Beatrice PEDRETTI – XXXVIII Cycle

DEVELOPMENT OF A HIGHLY SEGMENTED MONOLITHIC SDD ARRAY AND AN ACTIVE COLLIMATION METHOD FOR HIGH-THROUGHPUT X-RAY SPECTROSCOPY AT SYNCHROTRON FACILITIES
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Abstract:

X-ray fluorescence spectrometers support researchers across a wide range of applications, from materials science and biomedical research to environmental studies and non-invasive analysis of cultural heritage. Many of these applications rely on the intense X-ray beams provided by synchrotron radiation facilities to investigate the fundamental properties of matter and perform elemental analysis of samples. However, as beamtime at synchrotron facilities is a scarce resource, increasing the detection throughput is essential to minimize scan times and maximize experimental efficiency. The continuous evolution of these sources, from advanced thirdgeneration facilities to emerging fourth-generation storage rings, has dramatically increased the available photon flux and brilliance. Consequently, the experimental bottleneck has shifted from photon generation to signal detection, creating a need for energy-dispersive detection systems capable of matching these unprecedented fluxes without saturation. While traditional multichannel detectors constructed from discrete single-element Silicon Drift Detectors (SDDs) are widespread, they suffer from significant dead area between elements. To overcome this, current research is moving toward monolithic detector configurations, which minimize the source-detector distance and maximize solid angle coverage. This dissertation addresses the "detector bottleneck" through a system-level approach within the framework of the ARDESIA project. It focuses on the development of a high-throughput detector based on monolithic SDD arrays, exploring two complementary strategies: optimizing per-channel processing capability and increasing aggregate throughput via high detector segmentation within a compact active area. As for the first strategy, to identify the optimal readout strategy for highly parallelized detector arrays, Chapter 3 establishes the performance boundaries of single-channel readout chains through a systematic evaluation of state-of-the-art Digital Pulse Processors (DPPs). Three distinct architectures were characterized: a commercial trapezoidal shaper, a model-based processor, and a custom firmware solution on an open-FPGA platform. The results quantified the inherent tradeoff between energy resolution and event throughput, demonstrating that while trapezoidal shapers offer superior resolution at moderate rates, model-based processors can withstand extreme fluxes, sustaining output rates exceeding 2 Mcps per channel. Additionally, a novel 20-bit direct preamplifier sampling architecture was characterized, paving the way for high-dynamic-range front-end electronics. The second strategy drives the core contribution of this work: the design, development, and characterization of ARDESIA-64 (Chapter 4), a detection system based on a monolithic 8×8 SDD array designed to quadruple the channel density and aggregate count rate of the previous-generation ARDESIA detector. By implementing 64 channels within the same 24 mm

× 24 mm footprint as its predecessor, the system targets an aggregate throughput exceeding 70 Mcps. Realizing this module required a multidisciplinary design approach to accommodate the high-density array within strictly constrained spatial volumes, without compromising spectroscopic performance. The work details the development of a custom modular architecture for the first ARDESIA-64 demonstrator, which includes low-noise electronic readout, precision mechanical assembly, and thermal management system. These innovations address the critical challenges introduced by scaling, including dense interconnection, channel uniformity, and thermal dissipation. Furthermore, an extensive characterization campaign was conducted on monolithic SDDs arrays of varying thicknesses. The sensors were systematically evaluated across a wide range of operating temperatures to investigate the effect of temperature-dependent noise sources on spectroscopic performance. Experimental validation demonstrated outstanding spectroscopic performance, achieving an average energy resolution of 129.3 eV FWHM at 5.9 keV for a collimated 1 mm-thick sensor and 125.9 eV for a collimated 450 μm-thick sensor. Furthermore, the system exhibited remarkable thermal stability, maintaining sub-140 eV operation for thinner sensor variants even close to room temperature, proving its viability for environments where aggressive cryogenic cooling is not feasible. To fully exploit the benefits of high segmentation, this thesis finally addresses a critical side effect: charge sharing (CS) between adjacent pixels. As pixel pitch decreases, the probability of a single X-ray interaction depositing charge across multiple pixels increases, leading to spectral distortion. Traditional mechanical collimation becomes inefficient in highly segmented geometries, potentially masking up to 36% of the active area in ARDESIA-64 and significantly reducing the detector's collecting power. To overcome this limitation, the active collimation paradigm was introduced in Chapter 5. The dissertation presents CASPER (Charge- Sharing Analysis and Spectroscopic Performance Enhancement via Reconstruction), an algorithmic approach that identifies split events via coincidence timing and rise-time discrimination. Without this correction, partial energy events are effectively lost to the spectral background even in uncollimated setups. By summing the correlated partial signals to reconstruct the full photon energy, CASPER maximizes the effective detection efficiency, recovering events that would otherwise degrade the spectrum. A real-time FPGA proof-of-concept validated the feasibility of this approach for online operation. Furthermore, a machine-learning extension, CASPER-AI, was developed using Decision Tree classification to enhance performance. This machine learning approach significantly improves background suppression and peak-to-tail (PTT) ratio, achieving a 10.2-fold improvement in the PTT while maintaining charge-sharing recovery. In conclusion, this research addresses high-rate limitations by simultaneously combining sensor innovation, optimized readout electronics, and advanced signal processing. The ARDESIA-64 system leverages this multi-disciplinary approach, paving the way for experimental conditions previously limited by detector saturation, allowing for significantly faster X-ray spectroscopy experiments in synchrotron facilities.

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