X-RAY FOCUSING CRYSTAL VON HAMOS SPECTROMETER WITH A CCD LINEAR ARRAY AS A DETECTOR

A. Shevelko, A. Antonov, I. Grigorieva, Yu. Kasyanov, O. Yakushev
P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Leninsky Pr. 53, Moscow 117924, Russia
L. Knight, and Q. Wang,
Department of Physics and Astronomy, Brigham Young University, Provo, UT 84602

ABSTRACT

An x-ray focusing crystal von Hamos spectrometer was developed using mica and graphite cylindrical crystals (radius of curvature R=20 mm) with a CCD linear array detector. The commercial CCD (Toshiba model TCD1304AP) used for x-ray detection has 3724 pixels (8 μm width and 200 μm height) giving a total length of ~30 mm. The CCD detector was absolutely calibrated using laser-produced plasmas. The sensitivity of the detector was two-three orders of magnitude higher than the sensitivity x-ray photographic film (Kodak RAR 2492). In combination with a focusing von Hamos spectrometer the detector was used for absolute spectral measurements and the determination of the laser-produced plasma parameters. This spectrometer is promising for absolute spectral measurements of x-ray radiation of low-intensity sources and for numerous practical applications (e.g., x-ray fluorescence analysis and EXAFS).

INTRODUCTION

Charge coupled devices (CCDs) have found widespread use in fundamental research and practical applications as active detectors in soft x-ray imaging systems [1,2]. CCD x-ray detectors have the advantages of high sensitivity, good signal-to-noise ratio, wide dynamic range, and good spatial resolution. Hence, a two-dimensional multichannel CCD detector is a suitable replacement for photographic film in spectroscopic instruments. The x-ray sensitive CCD is a good real-time detector with known quantum efficiency and linear response with no need of complex developing. Examples can be found in [3-5] where CCDs were used in flat and spherical crystal spectrometers for x-ray spectroscopy of laser-produced plasmas.

Maximum efficiency is achieved when a CCD is used in the focusing schemes of crystal x-ray spectrometers. One of these is the von Hamos scheme [6,7]. This scheme has several advantages—the most important being high efficiency in a wide spectral range. In the von Hamos geometry x-ray spectra are formed on the spectrometer axis. Thus, it is possible to use a CCD linear array as the x-ray detector. In this research, a low-cost, commercial CCD linear array was used as an x-ray detector in a focusing crystal von Hamos spectrometer. The spectrometer was used for absolute spectral measurements and for the determination of the plasma parameters.

VON HAMOS SPECTROMETER

In the von Hamos scheme [6,7], a crystal is bent into a cylindrical surface. The x-ray source and the detector plane lie on the cylinder axis (see Fig. 1). The crystal diffracts x-rays with different wavelengths according to the Bragg law. Each wavelength, after diffraction from the crystal arc, is focused to a point lying on the spectrometer axis. This focusing geometry gives high spectrometer efficiency.

The width of the spectral band in the von Hamos geometry depends on the length of the crystal in the dispersion direction. For a long crystal, the wavelength band DI can be wide. Each wavelength in this band is focused to a unique spot on the axis of the crystal—hence, high efficiency. Note that in other focusing schemes the wavelength band and efficiency are mutually exclusive [7].
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schemes, the realization of maximum efficiency leads to a severe restriction of the recording wavelength bandwidth. However, the von Hamos scheme has high efficiency even when the spectra are recorded over a wide spectral range.

The spectra obtained with a von Hamos spectrometer form a two-dimensional image of the source for each wavelength [6,7]. The aberrations due to off-axis source point are limited so that spatial resolution cannot, in general, exceed the source size [7]. If a CCD linear array is used as an x-ray detector, each CCD pixel integrates the radiation over the pixel height in the direction perpendicular to the dispersion (see Fig. 1). Thus, only a one-dimensional image is observed: the width of each spectral line corresponds to the source size. But, at the same time, the integration over the pixel height leads to enhanced spectrometer efficiency.

Another distinctive feature of the von Hamos geometry is that it allows the use of mosaic crystals with high-integrated reflectivity. This increases spectrometer efficiency further. In this case, mosaic focusing in the direction of dispersion takes place. The result is high sensitivity without sacrificing spectral resolution [8,9].

EXPERIMENTS

Laser-produced plasmas
Laser-produced plasmas were used as x-ray sources for CCD calibration—sensitivity, spectral response, and quantum efficiency measurements. After the calibration procedure the CCD was used as an energy integration x-ray detector (energy integration mode). In this case the accumulated energy was measured in each pixel during one laser shot exposure. Absolute x-ray spectral measurements were performed using a focusing crystal von Hamos spectrometer and a CCD (wavelength dispersion mode). In both modes the instruments were used for laser-produced plasma diagnostics.

The laser-produced plasmas were created using the “Phoenix” Nd glass laser (0.53 mm/10 J/2 ns) at the Lebedev Physical Institute. The laser beam was focused onto Mg, Al, Ti, or Fe targets (see Fig. 2). The focal spot diameter was equal to ~15 mm.
CCD
The commercial CCD used for x-ray detection is the Toshiba model TCD 1304AP. It is a linear array with 3724 pixels. Each pixel is 8 mm wide (6 mm active) and 200 mm high. The total effective detection area is 200 mm by 29.8 mm (8 mm x 3724 elements). The front cover glass is removed for x-ray detection. At a temperature of 20° C with an integrating time of 100 ms, the dark current noise, 3σ, is 0.5 % of the saturation value. To prevent visible light illumination, a double Al-coated mylar filter (4.4 mm of mylar, 0.2 mm of Al) was used.

CCD calibration
The calibration procedure consists of irradiating the detector with monochromatic radiation of known intensity. The comparison of the CCD signal (counts/pixel) with incidence photon flux (phot/pixel) gives the absolute CCD sensitivity, N₀ (phot/count), in each pixel at a given photon energy. Laser-produced plasmas were used as an x-ray source.

Quasi-monochromatic radiation from laser-produced plasmas was generated using a special combination of target materials and x-ray filters [9,10]. Targets with middle atomic numbers Z_a = 12, 13, 22 were chosen, so [He]- and [H]-like ions were effectively excited in plasmas produced by the given laser. X-ray K-absorption filters isolated a narrow spectral band with only a few lines: only the radiation of resonance lines and corresponding satellites of [H] - and [He] -like ions were selected by the filters see Table 1.

The calibration experiment scheme is shown in Fig. 2. The CCD array and a photographic film camera were installed in a vacuum chamber at the same angle with respect to the target. Both channels used the same x-ray filters used to select the needed spectral band (see Table 1). Kodak RAR 2492 x-ray photographic film measured the absolute x-ray intensity that passed through the x-ray filters using the absolute calibration data [11]. These data were compared with the CCD signal (see Fig. 3), and the absolute CCD sensitivity, N₀ (phot/count), was determined (see Table 1). The noise performance of a CCD is one of the most important factors because it defines the CCD’s detection limit [2]. In our case there are two major noise sources: dark current noise and photon shot noise. 3σ of the dark current noise corresponds to ~ 20 counts. This value defines the CCD’s detection limit. According to the Table 1, 20 counts are equal to 3.6 phot/pixel for λ=8.4-9.2 Å (photon energies of 1.35-1.5 keV), and 1.2 phot/pixel for λ=2.6 Å (photon energy of 4.8 keV). These values correspond to exposures 3×10⁻³ phot/μm² and 1×10⁻³ phot/μm², correspondingly (the pixel area is 6x200 μm²). These exposures can be compared with the detection limit for the x-ray Kodak RAR 2492 photographic film. The film exposures for optical density D=0.1 are equal to 0.43 phot/μm² and 0.84 phot/μm² for the same wavelengths [11]. These estimates show that the CCD is 140—840 times more sensitive than the photographic film.

The other important source of noise is photon shot noise. The characteristic of this noise is that it grows as the incoming photon flux increases. The uncertainty follows a Poisson distribution and is proportional to the square root of the number of photons, N₁, depleted in silicon [1]. The photon shot noise can be used to estimate the quantum efficiency (QE) of the CCD. In Fig. 3, the noise envelope corresponds to ±3σ of the measurement, where s is the standard deviation of the measurement. Assuming the dominant noise source is photon shot noise, s is proportional to (N₁)¹/². The sensitivity, N₁, determined in this way is indicated in Table 1. The quantum efficiency is defined as QE= N₁/N₀, where N₁ is number of photons depleted, N₀ is the number of incident photons. The values of QE obtained are presented in the last column of Table 1. The QE values are in good agreement with [12,13] if we assume the Si layer thickness equals ~20 mm.
Fig. 2. Schematic diagram of the calibration geometry.

Fig. 3. Example of CCD shot noise (Mg laser-produced plasma);
CCD filters: 6.25; 12.5; 25 µm of Al
Von Hamos spectrometer

Crystals with radius of curvature R=20 mm were used in the von Hamos spectrometer. The spectrometer axis was installed perpendicular to the laser beam (see Fig. 2). Spectra of highly charged ions were recorded using the calibrated CCD positioned in the image plane. To prevent visible light illumination, a double Al-coated mylar filter (4.4 mm of mylar, 0.2 mm of Al) was used. Spectra were recorded in a single laser shot. To attenuate x-ray exposure on the CCD, Al filters of different thickness (up to 73 mm) were used. Total attenuation was up to 125 times.

Initially, a mica crystal (2d=19.84 Å) was installed in the spectrometer. The spectrometer was aligned using a He-Ne laser, and x-ray spectra were recorded. Then a graphite crystal was installed in the same place. The crystal was made from shaped, highly oriented pyrolytic graphite (HOPG, 2d=6.708 Å) \[14\] and was mounted on a special cylindrical holder with the same radius of curvature (R=20 mm). Spectra were recorded for the 1st, 2nd and 5th orders of mica reflection and for the 1st order of the graphite reflection. The crystal-integrated reflectivities were measured in \[7,9\]. These data, together with the CCD absolute calibration data, allowed us to record the spectra on an absolute intensity scale.

RESULTS

The x-ray spectra of highly charged ions excited in laser-produced plasmas are shown in Figs. 4-6. The spectra were recorded using the von Hamos spectrometer with mica (Figs. 4,5) and graphite (Fig. 6) crystals. The peak reflectivity ratio (~4) for graphite and mica crystals is in good agreement with the data \[9\]. The integrated reflectivity ratio for the same crystals is somewhat lower (30 versus 60 in \[9\]). The reason is that the CCD pixel height (200 mm) is not enough to cover the spectrum height (~350-400 mm).

X-ray spectra obtained with the mica crystal show high spectral resolution: spectral resolving power l/dl was equal to 800 and 2000 for Mg (1st reflection order) and Ti (IIIrd reflection order) laser-produced plasmas (see Figs. 4,5). The spectrum of Ti laser-produced plasma recorded by graphite crystal showed lower spectral resolving power: l/dl=200-300 (Fig.6). This value is lower than the one demonstrated in \[9\] (l/dl=500-700) but higher than l/dl=50 defined by the mosaic spread of the graphite crystal. Thus, mosaic focusing takes place, but it is spread. This is caused by mosaic defocusing in the direction perpendicular to the dispersion \[9\], which leads to a curved shape of the spectral lines.

The high spectral resolution of the mica crystal von Hamos spectrometer allowed us to observe resonance and intercombination lines of the [He]-like ions and corresponding satellite structure in spectra (see Fig. 5). The line intensity ratios were used for plasma diagnostics \[15, 16\]: determination of electron density \(N_e\) and

<table>
<thead>
<tr>
<th>Target</th>
<th>Ions</th>
<th>Filters</th>
<th>Photon energy E</th>
<th>N0, phot/count</th>
<th>N1, phot/count</th>
<th>QE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>[H] [He]</td>
<td>6.25; 12.5; 25.0 mm Al</td>
<td>1.35-1.5 keV</td>
<td>0.186±0.02</td>
<td>0.15±0.015</td>
<td>0.8</td>
</tr>
<tr>
<td>Ti</td>
<td>[He]</td>
<td>15.9; 31.8; 47.7 mm Ti</td>
<td>4.8 keV</td>
<td>0.065±0.007</td>
<td>0.056±0.006</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 1. Shows measured absolute values of CCD sensitivity and CCD quantum efficiency (laser-produced plasma source)
electron temperature $T_e$. Note that the spectra were observed at very low laser pulse energies (as low as 40 mJ for Mg plasmas). In most cases of spectra recording it was necessary to apply a severe attenuation of the incidence intensity to avoid CCD saturation. For this reason the spectrometer is very good for studying x-ray spectra of low intensity sources: femtosecond laser-produced plasmas, micropinches, EBIT sources, etc.

The very high efficiency of the von Hamos spectrometer with the CCD linear array as a detector makes it possible to use the device in x-ray fluorescence applications [17]. In this case it is necessary to cool the CCD to reduce the dark current noise to measure the low photon signal during long time exposures. When the CCD is cooled from 20°C to -30°C, the dark current noise over integrating time of 5 min corresponds to the exposure of 7 phot/pixel at photon energy of 4.8 keV. These estimations show that a very compact spectrometer for XRF applications can be developed.

In conclusion, this compact device is promising for absolute spectral measurement of x-ray radiation from low intensity sources and for numerous practical applications (x-ray fluorescence analysis, EXAFS, etc.).

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REFERENCES

Fig. 5. Spectra with Ti target and mica crystal

Fig 6. Spectra with Ti target and graphite crystal