



ELSEVIER

Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Nuclear Instruments and Methods in Physics Research A 548 (2005) 582–589

NUCLEAR
INSTRUMENTS
& METHODS
IN PHYSICS
RESEARCH
Section A

www.elsevier.com/locate/nima

Technical Note

High-precision measurement of the electron drift velocity in Ne–CO₂

J. Wiechula^{a,*}, P. Braun-Munzinger^a, H. Daues^a, U. Frankenfeld^a, C. Garabatos^a,
J. Hehner^a, R. Renfordt^b, H.R. Schmidt^a, H. Stelzer^a, D. Vranić^a

^a*Gesellschaft für Schwerionenforschung, Planckstr. 1, D-64291 Darmstadt, Germany*

^b*Institut für Kernphysik der Universität Frankfurt, Max von Laue Straße 1, D-60438 Frankfurt, Germany*

Received 19 May 2005; accepted 24 May 2005

Available online 22 June 2005

Abstract

The baseline gas mixture which will be used in the ALICE TPC is 90% Ne and 10% CO₂. The change of the drift velocity due to changes of the CO₂ concentration as well as N₂ addition has been studied in high-precision measurements at drift fields between 100 and 900 V/cm. Also a precise absolute measurement of the drift velocity has been made. All measurements are compared with calculations.

© 2005 Elsevier B.V. All rights reserved.

PACS: 29.40.Gx

Keywords: ALICE; TPC; Drift velocity; Ne–CO₂ mixture; CO₂ dependence; N₂

1. Introduction

For large TPCs it is very important to understand how the electron drift velocity behaves if the gas parameters such as composition, pressure and temperature change [1]. The ALICE TPC [2–4]—as other TPCs before (NA49, CERES)—is operated with a Ne–CO₂ gas mixture. For the ALICE TPC the gas composition is 90% Ne and 10%

CO₂. Ne is chosen mainly because of the high mobility of its ions and its long radiation length. This reduces the accumulation of charge in the drift volume in the high multiplicity heavy-ion collisions at the LHC. CO₂ was chosen as quencher to avoid ageing. Hydrocarbons such as methane would lead to severe ageing of the detector after a few years of operation [5]. The choice of the gas mixture also results in the desired feature of a small diffusion. However, the relatively low drift velocity in CO₂-based mixtures has to be compensated by a large drift field. Nonetheless, the drift velocity is non-saturated within

*Corresponding author. KP1, GSI, Planckstr. 1, 64291 Darmstadt, Germany.

E-mail address: J.Wiechula@gsi.de (J. Wiechula).

the technically feasible field strengths. This implies a strong dependence of the drift velocity on the temperature. Moreover, the drift velocity strongly depends on the exact amount of CO₂ as well as on N₂ admixtures.¹

To meet the detectors intrinsic position resolution in drift direction, a stability of the drift velocity of 1‰ is required. Therefore, it is essential to understand how this is reflected in the stability of the gas parameters.

For the ALICE TPC a recirculating gas system is used. Due to small leaks N₂ accumulates in the drift gas with time. A precise knowledge of how this affects the drift velocity is therefore necessary. Since the gas is mixed on site, the effect of a changing CO₂ concentration also has to be understood.

A dedicated measurement for a Ne–CO₂ [90-10] mixture investigating changes in the CO₂ concentration and on N₂ addition with high precision has not been carried out yet.

High-precision measurements also help to understand the quality of simulation programs and to develop them further.

In this paper we present measurements of the electron drift velocity investigating the above-mentioned changes in the gas composition. An absolute high-precision measurement has been carried out as well. All results are compared with calculations performed with the simulation program Magboltz [8].

2. Experimental set-up

The measurements were carried out employing a small, specially built TPC. Two ionising laser beams are guided through the gas volume at a distance of 37.5 and 187.5 mm from the readout chamber, respectively. The drift velocity is determined by the relative distance of the two laser beams and the difference of the electron arrival time at the readout chamber.

¹Recent investigations [5] showed that adding a few percent of N₂ to the Ne–CO₂ gas mixture greatly improves the stability of the readout chamber at high gain. The resulting changes of the drift velocity and gas gain are acceptable.

A sketch of the set-up is shown in Fig. 1. The size of the gas box is about (43 × 43 × 43) cm³. It includes the HV-plate (a), the field cage which is mounted on the HV-plate (b) and the readout chamber (c). To avoid breakthrough from the HV-plate or the field cage to the grounded gas containment box they are built much smaller than the box itself.

The field cage consists of 16 field strips which are connected by a resistor chain to degrade the potential and provide a homogeneous drift field. Fields up to ≈ 900 V/cm (20 kV on the HV-plate) can be reached. The power dissipation of the resistors at 20 kV is ≈ 1.2 W.

To monitor the temperature in the gas, three temperature sensors (d, cf. Section 4.2) are installed in the gas volume, but outside of the field cage. The sensor on the top is placed directly above the resistor chain.

The readout chamber is a small-size prototype of the ALICE TPC inner readout chamber [2]. It consists of a segmented cathode plane with 12 × 5 mm² readout pads and three wire planes: a sense wire plane, a cathode plane and a gating grid. Their distances from the pad plane are 2, 4

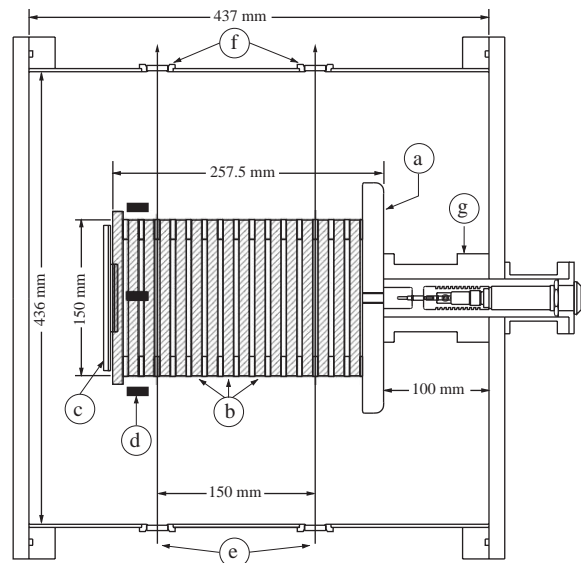


Fig. 1. Sketch of the experimental set-up: a—HV-plate, b—field strips of the field cage, c—readout chamber, d—temperature sensors, e—laser beams, f—quartz windows, g—support for the HV-plate.

and 7 mm, and the wire thicknesses are 20, 75 and 75 μm , respectively. Since the focus of the measurement is on the drift velocity, only the two most central pads are read out to minimize the influence of field distortions. All other pads are grounded.

A preamplifier and shaper-amplifier [6] of the ALEPH TPC are used to read out the pad signals. The shaper-amplifier signal is digitised by an ADC-board [7] which was built as a prototype for the ALICE TPC front end electronics.

A Nd–YAG laser² with a wavelength of 266 nm was used to ionise the gas in the TPC. The laser beam is widened by a set of lenses and split by a 50% mirror. The distance between the two resulting beams, 15 cm, is defined by two precisely machined (cf. Section 4) and aligned double diaphragms. The openings of the diaphragms (diameter 1 mm) select the most homogeneous part of the widened beam.

Essential parameters of the drift gas such as the O₂ and CO₂ concentration, as well as temperature and pressure, were constantly monitored by appropriate sensors. Their contribution to the accuracy of the measurement is discussed in Section 4. The sensors were read out by a 12 bit ADC system.³

Fig. 2 demonstrates the relative resolution of the set-up. Shown is the drift velocity as a function of temperature over a range of about 0.5 °C. The drift velocity is a function of ET/P and should, therefore, depend linearly on T at constant E/P . The measured deviation from a straight line fit is $\sigma = 0.04\%$.

3. Results

In this section we present the measured electron drift velocities in Ne–CO₂ [90–10] and their dependences on small variations of the CO₂ concentration and the addition of N₂, respectively. The results are compared with calculations done with the simulation program Magboltz [8].

²Spectron Laser Systems, Series SL 400, Model SL 404T.

³WAGO Kontakttechnik GmbH, WAGO-I/O-SYSTEM 750.

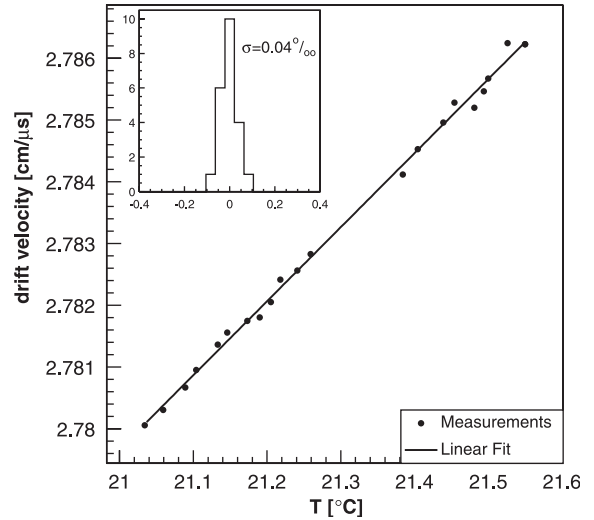


Fig. 2. Drift velocity as a function of the temperature at 400 V/cm, 9.82% CO₂. The inset shows the differential non-linearity in %.

The Magboltz program solves the Boltzmann transport equation. It uses a solution for the energy distribution function up to the third Legendre polynomial. With the known electron cross-sections for the different gases, it is then possible to calculate the electron drift velocity as well as the longitudinal and transverse diffusion coefficients.

The O₂ concentration in the gas was less than 10 ppm. Unless otherwise specified, all measurements are corrected such that they correspond to $T_0 = 300$ K and $P_0 = 1$ bar.

The pressure and temperature correction of the drift velocity is done in the following way:

The measured drift velocity w is plotted as a function of ET/P , where T and P are the mean values of the temperature and pressure during the measurement at each field strength E_i .

To correct the measurement at a given field E_i , the data are fit with a second order polynomial $\mathcal{F}(x = ET/P)$ in a region $E_i \pm 100$ V/cm. To obtain the corrected value of the drift velocity w_0 at the desired $E_i \cdot T_0/P_0$, we evaluate the polynomial at the desired point ($w_{0i} = \mathcal{F}(E_i \cdot T_0/P_0)$).

This correction procedure is preferred over a simple scaling of the electric field ($E'_i = E_i T_i / P_i \cdot P_0 / T_0$), because it allows one to compare

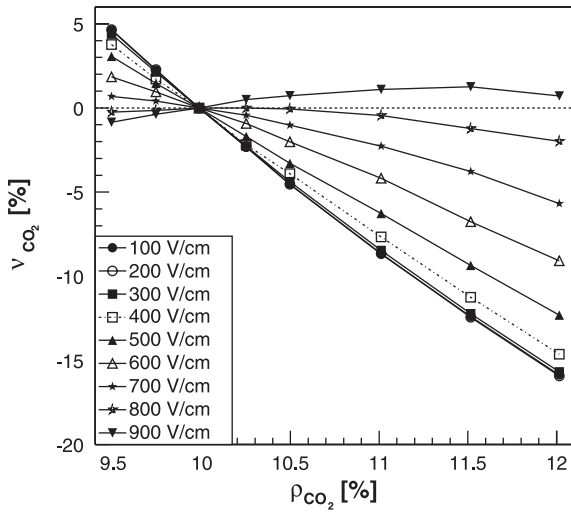


Fig. 3. CO₂ dependence of the relative change of the drift velocity around 10% CO₂. The lines are drawn to guide the eye. The error bars are smaller than the point size. For details see text.

measurements taken at different T_i and P_i for the same E_i .

3.1. CO₂ dependence

Fig. 3 shows the measured relative change of the drift velocity as a function of the CO₂ concentration. The CO₂ concentration (ρ_{CO_2}) was varied from 9.5% to 12%. The relative change of the drift velocity is defined as $v_{\text{CO}_2} = 100(w_\rho - w_{10})/w_{10}$ [%], where w_ρ and w_{10} are the measured drift velocities at a CO₂ concentration ρ and at $\rho = 10\%$, respectively.

Fig. 4 shows the relative change of the drift velocity per CO₂ change ($dv_{\text{CO}_2}/d\rho_{\text{CO}_2}$) at $\rho_{\text{CO}_2} = 10\%$ as a function of the field. The slopes ($dv/d\rho$) are obtained from a straight line fit to the curves of Fig. 3 including the point at 10% and the two neighbouring points. For example, a value of -7.7 at 400 V/cm means that changing the CO₂ concentration from 10.0 to 10.1% ($\Delta\rho = 0.1\%$) decreases the drift velocity by 7.7‰.

The experimental results (closed symbols) given in Fig. 4 are compared with Magboltz calculations (open symbols). The dependence of the measured value on the drift field is well reproduced by the calculations. It should, however, be mentioned

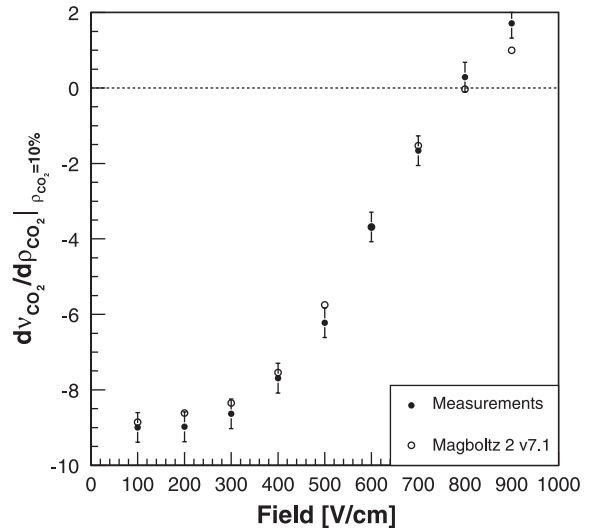


Fig. 4. CO₂ dependence of the drift velocity around 10% CO₂ as a function of the electric field.

that the experimental error bars represent a “methodical” error introduced by the ad hoc straight line fit to the data points in Fig. 3. The accuracy of the individual data points is much higher. The disagreement between data and calculations on a point-by-point comparison of drift velocities is up to 3% (for detailed discussion see Section 3.3).

3.2. N₂ dependence

Fig. 5 shows the relative change of the drift velocity if N₂ is added to the nominal gas mixture. The N₂ concentration is denoted with $\rho_{\text{N}_2} := V_{\text{N}_2}/V_T$, where V_{N_2} and V_T are the N₂ volume and the total volume of the gas mixture, respectively. The relative change of the drift velocity is defined as $v_{\text{N}_2} = 100(w_\rho - w_0)/w_0$ [%], where w_ρ and w_0 are the measured drift velocities at a N₂ concentration ρ and at $\rho = 0\%$, respectively.

Fig. 6 summarises the results of the different measurements presented in Fig. 5. Shown is the change of the drift velocity per added percent of N₂ as a function of the electric field. This value is obtained as the slope of a straight line fit over the full range applied to each curve in Fig. 5. Adding

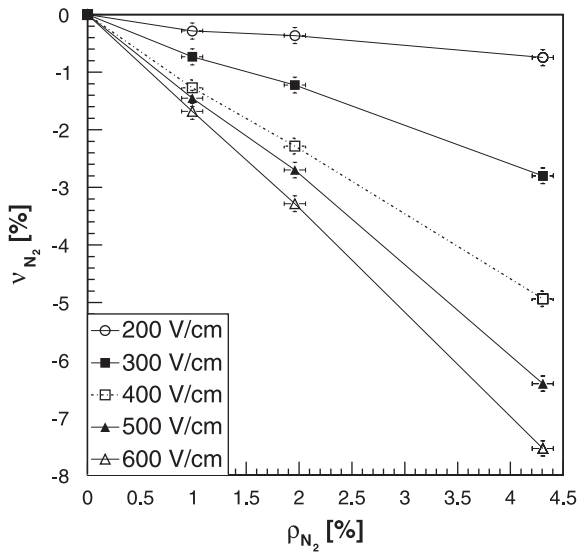


Fig. 5. N_2 dependence of the relative change of the drift velocity. The lines are drawn to guide the eye. For details see text.

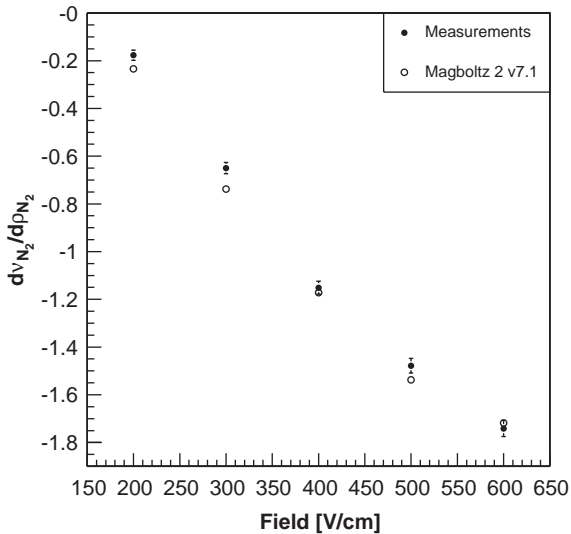


Fig. 6. N_2 dependence of the drift velocity as a function of the electric field.

1% of N_2 will thus result in a decrease of the drift velocity of 1.15% at 400 V/cm.

As can be seen from Fig. 6, Magboltz shows the same trend in the velocity change as the measurements. The agreement of the data points is,

however, only given within several percent. As already mentioned in Section 3.1 this results from a deviation of the absolute drift velocities up to 3% (cf. Section 3.3).

3.3. Absolute measurement of the drift velocity

Fig. 7 shows the results of an absolute measurement of the drift velocity as a function of the electric field in steps of 20 V/cm. The data are referred to $T_0 = 293.15$ K and $P_0 = 1$ bar.

The CO_2 concentration during the measurement was $9.82 \pm 0.01\%$. The uncertainty of the drift velocity is less than 1% and the accuracy of the corrected electric field ($E_i T_0 / P_0$) is better than 0.8%. These values are discussed in detail below (cf. Section 4).

At the given conditions, the drift velocity at the ALICE TPC nominal drift field (400 V/cm) is 2.799 cm/ μ s.

Comparing measurements and calculations we find a disagreement of up to 3% (see inset of Fig. 7). The uncertainty of Magboltz is in the order of 0.5% [9]. A reconciliation from the experimental side would require a systematic error in either ET/P of $\approx 2\%$, or in the CO_2

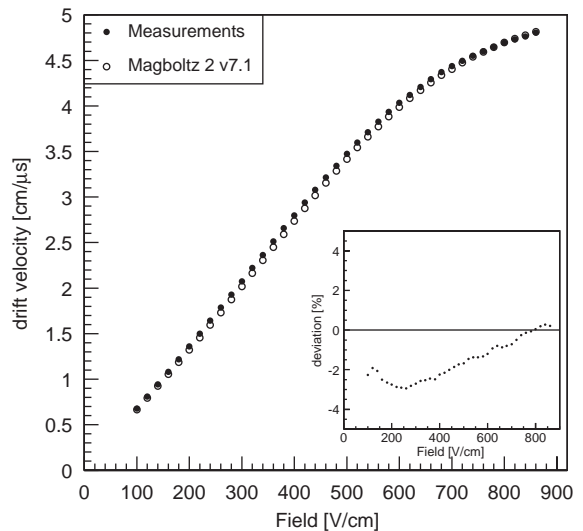


Fig. 7. Drift velocity scan in steps of 20 V/cm. The error bars are smaller than the point size. The inset shows the deviations of the calculations from the measurements.

concentration of about 3%; values which can be safely excluded (cf. Section 4) by the experimental uncertainties.

The effect of water contamination can be excluded because it would lead to a correction in the opposite direction.

In the analysis, all gases were treated as ideal gases. Effects of CO₂ not being an ideal gas have also been considered. They would reduce the discrepancy by at most 0.3%.

4. Calibration and uncertainties

In this section we describe the different sensors used and their precision, and discuss their contribution to the precision of the measurement.

4.1. CO₂ sensor

The CO₂ sensor⁴ used measures the CO₂ concentration via the thermal conductivity of the gas. The sensor is tuned to measure CO₂ in Ne. It was calibrated before each measurement. After the measurement the calibration was checked again. This was done using the internal two-point calibration method of the sensor. For this purpose a zero gas (100% Ne) and a gas mixture of known composition ($\rho_{\text{CO}_2} = 10\%$) were used. This mixture has a precision of 1‰, according to the manufacturer.⁵

The sigma of the fluctuations for multiple measurements of the combination sensor-readout is $\sigma_{\text{CO}_2} = 0.0031\%$. At 10% CO₂ this corresponds to a relative error of $\sigma_{\text{CO}_2}/\text{CO}_2 < 0.5\%$.

4.2. Temperature sensors

The temperature sensors⁶ are Pt1000 (Platinum, 1000 Ω at 0 °C) sensors. The temperature measurement is based on the ohmic resistivity change with temperature of metals, in this case platinum. The

relation between resistance and temperature is described in DIN EN 60 751.

The statistical error of the combination sensor-readout was measured to be $\sigma_T = 0.0085$ °C. At a temperature of 20 °C this gives a relative error of $\sigma_T/T < 0.5\%$.

For an absolute calibration, a calibrated sensor⁷ with a specified uncertainty of ± 0.01 °C was used, that corresponds to a relative error of 0.5‰. This sensor was read out by a Keithley 2700 multi-meter with a precision of 0.5‰.

4.3. Pressure sensor

The pressure sensor⁸ used operates on the piezo-resistive measuring principle. The output signal is a DC current that is proportional to the input pressure.

The accuracy of the sensor was defined as the sigma of fluctuations for multiple measurements of the combination sensor-readout: $\sigma_P = 0.11$ mbar. At a pressure of about 1000 mbar, the relative error is $\sigma_P/P \approx 0.1\%$.

For the absolute calibration of the sensor a high precision current meter (Keithley 2700) has been used. The calibration sheet of the sensor is used to calculate the pressure. The maximum systematic error is 0.4‰.

4.4. Electric field

The electric field E is given by $E = U/d$ where U is the applied high voltage and d the distance between the HV drift electrode and the zero volt plane. The exact location of the zero volt plane is depending on the applied HV on the HV electrode and on the anode wires. Even if the gating wires are set to 0 V, the field of the anode wires leaks through the cathode and gating grid thus pushing the average zero volt plane towards the HV-plate. To understand the size of this effect, electrostatic calculations were carried out with the simulation program GARFIELD [10].

⁴Panametrics, XMTC Thermal Conductivity Transmitter.

⁵LINDE AG, Spezialgase Produktion, Carl-von-Linde-Str.25, 85716 Unterschleißheim, Germany.

⁶JUMO, Surface resistance thermometer (90.2522), PT1000 4-wire circuit, Tolerance class A (DIN EN 60 751).

⁷Purchased from JUMO, calibrated by 'Deutscher Kalibrierdienst' at the 'Physikalisch Technische Bundesanstalt'.

⁸JUMO, 'Präzisions-Druckmessumformer' Type 4364-242/091.

The calculations show that the deviation in d between the zero volt equipotential line fixed at the position of the gating wires and one pushed towards the HV electrode due to the leakage of the anode wires is below 1.3‰. For the absolute measurement of the drift velocity, the calculated values of the field were used.

To determine the HV applied to the HV-plate, a voltage divider with a precision better than 10^{-4} was used. The voltage drop on the divider was measured with a voltmeter (Keithley 2700) with a precision better than 50 ppm. Therefore, the precision of the HV is in the order of 10^{-4} .

The uncertainty of d is given by the mechanical precision Δd of the field cage, which is better than 100 μm . For $d = 232.5\text{ mm}$, this results in the relative error $\Delta d/d \approx 0.43\%$.

The resulting relative error of the electric field is therefore $\approx 0.44\%$ and the calculated error of the corrected field ET/P is 0.78‰.

For the relative measurements presented in Sections 3.1 and 3.2, the precise voltage divider was not yet available. The precision of the HV for these measurements is in the order of 1%, therefore, it is the main source of error for the electric field and the electrostatic calculations have not been taken into account.

4.5. Drift velocity

The drift velocity w is determined as $w = \Delta l/\Delta t$ with Δl being the distance between the two laser beams, given by the distance of the openings in the double diaphragm, and Δt the difference of the electron arrival time.

Using a differential measurement, systematic effects affecting both beams in the same way, e.g., field distortions near the readout chamber, are cancelled. By averaging over 1000 measurements, the statistical error of w is minimized and is not taken into account.

The systematic error of Δt is mainly given by the precision of the ADC clock, for which an external frequency synthesiser⁹ with a precision of $<0.2\%$ was used.

⁹Wavetek Synthesized Arbitrary Waveform Generator model 395.

Table 1
Summary of statistical and systematic errors

Parameter	Stat. [‰]	Syst. [‰]
CO ₂	<0.5	1
T	<0.5	0.5
P	0.1	0.4
E		0.44 (10)
w	$\ll 1$	<1

The distance Δl of the openings in the diaphragms which define the laser beam distance was measured with a precision of better than 100 μm .

For the drift velocity w this results in a relative error better than 1‰.

4.6. Summary of errors

Table 1 summarises the errors discussed above. Listed are the statistical (stat.) as well as the systematic errors (syst.).

5. Summary

The electron drift velocity in Ne–CO₂ was measured up to about 900 V/cm at a relative resolution better than 0.1‰. The absolute precision is at the per mill level.

The measurements show that the drift velocity in Ne–CO₂ [90–10] is very sensitive to changes in the gas parameters:

Up to about 500 V/cm the drift velocity is, in good approximation, a linear function of the electric field. Above 600 V/cm the dependence flattens, but no plateau can be seen in the measured region.

For low fields, the drift velocity depends very strongly on the CO₂ concentration of the gas. Increasing the CO₂ concentration results in a decrease of the drift velocity. At a field of about 780 V/cm no dependence can be seen, and above this field strength the drift velocity rises with increasing CO₂ concentration.

The drift velocity depends almost linearly on N₂ additions of up to 4.5%. The drift velocity decreases with increasing N₂ concentration in the gas.

As described in Section 1 a drift velocity stability of 1‰ is required to fulfil the physics requirements for the ALICE TPC. To reach this goal a temperature stability of 0.1 °C is aimed at [2]. As the measurements presented in this paper show, the stability of the CO₂ concentration must be within $(10.000 \pm 0.013)\%$ and variations of the N₂ concentration have to be kept below 0.9%. As the requirements are very challenging we will install dedicated devices¹⁰ to constantly monitor the gas quality via the electron drift velocity.

Comparing the measurements with calculations performed with the simulation program Magboltz, a puzzling disagreement of up to 3% is seen. An explanation of this discrepancy in terms of experimental uncertainties would require corrections of 2% in *ET/P* or 3% in the CO₂ concentration. These values are beyond the quoted experimental uncertainties.

Acknowledgements

The authors would like to thank H. Junk for setting up the gas mixing station. The commu-

nication with S.F. Biagi about Magboltz was very helpful and we would like to acknowledge all his efforts on this topic.

References

- [1] V. Eckardt, et al., Nucl. Instr. and Meth. A 349 (1994) 56.
- [2] ALICE TPC Technical Design Report, CERN/LHCC 2000-001.
- [3] H. Stelzer, et al., ALICE-INT-2003-017.
- [4] U. Frankenfeld, et al., ALICE-INT-2002-030.
- [5] C. Garabatos, Nucl. Instr. and Meth. A 535 (2004) 197.
- [6] S.R. Amendolia, et al., Nucl. Instr. and Meth. A 289 (1990) 569.
- [7] J. Baechler, et al., Front-End Electronics for the ALICE TPC-Detector, in: Proceedings of the Fourth Workshop on Electronics for LHC Experiments, 1998.
- [8] S.F. Biagi, Nucl. Instr. and Meth. A 421 (1999) 234
Magboltz 2, version 7.1, is available from the author, sfb@hep.ph.liv.ac.uk.
- [9] S.F. Biagi, private communication.
- [10] R. Veenhof, Nucl. Instr. and Meth. A 419 (1998) 726
<http://consult.cern.ch/writeup/garfield/>

¹⁰In these drift monitors, the drift time is inferred from sampling the arrival times of electrons created by α -sources at two different positions relative to an electron pickup counter.