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Measurement of the coherence of synchrotron radiation

Y. Takayama,[a*] R. Z. Tai,[a] T. Hatano,[b] T. Miyahara,[c] W. Okamoto[d] and Y. Kagoshima[e]

[a]Department of Synchrotron Radiation Science, Graduate University of Advanced Studies, 1-1 Oho, Tsukuba, Ibaraki 305, Japan, [b]Research Institute for Scientific Measurement, Tohoku University, 2-1-1 Katahira Aobaku, Sendai 980-77, Japan, [c]Department of Physics, Faculty of Science, Tokyo Metropolitan University, 1-1 Minami-Ohsawa, Hachioji, Tokyo 192-03, Japan, [d]Photon Factory, Institute of Materials Structure Science, 1-1 Oho, Tsukuba, Ibaraki 305, Japan, and [e]Department of Physics, Faculty of Science, Himeji Institute of Technology, 1479-1 Kanaji, Kamigori, Ako, Hyogo 678-12, Japan. E-mail: taka@powerpc4.kek.jp

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The first-order spatial (transverse) coherence of synchrotron radiation has been measured using a Young's interferometer at BL28A (a helical-undulator beamline) of the Photon Factory, KEK. The range of the photon energy is about 70–180 eV. The visibility of the fringe was found to depend largely on the electron emittance and the intrinsic photon emittance. In principle, it is possible to gain knowledge of the very small electron emittance, of the order of 10^{-10} m rad, without disturbing the electron beam in the storage ring.

Keywords: coherence; Young's interferometer; visibility; emittance.

1. Introduction

Recently, a number of low-emittance storage rings as light sources have been constructed, and thus the coherence of synchrotron radiation becomes more and more important. Some experiments to measure the spatial coherence of synchrotron radiation in the hard X-ray region have been performed (Sutton *et al.*, 1991; Grübel *et al.*, 1994; Baron *et al.*, 1997; van der Veen *et al.*, 1997; Fezzaa *et al.*, 1997). In the soft X-ray region a wavefront-division interferometer has been used for measuring the refractive indices of materials (Svatos *et al.*, 1993).

We have constructed a Young's interferometer to measure the first-order spatial coherence of synchrotron radiation in the soft X-ray region (Hatano *et al.*, 1997). By measuring the visibility, which describes the contrast of the interference fringes, and the beam size on the transverse plane, one can evaluate the electron-beam emittance in the storage ring, using an analogy of the Michelson stellar interferometer.

2. Design of the interferometer

Our system of the Young's interferometer consists of an entrance slit, a grating, an exit slit and a photomultiplier tube detector (Fig. 1). The entrance slit has two apertures which are set parallel with a separation D = 30, 50, 100, 150 and 200 µm. Each aperture has a height l_1 = 100 µm and a width d = 5 µm. The resolution of the grating monochromator depends on the slit length, l_1, while the envelope of the interference pattern is determined by d. The exit slit width may be varied up to 500 µm. To scan the wavelength, we change the incident angle, α, the outgoing angle, β, and the entrance focal length, a. The photomultiplier tube, covered with the 5 µm vertical slit, is scanned horizontally to detect the pattern. The whole system can be rotated around the optical axis, which enables measurement of the spatial coherence along an arbitrary transverse orientation. We define the 'vertical' direction of the double slit when they are vertically separated. The 'horizontal' direction of the double slit is defined in a similar way. A detailed explanation of the design will be given elsewhere (Hatano *et al.*, 1997).

3. Visibility

In this section we will derive a simple relation between the visibility and the emittance in the Gaussian and monochromatic approximation (Kim, 1986; Coïsson, 1995; Takayama *et al.*, 1998).

The measured electric current is proportional to the square of the electric field on the photomultiplier tube,

$$I(x) \propto \langle |E(x, x_e, \varphi_e)|^2 \rangle. \qquad (1)$$

Here $\langle \ldots \rangle$ denotes the ensemble average for the electrons in the storage ring. $E(x,x_e,\varphi_e)$ is the superposition of two electric fields from the double slit, which is generated from an electron whose phase space coordinate is (x_e,φ_e), and given by

$$E(x, x_e, \varphi_e) = \int_{-D/2-d/2}^{-D/2+d/2} dx_1 E_g(x_1, x_e, \varphi_e) \exp(ikr_1) + \int_{D/2-d/2}^{D/2+d/2} dx_2 E_g(x_2, x_e, \varphi_e) \exp(ikr_2), \qquad (2)$$

where $E_g(x,x_e,\varphi_e)$ is the electric field at the double slit and r_1 and r_2 are the distances from each slit to the observation point. If we suppose that the electron phase space has a Gaussian distribution,

$$f(x_e, \varphi_e) = (N_e/2\pi\sigma_e\sigma'_e) \exp(-x_e^2/2\sigma_e^2 - \varphi_e^2/2\sigma_e'^2), \qquad (3)$$

and suppose $E_g(x,x_e,\varphi_e)$ to be a Gaussian beam, we obtain a

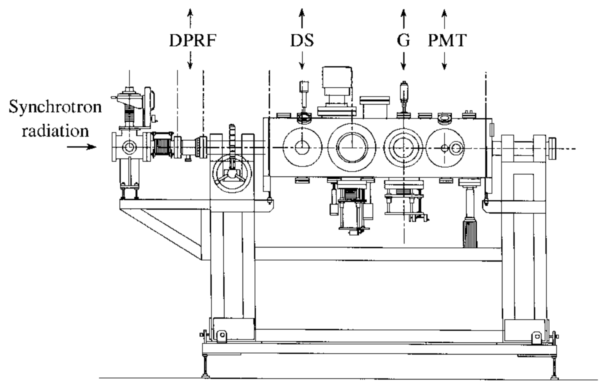

Figure 1
Side view of the Young's interferometer. DS, G, PMT and DPRF denote the double slit, the grating, the photomultiplier tube and the differentially pumped rotary feedthrough, respectively.

simple expression for the interference pattern,

$$I(x) \simeq I_0 F(x)[1 + V(D)\cos(kDx/L)], \quad (4)$$

$$F(x) = [\sin(kdx/2L)/(kdx/2L)]^2, \quad (5)$$

where k is the wave number and x is the position of the detector. I_0 is a constant, L is the distance from the double slit to the observation plan, and $F(x)$ is the Fraunhofer diffraction pattern which depends on the slit width, d. $V(D)$ is the visibility, which is a function of the separation of the double slit, D, and written as (Born & Wolf, 1980)

$$\begin{aligned} V(D) &= 2|\langle E^*(-D/2, x_e, \varphi_e)E(D/2, x_e, \varphi_e)\rangle| \\ &\quad /[\langle E^*(-D/2, x_e, \varphi_e)E(-D/2, x_e, \varphi_e)\rangle \\ &\quad + \langle E^*(D/2, x_e, \varphi_e)E(D/2, x_e, \varphi_e)\rangle] \\ &= \exp[-(\varepsilon^2 - \varepsilon_p^2)D^2/8\varepsilon_p^2\bar{\Sigma}^2], \end{aligned} \quad (6)$$

where $\varepsilon_p = \lambda/4\pi$ is the intrinsic photon emittance and ε is the convoluted emittance of the electron and photon beams. $\bar{\Sigma}$ is the beam size on the double slit. Equation (6) shows that the visibility is proportional to the first-order spatial coherence and the electron emittance can be obtained by measuring the beam size, $\bar{\Sigma}$, and the visibility, $V(D)$. It should be noted that the above formula does not include the Twiss parameters of the storage ring.

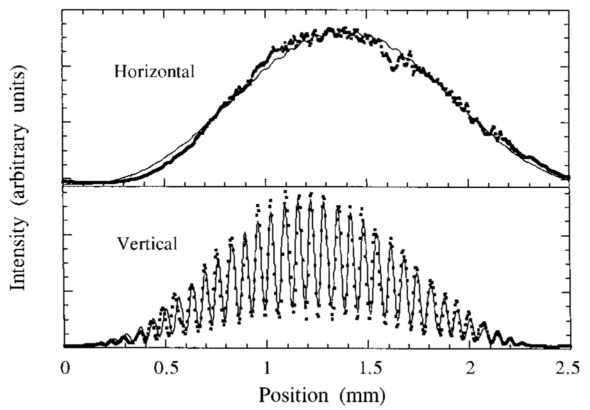

Figure 2
The interference patterns for E = 140 eV and D = 100 μm. The directions of the double slit are horizontal and vertical, respectively. The solid lines are the best-fit curves using (7), by the Marquardt–Levenberg algorithm.

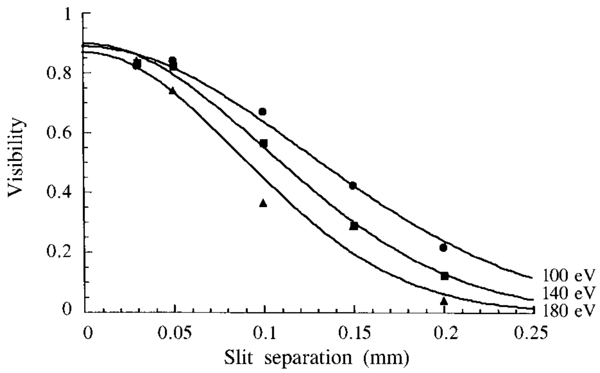

Figure 3
The dependence of the visibility, V, on the separation of the double slit, D. The solid lines are best-fit lines with $V(D) = (1 - \delta)\exp(-D^2/8\sigma_c^2)$, where δ and σ_c are fitting parameters.

4. Experimental

Our experiment to measure the first-order coherence was performed at BL28A of the Photon Factory, KEK. BL28 is a helical-undulator beamline of period length 16 cm and number of periods 12 (Kitamura, 1990). We mainly used the photon energies E = 100, 140 and 180 eV. The resolution of the monochromator is from about 100 to 200, which is enough to investigate the visibility because the range of visibilities we actually measured was worse than the temporal coherence derived from the above resolution. The photomultiplier tube to measure the interference pattern was scanned with a step of 5 μm. According to (4), the expected curve of the signal should be

$$\begin{aligned} I(x) &= I_0\{\sin[k_F(x - x_0)]/k_F(x - x_0)\}^2 \\ &\quad \times \{1 + V\cos[k_Y(x - x_0)]\} + I_{\rm drift}, \end{aligned} \quad (7)$$

where we supposed the drift current, $I_{\rm drift}$, to be constant and defined the central position by x_0. To calculate the visibility from the data, we fit them with $I(x)$ in (7) regarding I_0, k_F, k_Y, V, x_0 and $I_{\rm drift}$ as the fitting parameters. For example, the observed values of $2\pi/k_Y$ and $2\pi/k_F$ for E = 140 eV, D = 100 μm, in the vertical direction were 65.5 (μm) and 2.62 (mm), in good agreement with the theoretical values 65.4 (μm) and 2.37 (mm), respectively (Fig. 2). The dependence of the visibility on the separation of the double slit, D, is consistent with (6). One can see that the visibility for higher photon energies is smaller than that for lower ones because of the smaller phase volume of the coherence of each photon. The large difference between the visibilities for the vertical and horizontal directions is due to the difference between the electron emittances for the two directions (Fig. 2, Fig. 3). For the horizontal direction it is very hard to decide the visibility for large D because the dips are not clearly distinguishable.

The estimated value of the electron emittance is nearly 1 nm rad for the vertical direction, which is smaller than the expected value of 2.5 nm rad (Kitamura, 1990). This discrepancy is mainly due to the inaccurate estimation of the beam size on the double slit, $\bar{\Sigma}$. We are now improving our system to measure the beam size more precisely and it will be possible to obtain a more accurate value for the electron emittance.

5. Conclusions

We have constructed a new Young's interferometer and succeeded in measuring the spatial coherence of synchrotron radiation. We have verified the dependencies of the visibility on the slit separation, the wavelength and the slit direction, which are almost consistent with the simple Gaussian model. Our measurements enable us to estimate the electron emittance in a simple way. To obtain a more accurate value of the emittance we must improve the accuracy of the beam-size measurement on the double slit, which is not difficult and is in progress.

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