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Gas studies for the TPC of a detector for the future Linear Collider TESLA

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1 Introduction

This note discusses the optimization of gas mixtures for the time projection chamber of a detector for the future Linear Collider TESLA. Drift velocity and diffusion characteristics of gas mixtures are computed using the MAGBOLTZ program [1], which solves the Maxwell Boltzman equation and gives the transport parameters of gas mixtures.

A 3 T magnetic field parallel to the electric field of the TPC has been used for all these studies, unless otherwise stated. All numbers quoted in this note correspond to normal conditions of temperature and pressure.

2 Requirements

The following requirements have been considered:

1. The total number of electrons released per unit of length for minimum ionizing particles, N_t, should be large (typically 100 /cm), in order to allow a good dE/dx resolution.

2. The drift velocity, V_d, should be large, in order to empty the drift region as quickly as possible.

3. The plot of the drift velocity V_d versus electric field, E, should present a maximum at a value of electric field E_{max} as small as possible, and be rather flat around that maximum. This requirement is essential in order to be able to choose operation conditions of the TPC (electric field chosen to be E_{max}) such that the sensitivity of the system to distortions in the electric field is as small as possible, while the required operation voltage is technically realistic.

   As a measure of the "flatness" of the plateau of the electric field dependence of the drift velocity, we will quote in the following sections the change in drift velocity for a 10 V/cm change in electric field around E_{max} for each gas mixture studied in this note.

   Another way of giving a measure of the "flatness" could be to quote the change in drift velocity for a 1 % relative change in electric field around E_{max}. However, as will be seen later it turns out that the flatter the plateau, the higher the required operation electric field (E_{max}). This change in drift velocity then happens to be very similar for all gas mixtures studied in this note and in any case smaller than 2 10^{-4}. It therefore does not bring any useful information for selecting the best mixture.

4. The size of an electron cloud drifting from its point of origin to the end-cap sector is determined by diffusion and is given by $\sigma_T = D_T\sqrt{l}$ and $\sigma_L = D_L\sqrt{l}$ in the directions transverse and longitudinal to the drift direction respectively, where l is the drift length and D_T and D_L are the transverse and longitudinal diffusion coefficients of the gas in an electric field E_{max}. We shall take l to be the half-length of the chamber, 2.5 m, in what follows. The longitudinal diffusion coefficient, D_L, should be small in order not to loose resolution in the direction parallel to the electric field.

5. The attachment coefficient of the gas in an electric field E_{max} should be small, in order to avoid losses of drifting electrons. The attachement coefficient is negligible for all gas mixtures discussed in this note and its values will therefore not be quoted. However impurities such as oxygen have an important impact on attachment and this effect has to be studied and taken into account.

6. Multiple scattering should be small enough so that the momentum resolution of the TPC is good even for low momentum particles. In other words, the particle momentum, p_{ms}, below which the contribution of multiple scattering dominates the momentum resolution should be as small as possible (about 2 or 3 GeV/c).

   The momentum resolution, $\frac{\sigma_{p_T}}{p_T}$, is given by

$$\frac{\sigma_{p_T}}{p_T} = \frac{8\,p_T}{0.3\,B\,(R_O - R_I)^2}\,\sigma_s \tag{1}$$

   where $B = 3$ T is the magnetic field, $R_O = 1.6$ m and $R_I = 0.4$ m are the outer and inner radii of the TPC, p_T is the transverse momentum in GeV/c, and σ_s is the sagitta error and is given by

$$\sigma_s^2 = \sigma_{s,r\phi}^2 + \sigma_{s,ms}^2 \tag{2}$$

   Here, $\sigma_{s,r\phi}$ is given by the Glückstein formula

$$\sigma_{s,r\phi} = \frac{\sigma_{r\phi}}{8}\sqrt{\frac{720}{N+4}} \tag{3}$$

   with N being the number of measured points, and $\sigma_{r\phi}$ is the single point spatial resolution of the TPC.

   $\sigma_{s,ms}$ is due to multiple scattering and is given by

$$\sigma_{s,ms} = \frac{1}{4\sqrt{3}}\,(R_O - R_I)\,\frac{14.1}{p_T\,10^3\,\beta}\,Z\left(1 + \frac{1}{9}\log\frac{(R_O - R_I)}{X_0}\right)\sqrt{\frac{(R_O - R_I)}{X_0}} \tag{4}$$

   where X_0 is the radiation length of the gas in the TPC.

   The contribution, $\left(\frac{\sigma_{p_T}}{p_T}\right)_{ms}$, of the multiple scattering to the momentum resolution of the TPC is therefore

$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{ms} = \frac{8}{0.3\,B\,(R_O - R_I)}\,\frac{1}{4\sqrt{3}}\,14.1\,10^{-3}\left(1 + \frac{1}{9}\log\frac{(R_O - R_I)}{X_0}\right)\sqrt{\frac{(R_O - R_I)}{X_0}}. \tag{5}$$

The requested momentum resolution of the TPC is taken from the Conceptual Design Report, CDR, and is

$$\frac{\sigma_{p_T}}{p_T^2} = 2.8\ 10^{-4}\ \left(\frac{\text{GeV}}{\text{c}}\right)^{-1}. \tag{6}$$

The momentum resolution of the TPC is then dominated by multiple scattering when the momentum is smaller than

$$p_{ms} = \frac{\left(\frac{\sigma_{p_T}}{p_T}\right)_{ms}}{2.8\ 10^{-4}}\ \text{GeV}. \tag{7}$$

7. There should be as little as possible influence of potential polluants such as water and oxygen.

8. The gas should have as few H atoms as possible, because of their large interaction cross-section with a potentially high neutron background.

9. Gases such as DME, TMAE or CF_4 should be avoided as they are very agressive. For comparison with other gases, DME is however considered in this note.

3 Gas properties

A set of 3 gas properties are summarised in Table 1 for gases which are used in the studies presented here:

- the radiation length, X_0;
- the total number of electrons released per cm for minimum ionizing particles, N_t;
- the total neutron bound scattering cross-section [2], σ_n.

4 Neon versus argon

In Table 2 are listed some of the main properties of argon based and neon based mixtures with CH_4 as quencher:

- X_0, N_t and σ_n, defined previously;
- p_{ms}, the particle momentum below which the contribution of multiple scattering dominates the momentum resolution;
- The value of the electric field, E_{max}, for which drift velocity is maximal, and the value of this maximum, $V_{d\,max}$;
- The change in drift velocity for a 10 V/cm change in electric field around E_{max};
- The diffusion parameters: diffusion coefficients (D_L and D_T) and size of an electron cloud (σ_L and σ_T). As the diffusion parameters of a gas mixture strongly depend on the electric field, $D_{L,T}$ and $\sigma_{L,T}$ are given for the operation electric field E_{max}.

Neon based mixtures differ from argon based mixtures essentially in four ways.

- Neon has a much lower value of N_t, which yields a worse dE/dx resolution. Indeed, as can be seen in Table 2, the value of N_t for neon based mixtures is about 50 /cm (44 /cm for a mixture of 90 % neon and 10 % CH_4) and is around 100 /cm for argon based mixtures (90 /cm for a mixture of 90 % argon and 10 % CH_4). From a purely statistical point of view, the dE/dx resolution is proportional to $1/\sqrt{N_t}$, it is therefore about 40 % worse in neon based mixtures than in argon based mixtures (other effects limiting the dE/dx resolution, such as noise, are not considered).

- Neon has a higher value of X_0, which means that the contribution of multiple scattering is smaller, as shown in Table 2. A mixture of 90 % argon and 10 % CH_4 has a radiation length of about 120 m, and therefore p_{ms} is as large as 4.2 GeV/c. For a mixture of 90 % neon and 10 % CH_4 on the other hand, $X_0 = 362$ m, which yields a value of p_{ms} of 2.2 GeV/c, much smaller than in the argon based mixture. In any case p_{ms} is rather small and does not seem to be a big issue in this context.

- The plots of V_d versus electric field, E, shown in Figure 1 for various gas mixtures with 10 % CH_4, have different characteristics for argon based and neon based mixtures:

  - The maximum, $V_{d\,max}$, is lower for a neon based mixture than for an argon based mixture.
  - In addition, the maximum corresponds to an electric field E_{max} which is larger in the case of a neon based mixture. This means that neon based mixtures require a larger operation electric field than argon based mixtures.
  - Finally, the curve is flatter around the maximum for a neon based mixture, which means that the sensitivity to electric field distortions is smaller in a neon based mixture than in an argon based mixture.

- As can be seen in Table 2, the longitudinal diffusion coefficient, and therefore the spatial resolution along the drift field is larger in neon + CH_4 mixtures than in argon + CH_4 mixtures. The transverse diffusion coefficient, on the other hand is smaller in neon + CH_4 mixtures than in argon + CH_4 mixtures. Depending on the type of readout of the TPC, a smaller transverse diffusion coefficient might be an advange or a drawback.

A possibility would be to use both argon and neon, in order to combine the advantages of both gases, and to minimize their drawbacks. The main properties of neon and argon based mixtures with 10 % CH_4 are summarised in Table 3, and the corresponding plots of V_d versus electric field are shown in Figure 1. In addition to the parameters defined previously, Table 3 indicates the change in drift velocity for additions of 500 ppm water or 10 ppm oxygen in the gas mixture, as a measure of the influence of polluants on the performance of the TPC. It also gives the attachment coefficient of the gas mixture with 10 ppm oxygen.

One may see from Table 3 that the more neon there is in the gas mixture, the lower the values of p_{ms} and σ_L. In addition, the more neon there is, the smaller the influence of water and oxygen contamination on drift velocity: a contamination of 500 ppm water changes the drift velocity by as much as 7.7 % in a 90 % argon + 10 % CH_4 mixture, and by only 0.8 % in a 90 % neon + 10 % CH_4 mixture.

Unfortunately adding neon also presents drawbacks: indeed, the more neon is present in the mixture, the higher the required operation electric field, the lower the drift velocity and the lower the value of N_t. In addition, increasing the amount of neon also increases the sensitivity of the gas mixture to oxygen contamination in terms of attachment coefficient, but only slightly.

An acceptable compromise could be a mixture of 70 % argon, 20 % neon, together with 10 % CH_4 as a quencher: $p_{ms} = 3.8$ GeV/c would be acceptable, while $N_t = 80$ /cm is not too small, the required operation electric field $E_{max} = 170$ V/cm is low enough, the drift velocity $V_{d\,max}$ is still large enough (4.7 cm/μs) and the influence of electric field distortions is smaller than for a simple 90 % argon + 10 % CH_4 mixture (0.16 % instead of 0.29 % change in drift velocity for 10 V/cm change in electric field). Finally the presence of 500 ppm water in the mixture changes the drift velocity by 4.5 % rather than 7.7 % for a 90 % argon + 10 % CH_4 mixture.

5 Argon and helium

Another possibility consists in adding helium to argon. The main properties of argon and helium based mixtures with 10 % CH_4 are summarised in Table 4, and the corresponding plots of V_d versus electric field are shown in Figure 2.

Even a small addition of helium changes drastically the properties of the gas mixture, and more specifically the operation electric field and the drift velocity. The advantages and drawbacks for adding helium in an argon + 10 % CH_4 mixture are summarised here:

- The maximal drift velocity $V_{d\,max}$ decreases with the addition of helium, and is already as low as 4.2 cm/μs or 3.6 cm/μs for 5 % or 10 % helium. One should therefore not use more than about 10 % helium in the mixture.

- The operation electric field on the other hand does not increase too much (it is 190 V/cm or 240 V/cm with 5 % or 10 % helium) and is thus not a big issue here.

- The main reason for wanting to include helium in the gas mixture would be to decrease the value of p_{ms}. However, only 10 % helium does not change the radiation length enough to improve p_{ms} (p_{ms} is 4.2 GeV/c with no helium and is still as high as 3.9 GeV/c with 10 % helium).

- Concerning the effect of polluants on the properties of the gas mixtures, one may see that including a small amount of helium in an argon + CH_4 gas mixture decreases the sensitivities of the drift velocity to water and oxygen contamination. Figures 3 and 4 show the effect of a contamination of 500 ppm and 1000 ppm water on the dependence of V_d on the electric field for an argon + CH_4 and an argon + helium + CH_4 mixtures. It is clear that the effect is much smaller around the maximum drift velocity when helium is present.

- On the other hand the attachment coefficients of the gas mixtures listed in Table 4 with 10 ppm oxygen contamination do increase with the amount of helium included, but only slightly. The loss of primary electrons after a drift length of 2.5 m in a 90 % argon + 10 % CH_4 gas mixture is as large as 36 %; adding 10 % helium brings this loss to 45 %.

- Finally, adding 10 % helium in the gas mixture does not change too much N_t, as it goes from about 90 /cm to 81 /cm.

With the previous discussion and after comparing Tables 3 and 4 it seems clear that adding helium to an argon based mixture is not better than using a mixture of neon and argon. Neither option is fully satisfactory.

6 Quencher

In Table 5 are listed some of the main properties of argon based mixtures with 10 % methane, ethane, iso-butane, CO_2 and DME. Before going into details, one can immediately see that DME is ruled out as it requires a far too large operation electric field: 1000 V/cm.

The choice of quencher is critical. Various considerations come into play and will be discussed in what follows:

- A priori, one should use a quencher with as few H atoms as possible. Indeed the neutron scattering cross-section is much larger on H than on most other atoms. The best candidate for that point of view is then CO_2, rather than the classically used CH_4. Indeed, as quoted in Table 1, the total neutron bound scattering cross-section, σ_n, is as large as 333 barn for CH_4 and only 14 barn for CO_2.

  From Table 5, one can see that a 90 % argon + 10 % CH_4 mixture is about 17 times worse than a 90 % argon + 10 % CO_2 mixture, in terms of neutron scattering cross-section. The other two possibilities, C_2H_6 and iC_4H_{10} are even worse and should therefore be avoided if a high neutron background flux is expected.

- Plots of V_d versus electric field, E, are shown in Figure 5 for various 90 % argon based mixtures with 10 % CH_4, C_2H_6, iC_4H_{10}, CO_2 and DME. From these plots and from Table 5, one may conclude that:

  - DME is ruled out, as already mentionned, because of the too large operation voltage; in addition the drift velocity is as small as 4 cm/μs.
  - CO_2 is not a good choice as the maximal drift velocity occurs at a much too large value of the electric field (800 V/cm).
  - CH_4 requires a smaller electric field (135 V/cm), but does not show a very flat plateau and is therefore more sensitive to electric field distortions (a 10 V/cm change in electric field results in a 0.3 % change in drift velocity).
  - C_2H_6 is better: it does not require a too large electric field (about 200 V/cm) and has a flatter plateau (a 10 V/cm change in electric field induces a change in drift velocity as small as 0.05 %).
  - iC_4H_{10} has an even flatter plateau, but requires a rather large (but acceptable) operation electric field (about 450 V/cm).

- With respect to longitudinal diffusion, CO_2 is twice better than CH_4, which means that the spatial resolution in the direction parallel to the drift field is much better with CO_2 than with CH_4.

  For transverse diffusion, the behaviour is quite the opposite: less diffusion for CH_4 than for CO_2. As already mentioned in section 4 a smaller transverse diffusion coefficient might be an advange or a drawback, depending on the type of readout of the TPC.

C_2H_6 and iC_4H_{10} have intermediate diffusion properties.

DME gives the smallest longitudinal and the largest transverse diffusion parameters of all 5 mixtures.

- Concerning the sensitivity of the performances of the gas mixture to water contamination:
  - CO_2 is the best: 0.4 % change in V_d for a 500 ppm contamination of water.
  - CH_4 is the worst: the corresponding change in V_d is as large as 7.7 %.
  - C_2H_6 and iC_4H_{10} have an intermediate sensitivity to water contamination.
- The last point to be considered is the attachment coefficient due to oxygen contamination. Actually, as can be seen from Table 5 the attachment coefficients of the gas mixtures considered here with 10 ppm oxygen contamination are all about the same, between 0.0014 /cm (for CO_2) and 0.0024 /cm (for iC_4H_{10}). The loss of primary electrons after a drift length of 2.5 m in such a gas mixture is therefore between 30 % (for CO_2) and 45 % (for iC_4H_{10}).

7 Two quenchers: CO_2 and CH_4

According to the previous section, it is clear that both CO_2 and CH_4 present advantages and drawbacks. Using a mixture of these two quenchers might be a way to make use of the qualities of both gases without suffering too much from their respective drawbacks. A summary of the characteristics of argon based mixtures with both CO_2 and CH_4 used as quenchers is given in Table 6, with 10 %, 15 % and 20 % quencher. Gas mixtures containing too much CO_2 result in a too high operation electric field and are therefore not included in the table.

8 Mixtures of 4 gases

As mentioned in sections 4 and 5 adding some neon or helium to an argon based mixture (with CH_4 used as a quencher) improves some of the properties of the gas mixture. Let us now consider such a gas mixture with both CO_2 and CH_4 as quenchers. The characteristics of a set of such 4-component mixtures are given in Tables 7 and 8, and the plots of V_d versus electric field are shown in Figures 6 and 7 for mixtures with 10 % quencher (5 % CO_2 and 5 % CH_4).

9 Conclusion

As a conclusion I would say that the best gas mixture candidate for the TPC of the detector of the future Linear Collider TESLA is a 3 component mixture based on argon with both CO_2 and CH_4 as quenchers (for example 90 % argon, 5 % CO_2 and 5 % CH_4). One should however keep in mind three comments:

- If the neutron background in the detector turns out to be small enough, the neutron scattering cross-section of the gas mixture ceases to be important. One may then not need to choose a quencher with as few H atoms as possible. In that case, using CH_4 (or maybe C_2H_6 or iC_4H_{10}) as the only quencher should be the best choice.

- Before selecting the gas mixture to be used, one should also consider the influence of instabilities in the gas proportions on drift velocity and other characteristics of the mixture.

- One should also consider the quenching performances of the gas, and therefore the performance of a TPC readout system in the gas mixture chosen. Therefore, once the type of readout and other parameters of the TPC have been defined, one should still perform a full simulation of the TPC performances with the MAXWELL [3] and GARFIELD [4] packages and fine tune both readout and gas parameters. Such a detailed study is out of the scope of this note but will be performed at a later stage.

References

[1] S.F. Biagi, Nucl. Instr. Meth. A 283 (1989) 716.

[2] Neutron News, Vol. 3, No. 3 (1992) 29-37.

[3] MAXWELL, Electric Field Simulator by Ansoft Co. USA.

[4] GARFIELD, developed at CERN by R. Veenhof.

Gas	X_0[m]	N_t[1/cm]	σ_n[barn]
He	5299	8	1.34
Ar	110	94	0.683
Ne	345	43	2.628
CF_4	92.4	100	
DME	222	160	
CO_2	183	91	14.015
CH_4	646	53	333.631
C_2H_6	340	111	503.222
iC_4H_{10}	169	195	842.404

Table 1: Gas properties.

Mixture	X_0 [m]	p_{ms} [GeV/c]	N_t [1/cm]	σ_n [barn]	E_{max} [V/cm]	$V_{d\,max}$ [cm/μs]	ΔV_d for $E_{max} \pm 10$ V/cm [%]	D_L , D_T [μm/$\sqrt{(\text{cm})}$]	σ_L , σ_T [mm]
Ne 90 CH_4 10	362	2.2	44.0	35.7	275	3.53	0.15	292 , 127	4.6 , 2.00
Ne 80 CH_4 20	380	2.2	45.0	68.8	400	4.94	0.02	238 , 110	3.8 , 1.74
Ne 70 CH_4 30	401	2.1	46.0	101.9	475	5.99	0.02	213 , 97	3.4 , 1.53
Ne 60 CH_4 40	424	2.1	47.0	135.0	550	6.86	0.01	195 , 90	3.1 , 1.42
Ne 50 CH_4 50	450	2.0	48.0	168.1	605	7.61	0.02	182 , 84	2.9 , 1.33
Ne 40 CH_4 60	479	1.9	49.0	201.2	650	8.26	0.01	172 , 79	2.7 , 1.25
Ne 30 CH_4 70	512	1.8	50.0	234.3	700	8.86	0.01	163 , 76	2.6 , 1.20
Ne 20 CH_4 80	550	1.8	51.0	267.4	735	9.40	0.01	156 , 73	2.5 , 1.15
Ne 10 CH_4 90	594	1.7	52.0	300.5	780	9.89	0.02	149 , 71	2.4 , 1.12
Ar 90 CH_4 10	120	4.2	89.9	34.0	135	5.47	0.29	368 , 55	5.8 , 0.87
Ar 80 CH_4 20	132	4.0	85.8	67.3	220	6.99	0.11	281 , 56	4.4 , 0.89
Ar 70 CH_4 30	146	3.8	81.7	100.6	290	7.90	0.07	242 , 56	3.8 , 0.89
Ar 60 CH_4 40	165	3.5	77.6	133.9	355	8.53	0.07	217 , 56	3.4 , 0.89
Ar 50 CH_4 50	188	3.3	73.5	167.2	435	9.00	0.02	195 , 59	3.1 , 0.93
Ar 40 CH_4 60	219	3.0	69.4	200.5	505	9.37	0.02	181 , 61	2.9 , 0.96
Ar 30 CH_4 70	262	2.7	65.3	233.7	585	9.68	0.02	168 , 64	2.7 , 1.01
Ar 20 CH_4 80	327	2.4	61.2	267.0	655	9.93	0.01	159 , 65	2.5 , 1.03
Ar 10 CH_4 90	434	2.0	57.1	300.3	735	10.16	0.01	149 , 67	2.4 , 1.06

Table 2: Argon and neon based mixtures with CH_4 as quencher. B = 3 T.

Mixture Ar Ne CH_4	X_0 [m]	p_{ms} [GeV/c]	N_t [1/cm]	σ_n [barn]	E_{max} [V/cm]	$V_{d\,max}$ [cm/μs]	ΔV_d for $E_{max}\pm$ 10 V/cm [%]	ΔV_d for 500 ppm water [%]	ΔV_d for 10 ppm O_2 [%]	attachment coeff. with 10 ppm O_2 [/cm]	D_L , D_T [μm/$\sqrt{(\text{cm})}$]	σ_L , σ_T [mm]
90-0-10	120	4.2	89.9	34.0	135	5.47	0.29	-7.7	-0.005	0.0018	368 , 55	5.8 , 0.87
80-10-10	130	4.0	84.8	34.2	155	5.03	0.15	-5.6	-0.004	0.0020	349 , 65	5.5 , 1.03
70-20-10	141	3.8	79.7	34.4	170	4.70	0.16	-4.5	-0.003	0.0021	337 , 72	5.3 , 1.14
60-30-10	154	3.6	74.6	34.6	185	4.43	0.10	-3.6	-0.003	0.0022	326 , 80	5.2 , 1.26
50-40-10	171	3.4	69.5	34.8	200	4.21	0.09	-2.9	-0.002	0.0023	317 , 88	5.0 , 1.39
40-50-10	191	3.2	64.4	35.0	220	4.03	0.09	-2.1	-0.002	0.0024	307 , 98	4.9 , 1.55
30-60-10	216	3.0	59.3	35.1	240	3.87	0.06	-1.5	-0.002	0.0024	299 , 108	4.7 , 1.71
20-70-10	250	2.8	54.2	35.3	250	3.74	0.05	-1.3	-0.001	0.0025	297 , 113	4.7 , 1.79
10-80-10	296	2.5	49.1	35.5	270	3.63	0.05	-0.9	-0.001	0.0025	291 , 123	4.6 , 1.94
0-90-10	362	2.2	44.0	35.7	275	3.53	0.15	-0.8	-0.0003	0.0026	292 , 127	4.6 , 2.00

Table 3: Argon + neon based mixtures with 10 % CH_4. B = 3 T.

Mixture Ar He CH_4	X_0 [m]	p_{ms} [GeV/c]	N_t [1/cm]	σ_n [barn]	E_{max} [V/cm]	$V_{d\,max}$ [cm/μs]	ΔV_d for $E_{max}\pm$ 10 V/cm [%]	ΔV_d for 500 ppm water [%]	ΔV_d for 10 ppm O_2 [%]	attachment coeff. with 10 ppm O_2 [/cm]	D_L , D_T [μm/$\sqrt{(\text{cm})}$]	σ_L , σ_T [mm]
90-0-10	120	4.2	89.9	34.0	135	5.47	0.29	-7.7	-0.005	0.0018	368 , 55	5.8 , 0.87
87-3-10	124	4.1	87.3	34.0	165	4.61	0.33	-4.9	-0.003	0.0022	341 , 71	5.4 , 1.12
85-5-10	127	4.1	85.6	34.0	190	4.23	0.18	-3.4	-0.003	0.0023	322 , 83	5.1 , 1.31
80-10-10	134	3.9	81.3	34.0	240	3.61	0.14	-1.5	-0.001	0.0024	295 , 108	4.7 , 1.71

Table 4: Argon + helium based mixtures with 10 % CH_4. B = 3 T.

Mixture	X_0 [m]	p_{ms} [GeV/c]	N_t [1/cm]	σ_n [barn]	E_{max} [V/cm]	$V_{d\,max}$ [cm/μs]	ΔV_d for $E_{max}\pm$ 10 V/cm [%]	ΔV_d for 500 ppm water [%]	ΔV_d for 10 ppm O_2 [%]	attachment coeff. with 10 ppm O_2 [/cm]	D_L , D_T [μm/$\sqrt{(\text{cm})}$]	σ_L , σ_T [mm]
Ar 90 CH_4 10	120	4.2	89.9	34.0	135	5.47	0.29	-7.7	-0.005	0.0018	368 , 55	5.8 , 0.87
Ar 90 C_2H_6 10	118	4.2	95.7	50.9	205	4.39	0.05	-3.4	-0.002	0.0024	288 , 75	4.6 , 1.19
Ar 90 iC_4H_{10} 10	114	4.3	104.1	84.9	450	4.68	0.01	-1.3	-0.001	0.0021	206 , 104	3.3 , 1.64
Ar 90 CO_2 10	115	4.3	93.7	2.0	750	4.99	0.02	-0.4	-0.001	0.0014	184 , 152	2.91 , 2.40
Ar 90 DME 10	116	4.3	100.6		1000	4.02					172 , 184	2.72 , 2.91

Table 5: Argon based mixtures with 10 % quencher. B = 3 T.

Mixture Ar CO_2 CH_4	X_0 [m]	p_{ms} [GeV/c]	N_t [1/cm]	σ_n [barn]	E_{max} [V/cm]	$V_{d\,max}$ [cm/μs]	ΔV_d for $E_{max}\pm$ 10 V/cm [%]	ΔV_d for 500 ppm water [%]	ΔV_d for 10 ppm O_2 [%]	attachment coeff. with 10 ppm O_2 [/cm]	D_L , D_T [μm/$\sqrt{(\text{cm})}$]	σ_L , σ_T [mm]
90-0-10	120	4.2	89.9	34.0	135	5.47	0.29	-7.7	-0.005	0.0018	368 , 55	5.8 , 0.87
90-5-5	117	4.2	91.8	18.0	450	4.92	0.04	-1.3	-0.001	0.0017	217 , 119	3.4 , 1.88
90-10-0	115	4.3	93.7	2.0	750	4.99	0.02	-0.4	-0.001	0.0014	184 , 152	2.91 , 2.40
85-0-15	126	4.1	87.9	50.6	175	6.35	0.18	-7.1	-0.004	0.0016	318 , 54	5.0 , 0.85
85-5-10	123	4.1	89.8	34.6	510	5.38	0.02	-1.4	-0.001	0.0016	207 , 116	3.3 , 1.83
80-0-20	132	4.0	85.8	67.3	220	6.99	0.11	-6.0	-0.004	0.0014	281 , 56	4.4 , 0.89
80-5-15	129	4.0	87.7	52.3	570	5.78	0.02	-1.4	-0.001	0.0015	314 , 69	5.0 , 1.09

Table 6: Argon based mixtures with CO_2 and CH_4. B = 3 T.

Mixture Ar Ne CO_2 CH_4	X_0 [m]	p_{ms} [GeV/c]	N_t [1/cm]	σ_n [barn]	E_{max} [V/cm]	$V_{d\,max}$ [cm/μs]	ΔV_d for $E_{max}\pm$ 10 V/cm [%]	ΔV_d for 500 ppm water [%]	ΔV_d for 10 ppm O_2 [%]	attachment coeff. with 10 ppm O_2 [/cm]	D_L , D_T [μm/$\sqrt{(\text{cm})}$]	σ_L , σ_T [mm]
85-5-5-5	122	4.1	89.3	18.1	455	4.87	0.04	-1.4	-0.001	0.0017	217 , 121	3.4 , 1.91
80-10-5-5	126	4.1	86.7	18.2	465	4.82	0.04	-1.2	-0.001	0.0017	215 , 124	3.4 , 1.96
70-20-5-5	137	3.9	81.6	18.4	475	4.73	0.04	-1.2	-0.001	0.0018	214 , 127	3.4 , 2.01
60-30-5-5	150	3.7	76.5	18.6	500	4.64	0.02	-1.0	-0.001	0.0018	211 , 135	3.3 , 2.13
50-40-5-5	165	3.5	71.4	18.8	520	4.56	0.02	-0.8	-0.001	0.0018	210 , 141	3.3 , 2.23
80-5-5-10	127	4.1	87.2	34.7	525	5.32	0.02	-1.3	-0.001	0.0016	205 , 119	3.2 , 1.88
75-10-5-10	133	4.0	84.5	34.8	530	5.27	0.02	-1.3	-0.001	0.0016	204 , 121	3.2 , 1.91
65-20-5-10	145	3.8	79.6	35.0	550	5.17	0.02	-1.1	-0.001	0.0016	202 , 126	3.2 , 1.99
55-30-5-10	159	3.6	74.5	35.2	570	5.09	0.02	-1.0	-0.001	0.0016	201 , 131	3.2 , 2.07
45-40-5-10	176	3.4	69.4	35.4	595	5.01	0.03	-0.9	-0.001	0.0016	200 , 138	3.2 , 2.18

Table 7: Argon + neon based mixtures with a mixture of CO_2 and CH_4 as quencher. B = 3 T.

Mixture Ar He CO_2 CH_4	X_0 [m]	p_{ms} [GeV/c]	N_t [1/cm]	σ_n [barn]	E_{max} [V/cm]	$V_{d\,max}$ [cm/μs]	ΔV_d for $E_{max}\pm$ 10 V/cm [%]	ΔV_d for 500 ppm water [%]	ΔV_d for 10 ppm O_2 [%]	attachment coeff. with 10 ppm O_2 [/cm]	D_L , D_T [μm/$\sqrt{(\text{cm})}$]	σ_L , σ_T [mm]
87-3-5-5	121	4.2	89.2	18.0	475	4.66	0.04	-1.2	-0.001	0.0018	212 , 126	3.4 , 1.99
85-5-5-5	124	4.1	87.5	18.0	505	4.51	0.03	-0.9	-0.0009	0.0019	206 , 135	3.3 , 2.13
80-10-5-5	131	4.0	83.2	18.1	550	4.19	0.02	-0.7	-0.0007	0.0020	200 , 146	3.2 , 2.31
82-3-5-10	127	4.1	87.2	34.7	550	5.10	0.02	-1.1	-0.001	0.0016	200 , 125	3.2 , 1.98
80-5-5-10	130	4.0	85.5	34.7	570	4.94	0.02	-1.0	-0.001	0.0017	197 , 130	3.1 , 2.06
75-10-5-10	138	3.9	81.2	34.7	620	4.59	0.01	-0.8	-0.0009	0.0018	191 , 141	3.0 , 2.23

Table 8: Argon + helium based mixtures with a mixture of CO_2 and CH_4 as quencher. B = 3 T.

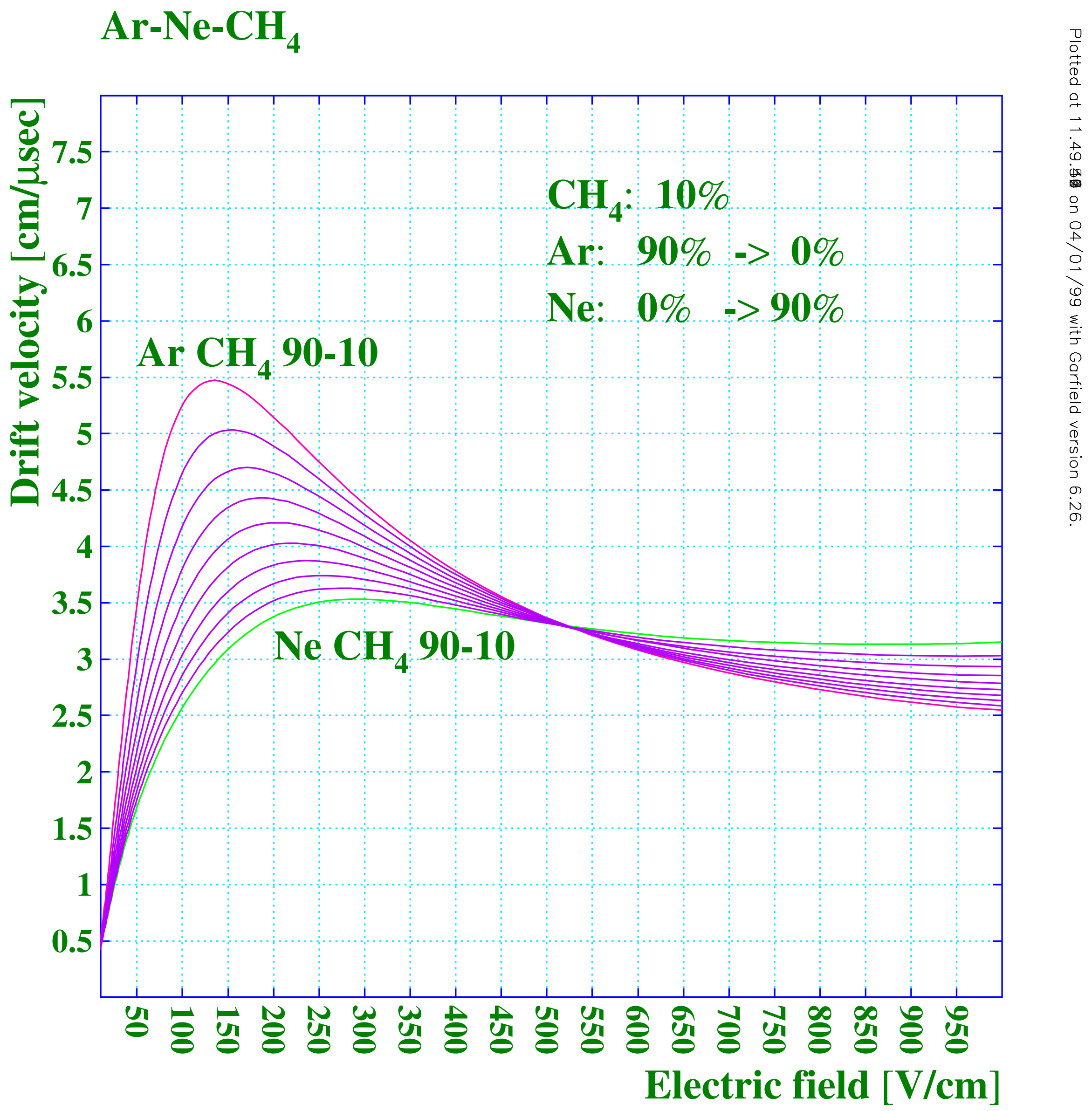

Figure 1: Drift velocity as a function of electric field for argon + neon based mixtures with 10 % CH_4 as quencher. B = 3 T.

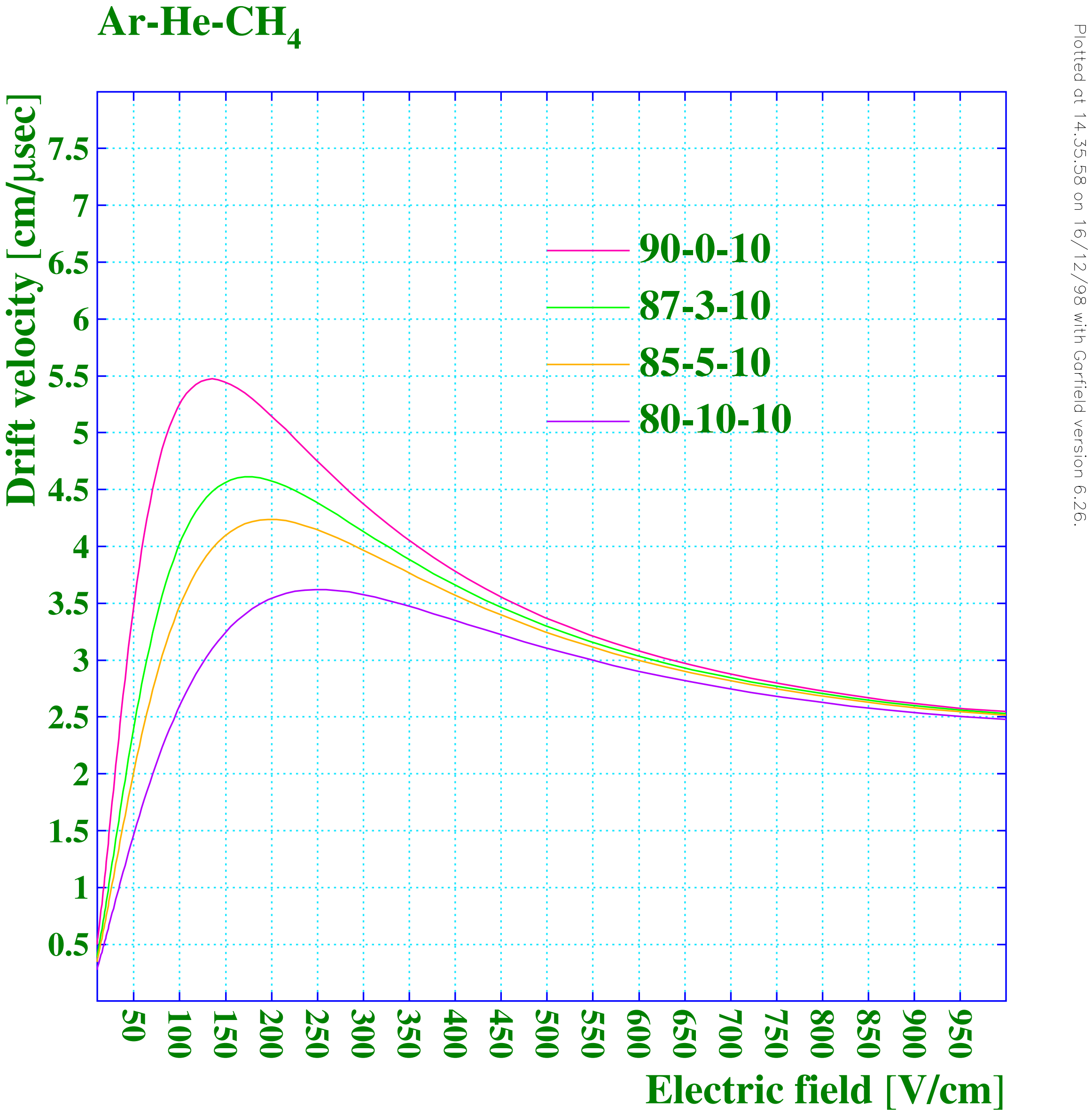

Figure 2: Drift velocity as a function of electric field for argon + helium based mixtures with 10 % CH_4 as quencher. B = 3 T.

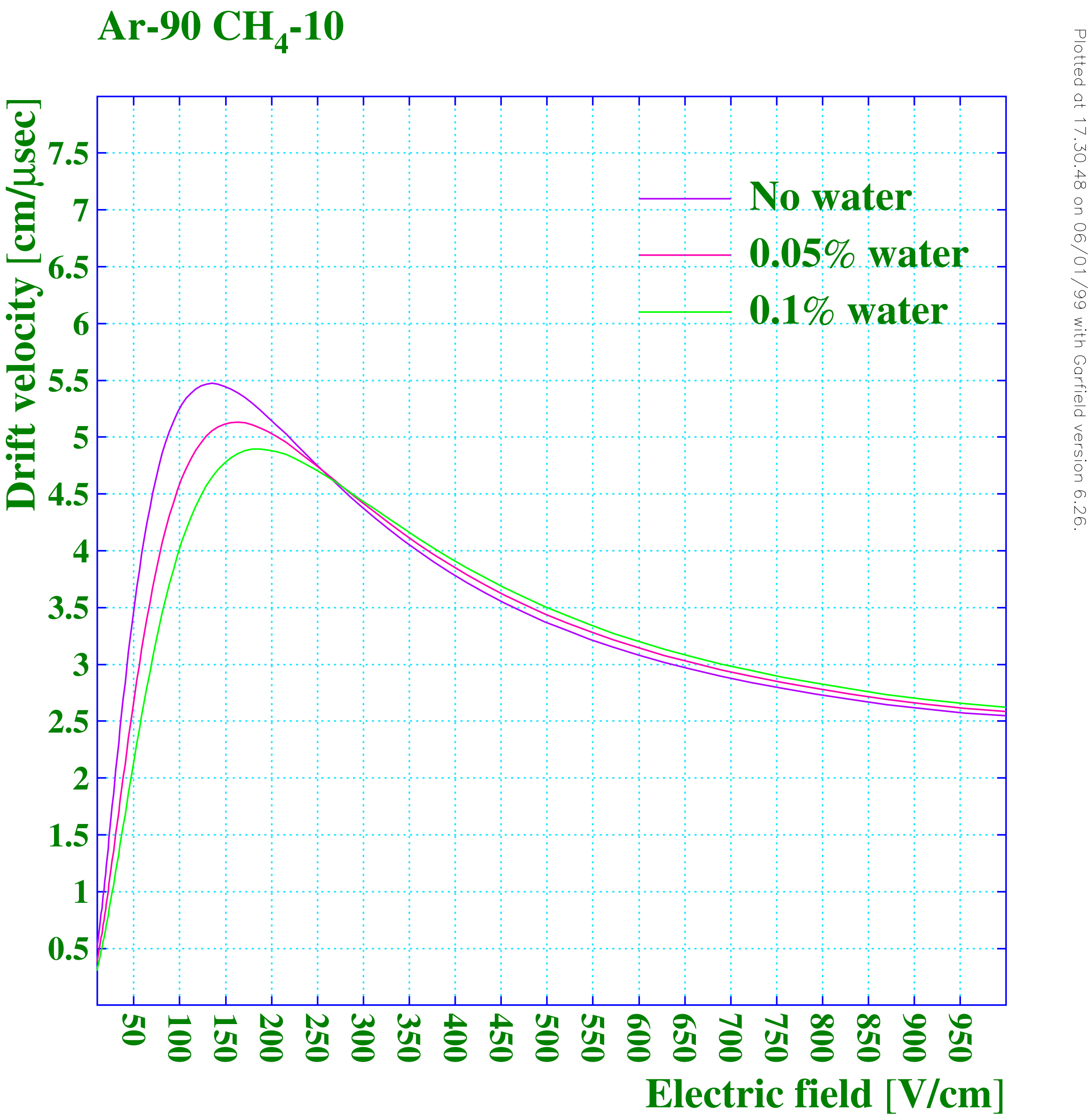

Figure 3: Effect of water contamination on the electric field dependence of drift velocity in a 90 % argon + 10 % CH_4 gas mixture. B = 3 T.

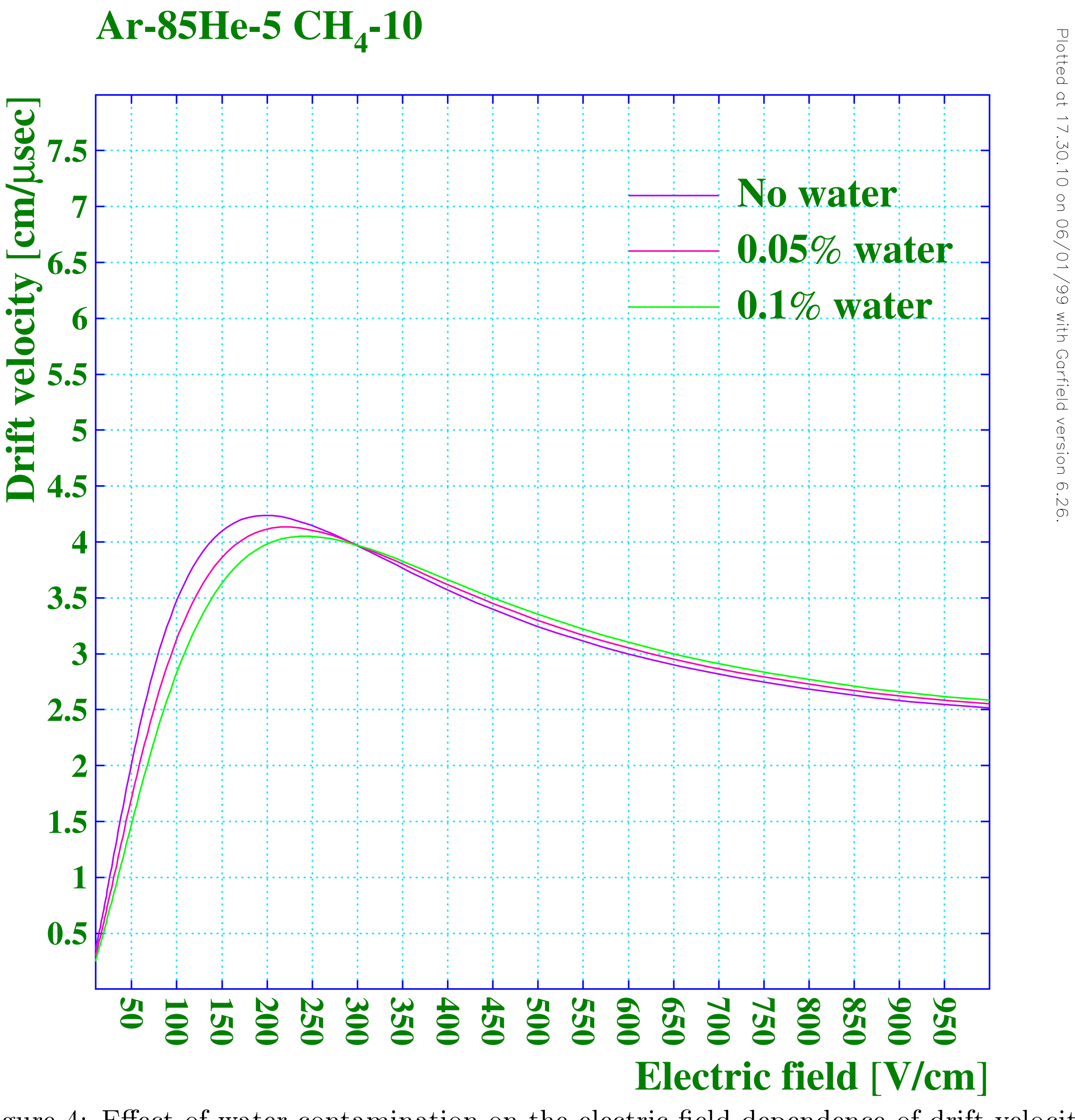

Figure 4: Effect of water contamination on the electric field dependence of drift velocity in a 85 % argon + 5 % helium + 10 % CH_4 gas mixture. B = 3 T.

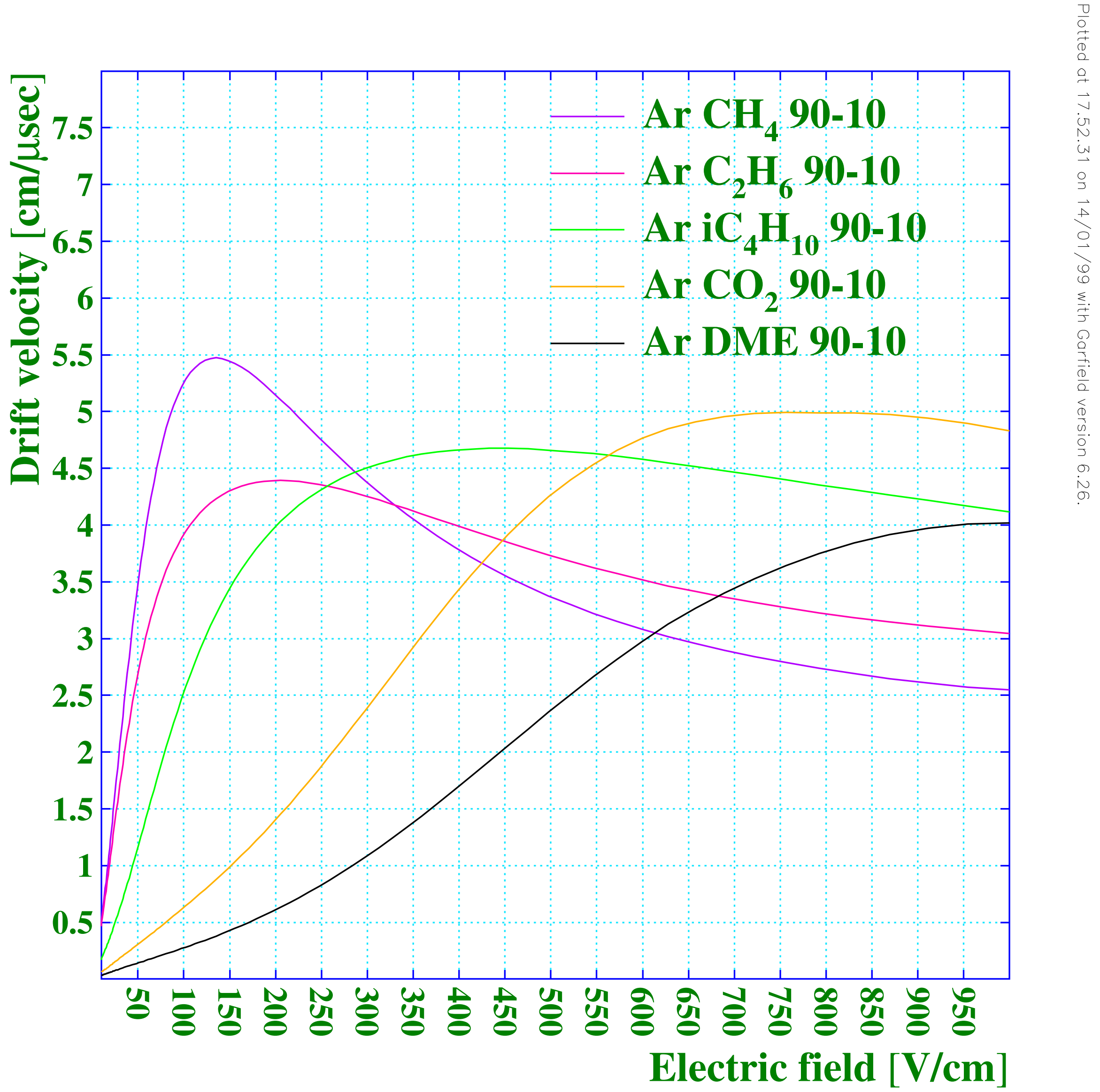

Figure 5: Drift velocity as a function of electric field for 90 % argon + 10 % quencher gas mixtures. B = 3 T.

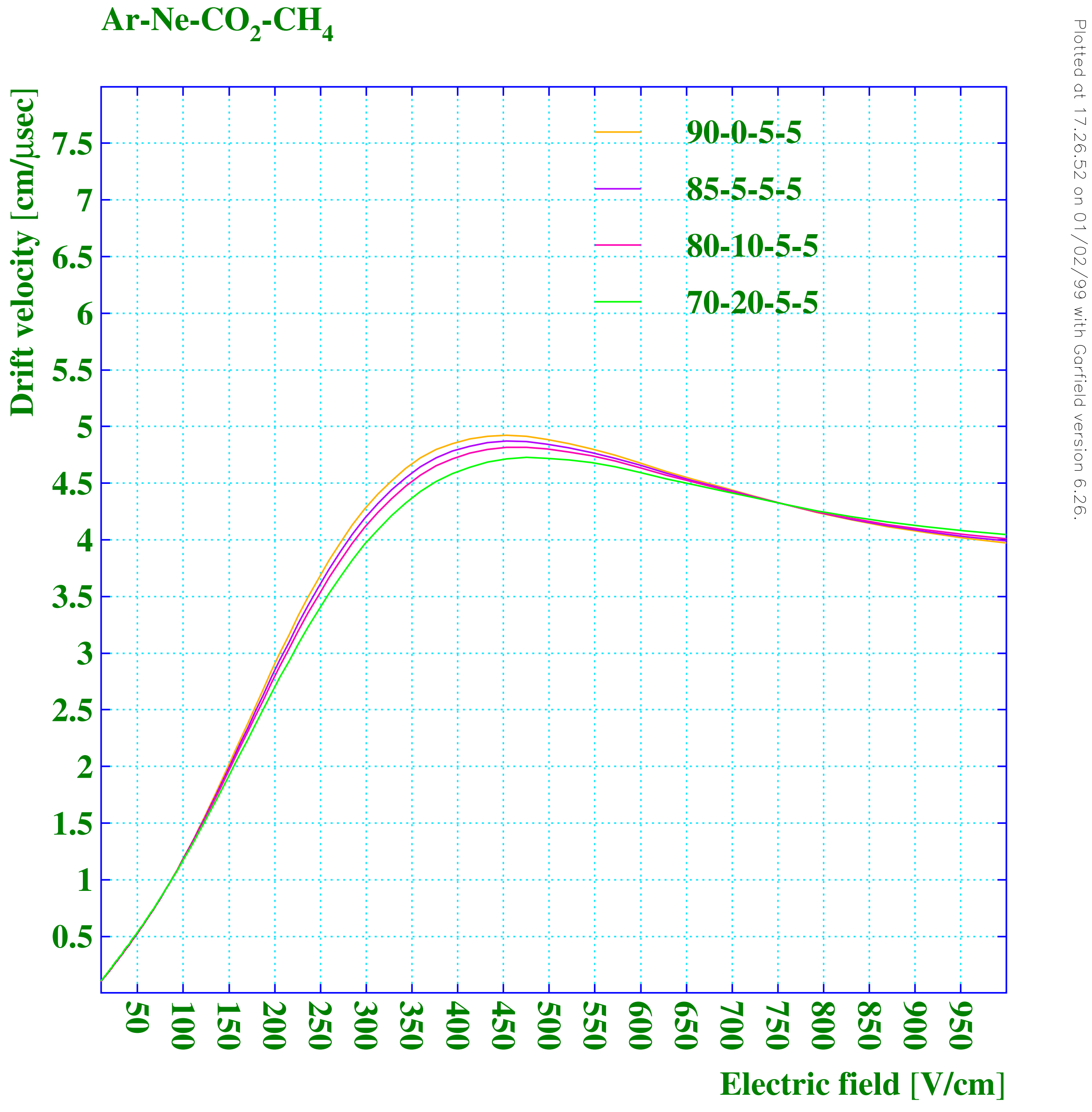

Figure 6: Drift velocity as a function of electric field for argon + neon based mixtures with 5 % CO_2 and 5 % CH_4 as quencher. B = 3 T.

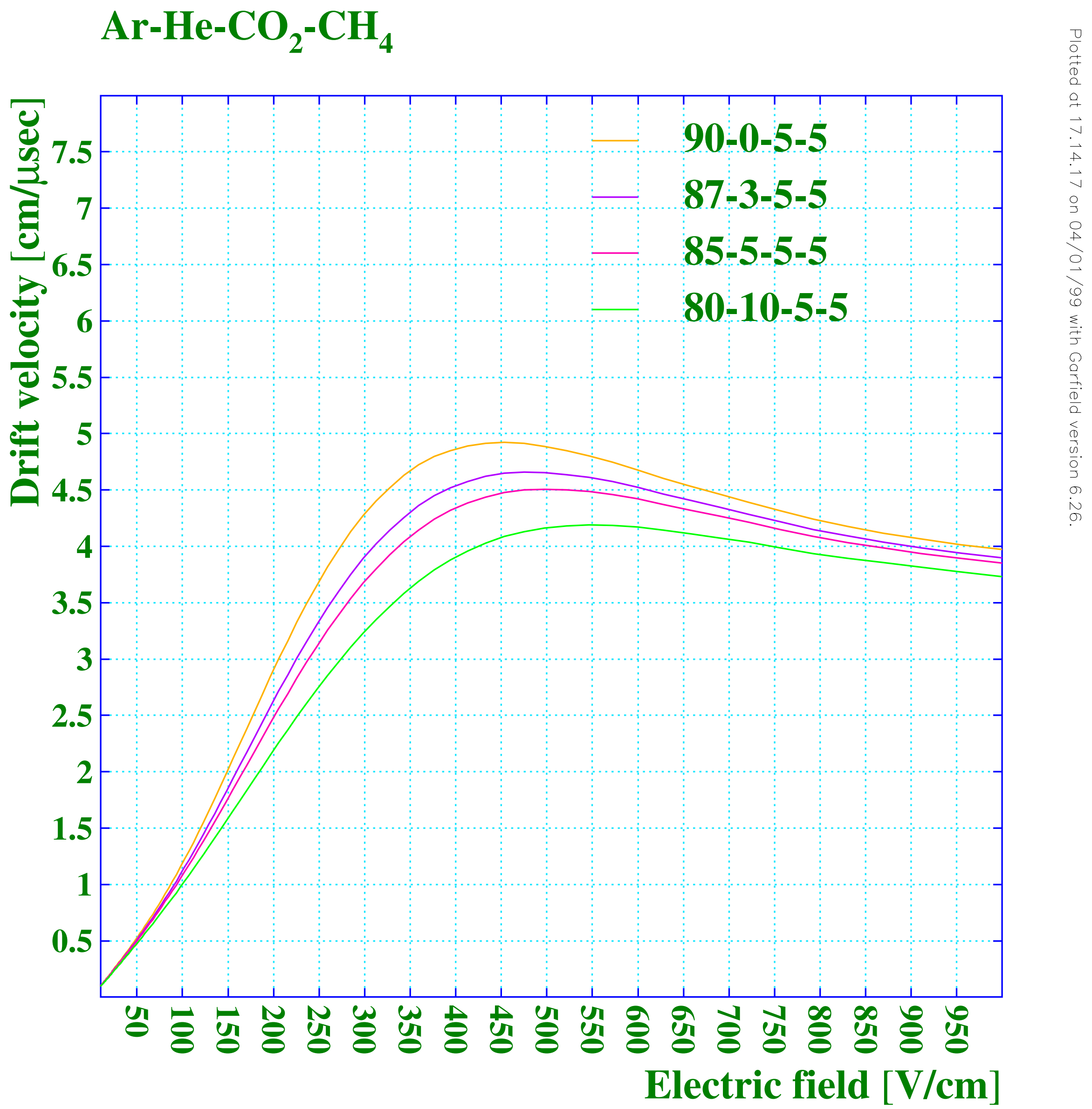

Figure 7: Drift velocity as a function of electric field for argon + helium based mixtures with 5 % CO_2 and 5 % CH_4 as quencher. B = 3 T.