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Spatial coherence measurement of X-ray undulator radiation

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Abstract

We measure the spatial coherence function of a quasi-monochromatic 1.1 keV X-ray beam from an undulator at a third-generation synchrotron. We use a Young's slit apparatus to measure the coherence function and find that the coherence measured is poorer than expected. We show that this difference may be attributed to the effects of speckle due to the beamline optics. The conditions for successful coherence transport are considered. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Third-generation synchrotrons are being constructed around the world to permit the production of highly coherent X-radiation for a range of experiments such as scanning microscopy [1], interferometry [2], coherent scattering [3], and phase measurement [4,5]. The observation of phase induced effects in the radiation [6], although useful for phase measurement [4,5], raises questions concerning the effect of the beam optics on the coherence of the radiation and whether the coherence of the undulator beam can be usefully transported to the experimental apparatus. In this paper we compare a measurement of the coherence function at the experiment station with our theoretical expectation. We attribute the difference between the expected and the measured result to the effect of phase distortions acquired as the beam propagates along the beamline.

At a synchrotron, X-radiation is transported to the experiment station through a complex set of optics. It has been asserted that the beamline optics may act to destroy the coherence of the radiation [7]. Although Liouville's theorem states that coherence may not be destroyed by static optics [8], the phase may be sufficiently disrupted that the coherent radiation may be rendered indistinguishable from partially coherent radiation for some experiments. The aim of the experiment

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described here is to explore the extent of such "coherence degradation" in an X-ray undulator experiment.

In order to explore the underlying physics of laboratory X-ray lasers, there has been considerable work determining the spatial coherence of soft X-ray laser beams [9–12]. By comparison, little experimental work has been reported exploring the coherence properties of undulator beams. Measurements of spatial coherence using Hanbury–Brown Twiss interferometry have been reported [13,14]. Very recently, a Young's experiment has been used to measure the spatial coherence function of EUV radiation [15] from an undulator. Coherence lengths of EUV radiation from a helical undulator have also been determined [17]. At medium energy Fresnel mirrors have been used to measure vertical and horizontal coherence lengths [18]. Measurements of the spatial coherence length of hard X-ray undulator radiation have been extracted from a Young's arrangement [19], single-slit and wire Fresnel patterns [7], and from nuclear scattering [16].

2. Experiment

Following the work of Chang et al. [15], we use a Young's apparatus to measure the coherence function. The experiments were performed at the 2-ID-B beamline at the Advanced Photon Source [20]. The 7 GeV electron beam has an elliptical cross-section with vertical size $\sigma_y = 21$ μm and divergence $\sigma_{y'} = 3.9$ μrad. The horizontal electron beam size is substantially larger than the vertical size at $\sigma_x = 359$ μm with horizontal divergence of $\sigma_{x'} = 23$ μrad producing a horizontal emittance of 8.1 nm–rad. Fig. 1 shows the beamline optical geometry. The coherent flux available at the experiment station of this beamline is 10^{10}–10^{12} ph/s/0.1% BW.

An array of seven Young's slit pairs (10, 20, 50, 80, 100, 150 and 200 μm separation) were fabricated on a common X-ray transparent substrate. The slits were manufactured by standard contact optical lithography followed by gold electroforming onto a silicon nitride support membrane. The gold layer of the slit array was 1.6 μm thick which ensured adequate attenuation (>99.9%) of the 1.1 keV radiation. The design slit width was 3 μm but this was reduced in practice due to imperfections in the metallisation. The effective slit width for 1.1 keV X-rays was determined to be 2.0–2.3 μm from the X-ray diffraction profiles of the slits.

The Young's slits were oriented parallel to the entrance and exit slits of the monochromator. All measurements of the Young's interference patterns were made in the horizontal plane of the 2-ID-B

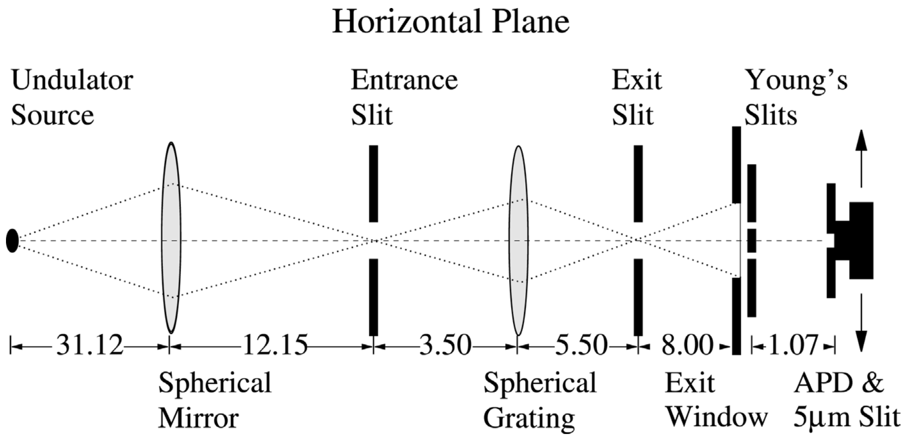

Fig. 1. The 2-ID-B beamline at the Advanced Photon Source showing beamline optics depicted as thin lenses in the horizontal planes. Distances shown are in metres. Distance from the exit slit to the experiment was 8.0 m and from the distance from the undulator source to the exit slit was 52.3 m. The Young's slits were placed 10 mm downstream of the beamline exit window which is 700 μm × 700 μm. The detector was an APD with 5 μm slit placed directly in front of the detector window.

experiment station, therefore we do not consider the vertical coherence function here. The intensity patterns were obtained by scanning an avalanche photodiode detector (APD) with a 5 μm wide by 3 mm high slit placed directly in front of it. The detector response under the experimental conditions was calibrated by two independent methods and the response function was consistent with a power law, $I_{\text{det}} = I^p + c$, where I is the input intensity, p describes the detector response as a power of the input intensity, c is a constant offset attributed to a deliberate small positive bias, and I_{det} is the measured detector output. The parameters p and c were determined to be $p = 2.0 \pm 0.1$ and $c = 4 \pm 4$ cps ($c \approx 0.4\%$ of maximum flux). This calibration has been applied to all the data presented in this paper.

We investigated the dependence of the spatial coherence on the exit slit width of the beamline monochromator (see Fig. 1 for their location in the beamline). The exit slit was located at the focus of the spherical grating in the horizontal plane as shown in Fig. 1. The exit slit has an offset for its zero position with an uncertainty of 15 μm, in part due to non-parallelism and irregularity of the slit blades, and this offset is included in the exit slit width whenever quoted.

3. Analysis and results

The fringe visibility was obtained by fitting the curve:

$$I(x) = I_0\left[\frac{\sin(\pi\alpha x/\lambda z)}{\pi\alpha x/\lambda z}\right]^2\left\{1+\mu_{12}\left[\frac{\sin(\pi\Delta\lambda x/\lambda z)}{\pi\Delta\lambda x/\lambda z}\right]\times\left[\frac{\sin(\pi\delta\beta/\lambda z)}{\pi\delta\beta/\lambda z}\right]\cos\left(\frac{2\pi}{\lambda z}\beta x\right)\right\} \quad (1)$$

to the data, where μ_{12} is the degree of coherence of the radiation we wish to measure. In this expression, the terms

$$\left[\frac{\sin(\pi\alpha x/\lambda z)}{\pi\alpha x/\lambda z}\right]^2 \quad \text{and} \quad \cos\left(\frac{2\pi}{\lambda z}\beta x\right) \quad (2)$$

are the conventional envelope and interference functions, respectively, of the two-slit diffraction pattern [8] where the Young's slits have width α and separation β. I_0 is the central intensity of the light. The fringes are assumed to be centred at $x = 0$. The radiation is of wavelength λ with wavelength spread $\Delta\lambda$ and is detected with a spatial resolution δ located a distance z from the slits.

The product

$$\left[\frac{\sin(\pi\Delta\lambda x/\lambda z)}{\pi\Delta\lambda x/\lambda z}\right]\left[\frac{\sin(\pi\delta\beta/\lambda z)}{\pi\delta\beta/\lambda z}\right] \quad (3)$$

then represents the effect on the conventional Young's result of the wavelength distribution and the detector resolution. The nominal slit size and width were known, but were adjusted within experimental error to obtain the best fit to the fringe envelope. The degree of coherence was then deduced by fitting the visibility of the fringes, taking into account the known detector resolution of 5 μm and the fitted detector response function. The monochromaticity $E/\mathrm{d}E$ of the beam is $\approx 10^3$ depending upon energy and monochromator slit widths.

This relatively high degree of monochromaticity means that the term taking account of wavelength distribution has little effect. In all cases the entrance slit width was 50 μm.

Two examples of the data with the fitted curve are shown in Fig. 2. Eq. (1) assumes that both slits were illuminated with equal intensity and that the slits are of equal width. If this were not the case, then the apparent fringe visibility and fringe envelope would be modified in a predictable manner. We modelled this effect and found that the observed fringe envelope symmetry was inconsistent with unequal illumination being the source of reduction in fringe contrast. Therefore, the reduced fringe contrast is attributed to the partial coherence of the radiation.

The modulus of the degree of coherence $|\mu_{12}|$ for the various Young's slit separations is plotted for two exit slit settings in Fig. 3. The detector resolution was not sufficient to resolve the interference fringes for Young's slit separations greater than 150 μm, so this data is not plotted.

To compare our results with theory we treat the undulator source as quasi-homogeneous [21]. That is, the mutual intensity function is described by

$$J(\mathbf{r}_1,\mathbf{r}_2) = I((\mathbf{r}_1+\mathbf{r}_2)/2)g(\mathbf{r}_1-\mathbf{r}_2), \quad (4)$$

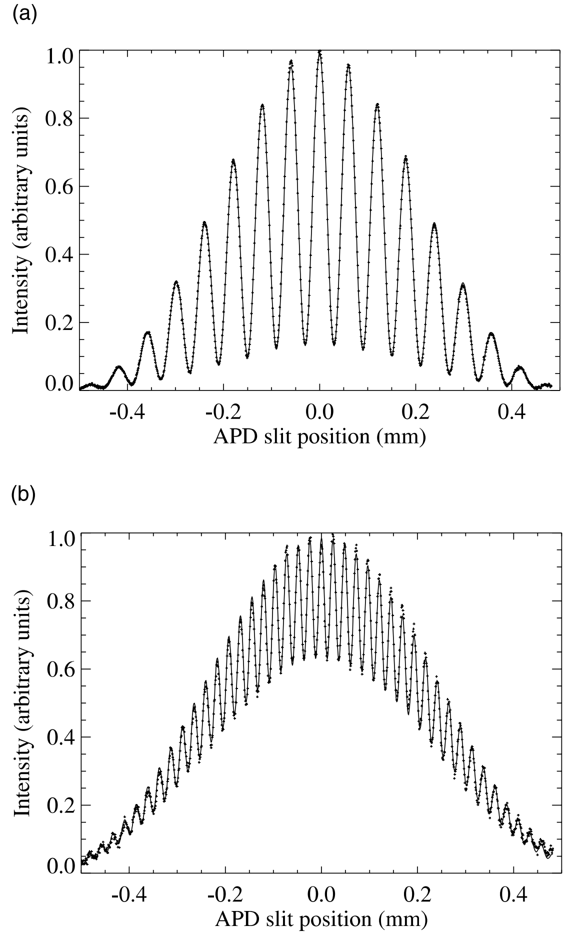

Fig. 2. Young's double slit interference pattern at an X-ray energy of 1.1 keV, as measured by a scanning 5 μm slit and APD detector. The monochromator entrance slit was 50 μm and exit slit was 200 μm. The data points are represented with crosses, whose size represents one standard deviation uncertainty. The solid line is a theoretical fit to the data used in the determination of the spatial coherence. (a) Young's slit separation of 20 μm and (b) Young's slit separation of 50 μm.

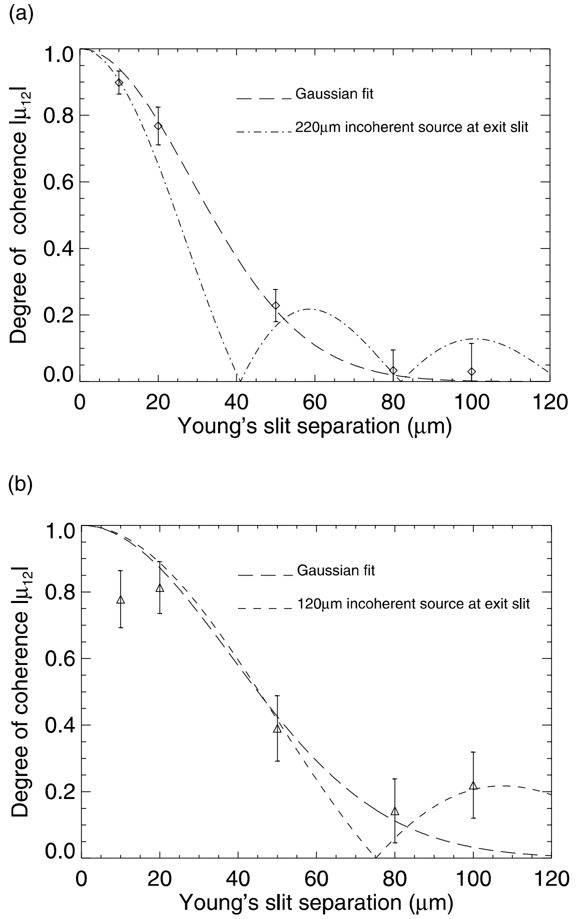

Fig. 3. Measured and theoretical degree of coherence for an entrance slit width of 50 μm with two exit slit settings. The theoretical profile is for an incoherent top-hat shaped source located at the exit slit. Gaussian fits to the data are shown in both plots. (a) Measured with exit slit at 200 μm (◇), theoretical profile for 220 μm and (b) measured with exit slit at 100 μm (△), theoretical profile for 120 μm.

where the factor $g(\mathbf{r}_1 - \mathbf{r}_2)$ describing the wavefield correlations may be estimated using the known divergence of the source [22]. Using the optical system shown in Fig. 1, the transport of the coherence properties of the radiation through the beamline may be calculated and we find that the radiation at the exit slit may also be considered quasi-homogeneous. In our experiment, the intensity distribution at the exit slit will be a magnified image of the entrance slit. We model the effective source at the exit slit as a Gaussian with FWHM of 92 μm and a coherence length of 1.8 μm where coherence length is defined as the length at which $|\mu_{12}|$ is reduced to 0.88 [8].

The coherence length l_c of a Gaussian quasi-homogeneous source propagates [23] as

$$l_c = \left(l_s^2 + \frac{z^2}{k^2 \sigma_I^2} \right)^{1/2}, \tag{5}$$

where l_s is the coherence length of the source, z is the propagation distance, $k = 2\pi/\lambda$, and σ_I is the

FWHM of the Gaussian source intensity distribution. This predicts a coherence length of 18.5 μm at our experiment station with the exit slit fully open.

Fig. 3 shows a Gaussian fit to the data as well as the coherence function that would be expected if the radiation could be modelled as being an incoherent source located at the exit slit. The incoherent source is assumed to have a top-hat shaped intensity distribution and to completely fill the exit slit. The coherence function at the experiment for the incoherent source model was calculated using the van Cittert–Zernike theorem [24]. The Gaussian fits indicated a coherence length of 14.5 ± 2.9 μm and 19.4 ± 4.6 μm when the exit slit had widths of 200 μm and 100 μm, respectively. These measurements are in reasonable agreement with our theoretical prediction of 18.5 μm.

When the exit slit width is 100 μm the effective source will be truncated by the exit slit and the effect of this is clearly apparent in Fig. 3(b), as can be seen by the departure of $|\mu_{12}|$ from a simple Gaussian profile. The degree of coherence at larger Young's slit separations was higher than expected since the exit slit selects a smaller volume of phase space and so the coherence function takes on a form that is dominated by the geometry of the slit. The measured coherence was in general somewhat poorer than expected, in particular for the wider exit slit setting, and we now consider the reasons for this.

3.1. Speckle size

Our Young's experiment measures the correlation between two locations in the radiation field. The speckle size [24] in an experiment is given by

$$\delta_s \approx \frac{\lambda z'}{L}, \tag{6}$$

where L is the characteristic size of the source or the exit aperture of the imaging system and z' is the distance from the aperture to the detector. If this spatial scale is greater than the characteristic width of the acceptance aperture, d_{ap}, of the experimental system then the experiment will be able to use the full coherence transported from the source.

In our experiment the minimum speckle size that can be produced is approximately 40 μm. This minimum occurs when the exit slit acts as the exit aperture and is at its wider (200 μm) setting. The minimum speckle size is therefore less than the Young's slit separation for some of our data and less than the vertical extent of each slit, but is much greater than the horizontal width of each slit (≈2 μm). Consequently, the field illuminating each of the slits will have a well-defined horizontal phase and we should see the full effects of the beam coherence if there is no vertical integration. However, the APD detector integrates a signal that is 5 μm wide and 700 μm high, so there may be some phase variation along the vertical. To check this, we obtained some two-dimensional fringe patterns using an X-ray CCD camera. Fig. 4 shows an example interference pattern obtained from Young's slits with 10 μm separation and 1.5 keV undulator radiation. The interference fringes show a clear horizontal shift in position between the upper and lower regions of the pattern consistent with the effects discussed in this paper. The effect of speckle is the most likely explanation for the discrepancy between the expected coherence and the measured coherence as shown in Fig. 3. It is also a direct observation of the "coherence degradation" referred to in Ref. [7]. The condition

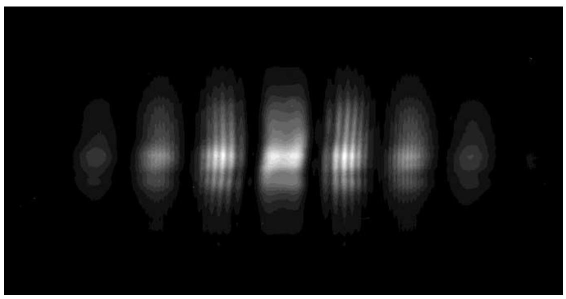

Fig. 4. Two-dimensional CCD camera image of Young's interference pattern with a slit separation of 10 μm at an X-ray energy of 1.5 keV. Image size is 0.82 mm by 0.42 mm and the fringe separation is 90 μm. The shift in the fringes which occurs between upper and lower regions of the image is evidence of the possible effect of speckle. The secondary fringes are due to interference between the diffracted beam and the weak beam transmitted through the incompletely opaque slits at this energy.

for being able to fully utilise the coherence of the beam can therefore be written as

$$\delta_s > d_{ap}, \tag{7}$$

where δ_s is the speckle size and d_{ap} is the width of the acceptance aperture of the experimental system.

4. Conclusion

In summary, we have performed Young's double slit experiments in the X-ray region on an undulator beamline to measure the coherence function of the undulator beam at the experiment station. The radiation at the beamline experiment station was shown to have high spatial coherence for transverse dimensions up to 100 μm. The measured coherence was in good agreement with that expected from the undulator source and beamline optics, provided speckle due to imperfect beamline optics is taken into account. We conclude that it is possible for the beamline to transport this coherence to the experiment station with minimal degradation in the horizontal direction. We further considered the conditions for the full transport of coherence and have established the basis for the realisation of a coherent X-ray optical experiment.

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