DEVELOPMENT OF AN MTCA.4-BASED HIGH-SPEED DATA ACQUISITION SYSTEM FOR GAS MONITOR DETECTORS AT S^3FEL*

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Abstract

This paper presents the prototype design of a high-speed data acquisition (DAQ) system for Gas Monitor Detectors (GMDs) at the Shenzhen Superconducting Soft X-ray Free-Electron Laser (S^3FEL), China's first high-repetition-rate soft X-ray FEL facility operating at up to 1 MHz. Six S^3FEL beamlines are each equipped with two orthogonal GMDs (horizontal and vertical configurations) to monitor pulse-by-pulse intensity (0.1 µJ–1 mJ range) and beam position in real time. Building upon custom front-end electronics (including a self-designed low-noise preamplifier and an adapter board with high-voltage filtering), the proposed MTCA.4-based DAQ system integrates AMC digitizer boards with a four-channel 1 GSPS sampling rate and 16-bit resolution ADCs. Key features include dual SFP fiber interfaces (primary for 1 MHz timing synchronization and secondary redundancy), PCIe-based backplane communication for per-pulse intensity data streaming, and EPICS-based slow control via dedicated CPU modules. This work details the DAQ system architecture, signal processing chain, and performance validation strategies for the GMD monitoring platform.

INTRODUCTION

Accurate measurement of absolute photon flux in Free Electron Lasers (FELs) remains a critical challenge for accelerator facilities, as its precision directly determines the reliability of experimental results across ultrafast sciences [1-3]. While conventional radiation detectors (e.g., semiconductor photodiodes, microchannel plates (MCPs), and photomultiplier tubes (PMTs)) have been widely adopted, Gas Monitor Detectors (GMDs) exhibit unique advantages in MHz-repetition-rate FEL environments, particularly for facilities like the Shenzhen Superconducting Soft X-ray FEL (S^3FEL) [4]. As China's first MHz-class superconducting soft X-ray FEL, S^3FEL requires six parallel GMD systems to deliver pulse intensity measurements spanning 0.1 µJ–1 mJ with sub-1% accuracy, sub-micrometer spatial resolution, and MHz-rate detection capability across its beamlines. To address these requirements, we have developed an MTCA.4-based data acquisition (DAQ) system building upon our custom front-end electronics [5], which integrates a self-designed low-noise preamplifier and a high-voltage filtered adapter board. The Advanced Mezzanine Card (AMC) digitizer module features four synchronized channels with 1 GSPS sampling rate and 16-bit vertical resolution. Dual SFP fiber interfaces ensure robust 1 MHz hardware timestamp synchronization from the event timing system [6], while the MTCA.4 backplane enables real-time pulse-by-pulse intensity data streaming via PCIe Gen3. A dedicated CPU blade running the Experimental Physics and Industrial Control System (EPICS) provides comprehensive slow control functionalities, including gain calibration, threshold adjustment, and system monitoring.

This paper is organized as follows: Section 2 details the design of the GMD detector and its front-end signal conditioning chain. Section 3 elaborates on the MTCA.4 DAQ architecture, encompassing both hardware implementation and software integration strategies. Preliminary test results are presented in Section 4, including ADC linearity, event timing jitter analysis, and PCIe throughput test. Finally, Section 5 discusses the roadmap for full-scale beamline deployment and potential applications in other FEL facilities.

DETECTORS

The GMDs at S^3FEL employ a dual-chamber ionization design with high-purity xenon or nitrogen monoxide as the detection medium. Each beamline integrates two orthogonal detector pairs (horizontal and vertical orientations) to enable simultaneous intensity and position monitoring. As illustrated in Fig. 1 and Fig. 2, each detector assembly contains four parallel copper electrodes (two electron-collection plates and two ion-collection plates) housed within a vacuum-sealed ceramic chamber with 30 mm inter-electrode spacing.

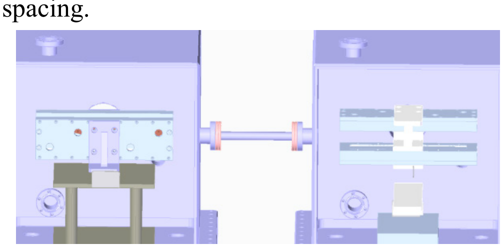

Figure 1: The model of two orthogonal detector pairs.

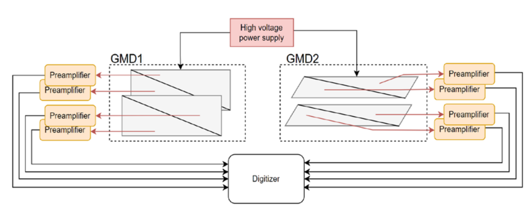

Figure 2: Four parallel copper electrodes and signal readout structure.

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The physical sample of the copper electrodes is shown in Fig. 3. Soft X-ray pulses (1–30 nm wavelength range) ionize the gas medium, generating charge pairs proportional to photon flux. A static electric field of 500 V/cm, supplied through a custom high-voltage adapter board with multi-stage filtering, ensures efficient charge separation while suppressing recombination losses. The front-end signal chain incorporates eight low-noise preamplifiers (one per electrode) featuring 100 MHz bandwidth and low input noise density, enabling precise pulse-by-pulse charge quantification across the full dynamic range (0.1 μJ–1 mJ).

DATA ACQUISITION SYSTEM

The MTCA.4-based DAQ architecture combines high-speed digitization with deterministic real-time processing. As shown in Fig. 4, the core digitization module utilizes an Advanced Mezzanine Card (AMC) equipped with four 16-bit ADCs (ADS54J60) operating at 1 GSPS, synchronized via a common jitter-cleaned clock. Dual SFP+ interfaces ensure robust timing synchronization, receiving 1 MHz trigger signals from the facility-wide event system with <100 ps RMS jitter, while a redundant fiber link enables automatic failover within 10 μs during signal interruptions. The actual AMC board is shown in Fig. 5.

A Xilinx Kintex UltraScale KU060 FPGA implements real-time algorithms for waveform shaping, baseline correction, and intensity/position extraction, streaming processed data through PCIe Gen3 x4 to the MTCA.4 backplane at 3.9 GB/s theoretical throughput. System control is managed through an EPICS-based software framework, with a dedicated CPU blade handling parameter configuration (gain calibration, trigger thresholds) and operational monitoring (temperature, voltage stability).

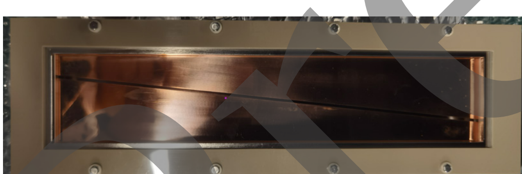

Figure 3: The physical sample of copper electrodes.

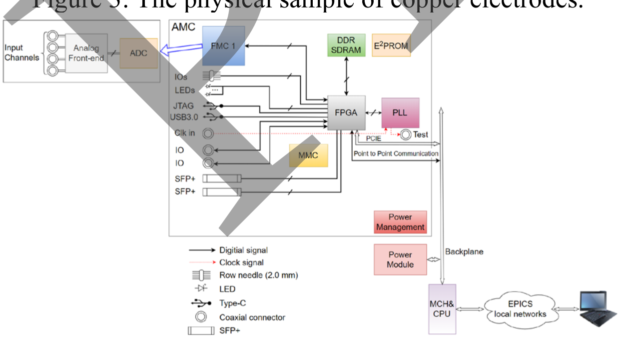

Figure 4: The diagram of the AMC board.

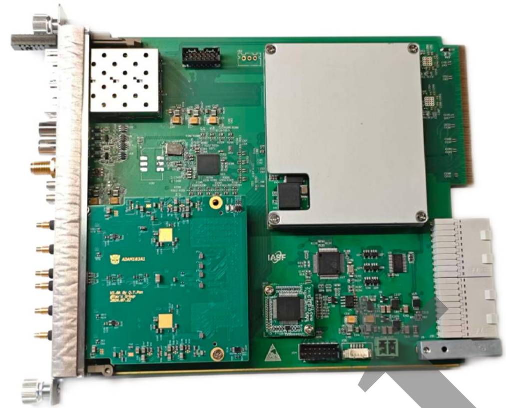

Figure 5: The actual AMC board.

PRELIMINARY EXPERIMENTS

Initial performance validation confirmed critical design specifications. ADC characterization using a calibrated pulse generator demonstrated ±2 LSB integral non-linearity (INL) and ±1.0 LSB differential non-linearity (DNL), achieving an effective number of bits (ENOB) of 10.65±0.01 at 100 MHz input. PCIe throughput tests verified sustained data transfer rates of >650 MB/s under continuous acquisition. Full-chain integration tests are currently underway to validate multi-channel crosstalk suppression and long-term stability.

FUTURE WORK

System deployment will focus on scaling the prototype to 12 GMD stations across S^{3}FEL's six beamlines, incorporating radiation-hardened front-end components for enhanced reliability. Long-term stability tests under 1 MHz simulated conditions will involve continuous operation to assess system reliability.

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