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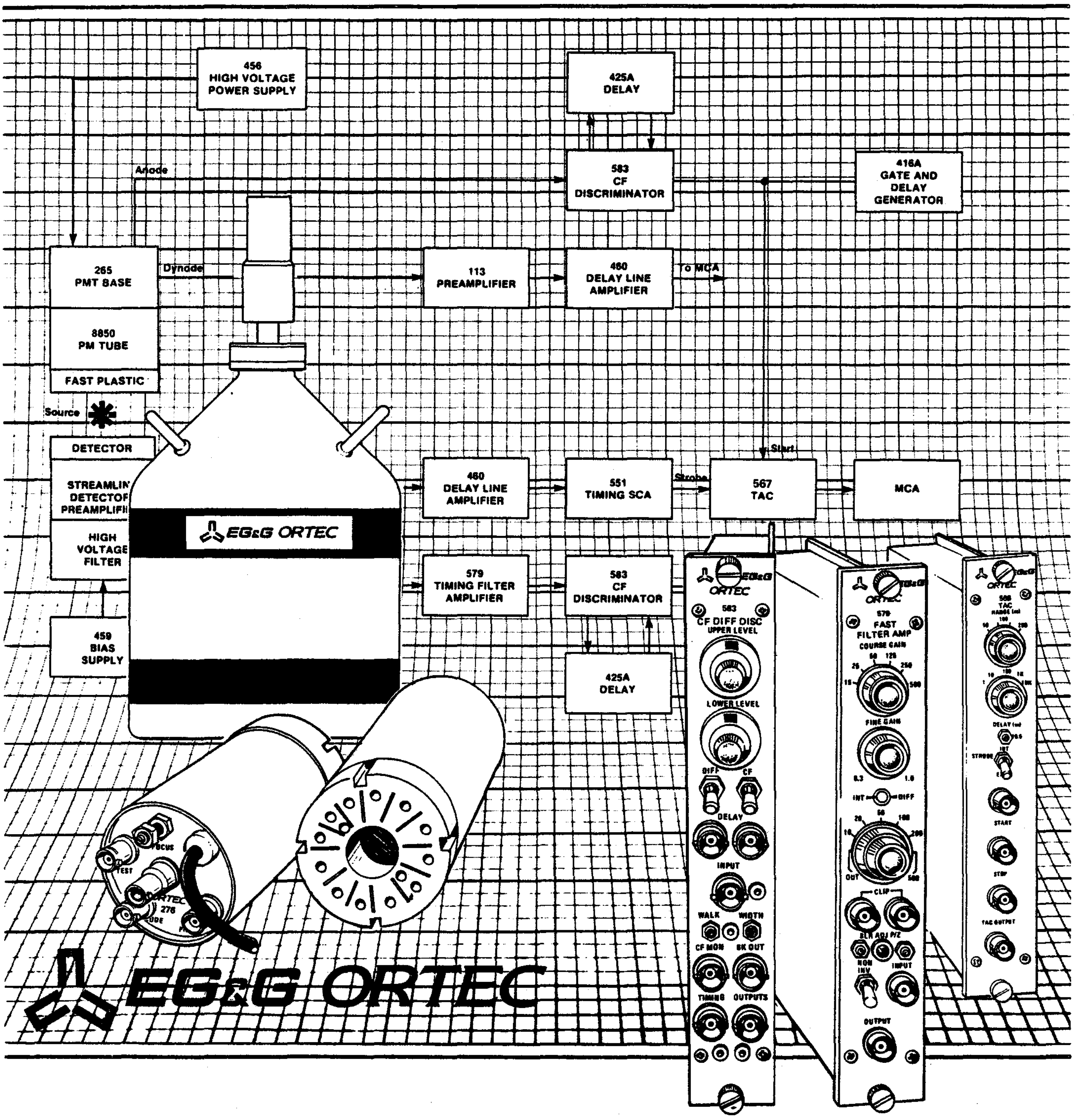
Principles and Applications of Timing Spectroscopy



Principles and Applications of Timing Spectroscopy

INTRODUCTION

A nuclear detection system consists of one or more detectors that sense the occurrence of nuclear events and of an assortment of instruments that provide information about the events, such as the energy of each event and the time of its occurrence. The term nuclear radiation applies to atomic particles, subatomic particles, gamma rays, and x rays.

This Application Note is concerned primarily with techniques for measuring the time of occurrence of a nuclear event. Much of the instrumentation that is applicable for time measurements is also common to the instrumentation used for energy measurements.

DETECTION METHODS

Methods for detecting nuclear radiation are usually based on either the excitation of atoms or the liberation of charge in the detecting medium caused by absorption of all or part of the energy of the incident radiation. An example of a device that operates on the principle of excitation of atoms is a scintillation detector. The basic process of detection in the scintillator involves the emission of light from atoms that are excited by the absorption of energy from radiation that passes into the detector. This emitted light is collected by a photomultiplier tube (PMT) and converted into a stream of electrons. Under proper conditions the charge in the current pulse from the PMT is proportional to the energy absorbed in the scintillator.

The principle of charge liberation is the basis on which a semiconductor detector operates. Charges (electron-hole pairs) are liberated in an electric field by the passage of radiation into the detector. A current pulse is produced as the charge is collected on the detector electrodes. Under proper conditions the total charge in the current pulse is proportional to the energy absorbed in the detector from the incident radiation.

ENERGY SPECTROSCOPY

For energy analysis the output current pulse from a PMT or from a semiconductor detector is often applied to a charge-sensitive preamplifier. The preamplifier produces a voltage pulse with a peak amplitude that is proportional to the total charge in the current pulse, which is proportional to the energy absorbed from the incident radiation. Amplifiers and filters are used to expand the range of the peak amplitude and to shape the signal from the preamplifier, a process that maximizes the signal-to-noise ratio for the system. For energy analysis the information of interest is represented by the peak amplitude of the shaped pulse.

NOTE: The "Bibliography," beginning on page 31, lists additional literature on timing techniques.

Discriminators and single-channel analyzers (SCA) can be used, following the signal shaping system, to determine the presence of certain energies of detected radiation. A discriminator produces an output logic pulse if its input signal exceeds a preset threshold level. An SCA produces an output logic pulse if the peak amplitude of its input signal falls within the energy window that is established with two preset threshold levels.

A multichannel analyzer (MCA) operates like a parallel array of single-channel analyzers that have been adjusted to have adjacent window segments within a range of energies. The MCA separates the output signals that are furnished from the signal shaping system into incremental ranges of pulse heights and accumulates the number of pulse measurements falling within each range. These increments correspond to ranges of energies in the detected radiation. The stored information can be used to provide a histogram representing the probability density of pulse heights, or energies, of the detected radiation. The MCA also provides means for the stored data to be displayed, printed, or plotted, or to be used by a computer for further analysis.

TIME SPECTROSCOPY

Time spectroscopy involves the measurement of the time relationship between two events. A particularly difficult problem in timing is to obtain a signal that is precisely related in time to the event. A time-pickoff circuit is employed to produce a logic output pulse that is consistently related in time to the beginning of each input signal. Ideally, the time of occurrence of the logic pulse from the time-pickoff element is insensitive to the shape and amplitude of the input signals.

A time-to-amplitude converter (TAC) can be used to measure the time relationship between correlated or coincident events seen by two different detectors that are irradiated by the same source. Figure 1 is a simplified block diagram of a typical time spectrometer used for making this type of timing measurement. A time-pickoff unit is associated with each detector, with the logic pulse from one time pickoff used to start the TAC and the delayed logic pulse from the other time pickoff used to stop the TAC. The TAC is usually implemented by charging a capacitor with a constant-current source during the time interval between a start input signal and the next stop input signal. The amplitude of the voltage on the capacitor at the end of the charging interval is proportional to the time difference between the two signals. The delay shown in Fig. 1 separates the start and stop signals sufficiently to permit the TAC to operate in its most linear region.

The amplitude information from the TAC is often applied to an MCA for accumulation of the data and display of the probability density of start-to-stop time intervals, commonly called a timing spectrum. Figure 2 indicates a type of timing spectrum that might be produced by coincident gamma rays. The shape of the timing spectrum is critically important in time spectroscopy. The timing resolution must be high (the timing peak must be narrow) so that the time

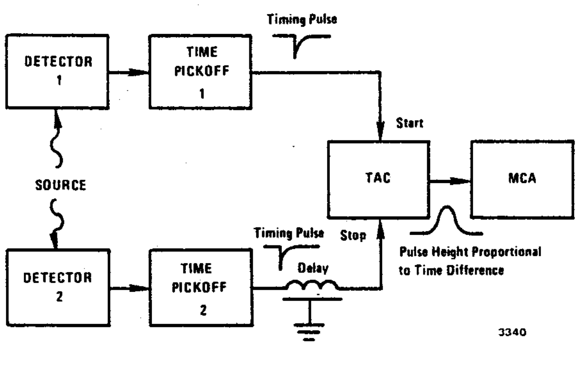


Fig. 1. Simplified Block Diagram of a Typical Time Spectrometer.

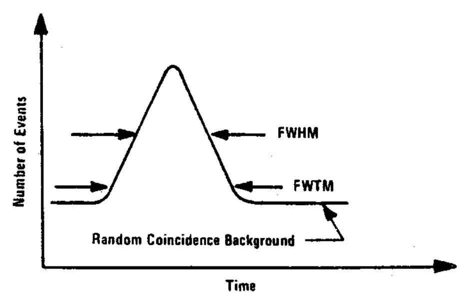


Fig. 2. Timing Coincidence Spectrum.

relationship between two closely spaced events can be measured accurately. It is important that the narrow width of the spectral peak be maintained down to a small fraction of its maximum height to ensure that all truly coincident events are recorded. One figure of merit is the full width of the timing peak at one-tenth its maximum value (FWTM). For a Gaussian time distribution the total number of counts included in this measurement represents about 98% of the true coincident events. Another figure of merit is the full width of the timing peak at one-half its maximum value (FWHM). The integral number of counts included in this measurement, for a Gaussian timing distribution, represents about 76% of the total number of coincident events. At some point the sides of the timing peak merge into the random coincidence background.

In some timing applications it is sufficient to know that two detected events were coincident within the limits of a short time interval. This type of measurement, as opposed to the multichannel method shown in Fig. 1, may be considered as a single-channel or time-window analysis. The term window indicates that there is a certain range of time during which, if both input signals are present, a logic pulse is generated to indicate the coincidence. Pairs of input signals that do not occur within this time window, relative to each other, are not recognized. The minimum permissible width of the time window is limited by the time-pickoff devices. If the time window is narrower than the width of the timing peak shown in Fig. 2, some of the events that are truly coincident will be rejected. Therefore the width of the time window is usually set slightly wider than the FWTM value of the time spectrum.

There are two general techniques for processing pulses in an overlap type of coincidence recognition instrument: the slow-coincidence method and the fast-coincidence method. The slow-coincidence method uses the width of the input pulses directly in a time overlap evaluation. The fast-coincidence method provides an internally reshaped pulse so that there is a standardized pulse width for each input signal and then detects any overlap of the standardized pulses. An advantage of using the fast-coincidence method is that the resolving time, or time window, can be controlled by adjusting the width of the reshaped pulses.

Figure 3 shows a simplified fast-coincidence system that uses single-channel or time-window analysis. The input pulses to the coincidence module are reshaped to a standard width, τ. If the reshaped pulses have a time overlap, a logic pulse is produced at the output. The resolving time or time-window width of the fast-coincidence circuit is 2τ. Although this system is simple in principle, some practical difficulties exist. One of the problems is that the relative delays of the input signals to the coincidence unit must be carefully adjusted to ensure that genuinely coincident events produce an output pulse. In addition, this system produces only a logic decision concerning the coincidence, neither resolving the actual time difference between two input signals nor indicating which of the two signals occurred first.

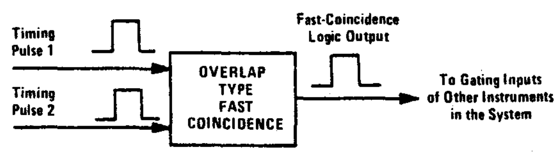


Fig. 3. Single-Channel Fast-Coincidence System Using an Overlap Type of Coincidence Circuit.

The coincidence system shown in Fig. 4 overcomes some of the disadvantages of the overlap type of system and also provides timing resolution information. In this system an SCA is used to select the range of pulse amplitudes from the TAC that represents true-coincidence events. The SCA window (i.e., the region of interest in the timing spectrum) can be set quickly and accurately while the timing information from the TAC is accumulated in a multichannel analyzer. The TAC output is used to generate a spectrum for display by the MCA, which is gated by the SCA output. The output of the SCA can also be used to gate other instruments in the system.

A second SCA may be used to monitor the random coincidence background, which in Fig. 4, is the area of the spectrum not included in the time window. The second SCA window width is set equal to the first but is positioned in the flat random coincidence background portion of the spectrum. Ideally the number of random coincidence events selected by the second SCA is then identical to the number that is detected by the first SCA. By recording a gated timing spectrum for each SCA, the true-coincidence spectrum can be corrected by a channel-by-channel subtraction procedure.

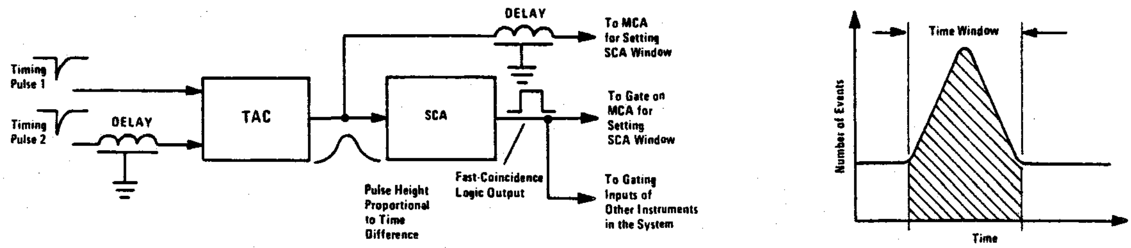


Fig. 4. Single-Channel Fast-Coincidence System Using a Time-to-Amplitude Converter, TAC, and the MCA Display to Set the Time Window.

TIME-PICKOFF TECHNIQUES

A time-pickoff element is essential in all timing systems. An ideal time pickoff produces a logic pulse at its output that is precisely related in time to the occurrence of an event. Three important sources of error can occur in time-pickoff measurements: walk (sometimes called time slewing), drift, and jitter.

Walk is the time movement of the output pulse from the pickoff element, relative to its input pulse, due to variations in the shape and the amplitude of the input pulse. Drift is the long-term timing error introduced by component aging and by temperature variations in the time-pickoff circuitry. Jitter is the timing uncertainty of the pickoff signal that is caused by noise in the system and by statistical fluctuations of the signals from the detector. Timing jitter is usually dominated by the statistical behavior of the signals from the detector system rather than by electronic noise.

In scintillator/photomultiplier timing systems, the sources of jitter are 1) the variation of the generation rate of photons in the scintillator; 2) the transit time variation of photons through the scintillator; 3) the transit time variation of photoelectrons in the PMT; and 4) the gain variation of the PMT. Jitter sources 1) and 4) can contribute to pulse-height variations of the PMT output signals. Sources 1), 2), and 3) affect the time of occurrence of the PMT output signals and to some extent their shape.

In semiconductor detector systems and more specifically in germanium coaxial detectors, timing properties are determined primarily by time slewing (walk) resulting from the shape of the detector output pulse. The detector pulse shape is dependent on the charge transit time, which is influenced by the electric field as a function of position in the detector, by electron and hole mobilities, and by the distribution of the charge created by the detected radiation. These three important sources of error are discussed in greater depth as they apply to the following principal types of time-pickoff techniques. Other sources of variations in charge collection time are charge trapping, which is due to crystal defects or impurities, and the plasma effect.

LEADING EDGE

A leading-edge discriminator is the simplest means of deriving a time-pickoff signal and produces an output logic pulse when the input signal crosses a fixed threshold level. A primary disadvantage of this technique is that the time of occurrence of the output pulse from a leading-edge trigger is a function of the amplitude and rise time of the input signal. This time slewing relationship restricts the usefulness of the leading-edge trigger as an accurate time-pickoff device to those applications that involve only a very narrow range of input signal amplitudes and rise times.

Figure 5 illustrates the time walk of an ideal leading-edge discriminator caused by variations in the amplitude and rise time of its input signals. Signals A and B are input pulses that have the same rise time but different amplitudes. Although these signals occur simultaneously, they cross the threshold level, V_{th}, at different times, t_1 and t_2. Signals B and C are input pulses that have the same amplitude but different rise times and that occur simultaneously but cross the threshold level at different times, t_2 and t_3. These differences in threshold-crossing time cause the output logic pulse from the discriminator to "walk" along the time axis as a function of the input signal amplitude and rise time. The walk is most pronounced for signals with amplitudes that only slightly exceed the threshold level. Walk is significantly reduced for signals with shorter rise times and for signals that greatly exceed the threshold level of the leading-edge discriminator.

An additional contribution to the time walk of a real leading-edge discriminator is its charge sensitivity, a term that describes the small amount of charge that is required to trigger a physically realizable threshold or crossover detecting device. Time walk due to charge sensitivity is also illustrated in Fig. 5. After an input signal crosses the discriminator threshold level, a small additional amount of charge is required to actually trigger the discriminating element. The time required to accumulate this additional charge is related to the areas of the shaded triangles by the impedance of the discriminator. Thus times t_{10}, t_{20}, and t_{30} are the times at which the output signals actually occur, relative to times t_1, t_2, and t_3, respectively, at which the input signals cross the threshold level. For input signals that have identical amplitudes the timing error introduced by charge sensitivity is greater for signals with longer rise times. For input signals that have identical rise times the time delay introduced by charge sensitivity is greater for signals with smaller pulse heights. In principle, for a flat top pulse of infinite duration the time required to accumulate the additional charge approaches infinity as the pulse height approaches the discriminator threshold. In practical cases, however, the walk due to charge sensitivity is limited by the width of the pulse above the discriminator threshold level.

Charge sensitivity introduces changes in the effective threshold level of a leading-edge discriminator, as well as changes in its effective sensing time. These changes are related to the slope of the input signal as it passes through the threshold. For simplicity it can be assumed that the input signal is approximately linear during the time, Δt, that is required to accumulate the charge-related area, k, indicated in Fig. 5. The error in the effective sensing time is related to the slope of the input signal by

$$\Delta T \cong \sqrt{\frac{2k}{\left.\frac{dV(t)}{dt}\right|_{t=T}}}, \qquad (1)$$

where V(t) is the input signal as a function of time and T is the threshold-crossing time of V(t). As can be seen in Fig. 5, although signals

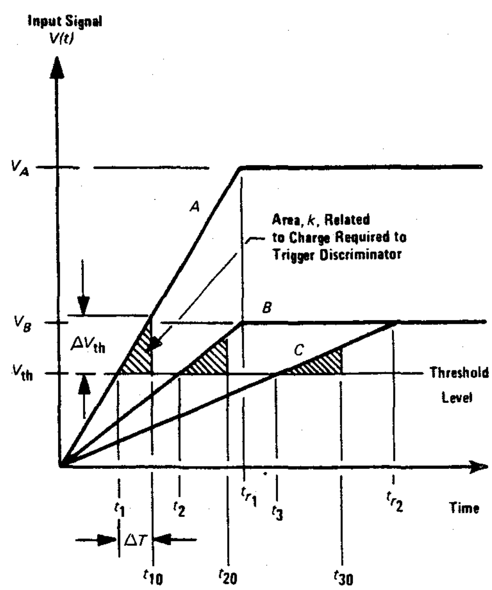


Fig. 5. Walk in a Leading-Edge Discriminator Due to Amplitude and Rise Time Variations and Charge Sensitivity.

with shorter rise times tend to decrease the time walk of a leading-edge discriminator due to charge sensitivity, they increase the error in its effective threshold level.

As was mentioned earlier, jitter, another major source of error in time-pickoff techniques, refers to the timing uncertainty caused by statistical fluctuations of the signals from the detector and by noise. The noise can be present on the detector signal, can be generated by the processing electronics, or can be generated by the discriminator itself. Statistical amplitude fluctuations of the detector signals and noise on the input signal to a leading-edge discriminator cause an uncertainty in the time at which the signal crosses the discriminator threshold level. These two sources of timing uncertainty are illustrated in Fig. 6 for an ideal leading-edge discriminator.

Assuming a Gaussian-probability density of noise amplitude with a zero mean, let the standard deviation (or rms value) of the noise be σ_V. The noise-induced rms uncertainty, σ_T, in threshold-crossing time for the leading-edge discriminator is given with reasonable accuracy by the triangle rule as

$$\sigma_T \cong \frac{\sigma_V}{\left.\frac{dV(t)}{dt}\right|_{t=T}} . \quad (2)$$

In obtaining this expression the input signal, V(t), is assumed to be approximately linear in the region of threshold crossing, and the discriminator threshold level is assumed to be removed from both the zero level and the peak amplitude of the signal by at least the noise width. The timing uncertainty caused by statistical amplitude fluctuations of the detector signal can be approximated in a similar manner for leading-edge timing.

If several sources of statistical timing uncertainty can be identified, the rms jitter due to each source can be determined. The total rms time jitter can be approximated by the square root of the sum of the squares of the individual rms jitter components. Timing uncertainty due to noise and statistical amplitude variations of the detector signals is directly related to the amplitude of the fluctuations of the input signal. The timing uncertainty due to these sources of jitter is inversely proportional to the slope of the input signal at threshold-crossing time. In general, signals with greater slopes at threshold-level crossing produce less time jitter.

When the leading-edge technique is restricted to those applications that involve a very narrow dynamic range of signals, excellent timing results can be obtained. Under these conditions timing errors due to charge sensitivity and jitter are minimized for input signals with the greatest slope at threshold-crossing time. The best timing resolution is most frequently found by experimenting with the threshold level.

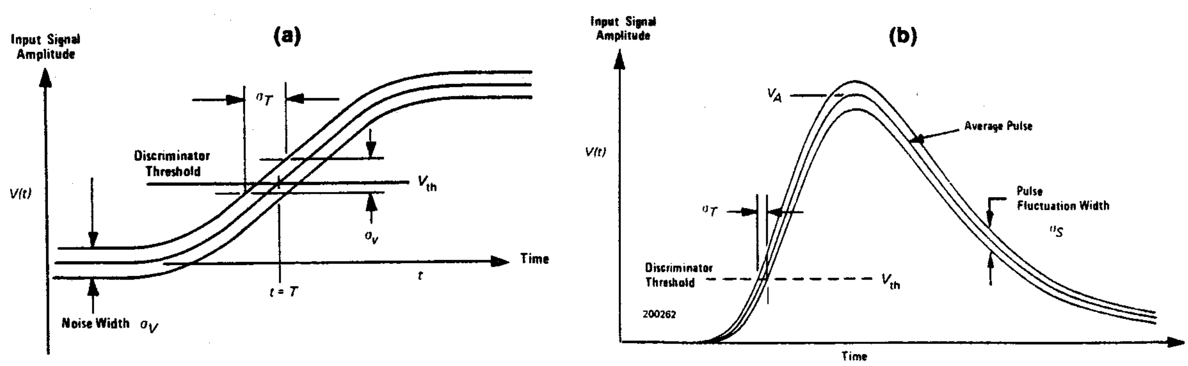


Fig. 6. Time Jitter in a Leading-Edge Discriminator Due to (a) Noise on the Input Signal and (b) Statistical Pulse-Height Variations.

CONSTANT FRACTION

The existence of an optimum triggering fraction for leading-edge timing with plastic scintillator/photomultiplier systems stimulated the design of a circuit that would trigger at the optimum triggering fraction regardless of the pulse height. Based on leading-edge timing data, the optimum fractional point on the leading edge of the amplifier output pulse was selected as the one at which the best time resolution could be obtained.

A functional representation of a constant-fraction trigger is shown in Fig. 7. In the constant-fraction method the input signal to the circuit is delayed, and a fraction of the undelayed pulse is subtracted from it. A bipolar pulse is generated and its zero crossing is detected and used to produce an output logic pulse. The use of a leading-edge arming discriminator provides energy selection capability and prevents the sensitive zero-crossing device from triggering on the noise on the constant-fraction baseline. A one-shot multivibrator is used to prevent multiple output signals from being generated in response to a single input pulse.

With the constant-fraction technique, walk due to rise time and amplitude variations of the input signals is minimized by proper selection of the shaping delay time, t_d. Jitter is also minimized for each detector by proper selection of the attenuation fraction, f, that determines the triggering fraction. Although difficult to implement, the constant-fraction trigger can provide excellent timing results over a wide dynamic range of input signals.

Two cases must be considered in determining the zero-crossing time of the constant-fraction bipolar signal. The first case is for true-constant-fraction (TCF) timing, and the second case is for the amplitude-and-rise-time-compensated (ARC) timing.

In the true-constant-fraction case the time of zero crossing occurs while the attenuated input signal is at its full amplitude. This condition allows the time-pickoff signal to be generated at the same fraction, f, of the input pulse height regardless of the amplitude. Figure 8 illustrates the signal formation in an ideal constant-fraction discriminator for TCF timing with linear input signals. The amplitude independence of the zero-crossing time is depicted for input signals A and B, which have the same rise time, t_{r1}, but different amplitudes. From signals B and C the zero-crossing time for the TCF case is seen to be dependent on the rise time of the input signal. For linear input signals that begin at time zero the constant-fraction zero-crossing time, T_{TCF}, for the true-constant-fraction case is

$$T_{TCF} = t_d + f t_r \,. \qquad (3)$$

Two criteria for the constant-fraction shaping delay, t_d, must be observed in order to ensure TCF timing for each linear input signal. The shaping delay, t_d, must be selected so that

$$t_d > t_r\,(1 - f). \qquad (4)$$

This constraint ensures that the zero-crossing time occurs after the attenuated linear input signal has reached its maximum amplitude. Practical timing experiments involve input signals

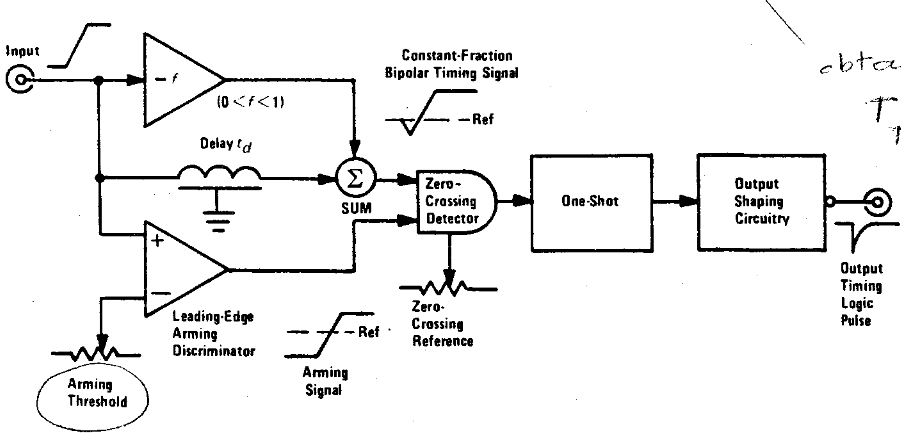


Fig. 7. Functional Representation of a Constant-Fraction Trigger.

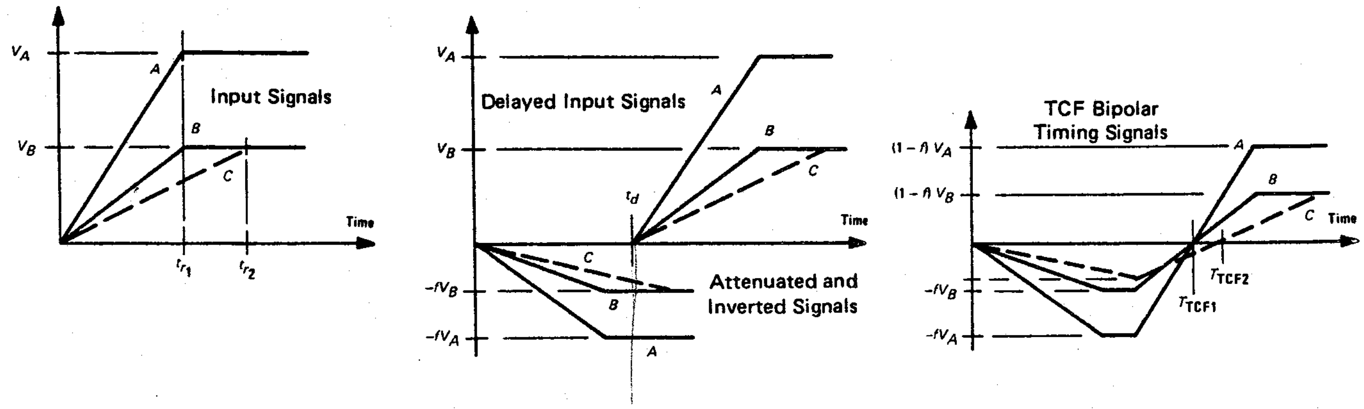


Fig. 8. Signal Formation in a Constant-Fraction Discriminator for TCF Timing.

with finite pulse widths; therefore the shaping delay, t_d, must also be made short enough to force the zero crossing of the constant-fraction signal to occur during the time that the attenuated signal is at its peak. Observing these two criteria allows the time pickoff signal to be generated at the fraction, f, of the input pulse height regardless of the amplitude.

From Eq. (3) and the criteria for t_d, true-constant-fraction timing is seen to have limitations in its application. TCF timing is most effective when used with input signals having a wide range of amplitudes but having a narrow range of rise times and pulse widths. These input signal restrictions favor the use of TCF timing in scintillator/photomultiplier systems. Any remaining walk effect can be attributed to the charge sensitivity of the zero-crossing detector and the slew limitations of the devices used to form the constant-fraction signal.

The second case to be considered in determining the zero-crossing time of the constant-fraction signal is for ARC timing, when the time of zero crossover occurs before the attenuated input signal has reached its maximum pulse height. This condition eliminates the rise-time dependence of the zero-crossing time that limits the application of the TCF technique. Figure 9 illustrates the signal formation in an ideal constant-fraction discriminator for ARC timing with linear input signals. The amplitude independence of the ARC zero-crossing time is depicted for input signals B and C, which have the same amplitude, V_B, but different rise times. For linear input signals that begin at time zero the zero-crossing time, T_{ARC}, for the ARC timing case is

$$T_{ARC} = \frac{t_d}{1 - f} . \qquad (5)$$

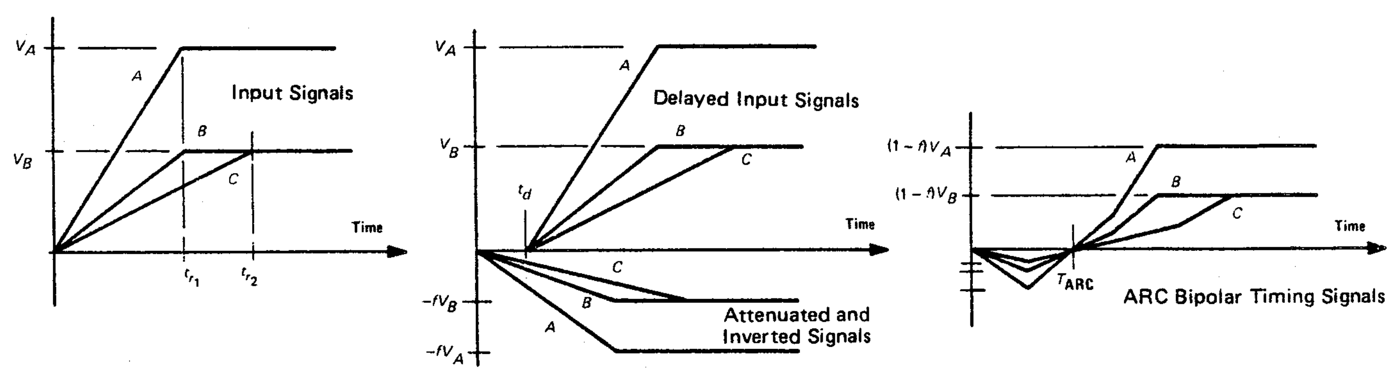


Fig. 9. Signal Formation in a Constant-Fraction Discriminator for ARC Timing.

One of the criteria for t_d that must be observed in order to ensure ARC timing with linear input signals is:

$$t_d < t_{r(min)} (1 - f), \qquad (6)$$

where $t_{r(min)}$ is the minimum expected rise time for any input signal. This constraint ensures ARC timing for all linear input signals with rise times greater than $t_{r(min)}$, regardless of the input pulse width.

In ARC timing the fraction of the input pulse height at which the time-pickoff signal is generated is not constant. The effective triggering fraction for each input pulse is related to the attenuation fraction, f, by the input signal rise time. Thus for linear input signals the effective ARC-timing triggering fraction is

$$f_{ARC(eff)} = \frac{f t_d}{t_r (1 - f)}, \qquad (7)$$

which is always less than f.

ARC timing is most useful when the input signals have a wide range of amplitudes and rise times making it especially suitable for use with large-volume germanium detectors that have wide variations in charge collection times. Jitter is a limiting factor in ARC timing with a narrow dynamic range of input signals.

As was mentioned previously, the constant-fraction trigger was originally developed to provide a time-pickoff signal at the fraction of input pulse amplitude at which timing error due to jitter is minimized. Noise-induced time jitter for an ideal constant-fraction trigger is illustrated in Fig. 10 for TCF timing with linear input signals.

The noise-induced rms uncertainty in the constant-fraction zero-crossing time, $\sigma_{T(cf)}$, is given with reasonable accuracy by the triangle rule as

$$\sigma_{T(cf)} \cong \frac{\sigma_{V(cf)}}{\left.\dfrac{dV_{cf}(t)}{dt}\right|_{t = T_{cf}}}, \qquad (8)$$

where

$\sigma_{V(cf)}$ is the standard deviation (or rms value) of the noise on the constant-fraction bipolar signal, $V_{cf}(t)$,

T_{cf} is the general zero-crossing time for either TCF or ARC timing.

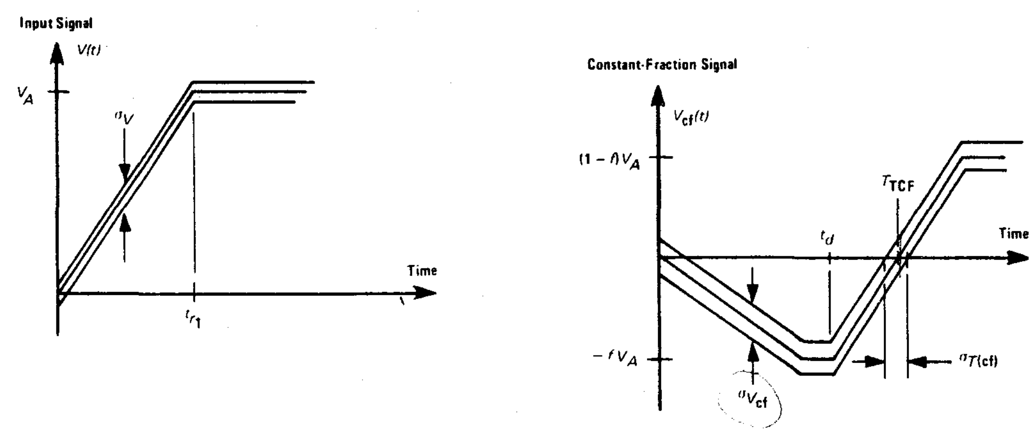


Fig. 10. Timing Uncertainty Due to Noise-Induced Jitter for TCF Timing.

In Eq. (8) the constant-fraction composite signal, $V_{cf}(t)$, is assumed to be approximately linear in the region of zero crossing, and the rms value of its noise can be related to the noise on the input signal. The following additional assumptions are also made to simplify this relationship: the noise on the input signal is a time-stationary random process, having a Gaussian-probability density function of amplitudes with a zero mean value; and the constant-fraction circuit is ideal, having an infinite bandwidth and contributing zero noise. Then

$$\sigma_{V(cf)} = \sigma_V \sqrt{1 + f^2 - \frac{2f\Phi(t_d)}{\overline{V_n^2(t)}}} \, , \tag{9}$$

where

σ_V is the rms value of the input noise,

f is the constant-fraction attenuation factor,

$\overline{V_n^2(t)}$ is the mean-squared value of the input noise,

$\Phi(t_d)$ is the autocorrelation function of the input noise,

t_d is the constant-fraction shaping delay.

For cases of uncorrelated noise the rms value of the noise on the constant-fraction signal is related to the rms value of the noise on the input signal by

$$\sigma_{V(cf)} = \sigma_V \sqrt{1 + f^2} \, . \tag{10}$$

Equation (10) is quite useful in estimating the timing error due to noise-induced jitter given by Eq. (8).

Determining the constant-fraction time jitter due to noise from Eq. (8) also requires a knowledge of the slope of the composite timing signal at crossover. For TCF timing with a linear input signal the slope of the bipolar timing signal at crossover is

$$\left. \frac{dV_{cf}(t)}{dt} \right|_{t = T_{TCF}} = \frac{V_A}{t_{rI}} \tag{11}$$

For ARC timing with a linear input signal the slope of the constant-fraction signal at zero crossing is

$$\left. \frac{dV_{cf}(t)}{dt} \right|_{t = T_{ARC}} = \frac{(1 - f)V_A}{t_{rI}} \, . \tag{12}$$

Combining Eqs. (10) and either (11) or (12) with Eq. (8) yields the following expressions for noise-induced time jitter with linear input signals:

For TCF timing

$$\sigma_{T(TCF)} \cong \frac{\sigma_V \sqrt{1 + f^2}}{V_A / t_{rI}} \, ; \tag{13}$$

for ARC timing

$$\sigma_{T(ARC)} \cong \frac{\sigma_V \sqrt{1 + f^2}}{V_A (1 - f) / t_{rI}} \, . \tag{14}$$

A study of Eq. (2) and Eqs. (8) through (14) leads to several interesting observations concerning noise-induced jitter for constant-fraction timing and for leading-edge timing. For example, for the uncorrelated-noise case, which is the simplest and most prevalent case, under identical input signal and noise conditions and for the same attenuation fraction, f, the timing error due to noise-induced jitter is usually worse for ARC timing than it is for TCF timing. Although the rms value of the noise on the bipolar timing signal at zero crossing is the same in both cases, the slope of the ARC timing signal at zero crossing is almost always less than the slope of the TCF signal at zero crossing.

Under the conditions of identical input signal, noise, and fractional triggering level, the timing error due to noise-induced jitter should be worse for TCF timing than for leading-edge timing. The rms value of the noise is greater on the TCF bipolar signal than on the input signal by a factor of approximately $\sqrt{1+f^2}$. Ideally, the slopes of the two timing signals would be the same at the pickoff time. However, TCF timing virtually eliminates time jitter due to statistical amplitude variations of the signals from the detector. Thus if statistical amplitude variations are more predominant than noise, the timing uncertainty due to jitter with TCF timing can be less than that with leading-edge timing.

Time walk due to the charge sensitivity of the zero-crossing detector should also be considered. Equation (1) indicates that the delay time due to charge sensitivity is inversely proportional to the square root of the slope of the timing signal at threshold-crossing (or zero-crossing) time. The timing signal is assumed to be approximately linear in the crossover region. Thus for identical input signals and for the same attenuation fraction, f, the time delay (or time walk) due to charge sensitivity is usually greater for ARC timing than for TCF timing. The slope of the ARC timing signal at zero crossing is almost always less than the slope of the TCF bipolar signal at zero crossing.

Although the constant-fraction technique is more difficult to implement than the leading-edge technique, it provides excellent timing results in a variety of applications. True-constant-fraction timing is most effective when used with input signals having a wide range of amplitudes but a narrow range of rise times and pulse widths. Amplitude-and-rise-time-compensated timing is most effective when used with input signals having a wide range of amplitudes and rise times, regardless of pulse width. For a very narrow dynamic range of input signal amplitudes and rise times, leading-edge timing may provide better timing resolution if the timing jitter is dominated by noise rather than by statistical amplitude variations of the detector signals.

In practice, an additional problem is encountered with the ARC timing technique: Leading-edge time walk can be produced by the constant-fraction discriminator. A leading-edge discriminator is commonly used to arm the zero-crossing detector in a constant-fraction discriminator. To provide ARC timing the zero-crossing detector must be armed during the time interval between the initiation of the constant-fraction signal and its zero crossing. If the sensitive crossover-detection device is armed before the bipolar timing pulse begins, the pickoff signal is generated by the random noise on the constant-fraction baseline. If the leading-edge arming signal occurs after zero-crossing time, the unit produces leading-edge timing. This type of timing error occurs most often in ARC timing for signals with exceptionally long rise times and for signals with peak amplitudes that exceed the threshold level by only a small amount.

Several techniques have been devised to eliminate leading-edge walk effects in ARC discriminators. A slow-rise-time (SRT) reject circuit can be used to evaluate the relative times of occurrence of the constant-fraction signal and the leading-edge arming signal and then to block the timing logic pulses produced by leading-edge timing. This technique improves timing resolution below the FWHM level at the expense of counting efficiency in the discriminator.

PRACTICAL CONSTANT-FRACTION CIRCUITS

Many different circuits have been used to form the constant-fraction signal. The discussion associated with Fig. 7 described the principal functions that must be performed including attenuation, delay, inversion, summing, arming the zero-crossing detector, and detection of the zero crossing of the constant-fraction bipolar timing signal. Since the input circuit sets many of the ultimate performance characteristics of the constant-fraction discriminator, a brief description of the principal circuits in use may be helpful.

The block diagrams of the input circuits of 4 EG&G ORTEC Constant-Fraction Discriminators are shown in Fig. 11. The simplest circuit is shown in Fig. 11(a) and is used in the EG&G ORTEC Model 584. The upper comparator is a leading-edge discriminator whose output arms the zero-crossing detector. The constant-fraction signal is formed actively in the input differential stage of the lower comparator. The monitor signal is taken at the output of the constant-fraction comparator and is clamped at about 400 mV peak-to-peak. The lowest threshold setting for the 584 is approximately 5 mV and is determined by the characteristics of the leading-edge comparator.

Figure 11(b) shows the input circuit* of the EG&G ORTEC Model 934. In this circuit, the constant-fraction signal is formed passively in a differential transformer. The bandwidth of the transformer is very high (>400 MHz). The monitor output is a close approximation of the actual constant-fraction signal since it is picked-off at the input to the constant-fraction comparator. The arming and zero-crossing detector circuits are the same as in Fig. 11(a). The minimum threshold is 30 mV.

The input circuit for the EG&G ORTEC Model 473A is shown in Fig. 11(c). An additional leading-edge comparator has been added. The upper leading-edge comparator sets the energy range while the lower leading-edge comparator performs the arming function. Any input signal that crosses the upper leading-edge comparator threshold is sufficiently large to ensure an overdrive signal to the arming comparator whose threshold is set at E/2. This dual comparator arrangement effectively removes leading-edge walk for a signal just slightly greater than the E threshold level. The minimum value of the E threshold is 50 mV. The monitor output is similar to that of the 584 and is limited to about 400 mV peak-to-peak. The 473A also has three internal delay cables nominally optimized for use with plastic scintillators, NaI(Tl) and Ge detectors. The appropriate delay is switch-selected on the front panel.

The input circuit for the EG&G ORTEC Model 583 is shown in Fig. 11(d). A third leading-edge comparator has been added to allow selection of an upper energy of interest. Thus the 583 is a differential discriminator that can be adjusted to respond to input signals corresponding to a limited energy range. An output is produced when the input signal exceeds the lower-level threshold and does not exceed the upper-level threshold. This feature is also useful when selecting a single photon level, double photon level, or some other unique input signal condition. The 583 uses the same differential transformer techniques as those used in the 934, Fig. 11(b), and its monitor output is a faithful reproduction of the constant-fraction signal. The arming threshold can be adjusted from 0.5 to 1.0 times the lower-level threshold setting. The minimum threshold is 30 mV.

FAST CROSSOVER

The fast-crossover time-pickoff technique was developed to overcome the serious walk effects inherent in the use of the leading-edge method with a wide dynamic range of signals. This technique is specifically intended for use with the anode signal from fast scintillator/photomultiplier systems. The anode current pulse from the photomultiplier tube is stub-clipped with a shorted delay line to produce a bipolar timing signal. After the zero crossing of the timing pulse is detected, it is used to produce an output logic pulse. For signals with the

*This basic circuit is patented by EG&G ORTEC.

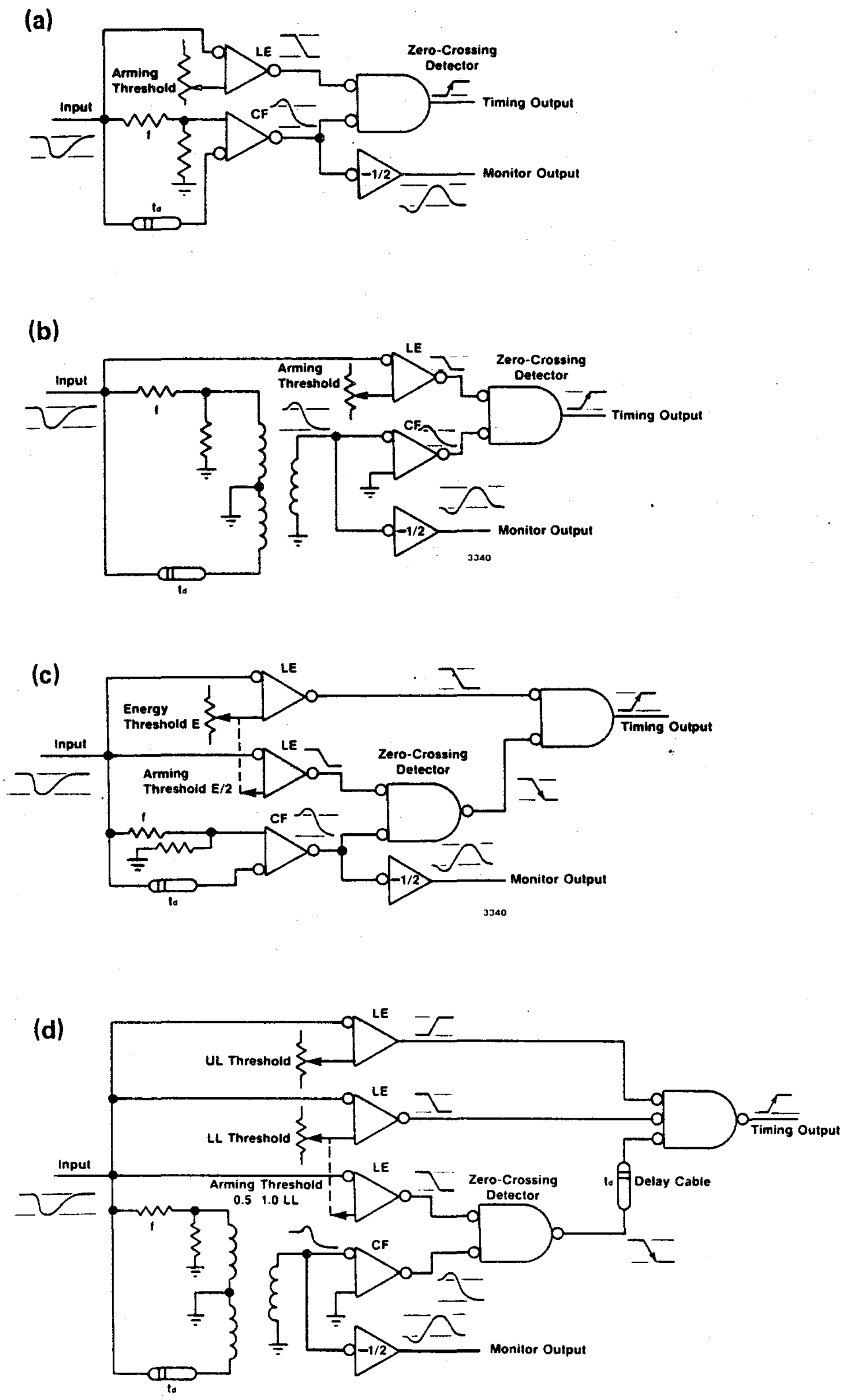


Fig. 11. Block Diagram of the Input Circuits of Four EG&G ORTEC Constant-Fraction Discriminators: (a) 584, (b) 934, (c) 473A, and (d) 583.

same pulse shape but with a wide dynamic range of amplitudes the zero crossing represents the same phase point on all input signals. Most of the amplitude-dependent time walk is eliminated, and what walk remains is due to the charge sensitivity of the zero-crossing detector.

Formation of the bipolar timing signal for the fast-crossover technique is shown in Fig. 12. The amplitude independence of the zero-crossing time is depicted for signals of different amplitudes that have identical pulse shapes. When this time-pickoff method is used, identical pulse shapes are critical.

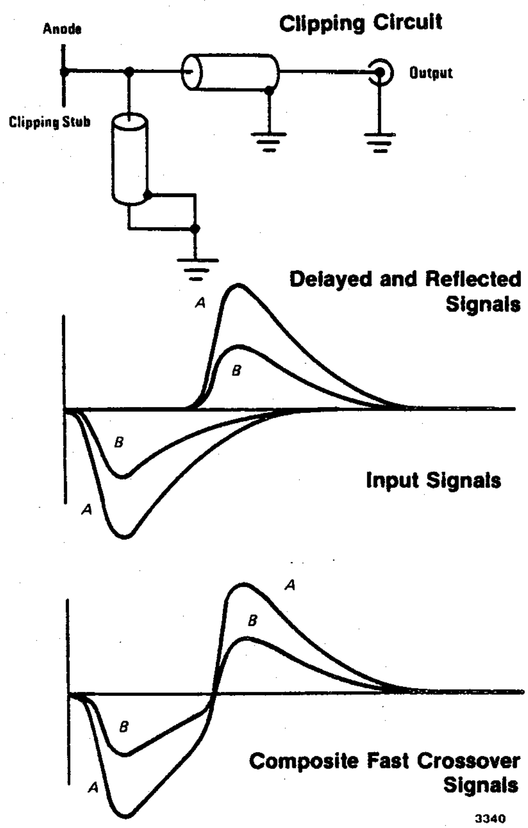


Fig. 12. Stub-Clipping Signal Formation for Fast-Zero Crossover.

The noise-induced rms uncertainty, $\sigma_{T(fz)}$, in the zero-crossing time of the fast-crossover signal is given with reasonable accuracy by the triangle rule as

$$\sigma_{T(fz)} \cong \frac{\sigma_{V(fz)}}{\left.\dfrac{dV_{fz}}{dt}\right|_{t = T_{fz}}} , \tag{15}$$

where

$\sigma_{V(fz)}$ is the standard deviation (or rms value) of the noise on the bipolar timing signal, $V_{(fz)}(t)$,

T_{fz} is the zero-crossing time.

The composite bipolar signal, $V_{fz}(t)$, is assumed to be approximately linear in the region of zero-crossing.

In Eq. (15) the rms value of the noise on the bipolar timing signal is related to the rms value of the noise on the input signal by

$$\sigma_{T(fz)} \cong \sigma_V \sqrt{(1)^2 + (1)^2 - \frac{2\Phi(2t_d)}{\overline{V_n^2(t)}}} , \tag{16}$$

where

σ_V is the rms value of the input noise,

$\overline{V_n^2(t)}$ is the mean-squared value of the input noise,

$\Phi(2t_d)$ is the autocorrelation function of the input noise,

t_d is the delay time of the shorted-delay-line stub.

The noise on the input signal is assumed to be a time-stationary random process, having a Gaussian-probability density function of amplitudes with a zero mean value. For the most prevalent case, which is for uncorrelated noise, the rms value of the noise on the fast-crossover bipolar signal is related to the rms value of the input noise by

$$\sigma_{V(fz)} = \sigma_V \sqrt{2} . \tag{17}$$

Determining the fast-crossover time jitter from Eq. (15) also requires a knowledge of the slope of the composite timing signal at crossover. The slope of the fast-crossover bipolar signal at zero-crossing time is less than the slope of the leading edge of the delayed anode signal.

For a narrow dynamic range of signal amplitudes, leading-edge timing and TCF timing should both provide less timing error due to noise-induced jitter than the fast-crossover technique. If only the uncorrelated noise is considered, the rms value of the noise is greater on the fast-crossover signal than on either the leading-edge timing signal or the constant-fraction bipolar timing signal. In addition, the slope of the fast-crossover signal at zero crossing is usually less than the slopes of either the leading-edge or the constant-fraction timing signals at their respective pickoff times.

The fast-crossover time-pickoff technique can provide excellent time resolution for a wide dynamic range of input signal amplitudes if the signal rise times and fall times do not vary significantly.

The fast-crossover technique has two major advantages and disadvantages. The advantages are: 1) the bipolar signal is simple to form for a specific application because the stub-clipping is passively implemented with a shorted 50 Ω delay line and 2) the zero crossing of the bipolar signal occurs well after the peak of the anode pulse. Thus a leading-edge trigger, used to arm the zero-crossing detector, does not interfere with the timing performance of the instrument. The disadvantages are: 1) for a narrow dynamic range of signals the timing jitter due to noise is greater than it is for either the leading-edge method or the TCF method and 2) changes in pulse shape cannot be tolerated.

CONVENTIONAL CROSSOVER

There are many applications in which a wide range of pulse amplitudes must be handled but optimum time resolution is not required. The linear side channel of a typical fast/slow coincidence system is a good example of this situation (see "Applications"). One solution to this problem is to utilize the zero crossing of the bipolar output signal from a pulse-shaping amplifier to derive timing information and to use the peak amplitude of the unipolar pulse from the amplifier for the energy range information.

Either double-delay-line-shaped pulses or RC-shaped pulses may be used, but the former provide better timing resolution. Timing walk resulting from amplitude variations is essentially reduced to the walk that is due to the charge sensitivity of the zero-crossing detector. The zero-crossing time is still a function of the pulse shape.

Pulse-shaping amplifiers are often designed specifically for energy spectroscopy. The energy information is derived from the peak amplitude of the amplifier's output pulse; thus the shaping filters in the amplifier are set to provide a maximum signal-to-noise ratio. To achieve the best signal-to-noise ratio, the amplifier bandwidth is limited by a differentiation network that is followed by at least one integration network. Integration significantly increases the rise times of the pulses from the shaping amplifier relative to the rise times of the pulses from the preamplifier. The resulting timing jitter is worse for techniques that derive timing information from the shaping amplifier signal than for the time-pickoff techniques that derive timing information from the leading edge of the preamplifier signal.

A comparison of leading-edge timing and conventional crossover timing can be made for scintillation detectors. A double-delay-line-shaped signal with no accompanying integration is used for the bipolar timing pulse in the analysis. The effective triggering fraction for this shaping method is approximately 50% of the collection time, with the rms value of the noise on the bipolar signal approximately twice that at the input. Compared to optimized leading-edge timing at 1 MeV the conventional crossover technique is theoretically shown to be 13.7 times worse for NaI(Tl) and 1.9 times worse for fast plastic scintillators.

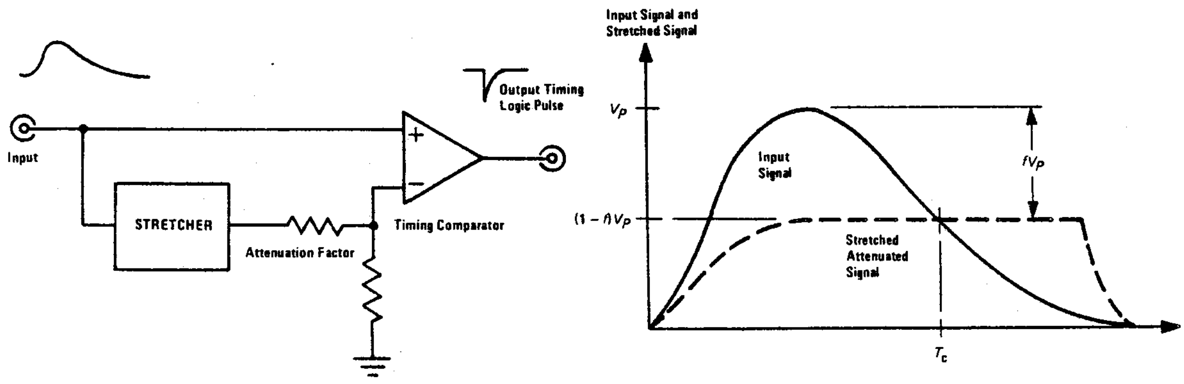
The conventional crossover technique is an attractive method for timing with a wide range of signal amplitudes if the best possible timing resolution is not required. This technique is used widely in timing-single-channel analyzers (TSCAs) because the zero crossing occurs well after the peaking time of the input signal.

TRAILING EDGE, CONSTANT FRACTION*

As was discussed in the preceding section, timing information can be obtained from the slow linear signals that are produced by the pulse-shaping amplifier in an energy spectroscopy system. The timing resolution obtained from these signals is generally not as good as the resolution obtained from the leading edge of signals from a fast-timing amplifier. However, the resolution obtained from the slow linear signals is entirely adequate in many of the cases that involve a wide range of signal amplitudes.

A trailing-edge constant-fraction technique can be used with either unipolar or bipolar signals to derive a time-pickoff pulse after the peak time of the signal from the shaping amplifier. This technique is extremely useful when incorporated in TSCAs and is illustrated in Fig. 13. The linear input signal is stretched and attenuated and then used as the reference level for a timing comparator. The time-pickoff signal is generated when the trailing edge of the linear input signal crosses back through the fraction reference level. The fraction, f, is the fraction of amplitude decay toward the baseline as measured from the peak of the input pulse. The amplitude-dependent time walk of the pickoff point is ideally reduced to the time walk associated with the charge sensitivity of the timing comparator. However, the time of occurrence of the pickoff signal is dependent on the shape of the input signal. Resolution can be optimized by careful experimentation with the fraction reference level.

*The basic circuit for implementing this technique is patented by EG&G ORTEC.



Block Diagram of Timing Circuit

Signals into the Comparator

Fig. 13. Signal Formation for Timing with the Trailing-Edge Constant-Fraction Technique.

APPLICATIONS

CONSTANT-FRACTION TIMING WITH SCINTILLATORS

Figure 14 shows a typical fast/slow timing coincidence system that can be used for timing with fast scintillators and PMTs. An integral mode constant-fraction discriminator is used as the time-pickoff device in each channel leading to the TAC. The 583 CFD can be operated as an integral discriminator or as a differential discriminator. An energy side channel is associated with each detector and is composed of a preamplifier, a shaping amplifier, and an SCA. The function of the SCA is to select the range of energies for which timing information is desired. If two detected events fall within the selected energy ranges, and if they are coincident within the resolving time selected for the coincidence unit, the precise timing information related to these events is strobed from the TAC. The timing information is accumulated and displayed by the MCA.

The TAC in Fig. 14 must handle the count rate associated with the single events exceeding the thresholds of the timing discriminators. This count rate can be an order of magnitude higher than the coincidence rate at which the TAC is strobed. Thus, a count rate limitation is imposed by the TAC in a fast/slow coincidence system. Resolution degradation can occur at high conversion rates in the TAC due to heating effects in the active circuitry and dielectric absorption in the storage capacitors.

Figure 15 shows a timing coincidence system that performs the same function as the fast/slow system shown in Fig. 14. In the system shown in Fig. 15, each constant-fraction differential discriminator generates the timing information and determines the energy range of interest simultaneously. If two detected events fall within the selected energy ranges, and if they are coincident within the resolving time selected for the coincidence unit, the TAC is gated on to accept the delayed, precise timing information. Thus, the TAC must handle start-stop signals only for events that are of the correct energy and that are coincident. Compared to

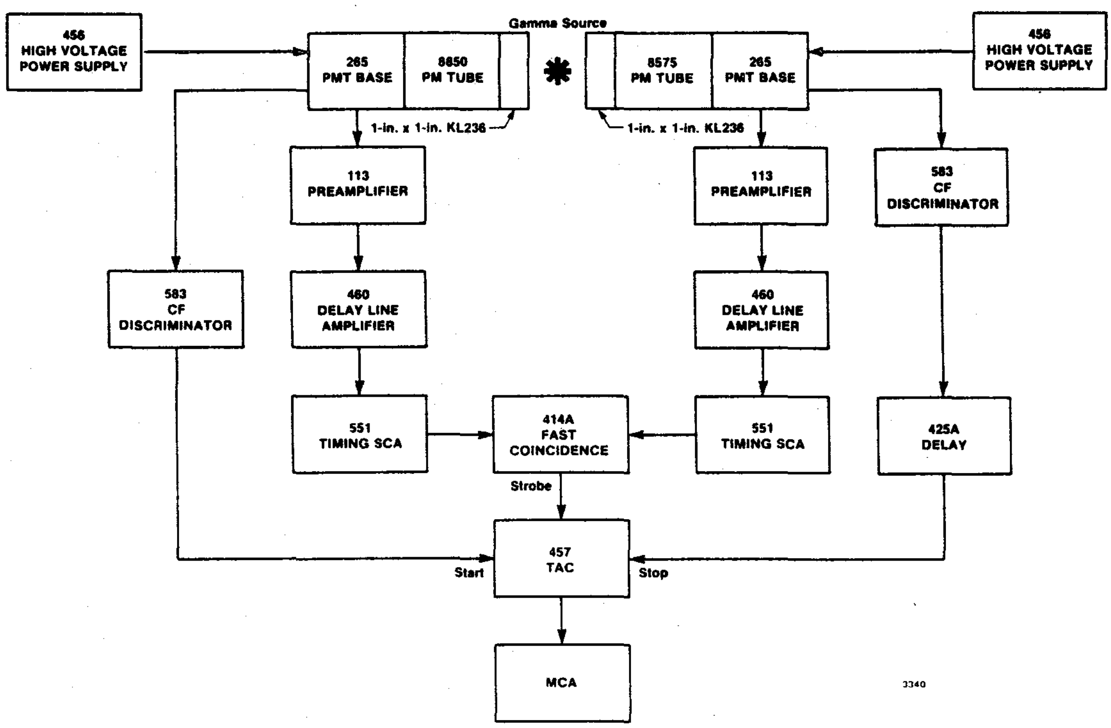


Fig. 14. Typical Fast/Slow Timing System for Gamma-Gamma Coincidence Measurements with Scintillators and Photomultiplier Tubes.

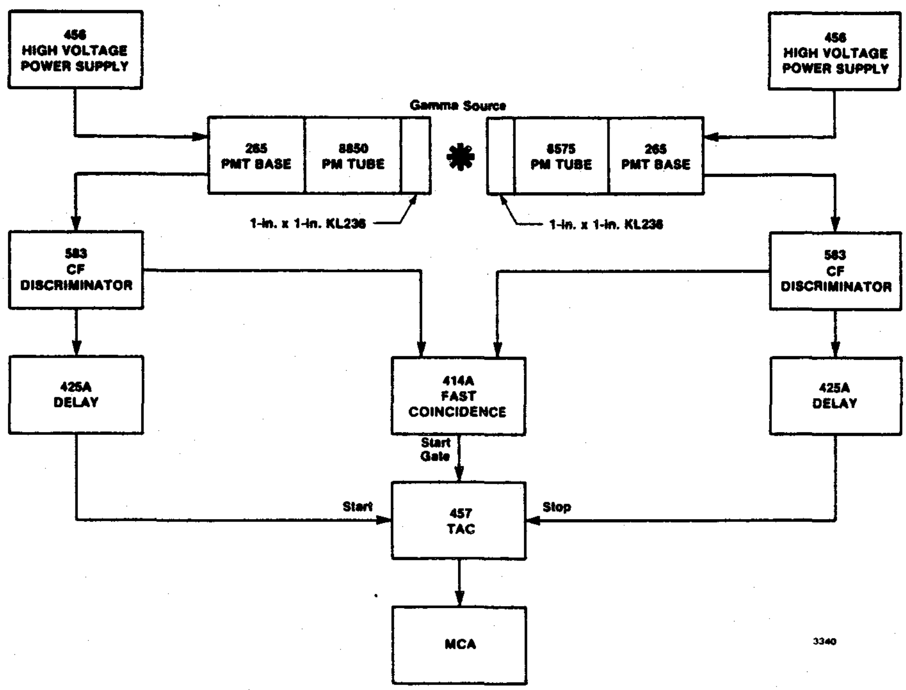


Fig. 15. A Fast-Timing Coincidence System for Gamma-Gamma Coincidence Measurements with Scintillators and Photomultiplier Tubes.

the fast/slow system, the fast system has fewer modules and improved count rate capability. The system shown in Fig. 15 is similar to the fast-fast (F^2) timing coincidence system.

Timing resolution was accumulated for two constant-fraction differential discriminators (INT mode) employed in the fast/slow coincidence system shown in Fig. 14. Figure 16 shows the resulting timing resolution with ^{60}Co as a function of the dynamic range of the input signals. The FWHM timing resolution ranges from 189 ps for a 1.1:1 dynamic range of signals to 336 ps for a 100:1 dynamic range. The upper-energy limit used in this experiment was 1.6 MeV.

Timing resolution was also obtained for two constant-fraction differential discriminators (DIFF mode) employed in the simplified, fast-timing coincidence system shown in Fig. 15. Figure 17 shows the resulting timing resolution with ^{60}Co as a function of the dynamic range of the input signals. The FWHM timing resolution ranges from 190 ps for a 1.1:1 dynamic range to 337 ps for a 100:1 dynamic range. The upper-energy limit for this experiment was 1.6 MeV. The data obtained with the fast coincidence system was within 5% of that obtained with the fast/slow coincidence system.

Timing resolution as a function of energy is another parameter in characterizing a timing system. Data was obtained for the fast-timing coincidence system using ^{60}Co and maintaining 100-keV energy windows with the differential discriminators. The resulting timing data is displayed in Fig. 18. Each axis represents the energy levels selected by the respective differential discriminator. The data included in each rectangle of the array is the FWHM, FWTM, and FW(1/100)M system timing resolution for the coincidence of the two selected energy ranges. The system FWHM timing resolution ranges from 176 ps for 950 keV to 1050 keV windows on both channels, to 565 ps for 50 keV to 150 keV windows on both channels.

Figure 19 is a plot of the timing resolution as a function of energy for each differential discriminator timing channel in the fast-timing coincidence system. Data points for this plot were

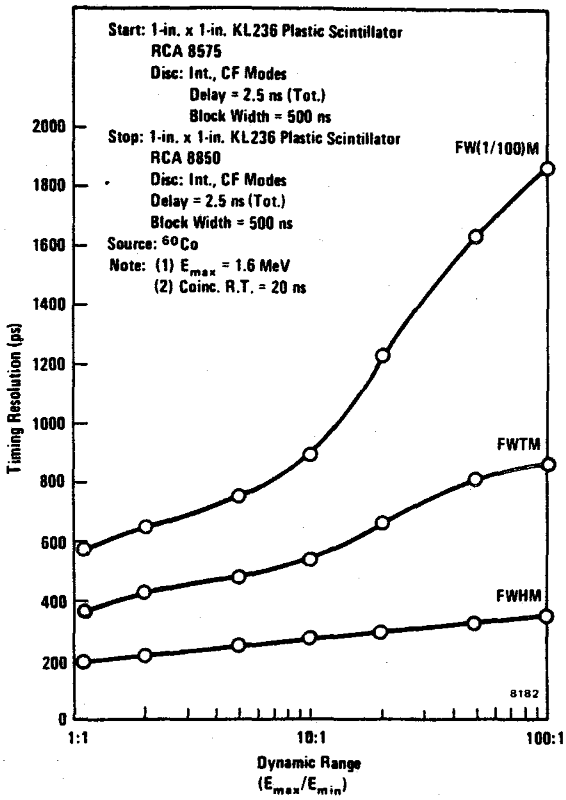


Fig. 16. Timing Resolution as a Function of Dymanic Range for Two Constant-Fraction Differential Discriminators in a Fast/Slow Timing Coincidence System (using the 583 CFD).

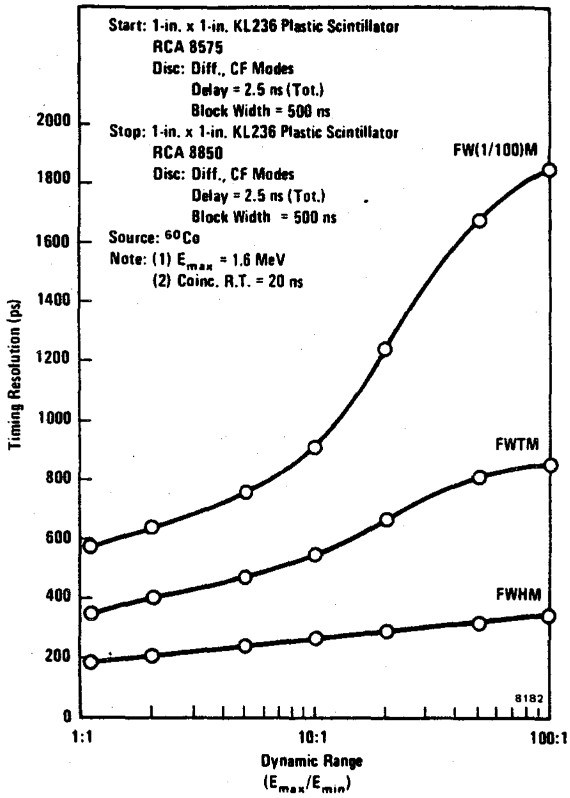


Fig. 17. Timing Resolution as a Function of Dynamic Range for Two Constant-Fraction Differential Discriminators in a Fast Timing Coincidence System (using the 583 CFD).

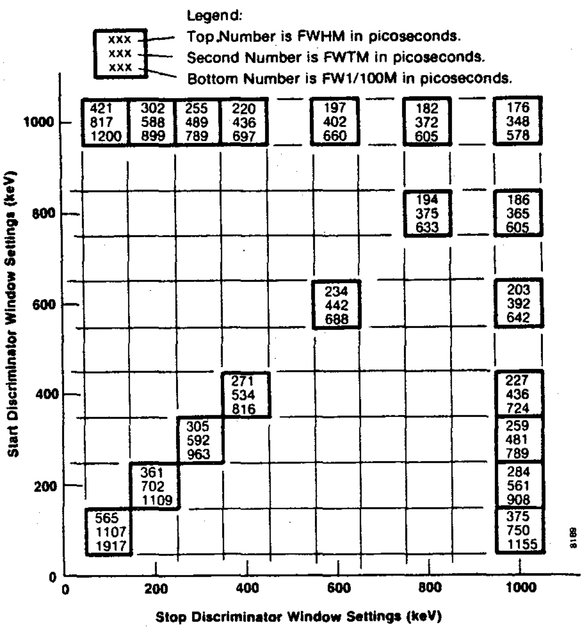


Fig. 18. Map of Timing Resolution vs Energy Using the Fast-Timing Coincidence System with a 1-in. x 1-in. KL236 Scintillator and ^{60}Co.

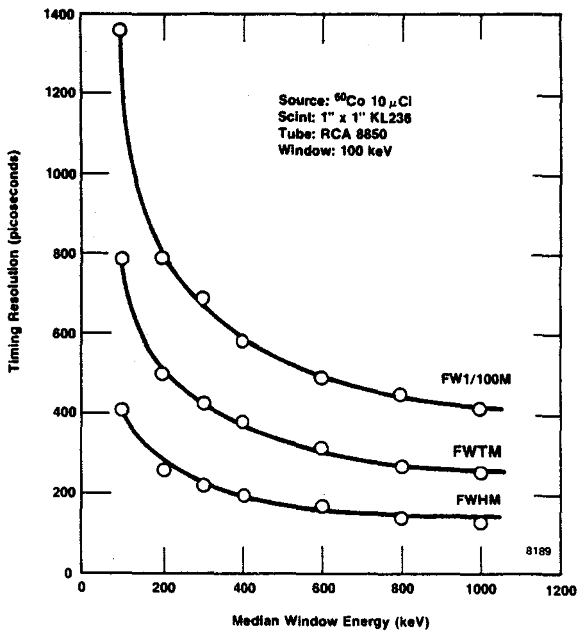


Fig. 19. Timing Resolution as a Function of Energy for Each Differential Discriminator Timing Channel in the Fast-Timing System.

obtained from the information along the diagonal array in Fig. 18, assuming equal contributions from each channel. The FWHM resolution for each channel ranges from 124 ps at 1 MeV to 400 ps at 100 keV.

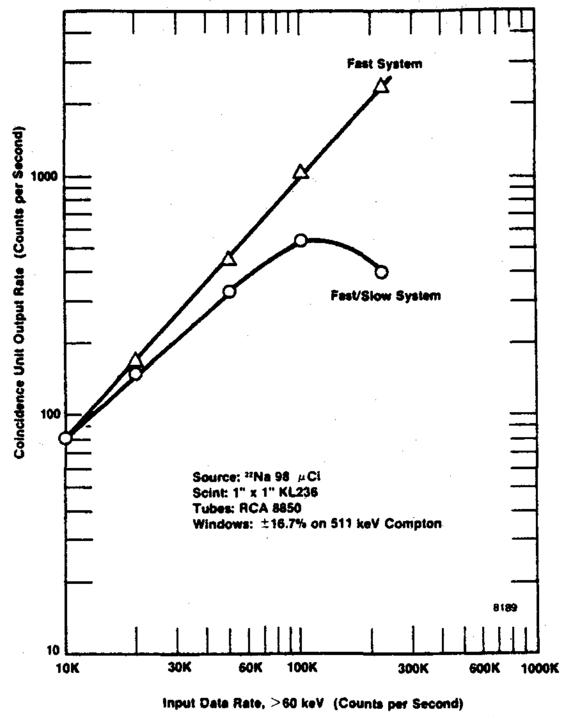


Fig. 20. Timing Coincidence Output Rate as a Function of Input Data Rate (using the 583 CFD).

Figure 20 is a plot of the output rate of the coincidence unit used in the two timing systems as a function of the input data rate. The coincidence resolving time was set at 50 ns for both the fast and fast/slow systems. In the fast-timing system, the coincidence output signals are used to gate the TAC for valid start signals, and the coincidence output rate shows a linear relationship to the input data rate. In the fast/slow system, the coincidence output signals are used to strobe the timing information from the TAC. The plot for the fast/slow system in Fig. 20 shows a marked decrease in the coincidence output rate for input data rates exceeding 100k cps. This decrease in coincidence output rate results in a direct decrease in the TAC output rate for corresponding input data rates. The decrease in coincidence efficiency in the fast/slow system is attributable to pile-up effects and baseline movement of the main shaping amplifiers at these high data rates. At an input data rate of 200k cps, the fast system showed a factor-of-6 improvement in coincidence rate.

The fast/slow timing coincidence system and the fast-timing coincidence system can also be used with NaI(Tl) scintillators. A unique problem encountered with NaI(Tl) scintillators is their long decay time ($\tau \cong 250$ ns). Individual photoelectron events near the trailing edge of the NaI(Tl) pulse can produce spurious timing output signals from the constant-fraction discriminator. This problem can be overcome by selecting the proper discriminator and adjusting

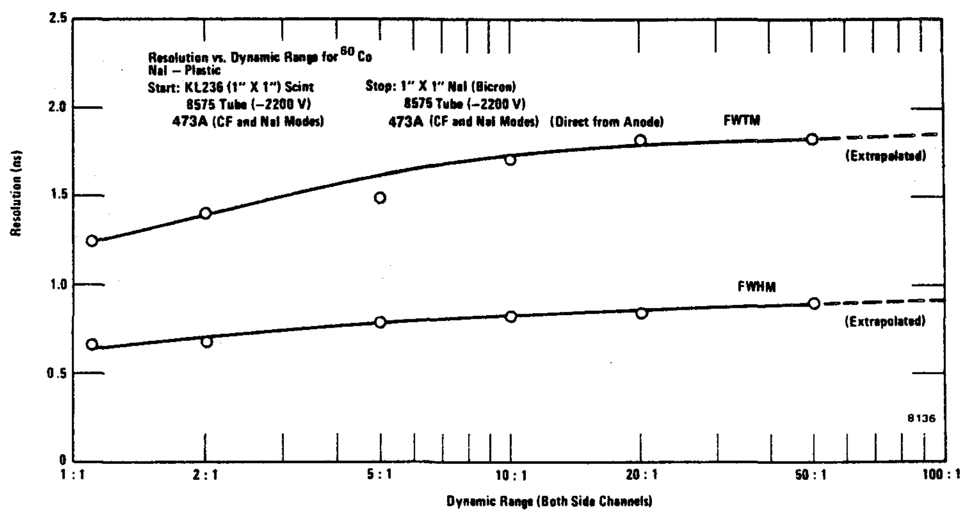


Fig. 21. Plot of Time Resolution vs Dynamic Range Using NaI(Tl) Detectors, RCA 8575 PMTs, and the 473A CFD.

the dead time that is comparable to the pulse width of the NaI(Tl) signal. EG&G ORTEC Models 473A, 583, and 584 are suitable for this application. Figure 21 is a plot of time resolution versus dynamic range for an NaI(Tl) detector that is mounted on an RCA 8575 PMT. The system is similar to that shown in Fig. 14 but with the NaI(Tl) detector used in the stop channel and a KL236 plastic scintillator used to trigger the start channel.

Some timing spectroscopy applications involve very high data rates. The EG&G ORTEC Model 934 is a Quad Constant-Fraction Discriminator capable of resolving pulses separated by less than 10 ns. Figures 22(a), (b), and (c) depict the response of the Model 934 to a burst of 5 pulses less than 10 ns apart. The Model 584 can resolve a 20 ns pulse pair, the Model 583 can resolve a 40 ns pulse pair, and the Model 473A can resolve a 50 ns pulse pair.

Proper adjustment of the delay and walk are critical for excellent timing resolution. With scintillators, the CFD is usually operated in the true-constant-fraction mode (TCF) described earlier. The shaping delay is chosen to cause the zero crossing of the constant-fraction signal to occur just after the peak of the attenuated input signal. Figure 23(a) shows a signal representative of the output from a fast PMT. Figure 23(b) shows the CF monitor signal (Model 583 or 934) for a properly chosen delay of about 1.5 ns.

Proper walk adjustment is also important. Figure 24(a) shows the output signal from the anode of an RCA 8850 PMT. Figures 24(b) and (c) show the corresponding CF monitor signal (Models 583 and 934) as seen on a sampling oscilloscope triggered by the discriminator output signal. The walk is adjusted to minimize the time spread of the zero-crossing point.

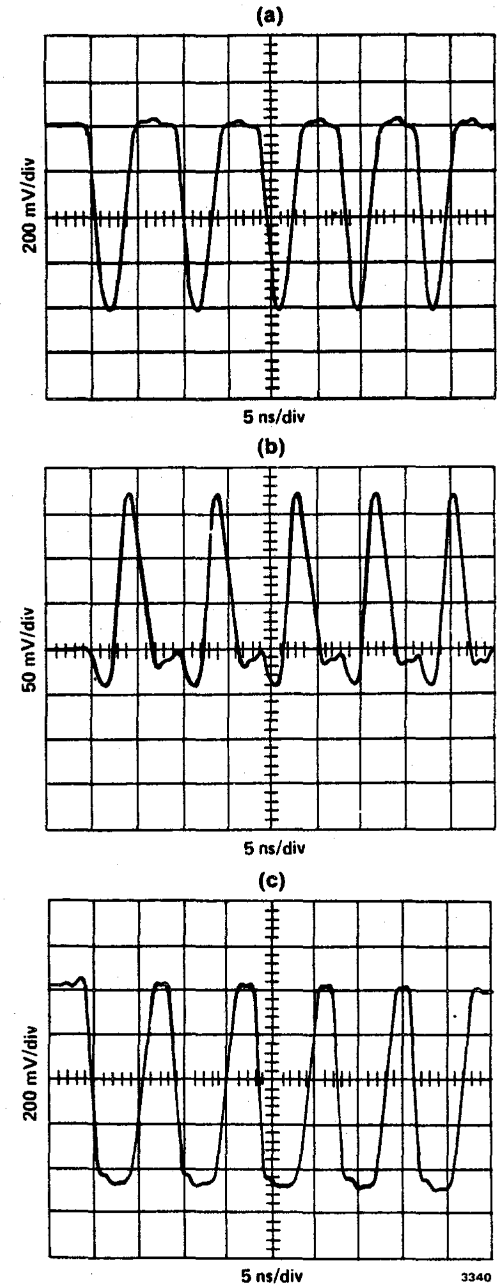


Fig. 22(a). Input Signal Burst of 5 Pulses to the 934 CFD. (b) Constant-Fraction Zero-Crossing Monitor Signal for the Burst Input. (c) Constant-Fraction Discriminator Output Burst Response.
(CF delay =1.5 ns; threshold = 30 mV.)

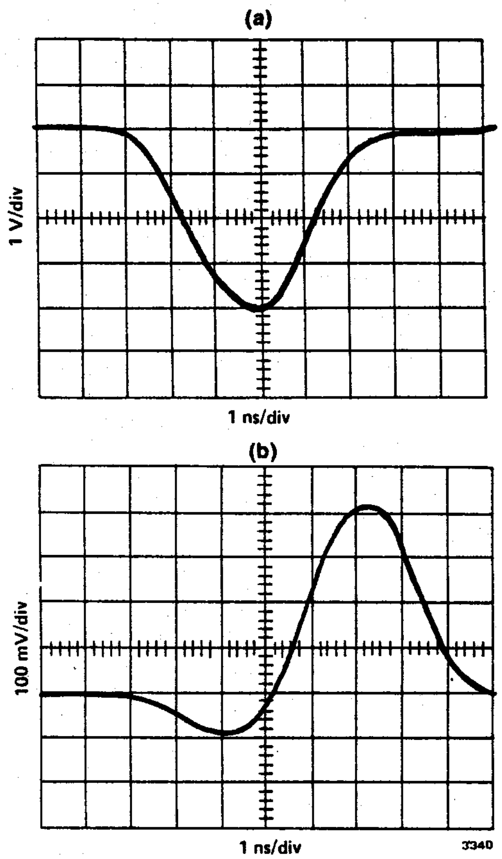


Fig. 23(a). Input Signal Shape for Time Walk Measurements Near Threshold. (b) Constant-Fraction Monitor Signal for the Input Signal Shown Above. (CF delay = 1.5 ns total.)

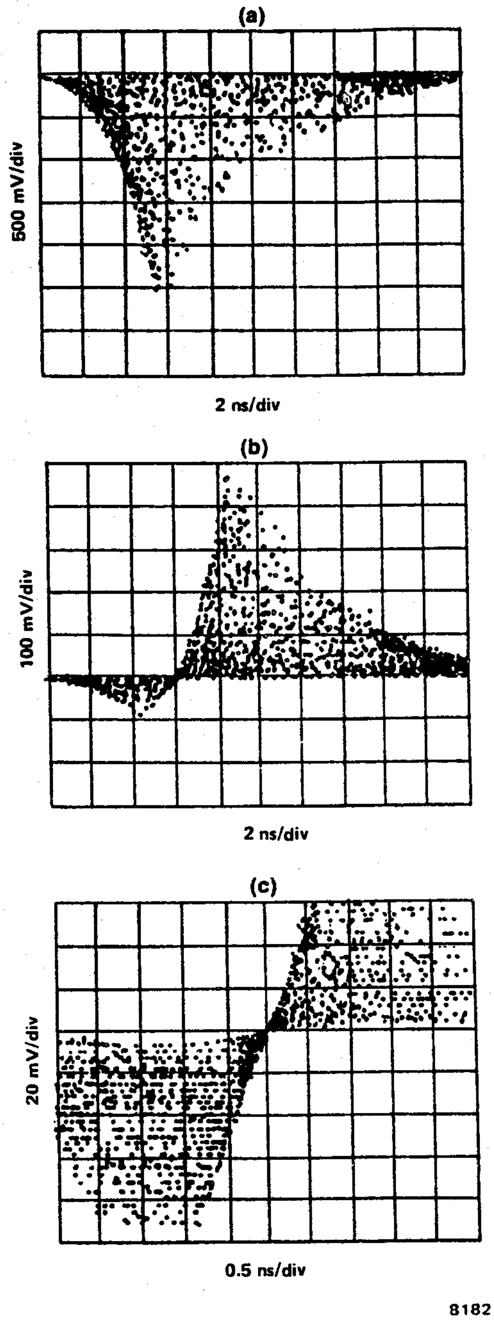


Fig. 24(a). RCA 8850 PMT Anode Signal with a 1-in. x 1-in. KL236 Scintillator and ^{60}Co. (b) Constant-Fraction Zero-Crossing Monitor Signal, Triggered by the Discriminator Output for the Anode Signal Shown Above. (c) Expanded View of the Constant-Fraction Zero-Crossing Monitor Signal. (CF delay = 3 ns; threshold = 30 mV.)

CONSTANT-FRACTION TIMING WITH GERMANIUM DETECTORS

A timing spectroscopy system suitable for use with germanium detectors is shown in Fig. 25. The start signal for the TAC is derived from a fast scintillator and PMT. The stop signal is derived from the germanium detector charge-sensitive preamplifier with additional shaping by the timing-filter amplifier (TFA). Timing data is strobed from the TAC by a TSCA set on the energy range of interest. The start CFD threshold was set at 150 keV. The preamplifier and amplifier connected to the dynode of the PMT are used to set the start CFD threshold. The system timing resolution was 176 ps per channel measured with a time calibrator. The timing properties of a series of 14 detector-preamplifier combinations were measured. Detector data is shown in Table 1. The initial step in optimization of the timing spectrometer for a given detector was to vary the stop CFD delay to determine its optimum value. A typical set of data is shown in Fig. 26 for Detector No. 7. In general, the FWHM curve shows a shallow minimum and the FWTM curve a more pronounced minimum. An optimum delay of 24 ns was selected.

Timing resolution also depends on the settings of the TFA and type of CFD used. Figure 27 shows timing resolution FWHM and FWTM as a function of the CFD type and the TFA time constant. CFD-1, EG&G ORTEC Model 583, uses a passive mixing technique to form the constant-fraction signal and has a much broader bandwidth than CFD-2, EG&G ORTEC Model 473A, which uses active mixing in an ECL line receiver. The best time resolution was obtained using the 583 and the minimum integration time constant on the TFA.

The threshold setting on the CFD in the germanium detector signal-processing chain has an important effect on timing resolution. Setting the threshold too low can result in triggering the CFD on noise and broadening the timing spectrum on the early or left side. Setting the threshold too high can result in leading-edge timing and broadening the spectrum on the late or right

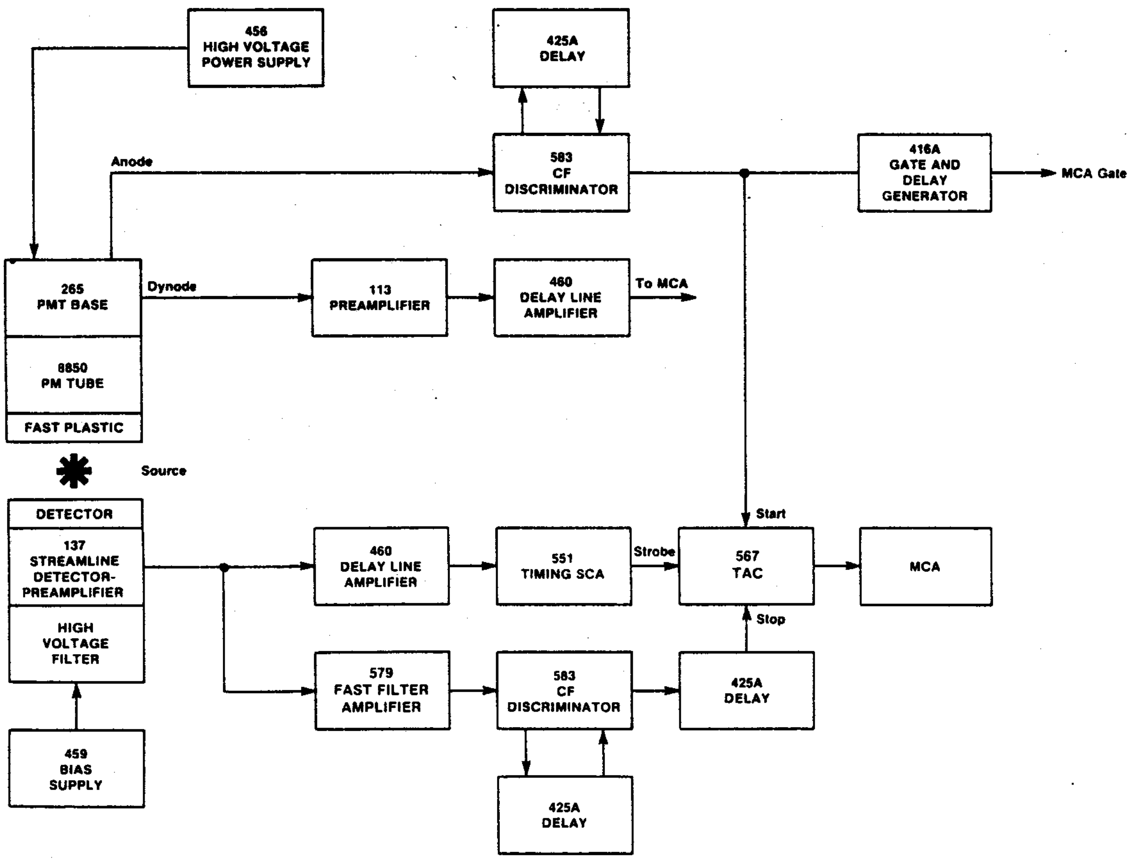


Fig. 25. **Block Diagram of Timing Spectrometer.**

Table 1. Detector-Preamplifier System Characteristics.

Detector System	Preamp Type	Detector Type	Serial No.	Efficiency (%)	Diameter (mm)	Length (mm)	Core in Hole (mm)	Resolution at 1.33 MeV (keV)	Pulser Resolution at 1.33 MeV (eV)	Depletion Voltage (V)	Bias (V)	Peak-to-Compton	Depth of Hole (mm)
1	Discrete	HPGe-P	P-13ZB	17.7	48	52.1	8	1.66	620	1800	+3000	59.0	37.2
2	Hybrid	HPGe-P	P-13ZB	17.7	48	52.1	8	1.64	590	1800	+3000	59.0	37.2
3	Discrete	HPGe-P	P-353	13.2	43	53.3	8	1.66	600	1800	+3000	51.8	39.9
4	Hybrid	HPGe-P	P-589	19.5	50	50.9	8	1.77	560	1500	+3500	55.7	32.6
5	Hybrid	HPGe-P	P-621	28	53.3	60.8	8	1.87	730	2400	+3500	70.9	45.8
6	Discrete	HPGe-P	P-633	22.5	48.6	64.8	8	1.85	660	2500	+3500	58.1	50.2
7	Discrete	HPGe-P	P-653C	11.0	45.6	36.3	8	1.61	510	1900	+3000	49.2	21.4
8	Hybrid	HPGe-P	P-654A	17.1	47.9	50.9	8	1.65	630	2200	+3500	55.9	35.7
9	Discrete	HPGe-P	P-9000	35	57	64	8	1.77	842	1500	+3500	69.6	52
10	Discrete	HPGe-N	N-491B	12.5	43.6	46	8	1.69	690	-1000	-3500	48	37.6
11	Discrete	HPGe-N[1]	N-492B	11.6	44.1	38.2	8	1.73	506	-1700	-2000	46	29
12	Discrete	HPGe-N	N-497B	15.7	46.5	48.5	8	1.84	550	-2200	-4000	45	40
13	Discrete	HPGe-N	N-529	19.8	48.1	54.8	8	1.99	760	−1200	-2000	47.7	51
14	Hybrid	HPGe-N	N-627B	16.4.	46.7	48.4	8	1.73	506	−1000	-1800	53.4	39.1

Notes: 1. Be Window.

side. These effects are shown in Fig. 28 for Detector No. 9. During this series of tests the TSCA was set at 511 ± 50 keV. Typically, the FWHM improves for threshold settings up to approximately 35% of the energy of interest while the minimum FWTM occurs for a threshold setting of approximately 15% of the energy of interest.

The tests described form the basis for optimizing the germanium detector timing spectrometer for measurements as a function of energy. The TFA was set at minimum integration and the gain was set so the 511-keV line of the ^{22}Na produced approximately a 1-V pulse. The stop CFD threshold was set at 50 keV. The TSCA window was set at 100 keV and data was taken for energies ranging from 150 ± 50 keV to 511 ± 50 keV using ^{22}Na. Additional data was taken using ^{60}Co for energies ranging from 511 ± 50 keV to 1330 ± 50 keV. The timing data is summarized in Table 2.

A plot of timing resolution FWHM and FWTM is shown in Fig. 29 for Detector No. 11. Leading edge walk is evident in the FWTM resolution for mean energies less than approximately 400 keV.

One comparison between the detectors is shown in Fig. 30 where the timing resolution at FWHM is plotted versus detector relative efficiency for the energy 511 ± 50 keV using ^{22}Na. A possible conclusion is that larger detectors tend to have poorer timing performance.

Many discriminators include the Slow Rise Time Reject (SRT) operational mode as well as constant fraction and leading-edge (Models 473A, 583, and 584). The function of the SRT circuitry is to eliminate leading-edge walk, a common occurrence in germanium timing systems. This leading-edge walk results from the wide spread of rise times that result from

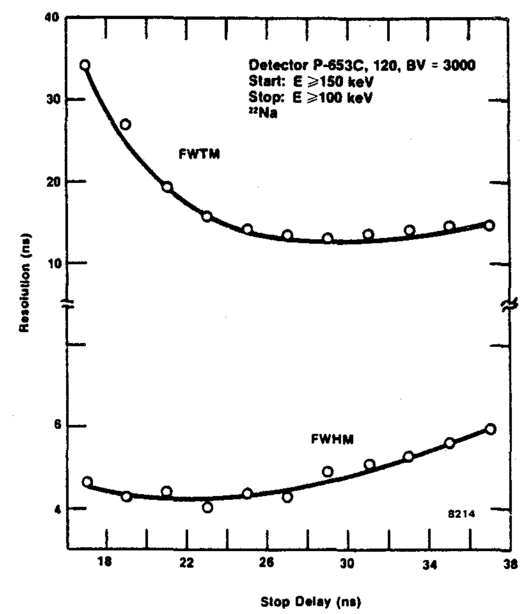


Fig. 26. Timing Resolution FWHM and FWTM as a Function of Constant-Fraction Shaping Delay.

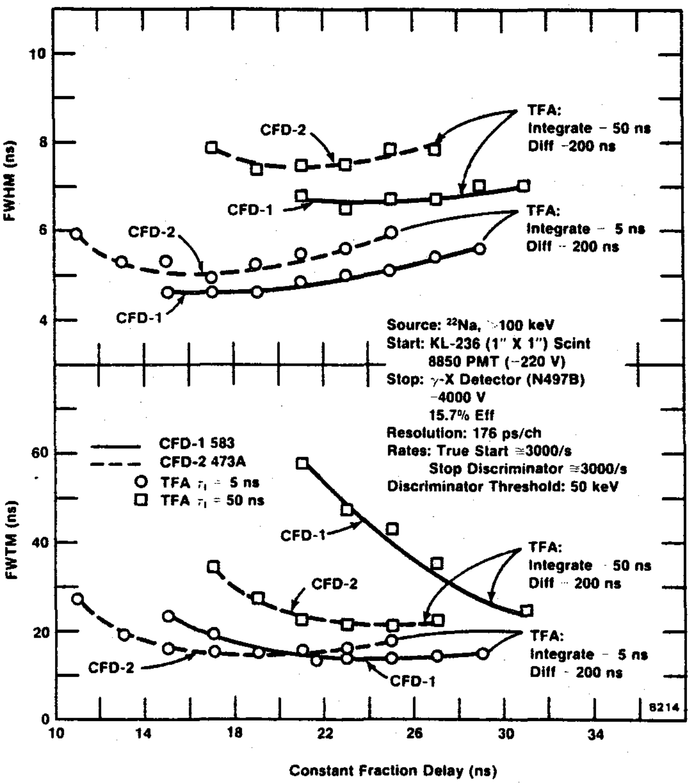


Fig. 27. Timing Resolution FWHM and FWTM as a Function of CFD Type and TFA Time Constant.

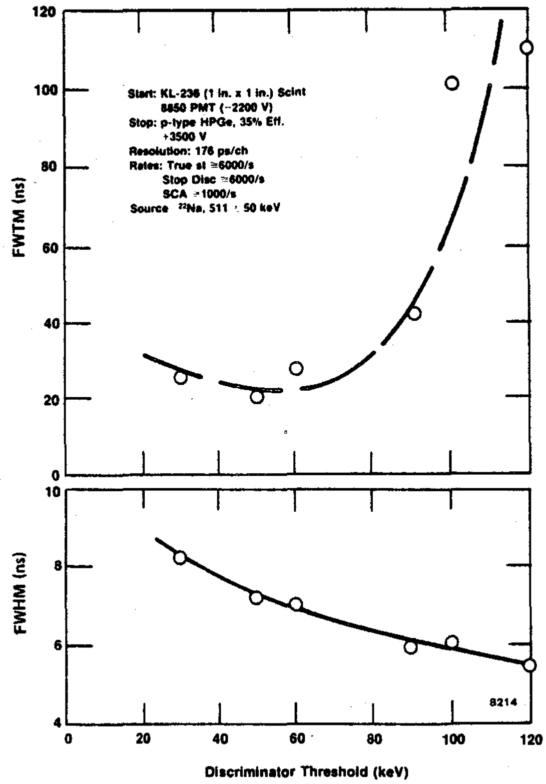


Fig. 28. Timing Resolution FWHM and FWTM as a Function of CFD Threshold.

Table 2. Timing Resolution as a Function of Energy for an Energy Window of ± 50 keV.

Detector System	Detector Type	Efficiency (%)	Optimum Delay (ns)	Measure	Timing Resolution (ns): Mean Energy (keV) Using ^{22}Na 150	250	350	511	Mean Energy (keV) Using ^{60}Co 511	750	950	1170	1330
1	HPGe-P	17.7	31	FWHM	10.2	6.9	5.9	4.4	4.8	4.1	3.7	3.0	2.5
				FWTM	—	53.7	24.8	10.2	10.6	9.3	9.0	7.5	6.7
2	HPGe-P	17.7	26	FWHM	9.2	6.9	5.6	4.2	4.2	3.7	2.8	2.6	2.2
				FWTM	—	41.2	12.8	9.0	9.9	8.6	7.6	6.0	5.8
3	HPGe-P[1]	13.2	32	FWHM	9.5	6.5	5.9	4.4	5.0	4.0	3.3	2.8	2.7
				FWTM	—	37.3	20.6	10.0	10.9	9.9	9.4	7.7	7.2
4	HPGe-P	19.5	33	FWHM	8.8	7.0	5.9	4.3	5.0	3.9	3.7	2.8	2.6
				FWTM	—	57.5	31.7	10.7	11.8	10.4	9.9	7.6	7.0
5	HPGe-P	28.0	34	FWHM	11.3	8.8	7.7	5.6	6.2	5.7	4.0	3.6	3.4
				FWTM	—	55.8	27.1	12.8	13.4	12.3	11.8	9.8	9.0
6	HPGe-P[2]	22.5	36	FWHM	—	39.0	14.2	6.7	7.4	5.70	4.5	4.0	3.7
				FWTM	—	—	100	21.1	36.6	16.9	10.9	8.8	8.4
7	HPGe-P	11.0	24	FWHM	9.2	6.7	5.8	4.0	3.9	3.0	2.60	2.0	1.7
				FWTM	—	45.3	22.2	9.9	10.2	8.4	7.5	5.6	5.1
8	HPGe-P[3]	17.1	36	FWHM	10.0	7.7	6.5	4.6	5.1	4.0	3.5	3.0	2.5
				FWTM	—	26.0	16.4	11.3	13.2	12.5	11.6	9.7	8.8
9	HPGe-P	35	25	FWHM	—	11.8	11.0	8.2	9.0	6.2[5]	5.6	4.8	—
				FWTM	—	62	34	25	45	17[5]	18.5	15.3	—
10	HPGe-N	12.5	24	FWHM	9.9	7.6	6.0	4.6	4.6	3.3	2.64	2.6	2.0
				FWTM	66.2	28.2	15.8	10.0	11.4	9.2	7.4	7.0	5.1
11	HPGe-N	11.6	23	FWHM	8.0	5.9	4.7	3.6	3.5	2.8	2.1	1.9	1.6
				FWTM	78	27.5	12.3	7.9	8.8	6.7	5.8	4.6	4.1
12	HPGe-N	15.7	23	FWHM	10.7[4]	7.2[4]	5.8[4]	4.4	4.1	2.8[5]	—	2.1	—
				FWTM	—	41[4]	15[4]	10.4	11	8.1[5]	—	5.8	—
13	HPGe-N	19.8	23	FWHM	12.5	8.6	7.0	4.5	4.9	3.7	3.1	2.2	2.0
				FWTM	84	33	18.1	10.2	11.8	8.6	7.7	5.5	4.9
14	HPGe-N	16.4	24	FWHM	8.6	6.7	5.6	4.1	4.2	3.1	2.7	2.3	2.0
				FWTM	77.3	22.5	16.2	9.7	10.7	8.1	7.4	5.5	5.1

Notes:
1. Operated at 1900 V.
2. Operated at 4800 V.
3. Operated at 2300 V
4. · Co.
5. 800 keV.

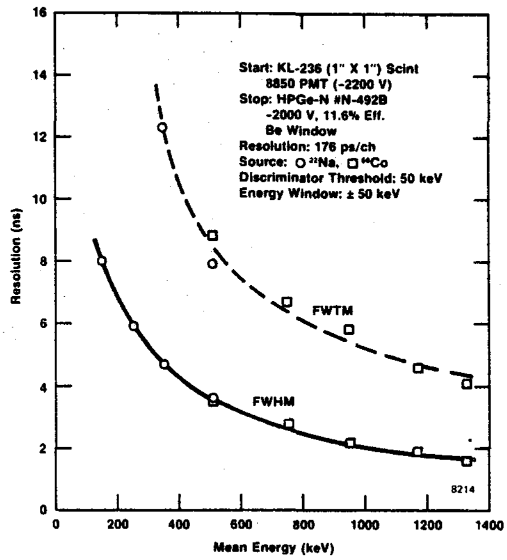


Fig. 29. Timing Resolution FWHM and FWTM for Detector No. 11 as a Function of Energy.

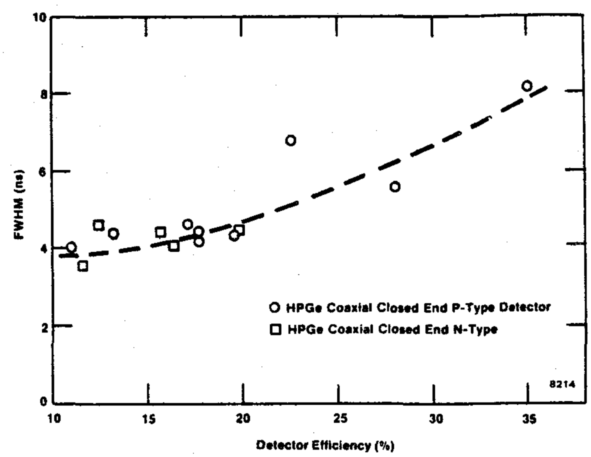
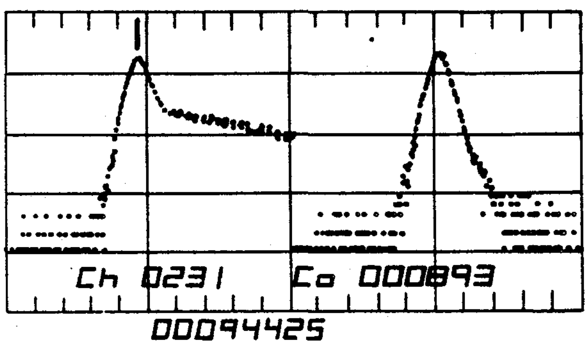


Fig. 30. Timing Resolution FWHM for 14 Detector Systems as a Function of Efficiency for the Energy Range 511 ± 50 keV for ^{22}Na (using the 583 CFD).

the charge collection time variations within the germanium crystal. The SRT circuitry is most effective when used with a wide dynamic range of energies. Figure 31 shows the dramatic improvement in timing resolution below the FWHM level and makes reliable timing data possible at even the FW(1/100)M level. The SRT circuitry provides this improvement in timing resolution by rejecting the timing output pulses that result from leading-edge timing. Since the input signals that cause leading-edge walk represent valid energy information, use of the SRT circuitry results in a loss in the counting efficiency of the system.

Low Energy Photon (LEPS) detectors are also used in timing applications. Typical timing resolution for a 6-mm LEPS system is shown in Fig. 32.



^{22}Na
Start: KL 236, RCA 8575 Photomultiplier Tube
Stop: Ge Coaxial Detector, 12.5%, 62.3 cc
10:1 Dynamic Range

	CF	SRT
FWHM	4.5 ns	4.4 ns
FWTM	13.2 ns	9.4 ns
FW 1/100 M	–	17.3 ns

Fig. 31. Timing Spectrum for a Wide Dynamic Range (10:1) (using the 473A CFD).

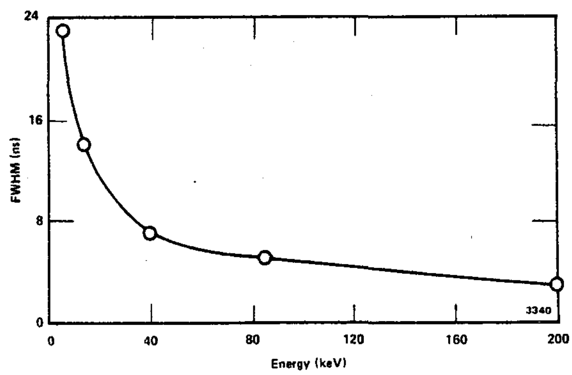


Fig. 32. Time Resolution vs Energy for a 6-mm LEPS Detector.

TIMING WITH SINGLE-CHANNEL ANALYZERS

As discussed in the sections "Conventional Crossover" and "Trailing Edge, Constant Fraction," some applications do not require the ultimate in timing resolution performance. Therefore a separate timing channel can be eliminated and adequate timing data can be obtained from an SCA used in an energy spectroscopy system. The total system cost and complexity can be reduced if the timing resolution obtainable from the TSCA is adequate for the particular application.

Figure 33 is a block diagram of a system that can be used to determine the timing characteristics of an SCA with a germanium detector. In this system the timing resolution is almost entirely dominated by the resolution of the channel that includes the germanium detector and the TSCA.

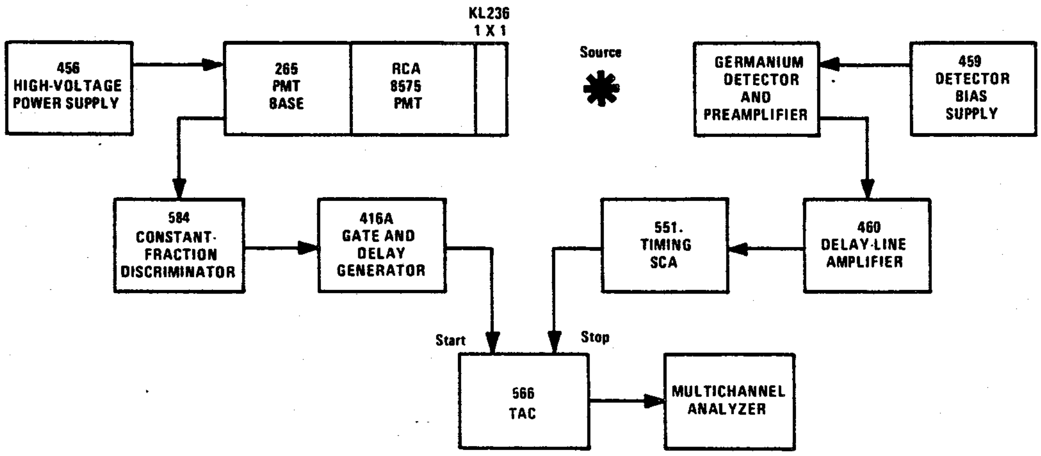


Fig. 33. Typical System for Determining the Timing Characteristics of an SCA Used with a Germanium Detector.

Figure 34 is a plot of timing resolution versus dynamic range for two types of detectors used in a system similar to the one shown in Fig. 33. Resolution curves are shown for the trailing-edge constant-fraction time-pickoff techniques. The bipolar signals used for timing were shaped by double-delay-line clipping. The timing resolution obtained by this technique can be worse by approximately an order of magnitude than the resolution obtained by the optimum constant-fraction technique discussed earlier.

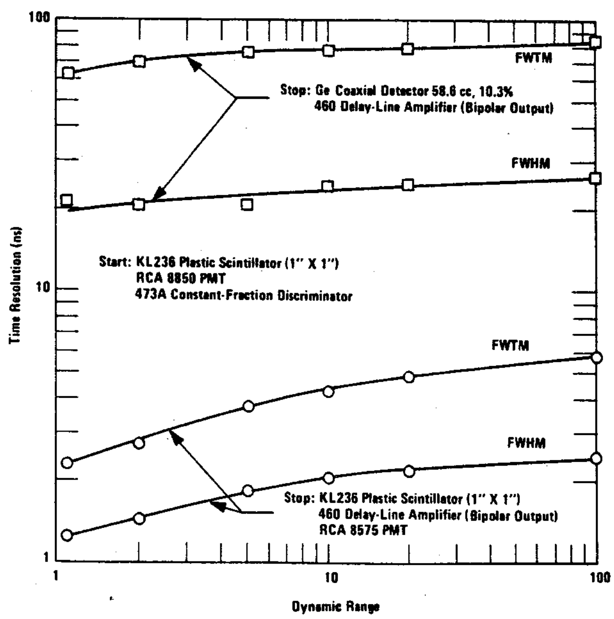


Fig. 34. Timing Resolution vs Dynamic Range, E_{max}/E_{min}, Where E_{max} is 1.6 MeV for the EG&G ORTEC 551 Timing SCA Using the Trailing-Edge Constant-Fraction Technique.

TIMING WITH SURFACE-BARRIER DETECTORS

A surface-barrier detector is fundamentally a large-area p-n junction diode, consisting of an extremely thin p-type layer on an n-type silicon wafer. It can be used in the detection of low-mass charged particles, fission fragments, and light signals in a wide variety of applications. The relatively short charge collection times in a surface-barrier detector allow it to be used in fast-timing experiments.

The system shown in Fig. 35 can be used to test a surface-barrier detector and preamplifier timing system. The timing resolution is determined by using a 904-nm light pulse that is generated by a laser diode pulser (LDP). Light pulses with subnanosecond durations can be obtained in this manner. A simulated timing test can be conducted for almost any equivalent energy level by calibrating the detected light with a weak alpha source placed in the vicinity of the detector. Although the detector response to the LDP is different from its response to charged particles, the test system and data presented here are useful for aligning and adjusting. Also, the measured timing resolution at a given equivalent energy represents the

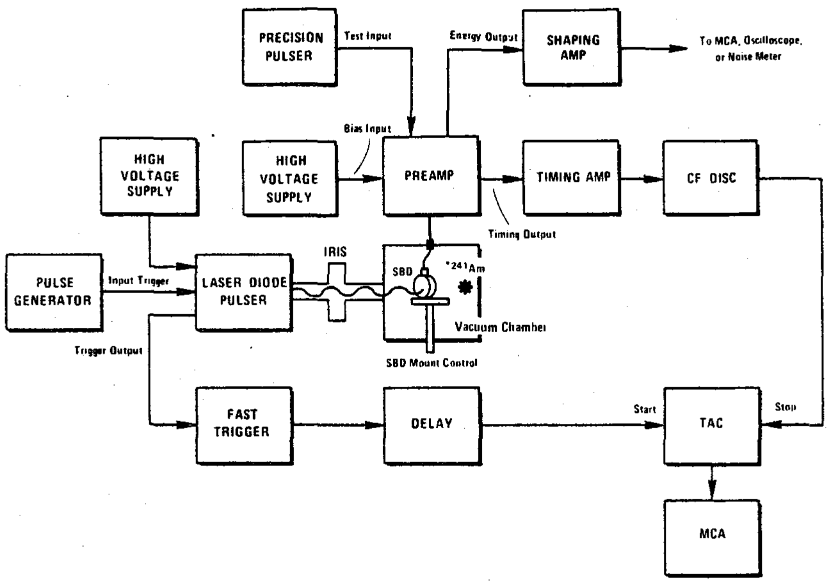


Fig. 35. Block Diagram of the Test System Used for Testing Charged-Particle Detectors with a Laser Diode Pulser.

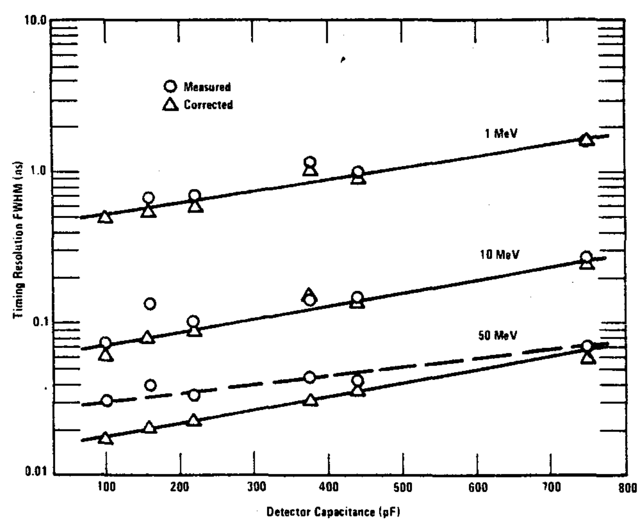


Fig. 36. Timing Resolution vs Energy for Surface-Barrier Detectors. The Measured Data Were Generated by a Pulsed Laser Calibrated to the 5.49-MeV Alpha of ^{241}Am, and the Corrected Data Were Obtained by Subtracting the System Resolution in Quadrature.

system timing error due to jitter. Timing resolution for six different surface-barrier detectors is shown in Fig. 36.

EG&G ORTEC manufactures a series of outstanding preamplifiers for use with surface-barrier detectors. The 142A is optimized for detector capacitance less than 100 pF. The 142B is optimized for use with detector capacitance greater than 100 pF. The 142A and B are fast rise time charge-sensitive preamplifiers. The timing output is derived by differentiating the energy output signal from the charge loop. The rise time can be easily adjusted in each application to ensure optimum performance.

EG&G ORTEC maintains a continuing R&D program to improve instrumentation used in timing spectroscopy. A new preamplifier, Model 152AT/BT, featuring a fast pickoff inside the charge loop, has been developed. This technique offers the potential of improved timing with surface barrier detectors.

NANOSECOND FLUORESCENCE SPECTROMETRY

The EG&G ORTEC 9200 Nanosecond Fluorescence Spectrometer is used in lifetime measurements of excited molecular states. In the specific application where the molecular structure is studied, the experimenter seeks to verify a complex model of a particular molecule or to determine how a particular molecule is altered by its surroundings. This type of experiment requires that the total efficiency, the exact energy, and the complete time function involved in the de-excitation of an electronic state be known so that the experimental results can be fit precisely to a model. Figure 37 shows the 9200 System, and Fig. 38 shows the detailed lifetime characteristics of a 0.1 N solution of quinine sulfate in sulfuric acid that was excited with impulses of light at approximately 340 nm with the 9200 System. The quantity of information available from such a lifetime measurement is illustrated by this set of data.

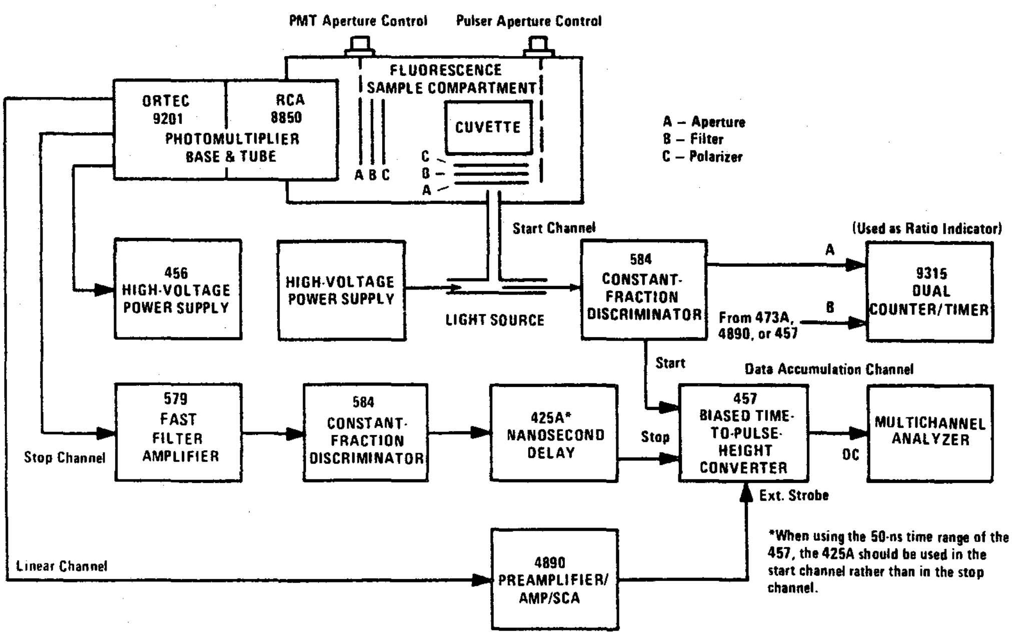


Fig. 37. Nanosecond Decay Time Fluorescence Spectrometer System.

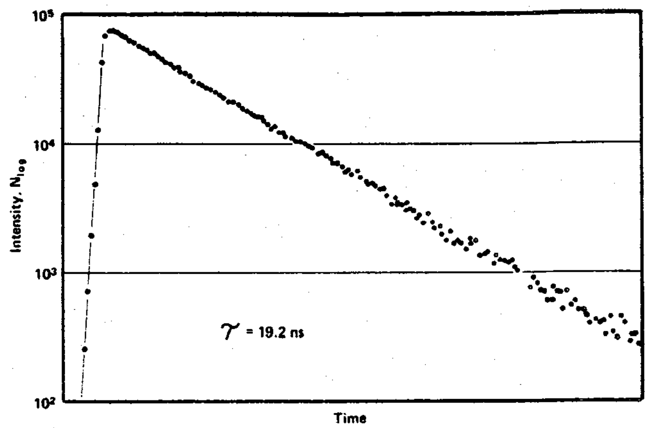


Fig. 38. Lifetime Spectrum of Quinine Sulfate in Sulfuric Acid.

RECOMMENDATIONS

Obviously, optimum timing results are obtained only when all components, including the detectors and the electronics, have optimum features for the particular timing experiment. A timing system backed by a manufacturer with a known record for performance and service in the field gives its users confidence in results obtained and assurance of minimum setup time. Also, the manufacturer should be able to provide almost immediate assistance through competent, experienced personnel if the experimenter runs into difficulties with timing experiments.

EG&G ORTEC products are used universally for different types of experiments because of our excellent specifications and dependable service record. If we can help to plan a timing system, or any other system requiring detectors and electronics, we are at your service. Call EG&G ORTEC, Oak Ridge, Tennessee U.S.A., (615) 482-4411 or contact the EG&G ORTEC sales engineer in your area for immediate attention.

BIBLIOGRAPHY

A complete listing of all the literature relevant to timing would be prohibitive. Only a few of the important works of some of the major contributors to the state-of-the-art are listed. The interested reader can use this partial listing as a starting point for an in-depth study of any particular aspect of timing. For convenience the references are categorized by application as follows:

Scintillator/Photomultiplier Tube Timing

Germanium Timing

Silicon Surface-Barrier Detector Timing

Photon Counting and Photomultiplier Tubes

General

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Selected Instruments for Timing Spectroscopy

Model No. and Description

113 Preamplifier
142A Preamplifier
142B Preamplifier
H242A/B Preamplifiers
142AG Preamplifier
142AH Preamplifier
142IH Preamplifier
142PC Preamplifier
152AT/BT Preamplifiers
265 Photomultiplier Base
266 Photomultiplier Base
269 Photomultiplier Base
270 Photomultiplier Base
271 Photomultiplier Base
276 Photomultiplier Base/Preamp
4001C/4002A Bin and Power Supply
4001C/402D Bin and Power Supply
4001M Minibin and Power Supply
403A Time Pickoff
414A Fast Coincidence
416A Gate and Delay Generator
418A Universal Coincidence
419 Pulse Generator
425A Nanosecond Delay
449 Ratemeter
456 High Voltage Power Supply
456H High Voltage Power Supply
457 Biased TAC
459 Bias Supply
460 Amplifier
462 Time Calibrator
473A Discriminator

Model No. and Description

474 Amplifier
535 Quad Fast Amplifier
541 Linear Ratemeter
550 Single Channel Analyzer
551 Single Channel Analyzer
552 Pulse Shape Analyzer
553 Single Channel Analyzer
566 TAC
567 TAC/SCA
570 Amplifier
571 Amplifier
572 Amplifier
574 Amplifier
575 Amplifier
579 Fast Filter Amplifier
583 Constant-Fraction Discriminator
584 Constant-Fraction Discriminator
590 Amplifier/SCA
871 Counter and Timer
872 Quad Counter and Timer
874 Quad Counter and Timer
875 Counter
878 Counter and Timer

Model No. and Description

905-5 Plastic Scintillator Detector
905-11 Plastic Scintillator Detector
934 Quad CFD
9201 PM Housing
9301 Fast Preamplifier
9302 Amplifier/Discriminator
9305 Fast Preamplifier
9310 Dual ÷10 Prescaler
9315 Photon Counter
9320 Sampling/Control Unit
9325 Digital-to-Analog Converter
9349 Ratemeter
AN302/NL Quad Fast dc Amplifier
AN308/NL Dual Octal Mixer (±6 V)
DB463 Delay Box
T105/N Dual Discriminator

3340