A STUDY OF GAS MIXTURES FOR ATLAS MDT

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Abstract

Results of a gas study for the ATLAS Monitored Drift Tubes are summarized in this report. The electron drift velocity, Lorentz angle, drift distance to drift time relations (R-T) and electron diffusion are calculated for selected gas mixtures by using the CERN drift chamber simulation code GARFIELD/MAGBOLTZ. Five groups of gas mixtures containing different quenchers are studied. The drift tube efficiency, gas gain, avalanche size and self-quenching fractions of the streamer (SQS) mode signals as functions of anode high voltage are measured by using radioactive sources for some gas mixtures. Discussions about the results and several promising gas mixtures for the ATLAS MDT are presented.

1 Introduction

Several crucial requirements make the choice of a gas mixture for the MDT difficult.

1. The MDT must work in a very high rate environment for many years. The maximum rate exceeds 100 Hz/cm^2 or $2 \times 10^5 \text{ Hz}$ per tube.
2. The MDT must work in a nonuniform magnetic field of the magnitude from zero to over one tesla.
3. The required single tube resolution of $60\mu\text{m}$ is very high.
4. A nonflammable gas mixture must be used.

In order to optimize the choice of the gas mixture, we have selected some gas mixtures and studied their properties. The fractions of hydrocarbon are kept low to ensure the nonflammability. The MDT is designed to be operated at 3 atmosphere pressure in order to minimize the Lorentz angle and improve the resolution. At 3 atmosphere pressure, only a very small percentage of hydrocarbon gas is needed in argon based gas mixtures to completely quench the UV photons generated in avalanches and prevent them from reaching the aluminum tube wall.

2 Computer Simulation

At 3 atmosphere pressure with a $50\mu\text{m}$ diameter anode, the typical operating voltage is in the range of 3.0 kV to 3.5 kV depending up on the gas mixture. We assume that the operating voltage is 3.2 kV in our calculations. A small deviation from the actual operating voltage will not fundamentally change the results of our study.

The electron drift velocity, Lorentz angle, R-T relations and electron diffusion are calculated for selected gas mixtures by using GARFIELD/MAGBOLTZ. The quenchers included in this study are CO_2 , CH_4 , N_2 , water vapor and DME $((\text{CH}_3)_2\text{O})$. The CH_4 can be replaced by other hydrocarbon gases such as C_2H_6 without changing the results significantly.

2.1 Drift Velocity and R-T relations

The calculated electron drift velocity as function of E/P for eight selected gas mixtures are shown in figure 1. In figure 2, the electron drift velocity is plotted as a function of distance to the center of the tube. It is more difficult to obtain a linear R-T relation at higher pressure because the range of the E/P inside the drift tube increases as the pressure increases. For example at normal pressure, the typical operating voltage is approximately 2.0 kV and the lowest value of E/P is approximately 0.3 V/cm-torr, whereas it is 0.15 V/cm-tor at three atmosphere pressure.

For ATLAS MDT at 3 atmosphere pressure and with a $50\mu\text{m}$ anode, the drift velocity in Ar- CH_4 mixtures such as P10 or P5 will be very nonlinear because the E/P range of the MDT varies from 0.15 V/cm-torr at the tube wall to 1.1 V/cm-torr at 1 mm from anode. This situation will not be improved by adding CO_2 . However, when a small amount of nitrogen (1-5%) is added into the Ar- CH_4 gas mixture, the uniformity of the drift velocity is greatly improved.

Improving the linearity of the R-T relation in the MDT by adding a small amount of nitrogen in the gas mixture was first proposed by the Freiburg group.[1] Nitrogen, however, is not a common gas used in the proportional gas counters. Although it is attractive because its stabilizing effect on the electron drift velocity, we have found that it also has some negative effects on the drift tube operation. These effects will be discussed in the next section.

The stabilizing effect of nitrogen gas to electron drift velocity has been observed experimentally in the Ar- C_2H_6 50:50 mixture [2] and in some Ar- CO_2 mixtures [3]. Results of the computer simulation studies performed by the Freiburg group also show such stabilizing effect.

We also studied the effect of adding small amounts of water vapor or DME. They appear

to be very useful as a fourth component in Ar-CH₄-N₂ mixtures. In addition of improving the the linearity of the electron drift velocity and lowering the Lorentz angle, water vapor and DME also have beneficial effects on anode ageing. We realize that adding a fourth component to the Ar-CH₄-N₂ mixture is a unwanted complication. However, adding water vapor or DME is not as bad as adding another gas.

The R-T relations at 3 atmosphere pressure for the eight gas mixtures are shown in figure 3. The linearity of the R-T relations in several gas mixtures which contains nitrogen are quite good.

The R-T relations at 3 atmosphere pressure in a 0.6 tesla magnetic field are shown in figure 4. The total drift time is generally longer compared to the case without magnetic field. The best linearity is obtained with the mixture Ar-CH₄-N₂ 90:5:5 in this case.

The electron diffusion (longitudinal) in the eight mixtures without magnetic field as computed by the GARFIELD/MAGBOLTZ is plotted in figure 5. Note that in the ATLAS toroidal magnetic field, the longitudinal diffusion is greatly suppressed by the component of magnetic field which is perpendicular to the electron drift.

2.2 Lorentz Angle

The Lorentz angle in argon-hydrocarbon mixtures tends to be quite large when the E/P is low. Once the tube geometry is fixed, the only practical way to limit the Lorentz angle is to use a gas mixture which has low electron drift velocity in the low E/P region. This can be achieved by adding a small amount of CO₂, N₂, DME or water vapor to argon-hydrocarbon mixtures. The Lorentz angle inside an ATLAS drift tube calculated by the GARFIELD/MAGBOLTZ is given in figure 6 for eight gas mixtures.

Adding a 'cool' gas such as CO₂ is an effective way of reducing the Lorentz angle. It is possible to limit the Lorentz angle to within 18° in 0.6 tesla magnetic field while limiting the total drift time to an acceptable level (<600 ns). The Lorentz angle can be reduced further by adding nitrogen in the Ar-CH₄-CO₂ mixtures. The Lorentz angle in Ar-CH₄-N₂ 90:5:5 mixture is not too large. But the Lorentz angle becomes quite large when the nitrogen is reduced to 1% (Ar-CH₄-N₂ 94:5:1). Water vapor has a very dramatic effect on the Lorentz angle. For example, by adding 0.2% water vapor, the Lorentz angle in Ar-CH₄-N₂ 95:5:1 mixture (Ar-CH₄-N₂-H₂O 93.8:5:1:0.2) is greatly reduced. The appropriate percentage of CH₄ in the rage of 2% to 5%. Other hydrocarbon gas can also be used. The range of water vapor content is approximately from 0.2% to 0.5%. Although the effect of water vapor is quite dramatic, we have noticed that the drift velocity is not very sensitive to small variations of water content.

Another 'cool' gas. DME, can also effectively reduce the electron drift velocity at low E/P and reduce the Lorentz angle. An example of this type of mixtures, Ar-CH₄-N₂-DME 95:3:1:1, is given. This mixture has rather linear R-T relation and also relatively small

Figure 1: Electron drift velocity as function of E/P without magnetic field. Only the E/P region below 1 V/cm-torr is important for the ATLAS MDT. The variations of drift velocity in the Ar-CH₄ mixtures such as P10 are rather large. When a small amount of nitrogen (1-5%) is added the uniformity of the drift velocity is greatly improved. Adding water vapor or DME can further improve the uniformity of the electron drift velocity in the Ar-CH₄-N₂ mixtures.

Figure 2: Electron drift velocity as function of distance from the anode in the ATLAS MDT without magnetic field. The uniformity of electron drift velocity in Ar-CH₄-N₂, Ar-CH₄-N₂-H₂O and Ar-CH₄-N₂-DME mixtures are all quite good.

Figure 3: R-T relations at 3 atmosphere pressure without magnetic field. The linearity of Ar-CH₄-N₂ mixtures is very good. Two other gas mixtures, Ar-CH₄-N₂-H₂O 94.8:5:1:0.2 and Ar-CH₄-N₂-DME 94:3:1:1, have the most linear R-T relations.

Figure 4: R-T relation in a 0.6 tesla magnetic field at 3 atmosphere pressure. The electron drift is generally slower in the magnetic field. Such differences in drift velocity are an important consideration for selecting gas mixtures for the MDT. We prefer the differences in drift velocity with and without the magnetic field to be as small as possible.

Figure 5: Longitudinal electron diffusion at 3 atmosphere pressure without magnetic field.

Figure 6: Lorentz angle inside a 30mm diameter drift tube with a 50 μm anode at 3 atmosphere pressure in a 0.6 tesla magnetic field. The Lorentz angle is small in mixtures containing CO₂. It is very large in P10 mixture. It is also quite large in the Ar-CH₄-N₂ 94:5:1. By adding a small amount of 'cool' gas (0.2% of water vapor or 1% of DME) into the Ar-CH₄-N₂ 94:5:1, the Lorentz angle is greatly reduced to a level similar to that in the Ar-CH₄-N₂ 90:5:5.

Lorentz angle. We expect that alcohol may have similar effects as DME. We have not studied alcohol yet.

2.3 Summary

1. The commonly used proportional drift tube gas mixtures such as Ar-CH₄ 90:10 or other argon-hydrocarbon gas mixtures would not perform well in MDT. In addition of the non-saturated drift velocity, the Lorentz angle is very large due to the high drift velocity in the low E/P region.
2. By adding a small amount of CO₂, the Lorentz angle can be greatly reduced. The variation of electron drift velocity in the tube, however, is quite large.
3. Mixture Ar-CH₄-N₂ 90:5:5 has reasonably small Lorentz angle and rather linear R-T relation.
4. Water vapor can help to improve drift properties of the gas mixture. The Ar-CH₄-N₂-H₂O 93.8:5:1:0.2 is an example of this type of mixtures.
5. DME also can be added to improve the drift properties of the gas mixture. Ar-CH₄-N₂-DME 95:3:1:1 is an example of this type of mixture.

3 Experimental Studies

Experimental studies were conducted by using a drift tube with a 50 μm anode and another one with 90 μm anode operated at 1 to 7 bar pressure. Only the results from the drift tube with 50 μm anode at 3 bar pressure are reported here. The motivation for this study is mainly to determine the operating range by measuring the efficiency plateau and gas gain as functions of anode high voltage for different gas mixtures.

The ATLAS MDT is designed to be operated in the proportional mode. The gas mixtures with small percentages of quenchers normally do not support the SQS mode operation at one atmosphere pressure. However, pressure dependence of the streamer formation is expected from the basic mechanisms of streamer formation process [4]. At higher pressure, the proportional avalanches are more compact in space because the mean free path of electrons is shorter and the space charge density is, therefore, higher at the same gas gain. The saturation of the proportional mode, which is a necessary condition for the SQS mode, is reached at lower proportional gas gain. In addition even though the percentage of quenchers is not large, the UV photon quenching, which is another condition for SQS mode, is sufficient because of the higher pressure. As a result, conditions are more favorable at higher pressure for the SQS mode.

SQS mode signals in drift tubes designed to be operated in the proportional mode can have harmful consequences because of the following reasons:

- The very large SQS mode signals can saturate the amplifiers designed for proportional signals, causing long dead time and baseline shift. In a high rate environment, once the streamer fraction reaches a significant level, the proportional counters can no longer be operated normally.
- The resolution can be affected because the rise time of streamer and proportional signals are different.
- The much larger amount of charges contained in the streamers can cause the anode to age faster than expected from proportional signals alone.

These problems are especially crucial for the high precision ATLAS MDT which will be operated in a very high rate environment for many years.

One should be aware of the fact that the rate of the anode aging depends on the avalanche size. In general for the same amount of charges deposited on the anode, the aging is more severe if the gas gain is lower [7]. The anode can tolerate much more charge before aging effect occurs when the counter is operated at SQS mode compared to the proportional mode operation at lower gas gain.

3.1 Gas Gain and Avalanche Size

The avalanche sizes of both proportional and SQS mode signals are measured by using a ^{55}Fe X-ray source and a charge sensitive amplifier with a long integration time constant. The gas gain can be deduced within good approximation by assuming that a ^{55}Fe X-ray interaction in the gas mixture creates 220 electron and ion pairs. The gas gain is also measured independently by using a ^{90}Sr β -source. The results of the two methods agree very well. Figure 7 shows the effect of nitrogen to the avalanche size in gas mixtures containing 5% of methane or ethane. Also, C_2H_6 and CH_4 appear to have different effects on the SQS mode size. Figure 8 shows effect of nitrogen in gas mixtures which also contain CO_2 .

The avalanche size of the SQS mode signals in the $\text{Ar-CO}_2\text{-CH}_4$ 92:3:5 gas mixture is rather modest. However, it is greatly increased when 2% nitrogen is added. Another mixture included in figure 8 is $\text{Ar-CO}_2\text{-CH}_4\text{-N}_2$ 95:2:1:2. The avalanche size of the SQS mode signals is quite large in this mixture indicating that the amount of quenchers also plays a role. Generally speaking, the avalanche size of the SQS mode signals becomes smaller when CO_2 is added. The effect of CO_2 on the the avalanche size of the SQS mode signals in the $\text{Ar-CH}_4\text{-N}_2$ mixtures is shown in figure 9. The avalanche size decreases as the CO_2 fraction increases.

As discussed in the previous section, although the gas mixtures such as $\text{Ar-CH}_4\text{-N}_2$ 90:5:5 is attractive because of its more or less saturated drift velocity, the avalanche size

Figure 7: Avalanche size vs anode high voltage for four gas mixtures containing Ar, CH₄, C₂H₆ and N₂. The avalanche size of the SQS mode signals increases as the amount of nitrogen increases. Also, it is much larger in Ar-C₂H₆-N₂ 90:5:5 than in Ar-CH₄-N₂ 90:5:5.

Figure 8: Avalanche size vs anode high voltage for four gas mixtures with Ar, CO₂, N₂ and CH₄. In general, the higher the N₂ concentration, the larger the SQS mode signal size.

of the SQS mode in this mixture is very large. Gas mixtures such as Ar-CO₂-CH₄ 92:5:3 without nitrogen will have less problems caused by SQS mode signals.

The issue of rate capability related to the SQS mode is of course influenced by how often the SQS mode signals occur at the operating condition of the MDT. The relationship between the frequency of the SQS mode signals and the proportional mode gas gain will be discussed in the next section.

Figure 9: Avalanche size vs anode high voltage for four gas mixtures with different amount CO₂

3.2 Efficiency Plateau and SQS Fraction

The efficiency plateau and the streamer fraction as functions of anode voltage measured by using a ^{90}Sr β -source are shown in figure 10. The amplifier used is a high gain and high speed amplifier [5]. The system trigger is provided by two plastic scintillation counters, one above and one below the drift tube.

Figure 10: Efficiencies and the fractions of SQS mode signals as functions of anode high voltage

3.3 Summary

We have observed that the fraction of SQS mode signals increases very rapidly once the SQS mode begins to occur. In the Ar-CH₄-N₂ or Ar-C₂H₆-N₂ 90:5:5 mixtures, the SQS mode signals begin to appear at a gas gain of only few times 10⁴ at 3 atmosphere pressure. In Table 2. the gas gain at which 0.5% signals are streamers is given.

Table. 2 Onset points for 0.5% streamers.

Gas mixtures	Anode HV	Gas gain
Ar-CO ₂ -CH ₄ 92:5:3	3.40 kV	1.4×10^5
Ar-CO ₂ -CH ₄ -N ₂ 90:5:3:2	3.51 kV	1.2×10^5
Ar-CH ₄ -N ₂ 90:5:5	3.66 kV	0.7×10^5

At gas gain 7×10^4 in the Ar-CH₄-N₂ mixture, the fraction of SQS mode reaches 0.5% which is perhaps already too high to be acceptable for the MDT operation. In addition, the avalanche size of SQS mode signals is on the order of a few hundred pC compared to a typical proportional signals of several pC. If it turns out that the MDT must be operated at gas gain higher than the desired gas gain of $(2 - 4) \times 10^4$, the SQS mode signals can become a real problem in this mixture. Reducing the fraction of nitrogen can ease this problem slightly. But the Lorentz angle becomes too large. We suggest that in this case the Lorentz angle can be controlled by adding water vapor or DME. Although we have not measured the streamer fractions of such mixtures, we do not expect that the small percentage of water vapor or DME can significantly change the behavior of the gas mixture regarding the SQS mode.

The effect of nitrogen on the streamer formation which we observed in our experiment is expected. It is well known [6] that a small amount of nitrogen gas can significantly increase the scintillation photon yield. The authors of ref. [4] have tried to increase the photon yield of SQS mode signals in a Ar-C₂H₆ 50:50 mixture. They have noticed that 2% nitrogen can significantly increase the duration of the SQS mode signals and the frequency of multiple streamers.

In a large drift chamber system, the gas mixture normally is recycled. Even when nitrogen is not intentionally added, contamination by nitrogen is difficult to avoid. It is important to understand the effect of nitrogen on the electron drift velocity and on the signals formation.

For the gas mixture Ar-CO₂-CH₄ 92:5:3, the SQS mode starts to appear at a gas gain of approximately 10⁵ and the fraction of the SQS mode signals reaches 0.5% at a gas gain of $\sim 1.4 \times 10^5$ which should give us enough safety margin in case we have to operate the MDT at higher gas gain.

4 Conclusions

Small amount of nitrogen can be added to the argon-hydrocarbon gas mixtures in order to improve the linearity of the R-T relations and reduce the Lorentz angle in the simple drift tube. For example by adding a small amount of N_2 (1-5%) in the Ar-CH₄ 95:5 mixtures, the linearity of R-T relations can be significantly improved. The gas gain, however, must be kept relatively low in order to avoid problems caused by the large SQS mode signals.

For ATLAS MDT, 5% N_2 is preferred because the Lorentz angle would be too large with less N_2 . However, the Lorentz angle can be controlled by adding a small amount of 'cool' gas such as CO₂, water vapor or DME as a fourth component. The percentage of N_2 can be reduced to $\sim 1\%$ and the linearity of the R-T is still very good.

The Ar-CH₄-N₂-H₂O is a promising mixture. The appropriate percentage of CH₄ is in the range of 3% to 5%. Approximately 1% nitrogen is required in order to make the drift velocity uniform across drift region in the MDT. The percentage of water vapor can be 0.2% to 0.5%. It is expected that the SQS mode problem is less in this type of mixtures with only 1% of nitrogen compared to the mixture containing 5% nitrogen. The water vapor should also help to slow down the anode aging.

Ar-CH₄-N₂-DME is another possible mixture. The mixture Ar-CH₄-N₂-DME 95:3:1:1 has rather linear R-T relation and also the Lorentz angle is relatively small. The exact mixing ratio can be adjusted in order to better suit our needs.

The experience of using nitrogen in the proportional gas counters is limited. It has been observed that the nitrogen may increase the rate of the tube aging [7]. More study should be done to fully understand the effect of nitrogen to the proportional tube operation.

In gas mixture Ar-CO₂-CH₄ 92:5:3, the avalanche size of the SQS mode is rather modest and the gas gain at which the fraction of SQS mode signals becomes significant is higher than in the other two gas mixtures with N_2 listed in Table 2. The electron drift velocity in this gas, however, is highly non-saturated. Achieving good resolution is more difficult in this mixture.

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References

- [1] M. Dold et al., Fast gas mixtures for the ATLAS monitored drift tubes.
- [2] Jean Marie et al., *Nucl. Instr. and Meth.*, 159:213-225, 1979.
- [3] T. Zhao et al., A study of electron drift velocity in Ar-CO₂ and Ar-CO₂-CF₄ gas mixtures. *Nucl. Instr. and Meth.*, A340:485-490, 1994.
- [4] M. Atac, A.V. Tollestrup and D. Potter, Self-Quenching Streamers. *Nucl. Instr. and Meth.* 200:345-354, 1982.
- [5] P. Pewiersma, The L3 Wire-Amplifier, Type NH19-6122, NIKHEF-H, Amsterdam, Feb. 1986.
- [6] A.J.P.L. Policarpo et al., The argon-nitrogen proportional scintillation counter. *Nucl. Instr. and Meth.* 55:105-114, 1967.
- [7] John A. Kadyk, Private communication