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Flexible X-ray imaging detectors using scintillating fibers

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ABSTRACT: We present early design and simulation work on a novel X-ray imaging detector. The intent of the FleX-RAY project is to create a digital X-ray detector that is capable of producing high-resolution images, is flexible enough to produce an image on a curved surface, and is capable of self-reporting its final shape. The X-rays will be detected on a sheet of scintillating optical fibers, which will guide the scintillation light to single-photon avalanche photodiodes. This setup allows the electronics and hardware to be moved out of the path of the X-ray beam, limiting the need for additional shielding. Self-shape-reporting will be achieved using a flexible ultra-thin glass substrate with optical waveguides and Bragg gratings, processed by femtosecond laser point-by-point writing. The functionalized glass substrate allows precise measurement of strains, which can be used to calculate the shape.

KEYWORDS: X-ray detectors; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Inspection with gamma rays; Inspection with X-rays

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1 Introduction

The FleX-RAY project aims to create a digital X-ray detector that is capable of producing high-resolution images, is flexible enough to produce an image on a curved surface, and is capable of self-reporting its final shape. Many applications of non-destructive testing require X-ray imaging of complex shapes, and therefore still require (flexible) photographic film [1]. The FleX-RAY design could modernize these applications.

The detector will be composed of two layers of scintillating fibers to measure x and y position of hits, with silicon photomultipliers at the ends of the fibers. In addition to allowing flexibility of the detector, this design allows the electronics to be moved out of the X-ray beam path, thus prolonging the lifetime of the detector.

2 Scintillating fiber technology

The initial prototype of the FleX-RAY detector will likely use commercially-available plastic scintillating fibers. However, scintillating liquids offer more flexibility in the choice of scintillating materials. This is important for optimizing photon yield and the timing characteristics of the scintillation. Several different design concepts based on capillaries filled with scintillating liquids have been proposed within the project, with fiber diameters from 125 µm to 350 µm. We are also examining multiple methods of coupling these liquid-filled fibers to standard optical fibers, one of which is shown in figure 1.

The light collection for the current example is estimated to about 7%, which is achieved by coating the capillary with a low index polymer. The coating increases the collection angle but also acts as a cladding and allows light to be guided in the glass wall of the capillary with very low loss.

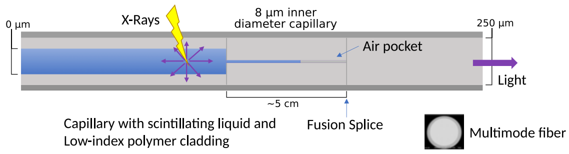

Figure 1. The proposed interface between a liquid-scintillator-filled fiber and a standard optical fiber. The smaller-diameter liquid channel in the middle section causes the air pocket (which is difficult to completely remove while filling the fiber) to block a smaller fraction of the light.

3 Electronics and TDCs

In FleX-RAY we will attempt to use the 'fast' output featured in some SiPMs, which extracts information from the junction of the diode that bypasses inactive microcells, allowing for significantly lower rise times. This approach can reduce the timing uncertainty at the expense of accurate energy information.

4 Shape self-reporting

The 3D shape self-reporting is necessary for the interpretation of the image on a curved surface. In addition to the two layers of scintillating fibers, a layer of flexible glass fibers or a sheet of ultra-thin glass will be integrated into the detector. On this layer, Bragg gratings are integrated into the fibers or into waveguides on the glass sheet. When a broad-spectrum light source is projected down these waveguides, the Bragg gratings act as spectral mirrors, reflecting a wavelength corresponding to their grating point distance. An increase or decrease in the reflected wavelength relative to the nominal value corresponds to a positive or negative curvature along the path of that waveguide. The overall shape of the detector can be calculated from this wavelength information using an algorithm relying on a geometrical interpolation or an artificial neural network.

5 Detector simulation

We have implemented a simulation of the detector in Geant4. This software simulates the X-ray scintillation and the transport of scintillation light to the SiPMs.

This simulation is being used to guide the FleX-RAY design process by evaluating the likely performance of the detector with various materials and X-ray sources. The novel scintillating fiber technologies that are being developed for the FleX-RAY project could significantly improve the detector performance.

6 Image reconstruction

We can reconstruct a 2D image from X-rays that interact in a single fiber by measuring the difference in light arrival time at each end of the fiber. This measurement has a large uncertainty (~10 cm) that's limited by the scintillation timescale and the number of photons detected.

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If the properties of the scintillating fiber are well-understood, the uncertainty in the location measurement is well-known and the image can be deconvolved. Since each hit is blurred in only one dimension (and never diagonally), the deconvolution algorithm can be very fast due to the sparse convolution matrix.

A small number of X-rays will interact in both layers of fibers, but relying on these events requires a less-intense X-ray source to avoid swamping the signal with falsely-coincident single-fiber detections. If the application allows long exposure times (~10 minutes), the resolution can be significantly improved with these 2D detections. Both of these reconstruction methods are depicted in figure 2 using simulated 100-keV X-rays.

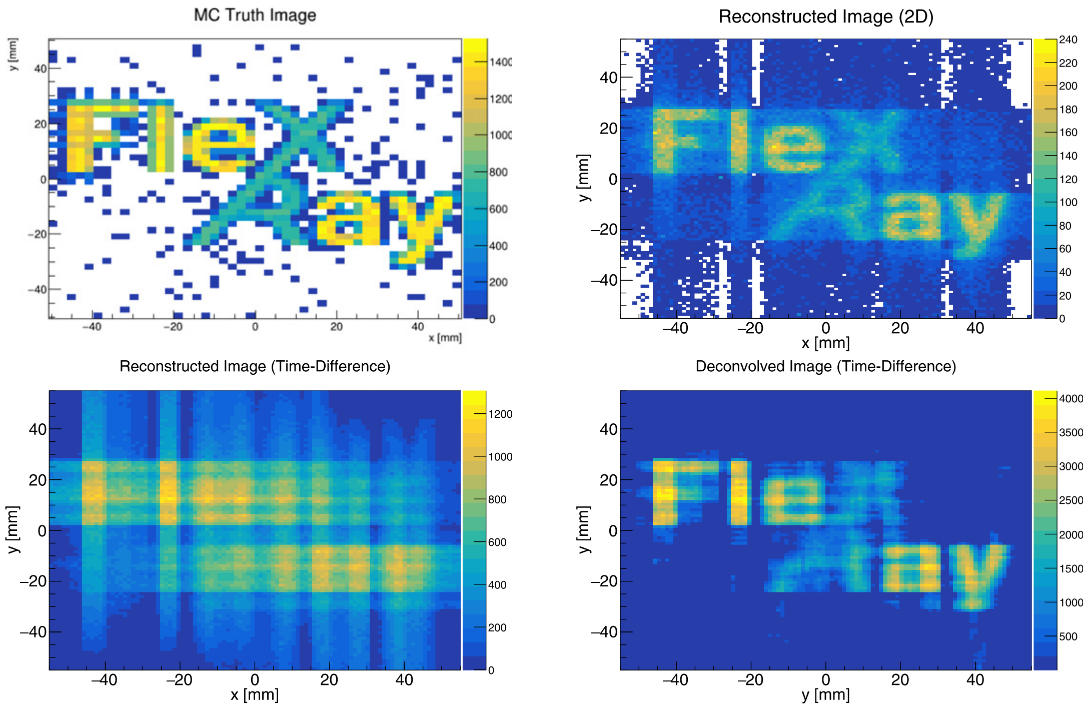

Figure 2. The Monte Carlo truth image from an exposure in the simulated detector, as well as the reconstructed image using two different methods. This simulation assumes the use of commercially-available plastic scintillating fibers and 100-keV X-rays.

Both detection methods are vastly improved in imaging applications that use gamma rays (e.g. from Co-60 decay). The higher energy allows both a higher light yield and an increased number of 2D detections, improving 1D resolution and 2D exposure time.

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