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Digital integration: a novel readout concept for XIDER, an X-ray detector for the next generation of synchrotron radiation sources

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Abstract: This paper introduces the incremental digital integration concept, a novel readout scheme for the front-end of 2D pixelated X-ray detectors. The readout scheme includes features found in both current photon-counting and charge-integrating devices and is particularly suitable for detectors that need to operate with very high photon flux, under strong pileup conditions, and have to provide high sensitivity with noise-free effective operation. The core concept of this scheme is to slice the total exposure time required to acquire a given image in very short time intervals of the order of one microsecond or less that we call subframes. The detector signal is integrated for each subframe in the analog domain and digitised individually at the pixel level. This scheme allows to identify and discard those values for which the measured signal is only built from dark current or noise contributions. The final pixel value is then obtained in the digital domain by summing up the values of the non-discarded subframes. In the proposed scheme all this signal processing happens at pixel level in the detector front end.

Reaching high dynamic range is not the only advantage of this method, digital integration offers the possibility of continuous cancellation of the dark current contributions even if they are not stable or fluctuate in time. This opens the possibility of building integrating detectors able to operate at high duty cycles, including continuous beam, with high-Z compound semiconductor sensors, a major challenge for the upcoming synchrotron radiation sources such as the ESRF Extremely Brilliant Source (EBS) currently under advanced construction that will become the first fourth-generation high-energy synchrotron facility worldwide. The XIDER detector, the first implementation of the incremental digital integration scheme, is planned to be a very fast and versatile high dynamic range detector optimised for high energy scattering and diffraction applications at ESRF-EBS and future similar facilities.

Keywords: Electronic detector readout concepts (solid-state); Hybrid detectors; X-ray diffraction detectors

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Contents

1 Introduction

New accelerator concepts and progress in magnet technology are bringing to reality a new generation of X-ray synchrotron radiation sources worldwide of unprecedented brightness and coherence [1]. The advent of these forthcoming 4$^{\text{th}}$ generation storage rings such as the ESRF Extremely Brilliant Source (EBS) compels to rethink the instrumentation that is used nowadays in these facilities. In the case of ESRF-EBS, the increase of source brilliance combined with more efficient optics is expected to provide two to three orders of magnitude more intense beams to the sample in certain experiments [2]. In particular, this will be the case for most of the diffraction and scattering beamlines. In this context building new fast and high dynamic range hard X-ray detectors that surpass the capabilities of current instruments is a crucial matter to fully exploit the new sources [3].

Photon counting hybrid pixel technology is the state-of-the-art for X-ray 2D detection in diffraction and scattering experiments at storage rings. Nevertheless, current detectors cannot operate with fluxes above few millions of photons per second per pixel due to limitations that are inherent to the photon counting readout. This limitation has been investigated with alternative readout schemes [4] and in the last decade has been addressed by developing specialised charge integrating front ends to build fast diffraction detectors for free-electron lasers (FELs) [5]–[7]. These detectors can cope with very intense X-ray pulses but are not well suited to fulfil two requirements that are crucial for applications at high energy storage rings: operation at nearly 100% duty cycle with continuous beams (deadtime free), and detection of photons of high energy up to 100 keV. Indeed, an important aspect to be considered is the proper management of the leakage current from the high-Z sensors that are required to achieve acceptable detection efficiency. Available sensors based on high-Z materials, such as CdTe or GaAs, present leakage values that are high or not stable, depending also on the contact technology employed for their fabrication. Moreover, some results [8] and unpublished observations, show that the sensor leakage currents are irradiation dependent, particularly when subjected to high photon fluxes, and therefore not easy to cancel or compensate for. Although this aspect may not be relevant for measurements of very short X-ray

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pulses at FELs, it might be critical for experiments requiring longer exposure times and deadtime free operation at storage rings.

This paper proposes a readout strategy for the front end of 2D integrating hybrid pixel detectors for the new generation of storage rings that can combine high dynamic range, high duty cycle operation and can operate with non-constant leakage currents from high-Z compound semiconductor sensors.

2 Incremental digital integration

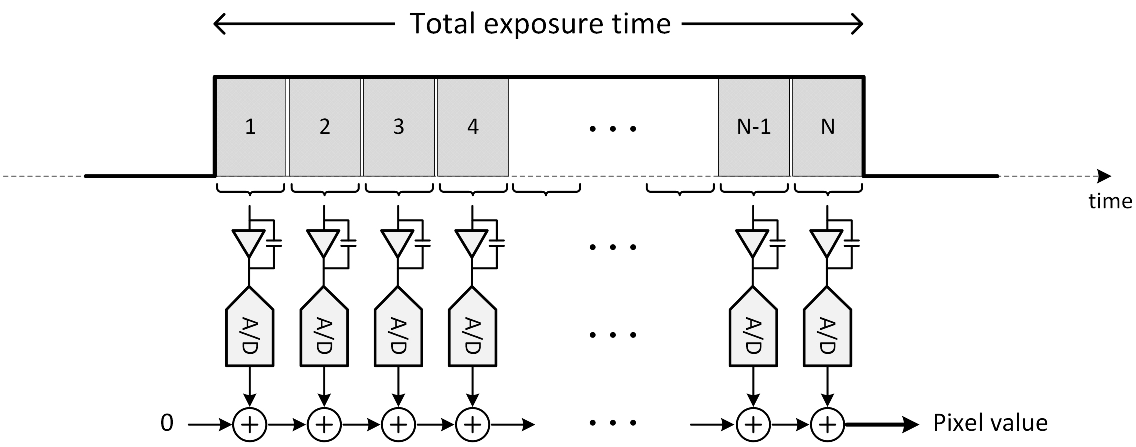

Figure 1. Basic principle of the incremental digital integration scheme: the input signal is integrated in N subsequent intervals (subframes), the result of each subframe integration is digitized and the digital values are summed sequentially to produce the final pixel value.

The incremental digital integration detection, or digital integration in a shorter form, is a readout scheme based on a concept that is relatively straightforward when compared with the conventional charge integrating approach: instead of integrating the detected signal during the total desired exposure time at once in the analog domain, the exposure interval is sliced in a certain number N of shorter intervals of identical duration that we call subframes. The detected signal is integrated separately for each subframe and digitised individually. Finally, the total measurement is obtained in the digital domain by adding all the N subframe values as it is depicted in figure 1. In practice, the process should happen sequentially at the detector front end, treating all subframes one after the other as time progresses. In that scheme, the values obtained after integrating and digitising each of the individual subframes can also be summed during the same sequential process by adding them into a digital accumulator.

In a general case, splitting a single measurement in N partial operations and summing the results is not a favourable strategy as any systematic error in the individual measurements is also multiplied by N and any uncorrelated noise builds up as $\sqrt{N}$. However, in the case of X-rays, as for any other particle detection, it is possible to take advantage of the quantum nature of the input signal, the detected particles, and revert the situation by applying discrimination and quantisation methods. These are the methods that are implicitly subjacent in photon counting detection and that

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make possible the implementation of instruments that operate noise-free (by noise discrimination) and that do not accumulate systematic residual errors (by signal quantisation).

Incremental digital integration detection can only present advantages if it operates with monoenergetic photons and if the digitising stage is properly configured to match the amplitude of the incident X-rays and to be used as a signal discriminator. In that case the detector mimics the characteristics of photon counting devices at low photon fluxes at the same time that it is able to provide high dynamic range and high flux operation, as conventional charge integrating detectors do. Other functional aspects, advantages and limitations of digital integration are further discussed in section 2.3 below.

2.1 Partial charge collection

As the digital integration method relies deeply on signal quantisation, the fact that not all the charge produced by each single X-ray photon is fully collected and integrated in the corresponding pixel and within the same subframe interval is one of the issues that may affect the quality of the data produced by the detector. Partial charge collection may happen both in the spatial domain (charge sharing) and in the time domain (incomplete integration).

Charge sharing between adjacent pixels is a well-known effect that in the case of photon counting hybrid detectors reduces detection efficiency, but it does not impact sufficiently the measurements to invalidate their successful application in synchrotron experiments. The implications for the digital integration readout have to be fully assessed but, given its characteristics and the fact that at low flux it can be functionally reduced to a photon counting scheme, we do not expect that spatial charge sharing will be a major obstacle to the successful implementation of this new method in a large number of scientific applications.

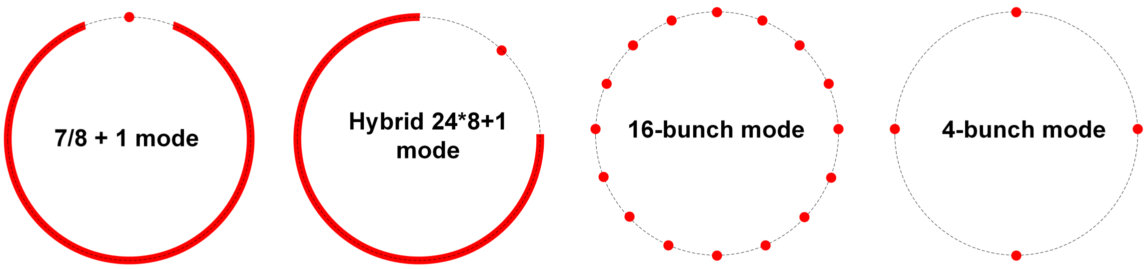

Figure 2. Electron filling patterns most frequently used at ESRF. The distribution of the electrons in the storage ring is indicated in red. The time structure of the produced X-rays matches the distribution of the electrons circulating at relativistic speed with an orbit period of 2.82 μs. Red dots represent single bunches and continuous lines sequences of contiguous electron bunches separated by only one radiofrequency cycle (2.82 ns).

The case of incomplete charge integration in time has to be considered differently. It depends on several independent factors such as the width of the signal pulses delivered by the sensors for each incident X-ray, the dynamic response of the analog integrator and the duration of the subframe intervals. It may be a severe difficulty that hampers the implementation of digital integration readouts with very short subframes, an approach that otherwise offers potential advantages as it is discussed in section 2.3. Fortunately, in the case of synchrotron radiation sources, most of the facilities operate with photon beams that are not continuous in time but present a time structure

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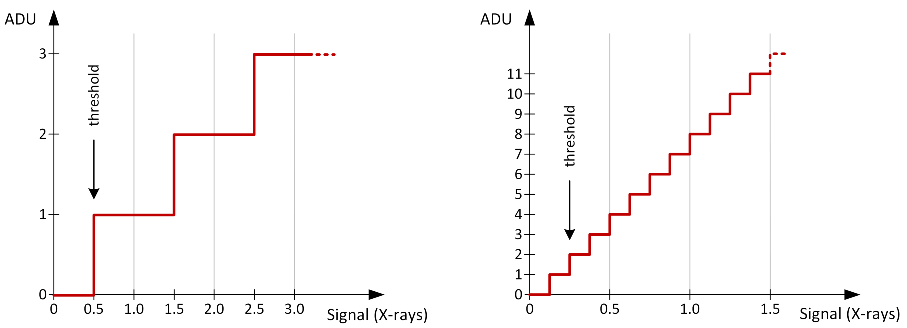
with gaps as it is illustrated in figure 2 for the case of ESRF. This circumstance is very beneficial for the implementation of digital incremental detectors as the time related effects can be minimised by operating the detector synchronously with the temporal pattern of the X-ray beams.

2.2 Subframe discrimination and signal quantisation

The simplest and most straightforward implementation of a convenient digitiser for a digital integrating front end is an analog-to-digital converter (ADC) with a mid-riser transfer function in which the amplitude of the conversion bin has been adjusted to match the signal corresponding to one X-ray photon. In this case, that is illustrated in figure 3a, the converter works implicitly as a discriminator: if the signal integrated during a subframe interval is smaller than 50% of the average signal produced by a single X-ray, the digital value is set to zero and the subframe is effectively discarded as it does not contribute to the accumulated signal. In this approach the quantisation interval, one X-ray photon, is the maximum possible value that can be implemented while preserving the single photon sensitivity of the detector. Implementing the largest quantisation interval is in general a convenient strategy as it helps to reject more efficiently undesired noise and leakage current contributions and because it minimises the resolution of the ADC, i.e. the number of bits, that is required to cover a certain measurement range.



(a) (b)

Figure 3. a) Transfer function of an ADC with mid-riser response and conversion bin matching one X-ray photon. b) Example of an ADC with a conversion bin set to one eight of one X-ray photon. In this case the transfer function is mid-tread and the discrimination level is assumed to be set to 2 ADU.

Nevertheless, implementing a quantisation interval that is smaller than a single X-ray photon may be useful in certain cases to account for partial charge collection. This approach reduces the effectiveness of the quantisation process to reject undesired contributions and requires a higher resolution ADC to cover the same measurement range. However, if the undesired contributions (noise, leakage, offsets) are sufficiently small, a finer digitisation may help to produce better quality data. Figure 3b presents as example the transfer function of an ADC with a conversion interval of one eight of an X-ray photon. In this case, if the front end implementation is configured for instance to set the discriminator threshold at 25% of one X-ray, it will require dedicated logic to discard and do not accumulate digital values below 2 ADUs.

2.3 Functional advantages and limitations

As introduced above, the key aspect of the proposed readout scheme is the potential ability to suppress the contribution of the leakage current from the sensor even if it drifts or fluctuates in time in a non-predictable manner. This phenomenon has been observed in all X-ray compound semiconductor detector materials when subjected to strong non constant irradiation conditions. That undesired contribution can be suppressed if the charge resulting from the integration of the leakage signal in each pixel during one subframe interval is small compared to the quantisation of the analog to digital converter. This implies that the leakage contribution in one subframe must be smaller than a fraction of the total charge produced by a single X-ray photon, which favours the implementation of digital integration readout with subframes as short as it can be possible.

Short subframes not only allow to work with high leakage sensors. As the maximum measurable value per exposure interval is N times the value achievable in each subframe, using short intervals facilitates reaching high effective dynamic range with ADCs of low or modest resolution. For instance, by using subframe intervals of the order or less than of one microsecond and ADCs with more than 4-bit resolution, it is possible to operate an incremental digital integration front end with continuous photon fluxes reaching up to few tens to more than a thousand Mcps. Those fluxes are substantially higher than the photon rates per pixel that are accessible to current photon counting systems for synchrotron experiments.

This type of front end can also operate with pulsed X-ray beams but in that case each pulse must be measured during a single subframe and the dynamic range is strictly limited by the resolution of the integrated ADC. This limitation makes incremental digital integration detection not particularly well adapted for applications at free-electron lasers but it may be very well suited for time resolved experiments with single-bunch pulses at storage rings where the intensities per pulse are much lower than for FELs.

The digital integration scheme inherently supresses electronic noise in a similar way that it does with the leakage current contribution; if the analog readout noise in each subframe is lower than the conversion interval of the ADC, noise can be totally suppressed by quantisation at low photon flux. This is analogous to noise discrimination in photon counting systems. At higher photon fluxes, when several X-rays are measured on average per subframe, both noise and leakage components become negligible with respect to the photon statistical fluctuations (Poisson noise) and in that condition they do not degrade the measurements.

In practical implementations digital integration front-ends will need to include trimming circuitry to correct for dispersion between pixels and to adjust the discrimination thresholds and internal conversion factors, usually setting the size and position of the ADC bins, to match the energy of the X-ray photons. It will be therefore necessary to go through elaborated calibration procedures as with any other pixel detector. However, if the front-ends are properly trimmed, the detector should be able to produce noise-free digital data very much as photon counting detectors actually do. In order to reach maximum quality, the data will need some additional treatment, such as flat field corrections, to compensate for detection efficiency variations due to sensor inhomogeneity or modulations of the entrance window transmission for instance. Those imperfections impact the signal that the readout electronics actually sees and cannot be corrected by front-end trimming. They will need data post-processing either online, in the readout electronics for instance, or offline. Anyhow,

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if the sensor quality is sufficiently good, the raw images produced by a properly trimmed digital integrating detector front-end should be very close to final and will not need systematic sophisticated processing as it is the case today with all 2D charge integrating pixel detectors. This aspect is particularly important for very high data throughput applications that require low latency on-line data analysis or on-the-fly data reduction. Implementing thorough image construction or calibration corrections in those cases can be extremely challenging and very computing resource consuming.

The capability of producing digital data at the pixel level has a number of additional advantages. It allows simple and efficient in-chip data storage and faster data readout. It also opens the door to the implementation of rich functionalities in the digital domain that can be tailored to particular experimental requirements.

From the previous considerations it can be derived that the incremental digital integration readout is particularly well adapted to X-ray applications with very high intensity beams at synchrotrons. However, to our knowledge there are no existing 2D detectors using this readout principle and the previous claim is exclusively based on the intrinsic features of the method and on some results of calculations and simple model simulations. The predicted features and potential issues introduced in this paper have still to be validated and further investigated with more complete simulations and real detector prototypes. This is the first objective of the XIDER project in which several matters will require particular attention. One of those matters is the investigation of the sensitivity of the produced data to offsets, drifts and other inaccuracies in the front-end electronics. It must be noted that any systematic error in the subframe acquisition that is not cancelled by the digitisation and discrimination process will be accumulated during the incremental integration phase.

Other important aspects to be investigated are the potential artefacts coming from the incomplete collection of the charge produced by the incident radiation. However, as discussed in section 2.1, this matter is not expected to be a major issue that will preclude the successful use of these detectors.

3 The XIDER detector

The XIDER project is the first implementation of the incremental digital integration readout scheme introduced in this paper. The project aims not only to explore this new concept when applied to high energy X-ray detectors but to build a fully operational instrument suitable to properly exploit the higher fluxes that will be available at ESRF-EBS and other similar new generation synchrotron radiation storage rings.

The project is at its early stages and a number of design specifications for the final detector are still open. The detector however will be optimised to operate at high X-ray energies with compound semiconductor sensors and one of the key objectives is to build an instrument able to operate with continuous photon fluxes of up to 10^9 photons per second per pixel, three orders of magnitude more than what currently used photon counting detectors can cope with. The detector is also expected to be able to operate with pulsed beams at 5.68 MHz, the repetition rate of the ESRF storage ring in 16-bunch filling mode. We believe that the incremental digital integration approach is the most suitable readout scheme to achieve the challenging goals of XIDER. The final implementation will require a front-end operating with subframe repetition as short as 176 ns, including the preamplifier reset time, and implementing digital conversion with 8 bits per subframe at the maximum sampling rate.

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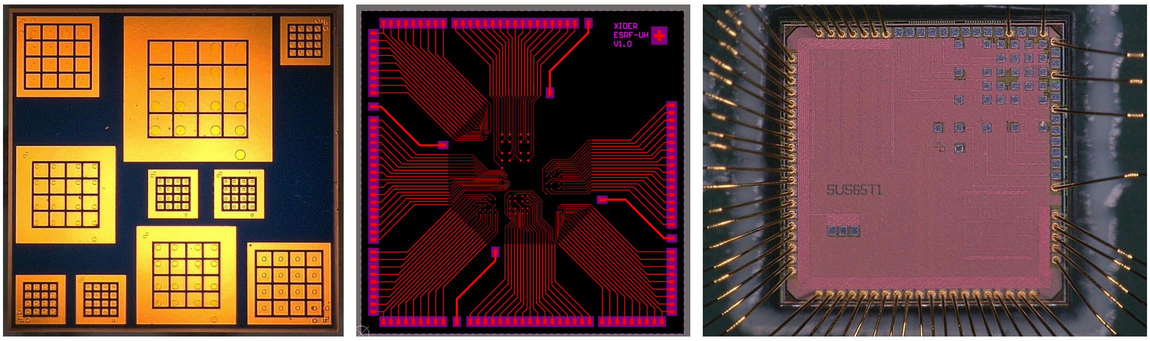
Another important objective of the project is to implement a versatile detector with various configuration options and different operations modes so that it can be adapted and optimised for a wide range of synchrotron radiation experiments. Enhancing the functional versatility will be possible thanks to the intrinsically digital readout and the possibility of producing trimmed calibrated data at the detector front-end. One of the features that we foresee to speed up the detector readout and increase the frame rate is to enlarge the effective pixel size by grouping pixels in 2×2 clusters in a way similar to the binning modes frequently found in CCDs for instance. Other non-usual operation modes such as special accumulation modes for time resolved experiments or advanced trigger schemes (e.g. post-triggering) will be possible by implementing in-chip image storage.



(a) (b) (c)

Figure 4. Components of the first XIDER test prototypes. The CdTe sensors (a) include several 4×4 pixel matrices with three different pixel pitches (100, 200 and 300 µm) that can be connected either via a silicon interposer (b) or by direct bump bonding onto the test readout ASIC (c).

We are building the first test prototypes with 4×4 pixel CdTe sensors to validate the readout concept and to explore various implementation options. The first readout ASIC has been designed in CMOS 65 nm technology. The main components of the first test systems are shown in figure 4. We plan to use a silicon interposer to connect the sensor and the readout chip to overcome severe difficulties in directly interconnection and to evaluate different pixel sizes with the same components. The target pixel pitch for XIDER is 100 µm but we plan to investigate 200 and 300 µm pitch configurations. The difficulties for direct hybridisation are consequence of the very small sizes of the test dies and the need of using low temperature bonding processes to avoid damaging the CdTe sensor.

4 Summary and outlook

The incremental digital integration scheme introduced in this work has been proposed to address the difficulties found with conventional charge integrating hybrid detectors built with compound semiconductor sensors, particularly when operating with high-flux high-energy X-ray beams. We expect to supress the harmful effects of the high and irradiation dependent leakage current observed in sensor materials such as CdTe by this novel readout scheme. The method relies on signal discrimination and quantisation methods that reproduces up to a certain extent features intrinsically found in photon counting devices that are being successfully used since decades. Another important advantage of the digital integration method is that it splits the overall signal collection and conversion

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process in two steps: a first analog integration of the input signal followed by a digital accumulation phase. This scheme reduces considerably the resolution requirements of the analog-to-digital converter and eases the possibility of implementing fast and high dynamic range front ends with digital readout that are suitable to deal with both pulsed and continuous X-ray illumination.

The XIDER project is a collaboration between ESRF and the University of Heidelberg that aims to build the first full detector based on the digital integration readout scheme. The first stage of the project has already started with the design of small scale test prototypes. It focuses on two main directions: the validation of the readout concept and the identification of suitable technologies and functional blocks that could be integrated in the final detector design. The objective is to validate and explore the range of applicability of the digital integration scheme with CdTe sensors that is the best candidate material today for applications with photon energies up to 100 keV. CdTe is also the material that presents leakage currents with the most unstable and irradiation dependent behaviour and, therefore, it is the most suitable to investigate the strengths and weaknesses of the method. Improvements in the quality of CdTe or the future availability of other promising materials with lower or more stable leakage current, such as CdZnTe, will extend or simplify the applicability of the digital integration readout scheme. Although the leakage current related effects have to be investigated with physical prototypes, we have also set up a simulation chain that we will use to complete the study, in particular to investigate the impact of partial charge collection. Simulation will be an important tool to get a better insight of the various physical effects, disentangle them and estimate their relative contribution in a way that will complement the experimental results.

The design of the readout ASIC for the XIDER detector will have to combine the specific features of the incremental digital integration readout with the functionality required to build a versatile instrument that can be tailored to a wide diversity of X-ray diffraction and scattering applications. The final detector specifications have still to be worked out based on the results of the study recently initiated but they will be compatible with the specificities of ESRF-EBS such as the timing and the filling patterns of the storage ring. Even though, it is expected that XIDER will be a suitable detector for experiments at other synchrotron radiation facilities with high flux continuous beams that will require devices surpassing the capabilities of existing photon counting detectors.

Acknowledgments

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