6
Fast electronics

Certain types of fast pulse electronics, such as discriminators and coincidence units, are used almost universally in particle physics experiments. In this chapter we review some important features of these and other electronic equipment, strictly from the point of view of a user.

6.1 Fast pulse instrumentation

An important function of fast electronics in particle physics experiments is to decide if the spatial and temporal patterns of detector signals satisfy the requirements of the event trigger. Fast in this context generally means circuits capable of processing pulses at a 100-MHz repetition rate. Most detectors produce analog signals. Discriminators are used to convert these analog signals into standardized logic levels. Logic units are available that can perform the logical operations: AND, NAND, OR, NOR, and NOT. The input and output signal amplitudes of these devices correspond to two possible states: 0 to 1 (or T or F). The logic unit signals can be joined together so that the final output is only true when a predetermined pattern of input signals is present. This output pulse can be used to signal the occurrence of a physical event of interest.

The need for certain electronic devices such as discriminators and logic units in practically every experiment lead to the establishment of the NIM standard. Devices that satisfy the NIM requirements must be housed in standard sized modules with standard rear connectors. Up to 12 units can be plugged into a NIM bin. The bin contains the power supplies for the modules and a slow gating pin that can be used, for example, to inhibit the operation of the units between beam spills. NIM modules are chiefly used in fast trigger logic. The NIM voltage levels corresponding to the states 0 and 1 are given in Table 6.1, along with levels used in the TTL and ECL families of integrated circuits.

6.2 Discriminators

A discriminator is an electronic device that converts an analog input signal into a standardized output pulse whenever the input signal amplitude exceeds some predetermined threshold voltage. Discriminators are routinely used with photomultiplier tube signals to provide uniform signals for triggering logic and for timing applications.

A block diagram for a typical discriminator is shown in Fig. 6.1. The input signal generates a pulse whenever the leading edge of the signal crosses the threshold voltage. A sharp signal corresponding to the leading edge is produced with a differentiation circuit. It is then reformed into a pulse of standard amplitude whose leading edge is related to the time of arrival of the input signal and whose width may be adjusted by the user. This circuitry introduces a delay of 10–30 ns between the arrival of the input signal and the leading edge of the output pulse.

Older model discriminators used shorted cable (clipping) stubs to shorten the input pulses. This was done so that the discriminator would only give one output pulse and so that the threshold would be independent of the event rate. This is unnecessary in modern discriminators designed to only give one output pulse regardless of the length of the input signal [1]. The threshold can vary slightly with temperature and the risetime and duration of the input signal. The threshold is usually adjustable from approximately 30 to 1000 mV, while the output width can be set in the range 5–1000 ns.

The coupling of the discriminator (or other analog signal handling device) to the input pulse has important experimental consequences. In ac coupling the pulse enters through a capacitor. In this case the time integral of a string of negative pulses must be balanced by an equal

Table 6.1. *Approximate logic levels (V)*

	State 0	State 1
NIM[a]	0.0	−0.8
TTL	0.2	2.5
ECL	−0.8	−1.6

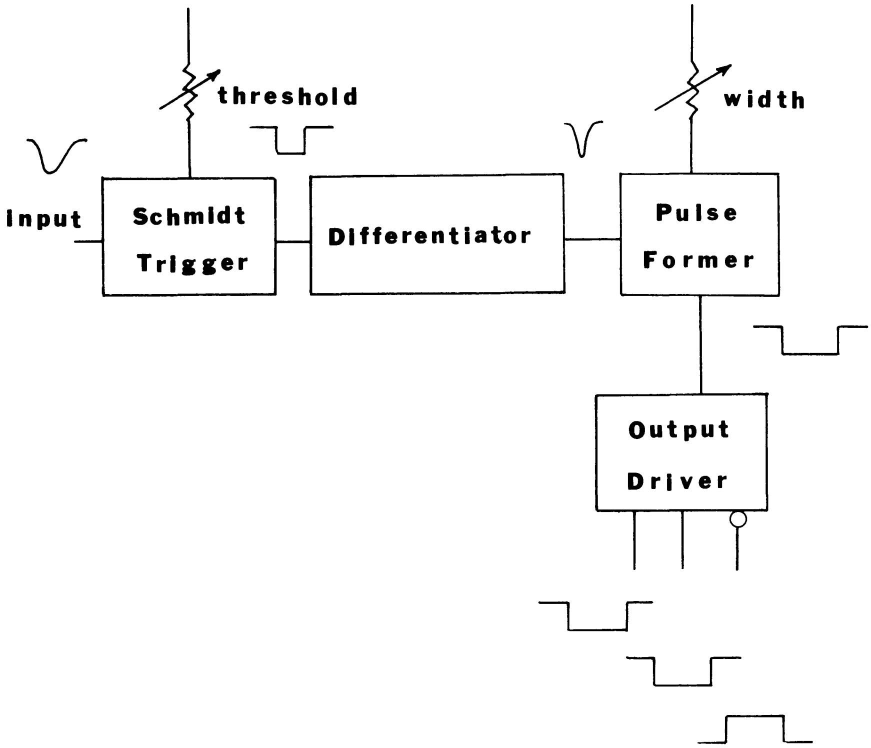
[a] Terminated into 50 Ω.
Source: Catalog, LeCroy Research Systems Corp., Spring Valley, NY, 1983.

amount of positive signal [2]. This results in a long overshoot with small amplitude. This overshoot produces a shift in the effective signal baseline, which grows in importance as the pulse rate is increased. This rate problem is eliminated in dc coupled circuits. However, dc coupled circuits are susceptible to dc offsets in the input signal.

The rate characteristics of a discriminator are specified in terms of double pulse resolution and continuous pulse train response. The time between the leading edges of the two most closely spaced input pulses for which the discriminator gives two output pulses is called the double pulse resolution. This is 5 – 10 ns in a good discriminator. The continuous pulse train response is the maximum frequency of a continuous, equally spaced pulse train for which the discriminator will give a corresponding output train. This is 100 – 200 MHz for modern discriminators.

The input – output delay time in the discriminator is affected by a number of factors. A variation in the time delay between triggering and formation of the output pulse arising from the shape, amplitude, or rise-

Figure 6.1 Block diagram of a typical discriminator.



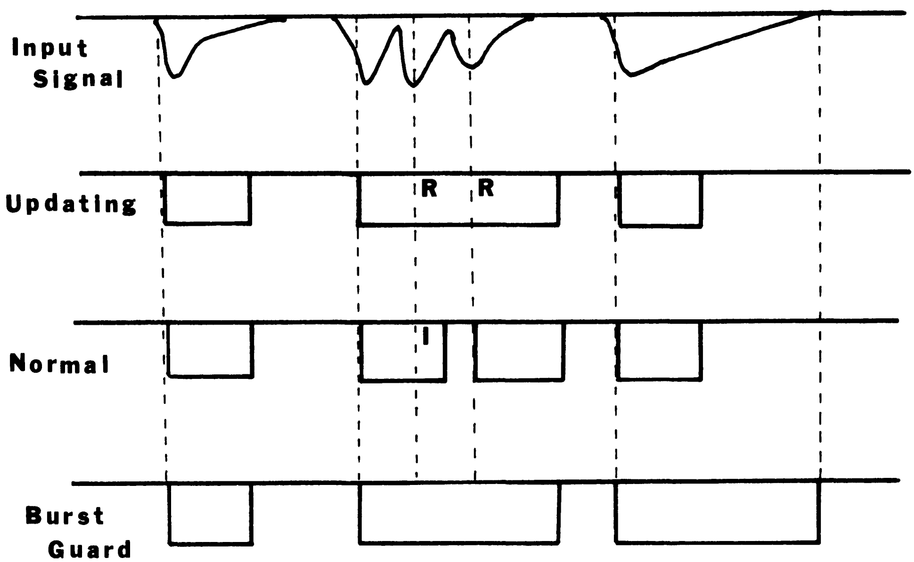
time of the input signal is referred to as time slewing or walk. This can be a large effect (~5 ns) for input signals only slightly above the threshold. The time delay also has small variations (drift) due to the aging of the components and temperature changes. A number of methods have been devised to compensate for time slewing in applications in which accurate timing information is important [3]. The most common method is to use a constant fraction discriminator. Discriminators of this type replace the leading edge method of determining the time of occurrence of an input signal with circuitry that gives a trigger signal nearly independent of the pulse height of the input signal [4]. The time walk of the output pulse can be reduced to ~200 ps for signals slightly above threshold.

Discriminators are available with a number of optional features.

1. Updating. This feature determines the action of the discriminator when a second input signal is received while an output pulse is still being generated. A nonupdating discriminator will ignore the second pulse as shown in Fig. 6.2. An updating discriminator will extend the output pulse for an additional full output width if the two pulses are separated by more than the double pulse resolution of the discriminator.

2. Burst guard. This feature allows the discriminator to respond reliably to a burst of input pulses separated by less than the double pulse resolu-

Figure 6.2 Comparison of discriminator outputs. The pulse at I is ignored in a normal discriminator. The pulses at R retrigger an updating or burst guard discriminator.



tion. The output is essentially the OR of the input signal with the output pulse width of the discriminator [1, 5]. This feature is important when considering the signals from a veto counter in a high rate environment. The burst guard feature maintains the veto signal during a rapid succession of events, thereby minimizing the possibility of a chance coincidence when the veto signal switches levels. A burst guard discriminator will maintain the output signal for the duration of an input with a long tail, as shown in Fig. 6.2. This can be important when using a proportional chamber signal as a veto in multiplicity logic.

3. *Inhibit.* This allows a fast logic signal to inhibit the operation of the discriminator. Input signals are ignored during the time the inhibit signal is present.

4. *Summing output.* Some multichannel units have a special summing output that provides a signal equal to −50 mV times the number of energized outputs. The signal could be used with another discriminator to provide an output when the input multiplicity exceeds a certain value.

5. *Inverted logic output.*

6. *Differential operation.* These discriminators have two adjustable thresholds and only provide an output pulse when the input signal is between the thresholds. It is also known as a single channel analyzer.

6.3 Coincidence units

There are many occasions when we wish to know if the signals from two or more detectors are associated in time. Consider the simple arrangement shown in Fig. 6.3. A particle passes through detector 1, travels a certain distance, and then passes through detector 2. If the signals are associated with the passage of the particle and not merely due to detector noise, we would expect that the signal from detector 2 will always come in a narrow range of times after the signal from detector 1. A coincidence unit is a device that can be used to determine if the two signals are simultaneously present.

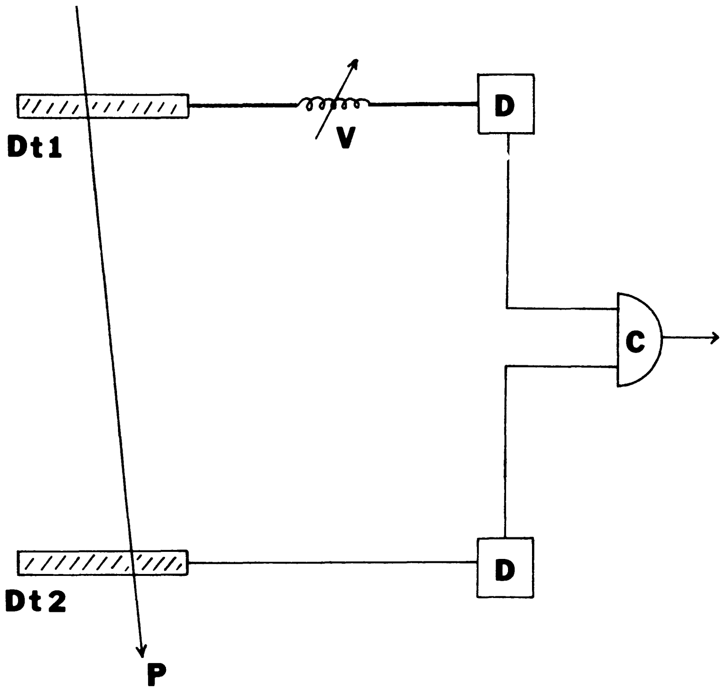
The input signals are usually discriminated to produce standardized pulses with well-defined leading edges. One of the inputs may be passed through a variable delay before entering the discriminator. This extra delay takes into account the head start received by the signals in detector 1 while the particle traveled to detector 2. The discriminator outputs are the coincidence unit inputs.

The minimum amount of time the input signals must be simultaneously present is referred to as the coincidence overlap and is generally ~2 ns. The time interval during which the coincidence unit can produce an output is called the coincidence width or resolving time [6]. This quantity is usually determined by the widths of the input pulses as shown in Fig. 6.4. We obtain an output so long as input signals 1 and 2 are present for more than the coincidence overlap. If we consider pulse 1 to be fixed and vary pulse 2, we will obtain an overlap from the time the trailing edge of pulse 2 overlaps the leading edge of pulse 1 to the time the leading edge of pulse 2 overlaps the trailing edge of pulse 1. Thus, the time resolution of the circuit is approximately the sum of the two input pulse widths.

The time resolution can be determined experimentally from a coincidence delay curve. In Fig. 6.5 we plot the number of coincidences as a function of the variable delay in one of the input signals. The coincidence rate grows as the input signals overlap more and more. The width of the curve is a measure of the resolving time. It should be obvious from this discussion that if we desire short resolving times, the input signals should have fast risetimes and small widths.

In any experiment a random background of particles unassociated with the process of interest is usually present. It is possible that purely by

Figure 6.3 A simple coincidence circuit. (Dt1, Dt2) detectors, (V) variable delay, (D) discriminators, and (C) coincidence unit.



chance two of these background particles (or noise in one or both detectors) will produce signals in the detectors within the resolving time of the coincidence unit. This leads to an accidental coincidence. These "accidentals" are responsible for the tails of the delay curve.

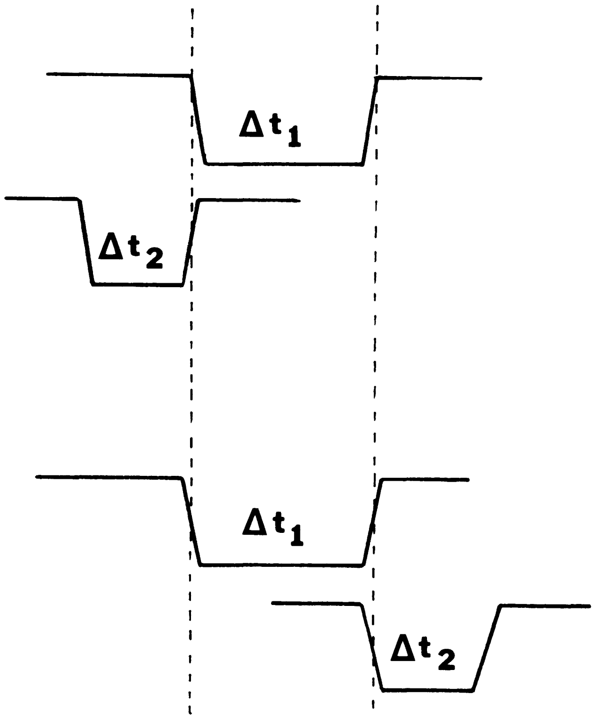
It is possible to estimate the number of accidentals. Let us assume in our example that both discriminator output pulses have widths τ. Detector 1 will produce a certain singles rate S_1, which we assume is mostly caused by accidentals. Then for a fraction of the time $S_1\tau$ there will be a signal present at input 1 of the coincidence unit, provided that S_1 is not so large that there is significant overlap of the S_1 signals. If a random signal from detector 2 arrives during this time, an accidental coincidence will occur. Assuming the processes are independent and adding the contribution with counters S_1 and S_2 interchanged, we find that the accidental rate is

$$R_{acc} = 2S_1S_2\tau \quad (6.1)$$

Note the dependence of the accidental rate on the resolving time 2τ.

Coincidence units are available with two types of output pulses. In the

Figure 6.4 Input pulses to a coincidence unit.



first the width of the output pulse is equal to the length of time the input signals overlap. In the second type an output pulse of fixed length is produced whenever the coincidence requirement is satisfied. The output width is usually adjustable from about 5 to 800 ns.

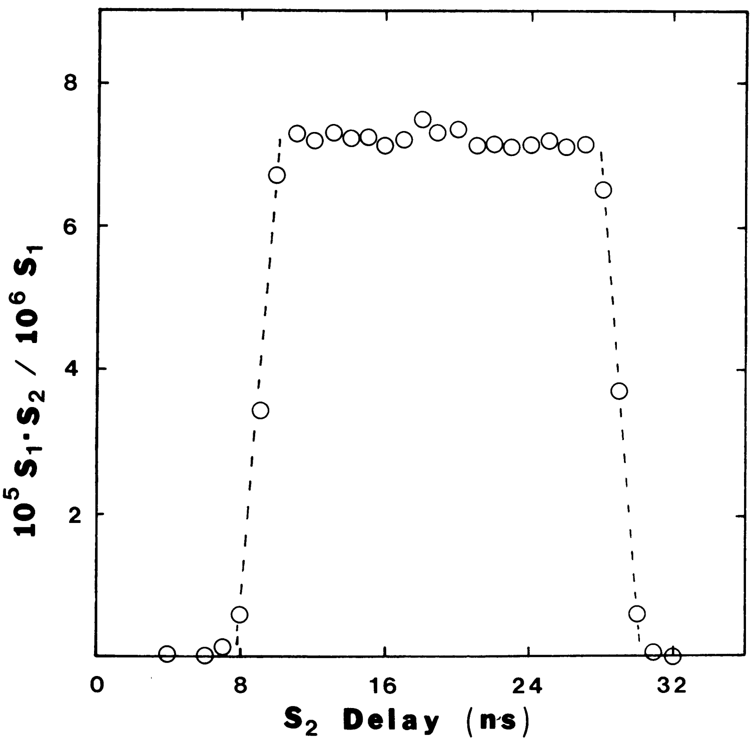
A large variety of coincidence units are available.

1. Logic units. These devices have three or more inputs and can perform combinations of the logical operations on the input. This permits fairly sophisticated trigger decisions to be made from the pattern of signals coming from the detectors.

2. Strobed coincidence. This device has a number of channels, all of which have a common coincidence input with the strobe signal.

3. Multiplicity logic unit. This device has a large number of input channels. When the number of simultaneously present inputs exceeds a specified threshold, it produces an output pulse. This could be used, for

Figure 6.5 Coincidence rate of a pair of counters as a function of the delay added to one of the inputs. The discriminator output widths were 17 and 6 ns. The coincidence rate was not 100% on the plateau because the counters were not geometrically matched.



example, with a counter array to indicate the presence of a certain number of particles.

6.4 CAMAC standard

During the last decade online computer systems have played a larger and larger role in the data acquisition of particle physics experiments. CAMAC is a widely used standard with specifications for data transfer and control in addition to those for mechanical and power distribution compatibility. Mechanically, a CAMAC system consists of a crate with 25 stations, backplane connectors for power distribution, and additional lines for communication with a computer. Several crates can be connected together on a data highway. Data from the experiment enters through connectors on the front of the modules. The communication between a specific computer and the CAMAC modules is handled by a specific interface device known as a crate controller.

Each module connects to the address, data, and control lines in the crate. A particular slot in the crate has associated with it a station number (N). A device plugged into the slot may be subdivided into channels, each with its own subaddress (A). Thus, the computer can specify a particular channel of a device by giving NA. A third signal (F) is used to specify the desired operation or function. Examples of tasks include reading data into the computer or clearing the contents of the module. The computer communicates with the specified module by forming the F, N, and A information into a word and moving it into a memory location, which is in reality a register in the crate controller. The controller decodes the word back into its F, N, and A components and relays the command along to the appropriate module.

Some of the standard CAMAC function codes are given in Table 6.2. Not all CAMAC modules respond to every function. Functions F0, F2, F9, and F25 are commonly used. These commands allow the basic tasks of reading and clearing data and checking the modules' operation.

There are also dataless control commands such as CLEAR, INITIALIZE, and INHIBIT. The CLEAR function clears all registers in the crate. The INITIALIZE function sets all registers to some predetermined conditions, while INHIBIT prevents operation of the modules.

Another CAMAC signal that is important to the user is called "Look at me," or LAM. Devices that require attention can send a signal to the controller over the LAM line assigned to its station. Such a signal may indicate, for example, that a scaler has overflowed its contents or that a data run has ended. Most controllers have the ability to interrupt the computer system when a LAM is received and to transfer control to another part of the program.

As experiments have become larger, inherent limitations of the CAMAC standard have become more evident [7]. The data transfer rate is low by modern standards. The number of crates permitted on a branch is limited, and no crate to crate communications are possible. The directly addressable register space in CAMAC modules is also restricted.

As a result of these difficulties, a new data acquisition standard known as FASTBUS has been developed. The modules are physically larger than those in CAMAC, allowing a very large number (e.g., 96) of channels per module. The FASTBUS data transfer rates are at least 10 times faster than those in CAMAC. FASTBUS uses a 32-bit bus for data and address communications. Direct communications between modules is possible. The large amount of address space permits memories or look-up tables to be incorporated in the modules.

6.5 Other fast pulse devices

A number of other NIM or CAMAC devices are commonly used in particle physics experiments.

1. Fan in/out. A fan-in is a device in which many analog or logical inputs can be summed to form one output. This can be used, for example, to form the OR of the signals from a set of counters. An analog or linear

Table 6.2. *CAMAC function codes*

Function number	Function
0	read group 1 register
2	read and clear group 1 register
3	read complement of group 1 register
8	test Look at Me
9	clear group 1 register
10	clear Look at Me
16	overwrite group 1 register
18	selective set group 1 register
24	disable
25	execute
26	enable
27	test status

Source: Catalog, LeCroy Research Corporation, Spring Valley, NY, 1983.

fan-in is also useful for combining signals from detectors with a large number of elements before entering an ADC channel. The fan-out is a device with one input and many outputs, so that a signal can be used for more than one purpose. All of the outputs in a logical fan-out have the same amplitude as the input.

2. *Register.* A coincidence register or latch is a device with a large number of input channels along with a common input gate. Whenever a signal is present on an input channel simultaneously with the occurrence of the gate signal, the corresponding bit is set in a register. The pattern of bits form a word corresponding to the pattern of input signals. This word can subsequently be read by a computer.

Sometimes coincidence registers have self-contained, low threshold discriminators for every channel, which make the units useful for recording hodoscope information. The gate signal is usually generated by the trigger fast logic. The duration of the gate signal can determine the coincidence width. In addition to the register word, there may also be an output whose amplitude is proportional to the sum of the bits set in the word.

3. *Gate generator.* This device provides a relatively long variable delay. Besides the signal output, it usually provides an inverted logic output as well for a period of up to 10 sec following the input pulse. This is useful for providing deadtime at various places in the trigger logic. For example, it is desirable to inhibit a system for several hundred milliseconds after spark chambers fire because of the noise generated.

4. *Scaler.* A scaler is used to count pulses. It usually has an adjustable threshold to allow it to accept pulses from a large variety of sources. Scalers may have their own display or may be "blind" in that they can only be read out by a computer or special purpose device. Modern scalers can operate at 100 MHz continuous rate and may provide a special signal if the scaler overflows. Fast logic INHIBIT and CLEAR inputs may also be provided.

5. *Analog to digital converter.* We have seen that the presence of an analog signal above a certain threshold can be indicated by a discriminator. More detailed information about the input pulse can be obtained with an analog to digital converter (ADC). This device produces an output pulse proportional to the peak value or the integral of the input current or total charge in the pulse. During the interval in which an external gate signal is present, the charge on the input line is stored on a capacitor. The capacitor is later discharged at a constant rate while oscillator pulses are counted in a scaler. The number of counts is then proportional to the collected charge.

Modern ADCs can have a sensitivity of 0.25 pC/count with a capacity of 1024 counts. The resolution depends on the dynamic range of input signal amplitudes. This can be increased if the ADC has a bilinear range, whereby small signals have a more sensitive conversion than larger ones. The response of the ADC should be very linear in each region. In general, an ADC gives some number of counts (pedestal) even when no input signal is present.

The pedestal signal is the sum of a constant term plus a contribution that is proportional to the width of the gate signal. For example, in the LeCroy 2249A ADC the residual pedestal charge in picocoulombs is given by $1 + 0.03w$, where w is the gate width in nanoseconds [1]. The gate width dependent part of the pedestal is due to a built-in dc offset.

6. Time to digital converter. A device that converts a time interval into a digital number is called a time to digital converter (TDC). The two timing signals enter the START and STOP inputs of the unit. Timing is usually measured from the leading edges of the input signals. After the arrival of the START pulse a capacitor is charged with a constant current. The charging is terminated after the arrival of the STOP pulse, and the capacitor is discharged at a uniform rate. During the discharge period oscillator pulses are counted in a scaler and then stored in a register for readout.

Modern TDCs have a resolution as low as 50 ps/count. Errors in the timing arising from a wide range of input amplitudes or discriminator slewing may be minimized by preamplifying the input signal. The timing resolution can also be improved by running a parallel input signal into an ADC and making an amplitude dependent correction to the TDC value.

Many other special purpose CAMAC and NIM devices are available commercially, including amplifiers, digital to analog convertors, digital voltmeters, and real time clocks [1, 8].

6.6 Signal cables

It is important that detector signals and logic pulses be transferred between electronic devices with a minimum of distortion. The interconnections in logic circuits are usually made using coaxial cables. A typical cable consists of a thin copper conductor surrounded by polyethylene insulation, a copper ground braid, and a vinyl jacket. The outer grounded conductor in the cable prevents the escape of electromagnetic radiation from the cable and pickup of the radiation from other nearby cables.

A section of coaxial cable of unit length can be represented as a series resistance r_s and inductance l and a parallel resistance r_p and capacitance C. The cable has a characteristic impedance per unit length [9]

$$Z_c = (Z_s Z_p)^{1/2} \tag{6.2}$$

where Z_s is the series impedance and Z_p is the parallel impedance per unit length. In high frequency operation

$$Z_s = r_s + i\omega l \approx i\omega l$$
$$1/Z_p = 1/r_p + i\omega C \approx i\omega C$$

Thus, the characteristic impedance is:

$$Z_c \simeq (l/C)^{1/2} \tag{6.3}$$

This represents a pure resistance independent of the pulse frequency and the cable length.

Table 6.3 lists properties of some commonly used coaxial cables. The thin RG174/U cables require LEMO type connectors, while the others use the BNC type. Note that the polyethylene dielectric in the space between the conductors causes the signal propagation velocity to be considerably less than c. The highest propagation velocities ($\beta \sim 0.95$) are achieved in air core cables. If we recall that

$$1\text{ dB} = 20 \log_{10} V_0/V_i \tag{6.4}$$

we see that an attenuation of 6 dB represents a factor of 2 loss in amplitude.

A coaxial cable should be terminated into its characteristic impedance. This is done either internally in an electronic module or by using a terminator plug, which is simply a resistance connected to ground. A cable that is not properly terminated will give rise to reflections. The ratio of the amplitude of the reflected signal to the amplitude of the in-

Table 6.3. *Properties of some common coaxial cables*

Type	Outer diameter (mm)	Ground shields	Z_c (Ω)	C (pF/m)	β	Attenuation[a] (dB/100 m)
RG8/U	10.3	1	50	85.3	0.78	5.9
RG58/U	4.95	2	53.5	93.5	0.66	13.5
RG58A/U	4.95	1	50	85.3	0.78	15.8
RG59/U	6.15	1	75	56.8	0.78	9.7
RG62A/U	6.15	1	93	44.3	0.84	10.2
RG174/U	2.54	1	50	101.0	0.66	28.9
RG214/U	10.80	2	50	101.0	0.66	6.6

[a] At 100 MHz.
Source: Belden Wire Corporation, Richmond, IN.

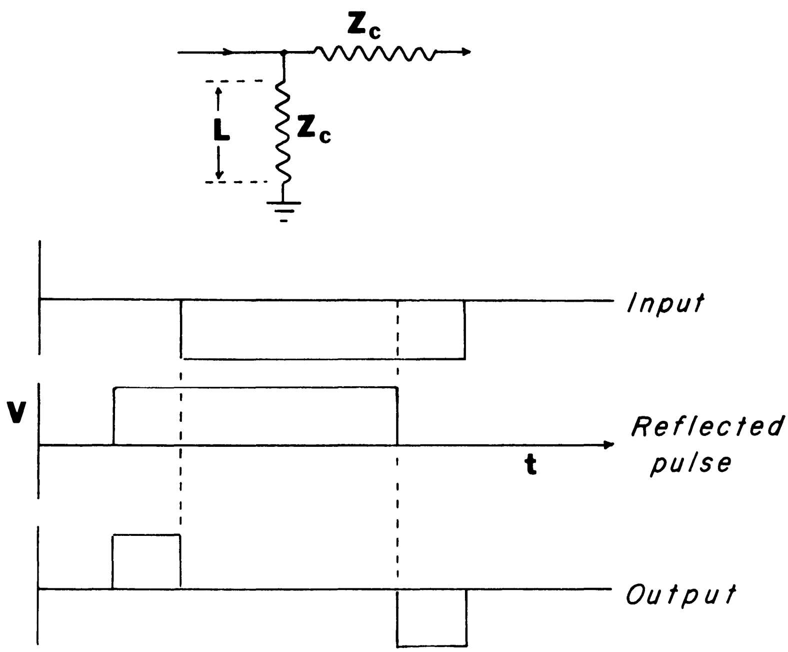
put signal is

$$\frac{V_r}{V_i} = \frac{R - Z_c}{R + Z_c} \tag{6.5}$$

where R is the value of the terminating resistor. We see that terminating with $R < Z_c$ gives a reflection of the opposite polarity. If the cable is not terminated at all ($R = \infty$), we get a reflection of the same amplitude and polarity as the input signal. A second characteristic of a properly terminated cable is that the input impedance looking into the cable will be Z_c, independent of the length of the cable.

Sometimes a section of cable is shorted at one end to form a clipping line. The reflected signal from the clipping line can be used to form a shortened (clipped) pulse. Figure 6.6 shows a clipping circuit. Half the signal goes down the clipping line to the grounded end. Here the pulse is reflected with the same amplitude and opposite polarity. It travels back up the clipping line and combines with the other half of the input signal, thereby canceling it. Thus, we get a pulse whose width is $\Delta t = 2L/\beta$, where L is the length of the clip line and β is the signal propagation velocity in the cable.

Figure 6.6 Signal waveforms with a clipping stub. Elements denoted Z_c are coaxial cables.



References

[1] Catalog, LeCroy Research Corporation, Spring Valley, NY 1983.

[2] R. Chase, *Nuclear Pulse Spectrometry,* New York: McGraw-Hill, 1961, pp. 27–9.

[3] B. Gottschalk, Timing discriminator using leading edge extrapolation, Nuc. Instr. Meth. 190: 67–70, 1981.

[4] Instruments for Research and Applied Science, EGG Ortec Corporation, Oak Ridge, TN.

[5] R. Mount, P. Cavaglia, W. Stockhausen, and H. Wahlen, Highly efficient scintillation counters, Nuc. Instr. Meth. 160: 23–7, 1979.

[6] A. Melissinos, *Experiments in Modern Physics,* New York: Academic, 1966, pp. 403–7.

[7] R. Dobinson, Data acquisition at LEP, Physica Scripta, 23: 487–91, 1981.

[8] A number of advertisements for such equipment is usually found in each issue of Physics Today and the CERN Courier.

[9] J. Brophy, *Basic Electronics for Scientists,* New York: McGraw-Hill, 1972, pp. 380–7.

Exercises

1. Show how a discriminator may be used to introduce a fixed deadtime after each yes signal from a coincidence unit.

2. What is the accidental rate for triple coincidence if S_1, S_2, and S_3 are the singles rate in three counters?

3. Prove Eq. 6.5.

4. Assume that the outputs from the readout electronics of two MWPCs are proportional to the number of hit wires. Show how commercial fast electronics may be combined to give a signal when there are two hits in the first chamber and four hits in the second.

5. An elastic scattering experiment has three detectors in the forwardly scattered direction (F), three detectors in the backwardly scattered direction (B), and three additional detectors (M) to monitor the overall event rate from the target. Lay out the electronics necessary to determine the elastic scattering rate. Suppose that you are suspicious that beam structure with a period of 70 ns is causing accidentals. What additional circuitry would be required to monitor the accidental rate?