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Beamline for calibration of transfer standard light sources in the UV and VUV regions

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A beamline which serves for calibrating transfer standard light sources (deuterium lamps, excimer lamps, Xe lamps *etc.*) in the UV and VUV regions is being constructed. The synchrotron radiation from the electron storage ring TERAS (750 MeV) is used as a primary standard of spectral radiant intensity. In order to use synchrotron radiation as a primary standard, the electron beam and synchrotron radiation beam parameters need to be evaluated. Uncertainties of synchrotron radiation flux evaluated by measurements of the magnetic flux density, the position of the electron orbital plane, the electron beam size and the distance from the synchrotron radiation tangent point to the detector system are expected to be about 0.003, 0.01, 0.05 and 0.1%, respectively.

Keywords: transfer standards.

1. Introduction

Various light sources in the vacuum ultraviolet (VUV) and ultraviolet (UV) regions have been developed and the demand for the radiant power calibration of these light sources has increased. A light-source standard or detector standard is needed for the calibration.

The radiant intensity of synchrotron radiation is calculated theoretically from Schwinger theory (Schwinger, 1949) and can be used as the primary standard light source (Einfeld *et al.*, 1978; Riehle & Wende, 1986; Tegeler, 1989). We have planned to make a transfer standard light source in the UV and VUV spectral regions from comparing synchrotron radiation with the transfer standard light source.

To calculate synchrotron radiation radiant intensity, some beam parameters (electron beam energy, electron beam current, magnetic flux density in the bending magnets, beam size, distance from the tangent point of synchrotron radiation to the first aperture of the calibration system, position of electron orbital plane) need to be evaluated (Hollandt *et al.*, 1992; Klein *et al.*, 1997; Lei *et al.*, 1996; Riehle, 1988; Tegeler & Ulm, 1988).

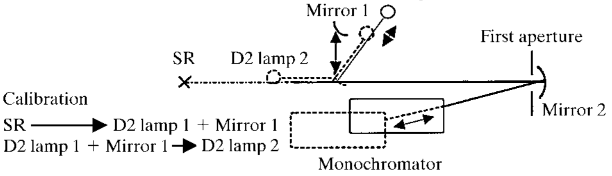

Figure 1
Principle of D2 lamp calibration by synchrotron radiation (SR).

We are constructing a calibration beamline in the electron storage ring TERAS in the Electrotechnical Laboratory and evaluating some of these beam parameters at the beamline.

In this paper, we will discuss these parameters and the total uncertainty of radiant intensity due to the uncertainty of these parameters. These parameters were measured at an electron beam energy of 750 MeV.

2. Properties of synchrotron radiation

The radiant power of synchrotron radiation is derived from Schwinger theory (Schwinger, 1949)

$$\begin{aligned} \mathrm{d}^2\Phi/\mathrm{d}\theta\mathrm{d}\psi &= \mathrm{d}^2\Phi_{||}/\mathrm{d}\theta\mathrm{d}\psi + \mathrm{d}^2\Phi_{\perp}/\mathrm{d}\theta\mathrm{d}\psi \\ &= (eIR^2/3\pi\varepsilon_0\gamma^4\lambda^3)(\Delta\lambda/\lambda) \\ &\quad \times \big\{[1+(\gamma\psi)^2]^2K_{2/3}^2(\xi) \\ &\quad + [1+(\gamma\psi)^2](\gamma\psi)^2K_{1/3}^2(\xi)\big\}, \end{aligned} \tag{1}$$

with

$$\gamma = E/m_0c^2, \qquad \xi = (\lambda/2\lambda_c)[1+(\gamma\psi)^2]^{3/2},$$

$$R + E/ecB, \qquad \lambda_c = 4\pi R/3\gamma^3.$$

In these equations, Φ is the radiant power of synchrotron radiation, $\Phi_{||}$ is the parallel intensity component (whose electric vector lies in the orbital plane) of the radiant power and $\Phi_{\perp}$ is the perpendicular intensity component (whose electric vector is perpendicular to the orbital plane). E, m_0, e and I are the electron energy, electron rest mass, electron charge and electron beam current, respectively. c, B and R are the speed of light, the magnetic flux density of the bending magnet and the radius of curvature of the electron orbit, respectively. $K_{1/3}$ and $K_{2/3}$ are modified Bessel functions, ψ is the vertical angle of incident synchrotron radiation from the electron orbital plane, and θ is the horizontal angle. These equations show that the radiant power of incident synchrotron radiation is dependent on the vertical angle.

3. Principle of transfer standard light source calibration using synchrotron radiation

Fig. 1 shows the principle of standard light source calibration using synchrotron radiation. We are planning to use a deuterium lamp (D2 lamp) for the transfer standard light source. Deuterium lamps radiate continuous spectra in the UV and VUV spectral regions and the degradation of the radiant flux due to aging is small (about 0.03% h^{-1}) after sufficient aging (about 100 h) (Zama *et al.*, 1996).

The calibration process is as follows: (i) measure the synchrotron radiation spectrum, (ii) measure the D2 lamp 1 spectrum which is reflected by Mirror 1 [in both (i) and (ii) the monochromator is set to the position shown by the solid line in Fig. 1 and the light-source images of synchrotron radiation and D2 lamp 1 are focused at the entrance slit of the monochromator]. Through the steps (i) and (ii), the spectral radiant flux from the D2 lamp 1 and Mirror 1 system can be calibrated by comparing the synchrotron radiation radiant flux spectrum. Then, the spectral radiant flux or spectral radiance of D2 lamp can be calibrated by the following steps. (iii) Set D2 lamp 2 on the synchrotron radiation light path close to Mirror 1 and move the monochromator so as to focus the image of D2 lamp 2 on the entrance slit of the monochromator (in Fig. 1 it is shown as a dotted line) and measure the spectrum of D2 lamp 2. (iv) Move D2 lamp 1 so as to make a virtual image of D2 lamp 1 at the position of D2 lamp 2 and measure the spectrum which is reflected by Mirror 1. (v) The spectral radiant flux or spectral radiance of D2 lamp 2 can be calibrated by comparing the spectral radiant flux from the D2 lamp 1 and Mirror 1 system.

4. Experiment

4.1. *Measurement of the magnetic flux density in the bending magnets*

We measured the magnetic flux density at the tangent point of synchrotron radiation. For the measurement, an NMR magnetic probe (Echo Technical Cooperation, EFS-800) was installed. Fig. 2 shows the change of the magnetic flux density at the tangent point of synchrotron radiation with the operation time of the bending magnet. Each point in this figure represents the average magnetic flux density during 20 min (the sampling time in this measurement is 1 s). The measurements show that the magnetic flux density of the bending magnet is stabilized, whose stability is under 0.002% after 4 h bending-magnet operation. The position of tangent-point synchrotron radiation varies over a few months. From measurements of the spatial profile of the magnetic flux density, the uncertainty of the magnetic flux density due to this reason is evaluated to be less than 0.003%.

It is shown from these measurements that the uncertainty of the magnetic flux density due to both its time variation and the spatial variation of the synchrotron radiation tangent point is less than 0.0036% after 4 h bending-magnet operation. In addition to the above, from the accuracy of the probe system, the total uncertainty of the absolute magnetic flux density is calculated to be less than 0.0037%. The magnetic flux density of the bending magnet is 1.24059 T. From these results and equation (1), the uncertainty of incident radiant flux due to the magnetic flux density is estimated to be less than 0.003%.

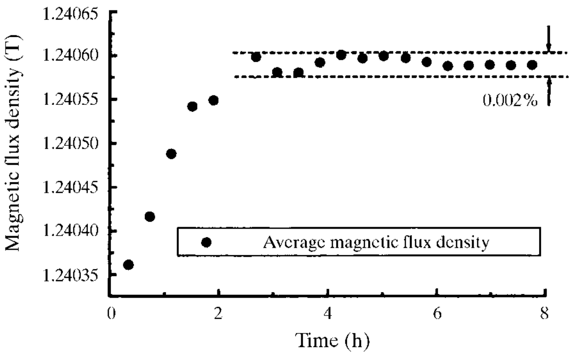

Figure 2
Change of the magnetic flux density at the tangent point of synchrotron radiation with the operation time of the bending magnet (which represents the average magnetic flux density over 20 min).

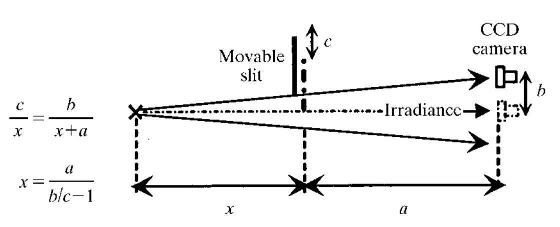

Figure 3
Schematic diagram of the distance measurement from the tangent point of synchrotron radiation to the first aperture of the calibration system.

4.2. *Measurement of the distance from the tangent point of synchrotron radiation to the first aperture of the calibration system*

The distance from the tangent point of synchrotron radiation to the first aperture of the calibration system needs to be measured to calculate the total radiation flux. Fig. 3 shows a schematic diagram for the measurement. A movable slit was installed in our calibration beamline. This slit can move horizontally. A CCD camera (SPECTRA SOURCE MCD600: 1 pixel is 10 × 10 µm) follows this slit. The distance, *a*, between the slit and the CCD camera is 2044.9 mm. The shadow of the slit edge was measured by the CCD camera.

Fig. 4 shows the relation of the displacement of the slit-shadow position and that of the slit position. All measurement points lie on one straight line. From the coefficients of this straight line, the distance from the tangent point of synchrotron radiation to the first aperture of the calibration system is determined to be 11 725 mm. The uncertainty of this distance is estimated to be less than 0.1%.

4.3. *Determination of the electron orbital plane*

Synchrotron radiation is strongly polarized and the radiant power of synchrotron radiation is dependent on the vertical angle ψ from the electron orbital plane. The perpendicular intensity component has a hollow distribution. At $\psi = 0$, the perpendicular intensity component should be zero. We evaluated the electron orbital plane at the first aperture of the calibration beamline by measuring the perpendicular intensity component of synchrotron radiation. For this measurement, a photodiode (VDT UV-100DRV), bandpass filter (peak wavelength 323 nm, bandwidth 20 nm) and polarizer are used. The photodiode, bandpass

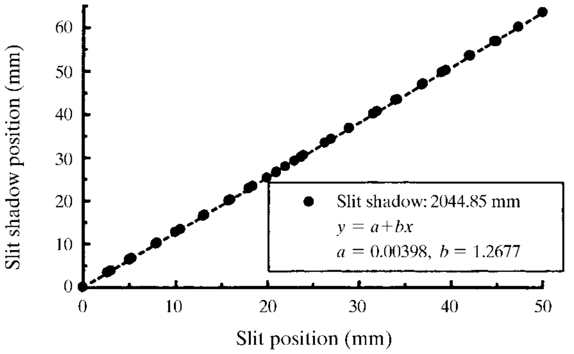

Figure 4
Position of the slit shadow *versus* slit position.

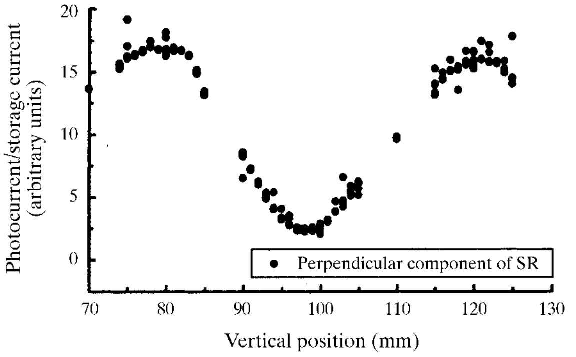

Figure 5
Perpendicular intensity component of synchrotron radiation (SR) *versus* the vertical position at the first aperture.

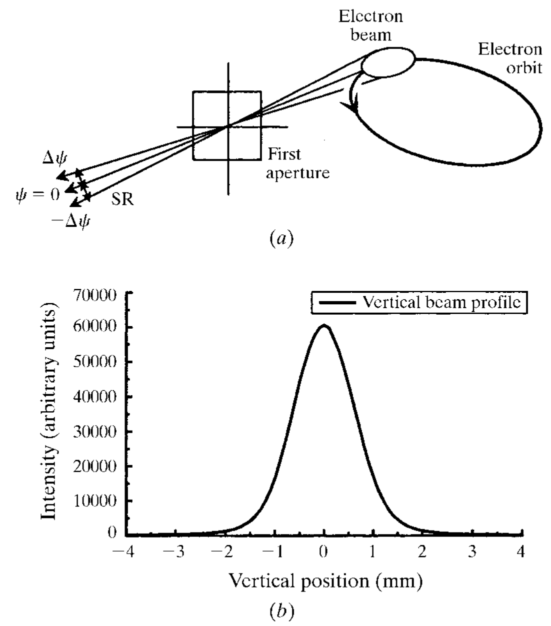

Figure 6

(*a*) The electron beam size effect of the intensity distribution of synchrotron radiation (SR). (*b*) Vertical beam profile of synchrotron radiation.

filter and polarizer were set in front of the first aperture and scanned vertically. Fig. 5 shows the vertical distribution of the photodiode signal. The signal of the photodiode is normalized by the storage current of the ring. From this measurement, the $\psi = 0$ position was determined. The uncertainty of the $\psi = 0$ position is 7.1×10^{-2} mrad. The vertical viewing angle of incident synchrotron radiation is between $\psi = -1.28$ mrad and 1.28 mrad, because the distance between the synchrotron radiation tangent point and the first aperture is 11725 mm and the aperture is 30×30 mm wide. From these results and equation (1), the uncertainty of calculated incident radiant flux at the first aperture is estimated to be less than 0.01%.

4.4. *Measurement of the electron beam size*

The beam emittance (beam size × beam divergence) of the electron beam in the storage ring affects the radiant flux of synchrotron radiation. In this section, we consider only the beam size effect. The beam size effect is shown in Fig. 6(*a*). The radiant flux of synchrotron radiation is dependent on the vertical angle ψ as shown by equation (1). In order to measure the beam size at the tangent point of synchrotron radiation, a lens (of focal length 1000 mm) and CCD camera were used. Fig. 6(*b*) shows the vertical beam profile of the beam cross section of the tangent point. It is found from Fig. 6(*b*) that the full width at half-maximum of the beam cross section on the vertical direction is 1.4 mm. $\Delta\psi$ shown in Fig. 6(*a*) is calculated to be 0.6 mrad. From equation (1), $\Delta\psi$, 0.6 mrad, gives about a 0.05% change of the incident radiation flux of the first aperture.

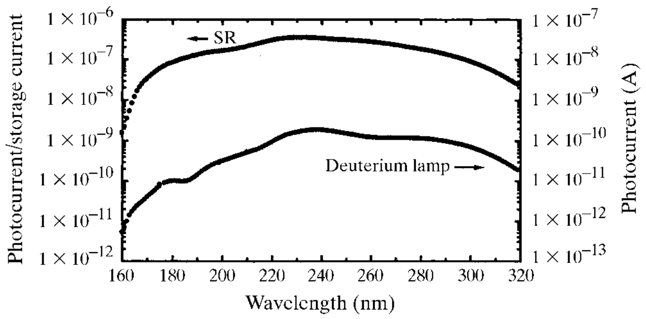

Figure 7

Synchrotron radiation (SR) spectrum and D2 lamp 1 spectrum which is reflected by Mirror 1.

4.5. *Spectrum measurement*

Fig. 7 shows the spectrum obtained from processes (i) and (ii) in §3. Now we are preparing the processes (iii)–(v). For these measurements, a deuterium lamp (KOTO BUNKOUGEN: D1323) is used for the transfer standard light source.

5. Conclusions

We have evaluated some beam parameters of synchrotron radiation which are needed for calibration of a transfer light source. Uncertainties of synchrotron radiation flux caused by the magnetic flux density, the determination of the orbit plane, the beam size and the distance are estimated to be about 0.003, 0.01, 0.05 and 0.1%, respectively. It appears that the uncertainty is mostly due to the distance measurement from the tangent point of synchrotron radiation to the first aperture of the calibration system.

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