Nuclear Instruments and Methods in Physics Research A 337 (1994) 598–602
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Investigation on the characteristics of synchrotron radiation emitted by the Hefei 800 MeV synchrotron radiation facility

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(Received 22 July 1993)

Based on Schwinger's theory, the spectral distribution, the angular distribution and the polarization of the Hefei 800 MeV synchrotron radiation facility were calculated. The measurement of the spectral distribution was carried out in the 300–800 nm range by using a tungsten halogen spectral irradiance standard source. The polarization and the angular distribution were investigated at 405 nm. A good agreement was found between experimental results and values predicted by the theory of synchrotron radiation derived by Schwinger. The difference of the relative spectral distribution between experimental and theoretical data is less than 1.5% in the 300–800 nm region and the difference between the angular distribution and the polarization is less than 5%.

1. Introduction

Due to relativistic effects, highly energetic electrons in a synchrotron facility can emit strong electromagnetic radiation in the direction tangent to the electron orbit. This electromagnetic radiation is called synchrotron radiation. Synchrotron radiation is an excellent source of radiation, especially in the VUV and the soft X-ray spectral range. It has the following characteristics:

1) a theoretically predictable broad continuous spectral distribution which covers a wide spectral range, from soft X-ray to infrared;
2) a high degree of polarization;
3) high intensity. Its radiation is confined to a narrow cone around its circular orbit.

For these reasons, synchrotron radiation can be widely utilized for atomic and molecular physics, solid-state physics, photochemistry, biochemistry, soft X-ray microscopy and lithography technology, and VUV and soft X-ray spectral radiometric metrology.

Since the 1950s, in order to establish the VUV and soft X-ray radiation standard using synchrotron radiation, synchrotron radiation has been investigated in detail. The Glasgow University 340 MeV synchrotron radiation is investigated by using a tungsten filament lamp, standard, whose spectral emission has been established by comparing it with a blackbody radiator at known thermodynamic temperature. The agreement between experimental and theoretical data of the spectral distribution is better than 1% in the 350–600 nm region. Codling and Madden [2] measured the angular distribution and the polarization of NBS 180 MeV electron synchrotron radiation at 550 nm. The agreement between experimental results and theoretical calculation is better than 3–5%. In 1986 Kostkowski et al. [3] compared the spectral irradiance of NBS SURF2 and tungsten FEL scale at 297 nm and 254 nm with an uncertainty of 1%. Lemke and Labs [4] studied 6 GeV DESY synchrotron radiation in the spectral 220–550 nm range. The results showed that the difference between the measured and the predicted spectral distribution is better than 2%. In short, in the last twenty years, based on studies of synchrotron radiation, several advanced industrial countries like the USA, England, Germany, France and Japan have established VUV and soft X-ray spectral radiometric standards by means of synchrotron radiation.

In our country, a synchrotron radiation source has been built in 1991 at Hefei University of Science and Technology. This source provides a necessary condition for establishing a Chinese standard of radiation metrology using synchrotron radiation. In this paper the measurement results of the spectral distribution, the angular characteristics and the polarization characteristics of the 800 MeV HESYR and a comparison between experimental results and theoretical values will be present.

0168-9002/94/$07.00
SSDI 0168-9002(93)E0618-3

2. Theoretical calculation of the 800 MeV HESYR

2.1. Spectral and angular distribution

Due to relativistic effects, the instantaneous radiation from an electron with an energy of several MeV is confined to a narrow cone in the forward direction of motion. As the electron proceeds around its circular orbit, this cone of radiation sweeps through the area of observation, causing the time-average distribution flux to be completely uniform in the direction parallel to the orbital plane. Thus the mentioned angular distribution is in the direction perpendicular to the orbital plane.

The angular and spectral distributions of synchrotron radiation have been calculated by Schwinger [5]; the power radiated by a monoenergetic electron in circular motion is given by

$$P(\theta, \lambda) = \frac{8\pi e^2 c^2}{3\omega_0 \lambda^4}\left(\frac{m_0 c^2}{E}\right)^4 (1+x^2)^2 \times \left[K_{2/3}^2(\xi) + \left(\frac{x^2}{1+x^2}\right) K_{1/3}^2(\xi)\right], \quad (1)$$

where $P(\theta, \lambda)$ is the power in erg/(s rad Å) and $\xi = (2\pi R/3\lambda)(m_0 c^2/E)^3(1+x^2)^{1/2}$, with $x = (E/m_0 c^2)\theta$. Here θ is the azimuth angle of observation, measured relative to the orbit plane, $\omega_0 = C/R$ is the orbital angular frequency, R is the radius of the electron orbit, λ is the radiation wavelength, and $K_{1/3}$, $K_{2/3}$ are modified Bessel functions for the second kind. So when the average beam current is I, the average radiation power P_λ (W/(Å mrad)) at wavelength λ, bandwidth 1 Å and per mrad angle parallel to the orbital plane is given by

$$P_\lambda(\lambda) = 1.406 \times 10^{-3} I B^2 E^5 \left(\frac{\lambda_c}{\lambda}\right)^3 \times \int_{\lambda_c/\lambda}^{\infty} K_{5/3}(\xi)\, d\xi, \quad (2)$$

where $\lambda_c = 186.4/(BE)^2$ is the critical wavelength.

The Hefei synchrotron radiation light source is a main facility dedicated to synchrotron radiation research. The main parameters of the storage ring are listed in Table 1. Based on the parameters of the Hefei 800 MeV synchrotron radiation facility listed in Table 1, the average radiation power per ampere beam current was calculated from Eq. (2) as shown in Fig. 1.

In Fig. 2, the angular power distribution is given for an electron energy of 800 MeV at three different

Table 1
The main parameters of the 800 MeV storage ring

Electron energy	800 MeV
Current intensity	100–300 mA
Bending radius	2.2221 m
Bending magnet field	12 kG
circumference	66.1308 m
Number of bending magnets	12
RF frequency	204.0 mHz

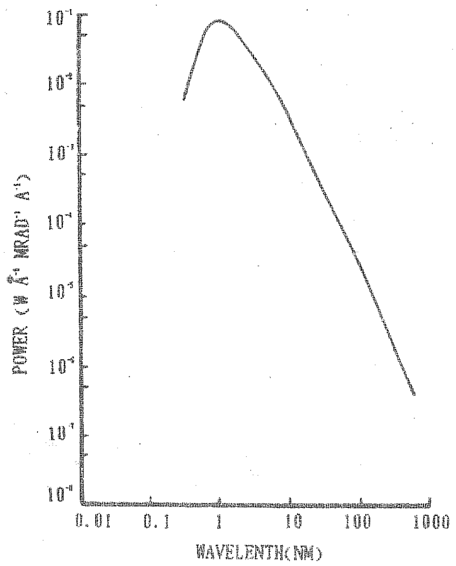

Fig. 1. Power radiated by HESYR as a function of waveleng.h.

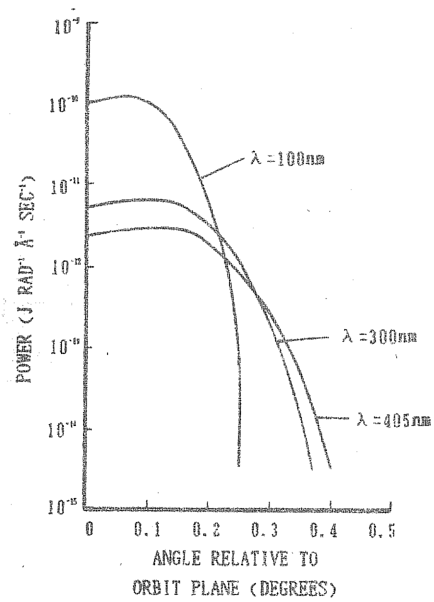

Fig. 2. Radiation power per electron as a function of the observation angle measured relative to the orbit plane.

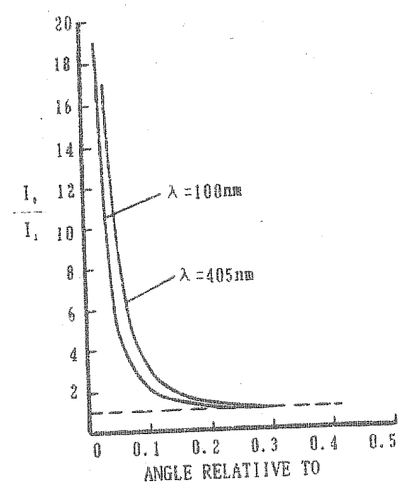

Fig. 3. Ratio of the intensity $I_\parallel$ to $I_\perp$ plotted as a function of the angle measured relative to the orbit plane.

wavelengths from Eq. (1). It can be seen that the radiation is indeed confined to a narrow angular cone, which increases in angular extent with increasing wavelength.

2.2. *Polarization*

Polarization is an important characteristic of synchrotron radiation. The radiation is predominantly polarized with the acceleration vector. In Eq. (1), the first term on the right hand side represents the contribution of polarization with its electric vector in a plane parallel to the orbital plane, while Eq. (1) reflects not only the spectral radiation power distribution, but also the relationship of polarization, wavelength, and the angle above or below the orbital plane. Therefore the following relationship exists for the ratio of the intensities of the two components:

$$I_\parallel / I_\perp = (1 + x^2)/x^2 K_{2/3}^2(\xi)/K_{1/3}^2(\xi). \quad (3)$$

The calculated variation of this ratio with the angle above or below the orbital plane is shown in Fig. 3.

It can be seen that when the angle approaches zero the ratio becomes infinitely large, and when the angle is increased the ratio approaches unity. This means that the radiation is 100% polarized in the orbital plane.

3. Experimental investigation

3.1. *The spectral distribution of synchrotron radiation*

The experiment was carried out at the Hefei Synchrotron Radiation Laboratory [HESYRL] in June 1992. The synchrotron radiation was guided through a beam duct to an experimental site, where an optical system was set up as shown in Fig. 4. The beam duct was closed by a quartz glass window. The measuremental equipment consists of a diffuse plate, a Czerney-Turner plane grating monochromator, a R928 photomultiplier detector (185–930 nm, Japan), a DC signal amplifier, a stepping motor driver for wavelength scanning and an IBM-PC microcomputer. The resolution of the monochromator is 0.1 nm and the spectral bandwidth for this measurement is 0.4 nm. The conversion for high voltage of the photomultiplier and the amplifier gain, the signal collecting and processing are all controlled by the computer.

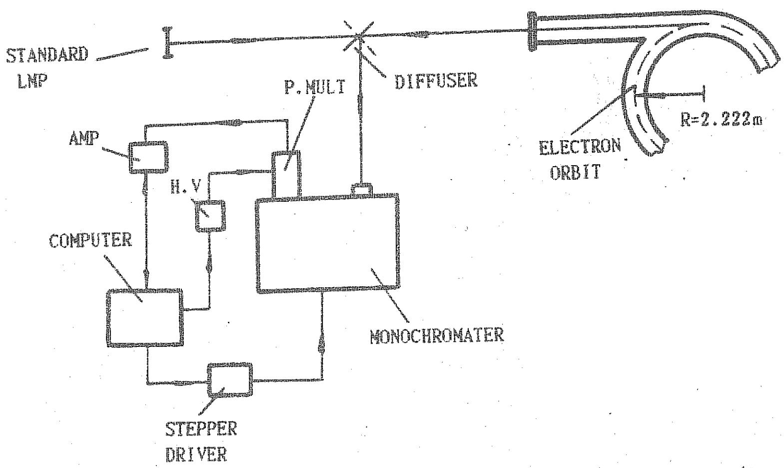

Fig. 4. Arrangement of the optical system for spectral distribution measurements.

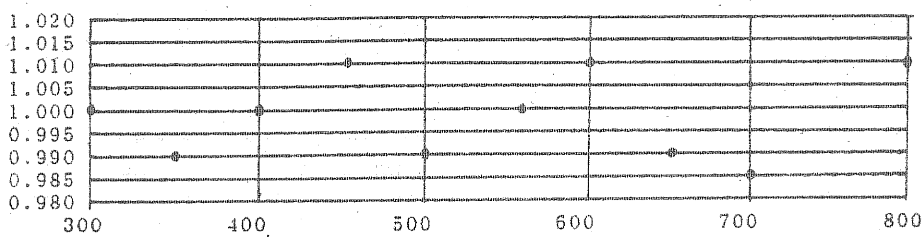

Fig. 5. Ratio of the measured and the calculated spectral distribution (I_{exp}/I_{cal}). The ratios are normalized at 555 nm.

In this experiment, the spectral irradiance transfer standard source is a 1000 W tungsten halogen lamp calibrated by the National Institute of Metrology of China with a blackbody radiator at a known thermodynamic temperature. This lamp is working in the 250–2500 nm range with a current of 8.5 A. The current stability of the power supply is better than 0.02% per hour.

The radiation from the synchrotron radiation facility through the diffuser plate entered the monochromator, and the detector output signals were collected by the computer. Then the transfer standard source was measured by turning the diffuser plate by 90°. Another detector has been used for monitoring the beam current signal drift. The signal of this detector is used for correcting the final results. In order to cancel the effect of the electronic system drift, the measurement mode of the synchrotron radiation source–standard source–synchrotron radiation source was employed, and the average ratio for each wavelength times the spectral irradiance distribution of the tungsten halogen standard source gives the spectral irradiance distribution of the synchrotron radiation. The measuring wavelength range is from 300 nm to 800 nm and the sampling interval is 0.1 nm. Fig. 5 shows the measured relative spectral distribution compared with theoretical data. The agreement is better than 1.5% in the 300–800 nm region.

The measurements were performed at various beam currents (from 45 mA to 150 mA) and the agreement is within 0.5%, the uncertainty of the relative spectral irradiance of the standard lamp is 1–2% in the 300–800 nm region, the transmittance variation of the fused quartz window of the beamline end in the 300–800 nm range is less than 1%, and the long and short term stability of the measurement system is better than 0.5%. Therefore the agreement between theoretical and experimental data is within the experimental error.

3.2. Polarization and angular distribution

The measurement system shown in Fig. 6 is utilized for studying the polarization and the angular distribution of radiation emitted by the 800 MeV HESYR. An aperture, 1 mm in diameter, and an interference filter (10 nm bandpass at 405 nm) was placed in front of the multiplier which could be moved vertically to scan the vertical distribution of the radiation. To examine the polarization characteristics of the radiation, a Glan–Taylor prism was interposed between the 1 nm aperture and the scanning photomultiplier. The transmission range of the prism is from 300 nm to 2500 nm and

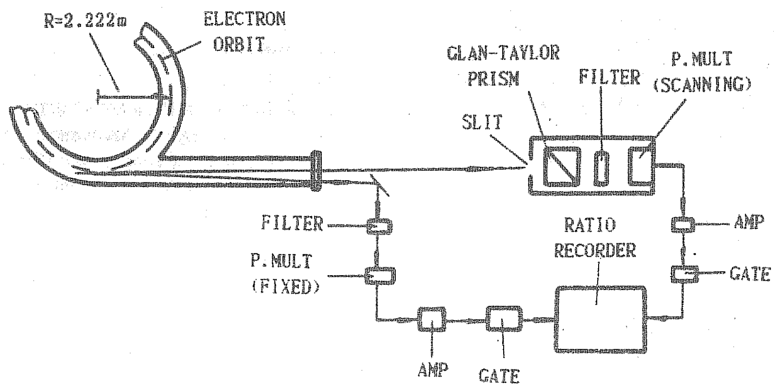

Fig. 6. Instrument utilized for the study of polarization and angular distribution.

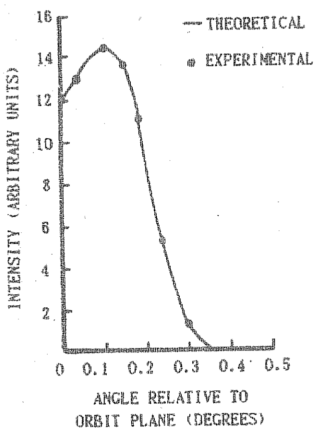

Fig. 7. Comparison of theory and experiment for the intensity radiated as a function of the observation angle measured relative to the orbit plane.

the extinction ratio is 10^{-5}. Because of the temporary strong variation of the number of electrons in the orbit, measurements were performed only when the stability was sufficiently good. Under the best condition the variation of the number of electrons was smaller than about 10% for 1 min or 2 min. To eliminate the intensity variations, and to obtain a normalizing signal, a ratio technique was used. A mirror was placed at 40° to the beam as shown in Fig. 7. This mirror intercepted a fraction of the synchrotron radiation which was then reflected, into a fixed photomultiplier through an interference filter, and a reference signal was recorded.

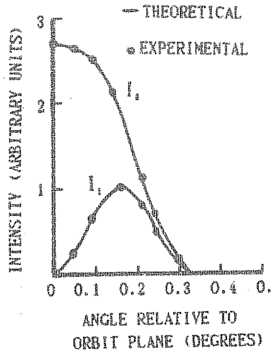

Fig. 8. Comparison of theory and experiment for the intensity radiated in each component of polarization as function of the observation angle measured relative to the orbit plane.

Typical results are shown in Figs. 7 and 8. It should be pointed out that the theoretical and experimental curves have been normalized at the peak of the parallel component. The agreement between theoretical and experimental values is within 5%. This disagreement comes from the following reasons: 1) The fused quartz window must be carefully selected to avoid noticeable distortion of the polarization distribution. For example, if the window rotates the plane of polarization, then a portion of the larger parallel component will be recorded erroneously as a contribution to the perpendicular component. 2) The effect of electron beam size. The finite size of the electron beam in this machine causes a small departure of the measured results from those theoretically predicted for a single electron. 3) The stability of the measurement system.

4. Conclusion

The study of the spectral distribution in the 300–800 nm range, polarization and angular distribution at 405 nm of the 800 MeV HESYR was performed. The results showed a good agreement between the measured and the calculated values within the experimental error. It has been confirmed that Schwinger's theory accurately predicts the characteristics of synchrotron radiation in the visible range. The following evaluation will be carried out in the near future: 1) A comparison between the synchrotron radiation and a spectral irradiance standard source deuterium lamp based on synchrotron radiation over the 200–350 nm spectral range supplied NPL, England. 2) A comparison between plasma blackbody limited lines from an argon wall-stabilized arc [6] and synchrotron radiation in the vacuum ultraviolet spectral range, and a VUV and soft X-ray spectral radiometric standard will be established by means of synchrotron radiation.

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