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Modular high frame rate detector for synchrotron applications

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Abstract

The development of detectors often lags the development in X-ray sources. However, advanced detectors are critical for fully utilizing and exploiting the capabilities of the new bright sources. We report on the development of a modular high frame rate detector for synchrotron applications such as small angle X-ray scattering (SAXS) and wide angle X-ray scattering (WAXS). The detector consists of four modules, each providing an imaging area of 5×5 cm² and capable of frame rates of 200 frames per second (fps) with full resolution, and 650 fps with smaller region of interest (ROI). Details of the detector design and experiments at synchrotron beamlines are discussed in the paper.

Keywords

Synchrotron; modular detector; high frame rate detector; SAXS; WAXS; co-doped CsI

1. Introduction

The development of detectors often lags the development in X-ray sources. However, the availability of advanced detectors is critical to fully utilizing and exploiting the capabilities of the new bright sources. Current choice of detectors for performing time-resolved studies at synchrotrons is very limited. This paper describes a modular high frame rate detector for synchrotron applications such as time-resolved SAXS and WAXS.

2. Design of the modular SAXS/WAXS detector

2.1. Requirements for SAXS/WAXS detector

Applications such as time-resolved SAXS and WAXS are inherently light starved. Therefore, detectors for such applications must have high sensitivity, a wide dynamic range, and good timing and spatial resolution. For a scintillator based detector, it means that a scintillator with a very bright emission is required. The scintillator should also have a fast

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decay time with negligible afterglow, have a high X-ray absorption efficiency, and provide a spatial resolution of better than 100 μm . To take advantage of these scintillator characteristics, the readout sensor must have a high pixel resolution, be capable of operating at high frame rates, and have a wide dynamic range. The detector should also have a reasonable imaging area of $\sim 10\text{cm} \times 10\text{cm}$ or larger. Although several kinds of detectors are currently used for SAXS and WAXS, they lack the capability to perform time-resolved studies.

2.2. Design of the modular detector

The modular detector described here is schematically shown in Fig. 1. It is based on a $5\text{cm} \times 5\text{cm}$ area high-efficiency microcolumnar film of cesium iodide co-doped with thallium and samarium (CsI:Tl,Sm) lens-coupled to a low-cost ($\sim \$1,200$ each), off-the-shelf CCD through an image intensifier. CsI:Tl,Sm is a material newly developed by RMD that has a high light output of $\sim 60,000$ photons/MeV [1],[2],[3], and even a $\sim 150\mu\text{m}$ thick CsI:Tl,Sm film, required for stopping over 99% of the 12 keV X-rays used in these experiments, exhibits over 16 lp/mm of spatial resolution. CsI:Tl,Sm also exhibits over two orders of magnitude lower afterglow compared to conventional CsI:Tl. Besides, CsI:Tl,Sm does not suffer from hysteresis effects that plague CsI:Tl when exposed to intense X-rays. Thus the co-doping of CsI with Tl and Sm ions makes it possible to use CsI for dynamic imaging applications where CsI could not be used until now [4],[5].

A GrasshopperTM CCD from Point Grey Research, Inc., (Richmond, BC, Canada) with a resolution of 640×480 pixels, and capable of operating at 200 fps and higher is used in the detector. To boost the signal, we have used MCP125, a 25mm diameter single stage image intensifier from Photek (East Sussex, UK). The relay lens is a C-mount f/1.2 lens with a focal length of 6mm and the imaging lens is a C-mount f/0.95 lens with a focal length of 50mm. A photograph of the prototype is shown in Fig. 2.

The detector consists of four modules, each capable of independently operating at a desired frame rate. Although the first prototype module was based on a lens-coupled design, it still had enough sensitivity to allow dynamic X-ray imaging at up to 275 fps, as described in the following section. However, we have further enhanced the sensitivity of the detector by incorporating a square-edged fiberoptic (FO) taper in the design. The FO taper version will allow detection of a single 12 keV X-ray photon with a signal-to-noise ratio (SNR) of >4 , whereas the lens-coupled versions had SNR of 2. The scintillator will be directly deposited on the large end of the taper to further improve the detector sensitivity. The specifications of the detector with a 3.6:1 FO taper are shown in Table 1. Due to the use of FO tapers, the modules can be seamlessly tiled or arranged in any desired geometry. For example, four modules can be arranged in a 2×2 or a 1×4 array, thereby providing active imaging area of $14.4 \times 10.8 \text{ cm}^2$ or $28.8 \times 5.4 \text{ cm}^2$, respectively. Furthermore, for WAXS the design of the modular detector will allow it to be placed to within 2 to 3 mm from the X-ray beam, which is not possible using current detectors.

3. Evaluation of the modular detector

The detector was evaluated for its dynamic imaging capability as well as its suitability for SAXS and WAXS by testing it both in-house and at synchrotron beamlines. These are described below.

3.1. Dynamic X-ray imaging

For dynamic imaging, the detector was exposed to X-rays from a GE Senographe 600T-FD, Senix H.F mammography source set at 28 kVp and 80 mAs, and images of a rotating phantom were recorded at frame rates ranging from 15 fps to 275 fps. The source-to-detector

distance was 220 cm. The X-ray exposure was adjusted by varying the mAs while maintaining a constant current. Although the intensifier can have a gain of over 10,000, it is usually operated at much lower gain to preserve the dynamic range and to minimize noise. In this case, the gain was chosen to prevent the detector from being saturated. The rotating phantom is a chopper consisting of a metal disc with two large central slots, and several small indexing slots along its periphery. The chopping frequency can be varied from 4 Hz to 3.7 kHz.

A brass phantom depicting the letters RMD was placed on the CsI film, and a series of X-ray images of the rotating phantom were acquired. A sequence of images were acquired at different phantom rotation speeds and detector frame rates. Some of these images are shown in Fig. 3, clearly demonstrating the dynamic X-ray imaging capability of the detector, and hence its suitability for time-resolved studies.

3.2. SAXS experiments at synchrotron beamlines

SAXS experiments were performed at the X9 beamline at the NSLS at BNL, and at the BioCAT 18-ID beamline at ANL using standard 12 keV SAXS instrumentation (wavelength of 0.103 nm and a camera length of 2.35 m). The SAXS intensity pattern obtained at X9 from gold nanoparticles coated with self-assembled DNAs is shown in Fig. 4(a). Several orders of diffraction are clearly seen. The intensity peaks correspond to the spacing between the nanoparticles, which is expected to be close to the ~25nm diameter of the gold nanoparticles. Fig. 4(b) shows the SAXS pattern for water scattering carried out at BioCAT, with the detector operated at 15 fps. These experiments clearly demonstrate the sensitivity of even the lens-coupled detector. Using a FO taper will only further enhance the detector sensitivity.

Due to the housing of the lens coupled detector, it could only be used for SAXS. However, the FO version being currently developed would allow the detector to be used for both SAXS and WAXS.

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References

- [1]. Bartram RH, Kappers LA, Hamilton DS, Lempicki A, Brecher C, Gaysinskiy V, Ovechkina EE, Nagarkar VV. Afterglow Suppression and Non-Radiative Charge-Transfer in CsI:Tl,Sm. IEEE Trans. Nucl. Sci. 2008; Vol. 55(Issue 3, Part 2):1232–1236.
- [2]. Nagarkar VV, et al. Suppression of afterglow in microcolumnar CsI:Tl by codoping with Sm²⁺: Recent advances. IEEE Trans. Nucl. Sci. 2009; 56(3):565–569. [PubMed: 20617107]
- [3]. Nagarkar VV, et al. Scintillation properties of CsI:Tl crystals codoped with Sm²⁺ IEEE Trans. Nucl. Sci. 2008; 55(3):1270–1274.
- [4]. Thacker SC, Singh B, Gaysinskiy V, Ovechkina EE, Miller SR, Brecher C, Nagarkar VV. Low-afterglow CsI:Tl microcolumnar films for small animal high-speed microCT. Nucl. Instrum. Meth. in Phys. Res. A. 2009; 604:89–92.
- [5]. Thacker, Samta C.; Gaysinskiy, Valeriy; Ovechkina, Lena E.; Miller, Stuart R.; Nagarkar, Vivek V.; Brecher, Charles; Lempicki, Alexander; Bartram, Ralph H. Characterization of the new codoped CsI microcolumnar films for high-speed radiographic imaging. Proc. SPIE. 2008; 6913:69130Q.

Fig. 1.
Schematic of a single lens coupled detector module.

Fig. 2.
A photograph of the prototype modular detector.

Fig. 3. Dynamic X-ray imaging of a 1mm thick brass phantom with 300 μ m diameter holes and 500 μ m pitch. X-ray images acquired at: (a) 60 fps, (b) 120 fps, (c) 175 fps, (d) 275 fps. Image resolution is 640 $\times$ 480 pixels in (a) and (b), and 320 $\times$ 240 pixels in (c) and (d) with no binning.

Fig. 4.

(a) SAXS pattern from gold nanoparticles coated with self-assembled DNAs using one lens-coupled module demonstrating the detector sensitivity at X9 beamline. Intensity peaks correspond to the spacing between the nanoparticles (~ 25 nm diameter of the gold nanoparticles). (b) Water scattering pattern at 15 fps at BioCAT.

Table 1

Specifications of the fiberoptic taper based detector.

Parameter	Specification
Image area (cm ²)	14.4 × 10.8
Pixel resolution (H×V Pixels)	1280 × 960
Frame rate: full resolution (fps)	200
Frame rate in ROI mode (fps)	650
Spatial resolution (μm)	112 (H) × 112 (V)
X-Ray dynamic range @200fps (bits)	10
SNR/12 keV photon: full resolution	4.0