Published by IOP Publishing for Sissa Medialab

Received: *November 28, 2021*
Accepted: *July 21, 2022*
Published: *September 27, 2022*

12th International Conference on Position Sensitive Detectors
12–17 September, 2021
Birmingham, U.K.

Advancing the JUNGFRAU detector toward low-energy X-ray applications

V. Hinger,* A. al Haddad, R. Barten, A. Bergamaschi, M. Brückner, M. Carulla, S. Chiriotti-Alvarez, R. Dinapoli, S. Ebner, E. Fröjdh, D. Greiffenberg, S. Hasanaj, T. King, P. Kozlowski, C. Lopez-Cuenca, D. Mezza, K. Moustakas, A. Mozzanica, D. Ozerov, C. Ruder, B. Schmitt, K.A. Schnorr, D. Thattil and J. Zhang

Paul Scherrer Institute, Forschungsstrasse 111, 5232 Villigen PSI, Switzerland

E-mail: viktoria.hinger@psi.ch

Abstract: The charge-integrating hybrid silicon pixel detector JUNGFRAU has found widespread use at free-electron laser and synchrotron facilities. The detector was designed for use with hard X-rays; yet, because of its low noise, high dynamic range, position resolution, and scalable size, JUNGFRAU is of high interest for soft X-ray applications. We discuss improvements of the readout chip and alterations of the entrance window at the back of the sensor that facilitate low-energy X-ray detection. The first use case of the improved system at a low-energy beamline demonstrates single photon sensitivity down to 800 eV. At lower energies, the readout noise of the hybrid detector hinders the resolution of single photons. We propose to couple the JUNGFRAU readout chip with charge-multiplying low-gain avalanche diode (LGAD) sensors to resolve X-ray photons with a minimum energy of 250 eV.

Keywords: Hybrid detectors; X-ray detectors; Solid state detectors

*Corresponding author.

https://doi.org/10.1088/1748-0221/17/09/C09027

2022 JINST 17 C09027

Contents

1 Introduction

X-ray photon science at free electron lasers (FEL) and synchrotron light sources fosters a large variety of research. Applications span from biology to solid state physics. Photon energies vary depending on application and experiment type. Hard X-rays with energies around 10 keV, for instance, are the probe of choice to determine crystal structures [1, 2]. Soft X-rays with energies between 250 eV and 2 keV, on the other hand, are more sensitive to spin, charge, and orbital degrees of freedom [3]. Experiments can exploit the presence of the K and L-edges of many light elements and 3D transition metals in this energy range [3, 4]. Consequently, low-energy X-rays are an important tool for research on new materials and correlated systems. And specialized soft X-ray branches are in high demand at FELs and synchrotron sources.

The detectors for such applications must be able to cope with the brilliance, repetition rate, and pulse duration of the X-ray sources. Large-area single-photon-counting [5, 6] and charge-integrating hybrid detectors [7, 8] are widely used for hard X-rays. At photon energies below 2 keV, experiments rely on charge-coupled devices (CCD) or CMOS monolithic sensors. These detectors, however, suffer shortcomings in terms of active area, dynamic range, readout speed, and radiation tolerance. With regard to these limitations, hybrid detectors become an attractive alternative.

The charge-integrating hybrid silicon pixel detector JUNGFRAU [9] offers low noise, high dynamic range, readout speed, and position resolution, scalable area, and single-photon resolution down to about 1.5 keV with readout chip version 1.0. At lower energies, the noise of the readout chip and the attenuation of photons in the non sensitive sensor entrance window limit detection efficiency. Optimizations of the readout chip and of the entrance window have improved the detection efficiency at low energies. The improved system was installed at the experimental station Maloja of the Swiss Free-Electron Laser (SwissFEL), marking the first use case of JUNGFRAU for low-energy X-ray detection. In the following, we discuss the capabilities of this system and introduce plans to combine the JUNGFRAU readout chip with low-gain avalanche diode (LGAD) sensors to extend the single-photon resolution down to 250 eV.

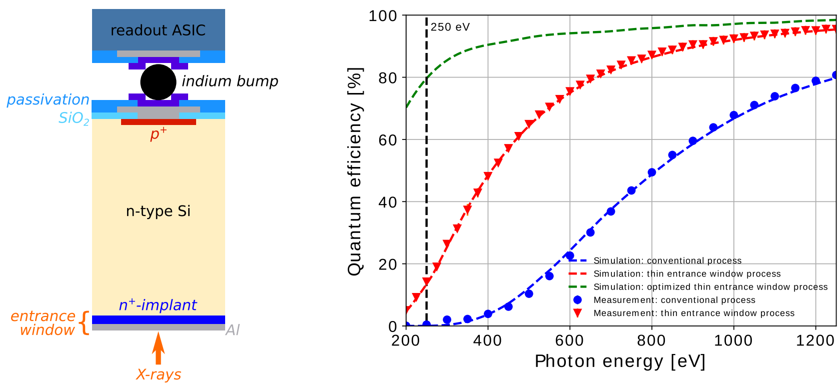
2022 JINST 17 C09027

2 The JUNGFRAU detector

JUNGFRAU [9] was primarily designed to cope with the brilliant, short (~10 fs) X-ray pulses of FELs. It combines a charge-integrating architecture and three linear, dynamically switching gains per pixel. With readout chip version 1.0, the detector can resolve single photons down to ~1.5 keV while providing a dynamic range of 10^4 photons at 12 keV. The maximum frame rate is 2.2 kHz. A single detector module contains 500k pixels with a size of 75×75 μm^2. Modules can be combined into larger systems; the largest systems to date feature 16 megapixels. Owing to its low noise, high dynamic range, and count rate capabilities, JUNGFRAU has extended its range of use from FELs also to synchrotron light sources [10].

Version 1.1 of the JUNGFRAU readout chip[1] improves the noise performance of the detector. In particular, the input capacitance of the preamplifier and the feedback capacitance in high gain were reduced, and a filtering resistor was added before the correlated double sampling stage. These measures reduce the average noise at 5 μs integration time from 52 electrons equivalent noise charge (ENC) for chip version 1.0 (see [9]) to 34 electrons for version 1.1.

The quantum efficiency of the sensor poses an additional challenge for low-energy X-ray detection. Sensors feature a non sensitive implant of high doping concentration at the back. This entrance window influences the quantum efficiency at low photon energies. The standard JUNGFRAU sensors feature a 1–2 μm thick n^+ entrance window (figure 1(a)), giving a quantum efficiency of ~80% for 1.2 keV photons, which decreases rapidly for lower energies (figure 1(b)). Sensors with a thinner n^+ layer (~200 nm), fabricated by Fondazione Bruno Kessler (FBK), significantly improve the quantum efficiency at low energies. Furthermore, simulations[2] indicate that a quantum efficiency of ~80% at 250 eV can be achieved by optimizing the quality of the entrance window process.[3]



(a) (b)

Figure 1. (a) Schematic cross section of a JUNGFRAU pixel with X-ray entrance window at the back of the sensor. (b) Quantum efficiency as a function of photon energy for sensors with different entrance window processes. Sensors with a thin entrance window (red triangles) are used for the JUNGFRAU system at Maloja (see section 3).

[1] An in-depth discussion of JUNGFRAU 1.1 exceeds the scope of this paper.
[2] Simulations are based on Synopsys TCAD. Details will be provided in a separate publication.
[3] FBK proprietary. Characterization results of prototypes will be addressed in a future publication.

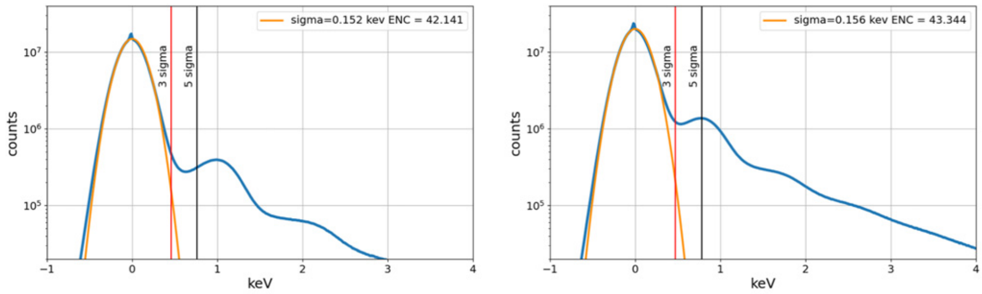
2022 JINST 17 C09027

3 First use case with low-energy X-rays

The first JUNGFRAU system that targets soft X-rays was installed at the experimental station Maloja in 2021. Maloja is part of the SwissFEL low-energy branch Athos [11]. It aims at atomic, molecular and non-linear X-ray physics and chemical dynamics. The JUNGFRAU detector at Maloja contains eight modules, which provide four megapixels in total. The modules operate version 1.1 of the readout chip and use standard sensors with a thin entrance window (figure 1(b), red triangles). The energy response of each pixel of the system was calibrated with a standardized procedure [12]. The procedure uses fluorescence photons from a secondary copper target (characteristic K_α line at 8 keV) to achieve an absolute calibration in high gain. The relative gain ratios in medium and low gain are determined using voltage pulses to the sensor backplane and an internal current source on the chip. This procedure corrects for pixel-level gain variations, about 2% for the system at Maloja.

The system was commissioned using X-ray forward scattering on xenon clusters. The detector was mounted at 34 cm distance to a pulsed supersonic gas jet emitting xenon clusters with radii of ~16 nm, and scattering images of the X-ray beam were recorded with 5 µs integration time per frame. 1000 frames were accumulated into one image. The measurement was repeated with X-ray energies of 1 keV, 800 eV, 600 eV, and 500 eV. All data analysis was performed for a contiguous subset of 730 × 490 pixels close to the center of the detector system. The subset contained a total of 134 (<0.4‰) faulty pixels, including pixels with faulty gain switching. This ratio can be considered representative for the full detector system.

The cumulative energy spectra across the subset of pixels (figure 2), corrected for pixel-level gain variations as described above, were analyzed to determine the energy resolution capabilities of the detector system. A Gaussian fit to the noise pedestal yields a standard deviation $\sigma \sim 150$ eV, which corresponds to ~43 electrons ENC. We attribute the broadening of the noise peak compared to separate measurements of JUNGFRAU 1.1 modules, which yielded 34 electrons ENC, to the complexity of the four-megapixel Maloja system. At 1 keV, the single-photon peak is separated from the noise by $\sim 5\sigma$ (figure 2(a)). The signal of 800 eV photons is separated by $\sim 3\sigma$ (figure 2(b)). For energies below 800 eV, single-photon signals cannot be distinguished reliably from the noise. With high photon intensities and for experiments that do not require single-photon resolution, however, the JUNGFRAU system can be applied at energies below 800 eV using multi-photon signals.



(a) (b)

Figure 2. Gain-corrected energy spectrum of 1000 images across all pixels in high gain at different photon energies, taken with the four-megapixel JUNGFRAU system at Maloja. (a) 1 keV. (b) 800 eV.

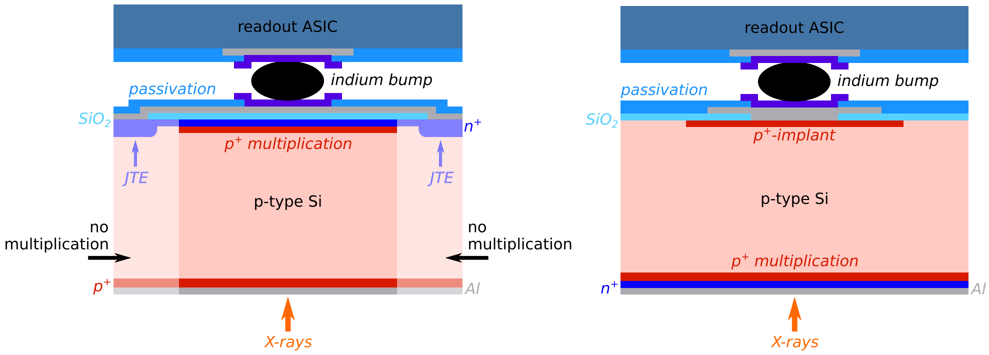
4 Combining JUNGFRAU with LGAD sensors

To push single-photon resolution to energies below 800 eV, either the detector noise must be reduced or the photon signal must be amplified above the noise threshold. In case of a hybrid detector, the capacitance introduced by the bonds between sensor and readout chip contributes significantly to the detector noise. Any means of amplification at the chip level must consider this noise contribution. Signal amplification at the sensor level would circumvent this issue.

LGAD sensors [13] intrinsically multiply the charge created by a photon hit by a factor of 5–20. A combination of the low-noise JUNGFRAU readout chip and an LGAD sensor would therefore improve the detector performance at low photon energies. A gain of 10, for instance, would shift the signal of a 250 eV photon to effectively 2.5 keV, which is well separated from the detector noise. The increase of resolution, however, reduces the dynamic range of the detector by the same multiplication factor. A gain of 5–10 would facilitate single photon resolution down to 250 eV while maintaining a dynamic range of $\sim 10^4$ photons at 2 keV.

Andrä et al. [14] have demonstrated the feasibility of using hybrid LGADs for low-energy X-ray detection and noted two critical points that require optimization: the sensor fill-factor and the quantum efficiency at low energies. In contrast to a standard LGAD design (figure 3(a)), an inverted design (iLGAD [15], figure 3(b)) would extend the multiplication region across the full sensor volume and is expected to achieve a fill-factor close to 1. To optimize the quantum efficiency of iLGADs, the design of the entrance window and the multiplication layer will need to be studied carefully. Prototypes featuring optimized thin entrance windows (see figure 1(b), green curve) and variations of the multiplication layer were included in a wafer run fabricated by FBK. They will be available for tests at the beginning of 2022.

2022 JINST 17 C09027



(a) (b)

Figure 3. (a) Schematic cross section of an LGAD pixel with junction-termination-extensions (JTE). (b) Inverted LGAD (iLGAD) design. Dimensions not to scale.

5 Conclusions

We have reported on the first application of the JUNGFRAU detector with soft X-rays at the SwissFEL end station Maloja. The system resolves single photons down to 800 eV. The low noise of the JUNGFRAU readout chip promotes the combination with LGAD sensors to extend the energy range to 250 eV. On the way to a hybrid LGAD for low-energy X-ray detection, quantum efficiency and sensor fill-factor will need to be optimized. We will perform tests on LGAD sensors with an inverted design and address results in future publications.

Acknowledgments

We acknowledge our collaborators at Fondazione Bruno Kessler (FBK, Trento, Italy), in particular, G. Borghi, M. Boscardin, M. Centis Vignali, F. Ficorella, G. Paternoster, and S. Ronchin. This project has received funding from the European Union's Horizon 2020 Research and Innovation Program under the Marie Skłodovska-Curie Grant Agreement No. 884104 (PSI-FELLOW-III-3i).

References

[1] A. Guinier, *X-Ray Diffraction in Crystals, Imperfect Crystals, and Amorphous Bodies*, Dover Publications Inc. (1994).

[2] W.H. Zachariasen, *Theory of X-Ray Diffraction in Crystals*, Dover Publications Inc. (2004).

[3] J. Fink et al., *Resonant elastic soft X-ray scattering*, *Rep. Prog. Phys.* **76** (2013) 056502.

[4] D. Liebscher et al., *On the influence of crystal size and wavelength on native SAD phasing*, *Acta Crystallogr. D* **72** (2016) 728.

[5] B. Henrich et al., *PILATUS: a single photon counting pixel detector for X-ray applications*, *Nucl. Instrum. Meth. A* **601** (2009) 247.

[6] A. Bergamaschi et al., *The MYTHEN detector for X-ray powder diffraction experiments at the Swiss Light Source*, *J. Synchrotron Radiat.* **17** (2010) 653.

2022 JINST 17 C09027

[7] B. Henrich et al., *The adaptive gain integrating pixel detector AGIPD a detector for the European XFEL*, *Nucl. Instrum. Meth. A* **633** (2011) S11.

[8] G. Blaj et al., *Performance of ePix10K, a high dynamic range, gain auto-ranging pixel detector for FELs*, *AIP Conf. Proc.* **2054** (2019) 060062.

[9] A. Mozzanica et al., *Characterization results of the JUNGFRAU full scale readout ASIC*, 2016 *JINST* **11** C02047.

[10] F. Leonarski et al., *Fast and accurate data collection for macromolecular crystallography using the JUNGFRAU detector*, *Nat. Methods* **15** (2018) 799.

[11] R. Abela et al., *The SwissFEL soft X-ray free-electron laser beamline: Athos*, *J. Synchrotron Radiat.* **26** (2019) 1073.

[12] S. Redford et al., *First full dynamic range scan of the JUNGFRAU detector performed at an XFEL with an accurate intensity reference*, 2020 *JINST* **15** C02025.

[13] G. Pellegrini et al., *Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications*, *Nucl. Instrum. Meth. A* **765** (2014) 12.

[14] M. Andrä et al., *Development of low-energy X-ray detectors using LGAD sensors*, *J. Synchrotron Radiat.* **26** (2019) 1226.

[15] M. Carulla et al., *Technology developments and first measurements on inverse Low Gain Avalanche Detector (iLGAD) for high energy physics applications*, 2016 *JINST* **11** C12039.

2022 JINST 17 C09027