A BEAM PROFILE MONITOR FOR THE NSLS VUV RING EMPLOYING LINEAR PHOTODIODE ARRAYS*

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Abstract

Among the most important parameters of a storage accelerator are the position and size of the particle beam. In an electron machine, these parameters can be derived from measurements of the emitted synchrotron radiation. We discuss a system which monitors the two-dimensional profile of the synchrotron light in the NSLS VUV ring using commercially available high-resolution linear photosensitive diode arrays. The optical system has been designed to match the size of the image space to the dimensions of the diode sensor area. The scanning rate is automatically adjusted to hold the peaks of the profiles constant over a wide range of beam intensity variations. Video signals from the diode sensors can be readily interfaced to a computer for beam diagnostic purposes. Optics and factors determining the overall resolution of the system are discussed. Preliminary results of beam observations are presented.

1. Introduction

In circular accelerators, synchrotron radiation is widely used to measure the position and cross-section of the beam. Synchrotron radiation (SR) is emitted tangentially to the arcs in the bending magnets with a small natural opening angle [1-3]

$$\psi \approx \frac{1}{\gamma} \left(\frac{\lambda}{\lambda_c}\right)^{1/3}, \qquad (1)$$

where λ_c is the critical wavelength. Observation of the beam in the horizontal plane is complicated by the fact that the light is emitted by all points along the arc and the beam sweeps through an angle θ in the plane of the orbit, as illustrated in Fig. 1. The arc length and the horizontal width of the apparent source are related to the observation angle as

$$s = \rho\theta \qquad (2a)$$

and

$$\Delta x = \frac{\rho\theta^2}{8} = \frac{s^2}{8\rho} \quad , \qquad (2b)$$

where ρ is the bending radius of the magnet.

Limiting θ reduces the depth of field but causes apparent widening of the source due to diffraction. The diffraction limit in this case is

$$\delta x = \frac{\lambda}{\sin\theta} \approx \frac{\lambda}{\theta} \qquad (3)$$

which is approximately equal to 0.9 FWHM (full width half max.) of the central maximum of the diffraction pattern. Equating (2b) and (3) gives the optimum value of the observation angle

$$\hat{\theta} = 2 \left(\frac{\lambda}{\rho}\right)^{1/3} \qquad (4)$$

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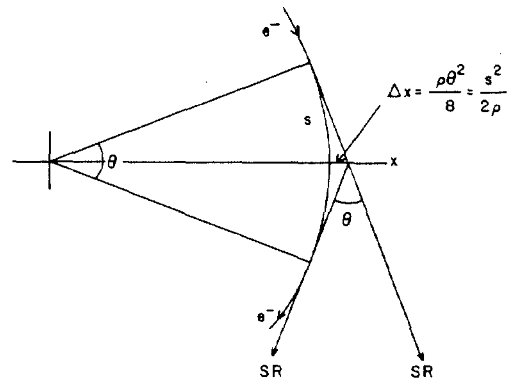

Fig. 1. Optical source in the horizontal plane.

In practice θ will be determined by an aperture of width $a = \ell\theta$ at a distance ℓ from the source. In the vertical direction this aperature should be matched to the natural opening angle of the radiation given in(1).

The observed SR can be focused on a detector with an optical system which in the simplest form may consist of a single focusing lens. From the expression in (3), it is clear that the shortest wavelength in the spectrum consistent with the response of the detector should be used. In some cases wavelength converters and intensifiers may be used to match the detector response to shorter wavelengths. In the design of the optical system, transmission characteristics of all elements including the vacuum window must be considered.

In the NSLS VUV ring, the size of the electron beam is on the order of 0.5 mm horizontally and 0.15 mm vertically, FWHM. The range of the beam motion in the horizontal and vertical planes can be as much as ±5 mm and ±3 mm, respectively. The spectrum of the synchrotron light ranges from the near UV through the visible, with $\lambda_c \approx 31$Å. The bending radius of the dipole magnet is 1.9 m. A vertical aperture of 6 mm at 0.4 m from the source determines the maximum opening angle of the system to be ±7.5 mrad. while the natural opening angle at 400 nm (for 90% of light collected) is only ±4.1 mrad. At the moment, the vacuum chamber windows are not UV transmitting.

Photodiode detectors have been introduced at the NSLS for beam profile measurement several years ago. These detectors had good spatial resolution but very small apertures. Detectors described in this paper have equally good resolution but are longer and have a much larger aperture. The design of the optical system has been simplified and the resolution improved. Cylindrical lenses have been introduced to match the size of the image space to the dimensions of the detector. An automatic scan control circuit has been developed to hold the peaks of the profiles constant over a wide range of beam intensity variation.

In this paper we discuss some of the resolution measurements of the optical system used in the monitor. We also present preliminary results of beam profile measurements at one of the VUV ring beam ports (U5).

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2. Detector

With the vertical beam size of approximately 200 μm FWHM, vertical resolution of the detector must be on the order of 20 μm, and the horizontal length of the sensor array must be > 10 mm. Containment of the beam image within the detector aperture requires either a large enough aperture or an adjustment of the magnification of the optical system.

Solid state self-scanning linear photodiode arrays which satisfy all but the transverse aperature requirement are available commercially [4]. These arrays which may contain up to 1024 diode sensors on 25 μm centers have an aperture of 2.5 mm. A 512 element array has an overall length of 12.8 mm. The width of each sensor element is 13 μm. In the array, light collected on a sensor area generates a charge which is proportional to the intensity of the incident light and to the integration period. Charges accumulated on the photodiodes are read out sequentially and processed by a sample and hold amplifier. The resulting video output signal appears as a sampled and held boxcar waveform.

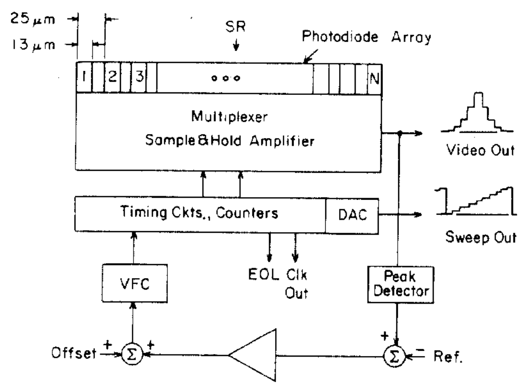

Fig. 2. Block diagram of detector electronics.

Since the dark current of the sensors at 25°C is on the order of 5 pA and the arrays can be read out at clock rates in excess of 1 MHz, a good signal to noise ratio can be obtained over a wide range of integration periods. The quartz-windowed version of the scanners has a responsivity of about 2.8 x 10^{-4} C/J/cm^2 and a spectral response range from 250-1000 nm. A block diagram of the detector electronics is shown in Fig.2. In the detector, the peak of the video output is held constant for slow variations of beam intensity by an automatic scan control loop which controls the clock frequency (output of VFC). The dynamic range of the loop is approximately 36 db and the bandwidth is 3 Hz.

3. Optics

In the VUV ring, two beam ports were available for observation of the synchrotron light. At U15 (side port), the distance from source to the outer surface of the vacuum window was 1.02 m and at U5 (vertical port), the distance was 1.94 m. It was decided to use a single lens system with unity conjugate ratio for each case to minimize errors. Two 50 mm symmetrical spherical lenses with focal lengths of 69 cm and 100 cm, respectively, were bench tested. For the case, where the D/f ratio is small, the error due to spherical aberration is small. In this case, the on-axis angular error, as given in Ref.5, is

$$\theta_s = (1/2)K(N)(D/f)^3. \qquad (5)$$

For fused silica lenses at λ=400 nm, $K(N) = 5.35\times10^{-5}$, which gives

$$\theta_s = 1.013\times10^{-8} \text{ radians.} \qquad (6)$$

A 400±30 nm bandpass filter was used to improve the resolution of the system by reducing the chromatic error. A cylindrical lens with f=25 mm was placed in front of the detector to give a magnification of 0.25 in the transverse direction.

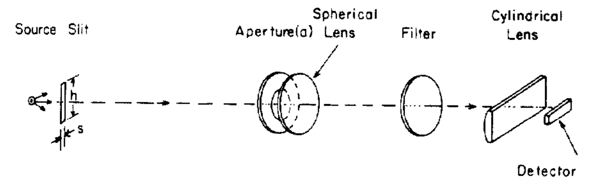

Fig. 3. Optical system used in bench measurements.

4. Bench Measurements

The spatial resolution of the optical system was measured in the laboratory using narrow slits illuminated by a 150 W incandescent source. A variable circular aperture with a maximum diameter of 30 mm was placed in front of the spherical lens to measure the contribution to the overall profile width by diffraction. A general layout of the laboratory setup is shown in Fig.3. A profile of a 25 μm wide slit (σ_s=7.2 μm)* with a=30 mm obtained with the photodiode array is shown in Fig.4a. Widths of profiles obtained with other slits are plotted in Fig.4b.

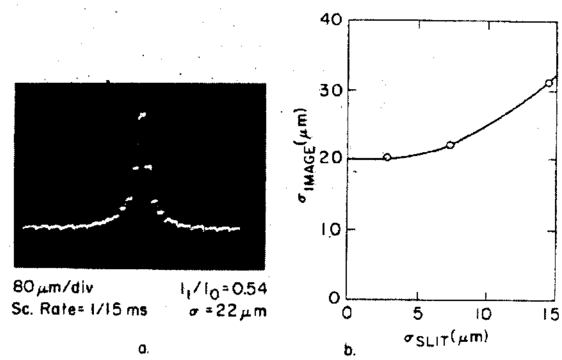

Fig. 4. (a) Profile of a 25 μm wide slit, (b) Profile width vs. slit width.

Variations of the profile width as a function of aperture were measured both with and without the filter and are shown in Fig.5a. The width due to diffraction error of the circular aperture, which can be defined as

$$\sigma_d = \frac{1}{2.35}\left(1.22\,\frac{\lambda\ell}{a}\right) \qquad (7)$$

is also plotted in Fig.5a.

Assuming that all errors are gaussian distributed and independent, and that the spherical error is zero, the maximum chromatic error for this case can be determined to be

$$\sigma_{ch} = \sqrt{(\sigma_b)^2-(\sigma_d)^2-(\sigma_s)^2} \qquad (8)$$

$$= \sqrt{(22)^2-(9.5)^2-(7.2)^2}\times10^{-6} = 18.5 \text{ μm},$$

*We let $\sigma_s = s_{rms} = s/\sqrt{12}$

where σ_b is the measured width and σ_s is the width of the slit. Calculation of the overall width using the above values of σ_{ch} and σ_s agree with the measured data in Fig. 5a.

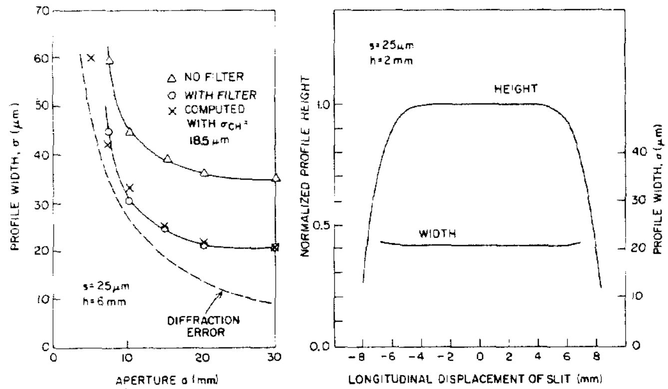

Fig. 5. (a) Measured profile width as function of aperture, (b) Profile height vs. long. displacement of slit.

For the case where the profile width approaches the resolution of the detector, as in Fig.4a, σ of the distribution (assumed to be $N(0,\sigma)$) can be determined from the ratio of signals generated by two adjacent sensor elements in the array. The signal developed by any given element, I, is proportional to the flux integral over the area, i.e.

$$I(\sigma) = K \int_{-a/2}^{a/2} \exp\left(-1/2(x/\sigma)^2\right)dx,$$

as illustrated in Fig.6. Since

$$\frac{I_1}{I_0}(\sigma) = \frac{\Phi\left(\frac{b+a/2}{\sigma}\right) - \Phi\left(\frac{b-a/2}{\sigma}\right)}{\Phi\left(\frac{a/2}{\sigma}\right) - \Phi\left(\frac{-a/2}{\sigma}\right)} \qquad (9)$$

where

$$\Phi(z) = \int_{-\infty}^{z} \exp\left(-1/2(x/\sigma)^2\right)dx,$$

σ can be determined for a given diode array geometry.

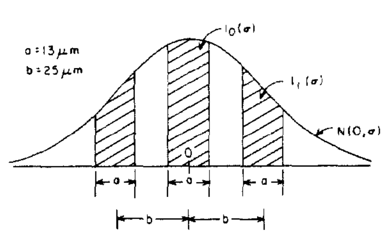

Fig. 6. Definition of integrals I_0 and I_1.

Sensitivity of the profile measurement to the movement of the beam in the transverse direction was checked by moving a slit axially with respect to the midplane of the detector. Results of this measurement, plotted in Fig. 5b, show that the system is insensitive to transverse motion over a ±6 mm range.

5. Beam Profile Measurements

At the U15 port, where a small part of the photon beam was deflected horizontally by two mirrors, beam observations were obscured by reflections from the edge of one mirror and problems due to beam polarization. At U5, where the beam was brought out vertically, reasonably good profiles were observed. The layout of the optics at U5 is shown in Fig. 7. The horizontal and vertical widths were measured to be 510 μm and 61 μm, respectively.

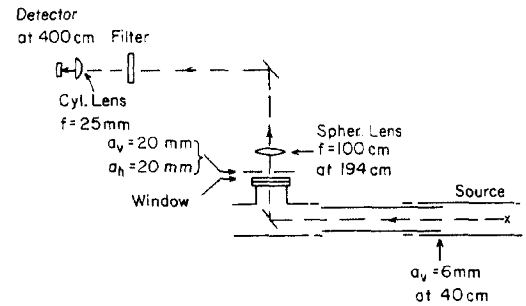

Fig. 7. Layout of optics at beam port U5.

Although the aperture was set at 20 mm H by 20 mm V, the vertical aperture was limited by the opening angle of the radiation to approximately 17 mm. Combining the error due to diffraction (σ_d = 400 x 10^{-3} x 1.94/2.35 x 17.10^{-3} = 19.4 μm) with chromatic error determined from data in Fig. 5, assuming that $\sigma_{ch} \propto a$, the total resolution error for the system at U5 was

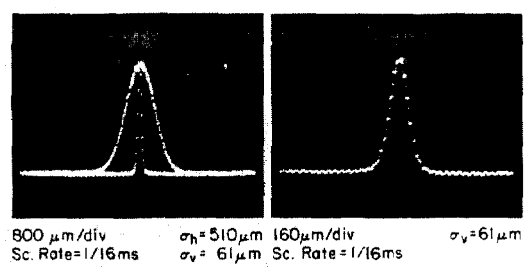

Fig. 8. Horizontal and vertical beam profiles at U5.

$$\sigma_e = \sqrt{(19.4)^2 + (12.3)^2} \times 10^{-6} = 23.0\ \mu m \qquad (10)$$

and therefore the actual vertical beam size could be estimated to be

$$\sigma_v = \sqrt{(61)^2 - (23)^2} \times 10^{-6} = 56.5\ \mu m. \qquad (11)$$

Acknowledgements

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