# VERTICAL EMITTANCE MEASUREMENTS USING A VERTICAL UNDULATOR

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*Abstract*

We have reported on initial work to measure vertical emittance using a vertical undulator. Using simulations, we motivate the important experimental subtleties in the application of this technique. Preliminary measurements of undulator spectra are presented that demonstrate the high sensitivity of vertical undulators to picometre vertical emittances. Finally, possible future applications of this technique are explored.

## INTRODUCTION

Electron storage ring light sources and damping rings continue to produce beams of increasingly small vertical emittance. With the recent report of the minimum observed vertical emittance of $\varepsilon_y = 0.9 \pm 0.4$ pm rad at the SLS [1], we require techniques sensitive to sub-micrometre electron beam sizes. At the Australian Synchrotron, we have developed a technique for measuring the vertical emittance of electron beams that we call vertical undulator emittance measurement [2].

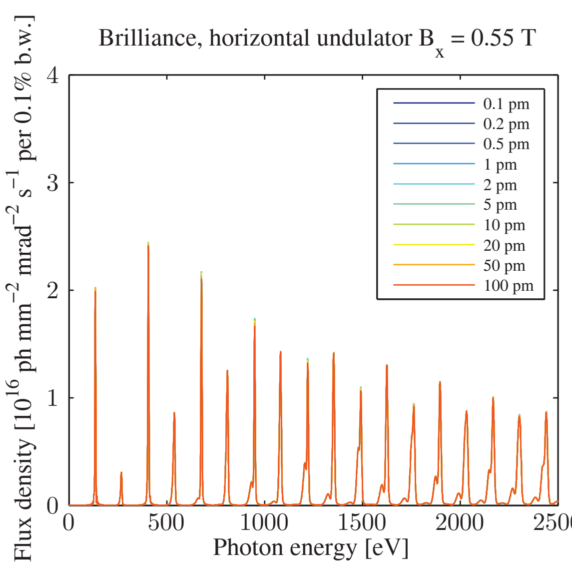
In these proceedings, we assess undulators as a beam diagnostic. In contrast to horizontal undulators being largely insensitive to picometre vertical emittance, we highlight the sensitivity of vertical undulators to the vertical emittance. We present preliminary results and simulations, as well as ideas for future vertical emittance diagnostics.

## THEORY

Undulators have been used as diagnostics of storage ring emittance. Horizontal undulators – undulators that deflect the electron beam in the orbit plane of the ring – have been demonstrated to give excellent measurement of the horizontal beam size and energy spread [3–7]. Where the electron beam emittance is close to fully-coupled, the brilliance of horizontal undulators exhibits some sensitivity to the vertical emittance [4]. Electron storage and rings typically design for transverse emittance ratios less than a few percent, with damping ring designs aiming for minimum vertical emittance. In this low vertical emittance limit horizontal undulators are identified as particularly insensitive to vertical emittance, limited by the single-electron opening angle of undulator radiation [3].

### *Photon Beam Brilliance*

Modelled in SPECTRA [8], the sensitivity of horizontal and vertical undulators to vertical emittance is illustrated in Figure 1 below.



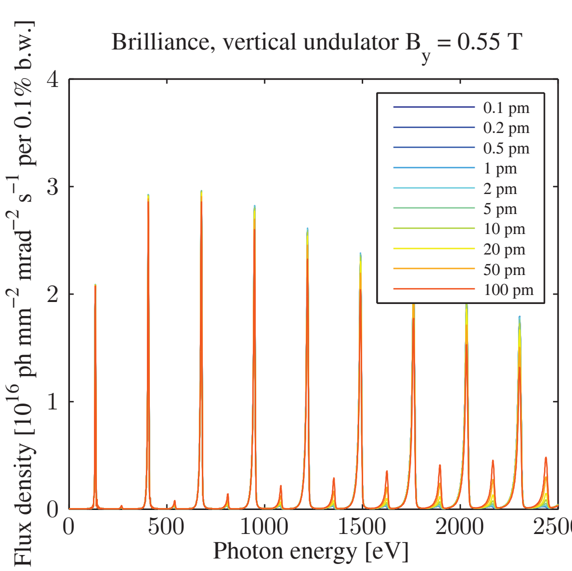




Figure 1: Photon beam brilliance, for horizontal undulator and vertical undulator of deflection parameter $K = 3.85$, for ASLS user lattice with $\eta_x = 0.1$ m in the insertion [9].

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Figure 1 illustrates the photon beam brilliance for horizontal and vertical undulators of equal deflection parameter. Over a range of operational vertical emittances there is no measurable change in brilliance for a horizontal undulator. However we see that for a vertical undulator, at high even undulator harmonics, the photon beam brilliance changes by orders of magnitude. Hence, measurements of the photon beam brilliance at the even harmonics exhibit a strong dependence upon the electron beam emittance [10].

To measure the brilliance of these harmonics, we consider the angular distribution of undulator radiation. In Figure 2 we present simulations [8] of the vertical profile of a horizontal undulator, and a vertical undulator in Figure 3.

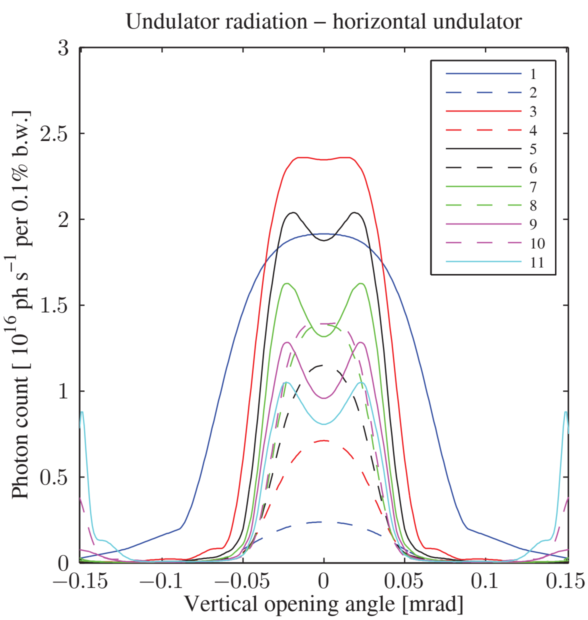


Figure 2: Simulated vertical profile of undulator harmonics, horizontal undulator. Vertical emittance $\varepsilon_y = 1$ pm rad.

For a fixed, low vertical emittance of $\varepsilon_y = 1$ pm rad and horizontal emittance $\varepsilon_x = 10$ nm rad, Figures 2–3 exemplify the difference between the horizontal and vertical direction of undulation. With undulations in the horizontal direction in Figure 2, we see the incoherent superposition of spontaneous undulator radiation from a beam with a comparatively large horizontal emittance.

In Figure 3 however, the small simulated vertical emittance of $\varepsilon_y = 1$ pm rad is indicative of the single-electron distribution of undulator radiation. The narrow spatial distribution of the interference pattern created at each undulator harmonic is of $\sin^2\theta$ distribution for odd harmonics, and $\cos^2\theta$ distribution for even harmonics. Hence an on-axis pinhole aperture passing a narrow angular distribution above and below the orbit plane of the undulator passes a maximum flux for odd undulator harmonics, and minimum for even harmonics, as illustrated in Figure 1.

The beam emittance is evaluated as a ratio of peak flux in the even harmonic to that of the adjacent odd harmonic.

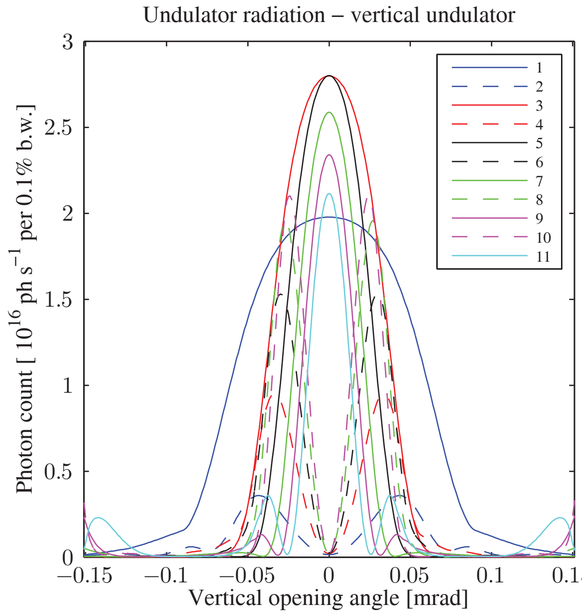


Figure 3: Simulated vertical profile of undulator harmonics, vertical undulator. Vertical emittance $\varepsilon_y = 1$ pm rad. Around $\theta_y \approx 0$, the narrow interference peaks of the even and odd harmonics are well-separated in amplitude.

This idea has also been proposed for measurement of horizontal beam emittance in plasma wakefield accelerated electron beams [6, 7].

## METHOD

We measure the undulator flux passing an on-axis pinhole. The pinhole is formed by closing white-beam slits on the beamline. As a spectrometer, we utilise the soft x-ray user beamline [11, 12].

### *Vertical Emittance*

A calibrated model of the storage ring lattice was measured using orbit response matrix analysis, and fitted using the LOCO technique [13]. The electron beam vertical emittance was adjusted by optimising skew quadrupole magnets in the lattice model [14].

### *Photodiode*

The preliminary measurements presented in Figures 4 – 5 were made using a Hamamatsu G1963 GaP/Au Schottky photodiode. The diode was selected as it is installed on the beamline as a standard diagnostic of photon flux. The responsivity of the photodiode was calculated over the relevant range of photon energies [15]. Over the desired photon energy range, the responsivity for this type of diode exhibits large discontinuities at absorption edges. To avoid this, use of a doped silicon photodiode should be considered.

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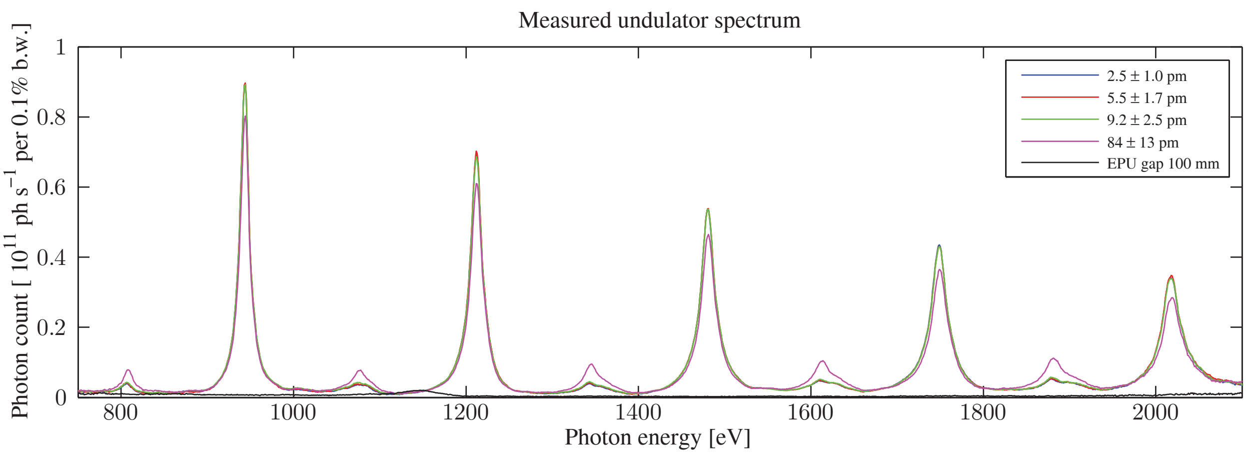


Figure 4: Measured vertical undulator flux passing an on-axis pinhole.

## RESULTS

### *Measured Undulator Spectra*

The measured undulator spectra are plotted in Figure 4 above. Four vertical emittance lattice configurations were considered, with the undulator closed to a gap of 17.1 mm, close to the minimum gap. This corresponds to an undulator deflection parameter of $K = 3.85$. The sensitivity of this technique to small vertical emittances is illustrated in Figure 5 below. The even undulator harmonics 6 – 14 are shown on an expanded vertical scale, to highlight the measurable separation in intensity of undulator spectra between beams of several picometre vertical emittance.

### *Background Flux*

The background was estimated by measuring the photon flux with the undulator open to 100 mm, close to the maximum gap. This is shown in black on Figures 4 – 5. With the undulator open to 100 mm, the first undulator harmonic is shown in the measured spectrum at 1140 eV, and is not a background feature.

### *Measured Flux Ratio*

The ratio of fluxes of adjacent harmonics is evaluated for 10 and 11. The results are summarised in Table 1 below. The vertical emittance and corresponding uncertainty was evaluated using orbit response matrix analysis. Uncertainty in the corresponding ratio of fluxes is estimated from systematics in measurement of the background flux, as well as statistical uncertainties. This measured ratio can be compared with simulation of the apparatus, however to extract a meaningful measurement of the emittance, the vertical dimension of the pinhole must be known. It can be seen that for this unknown pinhole dimension, that picometre beam emittances are resolvable at the level of a factor of two.

Table 1: Measured Flux Ratio $F_{10}/F_{11}$

| $\varepsilon_y$ [pm rad] | $F_{10}/F_{11}$ |
|---|---|
| $84 \pm 13$ | $0.204 \pm 0.006$ |
| $9.2 \pm 2.5$ | $0.083 \pm 0.005$ |
| $5.5 \pm 1.7$ | $0.078 \pm 0.005$ |
| $2.6 \pm 1.0$ | $0.074 \pm 0.005$ |

## DISCUSSION

Future diagnostics and applications of vertical undulators to synchrotron light source storage rings are summarised.

### *SOLEIL DiagOn*

Recently, direct of projections of undulator harmonics have been measured at SOLEIL [16]. Designed as a beam diagnostic for APPLE-II insertion devices, the reported DiagOn device measures the distribution of horizontally-polarised undulator radiation at a fixed photon energy. By rotating the device around the beam axis to pass photons of vertical polarisation, the inteference pattern at fixed energy could be measured to observe the vertical emittance.

### *Vertical Undulator*

As an aside to emittance measurement, vertical undulators may be used with existing storage rings to provide a more brilliant photon source. As shown in Figure 1 the brilliance of high, odd undulator harmonics is a factor of two greater for the undulator in the vertical rather than horizontal configuration, at vertical emittances of several pm rad. These small vertical emittances are achievable at many storage ring light sources.



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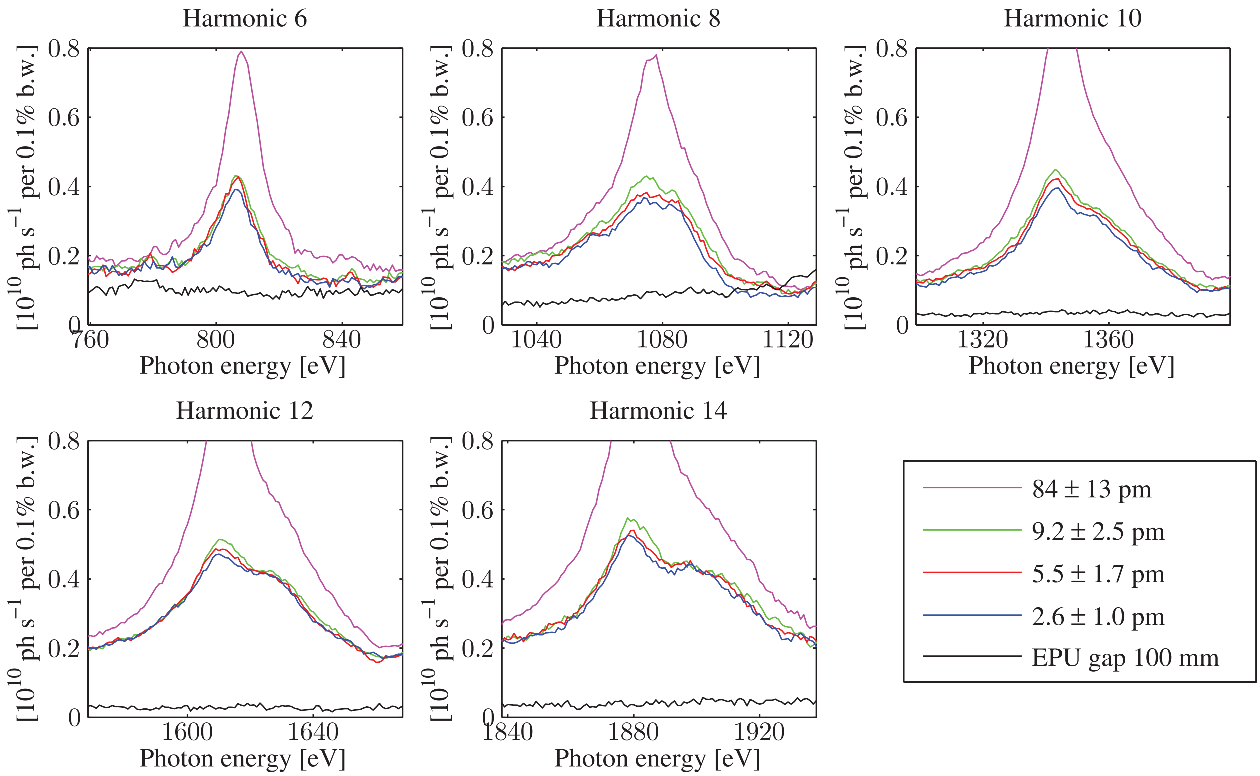


Figure 5: Even harmonics shown on expanded vertical scale, with background subtracted. The even harmonics 6 – 14 are illustrated for vertical emittances of 2.5, 5.2, 9.2 and 84 pm rad. Also shown in black is the undulator spectrum measured with the EPU open to 100 mm, for which the photon energy of the first harmonic is $E_{\mathrm{ph}} = 1140$ eV.

## CONCLUSION

We have reported on initial work to measure vertical emittance using a vertical undulator. Using simulations, we demonstrate the usefulness of vertical undulators as a diagnostic for vertical emittance. Preliminary measurements of undulator spectra are presented that demonstrate the high sensitivity of vertical undulators to picometre vertical emittances. Future applications of this technique are explored, notably the possibility of imaging the interference pattern at a fixed photon energy.

## ACKNOWLEDGEMENTS

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