Mechanism of Partial Discharges in Free Helium Bubbles in Transformer Oil

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ABSTRACT
Partial discharges (PD) in floating bubbles and in microspheres made from thin glass walls in transformer oil were studied experimentally and theoretically. In a test cell, the PD occurrence was a very rare event. Sometimes PD in bubbles occurred after exposure for more than 10 hours at a voltage that corresponds to a value three times the voltage in accordance with Paschen's law. In the case of a glass microsphere, PD takes place at a voltage according to Paschen's law after several hours but afterwards PD occurs more frequently. The reason for this is in the starting electrons which initiate the first avalanche. It is shown with 100 keV X-rays that PD occurs in all bubbles and its inception voltage corresponds to Paschen's law. Theoretical analysis shows that, at the conditions of PD occurrence in helium bubbles, breakdown fits the streamer mechanism. Registrations of electrical and optical signals of PD were performed to estimate apparent and true charges and the number of radiated photons. As a result of the evaluation, the number of electrons is approximately equal to the number of photons.

Index Terms — **bubbles, partial discharges, oil insulation, hydrodynamics, electric field effects, simulation**

1 INTRODUCTION

THE behavior of bubbles in oil filled high voltage equipment is a frequently discussed problem. Among all oil-filled apparatuses, the power transformer is one of the important and expensive units in power system. For this reason it must serve reliably for decades. According to failure statistics, a noticeable part of transformer outages is due to insulation damage. It is known that partial discharge (PD) activity leads to an accelerated aging and as result to breakdown of insulation.

There are different sources of local discharge processes in a transformer: corona from metallic protrusions in oil, PD in voids of solid dielectric, adhesive gas bubbles and surface discharges on pressboard. One of the most important elements in a power transformer is the oil-barrier insulation between the high and low voltage windings. Oil flowing in the channel between the barrier insulation and the high voltage winding has two functions: insulating and cooling of the windings. The appearance of free bubbles in the oil channel and PD in the bubbles may become the cause of insulation breakdown and transformer failure. So, this type of PD is the subject of the paper. Some PD characteristics (PD inception voltage as a function of the bubble size and phase-resolved patterns) are investigated in air and vapor bubbles [1].

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The aim of this work is to analyze the physical picture of PD in a free helium bubble. There were two reasons for using helium. First of all, the electrical strength of helium is lower than that of air, which makes it possible to reduce the test voltage and the level of interference during PD measurement. Second, for helium, a greater number of electrical, chemical and other characteristics are known, that simplifies our analysis of the PD mechanism. The analysis shows that under the conditions of occurrence of PD in helium bubbles, the discharge mechanism corresponds to the streamer one. The recording of the electrical and optical PD signals was carried out to estimate both the charge and the number of photons emitted from discharge area.

2 EXPERIMENTAL SETUP

The main part of experimental setup is shown in Figure 1 is nearly the same as described earlier [2,3]. However, two different experimental setups were used to obtain the results presented in this article. In the first case (free-floating bubbles), a high-speed video camera (6) and a photomultiplier tube (7) were used for registration. They were located coaxially. Illumination of the interelectrode gap was carried out in the upper part of the cell.

In experiments using an X-ray source (9), the photomultiplier was absent. The experimental setup included a high-speed video camera (6) installed coaxially with backlight (lamp) (7) for the optical detection of the PD in the bubble (3).

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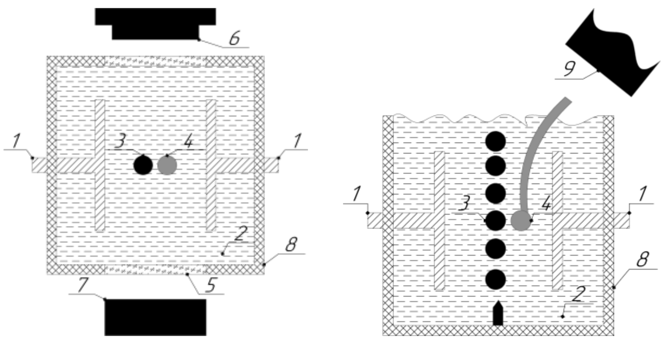
The X-ray unit (9) was installed at 45^0 above the high-speed video camera (6). Electrodes (1) were installed in the PMMA cell (8) with an interelectrode gap of 6.8 mm. Optical glass windows (5) were made in the cell walls. The cell was filled with the mineral oil GK (2) and PD was detected using a coupling capacitor and registered by the digital oscilloscope, Rigol DS 1204. Bubbles with diameters of 1.5 ± 0.1 mm were generated approximately at 50 bubbles per second. The calculated inception voltage for helium bubbles according to Paschen's curve was 6 kV. In our experiments, the voltage of PD inception was 15 kV. However, the waiting period of PD appearance sometimes exceeded 10 hours which is many times more than estimated [4].



a) view from above b) side view

Figure 1. Experimental setup.

2 EXPERIMENTAL RESULTS

2.1 FREE BUBBLE

The display of digital scope with traces of electrical and optical PD signals for a freely floating up bubble is shown in Figure 2. One can see that the pulses have the same shape, the leading edges of the pulses are the same, and the falling edges of the pulses are slightly different. The delay of optical signal followed due different lengths of measuring cables and the time of flight of electrons in a photomultiplier. The rise time of both signals was about 20 ns.

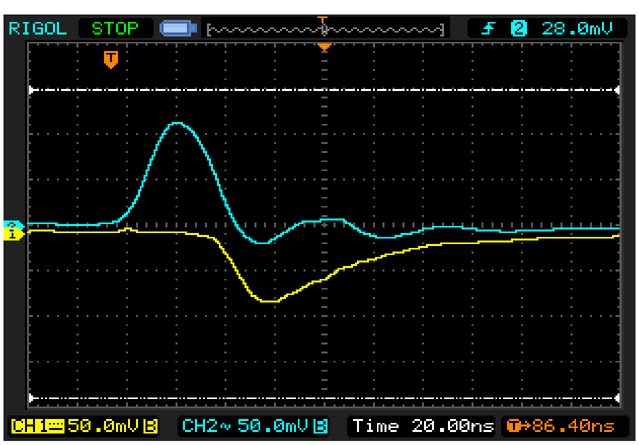


Figure 2. Electrical (upper blue curve) and optical (yellow lower curve) signals of PD.

2.2 FREE BUBBLE, GLASS MICROSPHERE AND TWO BUBBLES

Simulations of the PD in several closely spaced bubbles and spheres, with the purpose to find differences and to try detect the PD jump mechanism from one bubble to another, were performed earlier [5]. We performed the experiments to study the possible effect of PD in one bubble to the inception of PD in a neighbor bubble. We did not find any effect when the bubbles floating up at very close distances forming a chain oriented perpendicularly to the electric field lines. Then, we placed the stationary cavity (glass microsphere, Figure 3) inside the gap in such a way that the bubbles floating up touch the glass microsphere. Here we used helium bubbles and the microsphere was filled with air which was glued to a thin nylon thread. Thus, we anticipated that a partial discharge in the microsphere would lead to discharge in the bubble.

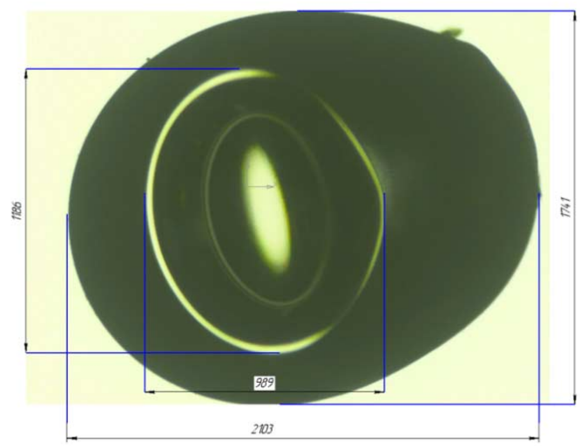


Figure 3. Microsphere, sizes in micrometers.

The average electric field strength in a gap was 3 kV/mm (at instantaneous voltage value of 30 kV and an interelectrode gap of 10 mm). At a given electric field strength, PD in the microsphere occurred frequently. Only several PD events in bubbles occurred but PD did not develop near the microsphere. At the same time, we managed to direct the bubbles in such a way that at some moment of time the bubble and the microsphere were in line with the electric field. More than 1000 contacts of the bubble and microsphere were observed, however, no inception of PD in the bubble was

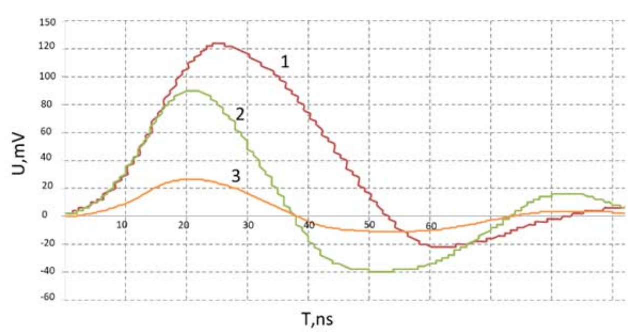


Figure 4. Electrical signals of PD in bubble at U=20 kV (3 kV/mm) – 1, in microsphere at U=33 kV (4.9 kV/mm) – 2, at U=22 kV (3.2 kV/mm) – 3.

registered. It should be noted that the PD in microsphere occurred at least several times during the passage of the bubble by the microsphere. It appeared that these events are independent ones.

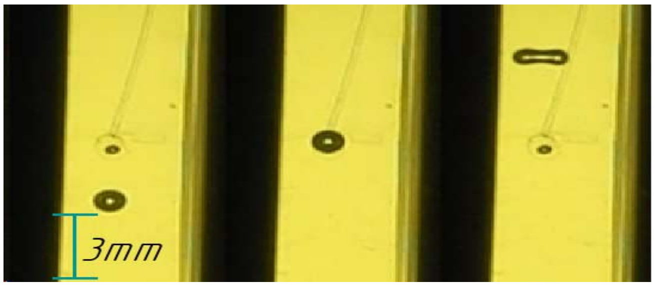


Figure 5. Bubble movement close to the sphere. First frame was made before contact with the sphere, second frame was at the contact, and the third frame was made after the bubble moved away to the long distance from the sphere and PD in the bubble occurred.

In addition, experiments were carried out with two bubbles located in the direction of the electric field. For this purpose, the bubble injector was modified so that it produced simultaneously two bubbles located on the same field line at the same time. PD was quite rare, but five registered cases of PD (out of more than a hundred bubbles) led to the development of PD in two bubbles, one after another (Figure 6). All these observations allowed us to believe that in the case of the microsphere, the charge deposited inside on its wall after PD is too small to increase significantly the intensity behind a fairly thick (~ 1 mm, Figure 3)) wall of the sphere. The electric field strength in experiments with two bubbles was 2.8 kV / mm (with the applied voltage of 28 kV and the interelectrode gap of 10 mm). Three subsequent frames representing the dynamics of the pairs of bubbles before and after PD are shown in Figure 6. The PD occurred in one pair only (upper one in the picture) but we can see that the discharge began in the left bubble and then jumped to the right bubble.

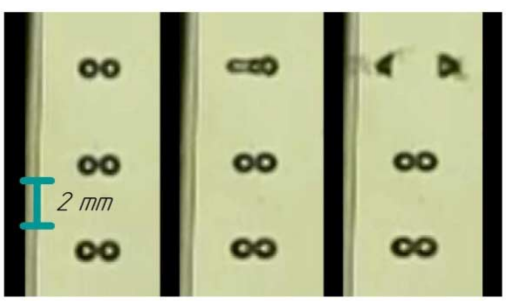


Figure 6. Two cases confirming the occurrence of PD in two closely spaced bubbles on the same electric-force line. Time in each frame is from left to right.

2.3 FREE BUBBLES WITH X-RAYS

To ensure the supply of initiating electrons, illumination from ultraviolet or x-ray radiation has been used by researchers. In nearly all reported work, a sharp decrease in the PD inception voltage was observed. In [6] x-ray unit (150 kV, 1200 mA) was used to test more than 340 epoxy support GIS 138 kV insulators produced with controlled defects. When exposed to x-rays, the frequency of the pulses of the PD increased and the voltage of occurrence sharply decreased; when irradiated with x-rays, PD inception was 25 kV and without x-rays, the PD inception was over 400 kV. From experience, the ideal dose to maintain the discharge activity was estimated at 0.5 mR/s (milliroentgen per second) in the area of the cavity in the body of the insulator when using radiation. More intense radiation led to overionization and high conductivity of the internal volume of the cavity. The x-ray tube was installed on a special table, and the beam could scan the entire volume of the sample. The beam could collimate with an error of up to 3 mm for error-free location of the place of PD in the insulator body.

Some manufacturers of electrical equipment use x-ray radiation of the internal volume of switchgear under high voltage tests [7, 8]. It was noted [8] that even a short duration (5 ns) pulse illumination by x-ray leads to a decrease in the voltage of the PD by 2-5 times (depending on the size of the cavities) at the standard rate of rise of the test voltage.

X rays were used as possible source of initiating electrons in our experiments. The first attempt was made using a 8 keV source and no PD was registered over several hours at 15 kV. The second attempt was with a MIRA 2D impulse x-ray source, with energy of 80 keV. Most of the experiments were carried out with helium bubbles. The voltage inception of partial discharges in helium bubbles of 1.5 mm diameter in transformer oil for our conditions was about 6.6 kV. Over the course of the experiments with X-ray radiation, it was revealed that Paschen's law is strictly observed, unlike in the case without using additional ionization sources [2,3]. Figure 7 shows frames of video recording of partial discharges of helium bubbles in transformer oil at a voltage of about 7.8 kV (amplitude).

Figure 7. Partial discharges in helium bubbles when exposed to x-rays.

PD was observed in all bubbles and without waiting time as observed in [2]. It should be noted that in absence of voltage the separate effect of X-rays was insufficient for bulk ionization of bubbles. The next series of experiments were performed with lower intensity of x-rays at voltages close to the PD voltage inception.

In Figure 8, in the third and the fourth frames, PD occurred in four of seven bubbles subjected to high electric field. The bubbles deformed but did not break into two bubbles. Other three bubbles had no visible deformation then PD did not occur in them. Nevertheless, in the case of a very large shielding (4 mm thick lead plate placed at the exit window of the apparatus), PD occurred occasionally. The action of the higher field in comparison with previous case results in bubbles being destroyed with PD in it.

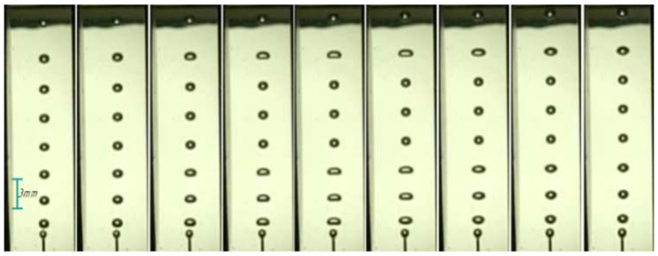


Figure 8. PD in free bubbles with decreased intensity of x-rays. Voltage amplitude 10.8 kV;10 mm interelectrode gap.

Then the similar experiment with air bubbles was carried out, the results were practically the same. Qualitatively, the partial discharge pattern in the air bubble does not differ from that in the helium bubble.

3 DISCUSSION

3.1 DIFFERENCES BETWEEN PD INSIDE BUBBLE, MICROSPHERE AND IN TWO BUBBLES

The shapes of the PD signals in a free bubble and in the microsphere are similar (Figure 4). The differences are in apparent charge and in time duration. In our opinion the reason of the last one is in changes of inner diameters of inclusions. The leading edge of the PD pulse is approximately 30 ns in the case of a bubble and 20 ns in the case of a microsphere. The diameter of a bubble is one and a half times greater than the inner diameter of a microsphere. That is why the electron transit time in the inclusion at a close velocity of the electrons is proportional to the size of the inclusion. Unfortunately, the rise time of oscilloscope was too large for correct estimation of velocity and mobility of electrons in discharge process.

As for as apparent charge, the computation (including form of microsphere wall) shows results close to experimental ones. The results for bubbles were presented earlier [2,3].

Computation of apparent charge in a microsphere took into account that the sphere is made of molybdenum glass with a dielectric constant of 7, the outer diameter was considered to be 1.6 mm, and internal diameter was equal to 0.95 mm. The distributions of the electric field component along the direction from one electrode to another are shown in Figure 9 before the beginning of PD and after PD. The relative dielectric permittivity was 2.2 that correspond approximately to the relative permittivity of mineral oil in our experiment. The white plots in Figure 9 show the component of the electric field along the symmetry axis. It is seen that charge deposition on the inner wall of cavity does not change significantly the value of the electric field stress on the outer wall of the cavity. Our calculations gave an apparent charge of 13 pC at 17 kV. The corresponding true charge inside the glass cavity was 159 pC.

Our measurements performed at the same voltage gives a value from 7 up to 17 pC. The reason of dispersion is due to adherent surface charge after previous PD. The amount of adherent charge depends on the voltage at the moment of PD which in turn the voltage depends on the amount of previous PD.

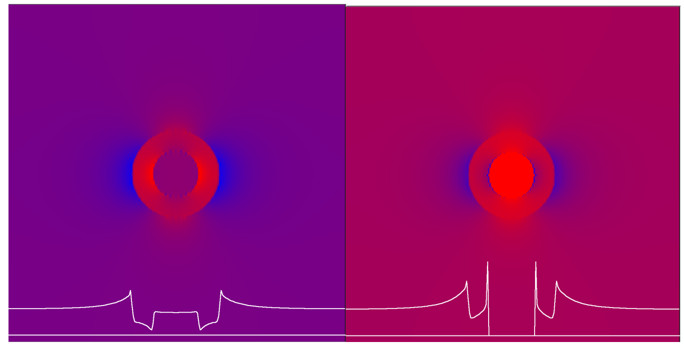


Figure 9. Electric field in dielectric with glass sphere before PD (left) and after PD (right). Red color corresponds to the lowest field values and blue color shows the highest field. Horizontal component of the field is shown (electrodes are on the left and right). Curves show the electric field stress along the axis of symmetry of the gap.

PD in a microsphere does not lead to PD in the nearby bubble. Experiments with PD in two bubbles located along the field line show that PD in one bubble surely led to the development of PD act in second one. In our opinion this may be due to several reasons: the sharp increase of electric field in second bubble past PD in the first one; the appearance of ions in the second bubble after PD in the first bubble due to their movement in the electric field; photoionization in second bubble.

3.2 MECHANISM OF BREAKDOWN IN A HELIUM BUBBLE

It is assumed that the breakdown nature in small gaps like bubbles is a multi-avalanche process [9,10]. Each avalanche produces next avalanche by the photoionisation or the ion impact on the surface. Nevertheless, the excess of experimental values of the PD inception voltage as compared with the estimates by the Paschen's curve leads us to test the possibility of implementing the streamer mechanism [12]. It was possible to find experimental data on the impact ionization coefficient in helium [13, 14] and the approximated curves are presented in Figure 10.

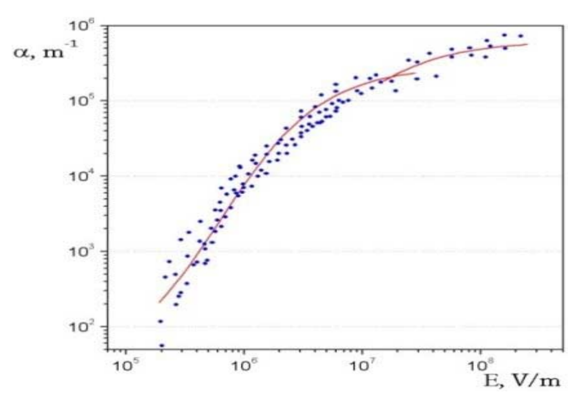


Figure 10. Approximation of the impact ionization coefficient α in helium. Blue points – experiments, curve – approximation [11].

Using an estimation of the field strength in the bubble, it can be determined that the impact ionization coefficient α is in the range $(4 \div 6) \cdot 10^4$ 1 / m, and for a bubble diameter of d = 1.5 mm, the product is $\alpha d > 20$, which indicates the streamer mechanism of PD inside these bubbles.

We carried out preliminary simulations of the initial stage of the discharge inception in a helium bubble placed to the center of the electrode gap filled with dielectric of relative permittivity of 2.2. The plane electrodes were used. We considered that bubbles are elongated in the external electric field and approximated the shape of the bubble with the ellipsoid of revolution. The diffusion-drift model was applied to simulate the avalanche development in helium. The equations of the model are similar to that in [15]. We took the detailed information on electron mobility at different electric fields, the first Townsend coefficient α and diffusion coefficients from known experimental data. The dependence of the electron mobility on the electric field was taken from [13, 16]. The experimental data [13, 14, 16, 17] on the Townsend coefficient cover the range from 0.001 to 370 Td and the diffusion coefficient within the range from 0.001 to 370 Td. It corresponds to the values of E from 100 kV/cm to 2 MV/cm at the atmospheric pressure in our case. The analytical approximations were made for these coefficients in the large range of the electric-field stress that were used in our simulations.

The diffusion and the mobility of ions are significantly smaller than for the electrons, and change not so greatly with *E*. Thus, the diffusion coefficient and the mobility for ions were considered to be constant for simplicity. The mobility and the diffusion coefficient for the helium ions in pure helium were taken also from [16]. The diffusion coefficient was D=0.27 cm^2/s and the mobility was μ=10.4 cm^2/V s. The recombination coefficient was taken from [18] for low density and low temperature. The average electric field E=V / d, the gap distance d, and the diffusion coefficient for ions D were taken as the basic units. In this case the time step in Figure 12 is measured in units of τ_0, where:

$$\tau_0 = 1.5 \cdot 10^{-5} \cdot d^2 / D_+ \quad (1)$$

D_+ is the diffusion coefficient of helium ions in pure helium.

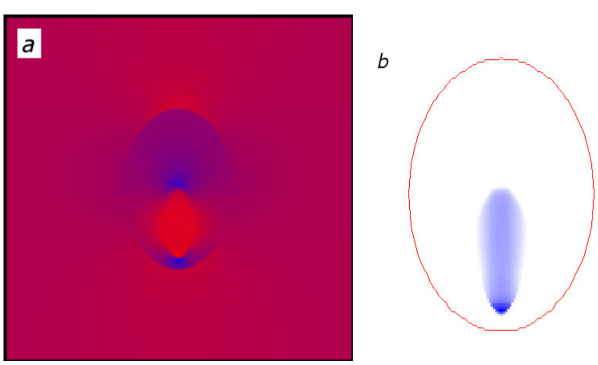


Figure 11. (a) Sketch of the electric field inside bubble, and (b) the shape of the streamer at the time point t4.

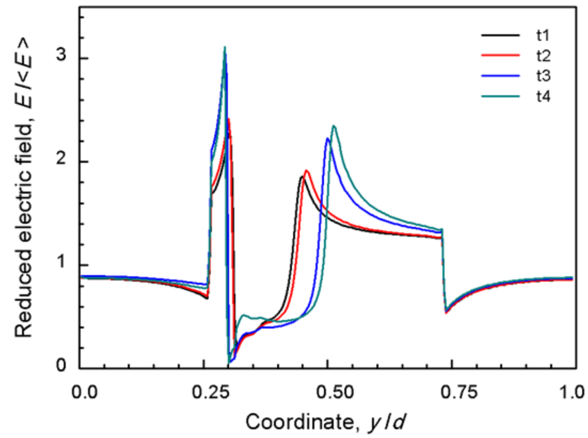


Figure 12. Profiles of the electric field $t_1=\tau_0$, $t_2=1.04\tau_0$, $t_3=1.44\tau_0$, $t_4=1.6\tau_0$.

The electrically neutral origin that was the mixture of electrons and helium ions with the Gaussian profiles was placed at that part of the bubble that is closer to the negative electrode. The calculations were performed for 12 kV applied to the gap, with 1.3 mm the maximum size of the bubble and 0.65 mm the minimum size (elliptic bubble).

The propagation of the avalanche increases the field ahead of the ionization front as shown in Figure 10 and Figure 11. It is seen that when the avalanche crosses approximately half of the bubble (along its large axis) the electric field at the head of the avalanche becomes comparable to the “external” electric field that was in the bubble before the ionization. It means that a streamer process starts at this distance. The role of the recombination is still small at this stage. Thus, we conclude that the partial discharge in a large enough bubble develops in form of a single streamer channel.

3.3 ESTIMATION OF PHOTON NUMBER IN COMPARISON WITH TRUE CHARGE NUMBER

The simultaneous registration of electrical signal of PD and the intensity of emitted light allow us to make estimation the ratio between the number of photons emitted and the number of charge carriers settled after the PD on the wall of a bubble. For usual avalanche the estimation of the ratio of emitted photons to charge of ions in avalanche gives 0.4 [9]. In our case, when streamer mechanism of PD inside bubbles is realized this ratio is unknown.

We analyzed of the number of photons taking into account their absorption in oil and assuming a uniform distribution within the solid angle [11]. We took into account also a sensitivity of the photo detector and the fact that only a part of photons hit it. These make it possible to estimate the number of photons. When the experimental work was planned, we assumed as one of the tasks of the work to determine the "radiation" coefficient equal to the ratio of the number of photons to the number of ionization events

$$n = N_p / N_i \quad (2)$$

Assuming the number of ionization events is equal to the number of ions deposited on the surface after PD, N_i value can be determined from the true charge value

$$N_i = Q / e \quad (3)$$

The true charge of PD, in turn, can be determined from the apparent charge by our method [20].

The estimation of the number of photons is less accurate. The current of the photomultiplier (PM) I corresponds to the light flux F (with the wavelengths in the visible region) using PM sensitivity S. Then

$$S = I / F \quad (4)$$

Here it is necessary to consider the combined spectrum of the two filters installed in front of the photocathode using the transmission characteristics of colored UV (300–400 nm) and blue (400–500 nm) glasses. This is the blue and near-ultraviolet part of the spectrum. To estimate, we take the wavelength at the violet edge of visible light of λ=400 nm. A photon with this wavelength has the energy of $Q=5\cdot10^{-19}$ J, its reciprocal value corresponds to the number of photons per second in 1 W radiation at λ_1 = 400 nm:

$$N_{ph}\,[1W]\,(\lambda_1) = 1 / Q\,(\lambda_1) = 2\cdot10^{18}\ [photons/sec] \quad (5)$$

For light with a wavelength of λ_2=555 nm, there the number of the photons N corresponds to the light flux F=683 lm

For a different wavelength, the light efficiency is lower by a factor of k_1, which means that the same number of photons will result in fewer lumens.

$$N_{ph[1lm]}\,(\lambda_1) = N_{ph}\,[1W]\,(\lambda_2) / 683/k_1 =$$
$$= 0.3\cdot10^{16}\ [photons\ /sec]/k_1 \quad (6)$$

Next, we use the PM spectral sensitivity S to determine the PM light flux incident

$$N_{ph[F]}\,(\lambda_1) = N_{ph}\,[1W]\,(\lambda_2) / 683/k_1/S\cdot I \quad (7)$$

The light flux emitted by PD will be larger, due to the geometric factor k_2 (the ratio of the area of the photocathode to the area of the sphere with a radius equal to the distance from the photocathode to the PD). In addition, it should be taken into account that the filters weaken the light flux. This coefficient k_3 was estimated through a decrease in the photomultiplier current when the filters were installed. Then the number of photons emitted by the PD is:

$$N_p = \frac{N_{ph}[F](\lambda_1)}{K_1 K_2 K_3} \quad (8)$$

For the conditions, in our experiments voltage U = 30 kV, the estimated true charge is about 2900 pC, and the number of ions deposited on the surface of the bubble was $1.8\cdot10^{10}$ particles. Estimates for Expression (8) for the number of emitted photons give approximately $0.7\cdot10^{10}$ photons. Then the value n in Equation (2) becomes ~ 0.3 ÷ 0.4, approximately.

Surprisingly, this value is close to the one previously determined in the classical work of Raether [9], n=0.4, despite of another gas and its pressure. The above estimates do not have high accuracy, and, apparently, it can be argued that for PD, the number of generated is approximately equal to the number of excited molecules or, more precisely, the number of emitted photons.

It is shown that if we take the registered apparent charge of PD, determine the true charge, and divide it by the electron charge, then this obtained value is approximately equal to the number of photons. It means, for a given kind of discharge (streamer one), that the number of the excited molecules is approximately equal to the number of the ions.

4 CONCLUSIONS

Analysis of the experimental data and simulations allow us to conclude that the PD inside a helium bubble develops in the form of a streamer. The number of excited atoms in this case is approximately equal to the number of ions in PD.

Partial discharge in the microsphere does not lead to PD in the nearby bubble. Experiments with PD in two bubbles located along the field line shows that PD in one bubble surely led to the development of PD in second one.

At x-ray action the partial discharges appear in all bubbles that are in the region of increased electric field strength. The waiting time of the partial discharge is absent.

ACKNOWLEDGMENT

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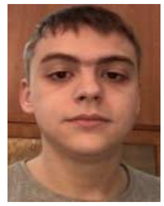

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