Fast Gases for the ATLAS Monitored Drift Tubes

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ABSTRACT

Gases containing Ar, CO_2, Ethane and N_2 have been analysed for their suitability for the Monitored Drift Tubes. Drift velocities, diffusion, Lorentz angles and space drift time relations for a non-flammable saturated gas and it's derivatives have been calculated. Contributions of several parameters to the resolution under the influence of the magnetic field are shown. Some of these gases have been tested in a 6m long prototype.

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1 Introduction

The Atlas collaboration has adopted the concept of 'Monitored Drift Tubes' (MDT) as the baseline for the precision muon chambers. Pressurized tubes offer the advantage of mechanical simplicity, excellent single wire resolution and control of the wire position, although a cylindrical cell geometry leads to some additional complications. The electrical field varies with 1/r, this means for a tube of 1.5cm Radius that E/p varies by an order of magnitude over 90% of the drift region. This leads to tight constrains on the choice of suitable gas mixtures, since several requirements have to be fulfilled simultaneously.
For operation in the Atlas muon spectrometer with high background rates and inhomogeneous magnetic fields the following requirements have been placed to ensure the desired performance [LAMA94].

- For safety reasons only non-flammable gas mixtures can be used.
- To limit chamber aging and occupancy the drift tubes should operate in proportional mode.
- The maximum drift time should not exceed 500 ns in order to keep the occupancy due to photon and neutron background sufficiently low.
- The diffusion should be small enough to allow a single wire resolution of about 60 μm at high pressure.
- The drift velocity should vary less than 0.1% per degree of temperature change.
- The pressure dependece of the drift velocity should not exceed 0.1% per 1mmHg.
- The Lorentzangle should be kept below 10° at 0.6 T.

Commonly used non-flammable gas mixtures like Ar-CO_2 80-20 can not be used, since the drift velocity is by far too low to obtain the a maximum drift time of 500 ns. Furthermore the drift velocity varies strongly with the electric field at low E/p which is relevant for the tubes. This leads to a highly non-linear space drift-time relation (SDR) and would make the detector very sensitive to e.g. field distortions.
In this note a new class of non-flammable gas mixtures containing Ar, CO_2, Ethane and N_2 is studied. They offer the possibility to fulfill all the requirements posed previously and could be canditate gas mixtures for the MDT detector.
The results have been obtained through computer simulation of gas properties and drift chamber operation with the MAGBOLTZ [BIAG90] and GARFIELD [VEEN94] programs and with testbeam measurements using 6m long pressurized drift tubes.
This report is organized as follows: In section 2 the simulation tools MAGBOLTZ and GARFIELD are described. Their reliability is tested with published measurements of various gas properties. Section 3 contains a description of the Freiburg prototype which was used in the test beam.
The simulation of Ar-CO_2-C_2H_6-N_2 mixtures and derivatives are presented in sections 4 through 8. In section 9 the results of the test beam measurements are presented. The last section summarizes the present results and gives an outlook for further studies.

2 Simulations

Computer simulations have been used as a first step to find a suitable class of gas mixtures using the GARFIELD and MAGBOLTZ programs. The most promising candidates were then tested with the prototype. The MAGBOLTZ program solves the Boltzmann transport equation under the influence of electric and magnetic fields, temperature and pressure with a numerical accuracy of 0.1% to determine e.g. drift velocity, Lorentzangle and diffusion for electrons moving in gases under these conditions.

The MAGBOLTZ program requires as input cross sections of elastic and inelastic electron scattering (ionisation, vibration, excitation) with atoms or molecules of a pure gas. These measured cross sections are summed up by S.F. Biagi [BIAG88, BIAG89].
GARFIELD is the CERN standard drift chamber simulation program and in the latest version it was possible to use the MAGBOLTZ calculated Lorentzangles as input for the space drift-time relations to study the influence of the magnetic field for the various gases.
We have tested the reliability of MAGBOLTZ by comparing the simulation with measured parameters of various gas mixtures. Fig.1 shows as an example the drift velocity of Ar-CO_2 82-18 and the Lorentzangle of Ar-CO_2-Methane 84-10-6 as a function of E/p. The measured drift velocity [BECK92] can be reproduced to better than 3%. The simulations of the Lorentzangle for Ar-CO_2-Methane 84-10-6 approximates the data to better than 0.9% in the region of E/p below 1Vcm^{-1}Torr^{-1} and to 7.8% in the region of higher E/p. For further tests of MAGBOLTZ see e.g. [BIAG88, BIAG89, CART89, VAVR92, SHAR93] and fig. 17. These comparisons encouraged us to use the MAGBOLTZ program for our studies. Prototype test with candidate gas mixtures are necessary to ensure that they allow a reliable operation with nominal HV settings and that they have acceptable aging properties.
All simulations determing SDR assume a tube with inner radius of 1.5 cm and a wire of 50 μm diameter. Ar-CO_2 80-20 as a standard non-flammable mixture is shown in comparison. The HV for Ar-Ethane-N_2 90-5-5 and Ar-CO_2-Ethane-N_2 86-4-5-5 at 3 bar and for Ar-CO_2-Ethane-N_2 88-2-5-5 at 3 bar and 4 bar are known from the testbeam setup while the other voltages are estimated.

3 The Aluminium Drift Tube prototype

The tubes of the Freiburg prototype are 6 m long and have an inner diameter of 28 mm. The wire has a diameter of 50 μm and is fixed only at the endplugs of the tubes. No spacers are used and the tubes follow the sag of the wire. The set up and the alignment of the prototype are described in fig. 2 and 3. The tubes were operated at 2.3 bar, 3 bar and 4 bar absolute in proportional mode using voltages of 3-4 kV depending on the gas mixture and pressure. The reduced electric field varies from $\sim$ 0.15 Vcm^{-1}Torr^{-1} at r=1.4 cm to $\sim$ 1.0 Vcm^{-1}Torr^{-1} at r=0.2 cm at 3 bar. In the testbeam 93 we operated with Ar-Ethane-N_2 90-5-5, Ar-CO_2-Ethane-N_2 88-2-5-5, Ar-CO_2-Ethane-N_2 86-4-5-5 and Ar-CO_2-Isobutane 82.5-15-2.5.
The readout of the tubes was done with multihit TDC's (LeCroy 2277, 32 channel CAMAC TDC). The pulse height studies were made by connecting one of the tubes to a linear preamplifier VV23 developed at the University of Heidelberg and a digital scope was used for readout. The pulse heights were not emlpoyed for corrections of the TDC data.
For a detailed description of the prototype see [SCHE94].

4 Drift velocity

Ar-Ethane-N_2 90-5-5 offers an extremely linear SDR (fig.5) and a plateau of the drift velocity at very low values of E/p compared to Ar-CO_2 80-20 (fig.4). Due to the saturation of the drift velocity in a region of E/p that covers $\sim$ 90% of the tube, this gas overcomes the strong variation in the E-field and leaves the SDR independent of field distortions, pressure and temperature variations compared to non-saturated gases like Ar-CO_2 80-20 where only 10% of the drift path are at constant drift velocity. The mixture is fast due to the contens of Ethane while N_2 has a smoothing effect on the drift velocity (fig.6). The smoothing effect of small amounts of N_2 to plateaus of the drift velocity has been observed for the flammable mixture Ar-Ethane 50-50 (+N_2) [JEAN79] and for non-flammable mixtures of Ar-CO_2 (+N_2) [ZHAO93]. In the latter case the plateau is in a region above 1 Vcm^{-1}Torr^{-1} as for Ar-CO_2 80-20 and thus not suitable for the application of drift tubes where 90% of the drift path has values of E/p below 1 Vcm^{-1}Torr^{-1}. The use of N_2 is rather known in scintillating drift chambers [CHAR76], spark chambers and in the plate imaging proportional counter [SEGM81] but is not common in proportional

chambers. The use of N_2 in the linear gas seems to be limited to higher pressures as in tests at 1 bar in a Honeycomb chamber of 12 mm diameter no proper point of operation could be found [OSCH94]. The pulses were very broad but small and made a readout via TDC nearly impossible. This might be due to the high diffusion at 1 bar.
However, Ar-Ethane-N_2 90-5-5 has a rather high Lorentzangle (up to 30°) and therefore small amounts of CO_2 were added to reduce the Lorentzangle. Gas mixtures with additions of CO_2 up to 4% to the linear gas offer maximum drift times close to 500 ns and reduce the Lorentzangle remarkably (fig.7 and 9). A disadvantage of these mixtures is the reduced linearity of the SDR with increasing contens of CO_2 (fig.5).
Using a gas like Ar-CO_2 80-20 would limit the cell size to roughly 9 mm radius if one wants to keep the maximum drift time below 500 ns. For a 15 mm tube the maximum is 1.6 μs which is not acceptable for ATLAS.

5 Lorentzangle

The Lorentzangle is defined as the angle between the drift velocity of the electrons and the electric field. And thus the larger the Lorentzangle the more the electrons will move on a helix to the wire. This lenghtens the maximum drift time (fig.9) and gives a higher uncertainty in the SDR due to an uncertainty in the knowledge of the magnetic field. For magnetic fields up to 1 T the Lorentzangle is scaling linear with the magnetic field.
Two methods of lowering the Lorentzangle of Ar-Ethane-N_2 90-5-5 were considered. The first method, as already mentionend, was to add small amounts of CO_2. This method is limited by the maximum drift time for larger amounts of CO_2 (fig.9).
The second method of lowering the Lorentzangle is to raise the pressure. The pressure dependence of the Lorentzangle in fig.8 indicates that 4 bar would give an average Lorentzangle of 10° for Ar-CO_2-Ethane-N_2 86-4-5-5 at 4 bar compared to 13.5° at 3 bar. But higher pressure leads to lower values of E/p. From the test beam measurements it is known that for the gas containing 2% CO_2 the operating voltage in proportional mode rises from 3300 V to 3700 V while the pressure changes from 3 to 4 bar reducing E/p by a factor of $\sim$ 0.85. This leads to a higher maximum drift time due to lower drift velocities at lower E/p for non-saturated gases. The reduced driftpath due to the lower Lorentzangle is not dominating here. The linear gas Ar-Ethane-N_2 90-5-5 in comparison is slightly faster since the drift velocity is constant in this region of E/p and the reduced drift path is relevant in this case (see table 1).
Thus the use of higher pressure is not only limited by technical reasons but by the increasing maximum drift time for non-saturated gases.

	Ar-Ethane-N_2 90-5-5	Ar-CO_2-Ethane-N_2 88-2-5-5	Ar-CO_2-Ethane-N_2 86-4-5-5	Ar-CO_2 80-20
3bar	560ns (3.1kV)	498ns (3.3kV)	585ns (3.3kV)	1589ns (3.9kV)
4bar	556ns (3.5kV)	530ns (3.7kV)	663ns (3.7kV)	1894ns (4.4kV)

Table 1: Maximum drift time, gas and pressure dependence at 0.6 T.

6 Diffusion

Diffusion is one limiting factor for the resolution of the detector. The diffusion shown in fig.10a is given for one single electron moving in the gas. This is not the direct contribution to the spatial resolution of the chamber. Since we are dealing with about 100 electrons moving to the sense wire and the electronics will detect not the first but say the 10^{th} electron, the 'effective' diffusion then

scales down to 30%-40% (or even less) of σ_L given in fig.10 [PALL75]. This estimation holds e.g. for Ar-Ethane-N_2 90-5-5. The average single electron longitudinal diffusion is about 170 μm/cm drift an the resolution at 1.4 cm distance from the wire is 77 μm (fig.18). That would mean a scaling factor of $\sim$ 32% if one considers the diffusion as the only contribution to the error. For detailed calculations of the contribution of the diffusion to the resolution see [BLUM93].
The diffusion of the gases decreases with increasing contens of CO_2. For higher magnetic fields the diffusion is increasing slightly (fig.10b). The diffusion scales with $1/\sqrt{p}$ for fixed values of E/p.

7 Error contribution

Here the contribution of uncertainty in the knowledge of B-field, tube placement, temperature and pressure are discussed. The definition of the error and the corresponding RMS is as follows: Assuming e.g. an uncertainty of the B-field of 1% two space drift-time relations are calculated. One for the 'ideal' case and one for the case of the 1% different B-field. The main error contribution here is the different Lorentzangle. The difference of the predicted distances for identical times at about 70 points of these two SDR is used to determine the RMS between these two predictions. Examples of the difference of two SDR for a 1% uncertainty in the B-field and for 200 μm tube displacement are shown in fig.12. The results for 0.6 T, 3 bar for temperature, pressure, high voltage, magnetic field and tube displacement are summed up in table 1. The B-field dependence of the total error is summarized in fig. 14b.

standard conditions vs.	Ar-CO_2 80-20	Ar-Ethane-N_2 90-5-5	Ar-CO_2-Ethane-N_2 88-2-5-5	Ar-CO_2-Ethane-N_2 86-4-5-5
T = 20°C ΔT = 1°C	16μm	2μm	6μm	11μm
p=2280Torr Δp = 1Torr	2μm	<1μm	1μm	2μm
HV ΔV = 10V	11μm (3.9kV)	5μm (3.1kV)	8μm (3.3kV)	11 μm (3.3kV)
B = 0.6T ΔB = 1%	<1μm,3bar (<1μm,4bar)	12μm,3bar (8μm,4bar)	8μm,3bar (5μm,4bar)	5μm,3bar (3μm,4bar)
200μm tube displacement	31μm	7μm	19μm	27μm
$\sqrt{\sum_{i=1}^{5} RMS_i^2}$	37μm	15μm	23μm	32μm

Table 2: RMS for some uncertainties at 3bar, 0.6T; the B-field dependence of the resulting RMS is shown in fig.14b.

We checked whether one can treat all effects independent, especially the combination of a displaced wire and a magnetic field off the nominal value might lead to additional effects. We calculated this effect explicitly and compared the RMS for these combined effects with the RMS calculated treating these effects as independant (fig.13). The difference of these two calculated RMS was for all gases below 0.6 μm. This indicates that one can treat these two effects as independent as is assumed in table 2.
The temperature and pressure dependence of gases is directly related to the drift velocity. With $v_d \propto T/p$ changes in the pressure and the temperature are directly proportional to the derivative of the drift velocity. Saturated gases offer better stability against these changes. The dip close to the

wire in the temperature dependence of Ar-Ethane-N_2 90-5-5 and Ar-CO_2-Ethane-N_2 88-2-5-5 is not yet understood and seems to be too large compared with the changes in the pressure dependence (fig.11). While the pressure dependence is below $< 0.1\%$ for all gases which leads to a RMS of 2 μm or less (fig. 11b) the temperature dependence has to be considered. Δv/v is about 0.4% for the gases containing CO_2, only the extremely linear gas Ar-Ethane-N_2 90-5-5 has a Δv/v in average below 0.1% as demanded. This leads to a low RMS per K for Ar-Ethane-N_2 90-5-5 (2 μm) compared to less linear gases.
From table 2 one can conclude, that the Lorentzangle is not the main effect to the resolution, but effects due to not saturated drift velocity. Ar-Ethane-N_2 90-5-5, the gas with the most linear SDR, having a Lorentzangle up to 30° offers the lowest over all RMS for field strength of the magnetic field up to 0.8 T (fig.14).

8 Further gas studies

From tests it was known, that Ethane and Methane do offer similar drift properties. Thus systematic studies were made to find further quencher which might be used instead of Ethane. Several quencher were found having nearly the same drift properties like Lorentzangle, drift velocity and diffusion (fig.15). Here the gas with 4% CO_2 is shown. Simulations without CO_2 show that these quenchers offer a similar plateau of the drift velocity like Ar-Ethane-N_2 90-5-5. The final choice of the gas should be determined by features like pulseheight (gas gain) in proportional mode, stability against radiation and aging properties.
The quenchers DME and Methylal are slow compared to the previous (fig.16). Comparing Ar-Ethane-N_2 90-5-5 with Ar-DME-N_2 90-5-5 and Ar-Methylal-N_2 90-5-5, one can see that the quencher DME and Methylal do not offer such a fast SDR as the previous quenchers do. Even without admixture of CO_2 the maximum drift time is about 690 ns assuming 3.3 kV operating voltage at 3 bar, 0.6 T in the 1.5 cm tube.
Helium based gases are slow compared to Argon based gases [SHAR93]. Even a fast Helium based mixture like He-Ethene 90-10 can not offer a SDR below 1 μs assuming 4 kV operating voltage at 3 bar pressure (fig.16).

9 Testbeam results

The best resolution and the best efficiency was obtained with Ar-Ethane-N_2 90-5-5 (fig.18). All gases presented offer a resoltution up to 65 μm over a wide range of the tube. Except Ar-Ethane-N_2 90-5-5 they all have a rather large range of $\sim$ 4 mm around the wire with comparable poor resolutions. This effect can be explained by the low pulse heights compared to Ar-Ethane-N_2 90-5-5 especially for tracks close to the wire. For the gases containing Ar-(CO_2)-Ethane-N_2 the pulse height is decreasing close to the wire, which is surprising, since the amount of primary ionisation is largest in this region. A low pulse height means, that one triggers on a rather high electron (when using the same trigger level), where primary ionization effects become dominant [BLUM93]. This could be an explanation for the poor resolution close to the wire. The low pulse height as well can explain the inefficiencies close to the wire for Ar-CO_2-Ethane-N_2 88-2-5-5 at 3 bar and 4 bar.
Since the shown pulse heights for Ar-Ethane-N_2 90-5-5 and Ar-CO_2-Ethane-N_2 88-2-5-5 (4 bar) were determined for lower operating voltages than the corresponding resolutions and efficiencies their absolute value is too low and can not be compared directly with the pulse heights of the other runs.
The low pulse height is probably caused by the fact that the electronics was not optimal adapted. This is shown by pulse height measurements for Ar-CO_2-Isobutane 82.5-15-2.5 in a test tube of 1 m length, 3 cm diameter with a 100μm wire using different electronics and cable length where the pulse height was about 3 times higher than the corresponding pulse height in fig.18 .

For the determination of the resolution only data from the TDC were used. No pulse height correction was applied.

10 Conclusions

Ar-Ethane-N_2 (+CO_2) are good canditate gas mixtures for the Monitored Drift Tubes. Some of them were tested in 6 m long tubes without spacers and their aptitude for proportional mode operation at 3 bar and 4 bar was shown.
Calculations of various effects under the influence of the magnetic field to the resolution did indicate, that a good single wire resolution should be possible even under the influence of the magnetic field. It could be shown, that the advantage of the linear gas Ar-Ethane-N_2 90-5-5 being independent to several distortions is not repealed by the disadvantage of the high Lorentzangle of this gas. If one assumes an uncertainty in the knowledge in the magnetic field of 1% the effect of the Lorentzangle to the resolution seems to be tolerable compared to other effects like tube displacement and temperature effects.
However, the calculations are lacking a proof by experiment. Further studies about aging, stability against radiation and gas gain were not subject of this work and have to be done.

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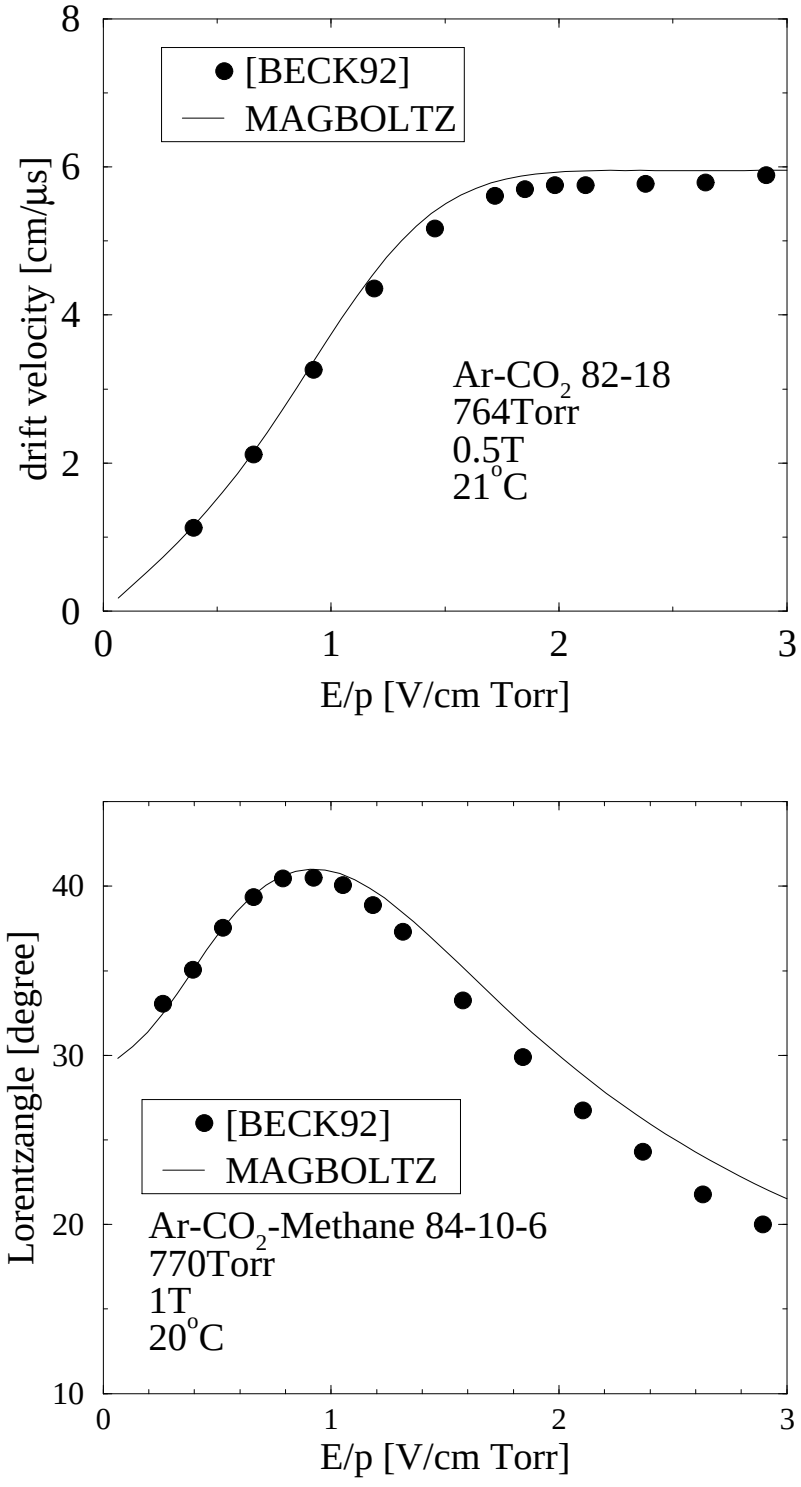

Figure 1: Comparison of measured data to simulated data. The deviation is in average 2.9% for the drift velocity and 6.2% for the Lorentzangle.

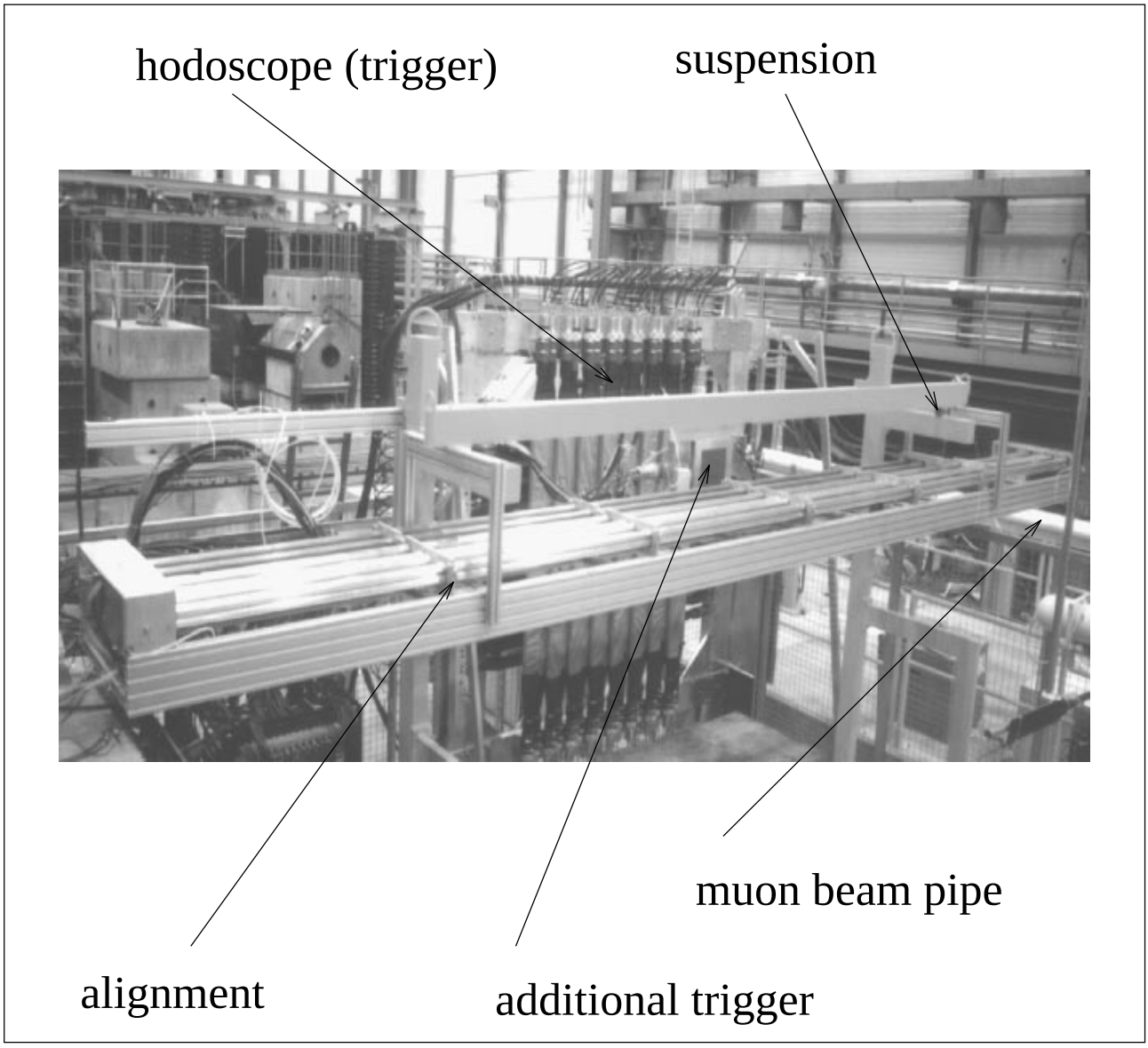

Figure 2: The prototype in the muon halo of the SMC experiment, CERN [SCHE94].

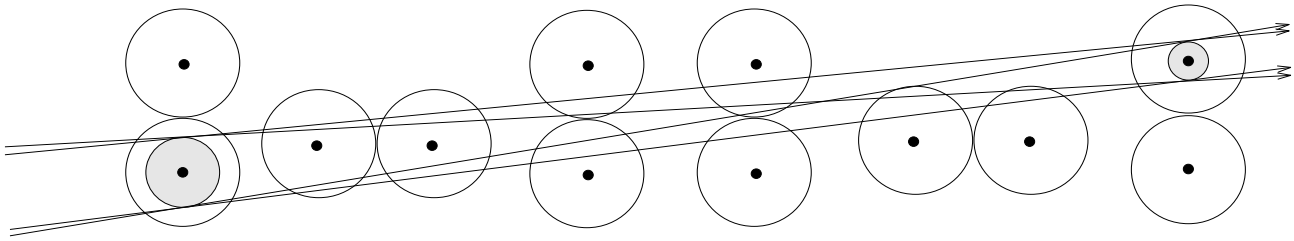

Figure 3: Alignment of the tubes [SCHE94].

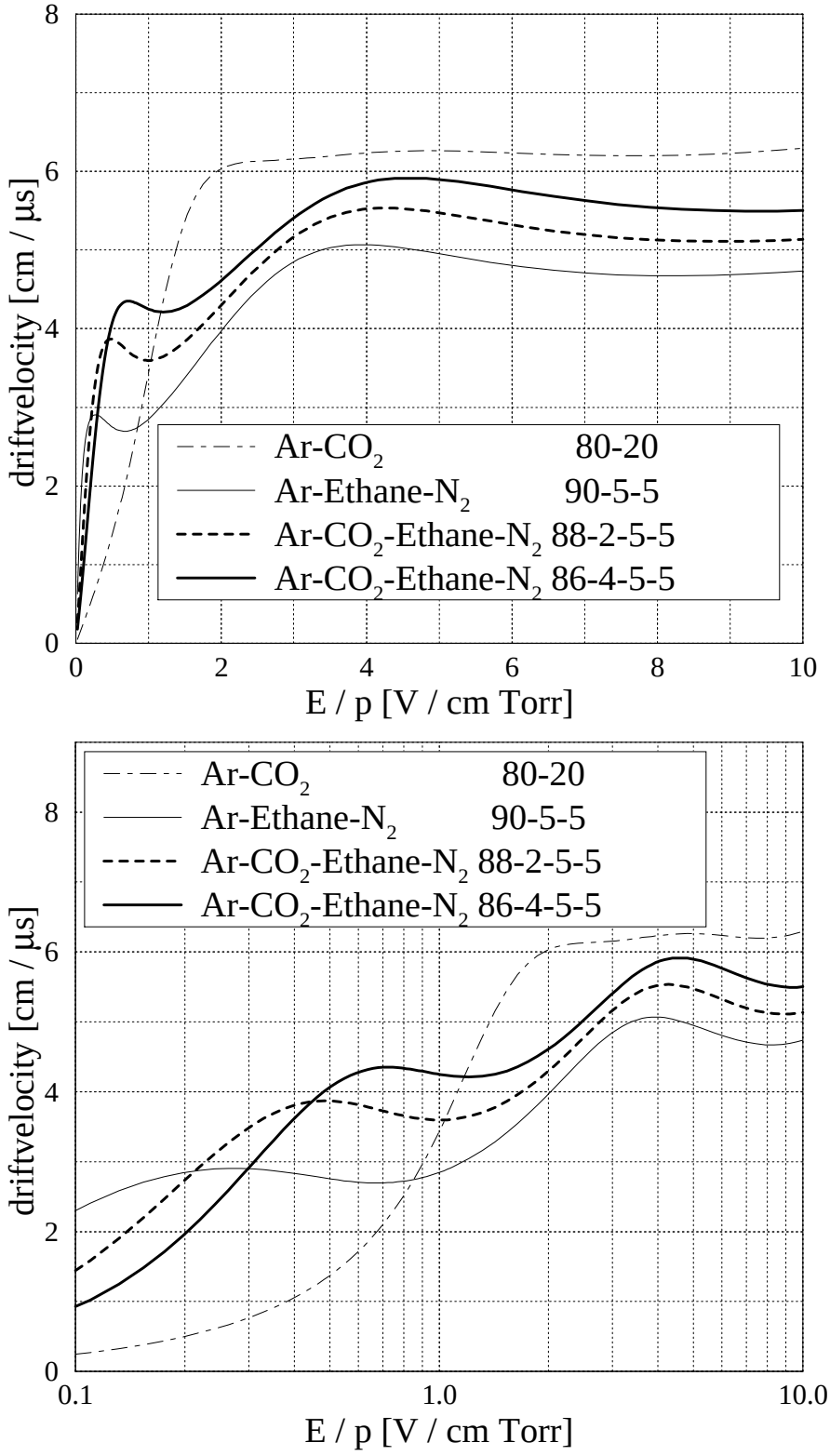

Figure 4: The logarithmic scaling makes the property of constant drift velocity of Ar-Ethane-N_2 90-5-5 compared to standard gases like Ar-CO_2 80-20 visible. In proportional mode 87% of the drift path is at E/p $<$ 1 V cm^{-1} Torr^{-1}. The plateau of Ar-CO_2 80-20 covers in proportional mode less than 10% of the drift path.

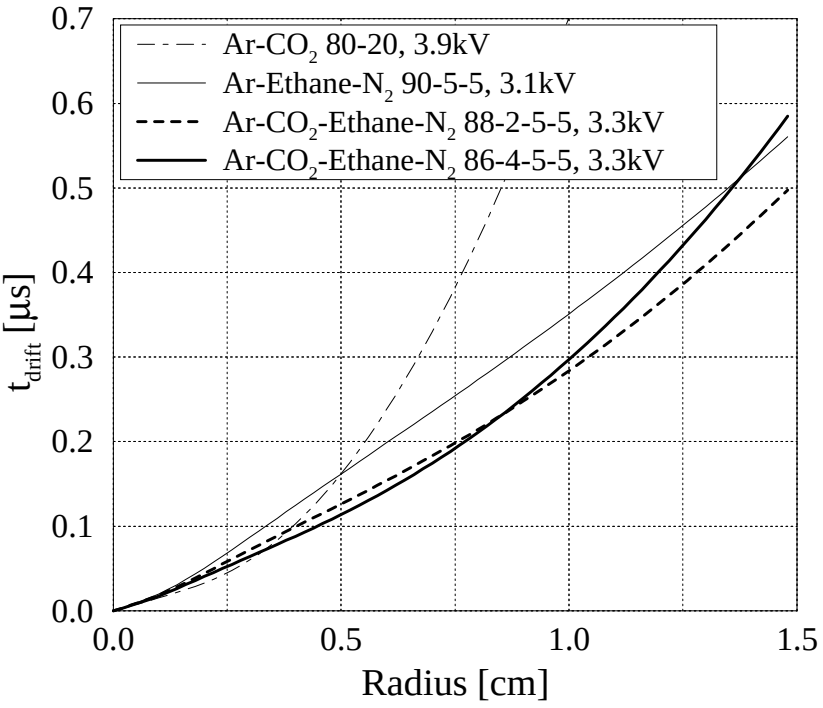

Figure 5: Space drift time relation for proportional mode operation at 3 bar, 0.6 T; the maximum drift time for Ar-CO_2 80-20 is about 1.6 μs.

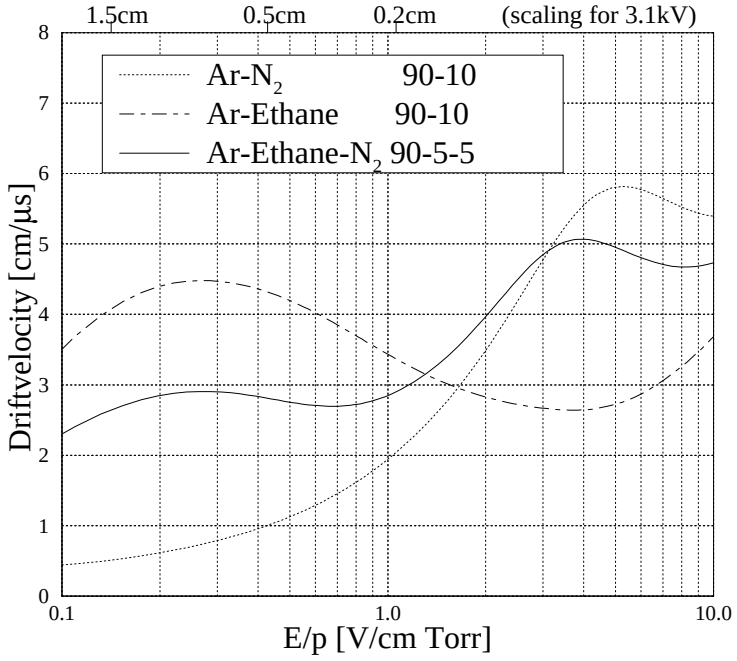

Figure 6: Influence of N_2 and Ethane in the linear gas.

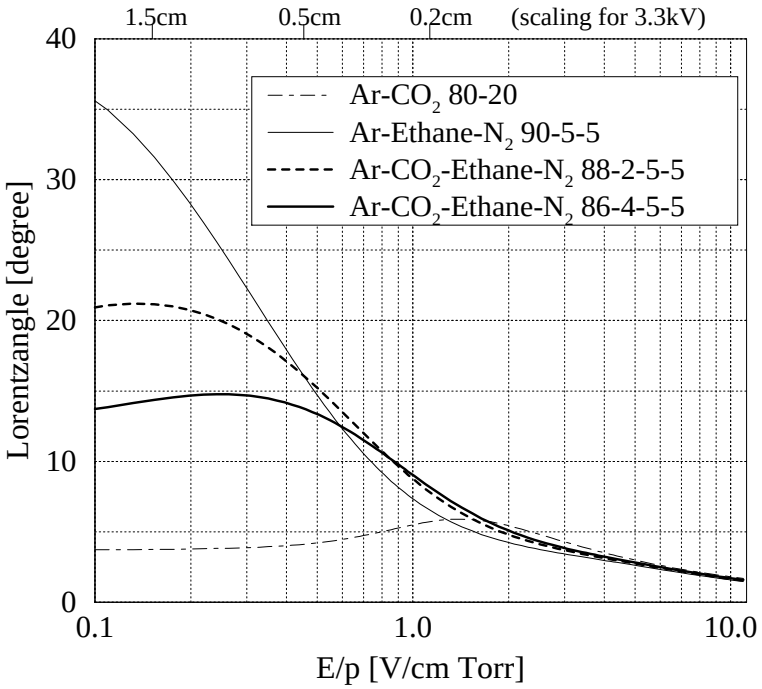

Figure 7: Lorentzangle at 3 bar, 0.6 Tesla.

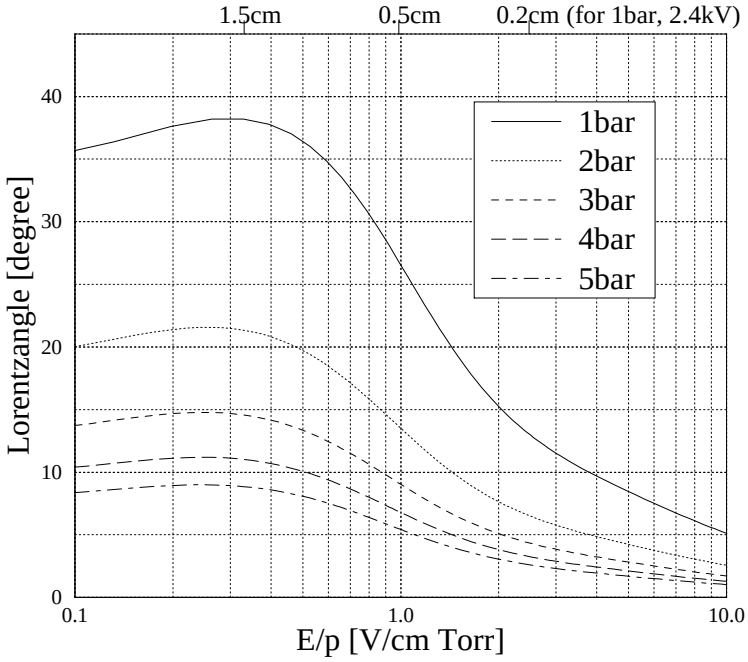

Figure 8: Pressure dependence of the Lorentzangle at 0.6 T for Ar-CO_2-Ethane-N_2 86-4-5-5.

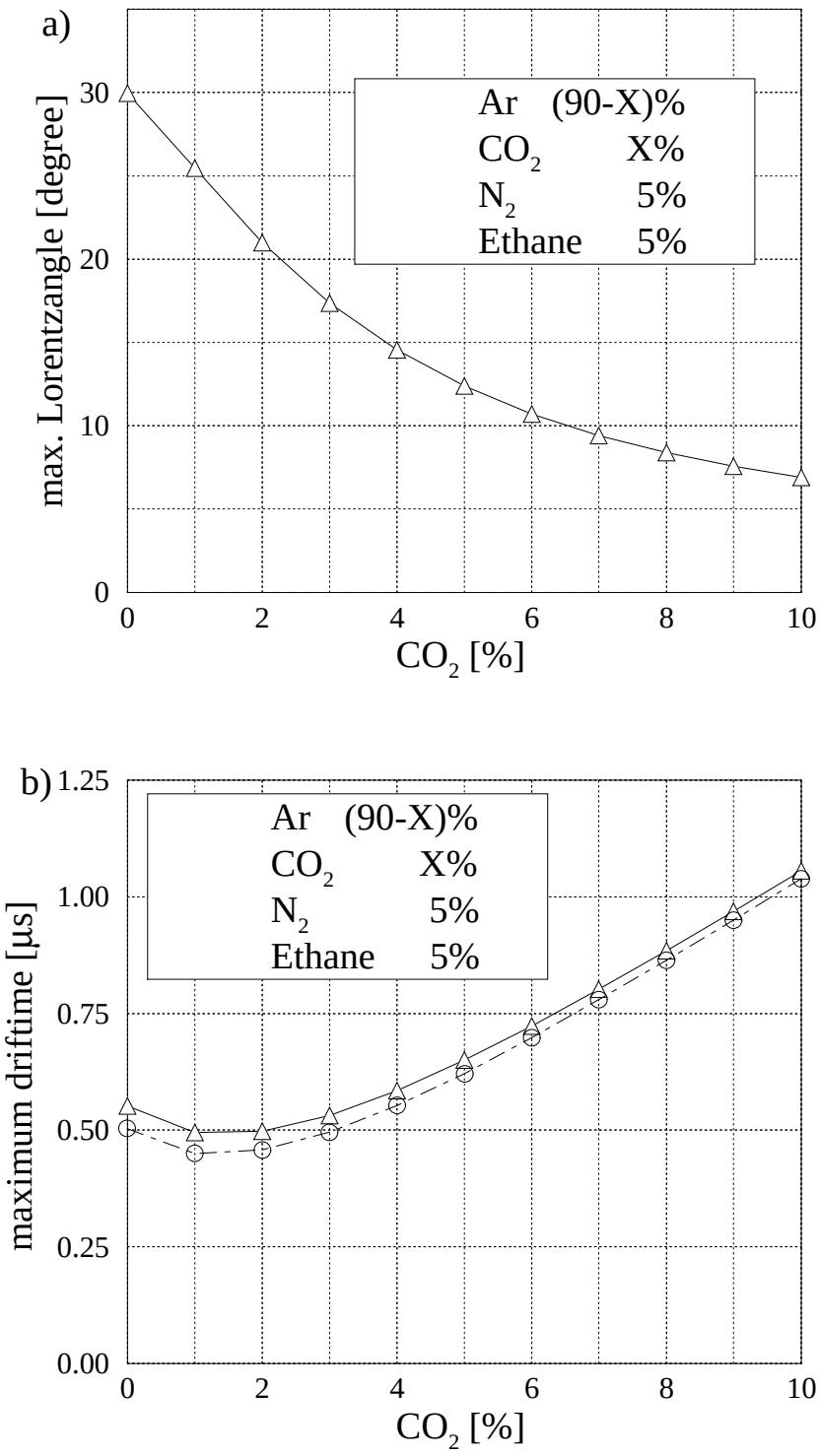

Figure 9: a) CO_2 dependence of maximum Lorentzangle at 1.4 cm, 3.3 kV, 3 bar, 0.6 Tesla, b) CO_2 dependence of maximum drift time in a tube of 1.5 cm radius at 3.3 kV, 3 bar, 0 Tesla(○) and 0.6 Tesla (△); lines to guide the eyes.

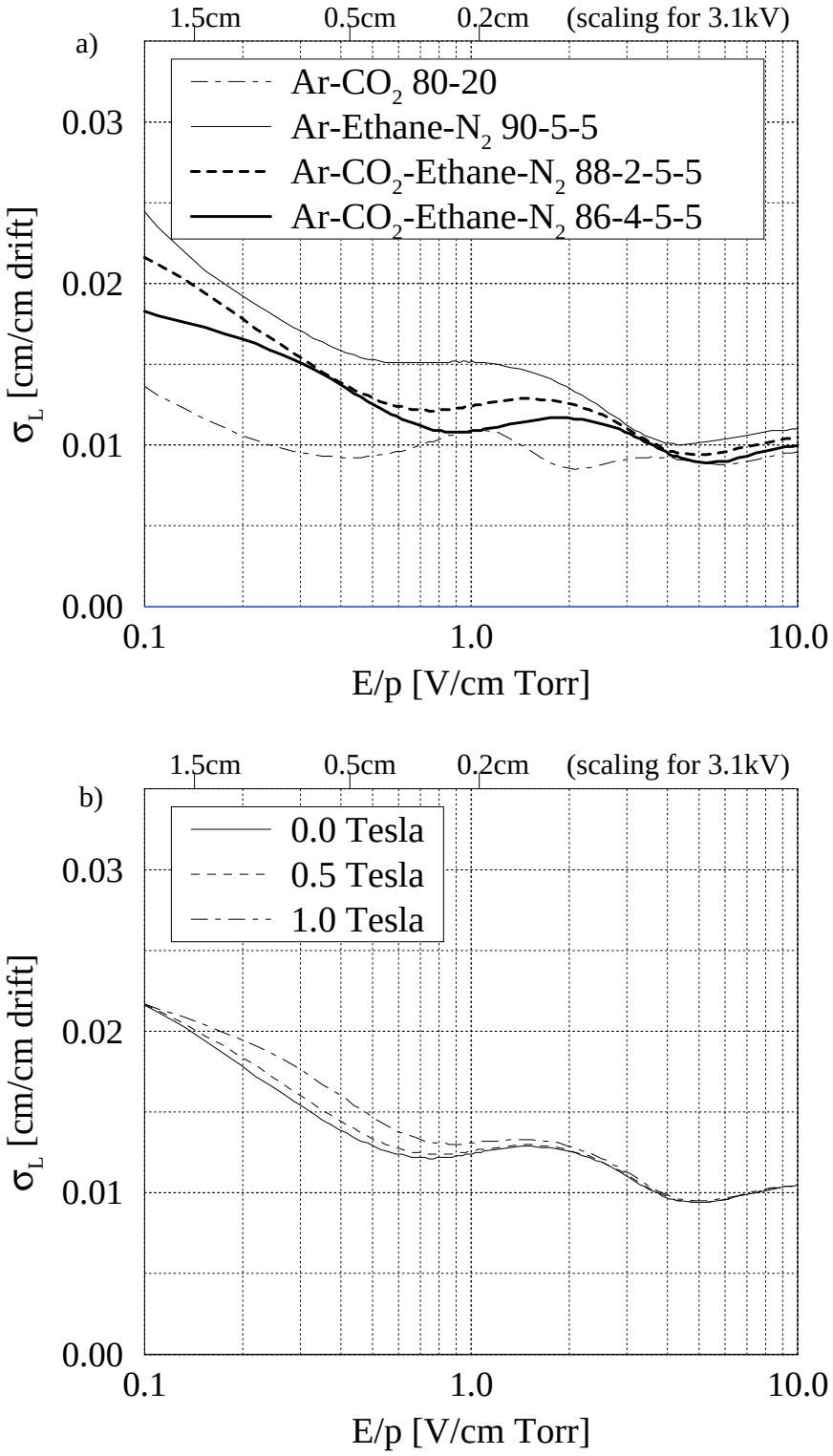

Figure 10: a) Single electron longitudinal diffusion at 3 bar, 0 T; b) Single electron longitudinal diffusion for Ar-CO_2-Ethane-N_2 88-2-5-5 at 3 bar, B-field dependence.

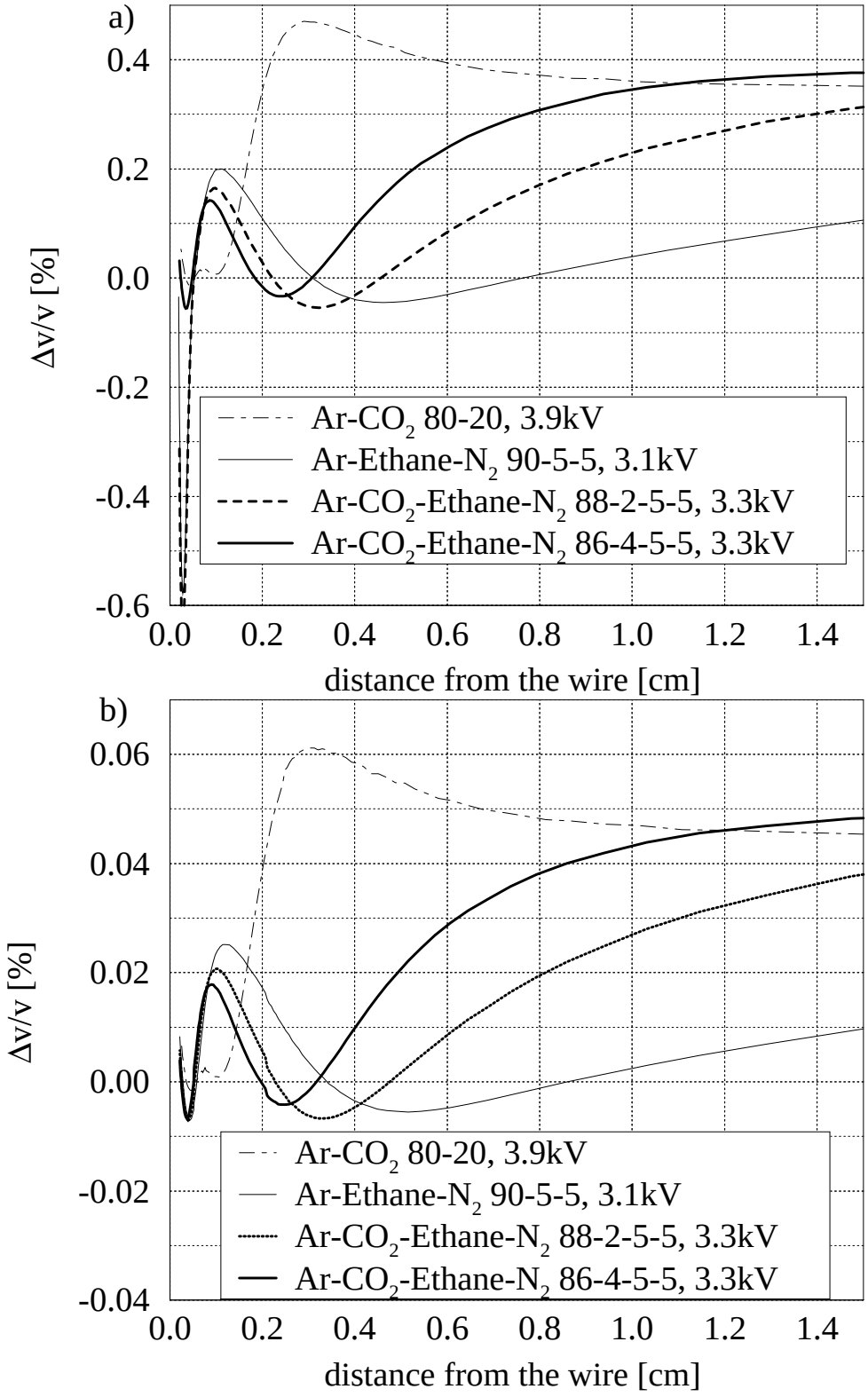

Figure 11: a) Temperature dependence of the drift velocity per °C at 3 bar, 20°C, 0 T, b) Pressure dependence of the drift velocity per mmHg at 3 bar.

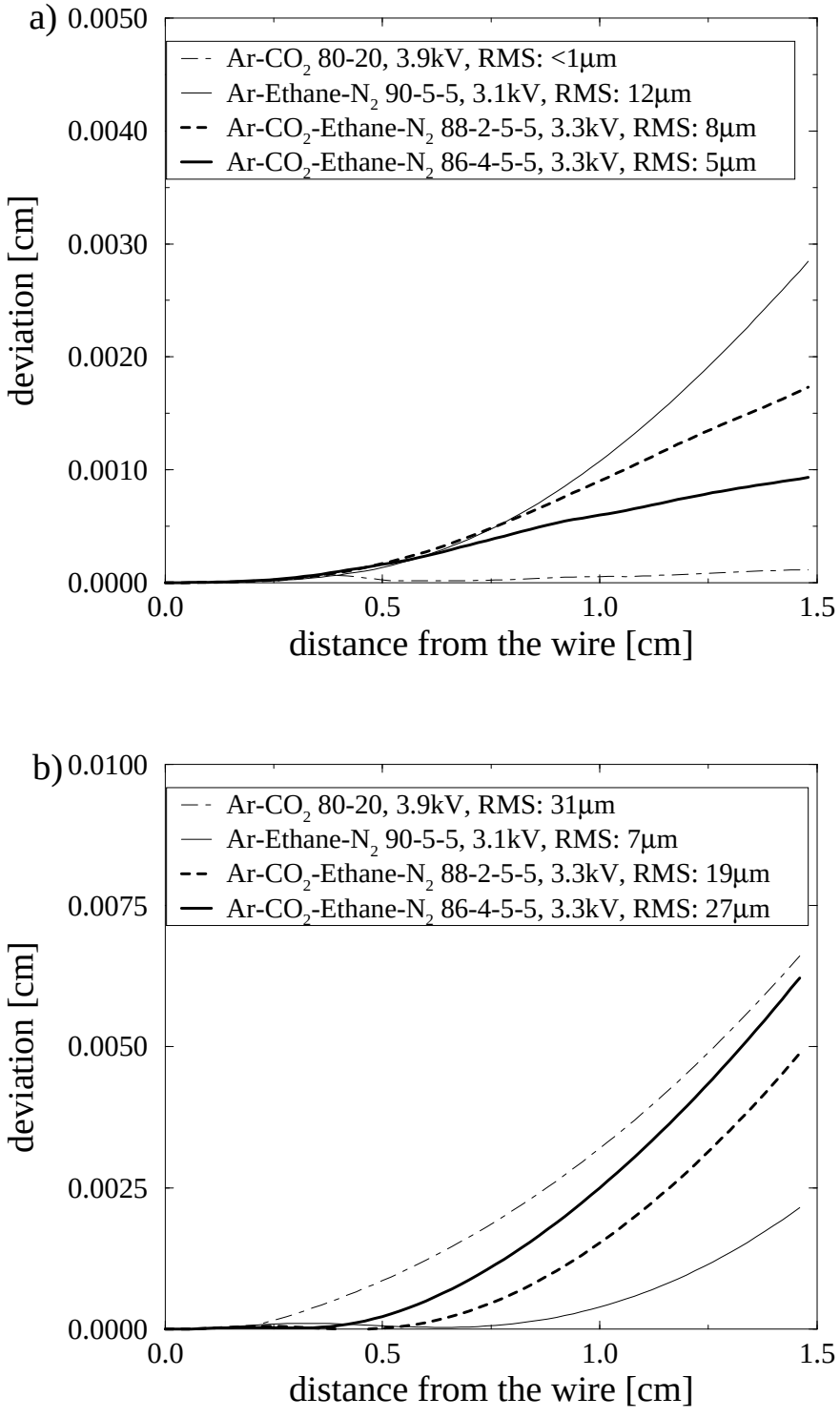

Figure 12: Difference of the predicted drift distance for a) 0.6 T and 0.606 T (tube ideal placed) and b) Ideal placed tube and 200 μm displaced tube at 0.6 T, 3 bar. The RMS are summed up in table 2.

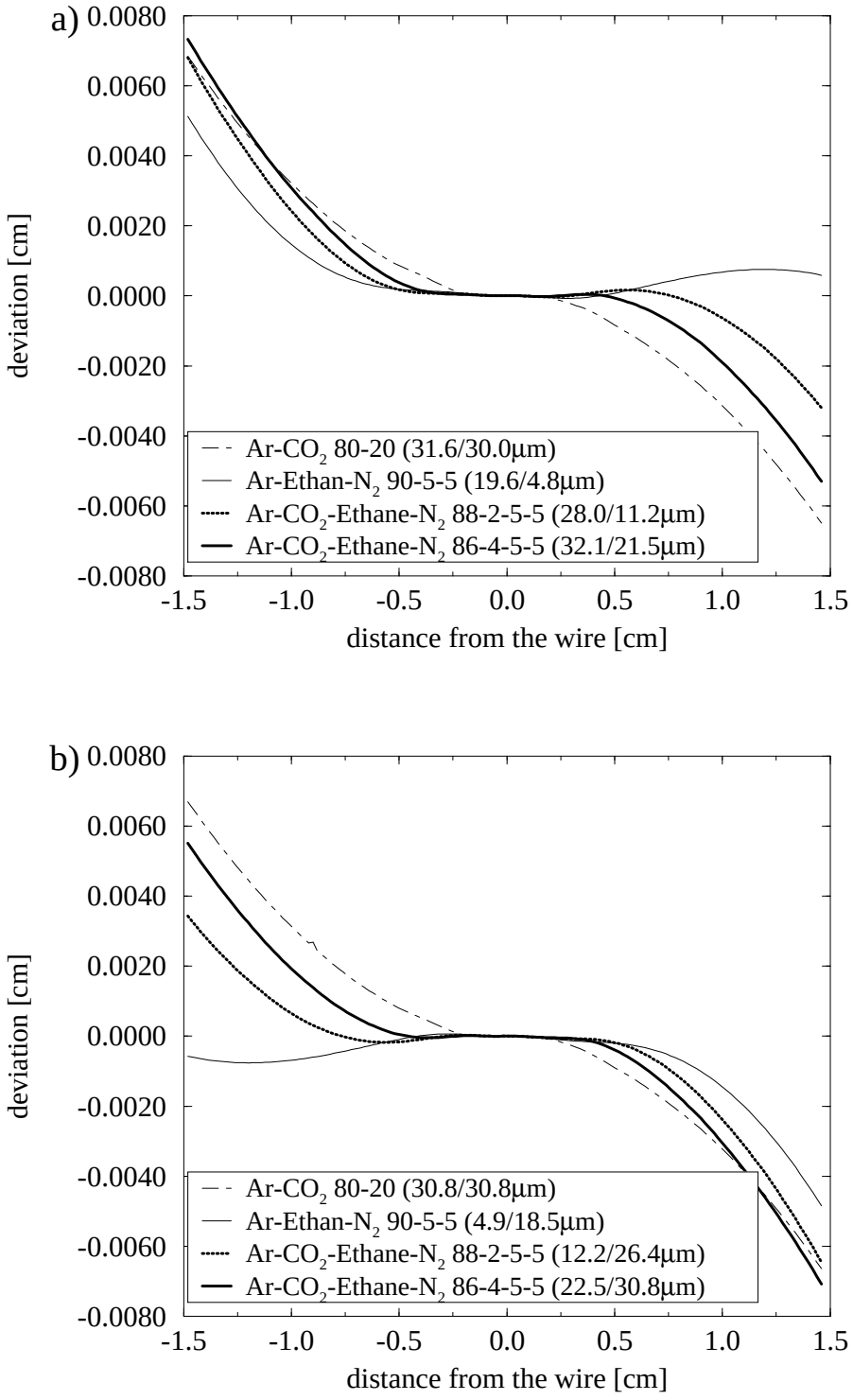

Figure 13: Difference of the predicted drift distance of the 'ideal' case versus a) Combined effect of 200 μm tube displacement to the left and a 1% higher magnetic field; b) Like the previous but 1% lower magnetic field. The numbers in brackets are the RMS separate for the left and the right side of the tube. The overall RMS calculated from the combined effect in the tube is for a): 30.8 μm, 13.9 μm, 21.4 μm, 27.4 μm; for b): 30.8 μm, 13.5 μm, 20.5 μm, 26.9 μm. The overall RMS calculated here is within 0.6 μm in agreement with the resulting RMS when these effects are treated as independent as in table 2.

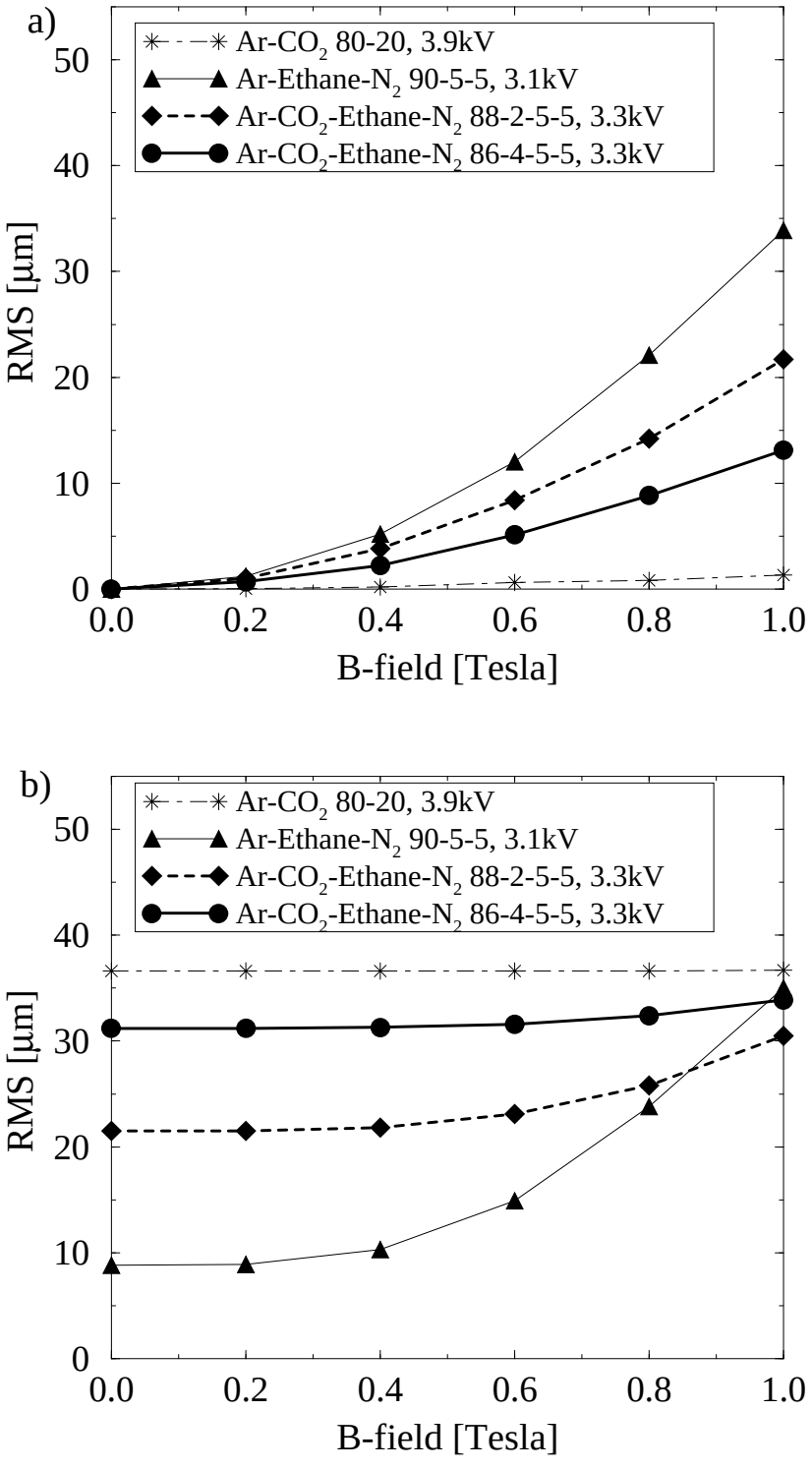

Figure 14: a) RMS for 1% uncertainty in the knowledge of B at 3 bar. b) Like the previous but RMS of temperature, pressure, HV and tube displacement added on top as in table 2; lines to guide the eyes.

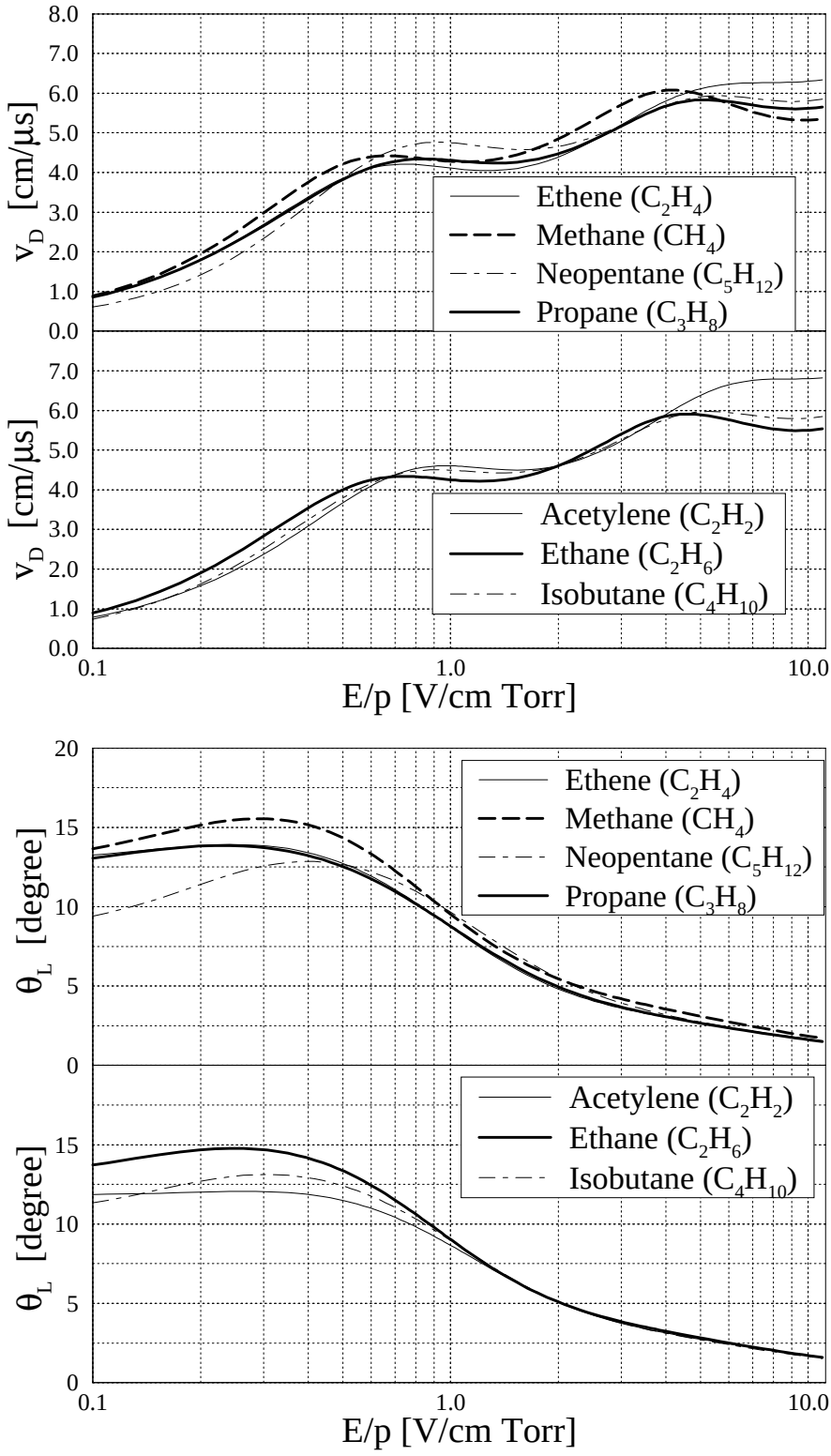

Figure 15: Drift velocity and Lorentzangle of Ar-CO_2-'*Quencher*'-N_2 86-4-5-5 at 3 bar, 0.6 T. Simulations without CO_2 show that these quenchers offer a similar plateau of the drift velocity like Ar-Ethane-N_2 90-5-5.

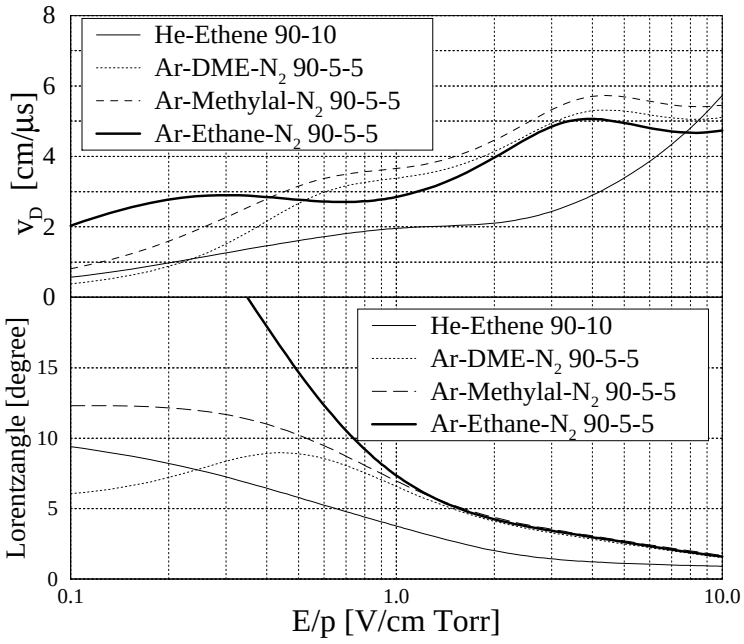

Figure 16: Drift velocity and Lorentzangle at 3 bar, 0.6 T for some slow gas mixtures (t_{max} >690 ns) in comparison with Ar-Ethane-N_2 90-5-5.

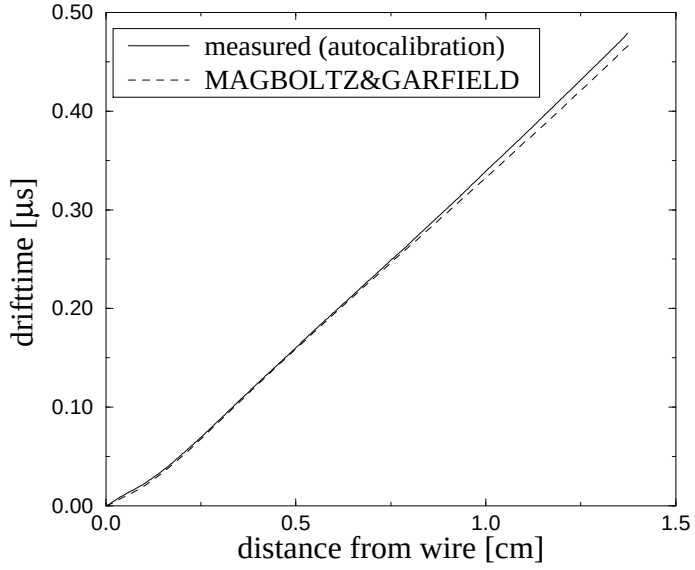

Figure 17: Measured and predicted SDR for Ar-Ethane-N_2 90-5-5 at 3 bar, 3.1 kV, 0 T in a tube of 1.4 cm inner radius, 50 μm wire. No corrections applied; the maximum drift time differs about 2.8%.

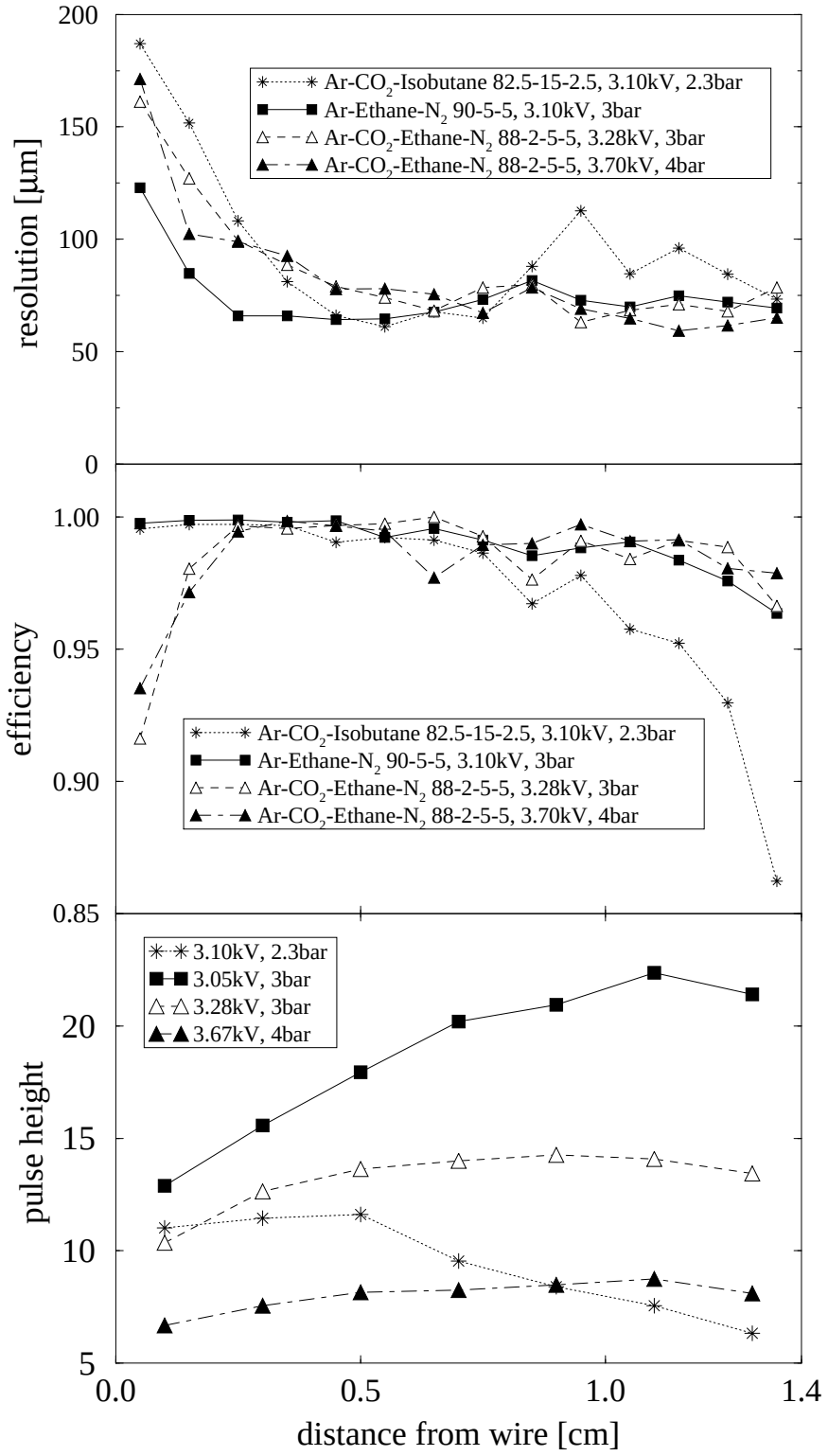

Figure 18: Resolution, efficiency and pulse height; the scaling for pulse heigts is arbitrary, since the voltages for the pulse height differ slightly in two cases from the voltages for the determination of the resolution and efficiency. However within one dataset the pulse heights along the drift path can explain the low efficiency close to the wire for the two runs with Ar-CO_2-Ethane-N_2 88-2-5-5 [PASC94][SCHE94]; lines to guide the eyes.