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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Count-loss mechanism of self-quenching streamer (SQS) tubes

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The counting response of SQS tubes is superior to that of conventional GM tubes. The count-loss mechanism of SQS tubes is governed by two different sorts of the space-charge effect, namely a local space-charge effect and a global space-charge effect. The existence of a dead zone leads to the local space-charge effect around each streamer; this effect is dominant at lower exposure rate conditions than 20 mR/h. On the other hand, the global space-charge effect comes from accumulation of slowly-drifting positive ions inside the whole tube, and is dominant at higher exposure-rate conditions than 500 mR/h.

1. Introduction

Self-quenching streamer (SQS) tubes are attractive devices for radiation monitoring in high exposure-rate conditions because the counting response of SQS tubes is much superior to that of conventional GM tubes [1,2].

The counting response of GM tubes is usually described by using the term "dead time"; GM tubes almost completely lose their sensitivity during a certain period (i.e. the dead time) after a Geiger discharge. On the other hand, as far as SQS tubes concerned, the details of count-loss behaviour have not yet been well understood. SQS tubes operate without severe count losses under high exposure-rate conditions where GM tubes are completely paralyzed. In such conditions, the count-loss mechanism of SQS tubes must be different from that of GM tubes. The most dominant factor for count losses of SQS tubes may be the continuous electric-field distortion caused by accumulation of slowly-drifting positive ions accumulated inside the whole tube.

So far, the counting response of SQS tubes has not been quantitatively studied yet. In this article we discuss the count-loss mechanism of SQS tubes comparing it with that of GM tubes. Some calculations are performed to explain the measured counting response of an SQS tube on the basis of two count-loss mechanisms.

2. Measurement of counting response

The counting response of the SQS mode was measured as the way described in our previous papers [1,2] and compared with that of the GM mode. The cylindrical gas counter used was made of a stainless steel pipe whose inner diameter was 14 mm; a gold-plated tungsten anode wire of 50 μm in diameter was stretched along the axis to have an effective counter length of 105 mm. The counter was filled with Ar(75) + $isoC_4H_{10}$(25). For selecting the counter-operation mode, the gas pressure was chosen to be 760 Torr for the SQS mode and 150 Torr for the GM mode.

The counter was irradiated by ^{60}Co γ-rays from the outside of the counter. Exposure rate of γ-rays at the counter position was changed by adjusting the distance between the source and the counter. The counting efficiency of this counter is 0.01 for ^{60}Co γ-rays in both the SQS and GM modes. The discrimination level of a scaler was set to be 1/10 of SQS- or GM-signal amplitude obtained at a low exposure rate of less than 5 mR/h. As shown in Fig. 1, the count rate is proportional to the exposure rate up to about 100 mR/h. Above this exposure rate, the count rate shows a drastic difference from the expected rate for the GM mode (HV = 1.5 kV). For the SQS mode (HV = 2.5 kV), the measured count rate follows exposure rate with some count losses and indicates saturation above 700 mR/h.

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3. Count-loss mechanisms

3.1. Count losses due to the dead zone (local space-charge effect)

The count rate of the GM tube in Fig. 1 shows a paralysable response. The paralysable model of dead-time behaviour for random events occurring at an average rate n (Eq. 4-27 of ref. [3]) explains the measured result well as indicated in Fig. 1, that is

$$m = n\,\mathrm{e}^{-n\tau}, \tag{1}$$

where m is the recorded count rate, and τ the dead time of the GM tube. In this estimation we assumed $\tau = 200$ μs.

In the paralysable model, the events that occur during a dead time are considered to be lost completely. This assumption is not adequate for SQS tubes because streamer-like discharges are limited along the anode wire and more than two streamers can grow simultaneously at different positions inside the tube. Hence the model is extended in order to evaluate the counting response of SQS tubes. A function $w(t)$ is newly introduced to express the sensitivity of tubes as a function of time as

$$w(t) = 1 - \frac{\delta(t)}{L}, \tag{2}$$

where t is the time after a pulse generation, $\delta(t)$ the dead length on the anode wire, L the whole anode wire length. The value of $\delta(t)$ is obtained from the measurement of dead-zone characteristics (Fig. 2) [4,5]. Dead-zone characteristics are related not only to the dead time but also to the dead length of the tube. Thus

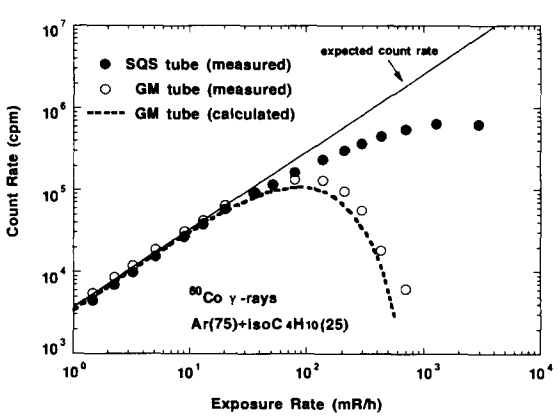

Fig. 1. Counting response of an SQS tube and a GM tube. A dot line indicates an estimated one for the GM tube according to the paralysable model, Eq. (1), with the dead time $\tau = 200$ μs.

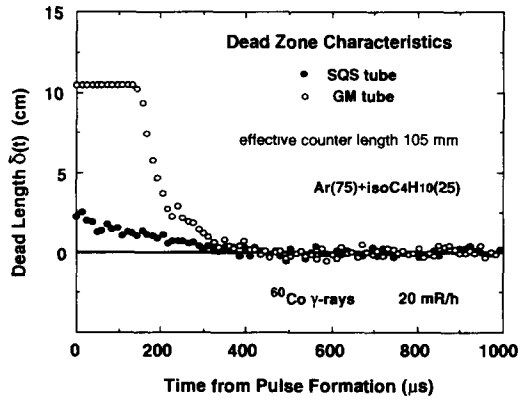

Fig. 2. Dead zone characteristics of an SQS tube and a GM tube.

the expressions of the paralysable model (Eqs. 4-25 and 4-27 of ref. [3]) become

$$P(t)\,\mathrm{d}t = n\,\mathrm{e}^{-n\tau}\,\mathrm{d}t, \tag{3}$$

$$m = n\int_0^\infty w(t)P(t)\,\mathrm{d}t, \tag{4}$$

where $P(t)\,\mathrm{d}t$ is a distribution function of time-interval between random events occurring at an average rate n.

This formulation is generally available for gas counters with various dead-zone characteristics and is also valid for GM tubes under a simple assumption such as

$$\begin{aligned}\delta(t) &= L, \quad 0 \leqslant t \leqslant \tau,\\ &= 0, \quad \tau < t.\end{aligned} \tag{5}$$

Hence $w(t)$ is expressed as

$$\begin{aligned}w(t) &= 0, \quad 0 \leqslant t \leqslant \tau,\\ &= 1, \quad \tau < t.\end{aligned} \tag{6}$$

Substituting Eqs. (3) and (6) into Eq. (4), we find that Eq. (4) agrees with Eq. (1).

The dead-zone characteristics of the SQS mode in Fig. 2 indicate that the space-charge effect due to a dead zone is valid only in the narrow part (about 2 cm just after the pulse formation) around the position where each streamer occurs (referred as "local space-charge effect"). In the present case, for simplicity of analysis, we expressed $\delta(t)$ of the SQS tube (in Fig. 2) as a triangle-shaped region;

$$\begin{aligned}\delta(t) &= -\frac{2.5}{400}t + 2.5, \quad 0 \leqslant t \leqslant 400,\\ &= 0, \quad 400 < t,\\ &[\delta(t) \text{ in cm}, t \text{ in } \mu\text{s}].\end{aligned} \tag{7}$$

Substituting these equations into Eq. (2) we get

$$\begin{aligned}w(t) &= 0.0006t + 0.76, \quad 0 \leqslant t \leqslant 400,\\ &= 1, \quad 400 < t, \quad [t \text{ in } \mu\text{s}].\end{aligned} \tag{8}$$

Consequently the count loss of the SQS tube due to the dead zone is described by Eq. (4) with Eqs. (3) and (8) at low exposure rates.

3.2. Count losses due to the accumulation of slowly-drifting positive ions (global space-charge effect)

Under higher exposure-rate conditions, more positive ions are generated by incident radiations coming into the tube with short time-intervals. They are accumulated in the whole tube volume because of their slow drift velocity. Those ions keep the electric field distorted by a space-charge effect during γ-ray irradiation (referred as "global space-charge effect"). As a result, the output pulse amplitude decreases; if the amplitude becomes smaller than the threshold of the discriminator, the event will not be detected.

Hendricks [6] presented an analytical formulation to allow the estimation of the electric-field distortion caused by the accumulation of positive ions in proportional counters, although the formulas described in the original paper contained a mistake, which has been pointed out and corrected by some authors [7,8]. According to the corrected formulation, if uniform irradiation is achieved throughout the volume of the co-axial proportional counter of a length L, the time-averaged ion density $\bar{\rho}$ in the counter is given as

$$\bar{\rho} = \frac{MPR \ln(b/a)}{2\pi L \mu V_0}, \tag{9}$$

where M is the number of ions generated from a discharge, which corresponds to avalanche size, P the pressure of the counting gas, R the mean incident rate on the tube, a the anode wire radius, b the cathode radius, μ the mobility of ions and V_0 the applied voltage to the anode. As found in Eq. (9), $\bar{\rho}$ is independent to the radial position in the tube.

By using Eq. (9), Poisson equation is solved under a proper boundary condition to obtain the electric field in the counter. Then the electric field around the anode wire is approximated as

$$E(r) \approx \frac{V_0}{r \ln(b/a)} - \frac{\bar{\rho} e b^2}{4\epsilon_0 r \ln(b/a)}, \tag{10}$$

where r is the radius of polar coordinate, e the charge of an electron, ϵ_0 the permittivity in vacuum. If now we put

$$\mathrm{d}V = \frac{\bar{\rho} e b^2}{4\epsilon_0}, \tag{11}$$

then we obtain from Eq. (10)

$$E(r) \approx \frac{V_0 - \mathrm{d}V}{r \ln(b/a)}. \tag{12}$$

Eq. (12) shows that space charges reduce the applied static electric field due to the applied potential by an amount of $\mathrm{d}V$. We refer to $V_0 - \mathrm{d}V$ as "effective applied voltage".

Here it should be noted that an actual $\bar{\rho}$ value cannot be obtained from Eq. (9) in a simple way because the calculated electric-field (Eq. (12)) again affects the value of M in Eq. (9). Repeating such a feedback process, the ion density will reach an equilibrium value. It is necessary, therefore, to evaluate the equilibrium ion density $\bar{\rho}_{\mathrm{equ}}$ for the discussion of SQS tubes, in which much more ions are generated by each discharge than those in proportional tubes. The equilibrium ion density $\bar{\rho}_{\mathrm{equ}}$ allows us to evaluate the reduction of pulse amplitude and the accompanied count losses by taking account of the avalanche-size curve and the transition-probability curve.

4. Calculated results and discussion

We calculated the count losses of the SQS tube by considering the two sorts of count-loss mechanisms mentioned above, namely the count losses due to the dead zone and those due to the accumulation of positive ions.

Firstly, we estimated the count losses due to the dead zone as the way described in section 3.1. Fig. 3 shows the normalized counting-response with calculated results. The result for the GM tube, the same one as in Fig. 1, is indicated again in a different way. As shown in the figure, the measured result is well explained by the calculation for the GM tube. On the other hand, the calculated result for the SQS tube does not agree with the measured values at high exposure rate [9]. Especially more than 200 mR/h, the count

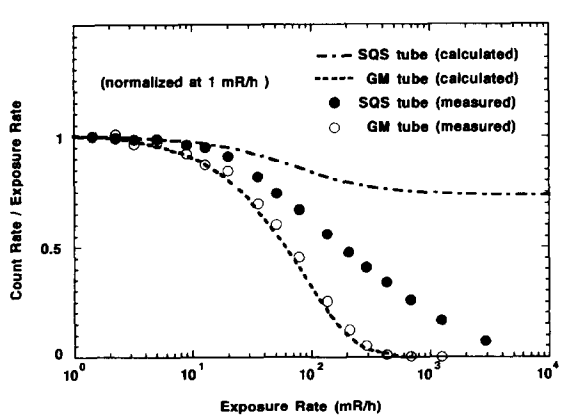

Fig. 3. Normalized counting-response of an SQS tube and a GM tube. The calculation was carried out by considering the count losses due to the dead zone only.

losses become almost constant since the interval distribution of pulses concentrates in short time intervals. It is necessary, therefore, to take another count-loss mechanism into account in such high exposure-rate conditions. Note that obvious superiority of the SQS tube over the GM tube observed around a few mR/h depends on the difference of their dead-zone characteristics.

Secondly, the count losses due to the accumulation of slowly-drifting ions were evaluated as the way described in section 3.2. The equilibrium ion density $\bar{\rho}_{\mathrm{equ}}$ was obtained by a reterative calculation using a personal computer.

In the calculation, the value of M was deduced from an approximated avalanche-size curve (solid line in Fig. 4a), which is expressed as

SQSmode:

$$N_{\mathrm{SQS}} = 9.06 \times 10^{(0.54V+7)},$$

proportional mode:

$$\begin{aligned} N_{\mathrm{pro}} &= 5.49 \times 10^{(3.9V-2)}, \quad V \leqslant 2.1, \\ &= 6.70 \times 10^{(2.43V+1)}, \quad 2.1 < V \leqslant 2.3, \\ &= 2.21 \times 10^{(0.9V+5)}, \quad 2.3 < V, \end{aligned}$$

[avalanche size in no. of electrons, V in kV]. (13)

Here the avalanche size of the SQS mode, N_{SQS}, is represented by that of double SQSs because double SQSs are dominant around the actual applied voltage of 2.5 kV. Fig. 4b shows the measured transition probability from the proportional mode to the SQS mode as a function of high voltage. This curve was simplified as follows;

$$\begin{aligned} P_{\mathrm{t}} &= 0, & 0 \leqslant V \leqslant 2.28, \\ &= 6.18V - 14.1, & 2.28 < V \leqslant 2.45, \\ &= 1, & 2.45 < V, \quad [V \text{ in kV}], \end{aligned} \tag{14}$$

where P_{t} is the transition probability. Finally, for a given high voltage, the value of M was calculated as

$$M = N_{\mathrm{SQS}} \times P_{\mathrm{t}} + N_{\mathrm{pro}} \times (1 - P_{\mathrm{t}}). \tag{15}$$

By using the obtained $\bar{\rho}_{\mathrm{equ}}$, the effective applied voltage $V_0 - \mathrm{d}V$ was determined at each exposure rate. The values of $V_0 - \mathrm{d}V$ and $\bar{\rho}_{\mathrm{equ}}$ are indicated in Fig. 5.

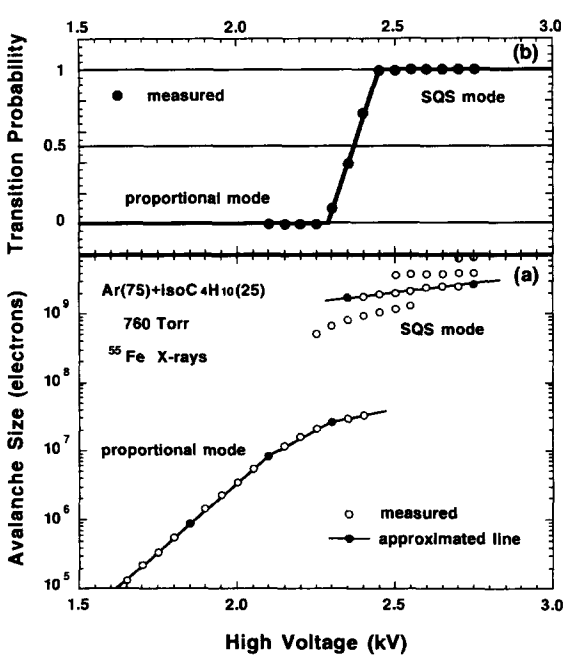

Fig. 4. Avalanche-size curve (a) and transition-probability curve from the proportional mode to the SQS mode (b). The fitting curves used for the calculation are also indicated.

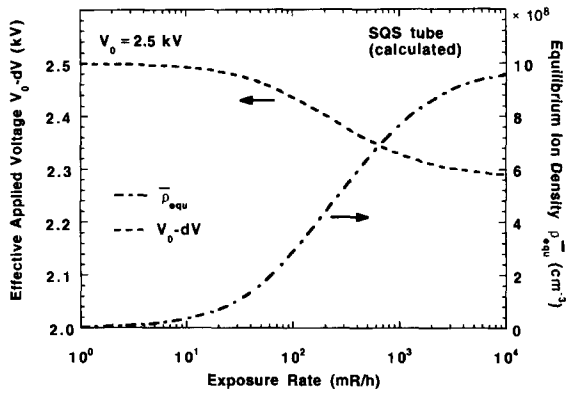

Fig. 5. Calculated effective applied voltage $V_0 - \mathrm{d}V$ and equilibrium ion density $\bar{\rho}_{\mathrm{equ}}$.

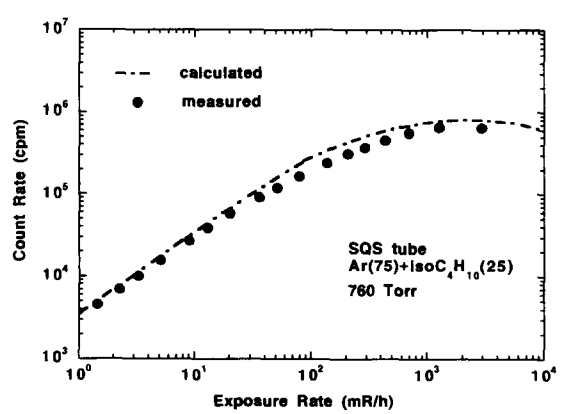

Fig. 6. Counting response of an SQS tube comparing with the calculated results. The calculation was carried out by considering the count losses due to both the dead zone and the accumulated ions.

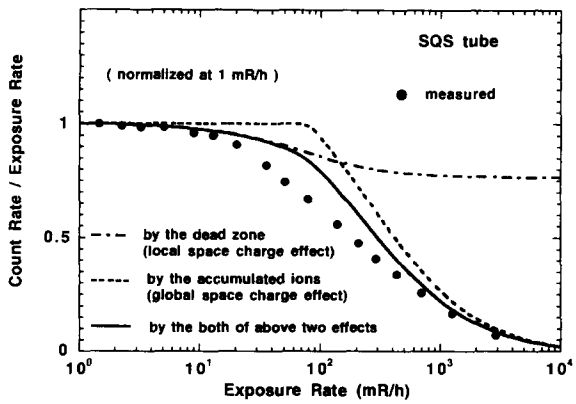

Fig. 7. Normalized counting-response of an SQS tube. The contribution of two different counting-loss factors to the estimated count losses are indicated separately.

The effective applied voltage deviates down from 2.5 kV at exposure rates more than 10 mR/h.

As shown in Fig. 4b, less than 2.45 kV, some pulses do not grow up to streamers and result in proportional mode pulses. Those pulses in the proportional mode are not detected because of their small pulse amplitude less than the discrimination level of scaler. If ions are accumulated so much at high exposure rates, the effective applied voltage becomes lower than 2.45 kV and count losses will start.

Fig. 6 shows the calculated result of the counting response of SQS tube by considering both influences due to the dead zone and the positive-ion accumulation. The calculation well explains the measured counting response through a wide range from 1 to 3000 mR/h.

Contribution of two different space-charge effects to the count losses is indicated separately in Fig. 7 for the purpose of discussing details of count-loss mechanisms of the SQS tube. The count losses due to the dead zone explain the measured results less than 20 mR/h. In other words, the counting response cannot be understood at all in such low exposure-rate region without taking account of the influence of dead zone. On the other hand, more than 500 mR/h, the experimental result is well explained by the count losses due to the accumulation of slowly-drifting positive ions.

The disagreement from 20 to 500 mR/h in Fig. 7 is chiefly caused by the change in the dead-zone characteristics. The dead-zone value may increase as increase in exposure rate [4] [#1]. That is mainly because the dead length becomes longer; plural streamers occur simultaneously at different positions inside the tube. We tentatively used the dead-zone characteristics obtained at 20 mR/h (Fig. 2) where uniform irradiation along the whole tube length was achieved. If the increase in the dead length is taken account exactly, Eq. (4) may be valid up to around a few hundred mR/h.

From Fig. 7, it is clear that the origin of count losses changes from the local space-charge effect to the global space-charge effect with increase in the exposure rate. At low exposure-rate conditions, such as 10 mR/h, the local space-charge effect around each streamer is important. This means that each incident radiation merely has some possibility to interact with the single discharge generated just before (within the dead time) and to be lost; the probability of such event depends both on the time interval between two successive incident radiations and on the incident position along the tube. Namely this kind of interaction is both time- and position-dependent. Therefore that is observed as the dead-zone characteristics which are derived from the deviation of output-frequency distribution from the expected one in no count-loss case [1,2,4,5]. On the other hand, in high exposure-rate conditions, such as 1000 mR/h, incident radiations feel continuous field distortion spreading whole the tube. In this case, the dominant factor for count losses is the global space-charge effect, which brings the reduction of the mean pulse amplitude. The global space-charge effect is an averaged effect on time and position.

[#1] Though we have not confirmed it experimentally, this increase in dead-zone value may saturate and begin to decrease at much higher exposure-rate.

5. Conclusion

The count-loss mechanism of SQS tubes is successfully explained by taking account of the space-charge effects due to the dead zone and the accumulation of slowly-drifting positive ions. The calculated results clarify that the chief influence of the space charges changes, as the increase of exposure rate, from the local effect around each streamer, which is time- and position-dependent effect, to the global effect over the whole tube, which is an averaged effect on time and position. The reduction of pulse amplitude due to cumulative ions finally becomes significant for the count losses of SQS tubes under high exposure-rate conditions; while the counting-rate capability of GM tubes is mainly limited by the dead-zone characteristics at the far lower exposure-rate conditions.

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