ISSN 1063-780X, Plasma Physics Reports, 2024, Vol. 50, No. 8, pp. 991–998. © Pleiades Publishing, Ltd., 2024.

LOW-TEMPERATURE PLASMA

# On the Processes of Charging the Wall of a Discharge Tube under External Illumination

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Received June 14, 2024; revised June 24, 2024; accepted June 25, 2024

**Abstract**—The breakdown and discharge ignition in discharge tubes with a diameter of about 1 cm and a length of 80 cm in inert gases (neon, argon, krypton, and xenon) at a pressure of about 1 Torr are studied experimentally. The tube is illuminated by radiation from continuous or pulsed light sources in the visible spectrum range. A ramp voltage with a small slope steepness (of about 50 V/s) is applied to the anode of the tube. Previously, the authors established that under these conditions external illumination can increase the breakdown voltage in several times. This effect was explained by the appearance of a charge on the tube wall as a result of photodesorption of electrons from its inner surface. In this work, it is found that charging the wall begins only when the anode potential approaches the breakdown potential measured without illumination. In addition, it is found that during the increase in the voltage on the anode and charging the wall, the anode potential differs from the breakdown potential by a constant and small value (less than 200 V).

**Keywords:** breakdown, discharge tube, ionization wave

**DOI:** 10.1134/S1063780X24601147

## 1. INTRODUCTION

Illumination of a discharge tube with visible radiation can significantly affect the breakdown characteristics in the tube: the breakdown voltage $U_b$ and the breakdown delay time (see [1] and references therein). In recent studies [2–4], it was found that the potential $U_b$ can change under illumination: either decrease or increase depending on the rise rate of the applied voltage $dU/dt$. The first option is implemented at a high rise rate of the voltage, and the second option at a low rate (Fig. 1). According to [3, 4], the initial cause in both cases is photoemission of weakly bound electrons adsorbed on the inner surface of the discharge tube caused by illumination. These electrons are affected by the field existing between the wall and the anode. At a rapid increase in the applied voltage, they are very likely to be in the strong field phase, which leads to their multiplication and the formation of an electron avalanche, initiating an ionization wave (IW) and the subsequent development of a breakdown. As a result, the breakdown delay time decreases, which, under conditions of a finite-duration pulse leading edge, reduces the breakdown potential. At a slow increase in voltage, desorbed electrons are in the weak-field phase most of the time, in which ionization is impossible. However, moving in this field, they create a current that charges the wall of the region near the anode. The potential difference between the anode and the wall decreases. As a result, an increase in the anode voltage is required in order to produce IW and breakdown. In [3], this is observed in xenon, and in [4] also in neon, argon, and krypton at low pressures (~1 Torr) and $dU/dt$ ~ 10–100 V/s. The results of these studies led to the conclusion that the breakdown voltage $U_b$ when the tube is illuminated is related to the breakdown voltage without illumination $U_b^0$ by the relation

$$U_b = U_b^0 + U_w, \tag{1}$$

where $U_w$ is the potential of the charged wall. The charge on the wall near the anode is confirmed by the behavior of the IW: as it moves from the anode to the cathode, it accelerates, in contrast to what is observed during a pulse breakdown with a steep voltage edge [1, 4].

The problem of how the process of wall charging develops over time after the anode potential begins to rise was not discussed in [3, 4]. Experiments [4] on illumination of the tube by pulsed light sources showed only that an increase in the breakdown potential during illumination is observed only if the light pulses begin no later than or end no earlier than the anode voltage reaches the $U_b^0$ value. In this work, studies are conducted that allow us to answer the question posed above, as well as to clarify the mechanism of wall charging during electron photodesorption.

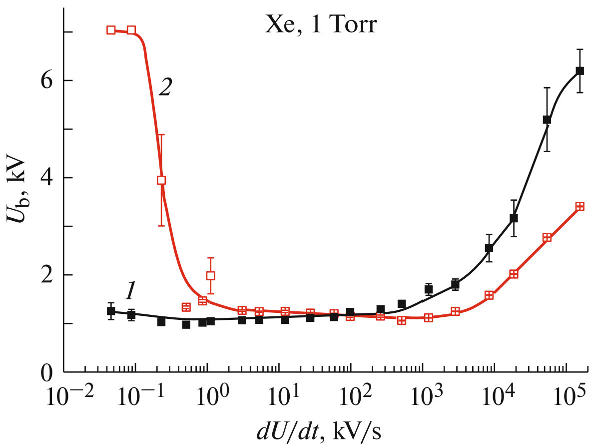


**Fig. 1.** Dependence of the breakdown potential on the rise rate of the anode voltage in the dark (*1*) and when the tube is illuminated by fluorescent lamps (*2*) [3].

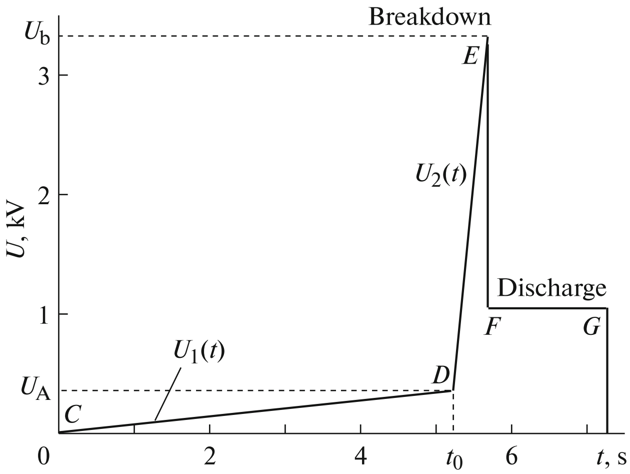


**Fig. 2.** Example of anode voltage diagram (for clarity, the DEFG interval is stretched).

## 2. EXPERIMENTAL

The measurements were carried out on a setup described in [3, 4]. Sealed discharge tubes with an inner diameter of 8–13 mm and a length of 75–80 cm were used. The tubes were filled with an inert gas (Ne, Ar, Kr, and Xe); the initial purity of the gases was 99.99%, and before filling the tubes, they were additionally purified with molecular sieves. A ramp voltage $U_1(t)$ with a slope of $dU/dt$ = 40–50 V/s (the line *CD* in Fig. 2) was applied to the anode. At such steepness, according to the data of [3, 4], a strong increase in the breakdown voltage is observed when the tube is illuminated. The potential $U_1(t)$, however, was cut off before the breakdown occurred, at a certain $U_A$ value (point *D* in Fig. 2), but at the same time, a pulse of a 10-ms duration and a leading edge $U_2(t)$ of high steepness—$7 \times 10^5$ V/s (line *DE*) arose. This pulse has already led to a breakdown, and such steepness provides the lowest breakdown voltage of $U_b = U_b^m$ (minimum on the curve of the dependence $U_b$ on $dU/dt$ [3, 4], Fig. 1). In addition, with such a $dU/dt$ value, the effect of the tube illumination on the breakdown potential is also minimal, or absent altogether [3, 4], i.e., $U_b^m = U_b^0$. The potential $U_2$ increased until the breakdown occurred (point *E*), causing the voltage to drop to the level of *FG*, the glow discharge voltage. This procedure thus made it possible to measure the breakdown voltage under conditions where the wall was pre-charged by the simultaneous action of illumination and anode voltage $U_A$.

The tube was irradiated with fluorescent lamps of general laboratory lighting plus a 30-watt fluorescent lamp installed along the tube at a distance of 0.5 m. Pulsed sources were also used: a LED emitting in the band of 395–410 nm and a diode laser ($\lambda$ = 405 nm). All results presented below, even if not specifically stated, were obtained under tube illumination conditions.

## 3. RESULTS AND DISCUSSION

Figure 3 shows the waveforms of the anode voltage for two gases: neon and krypton. A short period time near the moment of the breakdown was recorded. In this interval, the waveform segment corresponding to the inclined straight line *CD* in Fig. 2 looks horizontal. The lowest trajectory corresponds to the case without the voltage $U_1(t)$, i.e., at $U_A = 0$. The remaining waveforms correspond to different delays $t_0$ of the $U_2$ pulse with respect to the start of the increase in $U_1(t)$, from 5 to 60 s that corresponds to values $U_A \approx$ 200–2500 V. It is seen that the potential $U_1$ affects the breakdown voltage, but only if $U_A$ exceeds some critical value; the latter is close to the breakdown potential without illumination $U_b^0$ [4]. At lower $U_A$, the potential $U_1$ does not change the breakdown potential or changes it slightly.

Figure 4 shows the results of processing the waveforms of Fig. 3, as well as similar data for other gases. The abscissa axis shows the anode potential $U_A$, the ordinate axis shows the breakdown potential (point *E* in Fig. 2). In all cases, the same pattern is observed as in Fig. 3. For $U_A$ values that do not exceed a certain value, the breakdown voltage remains the same as for $U_A = 0$. When this value is exceeded, the breakdown voltage begins to increase. Figure 4c also shows the result of using an alternative method for measuring the breakdown potential $U_b$. In this case, at the time $t_0$, a rectangular rather than ramp pulse was applied. Its amplitude was selected such that a breakdown occurred at its minimum value. It is evident that both methods give similar results.

The dependence $U_b$ on $U_A$ is linear at $U_b > U_b^0$ with an angular coefficient close to unity (from 0.99 to 1.05), and can be described by the relation

$$U_b = U_A + u, \quad (2)$$

where the constant $u$ is in the range of 130–200 V depending on the type of gas. The physical meaning of the quantity $u$ is clarified below.

Thus, the slowly growing potential $U_1$ affects the breakdown voltage only if at the time $t_0$ of the start of the breakdown pulse $U_2$, the value $U_1(t_0) = U_A$ exceeds a value close to the breakdown potential without illumination $U_b^0$. As indicated in the Introduction, an explanation for the growth of the breakdown potential when the tube is illuminated in the case of a slowly increasing voltage was proposed in previous works [3, 4]. It consisted in the fact that photoemission of weakly bound electrons adsorbed on the inner surface of the tube occurs under the effect of illumination. Desorbed electrons, moving in the field of the high-voltage anode, produce a current that charges the wall and increases its potential. This leads to an increase in the anode potential, which is necessary for the generation of the IW, ensuring the further development of the breakdown, i.e., to an increase in the breakdown voltage. It follows from the results of the measurements carried out in this work that charging the illuminated wall does not occur during the entire time when the potential is applied to the anode; it begins only after this potential reaches a certain critical value close to $U_b^0$. In this case, it follows from equality Eq. (1) that after the anode potential has exceeded $U_b^0$, it is maintained at a level less than $U_b$ by a relatively small amount $u < 200$ V.

This is confirmed by additional experiments, the results of which are shown in Figs. 5 and 6. They illustrate the effect of pulsed illumination on the breakdown voltage. In Fig. 5, a light pulse of variable duration $\tau$ begins at the time the anode voltage begins to rise. It is seen that $U_b$ remains unchanged and close to $U_b^0$ up to the value $\tau = \tau_c \approx 13$ s. The waveform of the anode voltage $U(t)$, given in the insert, shows that at $t = \tau_c$ the voltage becomes equal to or close to $U_b^0$. The breakdown voltage begins to rise only from this time. With regards to the wall charging concept, this means that at $U(t) < U_b^0$ charging does not occur, despite illumination and an electric field between the anode and the wall. In Fig. 6, the delay $\Delta t$ of the leading edge of the light pulse with respect to the beginning of the anode voltage rise is varied. The pulse ends much later, after the breakdown has occurred. It is evident that the breakdown voltage significantly exceeds $U_b^0$ in the entire range of the $\Delta t$ variation and drops to $U_b^0$ at $\Delta t > \Delta t_c \approx 25$ s. The waveform of the anode voltage in the insert shows that $U(t) \approx U_b^0$ at $t = \Delta t_c$. Thus, if the light pulse begins later than the anode voltage has reached $U_b^0$—the breakdown value without illumination, then the breakdown occurs precisely at $U_b^0$, and illumination plays no role. This result seems quite obvious regardless of the mechanism of the irradiation effect. Another pattern is more interesting: $U_b$ remains constant over the entire interval $\Delta t$ from 0 to $\Delta t_c$. In other words, the illumination effect does not depend on the duration of such exposure. This observation, the same as in the previous case, is consistent with the assumption that the wall is charged at the very end of the light pulse, when the anode voltage reaches a value close to $U_b^0$. At the lower voltage, charging does not occur, despite illumination and an electric field between the anode and the wall.

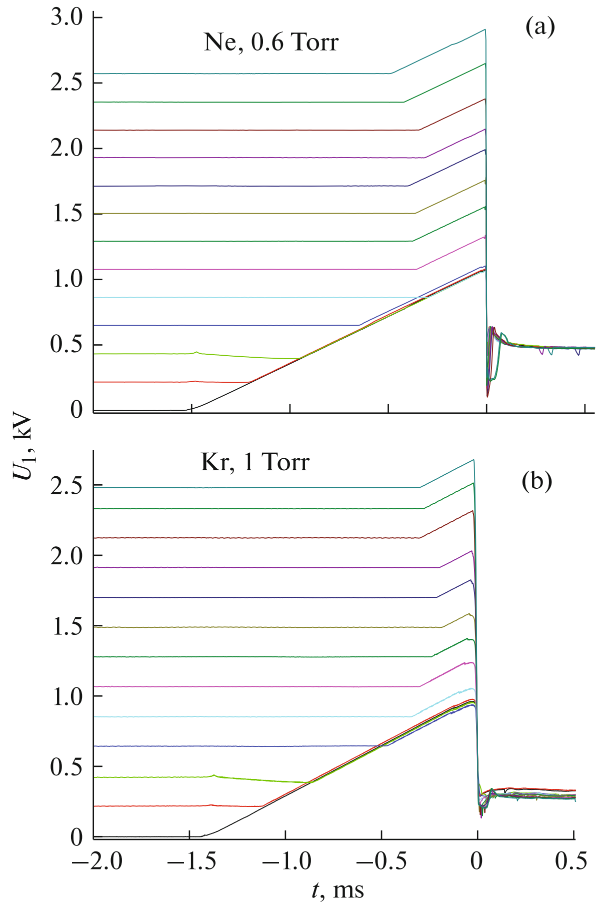


**Fig. 3.** Waveforms of the anode voltage when a sequence of two ramp pulses with a slope of 43.5 and 7.2 × $10^5$ V/s is applied to the anode with illumination by fluorescent lamps. The value $t = 0$ corresponds to the time of the breakdown.

On the other hand, it is obvious that charging the wall takes some finite time. To estimate this time, the following experiment was conducted. The linearly

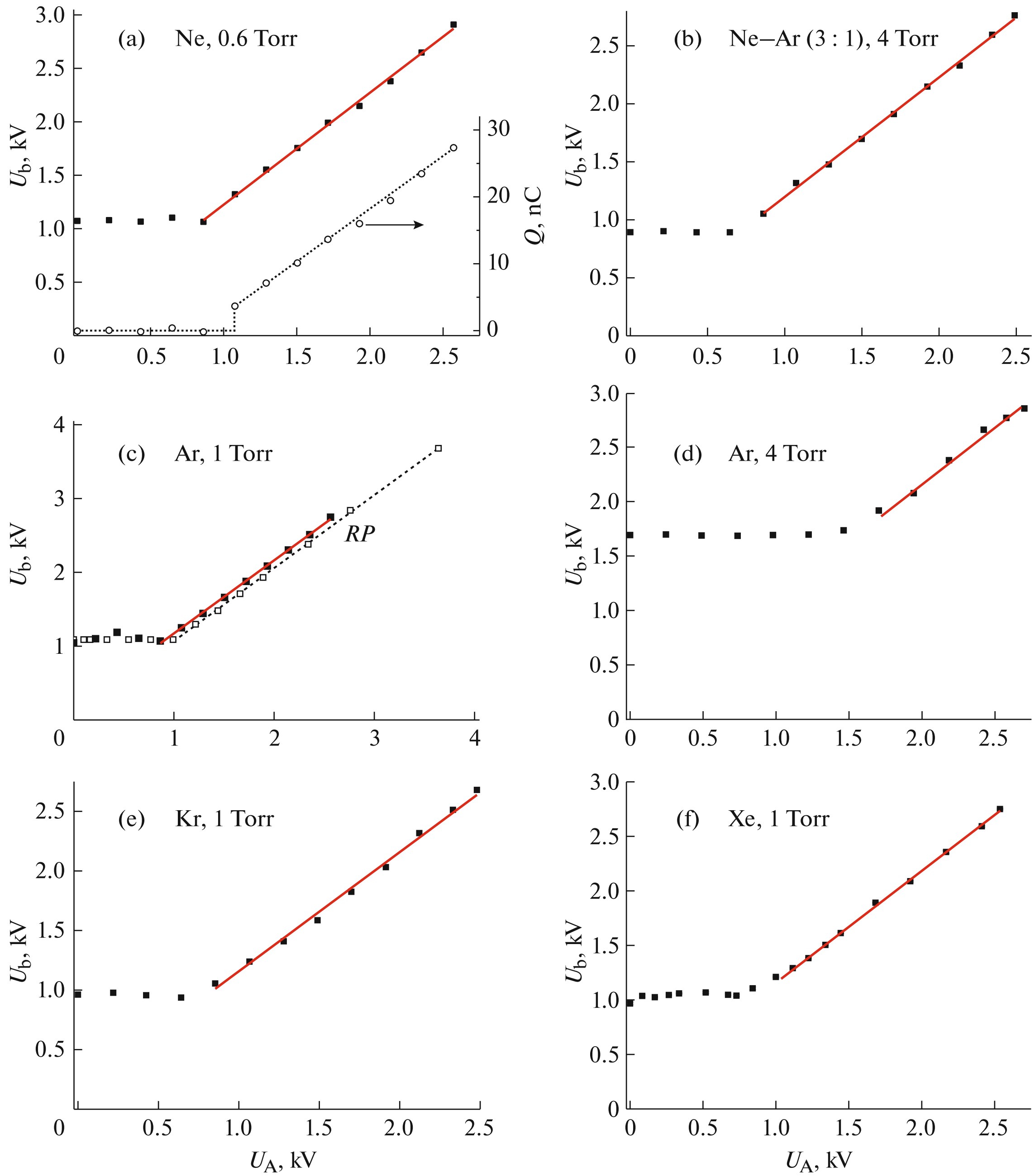


**Fig. 4.** Dependence of the breakdown voltage on the anode potential in different gases. Panel (a) also shows wall surface charge values, in panel (c), *RP* is for the breakdown by the rectangular pulse. The rise rate of the anode voltage $dU_1/dt$ = 37–48 V/s, fluorescent lamp illumination.

increasing anode voltage started not from zero, but from some finite $U_0$ value. In Fig. 7, waveforms of this voltage with different $U_0$ values are shown for the breakdown in argon. The pattern is similar for other gases. The point $t = 0$ ("hardware zero") corresponds to the time of starting the ramp voltage formation circuit. Waveforms with $U_0 > 0$ are shifted horizontally in such a way as to match the time of the breakdown. In this case, it can be seen from the figure that the breakdown voltage for all $U_0$ values is the same, despite the fact that the duration of the wall charging up to the time when $U = U_b^0$ is different for them. This again agrees with the fact that charging occurs when the anode voltage reaches a value close to $U_b^0$. Note that for all the waveforms given, $U_0 < U_b^0$. Figures 8a and 8b shows the region where $U_0 \approx U_b^0$ in more detail. In both

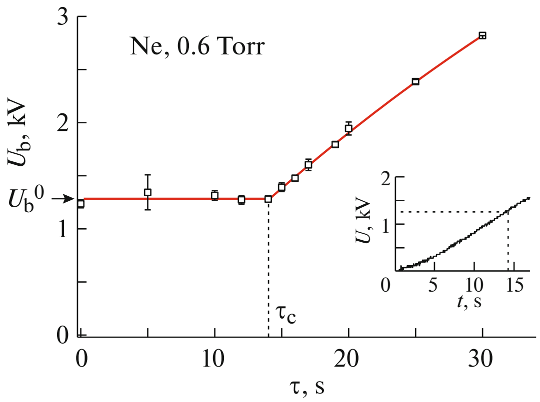


**Fig. 5.** Dependence of the breakdown voltage on the duration of the light pulse. The leading edge of the pulse coincides with the time of the beginning of the increase in the anode voltage. The insert shows the time dependence of the anode voltage. The light source is a diode laser.

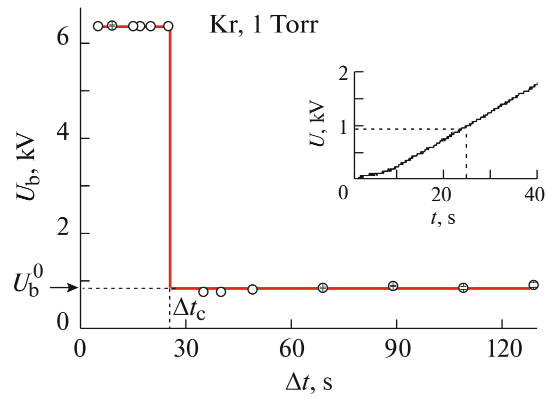


**Fig. 6.** Dependence of the breakdown voltage on the duration of the delay of the leading edge of the light pulse with respect to the start of the increase in the anode voltage. The pulse ends later than the breakdown and ignition of the discharge. The insert shows the time dependence of the anode voltage. Illumination with LED.

plots, the first two waveforms are shifted upwards for clarity. For them, $U_0 < U_b^0$ similarly to Fig. 7. Their upper, almost horizontal, segments are obviously the initial sections of the inclined straight lines in Fig. 7. Thus, they correspond to the situation when the wall is charged and therefore the breakdown at $U = U_b^0$ does not occur. The other two waveforms correspond to the inverse inequality, $U_0 > U_b^0$, in this case the wall is not charged at the time of the potential jump, and then the breakdown occurs at its leading edge. The short noisy segment corresponds to the flow of discharge current (the duration of the discharge pulse is 10 ms). The transition from one pattern to another occurs in a time not exceeding 0.1 s. Thus, this interval is sufficient for the wall to charge to a potential at which the breakdown at $U = U_b^0$ cannot occur.

We consider in more detail the case when $U_0 < U_b^0$. We can propose the following scenario of what happens in this case. Since the wall charging time does not exceed 0.1 s, it occurs instantly on the time scale of Fig. 7, and at the point where $U = U_b^0$, the wall potential $U_w$ changes abruptly by some value $u$ (Fig. 9). Since the wall becomes charged, the breakdown does not occur at this time, the potential $U$ continues to increase, which leads to further charging of the wall, maintaining a constant difference between its potential and the anode potential:

$$U - U_w = U_b^0 - u. \qquad (3)$$

This process continues until the wall charge reaches saturation [3, 4]. After this, the anode potential increases a little more, to a level where $U - U_w = U_b^0$, and at this time, according to Eq. (1), a breakdown occurs.

If against the background of a slow increase in the anode voltage, the breakdown is initiated by a voltage jump at the point where $U = U_A$, as described at the beginning of the section (Figs. 2 and 3), then we obtain from Eqs. (1) and (3)

$$U_b = U_A + u,$$

i.e., the relation Eq. (2). This clarifies the physical meaning of the quantity $u$, obtained earlier when processing the results of Fig. 4: $u$ is the jump in the wall potential that occurs when the anode potential approaches the $U_b^0$ value.

The surface charge of the wall can affect the passage of the pre-breakdown IW. According to the Nedospasov model [5], the wave motion is controlled by a local breakdown between the wave front and the

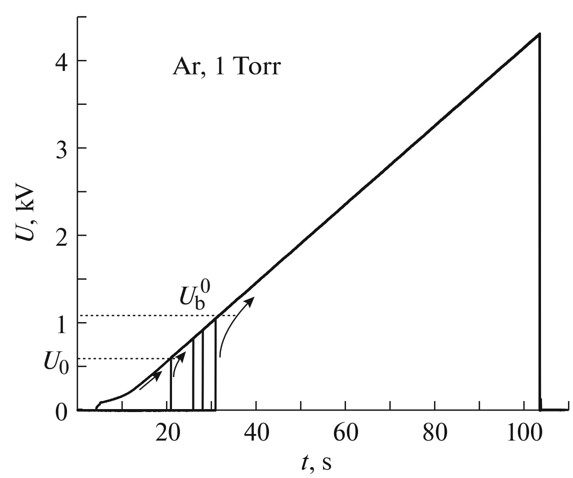


**Fig. 7.** Time dependence of the anode potential in the case of an initial jump.

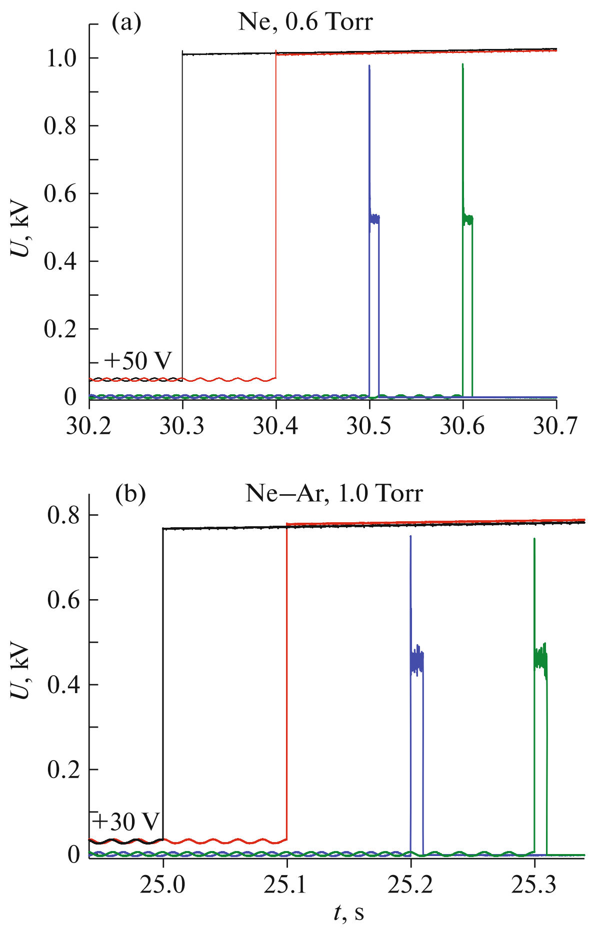


**Fig. 8.** Time dependence of the anode potential in the case of an initial jump on a large scale.

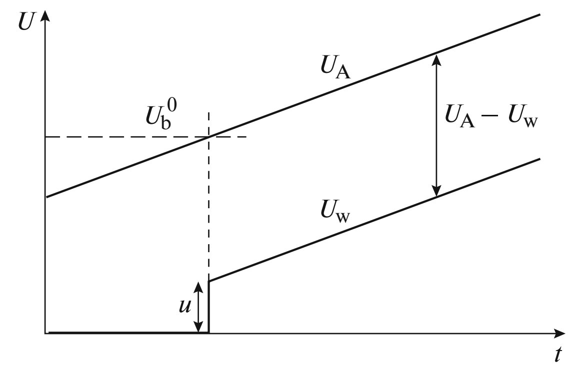


**Fig. 9.** Anode potential and (presumably) wall potential diagrams.

wall. The charge on the wall changes the potential difference between them. If it decreases during the wave motion, the wave slows down and weakens, up to complete attenuation. This was observed in [3, 4], where a linearly increasing voltage was applied to the anode of the tube, and when the anode potential reached a certain value (below the breakdown value $U_b^0$), a positive rectangular pulse was applied to the cathode. This pulse generated a positive IW moving toward the anode. When approaching the anode, the wave entered the region of a like-charged wall, due to which it lost speed during its motion and the greater the higher the anode potential *U*. Starting from certain *U* values, the wave decayed before reaching the anode. This confirmed the existence of a wall charge.

In this work, a similar experiment was carried out, but a negative rectangular pulse of 10-ms duration was applied to the cathode of the tube. This pulse also generated an IW moving towards the anode. The wave was recorded using a capacitive probe moving along the tube [4]. Figure 10a illustrates its motion in a situation where the anode potential is zero ($U = 0$). The probe output signal weakens with distance from the cathode, as is usually the case [1]. When IW arrives at the anode, a breakdown occurs. In Fig. 10b, the anode potential is nonzero. A strong change in the nature of the wave motion is visible: it accelerates noticeably (the travel time of the tube length decreases), and the change in the signal amplitude becomes non-monotonic.

Figure 11 shows the results of processing the data from Fig. 10 and similar plots—the time dependence of the IW path length (*xt* diagrams) for different *U* values. It is noteworthy that these curves change noticeably only starting with sufficiently large *U* values, namely, those that are close to the potential $U_b^0$. The origin for the distortion of the *xt* diagrams when applying potential to the anode can be explained as follows. Here, unlike the previous case, negative IW moves from the cathode, and, finding itself in the area of the positively charged wall, it intensifies and accelerates. The effect is more pronounced, the higher the anode potential, since this increases the wall charge. The fact that this is observed only for $U > U_b^0$ confirms that wall charging does not occur at a lower anode potential.

If we assume that the increase in the breakdown voltage at anode potentials exceeding $U_b^0$ is associated with the wall charge, we can estimate the value of this charge averaged over the length of the tube, accumulated by the time of the breakdown

$$\text{at } U < U_b^0 \quad Q = 0,$$
$$\text{at } U \geq U_b^0 \quad Q = C \times U_w = C \times (U_b - U_b^0),$$

where *C* is the tube capacitance. According to measurements and estimates [6, 7], for discharge tubes similar to those used in this work, $C \approx 15$ pF. The obtained *Q* values for one of them are shown in the plot of Fig. 4a. Similar values will obviously be obtained for other tubes. We clarify that we are talking about the value averaged over the length of the tube. In

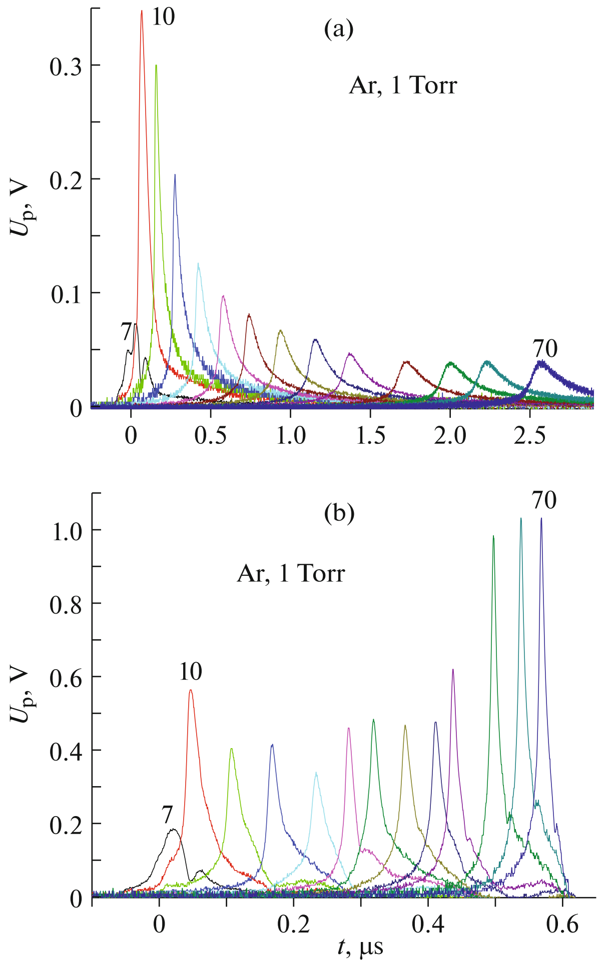


**Fig. 10.** Capacitive probe signals when recording an ionization wave initiated by a negative polarity pulse with an amplitude of –1.5 kV applied to the cathode. The anode potential is (a) 0 and (b) +3.5 kV. The numbers near the curves are the distance from the cathode in cm.

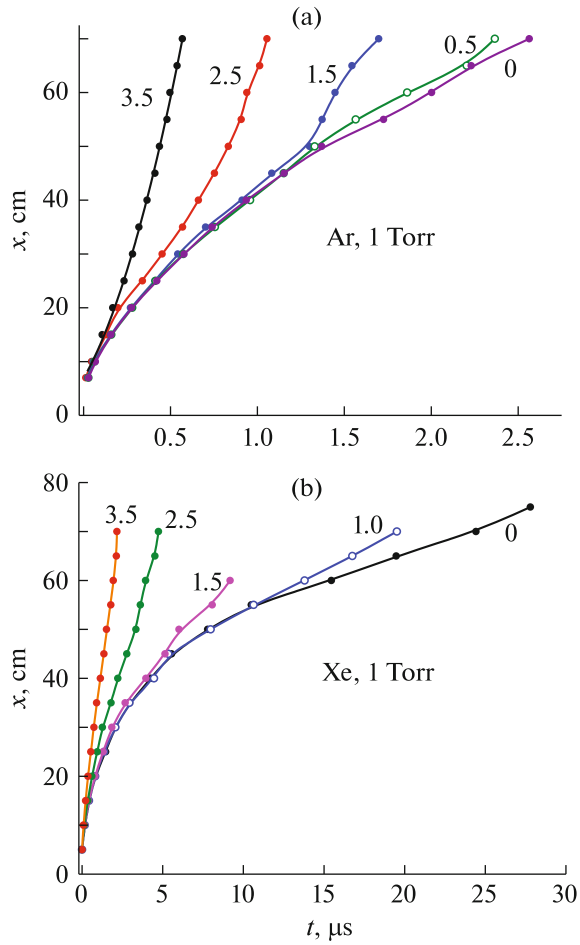


**Fig. 11.** *xt* diagrams of the ionization wave initiated by a negative polarity pulse with an amplitude of –1.5 kV applied to the cathode, at different values of the anode potential (indicated by numbers near the curves).

fact, the charge density is obviously maximum near the anode and decreases with distance from it.

The results obtained in this work indicate that the mechanism of charging the illuminated wall described in [3, 4] should be clarified. Namely, noticeable charging does not begin immediately from the time the potential is applied to the anode, but only when the anode reaches a sufficiently high potential close to $U_b^0$. To explain this fact, it can be assumed that the quantum yield of electron photodesorption $\gamma_{des}$ is so small that the photoemission current itself does not lead to noticeable charging of the wall. In [3], an estimate of the $\gamma_{des}$ value is given, which is necessary for illumination to increase the breakdown voltage by 1 kV under conditions similar to those of this work: $\gamma_{des} \approx 10^{-6}$. But this estimate was obtained under the assumption that wall charging occurs during the entire interval of the anode potential growth, i.e., it is average over this interval. If the $\gamma_{des}$ value is actually at least 1–2 orders of magnitude smaller, then the wall charge is too small to cause a noticeable increase in the breakdown voltage. However, at an increase in the anode potential, ionization in the gap between the wall and the anode (ionization amplification) becomes noticeable. The efficiency of this process depends on the reduced electric field strength $E/p$. When a gap between the anode and the wall is 1 cm, a pressure is 1 Torr and a voltage of 1 kV, we get $E/p = 10^3$ V/(cm Torr). The Townsend ionization coefficient η for inert gases in this case $\approx 10^{-2}$ V (see [8], Table 2.1), which gives an increase in photoemission current by three orders of magnitude. Since the dependence of η on $E/p$ is very sharp, the maximum current to the anode is obtained at the highest voltage $U \approx U_b^0$. In this scenario, the wall is charged mainly as a result of ions drifting onto it from the region near the anode. Obviously, the given explanation is purely qualitative and only one of the possible explanations.

## CONCLUSIONS

In the previous works of the authors [3, 4], it was found that at a sufficiently slow growth of the anode potential of the discharge tube (~10–100 V/s) the breakdown voltage $U_b$ in inert gases can increase significantly if the near-anode region of the tube is illuminated with visible radiation. The mechanism of this effect is proposed to be photoemission of weakly bound electrons adsorbed on the inner surface of the discharge tube caused by illumination. These electrons, under the action of the electric field between the wall and the anode, create a current that charges the wall near the anode. The potential difference between the anode and the wall decreases, as a result of which a higher anode voltage is required to create a prebreakdown ionization wave and breakdown. In the present work, this effect is studied in the same gases: Ne, Ar, Kr, Xe, and Ne–Ar mixtures. The discharge power supply circuit made it possible to measure the breakdown voltage under conditions when the wall is pre-charged to a certain potential. These studies clarify the mechanism described above. It was found that the charging of the tube wall does not start from the time the anode voltage begins to increase, but only when it approaches the breakdown voltage measured without illumination ($U_b^0$). In this case, the inner surface of the wall acquires a potential of 130–200 V in a time not exceeding 0.1 s. As a result, at the time when the anode potential becomes equal to $U_b^0$, no breakdown of the illuminated tube occurs. The potential difference between the anode and the wall is maintained at a further increase in the voltage, until the anode reaches the breakdown potential significantly exceeding $U_b^0$. The conclusion that charging of the tube wall begins only when the anode potential approaches $U_b^0$ is confirmed by experiments with pulsed illumination of the tube, as well as by observing the motion of the ionization wave initiated by an additional pulse supplied to the cathode before breakdown at a given anode voltage.

## FUNDING

This work was supported by ongoing institutional funding. No additional grants to carry out or direct this particular research were obtained.

## CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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*Translated by L. Mosina*