Design and prototyping of the X-ray Fluorescence Spectrometer for online component analysis

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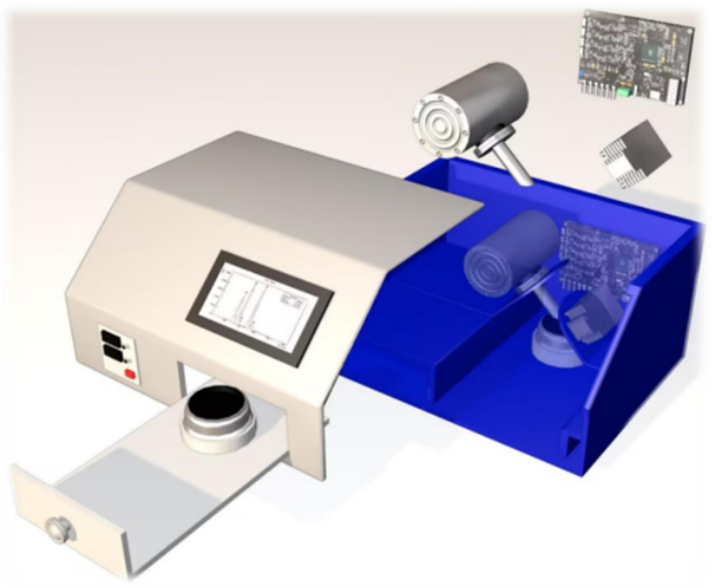
ABSTRACT

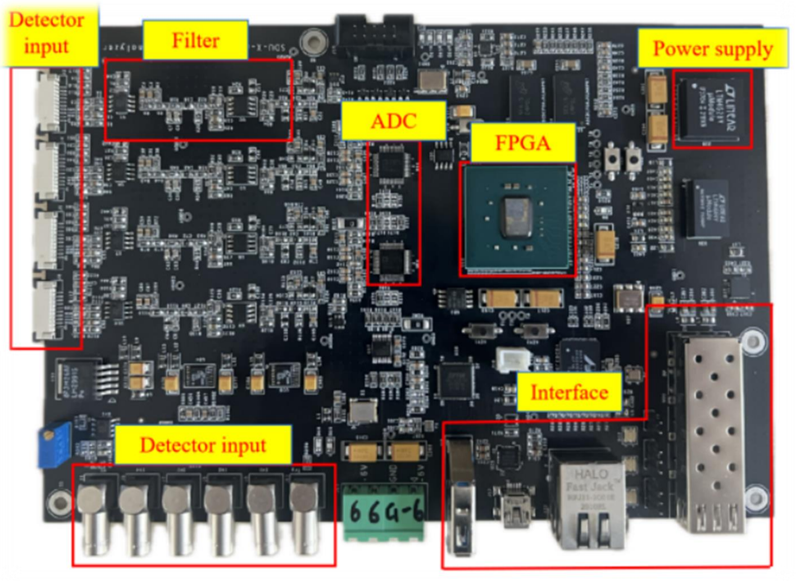
Traditional X-ray Fluorescence (XRF) techniques struggle to meet the requirements of low-latency response and continuous online measurement in industrial scenarios. To address this challenge, **this work develops a compact, cloud-deployable XRF spectrometer with real-time data acquisition capability for industrial online elemental analysis.**

The system integrates a Si-PIN detector with prototyping of the readout electronic (PRE), and employs a Kintex-7 FPGA as the core unit for high-speed digital signal processing. The trapezoidal shaping algorithm is implemented for spectral resolution enhancement and Geant4 simulation is used for air attenuation correction to ensure reliable performance under non-vacuum conditions. By integrating the USR-DR502 module and MQTT protocol, the established 3-tier host workstation system achieves low-latency data synchronization and supports automated measurement workflows, enabling simultaneous local and remote monitoring.

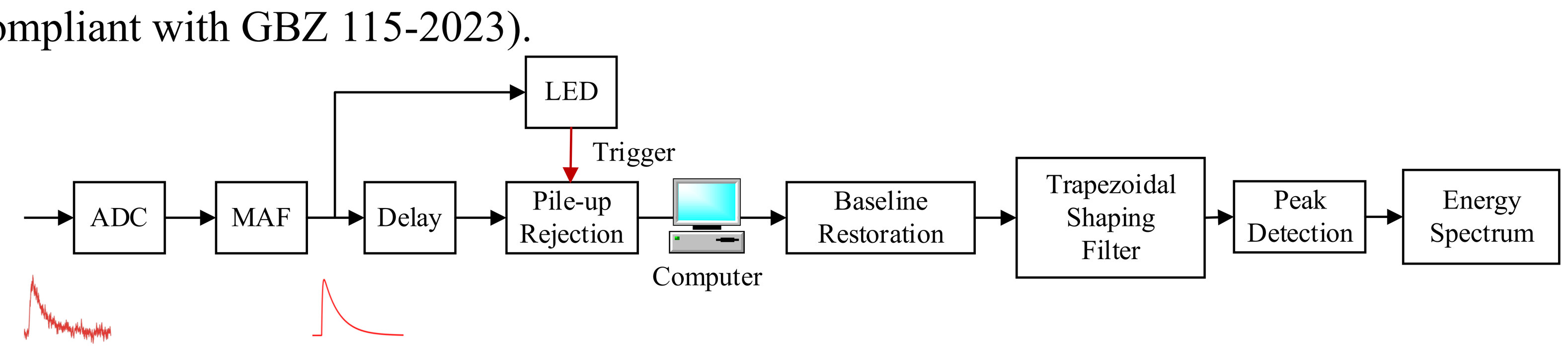
Test results show that the system achieves an **energy resolution of 266 eV at 6.40 keV** and an integral **nonlinearity of 0.15%**. Moreover, quantitative analysis of standard Fe-Ca samples yields **relative errors within 0.20%**, which validates the system's high accuracy and feasibility for practical industrial online applications.

System Architecture

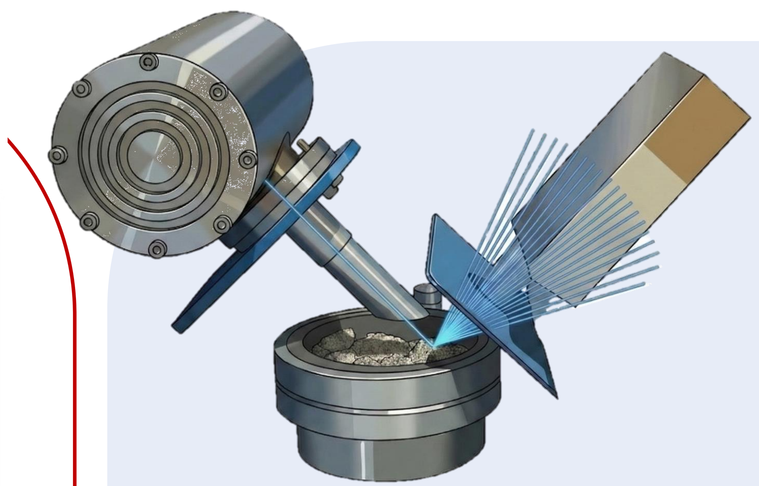




- **Device size:** 600×450×300 mm, 20 kg. 2mm lead shielding, leakage dose <1 μSv/h (compliant with GBZ 115-2023).
- **PRE module:** Xilinx Kintex-7 FPGA + 2×AD9248 ADC, 4-channel synchronous readout, scalable for multi-detector arrays.



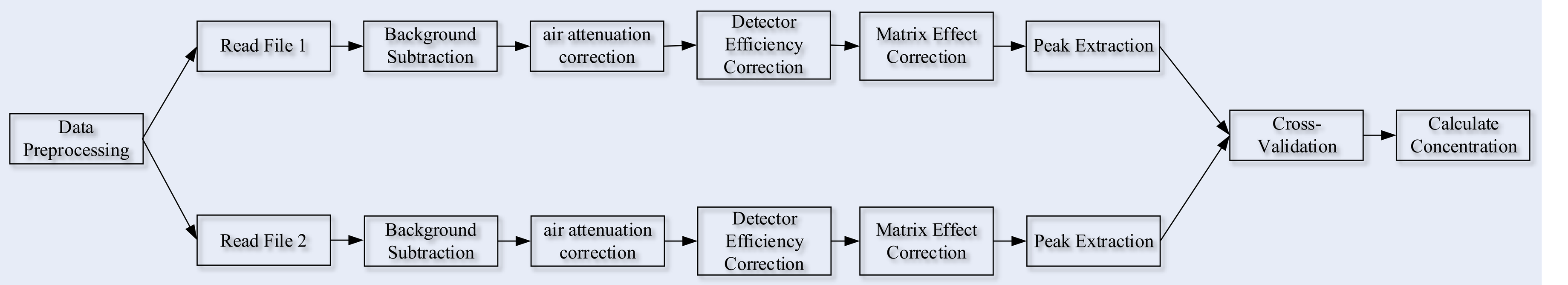
- **Pulse Signal Processing Flowchart:** The chain performs baseline restoration, trapezoidal shaping filtering, pile-up rejection, and peak detection to convert detector pulses into a clean energy spectrum.



- **X-ray Generator, Detector, Sample Holder and Schematic Diagram.**

X-ray Generator Parameter	Value
Input Voltage	≤ 50 kV
Anode Current	≤ 1 mA
Target Material	Ag (Silver)
Focal Spot Size	≤ 0.1 mm
Maximum Power	50 W
Si-PIN Detector Parameter	**Value**
Type	Si-PIN
Detector Area	25 mm^2
Thickness	500
Full Width at Half Maximum(FWHM)*	139 - 260 eV @ 5.9 keV
Count Rate	50 kcps

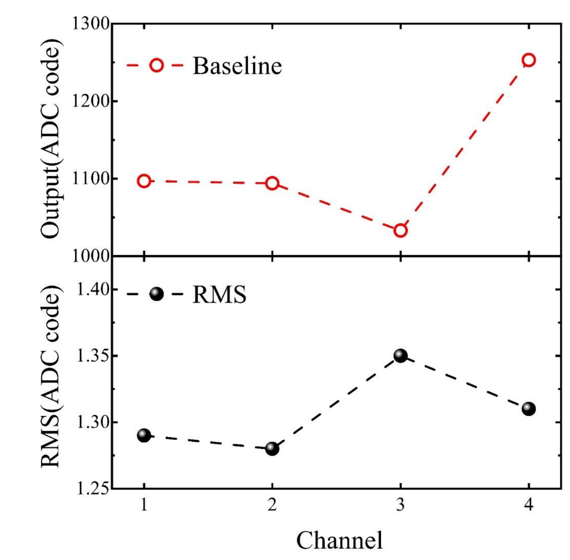
* Obtained by the ^{55}Fe standard source.



- **Dual-channel data processing for qualitative and quantitative analysis:** This system sequentially processes two independent measurement files by performing background subtraction, air attenuation correction, detector efficiency correction, matrix effect correction, and peak extraction, then calculates the final results through cross-validation.

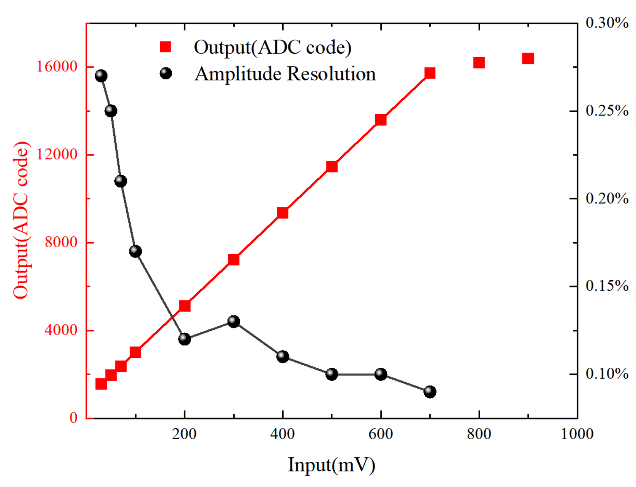
Performance Evaluation

System performance



Test Results of Baseline and Noise for Readout Electronics

- **Baseline Noise:** The RMS noise of the readout electronics is less than 1.35 ADC codes.



Test Results of Linearity and Amplitude Resolution for Readout Electronics

- **Channel Linearity and Amplitude Resolution:** As shown in the left figure, the channel linearity is excellent with a slope of approximately 21.When the input amplitude reaches 200 mV, the amplitude resolution is 0.15%.

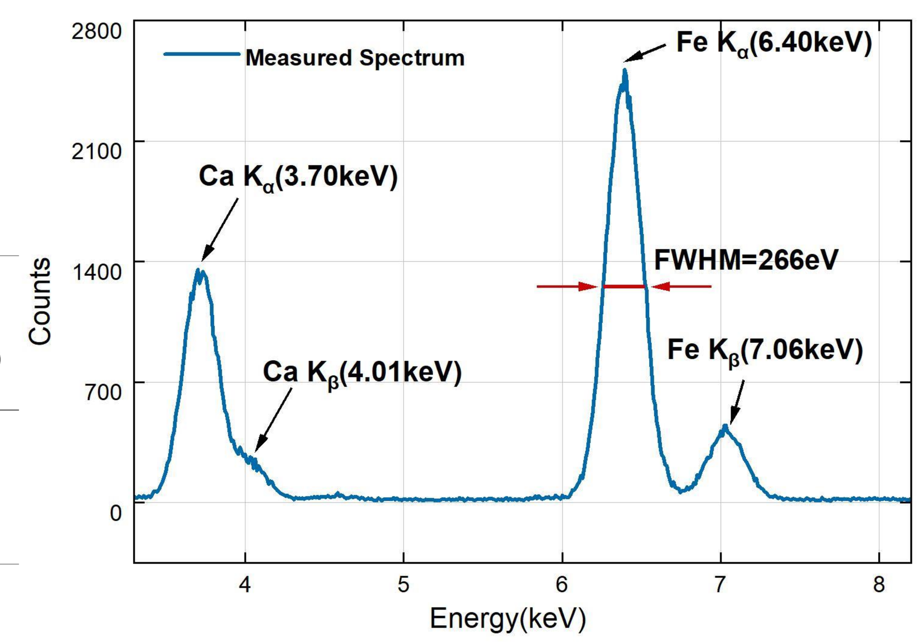
Experimental Performance

- **Energy resolution:** For a Ca/Fe mixed sample at 6.40 keV, **FWHM = 266 eV** (close to 263 eV at a standard source of 5.9 keV); on-site testing of iron ore at the factory at 6.40 keV, FWHM = 269 eV, can clearly distinguish the Kα/Kβ peaks of Ca and the Kα/Kβ peaks of Fe, with excellent stability and adaptability in non-vacuum industrial environments.
- **Quantitative accuracy:** For the Fe (41.75%)/Ca (58.25%) standard sample, the measured values are Fe = 41.67% and Ca = 58.33%, with an **absolute error of ±0.08%** and a relative error of less than 0.20%, indicating high accuracy of the quantitative analysis.

Comparison of Quantitative Analysis Results for Fe/Ca Mixture Sample.

Element	Reference Concentration(%)	Calculated Concentration(%)	Absolute Error(%)	Relative Error (%)
Fe	41.75	41.67 ± 0.40	-0.08	-0.19
Ca	58.25	58.33 ± 0.76	+0.08	0.14

Note : Calculated concentrations include theoretical counting errors (1σ)



XRF Spectrum of Fe/Ca Mixture Sample.