*J. Synchrotron Rad.* (1998). **5**, 756–758

# Absolute calibration of a soft X-ray spectrograph for X-ray laser research using white beam

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(*Received 5 August 1997; accepted 10 November 1997*)

Absolute calibration of a soft X-ray spectrograph has been performed using a white beam of synchrotron radiation. The calibrated spectrograph was a flat-field grazing-incidence spectrograph with an X-ray CCD detector for X-ray laser research. Absolute sensitivity of the spectrograph system can be obtained from transmitted spectra using filters made of several different materials, each providing an absorption-edge wavelength standard. The absolute sensitivity determined in this work shows nearly the same behaviour with wavelength as that in another calibration experiment using a laser-produced plasma as an X-ray source.

**Keywords: absolute calibration; soft X-ray lasers; flat-field spectrographs; white beams; X-ray CCD cameras.**

## 1. Introduction

In X-ray laser research, XUV or soft X-ray spectroscopy is an important diagnostic method of identifying lasing X-ray lines and of evaluating the X-ray laser output. Therefore it is necessary to calibrate spectroscopic instruments for these purposes. Furthermore, when the sensitivity of the observation system is known throughout its wavelength coverage in the range from 1 to 30 nm, one can obtain accurate intensity distributions of the relevant spectral lines to investigate the precise pumping mechanism and then determine plasma parameters in X-ray laser media.

Calibration studies for X-ray laser research have been performed using a vacuum spark (Milchberg *et al.*, 1986) or laser-produced plasmas (Chaker *et al.*, 1989). In these experiments the detectors used were photographic films or single-channel electron multipliers. It was difficult to determine the absolute photon flux directly from the source; however, a method of branching ratios has often been applied to obtain the absolute instrumental sensitivity (Irons & Peacock, 1973). Synchrotron radiation is now used as an established standard source of XUV and X-ray radiation, the absolute photon flux of which can be calculated and has been well investigated experimentally (Rusbüldt & Thimm, 1974). Usual calibration experiments on instruments for plasma spectroscopy have been carried out using monochromator beamlines, where it is difficult to measure the absolute sensitivity directly.

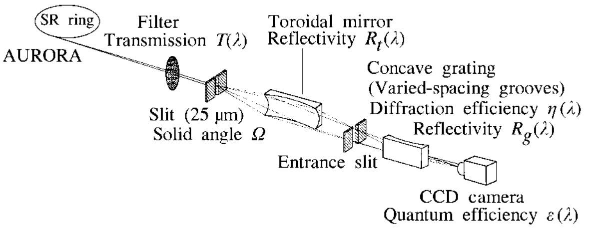

**Figure 1**
Calibrating system of a flat-field spectrograph using a white beam of synchrotron radiation (SR).

On the other hand, CCD cameras are often used as active recording detectors in soft X-ray imaging systems (Koppel, 1977). Advantages of this detector are good linearity for the wide dynamic range, high sensitivity, easy handling of recorded images and quick data acquisition (Janesick *et al.*, 1987). Compared with photographic film, no complicated development procedures are necessary, the response to exposures is linear and the quantum efficiency is well known (Wilhein *et al.*, 1994). Calibration work on spectrographs using a CCD camera, however, has not yet been reported.

In this work, we have performed an absolute calibration experiment utilizing a white beam of synchrotron radiation. Here the calibrated spectrograph is a flat-field grazing-incidence spectrograph with a concave grating, with grooves of varied spacing, and an X-ray CCD camera. The behaviour of the sensitivity with photon energy determined in this experiment is consistent with that in other experiments using a laser-produced plasma and a transmission grating.

## 2. Experimental set-up

The experimental set-up is shown in Fig. 1. The calibrated spectrograph consists of a toroidal mirror coated with Pt, a concave grating with grooves of a varied spacing used in a flat-field grazing-incidence optical system (Nakano *et al.*, 1984) and an X-ray CCD camera. A flat-field-type optical configuration is suitable for the use of a CCD or a streak camera for X-ray laser research. The grating (HITACHI, 001–0450) has a nominal groove density of 2400 grooves mm$^{-1}$, a blaze angle of 1.9° and a radius of curvature of 15920 mm. The grating is designed to cover a wavelength range of 1–5 nm with an incident angle of 88.7°. The grating is also coated with Pt. The X-ray CCD camera (Princeton Instruments, Inc., TE/CCD-1100-PB) uses a back-illuminated chip with 25.4 × 8.5 mm active area and 1100 × 300 pixels.

Calibration experiments have been performed using a white beam at AURORA at Ritsumeikan University. AURORA, a compact synchrotron radiation source, consists of an electron storage ring 1 m in diameter based on a single superconducting magnet (Yamada *et al.*, 1992). In the present experiment, as the sensitivity of the CCD detector is high, AURORA had to be operated at a low beam current of 50–60 mA to maintain detected counts within the dynamic range of the CCD detector. The irradiance of synchrotron radiation at a distance of 2 m from the source point of AURORA has been calculated (Yamada *et al.*, 1992). The number of photons was limited by a slit placed in front of the toroidal mirror. Using the geometrical conditions in this experiment and the operation parameters of the synchrotron radiation source, one can estimate the total number of photons entering the spectrograph system.

We used several filters for wavelength standards, observing absorption edges in the continuum spectral output of the spectrograph. The filter materials used were Ni, Ti and C, and the thicknesses of the filters were 0.5, 1.5 and 3.0 µm, respectively. Filters, for example, Al and Be foils, were used to cut off the higher-order light of the shorter-wavelength radiation. A lead plate of 2 mm thickness was set between the grating and the CCD detector to block the strong zeroth-order light.

### 3. Procedure for determining absolute sensitivity

A typical example of a spectrum obtained in this experiment is shown in Fig. 2(*a*). A clear edge structure can be seen in the measured continuum spectrum of the synchrotron radiation. A schematic diagram of the spectrum is shown in Fig. 2(*b*).

The readout count of the X-ray CCD detector at a wavelength slightly longer than that of the absorption edge, $\lambda_1$, can be written as

$$I_1 = \Delta t N(\lambda_1) S(\lambda_1) T(\lambda_1) + \Delta t N(\lambda_1/2) S(\lambda_1/2) T(\lambda_1/2) + I_{\rm scatt}\ [\text{counts}]. \qquad (1)$$

For a wavelength just below the edge, $\lambda_2$, the measured intensity is

$$I_2 = \Delta t N(\lambda_2) S(\lambda_2) T(\lambda_2) + \Delta t N(\lambda_2/2) S(\lambda_2/2) T(\lambda_2/2) + I_{\rm scatt}\ [\text{counts}], \qquad (2)$$

where $\Delta t$ is the exposure time, $N(\lambda)$ is the number of photons entering the spectrograph, $S(\lambda)$ is the spectrograph sensitivity and $T(\lambda)$ is the transmission coefficient of the filter at wavelength $\lambda$. The first term corresponds to the component due to the first-order light and the second term is that due to the second-order light. The last term, $I_{\rm scatt}$, includes the scattered light and the higher-order light components.

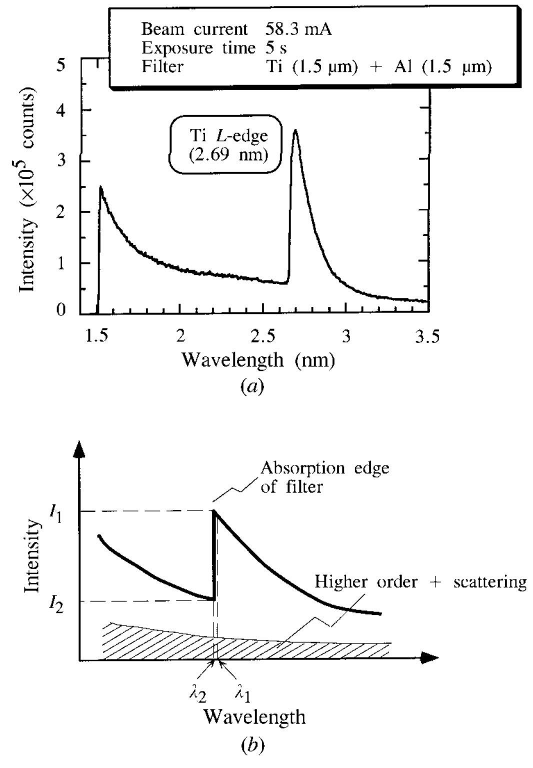

**Figure 2**
(*a*) Typical example of a spectrum obtained by the X-ray CCD camera. A discontinuity can be seen at the absorption edge of Ti, while a sharp cut at 1.5 nm corresponds to the position of the lead mask. (*b*) Schematic diagram of the spectrum.

Provided that $N(\lambda)$ and $S(\lambda)$ have slowly varying functions with $\lambda$, and the difference between $\lambda_1$ and $\lambda_2$ is very small,

$$N(\lambda_1) \simeq N(\lambda_2), \quad S(\lambda_1) \simeq S(\lambda_2)$$

and

$$N(\lambda_1/2) \simeq N(\lambda_2/2), \quad S(\lambda_1/2) \simeq S(\lambda_2/2).$$

While $T(\lambda)$ is a discrete function between $\lambda_1$ and $\lambda_2$, it varies slowly around half of the edge wavelength, $\lambda_1/2$ and $\lambda_2/2$,

$$T(\lambda_1/2) \simeq T(\lambda_2/2).$$

Under the above assumptions the second and third terms are equal. The expression of the sensitivity becomes

$$S(\lambda_1) = \frac{I_1 - I_2}{\Delta t N(\lambda_1)[T(\lambda_1) - T(\lambda_2)]}\ [\text{counts photon}^{-1}]. \qquad (3)$$

Thus, the absolute spectrograph sensitivity can be determined from the difference of the intensity jump at the absorption edge of a filter in the spectrum obtained from the CCD camera and the incident photon number. This method is advantageous for easy elimination of unknown higher-order diffracted light and scattered light components.

### 4. Results and discussion

Sensitivities of the spectrograph are plotted in Fig. 3 for wavelengths of 1.43, 2.69 and 4.36 nm, where each experimental error arises from those of the filter thickness, the source size of the synchrotron radiation and the exposure time. The sensitivity of the spectrograph gradually decreases as the wavelength becomes longer.

The sensitivity, $S(\lambda)$, can be written as

$$S(\lambda) = R_t(\lambda) R_g(\lambda) \eta(\lambda) \varepsilon(\lambda)\ [\text{counts photon}^{-1}], \qquad (4)$$

where $R_t(\lambda)$ is the reflectivity of the toroidal mirror, $R_g(\lambda)$ is the

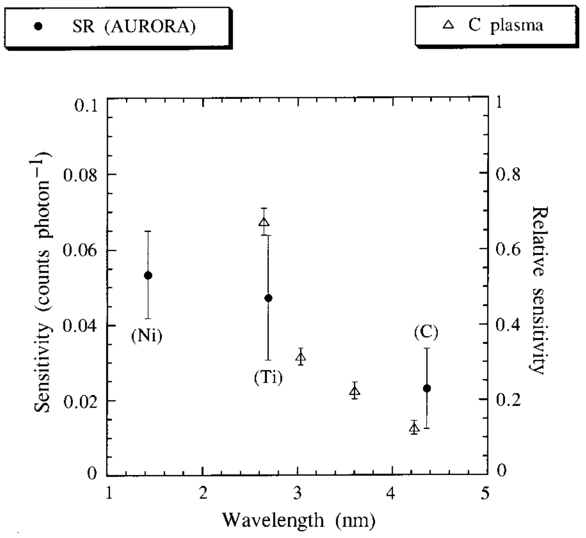

**Figure 3**
Absolute sensitivities of the flat-field spectrograph. The sensitivities of the spectrograph using a white beam of synchrotron radiation are shown as closed circles. The materials of the filter used are labelled under each data point. The results of calibration using a transmission grating and a laser-produced carbon plasma, which are obtained in a relative manner, are also shown as open triangles.

reflectivity of the grating, $\eta(\lambda)$ is the first-order diffraction efficiency of the grating and $\varepsilon(\lambda)$ is the quantum efficiency of the CCD detector. The values $R_t(\lambda)$ and $R_g(\lambda)$ show an increasing function with wavelength (Henke *et al.*, 1993). On the contrary, $\varepsilon(\lambda)$ shows an overall trend which decreases with respect to wavelength towards the Si $L_{\rm II,III}$-edge, 12.4 nm (Wilhein *et al.*, 1994). From these data, the multiplying function $R_t(\lambda)R_g(\lambda)\varepsilon(\lambda)$ is nearly flat. The grating used has an effective blaze wavelength of 0.84 nm, which is far less than the calibrated wavelength range. Therefore the diffraction efficiency gradually decreases with wavelength in the measured wavelength region. Accordingly, these features could explain the measured tendency of the spectrograph sensitivity.

Since synchrotron radiation is strongly polarized, one must measure the polarization properties of the spectroscopic system by rotating the whole apparatus around the axis of the incident radiation. Unfortunately, this experiment has been performed in only one direction, *P*-polarization. The calibration results have been compared with those determined by another experiment using a transmission grating and a laser-produced plasma, which is an unpolarized X-ray source (Fujikawa *et al.*, 1997), as shown in Fig. 3. Although these data are relative, being reduced from the throughput of the spectroscopy and the quantum efficiency of the X-ray CCD camera, the behaviour of the wavelength is nearly the same as that measured in the present experiment.

## 5. Application to plasma spectroscopy

The sensitivity in the 2–5 nm wavelength range is necessary to estimate the electron temperature and population densities of excited levels in highly ionized ions. We have observed soft X-ray spectra of Al ions produced in X-ray laser experiments using the calibrated spectrograph. In this experiment line plasmas were produced by line-focused laser irradiation. Observations were made along the axis of the line plasma. The electron temperature and population densities can be estimated from the slope of the recombination continuum and the intensity distribution of the resonance series lines, respectively. As a result, the measured electron temperature and population densities can be compared with those from the collisional radiative model in laser-produced plasmas (Kawachi & Fujimoto, 1997).

The authors thank Professor H. Iwasaki, Dr Y. Tokunaga, Mr Y. Yamamoto and members of the synchrotron radiation centre at Ritsumeikan University for assistance operating AURORA during the calibration experiment.

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