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Real-time *in-situ* X-ray beam diagnostics

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Abstract. We report on a novel diagnostics instrument for *in-situ* imaging and measurements of X-ray beam parameters in real-time. The instrument is based on the robust and simple idea of a pinhole camera that collects the weakly scattered radiation from a thin sheet of a low-Z material placed in the X-ray beam at an acute angle. We demonstrate how by recording the scattered radiation with an appropriate detector, high-resolution beam characterisation can be performed in real-time. We present a mathematical model that describes the imaging process and beam position measurements. The theoretical evaluation of the resolution limit of our device and its dependence on various parameters are also discussed. Reported experimental results demonstrate the instrument's capabilities in beam tracking and imaging applications.

1. Introduction

The requirements of experiments with synchrotron radiation are ever increasing and the ability to deterministically position the X-ray beam and control its shape and intensity distribution is one of the most challenging of them. Until now, the performance of well-established beam monitor technologies such as fluorescent chambers and screens, X-ray cameras and quad-diodes has been adequate to the needs of synchrotron users. However, with the advent of micro-focusing optics and new experimental techniques, they are no longer able to measure key beam parameters with the required ease, precision and speed. We propose a new method to monitor X-ray beam parameters which combines high precision of beam position measurements with outstanding versatility by enabling *in situ* beam imaging and monitoring of beam position, size and intensity in real-time.

2. Beam imaging

The proposed instrument is based on the idea of registering the radiation scattered by a low-Z material with a pinhole camera. A thin foil of a low-Z material is placed in the X-ray beam path at an acute angle. The pinhole camera is placed in such a way that only the radiation scattered by the foil at right angles to the beam propagation direction is captured (Figure 1). The combination of the thin foil and the pinhole camera creates a magnified cross-sectional image of the incident beam. This image is recorded by the X-ray image sensor located in the plane parallel to the propagation direction of the beam and well away from the potentially damaging high intensity X-ray radiation.

The choice of a low-Z material such as Kapton® is based on two considerations. First, such materials scatter only a small fraction of the incident intensity, thus making the beam monitor device virtually transparent. Second, their absorption spectra are normally very smooth and featureless which ensures that the new instrument does not introduce beam artefacts across a wide range of energies.

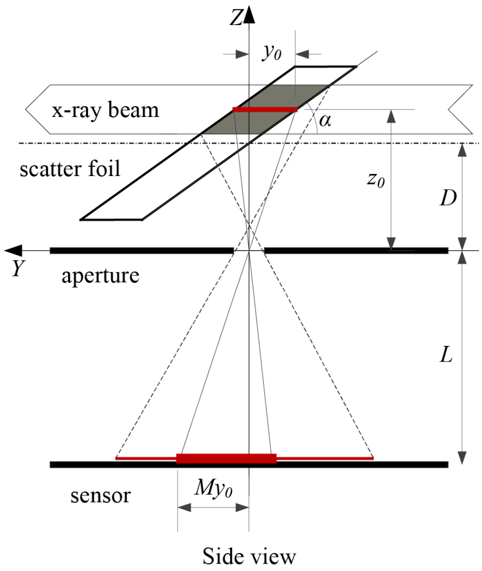


Figure 1. XBI diagram (not to scale). The x-ray beam hits a foil tilted at an angle α with respect to the incident beam. Scattered radiation (from the greyed area) passes through the aperture and is captured by the sensor. The thick red lines show the path of the infinitesimally narrow beam through the foil and corresponding image created by the ideal pinhole. The real beam image (thin red line) is the collective contribution of all infinitesimally small beams constituting the real beam viewed through a finitely sized aperture.

Let $s(x, y)$ be a projection of the X-ray intensity distribution across the bottom face of the scattering foil onto the image plane through the ideal pin-hole. Then, the X-ray beam imaging (XBI) process can be described as the result of convolution of $s(x, y)$ with XBI system's impulse response, $h(x, y)$:

$$i(x, y) = s(x, y) * h(x, y). \tag{1}$$

Due to the orientation of the scattering foil, y- and z-coordinates are linearly coupled, *i.e.* $z = D - y \tan \alpha$. The XBI impulse response can be expressed as a convolution of the aperture function, $a(x, y)$, projected onto the image plane and the foil impulse response, $f(x, y)$. The latter can be described as an image of an infinitesimally narrow X-ray beam with the Dirac delta-function cross-sectional intensity distribution captured by the XBI system with the ideal pinhole:

$$h(x, y) = f(x, y) * a(x, y) = \int_Y e^{\mu \frac{v + My_0}{M}} a\left(\frac{x + Mx_0}{M+1}, \frac{y - v}{M+1}\right) \mathrm{d}v, \tag{2}$$

where μ is the linear absorption coefficient of the scattering foil, x and y are coordinates in the image plane, x_0 and y_0 are the coordinates at which the beam hits the foil's bottom surface, and M is the XBI magnification, $M = L/z_0$.

Now, one can reconstruct the cross-sectional view, $s(x, y)$, of the incident beam from an XBI image, $i(x, y)$, by inverting (1). However, it should be noted that standard deconvolution techniques cannot be applied directly because $h(x, y)$ is not shift invariant: the magnification of the XBI system depends on the z-coordinate of the beam and, therefore, $M = M(y_0)$ in (2). Several computational schemes are available to simplify spatially varying deconvolution via decomposition of system's impulse response into a combination of spatially invariant components [1, 2].

3. Beam tracking and parameter estimation

Beam cross-section reconstruction described in the previous section is computationally intensive and too demanding to be used for real-time beam tracking. Instead, in order to obtain information about changes in beam position, size and intensity fast, we propose to analyse the XBI images directly. There are two major considerations that we take into account whilst doing so. Firstly, although images created by the proposed device are a distorted representation of the beam's true cross section, as we have shown above, there is a direct and reversible correspondence between the two. Due to this fact the measurements of XBI image parameters are normally sufficient to characterise the beam in the majority of applications, *e.g.* for generating control signals to an automatic feedback system. Secondly, XBI images contain much more information than is necessary to measure changes in the beam's basic parameters. Instead, we use two profiles obtained by accumulating pixel values along rows and columns of the raw image [3]. Fitting these profiles with a Gaussian function readily provides the estimation for beams position, width and intensity. It can be shown that, provided the beam stays close to its central position ($y = 0, z = D$), the changes of profiles' Gaussian mean, Δx and Δy, are proportional to the changes in the beam actual position, δx and δz [4].

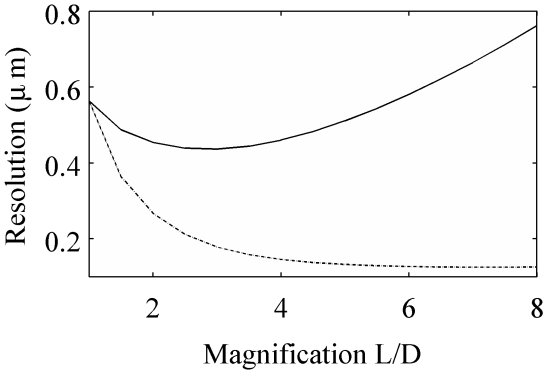
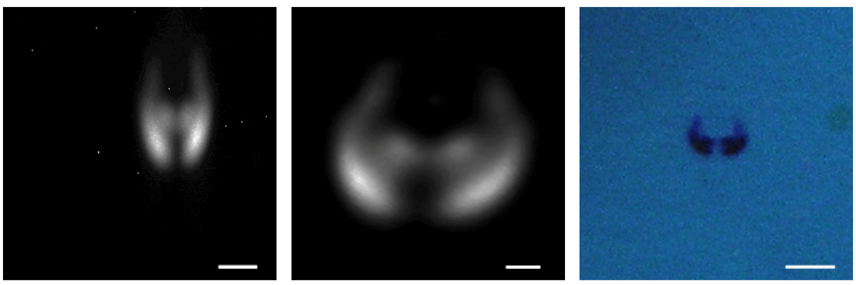


Figure 2. Theoretical resolution of the setup in measuring beam displacement (solid curve). XBI model parameters: incident beam with the square 5×5 μm cross-section, foil angle α = 27°, maximum image intensity at L/D = 1 is 100 arbitrary units (abu), image background level is 2.0 abu, pinhole diameter is 1 mm, and sensor readout noise is 1.74 abu. The dashed curve shows the expected resolution when the image peak intensity is constant for all L/D.

We have shown that this approach enables X-ray beam positioning with a sub-micron resolution [4]. The exact resolution values are determined by a number of parameters, such as image intensity, sensor noise, XBI magnification, beam size, aperture shape and size, and detector size and pixel pitch. Higher image intensity, lower noise, larger beam and smaller pixels improve the resolution. All the parameters are closely linked to each other so that for a particular detector and a given combination of the beam size and intensity there is the optimal combination of the aperture and magnification that provide the best resolution. The choice of the aperture is determined by how the device is used. For beam imaging, the achievable resolution of a pinhole camera is well-known to be set by the size of the aperture, whereas for beam positioning, as long as the whole image fits within detector's boundaries, a larger aperture will normally improve the resolution by ensuring higher image intensity. The choice of magnification is also determined by the compromise between image intensity and magnification impact on the resolution of position measurements. As magnification increases, smaller beam displacements cause measurable changes in detected images, thus improving resolution. However, the detected intensity is also spread over a larger area so that fewer photons are detected by each pixel. As a result, the signal-to-noise ratio drops and the resolution decreases. Figure 2 demonstrates the existence of the optimal magnification for a given fixed set of XBI parameters. The dotted line also demonstrates the progressively improving resolution that is possible if the signal-to-noise ratio is kept constant. This, for example, can be achieved by increasing the detector's integration or counting time but at the expense of a decreased measurements rate.



a *b* *c*

Figure 3. Focused beam images captured with the XBI setup (B16, Diamond Light Source, 2009): *a* – raw image, scale bar 2 mm; *b* – reconstructed image, scale bar 200 μm; *c* – beam footprint on a Gafchromic® film, scale bar 1 mm

4. Experimental results

The benefits of the imaging enabled by the proposed device are demonstrated by the images in Figure 3. Where standard beam monitors, such as quad diodes, ion chambers and fluorescent screens, are unable to detect any anomalies, the XBI system equipped with the Medipix2 sensor reveals clear focusing problems. The comparison of the shape and scale of the raw and reconstructed images shows the magnification and deformation introduced by the XBI system. The reconstructed image is a close match to the beam footprint acquired at the same location with a GAFCHROMIC® dosimetry film[1].

Figure 4 shows the effect of a feedback system based on the proposed beam monitor on beam positional stability during EXAFS scans. In EXAFS experiments performed with a non-fixed exit monochromator, the vertical position of the beam changes during the scan. This behaviour creates serious issues when probing small or inhomogeneous samples and appears at its worst at low energies, as demonstrated in Figure 4a. By installing the proposed beam monitor between the monochromator and the sample and by using its output to generate control signals for the vertically focusing mirror installed after the monochromator, we were able to keep the beam at the same position within 4.1 µm rms range (Figure 4b).

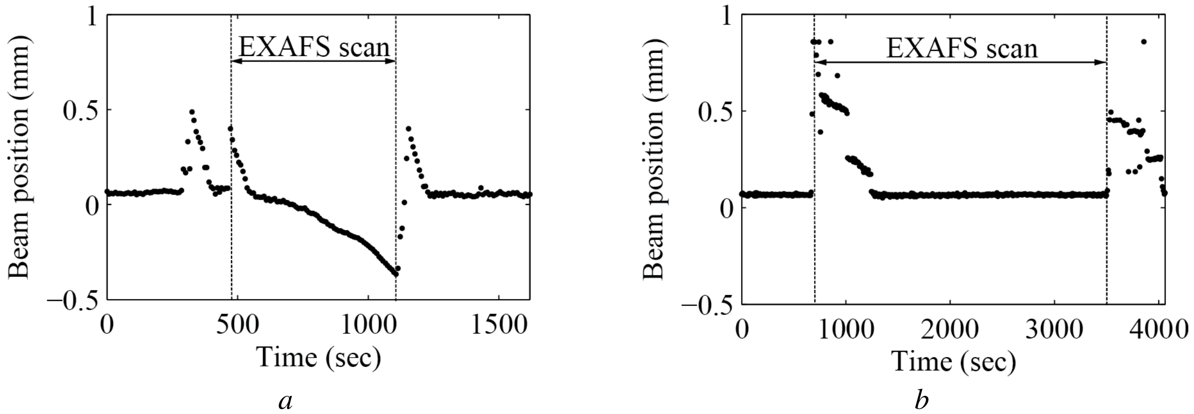


Figure 4. Position measurements during EXAFS scans at Ti K-edge (B26A DUBBLE, ESRF, 2012): *a* – without positional feedback, *b* – with positional feedback (at the beginning of the scan low signal intensity caused a delayed response from the feedback system, however, it recovered well before the scan reached the EXAFS region of the spectrum). Maximum photon flux at the monitor input was about 1.7×10^{10} photons/sec, maximum Kapton™ foil scattering efficiency about 2.8×10^{-5} at 4.8 keV, distance between the data points 8.1 sec.

5. Conclusion

We have described the novel transparent beam monitoring and imaging device that is suitable for *in situ* real-time beam diagnostics. The developed theoretical model and our measurements prove that the device provides both high-resolution beam position measurements and high-resolution images of the beam cross section – a combination that is currently beyond the reach of other *in situ* beam monitors.

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