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PASCHEN CURVES AND SPATIAL DISTRIBUTION OF EMITTED LIGHT OF GLOW DISCHARGE IN THE AIR

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Abstract

This paper deals with phenomena occurring during the conduction of electrical charge through gases at low pressure. The purpose of research was to determine Paschen curves for air, the yield γ of secondary ionization by ion impact on the electrode (the second Towsend's coefficient) as well as the spatial distribution of the emitted light depending on changes of pressure and intensity of electric current. Spatial distribution of light in discharges was recorded by means of a CCD camera connected to an IBM compatible personal computer (PC). The experiment was conducted in a parallel plate chamber. Paschen curves obtained for the first three series of measurements deviated from the expected *pd* dependence which is due to variable conditions on the cathode. The other two series of measurements, conducted after the conditioning of the cathode coincide with expected dependence. As for the γ-coefficient, the values obtained agree with the values in the literature but the detailed comparison is not possible because of the different conditions. The intensity of electric field on the cathode, as well as the change of the spatial distribution of emitted light were obtained by computer processing of the PCX format photographs of the discharge obtained by camera and digitised by the Video Blaster interface. The results obtained for dependence of the profile of radiation on the pressure and current are in good agreement with the dependence expected on the basis of the available literature.

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1. Preface

The experiment dealt with glow discharges. Under the influence of cosmic radiation or natural radioactivity of the environment there is some degree of primary ionization of gas which is otherwise insulating. Ions and electrons produced in this way are directed by external electric field to the electrodes. During the voltage increase the current increases up to certain value (saturation current) when all the particles formed by external ionization take part in the conducting of the current. If the voltage keeps increasing the electrons gain sufficient energy so as to be able to ionise the gas molecules by collision (α-process).

This current is not self-maintained because it depends on external ionization source. The ions can however produce additional ionization by producing secondary electrons from the surface of the cathode (γ-process). When a number of secondary electrons becomes equal to the number of electrons that initiated the discharge it becomes self-sustained and external ionization is not necessary for the discharge current to flow. The voltage when this occurs is called a breakdown voltage and for the higher voltages the current is self-maintained. Paschen curves give the dependence of the intensity of the breakdown voltage (U_p) and the pd product, where p is pressure and d is gap between electrodes. γ-coefficient represents the efficiency of producing secondary electrons per ion hitting the electrode and it depends on the cathode material, the ion itself and its energy which is determined by the ratio E/N (E-electric field, N — gas particle number density).

Since the positively and negatively charged particles have different masses the positive and negative charges move with different speed so that the space charges do not compensate one another completely. The outcome of this is an uneven division of the charged particles, electric field and voltage between the electrodes. The division of charged particles, electric field and voltage can be determined if we know the spatial distribution of photons which are the result of collision of accelerated particles. Different visible parts of the glow discharge are: cathode dark space, negative light, Faraday's dark space, positive column and anode dark space [1]. There are also Crook's dark space, cathode light that on the account of high pressure under which the experiment was conducted, was not possible to see (cf. Fig. 10).

2. Description of the method

Vacuum system and the measuring equipment were connected according to the scheme supplied (Fig. 1). It was conceived that a vacuum pump should pump the air out from the ionization chamber and that low leakage rate would enable us to operate with the sealed system for sufficient lengths of time. Different gases were to be used for the measurements. Unfortunately on the account of poor-quality pump such operation could not be achieved. Thus we operated in the gas flow regime with air as the only gas studied.

The mechanical pump pumping on itself reached pressures of 9.3 Pa. In the course of the experiment the following was measured: voltage (U), breakdown voltage (U_p), current (I), pressure (p). By means of a CCD camera connected to IBM PC compatible computer the light emission was also recorded. The high voltage was measured with an uncertainty of ± 5 V by a voltmeter which was installed in the high voltage source. The pressure was measured by two appliances: thermo couple gauge (TCG) and a capacitive gauge MKS Barathron. TCG was used for measuring the pressures above 266.6 Pa with an instrumental error of ± 66 Pa. The readout of the instrument was calibrated to take out the scale multiplying coefficient and the offset of the scale as can be seen in Table. Capacitance gauge was used for low pressure calibration, and atmospheric pressure was used for the higher part of the scale.

Table I. Comparison of pressure values measured by capacitive and thermo-couple gauges.

Measured pressure by Barathron [Pa]	Measured pressure by TCG [Pa]
101323	73315
133	133
13.3	26.6

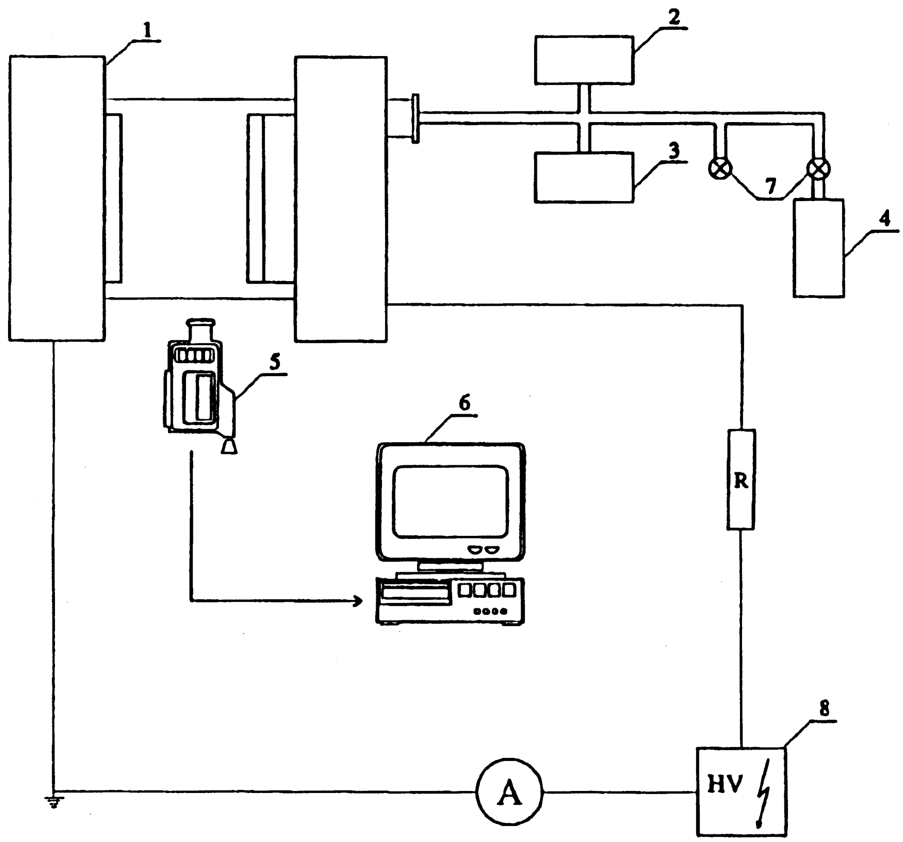

Fig. 1. Scheme of experimental set-up. 1. Parallel plate discharge chamber, 2. thermo couple gauge, 3. MKS Barathron, 4. vacuum pump, 5. CCD camera, 6. the IBM PC with video blaster interface, 7. valves, 8. high voltage generator.

Capacitance gauge was used for the pressure under 266 Pa, the uncertainty in this range comes down to an error in readout ±0.13 Pa and the error of the appliance itself which amounts to 0.2%, according to the manufacturer's data.

Light emission was recorded by a CCD camera, where one could not take off the IR filter, so that only the visible part of spectrum was recorded. The recordings were analysed by means of software written especially for the purpose of the experiment. The program itself self converts the picture in the standard PCX format to the matrix, parts of which had the values of the light intensity from the picture. The 8 bit analog to digital conversion sets the limit to the resolution of the intensity and corresponding spatial distribution.

There is an error setting the exact position of electrodes of approximately 5%. The lines which contain maxima of the light intensity were set from matrix. With a help of such graphic representations the length of the cathode dark space has been determined from the position of the maximum light intensity. Care was taken to ensure that there is no saturation of the camera.

During each dismounting of the chamber all the parts were cleaned by ethyl-alcohol. At first the breakdown voltage was measured for $d = 1$ cm, $d = 2$ cm, $d = 3$ cm as a function of pressure. Results changed significantly from a series of measurements to another. Stable operating conditions were achieved only when the current of 30 μA was used to condition the cathode for at least 30 min. The measurements were repeated for $d = 1$ cm, $d = 3$ cm.

3. Results

The results obtained during the measurements are presented in figures and tables. In the course of the first set of measurements Paschen curves for different gaps between electrodes varied from the expected scaling (Fig. 2).

In the second set of measurements (after cathode stabilization) Paschen curves obtained for different electrode gaps coincide and they also agree with theoretical curve (Fig. 3).

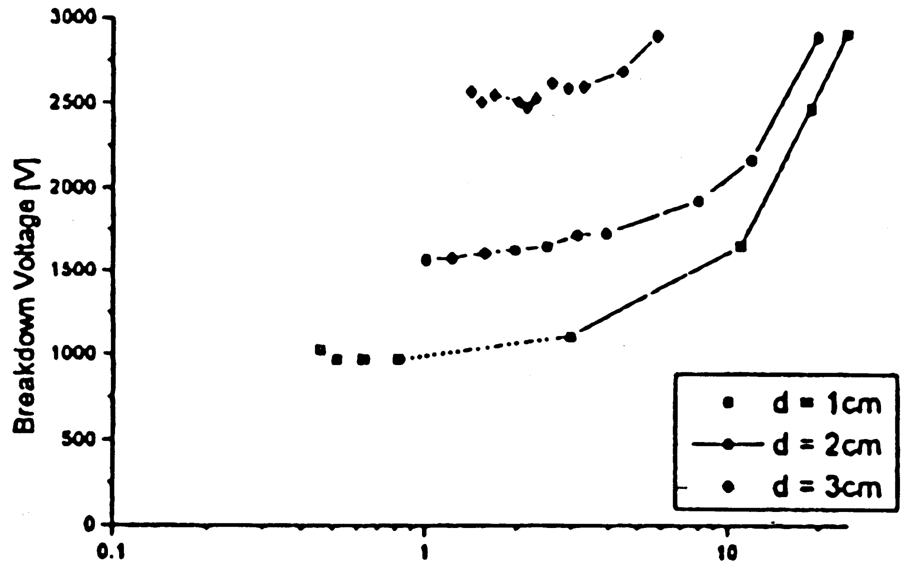

Fig. 2. Paschen curves obtained for measurement before the conditioning of the cathode.

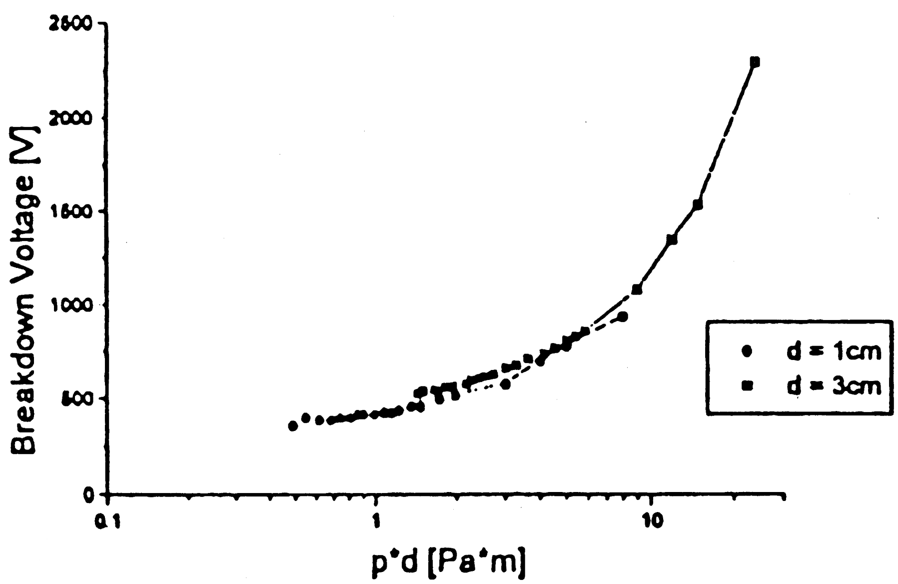

Fig. 3. Paschen curves obtained for measurements after the conditioning of the cathode.

Secondary electron yield γ was obtained from Paschen curves by transformation of the formula [2]:

$$U_p = \frac{Bpd}{\ln\left[\frac{Apd}{\ln(1+1/\gamma)}\right]}, \qquad (1)$$

into formula

$$\gamma = \exp\left[\frac{-Apd}{\exp\left(\frac{U_p}{pdB}\right)}\right], \tag{2}$$

where the values pd and U_p are obtained from experiment and A and B represent constants which determine the ionization rate coefficient taken from the literature [2]. In the first set of measurements, values of γ-coefficients do not coincide with one another. After the conditioning of the cathode (second set of measurements) the curve for γ-coefficient are in reasonable agreement (Figs. 4 and 5).

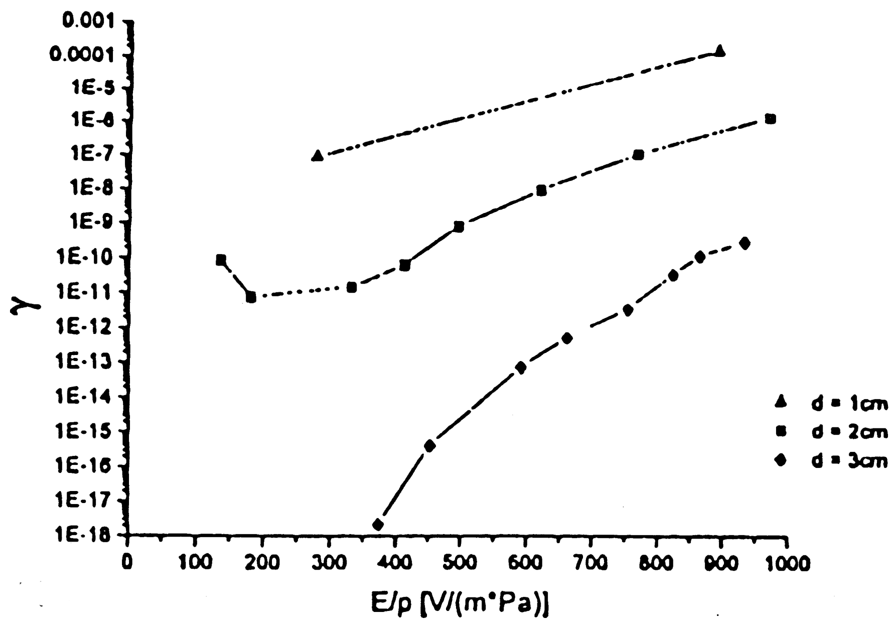

Fig. 4. γ-coefficient obtained from data in Fig. 2.

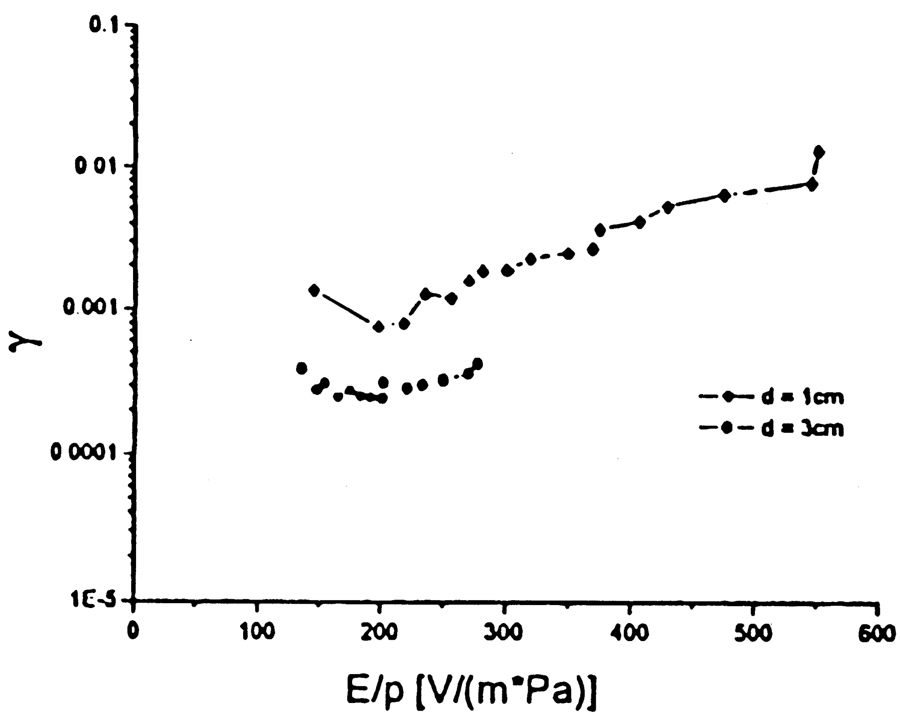

Fig. 5. γ-coefficient obtained from data in Fig. 3.

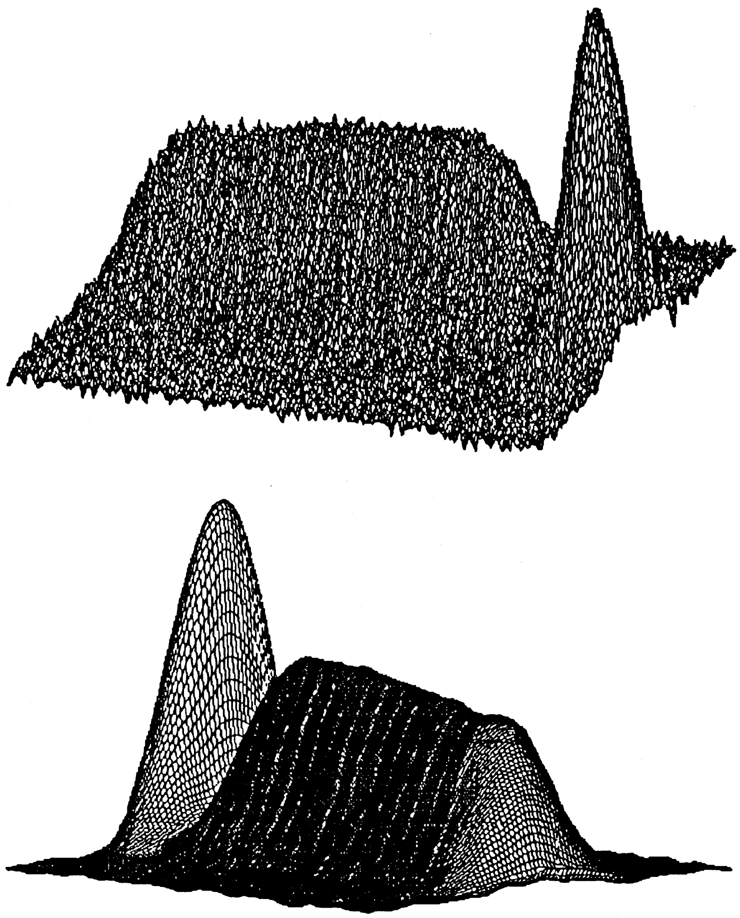

Fig. 6. An example of two-dimensional distribution of emitted light intensity. View on two opposite sides.

Matrices of the light intensity are shown by 3D graphs (Fig. 6). The 3D picture represents the convolution of the emission intensity and thickness of the cylindrical discharge, thus the maximum of intensity is in the middle of the radial profile. The axial profiles close to the maxima σ are taken to represent the axial distribution of emission. The axial profiles of light intensity as a function of the gas pressure and current are shown in Figs. 7 and 8, respectively. The position of the maximum intensity is taken to represent the edge of the cathode fall.

The intensity of electric field $E(x)$ on the cathode ($x = d_k$) is calculated assuming linear dependence of electric field [3]

$$E(x) = E_0 \left(1 - \frac{x}{d_k}\right), \tag{3}$$

$$U_k = E_0 \int_0^{d_k} \left(1 - \frac{x}{d_k}\right) \mathrm{d}x. \tag{4}$$

Hence, for $x = d_k$

$$E_0 = E(d_k) = 2\frac{U_k}{d_k}. \tag{5}$$

4. Discussion

For the first series of measurements of the breakdown voltage the Paschen curves considerably deviated from the expected values and did not coincide with one another.

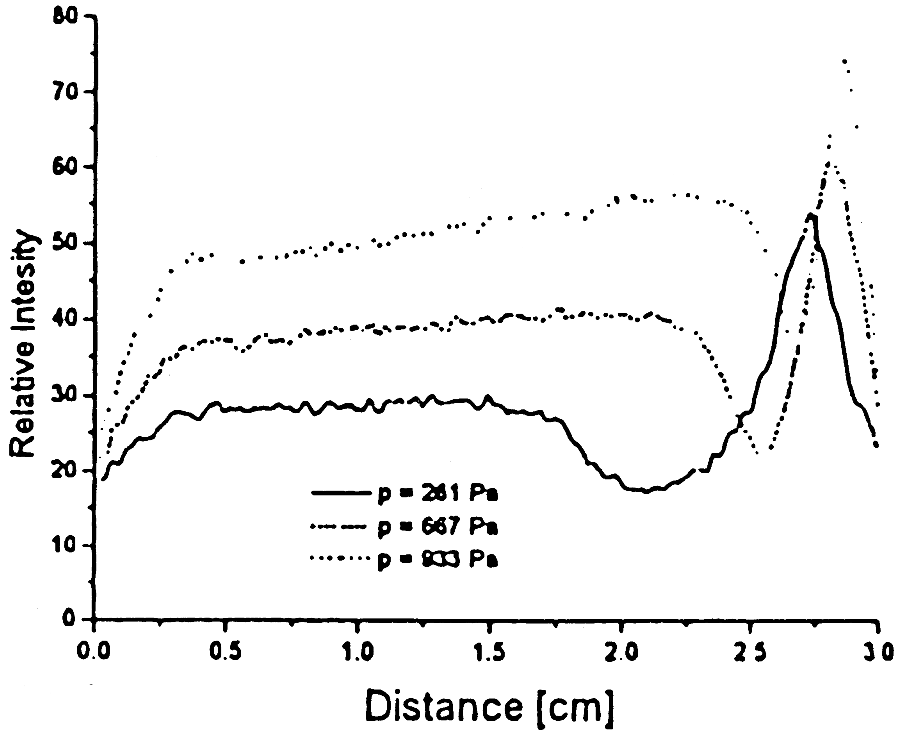

Fig. 7. Spatial distribution of emitted light as a function of the pressure ($I = 50\ \mu$A).

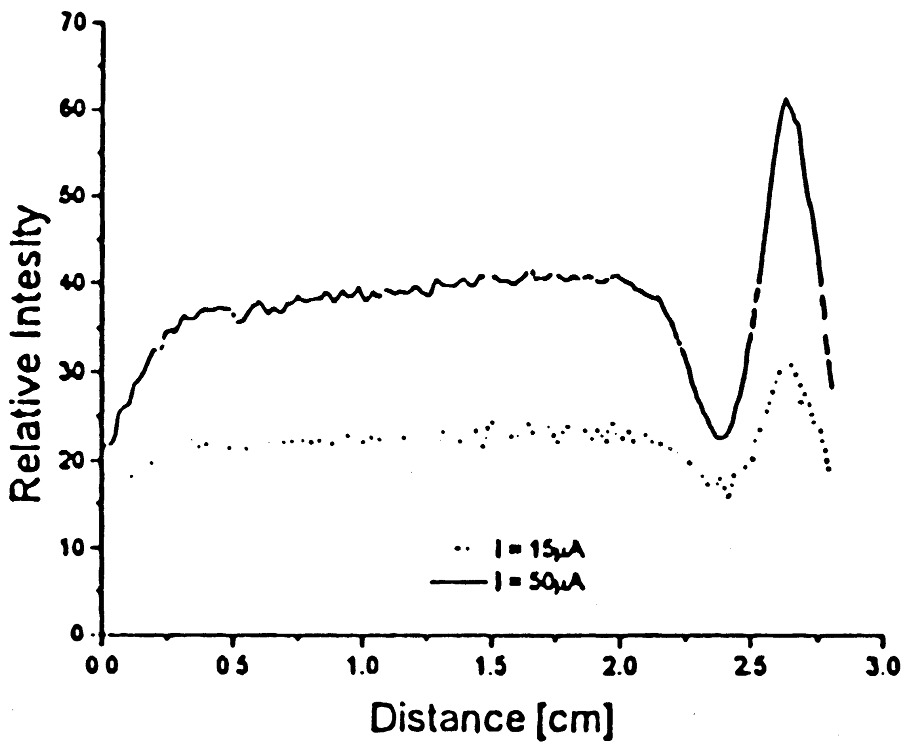

Fig. 8. Spatial distribution of emitted light as a function of the current ($p = 715$ Pa).

This disagreement was most probably the result of the variable conditions on the surface of the cathode. There are at least three possible layers on the surface of the cathode: an oxide layer, an adsorbed gas layer and an organic impurities layer.

The oxide layer is formed by oxidization of Cu in the air and it is stable. Its γ-coefficient is higher than the coefficient of the atomically clean Cu surface. The oxide layer, due to the different conducting characteristics changes the electric field on the surface of the cathode, decreasing the breakdown voltage (Malter's effect-electron emission caused by a large field which is formed on the oxide layer because of the accumulation of ions on the surface which cannot be neutralised).

The adsorbed layer consists of gas molecules which "get suck" into the cathode surface. Gas ions must have bigger energy so as to penetrate through the adsorbed layer and eject the electrons which on the other hand, must have enough energy to pass that layer and reach the gas. The adsorbed layer is, as a rule, connected with the gas in the chamber and stabilization should not change it. It is possible, however, by stabilization, to change characteristics of the surface with which the layer is connected, so that it is possible to effect this process too [4].

Finally, there is a layer of organic impurities on the cathode which was added in the course of assembly of chamber. In addition oil vapours can diffuse into the chamber because we did not have a cold trap and coat surface. Organic impurities were partly removed by ethanol. The cathode was also stabilised by applying 30 μA current during 30 min. By stabilization of the cathode the organic impurities could be removed. Using this method the adsorbed layer is removed, too, but it accumulates again after the ceasing of the current flow through the chamber. By stabilization of this kind oxide layer Cu cannot be completely removed.

The conclusion is that in order to obtain reproducible results in gas discharge physics, when results depend strongly on cathode processes, care must be taken to stabilise the surface of the cathode (Fig. 9). It is not certain which type of surface processes was responsible for the conditioning of the cathode but in this case it is most probable the removal of the organic impurities and homogenization of the oxide layer. The results of the second series of measurements and the Paschen curves obtained, within the experimental error, comply with the theoretical values.

The some failure of the results to be reproducible before conditioning is apparent from the graph of the γ-coefficient (Fig. 4). For the first series of measurements the graphs of γ-coefficient do not coincide with one another which indicates that the characteristics of the cathode in each measurement were different. The curves of γ-coefficient for measurements after stabilization of the cathode reasonably agree with one another (Fig. 5).

The 2D picture of the glow discharge as shown in Fig. 10 represents the anatomy of the discharge: cathode dark space, negative light, Faraday's dark space and positive column [5].

In the cathode dark space the electrons ejected from the cathode increase their energy and generate new electrons and positive ions by means of alpha process [6]. Positive ions have smaller directed velocity than electrons due to its large mass so that in the space of negative light, the electric field intensity drops to zero [3]. This process is called a cathode voltage drop and depends on the nature of gas and the nature of cathode. If the reduced width of the cathode dark space pd_k (d_k — width of cathode dark space, p — gas pressure) is known, it is possible to calculate the electric field on the cathode [2] assuming linear dependence of field (5)–(7).

Electrons that enter negative light could be divided into at least two groups. The first group consists of the electrons which originate from the cathode and have high energy. Some of those electrons have suffered a certain number of collision in the cathode dark space and negative light space. In those collisions secondary electrons are produced. The second group of electrons do not have sufficient energy so as to ionise gas molecules, but their energy is higher than the minimum excitation energy. A number of those electrons is greater than the number of electrons from the first group. Excitation by both groups is

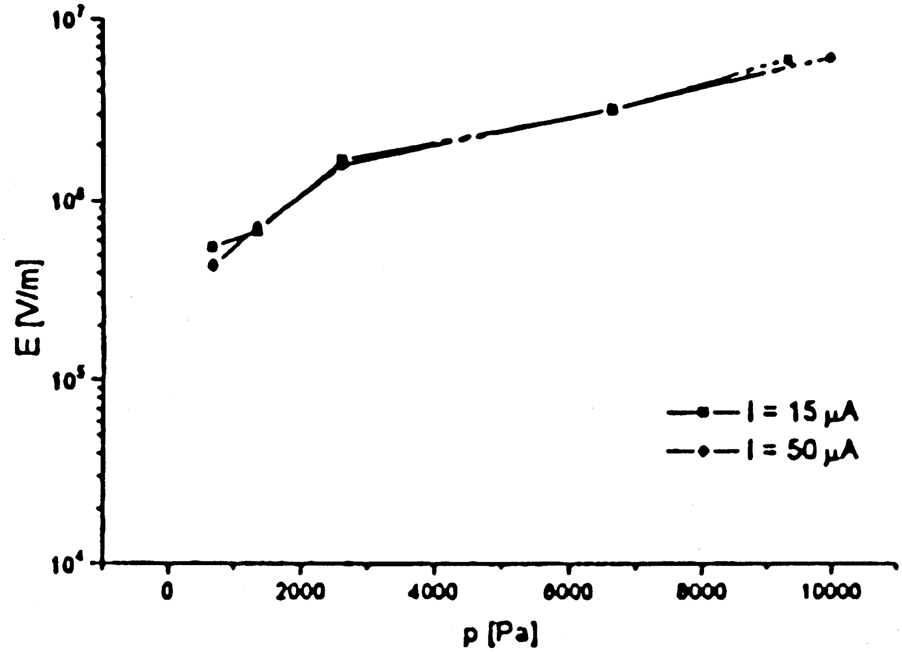

Fig. 9. Electric field on the cathode as a function of pressure.

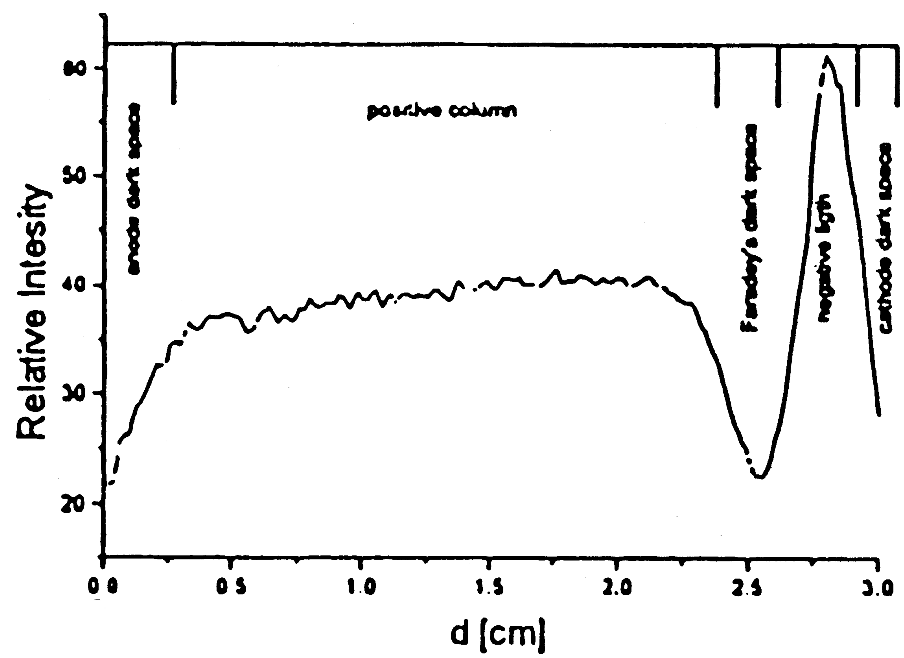

Fig. 10. Visible parts of glow discharge.

the source of strong emission in the negative light space. On the account of weak electric field recombination of the electrons and positive ions is possible [5].

Faraday's dark space, according to its characteristics, comes between negative light and positive column. In Faraday's dark space the electric field grows towards the positive column, where the recombination possibility decreases [3].

The positive column has a passive role. It follows the shape of the tube in which discharge takes place. Energy of electrons in the positive column is strong enough for ionization and excitation of gas molecules although the directed speed of electrons is low. The field in the positive column is small but it is non zero and it is required to compensate the losses of charged particles due to radial diffusion and recombination. The density of positive and negative ions is equal in each point of positive column. The ionised gas in the positive column is called plasma [6]. However, the positive column is not necessary for the discharge to operate. If the distance between electrodes is small enough the positive column can be omitted (Fig. 11).

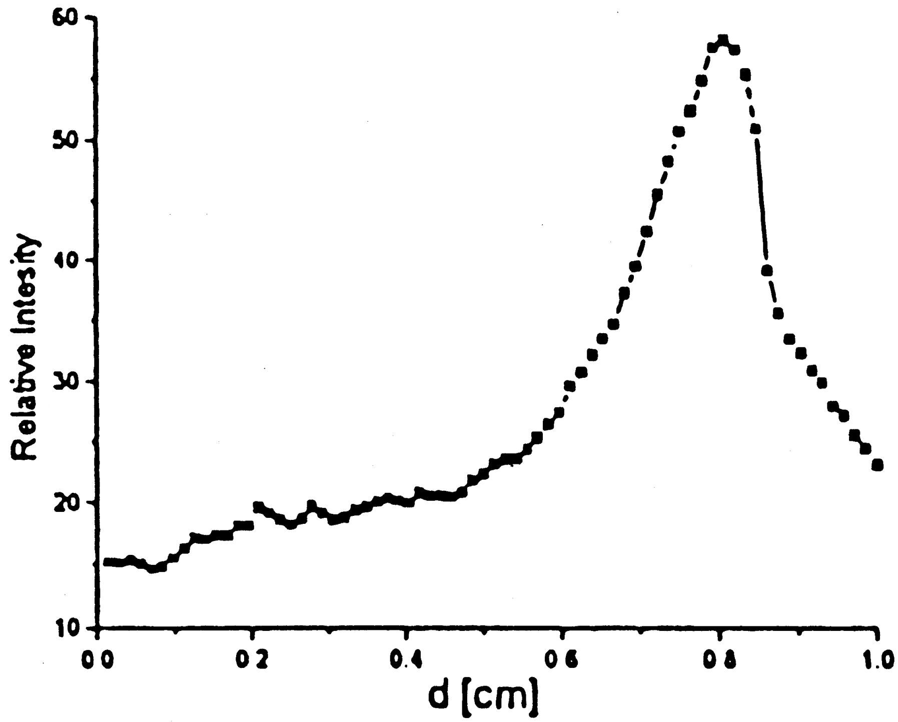

Fig. 11. Spatial distribution of emitted light.

Figures 7 and 8 illustrate the behaviour of these parts of discharge as a function of pressure and current. With the decrease in pressure the distance between light spaces is enlarged, boundaries between zones become diffuse, the positive column recedes towards the anode and light intensity decreases (see Fig. 7). When the current intensity is increased, while the pressure remains constant, discharge becomes lighter, it can acquire a different colour, and the zones, also, become more clearly demarcated (see Fig. 8).

5. Conclusion

Since the measured values, obtained after the cathode stabilization, agree generally with the values from the literature a conclusion can be drawn that impurities on the cathode change the breakdown voltage considerably, as the γ-coefficient. The variation of the spatial distribution of light on relevant parameters such as pressure and current appears as expected from the literature [5] as well as simple phenomenological description of the pertinent processes in the gas discharges as presented in standard textbooks [3]. It seems that impurities on cathode do not affect the variation of the light distribution. The results obtained for the intensity of electric field and γ-coefficient have large error bounds due to inaccurate pressure measurements. However the general trends and relative values behave as found in the scientific literature [5].

Considering the poor quality of the equipment that was available and a short period of three days in which the experiment was assembled and conducted one can be satisfied with the results obtained and their agreement with the expected values. Experiments should be repeated with the more precise equipment in order to determine correct influence (effect) of different impurities on the processes in gas. Nevertheless, the processes suited in this paper are of interest in fundamental studies of gas discharges and have been a subject of more serious and better equipped and recent studies [7].

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References

[1] H.J. Oskam, *Gaseous Electronics*, Vol. I, Academic Press, New York 1978

[2] J. Labat, *Fizika Jonizovanih Gasova*, Belgrade 1991 (in Serbian)

[3] A. von Engel, *Ionizied Gases*, Clarendon Press, Oxford 1965

[4] H.D. Hagstrum, *Phys. Rev.* **104**, 1516 (1956)

[5] B. Chapman, *Glow Discharge Plasmas*, John Wiley and Sons

[6] S.C. Brown, *Introduction to Electical Discharges in Gases*, John Wiley and Sons, 1966

[7] A.V. Phelis, Z.Lj. Petrovic, B.M. Jelenkovic, *Phys. Rev. A* **47**, 2825 (1993)