CERN-EP/82-09
22 January 1982

A TWO-DIMENSIONAL, SINGLE-PHOTOELECTRON DRIFT DETECTOR
FOR CHERENKOV RING IMAGING

E. Barrelet¹⁾, T. Ekelöf²⁾, B. Lund-Jensen³⁾, J. Séguinot¹⁾,
J. Tocqueville⁴⁾, M. Urban¹⁾ and T. Ypsilantis¹⁾

(Submitted to Nuclear Instruments and Methods in Physics Research)

-
- 1) Ecole Polytechnique, Palaiseau, France.
 - 2) CERN, Geneva, Switzerland.
 - 3) Univ. of Uppsala, Uppsala, Sweden.
 - 4) Collège de France, Paris, France.

1. INTRODUCTION

The Cherenkov light emitted by a high-energy particle traversing a dielectric medium may be focused to a ring image with the aid of a spherical mirror. The focus of the image is situated half-way between the mirror and its centre of curvature. The focal surface thus has the shape of a spherical shell with a radius half of that of the mirror, as illustrated in fig. 1.

The measurement of the radius of the Cherenkov ring allows a determination of the angle of emission of the Cherenkov light and thus of the particle velocity. If the particle momentum is also measured, this enables a determination of the mass of the particle and thereby its identity. A detailed analysis of the ring image optical quality and the concomitant resolution obtainable may be found elsewhere [1].

The basic technical problem in the utilization of this method is the detection of the position of single ultraviolet (UV) photons in the focal surface with good two-dimensional position resolution (~ 1 mm), high conversion ($\sim 50\%$) and counting efficiency ($\sim 90\%$). The conversion of photons to electrons is effected via the photoionization mechanism

where M is a suitable photosensitive molecule admixed with the detector gas. This process has been shown [2] to have a large quantum efficiency ($\sim 50\%$) for photons above the threshold energy E_t which is, for the molecules so far utilized, well into the UV region of the electromagnetic spectrum (i.e. $E_t \geq 5.4$ eV). High single-electron counting efficiency ($\geq 90\%$) has been achieved [3] by using pure methane (CH_4) as an amplifying gas in a multiwire proportional chamber (MWPC) geometry. As shown in fig. 2, we achieve unique two-dimensional determination of the photon conversion point by the use of a drift gap in which the photons are converted and drift to a MWPC array where they are detected and timed [3]. In an experimental situation where several radiating particles are expected to emerge together in collimated jets, it is essential that the many near-by photon points

in the focal surface can be reconstructed unambiguously in order to allow the pattern recognition of the circular images.

We have constructed a photon drift detector (type: time projection chamber), in accordance with the above criteria, which has a circular transmitting window of 127 mm diameter (open diameter 100 mm) sitting above a square drift gap of 140×140 mm in area and 15 mm (or 45 mm) in depth. In this paper we describe the construction of the photon detector and the results of test measurements, performed in a 5-20 GeV/c π^- beam from the CERN Proton Synchrotron (PS), to detect the ionization electrons produced in the drift gap by through-going beam tracks. The parameters which affect the precision of spatial localization of the electrons, such as wire spacing, time binning, drift velocity, and diffusion, have been investigated. In addition, an unexpected non-uniformity in the drift field, due to incomplete polarization of the entrance window, has been observed and corrected. In an accompanying paper we describe the ring images obtained with this detector, with triethylamine (TEA) and tetrakis(dimethylamine)ethylene (TMAE) as the photo-ionizing gases.

One of the aims of the present work is to explore the possibility of using this drift technique for UV photon ring-imaging over large, spherically shaped, detector areas (several m^2), as would be needed for ring-imaging Cherenkov (RICH) counters made to cover large solid angles (several steradians). On the basis of the experience gained with the photon drift detector discussed in this paper, we have designed and constructed a large modular counter unit having a large ratio of active to total area ($\sim 85\%$) and small matter density ($\sim 2 \text{ g/cm}^2$). Several such units can be mounted side by side at a slight angle to cover a large, approximately spherical surface.

2. PRINCIPLE OF THE SINGLE-PHOTOELECTRON DRIFT DETECTOR

The basic idea of the drift detector is illustrated in fig. 2. Photons generated in the Cherenkov radiator enter the photosensitive drift region of the detector through a transparent window and converge to a ring image on the focal

surface situated just behind this window. The drift region is filled with a suitable drift chamber gas such as methane, with a small admixture of a photo-ionizing vapour such as TEA or TMAE. These molecules may absorb a photon of energy E and produce a single photoelectron with probability $Q(E)$, i.e. the quantum efficiency for the process. The probability $Q(E)$ is null if $E < E_t$ with $E_t = 7.5$ eV for TEA and $E_t = 5.4$ eV for TMAE. The electron thus produced drifts in a uniform electric field, parallel to the window, into a MWPC plane where, after amplification in the intense electric field around a wire, the time of arrival (relative to an external trigger) of each electron is measured on the wire which it hits. The two coordinates (x,y) of the conversion point in the focal surface can thus be obtained for each detected photon, without ambiguity, from the measured drift time t ($y = v_D t$) and the corresponding wire address (x), where v_D is the electron drift velocity. Figure 3 shows the photon detector in two projections (side and top). The field-shaping electrodes are indicated by black dots and full lines, with the direction of the uniform electric field also indicated. A double entrance window is shown with field-shaping electrodes mounted on both sides of the inner window. The reason for this double window will be discussed in Section 3. Also shown in fig. 3 are open dots corresponding to photon conversion points in the drift volume, and the direction of drift of these electrons towards the MWPC plane where the corresponding impact points are indicated by crosses. The depth of the conversion point in the detector depends on the photon mean free path for absorption in the detector gas. Typically, this absorption mean free path was 5 mm for TEA and 15 mm for TMAE; thus the drift gap depths were 15 mm and 45 mm, respectively, so as to ensure essentially complete (95%) photon absorption. Figure 4 shows a cross-section of the mechanical construction of the detector and shows its mounting relative to the Cherenkov radiator gas volume.

2.1 The photosensitive drift region

The parallel electric field in the drift region is defined by wires stretched between the two legs of a U-shaped Stesalite frame as illustrated in fig. 5. There are two layers of 50 equidistant wires, each of 140 mm length and 100 μ m diameter,

mounted with a pitch of 2.54 mm. The wires are interconnected through 1 M Ω resistors (tolerance 1%) in a voltage divider chain, as shown in fig. 6. The photoelectrons drift in the space between the legs and the wire planes towards the open side of the U-frame where the MWPC is placed. The thickness of the frame, which determines the depth of the photoabsorption region, was either 15 mm or 45 mm, depending on the absorption length of the photoionizing agent used (TEA or TMAE).

The connection between opposite equipotential wires, one in each wire plane, is made through parallel conductive lines deposited on a 100 μ m thick Kapton foil using the printed-circuit technique. These foils are wrapped around the legs of the U-frame, thus making contact between the wire planes, on both the inside and the outside of each leg. This was done in order to avoid having a part of the surface of the U-frame where the potential would be undefined and where accumulation of electric charge leads to a transverse polarization of the frame material which gives rise to distortions of the electric field. This problem will be discussed in detail in a subsequent section (Section 3).

The U-frame is mounted with one of its wire planes touching one of the entrance windows that are placed between the radiator gas volume and the detector gas volume. In order to have the same electric field on both sides of this window, a second field-shaping electrode wire plane is used on the outside of the window, as shown in fig. 3. As a high-voltage connection is needed between corresponding wires on either side of the window, it was technically a problem to have this window also providing the gas-tight separation needed between the detector gas and the radiator gas. Although a solution to this technical problem of using only one window exists (Mark II), we have here used the simple method of adding a second window outside the first one. This outer window is glued with Araldite onto an extension tube (C_1 in fig. 4) mounted on the radiator gas container so as to ensure gas tightness between detector and radiator gases. An obvious disadvantage of this solution is that, because of the limited transmission of the windows in the UV, the second window reduces somewhat the overall photon detection efficiency. In fig. 7 is shown the transmission of 5 mm thick fused quartz (Corning 7940) and

calcium fluoride (Harshaw) entrance windows measured in the laboratory with a UV monochromator. We note that at the peak of TEA photoionization response (8.2 eV) the CaF_2 crystal has 68% transparency, whereas at the centre of TMAE response with fused quartz (6.7 eV) the quartz has 83% transparency. An advantage of this solution, at this stage of experimentation, is that of flexibility. For example, we were able to vary the domain of spectral transmission of the detector by changing the inner window from CaF_2 to quartz when the photoionizing molecule was changed from TEA to TMAE. This provisional solution furthermore avoided the problem of field-shaping electrode wire planes in the argon radiator gas, which would cause a glow discharge when the electric field exceeds 1 kV/cm.

The detector volume is closed, on the side away from the entrance windows, by a Mylar foil (see E in fig. 4). This foil is far enough away (7 cm) from the drift volume to cause a negligible influence on field uniformity in the gap. The third side of the U-frame is covered with a copper sheet, which is connected to the potential U_D defining the high-voltage end of the drift field. The U-frame is mounted inside the Araldite support box (see D in fig. 4). This support box contains the gas inlets and outlets, the high-voltage connections, the voltage division resistor chain, and the MWPC array (see G in fig. 4). The support box itself is mounted on an extension tube (see C in fig. 4) of the Cherenkov gas radiator.

2.2 The multiwire proportional chamber

The MWPC detects the lateral positions and the arrival times of the photoelectrons as they drift to the end of the electric field volume and into the MWPC array. Two different chambers were used, one having 43 anode wires of 20 μm diameter mounted with a pitch of 2.54 mm, the other having 86 anode wires of 10 μm diameter with a pitch of 1.27 mm. In both cases the wires are made of gold-plated tungsten, and the wire length is 6 cm. The cathode planes, placed 3.2 mm away on either side of the anode, consist of a woven stainless-steel mesh made of 50 μm wires with 500 μm spacing.

The MWPC chamber is mounted at position G as shown in fig. 4. In this position the chamber covers the end of the drift region, with the anode wires

perpendicular to the entrance window plane and to the direction of the electric field.

The gap between the last wire of the field-shaping electrode (U_1) and the MWPC cathode was 14 mm, and it had been foreseen to insert two additional wire-mesh planes into this gap. This would have enabled the detector to be operated with gaseous preamplification [4]. The gap between the first and second additional meshes was to be used to cause a discharge avalanche, and the gap between the second additional mesh and the MWPC cathode as a transfer gap. However, the measurements reported in this paper were made without the preamplification and transfer stages, as sufficient amplification was obtained using methane as the amplifying gas coupled with very sensitive detection electronics. This left, however, a rather large gap (14 mm) between U_1 and the cathode of the MWPC, which has repercussions on the time resolution of the detector as will be discussed in Section 5.

The MWPC is closed to the outside air by a Mylar foil mounted behind the outside cathode grid (see H in fig. 4). The electric potentials of the closest drift-gap wire (U_1) and the MWPC cathode have separate high-voltage leads and can thus be adjusted independently of each other. This allows us to maintain the same electric field in the drift region and in the gap between U_1 and the cathode when the MWPC voltage is varied.

2.3 The electronics and data-acquisition system

The basic layout of the electronics for the processing of the pulses from the anode wires of the MWPC is shown in fig. 8. The anode pulses are led through a 10 cm long flexible printed circuit-board conductor to the preamplifiers which are mounted outside on the support box. The detector electronics shown in fig. 9 are composed of fast MECL 10000 series amplifiers having a 100 MHz bandwidth. The preamplifiers (voltage gain of 50) are mounted on the detector and are connected to the anode (sense) wires of the MWPC by a flexible Kapton printed circuit, 10 cm in length. Every other channel on this circuit is connected to ground so as to

minimize cross-talk between neighbouring wires. The resistance to ground on the sense wire is 1.5 k Ω , with a measured stray capacity of 16 pF and thus an entrance filter time constant of 24 ns. The preamplifiers are protected against sparking in the MWPC by a 270 Ω resistance in series with two back-biased diodes.

The preamplified analog signals are transferred to the counting area via 20 m lengths of 120 Ω impedance twisted-pair cable, which reduces the bandwidth to about 80 MHz. In the counting area the analog signals are further amplified (voltage gain 60) by the first two stages of MC 10116 amplifiers (rated gain 12 $\times$ 12) with feedback, and discriminated in the third stage by a Schmitt trigger which gives 60 dB rejection of positive pulses induced on neighbouring wires. The discriminator has a hysteresis of 200 mV, which aids in noise rejection and allows for adjustment of the voltage threshold level by means of an external d.c. bias voltage. This threshold is adjustable for between 50 μ V and 5 mV signals on the anode wire. The r.m.s. noise level at the entry to the preamplifier (when not connected to the MWPC wire) is 50 μ V. When operating with the MWPC, this noise gives rise to a random counting rate of 10² Hz per wire when the discriminator level is set for a 150 μ V signal on the wire (i.e. 0.1 μ A on 1.5 k Ω), which for a capacity of 16 pF corresponds to a charge of 2.4 fC or 1.4 $\times$ 10⁴ electrons.

The voltage response of the MWPC and preamplifier entry filter is, for one photoelectron, given by the relation

$$\begin{aligned} v(t) &= \frac{eAC}{C_i} \int_0^t \frac{e^{-\tau/R_i C_i}}{t + t_0 - \tau} d\tau = \\ &= \frac{eAC}{C_i} e^{-(t+t_0)/R_i C_i} \left[\ln \left(\frac{t + t_0}{t_0} \right) + \frac{t}{R_i C_i} + \frac{(t + t_0)^2 - t_0^2}{4R_i^2 C_i^2} + \frac{(t + t_0)^3 - t_0^3}{18R_i^3 C_i^3} + \dots \right], \end{aligned} \quad (2)$$

where A is the MWPC gain, $C = s/2\pi a$ is the capacity of a MWPC wire per unit distance (s is the wire spacing, a the cathode-anode distance), $R_i = 1.5$ k Ω and $C_i = 16$ pF, and t_0 is a constant:

$$t_0 = \frac{s^2}{2CV\pi^2\alpha} \ln \left[1 + \frac{\pi^2 d^2}{8s^2} \right] = \frac{d^2}{16CV\alpha} \left[1 - \frac{1}{2} \left(\frac{\pi^2 d^2}{8s^2} \right) + \frac{1}{3} \left(\frac{\pi^2 d^2}{8s^2} \right)^2 - \dots \right], \quad (3)$$

where V is the cathode-anode potential, d the wire diameter, and μ the mobility of the positive ions ($\text{cm}^2/\text{V}\cdot\text{s}$). In the parameters of the detector ($R_1 = 1.5 \text{ k}\Omega$, $C_1 = 16 \text{ pF}$, $s = 0.127 \text{ cm}$, $d = 0.001 \text{ cm}$, $v = 3.5 \text{ kV}$, $a = 0.32 \text{ cm}$, $\alpha = 2$), we find $v_{\text{max}} (\mu\text{V}) = 21 \times 10^{-4} \text{ A}$ at $t = 7 \text{ ns}$, which decreases slowly to 10% of this value in about 150 ns. Taking 150 μV as the operating threshold level thus requires a gain $A = 7.0 \times 10^4$ so as to be sensitive to a single electron. Another operating condition of the detector was ($s = 0.254 \text{ cm}$, $d = 0.002 \text{ cm}$) which gives $v_{\text{max}} (\mu\text{V}) = 29 \times 10^{-4} \text{ A}$ at $t = 10 \text{ ns}$, hence single-electron sensitivity (150 μV threshold) when the gain $A = 5.2 \times 10^4$. The gain A of the methane-filled MWPC has been measured to be $\sim 1.8 \times 10^5$ by observing an extrapolated 5 V signal out of the preamplifier when the chamber was irradiated with 5.9 keV X-rays from a ^{55}Fe radioactive source. Since the voltage gain of the preamplifier is 50, this corresponds to a 100 mV signal on the wire. A converted X-ray in methane produces about 200 electrons. Thus the signal on the wire due to a single electron is 500 μV , which should be set equal to $28.6 \times 10^{-4} \text{ A}$, hence the value $A = 1.8 \times 10^5$. This value may be a lower limit because of saturation effects due to such large signals. The chamber gain is thus 2 to 3 times bigger than necessary for single-electron sensitivity. This additional gain is important because of the large fluctuations in pulse height for single electrons (causing a loss in counting efficiency), and to minimize the slewing error in the arrival time measurement. This latter factor can be estimated to give rise to an r.m.s. error in the measured arrival time of $\sim 8.5 \text{ ns}/\sqrt{12} = 2.5 \text{ ns}$ for a uniform pulse-height distribution.

The discriminated output (see figs. 8 and 9) for each wire is connected to a Drift Time Recorder (DTR Type 247 CERN) which digitizes the detection time of the input pulse, relative to a trigger pulse, at a frequency of 125 MHz. The DTR has 8 bits per channel and a memory which permits acceptance of up to 256 pulses on 16 wires (i.e. multi-hit capability). A time binning in 4 ns buckets is obtained by interpolation of the 8 ns period clock with a maximum time range of 2048 ns. The DTR modules are read via a standard CAMAC dataway by a fast microprocessor, called CAB (CAMAC Booster), developed at the Ecole Polytechnique. The microprocessor is based on the AM 2900 series (4-bit slices with 160 ns cycle time)

and has a programming memory of 4k 24-bit words, a data memory of 4k 16-bit words controlled by an index register of 12 bits, a hard-cabled TRW multiplier/adder block of 16×16 bits, and an arithmetic and logic block ALU (AM 2901 series). The digitized data from the DTRs are transferred to CAB, where appropriate calculations are performed for each event. The resultant histograms are transferred to a Tektronix 4052 calculator for display on a cathode-ray screen and printed out on an associated hard-copy printer with the additional option of transfer of the data to 3M cassettes for later analysis off line. As an example of the calculations performed in CAB for straight-line beam tracks passing through the drift volume, the time digitizations t_i from the i -th wire (wire position x_i) for N wires hit ($i = 1, \dots, N$) are summed to give the moments $N\bar{x} = \sum x_i$, $N\bar{t} = \sum t_i$, $N\overline{x^2} = \sum x_i^2$, $N\overline{t^2} = \sum t_i^2$, and $N\overline{xt} = \sum t_i x_i$. We fit the straight-line hypothesis $t = ax + b$ using least-squares analysis to obtain

$$a = \frac{\overline{xt} - \bar{x}\bar{t}}{\overline{t^2} - \bar{t}^2} \quad \text{and} \quad b = \frac{\overline{xt^2} - \bar{x}\bar{t}\bar{t}}{\overline{t^2} - \bar{t}^2}. \quad (4)$$

We calculate also the variance σ of the straight-line fit as

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^N (t_i - ax_i - b)^2 = \overline{t^2} + a^2\overline{x^2} + b^2 - 2a\bar{x}\bar{t} - 2b\bar{t} + 2ab\bar{x}, \quad (5)$$

which gives an estimate of r.m.s. error in a single point-time measurement. For each event (trigger) we calculate and histogram σ , N , $N(x_i)$, $N(t_i)$, where the latter two quantities are the number of times the i -th wire is hit or fills the t_i -th time bin. The probability that the i -th wire is hit is then $N(x_i)/N$, which allows an estimate of the number of primary dE/dx electrons produced in distance s (wire spacing), as will be discussed in Section 3.1. We have tested this complete read-out chain by pulsing the cathodes of the MWPC, which induced an equal time signal on each wire (hence simulating a horizontal beam track $t = \text{constant}$). A fit to these simulated tracks gave $\sigma = 3$ ns, which indicates the intrinsic time resolution of the electronics and binning. The σ expected with 4 ns time buckets is only 1.2 ns, the difference, in quadrature, of 2.7 ns being due to dispersion in the electronics.

3. MEASUREMENTS OF STRAIGHT BEAM TRACKS

There are several potential difficulties connected with the operation of a drift chamber that has a long drift (≥ 10 cm), such as drift-field inhomogeneities causing image distortion and loss of drifting electrons, electron absorption by electronegative impurities in the drift gas, and electron diffusion, resulting in a decrease in the measurement precision. These problems were investigated by making measurements of the ionization created by relativistic charged beam particles traversing the drift region. The experimental layout is shown in fig. 10. The detector is oriented in the beam so that particles pass through the drift region between the two field-shaping electrode planes in a direction parallel to these planes and perpendicular to the MWPC plane. When oriented in position (a) of fig. 10, the charged particle produces ionization on all MWPC wires at equal times, whereas when tilted slightly to position (b) of fig. 10 the trajectory has a slight slope.

The measurements were made in the c_{13} test beam of the CERN PS. This beam is a secondary beam derived from an extracted 24 GeV/c proton beam. The beam momentum could be varied between 5 and 20 GeV/c, with beam intensity between 5×10^3 and 5×10^4 negative particles (mostly pions) per 300 ns spill. The tests described here were done at 10 GeV/c with about 10^4 particles per burst. The trigger was defined by a fourfold coincidence between two pairs of scintillators, placed upstream and downstream of the detector; this corresponds to a beam of about 5 mm diameter, with a maximum divergence of 1.7 mrad (see fig. 10). The fourfold coincidence gave about 50 triggers/burst.

3.1 Measurements without the calcium fluoride window

Measurements were first made without the CaF_2 entrance window in the detector. A Mylar window, mounted at a distance of 7 cm from the closest field-shaping electrode plane, was used to close off the detector gas volume. The detector was aligned as described above, and the charge collection efficiency of different parts of the drift region was investigated by varying the position of the drift gap-width

w relative to the beam, and the distance d of the beam from the MWPC wire plane. The measurements were performed using a 15 mm thick drift gap with an argon (70%) + methane (29%) + TEA (1%) gas mixture (volume flow ratios corrected by $\sqrt{M_A/M}$, where M_A and M are the molecular weights of air and the flowing molecule) and a 1 kV/cm drift field. The indicated argon purity was 99.995%, while the methane was 99.95%. Both gases were further purified by passage through oxisorb and dryer chemical purifiers. The TEA liquid purity was 99.5%. The predominantly argon filling was chosen in order to produce a large number (~ 5) of primary ionization electrons on each wire. The MWPC used had 43 wires at 2.54 mm pitch. Examples of data from two superimposed single tracks are shown in fig. 11. Note that the tracks have a slight slope and that every wire except the first two and the last one are hit. This is because the first and last wires of the MWPC are 100 μ m in diameter (rather than 20 μ m) and hence have negligible gain. The straight lines shown are from the least-squares fit (see subsection 2.3) and give a variance $\sigma = 6$ ns (using only wires 5 to 39 to minimize edge effects).

For N through-going beam tracks the number of digitizations N_i of the i-th wire was measured to obtain a counting efficiency $\epsilon_i = N_i/N$. Assuming that the number of primary ionization electrons that are detected by the i-th wire is Poisson distributed with a mean value n_i , then the probability of not counting is $P(0) = e^{-n_i} = 1 - \epsilon_i$, hence

$$n_i = -\ln(1 - \epsilon_i). \quad (6)$$

If the efficiencies ϵ_i for 35 wires ($i = 5, \dots, 39$) are reasonably uniform, we average the n_i values to obtain the average number of primary ionization electrons $n_{pe} = \bar{n} = 1/35 \sum n_i$ and its variance $\sigma_n = \sqrt{n^2 - \bar{n}^2}$. In fig. 12a we see the values of n_{pe} (error bars σ_n) versus the position w of the beam relative to the drift gap at a drift distance d = 100 mm. This scan shows $n_{pe} = 5.4$ in the centre of the gap, with a linear fall-off when approaching the field-shaping electrodes that is compatible with an increasing fraction of the 5 mm diameter beam passing outside the drift gap. The value $n_{pe} = 5.4$ corresponds to the number of primary electrons collected on one wire spacing (2.54 mm); hence we find a value 21.3/cm. In

fig. 12b are shown the measured values of n_{pe} versus the drift distance d (when the beam is centred in the middle of the gap, i.e. $w = 7.5$ mm); this shows a plateau at $n_{pe} = 5.4$ with a similar fall-off when approaching the borders of the drift region as defined by the first (U_1) and last (U_D) field-shaping electrode wires. There is no indication of electron loss after a drift of up to 12 cm. In fig. 12c is plotted the recorded drift time (for flat equal-time tracks) as a function of the drift distance d . The drift time increases linearly with d , indicating a drift velocity which is independent of d , with a slope corresponding to a drift velocity of 5.6 cm/ μ s.

The data shown in fig. 12 indicate that the drift field is homogeneous throughout the drift region when the field strength $E_D = 1$ kV/cm. Varying the drift field strength, the collection efficiency remains constant from 1 kV/cm down to 0.2 kV/cm, as shown in fig. 13a for a drift distance $d = 100$ and $w = 7.5$ mm (closed circles). In fig. 13b the measured variation of the drift time with E_D is plotted, showing that the maximum drift velocity occurs between 0.4 and 0.5 kV/cm in the argon (70%) + methane (29%) + TEA (1%) gas mixture used for these tests. Note also that the drift velocity does not plateau to a constant value. Increasing the voltage threshold of the discriminators, the number of collected primary electrons n_{pe} was found to be constant for a discriminator threshold up to twice the normal value (150 μ V), as shown in fig. 14.

3.2 Measurements with an unpolarized calcium fluoride window

Performing the measurements described in the previous section with a calcium fluoride window installed outside the entrance field-shaping electrode plane (see fig. 5) gave results which strongly deviated from the earlier results and which changed with time. Figure 15 shows the average number of primary electrons n_{pe} collected per wire, obtained with the beam in the median plane $w = 7.5$ at a distance $d = 100$ mm from the MWPC anode plane as a function of elapsed time after the drift voltage was applied. During the first moments $n_{pe} = 5.4$ as before, but after half an hour n_{pe} falls to about 1, after which it slowly rises, during the following two hours, up to a value of 4. Further studies showed that n_{pe} continued to vary,

with some tendency toward stability but never reached the original high wire-collection efficiency (i.e. $n_{pe} = 5.4$).

Plotting the wire efficiency $\epsilon_i = N_i/N$ for each of the 43 anode wires for $N = 500$ events shows how the losses are distributed in the drift volume. In fig. 16, histograms collected with $d = 100$, $w = 7.5$ mm at different times after the drift voltage has been turned on, show how the deterioration of the collection efficiency occurs preferentially at the borders of the drift volume. Figure 17 shows histograms collected at approximately the same time, but with the beam positioned at $w = 7.5$ mm and different distances d from the MWPC plane. The depletion is seen to be large at large drift distances ($d \geq 80$ mm).

From these data we concluded that the deterioration in the charge collection efficiency is due to varying inhomogeneities in the electric drift field, which in turn are due to slow and irregular charging-up of the calcium fluoride entrance window.

In the measurements of figs. 15-17 the window was in direct contact with the field-shaping electrode plane, making charge collection from the window surface to the field wires possible. To check the influence of this collection, measurements were made with the window 0.2 mm away from the field-shaping electrode plane, again at $d = 100$ and $w = 7.5$ mm. Figure 18 shows the time evolution in this situation. Again the collection efficiency deteriorates, but in this case depletion occurs in the central part of the drift region.

3.3 Measurements with the calcium fluoride window polarized

From the results described above, we tentatively concluded that in order to define a stable and homogeneous drift field inside the drift volume in the presence of the dielectric calcium fluoride window, the potential had to be defined also on the outside of this window. Having a field-shaping electrode plane on both sides eliminates uncontrolled charge accumulation on the outer window surface and polarizes the dielectric medium parallel to the window surface. Since the CaF_2 window was already glued in place, a second CaF_2 window was added, inside

the drift volume, with field-shaping electrode planes on both sides of this inner window (see figs. 3 and 4). As already mentioned, this turned out to be convenient in later tests when this inner CaF_2 window was replaced by a fused quartz window for investigations with the photoionizing gas TMAE. In addition, to avoid charge accumulation in the legs of the U-frame, the potential-defining lines were made to encircle the U-frame legs.

In fig. 19a the results obtained with the window polarized are shown (open circles) and compared with the results obtained with the window unpolarized (closed circles). The collected charge (n_{pe}) remains high (≈ 5.4) up to a distance $d = 120$ mm, whereas with the window unpolarized it decreases significantly beyond $d = 80$ mm. Figure 19b shows the scan over the gap width w (at $d = 100$ mm), again indicating more efficient collection with the window polarized (open circles) than for the window unpolarized (closed circles). The former is as good as the measurement without window (see fig. 12a). The collected charge (n_{pe}) as a function of drift field is plotted in fig. 20 (open circles) and is compared to the unpolarized window case (closed circles). This curve shows efficient collection down to a field of 0.2 kV/cm, as was observed when no window was present. These data (open circles) are directly compared with the no-window data in fig. 13 (closed circles). We note that for the window unpolarized the drift field required for efficient collection is very high ($E_D \geq 1$ kV/cm) when $d > 100$ mm.

The equality of the collected charge $n_{pe} = 5.4$ when the window is polarized and without window, and its independence with drift distance, indicate that electron loss through drift-field distortions and gas absorption is small and that electron collection is efficient throughout the drift volume.

4. DRIFT VELOCITY MEASUREMENTS IN VARIOUS GAS MIXTURES

To measure the drift velocity the detector was placed in the 10 GeV/c pion beam such that the beam was incident normally to the entrance window and parallel to the MWPC wires. In this geometry all the ionization electrons drift to only one or two wires of the MWPC where the drift time is measured at a given value of drift

field strength E_D . The detector was then displaced a known distance, so as to increase (or decrease) the drift distance d , and the drift time was again measured. A plot of the measured drift time versus drift distance gave a straight line whose slope is the drift velocity v_D at the set value of electric field E_D .

The amplifying and drift carrier gas used in the photon drift detector should satisfy a number of requirements. It should have a large first Townsend coefficient so as to allow sufficient gas amplification; it should be opaque (or partially opaque) to the photons emitted in the avalanche amplification process so as to quench the discharge; it should have a small diffusion coefficient to allow accurate localization of the photon conversion point; and its drift velocity should not vary too strongly with drift field so as to allow stable operation. Furthermore, for use in Cherenkov ring imaging, it should be transparent over some range in the UV region where the photoionizing vapours (TEA or TMAE) are sensitive. As shown in ref. 3, methane satisfies all these requirements.

Various combinations of methane (CH_4), ethane (C_2H_6), isobutane ($\text{iso-C}_4\text{H}_{10}$), and carbon dioxide (CO_2) gases with small admixtures of TEA and TMAE were investigated. These gases are all transparent, to varying degrees, in the region up to 9 eV photon energy, as is shown in fig. 21. Also shown in this figure are our present best estimates of the quantum efficiency of TEA and TMAE. As can be seen from fig. 21 only methane can be used when the photoionizing vapour is TEA, whereas for TMAE, combinations of methane, ethane, and CO_2 are possible. The TEA and TMAE quantum efficiency curves shown have been measured with methane as a carrier gas so the high-energy cut-off reflects only the onset of methane absorption rather than an intrinsic decrease of quantum efficiency above 8.5 eV. Measurements using argon as the carrier gas (transparent to 11 eV) are planned so as to determine the quantum efficiency of TEA and TMAE in the 8.5 to 11 eV energy region.

The drift velocities measured are shown in fig. 22 versus the drift electric field. Note that the CH_4 + TMAE (curve a) and CH_4 + TEA (b) drift velocities plateau to a value of about 9.7 cm/ μs above 0.6 kV/cm, whereas the argon + TEA (curve f) drift velocity has a maximum at 0.6 kV/cm and subsequently decreases.

The other curves for CH_4 , C_2H_6 , iso- C_4H_{10} , and CO_2 show monotonically rising drift velocities with increasing electric field. The sharpest rise is shown by CH_4 with CO_2 mixtures (curves d and h). This strong dependence of v_D on E_D coupled with the low value of v_D at low electric fields ($E_D \leq 0.5$ kV/cm) argues against the use of CO_2 . From the viewpoint of fastest drift the CH_4 + TMAE and CH_4 + TEA mixtures are clearly superior, i.e. a total drift time of 2 μs for 20 cm drift distance. Mixtures of CH_4 + iso- C_4H_{10} , even though slower, are interesting because of their increased ability to quench the avalanche discharge around a MWPC wire and the almost exact match with the quartz transmission cut-off. In fig. 23 are shown the measurements of drift velocity versus the percentage of isobutane in methane + isobutane mixtures for the given fixed value of the drift field E_D . Even though the drift velocity in an argon + TEA mixture was measured (curve f in fig. 22) it is not considered as a useful drift and amplifying gas mixture because of its large diffusion coefficient (see Section 5) and because the single photo-electron counting efficiency is low without preamplification [3].

5. ACCURACY OF THE MEASURED DRIFT COORDINATE

Straight lines were fitted to 10 GeV/c pion beam tracks as illustrated in fig. 11 and outlined in Section 2.3. The variance σ [see eq. (5)] of the fit provides a measurement of the accuracy to which the drift time is determined. This quantity is limited by the amount of longitudinal diffusion of the drifting electron(s) in the gas, by the time binning and electronics dispersion, and by any inhomogeneities in the drift field. Figure 24 (taken from ref. 5) shows the measured or calculated values of the transverse diffusion coefficient σ_t for a single electron versus the drift field E_D in pure argon, CH_4 , iso- C_4H_{10} , and CO_2 . The measured longitudinal diffusion coefficient σ_l (as well as σ_t) for an argon (87%) + CH_4 (10%) + iso- C_4H_{10} (3%) mixture used in the JADE detector [6] has been added in fig. 24. From this figure we note that the diffusion coefficient σ_t in argon is extremely large, so to obtain highest precision a predominantly argon gas mixture should be avoided. Methane, isobutane, and CO_2 all have small diffusion coefficients; however, as indicated earlier, the low drift velocities

which characterize CO_2 mixtures mitigate against its use. Since efficient single-electron counting in methane has been proved possible, we have concentrated on measurements with methane and small admixtures of isobutane to enhance quenching. As seen from fig. 24, the longitudinal diffusion coefficient in the JADE gas mixture is about a factor of 2 smaller than the transverse coefficient. This inequality, $\sigma_l < \sigma_t$, has been shown [7] to be true for Ar, H_2 , N_2 , He, CO and C_2H_6 whereas for CH_4 and CO_2 these coefficients are equal. We plan to measure the longitudinal and transverse coefficients in methane + isobutane (or C_2H_6) mixtures (with TEA or TMAE) using a pulsed (2 ns) UV light source to produce single electrons in a long drift (~ 60 cm) volume inside a solenoidal magnetic field.

The measurements reported in this section were obtained with a second drift gap of the same construction as described previously but with a 45 mm gap (it was 15 mm) and the MWPC wire spacing changed from 2.54 mm to 1.27 mm, with 10 μm diameter wires rather than 20 μm . The gas mixture used was methane (89%) + isobutane (11%) at atmospheric pressure but at an elevated temperature. The temperature of the outer support box was kept at 34 $^\circ\text{C}$, hence the gas temperature inside was probably higher than this value. Through-going beam tracks at a gap depth w were observed and the ionization electrons were collected on the MWPC wires after drifting a distance d in a drift electric field E_D . For each track a straight line fit was made with variance σ , and histograms of σ , N , $N(x_i)$, and $N(t_i)$ were obtained for 500 tracks as described in Section 2.3. From the efficiency of each wire the number of primary electrons on each wire is calculated and this is averaged over the wires to obtain n_{pe} . The measurements are shown in fig. 25a, where n_{pe} is shown versus the position w of the beam in the gap. A constant value $n_{pe} = 1.5$ is observed throughout the 45 mm thick gap. Here, the value $n_{pe} = 1.5$ is smaller than the value 5.4 obtained previously (see fig. 12) because of a lower gas density, atomic charge, and wire spacing. Figure 25b shows a scan in drift distance d , where a slight decrease in collection efficiency perhaps occurs at short drift distances. In fig. 25c the local drift velocity v_D (measured time difference Δt of two flat equal-time tracks with incremental drift distance Δd) is

plotted versus drift distance d . We note a large increase in v_D between U_1 and U_{PC} indicating that field inhomogeneities remain in this 14 mm long region.

Figure 25d shows that n_{pe} and the variance σ are constant when the drift field E_D is varied from 0.4 kV/cm to 1.0 kV/cm. From the average constant value $n_{pe} = 1.5$ and wire spacing 0.127 cm we calculate that 11.8 primary electrons are produced in 1 cm of this CH_4 (89%) + iso- C_4H_{10} (11%) gas mixture at atmospheric pressure and temperature $\geq 34^\circ C$.

To measure the longitudinal diffusion coefficient, the square of variance $\sigma(ns)$ of the straight line fit was plotted versus d as shown in fig. 26. A straight line $\sigma^2 = \sigma_0^2 + \sigma_1^2 d$ has been fit to the data giving $\sigma_0 = 10.2$ ns and $\sigma_1 = 2.81$ ns/cm^{1/2}. Multiplying these quantities by the drift velocity $v_D = 5.75$ cm/ μs gives the space errors $\sigma_0 = 590$ μm and $\sigma_1 = 162$ $\mu m/cm^{1/2}$. The magnitude of the σ_0 error is due partially to electronics dispersion (2.7 ns) and to time binning (1.2 ns), but the remainder (9.7 ns) is attributed to the drift field inhomogeneity between U_1 and the MWPC cathode U_{PC} . This defect has been corrected in a later drift gap (Mark II) where $\sigma_0 = 5.6$ ns has been realized. The single-electron longitudinal diffusion coefficient σ_ℓ is related [8] to σ_1 through the equation

$$\sigma_1 = \frac{\pi}{2\sqrt{3} \ln n} \sigma_\ell, \quad (6)$$

where n is the total number (primaries + secondaries) of electrons which contribute to the measurement of σ_1 when the electronics is sensitive to a single electron. The total number of electrons is $n = kn_{pe}$ with k between 3 and 5; however, the resulting value of σ_1 is comparatively insensitive to the exact value of k . Using $k = 4$ and $n_{pe} = 1.5$ we obtain $\sigma_\ell = 1.48 \sigma_1$, hence $\sigma_\ell = 240$ $\mu m/cm^{1/2}$. This result may be compared with the data in fig. 24, which give the values $\sigma_t = 230$ $\mu m/cm^{1/2}$ for methane and $\sigma_t = 120$ $\mu m/cm^{1/2}$ for isobutane (calculated) at $E_D = 0.6$ kV/cm. Our result is $\sigma_\ell \approx \sigma_t$ for methane (since our gas mixture is predominantly methane), which agrees with the data of ref. [7] for σ_ℓ .

An improved drift cage (Mark II) has been constructed as shown in fig. 27. It has a 140 mm long drift distance between the extreme field-shaping electrodes

U_D and U_1 with a transfer mesh at voltage U_T between U_1 and the MWPC cathode U_{PC} . The distance U_1 to U_T is 4.8 mm, U_T to U_{PC} is 3.2 mm, and U_{PC} to the sense wire plane is 3.2 mm. The sense wires of 10 μ m diameter and 50 mm length are spaced 1.27 mm apart. The transverse dimension of the drift volume is 185 mm and the detector plane contains 145 wires. As may be seen in fig. 27, this drift cage is self-contained (i.e. not mounted inside an outer support box), with three sides of the box, 40 mm deep, made of 1.6 mm thick Stesalite on both sides of which are glued Kapton printed-circuit sheets. These printed circuits have parallel conducting copper strips, 100 μ m wide, every 2.54 mm. The fourth side of the box has a quartz rectangular entrance window (140 mm $\times$ 185 mm) on which are wound 100 μ m diameter wire loops, also with 2.54 mm pitch. This window is glued to the Stesalite-Kapton drift cage, with the wire loops in electrical contact with the Kapton printed-circuit strips. A resistance chain mounted near the box provides the electric potentials to the strips which, because of the contact between the strips and the loops, are conducted to both sides of the quartz entrance window. The fifth side of the box is closed by a Stesalite plane, fully copper plated on the inside of the box and connected to the high potential U_D . The sixth and last side of the box is closed by the transfer mesh and MWPC array. The box is gas-tight and has gas input and output leads located near the MWPC array. This unit is modular in the sense that it has been designed so that many such units can be mounted, for example, like the lines of longitude and latitude to cover a spherical surface.

The Mark II detector has been tested with through-going 10 GeV/c pion beam tracks, as described above, with two different gas mixtures i) pure CH_4 , and ii) CH_4 (89%) + iso- C_4H_{10} (11%) at atmospheric pressure and 20 °C. The average number of primary electrons n_{pe} measured is shown in fig. 28a versus drift distance d for the two gas mixtures. We find $n_{pe} = 1.1$ and 1.8, respectively, where the latter number should be compared with the value $n_{pe} = 1.5$ found using the original (Mark I) field cage with the same CH_4 (89%) + iso- C_4H_{10} (11%) gas mixture (see fig. 25); however at an elevated temperature ≥ 34 °C. This difference in n_{pe} for the two measurements is attributed to a difference in gas densities caused

by the disparity in temperatures. The local drift velocity v_D versus drift distance in Mark II is shown in fig. 28b, where we find $v_D = 9.9$ cm/ μ s and 5.4 cm/ μ s, respectively, with a rapid change of v_D only near the MWPC wire plane as expected. Thus a much better linearity of the electric field is observed compared to the Mark I drift cage (see fig. 25c).

In fig. 29 the variance of the straight line fits σ (ns) is plotted versus d , and straight lines of the form $\sigma^2 = \sigma_1^2 + \sigma_2^2 d$ are fitted to these data. The parameters are:

for i) $\sigma_0 = 5.8$ ns and $\sigma_1 = 1.74$ ns/cm $^{1/2}$; and with $v_D = 9.9$ cm/ μ s, giving
 $\sigma_0 = 574$ μ m and $\sigma_1 = 172$ μ m/cm $^{1/2}$;

for ii) $\sigma_0 = 5.4$ ns and $\sigma_1 = 2.80$ ns/cm $^{1/2}$; and with $v_D = 5.4$ cm/ μ s, giving
 $\sigma_0 = 292$ μ m and $\sigma_1 = 151$ μ m/cm $^{1/2}$.

Correcting for the total number of electrons $n = 4 n_{pe}$ we obtain i) $\sigma_\ell = 231$ μ m/cm $^{1/2}$ and ii) $\sigma_\ell = 234$ μ m/cm $^{1/2}$, respectively, for the two different gas mixtures. These numbers should be compared to $\sigma_\ell = 240$ μ m/cm $^{1/2}$ obtained with the previous (Mark I) detector. It is not thought that these numbers are significantly different, so the average of $\sigma_\ell = 235$ μ m/cm $^{1/2}$ represents the results of our longitudinal diffusion coefficient measurements in pure CH₄ or CH₄ (89%) + iso-C₄H₁₀ (11%) at a drift field of $E_D = 0.6$ kV/cm. There is, however, a significant difference in σ_0 for the Mark II detector. This value has been reduced to 5.6 ns, compared with 10.2 ns for the Mark I detector. This represents an approximately 4.7 ns contribution due to field inhomogeneities, compared to 9.7 ns for the Mark I detector, hence a significant improvement. In a slow gas mixture such as CH₄ (89%) + iso-C₄H₁₀ (11%) 5.6 ns corresponds to an intrinsic spatial error $\sigma_0 \approx 300$ μ m, whereas for a fast gas such as CH₄ this error becomes $\sigma_0 = 500$ μ m. The 2.7 ns contribution from electronics dispersion is not intrinsic and can largely be removed by calibrating each channel. However, this has not been done in treating the data reported in this paper.

6. SUMMARY AND CONCLUSIONS

A drift detector, capable of localizing single photoelectrons, has been constructed and tested by measuring ionization tracks from relativistic charged particles. A first conclusion from these tests is that it is necessary to apply field-shaping conductive strips to both the inside and the outside of the dielectric walls surrounding the drift volume in order to have a stable and homogeneous electric field inside. It is furthermore necessary to have the drift volume surrounded by potential-defining strips all the way up to the MWPC cathode plane, so as to avoid field distortions which produce timing errors.

The spatial resolution of the detector is limited by several sources of error. In the drift (longitudinal) direction, one component of the error is proportional to the square root of the drift distance and the proportionality constant has been measured to be $\sigma_\ell = 235 \text{ } \mu\text{m}/\text{cm}^{1/2}$ for predominantly methane gas mixtures. A second component of the error which is independent of the drift distance is due to error in the drift time measurement. This component has been determined, in the best case, to be $\sigma_{0\ell} = 5.6 \text{ ns}$ corresponding to a $300 \text{ } \mu\text{m}$ constant positional error. In the direction transverse to the electric field, there are also two error components, the first being again proportional to the square root of the drift distance with the proportionality constant given by the transverse diffusion coefficient σ_t . We have not here measured this quantity; however, classical Townsend electron diffusion experiments [9,10] give this quantity. The second component of the error in the transverse coordinate is due to the wire spacing of the MWPC that detects the drifting electrons. It has a value $\sigma_{0t} = s/\sqrt{12}$ where s is the wire spacing. For a drift over a maximum distance D , the average of the distance-dependent error is $2/3 \sigma\sqrt{D}$. Adding the independent error components in the quadrature we obtain

$$\begin{aligned}\sigma_y^2 &= \sigma_{0\ell}^2 + \frac{4}{9} \sigma_\ell^2 D \\ \sigma_x^2 &= \frac{s^2}{12} + \frac{4}{9} \sigma_t^2 D\end{aligned}\tag{7}$$

as the average square errors in the two directions (x,y) over the detector surface.

The intrinsic resolution of a Cherenkov ring image is given by $\Delta\theta_c$, the chromatic aberrations of the focused image [1]. This quantity depends on the optical dispersion of the Cherenkov radiating medium and is given approximately as $\Delta\theta_c = \Delta n / \sqrt{12n^2(n^2 - 1)}$ where n is the refractive index and Δn is the difference of refractive indices of the two extreme photon energies detected. The corresponding spatial resolution Δr is determined by the mirror focal length f as simply $\Delta r = f\Delta\theta_c$. An approximate optimization of error sources requires that the detector resolution $\frac{1}{2}(\sigma_x^2 + \sigma_y^2)$, averaged over the circular image, should be equal to $(\Delta r)^2$. Using eqs. (7) to solve for the optimal drift distance D as

$$D = \frac{2(\Delta r)^2 - \sigma_{\ell}^2 - s^2/12}{\frac{1}{9}(\sigma_{\ell}^2 + \sigma_t^2)} \quad (8)$$

As an example, for $\Delta\theta_c = 1$ mrad, $f = 1000$ mm we find $\Delta r = 1$ mm. Taking $s = 1.27$ mm, $\sigma_{\ell} = 0.3$ mm, $\sigma_{\ell} = \sigma_t = 0.235$ mm/cm^{1/2} as measured, we find $D = 36.2$ cm, corresponding to a drift length more than double that of the present detector (Mark II). To cover e.g. 1 m² of detection surface three drift zones, each of 33.3 cm in length, are separated by three rows of MWPC wires, 1 m in length, each containing 787 wires. Such a detector, covering 1 m², has 5×10^5 resolution elements (pixels) at the cost of instrumenting $3 \times 787 = 2361$ proportional chamber wires. Such a detector allows reconstruction of the ring images without ambiguity, with sufficient precision, at minimal cost.

For shorter focal lengths, Δr decreases; hence, from eq. (8), the diffusion coefficients must decrease if long (economical) drift distances are to be used. This can certainly be achieved with CH₄ + CO₂ drift gas mixtures where $\sigma_{\ell} = \sigma_t = 0.1$ mm/cm^{1/2} have been measured [7,10]; however, as previously discussed, such mixtures have low drift velocities. Other gases such as C₂H₂, C₂H₄, C₃H₆, C₃H₈, and SiH₄ have been measured to have low values of $\sigma_{\ell} \approx \sigma_t = 0.14$ mm/cm^{1/2}, however with reasonable drift velocities (2 to 4 cm/μs) at 0.6 kV/cm drift field. The first four of the above gases are transparent below 7 eV (SiH₄ has not been measured) and so could be used for Cherenkov ring imaging with TMAE and quartz.

We have not yet tried to count single photoelectrons with additions of these gases to methane but plan to do so in the near future.

We wish to acknowledge the aid and support of Dr. A. Wetherell and Dr. E. Gabathuler of CERN, Dr. P. Fleury of the Ecole Polytechnique, Dr. S. Kullander of the University of Uppsala and Dr. M. Froissart of Collège de France. The technical aid of D. Bernier, R. Bouhot, A. Brehm, C. Detraz, B. Goret, J.P. Hubert, G. Muratori, P. Quéro and C. Rivoiron, and the electronic design of Y. Kornelis were very important in this work, and to them we express our thanks.

REFERENCES

- [1] T. Ypsilantis, *Physica Scripta* 23 (1981) 370.
- [2] J. Séguinot and T. Ypsilantis, *Nucl. Instrum. Methods* 142 (1977) 377.
- [3] T. Ekelöf, J. Séguinot, J. Tocqueville and T. Ypsilantis, *Physica Scripta* 23 (1981) 718.
- [4] G. Charpak and F. Sauli, *Phys. Lett.* 78B (1978) 523. See also J. Séguinot, J. Tocqueville and T. Ypsilantis, *Nucl. Instrum. Methods* 173 (1980) 283.
- [5] V. Palladino and B. Sadoulet, *Nucl. Instrum. Methods* 128 (1975) 323.
- [6] H. Drum et al., *Nucl. Instrum. Methods* 176 (1980) 333, from the data of B. Schmitt, Diplomarbeit, Phys. Inst. der Univ. Heidelberg (1980).
- [7] E.B. Wagner, F.J. Davis and G.S. Hurst, *J. Chem. Phys.* 47 (1967) 3138.
- [8] W. Farr, J. Heintze, K.H. Hellenbrand and A.H. Walenta, *Nucl. Instrum. Methods* 154 (1978) 175.
- [9] T.L. Cottrell and I.C. Walker, *Trans. Faraday Soc.* 63 (1967) 459.
- [10] L.W. Cochran and D.W. Forester, *Phys. Rev.* 126 (1962) 1785.

Figure captions

- Fig. 1 : Schematic diagram of ring-imaging geometry. The outer spherical surface is a mirror and the inner surface a detector. Photons emitted when two particles emerge from the interaction region, near the mirror centre of curvature, will be focused by the mirror into two separate rings with half-angles θ_{D1} and θ_{D2} . These ring radii are related to the particle velocity β_i by the relation $\theta_{Di} = \cos^{-1} (1/n\beta_i)$ where n is the refractive index of the gas (or liquid) radiating medium.
- Fig. 2 : Schematic of the photon drift detector. The UV photons produced by a charged particle in the radiator are reflected by a spherical mirror and form a ring image, in the focal plane of the mirror, just below the entrance window (quartz or CaF_2). The photons are converted to photoelectrons by photoionization of molecules in the drift volume. A uniform electric field parallel to the entrance window and perpendicular to the MWPC plane causes the electrons to drift to the MWPC plane where they are amplified, counted and timed. The carrier drift gas is methane plus TEA or TMAE.
- Fig. 3 : A schematic side view (a) and top view (b) of the photon drift detector. A double entrance window is shown with field-shaping electrodes (full dots and lines) on both sides of the inner window as explained in Section 3.3. Photons coming through the entrance windows are converted in the drift volume at points represented by open dots and drift in the uniform electric field $\vec{E}$ to the MWPC plane, where the impact points are shown by crosses. The cathodes of the MWPC are also shown (dotted lines). The large full circle in (b) shows the extent of the circular entrance window relative to the larger square drift volume. In a later design (Mark II) the entrance window is square (or rectangular) and covers the full drift volume.

- Fig. 4 : Details of the photon drift detector: A - Gas radiator volume; B - End flange of gas container (stainless steel); C - Extension of gas container (stainless steel) in contact with radiator gas; C₁ - Araldite extension (glued to C) onto which the outer entrance window is glued; D - Support box (araldite) for drift gap and MWPC; E - Rear closure for support box with Mylar window; F - Drift volume with field-shaping electrodes and inner entrance window. Potential applied at the far side in U_D and the near side to the MWPC in U_1 ; G - MWPC array with wire mesh cathodes and wire anodes; H - Closure of MWPC array with Mylar window.
- Fig. 5 : View of the drift gap (F in fig. 4) with field-shaping electrode wires and Kapton printed-circuit channels covering the U arms. Also shown is the inner entrance window which abuts on the entrance field-shaping electrode wires. Not shown is a second plane of field-shaping wire electrodes which sandwich the inner entrance window.
- Fig. 6 : Voltage resistor chain for field-shaping electrodes. The negative potentials U_D and U_1 are defined by external supplies. The black dots correspond to the wires of the field-shaping electrodes.
- Fig. 7 : The photon transmission versus photon energy of fused quartz (Corning 7940) and a CaF₂ (Harshaw) single crystal windows. Both windows are 5 mm thick and 127 mm in diameter.
- Fig. 8 : Schematic diagram of drift detector read-out.
- Fig. 9 : Preamplifier, amplifier and discriminator circuits.
- Fig. 10 : Orientation of the drift detector to observe through-going beam tracks; a) flat tracks at equal time; b) sloping tracks at variable time.
- Fig. 11 : Examples of two superimposed sloping tracks produced by 10 GeV/c pions passing through the drift detector.

- Fig. 12 : a) The average number of primary electrons n_{pe} collected on each wire when the beam is scanned across the drift gap w at a fixed drift distance $d = 100$ mm.
- b) n_{pe} versus drift distance d when the beam is positioned in the gap centre $w = 7.5$ mm.
- c) Relative drift time versus drift distance d at $w = 7.5$ mm.

- Fig. 13 : a) The average number of primary electrons n_{pe} collected on each wire versus the drift field E_D when the beam is centred in the gap $w = 7.5$ mm at a distance $d = 100$ mm. Closed circles are with no entrance window and open circles for a polarized CaF_2 entrance window.
- b) Relative drift time versus drift field E_D with conditions as in (a).

- Fig. 14 : The average number of primary electrons n_{pe} collected on each wire versus preamplifier threshold level.

- Fig. 15 : Variation of average number of primary electrons collected per wire n_{pe} versus elapsed time Δt after turning on drift field with an unpolarized CaF_2 entrance window. Drift distance $d = 100$ mm, beam centred in gap $w = 7.5$ mm and $E_D = 1$ kV/cm.

- Fig. 16 : Wire efficiency ϵ_i versus elapsed time after turning on the drift field when the CaF_2 entrance window is unpolarized. Drift distance $d = 100$ mm, $w = 7.5$ mm, $E_D = 1$ kV/cm.

- Fig. 17 : Wire efficiency ϵ_i versus drift distance d when the CaF_2 entrance window is unpolarized. Drift field $E_D = 1$ kV/cm and beam centred in gap $w = 7.5$ mm.

- Fig. 18 : Wire efficiency ϵ_i versus elapsed time after turning on drift field when the unpolarized CaF_2 entrance window is not in contact with the field-shaping electrode (separation 0.2 mm). Drift distance $d = 100$ mm, $w = 7.5$ mm and $E_D = 1$ kV/cm.

- Fig. 19 : The average number of primary electrons n_{pe} collected on each wire with the CaF_2 entrance window polarized (open circles) and unpolarized (closed circles) versus a) drift distance d with $w = 7.5$ mm and $E_D = 1$ kV/cm, and b) position of beam in the drift gap w with $d = 100$ mm and $E_D = 1$ kV/cm.
- Fig. 20 : The average number of primary electrons n_{pe} collected on each wire with the CaF_2 entrance window polarized (open circles) and unpolarized (closed circles) versus drift electric field E_D when the drift distance $d = 100$ mm and $w = 7.5$ mm.
- Fig. 21 : Transmission T versus photon energy E of 10 cm long samples of methane (99.95%), ethane (99.97%), isobutane (99.95%), and carbon dioxide (99.9%) all treated by flowing through oxisorb and dryer chemical purifiers. Shown also are the quantum efficiencies Q of TEA and TMAE in methane. The decrease of Q at high energies (8.5 eV) is due to photon absorption in methane and does not reflect the true quantum efficiency of these molecules above 8.5 eV.
- Fig. 22 : Drift velocity v_D versus electric field E_D for a) 100% CH_4 flowing through liquid TMAE (27 °C), b) 88.5% CH_4 with 11.5% CH_4 flowing through liquid TEA (3 °C), c) 85% CH_4 with 15% C_2H_6 , d) 97% CH_4 with 3% CO_2 , e) 89% CH_4 with 11% iso- C_4H_{10} , f) 80% argon with 20% argon flowing through liquid TEA (3 °C), g) 100% C_2H_6 flowing through liquid TMAE (27 °C), h) 87% CH_4 with 13% CO_2 . The argon gas purity was 99.995%, that of TEA was 99.5%; the TMAE purity was unknown and the other gases as listed in fig. 21.
- Fig. 23 : Drift velocity v_D versus volume percent of isobutane in methane-isobutane mixtures for fixed values of the drift electric field E_D .
- Fig. 24 : Experimental values (from ref. 5) of the diffusion coefficients σ_t or σ_ℓ versus electric drift field E_D at atmospheric pressure. The iso- C_4H_{10} curve is calculated. The values of σ_t and σ_ℓ (from ref. 6)

for the JADE gas (87% argon + 10% CH₄ + 3% iso-C₄H₁₀) have been added. The measured values of σ_ℓ (from ref. 7) for C₂H₄ follow very closely the σ_t curve for iso-C₄H₁₀ and the σ_ℓ for CO₂ follows the σ_t curve shown for CO₂.

Fig. 25 : The average number of primary electrons n_{pe} collected per wire versus a) gap width w at drift distance $d = 100$ mm and $E_D = 0.6$ kV/cm, b) drift distance d at gap width $w = 22.5$ mm and $E_D = 0.6$ kV/cm. c) The local drift velocity v_D versus drift distance d at gap width $w = 22.5$ mm and $E_D = 0.6$ kV/cm. d) The n_{pe} and the variance σ of the straight line fit versus drift electric field E_D at drift distance $d = 100$ mm and gap width $w = 22.5$ mm.

Fig. 26 : The square of the variance σ of the straight-line fits plotted versus drift distance d for $w = 22.5$ mm and $E_D = 0.6$ kV/cm. The straight-line fit $\sigma^2 = \sigma_0^2 + \sigma_1^2 d$ has values $\sigma_0 = 10.2$ ns and $\sigma_1 = 2.81$ ns/cm^{1/2}.

Fig. 27 : Schematic view of the modular Mark II drift gap.

Fig. 28 : a) The average number of primary electrons n_{pe} collected per wire versus drift distance d in the Mark II drift gap with the beam centred in the gap and $E_D = 0.6$ kV/cm. The open circles are for pure methane and the closed circles for 89% CH₄ + 11% iso-C₄H₁₀ gas mixture. b) The local drift velocity versus drift distance d with conditions as in (a).

Fig. 29 : The square of the variance σ of the straight-line fits for the Mark II drift gap plotted versus drift distance i) for pure CH₄ and ii) for a mixture of 89% CH₄ + 11% iso-C₄H₁₀. The straight-line fits are of the form $\sigma^2 = \sigma_0^2 + \sigma_1^2 d$ with i) $\sigma_0 = 5.8$ ns and $\sigma_1 = 1.74$ ns/cm^{1/2}, and ii) $\sigma_0 = 5.4$ ns and $\sigma_1 = 2.8$ ns/cm^{1/2}.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Pulse height threshold level (units 150 μV)

Fig. 14

Fig. 15

Wire number

Fig. 16

Wire number

Fig. 17

Wire number

Fig. 18

Fig. 19

Fig. 20

Fig. 21

Fig. 22

PERCENT ISOBUTANE IN METHANE - ISOBUTANE MIXTURE

Fig. 23

Fig. 24

Fig. 25

Fig. 26

Fig. 27

Fig. 28

Fig. 29