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AN INTERIM REPORT

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S. K. Poultney

TECHNICAL REPORT NO. 862

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ABSTRACT

The precision of timing in the sub-nanosecond region using currently available photomultipliers and fast electronic equipment is examined at both moderate light levels and the single photoelectron level. A one nanosecond distance was measured using a light pulse three nanoseconds wide and of such an intensity as to yield not more than one photoelectron each pulse. In addition, the location of the single photoelectron level and the behaviour of the dark current at this level are discussed.

TABLE OF CONTENTS

I. Introduction

The study of timing to a precision of less than a nanosecond that was outlined last year (Poultney 1967) has been initiated. The Ortec 437 Time-to-Pulse-Height converter is the key element in both the study and in the evaluation of all the fast electronics. One uses either a standard electrical start pulse in conjunction with a simultaneous light pulse (e.q. PEK 118 TE nanosecond light source and Huggins 961D nanosecond pulse generator) or a split standard electrical pulse with identical start and stop channels of electronics. The TPHC is capable of measuring time differences (i.e. electronic jitter, discriminator walks, etc.) of 10 psec. An RCA 8575 in an Ortec 265 base was used to stop the TPHC in the study of leading-edge discrimination while an Ortec 264 fast timing base and 403A Time Pickoff Control was used in the study of fast zero-crossing discrimination. The relative merits of each method of discrimination for moderate light levels and typical signals were discussed previously (Poultney 1967). Basically, the wider the dynamic range, the more one gains in precision by using fast zero-crossing discrimination. This gain in precision is demonstrated below. It is especially important where a radar return is highly variable about some moderate level. The study of the relative merits of the two discrimination methods is being continued at low light levels (i.e. a single photoelectron released from the photocathode of the photomultiplier). It shows that one can measure a one nanosecond distance at this level with a light pulse of greater width (3 nsec FWHM), if only one can range a number of times before the target moves, but it does not clearly distinguish all the aspects of the discrimination problem due to the light pulse being wider than the expected walk. A Cerenkov light source is now being designed in conjunction with D. Currie to provide sub-nanosecond light pulses to resolve the remaining ambiguities.

The amount that large dynamic range affects timing precision with leading-edge discrimination depends both on how close one works to the discrimination level (which in turn depends on the gain in the photomultiplier and other amplitiers before the discriminator) and on the shape of the photomultiplier output pulse. Photomultiplier pulses have relatively sharp rise times which makes leading edge discrimination more useful than one first expects. The present combination of high-level leading-edge discriminators (designed for high counting rates), low-level fast amplifiers, and typical photomultipliers work so as to limit more than necessary the usefulness of leading edge discrimination. A low-level leading-edge discriminator or a high-level fast amplifier would help in this regard. Higher gain in the photomultiplier may also help, but, at the single photoelectron level, will probably greatly enhance the dark current. This enhancement of dark current above thermionic emission at high tube gains as well as means of suppressing thermionic emission is also being studied.

Finally, several methods of locating the single photoelectron level are discussed and evaluated.

In all of the above work, the use of a multichannel analyzer was of great value both in saving analysis time and in deciding on optimum experimental parameters at the time of the measurement. The analyzer that was used was borrowed and must soon be returned. The display of discriminator behavior was also accomplished by triggering a sampling oscilloscope with the discriminated signal and by viewing the input to the discriminator. The photographic record is, however, not quite as precise as that obtained with the multi-channel analyzer.

II. Leading Edge Discrimination Compared with Fast Zero-Crossing Discrimination at Moderate Light Levels.

At moderate light levels (300 photoelectrons per pulse), the PEK light source provides a photomultiplier output pulse of relatively uniform height and shape. Its rise-time is about 2 nsec and its amplitude variation is about 15%. Using the circuit in Figure 1, leading edge discrimination yields a walk of about 0.4 nanoseconds. Successive decreases in the incident light intensity (by changing only the value of the neutral density filter) causes the walk to increase progressively and causes the centroid of the walk to change its time position as shown in Table 1. Plainly, if the light signal that one receives fluctuates in an unknown way, both a systematic (delay) and a random (walk) error will enter. The delay obviously is due to discrimination at a later time on the smaller amplitude pulses (at the same level). The increase in walk with decrease in signal is probably due to greater relative fluctuations in the signal due to secondary electron emission or other cause.

The similar test using fast zero-crossing discrimination is outlined in Figure 2. Here the Ortec 264 must be carefully aligned as described in the manual. The tuning is different for widely different light levels. One method of tuning is to trigger a sampling oscilloscope with the discriminator output (or PEK pulse electrical signal) and display the input to the Ortec 264 discriminator. A TEK 564 with 353 and 3T2 plugins was used. (A tektronix 454 was generally used for preliminary measurements). A typical sweep speed was 2 nsec/$_{cm}$.

Zero delay was measured after tuning at ND 1.0 and ND 2.0. The walk increased from about 0.[illegible] nsec to about 1 nsec, but was entirely due to the input pulse jitter before the discriminator. The TPHC measurements are given in Table 2. The advantage of the zero-crossing discriminator with respect to systematic timing errors is obvious. The advantage with respect to the random error is little at these light levels although the lower light level may be a particularly bad choice for the tuning selected. The zero-crossing discriminator works by timing to the center of input signals of the same shape, but different amplitudes. The timing signal is generated as the differentiated input signal crosses back through zero. Changes in pulse shape at low light levels could cause the poor behavior there of the Ortec 264.

III Leading Edge Discrimination Compared with Fast Zero-Crossing Discrimination at or Near the Single Photoelectron Level

A. Location of the Single Photoelectron Level

Two techniques were used to locate the single photoelectron level for a particular photomultiplier - amplifier - discriminator combination. The first consists of measuring the differential pulse height spectrum when a low-level tungsten light is allowed to fall on the photocathode through a small opening in the light-tight photomultiplier housing*. One typically adjusts the light leak to equal about ten times the dark current, but not so great as to cause pulses to overlap. The resultant pulse height spectrum then allows one to select the efficiency of single photoelectron detection. One at times works at a lower detection efficiency than necessary if there is a rapid increase in dark current at the desired efficiency. The reasons for such a dark current enhancement and ways to circumvent it are discussed below.

The second technique for locating the single photoelectron level is the coincidence method. This technique is especially useful when dark currents are large. Either of the circuits in Figure 1 and 2 may be used.

Note: A special mini-light-tight box was designed which allowed the PEK lamp to be coupled to any one of the several photomultipliers under evaluation, but at the same time allow easy access to the inside of the box to change the neutral density filters in front of the photomultiplier. A shutter in front of the photomultiplier was also provided.

Amplifiers may be added between the photomultiplier and TPHC. The PEK light source and Huggins pulser provide simultaneous light and electrical pulses sixty times a second. Hence, at moderate light levels, one expects to obtain sixty counts per second at the output of the TPHC. A Hewlett-Packard 5245 L is used for counting purposes. (One might choose to use a coincidence circuit in place of the TPHC). One then attenuates the light and raises the system gain until one counts about 54 Cts/sec which does not increase with gain. This level is the 2.3 photoelectron level if the anode photoelectron distribution is Poisson. In our geometry, this level is obtained at 1.25 Kv on the lamp and a ND 3.0 filter. A further attenuation of the light by a factor of ten means that one should count 11 Cts/sec at a mean level of 0.23 photoelectrons. The probability of getting two or more photoelectrons at a time is 2% (one count). Again, the counting rate should not change with gain over a limited range. At lower gains, one, of course, eventually fails to detect the single photoelectrons. At higher gains, the dark current increases and causes accidental counts. With the TPHC and photomultiplier (and fast amplifiers, if used), dark current rates up to 50 MHZ would not be serious. For example, the RCA 8575 at 3100 V used with the Ortec 265 direct to the TPHC operated with 80% efficiency at the single photoelectron level and had a dark current rate of 37 KHZ.

B. Dark Current Enhancement at High Photomultiplier Gains

If one measures the dark current as a function of gain for the RCA 8575, one notices that it increases quite rapidly at higher gains. In order to determine whether or not this enhanced dark current was due entirely to thermionic emission, an Ortec 435 amplifier was used to maintain the single photoelectron level as the photomultiplier gain was reduced. In this case, the Ortec 435 output was sent to the Ortec 420 single channel discriminator whose timing output stopped the TPHC. The addition of this relatively slow amplifier also widened the TPHC time interval (4 μsec) and increased the accidentals rate. One would like to have identical start and stop channels to eliminate this fast-slow discrepancy, but a second channel has not yet been purchased. With the Ortec 435 gain at its maximum ($\sim$ 1600), one could work at the single photoelectron level (at 80% efficiency) with the RCA 8575 at 2100 Volts and the dark current at 8.5 KHZ; a five-fold reduction. The amplifier introduced no noise. However, this decrease in dark current can only be utilized if one uses fast amplifiers or two identical slow channels with low walk and jitter.

Means of further reducing the dark current are being studied. Cooling to dry ice temperature reduces the thermionic dark current by about a factor of 100. Use of a pancake magnetic coil at the photocathode can provide decreases in photocathode dark current directly proportional to the active area remaining. The magnetic field prevents photoelectrons from the outer edges of the photocathode from reaching the photocathode.

C. Leading-Edge Discrimination at the Single Photoelectron Level

The study of leading-edge discrimination was done with the circuit in Figure 1 with the exception that an EGG AN101 fast amplifier (gain = 4) was added between the anode and TPHC. The amplifier was used to raise the pulse amplitude (~ 1 volt) as far above the TPHC discrimination as was possible. The amplifier saturates at about the one volt level. At the single photoelectron level (PMT HV = 3000v), the FWHM of the walk distribution is 3.5 nsec. However, this width is probably the true width of the PEK light-pulse rather than the walk due to leading-edge discrimination. PEK Laboratories quotes 2 to 3 nsec for the width of the light pulse, but this claim could not be substantiated directly since the RCA 8575 has an anode pulse width of about 7 nsec at moderate light levels. In fact, the above measurement (or a similar one with the zero-crossing discriminator) is the only way we have at present to measure the width of the PEK light pulse. The behaviour of the leading-edge discrimination can then be stated at present as a walk of less than 3.5 nsec (probably less than 2 nsec) and an unknown systematic delay.

The way to circumvent this ambiguity is to construct the Cherenkov light pulser now being designed. Light pulses shorter than a nanosecond are expected. Part of the light of the Cherenkov pulse will be sent to the low-level stop channel. Most of it will be sent to an identical moderate light-level start-channel. In the interim, an attempt will be made to evaluate leading-edge discrimination using dark current photoelectrons themselves. It may be possible to display the PMT anode signal on the sampling oscilloscope using the discriminated signal as a trigger or using a differentially-selected dynode signal. The latter method would make use of the linear dynode signal from the Ortec 265, the Ortec 435, and the Ortec 420. Preliminary testing indicates that this latter method is probably not adequate.

D. Zero-Crossing Discrimination at the Single Photoelectron Level

The study of the zero-crossing discrimination at the single photoelectron level was done with the circuit in Figure 2. The Ortec 264 base and 403A Time-Pick-off unit are such that the sampling-oscilloscope display is made as a matter of course during the tuning of the discriminator. This display worked well using dark current photoelectrons, but not light pulse photoelectrons due to the width of the light pulse. Much of the lower-amplitude dark current could be discriminated against with the level discriminator of the zero-crossing discriminator. The level was set using the coincidence method described above. Unfortunately, the discriminator could not be tuned to work well at the single photoelectron level. The "zero-crossing" appeared on the oscilloscope to have a walk of about 0.7 nsec. However, this narrow part of the waveform did not occur at the true zero. The zero-crossing width at zero was 2 nsec due to incorrect tuning. At the 2.3 photoelectron level, the narrow part of the waveform (0.7 nsec) could be made to cross at zero. The TPHC measurement at the single photoelectron level gave a walk of 3.3 nsec (FWHM) which is the width of the PEK light pulse.

Again, the light pulse width was greater than the expected walk. The Cherenkov source will resolve the resultant ambiguity as described above. However, a more serious problem remains. An internal modification must be made in the Ortec 264 base in order to realize the 0.7 nsec walk that appears to be achievable. The modification probably consists in shortening the clipping line that differentiates the anode pulse. The Ortec

264 base was designed for fast-scintillator work so that we had shortened this cable at the outset. If shortening the cable does not improve the behaviour of the zero-crossing discriminator at low light levels, the cause will probably be too great a variation in pulse shape at this level. The study was initiated to settle this very question. If 2 nsec represents the best walk obtainable with zero-crossing discrimination at single photo-electron levels, leading-edge discrimination may still be competitive at these levels. The tests with the Cherenkov source should resolve this issue.

The Ortec 264 zero-crossing discriminator has one other problem. The PMT must be operated at highest gain which means enhanced dark currents. It is not possible to reduce the discriminator level and probably not possible to amplify the anode signal before (or after) differentiation.

As described above, one might use the linear output of the Ortec 264 in conjunction with the Ortec 435 and Ortec 420 to provide some selection of pulse amplitudes during the tuning (or timing) measurements. Either the Ortec 420 timing signal or a coincidence signal for the multichannel analyzer gate is available.

IV Measurement of a One Nanosecond Light Path Using a Three Nanosecond Light Pulse (FWHM) at Moderate and at Low Light Levels

One of the reasons the PEK light source was purchased was to prove that a short unknown range could be determined quite well at single photoelectron levels using a light pulse that was not as narrow; as long as a number of measurements could be made before the range changed. To this end, a hollow tube about 1.0 nsec in length was made so that the PEK light source could be moved that distance further away from the PMT (and still be in a light-tight environment). The circuits in Figure 1 or Figure 2 were again used. The hollow tube caused a light intensity decrease of four so that, unless great care were taken to re-adjust the light intensity by changing neutral density filters, leading-edge discrimination would be subject to possible systematic errors if an exact measurement of the tube length were made at moderate light levels. A measurement of tube length was made at moderate light levels with the leading edge discriminator. The light intensity was adjusted by eye using an oscilloscope to be equal before and after addition of the hollow tube. The result was a length of 1.3 nsec with a possible systematic error of several tenths of nanoseconds. The walk of 0.7 nsec is a random error and can be treated statistically. The same measurement made using zero-crossing discrimination at moderate light levels and using no particular care in re-adjusting the light intensity gave a result of 1.2 nsec with a systematic error somewhat less than the leading-edge measurement. The 0.3 nsec walk is again amenable to statistical treatment.

Once the length of the hollow tube was determined at moderate light levels, the measurements were repeated at low light levels. As expected, the walks increased to a value equal to the width of the light source ($\sim$3.5 nsec). However, the shift of the centroid of the walk distribution due to substitution of the hollow tube could still be measured. Although detailed statistical fits have not yet been made, preliminary calculations indicate that leading edge discrimination yielded a length of 1 nsec and zero-crossing discrimination yielded a length of 1.2 nsec at single photoelectron levels. The error in these measurements is probably limited by the walk in the discriminators rather than the statistical arrival of light pulse photons. Further studies are planned to clarify these points.

V. Conclusions and Recommendations

1. Zero-crossing discrimination has a decided advantage over level discrimination at moderate light levels due to the absence of systematic range error for a wide range of signal amplitudes. The random error due to signal amplitude fluctuation is also better for zero-crossing discrimination with presently available equipment.

2. The detailed behaviour at the single photoelectron level remains to be determined. A Cherenkov light source must be built and the zero-crossing discriminator must be further modified to work at this level. The assumption that the advantages of zero-crossing discrimination at moderate light levels will continue at lower levels still appears to be a relatively good assumption. At least one additional photomultiplier must be purchased.

3. A light pulse with a width (3 nsec) wider than a distance to be measured by time-of-flight (1 nsec) and wider than the walk expected in the discriminators was successfully used to measure that distance. Comparison of measurements at moderate and low light levels indicated that the zero-crossing disdrimination yielded the more reliable results (1.2 nsec). Assignment of error awaits statistical analysis of the random distributions and detailed study of each discrimination method with the Cherenkov source.

4. A multi-channel analyzer proved to be a great help in the above measurements. In as much as it was borrowed, I recommend that one be purchased as soon as possible. Also of use would be a second channel of Ortec 435 and Ortec 420 (or other fast amplifier and discriminator).

5. Other photomultipliers such as the EMI 9558 and the RCA IP21 will be studied with an eye to circumventing inherent conditions that now prevent nanosecond timing.

6. Investigations of improvement of level discrimination timing and of dark current minimization as discussed above will also be continued.

REFERENCES

S. K. Poultney, Univ. of Md. Tech Report #725, Aug 1967

Figure 1 Leading Edge Discrimination

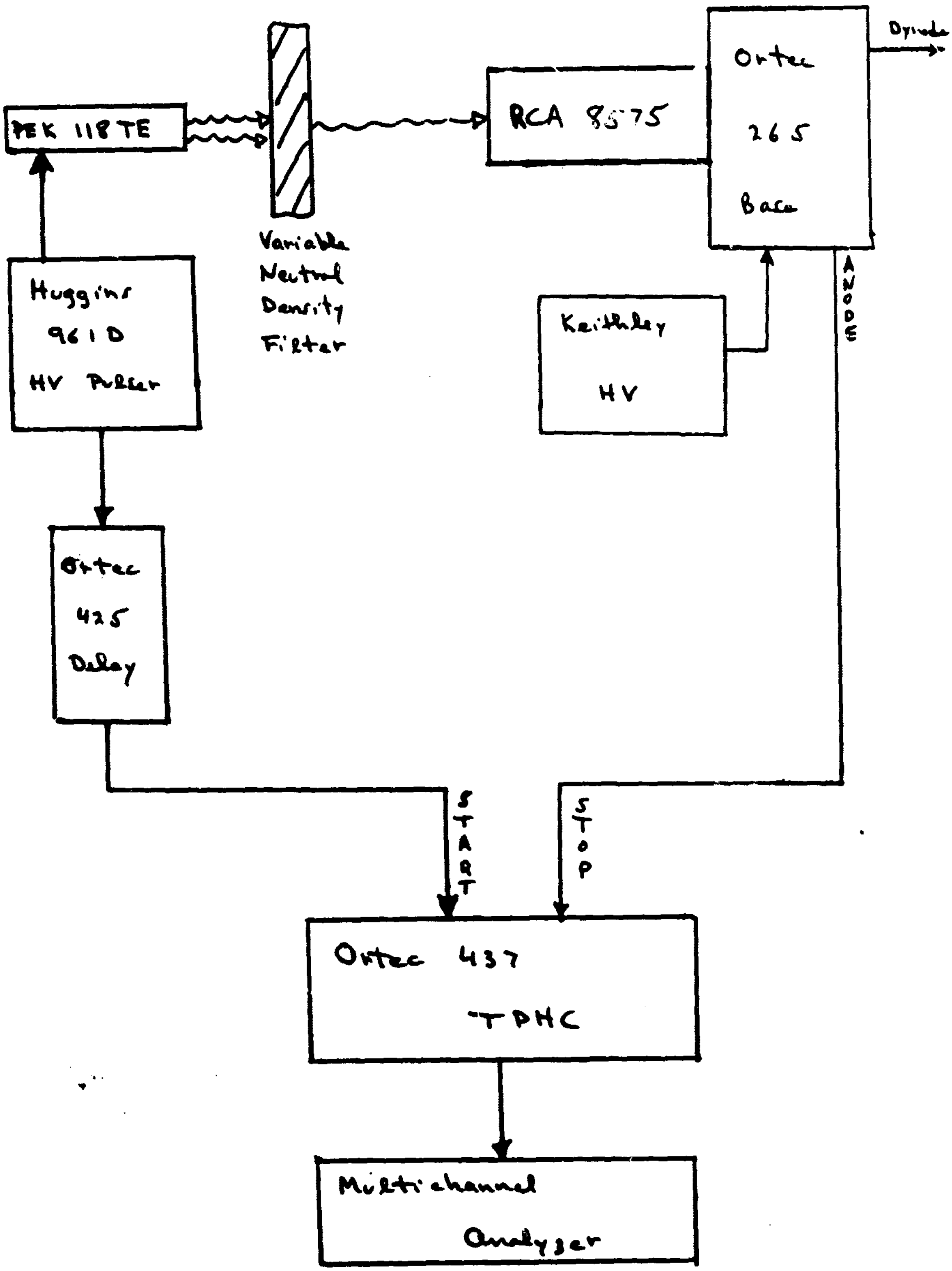

Figure 2 Zero-Crossing Discrimination

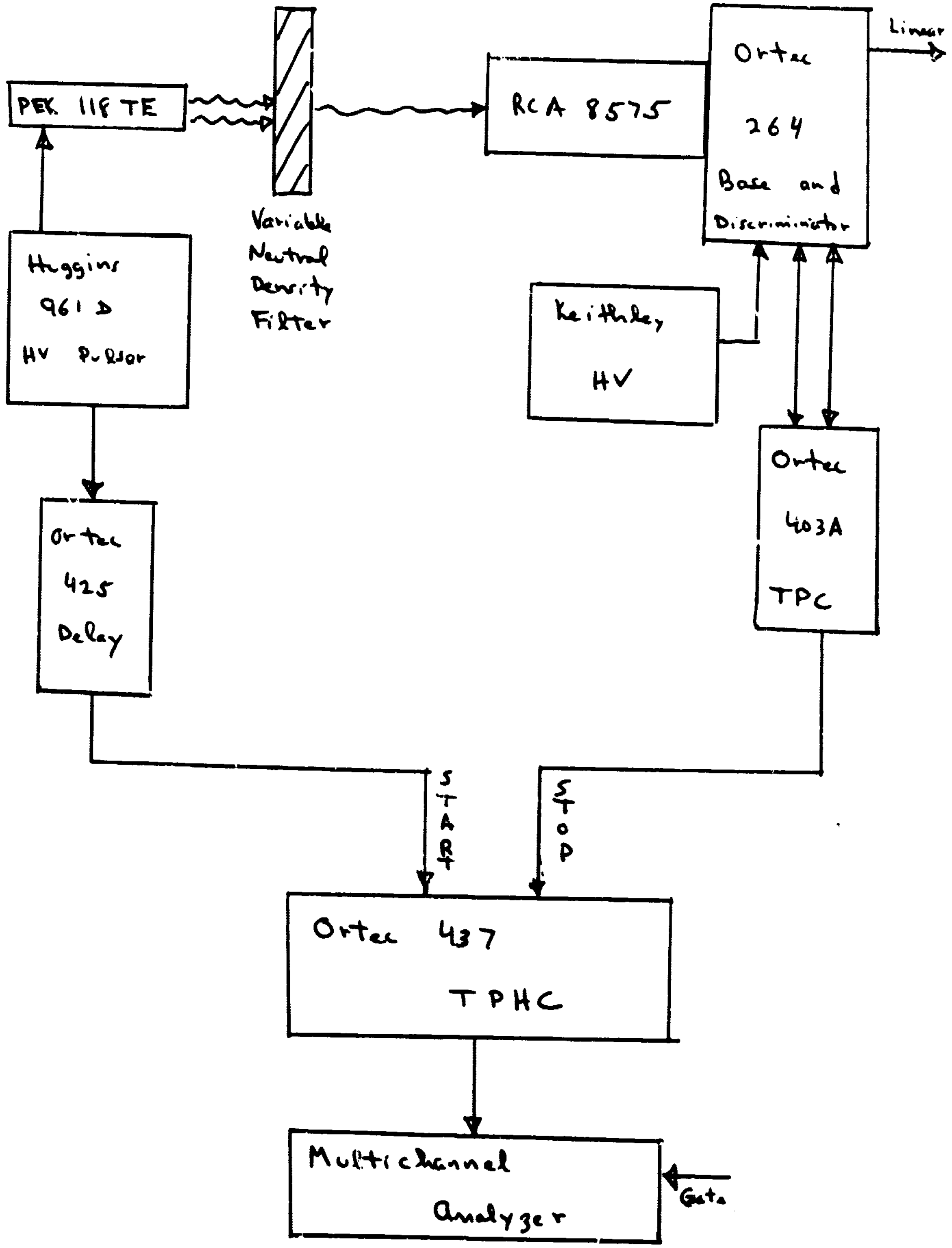

TABLE 1

Variation of Walk and Delay With Incident Light Intensity For The Ortec 437 TPHC Used as a Level Discriminator (Moderate Light Levels).

ND Filter	Anode Signal	Walk (FWHM)	Delay
0.7	∿ 4 v	0.3 nsec	- 0.4 nsec
1.0	∿ 3 v	0.4 nsec	0 nsec
1.3	∿1.3 v	0.5 nsec	+ 0.7 nsec
1.6	∿0.75 v	1.3 nsec	+ 1.0 nsec

Conditions:

High Voltage 2800 volts

PEK Lamp 1.25 Kv

TPHC Discrimination Level 250 mv

Positive Delay means later

Multichannel Analyzer Time Base calibrated using PEK Electrical Pulse and Ortec 425 Delay Box

TABLE 2

Variation of Walk and Delay With Incident Light Intensity For The Ortec 264 Fast Zero-Crossing Discriminator (at moderate light levels).

ND Filter	Walk (FWHM)	Delay	HV
1.0	0.6 nsec	0	2800
2.0	1.3 nsec	+ 0.2 nsec	
1.0	0.5 nsec	0	3000
2.0	1.5 nsec	- 0.2 nsec	

Conditions: PEK lamp 1.25 Kv

A Canberra 1460 Biased Amplifier was usually used between the TPHC and MCA.

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