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An algorithm for simulating the electronics threshold of the BCAL readout device

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The goal of this document is to outline an algorithm to simulate the electronics threshold for the barrel calorimeter (BCAL) in the GlueX Monte Carlo given a specific set of performance parameters of a readout device, *e.g.*, dark rate, PDE, etc. This document should *not* be considered a reference for hardware specifications or parameters, instead it documents how these parameters might affect the electronics threshold. This is one piece of an overall program to accurately model the efficiency and resolution of low energy showers. A typical shower distributes energy over several cells; therefore the readout threshold affects the response in two ways: (1) it sets a lower limit in the minimum photon energy that is detectable; and (2) it produces a leakage effect in reconstruction as it sets a limit on the energy that must be deposited in cells around the periphery of the shower in order for the cell be incorporated into the cluster. Any portion of the energy deposited in a cell that does not exceed the threshold is effectively lost. Both of these effects have implications on the overall performance of the detector and physics capabilities; therefore, an accurate model of the cell threshold is critical.

In addition to the affecting the electronics threshold, the parameters of the readout device are directly linked to the photon reconstruction resolution. Variations in photon detection efficiency and dark rate produce statistical fluctuations in measured energy an a cell. An extensive discussion of these effects can be found in Ref. [1].

1 Readout overview

1.1 The need for a threshold

It is helpful to first review the general strategy for reading out the BCAL. For the sake of discussion, we assume that the readout device in the inner layers of the BCAL will be a Silicon Photomultiplier (SiPM). There will be one SiPM on each of the upstream and downstream ends of a cell. Analog signals from the SiPM will be fed into a flash ADC[1]. For each triggered event the flash ADC must determine the total signal above pedestal for each of the analog inputs. It must then suppress those channels with zero signal and send the information for the remaining channels over the backplane of the crate and up the readout chain. This zero suppression, which is necessary to limit bandwidth requirements and raw event size, produces the need for a threshold.

[1] There will also likely be discriminators and TDCs in the BCAL readout scheme; however, they are not relevant to the present discussion.

1.2 What drives the threshold?

When triggered, the flash ADC processes a portion of its buffer for every channel. The buffer is examined using some signal processing algorithm to determine the total pulse height above pedestal. The most straightforward way to this is to compute a total charge Q as

$$Q = \sum_{i=1}^{N} (V_i - V_0), \tag{1}$$

where the sum runs over the N samples in the buffer, V_i is the pulse height for each sample, and V_0 is some previously determined pedestal corresponding to a DC offset of the analog input. Typically one sets the threshold such that when there is no signal in a particular channel, the probability that a fluctuation in the measured $\sum_{i=1}^{N} V_i$ from the value NV_0 exceeds the threshold is small ($\mathcal{O}(1\%)$). In the current discussion we will assume that V_0 is known precisely and that upward fluctuations in the measured $V_i - V_0$ are produced entirely by dark pulses in the SiPM and *not* electronics noise or small drifts in the actual pedestal from the assumed value V_0. At a typical rate of 4 dark pulses per buffer (40 MHz $\times$ 100 ns) the probability of having zero pulses in a buffer is less than 2%, which seems to validate this assumption.

2 Setting a photoelectron threshold

Let's now determine the pixel or number of photoelectron threshold. In the case of the SiPM one "photoelectron" is equivalent to one pixel in the array being turned on. The dark rate in the SiPM is the total rate at which single pixel pulses are coming out of an entire array. There is a secondary cross-talk effect in that turning on one pixel in the array sometimes turns on a neighboring pixel. Given some desired dark occupancy in the detector, *i.e.*, a rate at which cells with no energy pass zero suppression algorithm, we can compute the threshold needed to achieve this level of zero suppression.

2.1 Assumptions

The assumptions or input parameters needed are outlined below.

- **Dark Pulse Rate:** ν_d. This is the rate of single pixel pulses integrated over a full array. We assume $\nu_d = 40$ MHz.
- **Cross Talk Probability:** p_x. This is the probability that any one fired pixel will cause one neighboring pixel to fire. We assume $p_x = 0.03$.
- **Integration Window:** Δt. This is the size of the buffer in the fADC that is integrated. One should try to make this as small as possible with the restriction that the buffer size is large enough to contain the entire pulse from the readout device and also has sufficient margins on either side of the pulse to account for variations in the transit time of the signal, *e.g.* a photon that leaves the target intercepts the downstream end of the BCAL will produce a pulse in the upstream readout device tens of nanoseconds later than a photon that leaves the target and intercepts the upstream end of the BCAL. We assume $\Delta t = 100$ ns.

- **Maximum Occupancy:** $f_{\max}$. This is the limit on the fraction of the number of channels that are allowed to pass the zero-suppression algorithm in an event that no physics signal in the detector. The actual fraction of channels appearing in the readout stream will typically be slightly higher than $f_{\max}$. The limit $f_{\max}$ is directly related to bandwidth available out of the create and drives the BCAL portion of the raw event size. We assume $f_{\max} = 5\%$.

2.2 Calculation and behavior of threshold

The average number of dark pulses in an integration window μ_d is given by

$$\mu_d = \nu_d \Delta t. \tag{2}$$

Therefore, the probability of having n_d dark pulses in window is given by

$$P(n_d) = \frac{e^{-\mu_d}\mu_d^{n_d}}{n_d!}. \tag{3}$$

Given some actual number of dark pulses n_d. The average number of secondary cross-talk pulses is then $n_d p_x$, and the probability of having n_x cross-talk pulses is

$$P(n_x) = \frac{e^{-n_d p_x}(n_d p_x)^{n_x}}{n_x!}. \tag{4}$$

We need to build the probability for $P(n)$, where $n = n_d + n_x$. We have

$$P(n_d, n_x) = \left(\frac{e^{-\mu_d}\mu_d^{n_d}}{n_d!}\right)\left(\frac{e^{-n_d p_x}(n_d p_x)^{n_x}}{n_x!}\right). \tag{5}$$

Rewriting $n_d = n - n_x$ and summing over n_x which must have a range from $0 \to (n-1)$ gives

$$P(n) = e^{-\mu_d}\sum_{n_x=0}^{n-1}\frac{\mu_d^{(n-n_x)}e^{-(n-n_x)p_x}[p_x(n-n_x)]^{n_x}}{n_x!(n-n_x)!}. \tag{6}$$

It is a relatively simple task to compute $P(n)$ numerically[2]. All that remains then is to find the threshold $n_{\min}$ such that

$$1 - \sum_{n=0}^{n_{\min}} P(n) < f_{\max}. \tag{7}$$

This then sets the minimum number of photoelectrons a pulse must have to exceed the threshold. Based on the assumptions listed above, this threshold is 9 photoelectrons. Figure 1 shows how the threshold varies with each of the input parameters while the others remain fixed at the nominal values. For simultaneous variations of more than one parameter, the calculation should be repeated to obtain the correct threshold.

[2] Practically, for small p_x, such as the value we are assuming, the deviation of $P(n)$ from a Poisson is negligible; however, this formalism provides a framework for dealing with devices with significantly higher cross talk rate.

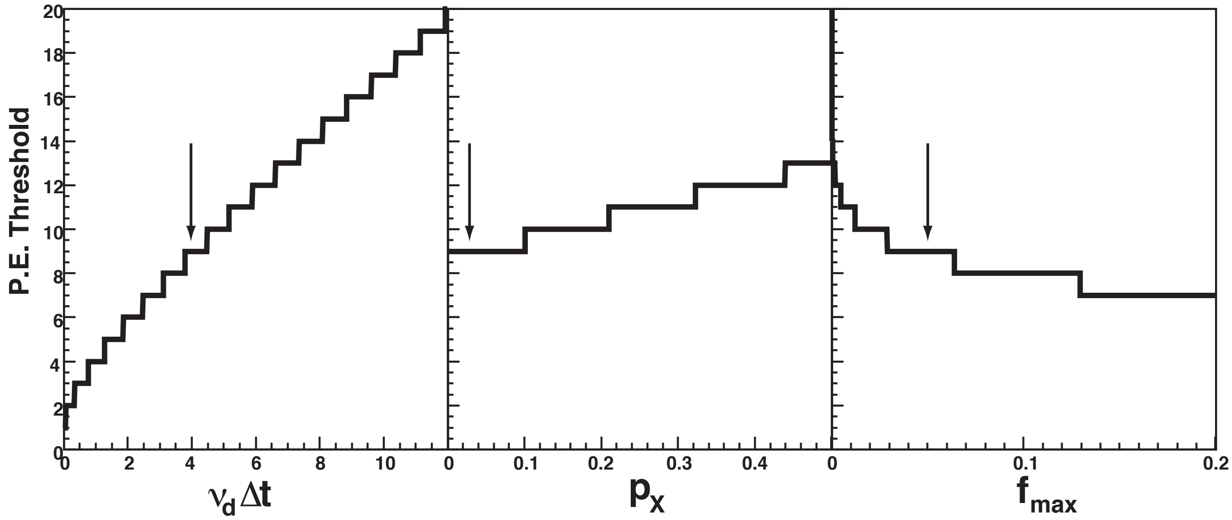

Figure 1: Plots of the dependence of photoelectron threshold ($n_{\rm min}$) on the inputs to the algorithm. The nominal values of each parameter are indicated by the arrows. For each plot, only the parameter plotted is being changed – all other parameters are held at the nominal values.

3 Setting the cell energy threshold

Once we know the minimum number of photoelectrons, what remains is to convert this into an effective energy deposited in the cell. The GEANT simulation records only total energy deposited in the lead/fiber/epoxy matrix – the details of the matrix are not simulated. The code "propagates" this energy from the point of deposition to either end of the module using a factor derived from the attenuation length of the fiber. One then needs to convert this "attenuated bulk deposited energy" into a number of photoelectrons, or, equivalently, cast the photoelectron threshold above in terms of the energy.

3.1 Assumptions

To do this, we need to again make several assumptions outlined below.

- **Number of Photons per Side per MeV Deposited in Fiber:** $\mathcal{G}$. This is the number of photons produced at the location of energy deposition that propagate down toward one end of the fiber. It should include only the component of the photon spectrum that is capable of propagating significant distances down the fiber; however, it should not include the effects of attenuation. We assume $\mathcal{G}$=75 photons/side/MeV. This number is derived from Table 1 of Ref. [2] after correcting for attenuation and estimated PDE of the device used in the referenced report.

- **Sampling Fraction:** $\mathcal{F}$. This is the fraction of the active volume of the detector that is occupied by scintillating fiber. We assume $\mathcal{F} = 0.15$.

- **Photon Detection Efficiency:** η. This is the efficiency with which a photon striking the readout device produces a photoelectron. In general this is a function of the wavelength of the photon; however, it is relatively constant over the more narrow emission spectrum of scintillating fiber. We assume $\eta = 0.12$.

3.2 Calculation of cell energy threshold

For some attenuated bulk deposited energy E, the number of produced photoelectrons is $\mathcal{F}\mathcal{G}\eta E$. Therefore we can cast the minimum number of phototelectrons n_{min} in terms of an energy threshold (in MeV) as

$$E_{\mathrm{min}} = \frac{n_{\mathrm{min}}}{\mathcal{F}\mathcal{G}\eta}. \tag{8}$$

Using the assumptions stated above, a 9 photoelectron threshold corresponds to threshold of 6.7 MeV of attenuated bulk deposited energy. It should be stressed that this estimation of the threshold assumes perfect signal processing. Any other electronics noise or variation in the pedestal that produces upward fluctuations in the measured pulse height will only increase the true operational threshold.

4 Implementation of threshold

The threshold derived above gets implemented in what is known as the `DBCALMCResponse_factory` which models the conversion of a deposit of energy in a cell (provided by GEANT) into a BCAL hit that can be processed by the clusterizer. The output of GEANT is a z location and quantity of energy deposited in a calorimeter cell. The response modeling first smears this energy to simulate fluctuations in the fiber sampling fraction, which have been independently studied [3]. Then, this smeared energy is attenuated to each end of the BCAL based on input attenuation length parameters. This creates an attenuated bulk deposited energy at each end of the module. Cells with an energy below threshold determined by Eq. 8 are then pruned from the list of BCAL hits.

References

[1] E. S. Smith, "Specifications and evaluation of BCAL readout options," GlueX-doc 795.

[2] A. Semenov *et al.*, "Number of photoelectrons extracted using a SiPMPlus array and BCAL module 2," GlueX-doc 1069.

[3] B. Leverington, "Sampling fraction fluctuations," GlueX-doc 827.