Realization of a flat-response photocathode for x-ray streak cameras

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Abstract: We present a novel photocathode which can make x-ray streak cameras to be of a flat spectral response in the x-ray energy range of 0.1-5 keV. The photocathode consists of two layers of gold foils with optimized thickness ratio and structures. The photocathode was calibrated, and it is shown that a flat spectral response has been achieved.

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References and links

23. Z. Pan, K. Jensen, and P. O'Shea, “Modeling the quantum efficiency of controlled porosity dispenser
via a combination with x-ray imaging, and they are also used to obtain time-resolved spectra
facilities, such as NIF, OMEGA and Shenguang, requires x-ray flux measurements with high
research field of inertial confined fusion (ICF) [4–6] as well as in high energy-density physics
X-ray streak cameras (XSC) [1–3] are extensively used for ultrafast x-ray diagnostics in the
1. Introduction
18. C. D. Bentley and A. C. Simmons, “Spectral response calibrations of x-ray diode photocathodes in the 50-5900
15. Y. Pu, T. Huang, M. Wei, Q. Tang, Z. Song, J. Yang, S. Liu, S. Jiang, and Y. Ding, “Spectroscopic studies of
11. Introduction
10. H. F. Robey, P. M. Celliers, J. L. Kline, A. J. Mackinnon, T. R. Boehly, O. L. Landen, J. H. Eggert, D. Hicks,
5. L. Kuang, L. Cao, X. Zhu, S. Wu, Z. Wang, C. Wang, S. Liu, S. Jiang, J. Yang, Y. Ding, C. Xie, and J. Zheng,
1. Introduction
X-ray streak cameras (XSC) [1–3] are extensively used for ultrafast x-ray diagnostics in the research field of inertial confined fusion (ICF) [4–6] as well as in high energy-density physics [7, 8] and fundamental research [9–11]. The ICF research performed on high-power laser facilities, such as NIF, OMEGA and Shenguang, requires x-ray flux measurements with high temporal resolution [12–15]. XSCs are used to obtain time-resolved images of fusion targets via a combination with x-ray imaging, and they are also used to obtain time-resolved spectra via a combination with x-ray crystal or grating spectrometers [16, 17]. Quantitative measurements of x-ray emissions are of importance for understanding laser absorption and energy transport in laser-fusion targets [17, 18]. However, conventional XSCs

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do not have flat spectral response, thus causing extra complexities to deduce the quantitative information. Usually, the photocathodes of XSCs are made of thin conductor or insulator materials which are of energy-dependent photoelectric conversion [19, 20]. As a consequence, the conventional XSCs have a complicated spectral response in the interested x-ray energy range [20–23]. To obtain the quantitative x-ray spectra, the images measured by XSCs must be corrected using a complex spectral response function of the photocathodes, and this procedure causes sophisticated uncertainties. Therefore, a flat-response, i.e., energy-independent, photocathode for XSCs is highly required for the quantitative measurements of ultrafast x-ray imaging or spectroscopy.

In this paper we present a flat-response photocathode for XSCs in the x-ray energy range of 0.1-5 keV. This type of photocathode does not need complex corrections in the interested x-ray energy range due to the flat-response characteristics. The accuracy of spectral data is thus improved. It is a technique to promote the quantitative studies of laser-produced plasmas in ICF research.

2. Design of the flat-response photocathode

The design is based on a reasonable assumption that the photoelectric coefficient is proportional to the absorption coefficient for the photocathode material [20, 21]. According to the formula for the yield of secondary electrons from a gold photocathode, the response of thin and thick gold foils complement each other. So the desired flat response in the range of 0.1-5 keV can be achieved with the help of the compound photocathode.

The energy-response function of the compound photocathode can be written as

$$S(E) = \rho u(E)\lambda_x [(1 - a)e^{-\rho u(E)/\lambda_x} - (1 - e^{-\rho u(E)/\lambda_x})/(1 - e^{-\rho u(E)/\lambda_x})]$$

where $\rho$ is the mass density of gold foils, $u(E)$ the mass photoionization cross section, $E$ the mean energy of the incident photons, $t_1$ and $t_2$ the thicknesses of the thinner and the thicker gold foils, $\lambda_x$ the x-ray attenuation length, $\lambda_s$ the effective escape depth of electrons, $a$ the ratio of irradiated areas of the thicker gold foil to the thinner one. The parameters $\rho$, $\lambda_x$, $\lambda_s$ are constants for a specified metal material, whereas $\lambda_s$ is the reciprocal of the product of $\rho$ and $u(E)$.

The flatness of the photon-energy response of the photocathode, which is defined as the ratio of the standard deviation $\sigma$ of the response in the energy range, $E_1$ to $E_2$, can be expressed as

$$\sigma = \sqrt{\frac{\int_{E_1}^{E_2} (S(x) - \bar{S})^2 \, dx}{(E_2 - E_1)^2 \bar{S}^2}}$$

where $\bar{S}$ was obtained by the formula of $\bar{S} = \frac{\int_{E_1}^{E_2} S(x) \, dx}{E_2 - E_1}$. Based on Eqs. (1) and (2), the flat-response of the photocathode for x-ray streak cameras can be achieved by optimizing the thicknesses and the ratio of irradiated areas of the two gold foils.

By simulations, the photon-energy response is flat if $t_1 = 50$ nm, $t_2 = 400$ nm and $a = 6/7$, as shown in Fig. 1(a). However, there is a disadvantage of this design. In experiments, the spot of the x-ray beam on the photocathode must be carefully adjusted with suitable apertures to ensure that the ratio of irradiated areas of the two foils is the same as designed, however, it is not easily realized.

In order to overcome this difficulty, we propose a new type of compound photocathode to achieve the flat response. As shown in Fig. 1(b) and 1(c), the structure-improved photocathode is composed by two gold foils with the same diameters, whereas the thicker one has uniformly distributed pinholes with a designed duty cycle. As shown in Fig. 1, the thicker

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gold foil with pin-holes, which can also emit photoelectrons, is used to adjust the duty cycle. The thicknesses of the two gold foils and the duty cycle of the pin-holes were carefully optimized to obtain a flat x-ray absorption coefficient in the interested x-ray energy range. With this type of compound photocathode, the restricted requirements on the shape and the size of x-ray spot can be largely eliminated. In fact, the requirement in experiments is only that the size of the x-ray beam spot must cover a few hundred pin-holes; this can be easily realized in practical experiments.

3. Fabrication and calibration of the flat-response photocathode

To fabricate the photocathode, a hybrid lithography including electron-beam lithography and x-ray lithography was used [22–27]. The thinner one is 50 nm ($t_1$) gold foil, the thicker one is 400 nm ($t_2$) and has an array of 5 μm- diameter pin-holes. There are $8 \times 10^3$ pinholes distributed on the thicker foil per square millimeter. Therefore, effectively, about 6/7 ($\alpha$) of the photocathode area is filtered with the 450 nm gold foil and the rest is filtered with the 50 nm gold foil. The optimized parameters satisfy the required at response in the x-ray energy range of 0.1-5 keV, as shown in Fig. 3. Usually, the spatial resolution of X-ray streak cameras is not better than 15 μm, the flat response photocathode with 5 μm pinholes does not affect the spatial resolution. If the spatial resolution of the camera is required to be better than 15μm, it can be achieved by reducing the pinhole diameter to 2 μm. So the spatial resolution of X-ray streak cameras with flat response photocathode will not be affected.

Two photocathodes with a diameter of 12mm were fabricated, and then calibrated on the Beijing Synchrotron Radiation Facility [28, 29] at the Institute of High Energy Physics, Chinese Academy of Science. The calibration-experiment arrangement is shown schematically in Fig. 2. The calibration procedure is almost the same as that by Campbell et al. [19]. A combination, which consists of a cylindrical mirror and a flat grating, was used as a monochromator to obtain quasi-mono-energetic x-rays with energies between 1.2 and 6 keV (beam-line 4B7A) and 0.1-1.6 keV (beam-line 4B7B), the energy spread is about 10 eV.

The monochromatic x-ray beam normally irradiated on the photocathodes which are placed at the center of a vacuum chamber. An aperture was placed in front of the...
photocathodes to ensure the x rays irradiate the active surfaces exactly. When the photocathode sample was irradiated by the x-ray beam, secondary electrons were collected by a Cu foil, and the current $I_1(E)$ was measured by an ammeter 6517B. A standard Si-photodiode detector (AXUV-100) was placed behind the photocathode sample. The current $I_0(E)$ was measured by the same ammeter with a different channel when the photocathode was moved out of the x-ray beam. The detecting sensitivity $R_{\text{sta}}$ of the standard photodiode detector was taken from NIST database, then the sensitivity $R(E)$, namely, the energy-response, of the photocathode was deduced by

$$R(E) = \frac{I_1(E)R_{\text{sta}}(E)}{I_0(E)},$$

(3)

Fig. 2. Schematic diagram of the calibration-experiment setup at the x-ray beam-lines at the Beijing Synchrotron Radiation Facility.

The calibration results of two photocathode are shown in Fig. 3, and it shows that the energy response of photocathode 2 is nearly flat in the photon-energy range of 0.1-5 keV. The corresponding response flatness is 5.3% in the range of 0.1-1.6 keV and 8.3% in the range of 2.1-5 keV. The uncertainty due to the calibration is smaller than 3%, which stems from the standard Si-photodiode detector. The response flatness of photocathode 1 is not good, especially at the lower photon-energies. The marked deviation in 280-300eV range for photocathode 1 was caused by the absorption edge of carbon, it is mainly contributed by the polyamide supporting membrane which was used as an x-ray lithography mask in the fabrication procedure [22–25]. Polyamide has some advantages, such as tolerance for high temperatures and good stress characteristic, which allow for much more freedom in choosing the condition parameters of the subsequent processing procedure. Furthermore, polyamide membrane has higher transmission efficiency than silicon nitride in the x-ray region, which leads to less heat accumulation on the mask during x-ray lithography. In order to minimize the carbon contamination from the polyamide membrane, etching with low-temperature plasmas was used for photocathode 2. In Fig. 3, it is clearly shown that photocathode 2 has much smaller deviation from the calculation than photocathode 2 in the low-energy region.
3. Conclusion

In summary, the time-resolved x-ray measurement using XSCs is an important diagnosing means in ICF experiments. We presented a novel photocathode which can make it possible for XSCs to have a flat spectral response in the x-ray energy range of 0.1-5 keV. The calibration experiments show that the fabricated photocathodes have flat-response with flatnesses better than 9% in the x-ray energy range of 0.1-5 keV. With the help of the novel photocathode which was designed for XSCs, the ultrafast x-ray diagnostics can be advanced, thus promoting ICF research. For instance, to achieve a high-gain in ICF research, shaped pulses are being used [30]. X-ray flux due to the shaped pulse has fast changes with time, consequently, temporal resolution of the flux measurement is required up to sub-100-picoseconds. A flat-response x-ray diode detector was realized to diagnose time-resolved x-ray flux, however, the typical temporal resolution is worse than 100 picoseconds [31]. Therefore, the ultrafast x-ray diagnostics in ICF research would benefit from the flat-response XSCs because the temporal resolution of XSCs could achieve 10 picoseconds.

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