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A new structure design and the basic radiation characteristics test of the intense current tube

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Abstract. As a kind of special G-M counter, the intense current tube (ICT) is characterized by small ratio of cathode to anode radius, high working current or count rate, and can be used as the detection units of ultra-high range radiation instruments. In this paper, a new design of ICT structure is introduced, not only does it have a minimum ratio of cathode to anode but it also has a cathode which directly sticks out from the sensitive gas. Using COMSOL Multiphysics, we simulated the electric field between the anode and cathode and finalized the optimal structure. The results of processes and experiments show that the structure has better properties, with plateau slope reaching up to 7.4% within 100V, and it also has a wider range of dose rate. The linear data between the bottom limit of 0.2mGy/h and the upper limit of 1Gy/h is quite accurate but it becomes less reliable beyond 1Gy/h. By using Paralyzable model, we deduce that the dead time of the said ICT is less than 13.4µs, and we will further optimize the readout circuit in order to reduce the resolution time of the circuit in the near future.

1. Introduction

Being a gas ionization detector, the Geiger-Müller counter (G-M counter) operates in the Geiger region. Although it dates back to more than 100 years ago, it is still in wide use nowadays. With large signal amplitude, good environmental adaptability and durability, it is widely used, especially in the military field, such as China's FFS06 portable radiometers, America's AN/UDR-14 and AN/PD-77 portable radiometers and Russia's fixed-type gamma monitoring devices in kilo-class submarines [1].

In recent years, domestic and foreign research mainly focuses on improving the detection efficiency of G-M counter [2] and expanding its dose range [3]. The general structure of G-M counter is shown in figure 1.

In figure 1, $a$ and $b$ are the radius of anode and cathode respectively. Hundreds of volts are added to the anode and cathode when the counter works. The electrons will ionize in sensitive gas and bring along avalanche effect in the strong electric field, then the electrons and positive ion sheath drift to the
poles, and the drift time determines the intrinsic dead time of the counter. Theoretically, the smaller the distance between the anode and cathode \((b/a)\), the smaller the dead time, and the higher the upper limit of the range of the counter, but the higher level manufacture technology is needed. At the same time, smaller distance means smaller sensitive gas space. It is detrimental to the halogen G-M counter tubes, because the halogen is very rare in the sensitive gases, for example, the mass fraction of bromine in ZP1200 type G-M counter accounts for only 0.498\% [4], however, such little bromine has a great effect on the working life of the counter. In the process of constant dissociated and combined, the bromine molecules will gradually die out, and consequently the performance of the counter becomes less reliable. This is especially true and more severe in small size counter. To ensure enough space for sensitive gas and maximize the working life of the counters, the distance between the cathode and anode is usually not extremely short. For instance, the 714 of America’s LND and the ZP1300 of Britain’s CENTRONIC both have diameter of cathode being around 5mm.

When \(b/a\) is small enough, the electric field between the anode and cathode will be evenly distributed, which makes it possible for the avalanche to take place anywhere in the sensitive field, consequently the positive ions generated will fill up the whole of the space. At this point, the electric field that generated by the positive ions is too weak to exert observable influence on the abort of the electrical discharge. The contribution of the positive ion drifting to the output signal is much less than that of the electron drifting. The G-M counter can be called an intense current tube (ICT) in this state [5-6]. Abort of the electrical discharge is solely controlled by the voltage drop generated by electron current on the output circuit and the abort happens when the voltage drops below the threshold voltage of the counter. A mini size ICT is designed and made in this study, the inner diameter of whose cathode is only 0.95mm, the diameter of the anode 0.3mm, and the distance between the two electrodes only 0.325mm.

2. Structural design

2.1. Design principles

The G-M counter is different from the ionization chamber and the proportional counter, which signal is not related to the initial ionization, as soon as even only one electron enters the sensitive gas, avalanche ensues. The electrons that lead to the avalanche come from the \(r\) space with \(r_c\) distance to the anode axis, the \(r_c\) is the distance start an avalanche [7], where the electric field intensity is \(E_x\),

\[
E_x = \frac{V}{r_c \ln b/a}
\]

\(V\) is the voltage between the anode and cathode, \(b\) is the radius of cathode, \(a\) is the radius of anode, when \(r = a\), its value is the intensity of electric field of the anode. \(r > r_c > a\). From formula (1), when the voltage between the anode and cathode is stable, the smaller the distance between the anode and cathode becomes, meaning when \(b\) comes very close to \(a\), the greater the intensity of the electric field becomes, and the more likely the avalanches will happen.

It has been pointed out in literature that [6], when the value of \(b/a\) is small enough, there will be no plateau for organic self-extinguishing G-M counter, so generally we adopt the value of \(b/a\) beyond 200; while the effects of \(b/a\) on the plateau slope have not been fully studied for the halogen G-M counter especially on the ICT, it is confirmed that the value is too small, the slope will increase. For example, the \(b/a\) of ZP1300 is 5, and the maximum plateau slope is 30\% within 100V; the J405 made in China have a cathode of 1mm and an anode of 0.2mm, meaning the value of \(b/a\) 5, and its maximum plateau slope is 20\%. In this study, the \(b/a\) value of the ICT with new structure is only 3.2.

2.2. Design improvements

Earlier some researches were carried out on the workmanship of ICT [8-9], whose structure was as follow (Figure 2):
Figure 2. Structure of the early ICT.

It can be seen that the general ICT contains metal cathode and anode, sealed by glass chimney, the lead wire of the cathode needs to be spot-welded at the end of cathode.

This study is about a new design of ICT as shown in figure 3; it contains anode, cathode, glass chimney, anode support insulator, anode seal and air hole. Compared to conventional ICT, the structure has several advantages as follows:

1) Part of the cathode is outside the glass chimney, saving the trouble of spot welding and enabling it to be used by coiling contact wires around it, this helps avoid metal burrs and point discharge and as a result it makes possible for the tube to work under a high voltage.
2) The length of cathode and anode can be adjusted flexibly, as long as the cathode and anode are parallel to each other, and that enhances the sensitivity and dose range of the tube.
3) The air hole is designed in the direction of the axis rather than on the glass wall, which not only helps reduce the size of the tube but also helps get rid of the impure air.
4) The glass chimney is intended to provide gas for the tube; its size can be adjusted flexibly and therefore also ensures ample gas in the tube and extend the working life of the tube.
5) The flexibility of the structure allows for a small size tube, with length being 30mm and diameter being less than 5mm; in fact we can make it smaller by shortening the cathode and minimizing the glass chimney.

2.3. Electrostatic simulation

The key problem this research intended to resolve is the insulation structure of cathode and anode ends. Due to the extreme effects of cathode and anode, irregularities will occur in the electric field. When the structure of the tube is not reasonable, there is no way we can achieve ideal results no matter how excellent the workmanship may be. In this paper, the COMSOL Multiphysics field coupling simulation software is used to simulate the electric field distribution pattern in line with the slight changes in structures of the cathode and anode. The COMSOL Multiphysics is a simulation software that is based on the finite element analysis method [10]. In the COMSOL Multiphysics simulations of the ICT, the “electric currents” interface of the AC-DC module was utilized. Through comparison and optimization, the optimal structure has been worked out with proved performance. Two types of glass sealing have been employed as shown in figure 4. The first one is solid glass, directly touching both the cathode and anode. The second one is hollow glass. It can be seen that the latter one has better effects in avoiding electron discharge.

As shown in figure 5, hollow glass is adopted in the anode front end; two types of sealing have been used in the back-end. In the first type, the anode threads the cathode and sealed in the glass supporters. In the second type, the end of the anode is hidden in the cathode; the glass supporter serves
to have the anode fixed in the central point of the cathode. The glass supporter used is made of oval pieces of glass. From the direction and magnitude of the electric field, we can see the latter type has better effects in preventing end discharge.

3. Results of test

Based on the afore-said optimized structure, the ICT is filled with combined air of bromine and neon after being pumped of original air. This research is focused on the plateau characteristics and dose rate of the enhanced ICT, and estimate of the dead time has been made in the end.

3.1. Plateau characteristics

The plateau characteristics of the counter include the basic parameters of original voltage, the plateau, the plateau relative slope, the ultimate operate voltage and etc. The plateau relative slope (the plateau slope) means the slope of the plateau and it represents the speed of the changes of the count rate in response to the changes in the voltage. The plateau slope $S$ can be expressed [11]:

$$ S(\% / V) = \left( \frac{N_2 - N_1}{(N_2 + N_1)/2} \right) \times \frac{100}{U_2 - U_1} $$

The count (rate) $N_1$ is produced by the ICT operating at the voltage $U_1$, and the count (rate) $N_2$ is produced by the ICT operating at the voltage $U_2$.

Ideally, the count rate does not change with the operating voltage but literally every counter has a certain slope. At best the change of the count rate is below 10% and at worst 30%, such may be seen in the afore-mentioned ZP1300 of the British Centronic Company. The starting voltage used in the tube studied in this paper is 350V, running up to 600V. The plateau slope when tube is tested within the range of 440 V and 540V is only 7.4%, and the plateau characteristic curve is shown in figure 6.
3.2. Dose rate characteristics
The G-M counter measures the radiation by stimulating the relation between count rate and dose rate. Due to the dead time and energy response, the corresponding curve basically moves in one direction but is not linear. Two aspects are the major indexes of the dose rate properties: a) whether the range is wide enough; b) whether the range has good linearity. The main factors affecting the two aspects are the radiation sensitivity and the dead time of the counter. The radiation sensitivity $\varepsilon$ of a counter can be expressed by formula (3):

$$\varepsilon = \frac{n_0}{\hat{D}} = \frac{n_0}{\hat{D}/K_a}$$  (3)

The $n_0$ represents the true count per unit time after dead time has been rectified, $\hat{D}$ represents the absorbed dose rate, $K_a$ represents the air kerma rate, and the value of $\hat{D}/K_a$ is a constant for single energy ray. A radioactive source with an average energy of 1.25MeV is used in this experiment. The standard values $K_a$ of air kerma rate is provided by a research institute. The relationship between $K_a$ and count rate is given in figure 7. It can be seen from the figure that the measuring range of the ICT is from 0.2mGy/h to 10Gy/h, and it covers 5 orders of magnitude. Over 1Gy/h, the linearity begins to become irregular.

Figure 6. Plateau characteristic curve of the new ICT.

Figure 7. The relationship between the count rate of ICT and the rate of air kerma.
3.3. Dead time

The oscillography method and dual sources method are the most commonly used in many dead time measurements [11]. The single pulse waveform observed by oscilloscope is shown in figure 8. It can be seen that the maximum pulse amplitude is about 1V, the pulse width is about 2.5µs, and the rising edge is about 200~300ns.

![Figure 8. Single pulse waveform of the ICT (the horizontal scale is 2.5 µs).](image)

The count rate is mainly affected by the intrinsic time of the ICT and the resolution time of system, called the dead time of system τ. The relation between the system count rate \( n \) and the real count \( n_0 \) of the radioactive source can be represented by the Paralyzable model [12]:

\[
n = n_0 e^{-n_0 \tau}
\]  

(4)

According to the formula (3) of the radiation sensitivity, it can be deduced that:

\[
n_0 = k \cdot K_a
\]  

(5)

In the formula (5), \( k = \frac{e \cdot D}{K_a} \) and \( k \) is constant under monoenergetic radiation. From formula (4) and formula (5), we can get:

\[
\ln \left( \frac{n}{K_a} \right) = \ln k - k \tau K_a
\]  

(6)

Taking the abscissa as \( \dot{K}_a \) and the ordinate as \( \ln(n/K_a) \), we have a straight line showed in the figure 9. The slope is \(-k \tau\) whereas the intercept is \(\ln k\). The dead time can be deduced from the slope and the intercept on the ordinate axis. Since \(k \tau = 0.0001\) and \(\ln k = 2.0097\), it can be deduced that the dead time \(\tau\) is 13.4µs. Thus, the intrinsic dead time of the ICT is less than 13.4µs.

![Figure 9. Paralyzable model of dead time curve fitting.](image)

4. Conclusions

This study is about a new design of ICT structure, which completely different from the other counters at home and abroad. The main distinctive features include small ratio of cathode to anode, spot-
welding free and sticking-out cathode, flexible sensitive gas space which can be adjusted according to
the size of the tube. The electrode structure can be well optimized by the COMSOL Multiphysics, and
it is proved to be a relatively reliable method in simplifying workmanship and improving the
performance of tubes.

The design of the ICT basically meets the usage requirements of general radiation measuring
instruments. The plateau slope is only 7.4% within the range of 100V, that's better than lots of ICTs
reported currently. This index needs to be further studied, because it is related to the structure, the
workmanship, the composition of the gas and so on.

If the ratio of cathode to anode is very small, the intrinsic dead time will be small. Besides, the
resolution time of the instrument with suitable circuit is small. so linear relation between counting
rate and dose rate is clearer. According to experimental results, the dose rate below 1Gy/h is basically
linear with the count rate, but becomes abnormal over 1Gy/h. The possible reason behind the
abnormality is the readout device. Because the oscilloscope display pulse width is only 2.5μs, while at
a high count rate, the resolution time is greater than the intrinsic dead time due to the threshold and
pulse accumulation of the readout device. Therefore, the dead time of the system calculated by
Paralyzable model reached 13.4μs, which includes the ICT’s intrinsic dead time and the resolution
time of the readout device. Besides, the pulse stacking effect was not considered in the case. Even so,
the dead time is shorter than most of the counters, close to the best level at present, such as ZP1300
which the dead time is 13μs. We can continue to optimize the readout device to reduce the resolution
time and make the linearity over 1Gy/h better.

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