Data Acquisition Upgrade at KOTO

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Abstract. KOTO is building a new data acquisition system which is a pyramid style architecture, composed of all new homemade optical fiber centers modules with high-speed ports that gather and build the event from over 4000 channels. It will be able to handle up to 30,000 triggers per second with minimal loss in the near future, which is a factor of six more than current rates. This will allow KOTO to handle a higher intensity K_L beam, as well as open up the possibility of adding new physics triggers such as one for $K_L \to \pi^0 e^+ e^-$. Additionally, the new architecture simplifies our data handling and allows for greater flexibility in adding late level trigger conditions since the event building is done before the data is sent to the server. This system is robust, flexible and easily scalable in the future and provides a foundation for moving forward to KOTO II.

1. Introduction

KOTO is searching for the ultra-rare $K_L \to \pi^0 \nu\overline{\nu}$ decay at J-PARC. This decay mode is direct CP-violating, and the branching ratio is proportional to the height of the CKM triangle. It is a physically interesting mode while having an extremely low theoretical uncertainty in the branching ratio of $\approx 2\%$ [1]. This makes $K_L \to \pi^0 \nu\overline{\nu}$ an ideal candidate for new physics searches.

KOTO uses an exceptionally efficient endcap calorimeter (CSI) to capture the signal of the $K_L \to \pi^0 \nu\overline{\nu}$ mode. The signal is comprised of two photons incident onto the CSI calorimeter with large transverse momentum, while observing no energy deposited in our hermetic veto system since the neutrinos escape undetected. Most of the background in the experiment consists of extra particles in the final state which means the hermetic veto system is crucial to controlling these backgrounds. The major parts of the detector can be seen in Figure 1.

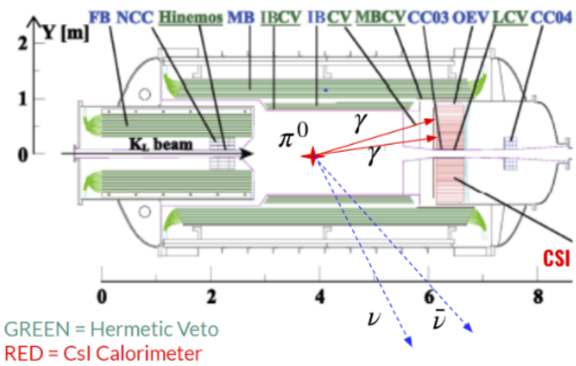

Figure 1. A signal decay example within the KOTO detector fiducial region.

1.1. The DAQ
The KOTO Data Acquisition System consists of nearly 4,000 independently read out channels. There is a spill-like data structure where the beam comes and goes in two seconds intervals. The KOTO trigger rate during the 2021 data-taking sessions is around 10,000 triggers per spill which corresponds to a beam intensity of 60 kW. Accelerator upgrades in the near future will push the beam intensity towards 100 kW meaning nearly a factor of two increase in trigger rates. The Level 2 Boards currently used by KOTO, which perform the data assembly for an ADC crate, cannot perform at such high rates. The Level 3 Nodes must finish the event building, as each one receives only a single crate of data. The box diagram for the current DAQ system is shown in Figure 2.

2. The Current Data Acquisition System
The bottleneck in the current system occurs due to the current level 2 (L2) trigger board. They cannot read and write simultaneously and are limited to a single 1Gbps output line. For each spill, the L2 Trigger Board will accumulate the data and during spill-off, the module will push out all of that data at 1Gbps. This limits the total throughput to 10-15k triggers per spill while also complicating the design strategy.

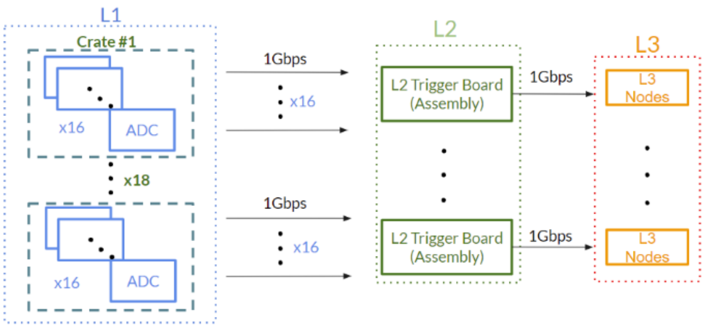

Figure 2. Data flow diagram through the current KOTO DAQ system

3. The New Data Acquisition System
The new DAQ system employs a pyramid-style structure (see Figure 3) which greatly simplifies the data-handling. The data for each crate will be assembled in an optical fiber center (OFC-1), and the entire event will be assembled in a high level OFC, called OFC-2, before it reaches Level 3. This simplification of data handling allows the flexibility to perform late level trigger in order to reduce output data rates.

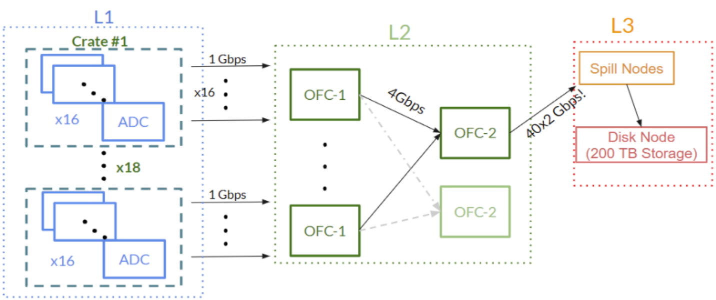

Figure 3. Data flow diagram through the new KOTO DAQ system

The new OFC modules, shown in Figures 4 and 5, have a hugely improved throughput relative to the old Level 2 modules. The OFC-1 has 18 SFP I/O which can transfer data up to 4Gbps while being able to read and write simultaneously. The OFC-2 has 9 QSFP I/O which can transfer up to 40Gbps each. This means our maximum throughput increased from 10-15k triggers per spill, to 30k (60k) triggers per spill with one (two) OFC-2 modules. That increase in throughput will give KOTO the ability to open up our physics trigger and take additional interesting physics data such as $K_L \to \pi^0 e^+ e^-$.

Figure 4. OFC-1 consists of an Arria 5 FPGA, and 18 SFP I/O (4Gbps). Most are used for the 16 ADC module output per crate, and only two are available for output.

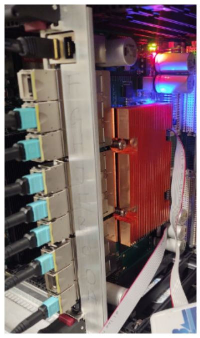

Figure 5. OFC-2 is a major upgrade from the OFC-1. The FPGA is a Stratix X with 8GB of high bandwidth on chip memory. There are 9 QSFP I/O which can send and receive data at 40Gbps.

Lastly, this system is expandable. By inserting a second OFC-2, the max throughput will double. Furthermore, if we ever need to increase our trigger rates even more than a factor of six, we can either add more OFC-1 or OFC-2 to the system to further improve the throughput. This means this DAQ system is robust to any future changes.

4. Conclusion

The KOTO DAQ required a major upgrade due to upcoming increases in beam power. The new system includes two new Chicago made modules to improve the data throughput by a factor of four. Simultaneously, the upgrade simplifies the DAQ architecture by implementing a pyramid-style structure. This opens up the level 3 for more complicated late stage trigger decisions, and allows KOTO to study additional interesting physics triggers. Moving forward, the new DAQ system will be able to handle upwards of 30k triggers per second with minimal loss, while being scalable and robust. This is necessary as the collaboration moves towards the development of KOTO II which is the next stage of the KOTO experiment aiming for 100 times Standard Model single event sensitivity of $K_L \to \pi^0 \nu\overline{\nu}$.

5. References

[1] Buras, A.J., Buttazzo, D., Girrbach-Noe, J. et al. $K^+ \to \pi^+ \nu\overline{\nu}$ and $K_L \to \pi^0 \nu\overline{\nu}$ in the Standard Model: status and perspectives. *J. High Energ. Phys.* **2015**, 33 (2015). https://doi.org/10.1007/JHEP11(2015)033