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**ANODE WIRE AGEING IN PROPORTIONAL COUNTERS:
THE PROBLEM OF ANALOG RESPONSE**

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Abstract

The analog response of aged proportional counters is shown to be determined by the local charge density distribution on an insulating sense-wire surface. It therefore depends on a number of parameters like spatial distribution of irradiation, counting rate, gas gain and surface conductivity of the insulating layer. Typical charge response time constants are derived from a dynamic model of the surface charge density. Experimental consequences like charging-up effects, time dependence of amplitude in irradiation burst environments, fluctuations of detector resolution as function of rate, and the influence of water admixtures to counting gases are described. The problem of deriving specific ageing parameters is quantified in a typical example.

1 INTRODUCTION

The problem of wire ageing is as old as the use of gaseous amplification for particle detection. The formation of insulating layers on the metallic electrodes of proportional counters has been and still is a major limitation to their use in long-term or high-rate experiments, especially where precise analog information is needed. Unfortunately, the deposition of thin, very high quality insulators is one of the major assets of gas discharge and avalanche processes. As such, it has even found industrial applications in the field of plasma chemistry [1].

Although the basic phenomenology of the ageing process has been studied and described in an impressive variety of experimental data, its quantitative description still meets with considerable difficulties [2]. This is because, on the one hand, of the very large number of physical and chemical parameters on which the deposition process itself depends. On the other hand, the presence of the insulating deposit modifies the space-time distribution of the electric field near the wire surface where the avalanche formation takes place. Amplitude loss and instability are thus determined by surface charge phenomena.

In this paper, we will concentrate on the latter aspect. Indeed, any quantification of the ageing process has to be preceded by a precise understanding of the mechanism of analog signal formation. If in the ideal case of metallic electrodes, the proportional signal depends on only a small number of calculable or measurable quantities (electrostatic field distribution, Townsend coefficient, electron and ion drift velocities), the presence of an insulating anodic surface layer introduces a large number of additional, often ill-defined parameters. The electric field becomes a dynamic quantity, fluctuating with specific time constants which are determined by local radiation density and rate, gas gain and surface conductivity. We will try to identify the relevant parameters, quantify their influence on the measured amplitude, and study the possibility to define ageing quantities, which depend as little as possible on the specific experimental situation.

2 EXPERIMENTAL SET-UP AND DATA ACQUISITION

2.1 Gas System

The data described in this paper have been obtained in an argon/20% CH₄ mixture from premixed bottles [3]. The purities of the two gas components are 99.996% for argon and 99.95% for methane. The gas passes through standard pressure reducers [4] and stainless steel or copper tubing into the test chambers. It is vented via Apiezon [5] oil bubblers or directly to air via long (more than 5 m) stainless steel tubes of 4 mm internal diameter. The flux of 1–5 l/h is controlled by mass-flow meters [6] or mechanical rotameters [7]. Standard, flexible, stainless-steel tubes, clamps and O-rings from vacuum technology are used to connect test tubes and gas lines. We have found our results to be independent of material and length of input gas tubing as well as of the kind of venting used. The oxygen contamination in the output gas was measured to be less than 10 ppm.

2.2 Test Chambers

Single-wire proportional tubes of quadratic cross-section ($8 \cdot 8 \text{ mm}^2$) with 20 μm diameter, gold-plated tungsten wires [8] have been used. The cathode material was brass. We have constructed two types of counters (hereafter denoted by type I and type II) with different source collimation and charge collection geometries. A schematic view of the counter cross-section is shown in Fig. 1.

Counter Type I

This counter has an azimuthally closed cathode. 5.9 keV photons from ^{55}Fe sources shine onto the sense wire through a 5 mm long collimator with 1 mm internal diameter. In order to obtain pulse-height spectra of good quality, the collimator is separated from the tube volume by a thin (10 μm) aluminized Mylar foil retracted by 0.5 mm. The proportional tubes are 60 mm long. They are fixed to an Al support which also carries the clamps for the sense-wire fixation. The tube assembly is mounted inside a cylindrical, stainless-steel envelope of about 0.5 l volume. We have tried to keep this volume to a minimum in order to avoid problems with water contamination and outgassing time constants. High voltage for the sense wire and the signal connection from cathode to outside preamplifier are brought in via glass feedthroughs. Temperature is monitored inside the chamber volume by RT100 thermal resistor probes. The construction allows for easy access to sense wire and cathode. Sense wires can thus be inspected and cathode material changed without handling other parts of the counters. Figure 2 shows a complete tube assembly together with an Al cathode mounted on its support and an exchange cathode machined in solid graphite.

Counter Type II

In order to study the dependence of the ageing process on source and charge collection geometry, we have constructed a second type of test counter. Here, the brass cathode (of dimension equal to type I) is opened up on top by a wire grid of 100 μm Cu-Be wires. The grid wires have 2-mm spacing and are in electrical contact with the brass cathode. Their direction is orthogonal to the sense wire. Charges are drifted into the tube volume through a drift channel mounted above the wire grid. The drift structure is 50 mm high, with an internal width of 8 mm matching the cathode dimension. The electric field is defined by an assembly of trapezoidal lead wires glued to both sides of 100 μm epoxy-fibreglass strips [9]. The drift field is about 200 V/cm. At a distance of 25 mm from the cathode, a ^{55}Fe source injects photons into the drift channel through a 5 mm long collimator of 1 mm internal diameter. The assembly is enclosed by an outer Al envelope of 25 cm length and 10 cm internal diameter.

2.3 Data Acquisition

An automatic pulse-height measuring system [10] using the G64 standard together with Camac has been developed for the data acquisition. After splitting, the analog signal is integrated during a 40 nsec gate on a Camac ADC [11]. The amplitude of the main photon peak from the ^{55}Fe source is then evaluated by averaging the pulse-height distribution between two cutoffs (10%) around the main peak. Typical pulse-height distributions from counter types I and II are shown in Fig. 3 for non-aged wires. The spectrum from counter type I is very clean with an r.m.s. of the main peak of about 7.4%, and a small background from photonic interactions in the brass walls visible between the main and escape peaks. The spectrum of counter type II shows a higher background originating from edge effects in the drift channel and from a small residual grid inefficiency. For comparison, we also show in Fig. 3 a simulated pulse-height spectrum from the Monte Carlo program described later.

2.4 Corrections and Precision

All data are corrected for pressure and temperature fluctuations, which is particularly important in our environment which could not be pressure stabilized. At our standard gas gain of about 10^4 , this correction amounts to 0.55% per mbar or -1.83% per $^\circ\text{C}$ in our

gas mixture. The statistical accuracy of each single-amplitude measurement (10^4 counts) is about 0.3%. Including long-term fluctuations in gas supply and corrections we estimate the overall systematic error to be smaller than 0.5%.

3 PULSE-HEIGHT DISTRIBUTION OF AGEING DETECTORS: LOCALITY OF DEPOSITION

If the suppression of pulse height in aged detectors is due to the presence of insulating layers on the anode wire, and if the build-up of this layer is some function of the local charge density arriving at the wire surface, the analog response must strongly depend on the distribution of this charge density. Local charge density is a convolution of avalanche geometry and space distribution of ionization electrons created by particles impinging on the detector. As long as the avalanche process is local, with azimuthal dimension small compared to the anode wire diameter, the insulating deposit should be an image of the incoming particle distribution with respect to the sense wire. It should therefore depend on the type of irradiation as well as on its collimation and on the collection geometry of the detector. For normal counter gases, this should be true for gas multiplications well below the Geiger limit, i.e. up to gains of about 10^5 . Some qualitative evidence for this picture of local deposition has been accumulated in the literature [12]. In order to quantify the underlying physical processes, we have obtained measurements of pulse-height distributions, as a function of ageing, in two different counter geometries and have compared these results with detailed Monte Carlo simulations.

3.1 Experimental Pulse-Height Distributions

Pulse-height spectra from the two different types of proportional counters described in Section 2 of this paper, are shown in Fig. 4 as a function of wire ageing. If the incoming radiation is collimated directly on the sense wire (counter type I), a rather complex pulse shape development results: An initial broadening of the spectrum is followed by the development of two distinct peaks with different ageing speed. Similar phenomena have been described in the literature [12].

In contrast, in the case of counter type II where the charges are drifted onto the sense wire from one side (see Fig. 1), the pulse-height distribution remains practically unchanged as the mean amplitude decreases in the course of the ageing process. In view of the complexity of the observed amplitude spectrum in counters of type I, the definition of a mean amplitude is not straightforward. This means that e.g. the measurement of the average current drawn by the counter as function of irradiation time might not be the best quantitative measure of the ageing process.

If we chose to plot the time evolution of both principal peaks independently, we obtain the time dependence of amplitude presented in Fig. 5. The amplitude decreases linearly down to about 85% of its initial value. For larger losses, a more hyperbolic shape of the time dependence is approached. The same phenomenon is observed for counter type II, see Fig. 6. In the linear part, a sizeable difference of slope, i.e. ageing speed, is evident for the two peaks of counter type I. This difference amounts to a factor of about four. The detailed shape of the time dependence of amplitude carries interesting information on the deposition process, especially on its dependence on irradiation rate and gas gain. We will come back to this in Section 7 of this paper.

3.2 Model Calculations

We have performed a Monte Carlo simulation which contains the detailed collimation and charge collection geometry of our detectors.

We define a Cartesian coordinate system with x along the sense-wire direction and y, z in a plane orthogonal to the sense wire. In this plane we define the azimuthal angle ϕ such that the iron source is positioned at $\phi = 270^\circ$ in counter type I and at $\phi = 90^\circ$ in counter type II, see Fig. 1.

The absorption path length of the 5.9-keV photons in the counter gas, the distribution of ionization electrons from range of the released 3-keV electrons, transverse diffusion over the drift path and transverse avalanche size are taken into account. The number distribution of ionization electrons for main and escape peaks follows a Gaussian including a Fano factor of 0.2. The single, avalanche amplitude distribution is exponential. This model yields a fair description of the analog response of non-aged counters to ^{55}Fe photons, as shown in Fig. 3. Most of the parameters entering into our simulation as defined above are sufficiently well-known for our purposes. Only the transverse avalanche size is at the same time critical to our results and relatively badly known. More precisely, it is the avalanche spread in azimuth which has to be carefully taken into account, the spread along the wire direction, x , being negligible compared to the width of collimation.

In this context it is interesting to note that the appearance of sharp structures in the pulse-height distributions as shown in Fig. 4 allows us to put upper limits to the azimuthal width of the avalanche. If each avalanche surrounded the wire completely, such structures would disappear and be replaced by smooth, single-peaked spectra. The biggest r.m.s. azimuthal avalanche spread compatible with the data is about 15° corresponding to a few micron transverse dimension. This holds for gas gains up to about $5 \cdot 10^4$. We will come back to this problem in the discussion of the complete dynamical model calculations in Section 5.5.

Charge density distributions over the anode wire surface resulting from our simulation are presented in Fig. 7 for both counter geometries. Characteristic differences are evident. Whereas the distributions projected along the wire direction, Fig. 8a, are similar and show the expected Gaussian shape corresponding to the source collimation, the projections on azimuthal angle, Fig. 8b, are very different. The drift detector (type II) receives electrons only on one wire hemisphere, whereas source collimation directly on the sense wire (type I) leads to two distinct peaks of different height due to the solid angle of collimation and photon absorption length.

We have checked this prediction by scanning the deposit on an aged sense wire from counter type I with electron microscopy at two different azimuthal angles, once facing the source (270°) and once opposite the source (90°). In this case, the insulating layer consisted of silicon oxide, such that the relative layer thickness can be measured from the intensity of the characteristic Roentgen fluorescence lines of the two elements with an accuracy of about 5% [13]. The measured thickness distributions are shown in Fig. 9 together with the corresponding charge density distributions from our Monte Carlo calculation. The good agreement proves that the deposition process is indeed local and dependent on the distribution of incident charge.

It should be mentioned that for the ageing factors discussed here the layer thickness corresponding to the scan of Fig. 9 is very small, such that it cannot be visualized by direct inspection of the wire in the electron microscope. The observed amplitude-loss can therefore not be attributed to a radius increase (and corresponding decrease of gas gain) of the sense wire.

3.3 Predictions for Pulse-Height Distributions

Given the correspondence between layer thickness and charge density distribution, we can now predict the observed pulse-height distributions as a function of ageing, if we make assumptions about the relation between local insulator thickness and effective amplitude suppression.

In a very simple static model we can postulate a linear dependence of gas gain on layer thickness. In this model the relative pulse-height distribution can be obtained as soon as we assign a value of amplitude loss to e.g. the point of maximum charge density on the wire surface. Amplitude spectra calculated with this assumption are shown in Fig. 10 for different values of maximum amplitude loss. A striking similarity with the observed spectra (cf. Fig. 4) emerges from this very simple model, in particular as far as the characteristic development of a two-peak structure in counters of type I and the shape stability of the spectrum in counters of type II are concerned. Although we can thus describe the salient features of pulse-height distributions by simple geometry, we have learned nothing about the underlying dynamical effects of surface charge build-up and discharge, and their equilibrium at fixed counting rate. This will be discussed by looking at rate-dependent effects in the subsequent chapters.

4 RATE DEPENDENCE OF AMPLITUDE AND PULSE-HEIGHT DISTRIBUTION IN AGED COUNTERS

The following simple experiment can shed some light on the mechanism of pulse-height suppression on aged wires. The amplitude of a counter is run down by irradiation at high rate, resulting in time-dependent pulse-height distributions as presented in Fig. 4.

At some ageing value, the amplitude distribution from the wire is measured with different source rates, keeping all other parameters unchanged. As demonstrated in Fig. 11, an exact inversion of the ageing development (Fig. 4) occurs with decreasing rate: the amplitude increases and the width of the pulse-height distribution shrinks. Asymptotically at 0 counting rate, both amplitude and pulse-height spectrum seem to approach their values for non-aged wires. Experimentally, however, it is difficult to obtain clean measurements at rates below the level of 1 Hz due to cosmic ray background as is visible in Fig. 11.

If we plot the amplitude of both principal peaks (for counter type I) or the single peak (for counter II) relative to the non-aged amplitudes as a function of rate, we obtain the result shown in Fig. 12. Over the measured range of rate (about three orders of magnitude) the apparent ageing can vary by as much as one order of magnitude. The dependence is about linear if plotted against the logarithm of rate, with a slope which evidently depends on the ageing state and counter geometry. This observation proves that the reduction of pulse height cannot be understood in a static way, e.g. by an increase of effective wire diameter by the deposit. On the contrary, we have to deal with a dynamic process governed by the build-up of surface charges (defined by distribution and rate of irradiation) in equilibrium with a discharge mechanism. Thus at rates low enough compared to the corresponding discharge time constant, the wire can recuperate full electric field between two hits.

We are dealing here with one of the (many) hidden parameters of the ageing problem, which has to be taken into account if one wants to extract experiment-independent quantitative information from a given ageing measurement. Otherwise, scale uncertainties of up to one order of magnitude can arise from this parameter alone.

We will now turn to a more quantitative evaluation of the underlying surface-charge process.

5 DYNAMIC MODEL CALCULATIONS

The Monte Carlo simulation described in Section 3.2 can be extended into a time-dependent model taking into account the mechanisms of build-up and decay of surface charges. The charge distribution from each incoming particle as well as the thickness distribution of insulator on the wire are known from simulation. At irradiation rate R , subsequent events follow each other with a time distance distribution as $\exp(-Rt)$. The dependence of gas gain on electric field is known to be $\exp(cE(t))$, where the parameter c is a measured gas and geometry dependent quantity. The electric field is now time-dependent, as it is defined by the difference of the (constant) charge density, ρ_0 , on the 'naked' metallic wire surface (which is proportional to the applied high voltage), and the charge density, ρ , of electrons on the insulator surface which will fluctuate with time. There is only one free variable in this calculation, namely the surface-charge decay time constant, which has to depend on layer thickness and which we will show to be dependent on charge density. If we start irradiation of an aged wire at time 0, it will take a certain stabilization time delay (also described by the model) until we reach a stable equilibrium amplitude. This equilibrium is driven by the very steep (in fact, exponential) dependence of gas gain on effective charge density.

In order to avoid, in a first stage, the complicated variation of layer thickness and pulse height over the wire surface, we will look at the behaviour of charge density in the maximum of insulator thickness. This maximum we have shown above to correspond to the peak with lowest amplitude in counters of type I (Section 3). The calculations will be performed for gas gain 10^4 which is used in our pulse-height measurements. Calculated and measured charge densities will always be normalized relative to the one found on the non-aged wire surface.

5.1 Calculations at Fixed Time-Constant

A very simple assumption about the discharge mechanism would be an exponential decay with fixed time constant.

The calculated equilibrium charge density (at maximum insulator thickness) resulting from this assumption, is shown in Fig. 13 as function of irradiation rate, for different time constants. The corresponding amplitude dependence is shown in Fig. 14. For a given time constant, a very steep rate dependence is predicted such that an aged counter would stop functioning beyond a certain well-defined rate limit. This evidently contradicts the measured rate dependence, Fig. 12 above.

5.2 Dependence of Time Constant on Charge Density

In order to compare our calculations with experiment, we can translate measured amplitudes into charge densities. The corresponding values for the lower peak of counter type I are superimposed into Fig. 13. In order to describe the data, the effective discharge time constant has evidently to be a strong function of charge density.

We can get a first idea of this functional dependence by investigating the crossing points, in Fig. 13, of the experimental rate dependence with the calculations at different time constants. As plotted in Fig. 15, this yields an exponential dependence of time constant on charge density.

We can parametrize this remarkably simple dependence as

$$\tau = \tau_0 \exp(-B\rho(t))$$

where τ_0 characterizes the discharge process at small density or low rate, and B gives the slope of the rate dependence of amplitude. The above parametrization is of course only valid inside the region of experimental observation. We do not expect the time constant to take a fixed value at $\rho = 0$, nor can it become arbitrarily small at large values of ρ .

In general, however, we see that the discharge process cannot be described by a simple capacitive model. The extremely strong dependence of τ on local charge density seems rather to indicate a process that passes via surface mobility of electrons. The radial electric field on the sense wire will be able to lock surface charges, at small charge densities, against transverse movement. With increasing irradiation intensity, ρ will become comparable to the charge density ρ_0 defined by the unperturbed electric field,

$$\rho_0 = \epsilon_0 \cdot E_0.$$

In this case, the internal electric field in the surface electron cloud can spread charge over the wire surface with small time constants.

5.3 Dependence on Layer Thickness

The rate effects discussed above at the point of maximum insulator thickness have to be complemented with a thickness dependence of the relevant parameters, if we want to obtain a complete description of the ageing phenomena. As the only variable in our simulation is the discharge time-constant, it must be thickness dependent such that, at thickness zero, we obtain infinitely small time constants (non-aged wire), and at maximum thickness we approach the results from section 5.2. This can be done by writing

$$B = B_0 \cdot f(d)$$

and

$$\tau = \tau_0 \exp(-B_0 \cdot f(d) \cdot \rho(t)).$$

We shall see later that the thickness dependence of the exponent B is a key feature in understanding the ageing evolution of a given counter, but it should be mentioned that d is not necessarily the physical layer thickness, as discussed in Section 8.3. We can get a first idea of the function $f(d)$ by using the pulse-height spectra from counter type I at fixed ageing. Here we have, for the same sense wire and the same external experimental conditions, two distinct amplitude peaks corresponding to two local maxima of the insulating layer with known relative thickness. As the discharge time-constant has to decrease with decreasing layer thickness, we will use the simple parametrization

$$f(d) = 1/d_{\text{rel}}^C$$

where d_{rel} is the relative layer thickness varying between 0 and 1 (maximum thickness).

Values for the three parameters τ_0 , B_0 and C can be obtained by fitting the predicted amplitude distributions, as function of rate, to the measured ones presented in Fig. 12. A fairly reasonable description of the overall phenomenon of amplitude dependence on rate is achieved simultaneously for counter types I and type II, as shown in Fig. 16. For the ageing state chosen, the optimum parameter values are

$$\begin{aligned} \tau_0 &= 10 \text{ sec} \\ B_0 &= 5.6 \cdot 10^{-8} (\text{e}/\text{mm}^2)^{-1} \\ C &= 1.3. \end{aligned}$$

This means, for example that the exponent B depends nearly inversely proportionally on layer thickness.

5.4 Description of Ageing Evolution

In order to make sense, our model has of course to describe the situation not only at one fixed ageing value, but over the complete evolution of ageing from full amplitude to arbitrary values of amplitude suppression. This has to be achieved by variation of parameter B only. Figure 17 shows the predicted amplitude behaviour as a function of rate, for different values of B . The measurements performed with counter type II also presented in Fig. 17 show indeed that the overall situation is well described over more than one order of magnitude in amplitude suppression and three orders of magnitude in rate. In the region of very low rate and very large amplitude losses, there are indications that eventually the simple parametrization with constant A has to be supplanted by some increase of A at low charge-density and large insulator thickness.

5.5 Amplitude Distributions

In addition to the behaviour of mean pulse heights, our model should also be able to predict the shape of the pulse-height distributions as a function of ageing for both counter geometries.

This is demonstrated in Fig. 18 where simulated pulse-height distributions from counters I and II are shown for different values of B . If compared with the experimental data (Fig. 4), a reasonable overall description is found, although the calculated spectra are generally somewhat wider than the measured ones. This can be quantified by comparing the r.m.s. width from counter type II with calculation, as a function of relative amplitude loss, see Fig. 19. Clearly the simulation predicts too much spread at larger values of amplitude loss. It is indeed astonishing how little the measured width changes with ageing, whereas the thickness dependence of the discharge time constant enforces a relatively important increase of width in the calculation.

We believe that this observation is another indicator for a surface discharge mechanism. The region of highest charge density will not discharge locally (as assumed in our simulation), but will spread charges along the wire surface to the regions of smaller charge density and hence bigger discharge time constants. This will tend to generate a more uniform charge distribution and thus, as a consequence, less fluctuation in pulse height. A mathematical description of such a surface propagation mechanism is, however, rather complicated and has not been attempted in our calculations.

At this point we can come back to the question of azimuthal avalanche spread discussed in Section 3.2. If we regard the r.m.s. fluctuation in azimuth, σ_ϕ , as a free parameter, we can carry out model calculations for different values of σ_ϕ . It turns out that the observed structure of the amplitude distributions implies a relatively well-defined upper limit for this spread. In fact the double peak structure in type I counters, Figs. 4a and 18a, vanishes in our calculations if the azimuthal spread σ_ϕ exceeds about 15–20°. This shows that the avalanches are confined to an azimuthal spread of a few μm in the range of gas gains used in our measurements.

5.6 Gain Dependence

Up to now, we have discussed analog signal formation at a fixed gas multiplication of about 10^4 . As the measured amplitude is determined by the surface charge density, a change in gas gain (at fixed rate) must influence the equilibrium density and thereby the amplitude suppression. It is therefore not clear a priori how the relative amplitude will behave as a function of gas gain.

Measurements of amplitude against chamber high voltage are shown in Fig. 20 for counter type II at different ageing values. At first view it is surprising to see how little the slope of the amplitude against high voltage changes with increasing ageing. Apparently the relative amplitude suppression is, to first order, independent of high voltage up to very large ageing factors.

A closer look at the slope of the observed amplitude dependence, Fig. 21, reveals, however, a small residual effect which reduces the slope factor with increasing ageing. This reduction is of order 10% for an amplitude variation of one order of magnitude.

Owing to its particular discharge mechanism, our model makes a rather strong prediction for this phenomenon.

Since high, initial charge densities are quickly drained away, whereas low densities are blocked for long time spans on the insulator, the relative charge density at fixed rate should depend very little on gas multiplication. This equilibration process is demonstrated in Fig. 22 where the time dependence of local charge is plotted for different initial densities. It is seen that at some fixed discharge time t (corresponding to a fixed rate of irradiation), all initial charge densities above a certain limit have decayed to the same value, whereas lower densities stay constant due to their longer discharge time-constants.

Predictions for the dependence of relative amplitude on high voltage are given in Fig. 23a for counter type II, at different ageing values (parameter B). The experimentally observed behaviour is very well described by the calculation, up to the second-order effects on the slope mentioned above and shown in Fig. 24.

If, however, the calculations are performed with fixed discharge time constant (cf. Section 5.1), a very strong voltage-dependence emerges, as demonstrated in Fig. 23b. This contradicts experiment.

We conclude that the analog signal formation in aged counters is governed by the rate of irradiation and almost completely decoupled from gas multiplication. These two parameters can thus be considered as orthogonal. This is in contrast to the ageing process itself which we will show in a subsequent paper [14] to be a function of wire current, i.e. the product of rate and gas gain.

6 EXPERIMENTAL CONSEQUENCES

The discussion of analog performance in the preceding chapters has shown how the response of aged counters depends on a precarious equilibrium of different parameters like irradiation rate and charge distribution, gas gain and counter geometry. The continued use of deteriorated counters as ‘analog’ devices is therefore inevitably accompanied by increased fluctuations and systematic errors, even if the original amplitude can be restored by increased operational voltage. To follow these systematic phenomena in quantitative detail it is a difficult undertaking. We will present a number of effects which touch directly on experimental applications of aged detectors, and which we can understand now in a more quantitative fashion.

6.1 Charging-up Effects

After switching on an aged detector, a certain time will be needed to establish the equilibrium charge density discussed above. This time constant will be defined by rate and ageing status of the wire surface. Figure 25 shows the calculated charging-up behaviour of a wire which has (in equilibrium) an amplitude reduction of 50% at 5 Hz, for different irradiation rates. As expected, the equilibrium amplitude is approached exponentially from above, at times which decrease strongly with increasing rate. This is seen in Fig. 26,

where the equilibration time is plotted against rate for different ageing values, as defined by parameter B . Already at modest rates this time constant is so small that it will hardly be observable. A real problem exists, however, at very low rate, i.e. in cosmic-ray environments or in low-intensity accelerator experiments. Here, charge-up times of many minutes will lead to very undesirable long-term fluctuations. As an example we show in Fig. 27 the measured switch-on behaviour of current for two detector units of the HPC calorimeter [15]. The equilibrium current of some tens of nA is generated in this case by alpha radioactivity from the lead converters. The corresponding rate is very low, of order 0.1 Hz/mm wire length. The detector units have lost about 50% of its initial amplitude by ageing, and the resulting charge-up time of several minutes is well described by our model calculation, see Fig. 26.

6.2 Bursts of Radiation

A closely related phenomenology exists in environments with varying irradiation load. This is typical of fixed-target experiments, where the beam arrives during periodic spills. In the inter-spill time the aged detector will start discharging with a time constant which is limited by the background radiation conditions. During spill, the amplitude will decrease depending on beam intensity. A complicated time pattern of amplitude will result with a pulse height oscillating somewhere between the non-aged value and the limit given by constant irradiation with beam intensity.

Calculated patterns for 2-sec spills with 10-sec spacing are shown in Fig. 28 for a detector with 50% amplitude loss at 5 Hz/mm and 5-Hz beam rate. The first spill comes down from full amplitude, whereas subsequent spills have a smaller amplitude variation of about a factor 1.5.

We have measured this effect in a 50-GeV electron beam at CERN, using an aged HPC calorimeter [15] test unit. The cycle was 2.3 sec beam and 10 sec interspill interval. The same unit had an ageing loss of 50% in amplitude at 5 Hz per mm wire length.

The experimental result is shown in Fig. 29. The expected decrease of analog signal during spill is clearly visible, as well as its dependence on beam rate, which varied between 200 and 4000 per spill. The level of suppression is well described by our calculations, also indicated in Fig. 29. The same measurement carried out with a non-aged counter did not show any amplitude variation.

6.3 Deterioration of Detector Resolution

At fixed irradiation rate, subsequent hits on the same wire segment follow each other with an exponential time-interval distribution (Section 5). Given a certain wire discharge mechanism, this will lead to fluctuations in amplitude which are rate and ageing dependent and which will tend to be bigger for smaller rates. Our model makes precise predictions for this behaviour. In Fig. 30 we show calculated event-by-event amplitude fluctuations for two wires which have the same amplitude suppression of about 40% once at 0.5 Hz/mm and once at 5 kHz/mm. A large difference in the size of fluctuation is visible once the amplitude has settled after switch-on. The predicted r.m.s. width of these fluctuations is plotted in Fig. 31 for different values of ageing and rate. An almost linear increase of the r.m.s. spread with increasing amplitude loss is visible, together with a strong rate dependence. The influence of this effect on experimental results will depend strongly on the local resolution of the measured quantities. Energy-loss distributions e.g. will in general be insensitive, given the very large local width of the Landau distribution. For calorimetric applications, fluctuations of order 10–20% can become limiting for the

overall resolution. This limit will already be reached at modest ageing, if the rates are on the level of cosmic-ray intensities.

We have been able to study this phenomenon directly using a radiation source of very high intrinsic resolution. Small quantities of radioactive krypton (mass number 83), added to the normal counter gas, decay to their ground state by the emission of two photons of 32 and 9 keV energy, with a lifetime of 1.8 hours and 150 nsec, respectively. Most of the 41-keV total energy is released into the gas by a number of internal conversion electrons of energy 1.8 to 30 keV, with the occasional escape of 9 or 12-keV photons. If the conversion electrons are spatially contained in a strong magnetic field, the resulting pulse-height spectrum shows two well-separated principal peaks with a 4% r.m.s. spread in the main peak.

The experimental pulse-height distribution shown in Fig. 32 was obtained in the HPC calorimeter unit [15] with an ^{83}Kr intensity of about 4 Hz per mm wire length. When the calorimeter unit was aged in a test up to about 50% amplitude loss, the krypton spectrum widened as demonstrated in Fig. 33. We were able to calibrate the corresponding wire gain fluctuation by adding a r.m.s. variation to a special Monte Carlo simulation describing the Kr decay process also shown in Fig. 33.

The experimental results thus obtained are superimposed on Fig. 31. They are well described by our simulation predictions.

7 EFFECTS OF WATER ADMIXTURE TO COUNTER GASES

The influence of water admixtures on ageing phenomena has been widely discussed in the literature [16]. Whereas there is some controversy on the eventual reduction of ageing speed by water, in general there is agreement on the improvement of analog response. This improvement is not surprising if one keeps in mind the essential role of surface charge effects — as discussed above — and the well-known fact that water tends to increase surface conductivity.

The problem with water is a very strong reduction of drift velocity even at small admixtures of a few hundred ppm [17] and a tendency towards high-voltage breakdown (which is another indicator for increased surface conductivity). This means that drift devices like our counter type II are impractical with sizeable water content.

We have therefore performed measurements with counters of type I which are much less sensitive to changes of drift velocity. Water was added by passing part of the counter gas through a bypass bubbler which allowed us to vary the water content between typically 0.1% and 1.5%. Above 1.5%, the counters tend to suffer HV breakdown.

Two counters with quite different source rates of 11 Hz and 5 kHz were used.

In a first experiment we measured the dependence of amplitude on water content for non-aged wires. As shown in Fig. 34, the amplitude starts to decrease above 0.2% of water and reaches 80% of its 'dry' value at about 1.7%. There is no rate-dependence visible.

The r.m.s. width of the ^{55}Fe main peak increases slightly however, from about 6.5% at 0 to about 7.5% at 1.7% water content, see Fig. 34. We have checked that this increase is not connected to a change of the time distribution of the photon signal which could result in a systematic effect on our pulse-height measurement. A decrease of gas gain by 20% should, on the other hand, not increase the width of the pulse-height spectrum.

It is therefore not clear whether the loss of amplitude can be attributed to a change of the Townsend coefficient or to secondary effects like electron capture at high water concentrations. This latter mechanism would explain the increase in r.m.s. fluctuation in a natural way.

In a second experiment, we have exposed aged counters to water admixtures. The two counters with different source rate mentioned above were aged to about the same amplitude suppression of 50%, resulting in the two-peak structure of pulse-height spectrum discussed in Section 3. By adding water of increasing concentration, these spectra evolved in the way shown in Fig. 35 in exact inversion of the ageing evolution shown in Fig. 4. The two-peak structure vanishes at about 1% of water content and the spectrum is very similar to the non-aged situation at about 1.5%.

We have analysed the amplitude development for the two principal peaks as a function of water concentration and corrected for the loss of amplitude shown in Fig. 34, in Fig. 36. The two peaks evolve in a strongly different fashion, until they merge again. It is amusing to note that complete restoration might happen at saturated water vapour pressure, i.e. a liquid layer on the wire surface. This restoration, however, seems not to develop the full amplitude. The small residual amplitude loss might be the only indication of a finite layer thickness on the wire surface.

It should be mentioned that, by taking out the water admixture again, the amplitude suppression and spectral shape of the preceding measurements is re-established. It is thus clear that no permanent change of the wire deposit has occurred during the experiment.

8 PREDICTION OF AGEING DEVELOPMENT WITH TIME AND EXTRACTION OF SPECIFIC AGEING PARAMETERS

The ageing behaviour of a given counter is usually specified by measuring the slope of the relative amplitude dependence on time,

$$-(dA/A)/dt.$$

If gas multiplication, irradiation rate and collimation geometry are known, one can determine the total charge accumulated per unit time and wire length,

$$dQ/(dl dt).$$

This allows us to introduce the specific ageing rate [2],

$$S = -(dA/A)/(dQ/dl)$$

usually expressed in $\%/(C/cm)$.

Two problems present themselves with this approach:

- (i) As we have seen above, the measured amplitude in an aged counter is rate-dependent. Therefore, the amplitude loss with time, $-dA/dt$, will also be rate dependent for the same deposition process.
- (ii) The charge normalization in C/cm used above, implicitly assumes that the ageing rate is given by the number of electrons arriving per unit wire length, independent of gas multiplication and rate. In reality, this assumption is not fulfilled. We have shown in a preceding paper [18] dealing with a Si contamination of Ar/CH_4 counter gas, that the specific ageing rate S depends on the wire current I , i.e. the product of amplitude and irradiation rate. In this case, S behaves as $1/\sqrt{I}$. We will see below

that this dependence can be even stronger, like $1/I$ for gases producing carbonic deposits. In general, the dependence of S on I can be rather complicated such that the simple parametrizations mentioned above are only valid over restricted ranges in current.

With the experimental study of the specific ageing rate we are approaching the physico-chemical processes of layer deposition and ablation well-known in plasma chemistry [1]. We will come back to this in a subsequent paper on gain and rate dependence [14]. In the context of analog signal formation discussed here, we will point out some effects influencing the extraction of quantitative ageing variables.

8.1 Time Dependence of Amplitude

Our model contains an explicit thickness dependence in the slope parameter

$$B = B_0/d^{1.3}.$$

Once we determine B_0 and make an assumption about the layer formation as a function of time and wire current, we can predict the time evolution of the amplitude.

It seems natural to assume that the layer thickness depends in a linear way on the number of electrons arriving per unit wire length. Following the discussion on specific ageing variables in the preceding paragraph, we have however to allow for an additional, nonlinear term in wire current, $g(I)$, such that we can write

$$d(I, t) = \text{const} \cdot I \cdot t \cdot g(I)$$

where t is the irradiation time and I can be expressed by the product of amplitude A and irradiation rate R .

We have calculated the amplitude suppression A/A_0 as function of slope parameter B and rate R in Section 5.4 above. The dependence is replotted in Fig. 37.

Once we know, for a given counter and a given rate, the initial amplitude loss per unit time,

$$-(dA/A)/dt, \quad dt = 1,$$

expressed e.g. in % per day, we can fix the constant B_0 from

$$B_0 = B(A/A_0) \cdot (d(A/A_0, t = 1))^{1.3}$$

and predict the complete time dependence of amplitude.

This has been done for the initial slope of the measured ageing curve of Fig. 6, $(dA/A)/dt = 6.8\%$ per day. We have used three different assumptions for the deposition nonlinearity term $g(I)$,

- (a) $g(I) = \text{const}$
- (b) $g(I) = \text{const}/\sqrt{I}$
- (c) $g(I) = \text{const}/I$.

The result of our calculations is shown in Fig. 38. A strong dependence on the behaviour of $g(I)$ is visible, and the experimental data favour assumption (c) above. The shape of the time-dependences in Fig. 37 is rather complicated, as the rate dependence of amplitude is fully contained in the model. None of the curves is of exponential shape as one could naively expect at least for assumption (c). We also understand now quantitatively

the remark of Section 3.1 on the linear behaviour of amplitude down to almost 30% amplitude loss.

Some information on the mechanism of insulator deposition can thus already be obtained from a single measurement of amplitude against time, if counter geometry and source collimation allow the quantitative measurement of pulse height down to small amplitudes.

8.2 Rate Dependence of Slope and Specific Ageing

Once the time dependence of amplitude has been calculated at fixed rate, we can also predict the ageing speed for different rates. If we do this e.g. for the nonlinearity function $g(I) = \text{const}/I$, assumption (c) above, we get

$$d = \text{const} \cdot t,$$

i.e. the thickness development does not depend on amplitude or rate. One might therefore expect the slope of the amplitude loss function to be independent of rate. The calculation, Fig. 39, shows that this is not the case. The sizeable rate dependence seen in Fig. 39 is a direct consequence of the charge equilibrium on the wire surface as discussed in Section 5. If we would extract the specific ageing S (%/(C/cm)) from data like Fig. 6 for different rates, we would not obtain the underlying nonlinearity function $g(I)$ but a steeper dependence. The deviation is given by the dependence of initial slope on rate in Fig. 39, plotted in Fig. 40. Practically the same result is obtained for other choices of the nonlinearity function $g(I)$. For the extreme case $g(I) = \text{const}$, the thickness d increases linearly with rate which yields, to first order, a linear increase of ageing speed with rate. If extracting the specific ageing S from this case, however, one will not get a constant but an increase with rate of the relative size shown in Fig. 40.

To add to the difficulty of extracting specific ageing parameters from experimental time dependences of amplitude, we should mention that a similar correction is not expected to hold for changes in amplitude (or gas gain). As we have shown in Section 5.6, the relative amplitude suppression changes very little with variations in gain. Therefore, in measurements at constant rate and variable gain, the specific ageing behaviour can be obtained without additional manipulations.

8.3 Some Remarks on Physical Layer Thickness

It should be clear from the preceding arguments that the 'thickness' used in our calculations has little to do with the real layer thickness on the surface of our aged sense wire, with the exception of the fact that it must grow in some relative function of time and current. A lot of unknown parameters like surface and bulk conductivity or dielectric constants have been contracted into the quantity B_0 used in the preceding section. The same physical layer thickness can have completely different influences on amplitude, depending on these parameters, and, of course, irradiation rate.

This might explain some of the discrepancies observed in the literature when one tries to deduce deposition efficiency from amplitude reduction. In particular in the presence of Si compounds in the counter gas in extremely small concentrations (on the ppb level), such calculations seem to request practically 100% deposition yield. In the absence of a complete understanding of the influence of dielectric quantities on amplitude, independent measurements of the bulk insulator thickness have to be used.

9 CONCLUSIONS

The mechanism of analog signal formation in aged proportional counters has been studied. It has been shown that the ageing-related loss of amplitude is generated by the formation of surface charges which reduce the effective electric field on the sense wire surface. A dynamical model describing the build-up and fluctuation of wire charge density has been developed. Comparison with experimental data allows the determination of discharge time constants and their dependence on charge density and layer thickness. The model offers a quantitative description of a number of experimental phenomena like rate dependence of amplitude, shape of pulse-height distributions and amplitude loss as a function of time. The problem of extracting specific ageing variables is discussed, especially with respect to rate dependence.

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FIGURE CAPTIONS

Fig. 1: Geometrical cross-section and charge collection geometry of proportional test tubes types I and II.

Fig. 2: Proportional counter type I: complete assembly showing outer gas envelope and electronics housing, tube support and cathode structure.

Fig. 3: Amplitude distributions from ^{55}Fe source for counter types I and II as well as Monte Carlo simulation.

Fig. 4: Experimental pulse-height distributions from counter type I (a) and type II (b) for different states of wire ageing.

Fig. 5: Dependence of relative pulse height on time, for the two principal peaks of counter type I (cf. Fig. 4). Up to about 15% amplitude loss, the two peaks are not separated ('single peak').

Fig. 6: Dependence of relative pulse height on time for counter type II.

Fig. 7: Two-dimensional charge density distribution over the wire surface of counters I and II, shown in azimuth (Φ) and along wire (x).

Fig. 8: Projected charge density distributions for counter types I and II.

Fig. 9: Layer thickness distribution in wire direction, for two values of azimuthal angle (towards and away from the irradiation source), calculations with linear deposition model, measurements from Roentgen backscattering intensity via electron microscopy.

Fig. 10: Calculated pulse-height distributions from static model for different amplitude suppression factors (corresponding to different ageing states), (a) counter type I, (b) counter type II.

Fig. 11: Rate dependence of ^{55}Fe pulse-height distributions obtained on aged wire, counter type I.

Fig. 12: Rate dependence of amplitude (a) for the two principal peaks from counter type I, (b) for the single peak of counter type II.

Fig. 13: Calculated charge density, expressed as a ratio to the density on the non-aged wire surface, as a function of rate for the model with fixed discharge time constants. Measurements indicated are for the lower peak of counter type I. Line drawn through data points to guide the eye.

Fig. 14: Calculated amplitude suppression as a function of rate, for fixed discharge time constants. Measurements indicated are for the lower peak of counter type I. Line drawn through data points to guide the eye.

Fig. 15: Discharge time constant as a function of surface charge density, as extracted from Fig. 13.

Fig. 16: Amplitude dependence on rate, predicted from dynamic model calculations for counter types I and II.

Fig. 17: Measured amplitude dependence on rate (counter type II) for different ageing values. Superimposed are corresponding calculations from dynamic model for values of slope parameter indicated.

Fig. 18: Predicted pulse-height distributions from ^{55}Fe source for different ageing states defined by slope parameter B , (a) counter type I, (b) counter type II

Fig. 19: Calculated and measured r.m.s. width of pulse-height spectrum (counter type II) as a function of ageing.

Fig. 20: Measured dependence of amplitude on tube high voltage (counter II) for different values of ageing.

Fig. 21: Slope of amplitude against tube high voltage (counter II) as a function of ageing.

Fig. 22: Calculated dependence of local surface charge density on time, for different initial values of charge density.

Fig. 23: Calculated dependence of amplitude on tube high voltage for different states of ageing (characterized by slope parameter B) (a) for dynamic simulation model, (b) for discharge with fixed time constant.

Fig. 24: Slope of amplitude against tube high voltage, calculated as a function of ageing.

Fig. 25: Calculated switch-on behaviour of pulse height of an aged counter, for different irradiation rates.

Fig. 26: Calculated charge-up time for different ageing states, as a function of irradiation rate.

Fig. 27: Measured dependence of detector current on time after switch-on, for counters with about 50% amplitude reduction from ageing. Current source natural alpha-radioactivity with about 0.1 Hz/mm. Lines drawn through data points to guide the eye.

Fig. 28: Calculated variation of amplitude variation of an aged detector in the presence of periodic spills of irradiation.

Fig. 29: Measured decrease of amplitude as a function of time during spill for shower detector with 50% amplitude loss from ageing. Beam rate 100–2000 Hz, 50-GeV electrons. Lines drawn through data points to guide the eye.

Fig. 30: Calculated amplitude fluctuation with time for detectors with similar amplitude loss from ageing, but different irradiation rates.

Fig. 31: Calculated and measured r.m.s fluctuation of amplitude on aged wires, as function of ageing and irradiation rate.

Fig. 32: Measured and calculated pulse-height distributions from ^{83}Kr decays in time-projection calorimeter.

Fig. 33: Observed widening of pulse-height spectrum from ^{83}Kr decays, for different ageing states, compared with calculations of the corresponding additional amplitude fluctuations.

Fig. 34: Measured amplitude decrease as a function of water admixture to Ar/20% CH_4 counter gas in non-aged counter. Lines drawn to guide the eye.

Fig. 35: Change of pulse-height distributions measured in aged counters of type I, for different water admixtures.

Fig. 36: Pulse-height dependence on water content, for the two principal peaks of counter type I. Above 1% water admixture, the two-peak structure contracts into a single peak. (a) Rate 5 kHz, (b) rate 10 Hz. Lines drawn to guide the eye.

Fig. 37: Predicted amplitude reduction against slope parameter B , counter type II, for different irradiation rates.

Fig. 38: Predicted amplitude reduction as a function of time, for different assumptions on the deposition efficiency as a function of tube current. Measurements from Fig. 6 superimposed.

Fig. 39: Predicted amplitude reduction as a function of time, for different irradiation rates.

Fig. 40: Predicted correction to measured amplitude loss rate per day due to rate dependence of amplitude.

8 mm

type I

type II

Fig. 1

Fig. 2

A

A

A

Fig. 3

Fig. 4a

Fig. 4b

Fig. 6

Fig. 5

Fig. 7

Fig. 8

$\phi = 270^\circ$

$\phi = 90^\circ$

Fig. 9

Fig. 10a

Fig. 10b

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18a

A

A

A

A

Fig. 18b

Fig. 19

Fig. 20

$$\frac{\Delta A}{\Delta V} (\Delta V = 50V)$$

Fig. 21

Q ($10^8 e^-/\text{mm}^2$)

Fig. 22

Fig. 23a

Fig. 23b

$$\frac{\Delta A}{\Delta V} (\Delta V = 50V)$$

Fig. 24

Fig. 25

Fig. 26

Fig. 27

A

time (sec)

Fig. 28

Fig. 29

Fig. 30

Fig. 31

Fig. 32

Fig. 33

Fig. 34

Fig. 35

Fig. 36 a

Fig. 36 b

Fig. 37

Fig. 38

Fig. 39

Fig. 40