Low-frequency one-electrode discharge in long tubes at low gas pressure

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Abstract
One electrode discharge (OED) was studied in long tubes filled with high purity neon or argon at a pressure of 1–4 Torr. The main feature of the discharge is a low rate (less than 10 kHz) of the voltage pulses of given polarity applied to only one electrode, while another one remains free or missing. The discharge is observed as a glowing plasma column which occupies either the whole tube or its part depending on actual voltage amplitude and rate. Current-volt characteristics, ignition thresholds and the OED length changing patterns demonstrate features unknown for RF discharges. It was found that the plasma generation mechanism actually is a formation of a set of ionization waves (IW). As a result, the discharge glow as well as its current can be presented as a set of pulses with duration equal to the IW propagation time (∼1 μs) that appear with the voltage frequency. The pulse form reflects the IW structure which represents itself as a front of high electrical potential and a plasma channel linking it with the electrode. It was shown that the wave motion is characterized by an attenuation of which the patterns were investigated by the time-position diagrams method. The attenuation specifies the length of the occupied plasma area as well as other OED parameters. The proposed simplified kinematic model of the wave propagation is based on the assumption that the attenuation is caused by the IW front potential decrease which in its turn occurs due to exponential falling of electric field strength in the plasma channel. This model allows to estimate the electric field in different OED points as well as to define average electron concentration via the current measurements. Typical values of the above parameters are 5 V cm⁻¹·Torr and 10⁹–10¹⁰ cm⁻³.

Introduction
Well studied capacitive discharges are widely used in various fields of plasma technology. Important examples of practical applications include excitation of CO₂ laser based on intermediate pressure discharges (1–100 Torr), and ion treatment of materials at pressures (10⁻³–1 Torr) [1, 2]. The capacitive discharge was mostly studied in plane-parallel geometry under uniform external electric field. The less well-understood are discharges in strongly inhomogeneous electric fields involving only one electrode. The second electrode in this situation does not exist, and its role is played by surrounding grounded elements of the setup. Within such a system, a one-electrode discharge (OED) is formed, a high-frequency form of which at atmospheric pressure and above, is also called a torch discharge [2, 3].

The OED studies carried out for the case of low pressure (∼1 Torr) are practically not found in recognized publications. The mechanism of such a discharge, especially at low frequencies, should radically differ from the known mechanism of ionization in the RF discharges. This work focuses on the experimental study of the OED formation in long tubes (where the length significantly exceeds the diameter) in neon and argon at pressures of 1–4 Torr, at voltages less than 4 kV and pulse repetition rates from 5 Hz up to 10 kHz.

There are a number of publications devoted to specific forms of capacitive discharge, outwardly similar to the OED. One of them was called the ‘discharge under unipolar gas breakdown’ or UBG discharge [4–7]. This discharge is also observed in long tubes in rare gases at low pressure, however, it is generated by a single external
electrode, which is a wire mesh located on the tube surface near one of its ends. The UBG discharge mechanism was explained by excitation and propagation of the wall surface potential wave. It is worth also mentioning several discharges at atmospheric pressure which are similar to the OED such as corona discharge and diffusive plasma jets [8–10]. The latest is known as apokamp and appears as offshoot from the channel bend of the pulse diffusive repetitive discharge between two electrodes at pressure ~100 Torr and more. The apokamp is driven by streamer (ionization wave at high pressure), and has a length by more than one order of magnitude greater than the discharge gap. A necessary condition for this phenomenon is the maintaining the discharge plasma at high potential. For this reason it is generated between two electrodes one of which is potential and the other one is capacitive coupled to ground which is close to the OED generation scheme.

The OED mechanism is closely related with the gas breakdown in a long tube. In the event of a break in the low-voltage electrode circuit, only the first stage of the breakdown is realized which is the ionization wave (IW) [11]. The ionization wave as a breakdown mechanism (pre-breakdown IW) in long tubes in gases at low pressure was the subject of experimental studies [12–15], and was also investigated theoretically in [16, 17]. As a rule, these studies were concerned with the ignition of fluorescent lamps. The propagation velocity of the pre-breakdown IW does not exceed $10^8$ cm s$^{-1}$ and these are classified as slow in contrast to fast ionization waves (FIW) [11, 18]. The IW mechanism is associated with the transfer of the high electrode potential through the discharge gap and, in general terms, can be presented as follows. When a voltage pulse is applied between the edge of the electrode and the tube wall (the point of zero potential), there is potential difference $\Delta \varphi$ between them, which triggers the avalanches developing from the initial electrons. If $\Delta \varphi$ exceeds the breakdown potential in this gap, then concentration of charged particles increases very quickly and causes the initial breakdown [19]. Plasma occurred in the field of the electrode is polarized with the formation of a leading charged front, the potential of which is close to the potential of the electrode. Ionization in the strong front field and subsequent inflow of the formed charged particles into the front lead to its advance into the tube or to IW movement. Strength of the electric field behind the IW front is much smaller than within it. In this field the electrons move to or from the electrode. Electron drift causes a current in the external circuit, which flows during the IW movement.

The IW propagation requires the presence of initial electrons. In the event of negative polarity, the electrons are removed by the field ahead of the front, the high-voltage cathode being their source. It is known that negative waves appear only after a cathode spot formation [20]. In the event of positive IW there is no such permanent source of electrons, and up to date there is no a common point of view on their exact nature. The study [21] where the breakdown by IW of a long discharge tube filled with helium was simulated at a pressure of several Torr, shows the high efficiency of the associative ionization mechanism in collisions of excited He$^+$ atoms with He, as compared with the photoionization mechanism. The latter is often considered as the main source of initial electrons appearing ahead the IW front. However, both mechanisms were criticized in [14] and it was shown that the most probable source of the initial electrons is the photoelectric effect at the tube wall. Partially, this point of view was confirmed in [22], where a 1–2 order reduction in the excitation time of the positive IW was observed upon irradiation of the tube walls with a source of visible light. Moreover, for waves of negative polarity this effect was not detected. In [23], a similar effect was found for plasma jets. The influence of initial electrons on the IW propagation results in effect of the voltage frequency on the breakdown. Such effect on IW excitation in long tubes at low gas pressure (memory effect) was described in [24] while the case of streamers and plasma jets detailed in [25]. Increase in the frequency leads to the stability of the IW generation and to a drop in the delay time. But in some cases high initial electrons concentration may damp the wave excitation.

As the IW moves, the tube wall charges up to the potential close to that in the front. If the opposite electrode is not coupled with the external circuit the wall charge cannot drain through the plasma and remains on the tube wall until the voltage pulse termination. When the active electrode voltage decreases, a potential drop occurs again between it and the wall, which leads to the initial breakdown repetition and to generation of another IW discharging the tube wall. Such waves were observed in [26] when a sinusoidal voltage was applied between the tube electrode and external conductive plates along the tube. In this case the occurrence of IW was observed both during the voltage growing and its decreasing. According to the authors the second wave corresponded to the discharge of the wall. In [27], this phenomenon was discovered and studied for rectangular voltage pulses and was called the ‘ionization wave of return breakdown’ (IWRB).

**Experiment**

The studies were carried out in sealed tubes 100 cm long and 1.5 cm in diameter, filled with high purity neon and argon up to the pressure of 1 and 4 Torr. The tubes contained two aluminum electrodes having the form of hollow cylinders 2 cm in length and 5 mm in diameter with ceramic collars mounted to the front edges. OED is very sensitive to the presence of any conductive objects near it. For this reason, the tube was fixed on thin
dielectric stands (made of plywood) so that the distance to the nearest conductive element would be at least 20 cm. Experiments have shown that this distance is sufficient to avoid the discharge of perturbation.

The experimental set up layout is shown in figure 1. The rectangular voltage pulses were applied to just only one electrode of the tube (1). The other electrode remained free (the break in the external circuit is conventionally shown via capacitor 15). The pulse repetition rate varied from 5 Hz to 10 kHz, their duration varied depending on the rate in such a way that the duty cycle of the pulses would be constant S = 20, and the amplitude would range from 1 to 3.5 kV. Both voltage polarities were investigated. The pulse front duration was determined by the response time of the switch on the field effect transistor (3) and by stray capacitances and did not exceed 100 ns, which corresponded to a voltage growth rate of \(2 \cdot 10^{10} \text{ V s}^{-1}\). Ballast resistor was not installed in the circuit.

The OED diagnosis consisted of electrical and optical measurements. The block diagram in figure 1 explains the layout of diagnostic system elements. The voltage at the electrode was measured using a high-voltage compensated divider (9) with a resistance of \(R_1 = 100 \text{ M} \Omega\), the signal from which was analyzed on Tektronix TDS 240 oscilloscope (10) with a 60 MHz pass band. The discharge current was recorded using an opto-electrical circuit [27], consisting of a fast high-voltage LED (6) and a photomultiplier PMT (5). The LED was installed in series with the active electrode. At passing of a current pulse the LED generated a light flash which was detected by PMT with the total response time of less than 80 ns. Due to distortion of the current leading edge the circuit calibration was carried out not against the given current, but against the charge transferred through the tube for a fixed time period. To do this, the breakdown current was studied in the same tube equipped with two electrodes. In these experiments small (50 \(\Omega\)) resistor (8) and opto-electrical circuit were connected in series with a low-voltage electrode. The voltage drop across the resistor is proportional to the flowing current. Then both signals from LED-PMT circuit and the resistor were integrated over the same time interval during which the current relaxed to the stationary discharge value. The value of the charge \(Q\), measured using a resistor was taken as a reference value. The value of the charge \(Q_\text{b}\), measured by opto-electrical circuit, was compared with it. The voltage of the PMT was selected in such a way that the device works in a linear mode and in this case the dependence \(Q(Q_\text{b})\) is linear.

Oscillographic study of the discharge radiation at various points of the tube was carried out simultaneously with electrical measurements. The studies have shown that the main contribution comes from the IW front. The IW emission was recorded using two optical fibers (12) mounted perpendicular to the tube axis and connected to one or two PMTs (13). One fiber collected the light from a point near the electrode and recorded the signal at the IW start while the second moved along the tube and transmitted the IW signal from a fixed point. For a certain coordinate of the fiber \(x\), it was possible to determine the IW movement time \(t\). The set of value pairs \((x, t)\) forms the \(x-t\) diagram of the IW. An analysis of such diagrams allows us to make conclusions about the IW movement character, to trace dynamics of its velocity as well as its reaction to experimental conditions. This method was often used in studies of high-speed ionization waves, for example in [28] and also in studies of mutual suppression of two pre-breakdown IWs in a long tube [29].

The IWs parameters could not be reproduced from pulse to pulse, especially with regard to the wave speed. The reason for this is that the delay time \(\tau_0\) of the initial breakdown is finite. As a result, if the voltage pulse

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Figure 1. The block scheme of the experimental setup. 1—discharge tube; 2—power supply; 3—high-voltage switch; 4—digital generator; 6—high-voltage LED; 5, 13—photomultipliers; 7—switch; 8—precision resistor (50 \(\Omega\)); 9—high voltage divider; 10—digital oscilloscope; 11—personal computer; 12—optical fiber; 14—semiconductor laser (\(\lambda = 405\) nm); 15—the total capacity of the tube; \(R_2 = 260 \text{ k} \Omega\); a resistor that forms a trailing edge of the voltage pulse.
amplitude is sufficient, the breakdown can occur both at the front of the pulse and at its steady state value. Another factor is the IW movement. It is known, for example, that this process strongly depends on the initial electron concentration \( n_{e0} \) near the potential electrode \([11, 30]\).

To obtain identical ionization waves in each voltage pulse at a low frequency \((f < 50 \text{ Hz})\), the active electrode was irradiated by semiconductor laser \((14)\) with \( \lambda = 405 \text{ nm} \). The effect of the laser irradiation consists in creation of a constant value \( n_{e0} \) due to the electrons photodesorption from the tube wall \([22, 27]\). According to the estimates carried out in \([31]\) laser irradiation causes the emission of electrons with frequency of more than \( 10^4 \text{ s}^{-1} \). In this work, under the influence of laser photodesorption the spread of the discharge ignition moments decreased from 1 ms up to 10 ns. With the pulse frequency over 100 Hz the spread of breakdown parameters decreased due to the memory effect \([22, 24]\). The memory effect mechanism lies in the fact that after the previous discharge, charged and excited metastable particles that maintain the value \( n_{e0} \) continue to be present in the tube. Due to the memory effect, stabilization of breakdown was achieved within 1 \( \mu \text{s} \), which made it possible to obtain almost identical ionization waves for different voltage pulses.

**Results**

Description of experimental data is drafted according to the following pattern. It starts with an external description of the discharge and of its main observable characteristics: the length of the plasma column and its glow, and their stability over time and space uniformity are considered. Then the following electrical characteristics are provided: ignition and damping thresholds, as well as the CVC. As the discharge mechanism is associated with ionization waves, their motion dynamics is considered separately, and its relation to the discharge voltage is identified.

**Phenomenology of the one-electrode discharge**

OED is observed as a luminous region of the plasma occupying the entire cross section of the tube while along its length it can occupy the entire tube or its part. The plasma length is unstable and can vary depending on the conditions of the discharge excitation. In the general case OED grows from the high-voltage electrode as a front separating the plasma area from the non-ionized gas (figure 2). It has a conical shape which is directed away from the electrode.

**Influence of voltage**

The plasma boundary propagates smoothly or stepwise depending on voltage parameters. In case of negative voltage the tube is smoothly filled with plasma while in case of positive voltage the OED length changes in a stepwise manner with a slight increase in the voltage. The boundary of the positive polarity OED is unstable and its position varies within 1–3 cm which was not observed for negative polarity discharges.

**OED minimum length**

The OED length \( (L) \) can vary depending on the gas type, pressure \((p)\), applied voltage \((U)\) and its frequency \((f)\) (figures 3, 4). It was found that there is a minimum \( L \), which was equal to 3–4 cm for positive polarity, and it
could decrease to 2 cm for negative polarity. The minimum length corresponds to the minimum voltage \( U_{\text{min}} \) a slight decrease of which leads to instantaneous OED extinction.

Effect of frequency on OED length

It was found that the plasma boundary shifts not only with the increase of \( U \), but also with the increase in \( f \) (figure 4). At \( f = 50 \text{ Hz} \) and \( U = 1.3 \text{ kV} \), the length is close to minimum. As the frequency increases, \( L \) grows uniformly up to 20 cm and at \( f \) equal to 230–240 Hz it jumps up to 60 cm. Further plasma extension proceeds smoothly with the increase in \( f \). OED of negative polarity does not experience length jumps, and the \( L \) values correspond to a given voltage. An increase in \( f \) leads just to an increase in the brightness of the plasma glow, but not in its length. It is noteworthy that the UBG discharge possesses the same properties: its length also has a jump that is observed at frequencies of \(~ 100 \text{ Hz} \) and only at positive polarity.

Glow of the OED

Figure 5 shows oscillograms of integral intensity of the OED radiation at three points: near the electrode (1), in the middle of the tube (2) and at its end (3). In all cases, a narrow (\(~ 100 \text{ ns} \)) peak is observed which corresponds to the IW front and transforms into a glow of the plasma channel behind it slowly varying with time. The highest intensity is observed near the electrode at time \( t_b \) when a discharge occurs. During the IW motion from \( t_b \) to \( t_{W} \),
the channel glow oscillates and then decreases monotonically. After the wave decay the glow slowly decreases and continues to be recorded up to a time $t_r$ exceeding $t_{IW}$. At points distant from the electrode only a peak of the $IW$ luminosity and the channel glow are observed.

**Spatial uniformity of OED**

For most conditions the OED has diffusive glow while spatial plasma structure in the form of stationary or running striations can also be observed (figure 6). The striations glow non-uniformly: there is a brighter side which is always directed towards the electrode. Their length varies from a few millimeters up to approximately the tube diameter. The OED stratification is the most prominent in neon at $p = 1$ Torr in a narrow range of the conditions determined by the voltage amplitude, frequency and polarity. Another important factor is the distance from the electrode: the larger the distance, the higher the voltage at which the striations are observed.

The diagrams in figure 7 show the areas of the striations existence (25 cm from the electrode). I—the area of stationary striations; II—the area of the running striations; III—homogeneous volume discharge. Stationary striations are clearly observed at negative polarity in the voltage range from the breakdown threshold $U_b$ up to 2.4 kV and at frequencies $f < 1.5$ kHz (figure 7(a)). They form a distinct structure near the cathode which decays with increasing distance from it. Beyond these boundaries the regular pattern of stationary striations is not followed, and irregular movement occurs.

In case of positive polarity the region of the stationary striations existence is indicated by shading in figure 7(b). They are observed only at high voltages and low frequencies ($5$ Hz $< f < 60$ Hz). However, the running striations for the positive polarity can be observed in a wider area than for the negative one and strongly depends on the effect of the jump in the OED length. So at $U < 2.0$ kV, the discharge occupies a part of the tube, and its column is homogeneous. When the threshold frequency is exceeded the plasma lengthens abruptly and traveling striations appear up to $f \approx 5$ kHz. At the higher voltage and lower frequencies the discharge already occupies the entire tube and stationary striations can be observed but the area of the running striations existence narrows sharply. An increase in pressure up to 4 Torr causes smoothing of the striations pattern in neon. In argon no strata were observed at this pressure.
Ignition of the OED

As was mentioned above, there is a minimum discharge length $L_{\text{min}}$ corresponding to the voltage $U_{\text{min}}$. However, the discharge is excited at $U_b > U_{\text{min}}$ with the plasma length several times greater than $L_{\text{min}}$. The difference in these voltages reaches 500–1000 V and depends on $f$ and the polarity.

It was found that for all gases the $U_{\text{min}}(f)$ shows a decrease in the region $f < 1$ kHz. In neon, this effect is more expressed than in argon. Dependence $U_b(f)$ has an insignificant minimum, giving a failure of the ignition voltage at 100–200 V, depending on the gas type and pressure. However, the frequency dependence for $U_b$ is much weaker than for $U_{\text{min}}$. The frequency $f_{\text{min}}$ at which the voltage takes its lowest value $U_{\text{min}}$ is $\approx 1$ kHz in neon (figure 8(b)), and in argon $\approx 0.6$ kHz (figure 8(b)).

Ignition of OED at negative polarity (figure 9) is distinguished by much less difference between $U_{\text{min}}$ and $U_b$ (less than 200 V). In neon at $f = 100$ Hz and $p = 1$ Torr this difference is completely absent, i.e. the discharge ignites and quenches at small changes in voltage, the $L_{\text{min}}$ is the smallest (about 2 cm) and plasma glow can be observed only in the vicinity of the electrode surface. As well as in case of positive polarity, in neon the minimum $U_b$ corresponds to $f = 1$ kHz, but it is much more expressed (figure 9(a)), and $U_{\text{min}}$ shows only a monotonic decrease with $f$ increasing (figure 9(b)).
The current-voltage characteristic (CVC) of the OED

**OED current**

The discharge current is basically a sequence of pulses of a specific shape that occur at the leading edge of the voltage pulse. The current time course depends on the voltage frequency and its polarity (figure 10). At the voltage leading edge the current peak occurring before the breakdown represents the displacement current flowing through the electrode capacitance. The development of the signal depends on the frequency. At $f = 5 \text{ Hz}$, the peak is followed by a pause lasting from several microseconds up to several milliseconds, which represents the initial breakdown delay time. After the pause, a pulse appears with well-defined structure: a broad maximum and a small ‘shelf’. The maximum corresponds to the initial breakdown while the ‘shelf’ to the current flowing to the wave front. If the IW speed doesn’t change significantly, the current also changes slightly. The IW decay is simultaneous with the current pulse breaking. Increase in the $f$ up to 100 Hz leads to the signal structure smoothing due to the memory effect [24] and to formation of a pulse with a steep edge. At negative polarity, the signal structure at low frequencies is less expressed.

We consider the average current $I_{av}$ (the amount of charge transferred through the tube per unit of time) as the discharge characteristic. Since the OED current is represented by pulses following at intervals equal to the voltage period then in line with definition of the average value over the period $T$, we obtain:
where \( Q_0 \)—total charge transferred through the active electrode during the voltage pulse, \( f \)—the pulse frequency. Thus, to obtain the average current it is necessary to know the magnitude of the charge transferred by the wave at a given \( f \). So, for example, with the increase of \( I_{av} \) the OED glow intensity increases like in DC discharges.

**Charge-voltage curves and CVC**

The CVC was found as a dependence of the average current on the voltage amplitude. We measured the charge transferred through the active electrode at various voltage amplitudes and frequencies. As a result, the set of the OED charge-voltage curves was obtained, the examples of which for both polarities are shown in figure 11.

The curves have a linear initial part up to the breakdown threshold \( U_b \), after which their nonlinear growth is observed. In case of negative polarity the breakdown is less pronounced, however, a slightly larger amount of the transferred charge is observed. Typical example of the OED current-voltage curve is shown in figure 12(a). The CVC has hysteresis when the voltage increases and falls, which is shown in the graph by two curves. The graphs also show a significant increase in average input power after reaching \( U_b \).

The OED has increasing CVC as well as that of the RF single-electrode and UPG discharges. The CVC structure indicates the following processes. Its initial part (from zero up to \( U_b \)) is associated with the electrode capacitance charging current, and the average current is proportional to the voltage: \( I_{av} = \frac{Q_0}{T} = fQ_0 \).
breakdown occurs and plasma forms in the tube volume. A further increase in voltage leads to a monotonic increase in the average current. The derivative \( \frac{d I_{av}}{dU} \) is higher when the discharge expands than when the tube is completely filled with plasma. It is known that the plasmoid of the RF torch \(^{[3]}\) has a capacitance in respect with surrounding objects. The AC flow through this capacitance is maintaining the current in the plasmoid. In the case of the OED we are also dealing with the plasma capacity with respect to the installation elements, which depends on the OED geometric dimensions. Based formally on the definition: \( C = \frac{I_{ax}}{U_f} \), it is possible to estimate the OED plasma capacitance. Figure \( 12(b) \) shows an example of such calculation together with OED length measurements. The hysteresis can also be noted for OED length. When \( U < U_0 \), the discharge has a zero length, the capacitance is constant \( C = 2.3 \text{ pF (electrode capacitance)} \). After the breakdown and the appearance of plasma the capacitance increases with voltage reaching an approximately constant value of \( \approx 8 \text{ pF} \) after the plasma occupies the entire tube.

The pre-breakdown IW

The main way to study the pre-breakdown IW motion is the \( x-t \) diagram method. The diagrams were recorded in different tubes at different pulse frequencies and voltage amplitudes. For these measurements, at each point of OED \( x \), up to 100 oscillograms of the IW optical signal were accumulated and then were compared with the signal (peaks at figure \( 5 \)) from a point \( x_0 \) near the electrode. The difference in the registration times in both points \( (t_f, t_a) \) gives the wave travel time to the point \( x: \tau = t_f - t_a \). The true value of \( \tau \) was taken as the sample average, which was mapped to the \( x-t \) diagram.

The diagrams in the figure \( 13(a) \) correspond to the situation when positive polarity OED occupies a part of the tube, and its length varies depending on the voltage amplitude. The initial almost linear section in graphs 1 and 2 relates to the IW movement with an approximately constant speed. The subsequent sections are not linear and have the negative second derivative. Then the IW velocity drops rapidly and the diagrams transform into the horizontal lines, i.e. the IW movement terminates. In reality, the wave decays when it reaches a certain minimum speed which was less than \( 10^5 \text{ cm s}^{-1} \).

The curve 3 corresponds to the IW, which strongly attenuates from the beginning of the movement and does not show any significant deviation of the curve. The graphs clearly illustrate the process of IW attenuation, which can be described as the IW motion with negative acceleration, accompanied by a decrease in the amplitude and widening of the front \(^{[29]}\). The fact that IW can decay is also known for two-electrode breakdowns \(^{[14]}\), but this process has not been studied separately.

At minimum breakdown delay time, the waves from different pulses travel for the same time through the same points along the tube, as if it were the same wave. But in the zone of strong attenuation the moments of the IW arrival time at the point demonstrate a scatter which is shown in figure \( 13(a) \).

Thus, the IW attenuation is accompanied by a violation of its stability. The discharge length equal to \( L_{cr} \) corresponds to the stable plasma column glow, at \( L > L_{cr} \) the column luminosity is intermittent, and the length varies depending on the IW attenuation part. For negative IW such instability of the discharge boundary was not observed. However, these waves are characterized by a larger attenuation and a lower velocity.

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**Figure 13.** \( x-t \) diagrams for IW of positive polarity, \( f = 100 \text{ Hz} \). (a) OED occupies part of the tube. Neon, 4 Torr. 1—\( L_{cr} = 25 \text{ cm} \) (1260 V); 2—\( L_{cr} = 50 \text{ cm} \) (320 V); 3—\( L_{cr} = 70 \text{ cm} \) (1360 V). (b) The discharge occupies the whole tube, Neon 1 Topp, 1—1.7 kV; 2—2.1 kV; 3—2.5 kV; 4—3.0 kV, 5—3.4 kV.
If the discharge occupies the whole tube, i.e. the IW moves without decay, then the $x$-$t$ diagrams show a monotonic increase. The graphs at figures 13(b) and 14 show $x$-$t$ diagrams for different amplitudes of voltage pulses plotted in semi-logarithmic scale. The observed shift of the diagrams along $t$-axis represents a delay in the IW start. From the graphs it follows that the waves traveling large distances have a larger initial slope of the diagrams, i.e. a higher initial velocity $v_0$. This parameter was separately measured at distances 3.5–4.5 cm from the high-voltage electrode as a function of its potential (figure 15). At small distances from the electrode the IW attenuation is negligible, and potential in its front coincides with the electrode potential. Changing the latter one can obtain a pattern of the IW speed change with a decrease in its potential due to attenuation. The graphs in figure 15 show the growth of the initial velocity with an increase in voltage close to exponential for both polarities. On the graphs the dots denote experimental results, the solid lines denote approximation.

**Ionization wave of reverse breakdown**

In addition to the pre-breakdown IW, the propagation of another ionization wave was detected at the trailing edge of the voltage pulse. According to the results of [22], under these conditions the so-called reverse breakdown from the charged wall to the former potential electrode occurs. It is similar to the initial breakdown from the electrode to the wall and also leads to the IW formation (ionization wave of reverse breakdown—IWRB), which also moves from the electrode. The direction of the current flowing behind the front of the IWRB

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**Figure 14.** $x$-$t$ diagrams for IW in different gases, $U = 2.5 \text{kV}, f = 100 \text{ Hz}$; Argon 4 Torr 1—negative polarity, 2—positive polarity; Neon 4 Torr 3—negative polarity, 4—positive polarity.

**Figure 15.** Initial velocities of the IW, $f = 100 \text{ Hz}$, Argon 4 Torr, positive polarity; Argon 4 Torr, negative polarity; Neon 4 Torr, positive polarity; Neon 4 Torr, negative polarity; Neon 1 Torr, positive polarity.
corresponds to the polarity opposite to that of the prebreakdown IW. Diagrams (x-t) for different polarities demonstrate the dynamics of the wave motion (figure 16). At the same voltage amplitudes, the transit time over the entire tube by the IWRB is 2–3 times longer than that of the prebreakdown IW, and the attenuation is higher. The experiment shows that the IWRB existence is limited by the voltage frequency rather than by amplitude. Table 1 shows the frequencies $f_{br}$ for the discharges in argon and neon above which the IWRB was not detected.

### Discussion

**Mechanism of the OED formation in a long tube**

The results obtained indicate that the OED is formed by periodic traveling (with frequency $f$) of the ionization waves. IW consists of a charged front carrying a high electric potential and a plasma channel through which the current flows from the front to the electrode. If the channel conductivity were infinite, then transmission of the high potential would occur without loss, and the electric field strength behind the front would be zero. In this case, all ionization processes would occur in the front, in the region of a large potential difference [11]. However, in reality the IW motion accompanied by the potential attenuation and an electric field exists in the plasma behind the front. The lines of this field are directed along the discharge axis, approximately like in a glow discharge. In this area additional ionization of the gas and its excitation occur, which leads to the channel glow. The current in the channel flows until the IW propagates. The next current increase in the tube occurs simultaneously with the voltage drop at the pulse trailing edge and with the occurrence of the IWRB. Then the patterns repeat at the next discharge pulse. At some frequencies plasma no longer decays and as a result the discharge column is formed with uniform electron density in cross section and slightly varying along its length. The OED length is completely determined by the IW attenuation. If the wave decays at distance from the electrode $L < L_t$ ($L_t$ is the tube length), then the discharge will occupy only a region with length $L$.

The IW movement is accompanied by the wall charging; as a result, after the movement completion, the wall remains charged approximately up to the IW front potential and contains a total charge of $\sim 10$ nC, which can persist up to several hours after the tube is quickly disconnected from the circuit [31]. The IW cannot propagate when the wall is charged because the potential difference between it and the electrode is significantly lower than 0

### Table 1. The boundary frequency for IWRB existence.

| Gas, pressure | Voltage polarity | $f_{br}$, Hz |
|---------------|------------------|--------------|
| Neon, 1 Torr  | Positive         | 150          |
| Neon, 1 Torr  | Negative         | 60           |
| Neon, 4 Torr  | Positive         | 160          |
| Neon, 4 Torr  | Negative         | 45           |
| Argon 4 Torr  | Positive         | 50           |
| Argon 4 Torr  | Negative         | 55           |
Under such conditions the IW generation would require an increase in the electrode potential up to approximately \(2U_0\), which is not observed, since there is a way for utilization of the wall charge. In our experiment there were two such ways: IWRB and charge draining into the external circuit through plasma.

**IW attenuation**

Analysis of the \(x-t\) diagrams makes it possible to obtain the IW motion characteristics and to estimate the magnitude of the reduced electric field \(E/p\) and the electron concentration \(n_e\) behind its front and consequently in the OED column. Let us consider the process of the IW complete attenuation which is most pronounced when the applied voltage barely exceeds the breakdown threshold. The plasma channel behind the front has the finite conductivity, therefore its electrical resistance increases with IW propagation. If the conductivity were infinitely large, then the potential in the front \(\varphi\) at any point would be equal to the electrode potential \(U\) and the \(x-t\) diagram of the IW would be a straight line. In fact, the conductivity is finite, and as the channel length increases, the voltage drop across it increases too, which leads to a decrease in the potential at the IW front. The lower is \(\varphi\), the lower is the electric field strength ahead of the front and the lower is the ionization frequency. Consequently, a smaller charge enters the front and flows through the channel, which means that the current falls down and the potential drop on it increases. As a result of such feedback, \(\varphi\) falls to a critical value \(\varphi_{\text{min}}\) at which the ionization processes terminate and the IW decays. At a slightly higher value of the potential, the wave exists and has the lowest velocity.

The empirical law that describes the decrease in the potential \(\varphi\) with the increase in distance traveled by the IW \(x\) from the electrode is known from the results of [11, 12, 19]:

\[
\varphi(x) = \varphi_0 e^{-\alpha x},
\]

where \(\varphi_0\) is the IW potential near the electrode \((\varphi_0 \approx U)\), \(\alpha\) is the attenuation coefficient. The relationship between the potential in the front of the IW and in [14] its velocity was suggested to be linear, but these studies were carried out for a narrow voltage range. Investigation of the IW velocity in the initial part of the tube as a function of the electrode potential shown in figure 15 allows for the following empirical formula:

\[
\nu_{\text{IW}} = \nu_m e^{k(\varphi_0 - \varphi)}.
\]

Where \(\nu_0\) is the IW velocity at the minimum possible value of the front potential \(\varphi_{\text{min}}\) and \(k\) is the coupling coefficient. At low voltages, dependence (2) becomes linear, as in [14]. Substitution of (1) in (2) gives the equation of the IW motion along the tube, in which the initial condition must be formulated as \(x(t = 0) = L_m\). The choice of the minimum observable OED length as the initial condition is due to the fact that a IW forms in a certain region near the electrode, the size of which does not exceed \(L_m\). The parameters \(\nu_0\) and \(k\) were obtained from the approximation of the experimental data by function (2). The obtained equation was solved numerically, however, estimates showed that \(\alpha \sim 10^{-3} \text{ cm}^{-1}\), and for most \(x-t\) diagrams it is permissible to use the linear approximation for equality (1). With this in mind, we can give the equation of the IW motion with slight attenuation:

\[
\frac{dx}{dt} = \nu_0 \exp[-\alpha k\varphi_0 x], \quad \nu_0 = \nu_m e^{k(\varphi_0 - \varphi)}
\]

where \(\nu_0\) is the initial velocity of IW at \(\varphi = \varphi_0\). Its solution is represented by the analytical function (4):

\[
x(t) = -\frac{1}{\alpha k \varphi_0} \ln[\alpha k \varphi_0 \nu_0 (t - t_i) + C], \quad C = e^{\alpha k \varphi_0 L_m} \approx 1
\]

in which the IW induction time \(t_i\) determining the shift of the \(x-t\) diagrams initial points is taken as one of the integration constants. Approximation of the results by expression (4) demonstrates good agreement between the model and the experiment (figure 17(a)) and allows to determine the attenuation coefficient as an approximation parameter for various \(\varphi_0\) values. If we assume that the IW potential at the start moment is approximately equal to the voltage at the electrode we obtain the dependencies shown in (figure 17(b)).

**Estimation of OED plasma parameters**

Analysis of the results provided in [32] allows to estimate the electron concentration \(n_e\) behind the front of the IW basing on the discharge current magnitude from the relation: \(I = ev_0 n_e S\), where \(e\) is the elementary charge, \(S\) is the tube cross section, \(v_0\) is the electron drift velocity in a longitudinal electric field \((E_e)\). The velocity \(v_0\) was determined for the field averaged over the length of the OED. The electric field strength \(E_e\) was calculated from the law of the IW potential \(\varphi(x)\) decrease obtained by the assumption that it is determined by the behavior of \(E_e(x)\) behind the front. In case of weak attenuation the field is close to constant: \(E \approx \alpha \varphi_0\) which is valid at high \(U\). But in the general case it is necessary to take into account the \(E_e\) decrease over the IW path (OED length) \(L\):
The electron drift velocities corresponding to $E_x$ obtained by (5) were taken from [33]. Since the measurements of the total charge $Q$ passing through the tube (figure 11) are more accurate than the current measurements, the final relation for the average in time $n_e$ has the form:

$$n_e \approx \frac{Q}{e\mu E \tau},$$

where $\mu_e$ is the electron mobility, $\tau$ is the IW travel time over distance $L$. The calculation according to formula (6) for different amplitudes of voltage pulses and both polarities is presented in figure 18. The graphs show that at a voltage close to $U_b$, the electron concentration is $\sim 10^5 \text{ cm}^{-3}$ for positive polarity and $\sim 10^7 \text{ cm}^{-3}$ for negative. The difference obtained is probably due to the fact that the formation of negative IW, as is known [11, 20], occurs after the cathode spot formation, which is accompanied by active emission of electrons from the cathode that makes a large contribution to the detected current. As $U$ increases, the charge density increases by several orders of magnitude and reaches $\sim 10^{10} \text{ cm}^{-3}$ at $U > 3 \text{ kV}$.

**Figure 17.** (a) Examples of the experimental results approximation (dots) by expression (4). Ne 1 Torr, positive polarity, 1—1.8 kV; 2—2.5 kV; 3—3.0 kV; 3.5 kV. (b) IW attenuation coefficient as a function of applied voltage. Positive polarity: 1—Ne 4 Torr, 2—Ar 4 Torr; negative polarity: 3—Ne 4 Torr, 4—Ar 4 Torr.

**Figure 18.** Average electron concentration estimation in OED column. Ne 4 Torr, $f = 100 \text{ Hz}$, $\circ$—positive polarity, $\triangle$—negative polarity.
Conditions behind the front of the ionization wave

At a pressure of 4 Torr the volume recombination is small and the main channels of electron escape from the discharge volume are drift to the electrode and diffusion. For definiteness, we consider a discharge at a voltage of 2.5 kV. According to formula (3), the average value of the reduced electric field strength is 3.4 and 3.8 V cm$^{-1}$ Torr$^{-1}$ in argon and neon, respectively. According to the empirical dependences of $D_e/\mu_e$ on $E/N$, given in [33], the average electron temperatures for the obtained $E/N$ are 6 and 5 eV for argon and neon respectively. At the obtained charge density and average electron temperatures in the channel, as well as under the condition: $T_e > T_i$, the Debye radius is: $\tau_0 \approx 0.05$ cm, which is much smaller than the tube radius ($r_0 = 1$ cm). Under such conditions, electron diffusion to the walls occurs in an ambipolar mode and is characterized by a diffusion coefficient $D_a$, which accepts values according to the formula: $D_a = \frac{1}{T_i} \mu_e$, where $D_i$ is the ion diffusion coefficient. In compliance with the estimates in [34], the thermalization time of electrons for argon under conditions close to our experiment is $100 \mu s$. For neon, this number is about 2 times less. In both cases, these values are several times greater than the duration of the current pulse and the channel glow, i.e. the plasma behind the IW front is nonequilibrium. Then the characteristic time of electron escape from the plasma is equal to $\tau_1 \approx 44 \mu s$, and $\tau_0 = \Lambda^2/D_a$, where $\Lambda = \frac{6}{2 \cdot 0.05}$ (for diffusion Ne$^-$ in Ne, $D_i = 20.3$ cm$^2$ s$^{-1}$ at $p = 4$ Torr [35]). For argon $\tau_1 = 120 \mu s$ (for diffusion of Ar$^-$ in Ar, $D_i = 7.4$ cm$^2$ s$^{-1}$ at $p = 4$ Torr [35]). Both values are almost an order of magnitude longer than the IW travel time.

The electron drift occurs in a weak field behind the IW front, which varies according to (1). Estimates of the electron drift time from a point along the channel to the electrode (figure 19) show that it is shorter than the diffusion time, but can exceed the time of the IW motion for the most distant points of the discharge. This does not contradict the IW mechanism, since its velocity is determined by the motion of electrons in the front, and not behind it. Thus, during the existence of the discharge pulse, the charges shift to the electrode and partially disappear in the external circuit forming the conduction current. Moreover, diffusion losses can be considered insignificant.

Decay of plasma in the channel

Let us consider the plasma after the travel of the IW. In the experiment the duration of the voltage pulse is $\tau_0 > \tau$ (IW travel time), i.e. the electrostatic field of the electrode acts on the plasma for some time after the IW decay. The influence of the electrostatic field reduces to maintaining a space charge near the electrode, but the current does not occur and the electrode potential is compensated by the potential of the tube, which remains charged. Due to this, the action of the electrostatic field does not lead to repeated breakdown. Since the switch maintains the constant pulses duty cycle ($S = 20$), their duration falls with the increased frequency, so that $\tau_0 = 1/(f \cdot S)$. As a result, at $f \sim 100$ Hz we obtained $\tau_0 \sim (4–10) \tau_a$. On the other hand, $\tau_0$ exceeds the thermalization time of electrons which leads to a slowdown in ambipolar diffusion and to an increase in $\tau_a$. If we assume that the diffusion lifetime is minimal until the fulfillment of the condition: $T_e = T_i$, then the plasma density will decrease by no more than an order of magnitude during the thermalization. When $T_e = T_i$ the ambipolar diffusion slows down ($D_a = 2D_i$) and $\tau_a$ exceeds the pulse duration. As a result, the plasma density during the $\tau_0$ decreases by no more than 1–2 orders of magnitude, and the IWRB occurs under gas preionization. If the latter is such that the gas conductivity achieved in the discharge channel is preserved, then the IWRB may not occur (see table 1).
Indeed, the diffusion lifetime of electrons in argon is almost three times longer than in neon; therefore, $n_e$, critical for the IWRB development in neon will be reached at a three times higher than in argon. This is precisely the result obtained in the case of the positive polarity OED. At negative polarity, the critical frequency for the IWRB generation remains the same in argon, while in neon it becomes three times lower.

In case when the IWRB is not formed, connection of the electrode to the ground leads to the flowing of charge from the tube wall through the remaining plasma. This process is followed by the plasma decay without the external fields and charges on the wall and electrode. Let us estimate the electron escape time under the above conditions. At high $f$ and a short $\tau_0$ when the charge leaves the walls, the $n_e$ differs slightly from the values in the discharge, i.e. $\sim 10^{9} - 10^{10} \text{ cm}^{-3}$; plasma decay occurs due to ambipolar diffusion. For $f < 1 \text{ kHz}$, the time from the stop of the IW up to the start of the next pulse significantly exceeds the electron thermalization time. For these $f$, we can assume that the $D_{a}$ is determined by the expression: $D_{a} = 2 D_{j}$, and the characteristic electron escape time at $p = 4 \text{ Torr}$ in neon is $t_{dif} = 4.2 \text{ ms}$ while in argon it is $t_{dif} = 11.7 \text{ ms}$. The plasma lifetime can be estimated as 10 $t_{dif}$ which indicates that deionization of neon does not occur already at $f > 50 \text{ Hz}$, and that of argon at $f > 10 \text{ Hz}$. Starting from these frequencies, the IW passage does not create plasma, but only restores the charge particles concentration.

The above physical picture of the OED, as well as estimates of electric fields strength behind the IW front and of charged particle concentrations, allow a number of conclusions to be drawn regarding the mechanisms of the observed effects. In particular, an explanation can be given to the plasma channel stratification behind the IW front, and to the behavior of the ignition voltage and to the minimum burning voltage. These results will provide the material for subsequent publications.

Conclusions

This paper presents an experimental work to study the low-frequency one-electrode discharge in long discharge tubes in argon and neon at pressures of 1–4 Torr. We investigated the thresholds of its ignition and suppression, main electrical characteristics and optical signals, as well as dependence of plasma column length on voltage parameters. We also obtained kinematic characteristics of the pre-breakdown ionization wave, which is the plasma generation and maintenance mechanism. Typical concentrations of charged particles in a nonequilibrium plasma of OED are $10^{8} – 10^{10} \text{ cm}^{-3}$ and are not the same for discharges of different polarity. It was found that the OED length is determined by the IW attenuation and exceeds a certain minimum distance from the electrode needed for the wave formation. It is shown that the observed luminous plasma column represents a repeatedly flashing channel behind the IW front. The IW attenuation leads to the longitudinal electric field in the channel which is sufficient for excitation and ionization of the gas atoms. In case of strong attenuation the inhomogeneity of the electric field and the concentration of charged particles along the discharge column can be large, which leads to the development of instabilities in the form of stationary striations. At a sufficiently high frequency of voltage pulses charged particles accumulate in the discharge volume which leads to uniformity of the plasma column. In conclusion, we note that, despite the fact that the RF case of the one-electrode discharge in a long tube has been studied previously (torch discharge at low pressure), no description of its low-frequency version can be found in widely known works. However, the mechanism of plasma generation by an ionization wave provides high densities of charged and excited particles, including metastable ones, which opens up prospects for various plasma-chemical applications.

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