Performance of Drift Tubes Under High Radiation

by

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Abstract
In this thesis, the aging and the rejuvenation of an ATLAS proportional drift tube are described. Firstly, the Diethorn model of gain is tested using pressure and sense-wire voltage measurements. The drift tube was then aged using P10 gas (Ar:CH$_4$ 90:10) and a small amount of Si oil vapor, with a tube section of radius $\sim$ 1cm being subjected to UV radiation. An aging current of 30$\mu$A was maintained and after the accumulation of 21 coulombs on the wire, the tube gain decreased to less than 70%. Subsequently, the tube was rejuvenated by the treatment with Ar:O$_2$ 99:1 gas, at reverse wire potential and an reverse ”rejuvenation” current of 30$\mu$A. Rejuvenation was successful after the accumulation of the equivalent of 3C from this current.

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Chapter 1

Introduction

1.1 Drift Tubes in the Big Picture

Monitored Drift Tubes (MDT) make up the muon chambers of the ATLAS (A Toroidal LHC Apparatus) Muon Spectrometer which is one of four detectors in the Large Hadron Collider (LHC) at CERN. The LHC will search for the theorized mass-generating Higgs boson, which if it exists can decay into two Z-bosons which decay into two pairs of muons:

\[ p^+p^- \rightarrow H + x + x' \]

\[ H \rightarrow ZZ \rightarrow 4\mu \]

In addition, supersymmetry (SUSY), an extension of the Standard Model, will be tested, searching for superpartner particles such as gluinos and squarks. In all these experiments, muon detection is essential, which means that good performance of drift tubes lining the ATLAS muon chambers is important.

The LHC will provide proton-proton collisions at a center of mass energy of 14 TeV, with luminosity of \(10^{34} \text{ cm}^{-2} \text{sec}^{-1}\) [4, 6] or one collision every 25ns. This is about 7 times more energy and 100 times more intensity than the current largest collider Tevatron [7]. An expected transverse momentum resolution of about 2% for 100 GeV and 8% for 1000GeV, needs to be achieved. ATLAS consists of three layers of muon chambers in superconducting air-core toroid magnet. (See Fig. 1-1) There are 317,488 MDT tubes in 1194 tracking
chambers, covering an active area of 5500cm². Each chamber has 3 to 4 layers of tubes. Each tube requires a spatial resolution of 80μm, giving each chamber a resolution of 40μm [1, 8]. Drift tubes are expected to work at high rates of ionization of at least 100 ionizing tracks per cm² per second [4].

In terms of the gas used, initially to obtain linear "radius-time" dependency Ar:CH₄:N₂(91:5:4) was proposed. However, this mixture had high aging properties, and was replaced by Ar:CO₂ (93:7) which is resistant to aging, despite its non-linearity. Calibrations must be compensated for non-linearities. Non-aging, linear gases such as Ar:N₂:CO₂ (92:6:2) and (94:2:4) had also been proposed [9, 10] and promises better spatial accuracy of reconstruction.

The tubes themselves consist of an aluminum tube, 3cm in diameter and 1-6m in length which is filled with non-inflammable Ar:CO₂ (93:7) gas (fig.[1-2]). The pressure of the gas is normally kept at 3 atmospheres to minimize diffusion and the Lorentz angle of particle tracking and therefore improve resolution. A small amount of CH₄ is added to absorb UV
photons from reaching the aluminum tube all [11] and thereby prevent sparking. A gold plated tungsten wire, 50\( \mu \)m in diameter, runs through its axis. This is kept at a high positive voltage (ATLAS operating voltage \( \sim 3kV \)). (See Table A.1).

Figure 1-2: ATLAS tube end view. The casing is aluminum (ALUMAN-100) 400\( \mu \)m thick and a gold plated tungsten wire of diameter 50\( \mu \)m runs through along its axis. [1]

A muon when passing though a MDT, ionizes the gas and frees electrons which multiply in number near the anode. This multiplication factor is called the gain (see Chapter 2). The gain dependence on tube gas pressure, anode voltage and temperature are measured and described in Chapter 4. It is important to predict gain from these measurable quantities, and in this paper, the Diethorn approximation is used and tested for this purpose.

At the high luminosity that ATLAS is expected to work, the deterioration of gain is inevitable over time with the accumulation of charge on the sense wires causing deposits. This aging effect needs to be understood for Drift Tubes. in this paper, I consider aging with Si in Chapter 5, using P10 gas (Ar/O\(_2\) 90:10) under high irradiation. After aging, a simple method of rejuvenation, with reverse wire potential and the introduction of O\(_2\), is
used and is discussed in Chapter 6. Because the replacement of tubes for the $80 million ATLAS detector is costly and often impractical, a rejuvenation process that do not need a large over-haul of the detector is important.
Chapter 2

Proportional Gain Models

2.1 Gain with Diethorn Approximation

[12] The performance of drift tubes is mainly related to signal formation after gas gain, \( G \), defined as the ratio of the number, \( N \), of electrons sensed by the wire to the primary electrons, \( N_0 \), caused by the initial ionization event. Diethorn suggested an approximation which I tested in relation to wire potential and gas pressure.

Firstly, when a high-energy particle like a muon passes though a tube, it ionizes the gas (mainly Ar) and freeing electrons called primaries, which move towards the anode wire. In the near vicinity of the anode, the electrons gain enough energy to cause more ionization and free electrons which repeat the process. Eventually an avalanche or cascade of electrons arrive at the anode wire (Fig. 2-1). The ratio of the electron number at the wire to the number of primaries is called the gain.

If \( N \) is the number of electrons at a radius \( r \) from the wire, then the increase by secondary ionisation is given by:

\[
dN = \alpha(\bar{E})dr
\]  

(2.1)

where \( \alpha(\bar{E}) \) is the Townsend coefficient depending on electric field \( \bar{E} \). Now the field near the wire is

\[
E = \frac{\lambda}{2\pi\varepsilon_0 r}
\]  

(2.2)
where $\lambda$ is the charge density. For a proportional drift tube, $\frac{\lambda}{2\pi \epsilon_0} = \frac{V}{\ln(b/a)}$ where $a$ is wire radius, and $b$ is the tube inner radius. Hence,

$$\vec{E} = \frac{V}{r \cdot \ln(b/a)} \quad (2.3)$$

Assuming $\alpha = \beta E$, then the gain can be approximated by the Diethorn formula as derived from [12] by integrating Eq.2.1 from the start of avalanche $r_{min}$ to wire radius and using Eq.2.1:

$$\ln G = \ln(N/N_0) = \int_{r_{min}}^{a} \alpha(r) dr$$

$$= \int_{E_{min}}^{E(a)} \frac{\lambda \alpha(E)}{2\pi \epsilon_0 E^2} dE$$
\[ \ln G = \frac{\ln 2}{\ln(\frac{b}{a})} \frac{V}{\Delta V} \ln \left( \frac{V}{\ln(\frac{b}{a}) \cdot a \cdot E_{\text{min}} \cdot (\frac{\rho}{\rho_0})} \right) \]  

(2.4)

where \( \rho \) is the gas density (\( \rho_0 \) is density at s.t.p). We take \( \beta = \frac{\ln 2}{\Delta V} \). \( \Delta V \) is the average potential required to produce one electron or the "effective ionization potential" for the gas. \( E_{\text{min}} \) is the minimum electric field to cause an avalanche at \( r_{\text{min}} \). \( \rho \) is the gas density and \( \rho_0 \) is density at room temperature and pressure.

\( E_{\text{min}} \) and \( \Delta V \) must be empirically obtained from experimental results and are unique to different gases. In Chapter 4, gain data is fitted to this Diethorn model and these parameters are extracted for P10 gas.

In the case of muons, the ionization energy of ions is about 14.3KeV in 3 atm[4]. Lacking an relatively intense source of muons, I used Co57 source to mimic this ionization energy. Co57 decays to an excited state of Fe57 by electron capture. Fe57 in turn settles into a ground state by gamma-emission of the 14.4KeV (See Fig.2-2).

Figure 2-2: Schematic of decay of \( ^{57}_{27}\)Co. Co decays into \( ^{57}_{26}\)Fe* by electron capture. 14.4KeV energy gap is brought about by gamma emission from 3/2- band to 1/2- band.
### 2.2 Aging and Rejuvenation

#### 2.2.1 ATLAS: Expected radiation and Tolerance Limit

ATLAS is expected to run for 10 years at an irradiation rate of about 100,000 particles per second per cm² of wire, at a gain of approximately $2 \times 10^4$. Considering that the effective ionization of Ar gas mixture to be 30eV (see Chapter 4.2), on average the number of primaries is 1100 per event. Hence the detector would collect about 0.12C/cm [5]. Allowing for inhomogeneity the ATLAS collaboration requires drift tubes to withstand at least 0.6C/cm [4].

#### 2.2.2 Aging: possible causes

The reduction of gain in a proportional drift tube over time is called aging. This is effect is inevitable for detectors that are run for an extended period of time. Aging is believed to be proportional to the amount of charge accumulated on the sense anode wire of the tube over time.

Aging is classically attributed to the plasma chemistry near anodes (a few radii length from wire) where the avalanche occurs. In the avalanche, free electrons and photons of 5-30eV can change many molecules in the gas, forming free reactive radicals and ions [14, 15]. Especially the radicals with large dipole moment, tend to form larger polymers when collected on the anode. The polymers coat the anode and not only increase the effective radius of the wire, but also shield its field from outside electrons. Both these factors are believed to contribute to gain loss [16, 17] and hence aging. Unless chemical reaction bond these polymers to the anode surface, the large molecules are held weakly and can drift down with the gas flow.

---

1Plasma chemistry is used most widely to explain the chemistry in the drift tubes (DT), although the conditions such as pressure, electron density, electric field, gas flow are quite different when compared to DT[13]. For example, plasma chemistry deals with pressure in milli-Torr while DT operate more than 1 atm(760Torr). Despite this discrepancy, the electron energies are very similar (5-10eV). Lacking anything better, plasma chemistry is still used today.
The Malter Effect

An extreme case of aging is displayed by the Malter Effect[18]. With a buildup of a non-conducting layer on the cathode (tube casing), positive ions can no longer be neutralized and adhere on top of the nonconducting layer. This causes a strong electric field across the dielectric film and induces electrons to be field emitted from the cathode. These electrons then penetrate the Malter layer, neutralize the ions but are also ejected into the gas starting an electron avalanche. This results in a self-sustained current, which does not disappear in the absence of an ionizing source. Once the Malter effect takes place, the cathode becomes increasingly sensitive to photons, since the electron work function is lowered and the electric field strengthened, which is due to the dipoles in the film “pulling” at the electrons of the metal. Thereafter Malter current easily appears.

Hydrocarbons

Hydrocarbons are used to “quench” gases. Recombination of ions, de-excitation of atoms within the gas leads to UV photo emission which creates unwanted secondary electrons. Quenching gases like hydrocarbons have large cross-section for photon absorption since being polyatomic, they have many rotational and vibrational degrees of freedom. In addition, hydrocarbons do not ionize easily or emit photons upon de-excitation which would cause further ionization. The advantages are avoiding sparks, improved energy resolution and reduced sensitivity to impurities [19]. However, the danger of using hydrocarbons is that they form radicals causing aging. It should be noted that since breaking a covalent bond in hydrocarbon requires 2 - 5 times less energy than to ionize the molecules [13], the radicals are in higher concentration than ions and are more likely to form polymers[15]. This paper will be mainly concerned with aging using Ar:CH$_4$ 90:10 gas (see section 5.1.1 for explanation).

Si as an Aging Pollutant

Almost all reports on detector wire aging agree that silicon contributes greatly to aging if allowed to accumulate on the wire [14, 13, 15, 17, 20, 21]. Silicon polymers can either
form silicate with oxygen \[
\left( - \quad O \quad - \quad \right)
\]
, or with hydrocarbon resulting in polysilicon
\[
\left( \quad \left( \begin{array}{c}
CH_3 \\
\vdots \\
\vdots \\
CH_3
\end{array} \right) \quad - \quad Si \quad - \quad O \quad - \quad \right)
\]
. These large, heavy polymers are not easily removable by gas flow.

Polymerization rate is higher for Si than for carbon [22] and more likely to form deposits on wires than hydrocarbons. It is relatively inert and unaffected by most solvents, hence difficult to remove. In gas systems they are found in many lubricants, adhesives, rubber, encapsulation compounds, grease, oils, O-rings, dust, gas impurities, aluminum alloys, diffusion pumps and flow regulators to name a few[14]. Aluminum itself may contain Si for hardening. In some cases the source of Si is not even known. For the purposes of this aging experiment, Si oil vapor is introduced through the gas flow for faster aging.

Other factors Affecting Aging

[20, 23] show that the rate of aging is independent of electrode material and purity of methane. The latter strongly suggests that CH\(_4\) itself polymerize and deposit on the wire.

It is not clear whether aging depends on irradiation dosage since some papers [24, 25, 26] claim the dependency and some [27, 28] who do not. If there is time for plasma and gas to fully recover between ionizing events, there should not be any reason to believe in the dose dependency. However, if there is a relationship, then high irradiation dosage should decrease the aging rate due to space-charge effects (see section 5.2.2).

Tube lifetime decreases with the high voltage applied on the anode sense wire [29, 30]. Understandably, the higher the potential, the higher the amplification, the higher the rate for secondary electron emissions, and faster the accumulation of charge per cm.

Aging may also vary with flow rate, but this depends on the individual setup itself. In general, a faster flow rate will discard the polymers that form faster, reduce deposition and hence aging[21, 30]. However, some have reported an increase in aging rate with flow rate [31, 32, 29] which may be due to contaminants entering the tubes with the gas from system components upstream, like bubblers.
2.2.3 Rejuvenation

The re-establishment of original gain level after a tube has aged is called rejuvenation or reanimation. Such processes, which mostly involve cleaning of the sense wires, need to be understood in case that detector performance deteriorates over long periods of operation. Suggestions for such cleaning processes have been made mainly in terms of the oxidation of wire deposits and the erosion of deposits by momentum transfer. Heating the wire or ablation is not considered practical.

Water vapor, alcohols and other molecules containing oxygen are effective in suppressing or stopping polymerisation [22]. This is due to the high electronegativity of oxygen, which easily form stable molecules with double bond e.g. CO, CO₂, H₂O and H₂ which can be transported away by the gas flow. In terms of P10 gas, the main dissociation product is CH₂: which forms,

\[
\text{CH}_2: + \text{O}_2 \rightarrow \text{CO} + \text{H}_2\text{O}
\]

\[
\text{CH}_2: + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2
\]

\[
\text{CH}_2: + \text{CO}_2 \rightarrow 2\text{CO} + \text{H}_2
\]

In addition, oxygen-containing radicals are not reactive, which “blocks” further film growth. However, the addition of oxygen will not affect Si deposits since the chemical equivalent to CO₂ is SiO₂ which is not in a gaseous form.

Physical bombardment of ions with Si substrates may work better to remove the substrate. The equivalent principle in plasma chemistry is a technique called “sputtering” (see Chapter 6). In this case, positive ions e.g. Ar⁺ are formed by glow discharge, near the sense wire which is at a negative potential. These ions bombard the coated wire surface and transfer momentum to the substrate molecules which detach, and drift both in the anode direction and also down with gas flow.

Rejuvenation has been reported as successful in several cases involving Ar:O₂ 99:1, Ar:CO₂ 93:7 [30] and pure Ar[24]. [30] notes that Ar:O₂ 99:1 gas is a better choice for reanimation, and that is the gas that is used in this paper.
Chapter 3

Experiment

Figure 3-1: Whole setup
3.1 Gas System

The gas system is shown in Fig.3-2, using P10 gas Ar:CH₄ 90:10. Gas flow is indicated by a bubbler. A back pressure is produced in the tube by controlling the flow with a flowmeter. Pressure is measured in PSI accurate to 0.1PSI. Gas tubing used is made of copper, and the gas is not recycled. Temperature (room temperature) is measured with a thermocouple attached to the middle of the tube. Gas equipment models are given in TableA.2.

A Co57 gamma source is used for gain calibration using the 14.4KeV peak. This energy signature is used because it is close to that made by a muon (~14KeV).

The tube is marked with points from gas inlet to outlet in 5.8cm intervals. This is done to facilitate gain profiles measurements taken along the tube. This is especially important in later aging experiments so that the gain of irradiated parts can be compared to parts that are not.
3.2 Electrical Apparatus

Figure 3-3: The electrical setup to measure gain of drift tube. Pulse of gain calibration see Fig.3-5

The sense/detector wire is held at high positive voltage directly through the pre-amplifier by the HV source. The ionizing source causes charges which are sensed by the 109PC pre-amplifier (Fig.3-4). See Fig.C-1 for circuit diagram of pre-amplifier. This unit differentially amplifies the charges proportionally and its output pulses is either directly sent, amplified
Figure 3-4: Pulse signals, from Co57 source and avalanche effect, detected through the pre-amplifier.

or attenuated before being displayed on the multichannel analyzer (MCA), and oscilloscope. The pre-amplifier can be tested/calibrated by feeding pulses into it from the pulse generator (PG); the resultant peak channel number shown on the MCA is the recorded in relation to generated pulse height. The MCA bins pulses into channels according to their pulse height. Appendix Fig.3-5 and shows the screenshot of a 14.4KeV peak on the MCA. Electrical equipment models are given in TableA.2.

3.3 Gain Calibration using Signal Generator and MCA

After the ionization of the drift gas, and the subsequent onset of the avalanche effect, electrons move towards the anode wire. The ions from the ionization drift to the cathode (tube wall), and cause a mirror signal on the anode (assuming no secondary emissions). An 1pF capacitor in the pre-amplifier subsequently charges up and outputs a voltage signal that is directly related to the energy and charge of the electrons that cascaded to the wire. The pre-amplifier for this setup has an amplification factor of 741mV/pC. The output signal of the pre-amplifier is then binned by the MCA according to its height and hence the MCA.
central peak channel number $C_{pk}$ (see Fig. 3-5), is directly related to the number of electrons at the wire and hence the gain.

The MCA and pre-amp are calibrated by injecting pulse signals into the 'test pulse' input of the pre-amp, and relating the pulse height (using oscilloscope) with the $C_{pk}$ by a linear conversion fit. Consequently in gain measurements, the charge deposited then is, $Q = (aC_{pk} + b) / 741$[mV/pC].

To find the gain, the number of primaries must be estimated. Argon has a (second) ionization energy of 27.6eV[12] (the actual ionization energy of the whole mixture is to be determined later). Co57 source delivers 14.4KeV, which means that $14400/27.6 = 522$ primaries are produced. Hence the gain is found to be:

$$G = \frac{Q}{1.6 \times 10^{-19} \cdot 522}$$  \hspace{1cm} (3.1)
Chapter 4

Gain, Pressure & Voltage Results and Discussion

Varying the pressure and high voltage, gain data were taken and fitted to the Diethorn approximation (Chapter 2), in order to determine the goodness of the model.

For all measurements of gain, temperature is compensated for, in a linear fit (Fig.4-1). Higher temperatures are simulated and controlled with a fan blowing along the tube axis, and a heating coil wound around the tube. A linear fit is sufficient for the relatively small range of temperatures concerned.

4.1 Gain and High Voltage

The gain rises exponentially with wire high voltage, keeping pressure constant. The gain is kept low to be safely in the proportional mode where Eq.2.1 is valid and \( \alpha(E) \) is linear with \( \bar{E} \). High gain may illicit the streamer mode or Geiger pulses. The latter are glow-discharges near the wire dominating the cascade and must be quenched electronically by lowering high voltage.

As shown in Fig.4-2, the Diethorn approximation Eq.2.4 provides a satisfactory fit. Parameters for \( E_{\text{min}} \) and \( \Delta V \) are extracted and listed in Table 4.1.
Figure 4-1: Linear temperature-gain fit in the experimental working temperature range.

Figure 4-2: Gain measurement varying high voltage on the sense wire, keeping pressure constant at 15.6PSI. Data is fitted to Diethorn. The systematic errors are included.
4.2 Gain and Pressure

Figure 4-3: Log plot of the gain variation with pressure, keeping high voltage constant at 2kV. The pressure ranges from 1 atmosphere to 3 atm. The Diethorn model seems to fit reasonably well.

Fig.4-3 shows gain decreasing in an exponential fashion, which fits reasonably well with Diethorn. The values for gas ionization potential $\Delta V$ and minimum electric field for avalanche effect $E_{\text{min}}$, can again be extracted as in the voltage-varying case. The pressure data has an advantage however over the voltage data in terms of evaluating $\Delta V$ since $\Delta V$ depends only upon $\delta G/\delta P$.

$$\Delta V = \frac{-V \cdot \ln 2}{(\frac{1}{\delta G/\delta P}) \ln (b/a) P/P_0}$$  \hspace{1cm} (4.1)

$E_{\text{min}}$ can then be calculated from $\Delta V$, $\delta G/\delta P$ and $\delta G/\delta V$ (see Appendix ??). The
parameters derived from fits are shown in Table 4.1. The $\Delta V$ calculated from both pressure and voltage measurements may be higher than the ionization potential for Ar, due to inelastic collisions between free electrons and the gas atoms. Free electrons can also interact with electric field of ions already present in the gas, and lose momentum. Instead of ionizing atoms, electrons may only have sufficient energy to bring atoms to an excited state.

Table 4.1: Results of parameters from Diethorn fit

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$\Delta V$ [V]</th>
<th>$E_{min}$ [kV/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure vs. gain</td>
<td>33 ±3</td>
<td>27 ±3</td>
</tr>
<tr>
<td>HV vs. gain</td>
<td>37 ±5</td>
<td>22 ±3</td>
</tr>
</tbody>
</table>

4.3 Discussion: Gain Sensitivity to Wire radius

From Eq. 2.4 from Chapter 1, the gain can be expressed as:

$$G = \exp \left[ \frac{C}{\ln \left( \frac{b}{a} \right)} \ln \left( \frac{K}{A} \right) \right]$$

where,

$$C = \frac{V \ln 2}{\Delta V}, \quad K = \frac{V}{E_{min} \frac{P_0}{P}}, \quad A = a \cdot \ln \left( \frac{b}{a} \right)$$

An increase in the wire radius $a$ can result in a change in gain:

$$\frac{dG}{da} = \left( \frac{K}{A} \right)^{\frac{a-C}{A}} \cdot \left( \frac{C}{A} \right) \left[ \ln \left( \frac{K}{A} \right) + 1 \cdot \frac{\ln \left( \frac{b}{a} \right)}{\ln \left( \frac{b}{a} \right)} - 1 \right]$$

Table 4.2 shows the gain predicted at increasing wire radius for ATLAS conditions (pressure = 3 atm, wire voltage = 3kV). Fig. 4-4 shows the predicted percentage decrease in gain for the increase in the wire radius. Hence disregarding the effects of shielding from a nonconducting layer, as we expect to be the case for the aging phenomenon, the tube wire performance would decrease to 70% of optimal (the ATLAS aging standard) if the radius is enlarged more than 1.5um.
Table 4.2: Predicted gain and wire radius

<table>
<thead>
<tr>
<th>Wire Radius [μm]</th>
<th>Gain ×10^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.00</td>
<td>3.51</td>
</tr>
<tr>
<td>25.25</td>
<td>3.27</td>
</tr>
<tr>
<td>25.50</td>
<td>3.05</td>
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<tr>
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<td>2.85</td>
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<tr>
<td>26.00</td>
<td>2.66</td>
</tr>
<tr>
<td>26.50</td>
<td>2.32</td>
</tr>
<tr>
<td>27.00</td>
<td>2.03</td>
</tr>
<tr>
<td>27.50</td>
<td>1.78</td>
</tr>
<tr>
<td>28.00</td>
<td>1.56</td>
</tr>
<tr>
<td>28.50</td>
<td>1.37</td>
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<tr>
<td>29.00</td>
<td>1.21</td>
</tr>
<tr>
<td>29.50</td>
<td>1.07</td>
</tr>
<tr>
<td>30.00</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Figure 4-4: The percentage decrease in gain with respect to wire radius. This prediction assume wire voltage at 3kV, gas pressure at 3 atmosphere at room temperature.
Chapter 5

Aging

5.1 Aging Setup

5.1.1 Choice of gas for Aging Experiment

It is found that argon/methane mixtures like Ar:CH₄:CO₂ showed increasing aging if the methane content is increased [24, 33, 34, 35]. This is in contrast to tests with different ratios of Ar:CO₂ mixtures (with methane above 30%) which reported no aging [5, 36, 37, 38, 30]. Ar:CO₂ 93:7 is presently used for ATLAS MDTs because of its resistance to aging.

In certain cases, self-sustained discharge (Malter current) was seen in Ar:CH₄ 80:20 mixtures [39] or the gain decreased to about 40% for this mixture [40].

Many experiments have demonstrated that Ar:CH₄ gas mixtures produce large aging effects [41, 15, 20, 19, 42, 43, 44]. P10 gas Ar:CH₄ 90:10 is well known for such effects [20, 23]. In the case of P10, CH₂⁺ is the main dissociation product, which has a large dipole moment and stick to electrode surfaces, polymerizing:

CH₂⁺ + CH₄ → C₂H₆
CH₂⁺ + C₂H₆ → C₃H₈ and so on.

Hence the gas of choice used in this experiment is P10 gas to promote aging.
Figure 5-1: Aging drift tube with P10 gas. Intense irradiation locally applied to ~1cm of wire through UV glass window, by a 500W Hg arc lamp. See Fig.C-2 in appendix for photo of setup. Sense wire is held at high potential (~2.5kV). The gas in the tube is around 1atm at room temperature. A continuous current results and is maintained during aging at about 30μA.
Because of time restraints, some factors are introduced to accelerate aging. In addition to using P10, Si is introduced via an oil bubbler at room temperature before the gas inlet and flown into the tube as vapor. As mentioned in 2.2.2, silicon and Si polymers are suspects for fast aging effects. The bubbler is not heated as this would introduce a temperature gradient in the tube, affecting gain differently along the sense wire.

The second factor to ensure fast aging is the exposure of 1cm of the wire to intense UV radiation through an UV window (see photo C-2). A 500W Hg arc lamp is used for this purpose (Fig.C-3). The radiation (lowest \(\lambda =240\text{nm}\)) by photoelectric effect at the wall should induce a large amount of ionization and charge accumulates on the wire very quickly. (See Fig.C-4 for spectral irradiance). Previous experiments show that an increase in irradiation area decreases drift tube lifetime, since more of the wire will be coated[30]. However, for my setup, only a small localized area (diameter \(\sim 1\text{cm}\)) is exposed to highly ionizing UV source. This is done so as to have points of comparison, between exposed and unexposed parts, along the same tube.

For simplicity, in this experiment, it is assumed that aging does not depend on irradiation dose, that is, the rate at which the charges are deposited. Although this is a popular assumption in other literature, it might not be the case (see discussion in section 5.2.2). Since the primary goal is to study the dependency of aging on accumulated charge, the aging rate is optimized in order to save time.

The determination of accumulated charge on the wire is simply done by integrating the anode current over time. The “aging” current is maintained at \(\sim 30\mu\text{A}\) by adjusting the wire potential. It is noted that this method is really only applicable if sparking discharges are negligible. Otherwise, the current would consist of large charge doses at localized points on the wire. This is taken into consideration and discussed in section 5.2.1.
5.2 Aging Results and Discussion

5.2.1 Aging Current

The current induced by arc lamp irradiation rises with the potential on the wire as expected. The measured result is shown in Fig. 5-2.

![Graph showing aging current and high voltage](image)

Figure 5-2: Aging current read on ammeter in series with sense wire, varying with voltage applied on the wire. Conditions are at room temperature and pressure.

As shown, there is clearly a "proportional mode" of operation, where the current is approximately linear with applied voltage. This is the mode in which the Diethorn model is valid, in which accelerated electrons produce proportional secondary ionisation (Chapter 2).

However, as electric field increases, the amplification of electron number becomes non-linear and eventually reach the "Limited Streamer Mode" (LSM). LSM is a source of space charge\[2\] in addition to normal space-charge. The space charge effect occurs where ionized electrons move towards the anode at a fast rate than the ions they leave behind, resulting in a sheath of positive charge around the wire. This effectively reduces the electric field and hence the gain at the wire. The LSM occurs within this sheath where ion pairs recombine, giving off photons which can further ionize gas molecules, not only in the sheath, but also...
outside of it. This produce very large amplification of signals at the wire. At gain of $\sim 10^5$, LSM takes over and the irradiation’s influence on the current becomes less. LSM is about 100 times larger than proportional pulses,[45], hence this effect can be responsible for accelerated aging.

A gain calibration at high wire potential results in the appearance of a double peak with the main Co57 peak. This is shown in Fig.???. The higher peak can be attributed to a small amount of streamers. This is consistent with results from [5] and [45].

If the field is increased any further, streaming may be so large that sparking occurs. To avoid sparking, an aging current is chosen (30µA) so that a small amount of LSM is present but is not so much as to spark the tube. Referring to Fig.5-4 we see that at about 2.8kV, a strong streamer mode appears.\(^1\) In Fig.5-2, at about 2.76kV, the current dependence is becoming non-linear, but has not reached strong streamer mode. At this point, the 30.0µA is only about 5% higher than the estimated linear value (28.6µA), hence the corresponding streamer current is not high enough to cause sparking.

5.2.2 Aging Charge Accumulated

At the rate of about 0.11C/hr, 21C of charge was accumulated by irradiation of the middle section of the wire. The aging effect is shown in Fig.5-5 for a point “X” near the gas outlet of the tube. “X” is chosen since it shows the most aging (discussed later). At 21C, the measured gain value has deteriorated to less than 70% of its original value before aging. (This according to the criterion set by ATLAS is an aged tube).

An increase in effective wire radius which may be caused by deposits will affect the gain as discussed in Section 4.3. Using Eq.4.2 and experimental operating parameters $V=1900V$ and $\rho/\rho_0 = 16.8\text{PSI} / 14.7\text{PSI} = 1.1$, $\frac{dg}{da} \sim 9.5 \times 10^6$ which means that the thickness of the wire deposit is not more than 1µm.

\(^1\)One might expect to see a dip in $\frac{dI}{dV}$ for Fig.5-4 just before the sharp rise, due to space charges accumulating around the wire, before streamers take over. However due to the resolution of the the plot, this is not possible to see.
Figure 5-3: A double peak begins to be evident at high wire potential (electric field density). HV = 2.71kV; pressure = 32PSI; temperature = 26.7°C. This is an indication of that the gain is entering the streamer mode. A higher pressure used ensures that the peak shape fits well into MCA display.

Co57 Peak of Pulse Distribution after Aging

Irradiation of the wire by the UV lamp is not uniform, i.e. the side facing the UV window sees more radiation and hence charge accumulation, than the other. This difference in charge, and in polymer deposition/growth between the two wire sides results in a double peak of the gain calibration using Co57 source. As Fig.5-7 shows for the irradiated point of the tube, not only does the central peak shift downwards (to the left), there is a broadening of the
Figure 5-4: Derivative $\frac{dI_{age}}{dV}$ with wire voltage. The sudden jump in the derivative is due to the appearance of LSM. This is in agreement with [2].

peak shown in Fig.5-7(b). Different parts of the irradiated section “M”, depending on its position relative to the radiation source, gain different substrate coating thicknesses, which leads to a wider distribution of gain characteristics. Eventually two distinct peaks can be seen (Fig.5-7(c)) at extreme aging. This result is in agreement with [23] using the same gas mixture P10.

**Tube Gain Aging Profile**

Not only did the overall gain decrease along the whole tube, but the section most aged was downstream of the gas flow shown in Fig.5-6. This is due to heavy ions and polymers which initially is produced at “M”, being carried down with the gas and hence accumulates more readily near the gas outlet. The change in tube gain profile is shown in appendix Fig.C-5. As more charge is accumulated Aging is a non-local phenomenon. This observation agrees with that of [29].

Surprisingly, the tube midpoint where UV radiation was concentrated at, did not show
significant aging. A hypothesis for this behavior is due to space charges building up quickly around sense wire. At large irradiation rates, ions are formed fast initially. But the electrons, due to their lower masses have higher mobility than the ions, and are sucked to the wire leaving the heavier ions to form a sheath of positive charge around the wire. The wire is
effectively shielded and the electric field weakened. The avalanche effect is stretched over a larger volume, decreasing the rate of polymerization and hence aging. In fact, in some reports[2, 23, 20, 14] aging is not shown to be proportional to irradiation rate, that is, the aging current on the anode. Hence the assumption I started with in section 5.1.2 is needs further study.

5.2.3 Silicon Deposits

SEM results of an aged tube wire is shown in Fig.5-8. As expected, 5-8(a) shows a high dose of gold from the wire coating. A small amount of aluminum could have been “sputtered” from the tube casing when the wire is at high voltage. Fig.5-8(b) shows that some sections of the wire exhibit gold coating flaws due to mechanical manufacturing process, and the tungsten underneath is exposed. However this does not affect aging much. The aged section of the wire, Fig.5-8(c), indicates that some areas are coated with a film of silicon substrate. Since there is a proportion of oxygen, the substrate can mainly be SiO$_2$. As previously predicted, Si is shown to be an aging agent.
Figure 5-7: Change in Co57 peak shape for irradiated point “M” 5-7(a) before aging 5-7(b) during aging and 5-7(c) after aging.
Figure 5-8: Scanning Electron Microscope pictures and spectra of different sections of a wire taken from an aged tube. A non-aged section is shown in a) and an imperfectly manufactured section is shown in b). An aged section is shown in c) with the blue line indicating the darker areas without silicon, and the red spectrum is taken from the lighter area. The latter shows an elevated amount of Si. SEM taken at the MIT Material Science Facility with the aid of Dr. Garrett-Reed.
Chapter 6

Rejuvenation

6.1 Setup

Since aging is directly related to substrate deposition on the sense wire, to rejuvenate the drift tube the wire surface requires “cleaning”. As explained in Section 2.2.3, this process involves the introduction of O$_2$ to the gas mixture to oxidize deposits and free-radicals, especially hydrocarbons. Methane content must be eliminated to reduce free-radical formation.

Si deposits are more difficult to remove. Oxidation does not help much in this case because the oxide is a solid which cannot be carried away with the gas flow. In fact, studies show that Si is likely to diffuse into the gold film, or at least form strong chemical bonds.
with gold[46]. Hence a more physical deposit-lifting process is required. In this setup, Si
substrate is bombarded with Ar ions, and the resulting momentum transfer causes Si to be
ejected from the surface. In order to achieve this a reverse negative voltage is applied to the
sense wire to accelerate positive argon ions to its surface[47]. Fig.6-1 shows the setup for
rejuvenation.

A previous report noted success with rejuvenation using Ar:O\textsubscript{2} 99:1 gas [30] and this
mixture is used here.

### 6.2 Results & Discussion

#### 6.2.1 Rejuvenation Current and Cathode Voltage

When a high negative voltage is applied to the wire, a current is seen on the wire after a
threshold voltage is passed. The current is of the opposite sign as the “aging current”. See
Fig.6-2 for this current behavior measured with respect to wire voltage and tube gas pressure.

As shown in Fig.6-2(a), the threshold voltage is about 1.6kV, after which the current
rises linearly. This is to be expected if any charges are involved, especially the Ar ions
which bombard the substrate surface to remove it.\textsuperscript{1} The pressure also affects the rejuvenating
current in an approximately linear way in the range measured (Fig.6-2(b)). At higher
pressure, the mean-free path of the gas ions decreases, which means that the probability
an ion would lose its energy due to collisions with other gaseous particles increase, before
reaching the wire. Hence the current decreases with increasing pressure.

It should be noted that the current is not measured to be depend upon an external
ionization source e.g. an UV lamp (hence it is left out of the setup). This means that the
current is self-sustaining.

\textsuperscript{1}See Appendix C for this author’s suggestion for a possible explanation of current in terms of the Malter
Effect and Ar ions.
Figure 6-2: These results taken with the help of Prof. Becker
6.2.2 Uniformity of Rejuvenation Current

The rejuvenation current is shown to be uniform along the wire, that is, the current is a non-localized phenomenon. This is done by setting up the current in the Ar:O2 gas mixture (with high cathodic wire voltage), then quickly injecting a quenching gas, like N2 in this case, into the tube. The change in current is noted as a function of the volume of N2 injected (volume is determined by the flow×time). Since the N2 is injected rapidly, one can assume that gas mixing is kept to a minimal, and that the N2 acts like an insulating "plug" that passes along the whole length of the tube (see Fig.6-4). The quenching N2 does not support current since it has no ions to provide, and the current decreases as the tube is filled. The reverse can be done by injecting Ar:O2 into N2 and observing how the current rises (Fig.6-3).

![Diagram](image)

Figure 6-3: Rej. current rises as Ar:O2 is quickly injected into quenching N2 gas. Ar:O2 acts as a plug moving along the wire. Only the left side of "total tube volume line" should be considered as after the tube is filled, there could be some remnants of mixing.

If the current source were localized along any part of the wire, there should be steps in the volume-current plots, but as shown, this is not the case. Instead a linear decrease indicates that the current is uniform. Uniformity in this case means that during the rejuvenation
Figure 6-4: Rej. current falls as quenching N₂ gas is injected into Ar:O₂. N₂ acts as a plug moving along the wire. Current decreases linearly to zero.

process, the entire wire is subject to the current.[10]

6.2.3 Rejuvenated Tube

The rejuvenation current is hypothesized to be due to Ar⁺ transfering their charge at the cathodic wire. Hence the amount of current or "reverse charge" at the wire is proportional to the extraction of Si substrate from the wire surface. If this current is allowed to run over time, the wire gain should rise back to its normal, unaged value. This is done, and indeed an rejuvenation effect is observed, indicated in Fig.6-5. Rejuvenation current of 30µA was maintained throughout. A lower pressure can result in faster restoration since the Ar⁺ ions, having a longer mean-free path (therefor velocity), would knock off deposits with more efficiency. But this could also strip the gold plating off the wire which is undesirable. The pressure is maintained at about 1 atm.
Reanimation of Aged tube

Figure 6-5: Restoration of gain with the amount of reverse charge accumulated by integrating rejuvenation current over time. Gain reached 98% of former gain before aging. This is gain measured at point “X”, which was the most aged section of the tube.

Rejuvenation Result

Not only did point “X” near the gas outlet regain its original gain, but all other sections as well (Fig.6-6).

The rejuvenated profile indicates that most of the wire sections have been restored to 95% or more of original gain. However, sections near the inlet of the tube seem to exhibit more resistance to rejuvenation. It should be remembered that during the aging process, the Si bubbler is in series, in front of the tube. Hence the inlet sections should see more Si deposition. This suggests that the presence of Si or heavy Si polymers that was not carried downstream with the gas flow, is more serious problem in terms of aging recovery.

It should also be remembered that aging was more severe near the outlet of gas flow as mentioned for Fig.5-6. And yet gain recovery was much better in these outlet sections. A possible explanation suggested is that the wire deposits near the outlet is lighter and more
likely to be ejected by Ar ion momentum transfer. The deposits near the outlet may also be higher in hydrocarbon content and hence more susceptible to oxidation.

6.2.4 Discussion for Future Studies

Some questions that may be addressed by further studies are:

- Does the rejuvenation current damage non-aged wires?
- Would a higher oxygen content in the gas speed up the rejuvenation process?
- What is the main source of rejuvenation current?
- Does the Malter Effect contribute to or hinder the rejuvenation process, and how much so?
- How does the magnitude of rejuvenation current affect the rate of rejuvenation?

![Figure 6-6: Gain profile along the tube after rejuvenation. Dotted line is average gain profile before aging.](image)
• Is the aging characteristics for Si deposits different from other polymer deposits such as hydrocarbons? In this experiment, gas outlet parts of the wire responded better to rejuvenation than inlet parts, suggesting that different deposits may be in higher proportions in some parts than others.

• How does irradiation rate affect aging rate? If it does, then the lifetime of drift tubes in the actual ATLAS setup would be shorter than is measured in the table-top setup.

• Does a rejuvenated tube age faster than those that does not have a history of aging?
Drift tube gain is well modeled by the Diethorm approximation to the first order and experimental results indicate that for P10 the gas ionization potential $\Delta V = 30.0 \pm 0.9$ V, and minimum E-field of gain avalanche $E_{\text{min}} = 29.5 \pm 0.8$ kV/cm.

Deterioration in gain is shown to with the corresponding deposition of charge. After 21C was deposited using irradiation from a Hg arc lamp, the gain near outlet has fallen to 68% of its original value. Surprisingly, the aging was most prominent near the gas outlet and not at the section subjected to radiation. Si contaminant is detrimental to tube lifetime, and hence must be avoided in detector setup.

Rejuvenation of an aged drift tube was successful, using reverse DC voltage bias on the wire, and using a mixture of Ar:O$_2$ 99:1. The cleaning of the wire using Ar$^+$ ion bombardment is reasonable, after about 3C of “reverse” charge is collected. The rejuvenation current is shown to be uniform along the entire wire (not localized to any point), although the source of the current needs further study. A simple rejuvenation process like the one used for this setup to restore tube performance is important for large detectors like ATLAS for which the replacement of tubes is expensive.
Appendix A

Tables

Table A.1: Parameters of Drift Tube [4, 1, 5]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Radius</td>
<td>25 ±0.5μm</td>
</tr>
<tr>
<td>Wire Composition</td>
<td>Au plated (3% by weight) on W:Re (93:7)</td>
</tr>
<tr>
<td>Working Voltage</td>
<td>3.08kV</td>
</tr>
<tr>
<td>Tube casing</td>
<td>Aluminum ALUMAN-100</td>
</tr>
<tr>
<td>Tube radius</td>
<td>1.5cm ±30μm</td>
</tr>
<tr>
<td>Tube wall thickness</td>
<td>400 ±20 μm</td>
</tr>
<tr>
<td>Tube Length (ATLAS)</td>
<td>1.6m ±500 μm</td>
</tr>
<tr>
<td>Gas composition (ATLAS)</td>
<td>Ar:CO₂ 93:7</td>
</tr>
<tr>
<td>Gas pressure (ATLAS)</td>
<td>3 atm</td>
</tr>
<tr>
<td>Gas circulation</td>
<td>None (this setup)</td>
</tr>
<tr>
<td>Gas circulation (ATLAS)</td>
<td>1 vol/day</td>
</tr>
</tbody>
</table>
Table A.2: Equipment model

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowmeter</td>
<td>Matheson FM 1050/1 series</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>Omega DPG1000B-100A (0-100PSI)</td>
</tr>
<tr>
<td>Pre-Amplifier</td>
<td>Ortec</td>
</tr>
<tr>
<td>HV Supply</td>
<td>Model AEC-5000 Nim Standard</td>
</tr>
<tr>
<td>HV volt meter</td>
<td>Keithley 485 autoranging pico-ammeter</td>
</tr>
<tr>
<td>Pulse Generator</td>
<td>Ortec 1419</td>
</tr>
<tr>
<td>Oscilloscope</td>
<td>Tektronix TDS220</td>
</tr>
<tr>
<td>MCA</td>
<td>Viking Norland 5500</td>
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<tr>
<td>UV lamp</td>
<td>Oriel 6285</td>
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<tr>
<td>Lamp housing</td>
<td>Oriel 66902</td>
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<tr>
<td>Lamp Power Supply</td>
<td>Oriel 66910 (50-500W)</td>
</tr>
</tbody>
</table>
Appendix B

Diethorn and Derivatives

The gain $G$, of a drift tube in the proportional mode can be approximated in the first order by the Diethorn model as mentioned in Chapter 2:

$$\ln G = \frac{\ln 2}{\ln \left( \frac{b}{a} \right)} \frac{V}{\Delta V} \ln \left( \frac{V}{\ln \left( \frac{b}{a} \right) \cdot a \cdot E_{\min} \cdot \left( \frac{P}{P_0} \right)} \right)$$  \hspace{1cm} (B.1)

The parameters $\Delta V$ and $E_{\min}$ can be derived by either direct fitting to Eq.B.1 using a software package e.g. MATLAB which would involve a non-linear fit, or by using the gain derivatives with respect to pressure and voltage:

$$\frac{1}{G} \frac{\partial G}{\partial P} = \frac{-V \cdot \ln 2}{\Delta V \ln \left( \frac{b}{a} \right) P/P_0}$$  \hspace{1cm} (B.2)

$$\frac{1}{G} \frac{\partial G}{\partial V} = \frac{\ln 2}{\Delta V \ln \left( \frac{b}{a} \right)} \left[ \ln \left( \frac{V}{\ln \left( \frac{b}{a} \right) \cdot a E_{\min} \frac{P}{P_0}} \right) + 1 \right] + 1$$  \hspace{1cm} (B.3)

Note, that since $\Delta V$ only depends upon $\frac{\partial G}{\partial P}$, the $\Delta V$ value extracted from a fit of gain and pressure is more reliable.
Appendix C

Figures

Figure C-1: Block diagram of pre-amplifier circuit. (Copied from [45])
Figure C-2: Photo of aging setup of schematic 5-1. The UV lamp is a 500W Hg arc lamp from Oriel, with an irradiation area of about 1 inch in radius.
Figure C-3: Optics of UV lamp. The lamp's back radiation is collected by the rear reflector, and the condenser collimates the radiation.[3]
Figure C-4: Spectral irradiance of Hg lamp. Note that the lowest wavelength is about 240nm, for which this lamp is chosen since maximum possible ionization is needed for fast aging.[3]
Figure C-5: Tube gain profiles with accumulated charge.
Appendix D

Addendum To Section 6.2.1

D.0.5 The Malter Consideration

Ions might not be the only source of rejuvenation current. A buildup of a non-conducting layer on the wire surface contributes to the Malter Effect (see section 2.2.2). Although the Malter effect is related to aging, in the rejuvenation case, if the Ar\(^+\) does not have enough energy to eject a substrate molecule from the film, the Ar\(^+\) will “stick” to the film which may lead to a buildup over time, producing an electric field across the film. The field can be strong enough to promote the emission of electrons from the cathode, especially where there is a break in the polymer film. These electrons would then either neutralize the Ar\(^+\), or cause further ionization in the gas if the wire potential is high (Fig.D-1). Otherwise, the electrons could drift to the grounded tube wall, contributing to the overall current.

From the evidence that the self-sustaining current does not vary in magnitude over the time length of the rejuvenation, the Malter current must have reached an equilibrium with respect to the ionization and recombination of Ar\(^+\) with ejected electrons.

Malter Effect itself should not contribute, however, to the rejuvenating process since it does not directly remove substrate materials. Further studies should be done on the Malter Effect and rejuvenation. And since rejuvenation *has* been successful in this experiment, I hypothesize that Ar\(^+\) ions, with enough energy for substrate-ejection from film, are sufficient in number over time to remove the substrate film.
Figure D-1: Summary cartoon illustrating the Malter effect (top), and the removal of substrate material by Ar\(^+\) bombardment (middle), during rejuvenation.
Bibliography


[47] Private communication with Dr.Kollefrath (Uni. Freiburg, Germany).