Surface contamination of the charge-coupled device

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Abstract An experimental method to study the influence of surface contamination of a thinned, backside illuminated charge-coupled device(CCD) upon its quantum efficiency in soft X-ray region is suggested. A transmission grating spectrometer(TGS), in which the transmission grating is coupled to a thinned, backside illuminated charge coupled device, is used to measure the continuum X-ray emission from the end of cylindrical target irradiated by laser. In the measured spectra, only the carbon K absorption edge at wavelength of 4.4 nm due to condensation of the vacuum oil on the CCD surface is clearly seen. The surface contamination is considered as an effective "carbon filter" and the filter absorption to correct the quantum efficiency of the CCD camera is taken into account. The effective thickness of the carbon filter is determined by comparing the jump height of the measured spectra at 4.4 nm with those of the carbon absorption coefficient curves obtained from various carbon thickness. The accuracy of this method is tested by comparing the X-ray spectrum measured by the TGS with that obtained by a soft X-ray spectrometer.

Keywords X-ray charge-coupled device (CCD), Surface contamination
CLC numbers O434.12, O472$^+$.3, O484.4$^+$1

1 INTRODUCTION

Laser-produced plasmas convert a large fraction of the incident laser energy into X-ray radiation in X-ray range below 2000 eV. As a result, quantitative measurements of the soft X-ray spectra from the laser-irradiated target play an important role in the investigation on inertial confinement fusion(ICF) physics, atomic and X-ray laser physics[1,2]. Recently, charge coupled device, especially the thinned, backside illuminated X-ray CCD, has extensively applied to record the soft X-ray spectra due to its good linearity, reproducibility and large dynamic range[3~6]. The backside illuminated X-ray CCD, operated with cooling, also has very high sensitivity. But at the same time, there exists surface contamination of the cooled X-ray CCD chip, which causes the decrease of quantum efficiency(QE) in some X-ray region and affects accuracy of the X-ray spectrum measurement. The decrease of QE at long wavelengths caused by condensation of vacuum oil has been observed previously by Hochedez and Stern[4,5]. In our work, we have clearly seen the jump of X-ray CCD QE at 4.4 nm which was attributed to the hydrocarbon absorption existing on the surface of the CCD chip.

Supported by the National High-Technolog Project (No. 863-416-3)
Manuscript received date:2000-06-12

In this paper, we present an experimental method to correct the quantum efficiency of the X-ray CCD (SX-TEA/CCD-1024) by determining the effective "carbon filter" thickness. This method does not require an absolutely calibrated standard X-ray source which is usually not available, and uses the continuum X-ray spectra from the laser-entered cylindrical gold cavity. By comparing the jump height of the X-ray spectra at wavelength of 4.4 nm measured with transmission grating and X-ray CCD system with those of the carbon absorption curves with various thickness, the carbon filter thickness has been obtained. At last, the validity of this method has been tested by comparing the TGS measured spectrum with that obtained by soft X-ray spectrometer.

2 EXPERIMENT

The experiments have been carried out on "Xingguang" laser facility. The experimental arrangement is illustrated in Fig.1. One beam of 0.35μm laser with energy of ~80 J in about 0.8 ns were focused in a cylindrical cavity and illuminated the gold foil which located in the cavity with distance of 100μm from the laser-injected hole. Inner diameter of the cylindrical cavity is about 400μm, and the length is about 1.0 mm. The laser-illuminated gold foil converts a large fraction of laser energy into X-rays. The inner wall of the cylindrical cavity behind the gold foil was heated by the X-ray emission from the rear

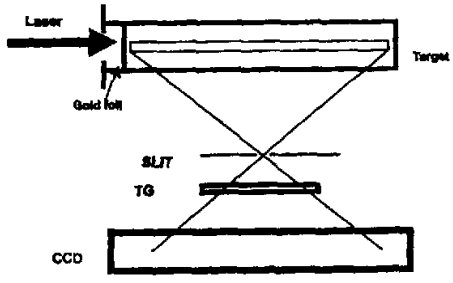

Fig.1 Experimental arrangement to measure the space-resolved X-ray spectra from the inner wall of laser-entered cylindrical gold cavity, which were applied to correct the quantum efficiency of the vacuum oil contaminated X-ray CCD chip

of the gold foil and the X-ray reemission from the other part of the inner wall, and re-emmits X-ray radiation. The reemitted X-ray spectrum tends to become continuum was the distance from the gold foil increases. A diagnostic slit with width of 100μm and length of 800 μm was opened on the cylindrical cavity wall along axis direction.

The X-ray spectra from the inner wall of the cavity were measured with a space-resolved transmission grating spectrometer. The transmission grating is a substrate-free grating of 1000 lines/mm. The X-ray CCD camera was coupled to the transmission grating and recorded the grating-dispersed X-ray spectra. The typical raw spectra recorded by X-ray CCD camera is shown in Fig.2. The carbon K absorption edge is clearly seen along the dispersive direction in Fig.2. Because the X-ray spectra near the end of the cylindrical cavity almost become continuum, and the transmission grating is substrate-free, the most possible reason to make the sharp decrease of the X-ray intensity at wavelength of 4.4nm in Fig.2 is the condensation of vacuum oil on the surface of the

cooled CCD chip. The unfold X-ray spectrum near the end of the cylindrical cavity is presented in Fig.3. Several shots of experiments have been carried out and almost the same intensity decreases of the measured X-ray spectra at the wavelength of 4.4nm have been obtained. The X-ray intensity at the wavelength of 4.4 nm sharply decreased to (21.6± 4.5)% in average.

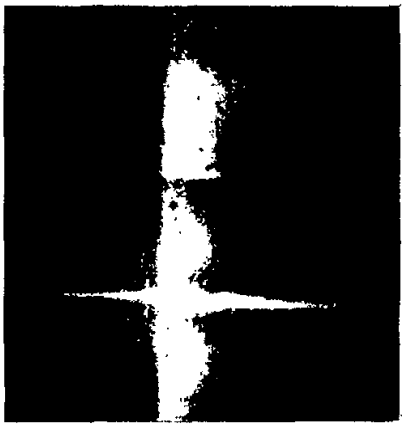

Fig.2 The typical raw spectrum image from the inner wall of the laser-injected cylindrical cavity, recorded by X-ray CCD. The spectrum image is space-resolved. The vertical direction is for grating dispersion direction and the horizontal direction is for spatial direction.

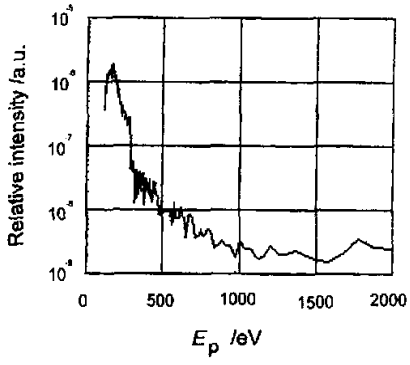

Fig.3 The typical unfolding X-ray spectrum from the inner wall of the cylindrical cavity end, which is 800μm far from the laser-irradiated gold foil, measured with the transmission grating spectrometer

3 QUANTUM EFFICIENCY CORRECTION IN SOFT X-RAY REGION

The nominal quantum efficiency of the CCD provided by the manufacturer is shown in Fig.4. There doesn't exist a jump at wavelength of 4.4 nm. Because the X-ray CCD works at –39°C and the target chamber was kept at 10^{-5} Torr during the experimental measurement, the vacuum oil was condensed on the surface of the X-ray CCD chip. The vacuum oil mainly consists of hydrocarbons. Therefore, the actual quantum efficiency of the X-ray CCD is expressed as $QEA(\lambda) = QEN(\lambda)\cdot\exp(\mu_c t)$

Where $QEN(\lambda)$ is the nominal quantum efficiency of the CCD, μ_c the absorption coefficient of carbon[7] (the hydrogen absorption of X-ray is neglected due to its small absorption coefficient in the photon energy range of 100 eV to 2000 eV, and its small effective thickness), and t the effective thickness of carbon. The second term of the above equation is attributed to the carbon absorption of X-ray. The dependence of jump height for carbon absorption, which results in the same X-ray intensity jump height of the spectrum at wavelength of 4.4 nm, on the effective thickness of the carbon has been exploited to determine the carbon thickness. The effective thickness of carbon is determined to be 0.26 μm. The actual QE of the X-ray CCD is also shown in Fig.4.

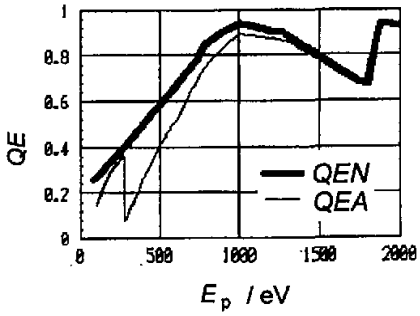

Fig.4 The nominal quantum efficiency of the X-ray CCD in the soft X-ray region, provided by the X-ray CCD manufacturer(QEN), and the corrected quantum efficiency of the X-ray CCD (QEA) obtained by this work

4 DISCUSSION AND CONCLUSION

By comparing the X-ray spectrum measured by soft X-ray spectrometer(SXS) with that obtained by transmission grating spectrometer, the accuracy of the corrected QE of the X-ray CCD can be tested. We have taken the spectra from the rear of the laser-irradiated gold foil simultaneously with the soft X-ray spectrometer and the transmission grating spectrometer. Thickness of the gold foil is about 0.17μm. The 0.35μm laser with energy of up to 80J in 0.8 ns irradiated the target with spot size $\sim$ 300μm. The soft X-ray spectrometer and the transmission grating spectrometer were positioned at 45° and 22.5° off the target normal in the same horizontal plane to measure the X-ray spectra, respectively. The target chamber was also kept at $\sim 10^{-3}$Pa.

The soft X-ray spectrometer combines various kinds of filter with X-ray diodes, and the filter absorption coefficient and the X-ray diode response to soft X-ray have been calibrated, respectively. A transmission grating is coupled to the soft X-ray CCD in the transmission grating spectrometer. The X-ray CCD also works at –39°C . The transmission grating is relatively calibrated at several photon energies, and the grating structure parameters except the fraction of support structure have been determined using grating model with rectangular wire cross section and the calibrated relative diffraction efficiencies at several photon energies. The overall diffraction efficiencies of the transmission grating in photon energy range of 100 eV to 2000 eV have been calculated with the grat-

ing model and the grating structure parameters. The corrected quantum efficiency of the X-ray CCD, shown in Fig.4, was used in unfolding the transmission grating spectrometer measured X-ray spectra.

The typical spectra measured by SXS and TGS, respectively, were shown in Fig.5. Taking into account the experimental error of both measurement methods, the two spectra are in good quantitative agreement with each other. This comparison showed that the corrected quantum efficiency of the X-ray CCD is reasonably accurate in soft X-ray region and the method to study the surface contamination of the X-ray CCD is applicable.

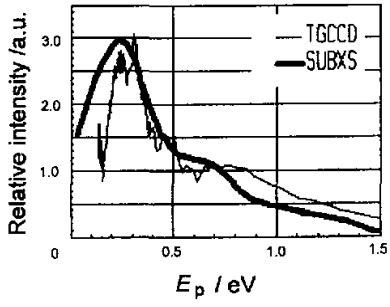

Fig.5 Comparison of transmission grating spectrometer measured X-ray spectrum with that obtained by soft X-ray spectrometer

Because in the laser plasma experiment, ultrahigh and clean vacuum is usually not available and the X-ray CCD chip works at very low temperature (for example, −39°C), the surface of the X-ray CCD chip is readily contaminated by vacuum oil. It is necessary to correct the quantum efficiency of the X-ray CCD constantly when it is used to measure reproducible and quantitative X-ray spectra. The method mentioned above is an applicable one. But at the same time, since the effective thickness of carbon existing on the surface of the X-ray CCD chip changes with working temperature and vacuum environment, the X-ray CCD QE correction experiments should be carried out at the same condition as at which the X-ray CCD is applied to measure quantitative X-ray spectra.

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