Enabling the Next-Generation Waveform Readout for the K-long and Muon Detector at Belle II

Chris Ketter[1]

[1]Department of Physics, The University of Hawaii at Mānoa

Overview

The Belle K-long and muon (KLM) sub-system was upgraded for Belle II to replace a large portion of the resistive plate counters with 18,560 scintillator channels. The scintillators are made from polyvinyl toluene, embedded with a central wavelength-shifting fiber, and instrumented with Hamamatsu silicon photomultipliers (SiPMs). SiPM hits are read out using the TARGETX waveform-sampling and triggering ASIC. These TARGETX ASICs have been operating in a triggering-only mode since the beginning of the Belle II experiment. This work describes the efforts and progress toward utilizing the waveform-sampling feature of these ASICs, with an emphasis on using the waveform-sampling firmware to perform a gain calibration on all of the SiPMs.

The TARGETX Waveform-Sampling ASIC

The TARGETX is a 16-channel waveform-sampling and triggering ASIC. Dubbed "The oscilloscope on a chip," it's capable of sampling all 16 channels at 1 GHz and storing each sample in a switched-capacitor array with a depth equivalent to 16 μs. It has 32 12-bit Wilkinson ADCs for each channel. Waveform data from selected storage cells can later be digitized and transmitted for downstream processing. Triggering is independent of sampling, and triggering threshold on each channel can be tuned with a 12-bit DAC. Dedicated trigger bits that encode which channels triggered are transmitted within 40 ns after detection.

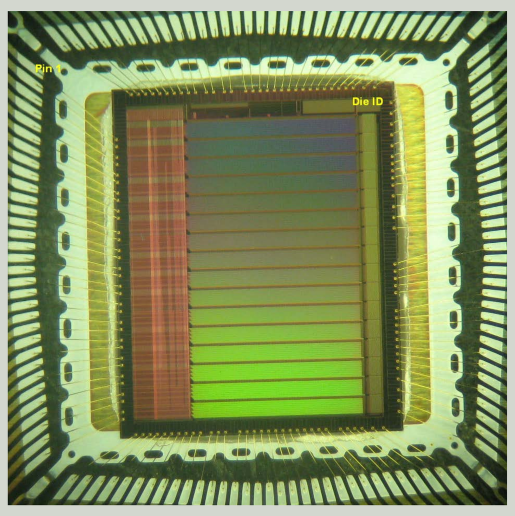

Figure 1: Die photograph of the TARGETX ASIC.

Firmware Requirements

- Triggers
  - Keep track of single channel triggers and trigger times after transmitting
  - Receive global triggers and determine if single channel triggers were present during lookback window of interest
- Rates
  - Be capable of handling global trigger rates up to 30 kHz (Poisson distributed)
  - Handle consecutive triggers within 200 ns of one another
- Feature extraction
  - Needs to analyze waveform data to determine precise charge and timing information
  - Be able to measure pedestal values and later perform pedestal subtraction on waveform data
  - Encode charge, hit time, trigger time, and channel ID in an 8-byte packet
- Calibration
  - Should have modes for calibrating trigger thresholds for each channel and bias voltages for each SiPM

Firmware Design

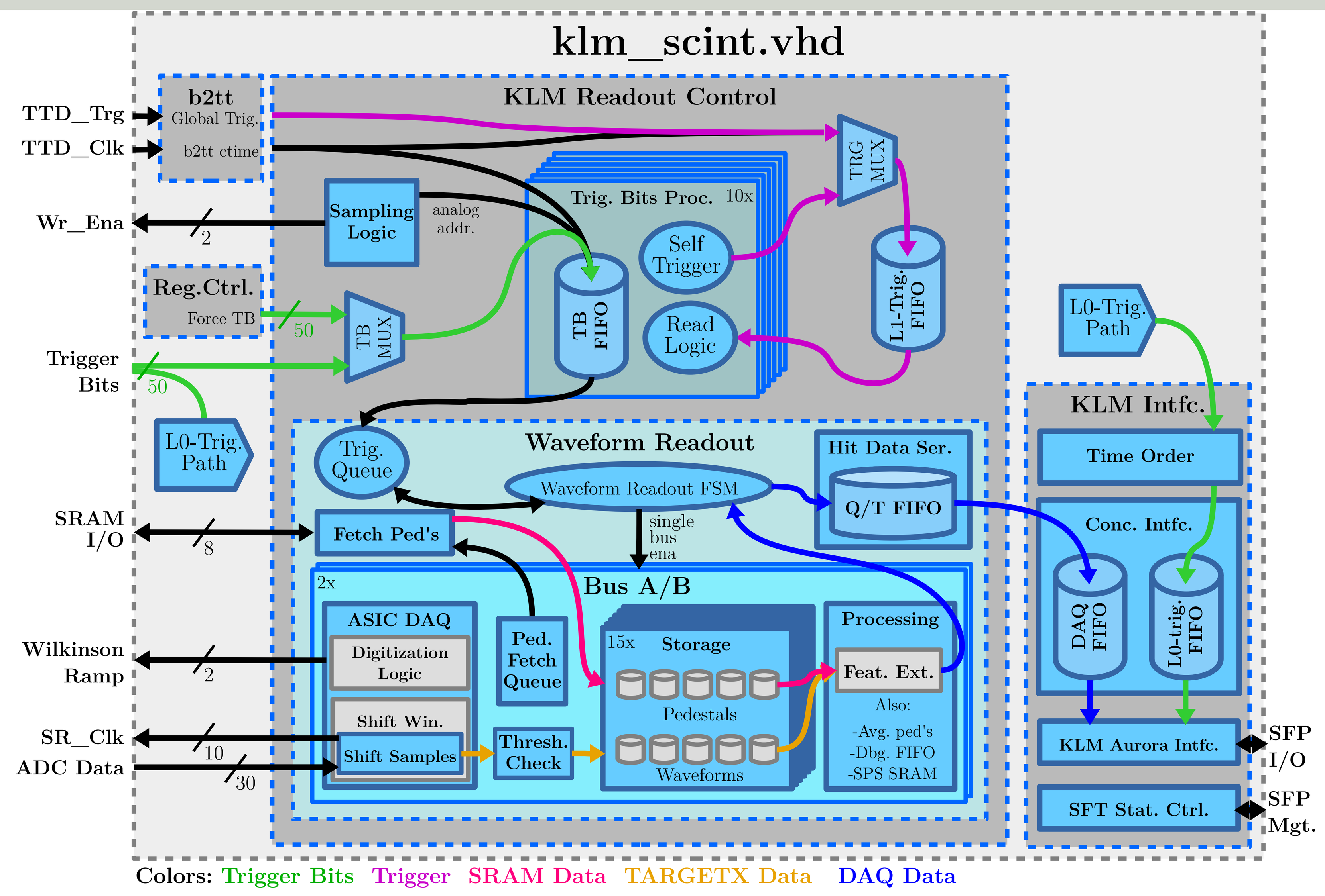

Figure 2: Block diagram depicting the structure of the KLM scintillator readout firmware. Firmware modules which are duplicated many times in the FPGA for parallel operation are indicated by the stacked blocks. This firmware project began as chalkboard sketch of this very diagram. It elucidates the value of diagrammatic planning for a complicated firmware project.

SiPM Tuning

Silicon photomultipliers output a pulse that is proportional to the number of pixels fired for a given event. The gain of the device can be determined by measuring the voltage difference per pixel fired.

Due to the large number of channels in the KLM detector and to limitations of the Belle II data acquisition system, we decided to extract the SiPM pulse features in firmware and create a histogram of the results using internal memory on the FPGA. The results are then accessed through the register interface and gain fits are performed offline using the equation

$$f(x) = A \sum_{i=1}^{N_{PE}} \chi^i e^{\frac{-(x-(ia_0+x_0))^2}{2(i\sigma_1+\sigma_0)^2}} \quad (1)$$

where A is a generic scaling parameter, N_{PE} is the number of photo-electron peaks in the fit function, χ is the optical cross-talk probability, a_0 is the mean separation between adjacent peaks, x_0 is a pedestal offset, σ_0 is a Gaussian width parameter describing electronic noise and ADC resolution, and σ_1 is a Gaussian width parameter that scales with the number of pixels fired.

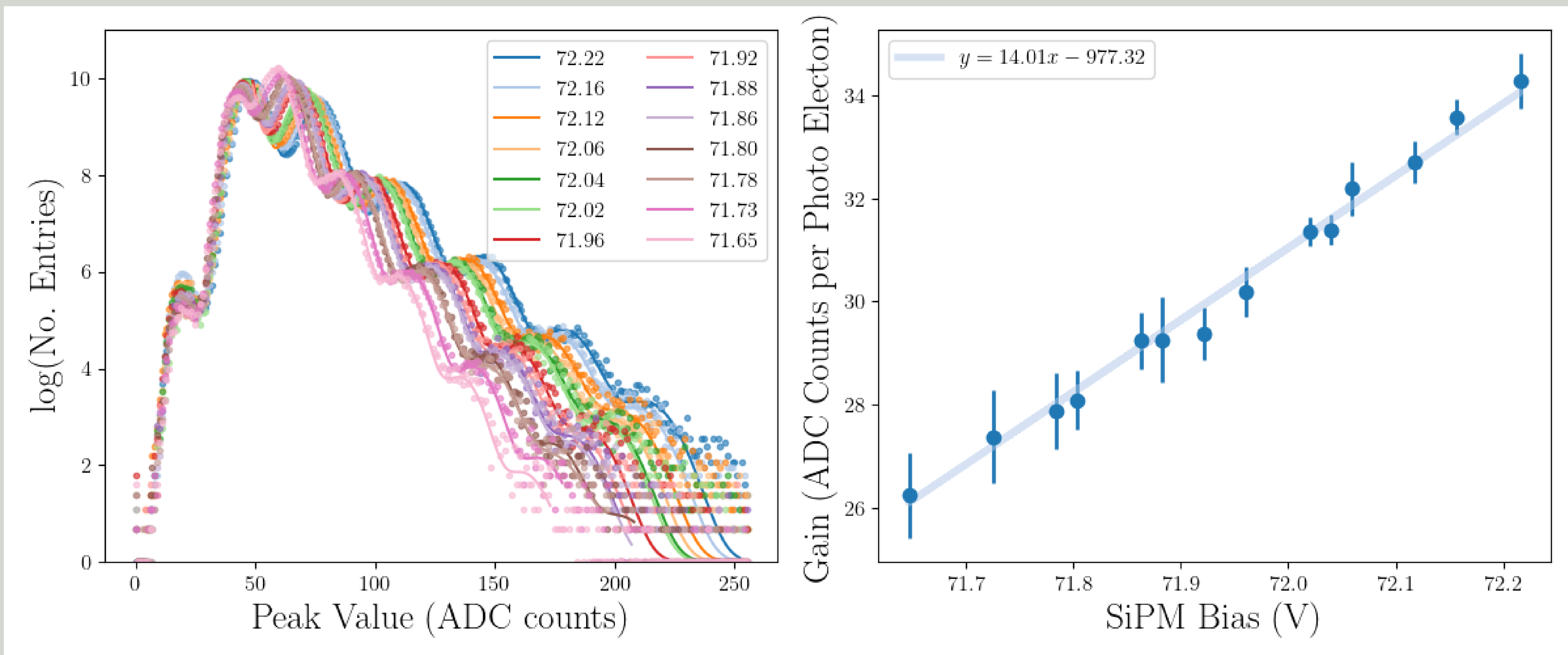

Figure 3: Example of the gain measurement procedure for a single SiPM channel in KLM. Left: several single-photon spectra collected at different bias voltages. Each one is fit to eq. (1) to determine the peak-separation parameter a_0. Right: linear fit of a_0 versus SiPM bias voltage.

Calibration Results

The above procedure was repeated for all 18,560 SiPM channels in the Belle II KLM detector. Knowledge of gain as a function of bias voltage allows us to pick one value for gain and set the bias voltage on every channel to match that gain as close as possible. Not all of the distributions were as well behaved as the example above. The following summarizes fit results for all channels.

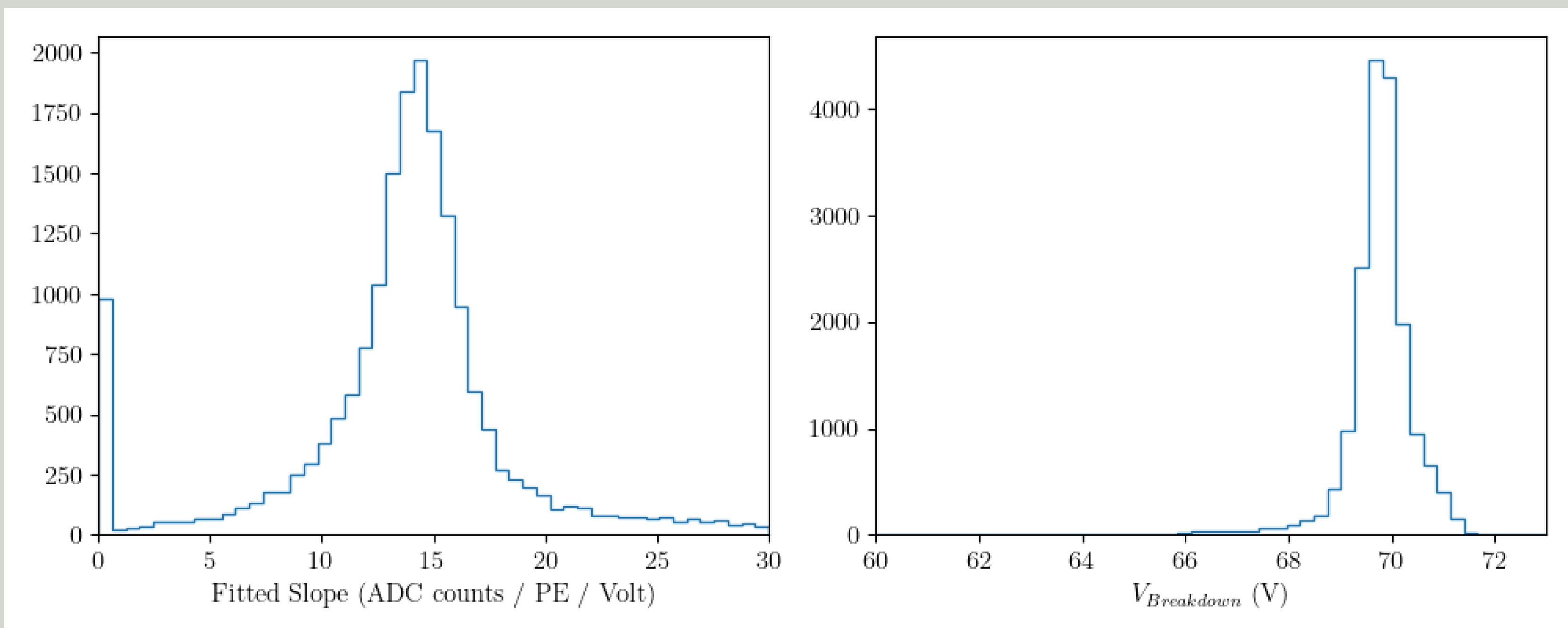

Figure 4: Summary of the gain fit results for all Belle II KLM SiPM channels. Left: Fitted SiPM gain/volt. The peak at zero represents channels that failed the fit. Future work involves trying to remedy many of these channels. Right: X-intercept of the gain/volt fits. The failed fits are suppressed here. This represents the breakdown voltage of the SiPMs.

Summary & Status

- **Completed** design of a firmware that meets all the requirements
- **Performed** precise gain calibration on all 18,560 SiPMs in the detector
- **Currently** testing the firmware performance on the Belle II detector in preparation deployment at start of next physics runs in 2024

Acknowledgments

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ckketter@hawaii.edu