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HIGH RESOLUTION LIQUID ARGON TOTAL-ABSORPTION DETECTORS:
ELECTRONIC NOISE AND ELECTRODE CONFIGURATION*

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Abstract

Ionization chambers in which almost all of the energy released in electromagnetic showers is absorbed in liquid argon are considered. Electronic noise is determined as a function of the electrode configuration. It is shown that in a multiple-plate ionization chamber the optimum interelectrode gap is determined as one third of the product of the electron drift velocity and the event resolving time. The lower limit for electronic noise is determined only by the chamber volume, electron drift velocity, event resolving time and the unity-gain frequency of the field-effect transistor. This limit is approximately the same for ionization chambers with one or more large gaps where the electron drift time is much longer than the event resolving time.

Introduction

Liquid argon ionization chambers as total-absorption detectors have been introduced previously.¹ These detectors have been used so far in the sampling mode. The detector is made as a multiple-plate ionization chamber, where the electromagnetic shower develops mostly in the electrodes made of a high density material (lead, for example), and the energy loss is "sampled" in the sensitive medium - liquid argon, by measuring the charge produced by ionization. The energy resolution of such detectors is limited by the sampling fluctuations. These detectors have been used extensively at the CERN intersecting storage ring.² There is also interest in higher resolution electron and photon detectors for an energy range of 0.1 to 2 GeV. In order to increase the resolution the sampling fluctuations can be reduced by reducing the energy loss in the electrodes until essentially all of the shower development and energy loss takes place in liquid argon. Some advantages of such a detector over scintillation detectors are:

- (1) Ionization chambers can be finely subdivided providing good position resolution along the particle track and normal to it. This gives information about the particle position and about the shower development.
- (2) Large detectors of arbitrary shape can be constructed.
- (3) The sensitivity is uniform over the whole detector volume.
- (4) Simple high-accuracy charge-sensitivity calibration is possible.

One of the principal limitations in the energy resolution is the electronic noise due to the large size (capacitance) of such ionization chambers.

In this paper the relations between the detector and amplifier parameters and the electronic noise are derived. Some optimum conditions are determined.

We first consider multi-plate ionization chambers in which the electron drift time across the interelectrode gap is shorter than the event resolving time. Next, we consider chambers with one or more large gaps in which the electron drift time is larger than the event resolving time. We find in this analysis that the event resolving time, i.e., the event rate plays a critical role in the ionization chamber design. Not unexpectedly, proper signal filtering is essential to achieve the required event resolving time and the lowest noise. In all cases discussed here we assume that the ionization chamber capacitance is matched to the amplifier capacitance - regardless of the method used to achieve this - as an independent condition for minimum noise.

Multiple-Plate Ionization Chambers

The most interesting practical case is that of a chamber with many parallel planes. In such a chamber the position information can be obtained by subdividing the electrodes into strips. The chamber can also be subdivided along the axis orthogonal to the electrodes, and the amount of charge can be measured in each gap or a group of gaps. Thus the position of particle incidence and the shower development along the particle track can be determined. The minimum size of such a chamber, or a subsection of such a detector in which particle energy can be measured, is determined as the volume required to contain the electromagnetic shower. Considering the whole chamber as one unit, there is only one essential parameter that determines the energy resolution and that is the interelectrode gap. The gap determines the chamber capacitance and the electrode drift time, both of which determine the signal-to-noise ratio. In liquid argon, only electrons contribute to the signal since the mobility of positive ions is several orders of magnitude lower than the mobility of electrons. In such a "single carrier device" the charge is weighted with a ramp function across the gap. For charged particles traversing the gap, the average weighting of the charge produced by ionization is one-half.¹ However, for shower products stopping in the gap, or those parallel to the electrodes, the variable weighting may produce significant fluctuations in the total charge measured if the gaps are not sufficiently small. This important effect will not be discussed further in this paper.³

We determine here the effect of the interelectrode gap on the signal-to-noise ratio. It will become obvious that there is an important measurement parameter, which affects the choice of the interelectrode gap. This is the resolving time, defined here as the width of response of the filter-amplifier to the signal from the ionization chamber. The resolving time is determined from the expected event rates, taking into account the gross features of the energy spectrum and the pileup effects allowed in the experiment.

Referring to Fig. 1, we define various ionization chamber parameters as follows:

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d = interelectrode gap
 n = number of gaps
 $D = nd$ = total active length
 A = electrode area
 $V = DA$ = total active volume
 v_e = electron drift velocity
 $t_d = d/v_e = D/nv_e$ = electron drift time across the gap
 Q = total charge produced by ionization
 $N = Q/e$ = number of electrons produced by ionization

The ionization chamber capacitance (with all gaps connected in parallel) can be expressed in the following convenient forms in terms of the parameters defined above:

$$C_d = \epsilon \frac{A}{D} n^2 = \epsilon \frac{V}{t_d^2 v_e^2} \quad (1)$$

We consider the signal next. We assume uniform charge distribution along the track of each particle in the shower. For a large number of gaps the effect of non-uniform charge distribution at the end of the tracks on the signal waveform will be small. If N_1 is the number of electrons in a track segment in one gap, it will induce a current of the form,¹

$$i_1 = N_1 e \frac{v_e}{d} \left(1 - \frac{t}{t_d}\right) \quad \text{for } 0 \leq t \leq t_d \quad (2)$$

Adding up the contributions due to all tracks, which produce a total number of electrons N , one obtains for the total current

$$i = N e n \frac{v_e}{D} \left(1 - \frac{nv_e}{D} t\right), \text{ or}$$

$$i = \frac{Ne}{t_d} \left(1 - \frac{t}{t_d}\right) \quad \text{for } 0 \leq t \leq t_d \quad (3)$$

This "sawtooth" waveform is shown in Fig. 2. It acts upon the whole preamplifier-filter-amplifier system whose overall impulse response is represented by $h(t)$. A bipolar function with triangular lobes which is optimal for impulse signals is used in the analysis presented here. The convolution of these two functions results in the output waveform. Two effects are apparent. One is that the width of the output, i.e., the resolving time λ_m , is the sum of the electron drift time across the gap and the width λ of the system impulse response, $\lambda_m = t_d + \lambda$. The other is that the amplitude of the output is reduced compared to that of $h(t)$ for impulse excitation. If we set a constraint on the resolving time λ_m , and vary the ratio of t_d to λ_m , from zero to unity, while maintaining the total charge constant, then the amplitude of the output decreases from unity to zero as shown in Fig. 3.

We now determine the equivalent noise charge for this case. The following assumptions are made:

- (a) The noise is generated by the field-effect transistor, and the noise due

to all other sources not related to the amplification mechanism is negligible.

- (b) The ionization chamber and the pre-amplifier are matched, i.e., $C_d = n_t^2 C_A$, where n_t is the transformation ratio, and C_A is preamplifier input capacitance.
- (c) Bipolar shaping is used in order to avoid centroid shift in the energy spectrum lines due to pileup,¹ under a variety of spectra encountered with total absorption detectors.

As shown in Ref. 1, the equivalent noise charge for an impulse (delta function) signal is given by

$$ENC_s = 4\sqrt{2} e_n C_A^{1/2} C_d^{1/2} \frac{1}{\lambda^{1/2}} \quad (4)$$

where:

e_n = rms equivalent series noise voltage density of the field-effect transistor [$V/Hz^{1/2}$].

λ is the width of the impulse response (i.e., the weighting function*), and it is a measure of the "integration time" and of the inverse of the system bandwidth.

The equivalent noise charge for the case of the "sawtooth" signal, Eq. (3) is obtained by multiplying Eq. (4) by $1/a(t_d/\lambda_m)$, where $a(t_d/\lambda_m)$ is the filter attenuation coefficient given in Fig. 3. By substituting Eq. (1) for the detector capacitance, one obtains

$$ENC_s = 4\sqrt{2} e_n \epsilon^{1/2} C_A^{1/2} v_e^{1/2} \frac{1}{v_e \lambda_m^{3/2}} \left[\frac{t_d}{\lambda_m} \left(\frac{\lambda}{\lambda_m} \right)^{1/2} a \left(\frac{t_d}{\lambda_m} \right) \right]^{-1} \quad (5)$$

The dimensionless term in square brackets is plotted in Fig. 4. It has a minimum value of 6.0 at

$$\frac{t_d}{\lambda_m} \approx \frac{1}{3} \quad (6)$$

With this value the minimum equivalent noise charge is

$$ENC_{s \text{ opt}} \approx 34 e_n \epsilon^{1/2} C_A^{1/2} v_e^{1/2} \frac{1}{v_e \lambda_m^{3/2}} \quad (7)$$

Thus, there is an optimum value of the interelectrode gap determined by the required resolving time and by the electron drift velocity,

$$d \approx \frac{1}{3} v_e \lambda_m \quad (8)$$

The equivalent noise charge is determined by the following parameters:

* The weighting function is a mirror image in time of the impulse response. The impulse response is used to determine the output response to an input signal. The term weighting function is used in the analysis of the effect of filters on noise.

- (1) Field-effect transistor noise parameters $e_n C_A^{-1/2}$. For a device with no excess noise sources, $e_n = 4kTR_s$, where R_s is the equivalent series noise resistance, and $(R_s C_A)^{-1}$ is proportional to the unity gain frequency.⁴
- (2) Ionization chamber volume V ;
- (3) Electron drift velocity v_e ;
- (4) Resolving time λ_m .

Equation (5) with Fig. 4 can be interpreted as follows. If t_d/λ_m is decreased (smaller gap) the chamber capacitance increases causing the noise to increase. If t_d/λ_m is increased above the optimum value (larger gap and longer drift time), the amplitude at the output of the filter decreases as the weighting function width λ decreases. Both result in an increase in the equivalent noise charge. The noise, however, is not a rapid function of t_d/λ_m in the vicinity of the minimum. In the region $0.2 < t_d/\lambda_m < 0.5$ the noise is less than 25% above the minimum value. For a given interelectrode gap ($t_d = \text{const.}$) the noise as a function of the resolving time is plotted in Fig. 5. This corresponds to the situation where an ionization chamber exists and the resolving time is varied. Except at the optimum value $\lambda_m/t_d \approx 3$, the noise would be lower at all other values of λ_m/t_d if the gap had an optimum value, according to Eq. (7).

Thus the resolving time λ_m is an important parameter in the design of this type of ionization chamber.

The analysis presented here is only an approximate one, since the filter weighting function assumed is an optimum one for the impulse signal only (small values of t_d/λ_m). The error in the calculated noise remains sufficiently small compared to the case of different optimum weighting functions for each value of t_d/λ_m , for the range of values shown in Fig. 4. One of the weighting functions used in practice, e.g., bipolar semigaussian function, is closer to an optimum function in the range $t_d/\lambda_m > \approx 0.1$ than the triangular function.

Ionization Chambers With One Large Gap

We consider here ionization chambers with several large interelectrode gaps or, in the limit, one gap containing the whole active volume. In such ionization chambers the electron drift time is much larger than the event resolving time. This means that the motion of charge over only a short distance results in a signal, which is a measure of the total charge produced by ionization. This case is illustrated in Fig. 6. An amount of charge Ne is produced by an ionizing particle or by an electromagnetic shower. For parallel plate geometry the initial value of the induced current is independent of the spatial distribution of charge. We consider the electron component only for which the current is given by

$$i_o = Ne \frac{v_e}{D} \quad (9)$$

This current remains constant, (provided there is no electron attachment to impurities in the liquid) until some of the electrons reach the electrode. As the electrons are collected, the current decreases to zero as shown in Fig. 6(b).

The induced current in the form of a step function acting upon the amplifier-filter with an overall

weighting function $w(t)$ produces an output amplitude corresponding to the charge,

$$Q_s = i_o \left[\int_0^t w(t) dt \right]_{\text{max}} \quad (10)$$

We call Q_s an "equivalent charge signal", since an equal output amplitude would be produced by a current impulse $Q_s \delta(t)$ applied to the system characterized by $w(t)$. (Note that the weighting function has unity amplitude by definition.) For a bipolar weighting function shown in Fig. 6(b),

$$Q_s = i_o \frac{\lambda}{4} = Ne \frac{v_e}{D} \cdot \frac{\lambda}{4} \quad (11)$$

The resulting filter output is unipolar (because the signal current is a step function). To obtain a bipolar output, a three-lobe weighting function of the type shown in Fig. 6(c) is required. The equivalent charge signal is then

$$Q_s = Ne \frac{v_e}{D} \cdot \frac{\lambda}{12} \quad (12)$$

The available charge induced by carriers of one polarity is $Ne/2$ (if we imagine a single particle track across the entire gap). This would be the output of the filter if the electron drift time were zero (i.e., much smaller than λ). It is with respect to this amount that the equivalent noise charge ("the signal that produces the same output as the noise") should be defined. The filter attenuation is then, for the two-lobe $w(t)$ in Fig. 6(b),

$$a(\lambda/t_D) = \frac{Q_s}{Ne/2} = \frac{1}{2} \frac{\lambda}{D/v_e} = \frac{1}{2} \frac{\lambda}{t_D} \quad (13a)$$

and for the three-lobe $w(t)$ in Fig. 6(c),

$$a(\lambda/t_D) = \frac{1}{6} \frac{\lambda}{D/v_e} = \frac{1}{6} \frac{\lambda}{t_D} \quad (13b)$$

The equivalent noise charge for the capacitive source matched to a charge amplifier is determined as described in Refs. 1 and 5. Including the filter attenuation, one obtains,

$$ENC_s^2 = \frac{1}{2} e_n^2 (4C_A C_d) \frac{1}{a^2(\lambda/t_D)} \cdot J_1 \quad (14)$$

where

$$J_1 = \int_0^\infty [w'(t)]^2 dt \quad (15)$$

This integral characterizes the weighting function completely as far as the field-effect transistor (series) noise is concerned.⁵ It can be evaluated easily for the weighting functions in Figs. 6(b) and (c),

$$J_1 = \frac{16}{\lambda} \quad \text{for the two-lobe } w(t) \quad (16a)$$

$$J_1 = \frac{18}{\lambda} \quad \text{for the three-lobe } w(t) \quad (16b)$$

Using Eqs. (13), (14), (16), $C_d = \frac{A}{\epsilon_D}$ and $AD = V$, the rms equivalent noise charge for the two-lobe weighting function in Fig. 6(b) can be expressed in the form

$$ENC_s = 8/2 \frac{e_n C_A^{\frac{1}{2}} \epsilon^{\frac{1}{2}} V^{\frac{1}{2}}}{v_e \lambda^{\frac{3}{2}}} \quad (17a)$$

The equivalent noise charge for the three-lobe weighting function in Fig. 6(c) is given by,

$$ENC_s = 36 \frac{e_n C_A^{\frac{1}{2}} \epsilon^{\frac{1}{2}} V^{\frac{1}{2}}}{v_e \lambda^{\frac{3}{2}}} \quad (17b)$$

The two-lobe weighting function gives lower noise but it produces a unipolar output. A bipolar output is preferable for total absorption detectors as discussed in the preceding section. The three-lobe function results in approximately the same amount of noise as for the multi-plate ionization chamber with optimized small gaps, Eq. (7). The functional dependence of noise on the chamber and amplifier parameters is the same for both types of chambers. Thus in both cases the noise is determined by the active volume of the ionization chamber. In the case of chambers with large gaps, the noise is independent of the gap provided that the resolving time is much shorter than the electron drift time across the gap. This is because, as the gap is increased, the decrease in the chamber capacitance and in the resulting equivalent noise charge is offset by an equal decrease in the signal charge, Eqs. (11) and (12).

The weighting functions used here for simplicity of calculation are based on optimum functions for an impulse signal. It can be shown that the optimum weighting functions for the step function signal, as is the case here, have parabolic instead of triangular lobes. The noise with these functions is, however, only about 15 per cent lower. Semigaussian filters, usually used in practice, approximate these optimum functions quite well.

It is important to note that functions with steep edges result in a higher noise, according to Eqs. (14) and (15). For example, this would be the case of delay line clipping without sufficient integration.

In ionization chambers with a long drift time (and short resolving time) the signal is associated with the beginning of the motion of the charge. Thus there is also an output at the end of the motion (where the electrons reach the electrode). The shape and amplitude of this "afterpulse" depends on the spatial distribution of charge. Such an output is indicated in Fig. 6(b). The afterpulse is smaller with a three-lobe weighting function than with the two-lobe function.

A note should be made about the use of a grid in ionization chambers with large gaps. If $\lambda/t_D \ll 1$, the grid would increase the capacitance of the readout electrode and the noise would be higher. But if $\lambda/t_D > 1$, a grid becomes essential to avoid the dependence of the signal on the initial position of the charge.

Discussion

For both types of ionization chambers considered, the electronic noise is determined by the active volume of the chamber. We now calculate the noise for an example of a total absorption (non-sampling) detector.

We determine the minimum volume of the detector (or of a section of a detector) by the requirement that it should contain an electromagnetic shower. We assume in this example a cylinder with a radius of 1 radiation length and a length of 15 radiation lengths (these requirements depend on the particle energy range and on the leakage of the shower energy allowed out of the detector). One radiation length in liquid argon is 13.5 cm, and the dimensions of the active volume are:

$$\text{Radius } r = 13.5 \text{ cm}$$

$$\text{Length } D = 200 \text{ cm}$$

$$\text{Volume } V = 0.115 \text{ m}^3$$

The saturated electron drift velocity in pure liquid argon is $v_e \approx 0.5 \text{ cm}/\mu\text{sec}$. The resolving time has to be determined carefully from the event rates and pileup effects for the particular application of the detector. We assume here (arbitrarily for this example) a resolving time $\lambda_m = 3 \mu\text{sec}$. From v_e and λ_m the optimum gap for the multi-plate ionization chamber is determined,

$$d = \frac{1}{3} v_e \lambda_m = 0.5 \text{ cm}$$

The parameters of state-of-the-art field-effect transistors for this purpose are, $e_n = 10^{-9} \text{ V/Hz}^{\frac{1}{2}}$ and $C_A = 35 \text{ pF}$ (including stray capacitances of the amplifier and matching components). The dielectric constant of liquid argon is $\epsilon' \approx 1.6$. With these values, Eq. (7) gives an equivalent noise charge

$$ENC_s \text{ opt} \approx 6 \times 10^4 \text{ rms electrons}$$

The energy loss per ion pair in pure argon is about 26 eV. Since only electrons contribute to the signal the energy loss per observed electron charge is 52 eV. Thus, the electronic noise represents a contribution to the line width in energy measurements corresponding to a

$$\text{FWHM} \approx 7.3 \text{ MeV}$$

For equal resolving time, the noise is about the same for multi-plate ionization chambers (where $t_d < \lambda_m$) and for chambers with large gap (where $t_D \gg \lambda$). In either case, the noise increases as $\lambda_m^{-3/2}$ as the resolving time is decreased. A reduction in the resolving time and/or noise can be achieved if the electron drift velocity v_e is increased according to Eqs. (7) and (17). An increase in electron drift velocity has been realized by the addition of methane to liquid argon.⁶

Multiplate ionization chambers can be realized with electrodes made of printed circuit boards, in which the energy loss is a small fraction of the energy loss in argon. Position information can be obtained easily by subdividing the conductive surface into strips. Chambers with large gaps might seem easier to construct. However, there is a problem of high voltages required over large gaps. While the insulation may not present a problem as far as major breakdown is concerned, minute discharges and various polarization effects in dielectrics may generate excessive impulse noise. The weighting of charge is uniform in chambers with large gaps, provided that there is no electron attachment over long drift distances. Position readout may require grids and/or drift time information depending on the coordinates required and accuracy. With such a readout, event rates will have to be much lower than with multi-plate ionization chambers. The above discussion is just to indicate some of the questions that have to be

considered in selecting the most appropriate electrode configuration.

In this paper we have considered ionization chambers with uniform electric field (planar electrode geometry). The electrodes can be realized, of course, as plates or as planes of wires. If the wires are closely spaced, the two are equivalent and the choice is a question of simpler construction. If the wire spacing is increased (with intent to reduce the capacitance) regions of nonuniform field will be created. This may result in incomplete charge collection, since it will be difficult to achieve high enough electric field in the low field regions to reach the plateau in charge collection.

Questions have been raised about the best electrode connections (parallel or series) for multi-plate ionization chambers with regard to detector-amplifier capacitance matching. There are three basic methods for detector-amplifier capacitance matching: series-parallel combinations of electrodes, transformer matching, and connection of a number of FET's in parallel. It can be shown that any one of these methods, or any combination of any two or of all three gives the same electronic noise if the capacitance of the detector is matched to that of the amplifier.

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Figure Captions

1. Multi-plate ionization chamber.
2. Current waveform for uniform ionization across the gap and single carrier collection; filter bipolar impulse response and filter output. The optimum case $t_d/\lambda_m = 1/3$ is shown.
3. Attenuation of the filter output peak response ("ballistic deficit") vs. the ratio of electron drift time and the event resolving time.
4. Equivalent noise charge as a function of the ratio of electron drift time and the event resolving time for multi-plate ionization chamber.
5. Noise vs. resolving time for a given interelectrode gap, i.e., $t_d = \text{const}$, for multi-plate ionization chamber. Note that for optimized gap $\text{ENC} \propto \lambda_m^{-3/2}$.
6. Single-gap ionization chamber
 - (a) Initial position of electrons due to a single ionizing particle and their motion in the electric field. Positive ions whose drift velocity is much lower are not shown.
 - (b) Induced current, bipolar filter weighting function and the resulting unipolar output. Example of an afterpulse when electrons stop moving is shown on reduced time scale.
 - (c) A three-lobe weighting function required to produce a bipolar output is shown.

Fig. 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

Fig. 6