High-throughput X-ray fluorescence imaging using a massively parallel detector array, integrated scanning and real-time spectral deconvolution

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Abstract. A step improvement in X-ray fluorescence imaging performance is demonstrated through close integration of a large detector array, dedicated data acquisition, stage control and real-time parallel data processing, to achieve efficient elemental imaging with <1 ms per pixel, image sizes in excess of 4 megapixels, full-spectral data collection and spectral deconvolution, at detected photon rates up to 6 M/s, in prototype tests at the NSLS using a 96 detector array.

1. Introduction

X-ray fluorescence microprobe imaging is commonly hampered by read-out delays. An alternative data acquisition strategy uses a multiparameter approach in which each photon event is tagged by sample XY position and detector identity, and these ‘events’ are streamed for further processing or storage. This strategy exhibits zero read-out overhead and enables faster raster scanning. Complex full-spectral SXRF data can be decomposed into elemental components using a matrix transform method called Dynamic Analysis (DA) [1,2] originally developed for PIXE imaging [3]. The simplicity of the method permits its execution on this event stream in real-time [4].

Large planar monolithic silicon detector arrays and dedicated application specific integrated circuits (ASICs) for signal processing offer the potential for large solid-angle collection, with the resulting high count rates spread over a large number of detectors. The speed of field-programmable gate array (FPGA) computation permits real-time processing of each event from such an array.

A new spectroscopy detector system is under development that combines a large detector array and custom ASICs development by BNL and a pipelined, parallel processor with embedded DA image projection developed at CSIRO. It subtends a solid-angle of ~1.5 sr, is closely coupled with sample

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scanning and performs real-time processing and projection of elemental images [5,6]. The project aims for a 384 detector array. This work reports on tests using a 96 detector prototype, called Maia-96.

2. Detector Concept

The detector comprises a low-leakage Si pad array developed at BNL [5], Peltier cooled to -35 °C. It is directly wire-bonded to CMOS ASICs each providing 32 low-noise preamplifiers with high order shapers and baseline stabilizers (HERMES [7]). Shaped pulses go to 32-channel peak-detector derandomizer ASICs, which capture pulse height and time-over-threshold (SCEPTER [8]).

![Figure 1. Major element Fe (left) and trace Y (right) grey-scale images of iron-oxide nodules, Rose Dam; 1625 x 2625 pixels (13 x 21 mm², 5 ms dwell per pixel), 7.5 μm pixels, using 17.2 keV X-rays.](image)

Outputs from SCEPTER representing both energy (E) and time-over-threshold (T) are digitized by dual 14-bit fast synchronous ADCs interfaced to the parallel processing engine HYMOD, developed at CSIRO for high speed instrumentation. HYMOD consists of a FPGA connected to 6 large static RAMs, a PowerPC processor and fast serial (12 x 3.125 Gb/s) and Ethernet ports (2 x 1Gb/s). FPGA code is written using a CSIRO-developed pipelined, parallel processing language called 3PL [9].

The processing pipeline comprises: (i) pile-up rejection, (ii) energy calibration, (iii) 4K spectrum accumulation, (iv) DA image accumulation, and optionally (v) event pre-scaling and logging. Each ET event is tagged by detector number and XY position. Pile-up rejection compares E with that expected for its T, with outliers discarded. The detector number selects energy calibration tables to map channel number onto DA matrix column, which provides the increments for elemental images for the current XY pixel [2]. DA accounts for changing elemental sensitivity across the array due to varying take-off angle, absorption and efficiency [10]. DA is implemented as 32 parallel pipelines, one per chemical
element, read out and displayed at XY pixel rate. In parallel, events can be pre-scaled to suppress intense lines when logging to disk. HYMOD also controls the stage, driving stepper motors directly.

3. Prototype Tests

Earlier tests demonstrated the concept using a 32 detector prototype with real-time DA projection into elemental images [11,6]. Tests at NSLS beam-line X27A [12] reported here used a 96 element prototype (called Maia-96) with the array bonded to three HERMES-SCEPTER pairs, and direct drive of a stage capable of 10 mm/s slew speed. These tests collectively demonstrated (i) count rates up to 6 M/s, (ii) image sizes up to 4.3 megapixels, (iii) dwell times as short as 0.8 ms (limited by stage speed for 7.5 µm pixels), (iv) image frames (560 x 280 pixels) as short as 6.5 minutes, (v) DA processing using HYMOD, using a second HYMOD to simulate a detector data-source, at 10^8 events per second and (vi) compression schemes designed to filter major element components in the raw data stream.

Figure 1 illustrates performance showing images of Fe and trace Y in iron-oxide nodules from Rose Dam, Western Australia, revealing an amazing diversity of zonation reflecting contrasting growth history and sedimentary sorting processes; Y concentrations vary up to ~100 ppm and average ~10 ppm. The pixel size was chosen to slightly over-sample given the beam size. The desired running time of ~6 hours determined the required stage speed of 1.5 mm/s and a dwell per pixel of 5 ms.

4. Conclusions

Development of a 384 detector system, integrating full-spectral data collection, high speed stage control and real-time data processing and image display are well advanced with successful tests of a 96 detector prototype at the NSLS, which features megapixel imaging at dwell times as short as 0.8 ms and count rates up to 6 M/s. Given these capabilities, the choice of pixel size and dwell time are now dictated by the needs of the application, and not by data acquisition limitations. Two 384 detector systems are under construction for installation at the Australian Synchrotron and the NSLS.

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References

[1] Ryan C G, Etschmann B E, Vogt S, Maser J, Harland C L, Van Achterbergh E and Legnini D 2005, *Nucl. Instr. Meth. B* 231 183
[2] Ryan C G 2000, *Int. J. Imaging Systems and Technology* 11 219
[3] Ryan C G and Jamieson D N 1993, *Nucl. Instr. and Meth.* B 77 203
[4] Ryan C G, Jamieson D N, Churms C L and Pilcher J V 1995, *Nucl. Instr. and Meth. B* 104 157
[5] Siddons D P, Beuttenmuller R H, O’Connor P, Kuczewski A J, Li Z 2004, *AIP Conference Proceedings* 705 953
[6] Ryan C G, Siddons D P, Moorhead G, Kirkham R, Dunn P A, Dragone A, De Geronimo G 2007, *Nucl. Instr. Meth. B* 260 1
[7] De Geronimo G, O’Connor P, Beuttenmuller R H, Li Z, Kuczewski A J, and Siddons D P 2003, *IEEE Trans. Nucl. Sci.* 50 885
[8] Dragone A, De Geronimo G, Fried J, Kandasamy A, O’Connor P and Vernon E 2005, *IEEE Nuclear Science Conference Record* 2 914
[9] Dunn P, Ryan C G, Kirkham R, Moorhead G, Davey P, submitted to *Nucl. Instr. Meth.* A
[10] GeoPIXE software for PIXE/SXRF imaging, [http://nmp.csiro.au/GeoPIXE.html](http://nmp.csiro.au/GeoPIXE.html)
[11] Siddons D P, Dragone A, De Geronimo G, Kuczewski A, Kuczewski J, O’Connor P, Li Z, Ryan C G, Moorhead G, Kirkham R, Dunn P 2006, *proc. of IEEE Nuclear Science Symposium, Medical Imaging and Room Temperature Detector Workshop*, San Diego, October 2006
[12] Ablett J M, Kao C C, Reeder R J, Tang Y, Lanzirotti A 2006, *Nucl. Instr. Meth. A* 562 487