Description of the Calibration Algorithms for the CLAS12 Central Neutron Detector

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Abstract: This document describes all the algorithms used for the CLAS12 Central Neutron Detector (CND) time based calibration and energy calibration procedures.

Contents

1 Introduction

The Central Neuteon Detector (CND) is a scintillator barrel detector located in the CLAS12 Central Detector. It is used to detect neutron at backwards angles ($40°<\theta<120°$). The CND consists of 3 radial layers of 48 plastic scintillator paddles of trapezoidal shape. Adjacent paddles are coupled two-by-two at their downstream end with a "uturn" lightguide. Three pairs of coupled paddles are stacked up, one over the other, forming a sector. Overall there are 24 sectors of 6 paddles, for a total of 144 scintillators. The scintillation light is guided from the upstream ends of the scintillators to the PMT through 1.5m-long lightguides. The readout is done by PMTs located at the end of the lightguides.

The calibration of the CND is done in two steps. The first step is the time based calibration which allow to exctract effective velocities and time offsets. This calibration is necessary to obtain timing and position information of CND hits. The second step is the energy calibration, in which attenuation lengths and energy conversion factors are exctracted.

2 Calibration constants for the CND

Step #	Constant name	Output	Number of constants
1	Left-Right timing offset	LR_{off}	72
2	Effective velocity	v_{eff}	144
3	U-turn time loss	u_{tloss}	72
4	Left-Right timing offset (adjusted)	LR_{offad}	72
5	Global time offset	t_{off}	72
6	Attenuation length	Att_L	144
7	Energy constants	MIP_D, MIP_I	144 each

Table 1: The steps of the CND calibration.

3 Time based calibration algorithms

There are four time based calibration constants for the CND. These constants are the Left-Right time offset (LR_{off} and LR_{offad}), the effective velocity (v_{eff}), the time loss in the u-turn (u_{tloss}) and the global time offset with respect to the start time (t_{off}). The calibrations of these constants must be done in the following order: LR_{off}, v_{eff}, u_{tloss}, LR_{offad} and eventually t_{off}.

3.1 TDC to time constant

Raw TCD values are converted in time using a TDC slope constant TDC_to_time. This constant is set to 0.0234ns for every paddle. The raw time $t_{L/R}$ from $TDC_{L/R}$ is given by :

$$t_{L/R} = TDC_{L/R} \cdot TDC\_to\_time \tag{1}$$

3.2 Left-right timing offset

The Left-Right time offset refers to the time misalignement between two coupled paddles. The goal of this calibration step is to find this offset. This offset is detemined in two steps.The first step relies on the u-turn structure of the CND to extract an estimate of this offset LR_{off}. The second part of the algorithm adjust this first value to the real value LR_{offad} by taking into account effective velocities of bothe coupled paddles. There is one value of LR_{off} and LR_{offad} for each pair of paddles.

There are two different algorithms to find LR_{off} depending if the solenoid magnetic field is on or off.

- If the solenoid field is off, the u-turn light guide coupling two adjacent CND paddles induces a gap in the time difference $t_R - t_L$ plots. The position of this gap is found by the calibration software. The algorithm to find the gap looks around the center of the whole time difference distribution for bins which content value is bigger than a predefined threshold. This allow to find the edges of the gap. The center of the gap is defined as the central value between the two edges of the gap. The LR_{off} constant is defined as the time difference value at the center of the gap.
- If the solenoid is on, double hits occurs. Double hits happens when the trajectory of a charge particles crosses two adjacent coupled paddles. This produces to signal with very close TDCs. Double hits are illustrated in Figure 1. Because of double hits, a peak is visible instead of a gap (see Figure 2). LR_{off} is defined as the position of the peak.

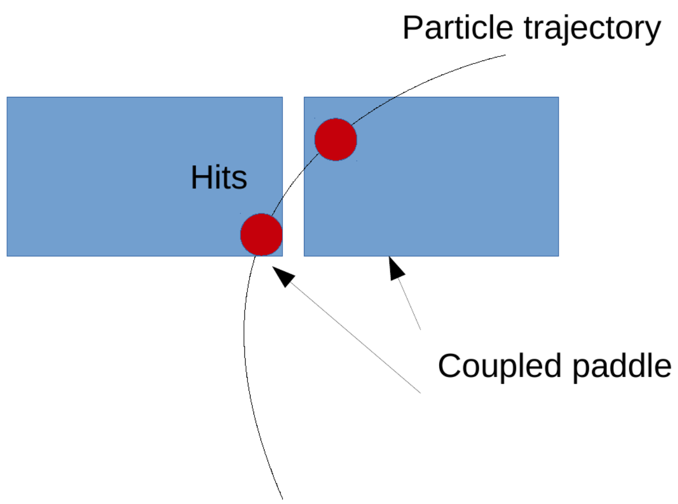

Figure 1: Double hits in the CND produced by the trajectory of a charged particle curved in a magnetic field. Both hits have similar TDCs resulting in a peak in the time difference distribution.

Both case are illustrated in Figure 2. Typical values of this offset are below 5ns. LR_{off} is not used in the reconstruction. It is however used to remove double hits from the next steps of calibration. LR_{offad} defined in the next paragraph is use in the reconstruction.

Once LR_{off} constants has been determined, they have to be adjusted to take into account the effective velocities difference between two coupled paddles.

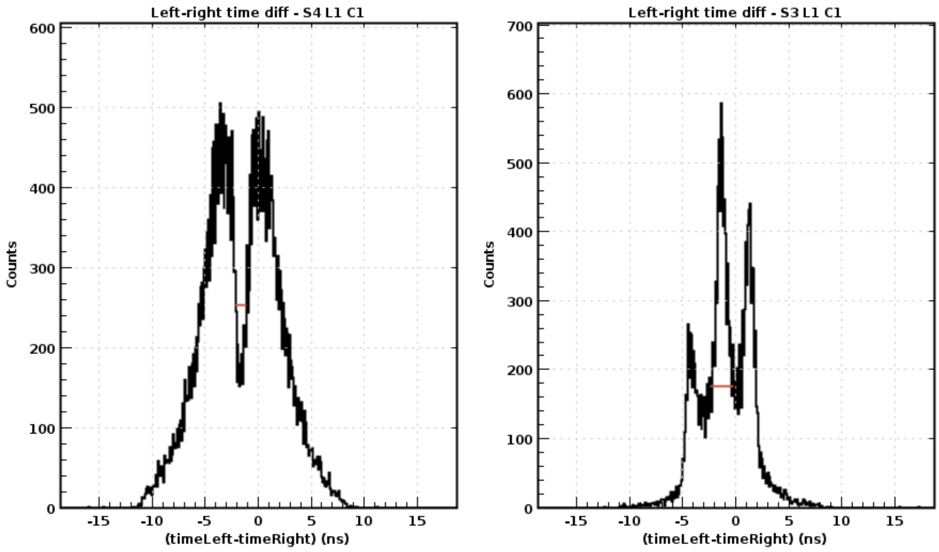

Figure 2: Time difference plots. The left plots is for no solenoid field. In this case the uturn light guide induces a gap in the distribution. The right plot is for data with magnetic field. In this case double hits are possible (see Figure 1). This double hits have both TDC equals resulting in a peak instead of a gap.

For hits in the left paddle, the two associated TDC can be decomposed as follow :

$$t_L = t_{off} + t_{tof} + \frac{z_{CND}}{v_{effL}} + Stt + t_{offL}, \tag{2}$$

$$t_R = t_{off} + t_{tof} - \frac{z_{CND}}{v_{effL}} + \frac{L}{v_{effL}} + \frac{L}{v_{effR}} + u_{tloss} + LR_{off} + Stt + t_{offR}, \tag{3}$$

where t_{tof} is the time of flight extracted from CVT information, L is the length of a paddle, Stt is the start time of the event, t_{offL} and t_{offR} are time offsets associated to the left and right coupled paddle.

LR_{offadd} is defined as:

$$LR_{offadd} = t_{offR} - t_{offL}. \tag{4}$$

Then one can write:

$$\frac{t_L - t_R}{2} = \frac{z_{CND}}{v_{effL}} - \frac{L}{2 \cdot v\_effL} - \frac{L}{2 \cdot v_{effR}} - \frac{u_{tloss}}{2} - \frac{LR_{offadd}}{2}, \tag{5}$$

thus the opposite of the intercept of the $\frac{t_L - t_R}{2}$ VS z_{CND} is equal to:

$$C_L = \frac{L}{2 \cdot v\_effL} + \frac{L}{2 \cdot v_{effR}} + \frac{u_{tloss}}{2} + \frac{LR_{offadd}}{2}. \tag{6}$$

For hits in the right paddle, the corresponding equation leads to:

$$C_R = \frac{L}{2 \cdot v_{effR}} + \frac{L}{2 \cdot v_{effR}} + \frac{u_{tloss}}{2} - \frac{LR_{offadd}}{2}. \tag{7}$$

Combining equations 13 and 14, LR_{offadd} is given by :

$$LR_{offadd} = C_L - C_R. \tag{8}$$

3.3 Effective velocity

The effective velocity v_{eff} is the speed of the scintillation light in the scintillators and light guides. There is one v_{eff} value for each paddle. v_{eff} is obtained using the following equation :

$$z_{CND} = (t_L - t_R) \cdot \frac{v_{eff}}{2} + cst, \tag{9}$$

where z_{CND} is the z position of the hit in the CND with respect to the upstream end of the CND paddles and cst an unkown constant. z_{CND} is obtained independently form CND using the CLAS12 Central Vertex Tracker (CVT). The above equation is true for hits in left paddles. For hits in the right paddles, the sign of the time difference has to be changed. v_{eff} is extracted by fitting the $\frac{t_R - t_L}{2}$ VS z_{CND} distribution as shown in Figure 3. The projections on $\frac{t_R - t_L}{2}$, for slices in z_{CND}, is fitted with a gaussian. For each slice, the mean of these gaussian is ploted against z_{CND}. The gradient of this distribution gives v_{eff}. The expected values for v_{eff} are around 16 cm/ns.

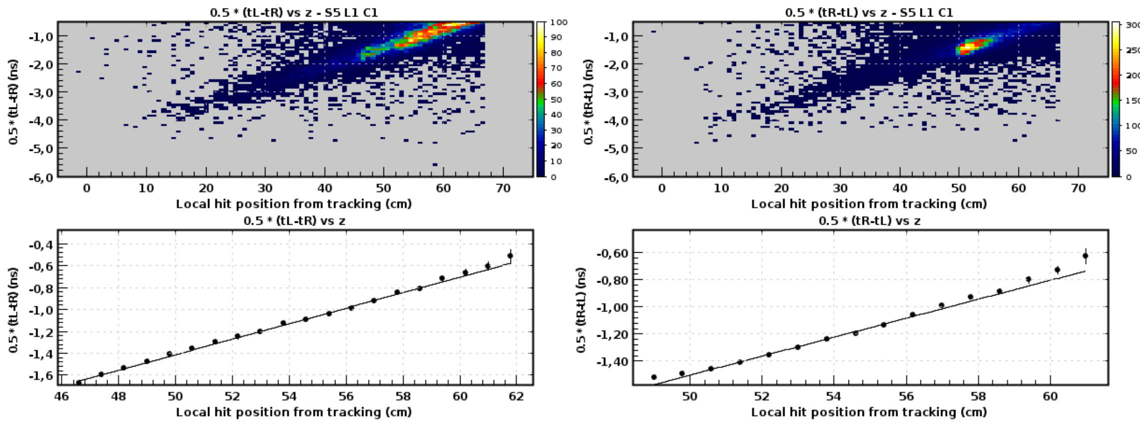

Figure 3: Plots used to determine the effective velocity for two coupled paddles. The two plots on the left correspond to the left paddle, plots on the right correspond to the right paddle. The top two plots are the raw $\frac{t_R - t_L}{2}$ VS z_{CND}, the bottom two plots are the fitted ones.

3.4 U-turn time loss

The U-turn time loss u_{tloss} is the time lost by the light to travel through the uturn light guide. It is used as a time offset on the indirect signal in the time and position reconstruction. There is one u_{tloss} value for each couple of paddle. The algorithm to extract u_{tloss} is very similar to the one used in the v_{eff} procedure: the intercept of the $\frac{tR - tL}{2}$ VS z_{CND} (see Figure 3) is extracted for both coupled paddles to get u_{tloss}.

For hits in the left paddle, the two associated TDC can be decomposed as follow :

$$t_L = t_{off} + t_{tof} + \frac{z_{CND}}{v_{effL}} + Stt + t_{offL}, \tag{10}$$

$$t_R = t_{off} + t_{tof} - \frac{z_{CND}}{v_{effL}} + \frac{L}{v_{effL}} + \frac{L}{v_{effR}} + u_{tloss} + LR_{off} + Stt + t_{offR}, \tag{11}$$

where t_{tof} is the time of flight extracted from CVT information, L is the length of a paddle and Stt is the start time of the event. The half time difference can be written :

$$\frac{t_L - t_R}{2} = \frac{z_{CND}}{v_{effL}} - \frac{L}{2 \cdot v\_effL} - \frac{L}{2 \cdot v_{effR}} - \frac{u_{tloss}}{2} - \frac{LR_{offadd}}{2}, \tag{12}$$

thus the opposite of the intercept of the $\frac{t_L - t_R}{2}$ VS z_{CND} is equal to:

$$C_L = \frac{L}{2 \cdot v\_effL} + \frac{L}{2 \cdot v_{effR}} + \frac{u_{tloss}}{2} + \frac{LR_{offadd}}{2}. \tag{13}$$

For hits in the right paddle, the corresponding equation leads to:

$$C_R = \frac{L}{2 \cdot v_{effR}} + \frac{L}{2 \cdot v_{effR}} + \frac{u_{tloss}}{2} - \frac{LR_{offadd}}{2}. \tag{14}$$

Combining equations 13 and 14, u_tloss is given by :

$$u_{tloss} = C_R + C_L - L \left(\frac{1}{v_{effR}} + \frac{1}{v_effR} \right). \tag{15}$$

The values for u_{tloss} are typically in the 0.5ns - 1.5ns range, with layer 1 values around 0.6ns, layer 2 around 1ns and layer 3 around 1.4ns.

3.5 Global time offset

The global time offset t_{off} refers to the time difference between the start time value and the vertex time computed by the CND. There is one t_off value for each pair of coupled paddles. t_{off} is given by the following equation :

$$t_{off} = \frac{t_L + t_R}{2} - Stt - t_{tof} - \frac{L}{2} \cdot \left(\left(\frac{1}{v_{effR}} \right) + \left(\frac{1}{v_{effL}} \right) \right) - \frac{u_{tloss}}{2} - \frac{LR_{offad}}{2}, \tag{16}$$

where t_{tof} is calculated using CVT information and assuming pion PID. To ensure a correct pion PID, a negative charge is required as most of the negative particles in the Central Detector are pions. The position of the peak of the above distribution gives t_{off} as shown in Figure 4. In practice t_{off} values depend greatly on the start time values (which is calculated using RF and FTOF), however variation of t_{off} between different pairs of paddle typically not exceed 10ns.

4 Energy calibration algorithms

There are three calibration constants for the energy determination in CND: the attenuation length (Att_L), ADC_to_Energy constants for direct MIP (MIP_D) and ADC_to_Energy constants for indirect MIP (MIP_I). These three calibration steps can be performed almost independently from time based calibration: LR_{off} is needed to determine if a ADC signal is direct or indirect (ie the hit happened in the considered paddle or in its coupled one).

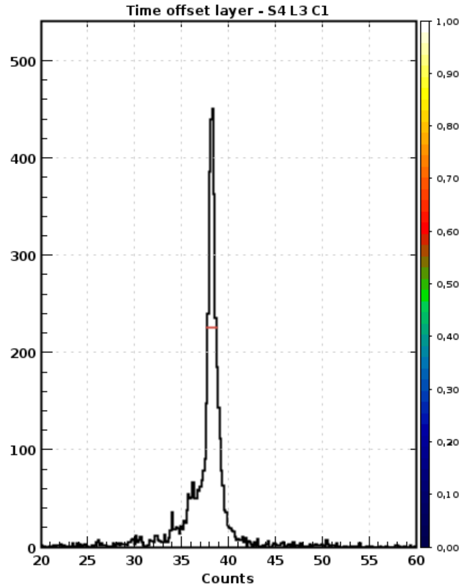

Figure 4: Plot to determine t_{off}. t_{off} is caluculated and plotted the position of the peak corresponds to t_{off}.

4.1 Attenuation length

The attenuation length Att_L accounts for the energy attenuation in the scintillators and light guides. There is an Att_L value for each paddle.

For hits in the left paddle, the two associated ADC can be written as:

$$ADC_L = \frac{E}{E_0} \cdot MIP_D \cdot e^{\frac{-z_{CND}}{Att_L}}, \tag{17}$$

$$ADC_R = \frac{E}{E_0} \cdot MIP_I \cdot e^{\frac{-(L-z_{CND})}{Att_L}}, \tag{18}$$

where L, z_{CND} have the same definitions as in the previous sections, MIP_D,MIP_I are constants defined in the next section, E is half the energy deposited by the particle in the scintillator and E_0 is half the energy deposited by a MIP in the scintillators. E_0 is given by:

$$E_0 = \frac{h \cdot 0.1956}{2} MeV, \tag{19}$$

where h is the thickness of each scintillator. All the above equations are valid for hits in left paddles, while for hits in the right paddles the corresponding equations are obtained by switching indices. From equations 17 and 18 the following equation is derived:

$$ln(ADC_L/ADC_R) = cst - \frac{2 \cdot z_{CND}}{Att_L}, \tag{20}$$

where cst is a constant depending on MIP_D,MIP_D and L. Att_L is given by the slope of the distribution of equation 20 as shown in Figure 5. Values for Att_L are typically around 150cm^{-1}

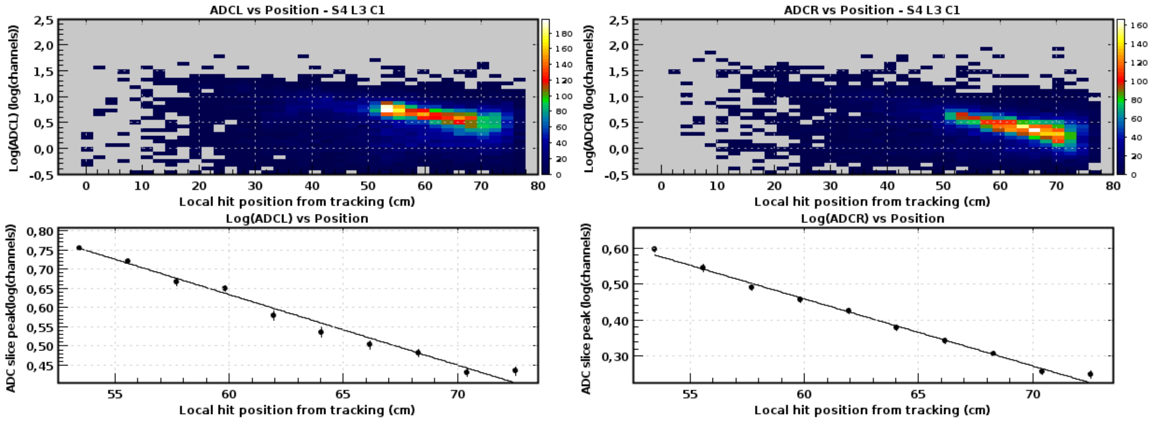

Figure 5: Plots used to determine Att_L. The right plots corresponds to the right paddle, the left ones to the left paddle. The top two plots show the raw $ln(ADC_L/ADC_R)$ VS z_{CND} distributions. Slices in z_{CND} are fitted with a gaussian, the mean is the plotted against z_{CND}. The corresponding ditributions are ploted in the two bottom plots.

4.2 Energy calibration

The final step of the calibration of the CND is the determination of the energy conversion parameters. These parameters are MIP_D and MIP_D. There are two energy parameters (MIP_D, MIP_I) for each paddle. Thus there are four energy parameters for each pair of coupled paddles, denoted as MIP_DL, MIP_IL, MIP_DR, MIP_IR in the calibration suite.

In the following, we only consider a hit in the left paddle. Equations for hits in right paddles are obtained by switching indices. For hits in the left paddle, only MIP_DL, MIP_IL can be obtained. In the following they are refered as MIP_D,MIP_I. From equations 17 and 18, one gets:

$$ln\left(\frac{ADC_L}{ADC_R}\right) = ln\left(\frac{MIP_D}{MIP_I}\right) + \frac{L}{Att_L} - \frac{2 \cdot z_{CND}}{Att_L} \tag{21}$$

$$\sqrt{ADC_L \cdot ADC_R} = \frac{E}{E_0} \cdot \sqrt{MIP_D \cdot MIP_I} e^{-\frac{L}{2 \cdot Att_L}}. \tag{22}$$

From equation 21, the intercept i of the $ln\left(\frac{ADC_L}{ADC_R}\right)$ VS z_{CND} distribution gives the ratio $\frac{MIP_D}{MIP_I}$. The same distribution as in Figure 3 are used to extract the intercept. The product $MIP_D \cdot MIP_I$ is obtained using equation 22 after filtering MIPs and correcting for the path travelled by the MIP in the scintillators. The path is obtained using the CVT track associated to the hit. Indeed for MIPs, E can be written as:

$$E = \frac{path}{h} \cdot E_0, \tag{23}$$

where $path$ is the path travelled by the MIP in the scintillator. Filtering MIPs and correcting for the path length remove the energy dependence from equation 22, which becomes:

$$\sqrt{ADC_L \cdot ADC_R} = \frac{path}{h} \cdot \sqrt{MIP_D \cdot MIP_I} e^{-\frac{L}{2 \cdot Att_L}} \tag{24}$$

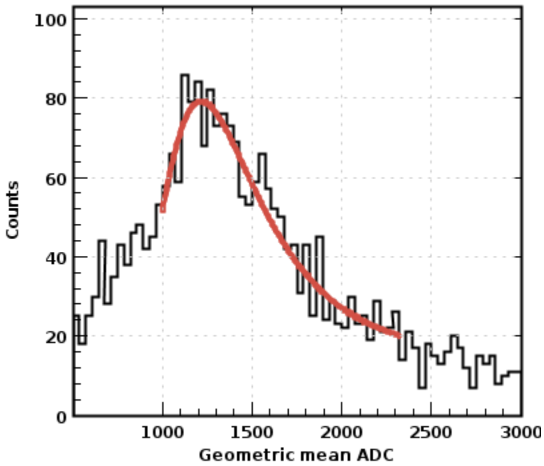

Figure 6: $\sqrt{ADC_L \cdot ADC_R} \cdot \frac{h}{path}$ distribution fitted with a Landau function. The events in this plot are identified as MIPs by requiring a pion. The PID is performed asking for negative charge, as most negatively charged particles in the Central Detector are pions.

The path travelled in the scintillator is obtained using the CVT tracking information by extrapolating the particle trajectory at the radius of the CND hit.

The distribution $\sqrt{ADC_L \cdot ADC_R} \cdot \frac{h}{path}$ is fitted with a Landau function and the position of the peak p is extracted as shown in Figure 6. MIP_D and MIP_I are given by:

$$MIP_D = \sqrt{e^{i - \frac{L}{Att_L}} \cdot e^{\frac{L}{Att_L}} \cdot p^2}, \tag{25}$$

$$MIP_I = \sqrt{e^{-\left(i - \frac{L}{Att_L}\right)} \cdot e^{\frac{L}{Att_L}} \cdot p^2}, \tag{26}$$

where i and p are the intercept and peak position defined above. MIP_D and MIP_I are typically around 2000 and 500 respectively.