PROCEEDINGS OF SCIENCE

FleX-RAY: A flexible scintillating detector for X-ray applications and beyond

Scott Wilbur,[a] **Kamal Abdelouadoud Saoucha,**[b] **Kristin Lohwasser,**[a] **Helen Maguire,**[a] **Christos Anastopoulos,**[a,*] **Nikolaos Panagopoulos**[c] **and Nikolaos Marinos**[c]

[a]*Department of Physics and Astronomy, University of Sheffield, Hounsfield Rd, Sheffield, United Kingdom*
[b]*University of Sharjah, Sharjah, United Arab Emirates*

E-mail: c.anastopoulos@sheffield.ac.uk

Photographic films are still used in a number of medical and industrial X-ray imaging applications that need to reconstruct an image on a flexible surface. We will present the FleX-RAY project, which aims to create a digital X-ray detector with the flexibility of photographic film, suitable for a variety of applications.
FleX-RAY uses a sheet of flexible scintillating fibers to detect X-rays and guide the scintillation light to arrays of silicon photomultipliers. The detector also self-reports its curved shape using optical waveguides with Bragg gratings on a flexible glass substrate, which act as strain sensors.
In this contribution, we present the detector concept, simulations of the expected detector performance for pipe-inspections and results of the initial tests on the FleX-RAY prototype.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

*Speaker

https://pos.sissa.it/

PoS(ICHEP2024)1212

1. Introduction

Pipelines are integral to the infrastructure of numerous industries, serving for efficiently transporting essential fluids. However, they are vulnerable to various forms of structural defects, predominantly cracks, which pose significant risks to their integrity and operational safety. The detection and characterisation of such cracks are therefore paramount for maintaining the reliability and safety of pipeline systems.

In response to these challenges, the field of Non-Destructive Testing (NDT) [2] has evolved, offering a spectrum of methodologies to detect and analyse defects within pipelines. X-ray imaging stands out as a particularly effective tool for internal structural analysis. However, traditional flat-panel X-ray detectors will necessarily lead to image deformation when testing a curved object like a pipe, and therefore many NDT applications use photographic film. Addressing this gap, this paper introduces a novel concept in X-ray detection technology: the flexible X-ray detector, or FleX-Ray. This advanced detector is designed for adaptability, offering a new method in imaging capabilities and representing a significant leap forward in NDT.

1.1 Flex-Ray detector concept

The FleX-RAY detector prototypes a novel concept in the domain of X-ray imaging. Central to its architecture are scintillating flexible fibres arranged in a grid with fibres running along the x- and y-axis of the detector. These fibres exhibit sensitivity to X-ray interactions, reacting through scintillation and emitting detectable light signals. These signals are then guided towards arrays of silicon photo-multipliers (SiPMs), integral components of the detector, converting optical signals into measurable electrical outputs. The distinctive character of the FleX-RAY detector lies in its intrinsic capability for self-shape reporting. This unique attribute is achieved by integrating optical waveguides with Bragg gratings into the detector architecture, allowing the detector to offer real-time insights into its own curvature and thus function as a responsive observer of its structural variations.

Scintillating fibres Image reconstruction relies on cross-correlating hits between fibres along different spatial directions to obtain a 2D space point. This process requires a fast response of a few nanoseconds. The resolution of the detector primarily depends on the size of these fibres. Commercially-available plastic fibres exist with diameters ranging from 250μm to 1mm [3]. Additionally, custom-made liquid-filled glass fibres have been developed with an inner active diameter of 50μm and an outer diameter of 120μm [4], offering resolution competitive with current state-of-the-art silicon X-Ray detectors.

Self-shape reporting Based on a 3D shape sensor using ultra-thin glass (100 μm) with wave guides and Bragg gratings, this system reflects light at specific wavelengths depending on material deformations. The 3D shape is calculated from the reflected light, enabling the detector to probe curvatures within a range of ±20 m^{-1} with high linearity (average R^2=0.998) [5].

Readout The current prototype uses Hamamatsu S13360-1375CS 1mm SiPMs coupled to the fibres. Signals are initially processed by a weeroc Petiroc2A board, with plans to transition to a custom front end for improved performance and cost efficiency.

2. Prototype Studies

We have built two proof-of-concept prototypes of the FleX-RAY detector, shown in Figure 1. The prototypes use 8 or 16 scintillating fibers in each direction, enclosed in a silicone matrix. The scintillation light is detected at the ends of the fibers by Hamamatsu S13360-3075CS 3mm SiPMs, and the SiPM signals are read out by a Weeroc Petiroc2A board.

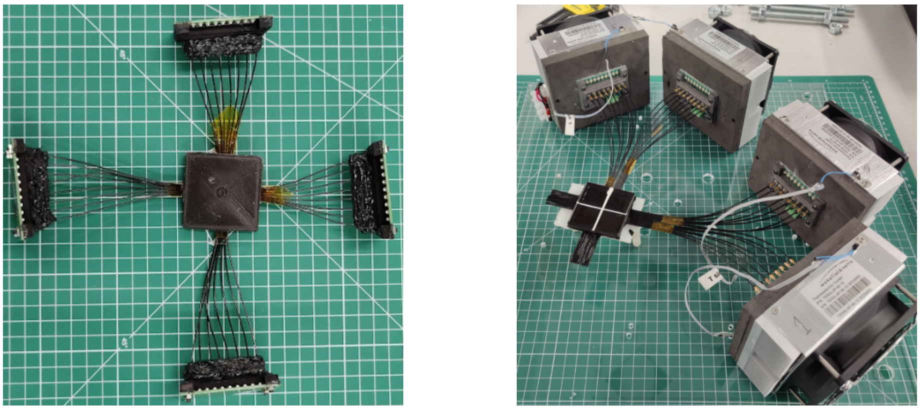

Figure 1: The fibers for the prototype are encased in a flexible silicone matrix. The initial prototype used only 8×8 fibers, with an SiPM on each end of each fiber. The later prototype used 16×16 fibers, with SiPMs on only one end of each fiber.

Initial tests were carried out using small radioactive sources that were readily available. An Sr-90 source delivering 546-keV electrons was used to test the scintillation properties of the detector and the image reconstruction algorithms, although such electrons are not sufficient for real NDT applications. A Co-60 source emitting 1.17-MeV and 1.33-MeV gamma rays served as a simulation of real NDT sources, although real applications require a higher activity that what was available.

A calibration run was performed with the Sr-90 source to ensure high statistics, since electrons are much more efficient at causing scintillation than gamma rays. With no object between the source and detector, a background image was reconstructed and then the hits in each fiber were multiplied by a normalization factor to obtain a homogeneous image.

Gamma rays from the Co-60 source showed that, as expected, we could acquire two-dimensional detections from single energetic photons for NDT applications. The Co-60 source that we had available was not active enough to acquire a clear image of a complex object, but sufficed to show that the concept is feasible; the detector could show the location of the source itself or the edge of a lead target object.

These test images acquired on the prototype detector are shown in Figure 2.

3. The FleX-Ray detector simulation

3.1 GEANT4 Simulation Framework

GEANT4 is a software toolkit for the simulation of the passage of particles through matter. It is widely used in high energy, nuclear physics, and medical physics, as well as in space and accelerator science[7, 8].

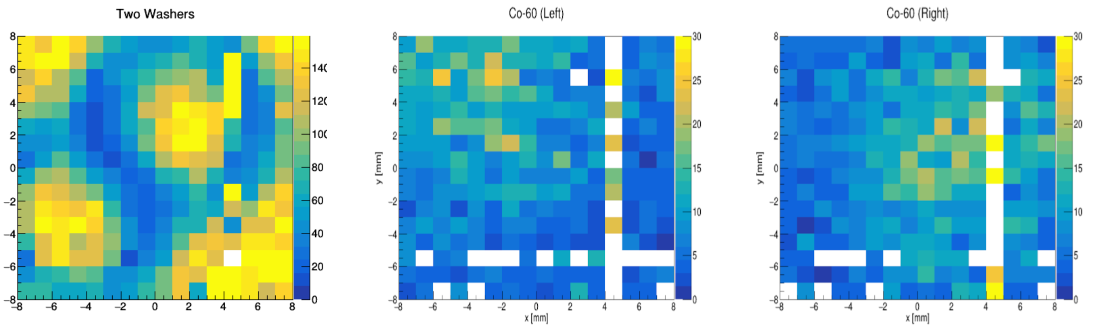

Figure 2: Reconstructed images on the 16×16 prototype detector. The left image shows the shadow of two washers on the detector illuminated by electrons from an Sr-90 source. The center and right images show a small Co-60 source illuminating two different spots on the detector. Two fibers in this prototype had been damaged and were very inefficient for these exposures, but the left image has sufficiently high statistics that a calibration run could normalize their response.

In the context of our study, GEANT4 is used to simulate the interaction of X-rays with the pipeline materials, including the presence of defects such as cracks, and then continuing to the FleX-RAY detector. The framework then simulates the production of scintillation light and the transmission of this light down the fiber to the SiPM. It then simulates the detector output in the same format as the data acquired from the prototype detector, and allows testing of the image reconstruction methods on larger detectors than the current prototypes.

4. FleX-RAY Simulation

The GEANT4-based simulation incorporates a cylindrical iron pipe model, Co-60 and Ir-192 X-ray sources, and the FleX-RAY detector. The experiment focuses on exploring the detection of cracks within the pipe. Various configurations of the pipe and crack dimensions are tested to evaluate the detector's imaging capabilities and its efficacy in identifying and characterising crack defects.

4.1 Pipe Model

The simulated iron pipe is a perfect cylinder with a fixed height of 30 mm, representing typical pipeline materials. To explore the detector's adaptability, the pipe's wall thickness is varied across different simulation runs, reflecting realistic variations in industrial pipe dimensions.

Cracks are modeled as air gaps within the pipe's structure. Parameters such as depth, width, and length of the cracks are systematically varied to assess their impact on the FleX-RAY detector's detection capabilities. A representative schematic of a pipe with a simulated crack is shown in Figure 3.

The simulation employs both Co-60 and Ir-192 sources for X-ray generation. Both sources are used in commercial NDT applications and are suited to imaging different materials and thicknesses. The source is positioned 400 mm from the pipe, emitting X-ray from 5mm circular window, with an isotropic angular distribution of the X-rays. This configuration ensures a realistic representation of the characteristics of the X-ray emission sources.

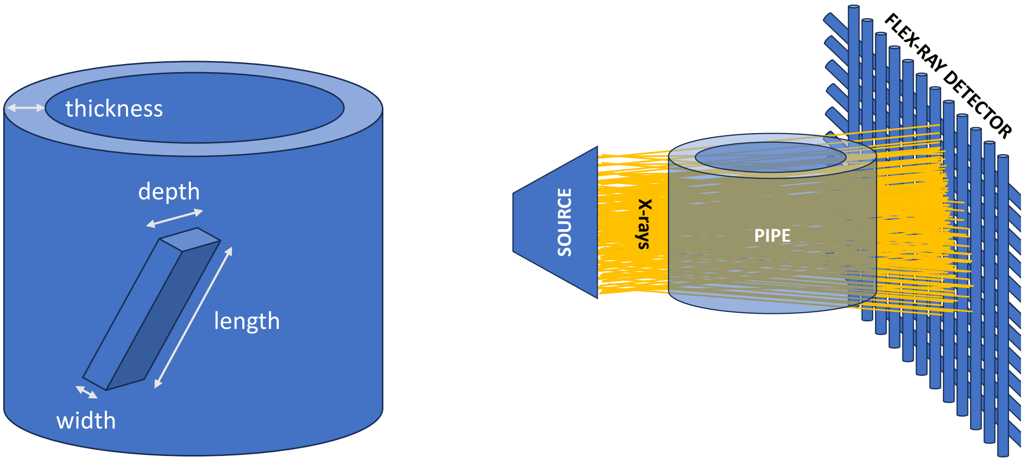

Figure 3: Schematic representation of a pipe with a simulated crack (left) and simulated experimental setup (right).

4.2 Simulation Results

The simulation is run with multiple simulated pipes, adjusting the pipe wall thickness, the dimensions and direction of the crack, and the characteristics of the source. The principal variable in the efficacy of the image reconstruction is the width of the crack relative to the width of the fibers. Using smaller fibers as well as smaller cracks barely affects the final image quality.

Figure 4 shows representative images of three cracks with very similar properties but with varying width of 0.5, 1, and 2 times the fiber active diameter. These images were taken using an Ir-192 source, of a 1-mm deep crack in a 5-mm thick pipe wall. The crack is visible when its width reaches about 1 mm, the pitch of the scintillating fibers in the detector. With smaller fibers (and a corresponding smaller spacing) the minimum detectable crack size will decrease proportionally.

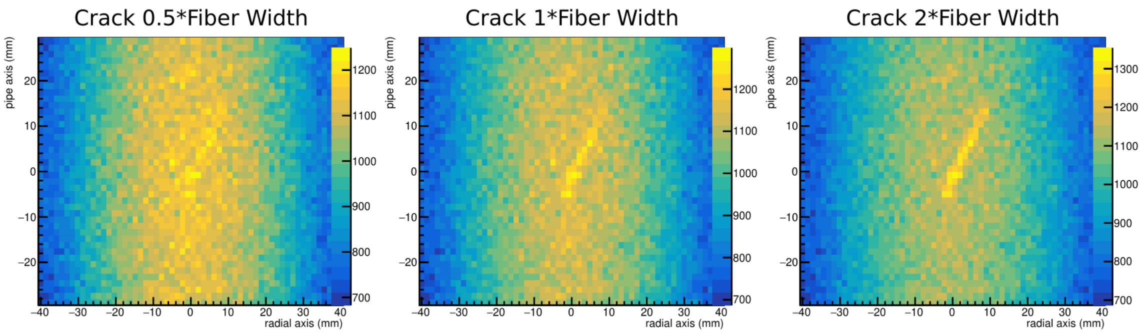

Figure 4: Reconstructions of three different cracks, with width 0.5, 1, and 2 times the pitch of the detector fibers.

5. Results and conclusion

The FleX-RAY prototype studies show that the detector works in practice, and the GEANT4 simulations show promising results in the simulated detection of pipeline defects. Cracks can be detected at a scale similar to the fibers' active width, so the 50-μm liquid-scintillator filled fibers will be important in bringing this technology to a marketable product. These findings, derived from simulations using both Co-60 and Ir-192 sources, provide a valuable foundation for future studies aimed at refining the capabilities of the FleX-RAY detector.

References

[1] S. Agostinelli et al., "GEANT4: A Simulation Toolkit", *Nuclear Instruments and Methods in Physics Research Section A*, vol. 506, no. 3, pp. 250-303, 2003. Available: https://geant4.web.cern.ch/

[2] M. Köppel and S. Maack, "Nondestructive Testing Methods for Condition Assessment of Concrete Components", In: *Handbook of Nondestructive Evaluation of Reinforced Concrete Structures*, 2020.

[3] Luxium Solutions, "Fibers", *Plastic Fiber | Scintillating and Light Transmitting*, [Online]. Available: https://www.luxiumsolutions.com/radiation-detection-scintillators/fibers. [Accessed: 24-Sep-2024].

[4] M. Lindblom et al., "Flexible Liquid-Filled Scintillating Fibers for X-Ray Detection", *IEEE Sensors*, Conference proceedings, Nov 2023.

[5] Jannis Koch et al., "3D shape-sensor based on integrated optics in ultra-thin glass", *Proceedings Volume 12424, Integrated Optics: Devices, Materials, and Technologies XXVII*, 1242417, 2023.

[6] M. C. Espirito-Santo et al., "Applications of GEANT4 in Astroparticle Experiments", *IEEE Transactions on Nuclear Science*, vol. 51, no. 4, 2004.

[7] Z. Kohley, "Modeling interactions of intermediate-energy neutrons in a plastic scintillator array with GEANT4", *Nuclear Instruments and Methods in Physics Research Section A*, vol. 682, pp. 59-65, 2012.

[8] Z. Li-Ming, "Simulation study for a single TOF scintillator using GEANT4", *Measurement Science and Technology*, vol. 15, 2004.

[9] C. C. Guimaraes et al., "Performance of GEANT4 in dosimetry applications", *Radiation Measurements*, vol. 43, issues 9-10, pp. 1525-1531, 2008.

[10] TEAM, Inc., "NDT Testing", *NDT Testing | Non Destructive Evaluation and Testing*, [Online]. Available: https://www.teaminc.com/services/inspection/conventional-ndt/. [Accessed: 10-Dec-2023].