LOW NOISE AND HIGH DYNAMIC RANGE OPTICAL INTERFEROMETER BEAMSIZE MEASUREMENTS

M. J. Boland, Australian Synchrotron, Clayton, Victoria 3168, Australia
T. Mitsuhashi, KEK, Ibaraki, Japan
K. P. Wootton, The University of Melbourne, Victoria 3010, Australia

Abstract

The technique of optical interferometry to measure beam sizes requires a low noise and high dynamic range digitisation system to push the performance to ultra low emittance on storage rings. The next generation of camera sensor Scientific CMOS (sCMOS) promises to provide the technology to improve optical interferometry. A series of measurements was performed on the Australian Synchrotron storage ring using a sCMOS and a intensity imbalance optical interferometer. The coupling in the storage ring was varied from maximum to minimum using the skew quadrupoles and the beam size at the optical diagnostic beamline was varied from over 100 microns to around 1 micron. A comparison is made between interferometer measurements using the sCMOS with and without an intensity imbalance and with previous measurements using a CCD system.

INTENSITY IMBALANCED INTERFEROMETER

The method of directly determining the beam size using an optical interferometer was pioneered at the Photon Factory [1] and later improved upon for measuring ultra small beam sizes at ATF [2] using the intensity imbalanced method [4]. The experimental setup used to make beam size measurements using an intensity imbalanced interferometer at the Australian Synchrotron in this paper are explained elsewhere [6]. This work is motivated by the achievement of ultra low vertical emittance in the Australian Synchrotron storage ring [3] and the desire for a direct measurement. The intensity imbalance method pushes the fundamental limit that can be measured with an interferometer down to approximately 1 μm under ideal conditions. The measurements presented here use the latest sCMOS technology to test the detectors ability to fulfill the interferometer requirements of low noise, high dynamic range and a linear response with light intensity variations.

EXPERIMENTAL SETUP

The experimental set-up is described in Ref. [6] and the resultant typical interference pattern is shown in Fig. 1. These interference patterns are fitted to extract the interference fringe visibility from which the beam size is determined as described below. The optical diagnostic beamline uses a frontend designed for x-ray extraction and is limited to extracting 1 mrad of visible light from the top part of the beam and thus only samples a fraction of the 5 mrad vertical opening angle of the optical synchrotron radiation. The limiting apertures of the beamline are in the dipole vacuum vessel and are to overcome without major reconstruction of the steel chamber. Design options are being considered to extract the beam symmetrically from the top and bottom part of the radiation fan but presently the beamline frontend aperture limits the spacial frequencies that are transmitted into the interferometer and prevent it from measuring beam sizes below approximately 40 μm.

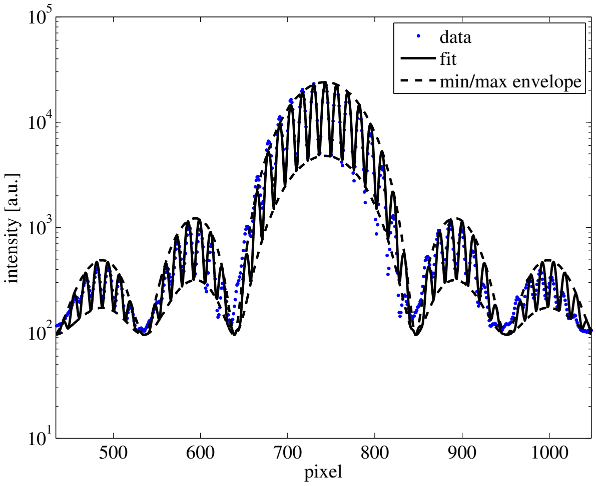

Figure 1: Typical interference pattern with the nodes in the envelope function returning to the background noise levels. A log scale is use on the vertical axis to illustrate the clarity of the higher harmonics of the interference pattern.

IMAGE SENSOR PERFORMANCE

A new sCMOS detector [5] was tested for its suitability to measuring interference patterns on the intensity imbalance interferometer.

Firstly, the dynamic range of the sensor was tested by observing an interference pattern and looking for higher order diffraction fringes (see Fig. 2). For the given field of view of the system the fringes were visible right to the edge of the sensor and above the background noise up to the 18th node of the sinc pattern.

Secondly, the linearity of the sensor was measured by recording the peak value on the image for a range of single bunch currents in the storage ring. A single bunch was injected into the same RF bucket and the current recorded with a DCCT. Figure 3 shows that over a one order of magnitude change in single bunch current the fitted peak amplitude varies linearly with a high degree of accuracy.

At the higher intensities there is trend away from linearity by approximately 1%.

Finally, the background noise of the sCMOS was observed in water cooled mode which drops the temperature of the sensor to approximately -20C. The camera was covered with a light tight cap and a dark field image was taking with a 9 ms exposure time (see Fig. 4). The noise level was 100 ± 3 counts per pixel or 0.15% of the full 16 bit ADC range. Even when the sensor is illumination with 300 ms exposure time is still has a background count of 100 per pixel (c.f. Fig. 1 and Fig. 4).

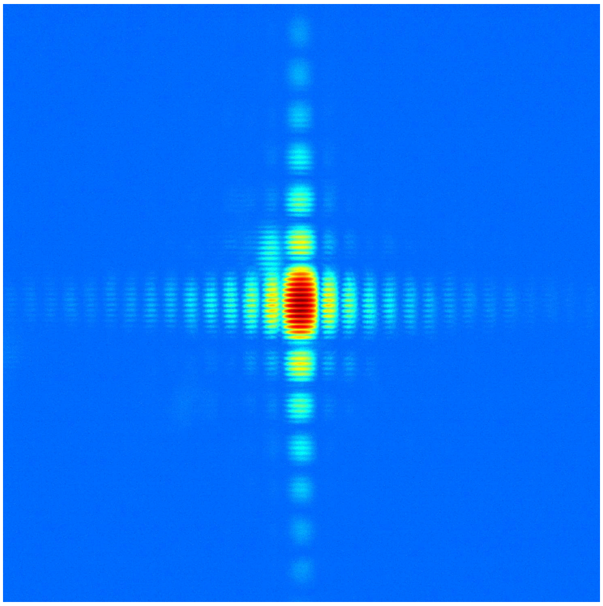

Figure 2: Image of the interference pattern recorded by the sCMOS sensor illustrating the high dynamic range.

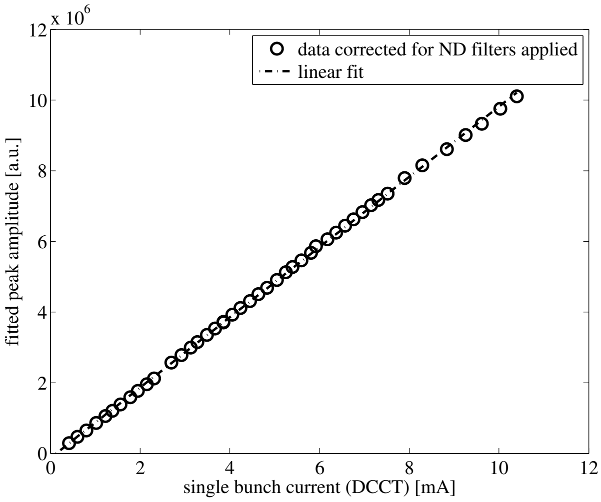

Figure 3: Peak beam spot intensity for a range of single bunch currents

The performance of the sCMOS seems ideal for taking high quality images of the interferometer beam size measurement apparatus.

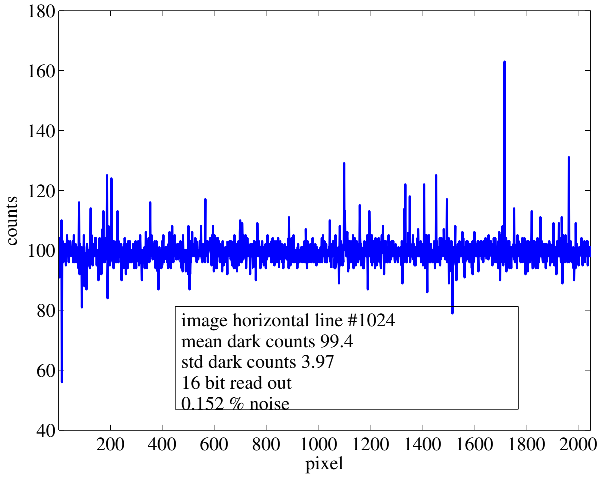

Figure 4: Dark field measurement using the sCMOS camera.

BEAM SIZE MEASUREMENTS

To extract the beam size from an interference pattern, a fit is made of the visibility $\mathcal{V}$ using the relation [4]

$$I(y) = I_0 \mathrm{sinc}\left(\frac{2\pi a}{\lambda R} y\right)^2 \left[1 + |\mathcal{V}| \cos\left(\frac{2\pi D}{\lambda R} y + \phi\right)\right],$$

and the beam size is then given by

$$\sigma_y = \frac{\pi D}{\lambda R}\sqrt{\frac{1}{2}\ln\left(\frac{1}{|\gamma|}\right)}.$$

The complex degree of coherence γ is related to the visibility by the intensity imbalance through the two slit by

$$|\gamma| = \mathcal{V}\frac{(1 + I_2/I_1)}{2\sqrt{I_2/I_1}}.$$

The beam size was measured for a range of different emittance coupling values to observe the change in the vertical beam size. For each setting of the coupling a optical model parameters of the storage ring lattice were obtained using LOCO measurements [7]. The Twiss parameters were then used to get a prediction of the beam size for comparison to the interferometer measurements. Figure 5 shows the vertical beam size increased with higher emittance coupling as expected and the measured values are slightly higher than predicted by the model fitted to the LOCO measurement.

The overestimate of the beam size compared with the fitted model is not unexpected since there is a well know 50 Hz beam orbit motion of the order of 10% of the beam size, as observed on the BPM measurements. Since the interference patterns were taken using 300 ms exposure times the pattern will become smeared by this motion and the visibility will be made worse than the instantaneous visibility.

For the very low coupling values the vertical emittance is only a few picometre and the corresponding beam size is a few micron. However, due to the cutoff of the higher order spacial frequencies by the beamline frontend mask as mentioned earlier, the minimum beam size measured with the interferometer is of the order of tens of micron. This indicates the ultra low vertical emittance cannot be directly measure with the present optical beamline and a new larger opening angle frontend needs to be designed to push the interferometer apparatus down to the fundamental limit.

In anticipation of being able to achieve a larger opening angle, the intensity imbalance measurements have been made to demonstrated that the apparatus works as intended. Figure 5 shows that the balanced and imbalanced measurements are in good agreement while Fig. 6 shows how the visibility is kept low in the imbalanced apparatus even for the lowest emittances, allowing the interference patterns to stay well above the noise floor of the sensor.

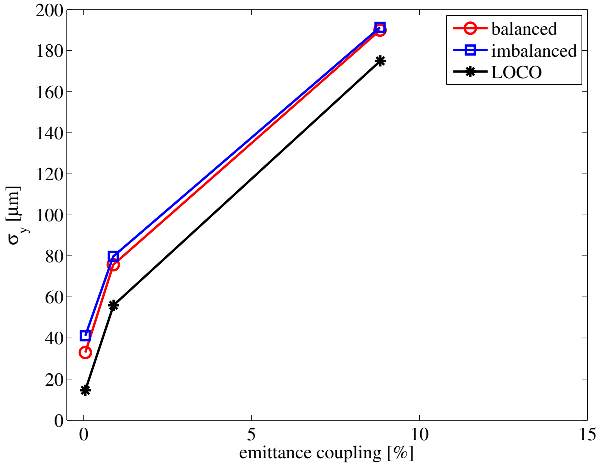

Figure 5: The vertical beam size was measured for a number of emittance coupling settings if the skew quadrupoles.

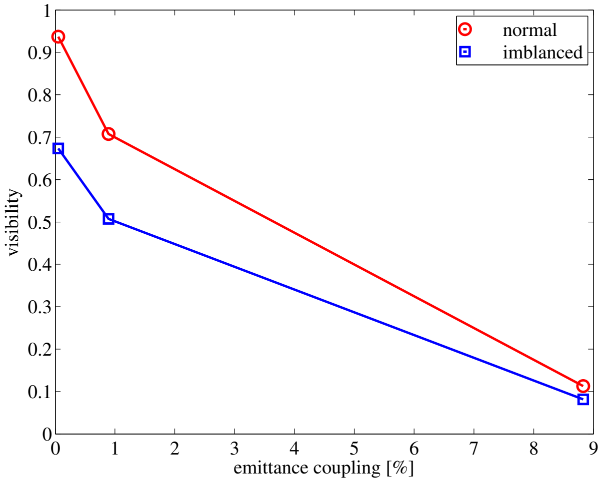

Figure 6: Comparison of the visibility measurements using the balanced and the imbalanced interferometer.

CONCLUSIONS

The sCMOS sensor has very low noise, high dynamic range and a linear response that is ideally suited to recording the interference patterns from an optical interferometer. The vertical beam size was measured using the SCMOS sensor for a range of different emittance coupling values in the Australian Synchrotron storage ring. The ultra low vertical emittance could not be observed due to the limiting factors of 50 Hz beam orbit motion and a small 1 mrad vertical opening angle on the optical diagnostic beamline. A new design of the visible light extraction system is being investigated to decrease the lower limit of the beam size that can be observed with interferometer apparatus.

ACKNOWLEDGMENTS

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