CLAS12 Central Time-of-Flight System
Monte Carlo Simulation Details

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Abstract

This write-up details the algorithms for the CLAS12 CTOF system for determining the ADC and TDC values for the Monte Carlo digitization routines, as well as the relevant performance and operating characteristics for this system to be modeled within the GEMC GEANT-4 Monte Carlo simulation.

1 CTOF Overview

The Central Time-of-Flight (CTOF) system is the CLAS12 detector used to measure the flight time of charged particles emerging from interactions in the target in the angular range θ from 35° to 125°. The system specifications call for an average time resolution for each counter along its full length of σ_{TOF}=60 ps. The CTOF detector surrounds the experimental target at a radial distance of 25 cm and consists of 48 92-cm-long scintillation bars having a trapezoidal cross section that form a hermetic barrel (see Fig. 1). The barrel will be positioned inside of the CLAS12 5 T superconducting solenoid magnet. Each counter is read out via a PMT on each end through long light guides to position the field-sensitive PMTs in reduced field regions. However, even in these positions, the PMTs will reside in inhomogeneous fringe fields from the magnet at levels as large as 1 kG, hence the CTOF PMTs must be operated within specially designed multi-layer magnetic shields. A summary of the CTOF technical parameters is given in Table 1.

The CTOF scintillation barrel is composed of 48 wedge-shaped counters of two slightly different designs that alternate in azimuth (see Fig. 1). The difference between the two designs is in the pitch angle of the upstream straight light guide and the upstream end of the scintillation bars where they attach to this light guide. This design feature is necessary to allow for sufficient spacing for the massive magnetic shields and their associated support structure. These two different designs are referred to as the "low-pitch" angle and "high-pitch" angle designs. The downstream elements of the design are identical for all counters.

2 CLAS12 CTOF Monte Carlo

The GEANT-4 Monte Carlo suite for CLAS12 known as GEMC [1], includes realistic representations for each of the CLAS12 detector subsystems based on their nominal design

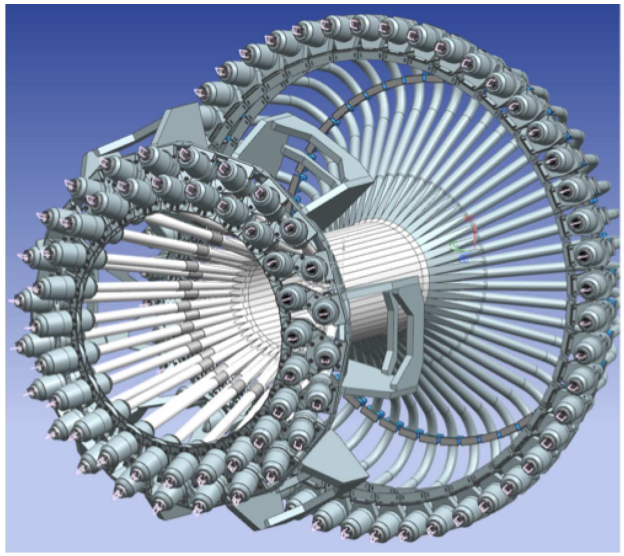

Figure 1: View of the CTOF system for CLAS12. The scintillation bars form a hermetic barrel and the PMTs are attached to the ends of long light guides.

Parameter	Design Value
Counters	48 BC-408 counters forming a hermetic barrel; double-sided readout
Angular Coverage	θ: (35°,125°), ϕ: (-180°,180°)
Counter Dimensions	Trapezoidal cross section $\sim 3 \times 3 \times 92$ cm^3
PMTs	Hamamatsu R2083 (H2431-MOD assembly)
Light Guides - Upstream	O.D.=2″, 1-m-long, focusing design, straight
Light Guides - Downstream	O.D.=2″, 1.6-m-long, focusing design, bent 135°
Magnetic Shields	3-layer cylinder: Co-netic, Hiperm-48, Steel-1008; compensation coils around inner Co-netic layer
Design Resolution	60 ps
π/K separation	3.3σ up to 0.64 GeV
K/p separation	3.3σ up to 1.0 GeV
π/p separation	3.3σ up to 1.25 GeV

Table 1: Table of design parameters for the CTOF detector system.

parameters. To assist with this modeling, a detailed geometry specification document has been prepared for the CTOF [2] system. The simulation is designed to provide as output the same quantities that are output from the readout electronics used for the detectors, namely the ADC and TDC values associated with the measured energies and times. The digitization of these quantities must ultimately match the measured characteristics of the counters in a highly realistic manner. In this section the algorithms for determining the ADC values based on the actual deposited energy values and the TDC values based on the actual hit times are described. In addition, the CTOF parameters that allow for matching the Monte Carlo output with the actual detector parameters are detailed. The digitization is carried out in the GEMC CTOF "hit process" routine [3]. The CTOF calibration database parameters are detailed in full in Ref. [4].

The calibration database for CLAS12 (called "ccdb") includes the following parameters for the CTOF:

- Hardware status for each PMT [status]
- Attenuation length and uncertainty for each counter [attenuation]
- Effective velocity and uncertainty for each end of the counter [effective_velocity]
- Minimum ionizing peak location and uncertainty for each end of the counter [gain_balance]
- Time offset parameters (end-to-end, counter-to-counter) for each counter [timing_offset]

Note that due to the use of constant fraction discriminators for the readout, no time-walk correction parameters are included in the database and such affects are not considered in the simulation.

In the following subsections, the algorithms for digitization of the ADC and TDC values are described in detail along with the parameters necessary to provide for a realistic Monte Carlo description of the counter responses.

2.1 ADC Digization

Detailed gain-matching of all CTOF counters has been completed in the CTOF assembly area using cosmic ray muons. The gain matching was based on adjusting the high voltage settings for each PMT to position the minimum-ionizing peak for normally incident tracks in a given channel of the FADC spectrum. This procedure balances the gains of the upstream and downstream PMTs for each individual bar. In fact, as the counters can be assumed to be identical, neglecting the slight differences between the low-pitch angle and high-pitch angle designs, all CTOF PMTs can be considered gain match to each other.

For the HV calibrations, to avoid issues with the attenuation of light for tracks that pass near the ends of the bars and to avoid issues with unbalanced photon statistics for the upstream and downstream PMTs, we combine the ADC information from the upstream and downstream PMTs to produce a geometric mean ADC spectrum for the counter through the quantity:

$$\overline{ADC} = \sqrt{(ADC_U - PED_U) \cdot (ADC_D - PED_D)}. \quad (1)$$

Given the finite dynamic range of the ADC, we have chosen to position the minimum ionizing muon peak in a particular ADC channel so that it is safely above the pedestal, but leaves sufficient range for the more highly ionizing charged tracks of our typical physics events. The position of the muon peak in the ADC spectrum is set by the PMT HV setting.

For the case of a normally incident muon passing through the extent of the counters, they deposit roughly 6 MeV as they pass through the 3-cm thick CTOF counters (using $dE/dx = 1.956$ MeV/cm for minimum ionizing particles in EJ-200). Note that the ADC distribution is described by a Landau distribution sitting on an exponentially falling background. Fig. 2 shows the average ADC spectra typical for the CTOF counters.

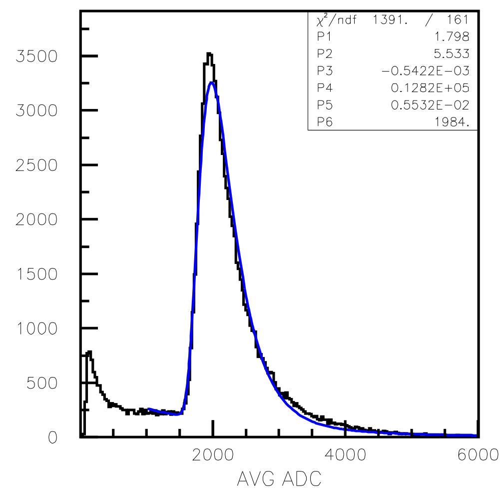

Figure 2: Average ADC spectrum for a representative gain-matched CTOF counter.

Given the actual deposited energy E_{dep} in the bar, the energy measured by the upstream and downstream PMTs is given by:

$$E_U = E_{dep} \exp\left[\frac{-y_U}{\lambda_U}\right], \tag{2}$$

$$E_D = E_{dep} \exp\left[\frac{-y_D}{\lambda_D}\right], \tag{3}$$

where,

- y_U and y_D are the distances along the bar from the hit position to the upstream and downstream PMTs, respectively (see Fig. 3)
- λ_U and λ_D are the attenuation lengths for readout through the upstream and downstream ends of the counter, respectively (see Section 2.2).

The geometric mean for the deposited energy is defined as:

$$\langle E_{dep}\rangle = \sqrt{E_U E_D} = E_{dep}\left[\exp\left(\frac{-y_U}{\lambda_U}\right)\exp\left(\frac{-y_D}{\lambda_D}\right)\right]^{1/2} = \mathcal{G}E_{dep}, \tag{4}$$

where the gain factor is given by:

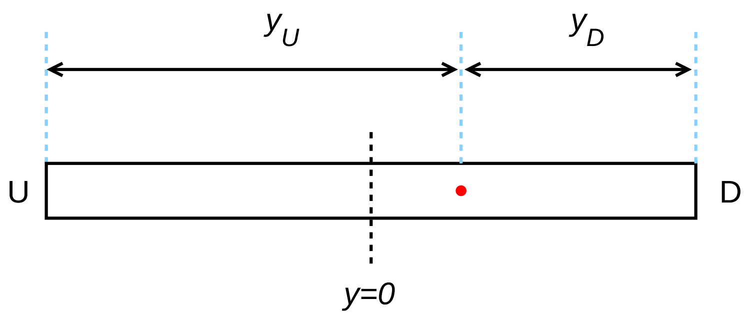

Figure 3: The track hit position along the scintillation bar is shown by the red dot and the distances along the bar from the hit point to the PMT, y_U and y_D, are shown.

$$\mathcal{G} = \left[\exp\left(\frac{-y_U}{\lambda_U}\right)\exp\left(\frac{-y_D}{\lambda_D}\right)\right]^{1/2} \tag{5}$$

Accounting for this gain factor in the determination of the ADC values allows for the reproduction of the geometric mean distributions shown in Fig. 2.

The simulation determines the energy deposited in a given scintillation bar from a passing charged particle along its path. The path is defined between the hit entry point and the hit exit point. The light generated by the passing charged particle then propagates to the PMTs at either end of the bar. The conversion of the truth value of deposited energy to the recorded ADC values (ADC_U and ADC_D) must take into account that the number of generated photoelectrons at each PMT is subject to Poisson fluctuations. The digitization of the CTOF ADC values for each counter hit proceeds using the following steps:

1. Compute the energies measured by the upstream and downstream PMTs based on the deposited energy and the distances along the bar from the hit point to the PMTs as given in Eqs.(2) and (3).

2. Determine the number of photoelectrons measured by the PMTs from the computed values of E_U and E_D. Based on studies carried out with the FTOF detectors, a reasonable parameterization of the number of photoelectrons N_{pe} is given by:

$$N_{pe}^U = E_U \cdot CONV \cdot QE, \tag{6}$$
$$N_{pe}^D = E_D \cdot CONV \cdot QE, \tag{7}$$

   where,

   - $CONV$ = 1800 photoelectrons/MeV deposited
   - QE = 27% (the quantum efficiency of the PMT).

3. Smear N_{pe} by a Poisson distribution. The resulting "smeared" number of photoelectrons based on the actual deposited energy is given by N_{pe}^{SMR}.

4. Determine the smeared values of E_U and E_D using:

$$E_U^{SMR} = \frac{N_{pe}^{U,SMR}}{CONV \cdot QE}, \quad (8)$$

$$E_D^{SMR} = \frac{N_{pe}^{D,SMR}}{CONV \cdot QE}. \quad (9)$$

5. Determine the "measured" values of the upstream and downstream ADCs using:

$$ADC_U = \frac{E_U^{SMR}}{\mathcal{K}} \cdot \frac{1}{\mathcal{G}_U} = \frac{E_U^{SMR}}{\mathcal{K}} \left[\exp\left(\frac{-y_U}{\lambda_U}\right) \exp\left(\frac{-y_D}{\lambda_D}\right)\right]^{-1/2}, \quad (10)$$

$$ADC_D = \frac{E_D^{SMR}}{\mathcal{K}} \cdot \frac{1}{\mathcal{G}_D} = \frac{E_D^{SMR}}{\mathcal{K}} \left[\exp\left(\frac{-y_U}{\lambda_U}\right) \exp\left(\frac{-y_D}{\lambda_D}\right)\right]^{-1/2}. \quad (11)$$

Here,

- The term

$$\mathcal{K} = \left[\frac{\left(\frac{dE}{dx}\right)_{MIP} \cdot t}{ADC_{MIP}}\right] \quad (12)$$

  is a conversion factor to go from ADC channel to energy.

- ADC_{MIP} = ADC value for normally incident MIPs at the center of the scintillation bar
- $\left(\frac{dE}{dx}\right)_{MIP}$ = energy loss for MIPs in the scintillation bars (1.956 MeV/cm)
- t = scintillation bar thickness (cm)

Note that in the Monte Carlo $ADC_{U,D}$ actually represents $ADC_{U,D} - PED_{U,D}$, the pedestal-subtracted ADC value from the data. Also note that the database includes separate values for λ_U and λ_D. In practice these values are the same such that $\lambda_U = \lambda_D = \lambda$.

2.2 Counter Attenuation Lengths

The attenuation length of the scintillation bars represents the distance λ into the material where the probability that the photon has been absorbed is $1/e$. For the scintillation bars, more light collected translates into better timing resolution, so it is important for the attenuation length to be as long as possible. For scintillators, it is generally hoped that the attenuation length is at least on the order of the overall length of the bars.

For scintillation counters there are actually two attenuation lengths that are used. The first is the attenuation length for the bulk material. For EJ-200, this bulk attenuation length is reported by the manufacturer as 380 cm [5]. However, the effective attenuation length for a finite geometry scintillation bar is considerably shorter to the reflections at the surfaces of the bar, which inherently depend on the specific geometry of the bar. Therefore, the true practical attenuation length of the material turns out to be about half the bulk attenuation length. The average measured value for the CTOF counters (see Fig.4) is roughly 140 cm.

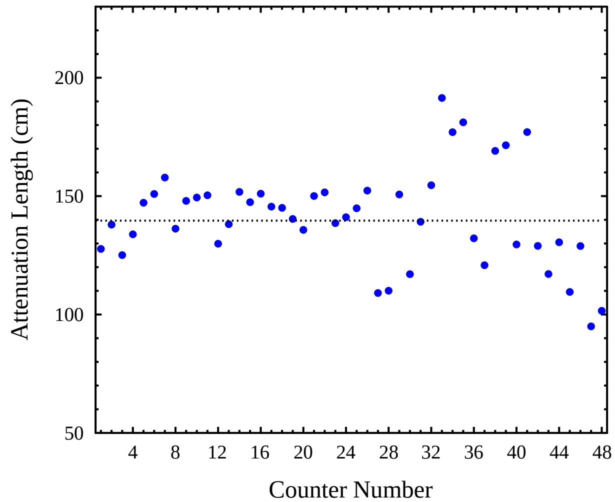

Figure 4: Measured counter attenuation lengths for all CTOF counters.

3 TDC Digitization

The digitized TDC value of the hit at the upstream and downstream PMTs should account for the propagation time for light from the relevant hit point of the passing charged particle on the scintillation bar. These TDC values also must account for the time resolutions of the counters. The digitization of the CTOF TDC values for each counter hit proceeds using the following steps:

1. Compute the time measured by the upstream and downstream PMTs based on the actual time of the hit t_{hit} using:

$$t_U = t_{hit} + \frac{y_U}{v^U_{eff}}, \tag{13}$$

$$t_D = t_{hit} + \frac{y_D}{v^D_{eff}}, \tag{14}$$

   where,

   - y_U and y_D are the distances along the bar from the hit position to the upstream and downstream PMTs, respectively
   - v^U_{eff} and v^D_{eff} are the effective velocities of light propagation along the bar toward the upstream and downstream PMTs, respectively (see Section 3.1).

   Note that the database includes separate values for v^U_{eff} and v^D_{eff}, although in practice these values are the same such that $v^U_{eff} = v^D_{eff} = v_{eff}$.

2. Smear the time values t_U and t_D based on the measured counter timing resolutions using a Gaussian distribution. The resulting "smeared" values are t^{SMR}_U and t^{SMR}_D.

   The data for the average CTOF counter timing resolutions are shown in Fig. 5. The resolutions can be approximated as:

- Low-pitch angle design: $\sigma_{counter} = 70$ ps
- High-pitch angle design: $\sigma_{counter} = 65$ ps

These resolutions are believed to be conservative upper limits. They are expected to be worse than the "true" counter resolutions due to the geometry misalignments inherent in the CTOF cosmic ray test stand. For the simulation a single counter time resolution of 65 ps can be assumed as a reasonable starting value.

Note that the Gaussian width for the smearing of the upstream and downstream PMT times is given by:

$$\sigma_{PMT} = \sqrt{2}\sigma_{counter}. \tag{15}$$

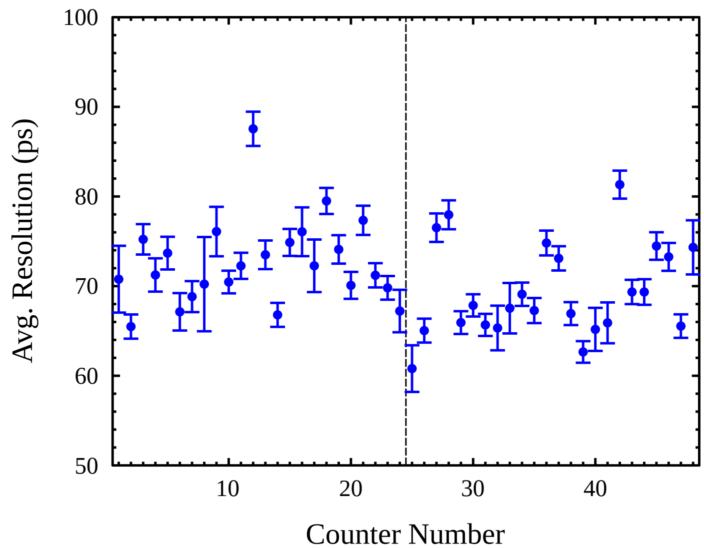

Figure 5: Average measured time resolutions for the CTOF counters vs. counter number.

3. Determine the digitized values of the upstream and downstream TDCs from the smeared times using:

$$TDC_U = t_U^{SMR}/\mathcal{C}_{TDC}, \tag{16}$$
$$TDC_D = t_D^{SMR}/\mathcal{C}_{TDC}, \tag{17}$$

where $\mathcal{C}_{TDC} = 0.024$ ns/bin is the TDC channel to time conversion factor.

3.1 Effective Velocity

For initial simulation modeling, the effective velocity of all CTOF counters should be set to $v_{eff} = 16$ cm/ns. This value can be updated for the different counters after the appropriate calibration data is collected and analyzed. The data for the CLAS TOF counters from the TOF NIM paper is shown in Fig. 6 [6].

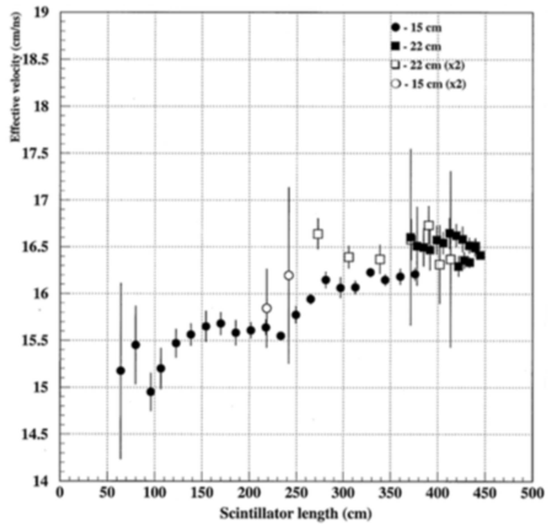

Figure 6: Average counter effective velocity (cm/ns) vs. counter length (cm) [6].

References

[1] GEMC, GEANT-4 Monte Carlo for CLAS12, http://gemc.jlab.org.

[2] V. Baturin and D.S. Carman, CTOF Geometry Document, CLAS12-Note 2016-001, (2016).

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