Measurement of high-energy (10–60 keV) x-ray spectral line widths with eV accuracy[a)]

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A high resolution crystal spectrometer utilizing a crystal in transmission geometry has been developed and experimentally optimized to measure the widths of emission lines in the 10–60 keV energy range with eV accuracy. The spectrometer achieves high spectral resolution by utilizing crystal planes with small lattice spacings (down to 2d = 0.099 nm), a large crystal bending radius and Rowland circle diameter (965 mm), and an image plate detector with high spatial resolution (60 μm in the case of the Fuji TR image plate). High resolution W L-shell and K-shell laboratory test spectra in the 10–60 keV range and Ho K-shell spectra near 47 keV recorded at the LLNL Titan laser facility are presented. The Ho K-shell spectra are the highest resolution hard x-ray spectra recorded from a solid target irradiated by a high-intensity laser. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4891726]

I. INTRODUCTION

The resolution of spectral line shapes and transition energy shifts enables the implementation of spectroscopic diagnostic techniques for the measurement of plasma parameters such as electron temperature and density, ion temperature, ionization, opacity, and strong magnetic fields. While sufficiently high resolving power ($E/\Delta E > 1000$) for implementing most of these techniques has been achieved at photon energies less than about 10 keV, achieving high resolution in the hard x-ray region is often difficult using wavelength dispersive spectrometers because of limitations on the length of the spectrometer and the typical low interaction of energetic photons with diffractive optical elements. In this paper, we demonstrate a spectrometer operating in the 10–60 keV range that has up to $E/\Delta E = 1800$ resolving power and is capable of measuring spectral line shapes and energy shifts with eV resolution.

The spectrometer is of the Cauchois type,[1] and the dispersion plane is illustrated in Fig. 1. The x-rays from the source are diffracted by a crystal that is cylindrically bent to a radius of curvature R_c equal to 965 mm. The diffracted x-rays converge through a slit aperture and diverge to the Rowland circle (RC) having diameter equal to the crystal bending radius. The spectrometer has the property that x-rays of a given energy from an extended source are focused on the RC. The quartz crystal has the (502) lattice planes perpendicular to the crystal surface facing the source and perpendicular to the dispersion plane. As illustrated in Fig. 1, a tungsten aperture was positioned in front of the crystal so that a selected length of the crystal was illuminated by the source. The center of the tungsten aperture was at an angle $\alpha = 11.8^\circ$ from the spectrometer axis, and a length of the crystal was illuminated that subtended $\pm 4.8^\circ$. This allowed the W Kα lines from the laboratory test source to be diffracted by the (502) planes near the center of the crystal when the source to crystal distance S was set to 296 mm. Additional tungsten apertures were placed between the crystal and the detector to block direct (undiffracted) high energy x-rays from reaching the detector.

II. LABORATORY TEST SPECTRA

Portions of the spectrum from the W laboratory source recorded on a Fuji TR image plate are shown in Fig. 2 as functions of the distance from the spectrometer axis (see Fig. 1). In addition to the W Kα_1 and Kα_2 lines diffracted by the (502) planes having lattice spacing 2d = 0.1624 nm and shown in Fig. 1(a), the same lines were diffracted by other planes that were rotated by angles δ from the (502) planes, where positive δ is in the clockwise direction as indicated in Fig. 1. These asymmetric planes and rotation angles are (602) and 2.78°, (702) and 4.80°, and (804) and −4.01°.[1]

In the small angle approximation,[1,2] a spectral line is dispersed from the spectrometer axis by the distance $x = R_c(\theta - \alpha)$, where R_c is the crystal bending radius and θ is the Bragg angle with respect to the diffracting planes. Since the asymmetric planes (602), (702), and (804) have larger Miller indices compared to the (502) planes, the lattice spacings are smaller, the Bragg angles are larger for a given x-ray energy, and so the spectral dispersion and resolution are larger. This enables the same spectral lines to be recorded with varying resolution and brightness from multiple planes of the same crystal.

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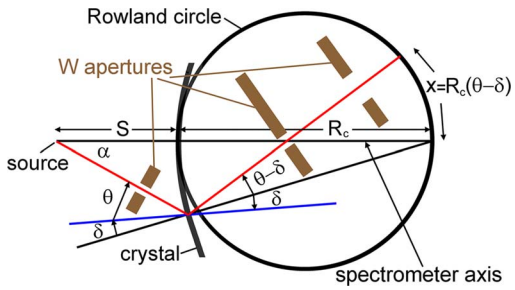

FIG. 1. Schematic of the HRCS spectrometer.

In addition to the W Kα lines, the W Lγ lines diffracted by the (201) planes were also recorded as shown in Fig. 2(b), and this demonstrates that the K and L lines from the same element can be recorded by multiple planes of the same crystal. Since the W Lγ lines were well resolved, they were analyzed in detail. Using the geometrical model of the spectrometer dispersion,[2] the instrumental broadening was determined by removing the detector spatial resolution and the known natural line widths of the stronger W L lines from the observed line widths, and the instrumental spectral resolving power was found to be E/ΔE = 1800.[1] This enabled the study of the line widths of the closely-spaced and partially blended W Lγ_4 transitions as illustrated in Fig. 3. By fitting Voigt profiles to the transitions, where the Gaussian component represents the (known) instrumental broadening and the Lorentzian component represents the natural line widths of the Lγ_4 transitions, the natural line width was measured for each transition. By subtracting the known natural line width of the L1 lower level,[4] the natural line widths of the O2 and O3 upper levels were determined to be 2.9 eV and 1.9 eV, respectively, with $\pm$0.4 eV random error and $\pm$0.3 eV systematic error.[1] Based on atomic code calculations, these widths were attributed to the O2O3O4 and O3O4O5 super Coster-Kronig processes in W. This demonstrates the ability of the high resolution crystal spectrometer (HRCS) spectrometer to measure line shapes with eV accuracy.

III. LASER-PRODUCED SPECTRA

The HRCS spectrometer was fielded at the Titan laser at Lawrence Livermore National Laboratory for the purpose

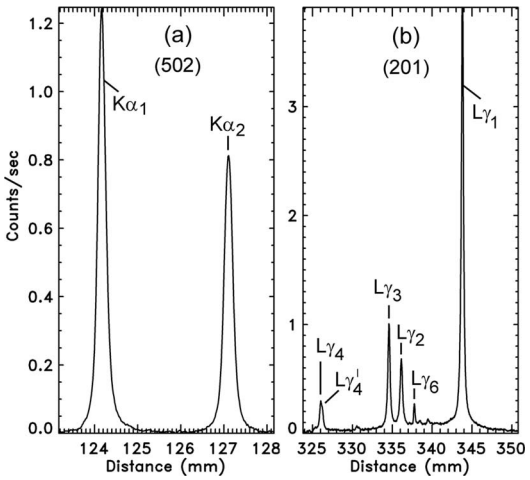

FIG. 2. The W K lines (a) and the W L lines (b) recorded by the HRCS spectrometer as functions of distance from the spectrometer axis.

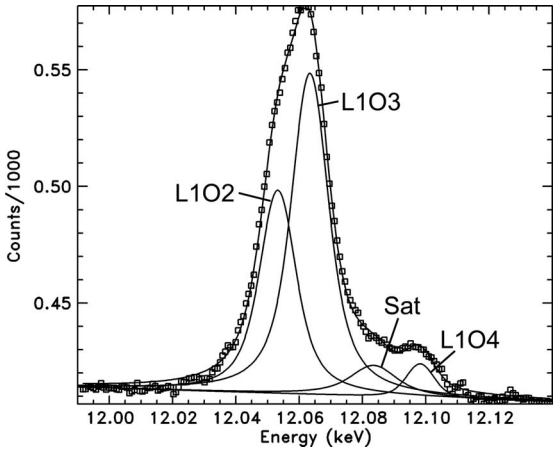

FIG. 3. Voigt profiles fitted to the W Lγ_4 spectral features.

of recording high-resolution spectra from laser-irradiated solid targets. In the initial experiments, the target was a Ho (Z = 67) wire of 0.5 mm diameter, and the Titan beam was focused onto the center of the wire. The intense laser pulse generated energetic electrons in the focal spot that propagated into the surrounding cold Ho metal and created 1s vacancies and Kα radiation.[3]

Shown in Fig. 4 is a comparison of the Ho Kα lines, diffracted by the quartz (502) planes, produced by (a) irradiating a Ho wire by the photon fluence from the W laboratory source and (b) irradiating a Ho wire by the Titan laser. The Kα_2 and Kα_1 lines having energies of 46.700 keV and 47.547 keV, respectively, are well resolved, and Voigt profiles were fitted to the two lines using the least squares technique. The eight variables were the two transition energies, two line intensities, two Gaussian component widths, and two Lorentzian component widths. In the case of the Kα_2 and Kα_1 lines recorded at Titan shown in Fig. 4(b), the Lorentzian components have 37.7 eV and 39.5 eV full width at half maximum (FWHM) values, respectively, which are somewhat larger than the 31.0 eV and 30.9 eV natural lifetime widths.[4] The Gaussian components have 74.9 eV and 63.1 eV FWHM values and can be compared to the 57.6 eV Fuji MS image

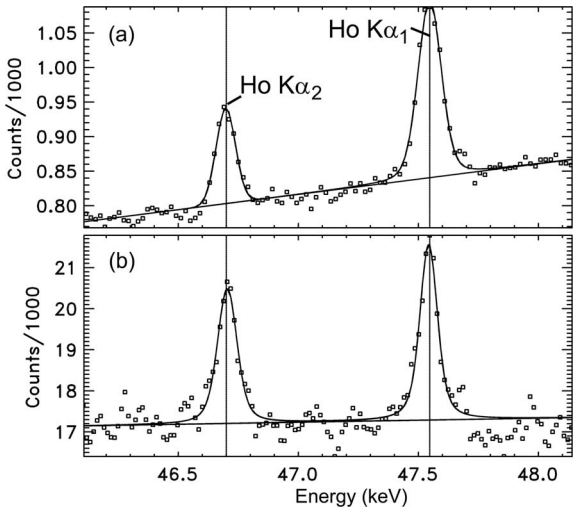

FIG. 4. Comparison of the spectra recorded by the HRCS spectrometer from (a) a Ho wire irradiated by the W laboratory source and (b) a Ho wire irradiated by the Titan laser.

plate broadening. Assuming the Ho Kα lines in the cold material surrounding the focal spot are not broadened by other mechanisms, the instrumental broadening of the (502) crystal at 47 keV photon energy is inferred to have 7.7 eV Lorentzian FWHM and 38.0 eV Gaussian FWHM and, when convolved, a resolving power E/ΔE of 1200. The Kα lines from the Ho wire irradiated by the W laboratory source shown in Fig. 4(a) are wider than recorded at the Titan laser because the weakness of the photon-induced fluorescence from the Ho wire required the use of an image plate having higher sensitivity and lower spatial resolution than the MS image plate used at the Titan laser. In both the Titan and laboratory spectra from the irradiated Ho wires shown in Fig. 4, the line to background noise levels are lower than in the spectra recorded directly from the electron-bombarded W anode shown in Figs. 2 and 3, and the quality of the Voigt profiles fitted to the Ho spectra would improve with better line to background noise ratio. In general, high crystal resolving power results from the utilization of lattice planes having a narrow integrated reflectivity, or rocking curve width, and the narrow integrated reflectivity results in lower instrument sensitivity. The trade-off between resolving power and instrument sensitivity must be optimized for the planned spectroscopic diagnostic application.

As part of the Titan laser experiments, multi-wire targets of the type illustrated in Fig. 5 were irradiated. The Titan laser beam was focused onto the tip of the central wire, and energetic electrons generated in the focal spot propagated to spectator wires of different metals that were oriented in the vertical and horizontal directions. The energetic electrons propagating from the focal spot created 1s vacancies in the central irradiated wire and in the spectator wires, and the ratios of the K-shell lines from the three different wire materials were used to infer the energetic electron fluxes propagating into the central wire, into the vertical wires in the plane of the laser beam polarization, and into the horizontal spectator wires perpendicular to the polarization plane. For the target shown in Fig. 5, the central irradiated wire is Ho, and the spectator wires are Gd in the vertical direction and Dy in the horizontal direction.

The spectra recorded on the same Titan laser shot by the HRCS spectrometer and by another spectrometer named Lawrence Livermore Crystal Spectrometer (LLCS) are compared in Fig. 6. The LLCS spectra are less resolved because, compared to HRCS, the LLCS spectrometer utilized both a crystal having larger 2d lattice spacing (quartz (101), 2d = 0.6684 nm), and a smaller Rowland circle diameter (254 mm).[3] While the HRCS spectrometer places the IP on the Rowland circle, the LLCS spectrometer has two image plate positions, on the RC (front IP in Fig. 6) and 200 mm behind the RC (rear IP). As seen in Figs. 6(a) and 6(b), the HRCS spectrum recorded on the RC has much higher resolution than the LLCS spectrum recorded on the RC. The LLCS spectrum shown in Fig. 6(c) recorded 200 mm behind the RC has higher resolution than the LLCS spectrum recorded on the RC but has much lower resolution compared to the HRCS spectrum.

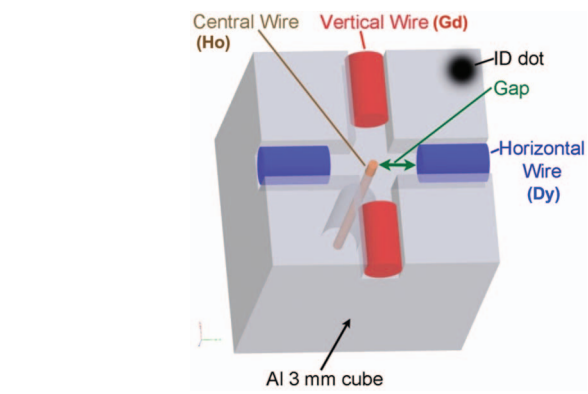

FIG. 5. The multi-wire target composed of a central irradiated Ho wire, vertical Gd wires, and horizontal Dy wires.

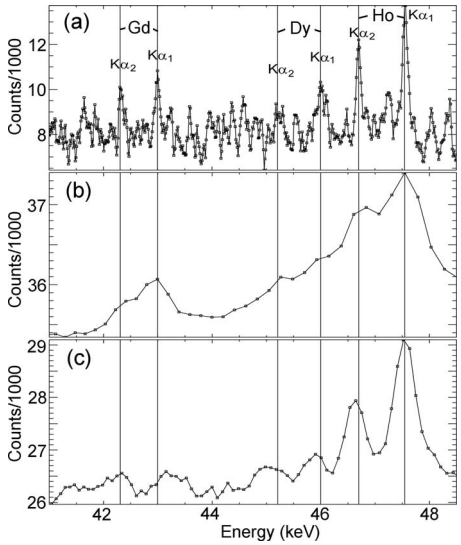

FIG. 6. Comparison of the spectra recorded on the same Titan laser shot by (a) the HRCS spectrometer and by the LLCS spectrometer's (b) front image plate and (c) rear image plate.

In summary, the newly developed HRCS spectrometer has the ability to measure spectral line shapes to eV accuracy in the 10 eV photon energy region and a few eV accuracy at 47 keV. This enables the implementation in the hard x-ray region of high-resolution spectroscopic diagnostic techniques for the measurement of plasma parameters inside solid-density targets irradiated by intense lasers.

ACKNOWLEDGMENTS

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Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the U. S. Government, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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