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Speckle-based imaging (SBI) applications with spectral photon counting detectors at the newly established OPTIMATO (OPtimal IMAging and TOmography) lab

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Speckle-based imaging (SBI) is an advanced X-ray technique that enables measuring phase and dark-field signals in addition to conventionally accessible absorption signals [1]. SBI uses random modulators such as sandpapers that, placed at a proper propagation distance from the detector, produce a reference speckle pattern. The technique requires the acquisition of two images; the first with the speckle pattern alone (reference image) and the second after introducing the sample in the beam (sample image). If compared to the reference image, the speckle pattern in the sample image is modulated in terms of reduction of intensity (transmission signal), lateral displacement (refraction), and blurring (dark-field signal). SBI reconstruction algorithms operate by comparing the reference and sample images to retrieve the three signals (transmission, refraction, dark-field). Among the existing algorithms for SBI, the Unified Modulated Pattern Analysis (UMPA) algorithm provides a fast solution for SBI image reconstruction [2].

Though an ideal setup for SBI requires a coherent source, such as a synchrotron beamline, SBI can easily be adapted to laboratory facilities with (quasi-coherent) micro-focus X-ray sources. The main advantage of SBI over other techniques, such as grating-based imaging and edge illumination, is the possibility to use cheap modulators such as silicon carbide sandpapers, although at the cost of reduced visibility of the reference pattern. To obtain optimal results in SBI, it is crucial to ensure the visibility of speckles. This is typically achieved through low-energy photons (<20/30 keV), which maximize the contrast of the speckles, and high statistics so that the variations of speckles intensities dominate over the Poissonian noise. These conditions are not always reproducible with compact X-ray sources. In this context, direct-detection CdTe X-ray photon counting detectors (XPCD) provide an attractive solution for SBI, featuring multiple advantages compared to widespread indirect charge-integrating flat-panel detectors. First, direct conversion with thick (>0.5mm) CdTe sensors allow for both high detection efficiency (up to 100 keV) and optimal spatial resolution. Second, the photon counting architecture counts each photon regardless of its energy. This leads to better speckle visibility in SBI compared to an ideal charge-integrating detector that, integrating the charge from all photons, weighs high-energy photons more than low-energy ones. Finally, by implementing one or more energy thresholds, XPCDs enable spectral capabilities, thus allowing a deeper characterization of the energy-dependent absorption, dark-field, and phase signals.

This work will present a newly established X-ray setup at the OPTIMATO lab hosted at the Elettra synchrotron (Italy), and discuss the main advantages of XPCDs in SBI applications. The lab, implemented in the framework of the S-BaXIT (Scattering-Based X-ray Imaging and Tomography) project, is equipped with a micro focal, high-brilliance liquid-metal-jet X-ray source (MetalJet D2+, Excillum, Sweden), featuring maximum acceleration voltage160 kV, power of 250 W, and adjustable focal spot sizes (>15 μm). The source can emit photons on two opposite sides, allowing the implementation of two semi-independent imaging branches. The experimental setup is assembled in a 7×2.5 m lead-shielded hutch. The first branch uses two coupled optical tables (2×0.8 m each), resulting in a maximum source-detector distance (SDD) of 4 m ('long branch'); the other uses a single table, allowing a maximum SDD of 2 m ('short branch'). The long branch, dedicated to SBI applications and micro-CT with a maximum achievable resolution of 15 μm, is equipped with two detectors. The first is the LAMBDA 350k (X-Spectrum, Germany), an XPCD made by 3×2 Medipix3 chips bump-bonded with a single 1

mm thick CdTe sensor. This detector has an active area of 28×42 mm2 (512×768 px) with 55 µm pixel pitch. The second detector is a charge-integrating flat-panel detector (Varex imaging's 1512 CMOS camera) with a 200 µm thick micro columnar CsI scintillator, featuring an effective area of 145×115 mm with a pixel pitch of 74.8 µm. On the long branch, samples can be mounted on a Meca500 robotic arm (Mecademic Robotics, Canada) with 5 µm repeatability. With 6 degrees of freedom (3 of translation, 3 of rotation), the robotic arm serves both for translations and tomographic acquisitions. The short branch, under development, will be devoted to imaging at resolutions of up to 1 µm. On both branches, modulators can be mounted onto a motorized translation stage (Newport 2×MFA-CC).
Images were acquired under identical conditions with both detectors available in the long branch to assess the potentials of XPCDs compared to flat-panels for SBI applications. The sample was a test object consisting of a row of three cuvettes (one filled with water), an aluminum rod, and a toothpick. The source-detector and source-sample distances were set to 300 cm and 150 cm. The source was operated at 60 kV and 4 mA with no additional filtration. Reference and sample images were collected at 20 different diffuser positions. The total exposure time for each image was 30 s for both detectors. As a first result, the visibility (usually defined as (Imax-Imin)/(Imax+Imin), with I the intensities in the speckle images) obtained with the XPCD is four times higher than the one obtained with the flat panel. Figure 1 shows how the XPCD outperforms the flat panel in terms of image resolution and contrast, especially for the dark-field and the differential-phase images, where optimal detected visibility is crucial for the convergence of SBI algorithms. The potential of the spectral weighting approach via multi-threshold acquisitions with XPCDs will be discussed.

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