VERTICAL BEAM PROFILE MEASUREMENT AND ANALYSIS WITH AN X-RAY PINHOLE

Mark J. Boland and Martin Spencer, Australian Synchrotron, Clayton, Victoria 3168, Australia.

Abstract

Imaging the electron beam profile at a synchrotron light source is commonly performed in the x-ray regime using a pinhole camera system. However, with machines pushing down the vertical emittance, including errors in source point optical parameters, pinhole manufacturing limitations and error analysis difficulties associated with diffraction and image capture, the pinhole imaging system has large errors, up to 50% for an emittance of a few picometre. An analysis has been done at the Australian Synchrotron (AS) looking at the effects of errors in determining the x-ray pinhole source point parameters.

MEASUREMENT TECHNIQUE

The simplest transverse beam profile measurement technique employed at electron storage rings is the age old *camera obscura*, or specifically an x-ray pinhole camera. There are many examples of such systems in use and they have been made better by improvements in engineering the pinholes and improved digital cameras. However, as the emittance of stored electron beams has decreased we seem to be approaching the limit after which no useful information can be gained from an x-ray pinhole camera. With non-coupling corrected emittances of 10 nm rad in the horizontal plane and 7 pm rad in the vertical plane, the Australian Synchrotron seems be reaching this limit.

Diffraction Contribution

A critical aspect of analysing images from the x-ray pinhole system is to get the input spectrum correct. The diffraction effects that need to be de-convolved from the images are strongly dependent on the wavelength of the x-rays. Photons passing down the x-ray diagnostic beamline impinge on the materials listed in Table 1.

Table 1: Materials and their thickness that x-rays pass through on the x-ray diagnostic beamline.

Material	**Thickness [μm]**	**Low Cut-off, λ [keV]**
Be	75	~5
Al	30	~10
YAG:Ce ($Y_3Al_5O_{12}$)	100	~7

The x-rays that do not pass through the pinhole impinge on 100 μm foil of W which has a transmission coefficient of < 10^{-9} up to 20 keV.

Note that we are interested in the transmission coefficients in the case of Be and Al and the absorption coefficients in the case of YAG, since the x-rays that interact in the YAG produce the visible photons that are imaged. Convolving the transmission and absorption coefficients [1] for materials in Table 1 with the synchrotron radiation spectrum from the dipole source from the storage ring, the diffraction effects of the pinhole system can be estimated. The sigma of the point spread function is then calculated and subtracted in quadrature from the measured beam sigma and the electron beam size is determined. Following Elleaume [2] for a simple analysis of the effect of the pinhole size and x-ray energy on the diffraction effect, Figure 1 shows how the $\sigma_{\rm diff}$ can be of the same order as the measured width and depend strongly on the pinhole size.

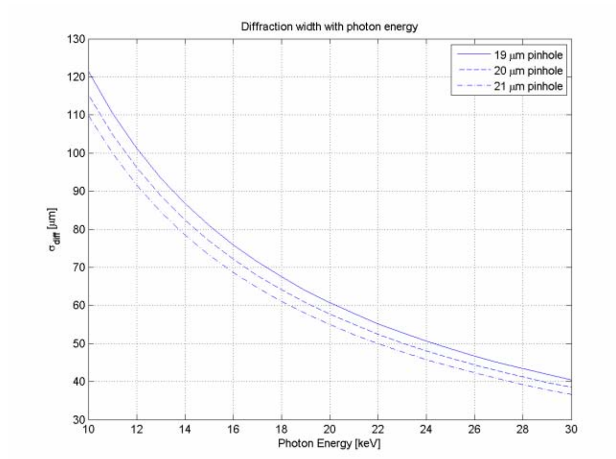

Figure 1: Sensitivity of diffraction effects to photon energy and pinhole size.

These diffraction effects seem to be the dominant contribution to the errors in the emittance measurement with the pinhole system. The effect of the uncertainty in the machine functions and the longitudinal source points will be examined in the following sections.

MODEL PARAMETERS

The machine functions for the source point are extracted from a calibrated model. MATLAB LOCO is used to fit the measured response matrices for different lattice configurations and determine the linear optics of the machine. Unlike Elleaume [2], non-zero vertical dispersion is used in the vertical emittance calculation, however this correction is only a 1% effect. The dominant contribution to the vertical dispersion is assumed to be due to the coupling, so this should be included for an accurate measurement of the emittance coupling. LOCO was applied to the three user optics of the storage ring with distributed dispersion in the straights of 0, 0.1 and 0.24 m. Normal user runs are with 0.1 m dispersion leaked into the straight sections. The results of the emittance measurement for the three lattices are shown in Table 2.

Table 2: Emittance measurements at AS using machine functions from LOCO fits and pinhole beam profiles.

Dispersion [m]	Horizontal Emittance [nm]	Vertical Emittance[pm]	Coupling [%]
0	19	21	0.1
0.1	14	14	0.1
0.24	10	7	0.1

SOURCE POINT ERRORS

Beam Trajectory through the Dipole

The dipole for Boomerang [3] is a gradient dipole and contains most of the vertical focussing strength in the lattice. As a consequence, the electron beam trajectory had to be carefully modelled to account for the resulting non-circular beam path. The method that was followed is described in reference [4] and resulted in a horizontal shift of the source points in the dipole of 1.5 mm compared with the original nominal source points.

Pinhole Alignment

Errors in the horizontal alignment of the pinhole on the x-ray diagnostic beamline translate into longitudinal errors in the source point position. Alignment errors of the pinhole and dipole have the same effect as a horizontal trajectory shift introduced by a gradient in the bending dipole as described above. With the AS survey network the pinhole and the dipole can be positioned relative to each other in the horizontal plane with an accuracy of 150 μm, while the vertical position of the pinhole relative to the centre of the nearest quadrupole is accurate to within a few microns.

Figure 2 shows a simple model of the alignment errors Δx on the source point s of the pinhole camera. The source to pinhole distance is d = 3384 mm and Δx is of the order of 1 mm, so the change in s is of the order of 1 mm. In this scheme, at the source point the bending trajectory can be considered circular and the change in Δx can be calculated geometrically in terms of θ and ρ.

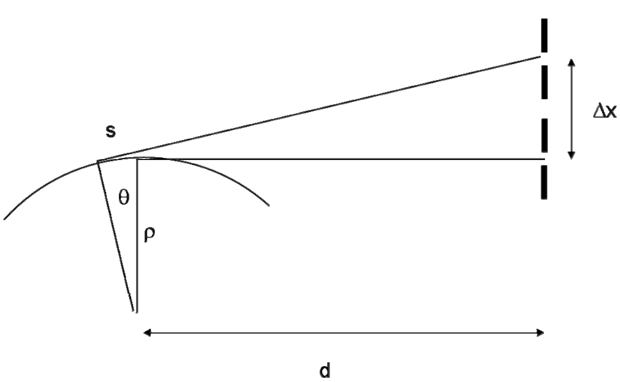

Figure 2: Effect of horizontal pinhole alignment on the longitudinal source point.

The functions are:

$$\Delta x = (d + \rho \sin\theta)\sqrt{\frac{1-\cos^2\theta}{\cos^2\theta}} - \rho(1-\cos\theta)$$

$$s = \rho\theta.$$

Figure 3 shows the longitudinal source point variation as a result of a horizontal offset of the pinhole or the electron beam trajectory through the gradient dipole at the AS. The properly modelled dipole trajectory shows a 1.5 mm offset horizontally which results in a 3.5 mm longitudinal source point offset.

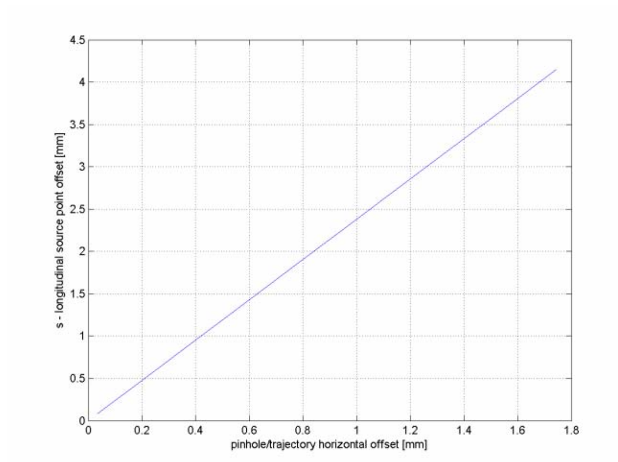

Figure 3: Longitudinal source point change with pinhole alignment and trajectory offset in the horizontal plane.

CALIBRATED MODEL

Source Point

The source point for the x-ray pinhole camera is in a gradient dipole (k = −0.33), so the beta-functions do vary significantly along the length of the magnet. Figure 4 shows the vertical machine functions for the x-ray pinhole dipole 10BM2.

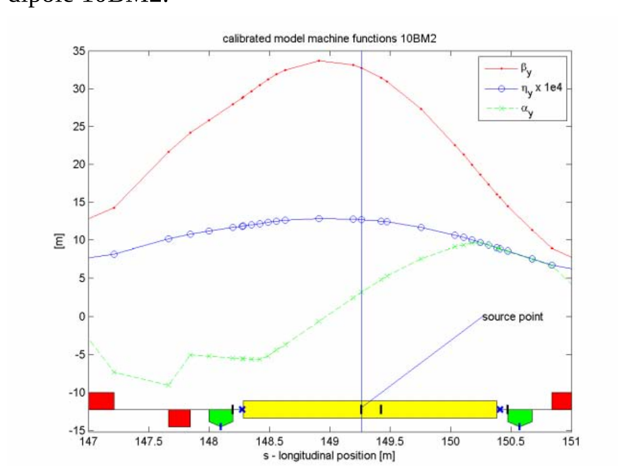

Figure 4: Lattice functions from calibrated model.

Vertical Beta Function

The variation in the vertical beta function due to alignment and dipole trajectory uncertainty is only relevant to machines with gradient dipoles. The LOCO calibrated model is estimated to be on the order of ±1% at a given source point, with a contribution due to the source point uncertainty as described above only contributing another ±0.1%. At the AS this translates into an absolute uncertainty in the vertical emittance of ~0.3 pm as seen in Figure 5.

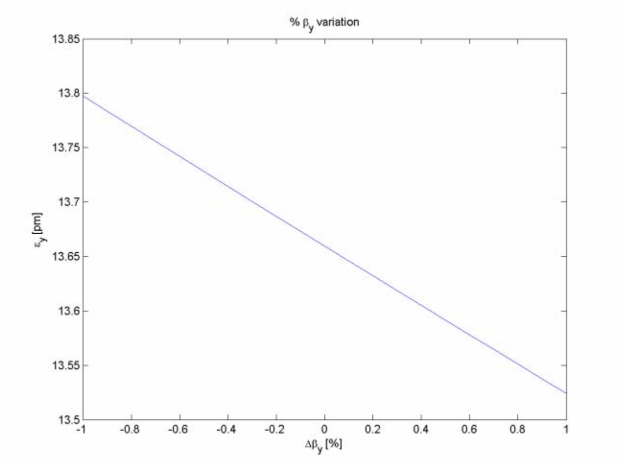

Figure 5: Lattice functions from calibrated model.

Vertical Dispersion

Extracting the vertical dispersion component from the measured vertical beam profile using the value obtained from the LOCO calibrated model decreases the measured vertical emittance by only 0.4% for the 0.1 m distributed dispersion lattice. The absolute contribution of the vertical dispersion is approximately 0.05 pm, so it is only a small fraction of the final uncertainty. Figure 6 shows the effect of adding vertical dispersion as measured with a response matrix and fit using LOCO for the AS storage ring.

FURTHER WORK

The x-ray pinhole system has been adequate as a diagnostic tool for measuring the design emittance and qualitative observation of the beam at the AS. However, for more detailed machine studies and to accurately measure the coupling corrected low emittance lattice an improved system is required. Planned upgrades include hardening the input spectrum with filters to reduce the diffraction effects, reduce the thickness of the scintillator by using a high resolution phosphor screen and increase the magnification of the visible CCD lens.

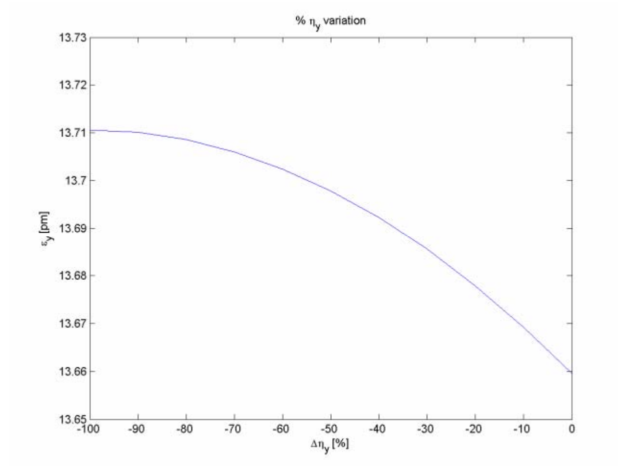

Figure 6: Sensitivity of vertical emittance to vertical dispersion.

CONCLUSIONS

When measuring the electron beam emittance on a lightsource storage ring using beam profile measurements from a synchrotron light source point in a gradient dipole, careful analysis of the beam trajectory is required. This is particularly critical for modern machines with low coupling and a vertical emittance of a few pm. Using an x-ray pinhole system the dominant errors are still in de-convolving the diffractions contributions to the beam profile and not so sensitive to the machine parameters and source point uncertainty. However the latest interferometric methods [5] in the visible range might be more sensitive to source point errors in future low emittance lightsources (e.g. reference [6]) with gradient dipoles.

REFERENCES

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