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Upgrades of the Data Acquisition System for the KOTO Experiment

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Abstract. The KOTO data acquisition system (DAQ) collects detector PMT waveform signals and saves digitized events to permanent storage using frontend ADC modules, two levels of hardware triggers, and a computing farm. The KOTO DAQ system ran stably in 2013 with 24 kW beam power. To maintain high DAQ livetime with increasing beam power, we implemented lossless data compression inside the ADC modules and developed a new L3 computing farm. The upgraded KOTO DAQ system was able to maintain livetime above 80% with 42 kW beam power during the 2015 and 2016 runs. To sustain high DAQ livetime for data taking with beam power of 50 kW and above, an upgrade of our hardware trigger is proposed.

1. Introduction to the KOTO Experiment

The KOTO experiment is located at the J-PARC facility in Tōkai-mura, Ibaraki, Japan. The goal is to measure the branching ratio of the direct CP-violating decay $K_L \to \pi^0\nu\bar{\nu}$, whose branching ratio is calculated to be $(3.00 \pm 0.30) \times 10^{-11}$ [1] in the Standard Model (SM). The high precision theoretical calculation for the branching ratio enhances the sensitivity towards probing for new physics beyond the SM. The KOTO experiment receives a secondary $\mathrm{K_L}$ neutral beam generated by a 30 GeV primary proton beam hitting on the gold target. The proton beam is slowly extracted in 2 seconds, with 6 seconds repetition. The decay of $K_L \to \pi^0\nu\bar{\nu}$ is measured by observing the two photons generated by the single π^0 in the calorimeter and nothing else in the other detectors. The KOTO detectors consist of a Cesium Iodide (CsI) calorimeter surrounded by veto detectors sensitive to photons, neutrons, and charged particles.

2. The DAQ System

2.1. The Current System

We built a DAQ system optimized to retain $K_L \to \pi^0\nu\bar{\nu}$ decays and filter out other $\mathrm{K_L}$ decays which are many orders of magnitude more frequent. The DAQ consists of the ADC modules, two levels of hardware triggers (L1 trigger and L2 trigger), as well as a computing farm (L3 computing farm). The L1 trigger accepts events by requiring a minimum energy deposit in the CsI calorimeter and no energy deposit in the veto detectors. The L2 trigger filters the signal

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from other neutral decay events by calculating the event Center-of-Energy (CoE), which is a position-weighted energy deposition in the calorimeter[2]. The L3 computing farm manages the event building. An online clustering algorithm is implemented inside the L3 software for potential future online filter usage.

2.2. The ADC Lossless Data Compression

Two types of ADC modules with 125 MHz and 500 MHz sampling rate are used in the DAQ system to accommodate different detector resolutions. The ADC modules shape the analog PMT waveforms into Gaussian waveforms using a 10-pole Bessel function filter, and digitize the waveforms with 8 ns sampling rate. Each waveform has a timing window of 512 ns. A 125 MHz ADC module digitized a detector waveform into 64 samplings and a 500 MHz ADC module digitized that into 256 samplings. A lossless data compression algorithm is used in the ADC firmware to reduce data size and increase the amount of data we can collect with our trigger system. The performance of the lossless data compression effectively increased the DAQ livetime as the beam power and the trigger rate increase, as shown in Fig. 1 below.

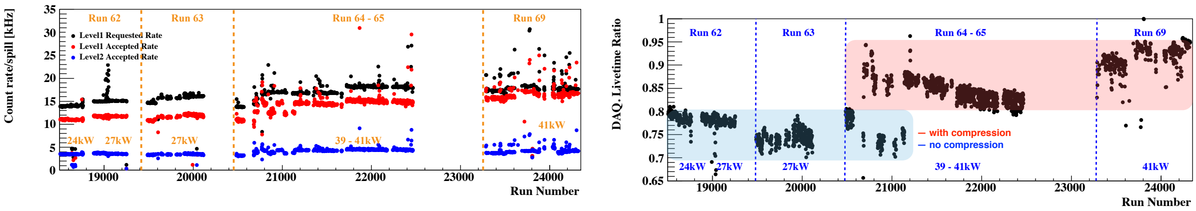

Figure 1. DAQ trigger rate and perfromance in 2015-16 experiment runs.
Left plot: DAQ trigger rates. The trigger rates increase as the beam power increases. The Level 1 (L1) request rate (black points) is the number of triggers generated by the L1 trigger. The L1 accept rate (red points) is the number of triggers being considered for the process in the L2 trigger. L2 accept rate (blue points) is the number of triggers passed the L2 trigger filter.
Right plot: DAQ livetime. The implementation of lossless data compression effectively increased the DAQ livetime, which is defined to be the ratio of L1 accept over L1 request.

2.3. The L3 Computing Farm

We upgraded the L3 computing farm in 2015. The new L3 computing farm consists of 2 head nodes and 47 computer nodes. A full-meshed computer network is implemented using Infiniband hardware with the Message Passing Interface protocol. We divided the computer nodes for event building into two groups - Type 1 and Type 2. Type 1 computer nodes receive the data from the L2 trigger through the Ethernet connection. Based on the spill information and event ID, Type 1 nodes send the data packet to Type 2 nodes via the Infiniband switch. Events in the Type 2 nodes are decompressed and compressed again after rearranging the data packet structure in a fashion more convenient for online event selection and subsequent offline data analysis.

2.4. L2 RPT hardware upgrade

Further increase in the beam power will lower the DAQ livetime ratio due to insufficient hardware resources. We decided to replace the L2 trigger hardware with the Reconfigurable Clustering Element (RCE) Platform Technology (RPT) developed by SLAC. This upgrade is expected to have the capability to process data up to minimum of 100 kW without the lossless compression inside the ADC modules.

The RPT hardware is shown in Fig. 2. It consists of an ATCA blade, called Cluster-On-Board (COB), and Rear Transmission Module (RTM) used to receive data from the detector. Each COB includes two flavors of mezzanine boards: four Data Processing Modules (DPM), each composed of two RCEs with Zynq-7045 FPGA, and one Data Transmission Module (DTM), containing one Zynq-7030 RCE. The RCE comes with both a Real-Time Executive for Multiprocessor Systems (RTEMS) and an ARM Linux operating system loaded on a micro SD card. The communication between each RCE and between each COB has to go through the Clustering Interconnect (CI) Ethernet switch on the COB. A replicated-mesh backplane will be used to assist the full communication between every RCE from different COBs.

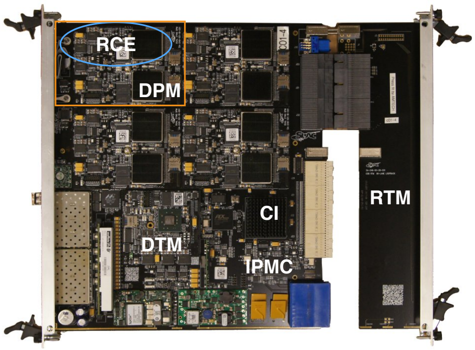

Figure 2. A Cluster-On-Board (COB) and a Rear Transmission Module (RTM). The Clustering Interconnect (CI) Ethernet switch handles all communication traffic between each RCE and is connected to replicated-mesh ATCA backplane. Multiple 10 Gbps links are available on the COB for these communications.

We plan to implement event building inside the new L2 trigger. Having a full event in the trigger system, we will be able to enhance the quality and the flexibility of the L2 trigger rejection. We will use a custom designed RTM to receive data from the ADC modules, as well as to transmit the processed data to the L3 computing farm for further online analysis, filtering, and storage. Each RCE on the DPM will receive event fragments from the ADC modules via the RTM. Each RCE will read the event ID information and via the CI redirect the event fragment to a single RCE where event building will take place. A flexible set L2 trigger filters, such as CoE decision or calorimetric cluster counting, will be implemented to the reject unwanted events. A 1 GB DDR3 memory is available on each RCE for temporary storage during event building and L2 filtering.

3. Summary

The lossless data compression inside the ADC modules increased the DAQ livetime as the beam power increased to 42 kW. To maintain the current DAQ system performance for beam power greater than 50 kW, we are developing an upgrade for the L2 trigger system.

4. Acknowledgments

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