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A laser-plasma source for CCD calibration in the soft X-ray range

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Abstract

A CCD calibration system based on a laser-plasma X-ray source has been developed. The system is particularly suited for CCD calibration in the soft X-ray spectral range and allows the user to continuously tune in energy the incident radiation. This last issue is of great interest when studying the X-ray response of Si detectors near the K-edge. We report on the use of this facility for calibration of a back-illuminated CCD for single-photon spectroscopy of laser-plasma emission.

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1. Introduction

Originally used in astrophysics (see Refs. [1,2] and references therein), X-ray detectors based upon Charge Coupled Devices (CCD) have now become a customary tool in different fields of physics. Very often, CCDs are used in combination with spectral dispersing devices (crystals,

grazing incidence gratings, etc.) to obtain X-ray spectra from 100 eV up to some tens of keV.

More recently, due to the increasing performance of these detectors, single-photon counting and spectroscopy has become possible. CCDs in this configuration are now routinely used in plasma physics, for example, to study X-ray scattering from strongly coupled plasmas [3,4] or X-ray emission from fs laser-produced plasmas [5]. In the single-photon detection regime, a very low flux of photons falls on the CCD array. Depending on the size of the CCD array, a large number of photons can be detected simultaneously in a single image. Each X-ray photon absorbed in the sensitive layer of the CCD gives rise to a signal (charge) localized in one or a few pixels. Since the

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measured signal is basically proportional to the photon energy, a spectrum of the X-ray radiation can be obtained directly from the histogram of the image, without the use of dispersing devices. The final spectral resolution in the energy range from 1 to a few tens of keV is typically below 10%.

This mode of operation requires that the spectral response (the spectral redistribution function) of the CCD is known as accurately as possible [6]. In other words, photon interaction processes occurring at different locations within the CCD array structure both in the transversal and longitudinal directions must be taken into account. Due to the different physical characteristics across the detector sensitive area, these processes give rise to low-energy-side peaks or, more generally, to a low-energy tail in the final spectrum when the detector is irradiated with monochromatic radiation [7]. Various experimental techniques, like the so-called mesh technique, as well as theoretical and numerical models have been developed in order to gain some insights on the role played by detector regions previously considered as dead layers. In this way, many interesting features of the processes leading from the primary photoelectron creation to the charge cloud generation and spreading have been discovered, particularly for front-illuminated CCDs [7–10].

The response function is usually studied using X-ray tubes as well as radioactive sources [8,11,12]. X-ray tubes have also been used in CCD calibration to excite K_{α} radiation from selected targets [13]. Ideally, an accurate evaluation of the CCDs spectral response would require a continuously tunable source. This is particularly true for the soft X-ray energy range below 2 keV. In fact, according to Monte Carlo simulations [14], strong variations of the mean electron-hole pair creation energy and of the Fano factor are expected in this spectral range. Significant energy dependence of the quantum efficiency (QE) and of the energy resolution, as well as a complex structure of the response function, have been observed in this spectral region, particularly near the Si K-edge. For this reason, synchrotron-based sources are now currently used in this kind of experiments [7,10,15]. Recently, the use of X-ray

emission from laser-produced plasmas has been considered as a possible tunable, easily accessible, alternative source [16].

In this paper we report on the use of a laser-plasma X-ray source for CCD calibration in single-photon regime. To our knowledge, this is the first time that laser-plasma X-ray sources have been used in this field. Our study clearly shows that such table-top, inexpensive X-ray sources are ideal for calibration measurements in the soft X-ray range.

A detailed description of the system is given in the next section followed by a brief account of preliminary measurements performed on a scientific-purpose commercially available back-illuminated CCD to be used in plasma spectroscopy.

2. Description of the source

A schematic view of the experimental arrangement of the calibration facility is shown in Fig. 1. The beam of a Nd:YLF laser, oscillating at a wavelength of $1.053 \mu\text{m}$, is focused in a vacuum, by means of an $f/4$ optics, onto a solid target.

The laser focal spot size on the target has been measured to be about $10 \mu\text{m}$. Since an average energy of 3 J is released in each 3 ns duration (FWHM) pulse, an intensity up to $5 \times$

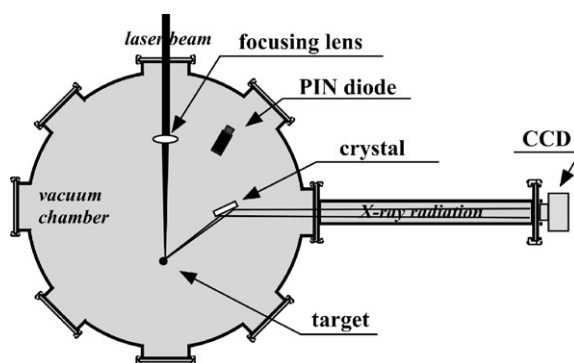


Fig. 1. Monochromator setup devoted to CCDs single-photon calibration. A hot, high-density micro-plasma, produced inside a vacuum chamber by a 3 ns Nd:YLF laser pulse interacting with a solid Cu target, acts as an X-ray source. A flat crystal, set in Bragg configuration, selects the photons with the required energy to be sent onto the CCD. The crystal-to-CCD distance is set in order to ensure a low-flux condition on the CCD.

10^{14} W/cm² is achieved in the focal spot. A hot, high-density micro-plasma is produced which acts as an X-ray source that has an effective typical size of about 70 μ m and a duration of the order of the laser pulse duration (see Ref. [17] and references therein). The X-ray emission, integrated over a 1–10 keV spectral band, is optimized, using a PIN diode, by varying the laser-target focusing distance. Detailed information on the spatial and spectral properties of the plasma produced in these conditions using different targets have been obtained in previous experiments [18,19]. In the experiment reported here a Cu target ($Z = 29$) is used in order to maximize the X-ray yield in the soft X-ray range for the above mentioned laser intensities. A spectrum of the Cu plasma emission in the 0.9–1.8 keV spectral range, which is particularly interesting for X-ray absorption studies near the Si K-edge, is shown in Fig. 2. The emission is mainly due to a large number of L-shell bound–bound transitions in Ne- and F-like ions and is quite intense in the region between 1 and 1.2 keV. Furthermore, Cu plasmas produced in these conditions exhibits a bremsstrahlung and recombination emission at higher energies, which makes this kind of target useful to detector calibration up to about 5 keV.

A crystal monochromator based upon a flat crystal (TIAP, $2d = 25.9$ Å) set in a first-order

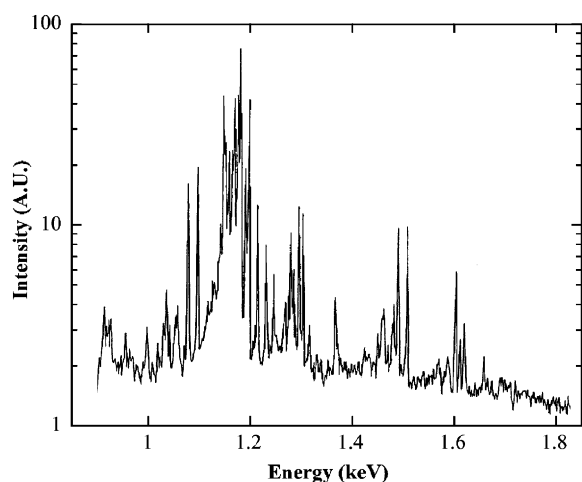


Fig. 2. X-ray spectrum of a Cu laser-plasma created in conditions similar to those used in the calibration facility.

Bragg configuration was employed to select the required photon energy for calibration. The distance from the crystal to the detector was of the order of 1 m. This distance was chosen in order to obtain a radiation beam with a spectral width across the whole CCD array of less than 30 eV at 1 keV. This is a major improvement compared to previous measurements based upon laser-plasma sources [16], where spectral selection was obtained using K-edge filters. The distance also ensures that a small photon flux (about 0.01 photons/pixel) falls on the CCD array, thus fulfilling the single photon condition. A PC-controlled system enables to vary the crystal geometry, thus modifying the X-ray energy range collected by the CCD.

3. Preliminary calibration of a back-illuminated CCD

The setup described above was used to perform a preliminary calibration of a CCD dedicated to laser-produced plasma single-photon spectroscopy. The detector, a commercially available Princeton Instruments CCD, is equipped with a SiTE back-illuminated chip consisting of 1100×330 pixels, each of 24×24 μ m². The active silicon substrate is between 12 and 14 μ m thick and the depletion depth is approximately 8 μ m. The chip was kept at a temperature of $-40 \pm 0.5^\circ$ C by means of a Peltier device. The CCD, operating in full-frame mode, was read using the 16 bit ADC at the read-out speed of 430 kHz. In order to correct for the dark charge pattern of the CCD, each image was processed by background subtraction using an unexposed image acquired under identical detector setting conditions. The lower limit to the final energy resolution one can get using single-photon spectroscopy is given by the width of the background histogram. In our experimental conditions this histogram was well fitted by a gaussian curve having a FWHM of 8.5 ADU.

Single-photon spectral data were taken at five different photon energies, four of these (1140, 1320, 1550 and 1650 eV) below the Si K-edge and one (1950 eV) just above the edge. A mean number of 12,500 photons were collected by the CCD in each shot. Three images were acquired for each

photon energy. This gave statistical fluctuations on the single-pixel histograms sufficiently small to enable a correct understanding of the main characteristics of the pulse height distributions.

Fig. 3 shows a typical single pixel histogram of the images acquired exposing the CCD to 1320 eV photons. This histogram clearly shows the main features of the response of a Si detector operating in single-photon mode [20,21]. Besides the large background peak around zero, a main peak is visible at an ADC level of approximately 80, which is generated by the actual monochromatic radiation at 1320 eV collected by the CCD. Histograms like these must be processed to extract the spectral response. In fact, it is well known that the raw histogram does not account for the so-called event splitting between neighbouring pixels, which occurs when the charge produced by a single photon diffuses radially in a plane parallel to the silicon surface. Event splitting may take place between two or more adjacent pixels. For this reason, event reconstruction algorithms are generally used in order to recover the exact ‘pixel shape’ of the real events. This kind of algorithms involve, in its simpler form, the usage of a rejection threshold to distinguish pixels with photon contributions from noise (see for example Ref. [22]). In our case we took an ADC level of $3w$ as a threshold, w being the FWHM of the background histogram curve.

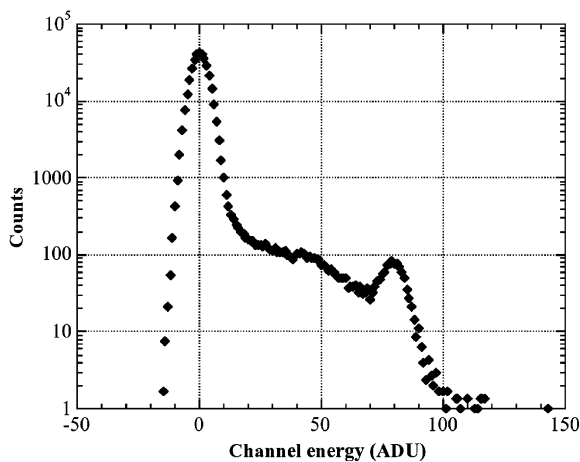


Fig. 3. Pulse height distribution for an incident X-ray photon energy of 1320 eV when no event reconstruction procedure is carried out on the image.

Performing such a kind of algorithm also enables to get separate histograms for the single events and for the different kinds of split events. Fig. 4 shows the histograms of the events respectively 1- (single events), 2- and 3-pixels wide, corresponding to an energy of the incoming photons of 1320 eV. In the case of isolated events, the plot clearly shows a peak at lower ADC levels with respect to the main peak. This is a typical feature of all our data-images. The relative intensity of the two peaks does vary with the energy of the photons. As explained for example in Ref. [20], a complex structure of the low-energy side of the pulse height distribution is always present in Si detector. The investigation of the intensity of the low-levels peak as a function of the energy and a full understanding of the physical mechanisms underlying it are beyond the scope of this paper. However, as already observed for back-illuminated CCDs [15], we believe that this peak is due to absorption of the incoming photon in the passivated backlayer of the CCD. This hypothesis is consistent with the fact that this low-energy peak is particularly intense for the photon energy just above the Si K-edge, where the attenuation length is comparable with the depth of the passivation layer. On the basis of these considerations, we used the high-level peaks of the 1-pixel histograms like the one of Fig. 4 to get a calibration, i.e. a relationship

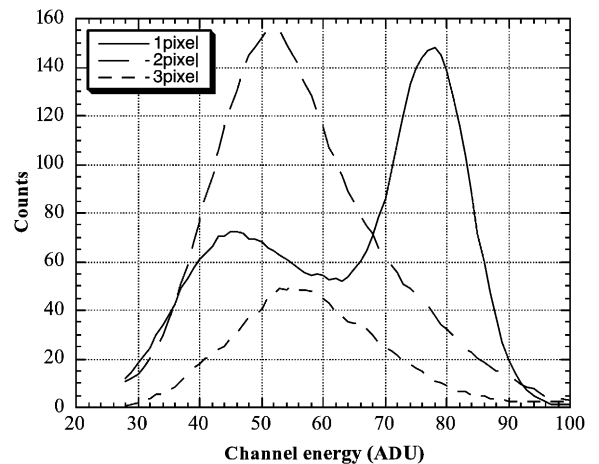


Fig. 4. Pulse height distribution for different kinds of events at a photon energy of 1320 eV.

between the ADC levels and the energy of the incoming photons. This relationship is shown in the inset of Fig. 5.

In order to validate the calibration of the CCD up to energies greater than those available using the laser-produced plasma source, a ^{55}Fe and an ^{241}Am radioactive sources were used. This time, 100 images were acquired using the same CCD settings as for the plasma source measurements. Due to the different lines emitted by the radioactive sources and to the more complex structure of the detector response at these higher energies, a bigger number of photons was necessary in this case, so that a mean total number of 8×10^5 photons were collected for each photon energy. In contrast with the case of low-energy photons examined above, pulse height distributions do not exhibit strong low-energy peaks in this case, although a low-energy tail is still visible. This can be explained considering the higher values of the attenuation length in Si at the energies of the Mn K_α and K_β lines from ^{55}Fe at 5.9 and 6.5 keV and of the line at 13.9 keV from ^{241}Am .

Fig. 5 shows the relationship between the ADC levels of our CCD and the energy of the incoming photons for all the energies considered. The plot shows a good linearity of the CCD in the whole spectral range. A slight departure from the

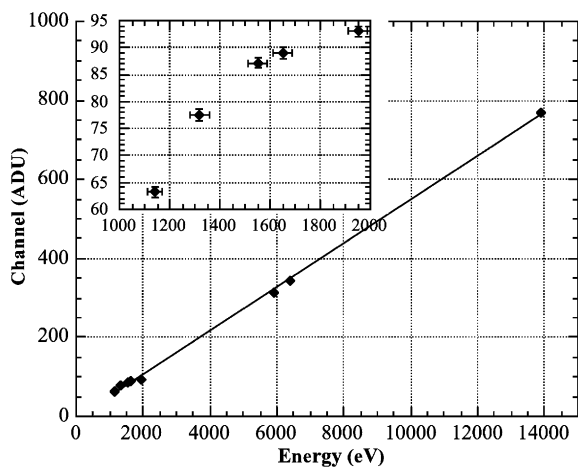


Fig. 5. Calibration of the CCD in the whole energy interval considered. The result of a linear fit of the points is also shown. In the inset a detail of the calibration points taken using the laser-plasma X-ray source is visible.

linearity is evident in the soft X-ray region, as is shown in the inset of the figure, particularly for the four points below the Si K-edge. This clearly shows the usefulness of a laser-plasma source for detector calibration in this energy range.

4. Summary and perspectives

In this paper we reported on the set-up of a laser-plasma X-ray source devoted to calibration of Si detectors in the soft X-ray spectral range. With respect to other sources based on characteristic X-ray line emissions from selected material, the source has the advantage of enabling a continuously tuning of the photon energy in the whole available range, while retaining a greater ease-of-use with respect to synchrotron-based sources. The source was used to calibrate a commercially available back-illuminated CCD in the energy range from 1300 to 1900 eV. We believe that our source could be useful in the response studies of Si detectors, in particular across the Si K-edge, where strong variation of the detectors properties are known to occur.

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