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First X-ray spectral imaging demonstration with the novel CITIUS detector operating in a spectro-imaging mode

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X-ray spectral imaging exploits the distinct energy dependence of the attenuation properties of different materials to produce quantitative maps of the chemical components inside a sample. In this context, the continuous development of new energy-sensitive detectors has led to a growing interest in X-ray spectral imaging, thereby enlarging the field of applications. The devices suitable for spectral imaging can be grouped into two categories: photon-counting and hyperspectral detectors. The first family of detectors analyzes the electrical signal generated by the interaction of an impinging photon with a semiconductor sensor, compares it to one or more energy thresholds, and stores the information (number of photons) in counters. Such detectors usually feature energy resolutions of > 1.5 keV (full width at half maximum at photo-peak) [1, 2]. Photon-counting detectors are suitable for a wide range of applications such as K-edge imaging [3, 4]; however, their broad energy resolution and limited number of adjustable energy thresholds limit their ability to discriminate materials with similar attenuation properties. As an alternative to photon-counting detectors, hyperspectral detectors may feature an energy resolution below 1 keV and allow for an undefined number of thresholds [4]. Such detectors are charge-integrating devices that implement very high frame rates so that each photon can be detected in an isolated cluster of pixels. Therefore, the recorded signals can be directly related to the energy of the detected photons. The acquired frames can be processed to obtain spectral images, where the impinging photons are binned into hundreds of energy bins at the single-pixel level. Owing to their high energy resolution and the possibility of post-processing the data to divide a polychromatic spectrum into a desired number of energy bandwidths, such detectors may represent invaluable tools for challenging tasks, such as the discrimination of elements with K-edge absorption close in energy or discrimination of elements with similar attenuation properties, such as water and plastic materials.

In this conference, the CITIUS detector, developed by RIKEN (Japan) [5,6] and its first spectral imaging application on radiographic images, is presented. CITIUS is a direct detection X-ray detector crafted by coupling a 650 μm-thick Si sensor to a CMOS readout ASIC. The chip features integrating-type pixels with 72.6 μm pitch. The detection system can operate in various modes. The imaging and spectral modes are relevant to the applications with continuous X-rays. In the standard imaging mode, the frame rate can be set to 17.4 kfps (kilo frames per second) at maximum, allowing the detection of a flux up to 30 Mcps (mega counts per second)/pixel at 12 keV. The count rate can be extended to 600 Mcps/pixel at 12 keV in an extended mode. In the spectral mode, the detector operates at a higher frame rate of 26.1 kfps, while keeping the detection capability of single photons in the acquired frames. In this study, the detector is configured to acquire 5000 frames with 36 μs integration time for each acquisition trigger. After data collection, post-processing analysis of the frames yields spectral images with user-defined energy binning. A dedicated library for CPU written in C++ and parallelized with OpenMP is used for this study. A faster version with FPGA acceleration is under development.

The spectral capabilities of CITIUS were demonstrated for the first time via the basis material decomposition of a multi-material test sample [3]. The sample comprised a stainless-steel support with three vials containing Ag solutions in water (20 mg/ml, 10 mg/ml, and 2.5 mg/ml) and one with a 20 mg/ml KBr water solution (see Figure 1a). The vials were attached to the support using polybutene-based glue. Radiographic images were acquired at the OPTIMATO laboratory [7] using a liquid metal jet source set to 35 kV and 1.7 mA with a 0.25 mm Cu filter. With a source-detector distance of 75 cm, ten trains of 5000 images were acquired, corresponding to a total exposure time of 1.8 s. Before material decomposition, spectral images with energy bins of 0.5 keV in the range of 0-35 keV were obtained from raw data. The spectral images were processed using the minimum-residual basis material decomposition algorithm presented in [3], whereby Ag, water, KBr, steel, polyethylene, and polybutene bases were considered. The first results obtained with the system are depicted in Figure 1b, and show that the CITIUS detector allows for the simultaneous decomposition of multiple materials, ensuring a sharp separation even among materials with subtle differences in the energy dependence of attenuation coefficients, such as water and polyethylene.

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