MEASUREMENTS OF SMALL VERTICAL BEAMSIZE USING A CODED APERTURE AT DIAMOND LIGHT SOURCE

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Abstract

Diamond Light Source produces a low emittance 3 GeV electron beam which is now regularly operated at 8 pm rad vertical emittance. This corresponds to a vertical beamsize of just 13 µm in the dipole, which is at a high vertical beta location and routinely used for observing the synchrotron radiation using a pinhole camera. Deconvolution of the images from the pinhole camera to maximise resolution is limited by uncertainty regarding the precise shape of the pinhole, resulting in uncertainty on its computed point spread function. Recently a coded aperture has been installed which offers the potential to improve upon the traditional pinhole measurement by offering both higher resolution and increased flux seen through a larger total aperture, however, at the cost of significantly more complex analysis of the recorded images. A comparison of results obtained using the coded aperture and those achieved using the conventional pinhole is presented.

INTRODUCTION

Diamond Light Source (DLS) is a third generation light source, nominally operating with a vertical beam size of 13 µm (0.3 % coupling) through the dipole arcs. Measurements of the transverse beam size are typically made by imaging the synchrotron radiation source point using a pinhole camera. A 25 µm x 25 µm square pinhole, located in air, is used to image the source for storage ring currents from below 1 to 300 mA. X-rays are passed from the vacuum chamber to air through a 1.0 mm aluminium window. They pass through the pinhole located at 3.8 m from the source, to a 200 µm thick LuAG:Ce screen located at 9.1 m from the pinhole. The total path length through air is 9.2 m. The spectrum of the synchrotron radiation is filtered by both the aluminium window and the 9.2 m of air, leading to a peak energy seen at the LuAG:Ce screen of 26 keV. Vertical electron beam size resolutions of better than 1 µm for 1 ms exposure time are achievable [1] [2].

To obtain a beam size measurement with this resolution the pinhole image must be deconvolved with the point spread function (PSF) of the system. At this bandwidth the resolution of the measurement is limited by uncertainty in the PSF, obtained analytically from the pinhole dimensions and scintillator screen properties [1]. Photon flux is sufficiently high that the statistical noise seen on the pinhole camera image for 300 mA stored beam is negligible compared to the errors in the calculated PSF. However, a 1 ms exposure time integrates several electron beam orbits of the DLS storage ring (circulation frequency = 534 kHz). Beam size measurements at turn-by-turn, or even bunch-by-bunch bandwidths require much shorter exposure times, reducing the observed photon flux. For short enough exposure times the statistical counting noise from the small number of photons passing through the pinhole would dominate the measurement errors.

To open up the potential to make beam size measurements of individual bunches with sufficient resolution (better than 1 µm for 13 µm vertical beam size), various alternative 'large aperture' approaches have been proposed. These aim to overcome the limitations in flux seen through the small aperture of a traditional pinhole camera [3].

CODED APERTURE

One such proposal is an adaptation of the coded aperture. This was first introduced as a tool for X-ray astronomy, originally using a collection of randomly distributed pinholes to produce an image that is made up of many overlapping images, unrecognisable as the original object. Figure 1 shows how the coded aperture operates. With knowledge of the location of each of the pinholes it is possible for the complex overlapping pinhole images to be unscrambled (originally described as 'rectification' in early papers, more commonly referred to as 'deconvolution' or 'decoding' in the modern era). This can be carried out either using optical techniques, or digitally using Fourier transforms [4] [5].

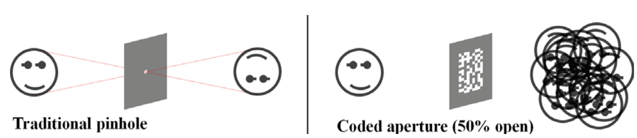

Figure 1: Left: The operation of a traditional pinhole camera. Right: A coded aperture with randomly distributed pinholes, and the resultant overlapping images.

Later, pseudo-random pinhole arrays ('uniformly redundant arrays') were introduced, with pinhole locations chosen such that they exhibit favorable properties for deconvolution [6]. The open aperture of these arrays can be up to 50 % of the total aperture size, giving them the ability to image very low intensity sources, or to image high intensity sources at very high bandwidths.

A vertical beam size monitor using a coded aperture has been proposed and developed for bunch-by-bunch measurements at SuperKEKB and CESR-TA [7] [8]. A 59 element 1-dimensional array produced for use at SuperKEKB has been installed for tests at DLS, intercepting the synchrotron radiation fan at the location of an existing X-ray pinhole (in air). In order to verify the performance of the analysis techniques that have been developed at KEK,

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images of the synchrotron radiation have been observed through the coded aperture using a CCD camera for a variety of beam sizes at 1 ms exposure times.

The coded aperture installed at DLS is a uniformly redundant array featuring an 18.2 µm thick gold mask on a 625 µm thick silicon substrate, with a 10 µm 'pixel pitch' (the smallest array element). It is important that the exact dimensions of the mask itself are known so that the point response function can be accurately calculated. Thus, the dimensions and the quality of the mask edges are measured by the manufacturer after production, and verified using a scanning electron microscope (SEM). Figure 2 shows the coded aperture, it's dimensions, and an example of one such SEM image.

For simplicity of manufacturing and analysis, 1-dimensional coded apertures have been produced for beam size measurements, capable of imaging the beam in one dimension. Since the vertical beam size is more challenging to measure than the horizontal (due to its smaller extent), and can be controlled via an adjustment of the emittance coupling ratio, the coded aperture has been oriented to measure this dimension (although it should be noted that it would, in principal, be possible to utilize a full 2-dimensional coded aperture in order to measure both the vertical and horizontal beam size).

A schematic of the coded aperture beamline layout is shown in Fig 3.

EXTRACTING ELECTRON BEAM PARAMETERS FROM THE CODED APERTURE IMAGES

Decoding of Coded Aperture Images

True deconvolution of coded aperture images in order to restore the original image is computationally expensive, and dependant on very precise knowledge of the aperture dimensions and PSF. Typically, if there are N elements in the coded aperture pattern, and M pixels on the detector used, then the deconvolution requires $N^2 \cdot M^2$ operations (multiplications) [9]. At DLS the X-ray images from the coded aperture are intercepted by a LuAG:Ce screen, and the fluorescence from this screen is recorded using a standard IEEE1394 (firewire) CCD camera with 1024x768 pixels. Assuming that the vertical X-ray beam image can be represented by single column of pixels from the camera, this results in some $59^2 \cdot 768^2 \approx 2e^9$ operations to decode the 1-dimensional beam profile. Binning can be used to reduce computation time at the expense of input resolution. Clearly the decoding of even 1-dimensional coded aperture images represents a computational challenge, but this is not insurmountable.

A greater problem is that coded aperture imaging and deconvolution as used in X-ray astronomy generally operates far from the diffraction region, and with uniform mask illumination. In the case of decoding images from synchrotron radiation sources diffraction and inhomogeneous

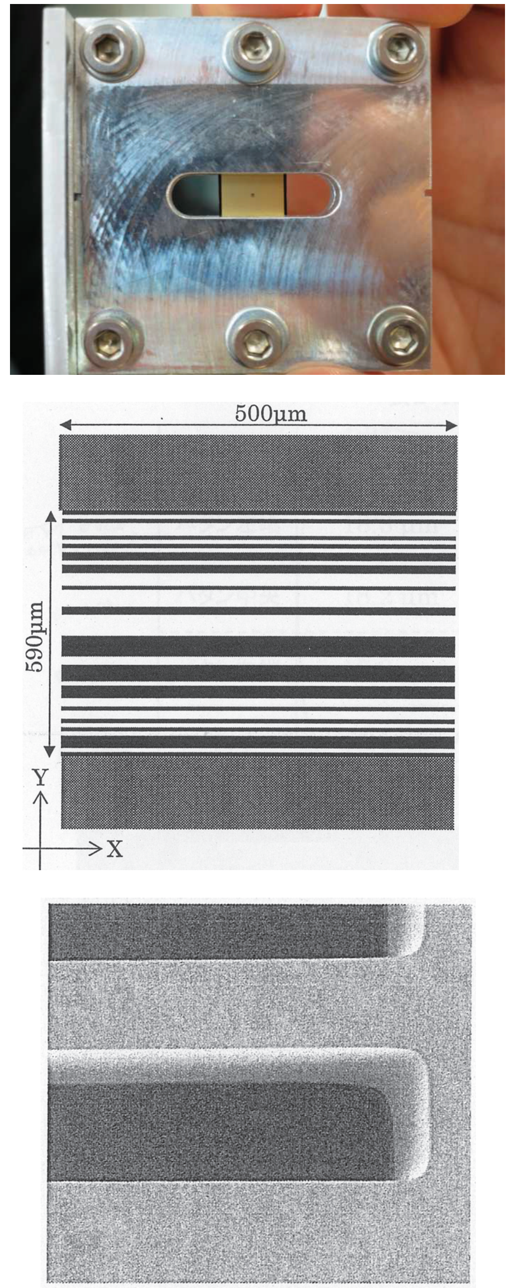

Figure 2: Top: The coded aperture mounted in an aluminium holder. The square gold mask is visible in the centre of the holder. Middle: The mask design. Bottom: An SEM image of the coded aperture at 5000x magnification.

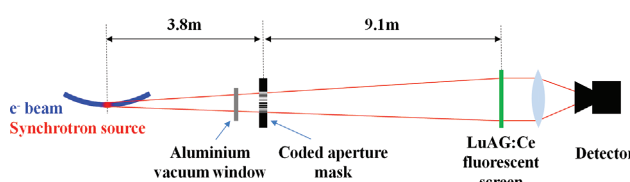

Figure 3: Basic schematic layout of the coded aperture beamline.

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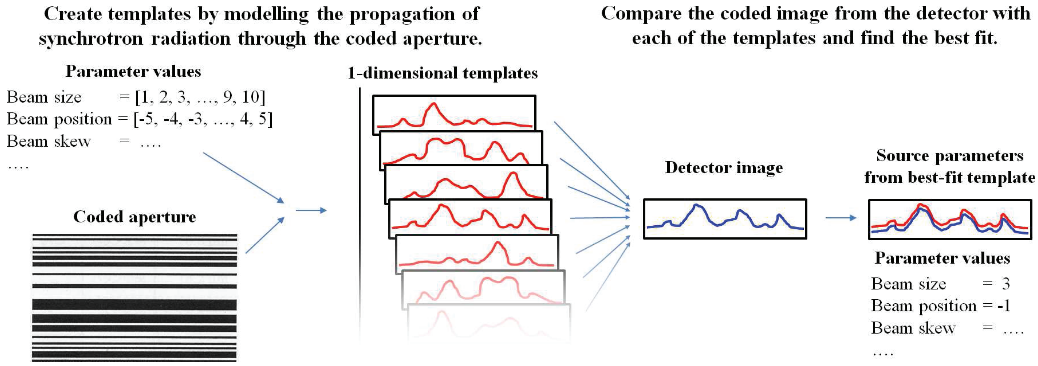

Figure 4: The process used to find the source parameters from the detected image.

illumination of the aperture (as well as X-ray scattering and noise) can prevent the recovery of the image [11] [3].

Fitting Coded Images to Pre-calculated Templates

As a perfect deconvolution of the 'coded image' to restore the original image is difficult or impossible, an alternative method of analysing the coded image is used in order to extract the electron beam parameters. Models of the expected flux seen through the coded aperture are produced for several initial electron beam parameters. The measured X-ray flux at the detector is then compared to these models.

The distribution of synchrotron radiation is well understood [10], and thus it is possible to model the projection of the synchrotron radiation wavefront through the coded aperture and simulate the flux seen at each pixel on the detector. One must take into account the spectra of the radiation, and the resulting attenuation and phase shifts due to the materials and path lengths along the beamline.

The simulation accounts for energy filtering from the aluminium vacuum window, from the 9.2 m of air along the beam path, as well as that from the silicon substrate of the coded aperture. The gold mask blocks the majority of the X-ray photons striking it, but what does pass through the mask is responsible for the observed scattering. This technique is discussed in detail in [8] (*Methods and tools*), and [11] (*Simulation Method*). At DLS we are employing the method described by Flanagan *et al* in [11].

A large number of 1-dimensional templates corresponding to different values of the initial source parameters are pre-calculated, and the measured coded image is compared to each of the templates, searching for a 'best-fit' using a least-squares method. The variable parameters for the pre-calculated templates include vertical position offsets between the source and the coded aperture, as well as vertical offsets between the coded aperture and the detector. Also included as variables are the size, the skewness, and the kurtosis of the source. A range of differing values for detector 'pedestal' (baseline offset) are also used. Assuming that pre-calculated templates are created with ~10 different values for each of these variables, the resulting number of 1-dimensional 768 pixel fits to perform will be ~$1e^6$. This is certainly a non-trivial number, yet it is still offers an improvement over attempting a direct decoding of the coded image.

The electron beam parameters are recovered from the coded image by identifying the template with the best-fit to the detected beam profile, as shown in Fig. 4. As the precision of the results is dictated by the size of the intervals between those values used to generate the templates, improved accuracy can be obtained by specifying a range of parameter values with smaller increments, re-generating a new set of templates, and running the fit again.

Figure 5 shows examples of the coded images captured by the camera for 1 ms exposure time for two different vertical beam sizes at DLS. Figure 6 shows the detected flux for a single column from such an image for nominal beam conditions, along with the simulated flux seen at each pixel of our detector for a range of simulated vertical beam sizes.

Each column of the camera image may be fit individually to the generated templates, and the beam size obtained from each column can be averaged to give a more precise measurement. The template generation and fitting is performed on a 16-core computer, with 64GB of available memory. Typically, some 100,000 templates have been utilised for fitting images obtained at DLS, taking a few

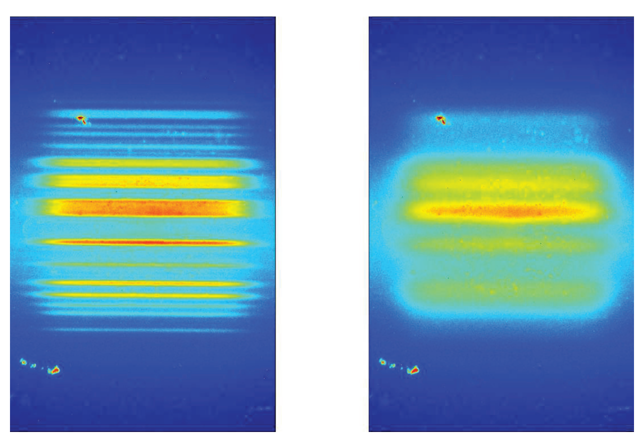

Figure 5: Images of the synchrotron radiation, as viewed through the coded aperture, acquired by the camera. Left: 6.1 μm vertical e^- beam size, σ_y (0.1 % coupling, κ). Right: 25.6 μm vertical e^- beam size, σ_y (1.1 % coupling, κ).

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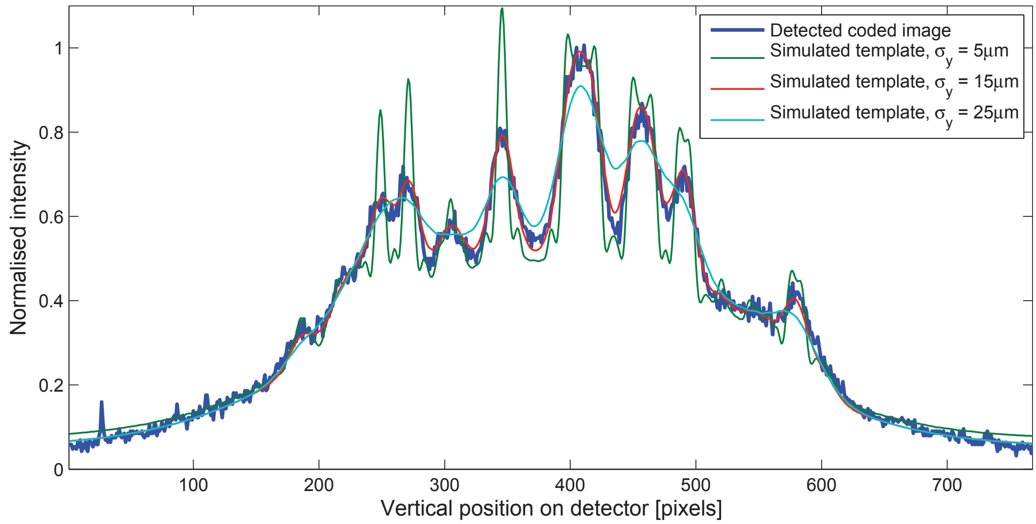

Figure 6: The detected flux for nominal beam conditions (~0.3 % coupling, κ) as seen by a single column of pixels from the camera, plotted along with the generated templates for flux seen at each detector pixel for three different vertical source sizes, σ_y.

10s of seconds to generate. The fitting itself is faster, taking <10 s to fit a few hundred columns from a coded image image with 100,000 templates. If faster fitting is required, processing times could be reduced by shrinking the range of values used to generate the templates. (In the case at DLS where fitting time is essentially unconstrained, memory becomes the limiting factor. This limits the number of templates that can be generated).

COMPARISONS OF CODED APERTURE AND PINHOLE MEASUREMENTS

Pinhole cameras are currently relied upon to give an accurate electron beam size measurement at DLS [1]. The vertical beam size can be changed by altering the currents through the skew quadrupoles, and thus the results of the coded aperture measurements and fitting routine can be compared with those obtained from existing pinhole measurements for a range of beam sizes. The very fine control of the electron beam size available at DLS also allows for smaller beam sizes than were available during the earlier CESR-TA tests, down to ~7 µm.

The measurement was carried out using a 'slow', 1 ms exposure time camera system, differing from that carried out at CESR-TA, and from that planned for SuperKEKB, where a 'fast' 1-dimensional diode array, capable of MHz, bunch-by-bunch, bandwidth is used. This 'slow' camera system has the disadvantage that bunch-by-bunch or turn-by-turn measurements are impossible as the 1 ms exposure time integrates some ~500 turns, but the advantage of an excellent signal-to-noise ratio at high spatial resolution. Thus, a detailed comparison of the actual beam distribution with the modelled templates can be made.

Figure 7 shows the electron beam size measurements from the coded aperture fit plotted against beam size measurements from a pinholes camera measuring synchrotron light from the same dipole. It is interesting to note that while the results generally correlate, the coded aperture measurements give a consistently smaller beam size than the pinhole camera. The reasons for this are not clear. At 7 µm beam size the error bars on the coded aperture measurement (the standard deviation measured from fitting each column from the coded aperture image) are ~0.3 µm.

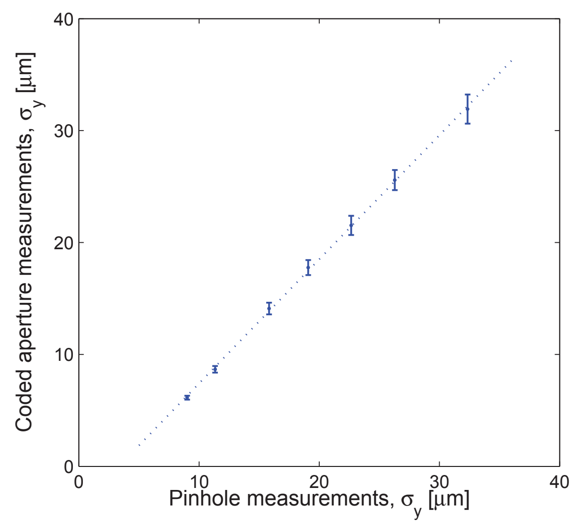

Figure 7: A plot comparing the vertical electron beam size measurements calculated from pinhole images, and calculated from from coded aperture images. A best fit line is shown.

CONCLUSIONS

The coded aperture measurements of vertical electron beam size correlate well with those measured by the existing pinhole cameras at DLS, although unexplained differences in the measured beam size are observed. The coded aperture measurements consistently give a smaller beam size than that found using the pinhole camera. Resolution of the coded aperture system is found to be on par with that obtained with the pinhole cameras, although the clear discrepancies between the measurements of the two systems require further investigation.

Analysis of the coded aperture images by fitting the detector output to pre-calculated templates is preferable to attempting to fully decoding the images. It is possible to produce simulated flux distributions closely matching that seen at each pixel on the detector, even at high spatial resolution. This gives confidence that the technique works correctly.

With the use of a higher bandwidth detector the measurement should be feasible at turn-by-turn bandwidths with acceptable resolution. 1-dimensional diode arrays offer the required bandwidths and noise properties to realise this measurement, though developing such an array capable of imaging X-rays at >20 keV still represents a challenge. The potential to observe vertical beam size instabilities at turn-by-turn rates has the potential to open up new accelerator physics experiments at DLS, and it is hoped that such a system can be realised in the coming years.

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