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Advanced X-ray PIxel Detector (AXPiDe v2.0): new modular multichannel detector based on SDD available at the XAFS beamline of Elettra

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Abstract. This contribution will report on a detection system specially designed and developed to fulfil the needs of X-ray Absorption Spectroscopy (XAS) experiments at the XAFS beamline of the ELETTRA synchrotron. It is composed of 8 monolithic multipixel arrays of Silicon Drift Detectors (SDDs), each comprising 8 cells (3x3 mm^2) fabricated on 450-μm-thick, n-type, high-purity silicon wafers, and it includes a Tungsten collimation system. This results in 64 independent cells for a total collimated area of 500 mm^2. All arrays are connected to separate back-end electronics, and they are calibrated, aligned and summed together by the acquisition software. The system includes custom-made, ultra-low-noise front-end electronics, a dedicated acquisition system, digital filtering, and temperature control and stabilization. The sensor is optimized to operate in the energy range 3-30 keV. A dedicated acquisition software, Fluorescence Instrumentation Control Universal Software (FICUS), developed using NI LabVIEW and fully integrated with the control system of the beamline, allows the instrument performance to be controlled, fine-tuned and monitored. Accurate characterization performed at room temperature at the XAFS beamline in Elettra demonstrated very interesting results in terms of energy resolution, with a FWHM below 170 eV at the 5.9 keV Mn-Kα line for the sum of all cells, a high count rate capability with an excellent peak-to-background ratio. All these specifications make it possible to collect high-data-quality XAS spectra on diluted elements embedded in heavy matrices, which can be exploited to improve the throughput of the beamline, as well as to follow slow kinetics.

1 Introduction

Over the years, the need to adapt the instrumentation to the capabilities of 3^{rd} generation synchrotron light sources has become increasingly evident, owing to the extreme, unique and ever-changing demands that characterize research using its light as a probe. The beamline detectors are an example where these limitations are most pronounced, and this is true in particular for Silicon Drift Detectors (SDD) [1, 2] used for fluorescence. Among the several spectroscopic techniques available at synchrotrons, X-ray Absorption Spectroscopy (XAS) is a powerful tool for the investigation of the electronic and local structure of matter. Standard measurements are performed in the transmission configuration but fluorescence detection mode is also usually available since it allows the investigation of very diluted system and thin films, or samples too thick to be analyzed using the transmitted beam.

Measurements performed in the fluorescence configuration require the isolation and quantification of the photons emitted by the selected element, i.e. its emission line, with respect to the overall signal generated by the other elements present in the sample under investigation, Figure 3 (right). Silicon Drift Detectors (SDD) are commonly used in the XAS technique because they can be designed to provide an excellent performance balance in terms of high count rate capability (this value depends on the sensor area, for an area of 9 $\text{mm}^2 \geq 100$ kcps), good peak/background ratio ($\geq 10^3$), and energy resolution (≤ 200 eV). Moreover, in order to avoid the introduction of systematic errors due to the processing of the signal it is fundamental to apply properly the correction for the deadtime. Finally, the system needs to be fully integrated with the control system of the beamline, reliable and easily maintainable.

In order to fulfill all these requirements and to develop a state-of-the-art detector for X-ray spectroscopies at synchrotron facilities, it is fundamental to keep the control of all details of the detector from the sensor to the back-end electronics following the whole acquisition chain both from hardware and software point of view. To gather all capabilities and knowledge needed to cover the whole process of development from the design phase up to the final commission at the beamline, a consortium of specialized researchers from Elettra, the Trieste branch of INFN, Politecnico di Milano, and FBK Trento was formed, and here we present the results of its work.

2 The Detector System: AXPiDe v2.0

The instrument, Advanced X-ray PIxel Detector (AXPiDe v2.0), shown schematically in Figure 1, is a modular system consisting of eight planes arranged in an aluminum case. It is composed of 8 rectangular monolithic SDD linear arrays, each carrying 8 cells, for a total of 64 channels reaching a uncollimated sensitive area of 570 mm^2 [3, 4]. The detector operates under a flow of dry N_2 and it is equipped with a 25 μm thick polyamide window coated with 50 nm of Al to protect the sensors from the visible light.

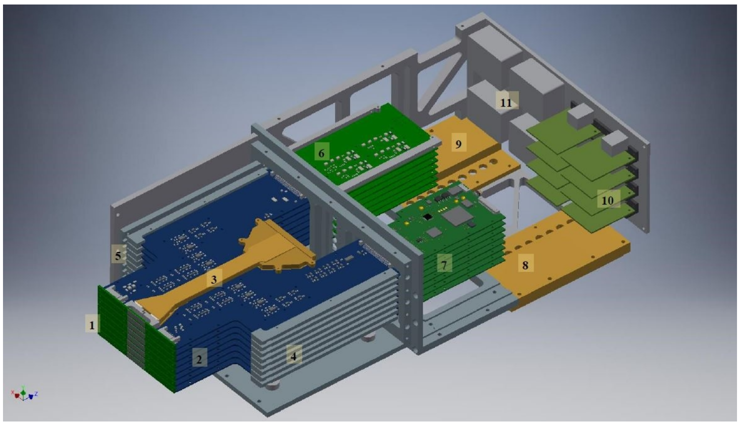


Figure 1: Scheme of the detection system: (1) sensors and Interface Board (IB) equipped with a collimation system, (2) Front-End PCBs, (3) brass profile for liquid cooling, (4) insertion guides at the flanks of the detecting heads, (5) rails for eight detection heads, (6) power supply and filters PCBs, (7) back-end PCBs, (8, 9) cooling distribution inlet and outlet, (10) ethernet PCBs, (11) power supply connectors [3].

AXPiDe is equipped with a cooling system based on Peltier elements and chilled liquid cooling, which serves to guarantee temperature stability across the system.

2.1 Sensor and collimation system

The multichannel modular detection system is composed of 8 independent sensors, each one having a thin entrance window. The sensor, designed by INFN-Trieste and fabricated by FBK (Trento), is a completely depleted volume of n-type, 450 μm thick silicon wafer with a resistivity of 9 kΩcm. It is organized as a linear monolithic array of 8 square SDD cells of 3 $\times$ 3 mm^2 area, providing an uncollimated area of 72 mm^2.

On the sensor front side a shallow uniformly implanted p+ entrance window common to all 8 cells enables good sensitivity down to few hundreds of eV. The back side of each sensor element is an arrangement of decreasingly negative biased p+ rings (drift cathodes). The common bias voltage is applied to the outermost drift cathode that separates the cells. In the center of each cell, there is a small n+ pad (readout anode) surrounded by the innermost cathode, which is kept at the smallest negative potential among the drift electrodes. Voltage dividers, integrated separately for each cell, connect drift cathodes and generate potential drops between them, thus setting up a drift field. The entrance window is biased separately with respect to the sensor backside in order to contribute to the full depletion of the detector bulk, and to ensure an effective charge collection. Outside the sensitive area of the whole array, both on the back and the front sides, several floating p+ rings (guard cathodes) serve to scale down the bias voltage to the ground potential. The sensor features an average leakage current below 100 pA/cm^2 at 20 °C and a capacitance of about 40 fF for each readout anode [3, 4].

In order to eliminate border effects on the signal charge collection, a 127 μm thick tungsten collimator is mounted 80 μm above the entrance window, reducing though the available sensitive area. The total collimated sensitive area of the entire detection system is 500 mm^2, with a 13,2% loss of active area [5].

2.2 Electronics

In the front-end section of each plane, each SDD cell is wire-bonded to the input of a dedicated Charge-Sensitive pre-Amplifier (CSA). The SIRIO-6 generation of CSA used for the AXPiDe detector targets a high resolution at sub-microsecond peaking times, fostering a reduction in the system dead-time, and thus allowing an increase of the overall output count-rate. The SIRIO version for the presented XAFS detection system is characterized by a dynamic range of approximately 250 keV and a conversion gain of $\simeq$ 1.6 mV/keV, and under optimal test conditions can reach an intrinsic equivalent noise charge of 3.2 electrons rms at room temperature [6, 7]. The preamplifiers operate in pulsed reset mode [8] with reset signals and test signals for the CSAs being distributed to all the 8 channels within the same strip. The preamplifiers are diced in triplets, which allows a quick and easy backup replacement in case of malfunctions due to accidental damage during the bonding and mounting process, on a compact total footprint of 1.8 × 0.7 mm^2.

The CSAs are connected to an Interface Board (IB) which provides both signal conditioning and configurable analogue pre-shaping, as well as routing front-end resets, pulser signals and power supplies. The IB is then connected to the back-end (BE) PCB, which hosts an 8-channel, 12-bit ADC and an FPGA responsible for the data processing and the control of the entire plane. The pre-shaped signals are sampled at a rate of 40 MHz and passed through an optimized Finite Impulse Response (FIR) filter of variable length. After the digital processing, the data are transmitted by a dedicated ethernet adapter to a host computer running a software for control and acquisition.

2.3 Software: FICUS (Fluorescence Instrumentation Control Universal Software)

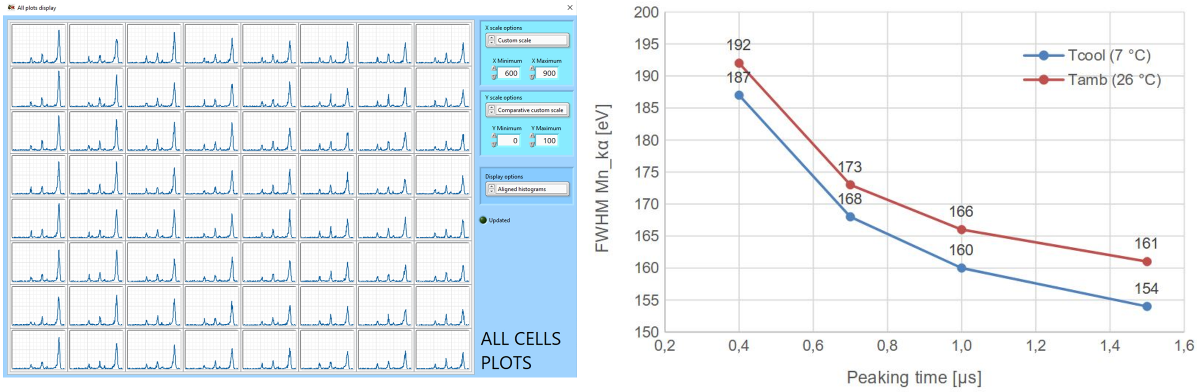
FICUS (Fluorescence Instrumentation Control Universal Software) application is designed to provide a versatile control software for a varied series of SDD-based detector systems. Its main goal is to provide a robust set of presets, adjusted for different operating conditions, such that the detector system is readily fine-tuned and calibrated. Additionally, data come intrinsically corrected against dead time and pileup effects. Acquisitions can be synchronized using an external gate signal to permit the normalization of data against the incoming photon flux. FICUS adjusts its appearance for users, beamline staff or detector experts, thus allowing an effective and reliable operation of the detector system.

3 Performance of AXPiDe v2.0

To characterize AXPiDe, thus verifying its performance, the detector was subjected to laboratory and beamline tests using standard samples. In Figure 2 (left) it is possible to note the uniformity of behavior between the detector cells, whose sum signal is used for the final output spectra. [9, 10]

In Figure 2 (right) the energy resolution (FWHM) for the Mn Kα emission line at 5.9 keV is shown as a function of the peaking time, revealing little difference between the lightly cooled detector (blue line) and room temperature operation (red line), demonstrating the very low noise level associated with the SDD leakage current, and the effectiveness of the temperature stabilization across the system [10, 11].

One of the improvements introduced in the this instrument, AXPiDe v2.0, with respect to its first version [11], is a tungsten (W) collimation system. This allows to improve the peak-to-background ratio (P/B) by a factor of almost 4, and correspondingly boosting the sensitivity of the instrument for samples having very diluted elements, while keeping the large sensitive area offered by the large number of detection elements. Furthermore, by reducing the low energy tail of the peaks caused by charge loss to



All plots display

X scale options: Custom scale
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Y scale options: Comparative custom scale
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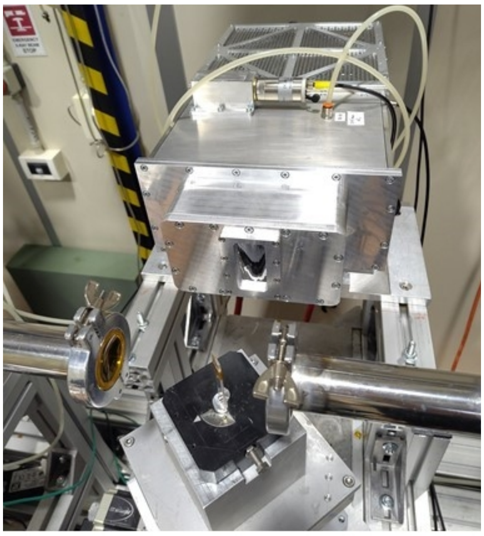
ALL CELLS PLOTS

Figure 2: On the left: Screenshot from the FICUS software: simultaneous live acquisition of the 64 channels with the calibration sample (K, Ti, Mn, Zn, Br, Zr). As one can see, all channels are uniform in characteristics and performance [4]. On the right: energy resolution versus peaking time at room temperature (red line) and for the lightly cooled detector (blue line), with an average sensor temperature of 26 °C and of 7 °C, respectively.

neighboring SDD cells, the collimation somewhat improves the spectral performance, and allows obtaining the performance shown in [5].

4 AXPiDe V2.0 at XAFS Beamline in Elettra Sincrotrone Trieste



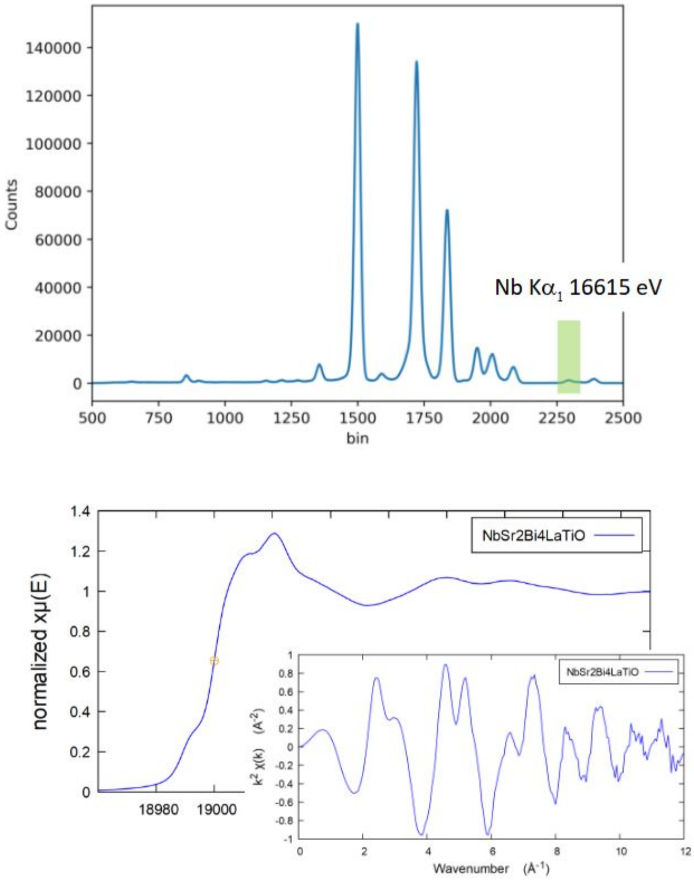


Figure 3: On the left: AXPiDe v2.0 at XAFS Beamline in Elettra. On the top Right: XRF spectrum collected with an incident energy of 19500 eV on Nb doped perovskite. On the bottom right: XANES and EXAFS spectra collected at Nb k-edge (18986 eV).

XAFS is a beamline at the Italian synchrotron ELETTRA located in Trieste. The X-ray source is a bending magnet and the beamline is dedicated to perform XAS in the energy range 2.4 - 25 keV . It can operate in different collection modes using various sample environments and its research activity ranges from fundamental physics to catalysis, form solid state physic to environmental science [12].

AXPiDe is installed at XAFS beamline in the standard configuration with the detector placed 90 degrees with respect to the direct beam, and 45 degrees with respect to the sample, as in Figure 3 (left). The distance between the detector and the sample can be changed according to the needs of the experiments. The detector, as mentioned above, is equipped with a polyamide window: in comparison to a system equipped with a Be window, this solution implies a higher X-ray absorption especially at low energy but, on the other end, it is quite cheap and easy to handle. The fraction of transmitted beam is still acceptable at the energy of Ti-Kα_1 (4512.2 eV) with a fraction of transmitted beam of 88%. But this value decreases rapidly with the energy limiting the useful range of the detector: as an example, at the S k edge the fraction of transmitted beam is only 40% with respect to the 80% of Be window. Lastly, the material and the design of the window mounting mechanism makes the system quite robust and suitable to perform in situ and operando experiments, where the detector could be placed close to the sample environment at high temperature.

5 AXPiDe V2.0: dead time correction

The main limitation for this kind of detector is the relatively long time needed to process the signal, especially at high count rates, leading to dead time and pileup effects that reduce its counting capabilities. The intensity of the signal provides fundamental information related to the system under investigation, like the geometrical configuration and the coordination number (CN) of the absorbing atoms. For this reason, correcting the measurements to account for these effects is of paramount relevance, in the XAS technique, to avoid the introduction of a systematic error in the data, like the underestimation of the coordination number extracted by quantitative analysis on EXAFS data [13].

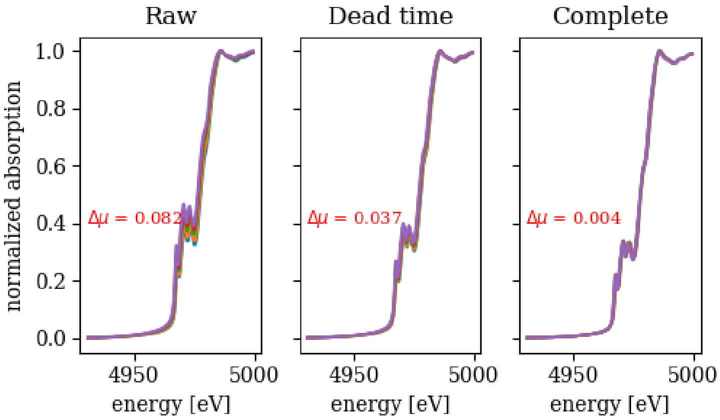


Figure 4: TiO_2 XANES spectra on Ti k-edge (4966 eV) normalized to the white line collected at increasing count rates resulting in a dead time ranging from 10 to 20%. On the left: data not corrected. In the middle: data corrected for count loss due to dead time. On the right: data corrected for both dead time and pileup. In red the intensity difference of the second pre-edge peak is reported.

The dead time correction allows to estimate the total number of events reaching the detector from the count of those that occur during its live time, and it is sufficient when the energy of the photon is not relevant for the measurement. The value of the fluorescence technique in the XAS analysis comes from its ability to single out the photons of the element under analysis from all the others. Event pileup distorts the acquired spectra by shifting to higher values the measured energy of a fraction of the photons due of partial superposition with other events occurring while their signal is processed. This process leads to a count loss in the region of interest (ROI) of the spectra. The pileup correction allows to estimate the total number of events with energy within the ROI that took place in the detector live time from the corresponding counts in the acquired spectrum. As shown in Figure 4, which reports a TiO_2 XANES spectra on Ti k-edge measured by the AXPiDe detector with the faster filter (rise time of 0.7 μs), both dead time and pileup corrections are needed to obtain measurements that do not depend on the counting rate. The normalized spectra shown superimposed in Figure 4 have been acquired at varying SDD cell input rates, ranging from 3÷9 kHz before the edge to 100÷270 kHz at the edge, with maximum dead time that changed from 10% to 20% and a maximum total count rate of almost 9 Mcps. The shape of the spectra differ because of count loss. Because of the normalization, which defines the initial value and that at the edge, a measure of this problem is given by the spread in the intensity of the second pre-edge peak, as reported in the figure.

The AXPiDe detector integrates an algorithm that allows an unbiased correction for both dead time and pileup at any input rate when using filters with rise time higher than 1 μs, and up to at least 100 kHz with the faster filters. The residual error still present in Figure 4 (right) is due to an issue present in the trigger system that will be resolved soon.

6 Conclusions

The AXPiDe detector demonstrates state-of-the-art performance and, after careful characterization tests and optimization, has proven to be a reliable system. It has been installed and is successfully operating at the XAFS beamline of Elettra Sincrotrone Trieste since several months, and is available for users.

Work is under way to complete the optimization of the dead time and pileup correction algorithm that will be validated experimentally.

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