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Design and performance of coded aperture optical elements for the CESR-TA x-ray beam size monitor

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ABSTRACT

We describe the design and performance of optical elements for an x-ray beam size monitor (xBSM), a device measuring e^+ and e^- beam sizes in the CESR-TA storage ring. The device can measure vertical beam sizes of 10–100 μm on a turn-by-turn, bunch-by-bunch basis at $e^\pm$ beam energies of ~2–5 GeV. x-rays produced by a hard-bend magnet pass through a single- or multiple-slit (coded aperture) optical element onto a detector. The coded aperture slit pattern and thickness of masking material forming that pattern can both be tuned for optimal resolving power. We describe several such optical elements and show how well predictions of simple models track measured performances.

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1. Introduction

Precision measurement of vertical bunch size plays an increasingly important role in the design and operation of the current and future generation of electron storage rings. By providing the operator with real-time vertical beam size information, the accelerator can be tuned in a predictable, stable, and robust manner. Challenges persist in obtaining adequate precision at small beam size, low beam energy, and/or low beam current. The CESR-TA x-ray beam size monitor [1–13] (xBSM) images synchrotron radiation from a hard-bend magnet through a single- or a multi-slit optical element onto a 32-strip photodiode detector with 50 μm pitch and sub-ns response. Here we extend the characterization of that device, focusing on comparing measured with predicted resolving power for each of several different optical elements. To the extent that a prediction matches measurements, one can gain confidence that the associated model can be used to optimize optical element design in other specific situations.

A simplified schematic of the CESR-TA xBSM setup is shown in Fig. 1, with relevant dimensions in Table 1. Separate installations exist for electrons and positrons.

Ref. [13] describes our use of both single-slit (pinhole) and multi-slit optical elements, the latter of which are known as coded apertures. Coded aperture imaging [14] can, in principle, improve upon the spatial resolution of a pinhole camera. This can be achieved by having greater x-ray intensity at the image (due to more open area at the optic), carefully designed slit sizes and spacings, and a well-tuned thickness of the semi-opaque masking material between the slits. An optimized mask may be thin enough to partially transmit x-rays with a phase shift. Through interference, light passing through the slits and mask will affect the *point response function* (`prf`) [13] for good or ill, depending on the coded aperture pattern, mask thickness, and x-ray spectrum. Our coded apertures use a gold masking material of 0.5–0.8 μm thickness on top of a 2.5 μm thick silicon substrate (which also absorbs x-rays, but does so identically for both slit and mask regions). Masking of an intermediate thickness can be more effective than a thicker choice because it introduces a significant phase shift while preserving a larger fraction of the incident intensity for distribution among the peaks and valleys of the `prf`. As with the pattern of slits, masking thickness and associated cooling must be chosen to balance improved beam size sensitivity in the `prf` against possible radiation damage.

Optical elements used at CESR-TA are listed in Table 2, and include wide-open (WO), an adjustable vertical pinhole (PH), and two coded aperture designs (CA1 and CA2). Our coded apertures were acquired from Applied Nanotools, Inc. [15], and are created with a proprietary process which lays out a patterned gold

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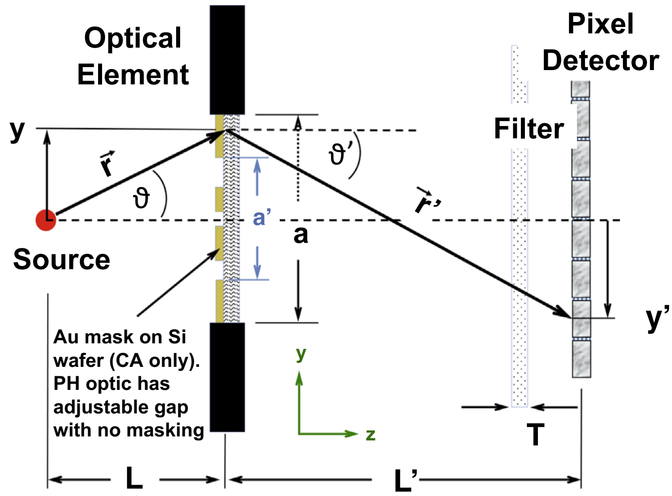

Fig. 1. Simplified schematic of xBSM layout (not to scale). The distinction between a and a' is that a is the total vertical extent of partial transmission through the mask material, and a' is the vertical extent of features (slits) in the mask.

Table 1
Geometrical parameters defining the CESR-TA xBSM beamlines. Geometrical quantities are defined in Fig. 1. Distances assume the coded aperture optic; the pinhole optic is 25 mm closer to the source point and hence has a magnification value about 1% larger than shown. The uncertainties on L are from an optical survey. The uncertainties on L' are from the survey, CESR orbit, and the associated depth of field.

Parameter	e^- beamline	e^+ beamline
L	4356.5 ± 3.9 mm	4485.2 ± 4.0 mm
L'	$10,621.1 \pm 1.0$ mm	10011.7 ± 1.0 mm
$M \equiv L'/L$	2.4380 ± 0.0022	2.2322 ± 0.0020
a'	≈ 50–300 μm	same as e^-
a	≈ 50–1000 μm	same as e^-
$2\theta_{max} = a'/L$	11–69 μrad	11–67 μrad

masking layer on a 2.5 μm thick silicon substrate chip. The two coded aperture designs that we have used appear in high resolution photographs in Fig. 2, and have parameters summarized in Table 2. Optical measurements indicate that the systematic placement of features is within 0.5 μm of the specifications. Edge quality is better than 0.1 μm rms deviation.

2. Resolving power

Design and quantitative evaluation of optical elements requires a figure of merit for beam size determination. The goal in optic design is to obtain the broadest possible regions of beam size where the figure of merit for a particular design is larger than the alternatives in the relevant ranges of beam size and current. For sufficiently large current, the figure of merit should approach being current-independent; however, its usefulness is at low current, where significant current dependence remains. The regime for which it is most difficult to obtain adequate sensitivity is that of simultaneous small beam size and low beam current.

In Eq. (16) of Ref. [13] we restricted ourselves to an idealized figure of merit wherein effects from fitting for the beam size and other parameters on a turn-by-turn basis were ignored. The resulting function $\mathcal{Q}(\sigma_b)$ expressing a simplified statistical power of a particular optical element at beam size σ_b. $\mathcal{Q}(\sigma_b)$ is a χ^2-like quantity based on the assertion that the pulse height in each of the 32 pixels is proportional to the number of incident photons

Table 2
CESR-TA xBSM optic element parameters. Geometrical quantities are defined in Fig. 1. Coded aperture patterns are shown in Fig. 2.

Category	Parameter	Value
WO (wide-open)	$a' \equiv a$	40 mm
PH (pinhole)	Tungsten blade T	2.5 mm
	Downstream taper	2°
	a	0–200 μm
	a'	$\equiv a$
CA1 (coded aperture)	Si T	2.5 μm
	Au T (2 chips)	0.54 ± 0.05 μm
	Au T (2 chips)	0.69 ± 0.05 μm
	Au T (1 chip)	0.75 ± 0.05 μm
	a	1000 μm
	a'	280 μm
	# Slits	8
	Min/Max slit width	10/40 μm
	Transmitting fraction of a'	54%
	Feature placement accuracy	0.5 μm
	Edge quality rms deviation	0.1 μm
	Pattern: S = slit, M = mask (μm) 20S-10M-20S-10M-40S-30M-10S-10M-10S-10M-30S-40M-10S-20M-10S	
CA2	Si T	2.5 μm
	Au T	0.62 ± 0.05 μm
	Au T	0.75 ± 0.05 μm
	a	1000 μm
	a'	296 μm
	# Slits	5
	Min/Max slit width	10/68 μm
	Transmitting fraction of a'	65%
	Feature placement accuracy	0.5 μm
	Edge quality rms deviation	0.1 μm
	Pattern: S = slit, M = mask (μm) 24S-10M-38S-42M-68S-42M-38S-10M-24S	

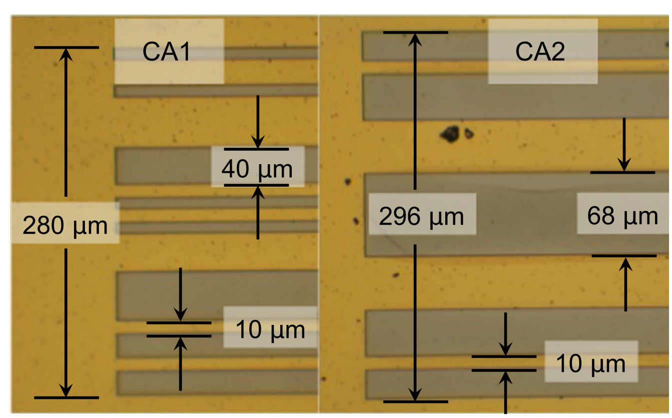

Fig. 2. Photographs of portions of CESR-TA xBSM coded aperture optical elements CA1 (left) and CA2 (right). Dark strips indicate transmission slits, while lighter areas represent the gold coating. The imperfections (black spots) are remnants of etching resist with thickness ~0.01 μm, which are essentially transparent to x-rays.

depositing energy there and which will fluctuate according to Gaussian counting statistics. The $\mathcal{P}_0$ term present in that formula represents the electronic pedestal noise, the rms variation in each channel's pulse height when no charge has been deposited. $\mathcal{P}_0$ introduces an explicit beam current dependence to the prediction because its size relative to peak values will change with current. A reasonable parameterizaton is $\mathcal{P}_0(I) = p_0/I$, with the current-independent parameter p_0 determined from experiment. With this modification, we rewrite Eq. (16) of Ref. [13] as follows, an

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