au was recorded by the Laue spectrometer and an ESM was located from the back surface for the hot electron temperature. The $\eta_{TE}$ as a function of laser intensity is shown in Fig. 3. As a general trend, the $\eta_{TE}$ is increased by increasing the laser intensity.

The cone-guided configuration is shown in Fig. 4. A cone is attached with a hemi-CH shell, which was irradiated by three beams of Gekko-XII laser [1]. A dense plasma surrounding the tip of the cone was produced to mimic the condition of the fast ignition Au cone+CD shell target [1]. The Ta cube was attached as the K\(\alpha\) tracer after the hemi-CH shell. Four types of cone were used, as shown in Fig. 4 (b)-(e): (b) is the standard Au cone with 7 \(\mu\)m thickness; (c) is

Figure 3. The $\eta_{TE}$ as a function of laser intensity for the planar and cone-guided targets.
the open-cone without the tip; (d) is the W-cone with double Au layers; and (e) is the diamond like carbon (DLC) cone. The estimated $\eta_{TE}$ was shown in Fig. 3.

![Figure 4](image-url)

**Figure 4.** (a). The configuration of a cone+CH hemi shell+Ta cube target; (b). Standard Au cone; (c). Open Au cone; (d). W-cone; (d). DLC cone.

5. Conclusion

Kα line spectroscopy, particularly for hard-x-ray region, has been proposed for quantitative measurement of cone-guided fast ignition experiment. The Au and Ta Kα lines were observed and energy transfer efficiency was provided as a preliminary study. Compared with the planar geometry, the LFEX laser transfer efficiency is significantly enhanced with a guiding cone. In near future, absolute measurement of hard x-ray continuum will be made together with that of the Kα line to improve the accuracy of energy transfer measurements in the cone-guided fast ignition targets.

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