High resolution hard x-ray spectroscopy of femtosecond laser-produced plasmas with a CZT detector

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We present measurement of characteristic $K\alpha$ emission from Mo, Ag, and La targets irradiated by a 60 fs, 600 mJ, 10 Hz Ti:sapphire laser pulse at 10^{17}–10^{19} W/cm^2. These x-ray emissions can potentially be used in applications from laser-based hard x-ray sources to x-ray mammography so detailed knowledge of the spectra is required to assess imaging of the figure of merit. We show here that high resolving hard x-ray spectroscopy can be achieved, with resolving powers $(E/\Delta E)$ of 60 at 18 keV, with cadmium–zinc–telluride detection system. The $K\alpha$ conversion efficiency from the laser light to the $K\alpha$ photon was optimized thanks to this diagnostic and values as high as 2×10^{-5} were obtained. [DOI: 10.1063/1.1628824]

I. INTRODUCTION

Hard x-ray emission from femtosecond laser-produced plasmas has been extensively studied in the past few years.[1–15] These hard x-ray sources have a number of interesting applications in the dynamic probing of matter and in medical imaging.[16–23] However further development of both sources and detection systems is needed for practical application. Quantitative assessment of the image quality obtained with a laser-based x-ray source can be made by modeling the imaging process and by evaluating the figure of merit (FOM), which is defined as the quotient of the signal-to-noise ratio and the square root of the integral dose,[23,24] for various imaged objects and x-ray source characteristics. Thus detailed knowledge of the x-ray source (spectrum, source size, and x-ray yield) as a function of the laser and target parameters is essential for optimization of the imaging parameters.

In some previous studies the hard x-ray spectrum, with photons energies above 10 keV, has been measured by a photomultiplier coupled to NaI scintillators using the Ross filter technique.[8] The resolution of this technique is rather limited because of the low number of elements. Combinations of ionization chambers and scintillators coupled to a charge coupled device (CCD) with different absorption filters have also been used for hard x-ray diagnostics and have better resolving power $E/\Delta E$.[25] Since detailed spectra are crucial as input parameters for FOM calculations, high-resolution spectroscopy is needed for a quantitative comparison between measured and calculated FOMs. Here we present measurements with a high resolving cadmium–zinc–telluride (CZT) detection system. This single-photon-counting CZT detector can be used to measure hard x-ray spectra with resolving powers $(E/\Delta E)$ of 60 at 18 keV and 86 at 60 keV.

II. EXPERIMENTAL APPARATUS

Experiments were carried out with the INRS 10 TW Ti:sapphire femtosecond system. This laser delivers 60 fs pulses at 800 nm with 600 mJ energy, at 10 Hz repetition rate. The *p*-polarized beam is focused with an off-axis parabola at an incidence angle of 56° into a focal spot of 10 μm diameter, giving rise to maximum intensity of 5×10^{18} W/cm^2. The pulse contrast at the fundamental frequency was measured with a third-order autocorrelator and was around 1×10^{-5} and 1×10^{-4} at 100 ps and a few picoseconds before the main pulse, respectively. The target was rotated to ensure that each laser shot was incident on a fresh target surface. Thick flat Mo, Ag, and La targets were used in the experiments.

High-resolution line spectra were measured with a CZT detector[26] coupled to a charge sensitive preamplifier (Amptek model A250) and to a multichannel analyzer (MCA) (micro-ACE from Ortec with 2048 channels and MAESTRO-32 MCA emulator software). The thermoelectrically cooled $Cd_{0.9}Zn_{0.1}Te$ detector (model XR-100T-CZT) has a light and vacuum tight 250 μm beryllium window in front to enable hard x-ray detection. The CZT detection efficiency remains constant in the energy range of 8–100 keV. The MCA has zero adjustment to reduce noise and each channel corresponds to 61 eV. This system includes rise time discrimination (RTD) that can be used to internally gate the shaped pulses thus allowing pulses corresponding to real x-ray events to be sent to the MCA for analysis. With RTD, partial charge collection can be expelled thus increasing the energy resolution. The detection system was calibrated with two radiation sources, ^{133}Ba (at 14 and 60 keV) and ^{241}Am

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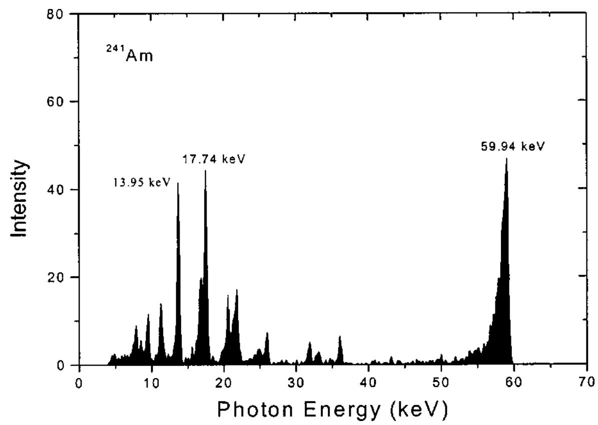

FIG. 1. Calibration of the energy resolution for a CZT detector system with a ^{241}Am radiation source.

(at 31 and 80 keV). Figure 1 shows the energy resolution obtained with the Am source (and zero adjustment of the MCA). The resolving power $E/\Delta E$ [full width at half maximum (FWHM)] of this detection system is 60 for 18 keV radiation and 86 for 60 keV radiation. This resolving power is close to the one obtained with detection systems based on crystals at the same photon energy. The background noise was measured as very low (20 counts in the energy range of 10–120 keV for 500 s operating time) so no gating was used in the experiments. A small pinhole was used in front of the detector to decrease the solid angle and to increase the detection distance in order to reduce the counting rate (<0.4) thus minimizing pile-up effects.

The spectra measured with this CZT-based system have been compared to spectra obtained in the same experiment with a crystal spectrometer composed of a cylindrically bent crystal, a slit, and a CCD.[27] In addition, low-resolution spectra and the x-ray yield have been measured with a photomultiplier/scintillator system used with a matched pair of Ross filters.[8]

III. RESULTS AND DISCUSSION

The hard x-ray spectra were measured between 10 and 100 keV for various intensities and laser pulse durations. All the spectra exhibited a continuum bremsstrahlung emission and individual characteristic *K*-line emission, as shown in Fig. 2(a) (measurement with the CZT detector without any filter) for a Mo target irradiated at $2\times10^{17}\,\mathrm{W/cm^2}$. Assuming that the hot electrons generating the x-ray spectrum can be represented by a Maxwellian distribution $[f(E)\propto e^{-E/KT_h}]$, the slope of the continuum spectrum gives the hot electron temperature, KT_h. The scaling law deduced from the spectra recorded at various intensities ranging from 1×10^{17} to $5\times10^{18}\,\mathrm{W/cm^2}$ with pulse durations between 60 and 400 fs has the following form: $KT_h=6\times10^{-5}(I)^{0.33}$, where KT_h is the temperature in keV and laser intensity I is in W/cm^2. The 20 keV x-ray source size, measured with the knife-edge technique, was around 50 μm, indicating the presence of lateral plasma transport, as already observed previously by us and in some other experiments under different conditions. At these high laser intensities, the pedestal plays a very important role and affects the generation, dynamics, and trajectories of the hot electrons.

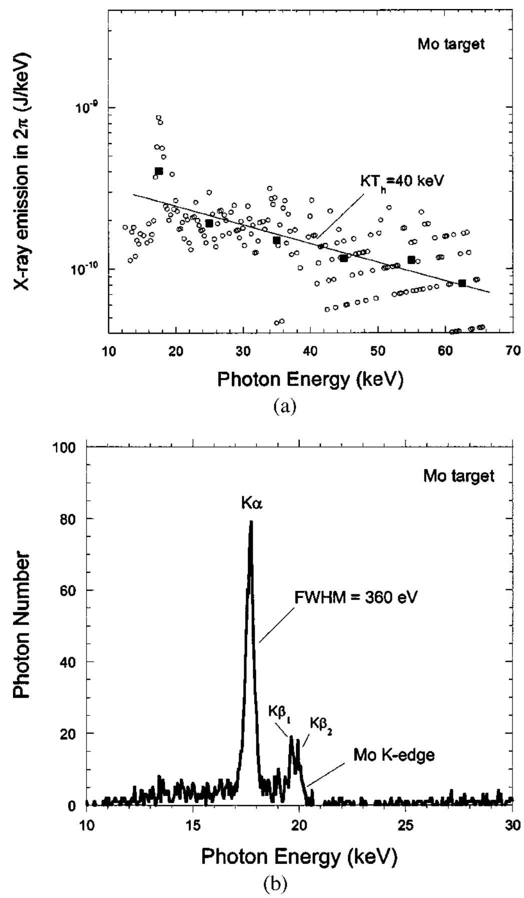

FIG. 2. Mo hard x-ray spectrum obtained with the CZT detector. (a) Spectrum obtained without filter in front of the detection system (open circle, the *Y* axis converted from photon numbers to emitted x-ray energy in J/keV intervals). The solid line represents a Maxwellian fit with $f(E)\propto e^{-E/KT_h}$ of the continuum based on an average value of flux every 10 keV (closed square). This fit gives a hot electron temperature of 40 keV; (b) spectrum obtained with a 50 μm Mo filter in front of the CZT detector.

Figure 2(b) shows a high-resolution spectrum of Mo K lines measured with a 50 μm Mo filter placed in front of the detector. This spectrum was obtained with a 200 fs pulse incident at $2\times10^{17}\,\mathrm{W/cm^2}$ on thick Mo targets. Under these conditions, the bremsstrahlung emission around the K lines is sufficiently reduced to allow characteristic emission to dominate the spectra. The resolving power is around 70 and the FWHM of the Mo $K\alpha$ line is around 360 eV. Thus, the two $K\alpha_1$ and $K\alpha_2$ lines, which are separated by 100 eV, are not resolved here. However, we do clearly see the $K\beta_1$ (19.61 keV) and $K\beta_2$ (19.96 keV) line emission.

This spectrum can be compared to the spectrum obtained under exactly the same experimental conditions on the same shots with a National Institute for Standards and Technology (NIST) bent crystal spectrometer. Figure 3 shows the characteristic line emission obtained with resolving power for Mo $K\alpha$ emission of about 80, which is just slightly higher than the CZT detector's resolution. Compared with the CZT detector, this crystal spectrometer has slightly better resolution but a more limited range of detection (12–60 keV).

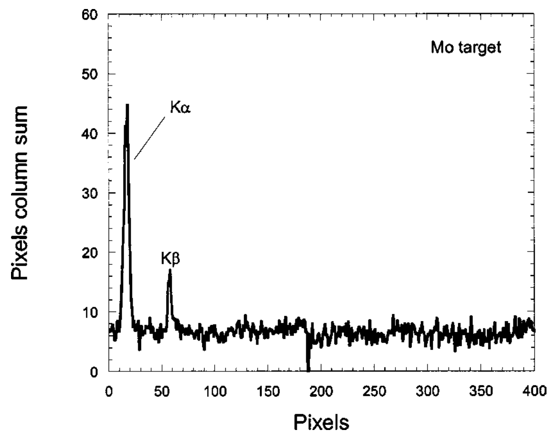

FIG. 3. Mo spectrum measured with the NIST spectrometer and without any filter in front of the spectrometer.

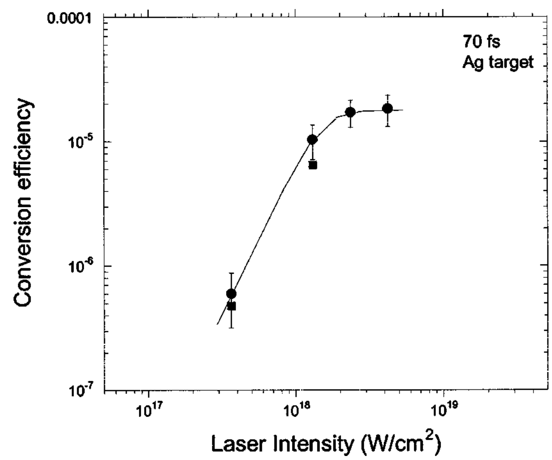

FIG. 5. $K\alpha$ conversion efficiency as a function of the laser intensity measured with a pair of Ross filters (closed circles) and with the high resolution CZT system (closed squares) for Ag targets irradiated by 70 fs pulses.

Furthermore, absolute calibration and secondary data reconstruction are needed to get a quantitative evaluation of the emission yield. Compared to the CZT, the crystal system has a nonlinear response in the photon energy range of interest here and that is why we cannot observe the continuum x-ray emission or monitor the hot electron temperature.

Figure 4 shows a spectrum obtained with a La target irradiated with 60 fs pulses at 2×10^{18} W/cm^2. The CZT detector is in this case used 100 μm Sm filters. Individual K lines ($K\alpha_1$ at 33.44 keV, $K\alpha_2$ at 33.03 keV, and the $K\beta$ line at ~38 keV) are clearly resolved. The observed peak intensity ratios are $K\alpha/K\beta=6-7$ and $K\alpha_1/K\alpha_2=2$; the measured FWHM for single $K\alpha$ line is 400 eV limited by the CZT detector resolution at this energy. The dotted line in Fig. 4 is the calculated spectrum[24] assuming that the line shape of the K lines is Lorentzian with a 100 eV bandwidth and that 15% of the laser energy is transferred to the hot electrons.

The conversion efficiency η from laser light into $K\alpha$ emission (emitted in 2π srd) deduced from the high resolution CZT measurements with an Ag target was compared to the one inferred from photomultipliers coupled to a pair of Ross filters composed of a 100 μm Mo and 75 μm Ag foil. Figure 5 presents the variation of η as a function of the laser intensity for both measurement techniques. We observe good agreement between the two methods and we see that, in this experiment, η increases with the laser intensity and then saturates at around 2×10^{-5} for laser intensities above 2×10^{18} W/cm^2, resulting in average x-ray power of 0.1 mW in one line emission at 25 keV (for laser average power of 6 W). At this intensity the total conversion efficiency in x rays with photon energies above 10 keV is 4×10^{-4}.

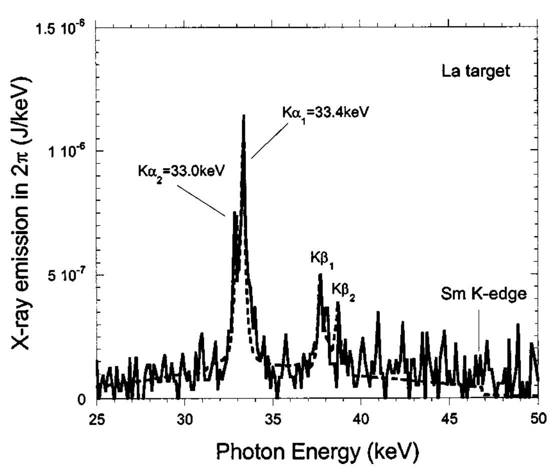

FIG. 4. La spectrum measured with a 100 μm Sm filter in front of the CZT detector. The dotted line represents the theoretical calculation assuming 15% laser energy in hot electrons.

Compared to a germanium detector,[28] which must be cryogenically cooled with liquid nitrogen, the CZT detector is easier to use and has the advantage of having a more uniform energy response in the range of 8–100 keV (no absorption edge contrary to Ge). In addition, the CZT detector is not spatially limited, has no time gating, and does not require a Compton scattering geometry detector or data corrections. In conclusion, our results indicate clearly that this kind of solid, small size, high resolving detection system is very suitable for laser-based hard x-ray spectroscopy in order to measure the hot electron temperature and $K\alpha$ conversion efficiency.

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