Nuclear Instrumentation: Lecture 5

Pulse Timing Systems

5.1 INTRODUCTION

For many applications, information on the precise arrival time of a pulse in the detector is of particular interest. To obtain this information, the pulses from a detector are handled very differently than they would be, for example, in a pulse-height analysis system.

The accuracy to which the time information can be determined depends both on the detector properties and on the type of electronics used to process the signal. Clearly, the best time response can be obtained from fast detectors, i.e. those from which the charge is collected quickly. Of the detectors which have similar charge collection times, those that generate the most charge will have the best timing properties.

5.2 TIMING

5.2.1 Timing discriminator

Marking the arrival time of events with precision and consistency is the task of a timing discriminator.

Achieving the optimum time resolution is important whether the object is to do time spectroscopy or just to determine whether events occurred simultaneously in two or more detectors (coincidence spectroscopy).

The techniques for achieving optimum timing resolution depend on detector type. Therefore, the correct timing discriminator must be chosen to match the characteristics of the detector.

5.2.2 The limiting factors: Jitter, Walk and Drift.

Jitter, walk and drift are the three major factors limiting the system time resolution. They can be most easily understood by reference to Figures 5.1, 5.2 and 5.3.

In these figures, the arrival time of the pulse is measured using a **leading-edge discriminator**, which has a simple voltage comparator with its threshold set to the desired voltage. At the time when the amplitude of the input pulse exceeds this threshold voltage, the discriminator generates an output logic pulse.

Jitter:

If life were perfect, there would be no noise (amplitude variations) on the input pulse and the leading-edge discriminator would mark the arrival time of each pulse with precision.

Life is seldom perfect!

Most pulses include a non-negligible amount of electronic noise (Figure 5.1), which causes an uncertainty in the time at which the pulses cross the threshold. This is known as **time jitter**.

To minimize time jitter one can:

- Minimize the electronic noise.
- Set the threshold at the point of maximum slope of the input pulse.
- Preserve the fastest possible rise time for the input pulse.

Electronic noise makes a significant contribution to timing jitter with Si and Ge detectors and also with microchannel plates, fast photodiodes, and PMTs.

For scintillation detectors, the electronic noise contribution is usually negligible but statistical fluctuations in the arrival time of the pulse at the detector output is an important source of time jitter.

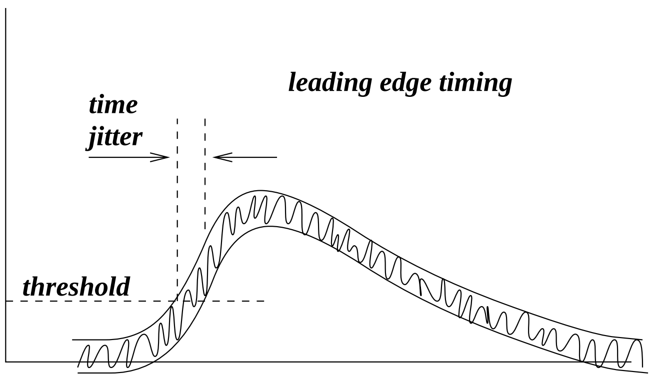


Figure 5.1 Time jitter arising from random electronic noise. The solid lines indicate the `envelope' of pulses.

Walk

Amplitude walk associated with a leading-edge triggered system is illustrated in Figure 5.2. Shown are two pulses with the same rise times but different amplitudes.

The output logic pulses differ dramatically in their timing, since the times at which the pulses cross the voltage threshold are different.

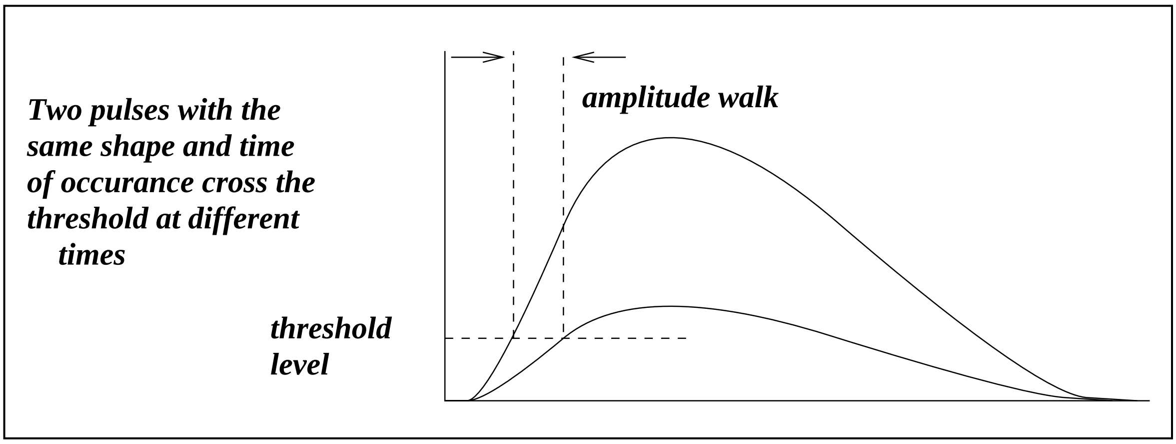


Figure 5.2 Amplitude walk in leading-edge triggered systems

Under extreme conditions, the amplitude walk can amount to the full rise time of the input pulse!

Constant fraction, arc timing and other zero-crossing techniques can be used to eliminate or minimize amplitude walk (see below).

Ge detectors have special problems because the rise times of the pulses from these detectors vary over a large range. This variation in pulse rise time is an important source of time walk for Ge detectors (see Figure 5.3).

Drift:

Drift is a long-term error introduced into the system by component aging, by temperature variations in the discriminator circuits, etc. etc.

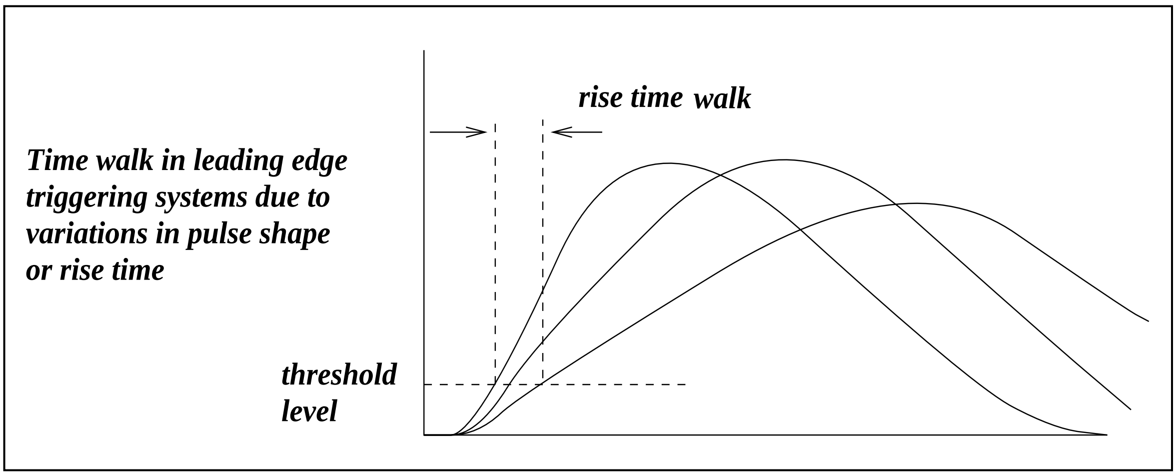


Figure 5.3 Time walk in leading-edge triggered systems due to different pulse shapes or rise times.

5.3 LEADING-EDGE TIMING

Leading-edge timing, as described above, is normally used when the optimum time resolution is not essential.

- The dominant limitation with this method usually is `walk'.

The rise time of the linear input pulse at the discriminator can be used as a rough estimate of the contribution `walk' will make to the time resolution of the system when a wide range of pulse amplitudes must be processed.

5.4 CROSSOVER TIMING

When leading-edge timing is applied to pulses with a wide dynamic range of amplitudes, amplitude walk can result in large timing variations.

Another time pick-off method, *crossover timing*, can greatly reduce the effect of amplitude walk.

Crossover timing requires that the pulses have a bipolar shape as illustrated in Figure 5.4. In theory, even though the pulses have different amplitudes, the time at which the waveforms cross zero volts is the same, and depends only on the amplifier shaping constants chosen to produce the pulses.

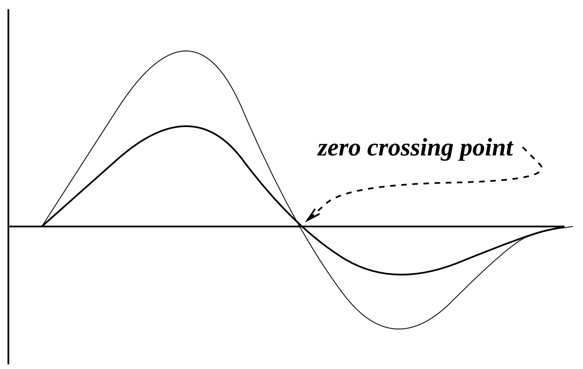


Figure 5.4 Bipolar pulses with different amplitudes but the same zero-crossing time.

In general, compared to leading-edge timing, crossover-timing methods greatly reduce the amplitude walk, but at the expense of increased time jitter. This is due to the additional noise introduced by the shaping stage and the increased susceptibility of the zero-crossing point to statistical fluctuations.

5.5 CONSTANT-FRACTION TIMING

If the range of input pulse amplitudes is small, then leading-edge timing results in superior timing performance compared with crossover timing.

Empirically, it is found that the optimum leading-edge timing characteristics are obtained when the threshold is set to about 10-15% of the maximum pulse amplitude.

These two facts lead to the development of a circuit that is triggered at a fixed time after the leading edge of the input pulse reached a **constant fraction** of its final amplitude.

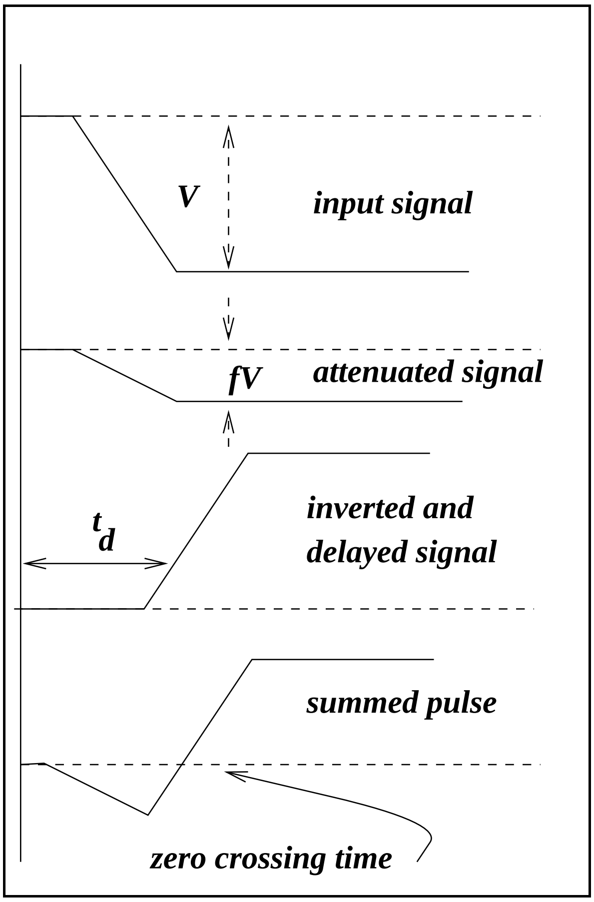


Figure 5.5 Pulse shapes in a constant-fraction discriminator.

- The time of the output pulse is independent of the pulse amplitude as long as the pulses have the same shape.
- Therefore, a much wider dynamic range of pulses can be accepted with all the good timing characteristics of leading-edge timing but without the amplitude walk.

The steps necessary to carry out constant fraction timing are illustrated in Figure 5.5.

- The input pulse (which could be the preamplifier output or the output of a fast timing amplifier) is attenuated by a **constant fraction *f*,** which corresponds to the desired fraction of the full amplitude.
- Secondly, the input waveform is inverted and delayed by a time greater than the pulse rise time.
- The attenuated pulse and the delayed/inverted pulse are then **summed** to give the

waveform shown in the bottom of the figure.

The time that this pulse crosses the zero axis, is independent of the pulse amplitude.

- The length of the delay is chosen to make the optimum fraction point on the leading edge of the delayed pulse line up with the peak amplitude of the attenuated pulse.

In a constant-fraction discriminator (cfd), the time at which the logic pulse is generated depends on the zero crossing point of the bipolar pulse.

Since this is independent of pulse amplitude, walk is virtually eliminated.

However, the energy threshold in the cfd is set by a leading-edge discriminator.

This discriminator is set to prevent the sensitive zero-crossing comparator firing on electronic noise. A schematic circuit diagram of a constant-fraction discriminator is shown in Figure 5.6.

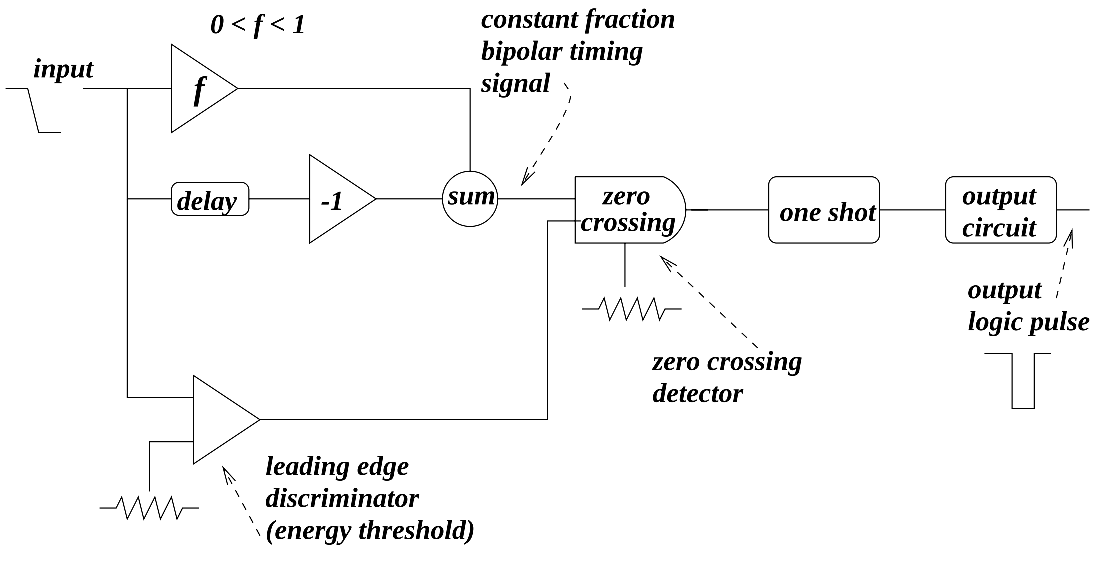


Figure 5.6 Schematic representation of a constant-fraction discriminator.

5.6 AMPLITUDE AND RISE-TIME COMPENSATED (ARC) TIMING

The shape or rise time of the preamp output pulses can vary, particularly for large Ge detectors. This is due primarily to differences in the charge collection time for low/high energy events and for events occurring in different regions of the crystal.

- In this event, even constant-fraction discriminators cannot eliminate time walk.

Some different preamplifier output pulse shapes for Ge detectors are depicted schematically in Figure 5.7.

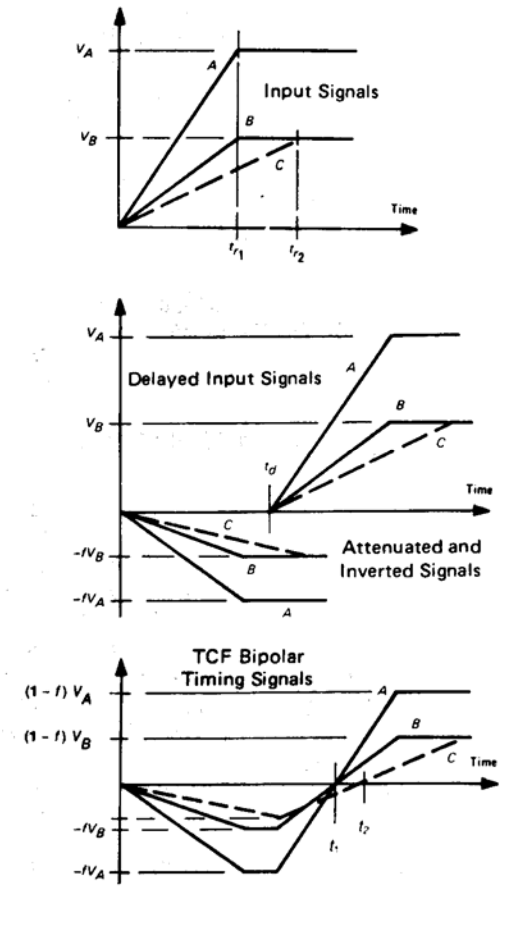


Figure 5.7 Ge preamp pulses processed by a conventional cfd.

The longest charge collection times (pulse C in Figure 5.7) are caused by interactions occurring near one of the electrodes. In this case, one of the charge carriers (either the electron or the hole) has the longest distance to drift to its electrode.

The minimum charge collection times (pulses A and B) occur for interactions midway between electrodes. The minimum charge collection time is about half of the maximum.

The longest charge collection time can be about 600 ns for large coaxial Ge detectors.

As illustrated in Figure 5.7, conventional constant-fraction timing will eliminate the walk caused by the different amplitudes of pulses A and B but not the timing uncertainty caused by the different rise times of pulses B and C. As can be seen, these pulses cross the baseline at different times.

Amplitude and rise time compensated (ARC) timing techniques will minimize the effect of different rise times, essentially by timing only from the very early part of the leading edge of the pulse.

As illustrated in Figure 5.8 the desired fraction of the maximum pulse amplitude is left at its normal setting (0.2 - 0.3), but the delay time is significantly shortened.

Instead of setting the delay to correspond to the maximum of the attenuated pulse, it is set to correspond to approximately 30% of the minimum rise time.

With the shorter delay the bipolar pulses for all three pulses cross the baseline at approximately the same time, in spite of the different rise times (see Figure 5.8).

In theory, ARC timing will generate an output pulse at a time which is independent of rise time and amplitude variations, provided that the slope of the input pulses are constant throughout their leading edges.

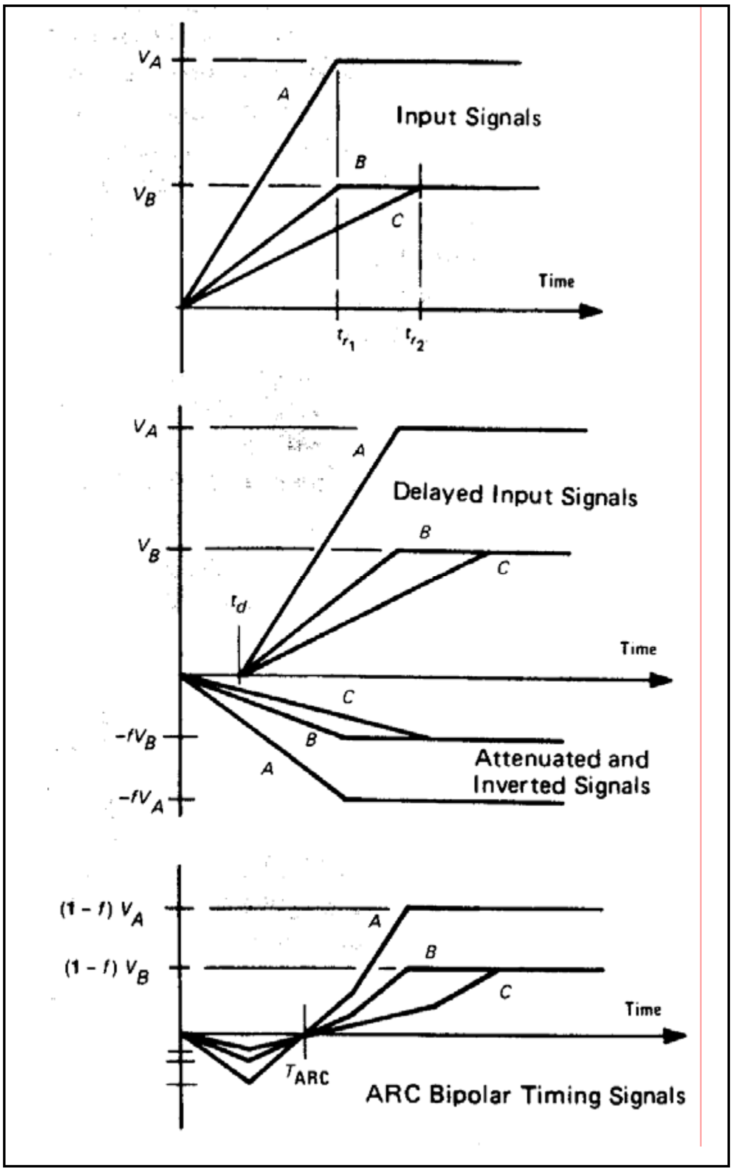


Figure 5.8 Signal processing in ARC timing.

In practice, of course, this is not really true. Pulses with either the maximum or minimum rise times do have constant slopes. However, for pulses with intermediate rise times the slope will abruptly change when the charge carrier that experiences the shorter drift reaches its electrode. To minimise this effect, the delay is deliberately kept very short.

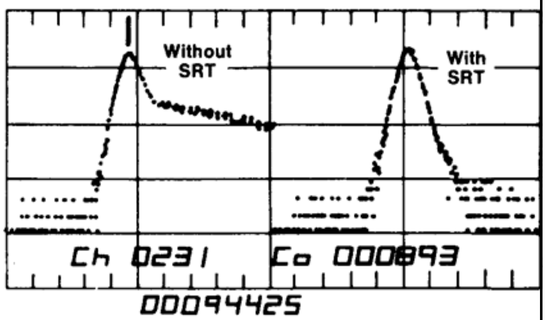
5.7 ARC TIMING WITH SLOW RISE-TIME REJECTION

Occasionally Ge preamplifier pulses with much longer rise times occur. These may be caused, for example, by interactions in regions of the Ge crystal where the electric field is weak (e.g. corners), or in damaged areas of the crystal (trapping centres) with a correspondingly slow charge-collection time.

When ARC timing is applied to such pulses, the zero-crossing comparator can trigger before the leading-edge discriminator. As a result, the output timing of the constant-fraction discriminator will be determined by the leading-edge time discriminator, rather than the zero-crossing time. Hence, such events will have excessive walk associated with them.

Some constant-fraction discriminators, have a slow rise-time reject (SRT) mode which can be used to eliminate such ugly pulses! SRT discriminators inhibit the timing logic pulse whenever the zero-crossing discriminator triggers before the leading edge.

The effect of SRT on the timing peak of a scintillator is illustrated in Figure 5.9. As can be seen, the time response is much improved. However, it should be noted that this improvement is achieved by rejecting pulses that would otherwise appear as full-energy peaks in the energy spectrum, i.e. there is a loss of efficiency. Thus, sometimes a compromise needs to be reached between optimum efficiency and time resolution.



^{22}Na
Start: KL236, Burle 8575 Photomultiplier Tube
Stop: HPGe, 12.5% 52.3 cc
10:1 Dynamic Range

	Without SRT	With SRT
FWHM	4.5 ns	4.4 ns
FW.1M	13.2 ns	9.4 ns
FW.01M	—	17.3 ns

Figure 5.9 The effect of slow rise time reject on a time spectrum from a Ge detector.

5.8 FIRST PHOTOELECTRON (FPET) TIMING

This is a timing technique used with scintillation detectors, which can be applied when the experimental conditions limit the possible trigger times to a relatively small interval.

In this case, excellent timing can be achieved by sensing the arrival of the first photoelectron at the photomultiplier (assuming that the frequency of single electron noise from the PM tube is less than the frequency of real pulses).

- This timing method corresponds in effect to leading-edge timing with the threshold set as low as possible.
- Low-noise, bi-alkali PM tubes are used in which the single-electron noise (sen) rates may be as low as a few hundred per second.

5.9 COMPARISON OF TIME PICK-OFF METHODS.

- As a general rule, leading-edge timing will give the best time resolution for pulses with a limited dynamic range of amplitudes. However, for pulses with a large range of amplitudes, leading-edge timing methods show large time walk.
- Constant-fraction timing methods eliminate this walk in situations where the pulse shape does not change.
- For detectors that produce pulses with a range of rise times, amplitude and rise-time compensated, ARC, timing can eliminate much of the time walk associated with pulse-shape changes.

The time resolution achievable with any of these methods varies with detector type and is primarily determined by the characteristics of the charge-collection process.

5.10 MEASUREMENT OF TIMING PROPERTIES.

5.10.1 The time-to-amplitude Converter (TAC)

The time-to-amplitude converter is a device which produces an output pulse whose amplitude is proportional to the time difference between two input pulses, the so called `start' and `stop' pulses.

The distribution of TAC output pulses can be recorded using a conventional multichannel analyzer and is commonly referred to as a **time spectrum**. The x-axis corresponds to time rather than energy, of course.

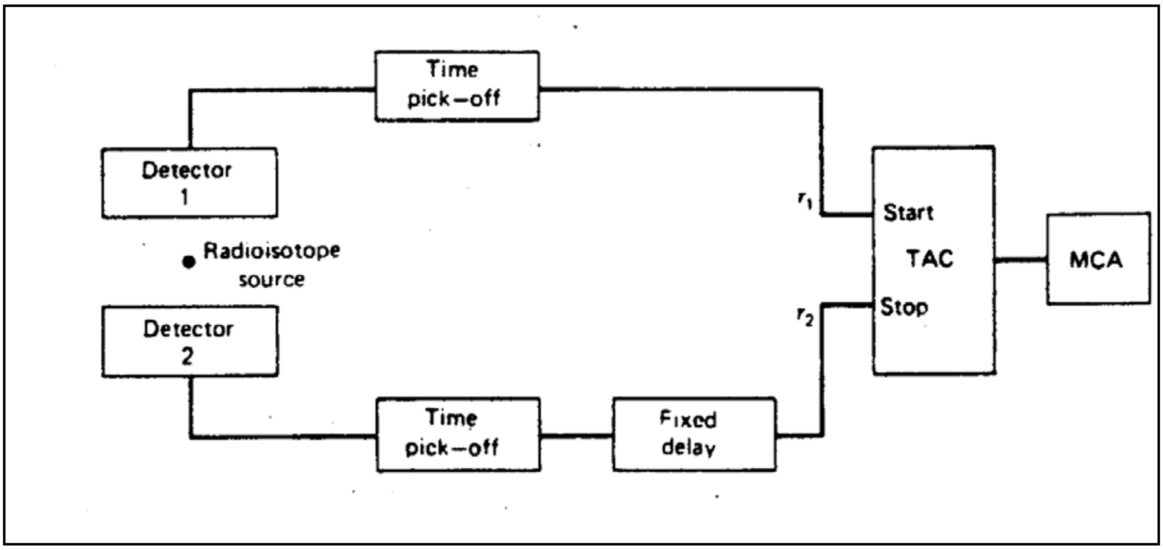


Figure 5.10 A schematic diagram of a system used to record a time spectrum from a source emitting coincident radiation.

The system shown in Figure 5.10 can be used to measure the time spectrum of a source that emits coincident radiation.

Note: It is possible that the event rates recorded in detectors 1 and 2 will be different. In this case, to minimize dead time, the TAC should be started with the pulse with the lower count rate and stopped with the pulse with the faster count rate.

The time spectrum from a source, recorded using a TAC will have the general appearance shown in Figure 5.11.

True coincidence events will be detected simultaneously in both detectors. Hence, they will appear in the same region of the time spectrum, forming the prompt or true coincidence peak. The position in the spectrum at which this prompt coincidence peak appears is determined by the fixed delay in the stop pulse shown in Figure 5.10. For example, increasing the delay value will move the entire peak to the right in the spectrum.

- The time resolution of the system is conventionally given by the full width at half max of the prompt coincidence peak.

The `constant' background in the spectrum is produced by random coincidence events. In this case, one detector may see a true source event but the second picks up a chance/random event. These events are referred to as `chance' or `random' coincidences and their intensity (the background level in the time spectrum) depends on the count rate in each detector (the so-called singles rate). If the singles rates are not high compared to the reciprocal of the time range of the TAC, these chance events will be uniformly distributed over the entire TAC range as shown.

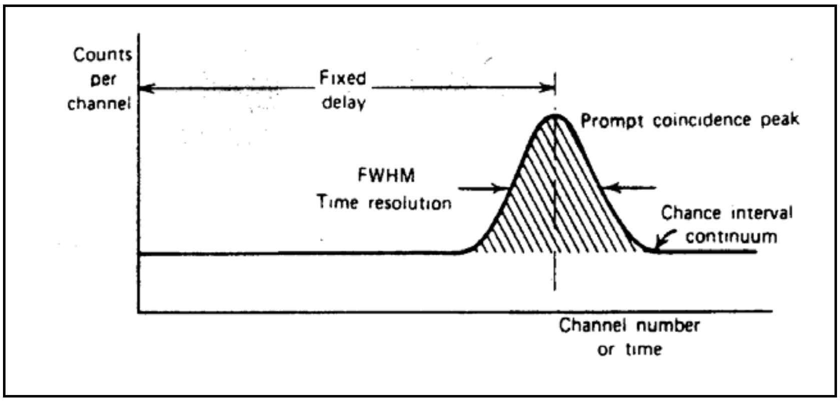


Figure 5.11 Typical example of a time spectrum. The hatched area gives the number of recorded coincidence events.

The amplitude of the chance coincidence distribution can be determined from the rates r_1 and r_2 of uncorrelated start and stop pulses. Typically, these rates will be much larger than the true coincidence rate between detectors 1 and 2 and usually be taken equal to the singles rates in the detectors.

Ignoring dead time in the TAC (i.e. if r_1 not small compared to the inverse of the TAC range), after each start pulse, the differential probability that a stop pulse will occur in a time interval t to t+dt is

$$r_2 \mathrm{e}^{-r_2 t}\,\mathrm{d}t \tag{5.1}$$

(cf Lecture 4, dead-time discussion). The rate at which such random stop pulses occurs is then simply the start rate multiplied by this probability or

$$r_1 r_2 \mathrm{e}^{-r_2 t}\,\mathrm{d}t \tag{5.2}$$

As long as r_2 is small compared to the inverse of the TAC range, $r_2 t$ is small and the exponential can be approximated by unity. In this case, the differential distribution of random events dr/dt is constant and equal to $r_1 r_2$. If the time calibration of the TAC is ΔT per channel, the chance rate per channel is just $r_1 r_2 \Delta T$.

5.10.2 Overlap coincidence units

As the name suggests, only logic pulses that overlap in time at the input produce an output logic pulse.

Thus, an overlap coincidence unit will produce an output only when the time difference between the inputs is less than the resolving time τ of the system.

A simple circuit to measure the coincidence rate from two detectors using a coincidence unit is shown in Figure 5.12.

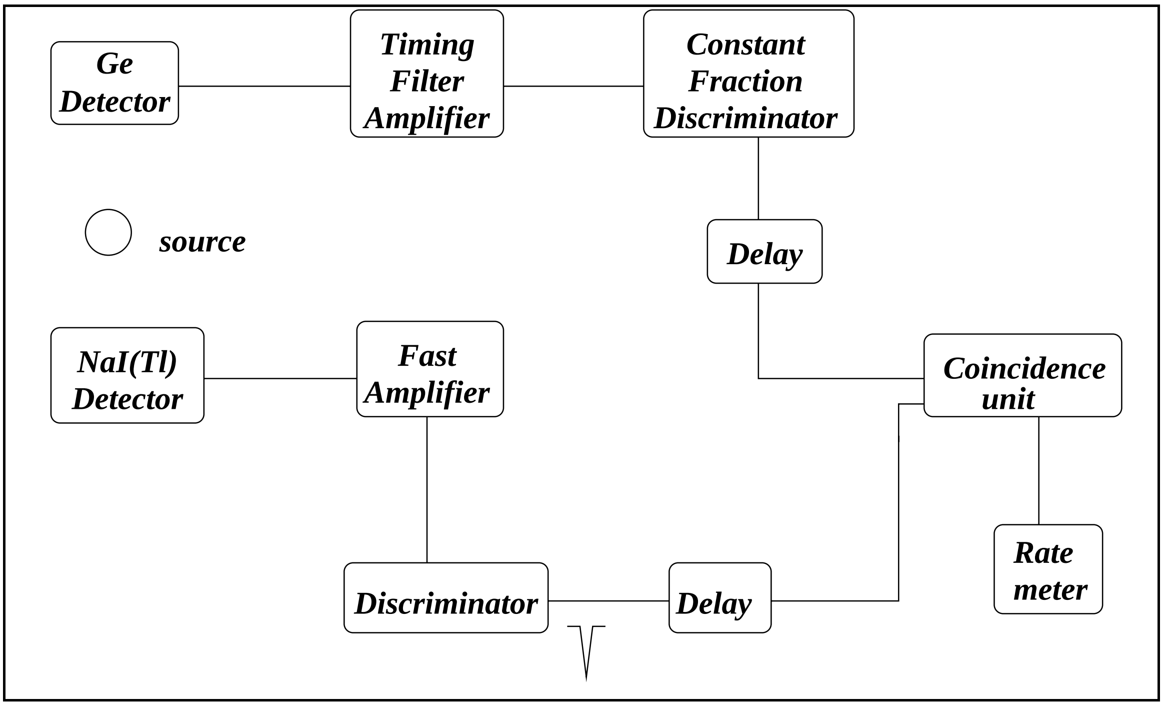


Figure 5.12 A circuit to measure the coincidence rate between two detectors.

In standard coincidence measurements. the recorded coincidence rate must be corrected for chance events in order to establish the true coincidence rate.

- In general, for any twofold coincidence unit, the chance coincidence rate from uncorrelated inputs at rates r_1 and r_2 is given by $r_{ch} = 2\tau\, r_1 r_2$.

Thus, the chance coincidence rate is calculable if the resolving time and the single rates are known.

Alternatively, the chance coincidence rate can be measured by inserting a long delay into one branch of Figure 5.12 so that the acceptance time of the coincidence unit does not correspond to the true coincidence time. The system then just measures the chance coincidence rate directly.

5.10.3 Finding the coincidence resolving time

Several methods are available:

- Supply totally uncorrelated inputs and measure both the singles and chance coincidence rates and hence determine τ. In setting up such a measurement care must be taken that the inputs are truly uncorrelated!
- The resolving time can also be measured by recording a coincidence-delay curve such as shown in Figure 5.13.

To generate such a curve, the coincidence rate is recorded for various values of the variable delay shown in Figure 5.12. The width of the `peak' in Figure 5.13 corresponds to twice the coincidence resolving time. For this method to work, a source with a sufficiently high probability of true coincidence emissions must be used to ensure that the true coincidence rate stands well out above the background chance coincidence rate!

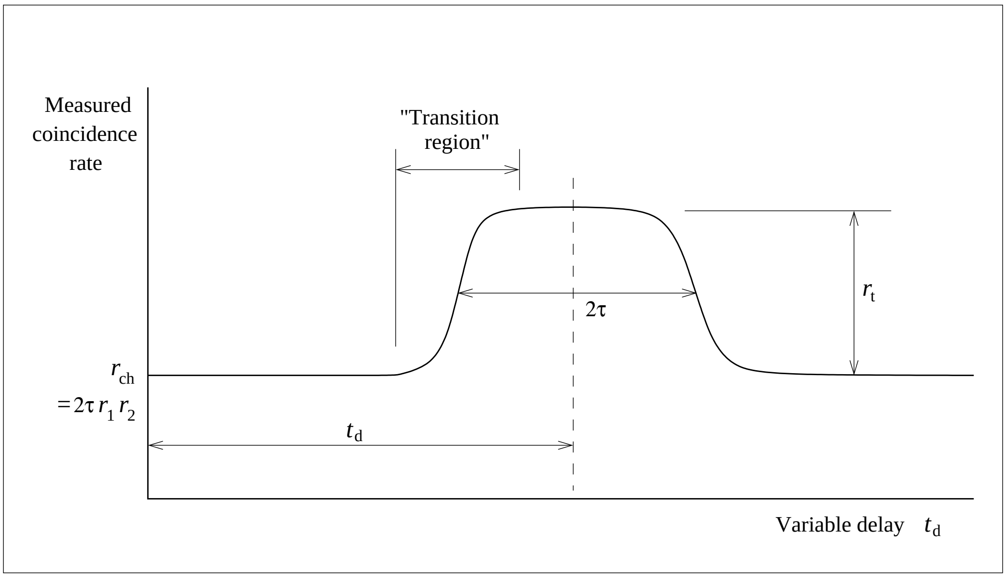


Figure 5.13 Coincidence decay curve.

5.11 MEASURING BOTH TIME AND ENERGY

For the optimum time information, the time constants of the shaping amplifier are usually chosen to be fast to preserve the rise time of the pulse from the preamplifier. However, such `fast'

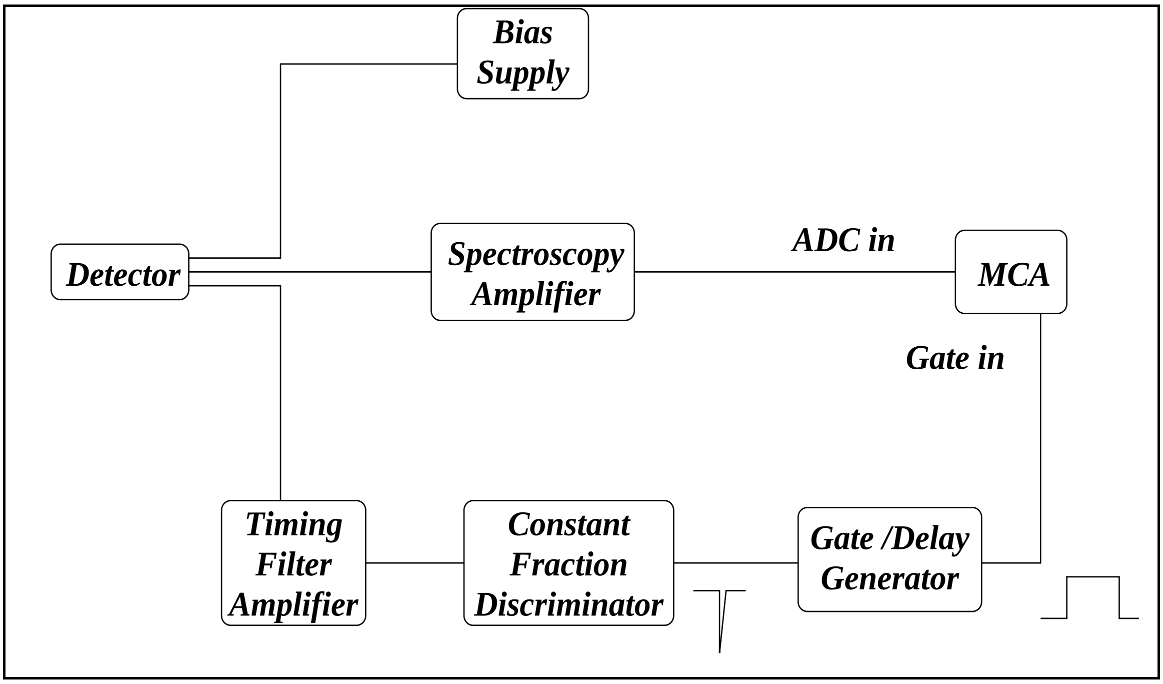


Figure 5.14 Set up for obtaining timing and energy information from a detector.

linear pulses will usually have inferior pulse-height information, when compared to the integrated tail pulse provided from spectroscopy amplifiers (much longer time constants are used in spectroscopy amplifiers).

Thus, in applications when both timing and energy (pulse height) information is required, it is common to arrange a fast-slow instrumentation scheme, such as is shown in Figure 5.14. Separate signals for timing and energy information are processed through the fast and slow branches respectively, so that appropriate choices may be made for the shaping time constants to optimise each branch.

The output from the timing branch can then be used to `gate' the adc/computer etc. so that only the corresponding energy pulses are accepted. Of course, the opposite can also be true, the energy pulse can be used only to accept certain time pulses.

5.12 SOME COMMON MODULAR TIMING INSTRUMENTS

The following list includes some common modular instruments used in timing measurements:

Coincidence Units:

Most commercial units are based on the overlap coincidence principle, so that the width of the input pulses determines the coincidence resolving time.

Commercial units often have multiple inputs (four or more) and some have at least one anticoincidence or veto input. If this input is used, then an output is generated only when a normal input pulse is NOT accompanied by a pulse at the anticoincidence input.

Time-to-Amplitude Converter (TAC):

A TAC will produce an output pulse with an amplitude that is proportional to the time difference between two input pulses. TACs are very popular for measuring time differences between events or, perhaps, lifetimes of nuclear levels down to a few nanoseconds.

Time to Digital Converter (TDC):

This is essentially a TAC but with a direct digital output instead of the analog from a standard TAC.

Time Delays:

Time delays are commonly introduced into timing circuits for time adjustment. For example, one may need to correct for delays introduced by different charge collection times in different detectors, or for different pulse transit times in cables, or for calibration purposes, etc, etc.

On a nanosecond scale, lengths of cables can be used as time delays. However, beyond about 100 ns, the cables become excessively long (> 30 m) and, in addition, can distort the pulse shapes of fast pulses (attenuation of high-frequency components).

For longer delays (μs and above), special active delay modules are available. One type is based on generating a ramp voltage and sensing when the ramp exceeds a discriminator level.

Fast Amplifiers:

If the output of the detector is too small to supply a pulse directly to a time-pickoff unit, such as a leading-edge discriminator, the detector output must be amplified. To preserve the fast linear rising edge of the detector or preamplifier pulse, i.e. to preserve the good timing information, an amplifier with a linear response to as high a frequency as possible is desired but without much emphasis on preserving the full pulse amplitude (energy resolution). In nuclear counting applications, such wide-band amplifiers are commonly referred to as fast amplifiers. An ideal fast amplifier will just reproduce the input pulse shape, except larger.