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ABSTRACT

This report presents the performance of drift chambers operated in the limited streamer mode with 9.4 cm maximum drift distance and position sensing along the 4.35 m long anode wire through delay line timing. Using only three timing channels a position resolution of $1 \times 3 \text{ mm}^2$ is obtained over a detector surface of $19 \times 435 \text{ cm}^2$.

In this contribution, the emphasis is mainly put on the performance of the delay line and on the drift behaviour in streamer mode using safe gas mixtures.

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1. INTRODUCTION

The drift chambers presented here are designed for the end-cap muon identifiers of the DELPHI detector [1] which will be installed at the LEP e^+e^- collider. Each end-cap muon detector consists of 2 detection planes made of 4 quadrants, each covering an area of about $4.35 \times 4.35 \text{ m}^2$ and consisting of 2 layers of 22 drift chambers with anode wires crossed at 90° . The main characteristics of one drift chamber, constituting the unit detector cell, are given in table 1 and a transverse cut of an individual chamber is shown in figure 1.

The position of particle impacts will be recorded by drift time measurements whereas the left-right ambiguity will be resolved using the delay line information of the crossed layer.

Results of prototype tests of such chambers operated in the limited streamer mode using a "standard" $\text{Ar-IC}_4\text{H}_{10}$ mixture have been reported recently [2]. It was demonstrated there that such a "streamer drift chamber" is an adequate detector for muon identification in an e^+e^- environment. These results are briefly reviewed below. In this report, after a short motivation for streamer operation, emphasis is put on the performance of the delay line and the investigation of alternative safe gas mixtures adequate for streamer operation in conjunction with relatively long drift (up to 9.4 cm).

2. MOTIVATIONS FOR STREAMER AS OPPOSED TO PROPORTIONAL OPERATION.

For the DELPHI muon identifier, the aim was to develop detector cells reaching a space resolution of 1 mm in drift and less than 10 mm along the anode wire. On the other hand, due to the large area covered by the detector, an easy construction and a reasonable number of readout channels had to be pursued. These requirements have been fulfilled in the design of 20 cm wide drift chambers operated in streamer mode, the main advantages of streamer operation being the following :

- the anode wire (100 μm diameter non magnetic stainless steel) is robust enough to be directly stretched through the chamber without supporting spacers, allowing the use of extruded Al tubes as unit drift cells. This ensures not only an easy construction but also gastightness.

- as can be seen from figure 2, the streamer signal is characterized by both a fast rise time (< 5 ns) and a large pulse height (> 50 mV into 50Ω). Anode amplifiers are therefore unnecessary and anode time slewing is small. Moreover, sizable signals are induced by capacitive coupling on the delay lines, making the attenuation problem less critical. Relatively slow lines can thus be used and resolutions of the order of $1^\circ/\circ$ of the anode length can be envisaged.

It should also be pointed out that the rather long dead time of the streamer regime [3,4] is not a limitation for a muon detector with a low counting rate.

3. BRIEF REVIEW OF THE CHAMBER PERFORMANCES IN Ar- iC_4H_{10} (1-2) [2]

The main drift properties in Ar- iC_4H_{10} (1-2) can be summarized as follows :

- the drift over approximately 10 cm is essentially 100% efficient ;
- the length of the plateau is several hundred volts for minimum ionizing particles ;
- the time-drift distance relation is linear ;
- the resolution on the drift distance is ≤ 1 mm.

4 DELAY LINE RESULTS

4.1. DESCRIPTION OF THE DELAY LINE

The delay line is of the wound coil type and constitutes one of the earthed cathodes facing the anode wire. To avoid charge pile up, a bare Cu wire ($200 \mu\text{m}$ diameter) is used and successive turns are insulated from one another by a nylon wire ($80 \mu\text{m}$ diameter). The pitch of the winding, performed on a modified lathe, is about $265 \mu\text{m}$. The core of the coil consists of a PVC profile of cross section $1.4 \times 14 \text{ mm}^2$ and encloses a $200 \mu\text{m}$ thick, 10 mm wide, copper strip. Built in this way the inverse velocity $V^{-1} \propto \sqrt{LC}$ of the line is rather insensitive to slight variations in the core dimensions, as will be shown below.

The layout of the line is shown in figure 3 and its main characteristics are given in table 2.

4.2. BENCH TESTS OF THE DELAY LINE

Each delay line is tested by injecting a signal from a pulse generator by contact every 10 cm along the line and by recording the propagation time of the signal to both ends. These times are labelled T1 and T2. The velocity V of the line is obtained from a fit to these measurements.

Figure 4 plots the quantity :

$$(T1 - T2) - \frac{2X}{V}$$

as a function of the position X along the line. The deviations from linearity never exceed a few nanoseconds, to be compared to a total propagation time of the signal along the line of 2588 ns. Based on the measurement of about 50 lines the dispersion of the inverse velocity around the average value of $V^{-1} = 600 \text{ ns/m}$ is found to be $\sim 1\%$.

4.3. DELAY LINE PERFORMANCE IN A DRIFT CHAMBER

The measurements are performed using cosmic ray muons. The chamber is horizontal and in sandwich between two $1 \times 30 \text{ cm}^2$ finger scintillators perpendicular to the anode wire of the chamber. The readout is triggered by a coincidence between these two scintillators and a third $40 \times 40 \text{ cm}^2$ scintillator under the chamber. The last scintillator is covered by 7 cm of lead to reduce the soft component in the cosmic rays. The spread of the muons due to the finite size of the scintillators has a r.m.s. error of 2.1 mm along the delay line. Each end of the delay line is connected to a buffer amplifier which matches the characteristic impedance and provides a conversion gain of $2 \text{ mV}/\mu\text{A}$. The delay line signal arrival times are measured with a Lecroy T.D.C. 2228A. The T.D.C. is started by the anode signal and has a least count of 1.5 ns. For these measurements the chamber is filled with $\text{Ar}-i\text{C}_4\text{H}_{10}$ (1-2) which produces streamer pulses of typically 50 mV into 50Ω . Figure 5 shows the inefficiency of the delay line (either T1 or T2 missing) as a function of the threshold setting. This measurement is performed at 12 cm from one end of the line where the inefficiencies are maximal since one of the signals is absorbed over the full 4.2 m length of the line. It is seen that the efficiency is better than 99% for thresholds of 20 μA or less. For thresh-

hold settings below 20 μA a small prepulse arriving 40 ns before the main pulse eventually passes the threshold. This prepulse is easily distinguished from the main pulse since it is always shorter than ~ 10 ns, whereas the main pulse lasts for at least 50 ns. This prepulse is easily discarded. The position along the line is obtained from T1 and T2 by :

$$X = (T1 - T2) \frac{V}{2}$$

or by

$$X = \frac{T1 - T2}{T1 + T2} \frac{L}{2}$$

The dispersion of the position measurement along the line with both methods is shown in figure 6. For the second method, the error is ~ 3 mm r.m.s. everywhere along the line. Note however that the beam spread alone is already 2.1 mm r.m.s.

5. STUDY OF SAFE GAS MIXTURES FOR A STREAMER DRIFT CHAMBER

5.1. INTRODUCTION

The safety considerations lead to the search for another quencher gas than $i\text{C}_4\text{H}_{10}$, subject to the following constraints for the operation of streamer drift chambers in our application :

- large pulse height for the streamer (> 50 mV into 50Ω) in order to induce sufficient signal into the delay line ;
- full detection efficiency at all drift distances with a threshold voltage of 20 mV on the anode signals ;
- anode voltage plateaux of sufficient length (> 100 V) to allow a single high voltage supply to power 22 chambers;
- acceptable level of afterpulsing ($< 10\%$) ;
- a drift velocity between 0.6 and 1.5 cm/ μs , the maximum drift field being limited to 1 kV/cm. These limits on the drift velocity are imposed by the beam crossing and by the presence of a magnetic field (up to 0.12 T) in the DELPHI end-caps [1].

Being non-inflammable, CO_2 is a good candidate either as substitute to iC_4H_{10} or as major quencher constituent. Moreover, gas mixtures containing a large concentration of CO_2 which is a cool gas [5], lead to a low drift velocity ($< 1\text{cm}/\mu\text{s}$) together with a small diffusion coefficient. Binary and 3-component gas mixtures composed of Ar , CO_2 and iC_4H_{10} were thus tested in streamer drift chamber prototypes.

5.2. PROTOTYPES AND EXPERIMENTAL SET-UP

Two 20 cm long prototypes are used to study the different possible gas mixtures.

One of them presents the final configuration of the DELPHI μ chambers and is tested in a cosmic ray hodoscope consisting of 3 scintillators and a lead absorber. Drift time and charge distributions are recorded by means of a Lecroy 2228A T.D.C. and a Lecroy 2250Q A.D.C. when detecting minimum ionizing particles.

In order to perform tests with radioactive sources, the second prototype has thin windows (70 μm aluminized mylar) and copper strips stretched in the gas to provide the drift field. This prototype is useful to determine the drift velocity and to study the chamber performance as a function of the drift distance.

The detector operation is investigated using 5.9 keV X-rays from Fe^{55} and β rays from Sr^{90} . Minimum ionizing β particles are selected by coincidence with a small thin plastic scintillator coupled to a PM mounted on the opposite side of the chamber.

For both chamber prototypes, the detection efficiency is studied by measuring the ratio of coincidences between anode signals and PM signals with respect to PM counts.

In order to minimize the loss of electrons during drift, care is taken to ensure gas purity : the use of glass and copper piping associated with the monitoring and trapping of electronegative impurities (H_2O and O_2) reduce oxygen to less than 10 ppm and water vapour to less than 20 ppm at the chamber exit when flushing at a rate which renews the gas 12 times per hour.

5.3. RESULTS OF GAS INVESTIGATIONS

Keeping in mind the safety requirement and the operational constraints mentioned above, we have tried gas mixtures composed of Ar, CO₂ and iC₄H₁₀ in various concentrations. Ar is used because it is a cheap noble gas, CO₂ for its safety and its quenching properties and iC₄H₁₀ because it is known to be one of the best quenchers among gaseous hydrocarbons.

In all gas mixtures, a comparison is made between proportional mode and streamer mode. The proportional mode is known and taken to be fully efficient and the streamer efficiency curves presented here are normalized to the proportional level. In this way, geometrical acceptance is taken into account.

A summary of the gas investigations is given in table 3 from which the following conclusions can be drawn :

1. As reported by several authors [6,7], the use of a better quencher or a higher concentration of quencher in the gas mixture leads to shorter streamer pulses and to longer plateaux. This is illustrated in figure 7 where the efficiency plateaux obtained in different gas mixtures using minimum ionizing β particles are shown.
2. For the binary mixtures composed of Ar and CO₂, the streamer pulses are large enough and well saturated but the detection efficiency drops dramatically with the distance from the anode wire, although less than 10% of primary electrons are lost during drift. This is confirmed by the study in proportional mode of pulse amplitude versus drift length for 5.9 keV X-rays.
3. The major problem with a CO₂-iC₄H₁₀ binary mixture is the height of the streamer pulses which are not saturated : about 10% of the signals remain under 20 mV into 50 Ω .
4. The 3-component mixtures can fulfil the conditions of safety and efficiency. Among them, the most suitable up to now is Ar-CO₂-iC₄H₁₀ in the proportions 15-70-15 ; figure 2 displays typical streamer pulses from a Sr⁹⁰ source and figure 8 a charge distribution recorded when exposing the chamber to a cosmic flux. Efficiency plateaux for both cosmic muons and beta's are shown in figure 9 for this mixture.

5.4. GENERAL OBSERVATIONS IN SELF QUENCHING STREAMER MODE

From the analysis of streamer signals, it is observed that pulse height and charge are independent of the drift distance and of the nature of the ionizing particles (X , β or μ) at fixed anode potential (figure 10) and increase with operating anode voltage.

The present study does not allow firm conclusions to be drawn about the streamer formation mechanism but the tests carried out with Fe^{55} and Sr^{90} indicate that the streamer threshold is related to the density of primary electrons arriving at the anode wire. This is illustrated by the plateaux taken at different distances from the anode wire using the radioactive sources Fe^{55} and Sr^{90} (figure 11).

Indeed, for the 5.9 keV X-rays which produce a local ionization of around 200 primary electrons, the streamer mode is found to be as efficient as the proportional mode in most mixtures. As can be seen from figure 11.a, the streamer singles rate plateaux are at the same level as those in proportional mode. The reduction of the counting rate with drift length is due to the reduction of the collection gap.

Minimum ionizing β particles are selected to measure the detector efficiency ; these β rays ionize the gas along their trajectory and create about 100 primary electrons per cm. The chamber's collection gap being of the order of 1 cm, the primary charge density is smaller than in the case of 5.9 keV X-rays. It is found that the streamer plateaux for the β particles can only be reached for higher anode potentials. Although the different efficiency plateaux are superimposed in proportional mode, in streamer mode they become shorter as the drift distance increases and eventually even disappear. (figure 11.b). This could be explained by a reducing number of primary electrons arriving per unit time at the anode wire. Several factors contribute to this effect. On one hand, due to the detector geometry, the reduction of the collection gap and the configuration of the drift lines leading to non isochronous electron arrival. On the other hand, inherent to all detectors, the phenomena of diffusion and attachment decrease the electron density.

Depending upon the gas mixture and the anode voltage, the passage of a single particle can induce a chamber response consisting of multiple pulses. This phenomenon arises either through oscillations on the trailing edge of the initial streamer or through afterpulsing due to electron extraction from the cathode. The former has no particular time structure whereas afterpulsing shows clear time intervals related to the anode-cathode distance. Both phenomena harm the detector performance and have to be considered in the choice of a suitable gas mixture. The relative amount of multiple pulses, called afterpulsing in table 3, has been determined by counting the chamber pulses, exceeding a 30 mV threshold, during a 30 μ s gate started by the trigger.

6. CONCLUSIONS

Drift chambers with about 10 cm maximum drift have been shown to operate successfully in the limited streamer mode. The important pulse height of the streamer signals allows the use of relatively slow and more absorbing delay lines. The tests of such a delay line with inverse velocity around 600 ns/m show a position resolution of better than 4 mm over a length of more than 4 m. The extensive study of several gas mixtures adequate for streamer production, shows that efficient chamber operation can be obtained in gas mixtures where a large fraction of hydrocarbon quencher is replaced by CO₂. Such mixtures are not only more attractive from the safety point of view, but also meet better our specific needs concerning streamer charge and drift velocity.

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TABLE 1

Main characteristics of the detector

LENGTH :	4350 mm
WIDTH :	197 mm
GAS GAP :	20 mm pinched to 14 mm in anode region
ANODE WIRE :	stainless steel, 100 μ m diameter, non magnetic
DRIFT FIELD ELECTRODES :	Cu strips 6 mm wide, 8 mm apart
NUMBER OF CHAMBERS/QUADRANT :	2 x 22
NUMBER OF QUADRANTS :	16

TABLE 2

Delay line characteristics

LENGTH :	4325 mm
WIDTH :	15 mm
THICKNESS :	1.8 mm
WINDING PITCH :	265 μ m
CHARACTERISTIC IMPEDANCE :	$\sim 620 \Omega$
INVERSE VELOCITY :	~ 600 ns/m
EXPONENTIAL ATTENUATION FACTOR :	$\alpha \sim 0.6 \text{ m}^{-1}$
FRACTION OF SIGNAL LEFT AFTER 4 m :	10%

TABLE 3

Summary of investigated gas mixtures ($O_2 < 10\text{ppm}$; $H_2O < 20\text{ ppm}$)

CO_2 -Ar- iC_4H_{10} (X - X - X)	PULSE (+) height duration (mV) (ns)		afterpulsing (0) (X)	EFFICIENCY $V_{th} = 30\text{ mV}$ 100% reached	anode plateau length at all drift distances for min. ioniz. part.	drift velocity (*) (cm/ μ s)	safety
0 - 35 - 65	60	50	10	OK	~ 250 V	3.0	bad
50 - 50 - 0	80	150	not measured	eff.(d) drops	---	1.15	OK
80 - 20 - 0	120	70	not measured	eff.(d) drops	---	0.85	OK
90 - 0 - 10	10X<20	70	not measured	OK ($V_{th}=5\text{mV}$)	~ 250 V ($V_{th}=5\text{mV}$)	0.6	OK
47 - 48 - 5	80	140	50	OK	~ 50 V	1.15	OK
45 - 45 - 10	130	120	50	OK	~ 50 V	1.25	OK
72 - 23 - 5	100	70	not measured	OK	~ 100 V	not measured	OK
70 - 15 - 15	100	80	8	OK	~ 200 V	0.7	OK

(+) approximate values given

(0) for minimum ionizing particles

(*) drift velocities measured for a drift field of 800 V/cm

FIGURES CAPTIONS

- Fig. 1. : Transverse cut of an individual drift chamber, unit detector cell of the DELPHI end-cap muon identifiers (units in mm).
- Fig. 2. : A typical oscillogram of streamer pulses in a 15/70/15 Ar-CO₂-iC₄H₁₀ gas mixture.
- Fig. 3. : Layout of the delay line.
- Fig. 4. : Linearity of the time-distance relation of the delay line tested on a bench. The departure from linearity is shown versus position.
- Fig. 5. : Inefficiency of the delay line as a function of threshold settings for muons incident at 12 cm of the delay line edge.
- Fig. 6. : Position resolution along the delay line for a threshold of 10 μ A.
- Fig. 7. : Efficiency plateaux obtained in streamer mode for different gas mixtures using minimum ionizing β particles from a Sr⁹⁰ source placed at 1.2 cm from the anode wire.
- Fig. 8. : Streamer charge distribution recorded in a Ar-CO₂-iC₄H₁₀ (15-70-15) gas mixture when exposing the chamber to a flux of minimum ionizing cosmic muons.
- Fig. 9. : Efficiency plateaux in Ar-CO₂-iC₄H₁₀ (15-70-15) gas mixture. Fig. 8.a shows the streamer plateau obtained with minimum ionizing β particles from a Sr⁹⁰ source placed at 1.2 cm from the anode and fig. 8.b for an exposure of the chamber to minimum ionizing cosmic muons.
- Fig. 10. : Variation of the streamer pulse height as a function of the anode voltage for both radioactive sources Fe⁵⁵ and Sr⁹⁰.
- Fig. 11. : Comparison of the chamber performance in both modes of operation : streamer and proportional, in a Ar-CO₂-iC₄H₁₀ (45-45-10) mixture. Fig. 11.a displays the Fe⁵⁵ singles rate plateaux and Fig. 11.b the Sr⁹⁰ efficiency plateaux, the radioactive sources being placed at different distances from the anode wire.

Figure 1

Fig. 2

Figure 3

Fig. 4

Figure 5

Figure 6

Figure 7

Figure 8

Ar-CO₂-iC₄H₁₀ (15-70-15)

Figure 9

V streamer (mV)

Fe⁵⁵

Ar-CO₂-iC₄H₁₀ (45-45-10)

STREAMER MODE

PROPORTIONAL MODE

Figure 11 a

Sr^{90}

$\text{Ar}-\text{CO}_2-i\text{C}_4\text{H}_{10}$ (45-45-10)

Figure 11 b