Computer Physics Communications

Gas gain and space charge effects in aging tests of gaseous detectors

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Elsevier use only: Received date here; revised date here; accepted date here

Abstract

We present the results of investigations of the gas gain in straw drift-tubes under different irradiation intensities from a ^{90}Sr β-source. Tests were performed with a gas mixture of 70% Xe + 10% CO_2 + 20% CF_4. The goal of this investigation was to show how to optimize the choice of high voltage for quick aging studies of modern gaseous detectors. In order to perform aging tests within a reasonable time period, the rate of accumulating charge must be at least 10 times higher than what is expected in a real experiment. This means a reasonably quick charge accumulation of about 0.1 – 0.2 C/cm per day (1 – 2.3 μA/cm). In order to be as close as possible to the real experimental conditions, the high voltage should be chosen so as to compensate for the space charge effect, which changes the gas gain in such quick aging tests. It is shown that the limited streamer mode becomes quite noticeable starting at a gas gain of 4.5×10^4.

PACS: 29.40.Cs

Keywords: space charge, aging, gas gain, streamer.

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1. Introduction

High-energy physics detectors proposed for the Large Hadron Collider (LHC) demand a higher performance than what has been available previously from conventional gas detectors. For instance, very high counting rates are expected for the ATLAS TRT, where an accumulated charge of up to 8 C/cm is expected for 7 years of operation at full LHC luminosity [1].

In order to perform aging investigations of straw drift tubes and obtain experimental data in a reasonable time (not more than a few months), an irradiation current at least 10 times larger than the one expected in the real experiment must be used. This forces one to choose a rate of charge accumulation of about 0.1 C/cm per day (1.15 μA/cm), thus providing a quick aging test. The main goal of this article is to investigate how the space charge affects the gas gain for different irradiation rates and high voltages.

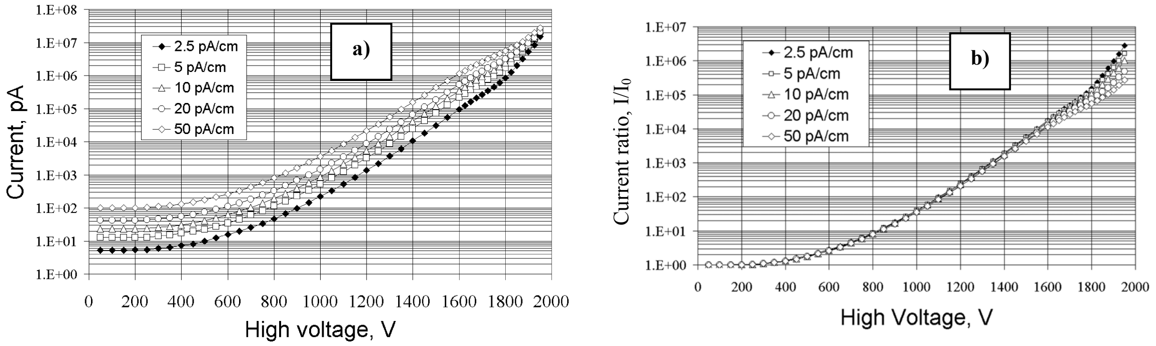

Fig. 1. Current (Fig. 1a) and the current ratio I/I_0 (Fig. 1b) versus high voltage for different irradiation densities.

2. Test set-up

The measurements were carried out with straw drift-tubes equipped with gold-coated tungsten anode wires with a diameter of 35 μm, operated in a 70% Xe+20% CF_4+10% CO_2 gas mixture [2]. Straw drift-tubes used in the investigations had a diameter of 4 mm and a length of 32 cm. The cathode consisted of a 50 μm carbon-coated kapton film. The test of the detector was carried out using a ^{90}Sr β-source. The size of the irradiated zone along the wire was defined by a 2 cm long collimator. The gas gains were measured for different irradiation rates, which were determined from distances between the β-source and the straw tubes. This source provided a rate of charge accumulation from 0.075 to 1.5 μA/cm for a gas gain of 3×10^4.

3. Test results

The irradiation current behavior versus high voltage was measured for different irradiation rates. As one can see (Fig. 1a), the current becomes practically independent of the irradiation rate above a high voltage of 1.95 kV, in spite of a factor of 20 difference in beam intensity obtained from the corresponding current range (2.5÷50) pA/cm for the ionization plateau. Because the constant current (I_0) at lower voltage corresponds to the nominal ionization current, this allows a direct evaluation of the gas gain at higher voltages: $G = I/I_0$, as shown in Fig. 1b. The gas gain values have been calculated for different current densities.

In order to clarify the space charge contribution to the gas gain, the derivatives $d(\ln(I/I_0))/dV$ and $d(\ln(I/I_0))/d(I/I_0)$ have been calculated for each of the plots. As is shown in Fig. 2, all derivatives have a minimum at the same gas gain of 4.5×10^4, independent of the current rate. An unexpected effect has been observed at higher current ratios, $I/I_0 \geq 4.5\times10^4$, where all the derivatives rise strongly. A comparison of these results with the peak position of the ^{55}Fe amplitude spectra versus high voltage leads us to conclude that the fast rise of the derivatives directly correlates with the appearance of the limited streamer mode (LSM) in the gas discharge [3]. The limited streamer mode, which is an additional strong source of space charge production, becomes quite noticeable starting at a gas gain of about 4.5×10^4. It contributes about 1% to the total number of events [3] at this voltage and quickly rises

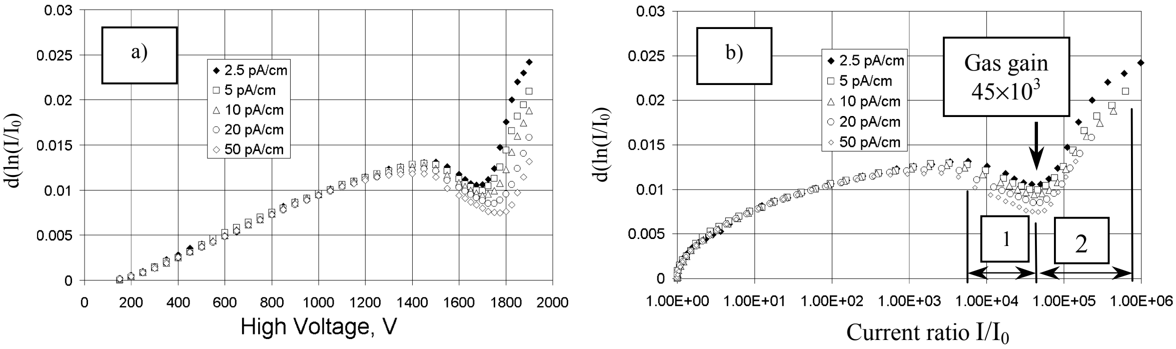

Fig. 2. Derivative d(ln(I/I$_0$)) versus high voltage (a) and current ratio I/I$_0$ (b) for different irradiation densities. The drop of the derivatives in zone 1 corresponds to classical space charge effects on the gas gain. Rising of the derivatives in zone 2 demonstrates the appearance of strong streamer mode.

with high voltage. Due to this LSM appearance the current ratio I/I$_0$ cannot be used as the gas gain above a value of $I/I_0 \geq 4.5\times10^4$.

In order to calculate the gas gain correctly above this critical value, the proportional peak behavior [3] has to be taken into account. It was found that the maximum gas gain which can be achieved is 1.2×10^5 at HV=1.95 kV. At this voltage, the contribution of the LSM is so large that it amplifies the current ratio I/I$_0$ to a very high value of 3×10^6.

The effect of the space charge in reducing the gas gain for different irradiation intensities is presented in Fig. 3. These data have been calculated by normalizing all the plots from Fig. 1a to the one corresponding to the smallest beam intensity (ionization current - 2.5 pA/cm). We have seen that at HV=1.65 kV and a rate of charge accumulation of 1.5 μA/cm (ionization current is 50 pA/cm) a 45% reduction of the nominal gas gain (3×10^4) occurs.

The relative gas gain versus irradiation rate for different high voltages is displayed in Fig. 4 after recalculation of the data presented in Fig. 3.

These data prompted us to propose a possible explanation for the results obtained in [2], where the aging of the straw drift-tubes has been investigated. The aging test was carried out using a ^{90}Sr β-source of two-Curie strength. A collimator defined a circular irradiation zone of 1.8 cm in diameter. In order to monitor the gas gain measurements, a scan along the wire length was performed with a collimated ^{55}Fe X-ray source. The high voltage was chosen so as to compensate for the space charge effect arising from the high intensity of irradiation, which decreased the gas gain in the center of the irradiation zone. This forced the authors to perform the test at 1.75 kV, which produced a gas gain of $2.7\cdot10^4$ in the center of

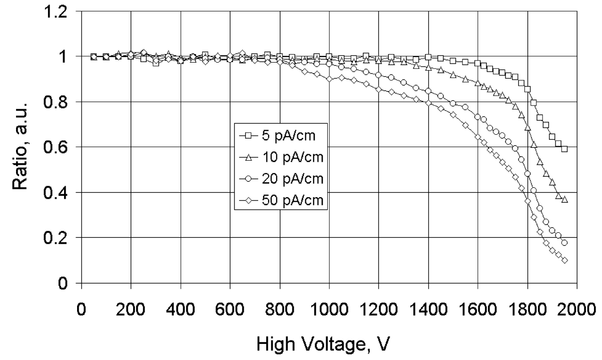

Fig. 3. The effect of space charge on the gas gain for different irradiation intensities

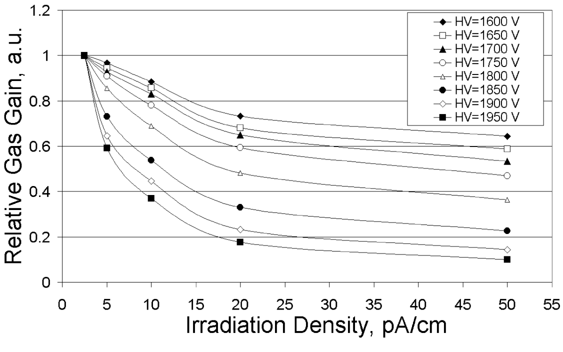

Fig 4. The relative gas gain (I/I$_0$) versus irradiation density for different high voltages.

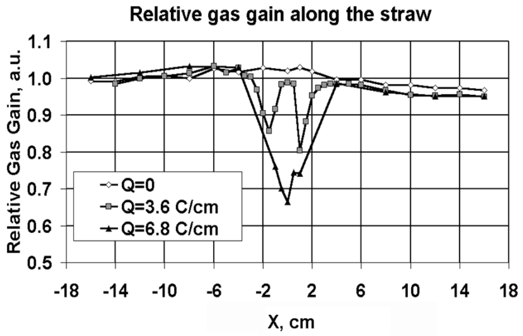

Fig. 5. Relative gas gain along the straw-tube for different accumulated doses.

the irradiated area.

It was demonstrated [2] (see Fig. 5) that after an accumulation of 3.6 C/cm, the aging degradation is practically negligible at the center of the irradiated zone. Aging processes were developing much more intensely at the edges of the irradiation zone. The distance between these zones is about 30 mm. The gas gain decreased about 18% for both edges of this area. After an accumulation of 6.8 C/cm, these two zones finally joined together and the gas gain decreased by 34% in the centre of the irradiated zone.

Taking into account the results presented in Fig. 4 and the measured beam profile, the gas gain distribution across the beam has been calculated (Fig. 6) at a working high voltage of 1.75 kV. We see that the LSM can appear only at the edges of the beam profile - |X|≥13 mm, because there the gas gain exceeds the critical value of 4.5×10^4, eventually reaching a value of 6×10^4 outside of the beam. Thus, the gas gain at the edges of the irradiated zone is high enough to cause the appearance of streamers, while in the central part no streamers can be generated.

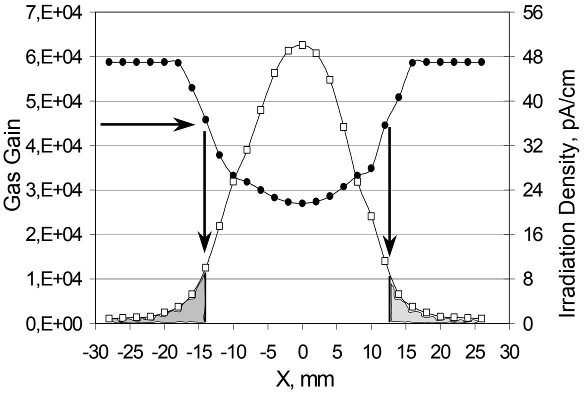

Fig. 6. The gas gain distribution across the beam profile. The beam profile was studied by measuring the irradiation current density for different straw position across the beam. Gray background labels two zones where the LSM can appear.

As one can see, a direct correlation between the appearance of LSM at the edges of the irradiation zone (Fig. 6) and the areas where the aging processes were developing much more intensely (Fig. 5) has been demonstrated.

4. Conclusions

1. For straw drift-tubes operating with a 70% Xe+20% CF_4+10% CO_2 gas mixture, the streamer contribution to the gas avalanche development becomes essential starting at a gas gain of 4.5×10^4, independent of both the irradiation rate and the type of particles (photons, electrons) in the beam.

2. There are two options in choosing the high voltage for a quick aging test:

2.1. The first one is to fix the gas gain at a certain high voltage under low beam intensity and to carry out the aging test under intense irradiation. However, we have shown that with a rate of charge accumulation - 1.5 μA/cm (0.13 C/cm per day), the gas gain drops by 45% due to the space charge effect. Strong space charge contributions to the gas avalanche development cause an inadequate extrapolation of results obtained in quick aging tests to long term real experimental aging.

2.2. In the second option, the high voltage is chosen so as to compensate for the space charge affecting the gas gain in the center of the irradiation zone. We consider this approach preferable because the aging conditions more closely match those in the real experimental conditions. It is important to note that this approach causes specific boundary conditions at the edges of the irradiation zone, which result in an increase of gas gain and, in the case of the $Xe/CO_2/CF_4$ gas mixture, in the appearance of limited streamer mode. To minimize this effect, it is important to perform any aging test with as wide a beam width as possible.

3. These results lead us to conclude that the appearance of LSM at the edges of the irradiation

zone is a quite reasonable explanation for the accelerated aging observed in these areas [2].

Acknowledgements

We are grateful to Prof. A. Vorobyov (PNPI) for his strong support of this work and fruitful discussions of the results. We express thanks to E. Kuznetsova, G. Gavrilov, A. Fetisov, and S. Kovalenko for many useful discussions and help. We would also like to acknowledge E. Ivanov, L. Schipunov, and E. Lobachev for their very friendly help.

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