TWO-PLANE FOCUSING OF 30 KEV UNDULATOR RADIATION WITH A REFRACTIVE LENS

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Recently a simple type of refractive lens has been proposed and successfully tested in the X-ray range with a photon energy of 14 keV [1]. Such lenses are made by drilling a series of small holes with a diameter of the order of a millimetre in a low Z material such as aluminium. These lenses are expected to be resistant to heatload and simple to build resulting in an astonishing low cost. Their drawbacks are their limitation to high photon energies above 4 keV due to absorption, their strong chromatic aberrations and low aperture. However they appear extremely well-suited to the focusing of the undulator radiation of the new hard X-ray third generation synchrotron sources such as the ESRF. The object of this paper is to report the results of some tests and to discuss the potentialities of these lenses.

DESCRIPTION OF THE EXPERIMENT

The original interest for these tests was the imaging of the electron beam sizes at the source of the undulator in the ID6 Machine Diagnostics beamline as a complementary emittance diagnostic. To do so, a lens was built by drilling 34 holes of 1 mm diameter with a vertical axis followed by 41 holes of the same diameter with an axis in the horizontal plane (see Figure 1). The holes are drilled in a 2 mm thick aluminium plate. As we shall see later, aluminium is not the best material but it was selected for its reasonably low Z, easy machining and short-term delivery. The vertical source size in the middle of the undulator is around 10 microns rms for the 40 pm emittance routinely achieved. For a proper magnification of the source, one needs to place the lens as close as possible to the source which conflicts with the severe heatload. In all cases water cooling is essential. The only places where sufficient water cooling is available on the ID6 beamline are the X-ray beam position monitor (xbpm) motorised stages called xbpm-1 and xbpm-2 located at a distance of 10.7 m and 22 m from the source. The design of the lenses was strongly inspired from the design of the tungsten blade of the xbpm [2] for which severe heatload problems have been carefully studied and solved. The shape of the lens is shown in Figure 1. The 8 lower large diameter holes are used for clamping. Of the 14.5 mm height of the lens, only the upper 5 mm emerge from the heavily cooled copper fastener. The entrance face of the lens is inclined at a low incidence angle to spread the heatload and reduce the temperature of the lens at the point of impact of the X-rays. To minimise the heatload issue, it was

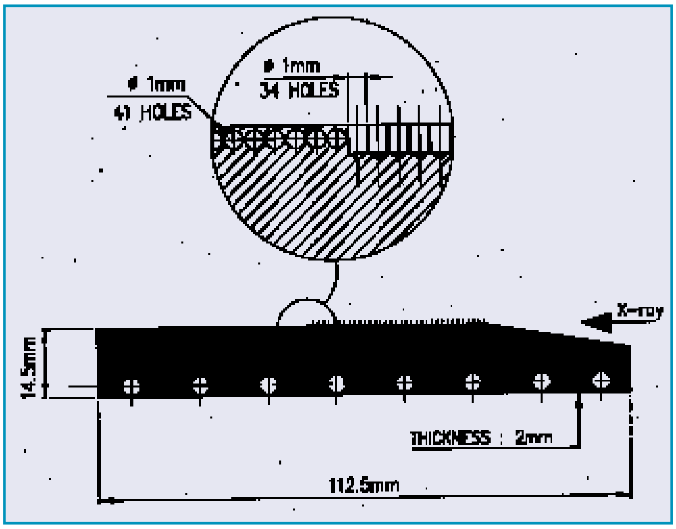
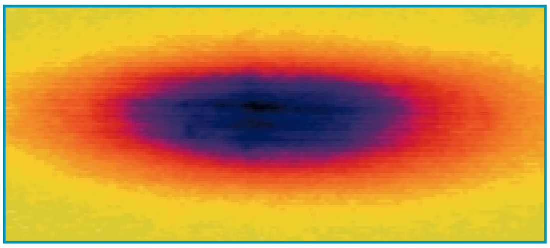


Fig. 1: Drawing of the two-plane refractive lens used in ID6. The input face is set at grazing angle to spread the heatload.

Fig. 2: Spot size of the seventh harmonic of the undulator at 29.5 keV observed at a distance of 32.2 m without lens. The rms sizes are 0.60 and 0.30 mm in good agreement with the emittance derived from the pinhole camera and the beta function of the source point.



decided to place the lens on xbpm-2 even though xbpm-1 would have been a better choice (size of image, spherical aberrations...). After passing through the lens the X-rays go through the graphite/beryllium window assembly placed in the front-end part of the beamline. The transmitted beam is then monochromatised by a 3 1 1 silicon crystal diffracting in the horizontal plane. The monochromatic beam is converted to visible light by means of a 1 mm thick CsI(Ti) scintillator and imaged by a CCD video-camera. The whole experiment was controlled and performed from the storage ring control room. The scintillator is placed at 32.2 m from the middle of the ID6 straight section. Such an imaging set-up has been in use for more than 4 years at the ID6 beamline and for more than two years as the primary emittance diagnostic of the electron beam [3]. The image of the X-ray beam when the monochromator is precisely tuned to the photon energy of one of the harmonics of the undulator spectrum on axis of the electron beam is essentially an intense ellipsoidal spot. This spot is the foot print of the undulator central cone on the scintillator. The focusing of the lens in both horizontal and vertical planes was selected for minimising the spot size of the image at a photon energy of 25 keV. A different number of holes was used for the focusing in the horizontal plane. This is due to the large beta function of the source (low divergence of the photon beam) responsible for a small violation of the geometrical optics laws (same as for visible lasers). The undulator used for this experiment is a single segment of 36 periods of 46 mm. The spectrum is tunable with a deflection parameter K between 0 and 2.2. The experiment has been performed at a full ring current of 200 mA with a gap ranging from 20 to 40 mm corresponding to a maximum angle integrated power of 1.7 kW and a normal incidence power density as high as 100W/mm^2 at the position of the lens.

RESULTS

Figure 2 presents the image of the 7th harmonic at a photon energy of 29.5 keV of the undulator before insertion of the lens. The rms horizontal and vertical sizes were measured to be 0.55 and 0.30 mm in good agreement with the beta function and emittance deduced from the pinhole camera [4]. The horizontal lines are produced by the unpolished beryllium window and graphite filters located 2 meters downstream from the lens. Figure 3 presents the same image after insertion of the lens and removing some attenuation. The central spot originates from the focusing of the lens in both the horizontal and vertical planes. As expected, the spot can be displaced on the camera by moving the lens and vanishes for large displacements of the lens due to stronger absorption in the aluminium. Table 1 summarises the measured rms sizes.

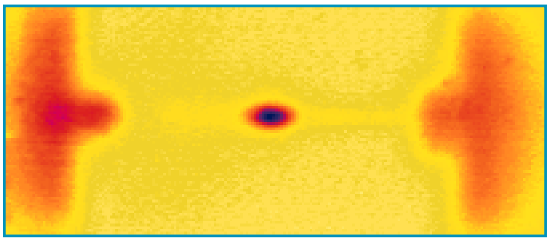


Fig. 3: Same image conditions as in Figure 2 after insertion of the lens and removal of some attenuation. The central spot is the result of the focusing of the radiation by the refractive lens. Some radiation is visible on the right and left hand side which is not passing through the lens.

These results are very encouraging. Horizontally the expected spot size is 0.11 mm. However, one would have expected a 0.010 mm rms vertical spot size around 25 keV. This discrepancy is not yet understood and several explanations are being studied such as the material inhomogeneity, aberration induced by the graphite and beryllium filters.

DISCUSSION

For a 30 keV radiation, the focal length of the lens is 12.2 m (10.2 m) in the horizontal (vertical) planes. As a result the corresponding apertures Σ are 0.18 mm (0.16 mm) to be compared with the rms beam size σ of the central cone of 0.45 mm (0.12) mm. The minimum thickness of aluminium is 0.1 x (34 + 41) + 4.2 = 11.7 mm. Consequently the overall transmission is 0.07 (material transmission) x 0.37 (horizontal aperture) x 0.81 (vertical aperture) = 0.021 which corresponds well to our observation. Derivation of the analytical expressions for the transmission of such lenses can be obtained from [5]. The rms aperture Σ of this lens is

$$\Sigma^2 = \frac{\delta}{4\pi\beta}\lambda F$$

where F is the focal, $1-\delta$ and ß are respectively the real part and imaginary part of the index of the material constituting the lens. If one replaces the aluminium with beryllium with the same hole radius and shape but a larger number of holes to achieve the same focal length, the overall transmission is 0.95, 0.75 and 0.4 at the photon energies of 30, 15 and 10 keV. In addition the temperature rise of the beryllium would be reduced due to its

Table 1: Measured rms photon beam size with and without the lens.

	Rms Horizontal Spot Size [mm]	**Rms Vertical Spot Size [mm]**
No Lens	0.55	0.30
29.5 keV	0.12	0.058
27.5 keV	0.11	0.056
25 keV	0.11	0.061

lower absorption. Other low Z materials are worth studying such as graphite, boron-nitride or boron-carbide. A lens made of beryllium would be almost absorption-free at any photon energy above 10 to 15 keV. A typical lens design for 1 to 1 imaging would need 60 times less holes than a lens design for a microfocus of say 30 to 1 ratio. This large difference comes both from the focal length required and from the positionning of the 1 to 1 lens at a shorter distance from the source allowing a smaller diameter for the hole. As a consequence of both the smaller number of holes and the longer focal distance, the 1 to 1 imaging lens is expected to have a much higher transmission and therefore efficiency. Such lenses could be very useful for a number of experiments. They could produce a vertical spot size of 10 microns rms on a sample placed at a 30 m distance from the source without modification of the divergence. Lower spot sizes are expected in the horizontal plane due to the higher emittance. Altogether, the spectral flux per unit surface on the sample at photon energies higher than 10 to 15 keV would therefore be more than 40 times higher than the present situation without affecting the divergence. Another important application of these lenses is in the use of the undulator spectrum without monochromator. The photon energy from each harmonic is focused differently. If one places a small aperture at the imaging plane of a specific harmonic, one would discriminate the other harmonics. The transmitted spectrum would be that of the selected harmonics with all the others attenuated. The lower the number of the selected harmonic the more efficient is the harmonic discrimination. The resulting number of photons per second per unit surface over a 1% bandwidth is several orders of magnitude higher than that presently achieved. Each lens is optimised for a specific photon energy, but operation over a large energy range can be achieved by installing an array of such lenses on a movable stage. A user would select a lens according to the application. The xbpm set-up presently in place in the ID6 beamline and optimised for a different goal (beam position measurement) allows the insertion of 4 different lenses without any modification. The power per unit surface on the sample or monochromator located at the image plane should not be significantly modified by the presence of the lens since only a small fraction of the spectrum is focused to a narrow size and a part of the power is deposited in the lens itself. Obviously to approach these performances, a number of issues need to be properly addressed such as the constraints induced by heatload, stability of the lens positioning system, required homogeneity and low rugosity of the low Z material etc.

CONCLUSION

Two-plane refractive lenses have a tremendous potentiality for a further optimisation of the undulator beamline of the ESRF. The potential improvement is so large that even if the ultimate performances are not reached, one could make use of imperfect lenses and still have a much higher spectral flux per unit surface without affecting the brilliance and the divergence of the radiation. ■

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Nota Bene:
In the course of writing the paper, I have been informed that A. Snigirev achieved a 18 x 8 micro-meter spot size on a two-plane focusing lens at 30 keV with a focal length of 2 m made with 200 holes.

ACKNOWLEDGEMENTS

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