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Emission of electromagnetic radiation and ionisation phenomena in inhomogeneous fields in air under lightning impulse voltages

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Abstract

This Letter deals with the ionisation phenomena in non-uniform medium air gaps stressed by lightning impulse voltages. The application of the Townsend theory for homogeneous fields, still yields quite reasonable results for the tested inhomogeneous experimental electric field setup. Measurements taken on rod–plane air gaps, with clearance of 20 to 50 cm, show that the inception of the ionisation phenomena is related with an increase of the voltage across the gap that is characterised by a potential step of the voltage waveform. This phenomenon is related with the emission of infrared radiation. © 2000 Published by Elsevier Science B.V.

Keywords: Inhomogeneous field; Townsend theory; Ionisation; Potential step; Standard lightning impulse; Electromagnetic radiation

1. Introduction

Air has been the insulating ambient most commonly used in electrical installations. Among its greatest assets, in addition to its abundance, is its self-restoring capability after breakdown. The more significant mechanisms for ionisation in a gas discharge are: cosmic rays, X-rays, and nuclear radiation. The processes considered include ion generation by electron impact, photoionisation and interaction with metastable atoms, thermal ionisation and electron detachment.

In a given two-electrode configuration in air, the space charges are gathered near the electrode with the opposite polarity and in this way they form a cloud of space charges. If the space charges are stationary, the field is electrostatic and more precisely a space-charge field. It can be assumed that equilibrium exists between the applied Coulomb forces up to a specific value of the applied voltage, so that the field is still electrostatic. For higher voltage values, which do not lead to a breakdown, the equilibrium disappears and partial discharges are developed. The value of the applied voltage for the inception of partial discharges is called partial discharges' inception voltage or inception voltage. The relevant value of the field strength, for the inception of partial discharges, is called partial discharges' inception field strength or inception field strength [1–4].

Consider a uniform field between two electrodes in the air. A cloud of free electrons is formed around the anode. The rise of the applied voltage causes

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movement of the free electrons, partial discharges and finally leads to the breakdown. In other words, the inception voltage in the homogeneous field is the identical with the breakdown voltage [2–4].

Two typical gas breakdown mechanisms have been known: the Townsend mechanism and the streamer (or channel) mechanism. For several decades there has been controversy as to which of these mechanisms govern spark breakdown. The mechanism of the appearance of the ionisation phenomena in air is approximated satisfactorily for field factors (the ratio of the homogeneous field strength to the maximum inhomogeneous field strength for the same gap length) greater than 0.2 with the ionisation theory according to Townsend, to Paschen law and to channel theory [2,3].

If the cloud of free electrons is formed in inhomogeneous electrostatic field, with field factor less than 0.2 i.e. in a space-charge field, the inception field strength and the relevant inception voltage can not be calculated but only be measured [1–4]. The experiments presented in this Letter have been carried out under normal conditions ($p = 1.013$ bar, $\theta = 20°$C). It is well known from experimental tests that these values depend on the shape of field electrodes, the atmospheric conditions (temperature, humidity, pressure, pollution, etc.), the duration of voltage application and the shape of the applied voltage. These parameters also influence the value of the breakdown voltage and the value of the respective electric field strength, which decrease with the increase of the space-charge density [2–4].

More information concerning the mechanism of the inception of the ionisation phenomena and generally the breakdown in gases in strongly inhomogeneous fields can be attributed to the released energy of free electrons after their forced retardation at the anode. The respective mechanism in solid insulating materials has already been investigated in [5–7].

The aim of this Letter is to investigate the ionisation phenomena in strongly inhomogeneous fields in medium air gaps under normal conditions and in particular to examine whether the application of the homogeneous Townsend theory still yields reasonable results for a particular inhomogeneous electric field setup. The spectrum of the electromagnetic radiation that is emitted at the beginning of the ionisation is also estimated.

The test voltage is the standard lightning impulse of the waveform 1.2/50 μs (Front time $1.2 \pm 30\%$ μs, half time $50 \pm 20\%$ μs). The impulses are positive. The equation of voltage is $U_0(\mathrm{e}^{-t/68.5} - \mathrm{e}^{-t/0.4})$ where t is introduced in μs. From this equation one can obtain the peak value of the applied voltage; it is $0.96U_0$. This type of voltage facilitates the detection of the ionisation phenomena, isolating them from other factors as the long duration of the voltage stress or the change of the polarity. The influence of the peak value (from 40 up to 90 kV) of the applied voltage to the inception of the ionisation and to the spectrum of the radiation is also investigated.

2. Test arrangement and measuring procedure

The investigated electric field is a vertical rod-to-plane air gap with a gap length d varying between 20 cm and 50 cm which is placed in a humidity and temperature controlled chamber. The diameter of the rod electrode is 16 mm. The tip of the rod electrode is terminated with a cone that ends to a spherical surface. The radius R of the tip is 0.5 mm. The dimensions of the grounded plane electrode are 1.25×1.25 m^2. The rod and the plane are made of brass.

The test arrangement is shown in Fig. 1. It includes an 8-stage high impulse voltage generator with a charging capacity of up to 200 kV and with energy of up to 2 kWs per stage. The impulse voltage is measured by means of a 1.2 MV damped capacitive voltage divider. The control apparatus and the measuring instruments (fast transient digitizer, oscilloscope, peak-voltmeter, voltmeters, ammeters, etc.) are placed in a Faraday cage with a 50 dB signal attenuation up to 1 GHz. A high frequency reject filter and an isolating transformer shield the power supply of the instruments from noise and disturbances. The mains supply is regulated to a constant value of $230 \pm 0{,}1$ VAC, 50 Hz by means of a voltage stabiliser. The atmospheric conditions are kept constant and repeatable throughout the experiment, using the mentioned chamber. The repetition time of successive impulses was at least 1 min (minimum permissible time interval between discharges of the used impulse generator) up to 15 min. No influence of the repetition time of successive impulses on the results could be stated.

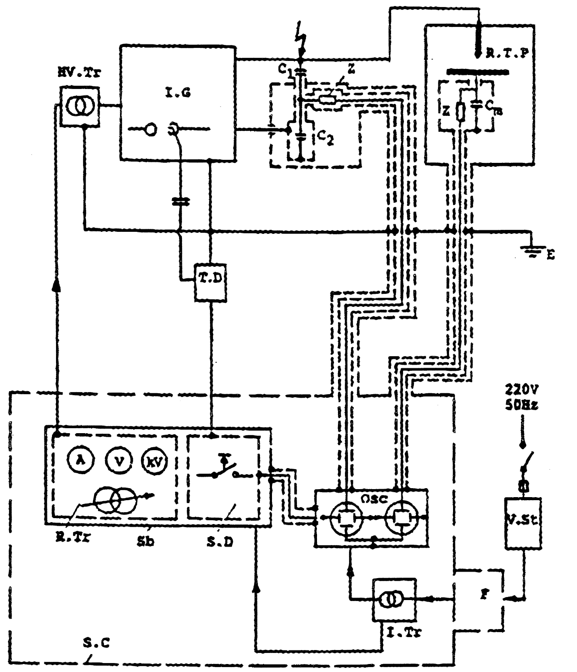

Fig. 1. Simplified circuit for the measurement of the charge impacts V.St: Voltage stabiliser F: Line voltage filter S.C: Shielded cabin Sb: Switchboard and control panel I.Tr: Isolating Transformer R.Tr: Regulating transformer S.D: Synchronising device T.D: Triggering device HV.Tr: High voltage transformer I.G: Impulse voltage generator C_1, C_2: Capacitive voltage divider C_m: Measuring capacitance Z: Series matching resistance Osc: Impulse voltage oscilloscope R.T.P: Rod-to-plane air gap

The applied voltage U_k (its polarity is controlled by the orientation of the rectifiers inside the impulse generator) is measured by means of the capacitive voltage divider C_1, C_2, whereas the potential steps ΔU are measured by means of the capacitive quadripole $C_m = 0.1$ μF. Therefore, the partial discharges in the field may be recorded by the potential increase on the measuring capacitor C_m (Fig. 1). This procedure was also followed for the observation of ionisation phenomena in surface discharges [6].

Each tested air gap is stressed by successive impulses. The peak value of the impulses is gradually increased step-by-step until the observation of the first distortion of the voltage across the capacitor C_m. The distortion appears as a potential step on the recorded waveform. This distortion indicates a partial discharge i.e. the inception of ionisation. The amplitude ΔU of the distortion is the measure of the electric charge of the discharge.

3. Experimental results and discussion

Figs. 2a, 3a and 4a demonstrate the impulse voltage applied on the tested electrode configuration with a gap length of 40cm and different voltage peak values. Typical recordings of the voltage across the capacitive quadripole C_m are presented in Figs. 2b, 3b and 4b. The measurements show that only one potential step appears on all the recorded waveforms. The amplitude ΔU of this step increases with the increase of the peak value U_k of the applied impulse voltage. It can be assumed that there is a certain number of free electrons that are collected by the anode (rod electrode); the number of free electrons depends on the value of the applied field.

The maximum value of the applied field before the appearance of the potential step that has been calculated using the analysis of hyperbolic tip [8], is given by the following equation:

$$\hat{E}_k = \frac{2\hat{U}_k}{R\ln(4d/R)} \tag{1}$$

where R is the radius of the rod tip and d is the gap length. Defining the mean field strength:

$$\overline{E} = \frac{\hat{U}_k}{d} \tag{2}$$

the field factor of the electrode arrangement is [2–4]:

$$n = \frac{\overline{E}}{\hat{E}_k} = \frac{R\ln(4d/R)}{2d} \tag{3}$$

The field factor of the electrode arrangement for $R = 0.5$ mm and $d = 20\ldots50$ cm is given in Table 1. As it can be seen in this table the field is strongly inhomogeneous ($n < 0.2$ [2]) in all the investigated gaps. Therefore the relations concerning the impact ionisation phenomena from Townsend theory do not apply [1–3]. In this case the study of the inception of ionisation phenomena can be performed exclusively by means of measurements.

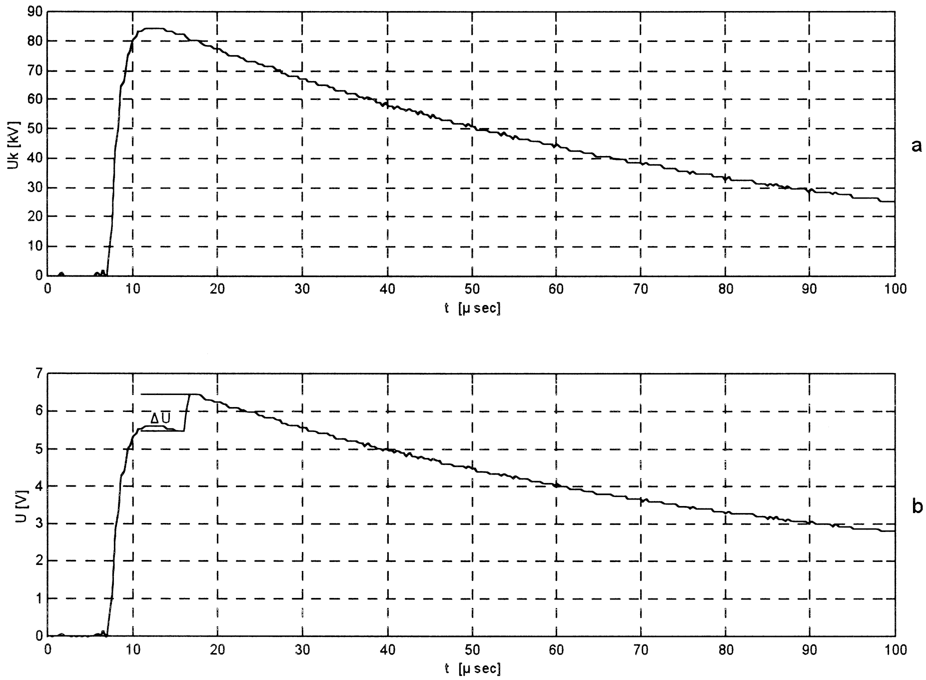

Fig. 2. a: Applied impulse voltage U_k with a peak value of 84.4 kV b: Voltage across the capacitive quadripole C_m under the above impulse voltage, Potential step $\Delta U = 1.1$ V.

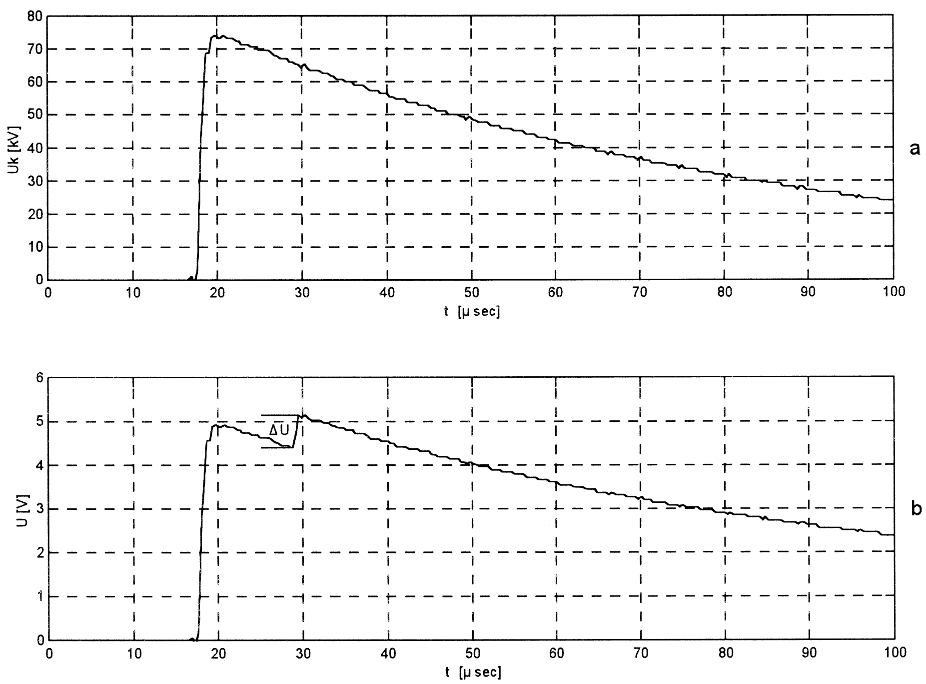

Fig. 3. a: Applied impulse voltage U_k with a peak value of 74.1 kV b: Voltage across the capacitive quadripole C_m under the above impulse voltage, Potential step $\Delta U = 0.8$ V.

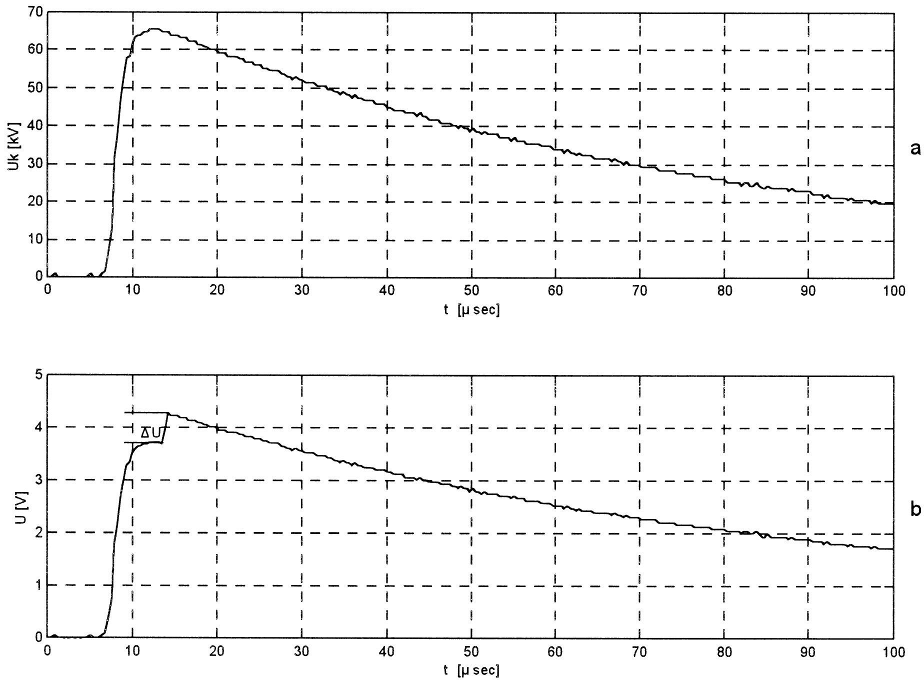

Fig. 4. a: Applied impulse voltage U_k with a peak value of 65.6 kV b: Voltage across the capacitive quadripole C_m under the above impulse voltage, Potential step $\Delta U = 0.6$ V.

The pressure value in inhomogeneous fields is an important parameter. Up to a critical pressure p_k, depending on the nature of the gas, the field is strongly inhomogeneous, i.e. the field strength E_a for the inception of the ionisation is less than the breakdown field strength E_d. For pressure values higher than the critical one it is $E_a \cong E_d$. The critical pressure for the air is 12 bars [2]. Due to the fact that the measurements are performed under normal conditions ($p = 1.013$ bar, $\theta = 20°$C) it is:

$$E_a < E_d \tag{4}$$

This means that the ionisation phenomena appear before the breakdown (Figs. 2, 3 and 4).

The electric charge Q of the partial discharges can be calculated from the following formula:

$$Q = C_m \Delta U \tag{5}$$

The variation of charge Q upon the peak value U_k and the electrode distance d is shown in Fig. 5. From this figure it is obvious that more charge is transported (associated with ionisation) at a constant voltage level with decreasing distance.

The approximation of the relation $Q = f(U_k)$ using curve fitting methods results to the following formula:

$$Q = f\left(\hat{U}_k\right) = A e^{B \hat{U}_k} \tag{6}$$

where A and B are constants. The values of them for different electrode distances d are given in Table 2. The constant A is given in electric charge units (nC) and the constant B in 1/kV for U_k is expressed in kV.

The exponential increase of the charge is attributed to the proliferation of free electrons by means of their impact on the air molecules. It seems

Table 1
Field factor of the air gaps

d (cm)	n
20	0.173
30	0.115
40	0.086
50	0.069

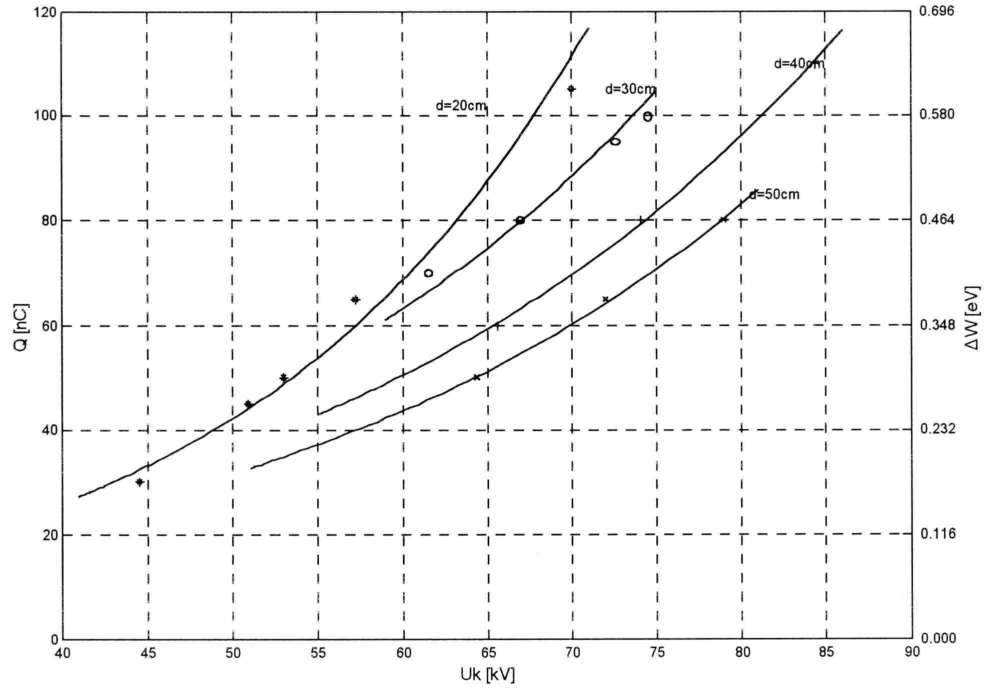

Fig. 5. Electric charge Q of partial discharges versus the peak value U_k of the applied voltage. Energy of the air gap versus the peak value U_k of the applied impulse voltage.

that the Townsend mechanism applies to the investigated fields, as in any inhomogeneous field with field factor $n < 0.2$. According to Townsend the charge is given by this formula:

$$Q = n_0 q \mathrm{e}^{\int_0^l \alpha ds} \tag{7}$$

where n_0 is the number of the free electrons existed initially, q the electron charge, α the ionisation coefficient and l the mean length of the field lines in the area where the ionisation appears. Assuming that $l = d$, it is obtained:

$$Q \cong n_0 q \mathrm{e}^{\alpha d} \tag{8}$$

The electric charge Q of the partial discharges is greater under voltages with higher peak values U_k (Fig. 5) because of the faster rise (du_k/dt) of the applied voltage.

As it is shown in Fig. 5 the phenomena of the ionisation inception become stronger with the increase of the insulation distance d. This is justified because the field factor n is inversely proportional to the distance d (Table 1).

The observed potential steps on the measuring capacitor may be attributed to the excess charging brought about during the intervals of high conductance. Treating the change of charge on the reference capacitor as equivalent to the same amount of charge traversing the specimen directly from its point electrode to the plane, one can get the net charge transferred by individual currents pulses, or even, the number of transferred electrons. Assuming that the change of energy of the measuring capacitor is completely transferred into kinetic energy of the injected electrons, it follows that the average electronic energy within a pulse may be given by the potential

Table 2
Coefficients A and B of $Q = f(U_k)$ versus the gap length d.

d (cm)	A (nC)	B (kV^{-1})
20	3.71	0.0486
30	8.35	0.0337
40	7.30	0.0322
50	6.31	0.0322

increase on the measuring capacitor [9]. The analytic expression for the evaluation of the net energy increase in the electric field of the measuring capacitor may be written as:

$$\Delta W = \tfrac{1}{2} Q \Delta U \tag{9}$$

where ΔW is the energy increase in the electric field of the capacitor for a given potential step ΔU. The factor $\frac{1}{2}$ results from the average velocity of the electrons which are stopped after collision and reach maximum kinetic energy prior to collision. The number of the electrons N required to form the potential step ΔU on the measuring capacitor is given by the ratio $\Delta Q/e$ where e is the charge of an electron. The average kinetic energy of the above electrons (in eV) for each of the potential steps, may be given by the equation [9]:

$$\frac{\Delta W}{N} = \tfrac{1}{2} f \Delta U \tag{10}$$

where f is a correction factor, depending on the value of the measuring capacitance and is associated with the time constant of the measuring circuit. The value for the factor f is 1.16 for the investigated set-up [9].

It can be concluded from the expression $\Delta W = f(U_k)$ of Fig. 5 that the inception of the ionisation phenomena is related to the emission of infrared radiation (as the spectrum of infrared radiation is in the range of 0.002–2 eV). It may be assumed that the breakdown channel appears (streamer or leader) when this radiation becomes ionising by a further voltage increase [2].

The relation $\Delta W = f(U_k)$ is fitted by the following analytical expression:

$$\Delta W = f\left(\hat{U}_k\right) = A_1 \mathrm{e}^{B_1 \hat{U}_k} \tag{11}$$

where A_1 and B_1 are constants that are given in Table 3, in dependence upon the electrode distance d. The constant A_1 is given in μJ and B_1 in kV for ΔW expressed in μJ and U_k in kV.

It is concluded from Eqs. (6), (8) that:

$$ad \cong B\hat{U}_k \tag{12}$$

Substituting the value of $\hat{U}_k$:

$$\hat{U}_\mathrm{k} = \frac{\ln\left(\dfrac{\Delta W}{A_1}\right)}{B_1} \tag{13}$$

from this equation in Eq. (12), the following form is derived for the ionisation coefficient α versus the gap length d:

$$\alpha \mathrm{d} = \frac{B}{B_1} \ln\left(\frac{\Delta W}{A_1}\right) \cong \ln\left(\frac{\Delta W}{A_1}\right) \tag{14}$$

This equation seems to govern the mechanism of the formation of free electrons, due to collisions during the self-maintained or even the non-maintained ionisation, depending on the value of ΔW. Therefore the breakdown is related to the appearance of radiation. According to measurements, this radiation is in the range of infrared 0.002–2 eV. Therefore the following relation is valid for the breakdown:

$$\ln\left(\frac{0.002}{A_1}\right) < ad < \ln\left(\frac{2}{A_1}\right) \tag{15}$$

where the constant A_1 is expressed in eV.

Table 3
Coefficients A_1 and B_1 of $\Delta W = f(U_k)$ versus the gap length d.

d (cm)	A_1 (eV)	B_1 (kV^{-1})
20	0.0249	0.0459
30	0.0726	0.0279
40	0.0427	0.0321
50	0.0370	0.0321

4. Conclusions

The theory of Townsend for homogeneous fields has been applied to the inhomogeneous electric fields that were investigated in this Letter. The results of the application are reasonable for this particular inhomogeneous electric field setup. From the measurements performed, it is concluded that the inception of the ionisation phenomena is related with a potential step. The initially existing free electrons for the inception of impact ionisation can be attributed to field emission as well as to terrestrial radioactivity and to cosmic radiation. The increase of free electrons is exponential. It is related with the emission of infrared radiation that can be attributed to the forced retardation of electrons at the anode. It can be assumed that the breakdown channel appears (streamer or leader) when this radiation becomes ionising due to a further voltage increase.

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