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REVIEW OF RECENT STATUS OF CODED APERTURE X-RAY MONITORS FOR BEAM SIZE MEASUREMENT*

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Abstract

X-ray beam profile monitors based on coded aperture imaging use an array of pinholes or slits to achieve large open apertures, which provide improved photon collection efficiency over single pinholes or slits. The resulting improvement in photon statistics makes possible single-bunch, single-turn measurements at lower bunch currents than are possible with a single pinhole or slit. In addition, the coded aperture pattern provides extra information for beam profile reconstruction, which makes possible somewhat improved resolution, as compared to a single slit. The reconstruction algorithm for coded aperture imaging is more complicated and computing-intensive than that for a single slit, though with certain classes of coded apertures a faster reconstruction method is possible. This paper will provide a survey of efforts to use coded aperture imaging for beam profile diagnostics at accelerators to date, covering principles and practical experiences with the technique, as well as prospects for the future at SuperKEKB, where it forms the primary means of measuring vertical beam sizes.

INTRODUCTION

Coded aperture imaging is a form of wide-aperture imaging with roots in x-ray astronomy. This paper will start with reviews of wide-aperture imaging in x-ray astronomy, including coded aperture telescopes. This will be followed by a review of the principles of coded aperture imaging. Finally, there will be a discussion of experiences at Diamond Light Source, CesrTA, ATF2 and SuperKEKB, and a summary.

WIDE-APERTURE IMAGING IN X-RAY ASTRONOMY

The existence of x-rays coming from outside the solar system was first discovered in 1962, using non-imaging detectors [1]. This gave birth to the field of x-ray astronomy, for which Riccardo Giacconi later received the Nobel Prize. Due to the attenuation of x-rays in the atmosphere, x-ray telescopes need to be placed on rockets, high-altitude balloons, or satellites. The first fully imaging x-ray satellite dedicated to extra-solar astronomy was the HEAO-B (Einstein) satellite, which operated from 1978 to 1982 [2]. Imaging was accomplished via grazing-incidence mirrors. To increase the light collection efficiency (open aperture), a set of 4 nested mirrors was used. This worked for x-rays up to 8 keV.

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This basic approach has evolved over the years, with ever-increasing numbers of nested mirrors employed. For example, the NuSTAR satellite [3] employs 133 nested mirrors. In addition, it employs multi-layers on the surface of the mirrors, made up of alternating layers of high- and low-index of refraction materials. The multi-layers enhance reflectivity through constructive interference at higher x-ray energies, giving the satellite a usable spectral range of 3-79 keV, limited by the optics.

Another approach used for x-ray and gamma-ray astronomy is coded aperture (CA) imaging, which will be discussed in the next section. An example of a CA-based x-ray telescope is the balloon-borne protoMIRAX experiment [4], which used a rectangular mask pattern of apertures to modulate the incoming x-rays. Advantages of CAs over reflective optics include wider angular and spectral acceptances (spectral acceptance being determined primarily by detector efficiency rather than optics), and a shorter required distance between optics and detector -- the NuSTAR satellite for example, requires 10 m separation between optics and detectors to focus at 79 keV (due to the required shallowness of the grazing incidence angle), while protoMIRAX reaches up to 200 keV in a much more compact package.

PRINCIPLES OF CODED APERTURE IMAGING

CA imaging is a technique developed by x-ray astronomers, gamma-ray astronomers and others using a mask made up of multiple apertures to modulate incoming light. The resulting image must be deconvolved through the mask response to reconstruct the object. The primary advantage of a CA mask over a single pinhole is increased light-collection efficiency, with typical CA masks in use having open apertures of around 50%.

X-ray astronomer R.H. Dicke proposed to use multiple pinholes to increase photon-collection efficiency [5]. He proposed a randomly-spaced arrangement of pinholes. Such an arrangement produces a complicated detector image, that can be recovered by deconvolution by cross-correlation with the original mask image.

In principle, however, any set of multiple apertures can be considered a “coded aperture.” Prior to Dicke (and prior to the advent of x-ray astronomy), the use of Fresnel zone plates (FZPs) had been proposed [6]. If an FZP is detuned so as not to act like a lens, then it provides a uniformly spaced set of aperture widths and spacings, for uniform spatial resolution over a range of sizes.

A notable class of coded aperture is Uniformly Redundant Arrays (URAs) [7, 8]. URAs are made up of a pseudo-random arrangement of apertures, designed to have the

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nice mathematical property that its auto-correlation is a delta function. This ensures that the reconstruction has no side-lobe artifacts, as tend to occur for truly random arrays (and FZPs).

Coded Aperture Image Reconstruction

Following [7], for an object O, aperture A and noise function N, the recorded image P is given by

$$P = (O * A) + N,$$

where * is the correlation operator. Two methods for finding the reconstructed object O^R from P are the Fourier transform method and the correlation method. In the former,

$$O^R = RF^{-1}\left[\frac{F(P)}{F(A)}\right] = O + RF^{-1}\left[\frac{F(N)}{F(A)}\right],$$

where F is the Fourier transform, F^{-1} the inverse Fourier transform, and R the reflection operator. In the latter,

$$O^R = P * G = RO * (A * G) + N * G,$$

where G is the postprocessing array, which is chosen such that A*G approximates a delta function. In principle, both methods should give the same result, though the Fourier method may be more sensitive to noise, depending on the mask pattern. In this paper, the above methods will be termed "direct reconstruction methods."

In practice, due to issues of dealing with background and detector noise, many practical applications of coded aperture imaging for x-ray astronomy have been based on iterative methods, rather than direct reconstruction. In such methods, one repeatedly modifies a proposed source distribution until it generates an image similar to the measured detector image, when propagated through a model of the system. In astronomy, one does not know what the source distribution should look like, and it is important not to create spurious sources through reconstruction artifacts.

For accelerator measurements, in addition to noise, we have additional issues due to not operating in the classical limit, which the direct reconstruction method assumes, and where x-ray and gamma-ray astronomy telescopes operate. In particular, diffraction effects need to be accounted for, as well as the variation of spectrum on- and off-axis in the synchrotron fan and how it affects transmission through the mask and folds into the spectral response of the detector as a function of angle off-axis. There is also the non-uniform intensity profile of the incident beam to take into account, unlike the uniform illumination that can be assumed for astronomical sources. These effects are not accounted for in the direct reconstruction methods.

In the case of a stable accelerator beam, unlike the case in astronomy, we generally do know what the source distribution should look like: usually a single Gaussian of unknown size and position, to be determined. A very successful technique that has used so far in such cases is template fitting: one creates a collection of simulated detector images representing different beam sizes and positions, then compares the measured image against the simulated images to find the closest match. This approach is very brute-force, but with multi-CPU construction machines, it is possible to keep up with measurement rates of one to a few Hz. It also permits more accurate beam size measurement in the case of stable beam than direct reconstruction does, since all the effects due to operating in a non-classical and non-uniform illumination regime can be accounted for.

The templates can be created in advance from a weighted sum of point-response functions (PRFs) that each represent the detector image from a point source, with the weighting chosen to represent the beam distribution. For each PRF, a set of source SR wavefront amplitudes is calculated [9], then propagated through a model of the system, with a Kirchhoff integral over the mask surface, and taking into account transmission and phase shift effects due to all materials in the system and detector response [10]. The source beam is considered to be a vertical distribution of point sources. This approach can also be applied to sources with non-zero angular dispersion and longitudinal extent, for more accurate simulation of emittance and source-depth effects. For the machines discussed below these effects are small, so for computational speed we restrict ourselves to 1-D vertical distributions.

Why a URA or Other CA Mask?

The question could reasonably be asked, if one is not going to use direct reconstruction, what are the advantages of a URA (or other coded aperture) pattern?

For accelerators, as for astronomy, the primary advantage of any coded aperture over a single pinhole or slit is greater open aperture for single-shot measurements at low currents, when photon statistics can become the dominant source of measurement uncertainty. At SuperKEKB, for example, optics tuning is done at low currents to protect the physics detector from beam-loss backgrounds, before ramping back up to full currents for collision data-taking. The optics group needs beam sizes at low currents to evaluate tuning effectiveness. In general, single-shot (single-bunch, single-turn) measurements are preferred for emittance measurements, so as to eliminate any effect of bunch position motion on apparent beam size.

In addition, even though CAs are essentially collections of multiple pinholes, CAs give somewhat better resolution than single pinholes due to the presence of peak-valley ratios in the image, in addition to the peak width, which provides more information to be fit. CA images also make use of more detector pixels than do single-slit images, and so are less sensitive to the presence of individual dead or mis-calibrated pixels.

Having decided to use a CA, how does one choose what pattern to use? What about a simple equally-spaced array of pinholes/slits, for example? One advantage of a URA pattern is a flatter spatial frequency response than an equal-spaced array (or random array or FZ). This gives a flatter response over a range of beam sizes (and shapes, if ones does direct or iterative reconstruction, for example). A URA or other non-repeating pattern also provides

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unique position determination, if that is important for one's application.

On the other hand, an equally-spaced array can offer superior resolution over a narrower range of sizes, at the sacrifice of poorer resolution outside that range. Such an array may, for example, be suitable for a very stable machine, such as a light source. For instability studies (due to electron clouds, e.g.) or other machine studies, or for a luminosity machine which is always running at the limit of stability, a URA mask may be more suitable for use over a broader range of expected bunch sizes (and shapes, depending on reconstruction method). The choice of optimal pattern thus depends on the intended application.

EXPERIENCES AT ACCELERATORS

In this section will be discussed experiences applying coded aperture imaging at 4 machines : CesrTA, Diamond Light Source, the ATF2 and SuperKEKB. All four machines are low-emittance electron and/or positron rings, with minimum beam sizes at the x-ray source point of 10 microns or less, and beam energies ranging from 1.3 to 7 GeV.

Experience at Diamond Light Source

Diamond Light Source is a third generation light source in Didcot, Oxfordshire, UK. It has a beam energy of 3 GeV. In 2013, a high-energy CA chip was installed in the x-ray beam diagnostic line. The pattern is a 10-micron minimum-feature-size URA, with 59 "pixels" (not apertures). The mask was made of 18.2 micron Au on a 625 micron Si substrate. The resulting image was detected on a 200 micron thick LuAG:Ce screen, viewed by a 1024(H)x768(V) pixel camera. This readout set-up only permits time-averaged measurements, not single-shot ones, but the high resolution of the images provided good verification that the template generation method provides good fits to observed images.

A study was then performed varying the beam size and comparing measurements made with the CA and with the pre-existing single-slit aperture [11]. Results showed good correlation between the CA and the single-slit measurements, though with a small systematic difference in measured sizes.

Experience at CesrTA

Single-shot measurements were carried out at CesrTA, an ILC damping ring and low-emittance ring test machine, with a focus on low-emittance tuning and electron-cloud studies, located at Cornell University in Ithaca, NY, USA. The majority of experiments were carried out at 2 GeV [12,13], with some at 4 GeV [14]. The detector was a 32-pixel InGaAs detector with 50-micron pitch, and the optics chips used were generally made of 0.5 micron Au on 2.5 micron Si substrate. In addition there was a single-slit aperture made of tungsten.

The readout system was designed to take single-shot, turn-by-turn data, which allowed for the demonstration of measurements of electron-cloud blow-up along a bunch train [15]. Two types of CA were used. The first one tried was a 31-"pixel" detector with 10 micron pitch, which turned out to be sub-optimal since it was not optimized for the detectable spectrum at CesrTA, although it was successfully used. An alternate CA design was also tried, not based on a URA design but based on the idea of intentionally designing slit widths and spacing in order to enhance diffraction peaks over the detectable spectrum, creating sharper edges in the PRFs. (Note that no monochromator was used, just the natural bandwidth of the detectable spectrum.) Both CAs showed better single-shot resolutions than the single-slit at the smallest beam sizes, with the second CA design outperforming the first between 10 and 50 microns at 2 GeV [13].

Experience at ATF2

The ATF is an ILC damping ring test machine, with an extraction line, the ATF2, designed for ILC final-focus optics and beam instrumentation testing. An x-ray extraction line was installed at the last strong bend before the straight section in the extraction line, and a 47-element URA mask installed close to the bend. Readout was done by scanning a single InGaAs pixel (of the same type as used at CesrTA) across the detector plane in 50-micron steps to build up the image over successive bunch extractions.

A study was carried out while changing the beam size via dispersion [16]. Preliminary results indicate that the minimum measured beam size was around 10 microns.

Experience at SuperKEKB

SuperKEKB is an e+ e- two-ring energy-asymmetric collider for new physics searches. It is an extensive upgrade to the KEKB B Factory collider. X-ray beam lines have been installed at both the 4 GeV Low energy ring (LER) and the 7 GeV High Energy ring (HER) for the purpose of beam size measurement. Phase 1 of SuperKEKB commissioning occurred in spring of 2016, with Phase 2 in spring of 2018. Phase 3 is planned for Spring of 2019.

A fast readout system capable of bunch-by-bunch, turn-by-turn measurements is being developed at the University of Hawaii, and a 128-pixel deep Si detector with 50 micron pitch has been developed at SLAC, both in collaboration with KEK. It is hoped to start commissioning this fast readout system during Phase 3 of SuperKEKB commissioning. Meanwhile, time-averaged measurements have been carried out using YAG:Ce and LuAG:Ce scintillators, viewed by cameras.

Three sets of optics chips, made of 18 microns of Au on a 600 micron CVD diamond substrate, were designed for each ring [17]: A single slit mask, a multi-slit CA mask, and a URA CA mask. The minimum slit widths of the masks were chosen to minimize the point spread of a single slit PRF. The multi-slit mask was hand-optimized to provide the best single-shot resolution at the smallest beam sizes; it is expected to outperform the URA mask below about 15 microns, with the URA mask outperforming above that. Both CA masks outperform the single-slit mask at all beam sizes. Since the performance and noise

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level of the fast readout system is not known yet, all single-shot resolution calculations were carried out based on photon statistics only. (For an example of one way to incorporate detector readout characteristics in the resolution calculation, see [12, 13].)

Commissioning: In Phase 1 of SuperKEKB commissioning, the online vertical beam size measurement system based on template fitting was implemented, and extensive calibration checks were carried out [18, 19]. In addition, electron-cloud blow-up studies were carried out in the LER [20], which involved measuring the beam size as the beam current was gradually increased, with beam blow-up due to electron-cloud-induced head-tail instability setting in above about 500 mA. Beam sizes from about 35 microns at currents below the blow-up threshold, and 250 microns at 850 mA, were observed. Very good fill-to-fill agreement between the single-slit, multi-slit and URA mask measurements was found, especially below 150 microns.

Emittance measurements were carried out in both rings, and compared to estimates made by the beam optics group [19]. In the LER, good agreement between measured and expected beam sizes was found, while in the HER, a large systematic smearing term was found that led to excessively large measured beam sizes as compared to the optics model. This was attributed to scattering due to an excessively thick Be filter upstream of the HER optics chips. For Phase 2, this filter was made much thinner (and the LER filter made thinner as well); measurements of the smearing in Phase 2 showed that it had been reduced to levels small enough that the smallest possible beam sizes in both rings should be measurable with the current system. Emittance measurements made in Phase 2 also agreed with the optics group's models, in both rings.

Direct reconstruction: Finally, study commenced on performing direct beam image reconstruction using the URA mask [21]. As discussed above, this is expected to be less accurate than template fitting, but should be much faster. This would prove particularly useful in beam instability studies, where it is often desirable to measure the turn-by-turn beam size of every bunch in the ring, which at SuperKEKB will be about 2500 bunches maximum. Measuring the sizes of all 2500 bunches over thousands of turns will generate an enormous amount of data, and a desire to be able to reconstruct much quicker than is currently possible with template fitting, even if less accurately. Another motivation for direct beam image reconstruction is that it would permit direct diagnosis of beam profiles becoming non-Gaussian, as is expected to happen in the case of electron-cloud head-tail instabilities, for example. Such direct observation of non-Gaussian beam profiles would itself provide evidence of what type of instability may be occurring.

Using URA data taken over a range of beam sizes, the raw detector images were reconstructed using both the Fourier transform method, and the correlation method. The resulting beam profiles were then fit with Gaussians, and the results compared with the results of template fitting. Good agreement was found with all three methods in the range between 40 and 80 microns, with the correlation methods agreeing somewhat better than the Fourier transform method. Outside that size range, systematic divergences were found between the direct reconstruction methods and the template fitting method. Further studies of the systematics involved are planned. This is believed to be the first application of direct beam image reconstruction using coded apertures.

For the next iteration of masks, it is planned to create a set of repeating URA mask patterns, such that the projection on the detector always contains the projection of one whole (cyclically shifted) URA pattern, even if the beam center shifts. The importance of this in preserving the delta-function nature of A*G, and thus minimizing reconstruction artifacts when the beam position shifts, is pointed out in [7].

SUMMARY

Coded aperture techniques have been tested for beam-size measurement at CesrTA, Diamond Light Source, the ATF2 and SuperKEKB, using both URA and other mask patterns. Coded aperture imaging forms the primary beam size measurement system at SuperKEKB.

Template fitting methods for measuring the beam size have been well demonstrated. Direct deconvolution has been tested for faster reconstruction at SuperKEKB, with further studies and improvements planned.

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