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Development of readout electronics for a high-speed event-driven neutron imaging detector based on Timepix4

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A high-performance event-driven readout electronics system based on Timepix4 has been developed for energy-resolved neutron imaging detectors at China Spallation Neutron Source (CSNS). The system achieves a position resolution better than 55 μm and a timing resolution better than 1 μs. The readout electronics feature a large-capacity cache, high readout bandwidth, and FPGA-based hardware acceleration algorithms for real-time data analysis. The system supports a sensitive area of 6.94 cm^2, counting rates up to 40 Mhits/cm^2/s, and a maximum readout bandwidth of 40Gbps. Neutron imaging test experiments have demonstrated the good performance of the readout electronics system.

Summary (500 words)

Energy-resolved neutron imaging is a crucial non-destructive measurement technique in industrial and materials research. It requires detectors and electronics with accurate time-of-flight (TOF) measurement for each neutron event and a position resolution better than 100 μm. Real-time data processing is desirable due to high neutron flux and large data volumes at the sample. The China Spallation Neutron Source (CSNS) has developed an energy-resolved neutron imaging detector based on scintillators using TPX3CAM with a limited area of 1.4x1.4 cm^2. This detector does not fully exploit the neutron flux of the CSNS Energy-Resolved Neutron Imaging Instrument (ERNI) beamline, which has an area of 20x20 cm^2. Additionally, it lacks data preprocessing capabilities. Therefore, we developed a camera based on Timepix4, and this talk will discuss the key components of the camera - the readout electronics.

Timepix4 is a 6.94 cm^2 hybrid pixel detector readout ASIC designed for detector tiling on 4 sides with 55 μm square pixels and sub-200 ps timestamp binning. Its maximum readout bandwidth of 160 Gbps poses a challenge for data acquisition. Our high-performance readout electronics system, based on ZYNQ MPSOC, addresses this issue by supporting up to 16 pairs of 10.24 Gbps data bandwidth from Timepix4 to the FPGA, incorporating 32 GB of external DDR4 SODIMM memory for burst data peaks, and implementing a 40 Gbps data acquisition (DAQ) readout interface based on QSFP. These features ensure efficient and stable data transfer from Timepix4 to the backend DAQ system.

To handle the high data readout rates (typically >10 Gbps) in neutron imaging experiments and enable real-time data analysis and imaging, we utilized the internal logic resources of the MPSOC to implement clustering and pixel-level TOF spectrum analysis algorithms originally performed in software. By implementing these algorithms in the electronics hardware, we achieved real-time data analysis and statistics, eliminating the need for the DAQ system to handle large amounts of data in real-time, thereby enhancing efficiency and speed.

In summary, we developed a high-rate event-driven readout electronics system for scintillator-based energy-resolved neutron imaging detectors using Timepix4. The system enables real-time data analysis and handles high event rates. The newly designed hardware platform increases the sensitive area to 6.94 cm^2 and supports counting rates up to 40 Mhits/cm^2/s, improving the performance of energy-resolved neutron imaging. FPGA-based data acceleration algorithms achieve real-time data analysis and statistics, enhancing the efficiency of energy-resolved neutron imaging experiments and significantly improving the overall effectiveness of these experiments.

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