X-RAY MONITOR BASED ON CODED-APERTURE IMAGING FOR KEKB UPGRADE AND ILC DAMPING RING*

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Abstract

We present here design considerations for an x-ray monitor for high-resolution (a few um) and fast response (sub-nanosecond) for beam profile measurements to be used at an upgraded KEKB and/or ILC damping ring. The optics for the monitor are based on a technique borrowed from x-ray astronomy, coded-aperture imaging, which should permit broad-spectrum, low-distortion measurements to maximize the observable photon flux per bunch. Coupled with a high-speed digitizer system, the goal is to make sub-bunch-length, turn-by-turn beam profile measurements.

INTRODUCTION

Our goal is to develop an X-ray monitor for transverse bunch-by-bunch beam profile monitoring, with high resolution (a few μm) and fast response (sub-nanosecond). Such a system would be useful for bunch-by-bunch diagnostics at present and future lepton accelerators, such as KEKB, an upgraded KEKB, or the damping ring of the ILC.

Most current lepton beam profile monitors are based on synchrotron radiation (SR) imaging or on SR interferometry. Imaging systems have a resolution determined by the aperture, or effective aperture due to the spread of the SR at visible wavelengths, which at KEKB, for example, leads to a point spread function on the order of the vertical beam size (≈ 50 μm). Interferometers have a resolution determined by the separation between the interferometer slits, which in turn is dependent on the spread of the synchrotron light. While the interferometer has a higher resolution than the imaging system (about 10 μm at the KEKB LER), it requires a band-pass filter which necessitates much longer exposure times than single-bunch/single-turn. The use of reflective optics makes it possible to take single-bunch data with a streak or gated camera without the reduction in light intensity that a bandpass filter would cause in a refractive optics system. However, in addition to the transverse resolution limitation noted above, the relatively low repetition rate (a few Hz or tens of Hz) means the system is limited to taking isolated snapshots in time, and it is not possible to take turn-by-turn data to get information on the dynamical behavior of a bunch.

X-ray cameras have been developed and used to measure beam sizes down to a few μm, generally based on the use of a Fresnel zone plate or pinhole[1, 2, 3]. The use of a Fresnel zone plate requires the use of a monochromator. This cuts the available photon flux down drastically, to less than 1% around the primary wavelength, typically. The monochromator is also typically sensitive to heat load, with heat distortions causing problems with its grazing-incidence optics. Pinhole cameras have the advantage that they can pass, in principle, all of the incident spectrum, but this advantage is negated by their small aperture.

To meet the requirements of high resolution and high flux, we are conducting research and development on an x-ray imaging system based on coded aperture imaging.

CODED APERTURE IMAGING

Coded aperture imaging is a technique well-developed among x-ray astronomers[4], which provides the spatial resolution of a pinhole camera, but with much greater x-ray photon collection efficiency. It consists of a pseudo-random array of pinholes, which project a mosaic of pinhole camera images onto a detector. This image is then decoded using the known mask pattern to reconstruct the original image. One example of such a pattern, called a Uniformly Redundant Array (URA)[5], is shown in Fig. 1. Also shown is the anti-mask, which is designed so that its cross-correlation with the mask is a delta-function. The original image is recovered by correlating the detected image through an anti-mask. The open aperture of the mask is 50%.

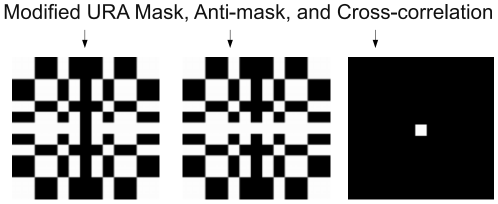

Figure 1: 2-D URA mask, and its autocorrelation.

To demonstrate the principle of this technique, a simulated beam image, shown in the upper left corner of Fig. 2, is projected through the mask from Fig. 1 to produce the blurred image on the image plane in the middle top, which bears little resemblance to the original image. After decoding the image through the anti-mask, the original is restored as shown at the upper right. The reconstructed horizontal and vertical beam profiles are overlaid on the original profiles in the left and right bottom plots, respectively, showing that the image has been reconstructed perfectly in this ideal case.

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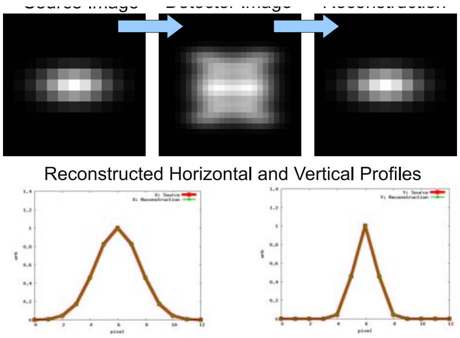

Figure 2: Example of image reconstruction using 2D URA mask.

DESIGN

Schematic Layout

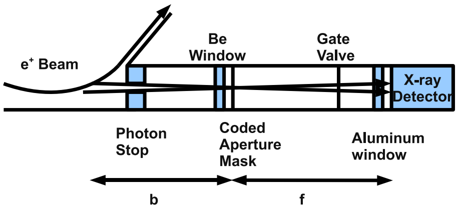

Figure 3: Basic schematic layout of a coded-aperture x-ray beam monitoring system. Magnification is $m = (f + b)/b$.

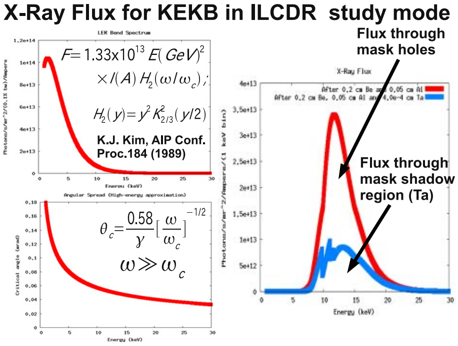

Figure 4: Calculated X-ray flux and angular distribution at the KEKB LER, in 2.3 GeV, low-emittance ILC DR study mode [7].

The basic layout of a coded-aperture x-ray monitor is shown in Fig. 3. To the left is the electron or positron beam, with synchrotron radiation exiting an extraction chamber that has a photon stop installed to cut down on unnecessary heat load on the downstream components. A thin beryllium window filters out the low-energy, long-wavelength components, passing higher energy ($>\sim 2-3$ keV) x-rays through to the coded-aperture mask, which is located a distance b from the source point. An aluminum window further filters out lower energy photons. The x-ray detector is located a distance f from the mask; the magnification of the system is given by $m = (f + b)/b$.

Flux

Figure 4 shows the calculated flux from the source bend of the KEKB Low Energy Ring (LER), when operated in ILC Damping Ring study mode. This is a low-emittance study mode under consideration [6] which has a lower energy (2.3 GeV) than the LER usually operates at, with a vertical beam size of $\sim 5\mu$m at the source point. Some future possible upgrades to the KEKB accelerator also call for a similar beam size, but at the same beam energy as the current LER (3.5 GeV). In that case, the beam current and photon flux are higher, as is the critical energy of the synchrotron radiation, but otherwise the basic design considerations are similar. The raw flux from the beam is shown in the upper left plot of Fig. 4. The angular spread of the flux as a function of x-ray energy is shown in the lower left plot; this determines the useful vertical mask size. The fluxes passing through the holes and mask regions of the mask are shown in the plot to the right. The Be window is taken to be 1 mm thick, the Al window 0.5 mm thick, and the mask is $4\ \mu$m Ta on a $2\ \mu$m SiC substrate. As shown, the ratio of photons passing through the holes of the mask to those passing through the tantalum mask material itself is about $3:1$. This background lowers the S/N ratio, but does not affect the basic decoding process. The spectrum used is primarily in the 10-20 keV range.

Diffraction

A factor omitted in the initial discussion was diffraction, which for sufficiently small mask element sizes cannot be ignored, even at x-ray wavelengths. As a result, one-pass decoding must be followed by or replaced with an iterative reconstruction procedure. Iterative reconstruction is very computing-intensive on a 2-D image, and we are primarily interested in vertical profile measurement, so as a starting point we will use a 1-dimensional mask, as shown in Fig. 5. Diffraction effects were modelled for the above spectrum using a commercial program (Zemax), and the results of using the resulting diffraction pattern to image a $5\ \mu$m beam at a magnification of $5\times$ ($b = 6$ m, $f = 24$ m) onto a detector with $25\ \mu$m pixels are shown in Fig. 6. In this simulation, the smallest mask feature size is $5\ \mu$m. A random noise function has been applied to the detector image to investigate the effects of that on the reconstruction as well.

Reconstruction

The iterative reconstruction method tested here was very simple, randomly adding and subtracting photons from "pixels" in the source image until the resulting image most closely resembles the detected image. As can be seen, even with this very simple method, the reconstruction ability is very good. However, one requirement for this method to work is that the "effective mask pattern" created by the diffraction pattern of a point source needs to be known. To simulate this diffraction pattern, we perform diffractive

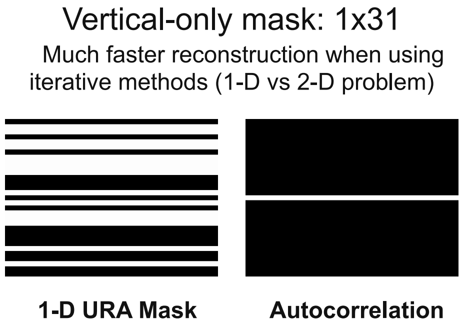

Figure 5: Vertical 1-D mask, and its autocorrelation.

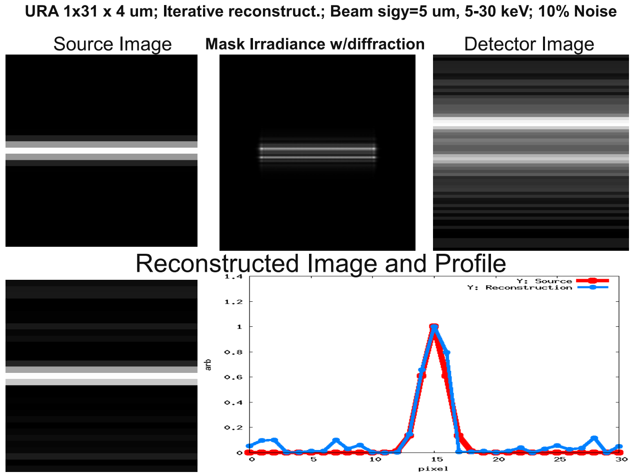

Figure 6: Simulation of coded aperture imaging with 1-D mask taking into account diffraction effects and noise.

ray-tracing in Zemax on both the mask pattern and its complement. The two resulting wavefronts are then combined vectorially, taking account of attenuation and phase shifts introduced by passage through the mask material (tantalum). This process is repeated over a range of wavelengths of interest, and a weighted sum is used to create the effective mask pattern.

PRESENT STATUS

Tests have begun at the CESR-TA ring in June 2008, using a prototype coded aperture mask made by NTT Advanced Technologies, consisting of a 4 μm-thick tantalum mask pattern on a 2 μm Ru/SiC/SiN membrane, similar in structure to that of Fresnel zone plates that the company makes for monochromatic x-ray imaging. The mask pattern is shown in Fig. 7, and the simulated detector images for several different beam sizes, taking into account the effects of diffraction over the beam spectrum, are shown in Fig. 8. The holes are of relatively large dimension in this prototype in order to test the ability to decode the mask data while minimizing smearing effects due to diffraction; future versions with finer structure are being prepared for runs at CESR-TA from Autumn 2008 on. Analysis of the data is underway, and will be presented in a future paper.

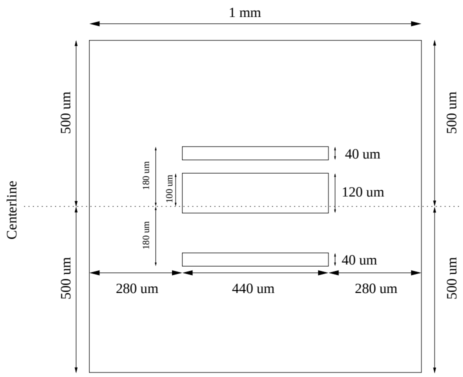

Figure 7: Prototype test mask dimensions.

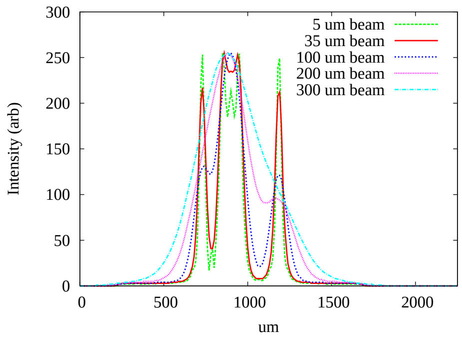

Figure 8: Simulated detector images for several beam sizes at the 2.1 GeV CESR-TA ring, folding in the effects of diffraction and passage through window, mask and other beamline materials, using the mask shown in Fig. 7.

SUMMARY

We are investigating the use of coded-aperture imaging techniques for x-ray beam profile monitoring in order to measure bunch-by-bunch profiles, which have the potential to permit higher-flux measurements than existing monitors, making high-speed measurements possible. We are also working on the development of fast x-ray readout systems to fully exploit the potential provided by such large open-aperture masks.

ACKNOWLEDGMENTS

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