PRAMANA
— journal of
physics

© Indian Academy of Sciences

Vol. 65, No. 2
August 2005
pp. 273–283

A high-performance, low-cost, leading edge discriminator

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MS received 7 September 2004; revised 10 March 2005; accepted 25 April 2005

Abstract. A high-performance, low-cost, leading edge discriminator has been designed with a timing performance comparable to state-of-the-art, commercially available discriminators. A timing error of 16 ps is achieved under ideal operating conditions. Under more realistic operating conditions the discriminator displays a timing error of 90 ps. It has an intrinsic double pulse resolution of 4 ns which is better than most commercial discriminators. A low-cost discriminator is an essential requirement of the GRAPES-3 experiment where a large number of discriminator channels are used.

Keywords. Discriminator; timing error; cosmic rays; extensive air showers.

PACS Nos 84.30.Qi; 84.30.Sk; 96.40.Pq; 98.70.Sa

1. Introduction

In cosmic ray experiments, scintillation detectors are widely used to detect extensive air showers (EAS) of charged particles at ground level, produced by energetic primary cosmic rays incident, at the top of the atmosphere. The scintillators produce a flash of photons lasting a few ns. The photon signal is converted into an analog electric pulse by a fast photo-multiplier tube (PMT). These analog pulses contain critical information on the physical phenomenon being studied.

In order to make a decision to record an EAS, the analog pulse has to be converted into a digital signal. The digital signal is, in turn, fed to a digital logic circuit, to generate a trigger to record the EAS. Another important parameter, pertaining to the analog pulse is its arrival time. The conversion of analog pulse into a digital signal, is generally accomplished, by the use of a comparator with adjustable threshold. Such a device is called a discriminator, as it does not respond to input pulses, below a preset threshold level and produces a standardized digital output, if the input pulse height exceeds the threshold.

A discriminator provides an interface, between the analog world of the detectors and a more ideal world of the digital logic systems. At the input, the discriminator has to handle pulses, of varying shapes and amplitudes, which arrive randomly in time. At the output it produces a standard pulse which is related in time to the leading edge crossing of the threshold. The output pulse has a constant height and width, which is completely independent of all other characteristics of the input signal, except for its time of arrival. While the height of the output pulse is constant, its actual magnitude depends on the logic standard being used such as NIM, TTL, ECL etc. The width of the output pulse can be adjusted according to specific experimental requirements [1–3].

The arrival time information can be used, to measure the time of flight of a charged particle or its velocity. In a cosmic ray shower, the relative arrival time of the secondary particles, at the observational level are used to determine the direction of the primary particle. In a typical cosmic ray EAS experiment, several hundred detectors are used to observe the shower particles. For example, in the GRAPES-2 [4] and GRAPES-3 [5] experiments, studies on the composition of primary cosmic rays are carried out, by using an array of 100 and 300 detectors respectively. The basic detector is a 1 m^2 area plastic scintillator, viewed by a fast 2-inch diameter PMT.

The shape of the PMT pulse depends on the density and the arrival time distribution of the shower particles and on the response of the detector elements. Due to large area of the scintillator, there is a spread in the arrival time of photons, which causes fluctuations in the shape of the pulse. Experimentally, it is observed that the shape of individual pulses varies from event to event. In general, there are two types of discriminators that are used in experiments. In the first type, called constant fraction discriminator (CFD), the triggering takes place at the time of crossing of a pre-determined (constant) fraction of the input pulse height. If the pulse shape remains invariant, then the CFD provides the best possible timing. However in our case, the use of CFD is not expected to offer a significant advantage because of the varying pulse shape. Also, in view of our requirement, of a large number of economical modules of fast discriminators, we have chosen to use much simpler leading edge discriminator, for the conversion of the PMT signal into a digital pulse.

In the case of a leading edge discriminator, the timing of the digital pulse varies with the amplitude of the input signal due to a fixed threshold. The variation in time, of the output pulse with amplitude of the input signal is called discriminator 'time-walk'. However, the intrinsic thickness of the disk of particles in an EAS is $\sim$1 m and given that there are fluctuations in the arrival time depending on the radial distance from the shower core, achieving a timing accuracy of better than 1 ns is not feasible. Therefore our goal was to design a leading edge discriminator with an intrinsic timing capability of better than 1 ns, which could be easily mass produced, in large numbers, at an affordable cost.

Worldwide, a variety of commercially available discriminators from several manufacturers (CAEN, LeCroy, Phillips Scientific etc.) are currently in use. These multi-channel discriminator modules come on different platforms such as NIM, CAMAC, VME, etc. We have designed a low-cost, fast discriminator based on comparator AD96687 from Analog Devices [6] on NIM platform. It performs the

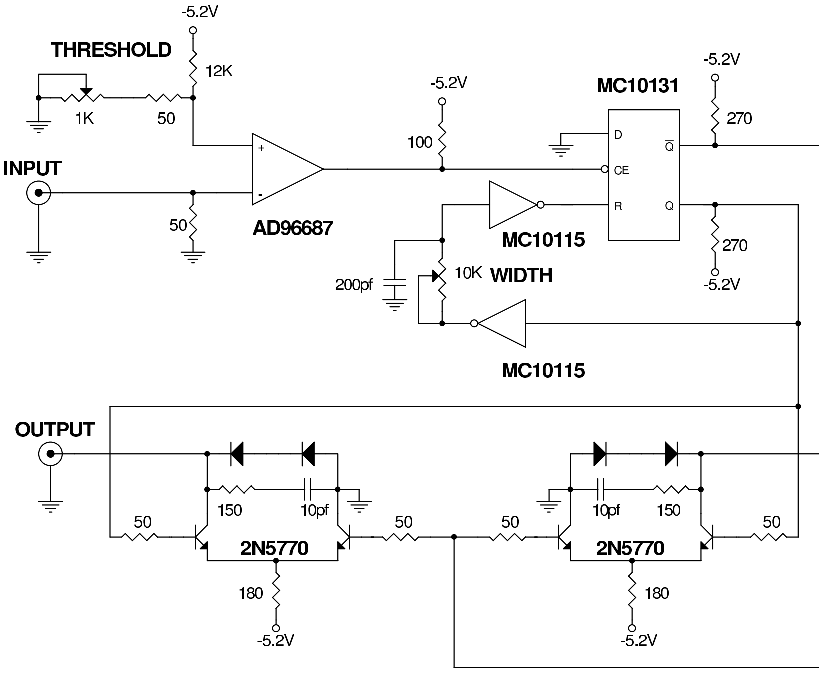

Figure 1. Circuit diagram for one out of eight identical channels of CRL discriminator.

task of setting the threshold and adjustment of the width of the output pulse, using passive components for good thermal stability. The output of the discriminator can be customized to suit the requirements of an application. In the present case, since NIM standard is used, the output level '0' is 0 V and level '1' is -800 mV. However, depending on the requirements of the experiment, other logic standards such as TTL or ECL can be readily implemented. At present, we have packaged eight channels in a single width NIM module and the threshold and width for each channel can be individually adjusted, to provide complete flexibility.

2. CRL discriminator circuit design

The selection of comparator AD96687 [6] as the basic building block, for our leading edge discriminator, is based on the following facts. It is a low-cost, dual comparator chip, which is fast with a propagation delay of only 2.2 ns, very low delay dispersion of 50 ps and relatively modest power consumption of 120 mW per channel. For clarity, the circuit diagram of only one out of eight channels, in the discriminator module, is shown in figure 1. As it was designed in the Cosmic Ray Laboratory of our institute, it is referred to as CRL discriminator.

As seen in figure 1, the threshold for the comparator is set by varying a 1 kΩ potentiometer. A 50 Ω resistor, connected to the non-inverting input, ensures that the lowest threshold is −22 mV. A 50 Ω resistor, at the inverting input provides impedance match with upstream electronics (PMT, pre-amplifier, co-axial cable etc.). The −5.2 V supply is derived from −6 V NIM supply by using a high current rating series diode. No significant variation could be seen in the magnitude of −5.2 V output voltage. During the operation of CRL discriminator spread over a period of one year in the GRAPES experiment no change was observed in its timing performance.

When triggered, the output of comparator sets the Q output of the ECL flip-flop MC10131 to state '1'. The change of state is inverted, by using one of the four gates of MC10115, and then integrated using an RC network consisting of a potentiometer (10 kΩ) and a capacitor (200 pf). The RC network causes a delay, in resetting the Q output of MC10131, back to state '0'. This results in the formation of a pulse at the output of the flip-flop and its width is determined by the product RC. The output width can be adjusted from 10 to 2000 ns. The threshold and width potentiometers are accessible from the front panel. The ECL pulse is then fed to a level shifter, formed with two discrete, high speed emitter coupled transistors 2N5770. This provides a level shift of +800 mV, to convert the ECL into a NIM level output capable of driving a 50 Ω load. Two independent level shifters provide two NIM outputs for each channel of the discriminator. It is to be noted that although faster ICs such as MC10EL series are available, MC10000 series has been used for forming the output pulse with adjustable width. This has been done as here, one is handling a logic pulse at this stage and requisite timing performance is achieved as shown later.

In figure 2, a picture of an 8-channel discriminator, packaged inside a single width NIM module is shown. The front panel contains eight input channels, accessed through Lemo connectors. Next to each input channel two potentiometers control the input threshold and the output pulse width respectively. Also the input threshold can be monitored through a socket provided on the front panel. Two NIM level outputs for each channel are available through two Lemo connectors mounted on the front panel. The circuit lay-out was prepared on a double sided printed circuit board, using OrCad capture and lay-out software [7]. Special care was taken in routing of signal tracks, to minimize the potential for cross-talk between channels.

3. Timing tests on CRL discriminator

A discriminator is triggered, if the input pulse height exceeds the threshold set. The difference in height, of the input pulse and the threshold, is defined as overdrive. A discriminator is characterized by its timing error which is defined as the change in propagation delay as a function of the overdrive. In general, timing error reduces with increasing overdrive.

Tests on CRL and other commercially available discriminators have been carried out, to measure their timing error, under two completely different operating conditions, namely with constant height NIM pulses and with PMT pulses of varying height. The response of the CRL discriminator has been compared to that of commercial discriminators under identical operating conditions.

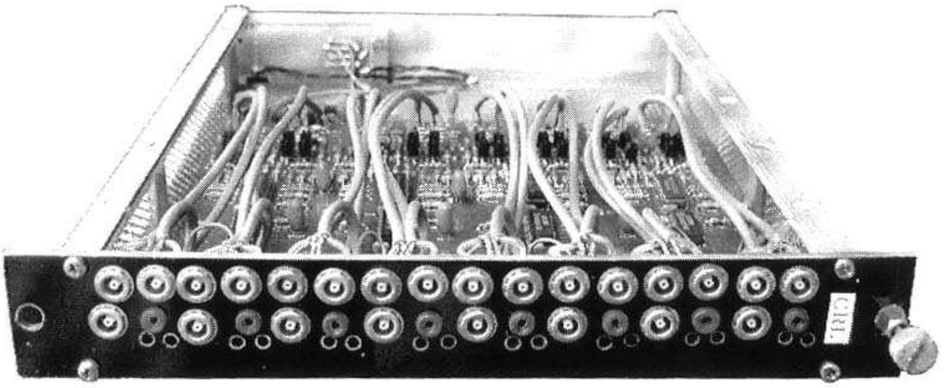

Figure 2. The 8-channel CRL discriminator packaged in single width NIM module. For each channel an input and two outputs (via Lemo connectors) along with a socket to monitor the threshold can be seen on the front panel.

3.1 *Tests with logic pulses*

To study the overdrive response of the discriminator under ideal conditions, we have used input pulses of −800 mV in height (NIM) for a threshold set at −30 mV. This resulted in a huge overdrive of ∼770 mV. The test set-up used is shown in figure 3.

A pulser is used to trigger a logic fanout unit with four identical NIM level outputs. One output is used to provide a common START to a Time to Digital Converter (TDC, Phillips Scientific 7186), operating at a resolution of 25 ps per count. The remaining three outputs are used to trigger three channels of test discriminators, one each from LeCroy model 623B [3], CAEN model N96 [8] and CRL modules. The output of the three test discriminators are used as STOP signals for three separate channels of the TDC. Since the input is a digital pulse with constant (2.5 ns) rise time, the 'time-walk' would be negligible. Therefore it is expected that the time distribution of the TDC would reflect the inherent timing error of the test discriminator.

In figure 4, the response for one channel each of LeCroy, CAEN and CRL discriminators respectively are shown as histograms. Superimposed on each histogram, a Gaussian fit to the observed distribution is also shown. In all three cases, excellent fits are obtained with a standard deviation σ=16 ps. This shows, that under ideal operating condition of very large overdrive, all three discriminators (LeCroy, CAEN and CRL) have identical response, resulting in a timing error of ≤16 ps. The location of the distributions on x-axis is arbitrary and has been chosen to fit all three distributions on a single plot. The small value (16 ps) of the timing error is consistent with the time jitter of ≤20 ps, specified by the manufacturer of this TDC [9]. Thus the actual timing error could be significantly smaller than 16 ps and therefore this value is to be treated as an upper limit.

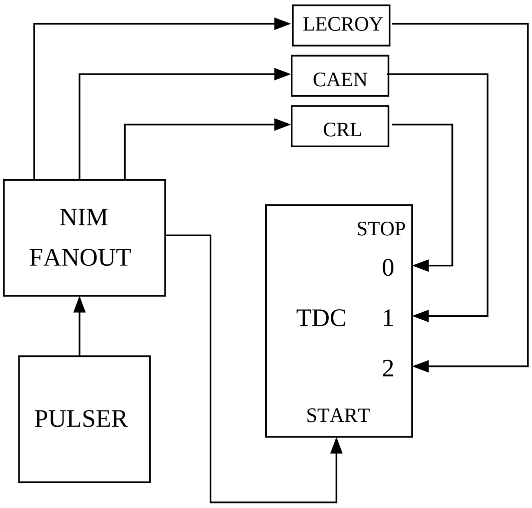

Figure 3. A test set-up to measure timing error of discriminator in response to NIM level pulses.

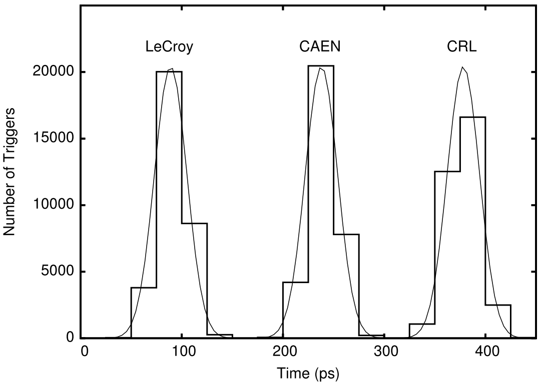

Figure 4. Timing error of LeCroy (623B), CAEN (N96) and CRL discriminators measured using NIM level trigger. Gaussian fit to the data is for $\sigma = 16$ ps.

3.2 *Tests with PMT pulses*

Under more realistic conditions, a discriminator is operated with pulses of varying height, such as those produced by a PMT, viewing a thin, large area scintillator. To study the response to PMT pulses, a set-up shown in figure 5 is used. Two small (15 cm × 15 cm) scintillation detectors, labeled A and B, are placed below a larger (100 cm × 100 cm) scintillator C. Each of these scintillators is viewed by a separate fast PMT. The PMT signals, A and B are discriminated at a threshold of -30 mV. The output from C is amplified and split equally into two pulses. One pulse after discrimination, is used to produce a 3-fold coincidence A·B·C. The second pulse is

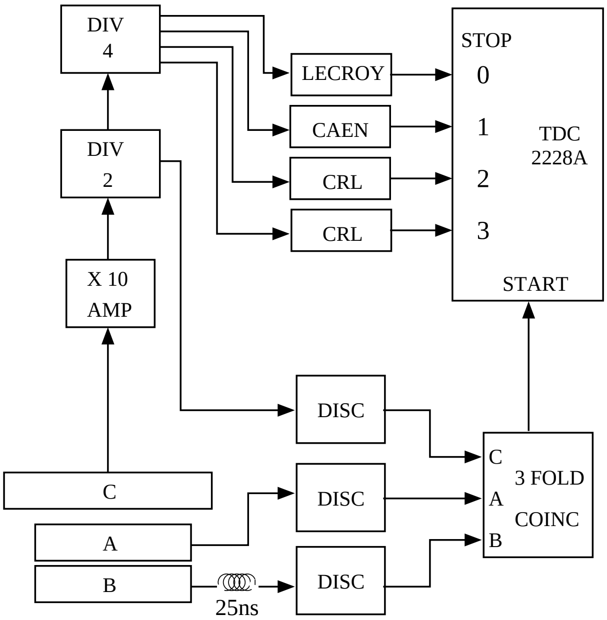

Figure 5. A test set-up to measure timing error of discriminator in response to PMT pulses.

further split, equally, into four pulses. Here, it is to be noted that signal B has been delayed by an additional 25 ns. This ensures that the arrival time of coincidence signal A·B·C as TDC START is entirely determined by the leading edge crossing of signal B, although all three signals A, B and C are required for its generation.

The passage of a charged cosmic ray particle through A and B produces a 3-fold coincidence A·B·C which is used as a common START for the eight channel TDC (LeCroy 2228A). After four-way division of pulses from C, it triggers the test discriminators at −30 mV, as shown in figure 5. The outputs of the test discriminators are used to STOP four separate channels of the TDC. The TDC count represents the time interval between the trigger A·B and C.

Charged cosmic ray particles are highly relativistic, but the combined rise time of the scintillator and PMT are relatively slower (∼3–4 ns). This results in a sizable time spread between the TDC START and STOP signals. This is clearly seen from the width of TDC distributions shown in figure 6 for CRL, LeCroy and CAEN discriminators. Full-width at half-maximum (FWHM) of 4.9 ns, in all three cases is consistent, with the expected response of the scintillator and PMT. As explained earlier, a leading edge discriminator displays considerable time-walk, which depends on the response time of the detector. Therefore, the performance of CRL discriminator can be obtained only by comparing its response to that of the commercial discriminators, under identical operating conditions. The value of FWHM as seen in figure 6 is over an order of magnitude larger than the expected timing error of the LeCroy and CAEN discriminators. To circumvent this difficulty, we measured the difference in the TDC values for a pair of discriminator pulses.

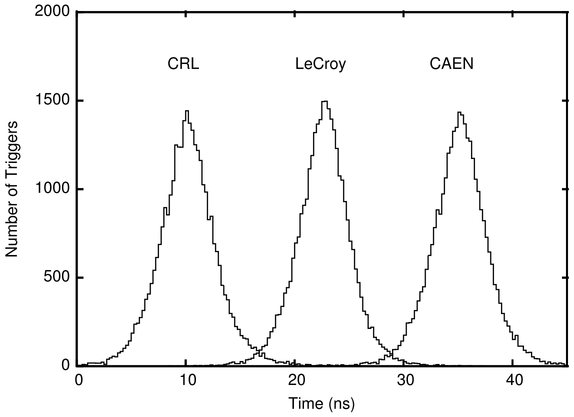

Figure 6. Time distribution measured using charged particle trigger for CRL, LeCroy and CAEN discriminators. The FWHM for these distributions is 4.9 ns.

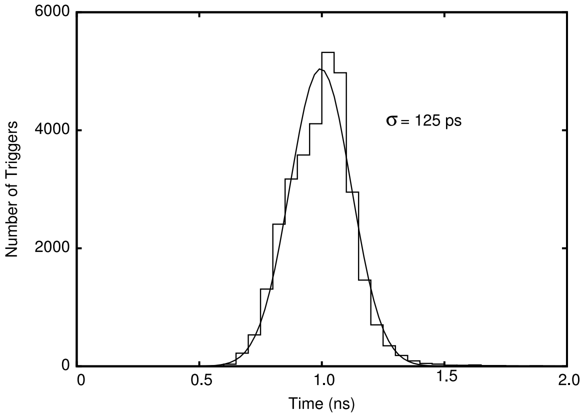

Figure 7. Relative time distribution for two channels of CRL discriminator. Also shown is a Gaussian fit to the data for σ=125 ps.

The timing effects of the scintillator and the PMT, common to both discriminators in question, get eliminated in taking the difference.

In figure 7, the distribution of difference in TDC values for two separate channels of CRL discriminator are shown. This distribution, when fitted to a Gaussian, shows a standard deviation of 125 ps. Similar distribution for two channels, one each from CRL and LeCroy discriminators, is shown in figure 8. A Gaussian fit to this distribution has a standard deviation of 135 ps. Finally in figure 9, the distribution for two channels, one each from CRL and CAEN discriminators is shown and a Gaussian fit has a standard deviation of 150 ps. However in the last two cases, where the comparisons are made with LeCroy and CAEN discriminators (figures 8 and 9) respectively, a tail in the distribution is visible. This is indicative of slightly different triggering response near the threshold (very small overdrive) for the CRL *vis-à-vis* the other two discriminators.

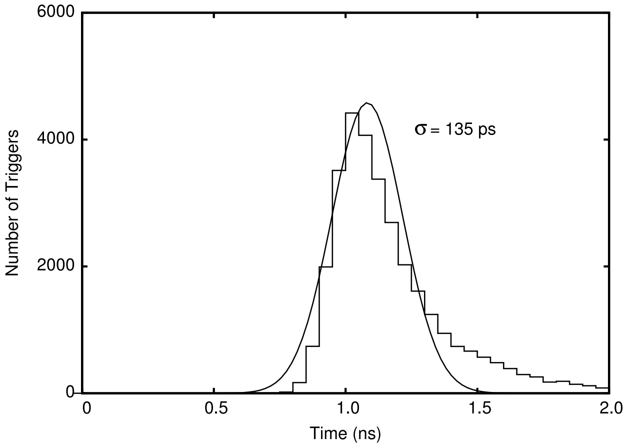

Figure 8. Relative time distribution for two channels one each from LeCroy and CRL discriminators. Also shown is a Gaussian fit to the data for $\sigma = 135$ ps.

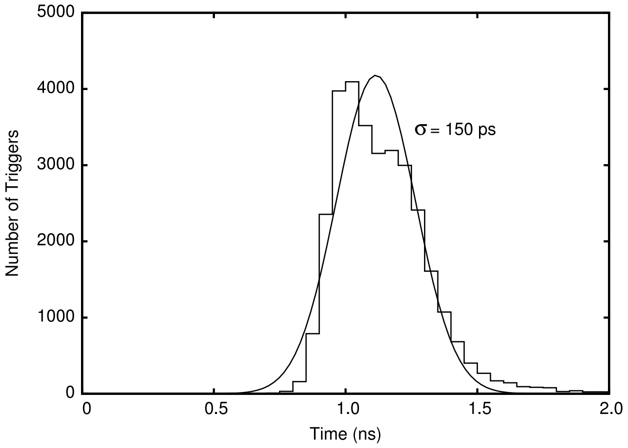

Figure 9. Relative time distribution for two channels one each from CAEN and CRL discriminators. Also shown is a Gaussian fit to the data for $\sigma = 150$ ps.

The timing error of 125–150 ps quoted above has been obtained from the distribution of difference in TDC values for two channels. Therefore, it represents combined statistical width of two separate distributions. Since all three distributions show similar widths, one can infer that the intrinsic widths are of comparable magnitude. Therefore, the timing error due to the intrinsic width of CRL discriminator is $\Delta T \approx 125/\sqrt{2} = 88 \approx 90$ ps. Similarly, for the LeCroy and CAEN discriminators, the corresponding values of timing error are ∼95 and ∼105 ps respectively.

3.3 *Double pulse resolution*

Another important parameter that defines the speed of recovery of a discriminator is its double pulse resolution (DPR). The DPR is defined as the minimum time interval between the leading edges of a pair of input pulses, for which the discriminator produces two separate output pulses [3]. Most of the discriminators have a DPR in the range of 5–10 ns. The DPR is also a function of the rise-time and the amplitude of the signal.

In order to measure the DPR of CRL discriminator, we carried out the following measurement. Two identical NIM pulses (width 150 ns) are differentiated using CR filters to produce two narrow pulses (rise-time 1.3 ns). One of the pulse is delayed by a co-axial cable of known length. The delayed and prompt pulses are passively combined. The combined output, when observed on a fast oscilloscope, shows a double peak structure and the peak separation can be varied using cables of different length. The double pulse is used to trigger the CRL discriminator and the output of the comparator is directly observed. The discriminator triggers only once, for delays up to 3.8 ns, but once the time separation of the two peaks reaches 4.0 ns, the comparator starts to trigger a second time. This indicates that the intrinsic double pulse resolution of the CRL discriminator is 4 ns. Extensive tests have been carried out to determine if input pulse given to one or more channels of the discriminator is picked up by any of the remaining channels (cross-talk). However, no evidence could be detected of any cross-talk using random pulses from a photomultiplier and periodic pulses from a pulse generator.

4. Conclusions

A low-cost, leading edge discriminator has been designed, which can be customized to suit the needs of individual experiments. It shows excellent timing performance comparable to state-of-the-art, commercially available discriminators. A timing error of ≤ 16 ps is seen under ideal operating condition with NIM level pulses. Under realistic operating conditions, using PMT pulses, all three discriminators provide similar relative timing, with an error of ~ 100 ps. The performance figure of 90 ps for the CRL discriminator is marginally superior to the other two discriminators, namely LeCroy (95 ps) and CAEN (105 ps). Even a timing error of ~ 100 ps is significantly better than the experimental requirement of 1 ns for the GRAPES experiment. The CRL discriminator also shows an excellent, intrinsic double pulse resolution of 4 ns. The flexible design of the CRL discriminator lends itself for easy modifications, to suit the large-scale requirements of discriminators in other low-budget experiments.

Acknowledgments

We thank K Manjunath, C Ravindran and S D Morris for their help in prototype wiring, testing and in the preparation of the figures. We thank colleagues at Cosmic Ray Laboratory in Ooty in India and at Osaka City University in Japan for numerous discussions.

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