

UFERI - Ultra-Fast Energy Resolved Imager for Next Generation Synchrotron Experiments

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Abstract—A new single photon-counting ASIC prototype called UFERI (Ultra-Fast Energy Resolved Imager) with a matrix of 42×42 pixels of $75 \mu\text{m}$ pitch is developed by the Detector Group of the SOLEIL synchrotron and the Microelectronics Group from AGH University of Krakow, in preparation for the upcoming upgrade of the SOLEIL synchrotron to a fourth-generation facility. The detector is dedicated to pseudo-Laue diffraction applications in intense, pink beams at photon energies between 5 to 30 keV. With its three thresholds and very small offset spread from pixel to pixel of about 1.1 mV, UFERI can discriminate three energy levels while its short dead time ensures a high count rate capability of up to 6 Mcounts/s/pix (10% count rate loss). To keep both, a low noise and a high count rate operation, a front-end amplifier's feedback capacitor discharge technique is implemented on-chip, enabling high-speed chip operation with an Equivalent Noise Charge (ENC) of 86 e- rms. The UFERI chip can operate with detector signals of both polarities (holes and electrons) and consumes $42 \mu\text{W}/\text{pixel}$. In this publication, we present a description of the ASIC's architecture as well as characterisation results. The energy calibration, threshold dispersion, gain spread, as well as noise and count rate performance of the UFERI prototype are presented.

Index Terms—X-ray imaging, high count rate, low-noise, single photon counting SPC, hybrid pixel detector, capacitance discharge technique, front-end electronics, charge sensitive amplifier CSA.

I. INTRODUCTION

SYNCHROTRONS with very high-brightness photon beams play a crucial role in material science and biology experiments. Nowadays many facilities prepare the new upgraded storage rings, which require a new generation of fast detectors [1]. After two decades of operation, the SOLEIL synchrotron facility also embarks on an upgrade project, the SOLEIL II [2], that will significantly push its performance boundaries. The new facility will offer beam with increased brilliance, coherence, and flux. This will provide a broad range of existing and new techniques for users' communities, allowing them to address challenges in advanced materials and

health. Among these applications, pseudo-Laue diffraction [3], including serial crystallography, and in vivo crystallography will strongly benefit from the enhanced source. However, this poses new demanding challenges for detectors. To perform pseudo-Laue diffraction with a multi-pink beam, a detector must cover an energy range of 5-30 keV with the capability of simultaneous measurements of photons at different energies with a resolution ≤ 2 keV. The detector must also handle a very high photon flux, which can exceed 10^{10} photons/s/mm² on the detector surface, to record data before the radiation damage to the sample sets in, which is particularly important for the biological applications. Additionally, to measure both low and high intensity signals simultaneously, an excellent signal-to-noise ratio over the whole dynamic range is essential.

As to the authors' best knowledge, currently there is no Single Photon Counting (SPC) detector which unites the above requirements of multiple thresholds, a very good energy resolution and the ability to handle very high photon flux at the same time. To address these challenges, the SOLEIL Detector Group and the Microelectronics Group from the AGH University of Krakow have started the development of a new photon counting readout ASIC prototype, named UFERI (Ultra-Fast Energy Resolved Imager) [4]. Usually, the design of SPC detectors is developed in two different directions:

- low noise of the front-end readout electronics to make it possible to distinguish and count input photons of different energies, however at the cost of relatively slow signal processing [5]
- or high speed of the front-end readout electronics to make possible detector operation with high photon fluxes, but at relatively high noise of the readout systems [6]–[8].

In the UFERI design, we combine both, low noise and fast digitally assisted signal processing of the front-end readout electronics at the same time. This combination will help UFERI to improve the trade-off between noise and speed performance to meet the requirements for pseudo-Laue diffraction experiments. UFERI's architecture details with a description of the readout front-end electronics are presented in Section II. Section III provides the measurement results considering offset correction, energy calibration, and noise in terms of count rate performance, including tests at the METROLOGIE beamline [9]. The conclusions are summarised in Section IV.

II. UFERI IC ARCHITECTURE

The chip core consists of a matrix of 42×42 square-shaped pixels with a pitch of $75 \mu\text{m}$ (see Fig. 1), which makes it

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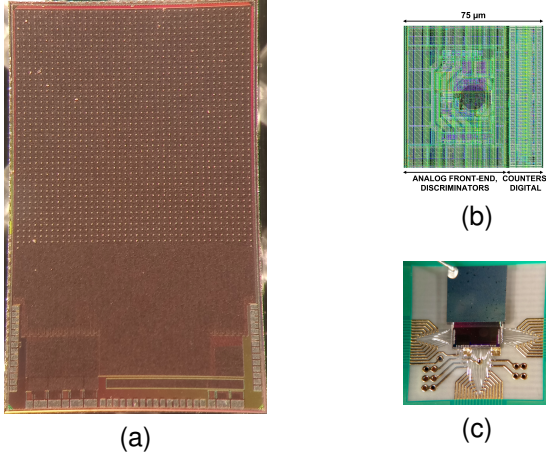


Fig. 1. UFERI IC: a) photo, b) single pixel layout, c) photo of the IC bump-bonded to a Si pixel sensor.

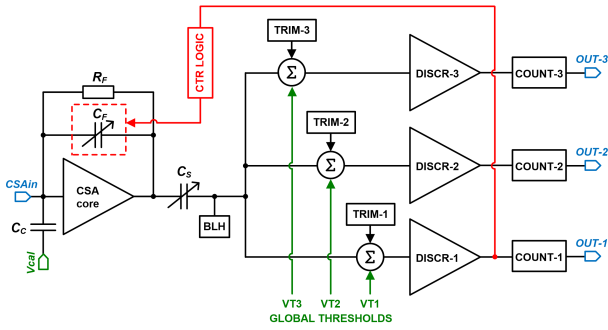


Fig. 2. Simplified block diagram of a single readout pixel.

suitable for most diffraction experiments. The peripheral area, located at the bottom part of the chip, contains a bandgap reference source, biasing DACs, I/O control logic, LVDS drivers and receivers, and wire-bonding pads. Each pixel operates in the SPC mode with three independent thresholds (three discriminators and three counters) and allows to process sensor signals of both polarities (holes and electrons). The chip is produced in 40 nm CMOS technology.

A. Scheme of the pixel readout channel

The simplified pixel readout channel block diagram is shown in Fig. 2. The single pixel contains analog and digital parts. The analog part consists of:

- Charge Sensitive Amplifier (CSA) with gain control (set by the CSA feedback capacitor C_F value) and the R_F block for the capacitor C_F discharge,
- Base Line Holder (BLH) to mitigate the problem of DC baseline shift while working with high frequencies of input pulses,
- Threshold Setting blocks with offset trimming DACs to reduce the mismatch effects,
- three discriminators (DISCR_x) with three independent energy thresholds capable of operating with input pulses of both polarities.

When an X-ray photon hits the sensor, it generates a charge, and a current pulse is induced at the CSA input. This current

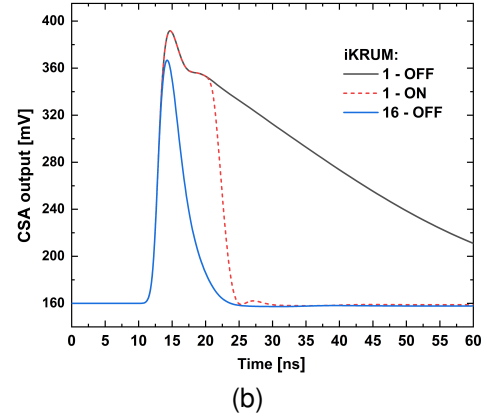
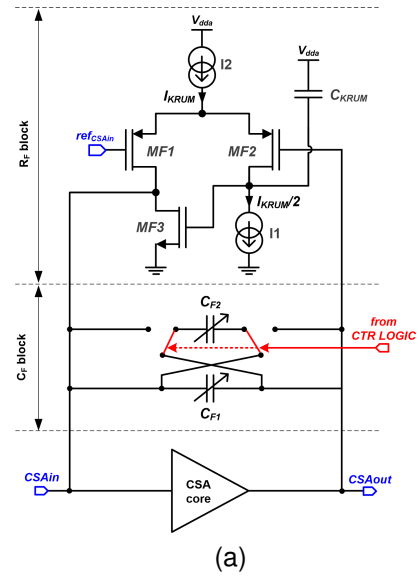


Fig. 3. CSA feedback: a) simplified scheme, b) CSA output pulses for different modes of the capacitor C_F discharge.

pulse charges the CSA feedback capacitor C_F and the CSA output voltage pulse (proportional to the photon energy) goes through the AC-coupled BLH stage to the discriminators' inputs. When the pulse amplitude crosses the set threshold at a given discriminator, its counter is incremented. Then, the CSA feedback capacitor C_F should be discharged as fast as possible, to be ready for the next X-ray photon hit.

B. CSA operating modes

Having in mind the two opposing requirements of fast signal processing and low noise operation, UFERI's design focuses on a fast core and a fast discharge process. Considering the CSA feedback capacitance C_F discharge process, the CSA can operate in two different modes depending on the effective resistance of the CSA discharge block:

- standard ultra-fast signal processing mode as a transimpedance amplifier [6],
- low noise operation mode with digitally assisted capacitor C_F discharge technique [5]

The CSA discharge block is based on the Krummenacher structure [10] and digitally controlled by the 5-bit I_{KRUM} DAC (Fig. 3a). In the transimpedance mode, the effective

resistance R_F of the CSA feedback discharge block is about $0.6 \text{ M}\Omega$, which results in the fast discharge of the C_F capacitor with an output pulse time width t_w of about 12 ns (see Fig. 3b, case $I_{KRUM} = 16$ - OFF). However, compared to the low noise mode with slow capacitor C_F discharge, the CSA output pulse amplitude is lower and noise contribution from the CSA feedback discharge block is significant [6]. In the low noise operation mode, the effective CSA feedback resistance is set very high (about $0.5 \text{ G}\Omega$), hence its contribution to the noise is negligible, but at the cost of prohibitively long capacitor C_F discharge time (see Fig. 3b, case $I_{KRUM} = 1$ - OFF). To solve this problem, we used the capacitor C_F active discharge technique. The capacitor C_F is split into two parts (C_{F1} and C_{F2} - see Fig. 3a), and when the output pulse crosses the threshold set in DISCR1, the connections of the C_{F2} capacitor plates are exchanged, which allows to shorten the CSA output pulse to tens of ns while keeping low noise operation at the same time (see Fig. 3b, case $I_{KRUM} = 1$ - ON). This technique was proposed in [5] for very low noise operation of the LNPIX chip, but relatively slow CSA operation was achieved (below 1 Mcounts/s/pix). In the UFERI chip, this technique has been adapted and effectively extends this limit several times up to 6 Mcounts/s/pix.

The CSA output signal is directed to AC-coupled three independently working discriminators, whose thresholds are set globally by three 10-bit DACs. Due to mismatch effects, the effective threshold level can significantly vary from pixel to pixel. To reduce the offset spread at the discriminators' inputs, each discriminator is equipped with a 6-bit trimming DAC with an independent 1-bit control range [11] and additionally, the gain of each pixel can be fine tuned with a 4-bit correction DAC. The pixel's digital part contains three 24-bit ripple counters, registers, and control logic. The counters in the pixels can operate in three different modes:

- normal mode with configurable counter length (12-bit, 4-bit, 2-bit, 1-bit),
- long counter mode with 24-bit counters,
- zero-dead time mode with configurable counter length.

In the zero-dead time mode, all three counters in the pixels are divided into two 12-bit halves. The corresponding discriminators' signals are connected to both of their increment inputs. In this mode, one half is always in the count mode, while the other one is in the shift mode (data is read out of this counter's part). During the data readout phase, the counters in each column form a shift register. The data from each column is loaded, bit by bit, into the peripheral fast 42-bit register and shifted out of the UFERI IC via LVDS links.

III. MEASUREMENTS

The presented tests were performed with the UFERI IC bump bonded to a silicon pixel detector with a pitch of $75 \text{ }\mu\text{m}$, a thickness of $320 \text{ }\mu\text{m}$, and biased up to 200 V (see Fig. 1c). During the measurements, the discriminators and the CSA were powered in nominal power consumption mode implying $42 \text{ }\mu\text{W}$ per pixel.

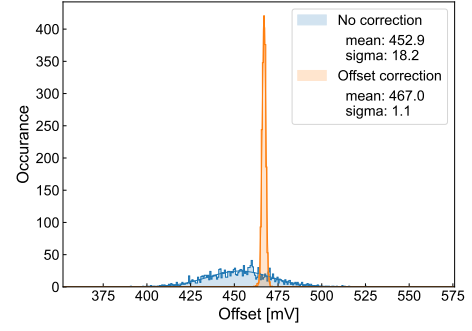


Fig. 4. Offset spread before (blue) and after (orange) the correction.

TABLE I
GAIN, ENC AND FWHM AS FUNCTION OF I_{KRUM} SETTINGS

I_{KRUM} [LSB]	Gain [mV/keV]	ENC [e- rms] with test pulses	FWHM [eV] @ 9 keV X-rays
0	7.68	69	725
1	7.42	86	991
8	7.17	100	1127
16	6.27	113	1269
24	6.14	126	1394

A. Offset and gain trimming, noise measurements

To compensate the mismatch of the offset between pixels, the effective thresholds of the discriminators were adjusted with the help of the corresponding 6-bit trimming DACs. Thereby, the offset spread among pixels is reduced from $\sigma = 18.2 \text{ mV}$ down to $\sigma = 1.1 \text{ mV}$ after correction (see Fig. 4).

The measurement with test injection pulses (by the use of the capacitor C_C - see Fig. 2) allows for checking the gain trimming functionality. The values of the capacitors C_F and C_S can be controlled in each pixel independently, which enables the reduction of the threshold dispersion from pixel to pixel from 5% (sigma/mean) before trimming to 1.5% after trimming. The measured Equivalent Noise Charge (ENC) strongly depends on the effective CSA feedback resistance R_F value set by the I_{KRUM} current (see Fig. 3a). For the small value of the I_{KRUM} current of the order of hundred pA (slow discharge of the CSA feedback capacitance C_F) the ENC = 69 e- rms, while for the high value of the I_{KRUM} current of the order of hundreds nA (fast discharge of the CSA feedback capacitance and fast signal processing) the ENC increases up to 126 e- rms (see Tab. I).

B. Energy calibration and FWHM

To relate the internal threshold DAC units to photon energy and determine the detector's response to X-rays, threshold scans were conducted with X-rays of different energies (ranging from 7 to 14 keV) at the METROLOGIE beamline [9] of the SOLEIL synchrotron. Examples of the obtained differential X-ray spectra are shown in Fig. 5a. The threshold scans were acquired for different values of the CSA feedback resistance R_F (i.e. I_{KRUM}) and the results of the energy calibrations are shown in Fig. 5b. The measured gain ranges from 7.7 to

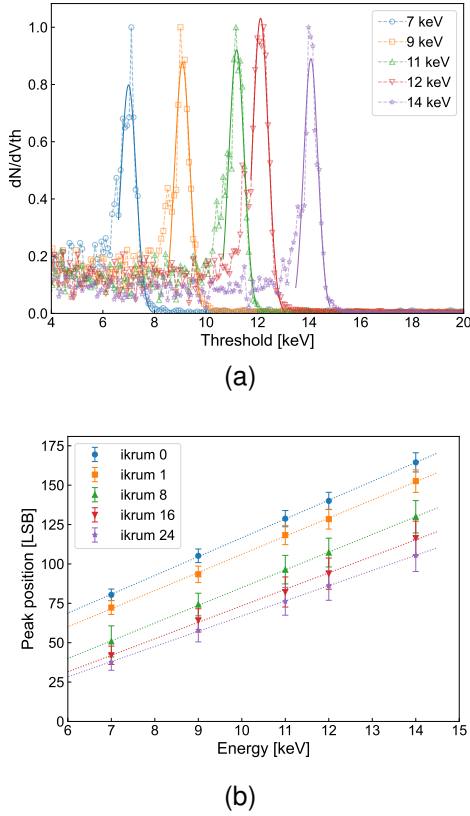


Fig. 5. a) Differential spectra for several X-ray energies for $I_{KRUM} = 0$, b) Energy calibrations for different values of I_{KRUM} .

6.1 mV/keV, while the energy resolution FWHM at 9 keV is in the range of 725 to 1394 eV, respectively, depending on the I_{KRUM} current. The summary of the gain calibration and energy resolution (FWHM) of our detector system is summarised in Tab. I. It is evident, that from the good energy resolution point of view, the best settings are with $I_{KRUM} = 0$ or 1, however in these cases, the very long time constant in the CSA feedback limits the count rate performance of the readout channel. This issue is addressed in the next section.

C. Count rate measurements in transimpedance mode

To estimate the ASIC's count rate performance, rate measurements were performed in the direct 12 keV X-ray beam at the METROLOGIE beamline. For photon flux intensity control, aluminium foils of different thicknesses were inserted into the beam, while a photo-diode provided the reference current for the effective incoming photon flux estimation. During rate measurements, an area of 18×18 pixels was illuminated and for the analysis the observed number of counts at a threshold level corresponding to half of the beam energy was taken into account. The measurements were taken for three different values of I_{KRUM} setting equal to 8, 16, and 24. The highest I_{KRUM} value means the shortest CSA output pulse width (corresponding to the best count rate performance as shown in Fig. 6), however at the cost of an increase of the ENC (see Tab. I). The resulting curves of the mean observed counts N_{obs} compared to the incoming photons N_{in} are fitted

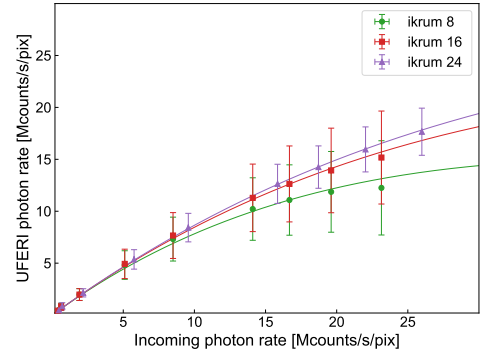


Fig. 6. Count rate performance for three different settings of I_{KRUM} . The best count rate performance is reached for $I_{KRUM} = 24$ with a dead time $\tau = 14.5 \pm 0.2$ ns.

with the paralyseable counter model [12]:

$$N_{obs} = N_{in} \cdot e^{-N_{in} \cdot \tau} \quad (1)$$

to determine the dead time τ of the processing channels. With $I_{KRUM} = 24$ the estimated dead time $\tau = 14.5 \pm 0.2$ ns, which corresponds to a count rate capability of 7.2 Mcounts/s/pix with a 10% count rate loss due to pile-up or 24.5 Mcounts/s/pix at 30% loss. These results are competitive to other recent developments, like e.g., SPHERD [7] featuring a dead time of 22.8 ns in standard SPC mode and 16.9 ns with the first-order pile-up compensation (VDIS1) method. Even though the UFERI's three thresholds are dedicated to the discrimination of different energies in a pink beam, in the case of a monochromatic beam, they can serve to boost the count rate performance. The proposed count rate correction techniques in [7], [13], [14] show that in the case of a monochromatic X-ray beam, it is possible to further improve the count rate capability of the UFERI IC by exploiting pile-up tracking with the two remaining thresholds.

D. Count rate measurements in low noise operation mode

Thanks to the low noise operation mode with digitally assisted capacitor C_F discharge technique ON, the ENC can be kept as low as 69 e- rms (for $I_{KRUM} = 0$ with calibration pulses) while reaching a count rate of 1.4 Mcounts/s/pix (10% count rate loss), compared to a maximum count rate of 0.7 Mcounts/s/pix in the standard signal processing mode for discharge technique OFF. Fig. 7 presents the full threshold scans taken at discriminator output with this method ON (dashed lines) and OFF (continuous lines) for different photon fluxes. In the standard case (discharge OFF), the effects of pulse pile-ups for high photon flux result in a loss of counts for the threshold set below the pulse amplitude, and an increase of counts for the threshold set above the pulse amplitude. This effect is significantly reduced with the discharge technique ON. For the case with $I_{KRUM} = 1$ the ENC is equal 86 e- rms, while the C_F discharge technique allows to reach a count rate of 6 Mcounts/s/pix (10% count rate loss), which is an important improvement in the typical trade-off between noise and speed performance.

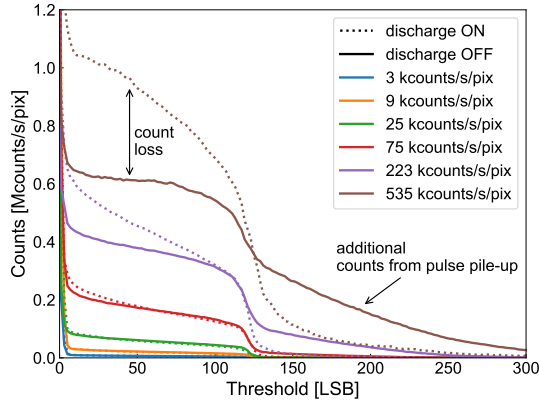


Fig. 7. Set of threshold scans in low noise operation mode with digitally assisted capacitor C_F discharge technique (ON, dashed lines) and standard signal processing mode (OFF, continuous lines) for different incoming photon fluxes (low flux in blue until high flux in brown).

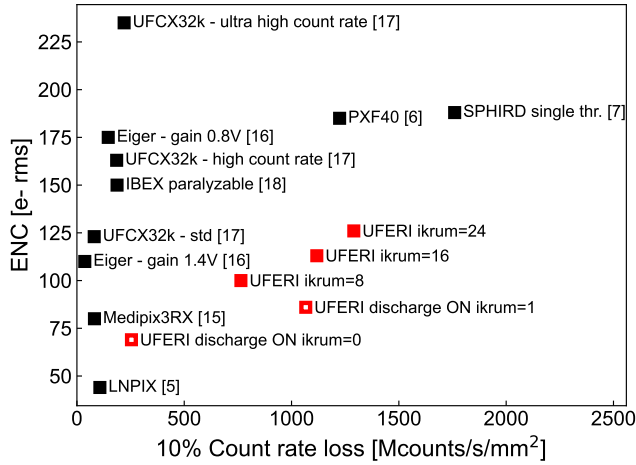


Fig. 8. Comparison of ENC vs 10% count rate loss for single-photon counting pixel readout chips with pixel pitch in the range from 50 to 100 μm . Reproduced from [7]-Table II.

IV. CONCLUSIONS

A prototype UFERI readout chip with a single photon counting architecture and three precisely trimmed discriminators per pixel was presented in this paper. The main achievement of this work is a good quality trade-off between low ENC value and very fast signal processing. By combining a digitally assisted CSA feedback capacitance C_F discharge technique with a modified Krummenacher circuit dedicated to low noise operation we proved the possibility of circuit operation up to 6 Mcounts/s/pix (10% count rate loss) with a noise level of only 86 e- rms, which is pushing the current limits compared to other state-of-the-art circuits (see Fig. 8 for a comparison). With its combination of good energy resolution and fast signal processing, the UFERI chip is a promising candidate for a future photon-counting detector dedicated to ‘pseudo’ Laue diffraction experiments in a pink beam and high photon flux environment at new generation of synchrotrons.

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