Optimization of 500 MHz Pixie Module for Fast Time Measurement

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ISOLDE Decay Station (IDS)

Abstract
In the CERN summer student programme 2023, I worked on optimization of digital system of 500 MHz pixie in ISOLDE Decay Station (IDS) by obtaining the best parameters of a filter. After obtaining a sorting process available of traces, time resolution of Constant Fraction Discriminator (CFD) was optimized by varying its shape parameters: CFD_Delay and CFD_Scale, and observing the FWHM of time difference of $\gamma - \gamma$ coincidence of ^{60}Co. The results suggest the parameters CFD_Delay = 8 ns, and CFD_Scale = 0.25.

Keywords
Fast Time Measurement, Digital System, CFD

1 Introduction: Physical Motivation

IDS measures lifetime of nuclear states. Lifetime can be used to probe the shape of nucleus,as well as the underlying configurations of nuclear states, which are key elements in studies of nuclear structure. Life times vary a lot in time scale: from years to picoseconds [4]. Figure. 1, which shows the ^{60}Co decay

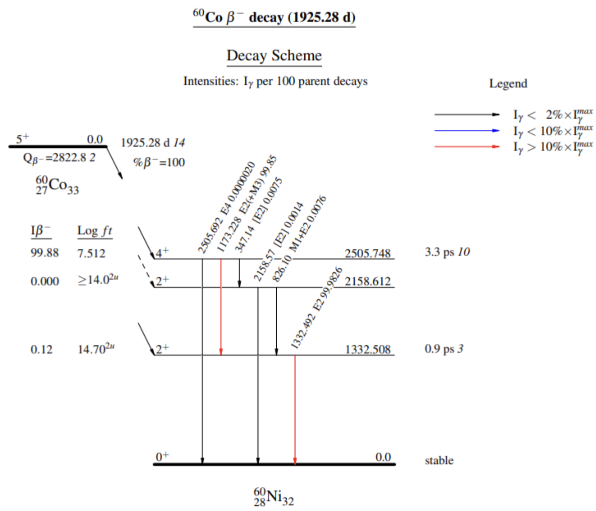


Figure 1: Decay Scheme of 60Co

scheme is one example. ^{60}Co itself has a half life of 1952 days, more than five years, but 1332 keV excited state of its decay daughter ^{60}Ni has half life of 0.9 ps. One of the challenge at IDS is to achieve high time resolution for these short living states, and this is where 500 MHz pixie module is introduced. With a 2 ns rate of data acquisition, it is expected to be practical for fast timing measurement. Therefore, optimization of 500 MHz module is required to give its maximum time resolution.

2 Theory

2.1 Detectors of IDS

IDS has two types of gamma ray detectors: clovers (HPGe) and LaBr detectors. Each type has its advantages and disadvantages, supporting the weak points of each other.

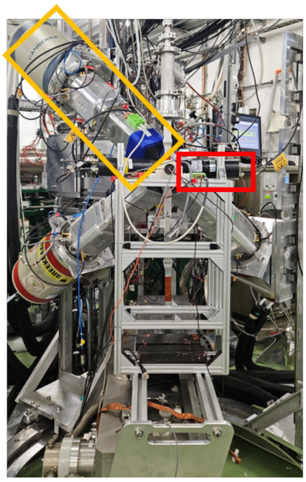


Figure 2: Detectors of IDS (Orange: Clover / Red: LaBr(Ce))

2.1.1 Clovers (HPGe)

Clover is a type of high purity Germanium (HPGe) detector. It is a semiconductor type detector, where the gamma ray produces excited electron-hole pair. Clover detectors are biased before its use, so electron and hole goes to cathode and anode, respectively. As the number of electron-hole pairs is proportional to the energy deposited, the energy of the radiation can be determined by measuring the electronic signal created by the motion of the charge carriers as they move inside the crystal. The time difference between arrival times of electron and hole can also be useful to get the position of gamma ray interaction. However, as the particle should "move" to the electrode, there is an internal time delay which limits the time resolution of the detector.

2.1.2 LaBr(Ce) Detector

LaBr(Ce) detector is a inorganic scintillator detector, where cerium is applied as an activator, adding an additional energy band in forbidden gap of LaBr. Gamma ray produces large number of electron-hole pairs, as electrons elevates to the conduction band from the valence band. The electron migrates until it encounters an activator atom, which is ionized by the positive hole as its ionization energy is relatively smaller. Electron occupies the excited energy state of activator, which is originally a forbidden energy level without impurity. The state has short lifetime, in order of 30-500 ns, giving fast reaction to incident ray. This is why LaBr(Ce) is considered for measuring short lifetimes.
However, there is no direct proportionality between number of pairs and the energy of the gamma ray. Furthermore, the possibility of background scattering and more exists, giving LaBr(Ce) a relatively low energy resolution compared to germanium detectors. Nevertheless, LaBr(Ce) has a high energy resolution compared to other inorganic scintillator detectors.

2.2 Analogue and Digital System

There are two types of data acquisition system: analogue and digital. The algorithms of filters used to gather data is practically the same, but the difference comes from how the filters are applied. For example,

if the data have to be copied and delayed, a connector and an additional wire that physically transports the signal is applied in the case of analogue system. In addition, analogue system charge/discharge a capacitor referring to trigger to get a signal; as the capacitor is precise without delay, time resolution is high in analogue systems. However, it needs the module to execute signal for each detectors and as our interest is usually on comparing pairs of signals, connections between the modules increase in N(N-1)/2. Furthermore, setting the desired delay is not a simple process as it should be done physically.
In contrast, digital system are more flexible, as adding a new detector is in principle only needs one additional channel. Delays and filters are applied after recording the data as a trace, so data obtained before can also used for simulation of different parameters of filters. However, the time resolution should be optimized in order to be comparable to analogue system.

2.3 Energy and Time Resolution

What information do we want to extract from a signal of a detected event? Its energy and the time it occurred. These values can be obtained with high precision by trapezoidal filters and CFD triggers.

2.3.1 Traperzoidal Filter

The energy of a signal can be obtained by integrating the area below the signal. This is because the number of electron-hole pairs of scintillation photons are proportional to the energy deposited, so the magnitude of the signal produced by a detector is proportional to the energy. It is a complicated process to calculate something with an exponentially decaying signal, where comes the idea of trapezoidal filter. Its initial idea comes from Knoll's paper [1]. The response of the filter, i.e. the resulting signal, can be written in a recursive form:

$$s(n) = s(n-1) + p'(n) + d^{k,l}(n)M, \quad (n \geq 0) \tag{1}$$

$$p'(n) = p'(n-1) + d^{k,l}(n), \quad (n \geq 0) \tag{2}$$

$$d^{k,l}(n) = v(n) - v(n-k) - v(n-l) + v(n-k-l) \tag{3}$$

where $s(n)$ is the response, $v(n)$ is the digital signal at step n, M is the time constant of the signal's decay, k is the rise time of the trapezoid, and $(l-k)$ is its flattop time. The shape of the trapezoid can be set by changing parameter k and l. For example, if $k = l$, the response signal will be a sharp triangle, with no flattop. The height of trapezoid will be the height of signal times p^2, giving it proportionality to the energy of the signal. To get the exact energy of the gamma, the result from the trapezoidal filter is usually calibrated with sources with known energy peaks such as ^{1}52Eu and ^{1}37Cs.

2.3.2 Constant Fraction Discriminator(CFD)

Digital signals has inevitable noise, due to various sources. To get the "timing" of the signal, it is necessary to filter out if it is an actual signal. This is the reason of having an energy threshold in data acquisition. However, deciding the timing of the signal as the moment where it passes the energy threshold has a problem in precision.

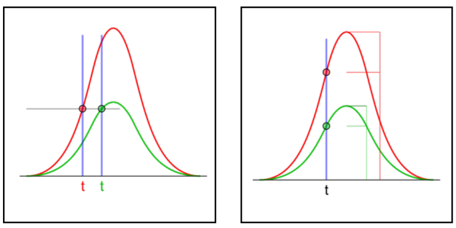


Figure 3: Time Walk (Left) and CFD (Right)

Figure 3 shows two simultaneous signals with different energies. As they are detected with identical instruments, the rise time and tendency will be similar. However if we use energy threshold as a trigger for timing, there is a time difference between the two, even though they are in coincidence. This time difference is also referred as the **time walk**, and it is a critical factor that should be avoided for high time resolution, such as in the case of fast time measurement. Using a constant fraction discriminator (CFD) trigger is a solution for the time walk. Evidently, the time measurement is triggered when the signal reaches a constant fraction of its maximum peak. The identity of the rising tendency will guarantee that the timing will be identical for simultaneous signals. The trigger time can be determined by certain calculations using two copies of the data.

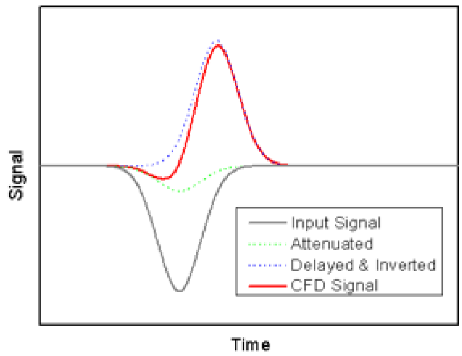


Figure 4: How CFD trigger is determined[4]

The CFD signal is obtained by attenuating one copy, inverting and delaying the other one, and then summing them. The red curve in Figure 4 shows the resulting CFD signal. The zero point (ZP) of this signal is the trigger point of our original signal. The reference shows that triggering on the maximum point of the original signal is the best, and can be done by using the equation below [4].

$$t_{delay} = t_{risetime} \cdot (1 - scale) \tag{4}$$

2.4 $\gamma - \gamma$ Coincidence of ^{60}Co

To test the time resolution of the experimental setting, known decay scheme with appropriate time difference was used. $\gamma - \gamma$ coincidence of ^{60}Co is used for time calibration of multiple detectors, and also as a reference in this project. Returning to Figure 1. After ^{60}Co β^- decay, there is a two-photon cascade to the ground state of the daughter nucleus, ^{60}Ni which are shown as red arrows in the scheme. The energy of these two gammas are 1173 keV and 1332 keV respectively, and the state in between these two has half life of only 0.9 ps. As the lifetime is much shorter than the timing resolution of our detectors, practically these two rays are in **coincidence**. So in theory, the detector should give 0 difference between these two gamma rays. By applying energy gates to signals from different detectors in same measurement, time differences between 1173 keV and 1332 keV gamma ray can be obtained, and can be used as a criteria of the time resolution, with the aim of minimising the width of the distribution in order to optimise the timing resolution.

3 Procedure

Optimization of CFD is done mostly by simulating its shaping parameters with recorded traces from measured data.

3.1 Trace of Signal

Pixie modules of XIA have the option to enable/disable recording the trace. Pixie-16 manual provides information of Channel Control Register A, which is a 22 bits long option with each bit representing one option. Bit 8, CCSRA_TRACEENA should be enabled to collect the trace of each signal. As a result trace of each signal was obtainable. Traces of digital signals are essential in the procedure, as it allows

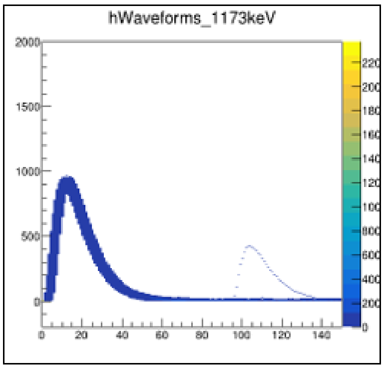
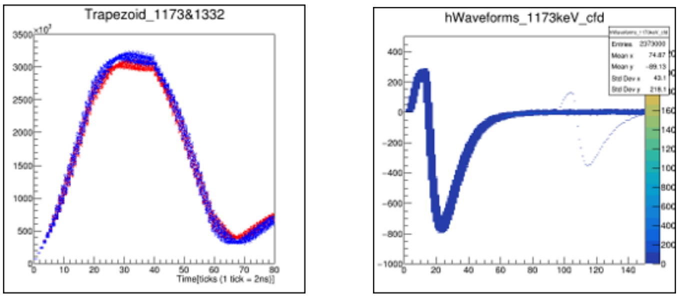


Figure 5: Trace of 1173keV gamma (60Co)

the simulation of different parameter settings of filters without live measurement all the time. To check if the trace is utilizable, a brief simulation of trapezoidal filter was done for two gamma rays of ^{60}Co (Figure 6a). The result was as expected: 1332 keV signal (blue) gives higher trapezoid compared to that of 1173 keV (red). In addition, the CFD signal was also simulated, and is shown, with no special optimization(6b).



(a) Trapezoid Filter Plot (b) CFD Plot (Not Optimized)

Figure 6: Filter Simulations for Utility Check

3.2 CFD Simulation

Three parameters of CFD are considered: CFD_Threshold, CFD_Delay, and CFD_Scale.
CFD_Threshold has been fixed to be high enough to remove noise and scattered signals, while the other two parameters determine the **shape** of the CFD. The ZP of the CFD can be derived with higher precision than the frequency of the acquisition, which is in 2 ns resolution. This can be done by linear regression of the CFD signal at the bin where it goes through the ZP, which can be probed by getting the value of the bin for every bin step. For example, if the CFD starts from positive and goes to negative after the ZP, the calculation for the ZP will be done when the value of the bin goes negative for the first time. This process has been implemented as C++ code, and written in appendix.

Now that the ZP of CFD can be obtained, adding it to the time stamp of the trace will give the timing of the signal. After gating on the energy of LaBr(Ce) detectors facing each other by selecting the 1173 keV and 1332 keV decays, time differences between the two can be obtained. For all coincidence cases, the time difference has been recorded, and FWHM of the distrubtion has been obtained by fitting a gaussian function in ROOT. Finally, while sweeping through two parameters, the FWHM for each pair of parameters has been recorded in order to find the minimum point i.e. the optimized combined settings for the two parameters.

4 Result

The following figure shows time differences between two decays of ^{60}Co. Figure 7 shows an example

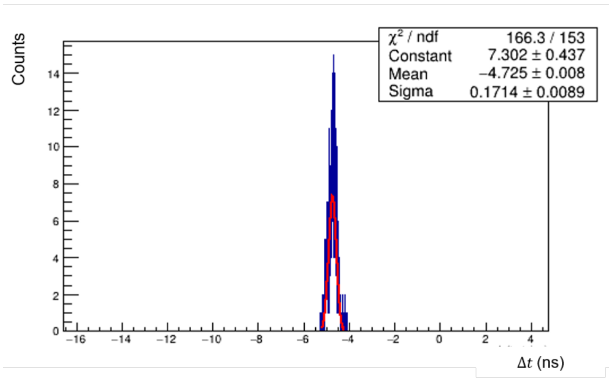


Figure 7: Time Difference of Coincidence of 60Co

of time difference of gamma rays of random set of parameters. The red curve is a fitted gaussian curve, whose FWHM is recorded in the 2D histogram. The curve is not centered in the middle because time calibration between two detectors is not done. The FWHM of the time difference curve has been analyzed

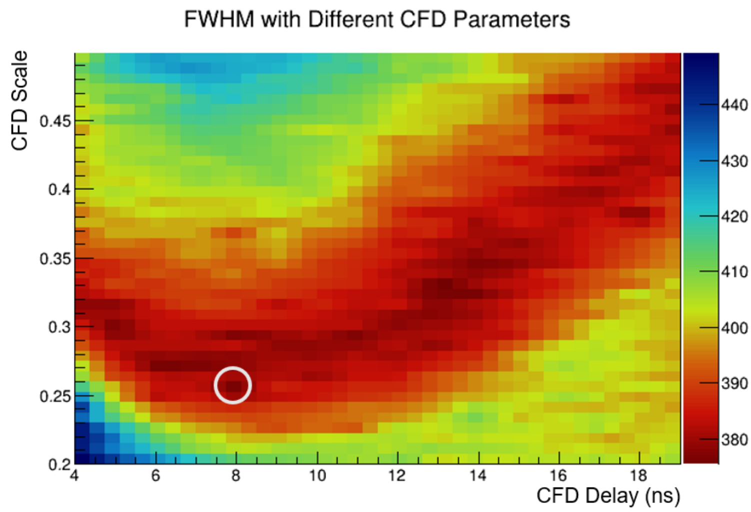


Figure 8: FWHM(ps) by CFD_Delay and CFD_Scale

for CFD_Delay = 4 - 20 ns in 1 ns steps, and CFD_Scale = 0.2 $\sim$ 0.5 with 0.01 steps. Figure 8 shows a dark-red region in the middle of the 2d histogram, where shape parameters of CFD gives better time resolution. Optimization suggested FWHM of 370 $\pm$ 20 ps. Delay greater than 12 ns is not usable as it is greater than the rise time of the original signal, and delaying greater than that can not satisfy the purpose: CFD measures the moment where the signal reaches constant fraction of its maximum while rising, not decaying.Therefore, considering the region with reasonable values, the optimal settings would be **CFD_Delay = 8 ns** and **CFD_Scale =0.25**. This not only considers the minimum point among the reasonable region, but also the systematic condition of pixie-16; According to its manual, pixie-16 modules have its CFD_Delay in multiples of 0.125 and its delay in multiples of one tick, which is 2 ns in

500 MHz case [3]. Furthermore, the 500MHz module has limit of flexibility due to the lack of resource of FPGA, and thus for physical firmware modification the result will be reliable as the parameter follows their principle of units.

5 Conclusion

Throughout the project, the shape parameters of the CFD, which supports time resolution of a detector, was optimized for a digital system of 500 MHz pixie module which will be used for fast time measurements in IDS. After sorting the data with its trace enabled, the CFD filter was simulated with collected $]\gamma - \gamma$ coincidences of ^{60}Co and optimized by narrowing the FWHM of the time differences of these events. The result suggests **CFD_Delay = 8 ns** and **CFD_Scale =0.25**.
The limit of the optimization was also obvious. A brief optimization done in winter gave FWHM around 330 ps, while the result of this project did not reach this. I propose that one reason for the increase of the time distribution is the position of the ^{60}Co source used. The LaBr(Ce) detector of IDS is shaped as a truncated cone, where the gamma rays of a source positioned in the middle of two detector either goes directly into the scintillator or never goes in. The tape station, which is the ideal position of the source was locked during this summer due to other experiments, so the ^{60}Co source was positioned at a distance from the center. This can increase the path difference of the two gamma rays, and even though it's a few centimeter difference, the travel time of light is more than tens of picoseconds. As this uncertainty will be convoluted with the original gaussian, it would give the observed effects to the results.
The other limit was that actual decay sequence has not been tested. With time differences between known gamma decay (like 1173 keV and 1332 keV of 60Co, but they are too instant). It would also be of interest to see how the optimised system performs when measuring the decay of a state with a known lifetime, that is long enough to be measured with the timing resolution of the LaBr detectors. For instance, the 121 keV state in ^{152}Sm which is populated by the decay of ^{152}Eu, and has $T_{1/2}$=1.4 ns. Here, we would expect to see a prompt gaussian distribution, convolved with an exponential decay curve. By fitting a convolution function of gaussian and exponential decay to this curve, experimental value of time constant (or half life) can be obtained, which can be used as a tool to evaluate the time resolution.
Nevertheless, having a way to get a trace of each signals if desired, and methodolgy of simulating CFD paramter is still a useful tool for further use, not only limited to 500 MHz pixie-16 module. I hope the result of my 8 week summer project can give support to further experiments of IDS of CERN.

Acknowledgements

All codes written in the procedure, without filtering out them by their importance, is provided as tar.gz file named IDS_Summer_2023.tar.gz in pcids010 server. If there are further question about the macros, any improvement, or suggestion to be shared, please contact me via mail: **johnl2001@kaist.ac.kr**. I would like to take this opportunity to again thank my supervisors for their supports. IDS was a great team to be in, and this summer was one of my best summer in my entire life.

6 Appendix

Listing 1: CFD Zero Point

```
long double CFD(int T[traceSize],double S,int D){
   /*Getting the Zero Point(ZP) by scanning
    through traces (Positive->ZP->Negative)*/
   /*T: Trace of the Signal (From TTree)
     S: Attenuation Scale of CFD (CFD_Scale)
     D: Delay of CFD (CFD_Delay)             */
   double T_sample = 2;
   double T_coarse = 0;
   double C_a, C_b;
   long double ZP;
   for (int j=D;j<traceSize;j++){
      C_a = (double)(S*T[j]-T[j-D]+(1-S)*T[0]);
      if (j == D) C_b = C_a;
      if (C_b>0. && C_a<0.)/*Zero Point of CFD Signal*/{
         ZP = T_coarse+T_sample*(C_b/(C_b-C_a));
         C_b = C_a;
         return ZP;
      }
      else if (C_b>0. && C_a>0.){
         T_coarse += T_sample;
         C_b = C_a;
      }
   }
   return -1;
}
```

Bibliography

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