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RATE EFFECTS IN HIGH-RESOLUTION DRIFT CHAMBERS

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Abstract

The impact of high counting rates on the spatial resolution of cylindrical drift tubes is investigated in detail and the results are compared with simulations. Electronics effects and space-charge effects are quantitatively analysed. A spatial resolution of $\sigma < 80\,\mu$m can be achieved even at rates as high as 1500 Hz/cm wire length (300 kHz per wire).

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1 Introduction

ATLAS [?, ?] is a general purpose experiment at the future Large Hadron Collider (LHC). Its muon spectrometer will require 1200 precision tracking chambers, consisting of a total of about 370,000 pressurized drift tubes, and will measure the muon tracks along a spectrometer arm of 5–15 m length embedded in a magnetic field of ~ 0.5 T. The LHC physics programme requires a momentum resolution of $\sim 10\,\%$ for a 1 TeV muon. Following a detailed optimization of the magnetic-field strength versus the chamber resolution, the ATLAS Collaboration opted for a drift-chamber system with very high spatial resolution, $\sigma < 80\,\mu$m.

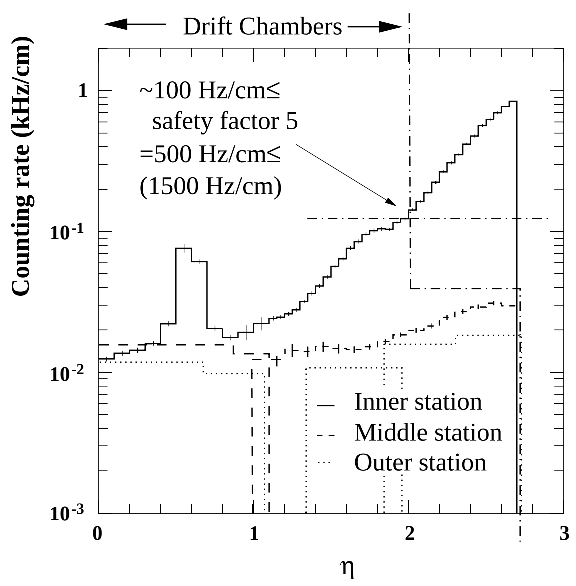

Figure 1: Pseudo-rapidity dependence of the total counting rate in the three precision-chamber stations at nominal luminosity [?].

The ATLAS muon system has to achieve this ambitious goal in a high-rate background environment. The simulation of the background in the ATLAS hall indicates count rates up to 300 Hz/cm wire length in one drift tube (see Figure ??, the tube diameter is 3 cm). Owing to uncertainties in the showering process in the absorber, the (n,γ) cross-sections, the chamber sensitivities, the total p–p cross-section, and the track multiplicity produced in the primary collisions, the collaboration has designed the system for a factor of 5 higher background than predicted. Hence the ATLAS drift tubes have to meet the requirement of a resolution $\sigma < 80\,\mu$m in the presence of a background rate of up to 1500 Hz/cm wire length.

The dominant background sources are low-energy neutrons, photons, electrons, muons and hadrons originating from primary hadrons interacting with the forward calorimeter, the shielding inside the end-cap toroid, the beam pipe, and other machine elements. Whilst most of the energy carried by secondary particles is absorbed in the calorimeters and the forward shielding, low-energy neutrons, one of the final products of the absorption processes, will escape the absorber and create, via nuclear n–γ processes, a low-energy photon ‘gas’.

The neutron sensitivity of a tube is $\sim 10^{-3}$ [?], and the γ sensitivity averaged over the expected photon energy distribution is measured to be $\sim 4.5 \times 10^{-3}$ [?]. Simulations determined the average energy deposit of a background photon to be $\sim$ 36 keV at a magnetic field of 0.6 T [?].

This paper discusses the impact of high background rates on the single-tube performance and investigates in detail the background rate dependence of the resolution. The measurements are compared with simulations and the very good agreement shows that the effects are well understood.

These studies are an important input for the choice of the front-end electronics and the drift gas.

2 Experimental set-up and rate environment

The rate studies were performed in the Gamma Irradiation Facility (GIF) in the SPS beam line X5 at CERN (Figure ??).

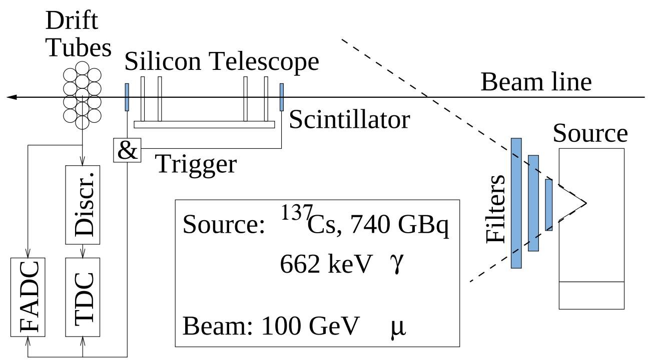

Figure 2: Sketch of the set-up in GIF.

This test facility has a 100 GeV muon beam and a ^{137}Cs source with an activity of 740 GBq emitting 662 keV γ's, which deposit on average an energy of about 36 keV in the drift tubes, simulating well the photon background in ATLAS. The actual γ rate can be adjusted by choosing an appropriate combination of several lead filters. The filters also smear the spectrum to lower energies by Compton scattering.

The tubes (inner/outer radius 1.46 cm/1.5 cm, W/Re wire of 50 μm diameter, typical length of about 2 m) that we used for our investigations were part of an ATLAS drift chamber prototype. The tubes were operated with $Ar/N_2/CH_4$ 91/4/5 and different Ar/CO_2 mixtures at 3 bar pressure at a gas gain of 2×10^4. The preamplifier and shaper peaking time was 15 ns (BNL preamplifier [?]). The discriminator threshold was set to $5 \times \sigma_{\text{noise}}$ to suppress noise hits, which was about the 25th primary ionization electron[1)] for the measurements with $Ar/N_2/CH_4$ 91/4/5 and the 20th primary ionization electron for the measurements with the Ar/CO_2 mixtures.

$Ar/N_2/CH_4$ 91/4/5 has a drift velocity which depends only weakly on the electric field, giving a linear space–time relation. We call it a linear gas. For Ar/CO_2 the drift velocity depends strongly on the electric field, hence we call it non-linear.

[1)] One primary ionization electron as a unit of signal height is defined as the peak of a pulse created by a single ionization electron.

A beam telescope was used as an external reference system for the resolution measurements. It had six silicon micro-strip detectors with $7\,\mu$m resolution each. The silicon telescope tracks were extrapolated to the chamber with an accuracy of $15\,\mu$m. The space-time relationship $r(t)$ was measured using the track prediction measured by the silicon telescope[2)]. The resolution was measured by fitting Gaussians to histograms of the residuals $\Delta r = r(t_{\mathrm{measured}}) - r_{\mathrm{predicted}}$ for ~ 10 ns drift-time slices (see Figure **??**).

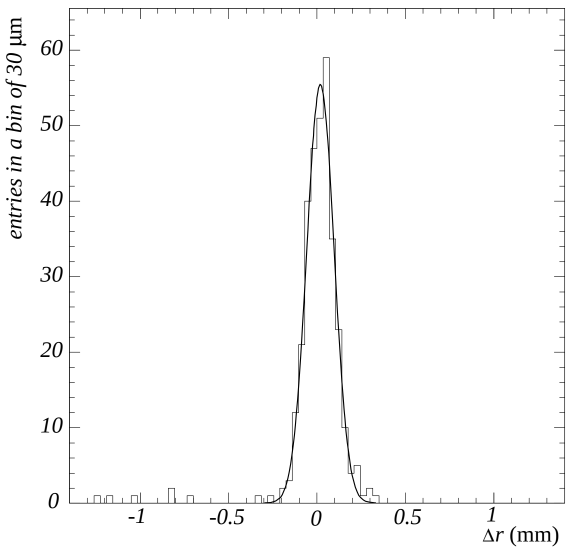

Figure 3: Residual distribution of the raw data in the drift-time slice 375 ns $< t_{\mathrm{measured}}$ $<$ 385 ns. The background rate of the tube was 333.5 kHz.

3 Contributions affecting the resolution

The spatial resolution of drift tubes in the absence of a high background rate has already been discussed in Ref. [**?**]. Here we wish to concentrate on the resolution deterioration caused by high-rate effects (see also Ref. [**?**]).

We distinguish two groups of high-rate effects:

– Electronics effects:
  The electronics effects depend on the total background rate of the tube, since for the readout all background pulses are relevant, independent of the position along the tube. The highest background rate per tube is 300 kHz. Two electronics effects have to be considered: baseline shift and baseline fluctuations. The quantitative understanding of these effects is crucial for the design of the front-end electronics.

– Space-charge effects:
  The space-charge effects depend on the rate per unit of length along the wire. The highest local rate is 1500 Hz/cm. At these rates the space charge of ion clouds drifting back to the cathode changes significantly the drift field and the gas gain. The resolution deterioration due to a change of the drift field depends on the non-linearity of a drift gas, hence the understanding of this effect is an important input for the drift-gas choice for drift tubes operating in a high background environment.

2) In ATLAS the space-time relation will be obtained locally by calibration with muon tracks.

3.1 Electronics effects

In this section we discuss in a quantitative way these two effects, which determine critically the design of the front-end electronics.

Since the signal trailing edge contains important information about the bunch crossing time and will help to reject out-of-time background pulses, unipolar signal shaping which preserves this information was found to be the most adequate. Thus signal shaping requires active baseline restoration in order to reduce the electronics contribution to resolution deterioration.

Alternatively, bipolar shaping can be used which would avoid the electronics effects described below without additional active circuits; it has, however, the drawback of losing the information contained in the trailing edge of the signal.

In the measurements described in this study unipolar shaping without baseline restoration but with a slight overcompensation of the ion tail was used. The shapers consisted in principle of two pole/zero filters. Each of them could be adjusted by potentiometers to yield the desired transfer function $f(s)$:

$$f(s) = \frac{s + \frac{1}{\tau_1}}{s + \frac{1}{\tau_2}}, \qquad \text{with} \qquad \begin{array}{l} \tau_1 = R_1 C \\ \tau_2 = \frac{R_1 R_2 C}{R_1 + R_2} \\ \tau_1 > \tau_2 \end{array} \tag{1}$$

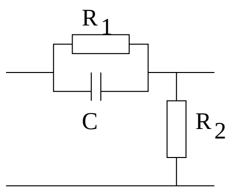

Table 1
Time constants of the pole/zero filters.

	τ_1 (ns)	τ_2 (ns)
First pole/zero filter	42.0	1.9
Second pole/zero filter	168.0	17.9

Table 1 shows the time constants which were used in this study. They were chosen in this way in order to produce a small undershoot after the actual muon signal (over-compensation of the ion tail). This undershoot reduces baseline shift and baseline fluctuations (see below).

3.1.1 Baseline shift

The tail of each signal caused by the ions drifting to the cathode is cancelled by the signal shaping to reduce dead time and pile-up.

While after each event the line charge on the wire recovers with a typical time constant of $2C_{\rm dc}R_{\rm l} = 1\,\rm ms$ (see Figure ??), the baseline will shift to negative values due to the AC-coupling between the tube and front-end electronics. This shift will be quite small for one event, but will sum up to rather big values at high background rates. Figure ?? (a) shows the principle. Subsequent muon pulses will start at the new baseline and hence the effective pulse heights decrease. The areas above and below the time axis have to cancel. This is the reason why an undershoot, which compensates already part ($\sim 20\,\%$) of the muon signal, reduces the baseline shift. With bipolar shaping the whole charge of the muon pulse is compensated immediately after the signal, hence there is almost no baseline shift (< 1 primary ionization electron) and no baseline fluctuations [Figure **??** (b)], causing only a very small resolution deterioration of $\sigma_{\text{shift}} - \sigma_{\text{no shift}} < 1\,\mu\text{m}$.

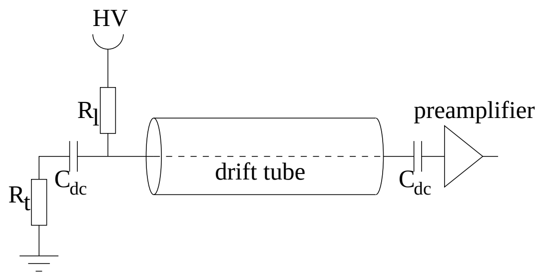

Figure 4: Diagram of the drift tube and the read-out electronics (loading resistor $R_{\text{l}} = 1\,\text{M}\Omega$, termination resistor $R_{\text{t}} = 380\,\Omega$, decoupling capacitors $C_{\text{dc}} = 500\,\text{pF}$).

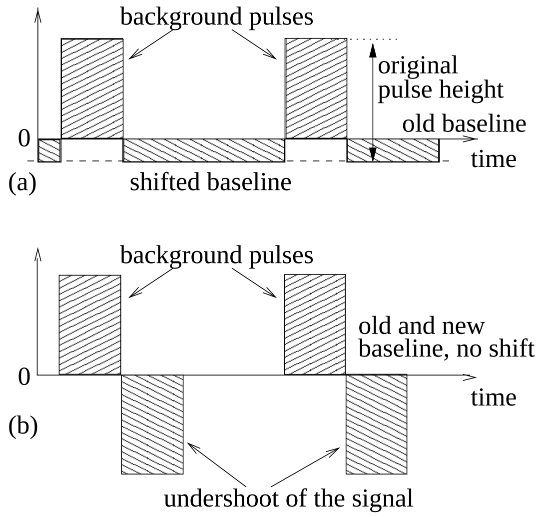

Figure 5: Sketch explaining the origin of the baseline shift for unipolar shaping (a) and bipolar shaping (b). The rectangular pulses symbolize background pulses, the areas above and below the time axis have to cancel each other.

With our test electronics the baseline shift was measured to be equivalent to nine primary ionization electrons at 300 kHz counting rate per tube.

This baseline shift deteriorates the resolution in the same way as a higher threshold level: The effective threshold level at high rates is the sum of the original threshold level and the baseline shift. Owing to variations in cluster size or gain which cause varying slopes of the signal leading edges, the threshold crossing times have a bigger jitter with higher thresholds. This effect is called time slewing and is the reason for the resolution deterioration.

For these measurements, preliminary ATLAS front-end electronics was used. The final front-end electronics will reduce the baseline shift to below one primary ionization electron.

3.1.2 Baseline fluctuations

Since the distances between background pulses are not equally but exponentially distributed, and the energy deposit also varies, we do not expect the baseline to be constant but rather to fluctuate around a mean value. The baseline fluctuations add quadratically to the electronics noise σ_{noise}[3]:

$$\sigma_{\text{noise+fluct}} = \sqrt{\sigma^2_{\text{noise}} + \sigma^2_{\text{fluct}}}\ . \tag{2}$$

Measuring the distribution of the baseline with ($\sigma_{\text{noise+fluct}}$) and without background rate (σ_{noise}) and applying Equation (**??**) yields $\sigma_{\text{fluct}} = 2.6\,\text{e}^-$ for our shaping scheme at 300 kHz counting rate per tube. This number is highly dependent on the tail cancellation. This dependence was checked by changing the time constants of the shapers. Without undershoot (time constants of the second pole/zero filter changed to $\tau_1 = 2\,\text{ns}$, $\tau_2 = 1.8\,\text{ns}$) the baseline fluctuations σ_{fluct} increased to $6.4\,\text{e}^-$.

Baseline fluctuations cause a jitter on the threshold crossing time because of the finite signal rise time (see Figure **??**). Hence the resolution deteriorates.

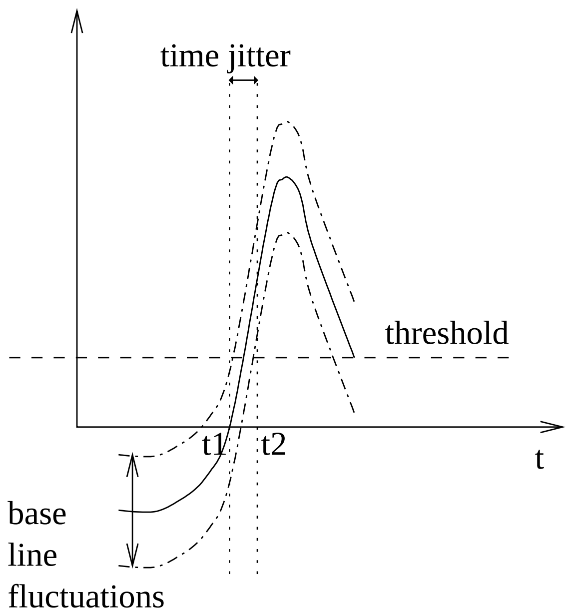

Figure 6: Jitter on the threshold crossing time caused by baseline fluctuations.

Even though baseline fluctuations have only a minor direct impact on the resolution, they increase the minimum threshold level ($5 \times \sigma_{\text{noise}} \rightarrow 5 \times \sigma_{\text{noise+fluct}}$) which deteriorates the resolution significantly (see discussion of baseline shift and gain drop in Section **??**). Hence baseline fluctuations should be kept to a minimum, as can be seen in the quantitative discussion in Section **??**.

3.2 Space-charge effects

For our tube geometry and working point, the ions created in the avalanche at the wire take about 4 ms to drift to the tube wall (cathode). The presence of ions in the drift

[3] The distribution of the baseline fluctuations was approximated with a Gaussian distribution.

region creates a space charge which modifies the electric field for subsequent events. This space charge lowers the electric field close to the wire and raises it close to the cathode.

Apart from considerations of tube lifetime during the duration of the experiment, the space-charge effects are the principal reason for a low gas gain ($G_0 = 2 \times 10^4$).

3.2.1 Gain Drop

Owing to the decreased electric field at the anode wire the electron multiplication close to the wire is reduced and the gas gain drops $G_0 \rightarrow G$ (Figure **??**). The measurements are compared with a simple analytical model and show good agreement. The ratio of the gas gain at the worst expected background rate (1500 Hz/cm) and the gas gain without space charge G/G_0 will be of the order of 0.88 at a gas gain of $G_0 = 2 \times 10^4$.

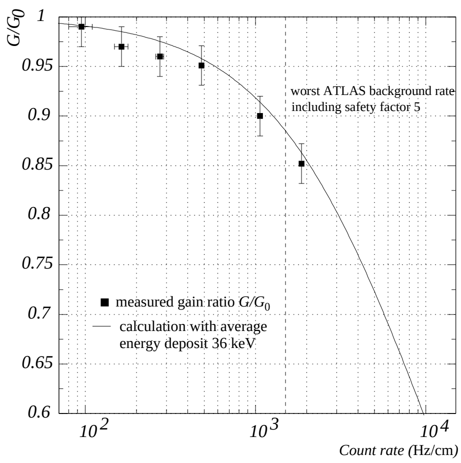

Figure 7: Gain drop versus background rate for a gas gain of $G_0 = 2 \times 10^4$. The solid line is a calculation using an analytical model for the space charge.

The impact of a gain drop on the resolution can be understood in the following way: the signals are scaled down whereas the threshold remains fixed. Consequently the threshold is effectively shifted to a larger number of primary electrons, which deteriorates the resolution.

3.2.2 Field fluctuations

The space charge changes the drift field and hence the space-time relationship. If this space charge were constant for a given hit rate, the drift field would be constant and there would be no deterioration of resolution. However, the electrons drifting towards the wire are affected only by the charge within approximately 1 cm along the direction of the tube and in such a slice there are on average only six ion clouds (1500 Hz/cm). Since the actual number n of ion clouds is Poisson distributed around this number, the drift field varies and the resolution deteriorates. This effect is rather small for gases such as $Ar/N_2/CH_4$ 91/4/5, where the drift velocity depends only weakly on the electric field, but becomes the dominating effect for gas mixtures like Ar/CO_2. Figure **??** compares the drift velocities as a function of the drift distance for two different gas mixtures. The drift field changes with $1/r$. Whereas for $Ar/N_2/CH_4$ 91/4/5 the drift velocity is rather constant over big distances in r, it changes a lot with the electric field for the Ar/CO_2 mixture. This explains why the latter is much more sensitive to field fluctuations.

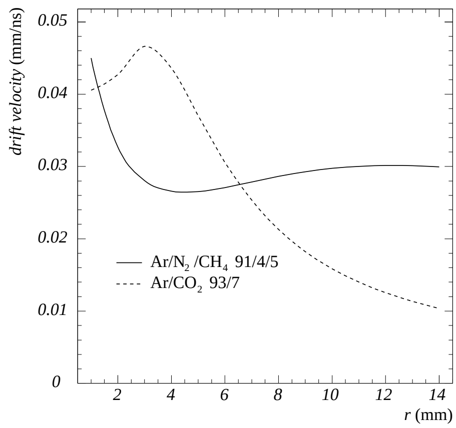

Figure 8: Drift velocity as a function of the drift distance (MAGBOLTZ [?]).

The resolution deterioration due to field fluctuations grows approximately with $\sqrt{\text{rate}}$ because the number n of ion clouds having an impact on one muon has an uncertainty proportional to $\sqrt{n}$.

4 Comparison of measurements and simulations

The drift tube response to charged particle tracks was simulated using GARFIELD [?], a drift chamber simulation program, MAGBOLTZ [?], a program to calculate transport properties of gas mixtures, and HEED [?], a program calculating the energy deposit of fast particles in gases. MAGBOLTZ and HEED are interfaced to GARFIELD.

The effects described above were introduced into the simulation. Figure ?? compares the predictions including all the electronics and space-charge effects with measurements for $Ar/N_2/CH_4$ 91/4/5. Owing to the linearity of the space-time relation the effect of the field fluctuations is very small. Figure ?? shows the resolution curves for the very non-linear drift gas Ar/CO_2 93/7. Only space-charge effects contributed to the resolution deterioration since only 3 cm along the tube were irradiated with photons, therefore the counting rate of the whole tube was small (~ 4.5 kHz). In the Ar/CO_2 mixture the field fluctuations are responsible for the strong deterioration. Both plots show the very good agreement between the simulations and the measurements. Note that even for the highest expected background rate the spatial resolution of the Ar/CO_2 mixture is on average[4)] approximately $80\,\mu$m. In ATLAS a time-slewing correction using the information of the leading-edge charge of the signal (see Ref. [?]) will be performed, which improves the resolution at the highest expected background rate to $\sigma < 80\,\mu$m.

[4)] The most convenient figure of merit for the resolution, characterizing best the performance of one tube in a chamber, was found to be the inverse quadratic average over the resolution as a function of the drift distance r, since the tubes will be weighted with $1/\sigma$ in the track fit.

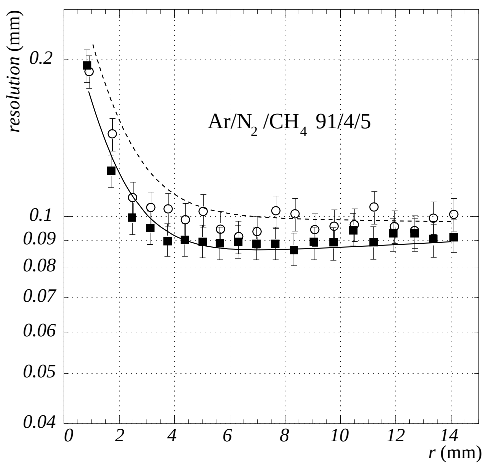

Figure 9: Comparison of measurements and GARFIELD [?] simulations. The full squares are measurements without background rate, the open circles measurements with a rate of 1850 Hz/cm (333.5 kHz per tube). The lines are GARFIELD simulations with and without background rate.

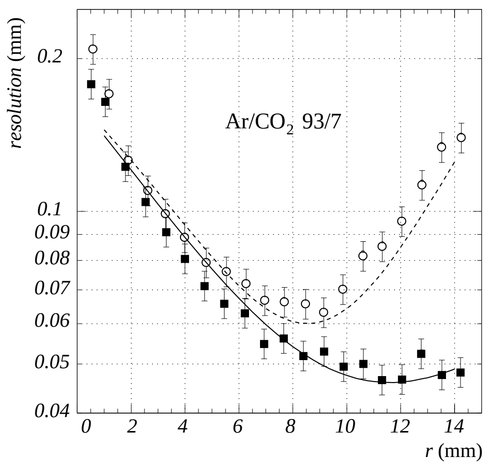

Figure 10: Comparison of measurements and GARFIELD [?] simulations. The full squares are measurements without background rate, the open circles measurements with a rate of 1400 Hz/cm (4.5 kHz per tube). The lines are GARFIELD simulations with and without background rate.

Figures **??** and **??** show the results of simulations, where individual effects can be studied. The quadratic difference between the resolution curves with the effect under study switched on and the resolution curve without background rate (see Figures **??** and **??**) is plotted. Based on these results the following comments can be made:

– The contribution of the field fluctuations is rather small for the linear gas (Figure **??**). Since the drift velocity is constant over big drift distances (see Figure **??**) variations of the drift field translate only into small variations of the drift time. For the non-linear gas mixture (Figure **??**) this contribution dominates.

– The baseline shift (nine primary ionization electrons) dominates the resolution deterioration of the linear gas. It shifts the threshold to higher electrons ($25\,e^- \rightarrow 34\,e^-$). The contribution of the gain drop ($G/G_0 = 0.87$) is smaller over the whole drift distance since the effective threshold shifts only to $25\,e^- \cdot G_0/G = 28.5\,e^-$. With a linear gas the pulse height increases with the radius[5)] and hence the leading edge becomes steeper. Therefore, raising the threshold affects the resolution less at bigger radii, hence both effects decrease with bigger drift distance r. In the non-linear gas mixture the drift velocity decreases with bigger radii (see Figure **??**), hence a jitter in the threshold crossing times translates into a smaller resolution deterioration at bigger drift distances.
– The baseline fluctuations in Figure **??** deteriorate the resolution slightly (see Figure **??**) since the threshold was kept at the 25th primary ionization electron ($5 \times \sigma_{\text{noise}}$). Raising the threshold to $5 \times \sigma_{\text{noise+fluct}}$ would result in a resolution deterioration comparable to the contribution of the gain drop.
– The difference between 'all effects on' and the quadratic sum of all effects in Figure **??** shows that there is a correlation between individual contributions. The quadratic sum underestimates the resolution deterioration because a baseline shift amplifies the effect of the gain drop: the baseline shift shifts the threshold from the 25th to the 34th primary ionization electron. Multiplying this with G_0/G yields a threshold of $39\,e^-$ which is higher than we obtain by summing up the two individual effects[6)].

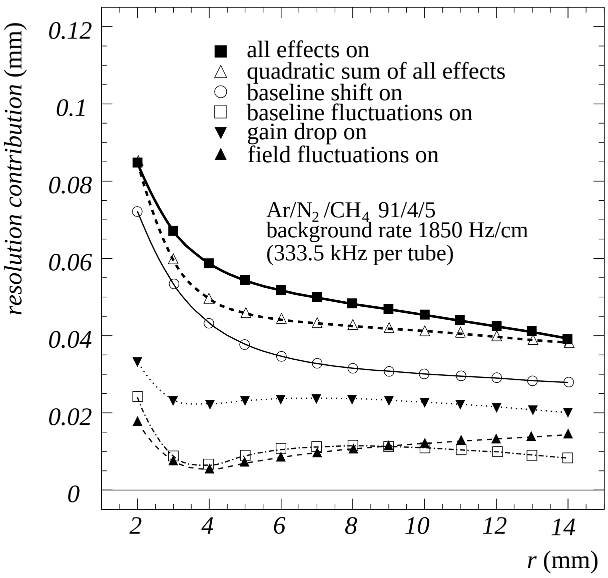

Figure 11: Contributions to resolution deterioration. The background rate is 1850 Hz/cm, the drift gas $Ar/N_2/CH_4$ 91/4/5, and the gas gain 2×10^4. The statistical errors are about $10\,\mu$m. The lines are drawn in to guide the eye.

5) In a linear gas the time difference between individual clusters of ionization electrons arriving at the wire becomes smaller with greater distances between the track and the wire, and consequently the pulse heights increase.

6) In this threshold region the resolution degrades linearly with higher thresholds.

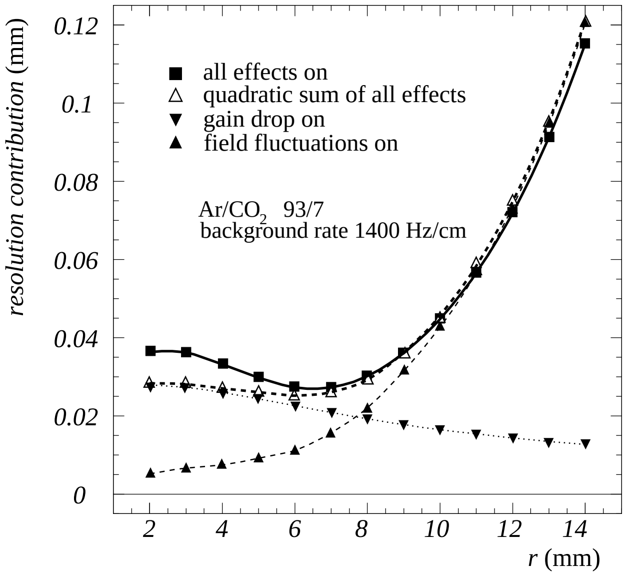

Figure 12: Contributions to resolution deterioration. The background rate is 1400 Hz/cm, the drift gas Ar/CO_2 93/7, and the gas gain 2×10^4. The statistical errors are about 10 μm. The lines are drawn in to guide the eye.

5 Conclusion

We have shown that drift tubes can be operated far in excess of the expected ATLAS background rates and still provide a spatial resolution of $\sigma \approx 80\,\mu$m. However, their behaviour depends critically on the front-end electronics. The impact of electronics effects like pulse shaping, baseline shift, and baseline fluctuations on the spatial resolution was measured and compared with simulations.

The resolution is also affected by space charge causing a gain drop, which increases the time slewing, and field fluctuations which induce variations of the space-time relationship. Simulations showed that the latter effect is dominant for gas mixtures like Ar/CO_2 where the drift velocity strongly depends on the electric field. Hence, beside the electronics design, the gas choice has a big impact on the high rate performance.

The good agreement between the measurements and simulations demonstrates the good understanding of the effects. It is possible to make predictions for different drift gases, different readout electronics or other working parameters.

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