

A ZONE PLATE BASED BEAM MONITOR FOR THE SWISS LIGHT SOURCE

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Abstract

At the Swiss Light Source, a source imaging set-up is planned on a dedicated dipole magnet beam-line. A transmission Fresnel Zone Plate will be used to generate a demagnified image of the source at a photon energy in the 1.8 keV range. The image will be acquired by scanning a pinhole in the image plane. A diffraction limited spatial resolution of approximately 2 microns can be anticipated. The concept has the advantage of having no components operated in reflection, and no components inside the front-end.

1 PRINCIPLE OF OPERATION

Source imaging can provide valuable information about the size, shape, position, and stability of 3rd generation synchrotron radiation sources, and allows for an optimisation of the brilliance by minimizing the coupling parameter [1-3]. At SLS, a bending magnet beamline (12-B) is reserved for diagnostics purposes. At this location electron beam size, emittance and coupling measurements are planned. Apart from that, bunch purity and bunch length measurements have to be performed at the same beamline using visible synchrotron radiation. For beam size measurements we are expecting 1-sigma horizontal beam size of 45 μm and 1-sigma vertical beam size of 40 μm for 1% emittance coupling. The horizontal emittance is expected to be 4.8 nmrad at 2.4 GeV beam energy. However, the storage ring design allows much smaller coupling values for different lattice modes. Emittance coupling of 0.1% would already lead to vertical 1-sigma beam size of 13 μm . Thus, a resolution in the micron range is necessary.

Apart from the required resolution, some practical constraints have to be taken into account. Firstly, it is desirable to have no reflective components in the imaging system that could introduce aberrations and thus affect the source size measurements. Secondly, it is advantageous to have no components inside the beamline's front end. This allows for easier access and alignment and it is possible to remove the set-up from the beam without complications to use the beamline for other experiments. In our case this means, that the first component of the monitor has a distance from the source of at least $g=10$ m. Generating a

magnified image of the source would thus require a very long, potentially unstable set-up. To keep the set-up short, we chose a demagnifying geometry.

The separation of two distant point sources that can be distinguished according to the Rayleigh-criterion is generally limited by the diffraction of the optics aperture [4]. This means that the distance between the images of two distinguishable source points is limited to: $B = 0.61 \cdot \lambda \cdot f / r \approx 0.61 \cdot \lambda \cdot b / r$, where λ is the light wavelength, f the focal length, and b the image distance. This corresponds to a source size that could be resolved of $G = B \cdot g / b = 0.61 \cdot \lambda \cdot g / r$. If we introduce the solid angle $\alpha = 2r/g$ collected by the optics, we see that

$$G = 1.22 \cdot \lambda / \alpha. \quad (1.0)$$

The angular divergence of the bending-magnet beam line 12-B is in the order of 0.5 mrad, which limits the useful optics diameter to 5 mm at 10 m source distance. According to eq. (1.0) this results in a resolution of 1.7 μm at 1.8 keV photon energy (0.7 nm wavelength). However, it should be noted that the resolution criterion applied in this calculation is very conservative. The size of a source which is larger than the diffraction limit of the set-up can be determined with much better accuracy by deconvolution with the point spread function of the optical system. This is especially true if the function describing the source profile is known and e.g. only the position and width of a gaussian have to be determined.

Fresnel zone plates have been successfully applied for focusing and high resolution imaging in the x-ray range. As a good approximation the radius r_n of the n^{th} ring follows the law

$$r_n = \sqrt{n \cdot \lambda \cdot f} \quad (1.1)$$

where f is the first order focal length. The outermost (smallest) zone width dr_n the total zone number n and the total radius r are linked by the following equations:

$$dr_n = r / 2n \quad (1.2)$$

$$f = 2r \cdot dr_n / \lambda \quad (1.3)$$

$$f = r^2 / (n \cdot \lambda) \quad (1.4)$$

The following properties of zone plates are of importance in the context of the presented set-up:

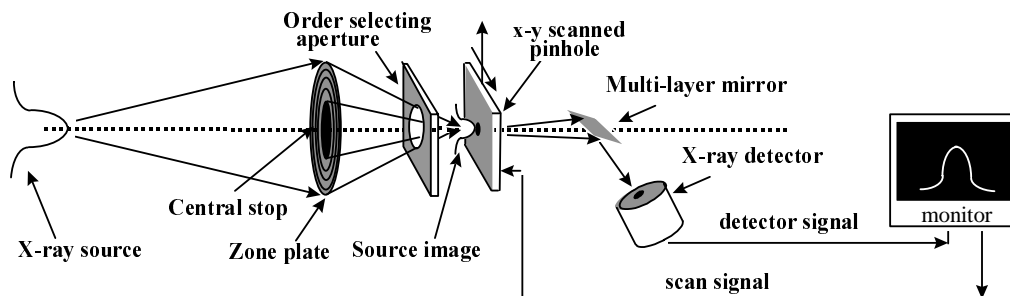


Fig. 1: scanning type set-up for beam monitoring planned for the SLS

- A zone plate's focal spot size δ is limited by its outermost zone width dr_n : $\delta = 1.22 \cdot dr_n$.
- Due to the high chromatic error according to (1.4), the bandwidth $\lambda/\delta\lambda$ has to be greater than the zone number n . For smaller bandwidth, the obtainable resolution gradually decreases. It has been calculated [5] that the resolution is reduced only by a few percent for $\lambda/\delta\lambda = 1/4 \cdot n$.
- For reasons of diffraction efficiency only the first focusing order is used in most cases. Other diffraction orders (especially the zeroth order) can be eliminated by a central stop near the zone plate plane and an order selecting aperture (see figure 1).

From Eq. 1.0 it is clear that for a given wavelength and source distance, the resolution in the source G depends on the optics diameter, but not on the outermost zone width dr_n . One has the freedom to choose this parameter within certain limits. A small outermost zone width only gives the advantage of a shorter focal length and thus a shorter optical set-up. On the other hand, such zone plates are more difficult to produce, and the image is more strongly demagnified which requires a smaller pinhole to avoid an additional loss in resolution. However, the most important consequence of a small dr_n is that a narrower band width is required to produce a diffraction limited image due to the larger zone number. This decreases the total signal, since for optimum resolution all intensity outside the allowed band has to be filtered out, and it increases the demands on the band pass filter. Thus, zone plates with larger dr_n and longer focal lengths should be preferred for beam monitoring purposes.

There are two principal ways of imaging a synchrotron source. Either the source image is collected by a spatially resolving detector like a phosphorous screen and a CCD camera. In this case, the granularity of the detector which is at least in the order of several microns requires a 1:1 or even a magnifying set-up. Under the constraint that the first optical element should be outside the shielding wall of the beam line, i.e. at least 10 m away from the source, this would result in an undesirably long set-up. This could be overcome by a two step imaging set-up, where the

(demagnified) intermediate source image is strongly magnified by a second lens. Such a set-up is very similar to that of the imaging type x-ray microscopes. Indeed these microscopes are capable of imaging the source. The set-up is, however, complicated, difficult to align, and it requires a costly, spatially resolving detector system. Furthermore, the source image contains contributions of defocused wavelengths if no monochromator is used. The use of such a (reflective) device has the inherent problem that one does not directly image the source but a possibly distorted image from the monochromator.

To avoid these difficulties we chose the principle based on scanning a pinhole through the image plane of a zone plate as shown in figure 1. The source is imaged by a single zone plate, the (demagnified) image is recorded by scanning a pin-hole in the image plane and detecting the transmitted flux. An order selecting aperture (OSA) and a central stop remove all radiation from other diffraction orders. Since the zone plate is highly chromatic, the focused source image for the wavelength corresponding to the distance between zone plate and pinhole is superimposed by the defocused images of other wavelengths. To suppress these defocused contributions, a multilayer mirror or a crystal can be used as a band-pass filter. This filter can be very small in size, furthermore it does not have to meet any further demands with respect to its flatness etc. As a detector a simple photo-diode can be applied. The set-up is easy to align, since all optical components except for the detector are on the optical axis.

2 OPTIMUM PHOTON ENERGY

The most important decision that has to be taken is the one about the used wavelength. Although the diffraction limit of the obtainable resolution becomes more favourable for shorter wavelengths, we propose to use radiation in the 0.8 nm wavelength range (1.8 keV photon energy) for a number of practical reasons: Firstly, this energy range is very favourable for the fabrication of zone plate optics with the required dimensions and high diffraction efficiency. Especially silicon, a material easy to pattern by reactive ion etching, has a very favourable ratio of phase shift and absorption. This means that phase zone plates with efficiencies up to 35% can be fabricated (see Fig. 2).

Secondly, the proposed method requires a pinhole for image formation with a sub-micron diameter. For hard x-rays such pinholes are extremely difficult to obtain with high optical contrast. For 0.7 nm radiation, the transmission of a 1 μm thick Ta layer is already below $1 \cdot 10^{-3}$, which allows for the application of thin film pinholes fabricated by Focused Ion Beam technology [6].

Compared to lower energies, 1.8 keV radiation has the advantage of a higher transmission for filters and support membranes (93% transmission for 1 μm thick Si). As a result of the above considerations, the planned layout of the beam monitor is given in Table 1.

Table 1: Parameters of a beam monitor for SLS

Wavelength	0.7 nm
distance source – zone plate	10 m
zone plate diameter	4 mm
central stop diameter	2 mm
diffraction limit of resolution	2.1 μm
outermost zone width	0.35 μm
focal length	2 m
distance zone plate - source image	2.5 m
demagnification factor	4
number of unobstructed zones	1700
required bandwidth $\lambda/\delta\lambda$	500
pinhole diameter	0.4 μm
field of view (3 \times expected FWHM)	300 μm
range of pinhole scanner	75 μm
Number of pixels	256 x 256

3 EXPECTED SIGNAL

The proposed layout is the basis for an estimation of the expected photon flux. The spectral flux density at the beamline 12 B has been calculated to be $3 \cdot 10^{11}$ photons/sec/0.1%BW/ mm^2 on the optical axis at 0.7 nm wavelength and 10 m distance from the source. By moving in the direction of the radiation, we can estimate the signal at the detector.

First element in the beam will be a transmission filter membrane to reflect most of the visible and UV spectrum. Its transmission is estimated to be 0.5. The zone plate has an area of about 12 mm^2 of which about 3 mm^2 is obstructed by the central stop. The effective collecting area is thus 9 mm^2 . If we assume a diffraction efficiency of a binary Si zone plate including support membrane absorp-

tion of 20%, we are left with a spectral flux of approximately $3 \cdot 10^{11}$ photons/sec/0.1%BW behind the zone plate. In the focal plane the spectral flux is drastically increased: assuming a source size of 100 μm x 20 μm (i.e. 0.1% coupling), the demagnified image will be 25 μm x 5 μm in size, which means that the flux will go into an area of about 10^{-4} mm^2 . This gives a spectral flux density of about $3 \cdot 10^{15}$ photons/sec/0.1%BW/ mm^2 in the focal spot.

The area of the pinhole is about $0.1 \mu\text{m}^2 = 10^{-7} \text{mm}^2$. This yields a spectral flux of $3 \cdot 10^8$ photons/sec/0.1%BW behind the pinhole. Assuming a band width of the multilayer band pass of $\lambda/\delta\lambda = 500$ and a reflectivity of 10%, we end up with $6 \cdot 10^7$ photons/sec at the detector. For a quantum efficiency of 20% this would mean a count rate in the order of $1 \cdot 10^7$ Hz in the center of the source image. As indicated in the table above, two dimensional scans should have in the order of $5 \cdot 10^4$ pixels. For an image acquisition time of 10 seconds this would still give 2000 counts per pixel. Taking into account a shot-noise of $n^{1/2}$ this would correspond to an image with 5-6 bit depth. Line scans to determine the source size and position in horizontal or vertical direction could of course be taken with scan frequencies of many Hertz.

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