論 文
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전극표면상 미소돌기의 극성에 의한 압축 SF_6개스의 절연파괴 Mechanism에 관한 연구

A Study on the Breakdown Mechanism of Compressed SF_6 by Polarity of a Protrusion on Electrode Surface

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요 약

개스압력 400Kpa 까지의 방전갭에서 전극표면의 미소돌기의 극성을 변화시킬때 방전선구 전류펄스의 파형을 계산하였고 또한 애벌렌체에 의한 선구전류펄스를 관측하여 비교분석하였다.

부극성 돌기시에 선구전류펄스의 성장에 대한 수학적 모델로부터 계산한 펄스파형은 관측한 파형과 일치하였다. 전계방출에 의한 대량의 전자방출은 관측할 수 없었다. 분명히 하나의 애벌렌체가 임계애벌렌체의 크기로 성장되면 전열파괴가 일어났다.

그러나 정극성 돌기시에는 계산한 펄스파형과 관측한 펄스파형과는 일치하지 않았다. 개스압력 200Kpa 미만에서의 절연파괴현상은 항상 일련의 연속된 여러개의 애벌렌체가 선행되었다. 이와 같은 현상은 개스중에서 광전리작용에 의하여 생성된 음이온이 정극성 돌기에 인접한 임계체적의 영역을 향하여 이동하여 이 영역내에 들어가면 음이온으로부터 전자가 분리하여 새로운 애벌렌체가 형성되기 때문이라고 해석된다.

Abstract- The general shapes of prebreakdown pulses in a discharge gap were calculated and the current pulses due to avalanche were detected in SF_6 by changing the polarity of the protrusion placed on an electrode at pressures up to about 400 Kpa. The mathematical model of prebreakdown pulse development with a negative protrusion shows agreement with the observed pulses. No evidence of intense bursts of field-emitted electrons was observed. Breakdown probably results from a single avalanche developing to a critical size.

However the calculated shape of prebreakdown current pulse does not agree with the observed pulses with a positive protrusion. The breakdown is preceded by multiple avalanche development at pressures less than about 200 Kpa. This observation has been interpreted as due to the formation of negative ions following photoionization in the gas which drift into the critical volume near a positive protrusion.

1. Introduction

At pressures less than about 100Kpa the temporal development of current in a discharge gap prior to breakdown has been extensively investigated.

One of the principal methods employed has been the electrical method which makes use of oscillographic observations of the pulses arising from avalanche growth in a discharge gap. These investigations have provided valuable information about the electrical insulation characteristics of gases at pressures less than 100Kpa[1, 2]

Several investigations[3-5]have indicated that similar techniques could be used to provide information about the electrical insulation performance of high pressure gases and in the present investigation this technique has been applied to compressed SF_6.

In this paper, the shape of prebreakdown current pulses in a discharge gap was calculated and the temporal development of prebreakdown activity in pressurized SF_6 was studied by observing the current pulses due to avalanche formation at a negative protrusion and near a positive protrusion under static uniform field at pressures up to 400Kpa. The general shapes of the observed pulses were compared with the calculated pulse shape.

2. Experimental Apparatus and Techniques

The stainless steel test chamber has a 65cm height and 50cm diameter. Bruce profiled stainless steel uniform field electrodes of 12.7cm overall diameter were finely polished with 0.1μm diamond paste and mounted along the vertical axis of the chamber.

The uniform field gap was perturbed by placing protrusion consisting of a 1000μm radius hemisphere or a 380μm radius hemisphere on an electrode. Before mounting protrusions on the electrode they were cleaned ultrasonically and with

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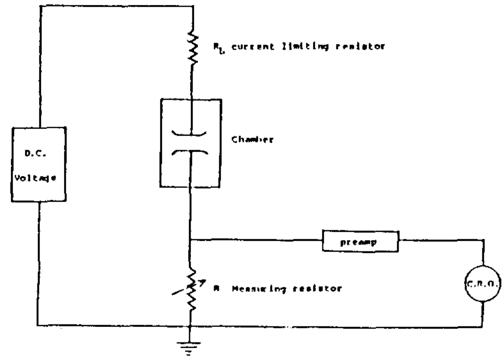


Fig. 1 Prebreakdown pulse measurement circuit.

acetone. After mounting the protrusions on the electrode the continuity between the electrode and each protrusions was checked electrically. The gap spacing was rechecked after allowing a suitable time for mechanical stabilization, when the pressure of the chamber was changed.

The test chamber and associated high voltage supply were fully shielded by aluminium housing to eliminate electrical noise.

The prebreakdown pulse activity in the gap was detected by recording the voltage wave form generated across a resistor connected in series with the stressed discharge gap. The circuit used is as shown schematically in figure 1. The variable carbon measuring resistor connected between electrode and earth was located inside a small aluminium box to minimize detection of spurious electrical noise. This box also contained a spark gap installed to protect the electronic detection equipment against damage following breakdown of the discharge gap. The measuring resistor was connected via a very short length of coaxial cable to a preamplifier. The preamplifier output was fed along a 70ns delay cable terminated with an impedance matching pad and displayed on an oscilloscope. A second much shorter cable supplied a signal to the trigger input. The traces displayed on the oscilloscope were photographed using high speed film.

3. Calculation of current Pulse Shape.

3.1 Negative Protrusion

The field along the axis of a protrusion heitht R on the cathode surface may be expressed as

$$E(u)=E_o \cdot f(u) \tag{1}$$

where

Z = the distance from the cathode

$u=Z/R \geq 1$

E_o : the macroscopic field

$f(u)$: the field enhancement factor introduced by the protrusion.

For SF_6, the value of the effective ionization coefficient $\bar{\alpha}$ at different distance from the tip of the protrusion is then given by (2)

$$\bar{\alpha}(u)=\bar{\beta} \cdot E(u)\bar{K} \cdot p/Z(p) \tag{2}$$

where

$\bar{\beta}=27.8[\mathrm{KV}]^{-1}$

$\bar{K}=24600[\mathrm{Kpa} \cdot \mathrm{mm}]^{-1}$

p : pressure[Kpa]

$Z(p)$: compressibility factor.

From equation (1) and (2)

$$\bar{\alpha}(u)=\{K\ f(u)-1\} \cdot \bar{K} \cdot p/Z(p) \tag{3}$$

where

$$K=\bar{\beta} \cdot E_o \cdot Z(p)/(\bar{K} \cdot p).$$

If no electrons are released simultaneously at the tip of the protrusion, the number of electrons passing through a point at normalized distance u from the cathode will be on average

$$n_-(u)=n_o \cdot \exp\{\bar{K} \cdot p \cdot R/Z(p)\int_1^u [K \cdot f(u)-1]du\} \tag{4}$$

Both Harris and Jones[6], and Teich and Sangi[7] show that the drift velocity of electrons in SF_6 may be described as a function of E/p by an equation of the from

$$v_-=c \cdot (E/p)^r[\mathrm{cm/sec}] \tag{5}$$

where

$c=4.8\times10^{14}\times(32.96\times10^{15})^{-0.51}$

$r=0.51$

For the present purposes this is expressed as

$$v_-(u)=v_{-o} \cdot [f(u)]^r\ [\mathrm{cm/sec}] \tag{6}$$

where

v_{-o} : the value of the electron drift velocity corresponding to the macroscopic field E_o.

If t_n is the time taken for the electrons to reach u_n then, with $t_n=0$ for $u_n=1$, equation (6) leads to

$$t_n=\frac{R}{v_{-o}}\int_1^{u_n}\{f(u)\}^{-r} \cdot du[\mathrm{sec}] \tag{7}$$

By equating the instantaneous value of the power supplied from the external circuit to the rate at which energy is supplied to the electrons by the local applied field, an expression for the instantaneous value of the electron current at time t_n can be determined, e.i.,

$$i_-(t_n)=\frac{q}{d} \cdot n_-(u_n) \cdot v_-(u_n) \cdot f(u_n) \tag{8}$$

where

q : the charge of an electron

d : the gap spacing.

Using equation (4) to (8) and the form of $f(u_n)$ appropriate to any particular protrusion shape, the electron current at time t_n can be computed.

It can be assumed that positive and negative ions are effectively stationary during the electron motion and so the number of positive and negative ions formed in distance Δu may be expressed as

$$n_+(\Delta u)=\alpha(u) \cdot n_-(u) \cdot \Delta u \cdot R$$
$$n_n(\Delta u)=\zeta(u) \cdot n_-(u) \cdot \Delta u \cdot R \tag{9}$$

where

α : the Townsend's first ionization coefficient of SF_6

ζ : the electron attachment coefficient of SF_6.

Using data[7] for ion drift velocities as function of E_o/p, corresponding components of currents due to the motion of these ions may be given by

$$i_+(\Delta u)=\frac{q}{d} \cdot n_+(\Delta u) \cdot v_+(u) \cdot f(u)$$
$$i_n(\Delta u)=\frac{q}{d} \cdot n_n(\Delta u) \cdot v_n(u) \cdot f(u) \tag{10}$$

where

$v_+(u)$: the positive ion dirft velocity at distance u.

$v_n(u)$: the negative ion drift velocity at distance u.

The time Δt required for positive and negative ions to drift for distance Δu may be expressed by

$$\Delta t_{+}=\frac{R}{v_{+o}}\cdot\int\frac{1}{f(u)}du$$
$$\Delta t_{n}=\frac{R}{v_{no}}\cdot\int\frac{1}{f(u)}du \qquad (11)$$

v_{+o} : the positive ion drift velocity in E_o
v_{no}:the negative ion drift velocity in E_o

In a manner similar to that described for the electron currents, the total positive and negative ion currents arising from the drift of corresponding ions during $\Delta t_{+}$and Δt_n respectively can be computed from equation (4), (9), (10) and (11) as follows,

$$i_{+}(\Delta t_{+})=\frac{q}{d}\cdot\Sigma\{n+(\Delta u)\cdot v_{+}(u)\cdot f(u)\}$$
$$i_{n}(\Delta t_{n})=\frac{q}{d}\cdot\Sigma\{n_n(\Delta u)\cdot v_n(u)\cdot f(u)\} \qquad (12)$$

By superimposing the electron current, and positive and negative ion currents, the characteristic shape of the current pulse arising from the occurrence of a single avalanche initiated at the tip of a negative protrusion may be calculated.

3.2 Positive protrusion

The shape of avalanches formed close to a positive protrusion may be similarly computed. However, in the case of a positive protrusion, due to the different space-charge distribution generated by the avalanche as it grows, the pulse shape will be slightly altered. For the negative protrusion the initiatory electrons may be considered to be emitted from the tip of the protrusion but for the positive protrusion electron must be provided within the vanishingly small critical volume. For the present calculation an avalanche at a positive protrusion is assumed to be initiated by an electron formed where $\bar{\alpha}=0$ at the minimum theoretical breakdown field strength.

4. Results and Discussion

4.1 Calculated shape of current pulse.

In the present experiments, under conditions colse to breakdwn, the electron component of a prebreakdown avalanche grows to maximum amplitude over a distance of a few hundred microns with a corresponding rise time less than one nanosecond. When such an avalanche occurs at a negative protrusion, the electron component is then very rapidly attenuated for $u>u_m$ [u_m=a normalized distance defined such that $E(u_m)/p=(E/p)_{lim}$]. Positive and negative ions are formed distributed about $u=u_m$. The positive ions drift on to the cathode and are removed from the gap after several hundred nanoseconds. Subsequently, the negative ions drift across the gap to the anode.

Figure 2 shows the calculated pulse shape for an avalanche initiated by a single electron at the tip

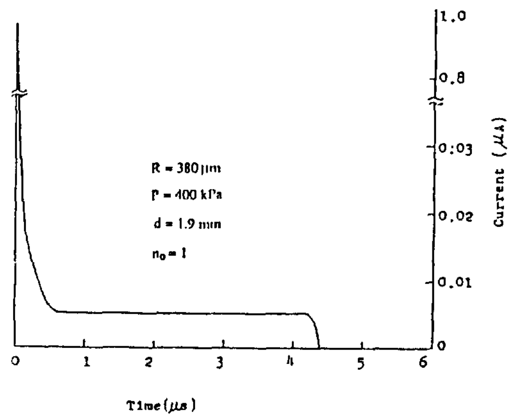


Fig. 2 Calculated shape of current pulse for a negative protrusion.

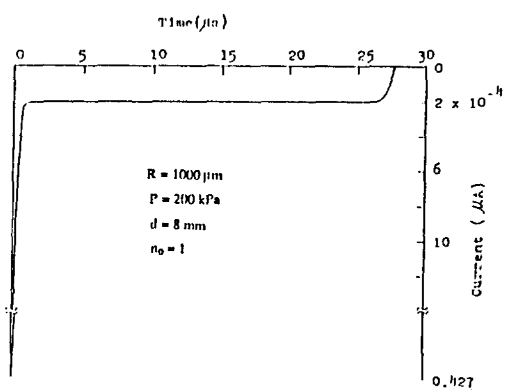


Fig. 3 Calculated shape of current pulse for a positive protrusion.

of a 380μm radius hemispherical protrusion on the cathode of 1.9mm gap at a pressure of 400Kpa at an applied field of theoretical E_{os}(16.6 KV/mm). The virtually instantaneous rise($\sim$0.7ns) of the electron component is followed by the slower decay of the positive ion component which falls to almost zero after about 100ns, following this the residual negative ion current is maintained at a constant level as these ions drift in the macroscopic field E_o until they reach the anode about 4.5μs after the initiation of the avalanche.

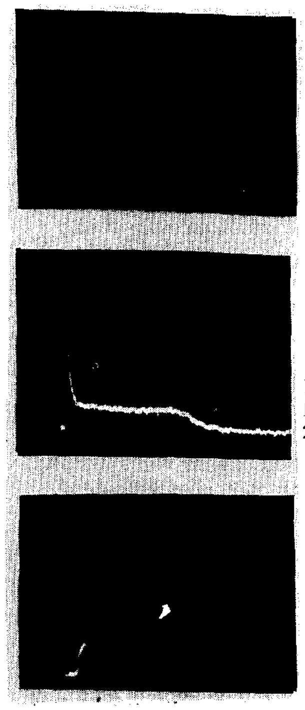
Essentially similar pulse shapes may be calculated for avalanches initiated in the gas close to a positive protrusion. Figure 3 shows the typical calculated pulse shape for an avalanche initiated by a single electron at the position of $\bar{\alpha}=0$ along the axis of a symmetrical protrusion of 1000 μm radius hemisphere placed on the anode of 8mm gap spacing at a pressure of about 200Kpa at an applied field of theoretical E_{os}(8KV/mm). After the instantaneous rise($\sim$0.6ns)of the electron component, most of the negative ions reach the anode in a relatively short time($\sim$50ns)and, in contrast to the case of a pulse formed at the cathode, the long plateau arises from the drift of positive ions to the cathode.

4.2 Observation of current pulses with a negative protrusion.

Typical oscillograms of the current pulses associated with a single prebreakdown avalanche formed at a negative protrusion with gas pressures of 100Kpa and 400Kpa are presented in figure 4.

Similar pulses were observed for all the combinations of protrusion shape and gas pressures investigated: the range of pR covered was from $\sim 2\times10^4$to $\sim 4\times10^5$Kpa $\cdot$ μm

Pulses were easily detected at pressures less than about 100Kpa, but, as pressure was increased towards 400Kpa, it became increasingly difficult to detect individual Prebreakdown avalanches which did not lead to breakdown: however, such events did occur and were occasionally recorded even at pressures as high as 400Kpa, as shown by the oscillograms of figure 4(b). At these high pressures, however, the typical event detected was



(a)
P=100Kpa d=11.3mm
Hemisphere radius=380μm
5μs/div 0.5μA/div.

(b)
P=400Kpa d=4.38mm
Hemisphere radius=380μm
2μs/div 0.5μA/div.

(c)
P=385Kpa d=5.3mm
Hemisphere radius=380μm
0.5μA/div 0.5μs/div

Fig. 4 Observed current pulses for a negative protrusion.

a very rapid growth to breakdown following the initial rise of the current pulse, as shown by figure 4(c).

The general shape of the obseved pulses, shown in figures 4(a) and (b), agrees with the form of the calculated pulse shape shown in figure 2. In particular the initial decay of the ion components shown a change in slope as the positive ions are swept from the gap and the pulse tail takes the form of a relatively long plateau.

The maximum value of E_{os} encountered in these experiments was about 20KV/mm with a gas pressure of 400Kpa. This corresponds to a field at the surface of the hemispherical protrusion of about 60KV/mm. No evidence of intense bursts of field-emitted electrons was abseved. This contrasts with the observation of such events in gaps containing nitrogen[3]or hydrogen[8] stressed at fields greater than 10KV/mm with tungsten electrodes.

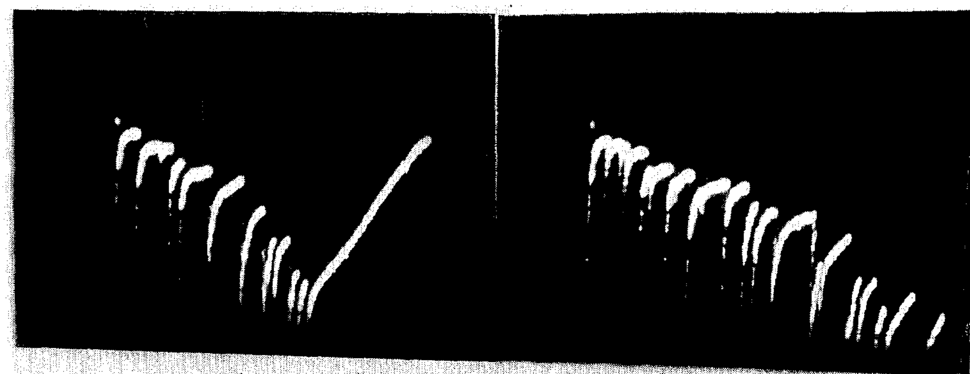
In general, the similarity in pulse shapes detected in the present experiments shows that no fundamental difference in the physical processes takes place and that breakdown probably results from a single avalanche developing to a critical size. The role of field emission appears to be in the production of initiatory electrons.

4.3 Observation of current pulses with a positive protrusion.

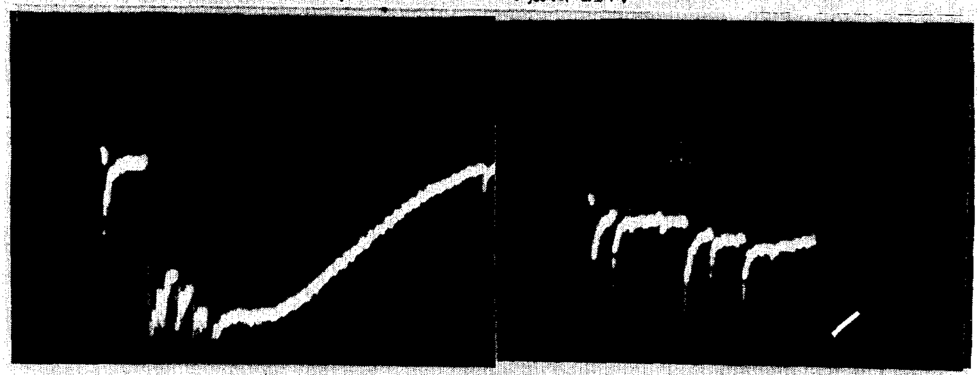
Long statistical time lags occur when breakdown at a positive protrusion takes place and the gap voltage can be raised to about 70%, in the unirradiated case, and 40%, in the radiated case, above the breakdown voltage predicted by the streamer breakdown criterion.

This long time lag was considered to arise because, in order to initiate a breakdown, an electron has to be produced within a small critical volume close to the positive protrusion tip. Consequently, in the present tests it proved to be very difficult to record single prebreakdown pulses. To detect prebreakdown activity at all it was necessary to overvolt the test gap and so, when an electron appeared in the critical volume, either breakdown or rapid multiple avalanche development was triggered.

Above a pressure of about 200Kpa breakdown always occurred very rapidly and no prebreakdown activity was detectable. Below about 200Kpa, however, the growth of current to breakdown took


(a) (b)

p = 100Kpa d = 10mm
Hemisphere radius = 1000μm
10μs/div 5μA/div.


(c) (d)

p = 195Kpa d = 8mm
Hemisphere radius = 1000μm
10μs/div 5μA/div.

Fig. 5 Observed current pulses for a positive protrusion on a very different form : typical oscillograms are presented in figure 5.

These oscillograms show sequences of pulses which apparently correspond to the repetitive formation of individual avalanches close to the positive protrusion tip. Figures 5(a) and (c) show quite clearly that such a sequence of avalanches might terminate quite abruptly.

Oscillograms (b) and (d) of figure 5 show the continuous development of sequences of avalanches leading to actual breakdown which itself occurs very rapidly. It is evient, therefore, that the occurrence of rapid breakdown does not depend on the build-up of prebreakdown activity to some threshold level and may be associated more with statistical variations in individual avalanches.

In order to form the sequences of avalanches as shown in figure 5 there must be some secondary electron formation mechanism which produces free electrons inside the critical volume after a short delay time, typically a few μs. The most possible mechanism of this observation may be considered as due to photoinoization.

Photoelectrons may be created outside the critical volume by photoionization in the gas following the first avalanche. These would attach to form negative ions, drift to the critical volume region and then, if detachment takes place, initiate the next avalanche in the sequence. The average time delay for secondary avalanche formation by this process depends on the average distance, from the critical volume boundary, at which photoionization takes place. This will be less than the ion transit time.

Assuming that the photoionization mechanism operates, a simple estimate of the mean dealy time (Δt) between avalanches in the sequence may be made as follows (see figure 6). The radiation emitted from the initial avalanche will form an electron at an average distance of λ mm from the tip of the positive protrusion, where $\lambda = 1/\mu$ and μ is the photon absorption coefficient. If this electron is formed in the low-field region outside the ciritical volume it is immediately attached and a negative ion formed. Approximating the field between the point of formation of the ion and the boundary of the critical volume by the macroscopic value E_o allows the ion drift velocity v_n to be estimated. Also, the distance from the tip of the protrusion to the center of the critical volume is approximately the critical avalanche length Z_o hence,

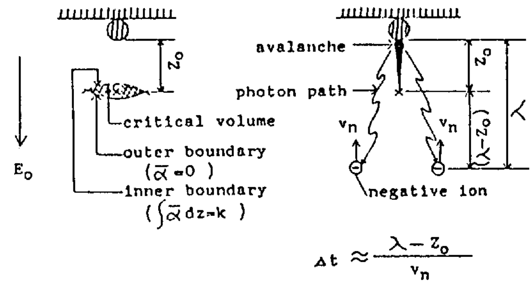


Fig. 6 Model explaining interval between avalanches formed at a positve protrusion.

$$\Delta t \approx (\lambda - Z_o)/v_n$$

the values of Z_o and v_n can be determined from reference[6, 7, 9]. The coefficient μ at 100 Kpa has been calulated by a number of investigators [10, 11]and it is reasonable to estimate that μ is of the order of 1 mm^{-1}

Figure 5(a) and (b) typical records with $p=$ 100Kpa and a protrusion radius of 1000μm. Thus the product pressure × protrusion height is 10^5 Kpa · μ_m and, from reference[9] the value of Z_o is aobut 0.15mm. These pulses were recorded with an irradiated gap and the applied field was about 6KV/mm thus $E_o/p = 0.06$KV (Kpa · mm)$^{-1}$ and so v_n is $\approx 40 \times 10^4$ mm/s. From above equation the value of the delay time between pulses is therefore

$$\Delta t \approx (1 - 0.15)/4 \times 10^5$$
$$\approx 2 \mu s$$

From figure 5(a) and (b) it can be seen that the observed delay is typically a few μs. The oscillograms of figure 5 which show results at $p \approx 200$ Kpa can be analyzed in an identical manner and a similar agreement is found with Δt again of the order of ~ 2 μs.

Further support for the validity of the above explanation may be obtained from the fact that such sequences of avalanches were not observed at pressures higher than about 200Kpa. This follows since the distance λ decreases faster than Z_o with increasing kpressure, thus eventually eliminating the delay time and so allowing the rapid development of breakdown to occur without the formation of sequences of separated avalanches.

5. Conclusions

In general the mathematical model of prebreakdown pulse development with a negative protrusion shows agreement with the observed pulses. The breakdown process itself has been observed to occur very rapidly, apparently from a single avalanche, and is therefore of a form consistant with the cept of critical avalanche. development. No evidence of intense bursts of field-emitted electrons was obseved. The role of field emission appears.

However the calculated shape of prebreakdown current pulse does not agree with the observed pulses with a positive protrusion. The breakdown is preceded by multiple avalanche development at pressures less than about 200Kpa. This observation has been interpreted as due to the formation of negative ions following photoionization in the gas which drift into the critical volume near a positive protrusion.

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