1

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TITLE OF THESIS/TITRE DE LA THÈSE "A Large Area Time of Flight Counter for Lass"

UNIVERSITY/UNIVERSITÉ Carleton University

DEGREE FOR WHICH THESIS WAS PRESENTED/
GRADE POUR LEQUEL CETTE THÈSE FUT PRÉSENTÉE M.Sc.

YEAR THIS DEGREE CONFERRED/ANNÉE D'OBTENTION DE CE DEGRÉ 1977

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The undersigned recommend to the Faculty of Graduate Studies acceptance of the thesis "A LARGE AREA TIME OF FLIGHT COUNTER FOR LASS", submitted by GERALD OAKHAM, B.Sc., in partial fulfillment of the requirements for the degree of Master of Science.

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Acknowledgements

I wish to thank Dr. Carnegie, my thesis supervisor for invaluable support, suggestions and encouragement throughout the experimental work and the production of this thesis.

I would also like to thank all the members of the SLAC-Ottawa group for discussions about the project and a lot of practical help. In particular, I would like to thank L. Bird, P. Estabrooks, F. Winklemann and J. Valvra from Carleton University, C. Hargrove and H. Mes from the High Energy Group of the National Research Council and D. Hutchinson, A. Killert, P. Kunz, S. Shapiro and B. Walsh from the Stanford Linear Accelerator Centre.

My thanks and appreciation to the members of the Carleton Science Workshops who built and installed the counter: in particular the precision installation team of B. Ellspermann, E. Fatica and L. Raffler.

ABSTRACT

This thesis describes the design, construction and properties of a scintillation counter hodoscope, which is being used as part of a time of flight identification system. The counter forms part of the Large Aperture Solenoid Spectrometer facility at the Stanford Linear Accelerator Center, where it will be used in an 11 GeV/c K^-p experiment in meson spectroscopy. This hodoscope will serve as a device to aid particle identification, and will also be a major element in the experiment's multiplicity trigger. The counters have a time resolution of 1.2 nsec F.W.H.M. which allows identification between π and K mesons for momenta less than 1.4 GeV/c with 84% confidence.

A LARGE AREA TIME OF FLIGHT COUNTER FOR LASS

BY

GERALD OAKHAM

A thesis submitted to the faculty of graduate studies in partial
fulfillment of the requirements for the degree of Master of Science.

Carleton University

Ottawa, Canada

November 1977.

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Chapter 1: Introduction

This thesis describes the design and implementation of a large area scintillation counter hodoscope, which has been installed as part of the Large Aperture Solenoid Spectrometer at the Stanford Linear Accelerator Centre. The hodoscope is to be used in an 11 GeV/c K^-p experiment which is to be undertaken at SLAC using LASS. This experiment has been designated by SLAC as E-132.

The LASS facility is situated at the end of one of SLAC's secondary beam lines. It is a versatile particle spectrometer, utilizing two analysing magnets; a solenoid and a dipole as shown in Figure 1. Particles are detected by a large number of chambers and counters arranged in and around the magnets. The time of flight (T.O.F.) hodoscope is one such detector. It has an active area which is roughly circular in shape (Figure 2), with an external diameter of 2.72 m and an internal diameter of 0.30 m; it is 1 cm thick. It is split into 24, 15° wedge shaped segments and is located in a vertical plane, approximately 1.4 m downstream of the end of the solenoid.

The hodoscope has two main functions: as an element in the experiment's trigger, and as an aid in the identification of secondary particles produced in the target. The latter function is accomplished by measuring the time interval between a beam particle hitting a small counter situated upstream of the target and an associated secondary particle hitting a T.O.F. counter. Subtracting the flight time of the beam particle from this measurement gives the time of flight of the secondary particle. The particle's velocity can then be calculated, and if its momentum is known, an estimate can be made of the particle's

FIG 1 CONFIGURATION OF LASS FOR THE 11 GeV/c K⁻p EXPERIMENT (E-132)

FIG 2 DIAGRAM OF T.O.F. HODOSCOPE

mass. In LASS the average path length of secondary particles between the target and the T.O.F. hodoscope is 5.5 m. Test measurements demonstrated that the counters have a time resolution of 1.2 nsec F.W.H.M. which allows 2σ separation up to 1.4, 2.3 and 2.7 GeV/c between π and K mesons, between kaons and protons, and between pions and protons respectively.

As a trigger the hodoscope is used in conjunction with four trigger quadrant counters that cover the hole in the T.O.F. array. The quadrant counters in turn form an annulus with a 0.076 m diameter hole through which the beam passes (Figure 2). Signals from all 28 counters are combined to form triggers of multiplicity $\geq 1, 2, 3$ and 4, which will be used to aid selection of that subset of the K^-p interactions of interest to E-132.

The use of the hodoscope as a T.O.F. and trigger device with special emphasis on the requirements of the K^-p experiment is discussed in Chapter 2. This Chapter also contains information on LASS and describes the function of the T.O.F. hodoscope within the spectrometer. Chapter 3 starts with a review of other current T.O.F. systems and the principles behind their designs, followed by an account of how these principles were applied to LASS and a discussion of the problems that arose during their implementation. The design finally selected is then described in detail.

Before the counters were installed, their properties were investigated. This involved establishing operating conditions for the photomultiplier tubes and bases using light emitting diodes attached to the ends of the counters. It also involved using the

LASS beam to investigate corrections that were to be employed in the experimental operation of the hodoscope. One of these was to correct for time walk variations due to the varying pulse height of the photomultiplier tube signals. Another was to correct for the differences in transit time of light coming from different parts of the scintillator. This latter correction took the form of a mapping of the surface of the counter for time delay. The LASS beam was also used to measure the resolution of the various sizes of counters and to test for variations in resolution at different points on the counter. The properties of the counters are described in detail in Chapter 4.

The mapping and corrections obtained in the tests described in Chapter 4 are preliminary. Final correction values must be found by an iterative procedure using real data. This process is described in Chapter 5 along with an account of the mechanical and electrical installation of the hodoscope. Two appendices are provided; one contains a description of LASS and the other gives construction details of the hodoscope.

Chapter 2: The Time of Flight Hodoscope as a LASS device

i) An 11 GeV/c K^-p experiment at LASS

The 11 GeV K^-p experiment involves an investigation of several questions in meson spectroscopy. Two or more charged particles in the final state will be required to trigger the LASS apparatus which will lead to the recording of a large variety of final states. This will allow a search for many of the states predicted by the quark model that have not yet been seen and provides clarification of other states, the existence of which is dubious or that have uncertain classifications.

The quark model predicts that mesons should be ordered in nonets with specific J^P , (spin^{parity}) assignments which can be grouped according to the constituent quarks' orbital quantum number ℓ . The $\ell = 0$ nonets, $J^P = 0^-, 1^-$ are now well established, the $\ell = 1$ nonets, $J^P = 0^+, 1^+, 2^+, 1^+$, however, have many missing states and uncertain classifications, while the $\ell = 2$ supermultiplet has very few well established states.

The reactions to be studied include the hypercharge exchange, and the K^* production reactions. Hypercharge exchange reactions are typified by $K^-p \rightarrow X^0\Lambda$ and $K^-p \rightarrow X^-\Sigma^+$ where X^0 and X^- are non strange mesons. Hypercharge (Y) is the sum of baryon number (B) and strangeness (S).

	K^-	p	$\rightarrow$	$X^0(X^-)$	$\Lambda(\Sigma^+)$
Y	-1	+1		0	0
S	-1	0		0	-1
B	0	1		0	1

The reactions are shown schematically in the diagram on the previous page along with the quantum numbers of interest. One can see that the intermediary particle (dotted line) carries strangeness and hypercharge, hence the origin of the name hypercharge exchange. The mesons represented by X^0 and X^- decay to a mixture of pions and kaons. A list of the final states is shown below. Possible meson states which could generate them are shown in brackets on the right.

K^* production reactions involve a non strange intermediary particle, so that the meson produced is strange. Data from these reactions should allow an investigation of high mass K^* (natural parity) states as well as a good investigation of the Q and L regions (unnatural parity states). Some typical reactions are

In both lists of reactions the final states contain a mixture of kaons and pions. This fact highlights the importance of good particle identification to this experiment.

ii) Large aperture solenoid spectrometer at SLAC

A plan view of the LASS spectrometer is shown in Figure 1. LASS can be conveniently thought of in two major sections: the solenoid, which includes C1 and the T.O.F. counter, and the dipole section, which includes the downstream chambers and those chambers between the two magnets. The target is 90 cm long and is situated in the center of the first coil of the solenoid. Low momentum particles produced by the interactions of an incident beam particle on the target, are analysed in the solenoid by a system of proportional and spark chambers. These include a set of cylindrical chambers around the target, and planar chambers downstream of the target, two of which are proportional chambers. Momenta are measured by reconstructing the particles' helical tracks through the solenoid. Particles with large momenta and those that are produced at small angles with respect to the incident beam are analysed in the dipole section. The dipole section employs eight spark chambers to provide track information. Time information is derived from three proportional and two scintillation counter hodoscopes.

Particle identification is accomplished in LASS by C1, a 38 element atmospheric pressure threshold Cerenkov counter, C2 an 8 element pressurized threshold Cerenkov counter and the 24 element T.O.F. counter. C1 is situated at the end of the solenoid and when

filled with Freon 114 gives π/K separation from 3.0 GeV/c to 8.5 GeV/c (ref. 2). The pressure in C2 can be adjusted to give particle identification in a range overlapping and extending that of C1. The T.O.F. counter provides identification for low momentum particles as described in Chapter 1. Comparing the performance of these three devices it can be seen that positive particle identification is not possible for each track. However, in the analysis of an event, physics constraints provide additional information which leads to a high overall efficiency in event identification.

The combination of solenoid and dipole gives LASS almost 4π geometric acceptance for detection of the secondary particles produced in the target. This and its ability to accept very high data rates makes LASS suitable for an experiment such as E-132.

LASS is situated in one of SLAC's secondary beam lines. The SLAC machine produces particles in pulses 1.6 μ sec long, with up to 180 pulses per second. There are several particles per pulse so that even though the average beam flux is low, instantaneous rates can be very high, 10^7 /sec. This can cause spurious effects even in fast devices such as scintillation counters.

iii) Particle Identification in LASS

The ability to clearly distinguish secondary pions and kaons is especially important for K^+p experiments. Particle identification was studied in three reactions typical of the ones that will be encountered in E-132. Momentum distributions of the reactions simulated by a Monte Carlo program are shown in Figure 3. The high average momentum of kaons mean that the majority can be identified by

FIG 3 MOMENTUM DISTRIBUTIONS FOR THREE K^-P REACTIONS

TABLE 1: PARTICLE IDENTIFICATION PROBABILITIES

Reaction	Particle	TOF	C1	C2	TOF +C1 +C2	all mesons identified	effective event i.d. efficiency
1) $K^- p \rightarrow p K^- \pi^+ \pi^-$	K^-	.07	.73	.08	.78	.34	.97
	$\pi^\pm$	.23	.50	.04	.71		
2) $K^- p \rightarrow \Lambda K^+ K^-$	$K^\pm$	.05	.65	.02	.70	.62	.79
	K^-	.04	.83	.11	.85		
3) $K^- p \rightarrow \Lambda K^- \pi^+ K_S^0$ $(K_S^0 \rightarrow \pi^+ \pi^-)$	$\pi^+(K^*)$	.29	.37	.04	.65	.23	.92
	$\pi^\pm(K^0)$	.31	.25	.03	.57		

C1 alone, however, a fair proportion of pions are in a momentum range covered by the T.O.F. counter. The contribution of C2 is highly limited by its small effective solid angle. The probability that particles are identified by these three devices is shown in Table 1, along with the probability that all the mesons are identified. An event identification efficiency is also shown in Table 1, which is based on combining individual efficiencies and invoking strangeness conservation. This process can be illustrated by examining the second test reaction, $K^- p \rightarrow K^+ K^- \Lambda^0$.

The probability of seeing the Λ is 0.41, based on the Λ reconstruction efficiency being 0.64 and the Λ branching ratio being 0.64. If the Λ is seen, then by strangeness conservation, the two final mesons must have net strangeness zero. So if either is identified, the event I.D. is established. The probability of this happening is $\{0.70 + (0.30 \times 0.70)\} \times 0.41 = 0.37$. If the Λ is not seen then the K^+ must be identified. This is sufficient to establish that both the other meson and the baryon have strangeness -1 and therefore also gives the event identification. The probability of this occurring is thus: $0.70 \times 0.59 = 0.41$. The overall event identification is the sum of the two methods $0.37 + 0.41 = 0.78$. It can be seen (particularly from example 3) that even in cases in which the probability of all products of a reaction being identified is low, the effective event identification can still be high.

Reviewing Table 1, it is apparent that C1 provides the dominant contribution to event identification in LASS. However, the secondary momentum range covered by the T.O.F. counter is quite

important for certain reactions, because it reduces absolute dead regions in the effective LASS acceptance of angular distribution of meson decays.

iv) Particle identification by T.O.F.

The principle of operation of the time of flight counter is a simple one. The time taken for a particle to travel a known distance is measured and used to calculate the velocity. The particle's momentum is measured by the other spectrometer devices, hence the mass of the particle can be calculated. The relationship between the time of flight measurement T and the mass of a particle is derived from

$$p = m \gamma v$$

and is

$$m^2 = p^2 [(T^2 c^2 / L^2) - 1] \quad (1)$$

where L is the path length, p is the particles known momentum and c is the velocity of light. Thus, it is sufficient to substitute values for p , T and L to obtain the mass m .

In practice extracting information from a T.O.F. system is more involved. Timing measurements are made between a start counter upbeam of the target and one of the T.O.F. counters using Time to Digital Converters (T.D.C.'s), see Figure 4a. The time interval measured includes the time of flight of the beam particle (T_k), the propagation delays along the scintillators (T_m) and an arbitrary cable delay (T_d). These quantities must be subtracted from the measured time difference (T_a) to obtain the time of flight of the secondary

B)

C)

FIG 4 THE PARTICLE IDENTIFICATION PROCESS

particle (T). A knowledge of the interaction point allows L_k and hence T_k to be calculated. T_d is chosen so that the TDC readings are in the middle of the TDC's range. T_m is a variable depending on the impact position of the particle on the counter. An approximate mapping of T_m across the counters has been made but it will be re-evaluated in the experimental situation by an analysis of $\beta=1$ particles.

Leading edge discriminators are used between the counters and the T.D.C.'s. The pulses from the T.O.F. counters have a considerable range of pulse heights which cause small timing differences due to the discriminators firing at different points on the photo-multiplier's voltage pulse (see below). This effect is known as time walk. A correction is usually made for this by measuring the pulse height using an Analog to Digital Converter (ADC) and then subtracting an appropriate time from T_a . The nature of this correction has been thoroughly investigated. Both this correction and the mapping of T_m will be discussed in Chapter 4.

The T.O.F. system after a number of corrections thus provides a value of T , the secondary particle's time of flight. The particle's path length L and momentum p are obtained from the spark chamber measurements. These quantities are then used in equation (1) to calculate a value of the apparent mass. T , p and L all have

uncertainties associated with them; however, the errors on p and L are insignificant compared to the error on T . The error in T (ΔT) is due to the basic limiting resolution of the T.O.F. counters. It gives rise to an error Δm^2 given by

$$\Delta m^2 = 2p^2 \sqrt{\left(\frac{m^2}{p^2} + 1\right)} \frac{\Delta T \cdot c}{L} \quad (2)$$

which can be approximated to

$$\Delta m^2 = 2p^2 \frac{\Delta T}{L} c \quad (3)$$

Thus the measured apparent mass of a number of particles will not be a delta function at each stable particle mass (π , K or p), but will have a statistical distribution about these points, the widths of which will depend on the resolution of the T.O.F. system and the momentum of the measured particles.

For low momentum particles, the resolution of the counters is not a limiting factor. A plot of the square of the apparent mass of an equal mixture of such particles would give rise to three distinct peaks as shown by the dashed line in Figure 4b. In this case it is evident that it is possible to assign positive identities to each particle. For higher momenta this is not the case. The solid line in Figure 4b shows the mass plot anticipated for a momentum band in which the π and K peaks are separated by two standard deviations of the individual particle's distributions. It is the sum of three distributions (dotted line) centred on the particle masses. By fitting a mass plot with three such distributions, the particle identification probability can be determined. For example, in Figure 4b, a particle with an

apparent mass of $0.6 \text{ (GeV/c}^2)^{1/2}$ has a zero chance of being a π , 50% chance of being a p and 50% chance of being a K. In practice the number of π s, Ks and Ps is unlikely to be equal and the apparent mass plot, plus fitted distributions are more likely to appear as in 4c. The use of the particle identification information will depend greatly on the reaction studied. Event identification is obtained by considering the probability of identifying each particle. In low cross section processes, background reactions could be a severe problem. Under such circumstances, a purer sample could be obtained by using only events with good (i.e., > 90%) identification probability.

It is possible to assign an order of merit to a T.O.F. system by calculating the maximum momentum up to which apparent mass distributions are separated by more than twice their standard deviations. This is done using equations (2) and (3), setting $\Delta m^2 = m_1^2 - m_2^2$ ($m_1 > m_2$), where m_1 and m_2 are the masses of the two particles of the separation channel under consideration, and $\Delta T = 2\sigma$ where σ is the standard deviation of the time resolution of the system. The resulting curves for the π/K , K/p and π/p separation channels are shown in Figure 5. From the graph, it is apparent that for a T.O.F. system with a time resolution of 1.2 nsec FWHM, 2σ separation is possible in the π/K channel up to a momentum of 1.4 GeV/c. Similarly separation is possible in the K/p and π/p channel up to momenta of 2.3 and 2.7 GeV/c respectively. Note that the curves in Figure 5 are only valid for particle tracks with mean length 5.5m.

FIG 5 MAXIMUM MOMENTUM FOR 2 σ SEPARATION AS A FUNCTION OF TOF SYSTEM RESOLUTION FOR MEAN PARTICLE TRACK LENGTHS OF 5.5m

Chapter 3: Design

i) Review of T.O.F. technique

A time of flight system has three major elements: a start counter, a stop counter and electronics to measure the relative transit times of particles between the two. The design of the start counter is not a problem as it can usually be placed in the beam which is spatially well defined. Only a small counter, which can easily be made to have good timing characteristics, is then necessary. Similarly, the electronics need not make a significant contribution to timing uncertainties. Sufficient commercially available electronics exists to assemble systems with 100 psec resolutions. The skill and art in the building of a T.O.F. system is in the design of the stop counter.

The stop counter or counters are usually large, and require sophisticated light collection systems to get the scintillation light to the photomultiplier tubes efficiently, while introducing minimum time jitter. The size and shape of the scintillator is largely determined by the application while the choice of phototube is limited to those tubes with good risetimes. If there is a large ambient magnetic field, then it might be necessary to choose the position and orientation of the tube to aid its magnetic shielding. The light guide joining the photomultiplier tube and the scintillator has to transform the exit cross section of the scintillator to a roughly circular cross section. This is usually accomplished by using twisted lucite strips to form an adiabatic light pipe. If there is an area mismatch between the ends of the light pipes and the photomultiplier, a cone of some

sort is used to join them.

The formation of a good time signal from a stop counter depends on a number of factors such as the geometry of the scintillator and light pipes, the discriminator and the choice of phototube. The major aim in the design of the stop counter is to get as much of the 'prompt' light to the phototubes as possible (reference 3). If insufficient light is generated initially, or too much lost, poor photon statistics will degrade the performance of the counters. These factors are to be discussed in some detail in the rest of this section.

Since light levels are so critical to good timing, it is of interest to briefly consider light levels normally found in scintillation counters. A minimum ionizing particle produces 20,000 photons per cm in its passage through scintillator. Ten per cent of this light may be considered as being emitted towards the light collection system. Attenuation will reduce the photon flux by a quarter and so will the quantum efficiency of the tube. Only 0.6% of the light produced is then seen as direct light by the photomultiplier. Thus, for a 1 cm thick counter, one would expect the phototube to see approximately 100 photons.

T.O.F. counters are usually made of plastic scintillator. NE110,¹ which has good light transmission properties is commonly used. It has an attenuation length of 2.5 m, comparable to that of lucite. The choice of thickness of the scintillator is important. B Ghidini et al (reference 5) made time resolution measurements with counters 1,

1 Nuclear Enterprises, San Carlos, California.

3 and 5 cm thick and 200 cm long. Their data (Table 2 below) shows comparatively poor resolutions for the 1 cm counter with minimum

GHIDINI ET AL			
a		b	
Thickness of Scintillator CM	FWHM for 200 x 20 cm Scintillator with 3x minimum ionizing protons psec	ionization of particle minimum ionization psec	FWHM for 200 x 20 cm Scintillator 1 cm thick psec
1	650	1	1250
3	600	3	650
5	500	5	500

LASS c	
ionization of particle minimum ionization	FWHM for 1200 x 38 cm counters 1 cm thick psec
1	1200
4	600

TABLE 2: Resolution of Counters of Different Thicknesses and with Particles of Different Ionization.

ionizing particles (1200 psec) and substantial improvements when 3 and 5 cm thick scintillator was used. The resolution was also improved when non minimum ionizing particles were used (FWHM 600 psec). This effect was observed with the LASS counters when tests with 100 MeV protons (4 x minimum) and minimum ionizing particles were compared (Table 2c). The data in Table 2 illustrates that the resolution of counters improves with increased scintillator thickness and with particles that are more ionizing. Effecting either change increases the number of photons that are generated in the scintillator which

improves the photon statistics. In current high energy experiments, the majority of particles are minimum ionizing and the desire for a thick counter is mediated by its cost and the effect of including more mass in a large spectrometer.

When a charged particle goes through scintillator, it produces a pulse of light that typically has a FWHM of 3.9 nsec and a very sharp risetime. The light is emitted isotropically and only a fraction of it travels towards the photomultiplier tube. Studies made in the LASS counter and studies made by others (reference 4 and 5) show that the effective velocity of light along the scintillator is about 70 to 90% of the velocity of light in bulk scintillator. This means that the photons seen by the photomultiplier tube have undergone successive reflections within the scintillator. They have also travelled paths of different lengths. As a result, the scintillation pulse becomes smeared in its passage through the scintillator.

The potential for degradation of the light pulse is even greater during its passage through the light pipe and therefore, the design of the light guide and devices for reducing its area is critical in T.O.F. applications. The lucite strips of which the guide is composed, must be approximately the same length and have bends that are made as smoothly as possible. Surface defects on the strips degrade the performance. The characteristics of twisted strip light guides has been investigated by T. Massam (reference 3) using a Monte Carlo type computer program. He showed that they worked best if bends in the strips are made such that the ratio of the width of the strips to the radius of the bend is kept to one eighth or less. Another study

indicated that a delta function pulse of light could be degraded to a risetime of up to 600 psec by passage through a light pipe with a moderately sharp bend. Massam also investigated devices for reducing the area of light guides and found that a simple conical adapter on the phototube gave the best results. Tests using the cone described by Hintenberger and Winston (reference 8) showed that it had the same efficiency as a standard cone.

The selection and design of phototubes and bases for T.O.F. counters has changed very little over the past decade. Common tubes in use are 56 AVP¹⁾, 58 AVP and RCA 8575²⁾. The larger tubes such as the 58 AVP (4 1/2" diameter) have larger transit time differences of the order of 1 nsec, as compared to less than 0.5 nsec for the 56 AVP (2" diameter). They have still been used quite successfully in T.O.F. systems (reference 5). Bases are usually adapted from those recommended by the manufacturers by increasing the resistors between the cathode and first dynode, to increase the voltage and thus reduce the transit time. The rest of the voltage chain is usually left unaltered. Braunschweig et al (reference 4) used zener diodes to clamp the voltage from cathode to first dynode at maximum working voltage. In general, bases must be tuned to the individual tubes to minimize transit spread of electrons within the tube.

The T.O.F. stop counter transforms a scintillation light pulse into a negative going electrical pulse which appears at the anode connection of the photomultiplier base. This transformation includes the optical characteristics of the scintillator, light pipe, and cone, plus the electrical characteristics of both the photomultiplier tube

1 Amperex Elec. Corp. 230G Duffy Ave., Hicksville, N.Y., 11802

2 RCA Electro Optics and Devices, RCA Solid State Div. Dept. 4, New Holland Ave., Lancaster, P.A., 17604

and the base. Thus, the point on the voltage pulse at which timing should be made is not a trivial problem. Timing signals are generated by discriminators which create a fast logic pulse when a preset threshold is exceeded. There are two properties of the pulse that affect the timing. One is that pulses of equal amplitude have different shapes because of quantum fluctuations (arrival times of the photons) and variations in gain of the photomultiplier tube. This gives rise to a timing jitter Figure (6a). The other is that pulses of different amplitude cause timing jitter due to time walk Figure (6b)

Figure 6: Diagram of Timing Considerations

There is very little to be done about the first problem except to select a point on the pulse where fluctuations are minimal. When geometry is not a problem, the best point is a small fraction (10-20%) of the total pulse height. However, a low level of discrimination is probably best for large area counters in which the counter geometry is a factor. There are a number of ways of coping with time walk. One is to use special discriminators such as constant fraction or zero crossing discriminators which can be adjusted to compensate for varying pulse heights. Another method is to measure the dynode pulse or a fraction of the anode pulse with an analog to digital converter. This A.D.C. value is then used to

calculate a small correction to the time measurement. As Massam points out (reference 3), this correction is most effective if the light guide excludes light other than 'prompt' light, where he defines prompt as being within 2 nsec of the arrival of the first photon. The reasoning behind this assertion is that most A.D.C.s measure the integral rather than the peak of the pulse and an assumption is made that the two are proportional. If only prompt light is detected, the correlation is improved. Cones are found to be a good device to ensure this condition. Using A.D.C. corrections, experimenters (reference 4) have obtained improvement in resolution from 600 psec to 500 psec F.W.H.M.

A method commonly used to improve the time resolution of counters is the use of two phototubes to view the scintillator. The act of collecting twice as many photons gives a factor of approximately $2^{-1/2}$ reduction in F.W.H.M. due to the improvement in statistics. An added attraction of the two phototube techniques is that by measuring the relative timing of the pulses from the two tubes, one can get a measurement of the position of the particle's track along the counter. The spatial resolution of this type of counter depends on the distance between the photomultipliers. Typical values range from a F.W.H.M. of 1 cm for a 30 cm long counter to 5 cm for a 600 cm long counter (reference 5). In a similar manner, the time measurements can be summed to give a measure of the time of flight which is independent of the impact position. This is to be contrasted with large one phototube systems, in which external tracking information is needed to correct for impact position. Good accounts of two tube systems can be found in the references (4, 5 and 7).

The time of flight technique has been developed over the past fifteen years to the stage where it is possible to build large area counters with time resolution of 500 psec (F.W.H.M.). To obtain these resolutions, enough light must reach the photomultiplier tubes to provide good photon statistics. Factors affecting the resolution are the scintillator thickness, rate of ionization of the particles, and light guide designs that are efficient in bringing prompt light to the phototube. Two phototube systems are desirable as they give a factor of $\sqrt{2}/2$ reduction in F.W.H.M. and require no external position information. In designing a time of flight hodoscope for an experiment, it is necessary to take into account any restriction imposed by the experimental layout. If track finding is done downstream of the hodoscope, it is desirable to keep the counter thin to reduce multiple scattering and absorption probabilities. Space restrictions, existing counters and magnetic fields must all be taken into account when a hodoscope is designed.

ii) Discussion of design criteria for LASS T.O.F. counters

a) Geometry

The time of flight hodoscope was intended to cover the area of the back face of the Cerenkov counter C1 in LASS. Various geometries were considered for the individual counters. These can be split into two types, $r - \theta$ geometries in which the counters are wedge or pie-shaped (as in Figure 1) and $x - y$ geometries in which the counters are rectangular strips.

The main attraction to the $x - y$ geometry is that it allows

the use of two phototube designs. The counters would be large (475 cm from tube to tube), but counters this size have been made with good resolution (reference 5). A central 'plug' of lucite could be used with hodoscopes of this ~~type~~ to prevent beam particles from triggering the counter. In another rectangular design studied, one phototube counters were considered with the hodoscope split down the middle.

Two $r-\theta$ geometries were considered, one with the angle of the wedge being 15° (final design) and one with an angle of 30° . The advantage of these geometries is that they can be made to match the cells of the Cerenkov counter C1 (Appendix 1). This allows the time of flight counter to be combined with C1 to define special purpose hardware triggers or offline event selection criteria in LASS. In general, a circular geometry is much more useful for trigger purposes. Combination triggers involving the time of flight, C1 and the proportional trigger chambers are possible only if all are $r-\theta$ devices.

It is desirable to have a hole in the centre of the hodoscope for both triggering and time of flight purposes. For triggering applications, the hodoscope should intercept as many of the secondary particles as possible, but it should not intercept the beam. Thus, for triggering purposes, the hole should be just larger than the beam or approximately 4 cm in radius. The mean velocity of secondary particles increases as the angle that their tracks make with the beam decreases. As a result, the hodoscope is not effective as a time of flight counter within a certain radius as the β of the majority of particles is close to 1. This radius corresponds roughly to the radius of the inner cell of C1 (i.e., 15 cm). It is not desirable to have the

time of flight counter cover smaller radii, as possible multiple hits in individual counters would reduce their usefulness. To accommodate all constraints, the time of flight hodoscope was made with an internal radius of 15 cm and four trigger counters were added to cover the resulting hole down to a radius of 4 cm.

As discussed in the previous section, the resolution obtainable with a time of flight counter is related to the thickness of the counter. In most systems, the time of flight counters are placed after the tracking devices. In LASS, however, the time of flight counters sit in between two sets of track finding chambers. The multiple scattering and absorption it can cause is thus of concern. For example, comparing 1 cm and 5 cm thick scintillators, one expects at 3 GeV/c the RMS multiple scattering to be 0.10 and 0.23 mrad, and the absorption to be 2% and 10% respectively. There is therefore, a conflict between using a thick counter to get good time of flight resolution and using a thin one to minimize disruption of particle tracks. Cost is also a factor in deciding the desirable thickness. The hodoscope is large, having a diameter of 3 m and its cost is roughly proportional to the thickness of the scintillator. Taking all these factors into consideration, a decision was made to build the counter using 1 cm thick scintillator.

b) Testing of Models

Tests were made on three prototype counters at the McGill cyclotron. The dimensions of those counters are shown in Figure 7. One of the counters was rectangular and two were wedge shaped with

30° TRIANGULAR RECTANGULAR 15° TRIANGULAR

FIG 7 MCGILL TEST; DIMENSIONS OF SCINTILLATORS, AND A COMPARISON OF RAY PATHS WITHIN THEM

FIG 8 RESULTS OF MCGILL TEST

angles of 15^0 and 30^0 . All were made of 1 cm thick NE110 scintillator. The McGill machine provides protons with a kinetic energy of 100 MeV ($p = 440$ MeV/c) which are approximately four times minimum ionizing in scintillator. The resolution of the counters was measured as a function of distance along the counter. The results obtained are shown in Figure 8.

The rectangular counter has the characteristics one would expect. The F.W.H.M. is a steadily increasing function with respect to the distance the light has to travel to the photomultiplier. Both triangular counters have the unusual property that their resolution is best at the point furthest from the photomultiplier tube. This behaviour is best explained by drawing ray paths of light emitted in the scintillator and thus calculating the variations in the light paths. This is shown in Figure 7 where it can be seen that the triangular geometry focusses the light; minimizing the spread in light path lengths and produces light which hits the edge of the scintillator at an angle closer to grazing incidence, reducing the number of bounces in the light guide.

The results obtained at McGill indicated that of the designs considered for the hodoscope, the 15^0 wedge counters gave the best resolution.

c) Magnetic Shielding

The time of flight counter is situated close to the solenoid where there are very strong magnetic fields of the order of 600 gauss. If the photomultiplier tubes are to work well, the field near and at

the photocathode should not exceed a fraction of a gauss. Thus, a good magnetic shielding system is essential.

Shielding is normally accomplished by surrounding the photomultiplier with tubes of magnetic material. The effect of such tubes on magnetic fields perpendicular and parallel to the tube axis is shown in Figure 9. Tests that were made on the effect of a mu-metal shield are related in the Phillips application book (reference 10). Their results indicate that a cylindrical shield is approximately forty times more effective with perpendicular fields than with parallel fields. It is, therefore, highly desirable to align the phototube perpendicular to the ambient magnetic field direction. A field map of the solenoid and the position of the time of flight counter is shown in Figure 9b. A study of this shows that to meet the shielding criterion, it is necessary to place the phototube axis at an angle with respect to the plane of the scintillator and it is therefore necessary to introduce an elbow into the light guide.

It is far more effective, and lighter, to make magnetic shields of concentric tubes rather than one thick walled tube. The field within a shell of high permeability material is derived in Jackson, reference 11 and is given by

$$B = \frac{9}{2\mu \left(1 - \frac{a^3}{b^3}\right)} B_0$$

where B_0 is the unperturbed external field, perpendicular to the shield, μ the permeability of the material and a and b are the internal and external radii of the shells. The formula does not take end effects

FIG 9a MAGNETIC SHIELDING EFFECT OF AN IRON CYLINDER FOR FIELDS
PERPENDICULAR AND PARALLEL TO THE CYLINDER'S AXIS

FIG 9b SKETCH OF SOLENOIDAL FIELD IN THE VICINITY OF THE TOF HODOSCOPE

into account. If we use this formula to compare the effectiveness of the two shields shown in Figure 10, which are made of material equal permeability ($\mu = 10^3$) we find that in the same ambient field, $B_1 \geq 30.B_2$.

Figure 10: Magnetic shells

The other advantage to using layers of shielding material, is that the inner layers can be made of materials of successively higher permeability. The use of very high permeability materials in the outer layers is not recommended as they tend to saturate at very low fluxes. End effects can be considerably reduced by requiring that each layer of shielding extend 1.5 times its diameter past the point at which shielding is required. This criteria also means that each layer overlaps the underlying layer, helping to reduce fields parallel to the tube axis. Often bucking coils are incorporated in a shield design to counteract parallel fields.

iii) Description of Scintillation Counter Hodoscopes

This section describes the hodoscope; for engineering details, see Appendix II.

a) Scintillator

The time of flight hodoscope is made of 24, 15° wedge shaped pieces of scintillator. The scintillator covers the active area of C1 except for a 30 cm diameter central hole (Figure 1). The bottom cells of C1 and the bottom six counters are smaller than the rest due to the limited distance between the beam and the floor. The scintillator used was 1 cm thick NE110. The counter was wrapped with black polyethylene and black PVC tape over a layer of aluminum. The aluminum served only as a light seal. Tests with materials of various reflectivity from velvet to aluminum foil gave no noticeable difference in performance. This indicates that only prompt, internally reflected light is affecting the timing, which shows that the counters are working correctly.

b) Light Guides

The light guides are split into three parts, the light pipe, elbow and Winston cone shown in Figure 11. Prior to installation and for transportation, the light pipes were glued to the scintillator and the elbows and Winston cones were glued to the photomultiplier tubes. To facilitate assembly of the counters 8.4 cm 'cookies' were glued to the free end of the light pipes and elbows. (Figure 11).

The light pipes and elbows are made of 1 cm thick lucite which is machined and flame polished to form lucite strips. These are then heated until pliable and hand shaped on formers to make the light pipes and elbows. Care is taken to minimize differences in the length of the strips, while keeping the light pipes as compact as possible. The angle of the elbows α were calculated using a map of

FIG II DIAGRAM OF TYPICAL COUNTER ASSEMBLY

the solenoidal field measured at SLAC. α ranged from 30 to 51° depending on the location of the tube. The Winston cones (reference 8) were machined from solid pieces of lucite and then coated with aluminum by vacuum deposition. All glue joints were made with N.E. 580, a glue which has to be desiccated prior to use and requires twenty-four hours to cure.

During installation, difficulties were encountered fitting the two parts of the counter together. Wedge shaped cookies with an average angle of 6° inserted in the joint, solved the problem.

c) Photomultiplier tube and bases

Amperex 56 AVP photomultiplier tubes were used for all counters. They are high gain tubes commonly used in scintillation counters. The 56 AVP's have good time characteristics with a manufacturer specified transit time difference of less than 0.5 nsec. The base used was an adaption of the standard LASS photomultiplier tube base. The resistors in the base were chosen to give a 1.5 ma current in the resistor chain and to raise the voltage between the cathode and first dynode relative to the rest of the chain, (see appendix II for further details).

d) Light Emitting Diodes for Test Purposes

A Light Emitting Diode (Monsanto 5353 yellow¹) was glued on to the tip of each counter for use in testing the counters. They were used prior to installation to set the potentiometers of the bases, and after installation to ensure that the counters were working correctly.

1) Monsanto Elec. Matls. Dept. G, P.O. Box 8, St. Peters, Mo 63376.

They will also be used during the active life of the counters to check their day to day performance. For accurate timing, it is necessary to drive the L.E.D.s with a mercury pulser such as a tectronix ¹⁾ 109 or equivalent. Used in this manner, L.E.D.s give light pulses with fast risetimes which approximate those of scintillation light pulses.

e) Magnetic Shields

The magnetic shields for the time of flight counters are made of two steel tubes and two mu-metal tubes. The arrangement of these is shown in Figure 12. The inner mu-metal shield is made of Eagle ²⁾ AA high permeability foil, taped into position. The outer μ -metal shield is made of the lower permeability Eagle A material. An attempt was made to design all layers to the criterion that they should extend 1.5 x their diameter past the sensitive area. This was not possible for the μ -metal shields due to the position of the Winston cone. A 250 turn bucking coil is wound on the inner shield. This is centered on the cathode - first dynode gap of the photo-multiplier, the part of the tube most affected by magnetic fields. The outer iron cylinder was shorter on some of the shields assemblies due to space restrictions on the lower six counters.

The assembled shield was heavy, weighing ~ 50 kg. It was also subject to a magnetic force approximately equal to its weight directed towards the solenoid, along with a torque tending to align

1) Tectronix Inc., Dept. G, P.O. Box 500, Beaverton Dr., 97077.

2) Eagle Magnetics Corp., 7417 Crawfordsville Rd., Indianapolis, IND., 46224.

FIG 12 DIAGRAM OF MAGNETIC SHIELD

the shield to the magnetic field. As the solenoid is turned on and off, the forces on the shield vary. So, to prevent possible movement of the shields stressing the glue joints of the counters, the shields had to be mounted rigidly. This was accomplished using a light aluminum four point clamping system.

f) Electronics

The electronics used for the time of flight counters are shown in Figure 13. The start pulse is derived from a 10 cm square, 0.6 cm thick counter with adiabatic light guides located in the incident beam, approximately 2 m upstream of the solenoid. The start counter was tuned in the same manner as the counters of the time of flight hodoscope. The pulse from the start counter is gated by the trigger logic and then used as the start for the Time to Digital Converters and the Gate for the Analog to Digital Converters. As the start signal is gated, T.D.C. and A.D.C. measurements are only made for triggered events.

High voltage for the counters is derived from two supplies. Good regulation is essential and it was found that with one supply, the current drain was close to the power supplies' maximum.

The anode signals are fed into LRS 623¹ discriminators which have thresholds that are adjustable from 30 mV to 1V. The thresholds were set to 50 mV. The outputs of the discriminators are then fed to the trigger logic and to the central room via long cables (380 nsec). The long cables caused considerable pulse degradation which would have introduced timing jitter, so a second discriminator was used to reshape the pulse before using it as the stop for the T.D.C.s. LRS 2228 time

1) LRS LeCroy Research Systems Corp., West Nyack, N.Y. 10994.

FIG 13 ELECTRONICS FOR TOF SYSTEM

to digital converters are being used and were adjusted to give a resolution of 100 psec/bin.

The dynode signals are fed directly to the ADCs after passing through an inverting transformer. The pulses are considerably degraded by the long coaxial cables (RG 58); however, this is not critical as precise pulse height measurements are not being attempted. The pulse height spectra obtained with this arrangement are however good, some signals even requiring attenuators to bring them within range of the ADCs. LRS 2249A ADCs have been used.

The bucking coils are connected to the LASS bucking coil distribution system which provides ± 5 amps per channel. The L.E.D.s are connected to a 30 Hz mercury pulser. The output of the pulser is passively split into a number of channels; the pulse height to the individual L.E.D.s is controlled by attenuators.

The information in the ADCs and TDCs is readout by the LASS camac data acquisition system after each event. The modules are then cleared by the system to enable them to accept the next event.

Chapter 4: Properties of Counters

i) Introduction

Prior to their installation, the counters were tested in the LASS beam in order to determine their properties. It was necessary to establish operating criteria for them; to find out how to tune the bases and adjust the high voltages for optimum performance. These tests showed that the bases and high voltages for the counters could be adjusted most reliably using LED's. The resolution of the counters as a function of impact position was measured in the beam. To interpret the timing measurements of a counter in an experiment, information is needed on the time delay of light pulses as a function of impact position. A mapping of time delay was made during these tests along with an investigation of the counters' resolution.

Initially, electronics dedicated to the tests were used; at a later point however, measurements were made using the full LASS data acquisition and computing facility enabling us to test a system which was similar to the planned experimental electronic configuration. These latter tests also permitted an investigation of the pulse height correction. This chapter presents a summary of these test results.

ii) Tuning of Bases Using Light Emitting Diodes

To get the best timing from a counter, the base must be adjusted to suit the counter's photomultiplier tube. This involves finding operating points for three quantities; the overall high voltages, the voltage on the focussing electrode and the voltage on the second dynode. The potential on the focussing electrode affects the electrostatic field between the photocathode and the first dynode. An example

of this field and the paths of electrons within it, is shown in Figure 14. The input system of a phototube is designed to collect as many photoelectrons from the photocathode as possible and deposit them on the first dynode. There is an additional constraint in the design of a fast photomultiplier tube such as the 56 AVP. Transit time difference of electrons originating from different points on the photocathode must be minimized. The transit time differences occur because of the different length paths travelled by the photoelectrons. It is cured by designing the electrostatic system to have fields in the region of the photocathode with higher gradients at points closer to the edge of the tube. Optimization of photon collection and timing are both determined by the relative voltage applied to the focussing grid (Figure 30). In an ideal tube, both conditions would be satisfied at the same voltage, however, this is not necessarily true in practice.

The dynodes of a photomultiplier work best when the voltage between each stage is approximately equal. However, this is not true for the voltage of the second dynode due to geometric factors arising from the shape of the first dynode, and transit time differences. The latter occur because the electrons hitting the first dynode have a relatively high velocity due to the large accelerating potential they cross. This means that electrons emitted by the first dynode and collected by the second have a higher initial velocity. Thus, a potential other than the mean between the potential on the 1st and 3rd dynodes is required for the 2nd dynode.

In general, optimum settings for the high voltage and the potentials on the focussing grid and second dynode vary from tube to tube due to manufacturing tolerances. So, adjustments for the second

FIG 14 INPUT SYSTEM OF 56AVP PHOTOTUBE WITH EQUIPOTENTIAL LINES AND
SOME ELECTRON PATHS FROM REF. 10

two are provided by potentiometers in the base of the photomultiplier tube. Only the ratio of voltages set by these potentiometers is important. Once set for one high voltage, they should be correct for any other high voltage. In standard applications the potentiometers are set to maximize pulse height, but as the bases in question are used with time of flight counters, the effect of the adjustment on the time resolution was investigated.

Tests were made on the counters using the L.E.D.s at the tips of the scintillators. Voltage pulses from a mercury pulser were used to drive the diodes. The voltage of the pulser was adjusted so that the photomultiplier output pulse was approximately the same as the pulse produced by real, minimum ionizing particles, about $0.8 + 1.0$ volts. A signal pulse was also derived from the pulser for use as a start signal. The counter's discriminated anode pulse formed a stop signal. Both start and stop signals were fed into an L.R.S. Q.V.T. module which was used to accumulate spectra of the time interval between the two signals. The position and full width at half maximum (F.W.H.M.) of the timing spectra along with the mean anode pulse amplitude were recorded for each set of voltages selected. The position of the spectrum corresponded to the time delay between the signals and the width to the time resolution of the L.E.D.-counter system. Both quantities could be read to ± 50 psec. The pulse height was measured on a scope by making a visual average which was good to $\pm 10\%$. There were four variables: the high voltage and the voltages on the focussing electrode, the second dynode and the L.E.D. The effect of varying these quantities on the pulse height, resolution and time delay was investigated.

Some curves typical of the ones obtained in these tests are shown in Figure 15. They illustrate the operating characteristics of the photomultiplier tube and base. There are two phenomena that are common to all graphs. One is that time walk in the discriminator of the anode pulse affects the time delay. The smaller the pulse, the greater the time delay. If time walk was the only factor, one would expect the time delay to mirror the behaviour of the pulse height. (i.e., for a maximum in pulse height, one would expect a minimum in the time delay. The second phenomena is that as low light levels were used in the test, factors which reduce the pulse height also tend to degrade the resolution.

The effect of varying the potentials on the electrodes is shown in Figure 15 a and b. The voltage at which the pulse height was a maximum was always close to that at which the resolution was at a minimum; the difference was rarely more than ten volts. This indicates that in this application setting the potentiometers for maximum amplitude is adequate. The shape of the time delay curve for the adjustment of the focussing electrode (a) is due to a combination of two factors. Time walk alone would give rise to a minimum (dashed line) and variations in overall transit time due to the size of the initial acceleration would give rise to the dotted line. Combining these two, one gets the observed characteristics. When the second dynode potentiometer is varied, there is a minimum in the time delay curve (b) at the same voltage at which there is a maximum in the pulse height curve. It is interesting to note that but for the time walk, one would expect the time delay curve to have a maximum due to transit time variations.

The effect of varying the voltages on the L.E.D.'s can be seen

(a)

(b)

(c)

(d)

FIG 15 ELECTRONIC CHARACTERISTICS OF THE COUNTERS

in Figure 15c. As the pulse height increases, both the resolution and time delay curves flatten, as the photon statistics increase. It has proved difficult in practice to get a mercury pulser with a stable amplitude to simultaneously drive the L.E.D.s in all the counters for experimental monitoring. The fact that the time delay curve levels off for large pulses suggests using large pulses for monitoring, and that is what is being done. The effect of varying the high voltage can be seen in 15d. The resolution exhibits a shallow minimum with good response from 1750 to 2100 volts. The resolution starts to deteriorate at large voltages due to random noise pulses being amplified sufficiently to trigger the discriminator. Most counters were tested and are being run at close to 1900 volts.

In this series of tests using L.E.D.'s, the following range of resolutions were found for the counters of the hodoscopes:

<u>Condition</u>	<u>F.W.H.M. (range)</u>
full size counters L.E.D. on tips of scintillators	550 - 850 psec
small counters L.E.D. on tips of scintillators	500 - 700 psec
supplementary L.E.D. attached directly to end of elbow	400 - 600 psec

Table 3: Resolution of Counters from L.E.D. Tests.

These values compare favourably to the absolute resolution expected from a phototube when the whole face is illuminated, 200 - 400 psec. It also agrees with rough calculations on the effect of the resolution of the geometry of the scintillators and light pipes.

(iii) Testing Methods

The resolution properties of the counters were investigated in two series of tests, the first of which was conducted during the set up period of the previous LASS experiment and the second during its data taking period. The location of the first test was upstream of the spectrometer, between the experiment's start counter S4 (Figure 15a) and C_k a beam cerenkov counter. This was an ideal position for testing the counters as it was close to the main focus of the beam. At this position the beam was well defined, less than one cm F.W.H.M., and relatively free of contamination with non-minimum ionizing particles. The second series of tests were made downstream of LASS (Figure 16) between C2 and the shower counter. At this position the beam was more diffuse, 4 cm F.W.H.M. and also contained reaction products and delta rays which effectively degrade the measured resolutions.

The first test set up consisted of three fixed counters S1, S2, and S3 to define the beam, and the time of flight counter under test S.T. S1, the start counter, used an 11 cm square, 1.1 cm thick piece of scintillator. S2, a position defining counter 2 cm square and 2 mm thick was centered on the beam. S3 was located downstream of C_k and was used to eliminate 'spray' produced by the collimator and any other non beam particles. The two parts of the time of flight counter (S.T.) were optically coupled by a grease joint and held together by clamps. The mechanical mounting of the counter allowed both horizontal and vertical motion so that the beam could go through any point.

The test counter could be positioned to ± 3.5 mm. The

FIG 16a ARRANGEMENT FOR FIRST SERIES OF TESTS (PLAN VIEW)

FIG 16b ARRANGEMENT FOR SECOND SERIES OF TESTS (ELEVATION)

distance between S1 and ST was approximately thirty cm. When the solenoid was on, the magnetic field in the test region was high, so it was necessary to use magnetic shields on the counters. Bucking coils were found to be unnecessary except for demagnetizing the μ -metal shields of the test counters, whenever a new counter was put into position.

The electronics used in this test were fairly simple. A beam particle was defined by a coincident signal from S1, S2, and S3. Coincidence between this and a low threshold signal from S1 provided the start for a TAC and coincidence between the beam and a low threshold signal from ST provided the stop. The TAC output was fed via a shaping amplifier to a Pulse Height Analyser. The TAC - PHA analyser system proved to be somewhat unstable in gain and d.c. offset the cause of which was not determined. However, variations occurred in a sufficiently systematic way to enable corrections to be made in the majority of cases. One interesting effect observed in this first test was that the measured efficiency of the counters depended on the beam current or instantaneous rate. At average beam currents, typical high voltage efficiency curves for counters showed a maximum at about 1800 volts. When the beam current was dropped so that there was less than one particle per SLAC machine pulse, the efficiency at higher voltages increased and the high voltage curves showed the plateaus that one expects for scintillation counters. The reason for this behaviour was the high instantaneous rate of the SLAC machine. A SLAC machine pulse is of the order of 10^{-6} sec long. Thus, five particles per pulse corresponds to a continuous rate of 5MHz. The conclusion

was that at high beam currents the test electronics became dead time limited.

In the initial test five counters were examined: two standard ones and one of each of the non standard geometries. For two of the counters, scans were made along the counters at a number of different high voltages to determine whether there was an optimum setting of high voltage for resolution at all points on the counter. It was found that there was a wide range of voltage in which to operate the counters which corresponded fairly closely to that found by using the L.E.D.'s. The counters were then scanned to map the time delay and resolution of signals from different parts of the counters. Initially measurements were made at intervals of 15 cm along and 6.5 cm across the counter. These measurements showed that there was very little dependence on impact position across the counter, so for some of the later tests, scans were only made along the counter. As mentioned earlier, a certain amount of drift was noted in the electronics. To check on this, one position on each counter was designated a reference point and rechecked frequently. Any variations noted in measurement from this point were used as corrections for the other measurements. Frequent checks were also made of the calibration of the TAC - PHA system to check on any changes in the gain.

In the second series of tests, the electronic instability problem was solved by using a LeCroy QVT module to produce time spectra from the start and stop pulses. Apart from this, the electronics were similar to those previously described. As the beam at the second test site was broader (4 cm) it was found that the small position

counter S2 cut down the rate by a factor of 10. However, it was found that S2 could be removed without affecting the measured resolution by orientating S1, the start counter, so that its phototube faced the same way as ST. This is because the variation in timing due to impact position in ST is compensated by similar timing variations in S1. A beam particle was therefore defined as a coincidence between S1 and S3. The test counter was mounted on a frame which hooked onto the LASS shower counter support structure. A series of pegs on the side of the frame allowed counters to be scanned along their length by 15 cm increments. No attempt was made to scan across the counters. It was surprising that even in the location of this second test, the solenoidal field was a serious problem. The iron in the cerenkov and shower counters act as a low reluctance path for the solenoidal fringe field giving rise to a strong field in the gap between them. The framework we were using was designed to carry only one layer of iron shielding and the phototube of the counter could not be orientated for optimum shielding. Consequently, when the counter was in the lower positions, it was necessary to use a bucking coil to counteract the field.

Nearly half the counters making up the time of flight hodoscope were tested in this second series including some of the non standard sizes. Several of them were also examined using the LASS computer data acquisition system. For this, the start and the stop signals were fed to a T.D.C. and the dynode signal was fed to an ADC gated by the start signals. Cables and electronics were chosen to simulate the final design.

1) Experimental mapping of resolution and time delay for T.O.F. counters.

This section describes results from both series of tests. For

each point measured, a time spectrum was obtained (typical spectra are shown in Figure 19). The F.W.H.M. and peak position of each spectrum were taken as the resolution and relative time delay respectively of the counter at the particular point. These quantities were read by eye from an oscilloscope display, this method was accurate to 50 psec. Sufficient counts were taken to ensure that statistical variations did not contribute to errors in either quantity. When the same point was measured repeatedly, variations of up to ± 60 psec were seen in some counters. This gives rise to an overall error in time measurements of between ± 70 and 80 psec. The consideration just outlined along with the errors in positioning mentioned in the previous section are the basis for the error bars in Figures 17 and 18. In the first test, one counter of each type was mapped while in the second, six standard counters were compared.

Mapping of the time delay as a function of position for the four different counter sizes are shown in Figure 17. The same quantity is plotted for six standard counters in Figure 18. If the apparent velocity of the light pulse along the counters was constant, one would expect the relationship between time delay and position to be linear and the apparent velocity derived from each curve to be the same. Careful inspection of Figures 17 and 18 reveals that the mapping for many of the counter departs from linearity by a slight upward bowing. The error bars on the points would make this effect dubious if only one counter had been tested, but as many counters show similar departures from linearity, the curvature must either be a property

FIG 17 RESOLUTION AND TIME DELAY AS A FUNCTION OF POSITION ALONG COUNTER
FOR THE FOUR DIFFERENT TYPES OF COUNTER

FIG 18 TIME DELAY ALONG COUNTER AS A FUNCTION OF POSITION FOR A NUMBER OF
STANDARD COUNTERS

of the counter or an experimental artifact. There are three possible explanations for this effect: stray magnetic fields, time walk caused by pulse height variations, and variations in the apparent velocity of the light pulse due to geometric effects.

The presence of magnetic fields reduce the pulse height and thus cause an increase in time delay. In the tests, the position of the phototube and counter are translated for each measurement. Thus, to explain the time delay curves, it is necessary to postulate an additional stray field for the central positions. This is the reverse of what would be expected from the geometry of the magnetic field and the orientation of the phototubes. This is therefore, unlikely to be the explanation. Time walk arises from variations in the pulse height causing the time at which the fixed threshold discriminates fire to vary. It is known that the pulse heights are smallest in the center of these counters, so one expects small relative time delays could cause the observed bowing near the center. The triangular geometry of the counters causes focusing in a region near the tip of the counter. This minimizes the number of bounces and causes light to follow a more direct path down the scintillator. This is to be compared with points near the light pipe which are not affected in this way. One would therefore, expect the apparent velocity of photons to be greater near the tip of the counter. This corresponds to a smaller slope in the right hand region of the delay curves, i.e., the observed effect. The latter explanation is also supported by the McGill test on the triangular counter. In these tests marked bowing was noticed even though a constant fraction discrimination was used which compensates for pulse height variations.

It was not possible, from the data available, to determine

to what extent these mechanisms contributed to the slope of the delay curves. In the experiment, time delay compensation curves can be produced for each counter directly from the experimental data, and hence the position dependence can be corrected for.

The average of the mean apparent velocity of the light in the counters was 16.5 cm/nsec, which is approximately 90% of the velocity of light in scintillator. The difference as explained in Chapter 3, is due to the average bounce angle of the light.

Tests were made for variations in time delay as a function of position across the counter. These tests showed that any changes were of the same order of magnitude as the resolution of the electronics. However, there was some evidence that light from points near the edge of the counter arrived earlier than from points near the center.

The variation in resolution with position for the five types of counters is shown in the upper half of Figure 17. This data shows that the resolution is independent of position, a constant resolution (shown by the horizontal line) is within the standard error of the best fitted line. The mean resolution, along with the standard error on the mean is shown for each counter on the extreme right hand side of each plot. The resolution for the smallest counter (A) was best at 950 sec F.W.H.M. while the midsize and fullsize counters B and S showed the largest resolution at 1200 psec. The resolution of the B counter is larger than its size would suggest. Comparing with the A and C counters, one would expect a resolution of 1 nsec. One possible reason for this is that the light pipe and elbow of the B counter had sharper bends than the other counters.

Similar resolution curves were plotted for the six standard counters along with a plot of the mean resolution of the six counters as a function of position. In all cases no statistically significant dependence of resolution on position was found. These counters showed a mean resolution of 1.4 nsec or 250 psec more than the standard counter did in the first test. This difference has been ascribed to the quality of the beam at the second test site where there was a reasonable probability of having two particles hitting the counter at the same time giving rise to time walk due to the larger variation in pulse heights. Evidence for this was seen in the ADC spectra in which there was often a second peak at approximately twice the height of the main peak.

It is of interest to compare these results with those of the prototype counter (see Section 3 ii). The resolution of the triangular prototype counter showed a marked dependence on position (Figure 8) varying between 450 and 650 psec F.W.H.M. with best resolution at the ends of the scintillator. A similar variation in resolution was not seen in the production counters. The difference can be explained in terms of the particles used in the tests. The production and prototype tests used minimum and four times minimum ionizing particles respectively. Thus, the lower light levels obtained in the production tests would give rise to statistical variations which would add in quadrature to the counter's basic resolution as measured in the McGill test. This would greatly reduce the observed position dependence (i.e., $\sqrt{(.45)^2 + (1.0)^2} = 1.1$ and $\sqrt{(.65)^2 + (1.0)^2} = 1.2$).

v) Investigation of Pulse Height Correction Using Computer System

A second phase of the second test program involved a full scale test of the proposed final electronics system for the counters, including the LASS computer data acquisition system (see Figure 13). This setup also provided a convenient means for investigating the effect on the time resolution of applying a proper pulse height correction. The correct cable lengths were used to ensure that signal degradation along the cables would not affect the resolution. It was found that the resolution measured with the TDC units and read by the computer was equivalent to that obtained with the LeCroy Q.V.T. module.

Pulse heights were measured by connecting the dynode of the counter to an ADC unit. A typical pulse height spectrum is shown in Figure 19. It exhibits a well defined peak, well separated from the noise which appears in the lowest bins. In these tests, several different TDC spectra were accumulated in the computer. These included one without any conditions and others binned according to the associated pulse height; one TDC histogram being defined for each one hundred ADC channels. Figure 20 shows two TDC spectra: the left hand one containing all counts and the right hand one containing those counts with pulse heights between 400 and 500 ADC units. It was found that the restricted pulse height spectra had better resolution than that of the raw peak. This improvement is due to the removal of time walk effects.

To investigate the relationship between time walk and pulse height, peak positions for each TDC spectrum were tabulated according to ADC bin. From these values, the time delay relative to the peak position of the distribution with the largest pulse height was

FIG 19 PULSE HEIGHT SPECTRA FOR STANDARD COUNTER

FIG 20 TIMING SPECTRA FOR COUNTER

LEFT HAND SPECTRUM (a) IS A RAW TIMING SPECTRUM WHILE (b) IS ONE OF THE SPECTRA OBTAINED BY BINNING PROCEDURE

calculated. This was done for each point measured on the standard counter. Statistics for low and high pulse heights were poor, so information from all the points measured were combined to give the delay curve of Figure 21. It is a characteristic of these correction curves that they become constant at large pulse heights. The process of binning by ADC value to produce a pulse height correction will be used to make corrections on the experimental data. The resolution of the counters does not warrant using a more sophisticated function fitting procedure.

The variation of resolution as a function of position as measured by the TDC/computer system for a standard counter is shown in Figure 22. The upper curve shows the 'raw' resolution and has a mean of 1.3 nsec. The lower curve displays the mean of the resolution of the most populated bins. These points in turn have a mean of 1.1 nsec and demonstrate the improvement obtained by applying a pulse height correction. The first curve again is consistent with uniform resolution, the lower curve however shows a marked similarity to the results of the prototype counter. The variation in pulse height is shown at the bottom of Figure 22. The focussing effect at the end of the counter is clearly visible. It is notable that this curve is a mirror image of the corrected resolution curve.

To summarize the results of sections V and VI: the measured resolution of the counters varies from 0.95 nsec F.W.H.M. for the smallest counter to 1.15 for the largest ones. The resolution measured in the downbeam tests was artificially high (1.3 nsec) due to beam conditions but was improved when corrected for pulse height variations (1.1 nsec). These results indicate that the resolution of the installed

FIG 21 TIME DELAY AS A FUNCTION OF PULSE HEIGHT

FIG 22 PULSE HEIGHT, AND RESOLUTION BEFORE AND AFTER A.D.C. CORRECTION

counters will be less than 1.2 nsec. Extrapolating from the McGill results some variation in resolution with position is expected, however, it is small and of the same order as the error in the measurement. This variation was seen only in the pulse height corrected results. Mapping of time delay versus position on the counter showed no variation across the counter and an almost linear relationship along it equivalent to an apparent velocity of light in scintillator of 16.5 cm/sec. Departure from linearity was small, amounting to less than one or two hundred psec.

Chapter 5: The T.O.F. Hodoscope in the LASS System

i) Mechanical Installation

The time of flight scintillation counter hodoscope was installed in LASS during April and May 1977. The hodoscope is mounted on the downbeam face of the cerenkov counter C1. A general view of the counter is shown in Figure 24. On the extreme left, the edge of the dipole can be seen. This photograph also clarifies the need for making the bottom six counters smaller. The counters are held in place by aluminum bars clamping on to the flat part of the light guide. The tips of the counters are held in position by a central disc of mylar and paper honeycomb (see diagram below and Figure 26). This ensures that the counters stay in the same plane and thus provide mutual support.

Figure 23: Honeycomb Central Support

The magnetic shields are rigidly mounted to the arms and brackets of the cerenkov counter, while the elbows of the counters are loosely held in place within them by sponge rubber. The original mounting fixtures for the shields were greatly strengthened during installation. This was to ensure that if the fixtures were stepped on or knocked,

coloured picture

FIGURE 25 DETAIL OF MAGNETIC SHIELD AND SUPPORT

FIGURE 26 ALIGNMENT OF THE HODOSCOPE

the existence of small light leaks that had escaped detection. To reduce the leaks, the front of the hodoscope was covered with black plastic. The counters were timed relative to one another at the output of the discriminators. This was done using fast secondary particles from beam interactions in the liquid hydrogen target which preferentially populate the tips of the counters. Timing spectra between the experiments' start counter and each counter in the array were taken using a LeCroy QVT module. The variation in the position of the peaks of the spectra were used to adjust the cabling so that the relative timing differences of the hodoscope's elements at the output of the threshold discriminators were less than 2 nsec.

High voltage curves were measured for all counters. For the time of flight counters, a software discriminator was constructed for this purpose; a counter was deemed to have fired if its ADC channel contained a signal greater than a fixed threshold. The time of flight counter had very good efficiency characteristics with plateaus at least 300 volts wide, typically between 1600 and 1900 volts. Some smaller counters were even better with plateaus from 1500 to 2000 volts. The high voltage settings were left at close to 1900 volts, as this was the point at which the counters had exhibited their best timing characteristics. The voltage on some counters were set slightly higher or lower (20 v) to aid equalization of the ADC spectra. The quadrant trigger counters did not perform as well, having narrow plateaus and operating voltages typically about 2300 volts. The poorer performance was attributed to the long rectangular light guide used which did not have the focussing properties of the time of flight

counters. However, as the quadrant counters are not going to be used for timing purposes, their performance is perfectly adequate. The counters were also tested with the LASS magnets on. It was found that only a nominal current (0.2 amp) was needed in the bucking coils to prevent timing shifts due to uncertainties in the magnetization state of the shields when the magnets were switched on or off.

The multiplicity trigger for the K^-p experiment was formed by summing the outputs of all 28 counters in the array, and discriminating the summed signal to detect the occurrence of ≥ 1 , 2, 3, or 4 hits occurring at the same time. The discriminator was set by measuring rate as a function of discriminator threshold. This produced three distinct plateaus (see Figure 27a) corresponding to ≥ 1 , 2, or 3

Figure 27: Trigger Set Up

hits in the array; the threshold for ≥ 4 was less clear. The time of flight experimental trigger was formed by the coincidence of a time of flight signal and a beam trigger. The beam trigger is a signal timed by the experiments' start counters and fires when a kaon has been detected entering the spectrometer. The time of flight signals were

made 25 nsec long and timed (as shown in Figure 27b to allow for the following timing variations; particle transit times (14 nsec), transit time of flight along the scintillator (6 nsec), and resolution jitter (2 nsec). This gives a minimum pulse overlap of 3 nsec.

All other possible triggers for the K⁻p experiment are timed in a similar way. As the beam coincidence signal has the timing of the experimental start counter, the basic experimental trigger always has the correct timing for use as a start signal for the TDC's and for use as a gate for the ADC's. So, a signal is taken directly from the trigger logic output to the time of flight electronics. This signal goes through fan-out units after which it forms the start for all the TDC units; stop signals for each TDC channel came from the individual time of flight counters. The start and stop signals are timed so that the output of the TDC is in the middle of its range. The trigger signal is also lengthened and put through a fan-out to form a gate for the ADC's. The dynodes of the time of flight counters are connected to the individual inputs of the ADC units with connecting cables that are adjusted to ensure that the signals are in time with one another. The width of the gate signal is set so that it is open for the duration of the stop counters' pulse.

This initial check of the time of flight hardware and electronics was very encouraging. The counters worked correctly and the hodoscope as a whole had a reasonably low noise rate.

iii) Experimental Operation of Time of Flight Hodoscope

During June and July of 1977, one hundred hours of data were taken for the K⁻p experiment giving a data sample of approximately six million triggers. This data represents a tenth of the total to be

taken for the experiment. The method that will be used to extract particle identification information from the K^-p data is described in this section. This is followed by an account of the method proposed to monitor and calibrate the time of flight hodoscope.

The data from the time of flight hodoscope consists of numbers read from the time-to-digital converters (T.D.C.) and Analog to Digital convertors (A.D.C.). These devices are enabled for every event and the data collected by them is read out along with all the other experimental data shortly after the event occurs. The data is transferred to SLAC's computer system where a small fraction of the events are analysed. All the events are recorded on magnetic tape. The fraction of events that are analysed are used to monitor the performance of the experimental devices. In the case of the time of flight hodoscope monitoring is intended to detect any gross errors in performance. This is done by checking photomultiplier pulse heights during special runs using the light emitting diodes and by periodic inspection of histograms of all ADC and TDC channels during data taking periods.

The data tapes collected during experimental runs contain information such as the raw coordinates of all sparks and other numerical values in block form. These tapes can be analysed using a program which finds tracks and transfers data such as TDC and ADC values into accessible arrays. The reconstructed events will then be written onto a data summary tape which will be used for physics analysis and for studying the performance of devices such as the time of flight counters.

For tracks of events of interest, the time of flight data is to be processed in the following way: Tracks are found in the solenoid, and in the region between the magnets (the twixt region). To locate the point at which a particle hits the hodoscope, the solenoidal track must be extrapolated to the hodoscope and if possible, linked with a twixt track. The existence of a twixt track will improve the accuracy with which the particle's impact point on the counter is known. A check is made to ensure that there is not more than one track going through each counter. From the track finding program the momentum, the interaction vertex and hence the length of both beam and secondary particle tracks can be found. Using the values obtained, it is possible to correct the TDC measurement and use it to calculate the apparent mass of the particle as described in Section (2iv).

Particle identification information is obtained by plotting the apparent mass of tracks of a number of the events to be studied. This plot is then fitted with curves that are distributions around the π , K and p masses as described in section (2iv). This allows assignment of identification probability to a track with a given apparent mass. The data can then be reanalysed and the probability values assigned to tracks by reference to the mass plot of the data sample.

There are errors associated with the quantities obtained from the track finding program. If there is no twixt track to aid in extrapolating the solenoid track to the time of flight hodoscope, the impact position is still known to within 1 cm, which is equivalent to a

time uncertainty of 0.06 nsec. There are also errors in the momentum and the length of the flight path. The error in the momentum is less than 2% which is equivalent to a timing error of 0.017 nsec. There are two uncertainties associated with the particle track: the length of the track and the position of the vertex. These are both expected to have associated errors of 1 cm. The effective error in the vertex for time of flight purposes will in fact be 1/3 cm due to the subtraction of the time of flight of the beam particle. Total error in flight path leads to an equivalent timing error of 0.04 nsec. Combining all these errors due to the track finding program gives a total error equivalent to 0.08 nsec which is negligible when added in quadrature to the time resolution of the counters.

The calibration of the hodoscope involves finding individual mapping and pulse height corrections for the counters using $\beta = 1$ particles from experimental data. There are two possible ways of doing this. The first is a brute force method which involves two dimensional binning of data for the hodoscope according to the impact position of the particles on the counters and the measured pulse heights. Plots of the binned data immediately give mapping and corrections information. The disadvantage to this procedure however, is that it would take all one hundred hours of data to produce sufficient statistics in each bin. The other possibility is to use an iterative procedure on a smaller data sample. The corrections described in Chapter 4 are used as a starting point and are applied to the timing measurements of $\beta = 1$ particles. A histogram of TDC values

minus the associated time of flight of the particles (beam and secondary) for any counter should have a well defined peak the width of which is the resolution of the counter. By making adjustments to both the mapping and pulse height corrections, it will be possible to minimize the distribution's width and hence optimize the counter. These correction constants can then be used in time of flight determinations. Due to the rate at which data can be reconstructed the second method is likely to be the one used.

A software monitor will be implemented to check on the performance of the counters. This will involve measuring the main TDC and ADC value for $\beta = 1$ particles going through the tips of the counters using only a crude mapping correction. Any changes in such quantities as high voltage or magnetization of the shields will cause variation in the mean pulse height affecting both ADC and TDC values. A check can then be made to see if these changes affect the resolution of the counters.

Chapter 6: Summary

A time of flight hodoscope was designed and built for use in the LASS system at SLAC. This involved extensive testing of both prototype and production counters to optimize the design and to assess the performance of the finished product. The hodoscope was installed in April 1977 and was first used in an experiment in June 1977.

The purpose of the time of flight system is to provide particle identification in the low momentum region. Combining this information with that obtained from the two cerenkov counters in LASS will lead to an efficient coverage of the possible momentum range of particles.

The hodoscope is made up of 24 counters using triangular pieces of scintillator. The triangular geometry was chosen because of the advantages of using a circular geometry in the LASS system. The thickness of the scintillator was limited to 1 cm to keep absorption and multiple scattering of particles to an acceptable level. A major concern in the design of the light detector part of the counter was optimization of the magnetic shielding of the phototube. This led to fairly sophisticated designs for the magnetic shields and imposed constraints on the shape of the light guides; namely the inclusion of an elbow to orientate the shield correctly.

A comparison of the resolution obtained with that of other systems indicates that it is performing well; the triangular geometry is very effective in improving the resolution at points furthest from the phototube. All studies done indicate that the resolution is limited by photon statistics. A better counter could be built by

increasing the number of photon getting to the photomultiplier tube. It might be possible to do this by improving the light guide.

Experience with the existing counters indicates that the use of an elbow might not have been necessary. Removing this and using a more gradual bend in the light pipe would undoubtedly improve the performance. Photon statistics could also be improved by using a thicker scintillator, providing an efficient light pipe could be designed for use with it. However, at the present time it is not certain that the improvement in resolution to be gained by these methods would lead to corresponding improvement in the physics data.

Extensive tests prior to the installation showed that a resolution of better than 1.2 nsec F.W.H.M. (full width at half maximum) would be obtained from the hodoscope. This will allow π/K , K/p and π/p separation to 1.4, 2.3 and 2.7 GeV/c with 90% confidence. This is expected to be essentially constant at all points on the counter. Mapping of the time delay due to propagation of light along the counter showed no variation across the counter and an approximately linear relationship along it, equivalent to an apparent velocity of the scintillator light of 16.5 cm/nsec.

Appendix 1: Configuration of LASS (Reference 1 and 12)

LASS (Large Aperture Solenoid Spectrometer) is a large general purpose particle spectrometer consisting of two analysing magnets, a solenoid and a dipole. It is situated at the end of one of SLAC's secondary beam lines which is capable of delivering e , π , $\bar{p}$ and K_s to the spectrometer at momenta ranging from 2 to 16 GeV/c. Beam selection is achieved by two R.F. separators. The trajectory of the incoming beam particles is defined by two proportional chambers ($\Delta\theta \sim 1\text{mr}$, $\Delta x \sim .5\text{ mm}$); particle identification is provided by two pressurized threshold cerenkov counters. A four inch square scintillation counter provides beam timing information and a smaller scintillation hodoscope close to the solenoid is used for centering the beam and rejecting 'spray' around the main beam.

The spectrometer (Figure 1) has two analysing magnets, a solenoid with a central axial field of 23 kgauss and a dipole with a vertical field of 27 kg-m. The solenoid is made of four superconducting coils and two iron end caps with 15 cm gaps between the coils. It has a useful diameter of 1.75 m and it is 3.5 m long. The liquid hydrogen target which is 36" long and 2" in diameter is situated in the first coil. The target is surrounded by 11 cylindrical chambers; the inner one is a proportional chamber and the outer ten are spark chambers with capacitive diode (C.D.) readout. The cylindrical system has 2 mm spacing (4 mm for the outer chamber) and gives a Z resolution of $\pm 1\text{ cm}$. Each gap between the solenoidal coils contains a package consisting of a C-D readout spark chamber with a small proportional 'plug'

covering the central deadened region of the spark chamber. The spark and proportional chambers have 4 and 3 read out coordinates respectively. Both have 1 mm wire spacing. There are also full bore proportional chambers (2 mm wire spacing) plus segmented induced cathode readout proportional trigger chambers situated within coils 2, 3 and 4. They are to provide time resolution constraints as an aid to track reconstruction.

Particle identification of solenoidal tracks is provided by a cerenkov counter and a time-of-flight hodoscope. The cerenkov counter (C1) covers the downbeam end of the solenoid and operates at atmospheric pressure. This counter is divided up into 38 cells, the arrangement of which is shown in Figure 28. When it is filled with freon 114, K/π separation can be realized between 3.0 and 8 GeV/c. The 24 element time of flight counter is mounted on the downbeam face of C1. It is divided into segments such that 2 counters correspond to one set of 3 radial C1 cells. This is also shown in Figure 28. The time of flight hodoscope gives good K/π separation up to 1.4 GeV/c, K/p separation up to 2.3 GeV/c, and π/p separation up to 2.7 GeV/c.

The dipole section of the spectrometer is a conventional spark chamber - dipole magnet - spark chamber spectrometer. The dipole magnet aperture is 1.75 m wide x 1.00 m high and 2 m along the beam. Spark chambers for positional information and proportional and scintillation hodoscopes for time information are arranged on each side of the dipole. Particle identification for this section is provided by a cerenkov counter C2, the gas pressure of which can be adjusted from 0 to 3 atmospheres.

FIG 28. ARRANGEMENT OF CI CELLS AND TOF COUNTERS (COMPARE WITH FIG 2)

Beam particles interacting in the target produce secondary particles with a large range of momenta. Slower particles with large production angles are best measured by the solenoidal system. Particles travelling in the solenoid follow helical paths, thus at least four sets of coordinates must be detected to reconstruct their tracks. The momentum and the charge of particles is determined from the track parameters. Particle identification is obtained by extrapolating tracks through the inhomogeneous field region at the end of the solenoid to C1 and the time of flight counters. Particles with relatively high momenta are not well measured in the solenoidal part of the spectrometer but pass through to the dipole section where a precise measurement of momentum is possible.

Data is transferred from the spectrometer to an analysing computer by a PDP 11 mini computer. A controller for each type of device packs the data into a format suitable for the PDP11's DMA system to read. Fast logic is used to select events of interest. Fast devices such as scintillation and proportional hodoscopes are used as inputs to the fast logic. When an event triggers the fast logic, data for that event is transferred to the analysing computer. Normally SLAC's 'triplex'* system is used in which case the data is partially analysed and all of it is recorded on magnetic tape. However, an IBM 1800 computer is available as a backup for recording data only. A small fraction of events are analysed on line on the triplex system and are used to monitor the performance of the spectrometer. The monitoring function of the analysis program is controlled by an interactive terminal located within the experimental control room.

* Two IBM 370 + ONE IBM 360

Appendix II: Hodoscope Design

1) Scintillator and Optical Assembly

The active area of the time of flight counter was chosen to cover the downbeam window of the cerenkov counter C1 except for a .304 m diameter hole centered on the beam. This was done by using 24, 15° sections of scintillator. Four different sizes were used labelled A, B, C, S. The labelling convention is shown in Figure 28. S is used for the standard counter. The sizes of the 1 cm thick pieces of scintillator were calculated geometrically, then an allowance of 1/16th of an inch was made for the thickness of the wrapping (i.e., 1/8th of an inch between counters). The design of the counters is shown in Figure 29, and the indexed dimensions are given in Table 4. All dimensions shown in Figure 29 and Table 4 are in meters. The light pipes and elbows are made of strips of lucite 1 cm thick, cut to size and flame polished. Their widths are chosen so that they have an approximately circular cross section at the joint between light pipe and elbow (see Figure 29). Light pipes and elbows are formed by heating the lucite and bending it to shape with the use of a former. The Winston cone is a solid piece of lucite machined to shape (Reference 8). The sides of the cone have a coating of aluminum by vacuum deposition with an outer coating of laquer to protect the aluminum. The pieces of the counter were glued together to form two components as shown in Figure 29, and were then wrapped; first with aluminum foil and then with black polyethylene sheet and tape. The component parts were shipped to SLAC, then assembled and glued on site. Due to alignment difficulties, wedge 'cookies' with an angle of approximately 6° between the faces

FIG 29 CONSTRUCTION DETAILS OF COUNTERS (SEE ALSO FIG 10)

TABLE 4: DIMENSIONS OF COUNTERS AS PER LABELLING OF FIGURE 29

Counter Type	r_1	r_2	x	d	α	a	b	c	n
A	0.872	--	0.270	0.064	30°	0.052	0.181	0.059	6
B	0.990	--	0.301	0.066	30°	0.055	0.198	0.059	6
C	1.247	--	0.369	0.074	30°	0.060	0.192	0.076	7
S	1.296	0.58	0.381	0.076	51°	0.129	0.292	0.076	7

2 2

OF/DE

were used between the two components.

2) Mounting

The counters are held in place by clamps across the light pipes and a flexible connection to the rigidly mounted magnetic shields. There is also a central doughnut shaped support made of mylar and paper to hold the tips of the counters in the same vertical plane. The tips of the scintillators are $15.2 \pm .2$ cm from the beam and the hodoscope is centered on the axis of the cerenkov counter C1 to ± 0.02 cm.

3) Base Electronics

The electronics used in the base for the 56 AVP photomultiplier tubes is shown in Figure 30. It is essentially the design recommended by the manufacturer of the tube with larger resistances between the cathode and first dynode to reduce the transit time of electrons between the two electrodes.

4) Design of Trigger Counters

Four trigger counters using quadrant shaped pieces of scintillator were mounted on the downbeam face of the time of flight counter. The design is shown in Figure 31. The upper drawing is the design of an individual counter and the lower one shows how they are put together. Construction techniques were similar to those used for the time of flight counter. The pieces of scintillator were made by machining a piece of 1/4" NE102 scintillator to an annular shape and then cutting it into four pieces using a bandsaw. The thickness of the blade being equivalent to the thickness of the wrapping. The angle of the light pipes were chosen so that the photomultiplier tubes sat between the arms of the cerenkov counter.

FIG 30 DIAGRAM OF BASE ELECTRONICS

TRIGGER COUNTER

QUADRANT TRIGGER COUNTER ASSEMBLY

FIG 31 TRIGGER QUADRANT COUNTERS

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