Soft X-ray detection with Megaframe rate at the European XFEL: the DSSC camera. Experimental results and future developments

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The DSSC camera was developed for photon science applications in the energy range 0.25-6 keV at the European XFEL in Germany. The first 1-Megapixel DSSC camera [1] is available and is successfully used for scientific experiments at the "Spectroscopy and Coherent Scattering" and the "Small Quantum System" instruments of the European XFEL. The detector is currently the fastest existing 2D camera for soft X-rays.

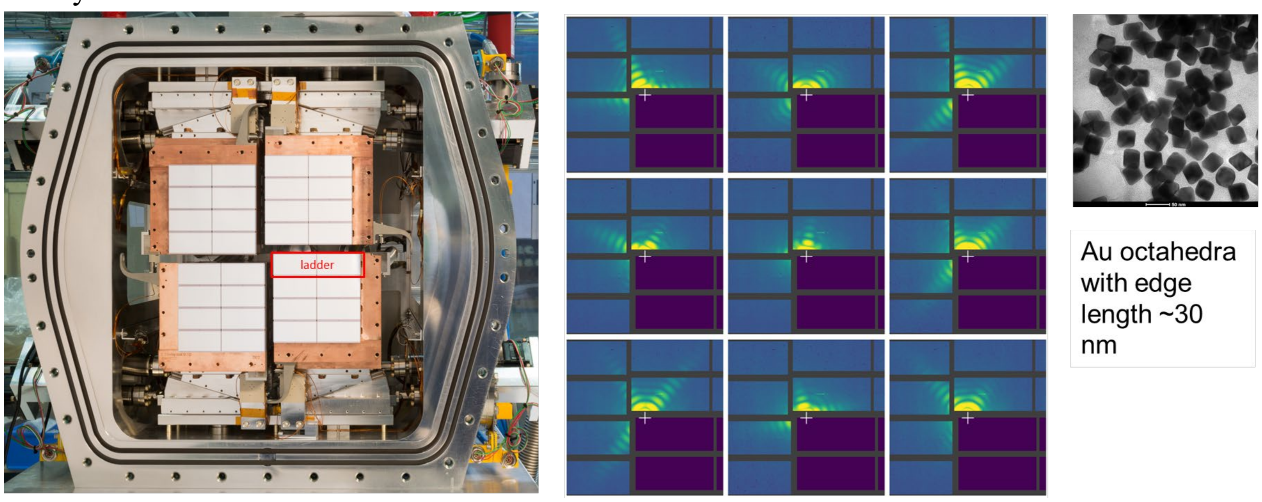

Figure 1. Left: Front view of the installed DSSC 1-megapixel camera. The camera is composed of 4 quadrants, each comprising 4 ladders and 8 monolithic MiniSDD pixel arrays. The active area is ~ 505 cm^2. Right: Example of X-ray Single Particle Imaging experiment. The figure shows 9 random class averages obtained with Au octahedra, a frame rate of 2.2 MHz and a primary photon energy of 3 keV (run 3004 at SQS, PIs H. Chapman, P.L. Xavier. Image courtesy of A. Morgan / P.L. Xavier). The obtained spatial resolution is 1.5 nm. In the same user experiment the first ever single-particle diffraction pattern of giant photoactive protein system exhibiting ps/fs bio-functional dynamics has been acquired with a photon energy of 1.2 keV.

The camera is based on Si-sensors and is composed of 1024×1024 pixels. 256 ASICs provide full parallel readout, comprising analog filtering, digitization and data storage. In order to cope with the demanding X-ray pulse time structure of the European XFEL, the DSSC provides a peak frame rate of 4.5MHz. The first megapixel camera is equipped with Miniaturized Silicon Drift Detector (MiniSDD) pixels. The intrinsic response of the pixels and the linear readout limit the dynamic range but allow one to achieve noise values of ~60 electrons r.m.s. at 4.5MHz frame rate. 40 electrons rms have been obtained at 2.2 MHz.

The challenge of providing high-dynamic range (~10^4 photons/pixel/pulse) and single photon detection simultaneously requires a non-linear system, which is obtained with the DEPFET active pixels foreseen for the advanced version of the camera. This technology provides lower noise and a non-linear response at the sensor level. The readout ASICs and the camera-head electronics are compatible with both type of sensors.

We will present the architecture of the whole detector system with its key features. We will summarize the main experimental results obtained with the MiniSDD-based camera. Several types of user experiments have been performed, including time-resolved holography and X-ray absorption spectroscopy, X-ray Photon correlation spectroscopy and Single Particle Diffraction imaging. We will give an overview of performed experiments, critically demonstrating the versatility of the camera under various experimental constraints. One of the highlights is the first ever single-shot acquisition of a single-particle diffraction pattern of a giant photoactive protein system exhibiting ps/fs bio-functional dynamics. The experiment has been performed with a photon energy of 1.2 keV and a peak frame rate of 2.2 MHz. Additionally, system calibration and data correction specific to the DSSC system are briefly addressed.

We will present the experimental results with complete single module of the DEPFET camera which is in the final stages of assembly. Measurements obtained with full size sensors and the complete readout electronics at the beamline under real experimental conditions have shown an unprecedented mean noise of about 8 el. rms with MHz frame rate and a dynamic range more than one order of magnitude higher with respect to the MiniSDD camera.

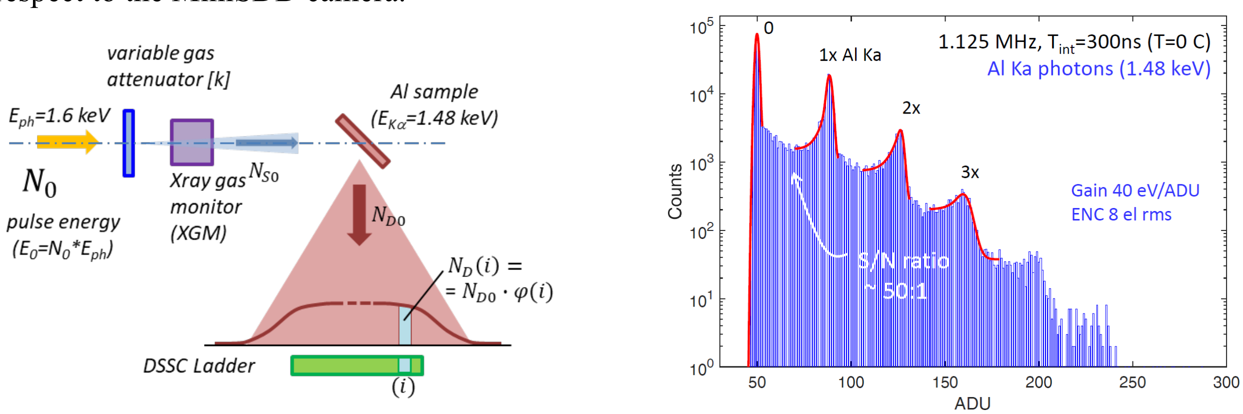

Figure 2. Left: sketch of the single module DEPFET DSSC setup at the XFEL SQS Instrument. Right: X-ray spectrum of Al Kα peaks at high gain. It is possible to distinguish individual 1.48 keV photons with a S/N>50 at a frame rate of 1.125 MHz. The measured noise at this frame rate is ~8 el. r.m.s.

Finally, we explore the potential adaptation of key features of the DSSC camera to develop a new generation of X-ray cameras for the European XFEL. Challenges include preserving existing functionalities and performance while reducing pixel area by a factor of approximately four. The DEPFET technology offers advantages over MiniSDDs and simple diodes, providing superior noise performance and the potential for pixel clustering at the sensor level to optimize and share readout electronics resources.

[1] M. Porro et al., IEEE TNS , vol. 68, no. 6, pp. 1334-1350, June 2021, doi: 10.1109/TNS.2021.3076602
[2] Maffessanti, S., et al., Sci Rep 13, 11799 (2023). https://doi.org/10.1038/s41598-023-38508-9