EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/83-81
June 17th, 1983

DRIFT PRECISION IMAGER

S. Bobkov¹, V. Cherniatin¹, B. Dolgoshein², G. Evgrafov¹,
A. Kalinovsky², V. Kantserov¹, P. Nevsky¹, V. Sosnovtsev¹,
A. Sumarokov¹, A. Zelenov¹

ABSTRACT

An analysis is given of possible ways of achieving extremely high coordinate accuracy and two-track-resolution in a drift chamber. A coordinate accuracy of 30 μm , and a two-track-resolution of 100 μm have been obtained for a 10 mm drift distance with the drift precision imager prototype. A large solid angle vertex detector is also discussed.

¹ Moscow Physical Engineering Institute, Moscow, USSR.

² Visitor at CERN, Geneva, Switzerland.

Submitted to Nuclear Instruments and Methods

1. INTRODUCTION

Particles produced in high energy collisions are expected to contain heavy quarks and have lifetimes of $\sim 10^{-13}$ sec. For their identification the separation of the decay vertex from the production vertex must be resolved and therefore a coordinate detector with extremely high spatial accuracy is needed. Such a detector is most efficient if it is close to the vertex and therefore a very good double track resolution is of great importance. Recently developed silicon detectors [1] could reach $\sim 10 \mu\text{m}$ accuracy and $\sim 150 \mu\text{m}$ resolution.

In this paper we describe a possible way of achieving results close to those mentioned above by means of drift chamber techniques. Experimental results from the testing of the drift precision imager (DPI) are also presented.

2. HOW TO MAKE A DPI

Three main components contribute to the intrinsic error of a drift chamber [2,5]. The first one is due to diffusion:

$$\sigma_d^2(X) = (2\epsilon X/eE) = (1/P) f(E/P) \quad (1)$$

where ϵ is the characteristic energy of an electron, X is the electron drift distance, e is the charge of an electron, E is the electric field and P is the gas pressure.

The minimum value of diffusion can be achieved by using "cool" gases where electrons are thermal ($\epsilon \approx kT$) up to high E/P as well as by using pressurized gases [3]. The best candidates for cool gases are polar molecular gases with a very high ($\sim 10^{-14} - 10^{-13} \text{ cm}^2$) momentum transfer cross section for thermal electrons, such as CO_2 , NH_3 and $\text{C}_2\text{H}_6\text{O}$ (dimethyl ether (DME)). The r.m.s. widths of diffusion in these gases are shown in Fig. 1 as functions of E .

The use of leading edge timing should give an error less than shown in Fig. 1 by a factor of ~ 2 . This means that in the case of cool gases the contribution to the measurement error due to diffusion can be estimated as

$$\sigma_d = 40/\sqrt{P} \mu\text{m}/\text{cm}^{1/2}$$

To achieve an accuracy of 10-20 μm for drift distances ≥ 1 cm it is necessary to use a pressurized ($P \geq \text{few atm}$) gas. An increase in the gas pressure has been studied systematically [5] and then used by the JADE Collaboration [6].

The second component contributing to the error of a drift chamber is due to fluctuations of primary ionisation on the track segments which go to the sense wires. It depends on the mean distance between two neighbouring ionisation clusters on the particle track and therefore decreases proportionally with increasing pressure. For small drift distances ($X \leq 5$ mm) $\sigma_i = 10^3/nP$ μm [2]. Here n is the mean number of primary clusters per cm of track length in the gas under normal conditions (~ 30 cm^{-1} for the gases mentioned above). Again it requires a pressure of at least a few atmospheres to achieved $\sigma_i \leq 10$ μm .

Other error components, independent of the drift distance, contributing to the error are due to long-range δ -rays, mechanical inaccuracies in the detector assembly, time fluctuations in avalanche formation and resolution of the electronics. Long-range δ -rays can be rejected, by deviation from the fitted track. The resolution of the electronics gives $\sigma_0 \approx 40$ μm for the standard drift velocity of 50 $\mu\text{m}/\text{ns}$ [2]. To reduce the contribution due to the limitation of the electronics as well as time fluctuations in the avalanche formation, the drift velocity should be as low as 5-10 $\mu\text{m}/\text{ns}$. It can be reduced by decreasing the electric field in the drift space (time expansion chamber [7]). Another method is to use a "slow" gas. It should be emphasized that the cool gases are always slow ones. Indeed, the drift velocity for thermal electrons is [8]:

$$V_{dr} = [(1/2)(e/m)(E/N)(1/\sigma(\epsilon)V)] \quad (2)$$

where m is the mass of an electron, N is the gas density in molecule/ cm^3 and V is the mean electron velocity depending on ϵ . Because the momentum transfer cross-section $\sigma(kT)$ is very large for cool gases, the drift velocity turns out to be rather small (see Fig. 2). Another feature of cool gases is the strictly linear dependence of drift velocity on the electric field, provided $\epsilon \approx kT$, as can be seen from Fig. 2 and expression (2).

In the case of a drift chamber operating in a magnetic field H , perpendicular to the electric field, the Lorentz angle should be kept as small as possible to avoid the worsening of coordinate accuracy, especially in the case of a non-uniform magnetic field. The Lorentz angle is given by the following expression [8]

$$\tan\theta_L = (eH/m) (1/NOV) \quad (3)$$

The value of σ is very large for cool gases, and θ_L turns out to be ≈ 0.03 (for CO_2) and ~ 0.01 (for NH_3 and DME) for $H = 0.5$ T. This is independent of the electric field, provided $\epsilon \approx kT$, (see equation (3)). With an increase of pressure, the Lorentz angle decreases as $1/P$.

Now we consider double track resolution. We begin with the case of ideal electron optics, that is zero mean drift-time difference of clusters originating from different places along the track segment. Then to obtain a good double track resolution ($\sim 100 \mu m$) it is necessary [3]:

- i) to minimize the electron diffusion (this has been discussed above);
- ii) to shape carefully the pulses by clipping the ion tail which is proportional to $1/(t+t_0)$. The value of t_0 depends on the ion drift velocity and, therefore, on the gas pressure (under normal conditions $t_0 < 1$ ns). The best signal shaping achieved so far is $\Delta_t \approx 10-15$ ns (FWHM) [9];
- iii) to keep the drift velocity low enough so that

$$(FWHM)_{\text{diffusion}} \geq \Delta_t v_{dr} \quad (4)$$

for $(FWHM)_{\text{diffusion}} \approx 50 \mu m$, $v_{dr} \leq 5 \mu m/ns$.

These requirements can be met by using pressurized cool gases (see Figs. 1 and 2).

The last question is how to approach ideal drift electron optics. The most radical approach is to detect the individual clusters in space [10]. Another method is to minimize the cluster drift time difference δ_t (and drift path δ_x difference), that is

$$\delta_x = v_{dr} \cdot \delta_t < (FWHM)_{\text{diffusion}} \quad (5)$$

The simplest way to meet this requirement is to use a drift geometry such as that shown in Fig. 3. As a first approximation, neglecting a drift velocity dependence on an electric field, for this drift geometry:

$$\delta_x^{\max} = 2R \sin^2 \theta/2 \approx a^2/8R < (\text{FWHM})_{\text{diffusion}} \quad (6)$$

For $(\text{FWHM})_{\text{diffusion}} = 50 \mu\text{m}$ and $R = 2 \text{ mm}$ (which is feasible in practice) $a < 900 \mu\text{m}$. The mean number of clusters produced on a track segment of 0.9 mm is ≈ 10 at $P = 4 \text{ atm CO}_2$. For the particles going at an angle β with the sense wire plane there is an additional condition:

$$\beta < \delta_x^{\max}/a \quad (7)$$

for $a = 0.9 \text{ mm}$ this means $\beta < 50 \text{ mrad}$.

Thus, from the above considerations one can conclude that a coordinate accuracy of $\approx 20 \mu\text{m/cm}^{1/2}$, a double track resolution of $\approx 100 \mu\text{m}$ and a Lorentz angle $\theta_L \leq 10^{-2}$ can be achieved if

- i) a cool gas at the pressure of a few atm. is used;
- ii) the drift velocity is low ($\sim 5 \mu\text{m/ns}$);
- iii) good electron optics are applied.

To check these conclusions tests of a DPI prototype have been carried out.

3. EXPERIMENTAL TEST OF DPI

3.1. Detector

The detector used in test measurements consists of two metal plates ($120 \times 60 \text{ mm}^2$) with a gap of 15 mm between them. In the lower electrode there are eight cylindrical proportional chambers (CPC) see Fig. 4. The walls of the 4 mm diameter holes in the electrode act as the CPC cathodes. The sense wires (gold plated tungsten, $\emptyset 20 \mu\text{m}$) were mounted to an accuracy of a few microns by positioning them with the aid of a microscope.

The detector was placed into a pressure vessel. In order to reduce multiple scattering in the walls of the vessel, their thickness was 1 mm of aluminium. The detector operated at pressures up to 9 atmospheres with CO_2 . Since CO_2 is a bad quencher, adding a few per cent (typically 8%) of isobutane C_4H_{10} considerably improved the proportional operation up to an electron gain of $\sim 2 \cdot 10^5$ (typically a gain of $5 \cdot 10^4$ was used).

The chamber operated with the sense wires at ground potential and the upper and lower electrodes at two different negative voltages. The sense wires were connected to current amplifiers with a 5 ns rise-time. For signal shaping a special active filter was used [9] in order to cancel the pulse tail. The resulting ionisation pulse from an Fe^{55} source had a symmetrical shape, with FWHM = 10 ns.

The gas had been purified to give an O_2 impurity level of less than 10 ppm.

3.2. Choice of Gas Pressure

The characteristics of V_{dr} and σ_{diff} with a gas mixture 92% CO_2 + 8% C_4H_{10} were studied with the help of a special chamber. The drift velocity was measured by means of α -particle current pulse time duration. Pu^{239} ($E_\alpha = 5.15$ MeV) placed on the cathode of a flat ionisation chamber was used as a source for these measurements. Fig. 5 shows the dependence of the electron drift velocity on the electric field for different gas pressures. Fig. 6 shows the ratio of $V_{\text{dr}}(P)/V_{\text{dr}}(P = 1 \text{ atm})$ for $E/P = \text{const.}$. Above 4 atm pressure there is a deviation from the law: $V_{\text{dr}} = f(E/P = \text{const}) = \text{const.}$ According to [11], at high pressures the drift of electrons in CO_2 is modified by the process

During a part of its drift time an electron might be bound in a $[\text{CO}_2]_n$ molecular complex. This should lead to the decreasing of drift velocity and to the appearance of delayed electrons which can give rise to "after pulses".

The measurements of electron diffusion have been made by means of the observation of pulses of point-like ionisation produced by an Fe^{55} gamma source ($E_\gamma = 5.9$ KeV) for a drift distance of 16 mm. The results are shown in Fig. 7. All curves rise at high electric field due to the increase of diffusion of "heated" ($\epsilon > kT$) electrons. It is necessary to note that the behaviour of the curves in Fig. 7 violates E/P scaling (especially for $P > 4$ atm) probably due to the process (8).

The pressure $P = 4$ atm looks most favourable and has been used in most of the coordinate measurements. The energy resolution (at $P = 4$ atm) was measured (for $E_\gamma = 5.9$ KeV) to be 22% (FWHM).

3.3. Experimental Results

The DPI has been tested in a 4 GeV/c hadron beam. The coordinate accuracy of the detector has been measured using events selected by fitting a straight line to at least seven (out of eight) points (sense wires). The overall loss of events due to the fitting procedure did not exceed 10%.

Further we define the coordinate accuracy based on the measurement of a quantity:

$$\Delta_2 = (t_{i-1} + t_{i+1} - 2t_i), i = 2, \dots, 6 \quad (9)$$

The measured distribution of Δ_2 is shown in Fig. 8. We fit a Gaussian curve to this distribution and determine σ_Δ . The final quantity is $\sigma = \sigma_\Delta / \sqrt{6}$. The dependence of the coordinate accuracy σ on the drift distance X is shown in Fig. 9.

The extrapolation to the value of $X = 2$ mm (the beginning of the drift space) gives $\sigma(X = 2) \approx 17 \mu\text{m}$. Using data shown in Fig. 7 it is possible to calculate the contribution of the diffusion in the anode space: $\sigma_a \approx 10 \mu\text{m}$. Thus one can calculate the contribution of the X -independent component (electronics, mechanical inaccuracies, etc.) to be about $7 \mu\text{m}$ and the diffusion in the drift space: $\sigma_{\text{diff}} = (27 \pm 1) \mu\text{m cm}^{-1/2}$.

The measurements of coordinate accuracy have been carried out for different electron drift velocities (Fig. 10) and gas pressures (Fig. 11). For gas pressures above 5 atm the coordinate accuracy is worse, probably due to the process (8) and the after-pulse rate increasing with increasing pressure.

Finally, for the chosen gas pressure of 4 atm and drift velocity $V_{\text{dr}} = 4 \mu\text{m/ns}$, the drift chamber efficiency for minimum ionising particles (for an individual sense wire) was found to be $> 97\%$.

3.4. Double Track Resolution

We define the double track resolution η as the distance between two tracks when the second track detection efficiency is 70%. To produce a sample of multi-track events a thin (4 mm) copper target was placed in front of the detector. The method of fixed discriminator threshold was used for two particle separation. The multihits on an individual sense wire were registered by a multiplexer and three TDC's allowing up to three hits.

Multi-track events were selected using a track reconstruction programme similar to the one mentioned in the previous section. Using fitted parameters the distance between tracks was determined for all sense wires. The second track detection efficiency was determined by checking if there was a pulse corresponding to the second track. The dependence of the second track detection efficiency on the distance between two tracks is shown in Fig. 12.

To study the influence of the "first" track on the coordinate accuracy of the "second" one, the distribution of the second track coordinate deviations from a straight line fit has been measured as a function of the distance between the two tracks. From the results shown in Fig. 13 it follows that this influence is very small for distances greater than 100 μm between the two tracks.

4. REMARKS ON A LARGE SOLID ANGLE DPI

The DPI described above has demonstrated excellent characteristics, with a coordinate accuracy of $\sigma \approx 30 \mu\text{m}$, and double track resolution of $\eta \approx 120 \mu\text{m}$. However, because of the considerable amount of matter concentrated in the cathode plates the use of this detector in its present version is strongly restricted to certain fixed-target experiments. In the case of experiments on colliding beams and other fixed-target experiments a vertex detector covering a large solid angle ($> 2 \pi$) is needed. We have studied particularly the requirements of an experiment for the CERN SPS [12].

Here we consider a large solid angle vertex detector (Fig. 14). In this configuration the thick metal cathode plates are replaced by very thin ($\sim 10 \mu\text{m}$) mylar sheets stretched on the support wires ("sawtooth" electrodes), the sense wires being inside. The drift electron optics in this geometry is very close to that of the DPI prototype described above, and it could be expected that the values of σ and η should be also close to those obtained experimentally.

The operation of the detector with the sawtooth electrode configuration has been simulated. The simulation programme accounted for:

- the real electric field configuration;
- the drift velocity and diffusion dependence on the electric field;
- the Poisson distribution of primary ionization clusters;
- the Landau distribution of cluster energy;
- avalanche fluctuations;
- the ion tail $\sim 1/(t + t_0)$;
- the response function of shaping electronics.

The comparison of the results predicted by this programme with the experimental ones is shown in Fig. 9 and Fig. 12. The good agreement with the experiment enables one to rely on the simulation programme when predicting the operating characteristics of the detector with the sawtooth electrode configuration.

When simulating the detector operation the particle tracks were considered to be parallel to the sense wire plane and the sense wire electric field was chosen to correspond to a gain of $\sim 10^4$. The response function of the shaping electronics was chosen in the form:

$$I(t) \sim \exp(-t^2/\tau^2)$$

The parameter τ was optimized in order to achieve the best two track resolution as well as the minimum false pulse rate.

The results of the simulation are shown in Figs. 15 and 16.

The sawtooth geometry offers, in principle, the possibility of measuring the coordinate along the sense wire by imprinting strips (or pads) onto the cathode sheet and detecting the distribution of induced signals.

5. CONCLUSION

The possibility of a high precision imaging detector has been demonstrated. A positional accuracy of $\sim 30 \mu\text{m}$ and double track resolution of $\sim 100 \mu\text{m}$ have been achieved. The positional accuracy of the DPI can be improved perhaps up to $\sim 10 \mu\text{m}$ by using gases with lower electron diffusion, and averaging measurements of several neighbouring sense wires. Thus, the DPI becomes comparable with the multi-electrode silicon detectors. The much simpler technology of the DPI and its pattern recognition possibilities should be additionally emphasized.

This approach could be used for the construction of high precision vertex detectors for fixed-target experiments as well as for experiments on colliding beams.

ACKNOWLEDGEMENTS

We would like to thank V. Kzasnokutsky and R. Shuvalov for their help with shaping electronics and to thank also G. Charpak, C. Fabjan, B. Sadoulet and W. Willis for many valuable discussions. The staff of the IHEP accelerator are acknowledged for help with the measurements.

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FIGURE CAPTIONS

Fig. 1: The r.m.s. diffusion width for a 1 cm drift distance as a function of the electric field E for different cool gases.

Fig. 2: The dependence of drift velocity on E for different cool gases.

Fig. 3: The simplest DPI geometry.

Fig. 4: The DPI prototype.

Fig. 5: The dependence of drift velocity on E for different pressures of CO_2 .

Fig. 6: The decrease of drift velocity with increasing gas pressure at fixed E/P .

Fig. 7: The dependence of longitudinal diffusion in CO_2 on E for different gas pressures.

Fig. 8: The measured distribution of the quantity $\Delta_2 = (t_{i-1} + t_{i+1} + 2t_i)$.

Fig. 9: The dependence of the coordinate accuracy (r.m.s.) on the drift distance X_{dr} . The results of Monte-Carlo calculations are shown by a solid line.

Fig.10: The dependence of the coordinate accuracy (r.m.s.) on the drift velocity for $X_{\text{dr}} = 5$ mm.

Fig.11: The dependence of the coordinate accuracy (r.m.s.) on the gas pressure $X_{\text{dr}} = 8$ mm.

Fig.12: The dependence of the second track detection efficiency on the distance X_{12} between two tracks. A dashed line represents the results of Monte-Carlo calculations.

Fig.13: The second track coordinate accuracy as a function of the distance X_{12} between two tracks.

Fig.14: The drift geometry of a large solid angle vertex detector (the sawtooth geometry).

Fig.15: The dependence of the coordinate accuracy σ and the two-track resolution η on the drift distance X_{dr} for the sawtooth geometry.

Fig.16: The dependence of the coordinate accuracy σ and the two-track resolution η on the gas pressure for the sawtooth geometry.

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