DINPAD: Digital-integration front-end for high dynamic range pixel area detectors

Paolo Busca,[1*] Marin Collonge,[1] Pablo Fajardo,[1*] Peter Fisher,[2] Marie Ruat,[1] David Schimansky[2]

[1] European Synchrotron Radiation Facility, 71 Avenue des Martyrs, 38000 Grenoble, France
[2] Institut für Technische Informatik der Universität Heidelberg, Im Neuenheimer Feld 368, 69120 Heidelberg, Germany

*Corresponding author: paolo.busca@esrf.fr, fajardo@esrf.fr

ABSTRACT

This paper introduces the incremental digital integration concept, an innovative detection scheme specifically designed for the forthcoming generation of synchrotron radiation sources under construction worldwide. This scheme combines features of both photon-counting and charge-integrating techniques, and it is particularly suitable for X-ray detectors that need to operate with very high photon fluxes, under strong pileup conditions, and have to provide high sensitivity with noise-free effective operation. The digital integration front-end can be concretely exploited to develop very fast and high dynamic range 2D pixelated X-ray detectors optimised for high energy scattering and diffraction applications, helping researchers to address global societal challenges and allow companies to develop a large range of innovative products.

Keywords: Hybrid detectors, X-ray diffraction detectors, Analogue electronic circuits, Electronic detector readout concepts (solid-state), Frontend electronics for detector readout.

1. INTRODUCTION

A new generation of X-ray synchrotron radiation sources of unprecedented brightness and coherence are under construction worldwide thanks to new accelerator concepts and progress in magnet technology [1]. The advent of the 4th generation storage rings will open up new frontiers for research opportunities, but at the same time will set serious limitations to some of the instrumentation routinely used in these facilities. In the case of the ESRF Extremely Brilliant Source (EBS), the first 4th generation high-energy synchrotron facility worldwide, 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].

The DINPAD project explores a new readout strategy, the incremental digital integration, for the development of 2D hybrid pixel detector for high-energy and time-resolved experiments. DINPAD targets a leap in performance with respect to the current state of the art, featuring:

- operation with continuous photon fluxes of up to 10^9 photons per second per pixel, three orders of magnitude more than photon counting detectors;
- the advantages of photon counting systems, such as single photon sensitivity in noise-free operation, readout dead time free and digital data;
- compatibility with both continuous and pulsed beams, with a maximum repetition rate of 5.68 MHz;
- operation at hard X-ray energies (20÷100 keV energy range) with compound semiconductor sensors;
- high throughput and frame rate to allow time-resolved experiments (up to 100 kframes/s);

The ATTRACT initiative has supported work for further progress and validation of the incremental digital integration readout concept in two main directions. First, for the simulation, design and test of first ASIC prototypes realized in TSMSC 65 nm technology to highlight the functionalities and limitations of the readout scheme. And second, in the development of small-scale test structures with 4×4 pixels CdTe sensors coupled to ASICs to perform a full characterization an evaluation of the systems.

2. STATE OF THE ART

Hybrid pixel detectors operating either in photon-counting or in charge-integration mode are today the state-of-the-art for most of the synchrotron radiation experiments requiring large area 2D X-ray detectors.

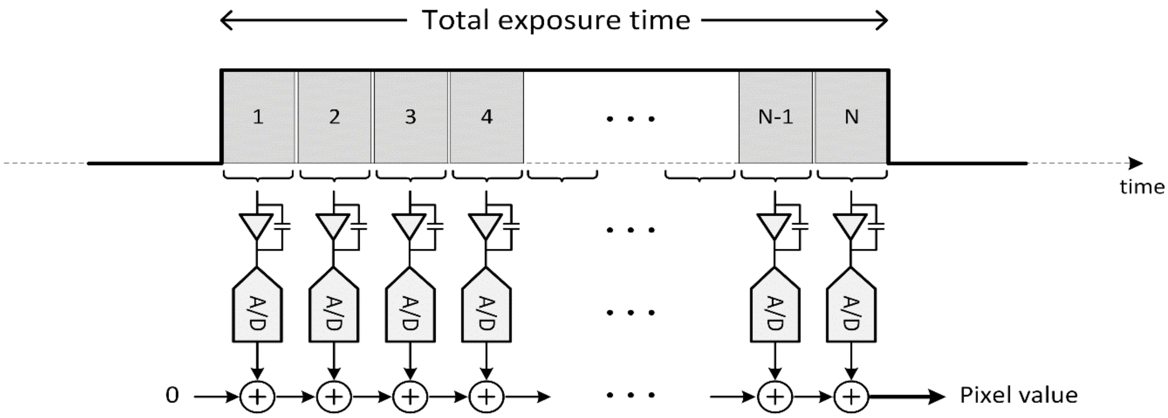

Fig. 1. Basic principle of the incremental digital integration scheme: the input signal is integrated in N subsequent intervals (subframes), the result of each subframe integration is digitized and the digital values are summed sequentially to produce the final pixel value.

Photon-counting detectors can provide single-photon sensitivity, noise-free data with an inherent digital readout and they are relatively simple to use. However, in most cases they suffer from signal sharing effects between pixels and are only suitable for low photon fluxes, of up to about one million photons per second and per pixel.

On the other hand, charge-integration detectors are not limited by photon pile-up, manage properly charge-sharing effects and can cope with photon fluxes that are orders of magnitude higher, only limited in terms of total integrated signal by the dynamic range of their analogue front-end. The front-end dynamic range can be extended by including stages with variable signal gain. They also provide single photon sensitivity, but only if they integrate over exposure time windows sufficiently short to prevent that the integration of the sensor dark current spoils the measurement, a major issue for hard X-ray detectors using compound semiconductor sensors. One of the direct consequences is that many of the detectors do not operate well in applications requiring continuous illumination and very high operation duty cycle close to 100%. Another of the drawbacks found with current charge-integrating pixel detector front-ends is their fundamentally analogue characteristic that severely limits the functionality and the signal processing capabilities that can be embedded and fully parallelised in the front-end circuitry itself.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The incremental digital integration is a readout scheme based on a concept that is relatively straightforward when compared with the conventional charge integrating approach [4]. Instead of integrating the detected signal during the total desired exposure time at once in the analogue 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 Fig. 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.

The digital integration scheme inherently supresses electronic noise in a similar way that it does with the leakage current contribution; if the analogue 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.

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.

4. PROJECT RESULTS

We present here a first implementation of the incremental digital integration readout scheme. The readout ASIC has been designed in TSMC 65 nm technology. The readout is based on a pipelined two-stage charge removal circuit, each stage is composed by three main blocks: a charge sensitive amplifier (CSA), a comparator and a charge pump (CP). A simplified scheme is shown in Fig. 2.

The first stage of the pipeline is designed to achieve high dynamic range whereas the second stage provides single photon sensitivity. Both stages have the same working principle: the generated charge is integrated by the CSA in the feedback capacitor, the corresponding output voltage is compared to a threshold and, when overcome, a charge pump is activated to subtract a well-defined charge packet from the input node. Finally, an associated counter is increased to provide output digital data. Thanks to this approach, the ADC conversion is performed on the fly while the CSA continues its integration.

In the first stage, both the threshold and the charge pump package are set to a value equivalent to N photons (N=8 for this first implementation). The value could be easily extended to 16 to further increase the dynamic range. The highest possible flux the single stage can handle is limited by the maximum driving frequency of the charge pump. This residual charge is then transferred to the second stage where the same principle is applied, but with a charge packet size to achieve single photon resolution. The typical measurement cycle is shown in Fig. 3.

We are now building small-scale test structures with CdTe sensors coupled to an ASIC to perform a full characterization of the system. The main components are shown in Fig. 4. The CdTe sensors (Acrorad) include several 4×4 pixel matrices with three different pixel pitches (100, 200 and 300 µm). An intermediate silicon interposer is used to connect the sensor to the readout chip to overcome severe difficulties in performing the direct connection between both dies. 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. At the time of writing, the first complete prototypes have been hybridised, fully assembled, and they are in the process of electrical and X-ray characterization.

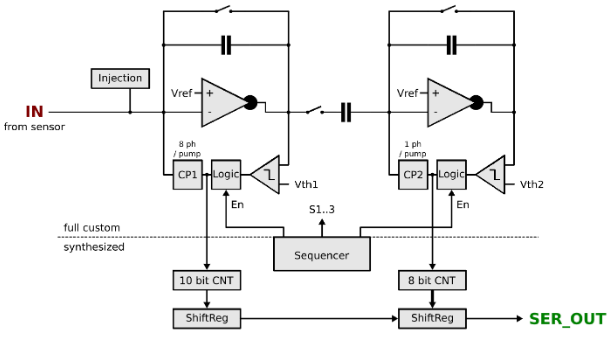

Fig. 2. Schematic overview of a possible implementation of the incremental digital integration scheme.

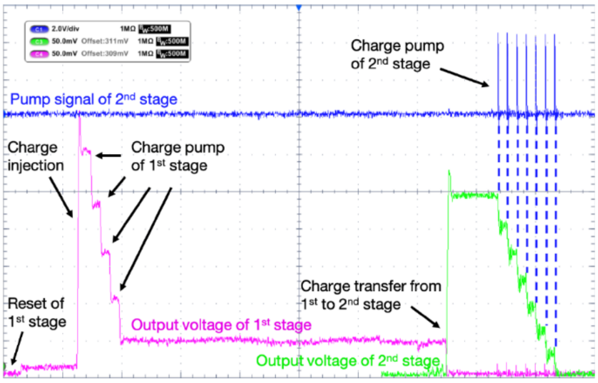

Fig. 3. Measured CSA output signals, monitored with an external oscilloscope.

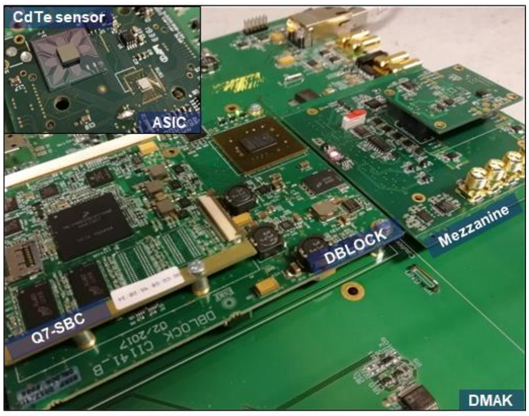

Fig. 4. Characterization setup to validate the digital integration concept with CdTe sensors.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

The first planned implementation of the novel incremental digital integration readout is a full-scale X-ray 2D detector system under the code name XIDER. This development requires several advanced engineering steps that are challenging but that rely on existing and consolidated technologies, particularly in the domain of microelectronics, but also related to efficient cooling and high throughput distributed data acquisition. This will require joining forces with specialized industrial and technology partners with suitable know-how and competences in three key areas:

- advanced interconnection with optimized use of through-silicon vias (TSV) and redistribution layers;
- fast digital data serialization;
- support for high quality Cd(Zn)Te sensors.

5.2. Project Synergies and Outreach

The XIDER detectors will be unique, overcoming limitations of existing instruments, and will become crucial for the proper exploitation of the considerable number of upcoming fourth generation synchrotron X-ray sources. Due to that singularity and boosted by the visibility provided by ATTRACT, we expect that this project will federate the synchrotron community around it. Consequently, we envisage to make the project evolve towards an European and world wide multi-facility initiative, also supported by their corresponding national funding agencies.
Dissemination activities at international conferences, workshops, and in the synchrotron community will continue and will be reinforced by using the social media channels that the ESRF offers to reach a wider audience.

5.3. Technology application and demonstration cases

XIDER, our first implementation of the DINPAD readout, focuses on the optimum exploitation of the extremely brilliant photon beams produced by the next generation of diffraction limited X-ray sources such as ESRF-EBS, that will take a qualitative leap forward in applied and fundamental research and stimulate industrial innovation and cutting edge applications over very wide range of domains. This will require however new detectors with the unprecedented and challenging combination of very high dynamic range, efficiency, readout speed and time resolution capabilities that XIDER can provide. The application fields are extremely diverse and affect a large number of scientific, technological and industrial areas. For illustration, two examples follow:

Laser shock industrial processing and testing of high-value materials

Methods based on laser shocks for material processing (e.g. laser peening [5]) or testing (e.g. spallation, LASAT: laser adhesion testing [6]) are in development to radically improve the properties of critical components in technology sectors such aeronautics or other high-end industries that also rely on advanced metallurgy, complex composite materials and additive manufacturing.

The new high brilliance X-ray sources equipped will high power pulsed lasers open the possibility to study, optimise and further develop these methods to a level not possible so far. This requires to closely follow dynamically the evolution of the shock waves and the associated irreversible structural transformations in the material with diffraction techniques at megahertz rate and a detector, capable of very high time resolution beyond what is achievable today.

Structural determination of large macromolecules, viruses and nanostructures in liquids

While X-ray diffraction techniques are routinely used to determine the molecular structure of large proteins and objects which are either crystalline or can be crystallised, other methods (e.g. SAXS, WAXS) are regularly applied to extract lower resolution information from larger organic and inorganic structures in solution. The brilliant beams of the upcoming X-ray sources will allow to close the gap between those two big families of experimental techniques by means of emerging methods such as fluctuation X-ray scattering (FXS), methods that require a detector like XIDER able to collect long sequences of scattering patterns at very high rates below the rotational diffusion times of the objects under study. These techniques can provide structural details not accessible with traditional X-ray methods and will be a big step forward in the investigation in vitro of viruses, large macromolecules, DNA origami and other objects such as biomedical nanorobots for instance [7-8].

5.4. Technology commercialization

This technology is potentially interesting for companies involved in X-ray detection activities for photon sources but also in fields such as medical imaging, non-destructive testing or X-ray analytical techniques, areas which we will prospect for investors and that expand the impact and application scope beyond science research infrastructures.

5.5. Envisioned risks

The engineering steps required to transform XIDER in a commercial and competitive product for the next decade carry some intrinsic technological challenges. Most of risk related to the XIDER project can be categorized as technological. The most straightforward contingency plan is to envisage solutions able to cope with both advanced and risky approaches and with existing and consolidated choices at the same time.

A typical example as reference could be the use of through-silicon vias combined with high-density compound semiconductors, well known to be delicate materials prone to get damaged when exposed to high temperature processes. A possible response plan could be to design the readout ASIC with pads compatible for TSVs, but also with standard wire bonding interconnection.

5.6. Liaison with Student Teams and Socio-Economic Study

The DINPAD-XIDER project is under development with the joint effort of the European Synchrotron and Heidelberg University. The integration of student teams in our research environment is a common and natural aspect of the project, for example, few MSc and PhD students have already been involved during Phase I. In addition, several persons in the team have already years of demonstrated experience in supervising and guiding students.

Socio-economic studies will be carried out during Phase II thanks to surveys and interviews in the synchrotron community.

6. ACKNOWLEDGEMENT

This project was initiated in the framework of the ESRF Extremely Brilliant Source Upgrade Programme (ESRF-EBS) funded by the ESRF Members and Associated Countries and has received financial support from the ATTRACT project funded by the EC under Grant Agreement 777222.

7. REFERENCES

[1] R. Hettel, 2014, *DLSR design and plans: an international overview*, J. Synchrotron Rad., 21: pp. 843-855.

[2] J. Susini et al., 2014, *New challenges in beamline instrumentation for the ESRF Upgrade Programme Phase II*, J. Synchrotron Rad., 21: pp. 986-995.

[3] P. Denes and B. Schmitt, 2014 *Pixel detectors for diffraction-limited storage rings*, J. Synchrotron Rad., 21: pp. 1006-1010.

[4] P. Fajardo et al., 2020, *Digital Integration: a novel readout concept for XIDER, an X-ray detector for the next generation of synchrotron radiation sources*, JINST, 15: pp. C0140

[5] L. Hackel et al., *2018, Laser peening: A tool for additive manufacturing post-processing*, Additive Manufacturing, 24: pp. 67-75

[6] R. Ecault et al., 2020, *Laser shock adhesion test numerical optimization for composite bonding assessment*, Composite Structures, 247

[7] M. Sevvana et al., 2018, *Refinement and Analysis of the Mature Zika Virus Cryo-EM Structure at 3.1 Å Resolution*, Structure, 26: pp. 1169-1177

[8] B. Esteban-Fernández de Ávila, 2018, *Hybrid biomembrane–functionalized nanorobots for concurrent removal of pathogenic bacteria and toxins*, Medical Robots, 3(18)