# Operation of a Single-Photon–Counting X-Ray CCD Camera Spectrometer in a Petawatt Environment

## Introduction

Single-photon–counting x-ray CCD (charge-coupled device) spectrometers are frequently used in ultrashort-pulse laser experiments, mostly for *K*-shell spectroscopy.[1–3] For single-photon counting, the incident x-ray flux is attenuated such that the probability that two x-ray photons hit a single pixel is small. Consequently, the pixel value of each readout pixel is proportional to the deposited energy from the incident x-ray photon. If the x-ray energy is not too high (<100 keV), a significant fraction of the x-ray photons deposit all their energy in one pixel. In this case, a histogram of the pixel values provides a good approximation of the incident x-ray spectrum. This technique has the advantage of requiring almost no alignment and the potential of providing absolute x-ray flux information. Consequently single-photon–counting x-ray CCD spectrometers are also used in astronomical satellites,[4,5] where an extensive set of calibration and characterization data exists. For the satellite data, the low number of incident photons is the biggest issue, whereas in ultrashort-pulse laser experiments, photon counts are generally very high. Signal-to-background issues, especially in a high-energy petawatt environment, become dominant.[3] Shielding strategies against background x rays must be carefully chosen to obtain high-quality spectra. In this article, results from a recent experimental campaign at the petawatt facility of the Rutherford Appleton Laboratory (RAL) are presented showing successful strategies to improve the signal-to-background ratio.

## Experimental Setup

The single-photon–counting x-ray spectrometer consists of a Spectral Instruments Series 800 Camera using a 2-k × 2-k-pixel, back-thinned CCD chip with a pixel size of 13.5 $\mu$m.[6] The CCD was cooled to –35°C to reduce the dark current, and the images were recorded with 16-bit resolution.

The camera was mounted 3.8 m from the target outside the target chamber on a 1-m vacuum tube. Mounting the camera in air and using thin vacuum windows was not possible because the x rays of interest—Cu *K*-shell radiation at ~8 keV—are strongly absorbed in air. The RAL petawatt target chamber is very well shielded with 10 cm of lead on three sides and on top. The side where the access doors are located is unshielded but backed by a curtain shield of 10 cm of lead and 60 cm of concrete (Fig. 98.38). The CCD camera was shielded against x rays scattered from structures close to the target with up to four lead collimators of 10-cm length inside the target chamber and the vacuum tube (inner shielding). The CCD camera housing was surrounded by up to 10 cm of lead to shield against x rays from the sides and the back of the CCD (outer shielding). A matched *K*-edge filter was used to attenuate the *K*-shell signal to maintain single-photon counting. Figure 98.39 shows the transmission of the 150 $\mu$m Cu filter used for Cu *K*-shell spectroscopy. Compared to a simple high-pass filter against the thermal radiation from the target, a *K*-edge filter attenuates the spectrum above the lines of interest, thus improving the signal-to-background ratio.

The targets were irradiated with 1053-nm pulses from the RAL Vulcan petawatt laser, which delivers up to ~500 J in ~1 ps in a 60-cm-diam beam.[7,8] These pulses are focused with an *f*/3 off-axis parabola to a focal spot of ~10-$\mu$m FWHM. Losses in the compressor and aberrations generally

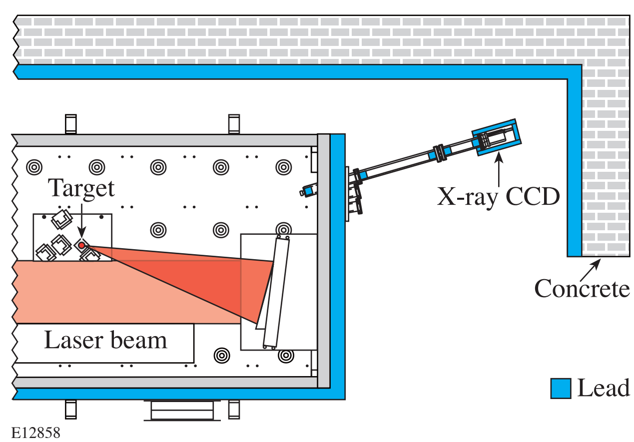


Figure 98.38
Setup of the single-photon–counting x-ray CCD at the RAL petawatt facility, showing the target-area shielding and the CCD shielding.

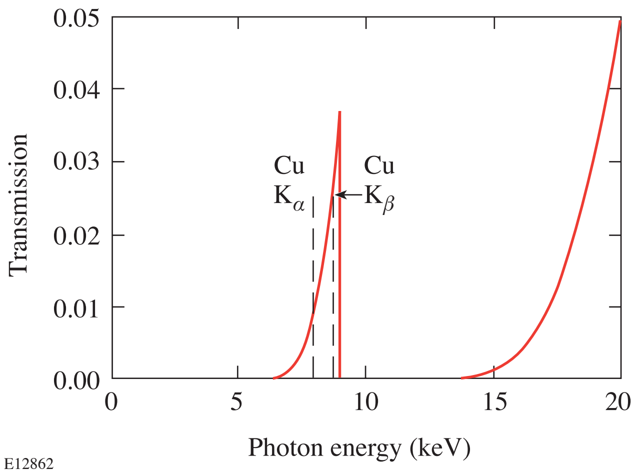


Figure 98.39
A matched $K$-edge filter was used to improve the signal-to-background ratio (150 $\mu$m Cu for Cu $K$-shell spectroscopy shown). The positions of the Cu $K_\alpha$ and $K_\beta$ lines are indicated in the graph.

limit the focusable energy to <50% of the laser energy. Consequently, the maximum intensity on target was estimated to be ~$2 \times 10^{20}$ W/cm$^2$.

## Optimizing the Shielding

A series of experiments were conducted to optimize the inner and outer shields and to assess the relative importance of the x-ray background from structures close to the target that reach the CCD from its face and fluorescence and scattered photons that reach the CCD from the side or back.

Figure 98.40(a) shows the histogram from a 20-$\mu$m-thick Cu target irradiated with an ~250-J, 1-ps pulse, at $1 \times 10^{20}$ W/cm$^2$ using 10-cm inner shielding and no outer shielding. Figure 98.40(b) shows the $K$-shell spectrum after background subtraction. The energy scale is inferred from the published energies of Cu $K_\alpha$ = 8.05 keV and Cu $K_\beta$ = 8.90 keV. The third line visible in the spectrum is identified as the $He_\alpha$ line of Cu at 8.36 keV.

The high background seen in these experiments distorts the spectrum and makes it almost impossible to discern the Cu $K_\beta$ line.

Adding 5 cm of lead as outer shielding around the CCD camera dramatically improves both the background and the quality of the spectrum as shown in Fig. 98.41. This indicates that most of the background is coming from either Compton-scattered primary x rays or x-ray fluorescence in the structures around the CCD. The spectrum shows the Cu $K_\beta$ line

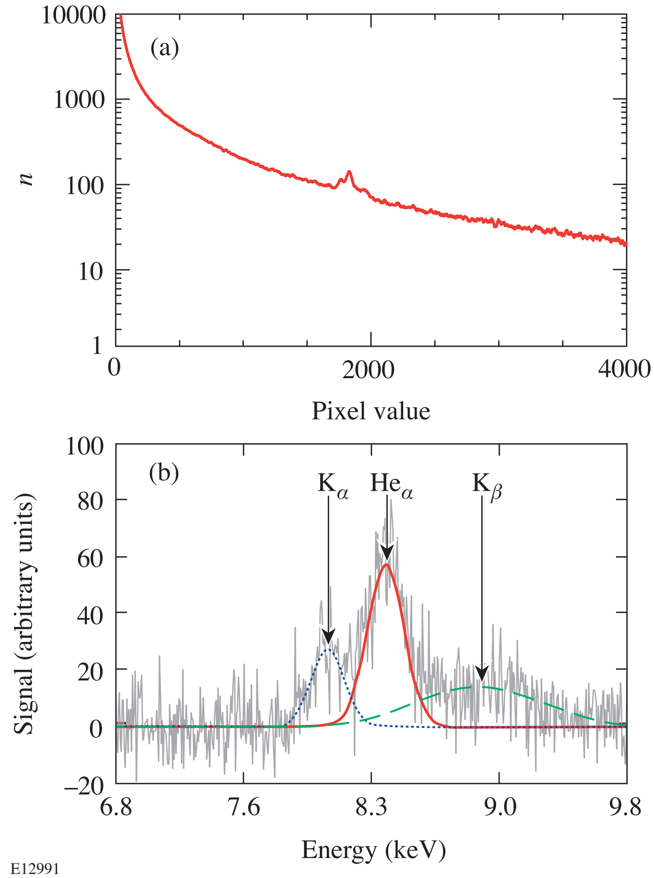


Figure 98.40
CCD histogram (a) and $K$-shell spectrum (b) from a 20-$\mu$m-thick Cu target irradiated with a ~250-J, 1-ps laser pulse, at $1 \times 10^{20}$ W/cm$^2$ using 10-cm inner shielding and no outer shielding.

clearly separated, and the Cu $K_\alpha$ and the He-like feature can be easily distinguished.

Increasing the laser energy by a factor of 2 results in a dramatically increased background. Even improving the inner shielding to 40 cm and the outer shielding to 10 cm does not prevent the background from rising by about a factor of 3 (see Fig. 98.42). Fortunately in this experiment the x-ray flux also rose by almost a factor of 3 and the spectrum is still well resolved. A new, fourth line is seen in the spectrum, which is identified as Cu $Ly_\alpha$ at 8.64 keV.

## Summary and Conclusions

Efficient shielding is required to obtain high-quality x-ray spectra from a single-photon–counting x-ray CCD spectrometer in a petawatt environment. Shielding the direct line of sight against x rays from structures close to the target was not sufficient to decrease the background. Only by shielding the

CCD camera from all sides with 10 cm of lead was it possible to reduce the background to a level low enough to be able to obtain high-quality spectra even at 500-J laser energy. Scaling the shielding to even higher laser energies or intensities could be difficult given the significant rise in background from 250-J to 500-J energy.

## ACKNOWLEDGMENT

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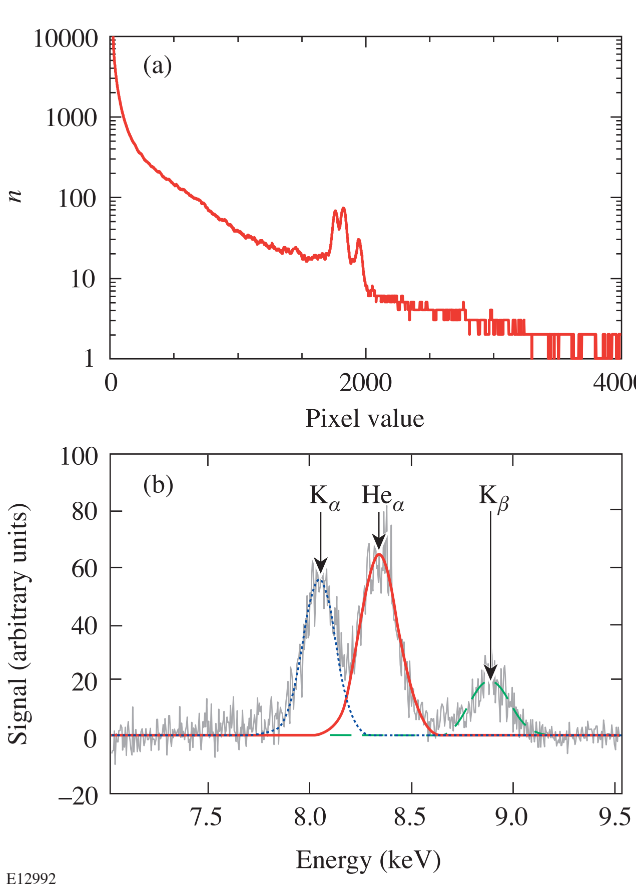


Figure 98.41
CCD histogram (a) and *K*-shell spectrum (b) from a 20-$\mu$m-thick Cu target irradiated with an ~250-J, 1-ps laser pulse, at $1 \times 10^{20}$ W/cm$^2$ using 10-cm inner shielding and 5-cm outer shielding.

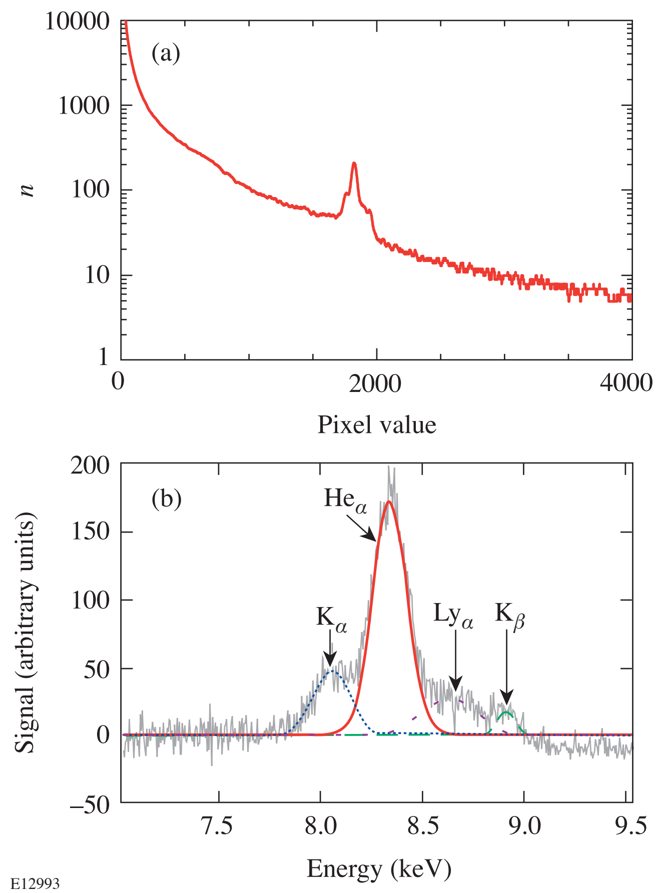


Figure 98.42
CCD histogram (a) and *K*-shell spectrum (b) from a 20-$\mu$m-thick Cu target irradiated with an ~500-J, 1-ps laser pulse, at $1 \times 10^{20}$ W/cm$^2$ using 40-cm inner shielding and 10-cm outer shielding.