Fermi National Accelerator Laboratory

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SELF-QUENCHING STREAMERS*

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Summary

Self quenching streamers in drift tubes have been observed both optically and electronically. The streamers of 150-200 μm width extend out from the anode wire to 1.5 to 3 mm at atmospheric pressures. Electronic measurements show that pulses with a rise time of 5 ns reach 30 mV directly into 50 Ω with a decay time of 40 ns at a two atmosphere pressure. Details of the experiments are discussed. There was no detectable residue on an anode wire after exposing it to 2×10^9 streamers for a 1 mm section.

Introduction

It has been traditionally accepted that gas electron multiplication goes through regions of ionization, proportional, limited proportional, Geiger, and discharge as high voltage of an anode wire is increased in wire counters.[1] This may be the case for some gas mixtures and pressures. Some recent works[2-8] show that unconventional gas multiplication phenomena occur under certain conditions. This paper is about a detailed study of the region above the proportional region which manifests itself as a discontinuous fast transition to a self quenching streamer formation under a continuously applied high voltage. A large current (approaching a milliampere) is produced in this region of operation in less than 100 nanoseconds. Optical investigations reveal that narrow streamers, 150-200 μm thick, are formed ortogonal to the anode with a length depending on applied voltage, the gas mixture, and pressure. The streamers quench themselves in a well controlled way providing uniform electronic pulses. The results indicate that the width and the height of the streamers decrease as the gas pressure is increased

Experimental Arrangement

For the majority of the experiments, extruded aluminum tubes containing anode wires of various thickness were used. Various combinations of argon-ethane-ethyl alcohol mixture served as the drift tube gas. Some preliminary results were obtained using 50 percent argon, 50 percent carbon dioxide mixture flowing through ethyl alcohol at 0° C. The results are very similar to that obtained from argon-ethane mixture.

The electronic arrangement was simply either a fast oscilloscope (Tektronix 485) or a pulse height analyzer (LeCroy QVT) for observing pulse shape or detecting charge provided by the self quenching streamer electrons. These devices were directly connected to the anode wire since there was no need for pulse amplification.

Experimental Results

A 12 x 12 mm^2 aluminum tube, 100 μm diameter gold plated tungsten wire and 49.3 percent A - 49.3 percent C_2H_6 - 1.4 percent CH_3CH_2OH gas mixture were used for the following results.

Fig. 1 shows the collected charge as a function of the high voltage starting from the proporational region. The avalanche process slows down as we approach a total charge of 8×10^6 electrons due to space charge saturation. Beyond this value, a discontinuous transition occurs to the self quenching streamer mode, and the gain increases much more slowly as the high voltage is increased. For this and the following, a gate width of 300 nsec is used for integrating the charge. Around this transition either the proportional state or the streamer state occurs with no intermediate pulse height observable in between as shown in Fig. 2a and b. These show that the pulse height distribution is Gaussian for cosmic rays as well as the 5.9 keV line of an Fe^{55} source. Fig. 2b indicates that some of the large angle cosmic rays can produce double streamers.

The probability of multiple streamers is a function of applied voltage and the track angle relative to the wire axis. For investigating this, a collimated Ru^{106} β-source and a telescope made from a pair of two small thin scintillator counters were used. Fig. 3a shows the probability of multiple streamers versus high voltage when the source angle was $90^{\circ} \pm 5^{\circ}$ relative to the anode wire axis. This small probability of double streamer formation may be due to δ-rays and/or a far reaching photon creating an electron. Unless the electric field is sufficiently high, a single electron could not produce a streamer, as explained further in the paper.

Fig. 3b shows the double to single streamer ratio as a function of the average track angle with 2.9 kV applied to the drift tube. The ratio is clearly dependent on the size of the drift tube. In this case, it was 12 mm, and the anode wire was 50 μm thick.

For a further investigation of the pulses, a FET probe (Tektronix P6201) with 3 pf capacitance was used between the wire and the scope as shown in Fig. 4. The pulse height was recorded as a function of the load resistor, R. Fig. 5 shows that the pulse height goes up linearly until the FET probe begins saturating. The shape and the magnitude of the pulses are seen in Fig. 6 with several different load resistors. They show that a peak current of 0.8 mA is provided by the drift tube as a current source. The pulse shape is independent of RC of the circuit indicating that it is governed by the motion of the electrons and the positions of the positive ions. The pictures were taken around the self quenching streamer transition, thus both the limited proportional pulses and the streamer pulses can be seen in the pictures.

Collimated 5.9 keV x-rays from a Fe^{55} source of 1 mm width were used for determining the rate capability of the drift tube for a constant flux. Fig. 7 shows that it is better than 2×10^3 per second per millimeter along the wire. Due to lack of high energy test beams, exact rate capability of the drift tube is not known at this time.

Efficiency for reaching streamer transition was measured for both 5.9 keV x-rays and minimum ionizing tracks. The results are shown in Fig. 8a and b. It takes considerably higher fields to reach the required space charge for minimum ionizing tracks.

*Operated by Universities Research Association under Contract with the United States Department of Energy.

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Self Quenching Streamers

Another drift tube of the type described above was constructed with a conductive transparent window for observing the multiplication process optically around the anode wire. The window is a thin sheet of mylar coated with a very thin film of In-Sn oxide[9]. A four stage magnetically focussed image intensifier tube was used for detecting photons emitted by the atoms involved in the streamer process. The tube stores, gates, and intensifies the image to be recorded on photographic film. Image storage occurs on the first stage phosphor; gating is accomplished by pulsing on the electric field of the second stage from its quiescently off state using the anode wire pulses. The typical gate width was about 1 microsecond. Fig. 9 shows the experimental arrangement. The photographs of the individual events shown in Fig. 10 leave no doubt that the first large electronic pulses are produced by those streamers which start from the wire and extend toward the cathode with a length from 1.5 mm to about 3 mm depending on the applied voltage. The width of the streamers was measured to be between 150-200 µm. They grow in the direction of the initial avalanche. The wire position is indicated at the sides of the pictures.

The above data and the further results which will be given suggest the following probable mechanism for the formation of the self quenching streamers:

The avalanche process in the drift tube with 100 µ wires follows the usual exponential behavior in the proportional region as seen in Fig. 1. The rate of growth of the avalanche slows down as the voltage exceeds 2800 V indicating that space charge saturation is felt by the multiplying electrons. There is a short limited proportional region. Beyond the measured number of 8×10^6 electron-ion pairs in the dense center of the charge clouds, the space-charge field may be so increased that it may negate the applied electric field. As a result, the electrons are cooled; a radiative recombination[10] of A^+ and e^- may occur,

$$A^+ + e^- \rightarrow A^* + h\nu$$

The energy distribution of these photons is expected to be a continuum since the electron can carry a wide range of energies. Thus, the energy is the sum of the kinetic energy and the binding energy of the electron in that state,

$$h\nu = E_e + (E_i - E_x),$$

E_i and E_x are electronic states. Therefore, we may expect some energetic photons reaching outside of the space charge cloud and producing electrons from ethane (first ionizing potential of C_2H_6 is 11.78 ev.). A few of these electrons may reach distances of 50-100 µm to drift back and multiply at the tip of the positive ion cone where the field is the highest. Multiplication should not occur around the cone due to the low field. An artist's view of the phenomena is shown in Fig. 11. Of course, if an electron is created far enough along the wire (possible 500 µm) further multiplications could occur, but in this gas mixture such energetic photons (vacuum uV) do not have that chance until the electric field is very large thus the recombination photon number is large. Streamer action along the wire happens in Geiger counters due to either low pressure (1/10th of atmospheric pressure) or small amount of quenching gas like 3 percent C_2H_6 Br at atmospheric pressures. Occurrence of Geiger action (spread of the avalanche along the anode wire) in 3 percent C_2H_6 Br - 97 percent A, but not in 50 percent C_2H_6 - 50 percent A is important evidence that the electrons produced by recombination photons which mediate the self quenching streamers result from ionizing ethane molecules not argon atoms by the process,

$$h\nu + C_2H_6 \rightarrow C_2H_6^+ + e^-$$

The electric field at the tip of the streamer gets weaker as the length of the streamer gets longer (longer length of positive ion swarm sharing the charge density distribution on the cathode). The streamer photographs show that they get thinner as they extend further from the anode (Fig.10). A small amount of nitrogen (2 percent by flow rate) was added to 50 percent A - 50 percent C_2H_6 gas mixture with the hope that it would increase the number of photons detected[11]. It resulted in a very visible spread of the streamers as shown in Fig. 12. Frequent occurrence of the closely spaced double streamers (Fig. 12a) indicate that the recombination photons are allowed to penetrate further in this gas mixture. Wire pulses corresponding to these events have long tails as shown in Fig.13 . None of the 400 photographs of the streamers showed any evidence of spread along the anode. Therefore, the long tail can be explained by large space charge slowing down the electrons as they drift through the charge cloud.

The following experiments provide more evidence that support the theory above.

Pressure Tests

For the following experiments, ethyl alcohol was excluded from argon-ethane gas mixture to remove one complication in understanding the self quenching streamer mechanism. This required larger size drift tubes to prevent photons reaching the cathode walls and knocking out wall electrons. Fig. 13 like phenomenon may occur when the ultraviolet photons reach the cathode walls and produce electrons from the walls. These electrons may drift to the streamer front and continue the multiplication process. This is shown in Fig. 12 that produces branches. This appears as a transition from streamer to limited Geiger operation. The pulse width in this mode is about 2 microseconds. The time difference between the rising edge of the streamer pulse and the appearance of the limited Geiger pulse is about 60 nanoseconds which corresponds to an electron drift time from the cathode to the anode wire with 6 mm separation. The picture was taken for a high voltage value around the transition.

2 cm x 2 cm size extruded aluminum tubes provided 400-450 volts wide streamer plateau for anode wires of 50-150 µm diameter.

Fig. 14 shows how the full width of the electronic pulses vary as a function of the pressure for 50 percent C_2H_6 - 50 percent A gas mixture around the streamer transition. It indicates that the streamers get shorter as the pressure is increased due to absorption of recombination photons in shorter distance. Indeed the photographs (Fig. 15) taken at the corresponding pressure are in full agreement with this. 1.4 percent ethyl alcohol was then added to the gas, and the streamer photographs were taken at the same pressures. Fig. 16 indicates that the streamers get shorter and thinner than the previous case.

Streamer pulse height was measured (across 50 Ω directly) around transition field values (given in Fig. 17) for various pressures and anode wire thicknesses.

This study indicated that lower E/p values are required with thicker wires. An explanation for this is that avalanche may be rolling around the thin wires[12], thus a substantial fraction of positive ions are shielded from each other. This affects the space charge saturation mentioned earlier thus requiring a higher field for space charge to grow further to make A^+ and e^- recombination possible. The pulse heights of the limited proportional pulses just below the transition are indicated in Fig. 18. This is another confirmation for reaching space charge saturation with smaller avalanche spread around the anode. The avalanche size in the limited proportional region is further reduced (Fig. 18) by a 1.4 percent admixture of ethyl alcohol to 50 percent C_2H_6 + 50 percent A gas. This is achieved by bubbling the gas through CH_3CH_2OH at 0° C.

Light Signals

Light emitted from the initial avalanche and the streamer development was further investigated in establishing the time relation between the emission of photons and the wire signal. Fig. 19 shows the experimental arrangement. A drift tube having a transparent window was placed in a dark box with a special photomultiplier tube (Hamamatsu R1294UX) containing a microchannel plate. Transit time of the phototube was 4.2 nanoseconds with a pulse rise time of 350 picoseconds. A Tektronix 485 oscilloscope was sufficiently accurate to measure time differences between the two signals to 1 nsec in real time. Fig. 20 shows the pulses in coincidence. As seen in the photograph, the wire pulses follow the phototube pulses well up to 100 ns. The wire current continues to flow up to 170 ns, while the phototube current diminishes around 120 ns indicating that the electrons produced at the tip of the streamer are drifting to the anode wire. Positive going pulses, which are the light pulses, have a considerably wider distribution than the negative going wire pulses. This is due to the time structure of the photons emitted during the successive avalanche formation. Superimposed pulses with such structure widens the pulse height distribution. The time relation as a function of the gas pressure is shown in Fig. 21. The time difference between the trailing edges gets smaller as the pressure is increased (indicated in Fig. 22) showing that the height of the self quenching streamers is decreased. The minimum height is around 2.5 mm at one atmosphere pressure, and it goes down to 0.3 mm at two atmosphere taking a drift time of 200 nsec per centimeter.

Life-Time Test

An aluminum drift tube containing 75 μm thick anode wire was exposed to a narrowly collimated Sr^{90} source for a month to determine if large streamer ionization > 4×10^8 ion pairs per streamer, would leave a polymer residue on the anode surface or the cathode wall. The collimated width of the β-source was 1 mm. Using our argon-ethane-alcohol gas mixture, a total of 2×10^9 streamers were detected. During this period, neither count rate nor pulse shape showed any detectable change. The wire was then removed and examined under a microscope. The active section of the wire looked the same as the rest. There was no visible difference. This total number of 2×10^9 streamers corresponds to 2×10^{10} streamers/cm along the wire. The total ionization is equivalent to more than 2×10^{12} typical drift chamber pulses running in the proportional mode. The lack of color change of the wire gives us hope that the wire could be exposed to at least an order of magnitude more streamer pulses without degradation.

Acknowledgment

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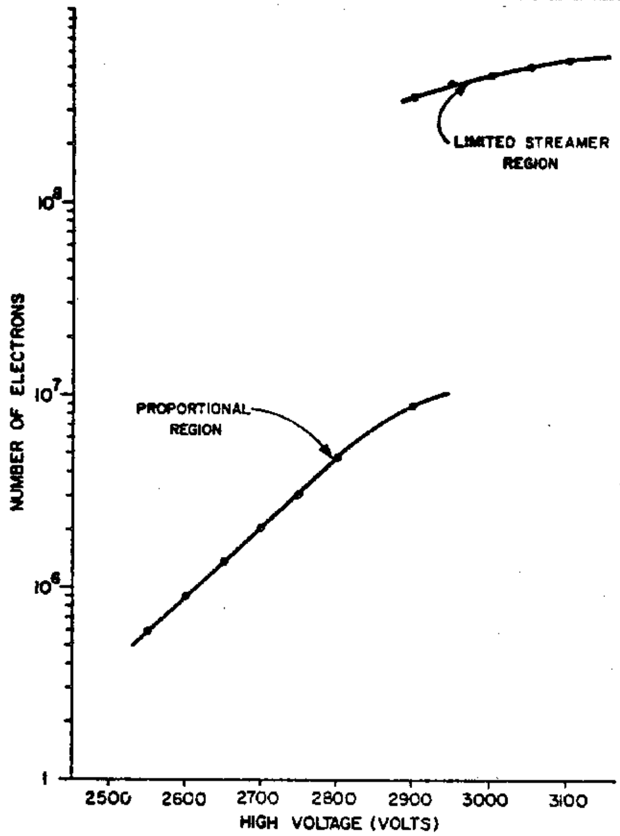


Fig. 1 Measured charge as a function of the high voltage for a gate width of 300 nsec.

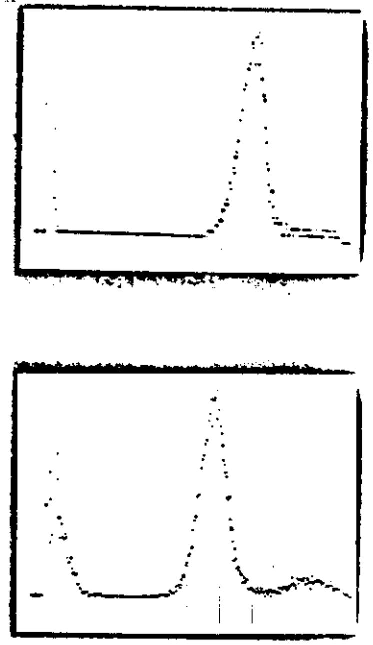


Fig. 2 Self quenching streamer pulse height distributions for 5.9 keV x-rays and cosmic rays. The second peak in the latter case is due to double streamer formation for large angle cosmic rays.

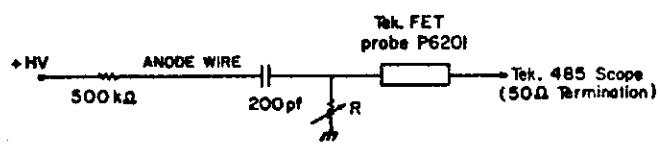


Fig. 4 The circuit diagram for observing the pulse shape.

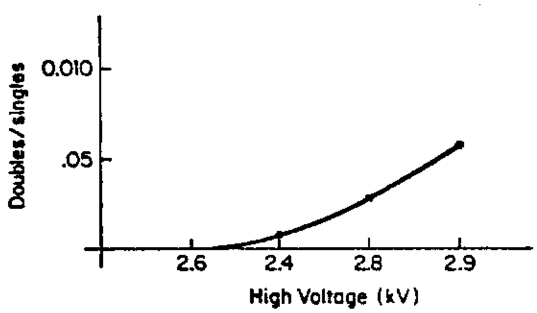
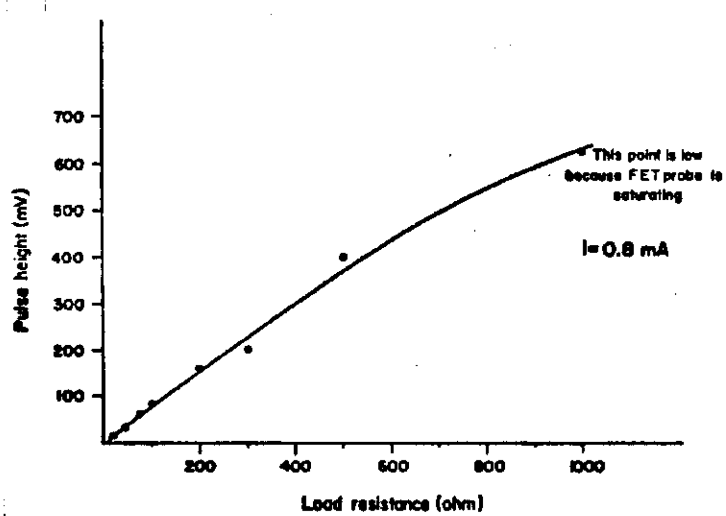


Fig. 3a Double to single streamer ratio as a function of high voltage when the source angle was 90° ± 5° relative to the anode wire.



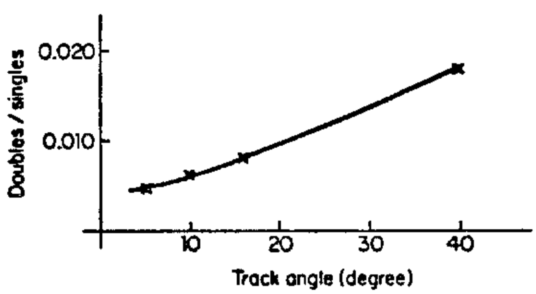


Fig. 3b Double to single streamer ratio as a function of the track angle.

Fig. 5 Pulse height versus the load resistance.

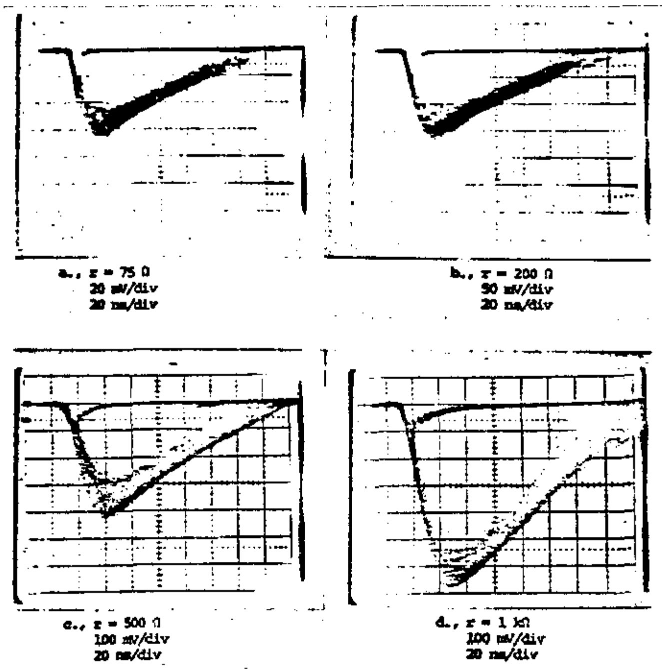


Fig. 6 Streamer pulses with various load resistors.

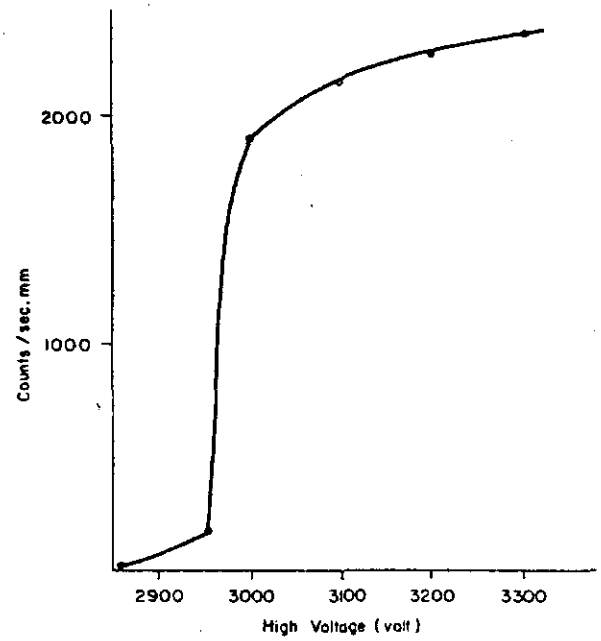


Fig. 7 Count rate capability of a wire in the streamer mode.

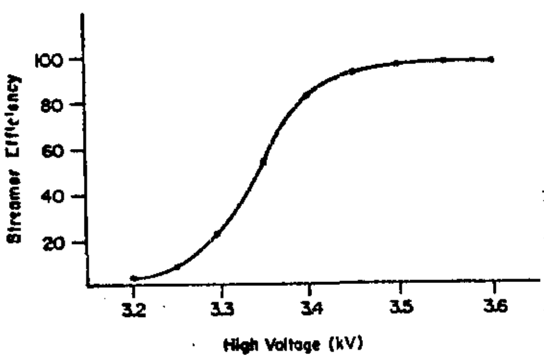


Fig. 8a

Streamer transition efficiency for 5.9 keV x-rays.

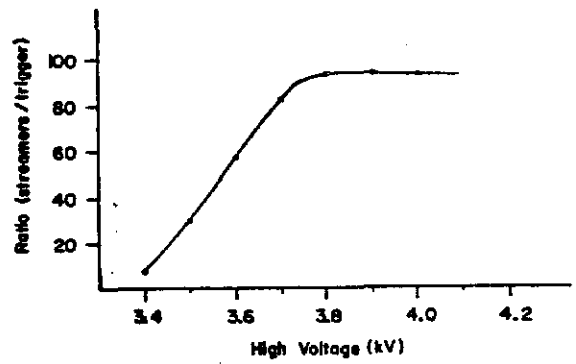


Fig. 8b Streamer transition efficiency for minimum ionizing hadrons.

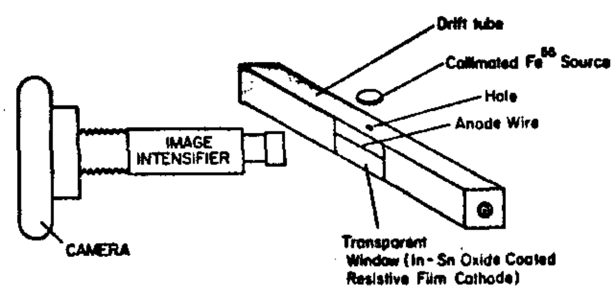


Fig. 9 Experimental arrangement for photographing individual streamers.

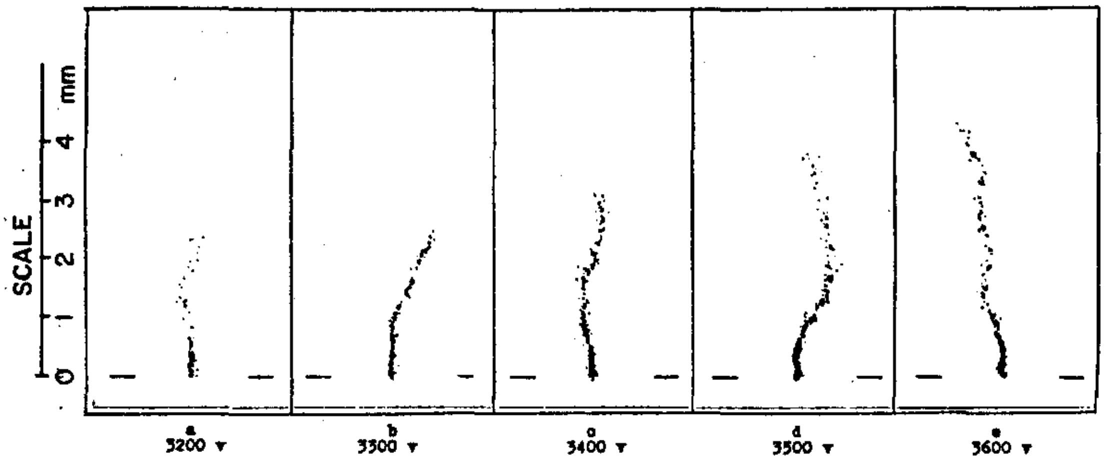


Fig. 10 The photographs of the individual self quenching streamers at various voltages. Anode wire position is indicated at the sides of the pictures.

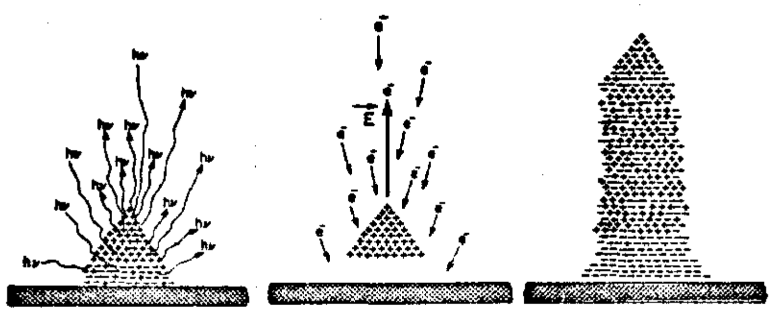


Fig. 11 Artist's description of the self quenching streamer phenomena.

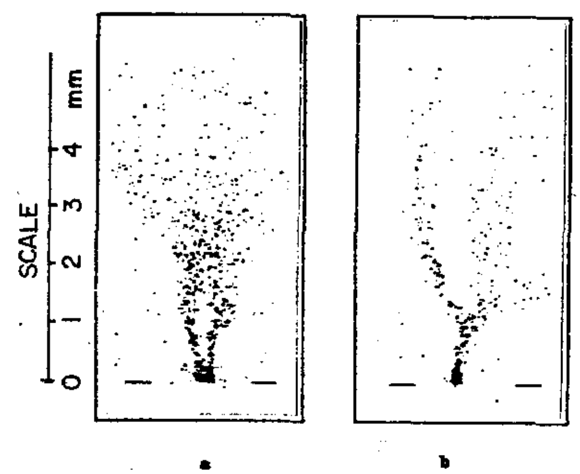


Fig. 12 Double and multiple branch formation of streamers with the addition of nitrogen gas.

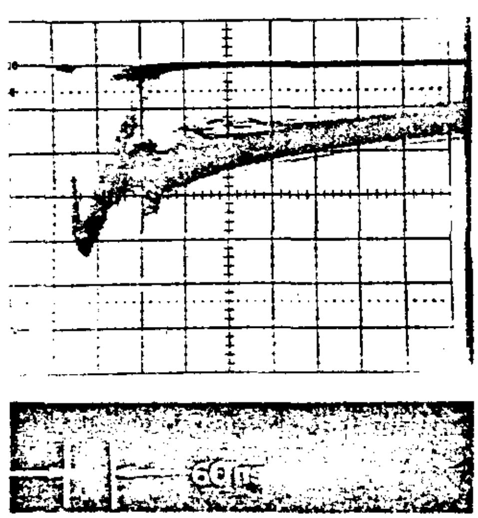


Fig. 13 Self quenching streamer and limited Geiger pulses superimposed.

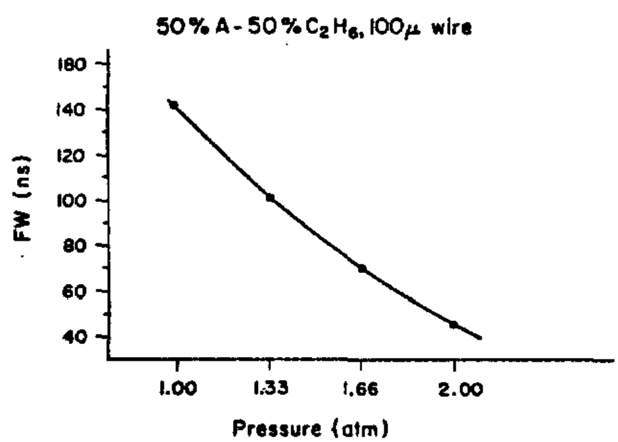


Fig. 14 Full width of streamer pulses as a function of gas pressure just above the streamer transition threshold.

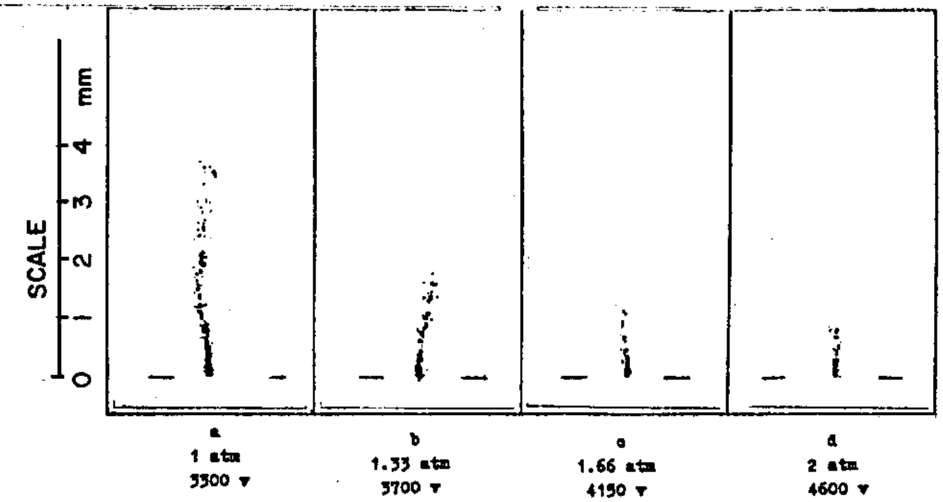


Fig. 15 Self quenching streamers at various pressures using 50 percent argon, 50 percent ethane, and 100 µm anode wire.

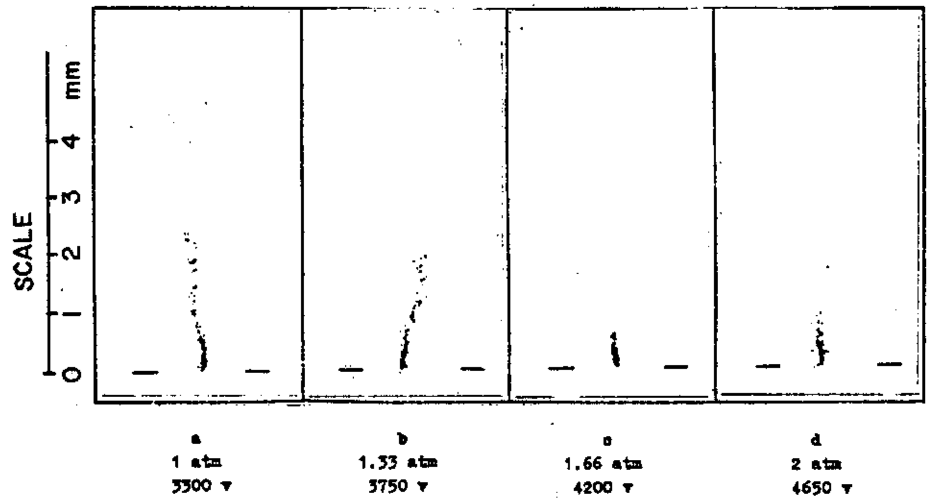


Fig. 16 Streamers at various pressures using 49.3 percent A - 49.3 percent C_2H_6 - 1.4 percent CH_3CH_2OH gas mixture and 100 µm anode wire.

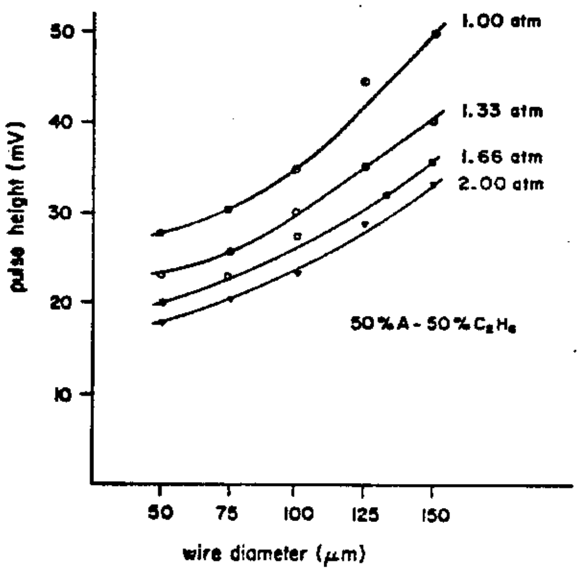


Fig. 17 Streamer pulse height as functions of pressure and wire diameter just above the streamer threshold.

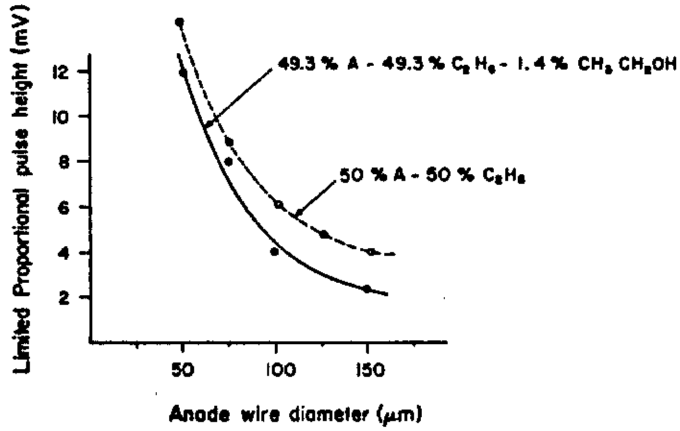


Fig. 18 Limited proportional pulse height as a function of the wire thickness.

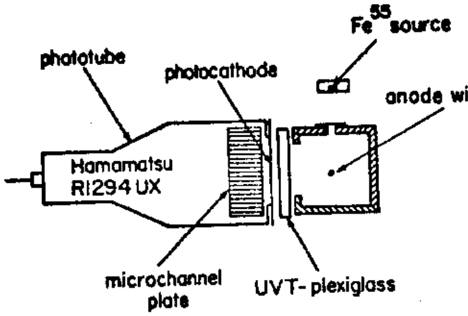


Fig. 19 Experimental arrangement for measuring timing between the photon and the wire current during the self quenching streamer formation.

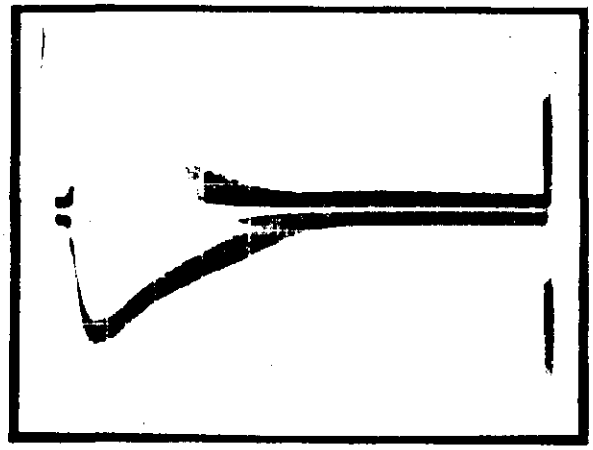


Fig. 20 Phototube and the wire pulses are superimposed. Positive going ones are the phototube pulses. Horizontal scale is 50 ns/division, vertical scale 20 mV/division.

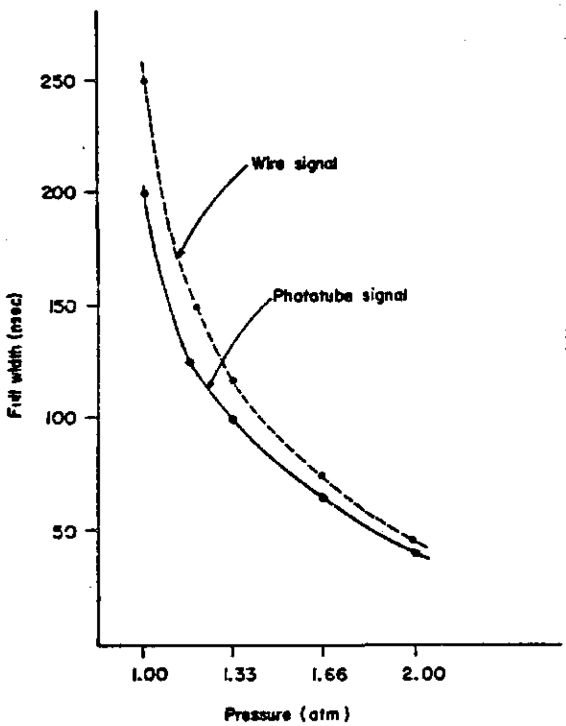


Fig. 21 Full width of the wire and the phototube signals as a function of the gas pressure.

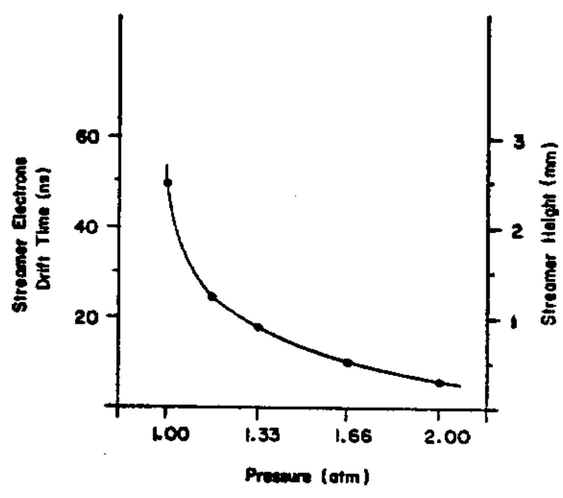


Fig. 22 Drift time and streamer heights as a function of the gas pressure.