Absolute measurement of radiation brightness of New SUBARU undulator

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Abstract

Absolute measurement of the radiation spectrum in soft X-ray region from New SUBARU undulator is planed. The principle of the measurement is based on energy analysis of photoelectrons emitted by a rare gas which has well known photoionization cross section, using a hemispherical electron analyzer. In this paper the undulator profile, measurement procedure and expected results are described.

1 Introduction

1.5 GeV electron storage ring "New SUBARU"[1] is under construction in the SPring-8 site. The ring has 4 straight sections for insertion devices; two planar undulators, super conducting wiggler and optical klystron FEL. One of the two undulators is a 10.8m long device with 200 periods that provides high-brightness soft X-ray radiation.

For both radiation users and accelerator scientists it is important to know the performance of the undulator which should be verified by measuring the absolute value of photon flux or brightness. The spectral distribution, peak height and fractional bandwidth of radiation depend on the actual machine parameters such as a finite beam emittance, a finite angular aperture of observation and K parameter. Several papers on the absolute measurement of the brightness of undulator radiation from VUV to X-ray have been published[2, 3, 4, 5, 6]. In the range of photon energies under about 1 keV, the photoionization method is often used because the cross section of photoionization of a rare gas is well known[7] both theoletically and experimentally and is relatively large. By measuring the energy distribution of the photoelectrons the absolute intensity and the band width of radiation can be evaluated. The idea of this method was originally described by Sasaki et al. [2] and applied to the absolute measurement of undulator brightness at SOR-RING[3] and PF[4, 5] by Maezawa et al. In this technique they used cylindrical mirror analyzer(CMA) to measure the energy of photoelectrons. In contrast, the higher energy region that photon energy exceeds 1 keV suffers a rapid decrease of the photoionization cross section of a rare gas. In this energy range, X-rays scattered by He gas is measured using energy dispersive solid state Si detector to evaluate radiation profile[6].

In New SUBARU the photon energy from the undulators is under 1 keV. Thus the photoelectron counting technique would be possible and we are planning to measure the radiation intensity in an absolute scale by a hemispherical electron analyzer instead of CMA. A hemispherical analyzer is frequently used in X-ray Photoelectron Spectroscopy(XPS) and Ultraviolet Photoelectron Spectroscopy(UPS) to analyze chemical information or surface band structure of samples by a detected energy distribution of photoelectrons. An advantage of hemispherical analyzer over CMA is that a hemispherical analyzer is insensitive to sample position, that is, an electric lens can quickly and easily be focussed on the sample without the need for careful sample positioning and set-up. And it is possible to measure an angular distribution of emitted photoelectrons by a hemispherical analyzer, though the number of collected electrons is small compared to CMA.

2 New SUBARU undulators

The main parameters of New SUBARU storage ring are shown in Table 1. Two undulators whose total lengths are 10.8m and 1.4 m will be installed in the staright sections. The first experiment of brightness measurement will be performed using the long undulator. The main parameters of the undulator are summarized in Table 2. It will be inserted into one of two 14 m long straight sections of the ring.

Table 1
Main parameters of New SUBARU ring

Beam energy	1.5 GeV
Current	500 mA
Natural emittance	67π nm-rad.
Betatron tune	X:6.21 / Y:2.17
Circumference	118.716 m
Energy spread	0.072 %
Life time	10 hour

Table 2
Main parameters of New SUBARU long undulator

Wavelength	54 mm
Number of period	200
Total length	10.8 m
Gap length	25 - 44.5 mm
Field strength	0.49 - 0.16 T
K parameter	2.5 - 0.8
Wavelength of radiation	13 - 4.1 nm

The radiation profile of the long undulator are summarized here. The intrinsic half-angular divergence of the undulator radiation emitted by a single electron, θ_n, is given by

$$\theta_n = \frac{1}{\gamma}\sqrt{\frac{1+K^2/2}{2nN}}, \quad (1)$$

where n is the harmonic number of radiation and N is the number of periods of the undulator. In our case the half-angular divergence of the fundamental radiation, θ_1, is 0.034 mrad for K=2.5.

The fractional bandwidth of the nth harmonic for a single electron, $\Delta\lambda_n/\lambda_n$, is given by

$$\frac{\Delta\lambda_n}{\lambda_n} \sim \left[\left(\frac{1}{nN}\right)^2 + \frac{\gamma^2\theta_{obs}^2}{1+K^2/2}\right]^{1/2} \tag{2}$$

where θ_{obs} is the half-angular acceptance of obserbation. Assuming θ_{obs}=0.04 mrad, it is found that $\Delta\lambda_1/\lambda_1$=0.058 for the fundamentl at $K = 2.5$.

The peak brightness of the nth harmonic undulator radiation for the case of the zero emittance and infinitesimal aperture is given by

$$\begin{aligned} B_n &= 1.74\times10^{11}\cdot E^2[GeV]\cdot N^2\cdot I[mA] \\ &\times\frac{n^2K^2}{(1+K^2/2)^2}\left[J_{\frac{n+1}{2}}(\xi) - J_{\frac{n-1}{2}}(\xi)\right]^2 \\ &(photons/s\cdot mrad^2\cdot 0.1\%b.w.), \end{aligned} \tag{3}$$

where E is the electron energy in GeV, I is beam current, J_m is the mth order Bessel function and $\xi = \frac{n^2K^2}{4+2K^2}$. The calculated peak brightness reaches to 4×10^{18} at its maximum.

When the finite aperture of observation and the finite beam emittance are taken into account, the brightness is reduced as

$$B_{eff} = B_n\cdot\frac{1}{nN}\frac{\lambda_n}{\Delta\lambda_n}\frac{1}{\sqrt{1+\left(\frac{\sigma'_X}{\theta_n}\right)^2}\sqrt{1+\left(\frac{\sigma'_Y}{\theta_n}\right)^2}}. \tag{4}$$

In New SUBARU the beam divergence σ'_X and σ'_Y are 0.09 and 0.03 mrad, respectively. So the effective brightness will be reduced to $B_{eff} = 1\times10^{17}$ in our case. This value is about four order higher than PF undulator measured by Maezawa[4].

3 Absolute measurement of brightness

3.1 Measurement procedure

Fig. 1 shows a schematic drawing of the beamline set-up for the measurement. A differential pumping will be used to separate the ionization chamber operated in the $10^{-4}\sim10^{-5}$ Torr range from the high vacuum of the storage ring. A deflection mirror will be used to avoid γ-ray background which is generated by collisions of the stored electrons with the nucleus of residual gas atoms or ions trapped in the orbit of the electrons.

Fig.2 shows the principle of the measurement. In the monitor chamber a gas cell is placed on the axis of radiation beam. The rare gas such as He and Ar is loaded into the cell and maintained at a constant pressure about $10^{-4}\sim10^{-5}$ Torr. Irradation of the rare gas with soft X-rays ejects photoelectrons from atoms. Some electrons generated in the cell go through an aperture on the cell and are detected by the hemispherical analyzer. The spherical analyzer acts as a narrow bandpass filter and passes only those electron having a specific energy. Electrons entering the channeltron strike the channeltron wall and cause secondary emission, accelerating along the wall of the tube, the repeated collisions have an avalanche effect. Thus a single electron input gives rise to an output pulse of up to a hundred electrons. The analytical information is then derived from measurements of the energy distributions of the emitted electrons. The kinetic energy of the emitted electron E_{ke} is given by

$$E_{ke} = h\nu - \phi, \tag{5}$$

where $h\nu$ is photon energy and ϕ is a threshold energy of ionizing an atom from its ground state to the ion. Therefore, once the energy distribution of emitted photoelectrons is measured, the relative spectrum of incident radiation could be known.

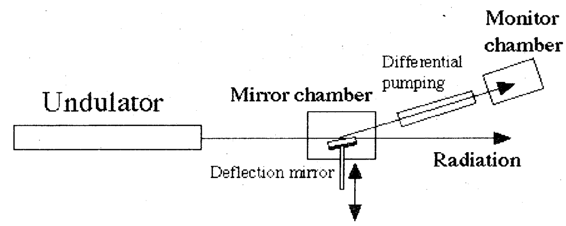

Fig. 1 Schematic drawing of the undulator beamline for absolute measurement of radiation intensity by photoionization of a rare gas.

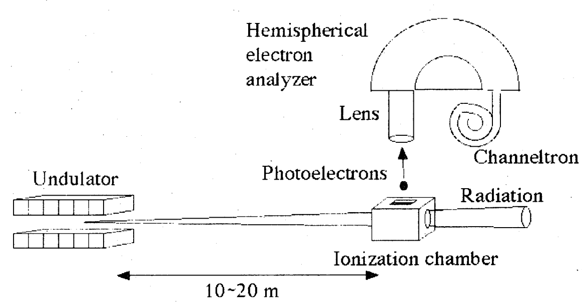

Fig. 2 Schematic drawing of the absolute measurement of undulator brightness by use of a hemispherical electron analyzer.

The bandwidth of the fundamental radiation, $\Delta E/E$, is 0.058. This corresponds to ΔE=5.5 eV for K=2.5. We will use VG100AX of VG MICROTEH Co. as the hemispherical analyzer, whose energy resolution is about 0.05% and enough to measure the bandwidth.

The linear polarization of radiation from a planar undulator causes asymmetric angular distribution of emitted photoelectrons. The angular distribution is given by

$$I(\theta) = \frac{\sigma}{4\pi}\left[1+\frac{\beta}{2}(3\cos^2\theta - 1)\right], \tag{6}$$

where σ is photoionization cross section, θ is the angle between the electric vector of radiation and the direction of emitted photoelectron, β is called asymetric parameter and $-1 < \beta < 2$. The measurement will be performed at the angle $\theta = 0°, 90°$ or at the magic angle $\theta = 54.7°$ where the effect of asymetric parameter vanishes.

For absolute measurement of radiation intensity the counting efficency of the device must be calibrated. That is, it is nessesary to know the relation between the number of incident photons and the number of electrons counted by the channeltron. The total number of photoelectrons generated in the ionization volume per second, dN_1, can be calculated from the incident photon number with photoionization cross section[7] and the number of atoms of a rare gas in the ionization volume

$$dN_1 = \sigma n_n \ell I, \tag{7}$$

where σ is photoionization cross section, n_n density of atoms, ℓ the length of ionization volume and I is the intensity of radiation in photons/sec. The number of photoelecton injected to the electric lens of the analyzer, dN_2, is derived from the total number of photoelectron

$$dN_2 = f dN_1 \tag{8}$$

where f is a factor which depends on both angular distribution of photoelectrons and a solid angle that sees the aperture of the electrostatic lens. The number of electrons counted by the channeltron, dN_3, depends on the number of injected photoelectron, dN_2, and several parameters of the analyzer such as channeltron voltage V

$$dN_3 = \zeta(V) dN_2 = \eta dN_1, \tag{9}$$

where $\zeta(V)$ is an amplification factor of the channeltron which depends on the channeltron voltage V, η is the total efficiency of the measurement. Therefore, once the total counting efficiency of the device, η, is calibrated, the absolute brightness of the radiation can be evaluated from the counted number of electrons.

For calibration of the device, we will use an electon gun whose beam properties such as current and beam size are known and investigate the relation between the number of electrons form the gun and the counted number of electons amplified in the channeltron under the same experimental conditions as the actual measurement. According to this calibration data, we can estimate the brightness of undulator radiation from the number of counted electrons. The efficiency could be increased by an optimization of the dimension of cell, an increase of the pressure of rare gas and an suitable choice of the kind of rare gas whose cross section is large at the desired photon energy region.

3.2 Expected results

Here we can estimate the number of electrons which can be counted by the channeltron in the case of New SUBARU long undulator. Assuming that ℓ=1cm, $n_n = 1.6 \times 10^{12}$, K=2.5, radiation wavelength 10nm and He as a rare gas, the total number of photoelectrons generated in the cell, dN_1, is about 750 electrons/sec. Assuming the isotropic distribution of emitted photoelectrons for simplicity, the number of photoelectron injected to the analyzer, dN_2, is about 10 per seccond in 0.1%bandwidth. Thus the counting rate in the channeltron is expected to be about 1000 electreons per sec. For precious estimation of the number of photoelectrons, both the precious measurement of the pressure of rare gas in the cell and the precious calibration of η would be key-issues in this method.

4 Summary

Measuring the photoelectron emitted from rare gas atoms with the hemispherical electron analyzer, the radiation profile of the New SUBARU undulator in soft X-rays will be evaluated. The energy distribution of emitted photoelectrons gives the bandwidth of radiation. And when the device is well calibrated, the brightness can be evaluated in an absolute scale. The precious measurement of the density of rare gas and the precious calibration of the device would be important. The counting ratio could be increased by optimazation of the device and set-up parameters. The experiment will be performed after the install of the long undulator.

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