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TRANSVERSE EMITTANCE MEASUREMENT USING UNDULATOR HIGH HARMONICS FOR DIFFRACTION LIMITED STORAGE RINGS*

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Abstract

A particular challenge for diagnostics in diffraction limited storage ring light sources is the measurement of electron beam transverse emittances. In the present work, we present measurements and simulations of vertical electron beam emittance using high harmonics from an electromagnetic undulator in the present Advanced Photon Source storage ring. Based on these results, using simulation we motivate an undulator-based horizontal and vertical transverse emittance monitor for diffraction limited storage rings, using the Advanced Photon Source Upgrade as an example.

INTRODUCTION

Over the coming years, the Advanced Photon Source Upgrade (APS-U) project will convert the existing Advanced Photon Source (APS) facility to a high brilliance diffraction limited electron storage ring (DLSR) light source [1]. The horizontal emittance of the APS-U storage ring lattice will be 41.7 pm rad [1]. In that regard, measurement of the horizontal emittance at DLSRs presents similar challenges to measurement of the vertical emittance measurement at existing third generation storage rings [2–8].

Dedicated emittance and electron beam energy spread monitors have been designed for the APS-U storage ring employing bending magnet radiation sources [9]. These monitors have been optimised to confirm the small transverse horizontal and vertical emittances of the proposed APS-U storage ring.

A technique that has previously been used to measure pm rad scale vertical emittances employs a vertical undulator undulator by mapping the energy and spatial profile of the ID beam by coordinated scans of the monochomator and aperture [10–14]. In the present work, we use the Intermediate Energy X-ray (IEX) beamline to measure the vertical emittance of the existing APS storage ring. Based on these results, using simulations we motivate that this technique could be used to measure transverse emittances of DLSRs, using the APS-U as an example.

IEX BEAMLINE

This experiment was conducted using the APS storage ring and the Angle-Resolved Photoemission Spectroscopy branch line of the IEX beamline [15, 16]. The IEX beamline is a user beamline at the APS storage ring. A schematic of the IEX beamline is given in Fig. 1.

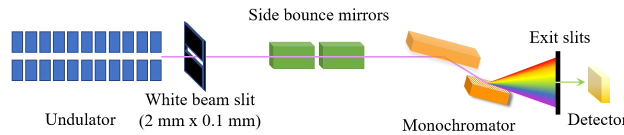

Figure 1: Schematic of IEX beamline components used in the present experiment.

The IEX undulator is an electromagnetic insertion device (ID), able to operate in horizontal, vertical and left and right-hand circular polarisation modes [16–19]. It is possible to operate the ID in quasi-periodic mode [19, 20], but for this experiment the ID was operated with full periodicity. Parameters of the electron beam and ID for both experiment and simulations are summarised in Table 1.

The white beam slits correspond to the first optical element ofthe beamline and are located at a longitudinal position of 28.8 m downstream of the centre of the ID and was used to define the portion of the ID radiation being sampled [15]. This is the longitudinal position at which all simulations and measurements in this work are evaluated. The photon beam is horizontally deflected by two gold coated planar mirrors which are located just downstream of the white beam slits. The second mirror has the largest angle of incidence, 1.5 degrees, and is responsible for maximum energy cutoff of ~3000 eV. Downstream of these mirrors is a variable line-spacing plane grating monochromator which focuses the beam on the exit slit for all photon energies.

Table 1: Parameters of electron beam and undulator for APS (experiment and simulations), and APS-U (simulations)

Parameter		**APS**	**APS-U**	**Units**
Electron beam				
Energy	E	7.0	6.0	GeV
Horiz. emittance	ε_x	3100	41.7	pm rad
Horiz. beta	β_x	19.1	5.19	m
Vert. beta	β_y	3.20	2.40	m
Horiz. dispersion	η_x	167	0.39	mm
Energy spread	$\Delta E/E$	0.096	0.135	%
IEX undulator				
Peak magnetic field	B_x	0.322	-	T
Peak magnetic field	B_y	-	0.322	T
Undulator period	λ_u	0.125	0.125	m
Number of periods	n_u	38	38	–
First harmonic	ϵ_1	461	339	eV
IEX beamline				
White beam slits		28.8	28.8	m

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Just after the exit slit the photon flux was measured with a calibrated silicon photodiode.

APS SIMULATIONS

Simulations of ID radiation were computed using SPECTRA 10.0 [21–23]. As shown in previous studies, the highest sensitivity to small vertical emittances is observed at highest available harmonics [11,13]. Hence for this present work, we chose to operate the insertion device close to the maximum field for the vertical polarisation. An example simulated distribution of undulator radiation at the longitudinal position of the white beam slits is given in Fig. 2.

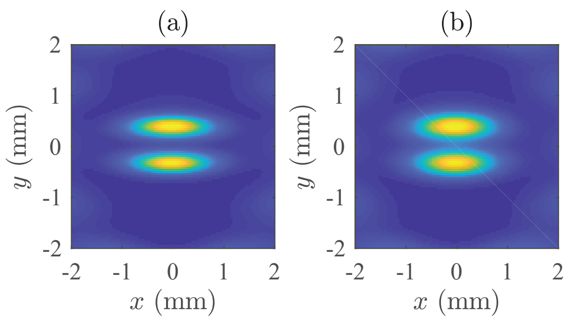

Figure 2: Simulation of the 6th harmonic in APS at 2755 eV (peak flux), for electron beam and ID parameters in Table 1. (a) Vertical emittance $\varepsilon_y = 16$ pm rad. (b) Vertical emittance $\varepsilon_y = 128$ pm rad. Effectively, the non-Gaussian radiation distribution is convolved with a larger Gaussian electron beam distribution in the vertical.

We simulate the horizontal aperture of the white beam slits by integrating the undulator radiation within -1.0 mm $< x <$ 1.0 mm. The vertical profile of undulator radiation is plotted in Fig. 3. Effectively, observing undulator radiation from a vertical undulator at an even harmonic gives a null in intensity about $y = 0$ mm at the limit of smallest vertical emittances. As the emittance is increased, the undulator radiation profile approaches a Gaussian distribution.

APS EXPERIMENT

The undulator radiation of the IEX ID was measured while varying vertical emittance in the APS storage ring. The IEX ID was energised to produce a horizontal magnetic field (vertical polarisation), per the parameters given in Table 1. The vertical emittance was varied by adjusting the betatron coupling using skew quadrupoles around the ring.

The four independent slit blades were closed to form a rectangular pinhole aperture to selectively pass undulator radiation. The white beam slits were set to pass a horizontal width of 2 mm, centred horizontally on the undulator radiation distribution (-1.0 mm $< x <$ 1.0 mm). The 2 mm width ensures that the entire central cone of the ID beam is sampled. The vertical slits were minimised to a full aperture of 0.1 mm. The vertical slit position of the rectangular pinhole was scanned by scanning both the upper and lower

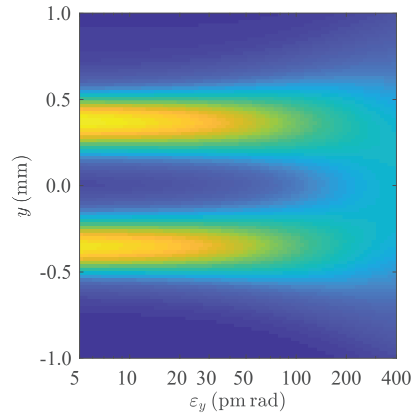

Figure 3: Simulation of the 6th undulator harmonic in APS at 2755 eV, for electron beam and ID parameters in Table 1. The colour scale shows the integrated intensity of undulator radiation within -1.0 mm $< x <$ 1.0 mm, normalised by the peak at 5 pm rad. The electron beam vertical emittance was varied over the range 5 to 400 pm rad, with greater contrast peaks in the vertical profile at small emittance, approaching a Gaussian distribution as the emittance increases.

vertical blades together. The energy profile of the beam is characterized by scanning the monochromator. These spectrally and spatially-resolved scans are plotted in Fig. 4.

There are several features of note in Fig. 4. The first was that an unknown extraneous flux of undulator radiation was observed at photon energy 2760 eV, $y = -0.4$ mm. This flux was not observed to move as the electron beam was steered through the insertion device. The second is a saddle point in flux was observed at 2760 eV, corresponding to the 6th undulator harmonic. As the vertical emittance is reduced, this saddle point becomes more pronounced. Vertical profiles of this saddle point at 2760 eV are illustrated in Fig. 5.

Figure 5 shows good agreement between the measured vertical undulator radiation profile and simulations of the undulator radiation profile for the measured vertical emittance.

APS-U SIMULATIONS

In particular, we consider the horizontal emittance of the APS-U beam. Simulations of ID radiation were computed using SPECTRA 10.0 [21–23], with parameters for APS-U given in Table 1. One change of the APS-U is that the electron beam energy drops to 6 GeV, which for a given undulator magnetic field shifts the photon energy of the first harmonic down to $\epsilon_1 = 339$ eV. This has the advantage that higher undulator harmonics fit within the 3000 eV reflectivity limit of the beamline mirrors, so the 8th harmonic (2699 eV, peak flux near 8th harmonic) was considered. For this present simulation, we chose to use the same magnitude of the ID peak magnetic field, but in this case the field orientation is vertical (horizontal polarisation of undulator radiation). An example simulated distribution of undulator radiation at

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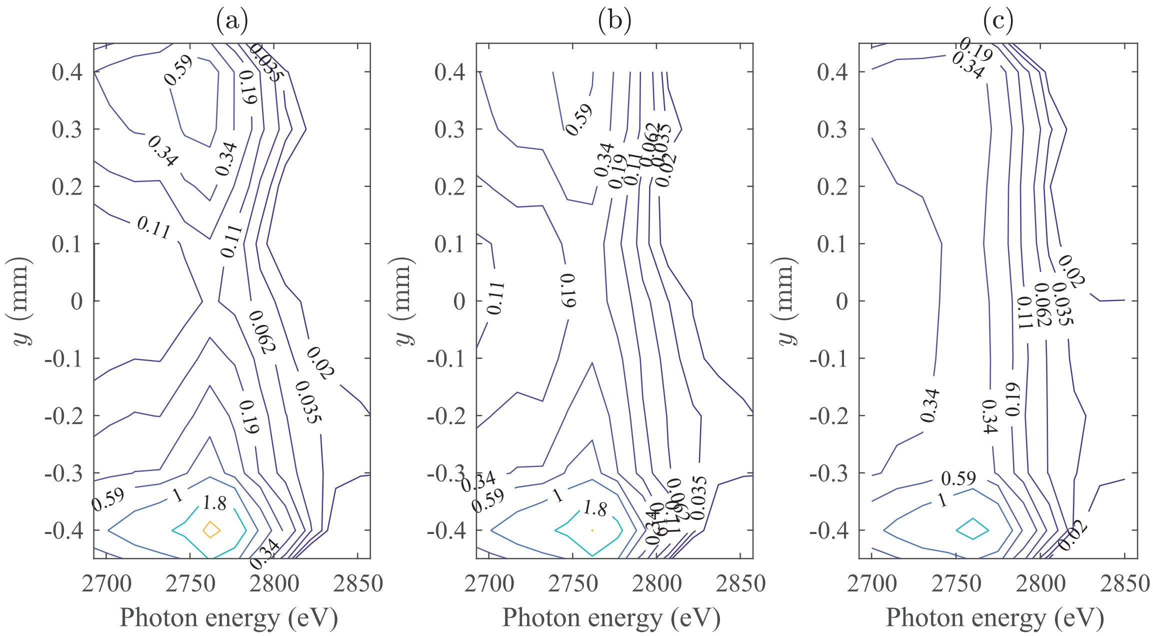

Figure 4: Measured undulator radiation flux passing slit at vertical emittances of (a) ε_y = 33 pm rad, (b) ε_y = 68 pm rad, (c) ε_y = 141 pm rad, plotted in arbitrary units in terms of the photon energy and vertical position y of the slit centre. A saddle point in flux is observed at 2760 eV, corresponding to the 6th undulator harmonic. An unknown peak in undulator radiation was observed at photon energy 2760 eV, $y = -0.4$ mm, which was not observed to move as the electron beam was steered through the insertion device. Bending magnet radiation background has been subtracted.

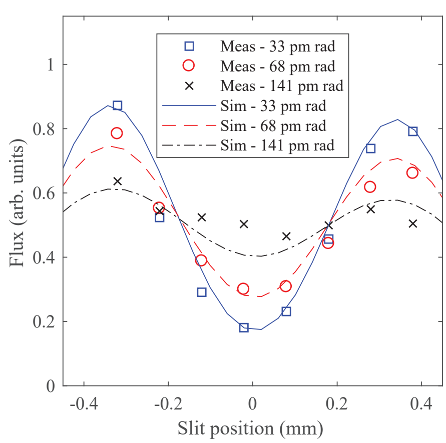

Figure 5: Vertical profile of 6th undulator harmonic at 2760 eV. Measured data are line profiles in y from Fig. 4(a-c). Simulations are calculated using SPECTRA. The amplitude is an integral of the flux over -1.0 mm $< x <$ 1.0 mm. Bending magnet radiation background has been subtracted from the measurements.

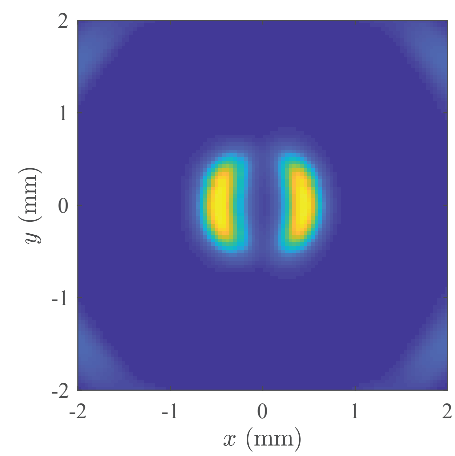

Figure 6: Simulation of APS-U 8th harmonic (2699 eV, peak flux near 8th harmonic) with IEX undulator set for horizontal polarisation at 338.8 eV. The horizontal emittance in this simulation is ε_x = 41.7 pm rad.

the longitudinal position of the white beam slits is given in Fig. 6.

Figure 6 shows the horizontal distribution of undulator radiation with the IEX ID operating in the horizontal polarisation mode, on the APS-U storage ring. One can see that the horizontal undulator radiation distribution of even harmonics will be very similar to operating the device as a vertical undulator, as given in Fig. 2. Similarly, we calculate the 8th harmonic flux passing a narrow vertical aperture (-1.0 mm $< y <$ 1.0 mm), to simulate scanning this aperture horizontally across the radiation distribution in Fig. 6. This is plotted for varying horizontal emittance in Fig. 7.

Figure 7 (horizontal polarisation in APS-U) can be compared to Fig. 3 (vertical polarisation in APS today). Effectively, observing undulator radation from a horizontal undulator at an even harmonic gives a null in intensity about $x = 0$ mm at the limit of smallest vertical emittances. As

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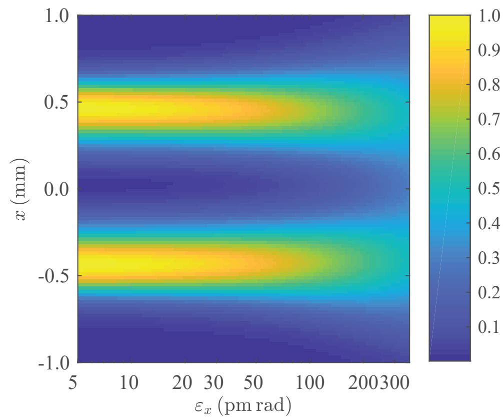

Figure 7: Simulation of APS-U 8$^{\text{th}}$ harmonic (2699 eV, peak flux near harmonic) with IEX undulator set for horizontal polarisation at fundamental $\epsilon_1 = 338.8$ eV. The colour scale shows the integral of intensity over $-1.0\,\text{mm} < y < 1.0\,\text{mm}$.

the emittance is increased, the undulator radiation profile approaches a Gaussian distribution. For a given horizontal emittance ε_x, we choose to define a ratio R of the intensity distribution,

$$R = \frac{F(x=0, \varepsilon_x)}{\max F(x, \varepsilon_x)}, \tag{1}$$

which is effectively the ratio of the valley to the peak in intensity, for a given emittance. For the APS-U simulation in Fig. 7, this is plotted in Fig. 8.

The design horizontal emittance of the APS-U storage ring operated in brightness mode is $\varepsilon_x = 41.7$ pm rad [1]. As this is comparable with the vertical emittance in the APS storage ring today, confirmation of the horizontal emittance of the APS-U using the IEX beamline appears to be feasible. Similarly, the vertical emittance could be measured using the undulator operated in the vertical polarisation at small emittances, as presented in the present and previous studies [13].

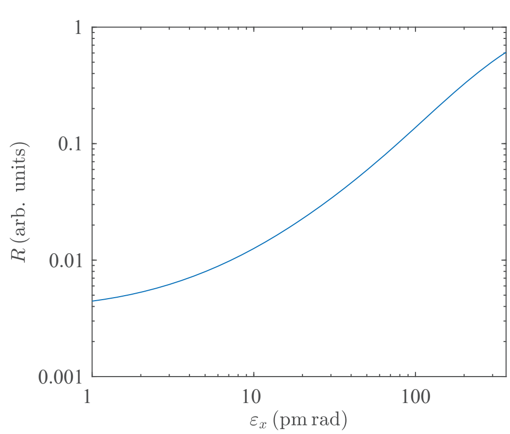

Figure 8: Simulation of APS-U 8$^{\text{th}}$ harmonic (2699 eV, peak flux near harmonic) with IEX undulator set for horizontal polarisation at 338.8 eV. The ratio R given by Eq. (1) is evaluated for the emittances in Fig. 7.

FUTURE WORK

In comparison with previous work, these measurements were performed at a single photon energy and single undulator deflection parameter. This enables the possibility of imaging the undulator radiation using a DiagOn device [24, 25]. At present, two imaging devices are installed on the IEX beamline frontend (one for each of the vertical and horizontal polarisations), making this an option as a diagnostic for characterising transverse emittances.

CONCLUSION

In conclusion, in the present work, we presented measurements of vertical electron beam emittance using the 6$^{\text{th}}$ harmonic from an electromagnetic undulator in the present APS storage ring. Simulations agreed well with measured radiation profiles. Based on these results, using simulation we demonstrate that measurement of horizontal emittance in DLSRs is feasible, using parameters of the APS-U as an example.

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