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Double pinhole diffraction of white synchrotron radiation

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Abstract

The spatial coherence of hard X-rays provided by a bending magnet of the storage ring BESSY II was investigated by performing Young's interference experiment. The interference pattern was created by the diffraction of two 2 μm pinholes drilled into a thin tantalum foil by focused ion sputtering. Using an energy-dispersive detector with an energy resolution of 200 eV the interference patterns were detected simultaneously between $5\,\text{keV} < E < 16\,\text{keV}$ scanning a 5 μm pinhole through the detector window. The set-up is suitable to characterize the coherence properties of the beamline in a simple manner, i.e. to deduce parameters as the effective source size, the coherence length and the visibility. For the present case the visibility was close to 100% at 5 keV and decreased to 20% at 16 keV.

Keywords: Double slit experiment; Coherent X-rays; White X-ray radiation

1. Introduction

The coherence properties of hard X-rays can be exploited in a number of experiments in X-ray imaging, investigation of speckle pattern or time-correlation spectroscopy [1]. The characterization of the X-ray beam, in particular its coherence properties, is of large interest for quantitative interpretation of experimental data. The coherence properties of hard X-rays have already been investigated using several experimental techniques [2–10]. Compared to other techniques the double slit experiment presented here needs a relatively simple set-up. It is a standard technique for probing the coherence properties of radiation in the visible spectral range provided by lasers, soft X-rays or even elementary particles and atoms. Recently, this technique was applied on hard X-rays as well, probing the coherence properties of monochromatic radiation with large longitudinal coherence length [7]. Temporal coherence length: $l_L = \lambda^2/\Delta\lambda$ depends on the monochromaticity of the radiation or in our case of a white beam, it depends on the energy resolution ΔE of the energy dispersive detector. Assuming a realistic value of $\Delta E \sim 200\,\text{meV}$ we obtain $l_L = 0.07\,\text{Å}$ for $E = 6\,\text{keV}$ and $0.01\,\text{Å}$ for $E = 15\,\text{keV}$. It is the

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maximum optical path difference or length of the wave trains which still allows interference of a split wave.

The transversal coherence length l_T is determined by the size s of the chaotic X-ray source and the source-to-object distance L and follows $l_T = L\lambda/s$. The transversal coherence length decreases with increasing source size and gives the maximum dimension of an object which can be coherently illuminated at given geometry. Because the interference pattern observed behind a double slit is a superposition of interference patterns of individual point sources one can determine the source size by measuring the visibility (contrast) of the interference fringes.

Here we report on our recently performed double-pinhole diffraction experiments using an incident white synchrotron radiation beam at BESSY II. BESSY II is a third generation synchrotron source at Berlin (Germany) operating at 1.7 GeV, which provides hard X-rays up to about 20 keV whereas it mainly delivers radiation in the soft X-ray range.

The aim of our activities was to characterize the coherence properties of the X-ray source and to verify the feasibility of experiments with coherent X-rays at a bending magnet beamline.

The diffraction pattern of a pair of micrometer pinholes separated by a few micrometre was recorded in a distance of about 1.4 m using an energy-dispersive detector with an energy resolution of about 200 eV. For high spatial resolution a small pinhole was scanned in front of the detector. With this set-up we measured the Young fringes within the spectral range from 5 to 16 keV, while simultaneously performing a single detector scan.

2. Experiment

The experiment was conducted at the energy-dispersive reflectivity (EDR) beamline at the BESSY II storage ring. A description of the beamline can be found elsewhere [11,12].

The experiment exploits the white X-ray beam emitted from a bending magnet which is exponentially decaying in intensity from 1 keV towards higher energies. The only optical elements in the beam path were two Beryllium vacuum windows, various guiding slits and two 75 μm capton windows. The white beam leaves the vacuum system about 30 cm before the tantalum foil (Fig. 1). In order to reduce air absorption an evacuated tube of 1 m length was placed in between the detector and the pinhole mask.

In the experiment the two pinholes were separated in vertical direction in order to profit from the much smaller vertical source size of the X-ray beam which promises higher contrast of the interference fringes. The energy-dispersive detector (XFlash by Fa. Roentec) was placed at a distance of 1.38 m behind the tantalum foil. The energy resolution of the detector was about 200 eV. A small pinhole of 5 μm diameter was accurately scanned in the vertical direction in front of the detector opening. Using this the energy spectrum behind the pinhole mask could also be recorded with a good lateral resolution. The detectable spectral range was limited by air absorption outside the evacuated tube to a minimum of 5 keV and by the low emitted intensity of the bending magnet to a maximum of 16 keV. At the position of maximum intensity the typical total count rate at the detector was about 80 000 counts per second in the whole spectral range.

The double pinhole microstructure was fabricated by a Focused Ion Beam-system (FIB200-Fa. FEI). This system uses a beam of Ga^+-ions with an energy of 30 kV which can be focused down to a spot of 8 nm diameter. Using a 2700 pA beam current it took finally about 1 h to sputter a single pinhole into the 30 μm thick tantalum foil. As seen

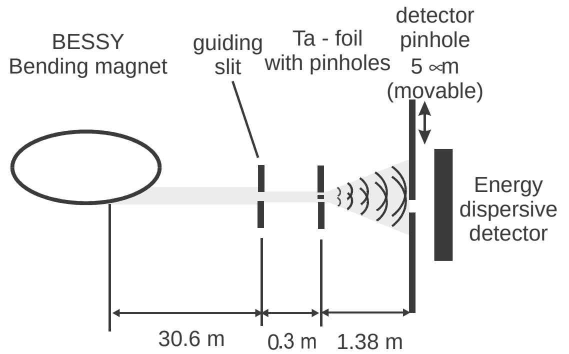

Fig. 1. Experimental set-up at the EDR-beamline at BESSY II.

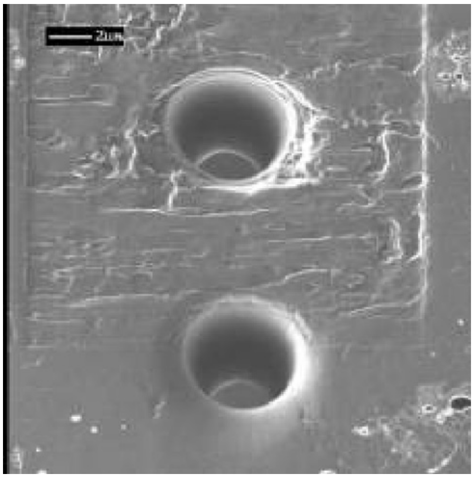

Fig. 2. Electron microscope image of the 30 μm tantalum foil containing the two micro-pinholes 11 μm separated (exposure at 10° tilt angle).

from the SEM-image shown in Fig. 2 the surface of the pinhole is very smooth. The holes are nearly circular but its shape is slightly different for each individual pinhole.

3. Results

Some experimental results are shown in Fig. 3. The grey-scale map summarizes the normalized diffraction profiles over a large range of X-ray energies. The interference fringes are clearly visible between 5 and 16 keV. The fringe spacing decreases with increasing energy. Only in the region just below the Ta-absorption edge of 9.9 keV, the diffraction curves are not detectable as a result of the low absorption of the tantalum foil.

Due to limited space in the experimental hutch we were restricted to a small distance between the double pinhole and the detector of $L = 1.38$ m. At this distance the assumption of far-field diffraction was not entirely fulfilled and we still have the condition of near field diffraction where the visibility of the interference fringes is reduced.

A first evaluation of the data was done by fitting the experimental data to an analytical expression

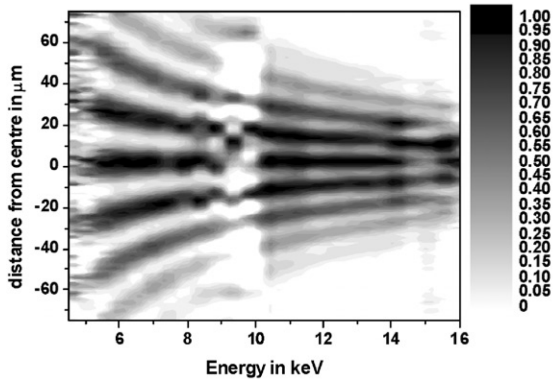

Fig. 3. Normalized diffracted intensity as a function of energy and the distance from the optical axis.

for the intensity distribution of the interference pattern in the far field [13,14].

$$I(x) = I_0 \left(\frac{\sin(k_d x)}{k_d x} \right)^2 (1 + V \cos(k_D x)) + I_b$$

with

$$k_d \approx c\frac{Ed}{z} \quad \text{and} \quad k_D \approx c\frac{ED}{z}, \tag{1}$$

where the variables have the following meaning: x is the co-ordinate in the diffraction plane, E the energy [keV], c—5.07 [nm^{-1}] = 2π/1.239 [nm^{-1}] conversion factor from the wavelength to the energy domain, L the source-to-pinhole distance, D the pinhole separation, d the diameter of the pinhole, and z the pinhole-to-detector distance. The parameter V is the visibility of the interference fringes, given by [13]

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{\sin(c(s\,ED/4L))}{c(s\,ED/4L)}. \tag{2}$$

Here $I_{\max}$ and $I_{\min}$ are the maximum and the minimum intensities close to the central peak. Some single diffraction curves are shown in Fig. 4. Using Eq. (1) the pinhole parameters were determined to be $d = 2.0$ μm, $D = 11.3$ μm verifying the values determined by microscopy.

The energy dependence of the visibility should follow a sinc-function with the "effective source size" s as a parameter, which is qualitatively reproduced in Fig. 5. The calculated values for the

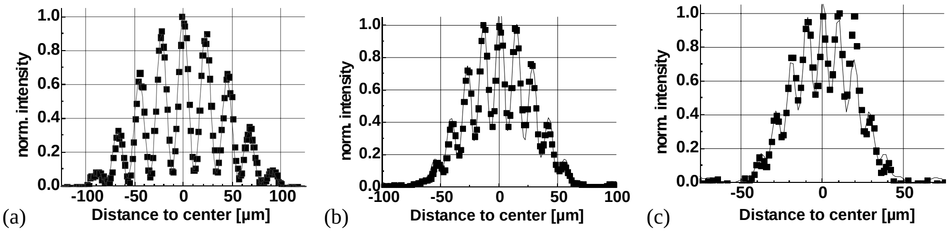

Fig. 4. Normalized interference fringes obtained with the double pinhole at three different energies (a)–(c) 6 keV, 10 keV and 14 keV. The squares indicate the measured data from Fig. 3 and the lines indicate the results of the best fit of Eq. (1).

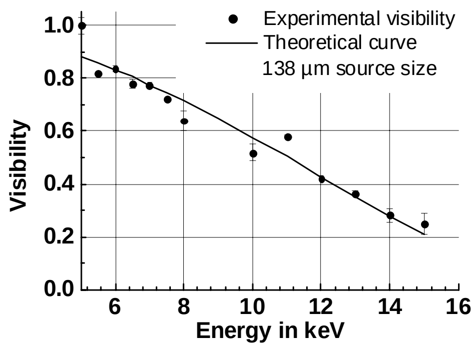

Fig. 5. Visibility of the interference fringes as a function of energy.

fringe visibility are shown in Fig. 5. As expected it becomes maximum for a large wavelength and decreases to a smaller wavelength. At 5 keV the visibility is close to unity, which is the preferred energy range for further coherence experiments.

According to Eq. (2) the source size s has a value of approximately 140 µm which is much larger compared to the values measured with a pinhole camera [15]. From this value follows the transversal coherence length of 45 µm at 6 keV and 19 µm at 14 keV.

The relatively large experimentally determined source size might be due to different reasons. First, it is due to the insufficient consideration of the small detector distance which does not match the far field expression used by Eq. (1) and the relatively large size of the detector pinhole which influences the measurable visibility especially for smaller fringe distances. A numerical simulation of the experiment is being carried out at the moment and will be presented in a following article. A second influence which increases the source size might be the imperfections of the beryllium windows which reduce the beam coherence. An unpolished window might act as a "secondary source" appearing much closer to the experiment as expected for the true X-ray source [17]. This assumption will be investigated in more detail in future experiments.

4. Summary

In summary we have shown that the coherence properties of a synchrotron white beam can be measured by means of Young's double slit experiment using an energy-dispersive detector. As expected the visibility of interference fringes is maximum at low energies, which favours this energy range for any kind of coherence experiment. The difference between the estimated effective source size and the true one is mostly a result of the application of a very rough approximation of far field diffraction which will be investigated quantitatively in a following publication. In addition the possibility of the improper quality of optical elements within the ray path has to be checked in further experiments. Nevertheless, the EDR bending-magnet beamline at BESSY II is suitable to perform experiments with coherent hard X-ray radiation. Recently, we have reported the observation of static speckles in reflection geometry [16]. The registered coherent photon flux seems to be sufficient for X-ray photon correlation spectroscopy measurements on subsecond time scale.

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