PROCEEDINGS OF SCIENCE

Data-Acquisition System Upgrade for the KOTO Experiment

Chieh Lin*

Enrico Fermi Institute, University of Chicago
933 East 56th Street, Chicago, Illinois 60637, USA

E-mail: chiehlin@uchicago.edu

We are upgrading the KOTO data-acquisition system to collect $K_L^0 \to \pi^0 \nu\bar{\nu}$ data efficiently toward a higher K_L^0 beam intensity. The upgrade includes the expansion of the data throughput and the third-level trigger decision at the PC farm. The University of Chicago designed electronic modules with numerous high-speed optical links to transfer data from analog-to-digital converters, perform the event-building, and deliver complete events to the PC farm for the level-3 trigger evaluation. By maintaining the loss due to the network congestion to be less than 1%, the maximum event rate was improved from 8k events/sec to 15k events/sec. This limit can be further extended by horizontally connecting more modules if needed.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

PoS(ICHEP2022)242

1. Introduction

KOTO is a dedicated experiment searching for the ultra-rare decay $K_L^0 \to \pi^0 \nu\bar{\nu}$ [1, 2]. The KOTO detector consists of an endcapped calorimeter and a veto system enclosing the fiducial K_L^0 decay region. The calorimeter is made of an array of CsI crystals to measure the incident photon energies and positions from a π^0. Because neutrinos are undetected, any hit in other detector components is presumably induced by a background.

The K_L^0 beam, which has the momentum peaking at 1.4 GeV/c, is generated by protons that constantly hit the gold target for a spill of 2 seconds once every 5 seconds. The K_L^0 beam received at the KOTO detector has the timing structure shown in Figure 1. This structure results in a large variation in the instantaneous event rate, which needs to be taken into account while designing the data-acquisition (DAQ) system.

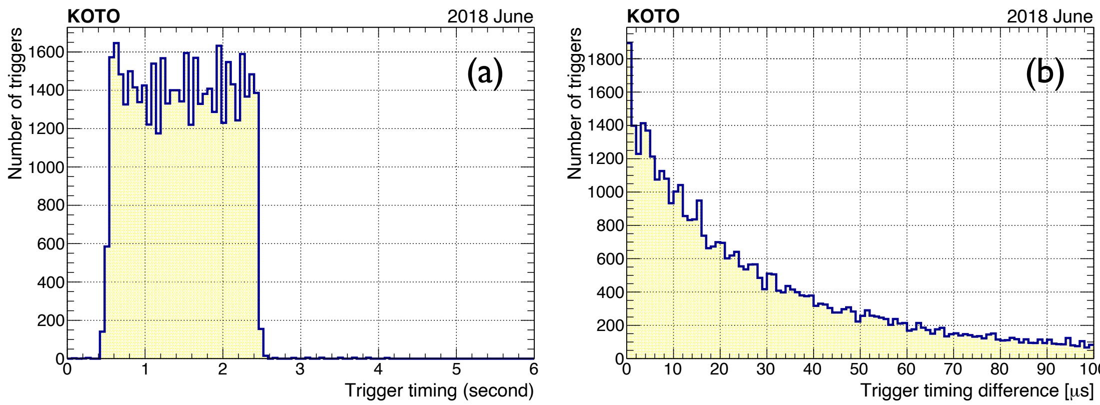

Figure 1: Distributions of (a) trigger timing and (b) timing difference between two adjacent triggers. This was the result of the 51-kW K_L^0 beam measured in June 2018. A trigger was issued if the energy sum in the calorimeter was larger than 1.5 GeV. The trigger timing was the elapsed time since the start signal given by the accelerator.

The Standard Model predicts the branching fraction of 2.9×10^{-11} [3], and KOTO has reached the single event sensitivity of 7.2×10^{-11} using the data collected from 2016 through 2018 [4]. More K_L^0s are required for KOTO to explore the regime where New Physics can contribute. The proton beam intensity will be increased from 64 kW to 100 kW. The DAQ system upgrade is thus vital to achieve this objective.

One major upgrade is the expansion of the data throughput. If the loss due to the network congestion is required to be less than 1%, the maximum event rate that the current DAQ system can handle is 8k events/sec (equivalent with 38.0 Gbps). This number is smaller than the expected event rate at 100 kW, which is 10k events/sec (equivalent with 47.6 Gbps). The data throughput expansion is required to fully collect the $K_L^0 \to \pi^0 \nu\bar{\nu}$ signals. Depending on the increment of the data throughput, KOTO can further collect more data for other potential physics topics, such as dark particle searches, other rare K_L^0 decays, etc.

Another major upgrade is the introduction of the level-3 trigger. According to the $K_L^0 \to \pi^0 \nu\bar{\nu}$ signature, KOTO currently has the two-level trigger selections [5]. The level-1 trigger requires that the energy sum in the calorimeter is larger than 0.5 GeV and no hit is detected in the veto system.

PoS(ICHEP2022)242

The level-2 trigger requires that the number of photon hits in the calorimeter is equal to two. After data is received at the PC farm, a sophisticated level-3 trigger can be performed to further select the events to be kept for analyses.

2. Apparatus

The KOTO detector has nearly 4000 analog signals read out by 288 flash analog-to-digital converter (FADC) boards [6]. Figure 2 shows the data of a readout channel recorded by a FADC board. The FADC board has the dynamic range of 14 bits. When a trigger is received, 64 samples around the trigger timing are selected and sent to the downstream modules.

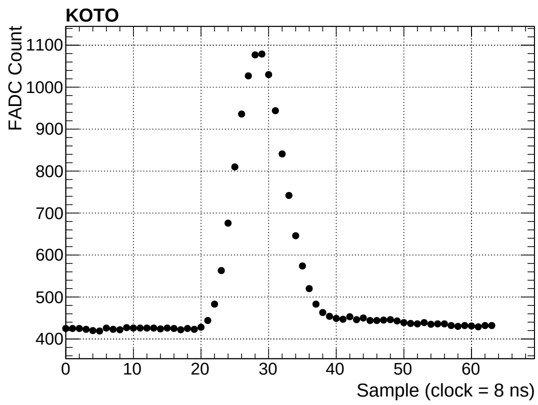

Figure 2: Data of a readout channel recorded by a FADC board.

The data transfer between the FADC boards and the PC farm requires a large throughput. University of Chicago designed two types of modules with numerous high-speed optical transceivers, named optical fiber center (OFC) [7], as shown in Figure 3. The OFC-I board has 18 SFP (small form-factor pluggable) transceivers supporting the maximum speed of 4 Gbps and an Arria-V FPGA (field-programmable gate array) that maximally holds 50 events (equivalent with 13.2 Megabits). The OFC-II board has 9 QSFP (Quad SFP) tranceivers supporting the maximum speed of 40 Gbps and a Stratix-X FPGA that maximally holds 20 events (equivalent with 95.1 Megabits).

3. Architecture

Figure 4 shows the architecture of the KOTO DAQ system. Each OFC-I board receives the data from 16 FADC boards via 2-Gbps optical links, and sends the packed data to the OFC-II board via a 4-Gbps optical link. The OFC-II receives all the pieces of an event from 18 OFC-I inputs, performs an event-building, and sends a complete event to the PC farm in the control room via two 40-Gbps Ethernet optical links.

The PC farm consists of two types of computers: spill nodes and disk nodes. A spill node receives data, processes the level-3 trigger selection with 20 CPU cores, and compresses data with a GPU. A spill node receives all events collected in a spill and then rotates to another spill node. Because there are six spill nodes, a spill node has approximately 24 seconds to process the level-3

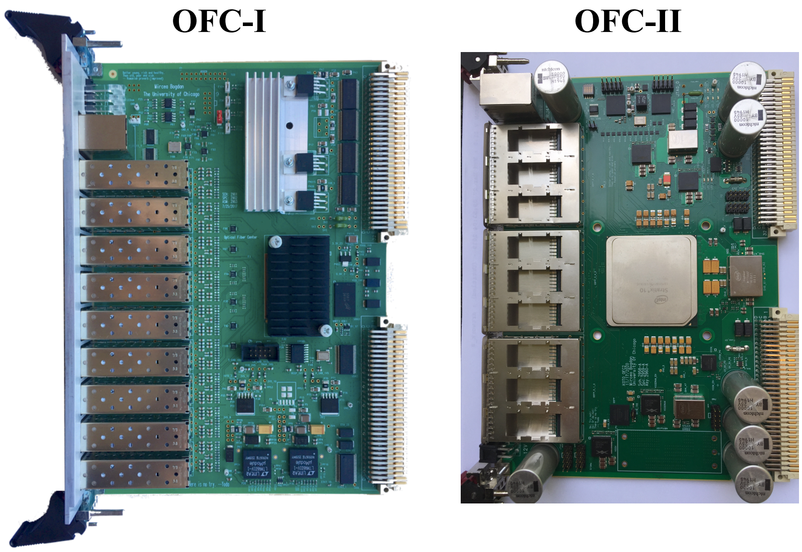

Figure 3: Pictures of OFC-I (left) and OFC-II (right).

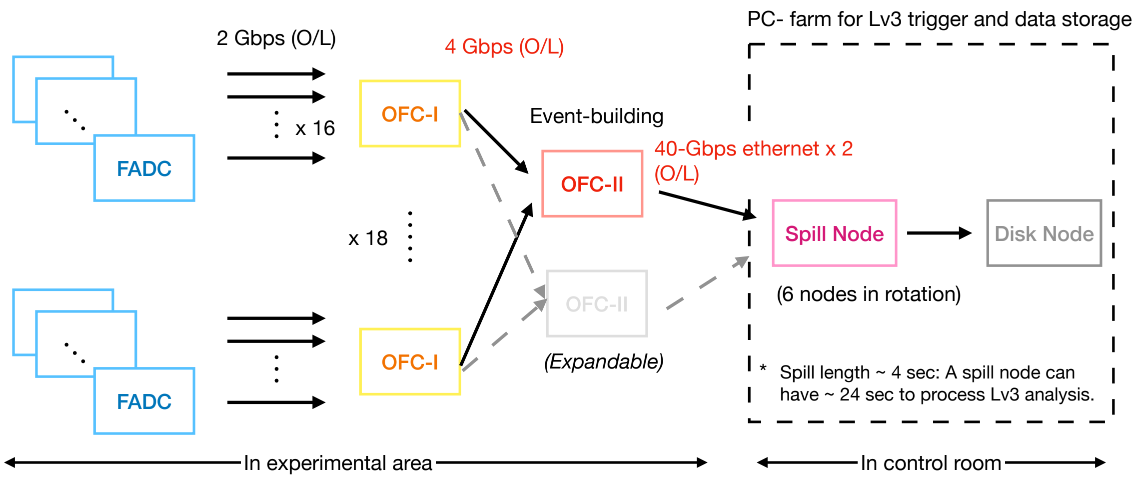

Figure 4: Architecture of the KOTO DAQ system to transfer data from the FADC boards to the PC farm. O/L represents the optical link. The gray dashed arrows and the OFC-II box indicate the possible horizontal expansion.

trigger. A disk node has a 96 TB storage as a buffer before delivering the data to the computing center.

The average OFC-I input rate is expected to be 2.6 Gbps at 100 kW. However, because of the high instantaneous rate brought by the K_L^0 beam shown in Figure 1, OFC-I might receive the maximum input rate of 2 Gbps $\times$ 16 = 32 Gbps, which is larger than the maximum output rate of 4 Gbps. In contrast, the OFC-II board has the maximum input rate of 4 Gbps $\times$ 18 = 72 Gbps, which is smaller than the maximum output rate of 40 Gbps $\times$ 2 = 80 Gbps. Therefore, the congestion is expected to happen at the OFC-I boards. When the OFC-I memory buffer is almost full, a busy signal is sent from OFC-I to prevent itself from receiving more data. Any event that is dropped due to the OFC-I busy signal is defined as a loss. If the loss is not acceptable, each OFC-I board can be connected to multiple OFC-II boards in order to increase the output rate, as indicated in Figure 4.

4. Performance

The loss versus the event rate was measured by the following setup. A trigger manager issued triggers to the FADC boards and the OFC-I boards in accordance with the timings collected in Figure 1. A higher rate was generated by merging multiple spills into one. The OFC-I board constantly received data from FADC boards and monitored the status of its memory buffer. The OFC-I busy signal was sent to the trigger manager if the congestion was foreseen. Any loss due to the OFC-I busy was recorded.

Figure 5 shows the result of the one OFC-I system. If the loss was required to be less than 1%, an event rate of 15k events/sec (equivalent with 71.3 Gbps) was achieved. This number was 5k events/sec more than the expected rate at 100 kW beam. This extra room enables other K_L^0 physics measurements at KOTO in the future.

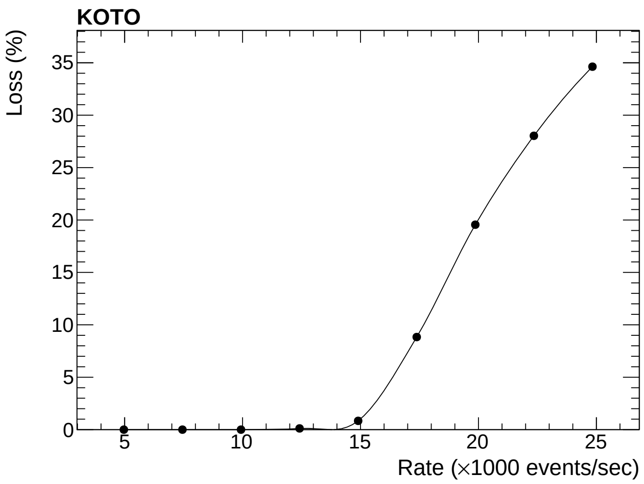

Figure 5: Loss versus the event rate of the one OFC-I system.

5. Conclusion

KOTO is upgrading the DAQ system to fully collect $K_L^0 \to \pi^0\nu\bar{\nu}$ signals toward a higher beam intensity. Boards equipped with numerous optical links and large memory size are utilized to transfer data. Because the boards are connected in a pyramid architecture, the PC farm directly receives complete events. By requiring the loss due to the network congestion to be less than 1%, a maximum event rate of 15k events/sec (equivalent with 71.3 Gbps) is achieved. This is larger than the target rate of 10k events/sec (equivalent with 47.6 Gbps). Events can be further selected by the level-3 trigger performed at the PC farm. With the features mentioned above, KOTO is ready to explore the unprecedented regime.

References

[1] T. Yamanaka and for the KOTO Collaboration, *The J-PARC KOTO experiment*, *Prog. Theor. Exp. Phys.* **2012** (2012) 02B006.

[2] J. Comfort et al., *Proposal for the $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ Experiment at J-PARC*, 2006.

[3] A.J. Buras and E. Venturini, *Searching for New Physics in Rare K and B Decays without $|v_{cb}|$ and $|v_{ub}|$ Uncertainties*, 2021. 10.48550/arXiv.2109.11032.

[4] KOTO collaboration, *Study of the $K_L \rightarrow \pi^0 \nu\bar{\nu}$ Decay at the J-PARC KOTO Experiment*, *Phys. Rev. Lett.* **126** (2021) 121801.

[5] C. Lin et al., *The Data-Acquisition System with Cluster-Finding Trigger at the J-PARC KOTO Experiment*, *J. Phys.: Conf. Ser.* **1526** (2020) 012034.

[6] M. Bogdan, J.-F. Genat and Y. Wah, *Custom 12-Bit, 500MHZ ADC/Data Processing Module for the KOTO Experiment at J-Parc*, *2010 17th IEEE-NPSS Real Time Conference* (2010) 1.

[7] M. Bogdan, C. Lin, Y. Luo, Y. Tung and Y. Wah, *Optical fiber center module for the KOTO experiment*, *Nucl. Instrum. Methods. Phys. Res. A* **936** (2019) 340.