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Fast ionisation waves under electrical breakdown conditions

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Abstract. An analysis of experimental and theoretical investigations is the basis of this state-of-art review of models of fast ionisation waves (FIWs) and of characteristics and properties of these waves. The attention is concentrated on waves with the maximum possible velocities of $10^9 - 2 \times 10^{10}$ cm s^{-1} when the amplitudes of voltage pulses are $20 - 300$ kV. At low and moderate pressures the reduced intensity of the electric field in the front of a wave is so high that the front becomes a moving source of a beam of high-energy electrons in which the current can reach several kiloamperes. At moderate pressures the high-energy electrons in the wave front overtake the front and cause preliminary ionisation of the gas ahead of the front. At low pressures these electrons determine mainly the mechanism of the motion of the front. At high pressures (in excess of 200 Torr) the main source of such preionisation is the radiation emitted by the front. The high rate of filling of the discharge volume with a plasma, high electric fields and high energies of the electrons in the front, and the slight heating of the gas make fast ionisation waves attractive for applications.

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1. Introduction

Electrical breakdown of a gas in a discharge gap may give rise to ionisation waves usually observed as moving luminous fronts. The ionisation caused by these waves and their velocities depend on a number of experimental conditions. The velocities may have values in a wide range from 10^5 to 10^{10} cm s^{-1}.

Ionisation waves travelling at relatively low propagation velocites of $10^5 - 10^7$ cm s^{-1} frequently appear in gaps where the electric field is homogeneous and the velocity of the ionisation front is governed by the electron drift. Such waves appear also when heavy particles participate in ionisation breakdown; for example, as a result of motion of a leader which forms in long sparks because of the heating of a gas in a channel. The current associated with the motion of the front of slow ionisation waves is relatively low and is of the order of few to tens of amperes.

Ionisation waves travelling at subluminal velocities of $10^8 - 10^{10}$ cm s^{-1} frequently appear in the final stages of electrical breakdown when usually a plasma already exists in a discharge gap. The currents associated with these waves are high; for example, in lightning during motion of a return-stroke wave the current may reach tens and hundreds of kiloamperes.

Under certain conditions it is possible to generate fast ionisation waves (FIWs) with large amplitudes of the current also during the initial stages of electrical breakdown. The most important factor is a steep slope of the leading edge (or a short rise time) of a high voltage pulse applied to a discharge gap and the occurrence of preliminary ionisation (preionisation) in the gap. As a rule, the shorter the rise

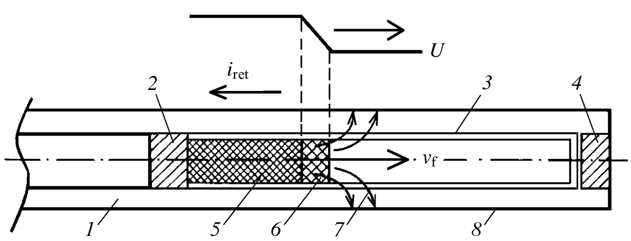

Figure 1. Motion of an ionisation wave: (*1*) coaxial transmission line; (*2*) high-voltage electrode; (*3*) discharge tube; (*4*) low-voltage electrode; (*5*) high-conductivity plasma column behind a wave front; (*6*) wave front; (*7*) lines of force of the electric field; (*8*) cylindrical metal shield around the discharge tube; i_{ret} is the return current flowing along the shield in the opposite direction relative to the wave current; U is the distribution of the potential along the discharge tube for the wave position indicated below.

time of the applied voltage pulse and the stronger the pre-ionisation of the discharge gap, the higher the velocities of ionisation waves starting from the high-voltage electrode. For example, in the case of pulses with a rise time of a few nanoseconds and an amplitude increasing from 60 to 300 kV during this time, the velocity of ionisation waves increases to the range from 3×10^8 to 2×10^{10} cm s^{-1}. The motion of such breakdown waves is accompanied by a large transport current, a con-siderable energy deposition in the gas, and a high degree of ionisation of the gas, so that the discharge gap breaks down during the first passage of a wave.

The recent intensive investigations of FIWs have been made in order to obtain information on the fast breakdown stages and on potential applications of these waves in contemporary physics and technology.

The majority of these experiments have been concerned with ionisation waves caused by pulsed breakdown in long tubes. This configuration has the advantages of stable spatial and temporal discharge characteristics, and easily varied boundary conditions, which facilitates comparisons with theoretical models. Moreover, such configurations are used most frequently in practice.

A high-voltage nanosecond pulse (with a voltage rise time amounting to several nanoseconds) is usually transmitted to an electrode of a tube along a coaxial transmission line (Fig. 1). The discharge tube is then a continuation of the central conductor of the transmission line and it is surrounded by a cylindrical metal shield. Ionisation waves start from the high-voltage electrode and travel along the tube. A high-conductivity channel forms behind the front of a wave and this channel can be regarded as a continuation of the central conductor of the transmission line along which a potential is transmitted to the wave front, subject to some attenuation. The conduction currents flow along the plasma (and along the central conductor rod); in the wave front they are closed at the shield by the displacement currents. A 'reverse current' flows through the shield and its value is equal to the current in the central conductor but its direction is opposite.

The electric field intensity in the plasma behind the front is zero in the ideal case and therefore all the ionisation processes occur in the region of the voltage drop in the front of the wave. Since the ionisation efficiency is an exponential function of the reduced electric field E/N (or E/P), where N is the gas density in the tube, such a distribution of the electric field is much more likely to cause ionisation breakdown of the gas than the distributions realised in other known electric discharges. It should be pointed out that the plasma zone in the front of an FIW is very far from an equilibrium. Electron fluxes with energies of tens of kiloelectron-volts or higher may appear in it. Such a zone may be created far from the electrode. This minimises the influence of the electrode processes and it is desirable also in many applications. The high rate of filling of the discharge gap by the plasma, the high intensities of the electric field in the front, the efficient excitation of high energy levels of particles accompanied by only slight heating of the gas, the absence of pinching, and the stability make FIWs promising for applications in the currently rapidly developing high-power pulse techniques, as well as in lasers, light sources, etc.

2. Early investigations of ionisation waves

Fast subluminal ionisation waves were discovered by J J Thomson in 1893 [1] in a study of a pulsed electrical breakdown in a long (15 m) discharge tube with a diameter of 5 mm. An induction coil connected to the ends of the tube served as the source of the voltage pulses in these experiments. A rotating mirror revealed that the luminous front always moves from the positive to the negative electrode at a velocity not less than half the velocity of light in vacuum.

Subsequent investigations of FIWs have been closely related to the development of the technique of generation of high-voltage pulses and recording of fast processes. In 1937 Beams, Snoddy, and Dietrich [2] used an electron-beam oscilloscope whose plates were subjected to signals from two additional electrodes placed on top of a tube. They found that during breakdown a front of a potential travels from the high- to the low-voltage electrode (irrespective of the polarity of the former) and the velocity of this front is equal to the velocity of light pulses. The velocity increases with the amplitude of the voltage pulses from 1.7×10^9 cm s^{-1} at 73 kV to 3.7×10^9 cm s^{-1} at 175 kV. When the potential wave reaches the ground electrode, a reverse wave is generated and its velocity exceeds the velocity of the primary ionisation waves and is approximately one-third of the velocity of light. The current in the primary wave can reach 90 – 200 A and the current density is 90 – 4000 A cm^{-2}, so that the amplitude of the potential over a distance of 12 m can decrease by about 10%.

A decade later, Mitchell and Snoddy [3] placed for the first time a discharge tube in an earthed shield and postulated that the current in the wave is governed by charging of the discharge-tube capacitance relative to the shield up to the potential of the applied high-voltage pulses. They pointed out that this type of breakdown resembles the return stroke in lightning [4, 5], which appears when a leader moving from a cloud reaches the earth. A similar stage with a fast luminous front is found in long sparks under pulsed breakdown conditions [6, 7] during the pulsed corona stage [6] or when a long gap is closed during the main stroke stage [6].

Fast ionisation waves can appear not only as a result of pulsed breakdown, but also in the course of transient processes which are accompanied by a change in the space charge or a redistribution of the potential in the discharge gap. Westberg [8] observed FIWs which appeared in a glow-discharge plasma because of spontaneous breakdown of an oxide film on the cathode, causing a strong injection of electrons in the cathode region and a redistribution of the potential after the passage of a series of forward FIWs and those reflected from the anode. It was reported that the electron density in the plasma increased and the glow discharge became an arc.

Loeb [9] used these investigations to establish general features of this effect and called it the 'ionisation waves of the potential gradient'. He also postulated that fast stages of the breakdown in other discharges, such as the return stroke in lightning or in a long spark, which are associated with a fast moving luminous front, involve ionising potential-gradient waves and that those processes are evidently essential for the completion of the majority of the known discharges.

Another decade later this phenomenon was analysed in the review of Flower [10] on the basis of extensive experimental and theoretical material obtained by Fowler and his colleages, the data reported by Winn [11], and the published data on the development of lightning and long sparks. Fowler called this effect the 'nonlinear electron acoustic waves' in accordance with the theoretical model proposed by him.

In a later review Asinovskii et al. [12] presented a detailed analysis of the fast stages of the breakdown in short discharge gaps (1 – 10 cm), in a long laboratory spark (0.5 – 10 m), in lightning, and also the results of studies of fast ionisation waves in discharge tubes. The main stress in this review was on the determination of the velocity of ionisation waves, which at the time has been the only quantity measured sufficiently accurately in experiments. Asinovskii et al. discussed the dependences of the velocity of ionisation waves on the nature of the gas and its pressure, on the amplitude of the voltage pulses and their rise times, and on the density of electrons present initially in the gap. The difficulties encountered in a theoretical explanation of the high velocity of these waves in the absence of any electrons in the gap were specially pointed out.

In the decade since the publication of the review of Asinovskii et al. [12] a qualitatively new stage has been reached in studies of FIWs because of the extensive use of modern nanosecond-pulse techniques both in the generation of ionisation waves and in their diagnostics. New fundamental data have been obtained not only on the velocity of these waves, but also on the transport of current by the waves, on the attenuation of the wave amplitude, and the reduction in the velocity in the course of the motion along a discharge tube, on the dynamics of the wave front, and on the mechanisms of formation of the front as well of the appearance of high-energy electrons. These results have been obtained at high-voltage amplitudes and they have altered drastically the existing ideas on the mechanism of motion of FIWs. This period has seen also the first practical applications of FIWs in fast generation of a plasma needed in plasma–chemical reactions, in pumping of lasers, in pulsed radiation sources, and in fast-response switches and peaking devices.

These circumstances have provided a stimulus for writing this review, which presents the lastest experimental data on FIWs and current ideas on the mechanisms of their formation and propagation. In view of the limited space, we shall ignore practically completely the work done on applications of FIWs. It should be mentioned that throughout this time the experimental investigations of FIWs and qualitative models based on them have been well ahead of theoretical analyses. This is true even at present, so that the main data on the reported properties of FIWs are based on experimental investigations of these waves in long tubes. Since extensive experimental material has already been presented in the review of Asinovskii et al. [12], we shall confine ourselves mainly to the recent results that have made a considerable contribution to the development of current ideas on the nature of FIWs.

3. Experimental setups

Investigations of FIWs in long discharge tubes have been made by many authors using different apparatus, but the basic approach in these experiments has been the same. Therefore, we can present a generalised diagram showing the apparatus used in such investigations (Fig. 2). Detailed descriptions of the experimental methodology can be found in, for example, Refs [12 – 17]. High-voltage pulses produced in a generator (*1*) are transmitted along a coaxial line (*2*) to a high-voltage electrode (*3*) of a glass or quartz discharge tube (*4*) which is a continuation of the central conductor of the coaxial line (*2*). The discharge tube is surrounded by a cylindrical metal shield (*5*) which is connected to the screen of the coaxial line on the side of the high-voltage electrode to an earthed electrode (*6*) at the opposite end. A shunt (*7*) serves to measure the current which flows through the discharge tube when it is short-circuited by the discharge. The earthed electrode (*6*) is a hollow cylinder and it has a window (*8*) at its end, so that radiation can be coupled out of the tube. In some experiments this window has been made of a Mylar film 12.5 μm thick (serving as the energy threshold for the transmission of 40 keV electrons), which ensures that only high-energy electrons escape from the tube and recorded [14] with a Faraday cup (*9*). The discharge tubes used in such experiments have diameters ranging from 1 – 2 mm to 5 cm and their lengths are from 10 cm to 5 m. At sufficiently high amplitudes of the voltage pulses (100 – 300 kV) the space between the discharge tube and the shield is filled with transformer oil (permittivity $\varepsilon \approx 2$) or with distilled water ($\varepsilon \approx 80$) in order to avoid breakdown. The coaxial transmission line is a cylinder with an inner diameter of the order of 5 cm and a high-voltage central conductor in the form of a rod whose diameter is varied to provide the range of the wave impedances of the line from 10 to 90 Ω. The space inside the transmission line is also filled with oil or water. At pulse amplitudes up to 20 – 30 kV the transmission line is usually a coaxial cable of the RK50-11-11 type. Therefore, in these experiments the amplitude of the voltage pulses ranges from 10 to 300 kV and their duration is 20 – 100 ns; the rise time of the leading edge of the pulses is 2 – 10 ns.

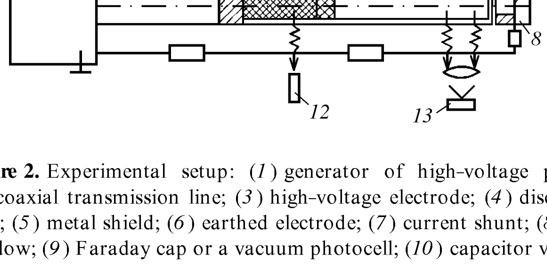

Figure 2. Experimental setup: (*1*) generator of high-voltage pulses; (*2*) coaxial transmission line; (*3*) high-voltage electrode; (*4*) discharge tube; (*5*) metal shield; (*6*) earthed electrode; (*7*) current shunt; (*8*) exit window; (*9*) Faraday cap or a vacuum photocell; (*10*) capacitor voltage divider; (*11*) return-current shunt; (*12*) photocell; (*13*) image-converter camera.

The parameters of the voltage pulses in the transmission line, at the high-voltage electrode, and along the discharge tube are measured with a capacitor voltage dividers (*10*) characterised by a subnanosecond time resolution [18]. The current in the transmission line and in the discharge tube is measured by return-current shunts (*11*) included in a gap in the shield. The shunts are made of inductance-free resistors of the TVO type or of titanium foil [19]. In some experiments the current has been deduced from a change in a magnetic field [16] in a closed single-turn circuit with an integrating resistor. Radiation is recorded at optical wavelengths by photocells (*12*) of the FÉK or FK19 and NSD-1850 (made in Britain) types with a time resolution of 0.1 ns, high-current photomultipliers of the ÉLU-FS type (resolution 0.7–1.5 ns), image converters based on UMI-93 and employed in the framing mode with an exposure of 1.5 ns [15], and an AGAT-SF3 image-converter streak camera operated continuously with a time resolution of 0.5 ns [14]. Electrical signals are applied to fast-response oscilloscopes with a pass-band of at least 1 GHz (Tektronix-519, S7-19, 6LOR-04, KOI-3). The ionisation wave velocity is deduced from the time delay between the signals from two capacitor dividers or two photomultipliers. The velocity dynamics along the tube length is also determined from the $X-t$ diagrams of signals provided by a capacitor divider which is moved along the tube [13]. In another method the dynamics of the wave velocity is deduced from records obtained with the aid of the AGAT-SF3 image-converter camera and analysed by computer [14].

The energy (and power) dissipated in the discharge is determined with a divider or a reverse-current shunt in the transmission line by the following methods [20]. It follows from the theory of transmission lines that the current I and the voltage U of a pulse are related in the travelling regime by $U = IZ$, where Z is the wave impedance of the line. When a pulse arrives at a point with a different resistance R or with a different wave impedance, a part is reflected and the amplitude of the reflected pulse is $U_{\text{refl}} = U(R-Z)/(R+Z)$; the voltage amplitude at this point is $U_R = 2UR/(R+Z)$. Initially the discharge tube has a high resistance so that the voltage amplitude is twice the amplitude of the pulse in the transmission line and the amplitude of the reflected pulse is close to the amplitude of the incident one. Therefore, the energy absorbed in the discharge is equal to the difference between the energies of the incident and reflected pulses, which are measured with the aid of a reverse-current shunt or a voltage divider:

$$W = \int I^2 Z\,\mathrm{d}t - \int I_{\text{refl}}^2 Z\,\mathrm{d}t\,. \qquad (3.1)$$

In measurements of this kind it is necessary to ensure that the electrical length of the transmission line from the point where the divider or reverse-current shunt is located to the discharge tube is greater than the duration of the voltage pulses, so that the reflected pulse cannot become superimposed on the incident pulse.

X rays generated during the motion of FIWs are recorded with a scintillator and a fast photomultiplier of the FÉU-87 type with an overall time resolution of 2 ns. The fluxes of high-energy electrons generated in the front of an FIW are recorded by a Faraday cup on the side of the earthed electrode.

At voltage amplitudes of 100–300 kV the experiments are carried out under single-shot conditions without preionisation of the gas. At amplitudes of 10–30 kV the pulse repetition frequency is 10–100 Hz. Preionisation in the tube is created by exciting a continuous (or pulsed) glow discharge and the initial electron density is varied by altering the glow-discharge current.

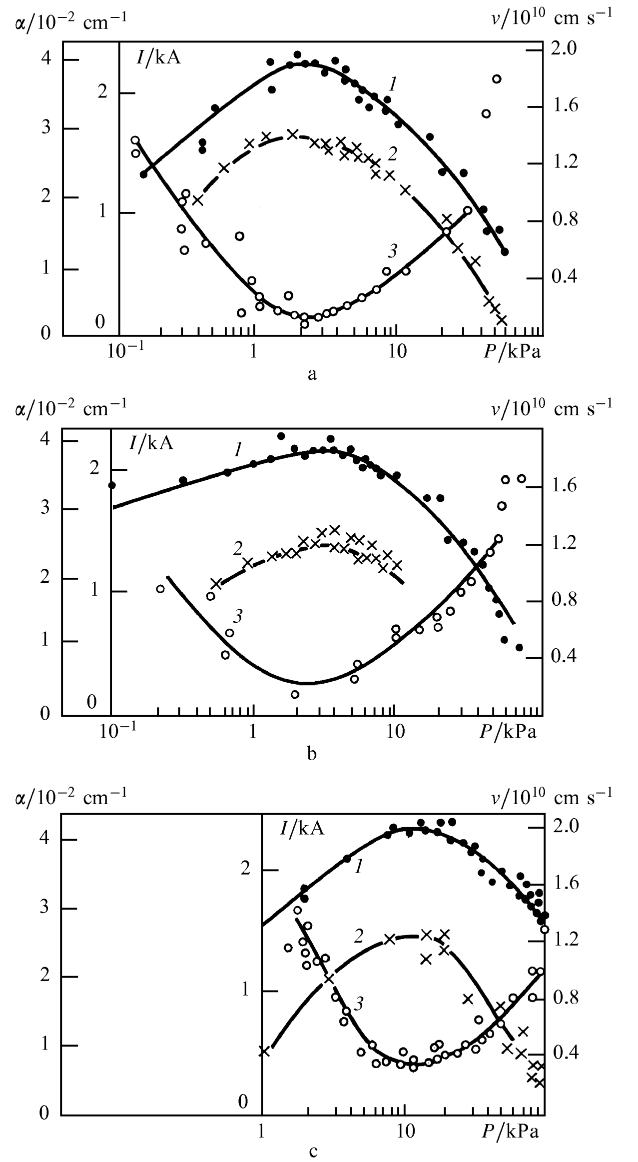

Figure 3. Dependences of the ionisation wave velocity (*1*), current (*2*), and attenuation coefficient (*3*) on the gas pressure: (a) nitrogen; (b) air; (c) helium. Voltage amplitude 250 kV. Tube 47 cm long and 0.4 cm in diameter. Nitrogen insulator [21].

4. Velocity of fast ionisation waves

The velocity of a front is the quantity most frequently determined in experiments and, therefore, much more data are available on this velocity than on other wave characteristics. However, a comparison of these data is very difficult because the wave velocity depends on many experimental conditions and the nature of the dependences on these conditions is not yet known sufficiently well for reliable extrapolations. As a rule, the results quoted below apply to the average velocity of FIWs in a discharge tube.

We shall now consider the main relationships obeyed by the average velocity of propagation of FIWs. The dependence of the wave velocity on the gas density is nonmonotonic (Fig. 3) [21]. In a certain range of pressures, which depends on the type of the gas, the velocity reaches its maximum value. The same pressure dependences of the velocity are also observed at much lower voltage amplitudes [11, 12, 22]. An increase in the amplitude of the voltage pulses increases the maximum velocity of the waves and increases the pressure at which this maximum velocity is reached. A comparison of the velocities obtained in different experiments is very difficult, but according to Ref. [22] the maximum velocity of FIWs at voltage amplitudes of 25–30 kV is reached in air and in nitrogen at a gas density of $\approx 6\times10^{16}$ cm^{-3}, which is approximately an order of magnitude less than the density at which the maximum velocity is reached for 250 kV voltage pulses (Fig. 3).

The values of the maximum velocity reached at 250 kV in different gases (Fig. 3) are approximately the same ($\approx 2\times10^{10}$ cm s^{-1}) and at present these are the highest velocities recorded for ionisation waves under laboratory conditions. In these experiments the maximum velocity of the ionisation waves agrees, within the limits of the experimental error, with the velocity of a freely travelling electron whose energy is ~ 250 keV. At amplitudes of the voltage pulses an order of magnitude less the maximum velocity depends on the nature of the gas [12, 22]. We may therefore conclude that the maximum velocity at the selected voltage amplitude is that reported in Ref. [21].

The maximum possible velocity of FIWs is influenced strongly by the effective permittivity of the insulator surrounding the discharge tube. The effective permittivity $\varepsilon_{\rm eff}$ is determined by the combined insulator distributed along the radius: this insulator is glass and a filler (water or oil). The maximum wave velocity decreases as the permittivity becomes higher [14–16, 23–26] (Figs 4, 6, and 7). Figs 4 and 5 give the FIW velocities obtained for the majority of gases using the same apparatus with a water insulator. The maximum velocity of the motion of the wave front is in this case governed by the rate of supply of the electromagnetic energy to the front along the coaxial transmission line

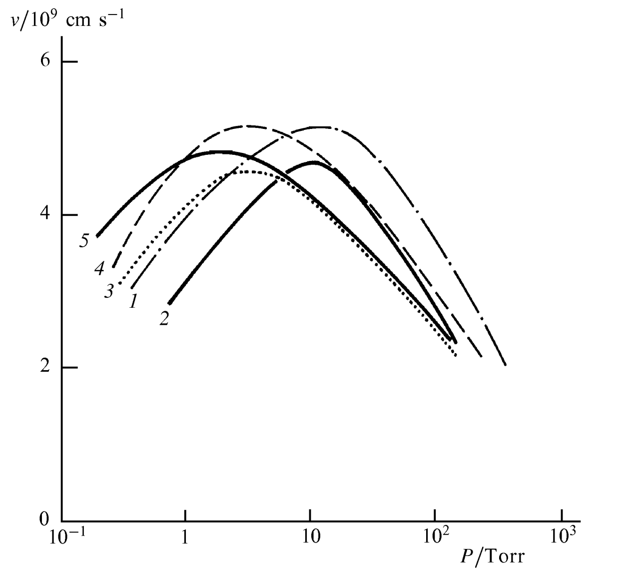

Figure 4. Dependences of the FIW velocity on the gas pressure: (*1*) neon; (*2*) helium; (*3*) argon; (*4*) krypton; (*5*) xenon. Voltage amplitude 200 kV. Tube 47 cm long and 1.5 cm in diameter. Water insulator [24].

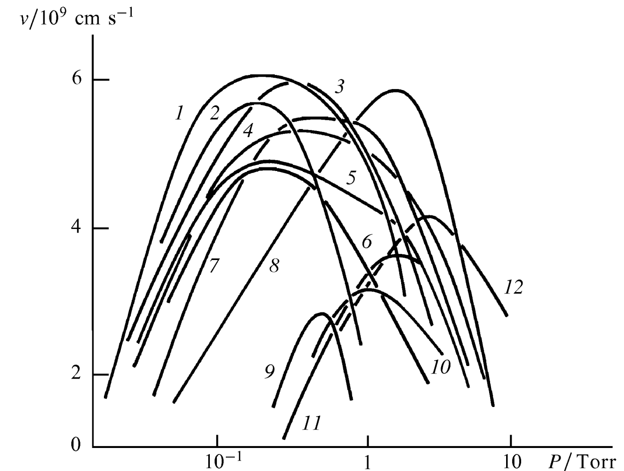

Figure 5. Dependences of the average FIW velocity on the gas pressure obtained for different polarities of voltage pulses (200 kV): (*1*) SF_6; (*2*) CCl_4; (*3*) propane–butane mixture; (*4, 12*) CO_2; (*5, 11*) N_2; (*6, 10*) acetone; (*7*) air; (*8*) He; (*1–8*) negative polarity; (*9–12*) positive polarity. Tube 47 cm long and 1.5 cm in diameter. Water insulator [25].

where the central conductor is a high-conductivity plasma column. A glass or quartz tube reduces strongly, even when its wall is very thick, the effective permittivity: for example, if water is used as the filler, the permittivity decreases from 80 to 25–30, so that the maximum velocity of FIWs is a factor of 5–6 less than the velocity of light ($\varepsilon_{\rm eff}^{1/2}$), which is illustrated in Fig. 6.

It therefore follows that an increase in the amplitude of the voltage pulses increases also the maximum velocity of FIWs until the velocity reaches its limit. At high amplitudes of the voltage pulses the range of the gas pressures in which FIWs travel a velocity close to the limit can be very wide (Fig. 6). The maximum of the pressure dependence of the velocity is clearly manifested at low voltages [11, 12].

As pointed out by Asinovskii et al. [12], FIWs may appear at different stages of electrical breakdown. At low pulsed voltages they form during the concluding stages of the breakdown, which is due to the more favourable conditions for their formation and motion when the discharge zone is characterised by a sufficiently high initial electron density. In some investigations the name given to FIWs formed without preionisation is 'electrical breakdown waves' and in the presence of a plasma they are called 'secondary breakdown

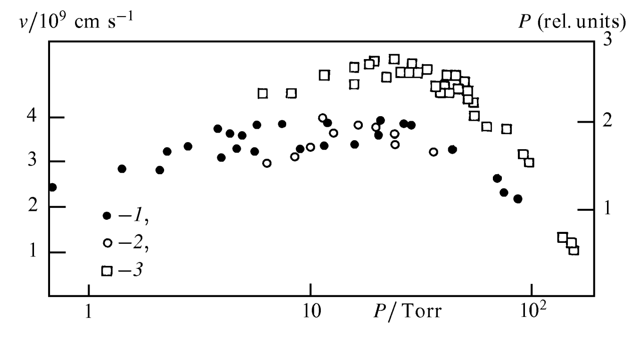

Figure 6. Dependences of the average FIW velocity (*1*), of the velocity of laser radiation waves (*2*), and of peak nitrogen laser power (*3*) on the air pressure. $U_0 = 300$ kV. Tube 41 cm long and 0.5 cm in diameter. Water insulator [23].

waves'. The lower the voltage amplitude, the stronger the effect of the initial ionisation, which is manifested particularly strongly when FIWs are excited by pulses of different polarity. When the amplitude of the pulses is 3 – 20 kV these waves appear when the polarity of the pulses is positive and there is a plasma in the gap, whereas in the case of negative-polarity pulses the waves may not appear during a pulse [11, 12]. This can be explained as follows. When the polarity of the pulses is positive, electrons begin to escape from the plasma to the electrode and form a space charge layer as a result of which the electrode potential is shifted to the gap. The electric fields generated in this way cause strong ionisation and this leads to the formation of FIWs and their motion to the other electrode. When the applied voltages are of the negative polarity, electrons escape from the electrode and screen the plasma from the electrode potential. Waves can then form only after the appearance of an intense source of electrons at the cathode, for example, at the cathode spot as found by Winn [11]. The time of formation of the cathode spot can exceed the pulse duration (100 ns, 24 kV) [11] and therefore the formation of the spot has been faciliated by employing electrodes of special shape [11]. The velocity of FIWs excited by negative pulses is nevertheless always higher than for the positive polarity.

An increase in the initial electron density increases the FIW velocity [11 – 13, 27] and if the conductivity of the plasma column is sufficiently high, a voltage pulse travels at the velocity of an electromagnetic signal, exactly as in a coaxial line with losses. Therefore, if several such waves form on breakdown, the velocity of secondary waves is always higher, because they move along a channel with a higher conductivity. A reduction in the initial density of the gas and the application of pulses with relatively low amplitudes (3 – 20 kV) reveals a threshold below which FIWs do not form even when the polarity of the pulses is positive ($10^7 - 10^8$ cm^{-3}) [13]. According to Fower [10], the FIW velocity cannot be less than a certain critical value which is of the order of $(1-3)\times 10^8$ cm s^{-1} and is governed by both the amplitude of the pulses and the initial ionisation in the discharge gap.

5. Current in fast ionisation waves

When an FIW moves along the plasma column, a conduction current flows behind the front of the wave and this current is closed in the front by the metal shield (or in the surrounding space) via the displacement currents. Therefore, the profile and the amplitude of the current pulses measured with a sensor depend on the position of this sensor along the discharge tube and, generally speaking, also on the method used to detect the current. The current begins to flow through the high-voltage electrode immediately when the wave begins to move after the launch of the wave. If the front of the wave does not cross the whole length of the tube during a pulse, the current may not flow at all through the earthed electrode at the other end of the tube. The current behind the wave front is approximately equal to the current needed to charge, up to the potential in the front, a cylindrical capacitor formed by the strongly conducting plasma column behind the front and the cylindrical shield. If the FIW velocity is constant along the tube and the potential in the front is equal to the electrode potential, the current flowing into the tube is also constant and equal to $i = c_i v U_0$, where c_i is the instantaneous velocity (per unit length), v is the velocity of the front, and U_0 is the voltage applied to the electrode. The constancy of the current flowing into the tube was first observed experimentally by Asinovsky et al. [28]. At high velocities an FIW reaches the earthed electrode and is reflected there in accordance with the laws of reflection of electromagnetic pulses in the presence of an inhomogeneity in a transmission line. The voltage across a short-circuited connector falls to zero and the current is twice the current of the wave in the transmission line. At breakdown, a series of FIWs may form and the current then rises consecutively [29, 30].

Already the early work [3] has established that the currents in the initial wave are high and amount to 150 – 200 A. An increase in the voltage amplitude to 250 kV has made it possible [21] not only to increase the transport current up to 1.7 kA, but also to determine for the first time the dependence of the amplitude of the transmitted current on the gas pressure (Fig. 3). It is evident from the graphs that the current reaches its maximum value at the same pressures as the velocity. A further increase in the current in the wave can be achieved by increasing the instantaneous capacitance if the discharge tube is surrounded by a light high-ε insulator, for example, water [14, 16, 23, 26]. The velocity of the front then falls by a factor $\varepsilon_{\text{eff}}^{1/2}$ and the running capacitance rises proportionately to ε_{eff}, so that the wave current increases by a factor $\varepsilon_{\text{eff}}^{1/2}$. The current density behind the front of an ionisation wave exceeds 10 kA cm^{-2}, which implies promising potential applications of FIWs as a powerful pulsed source of a plasma, in pumping of pulses lasers, etc.

6. Potential drop across the front of a fast ionisation wave and wave attenuation

The motion of the front of an ionisation wave along a tube charges the resultant capacitor to the potential of the front. The excess charge needed in this process is ensured by the conduction current flowing towards the front along the plasma column. Since this column has a certain finite average conductivity σ, an electric field E should exist in the front so that the current $I = \pi r^2 \sigma E$ flows and the potential drop in the front of a wave should be always less than the amplitude of the voltage applied to the high-voltage electrode. The amplitude of the front of a wave thus decreases as the wave travels further from the electrode. This process can be described and various experimental results can be compared if we know the relationship governing the attenuation of the amplitude of an FIW. One of the successful variants describing this relationship is the exponential attenuation law $U(x) = U_0 \exp(-ax)$, where $U(x)$ is the amplitude of the front of a wave at a distance x from the high-voltage electrode, U_0 is the initial amplitude of the wave at the electrode edge, and a is the attenuation coefficient. Measurements of the attenuation coefficient in a wide range of pressures were first carried out by Asinovskii et al. [21] and the results are presented in Fig. 3 for nitrogen, air, and helium subjected to pulses of negative polarity and of 250 kV amplitude. The most important property of the curves in Fig. 3 is that the values of the attenuation coefficient are minimal approximately at those pressures where the velocity and the current in the wave are maximal. These pressures depend on the nature of the gas and, for example, differ by almost one order of magnitude between nitrogen and helium. Therefore, for each gas there is a range of pressures most favourable for the propagation of FIWs.

An increase in the voltage increases also the pressure at which the velocity of propagation of FIWs reaches its maximum. It is of interest to extrapolate results obtained to the atmospheric pressure, i.e. to estimate the feasibility of formation of longer sparks in the form of FIWs in the atmosphere. The results in Fig. 3 yield the value of the voltage in the front of a wave necessary for this purpose: it is about 10 MV [21]. Since clouds are usually charged negatively relative to the earth, this extrapolation applies also to lightning. The current which is then flowing during the return-stroke phase is of the order of $U/Z_0 \approx 30$ kA, where Z_0 is the impedance of free space (377 Ω). In spite of the roughness of the extrapolation, these values are in satisfactory agreement with the known currents in lightning [5].

The pressure dependences of the velocity, current, and attenuation of the amplitude of FIWs retain their form also in those cases when the insulator in the transmission line and in the discharge zone is oil or water [14, 23, 26] and also when the polarity of the pulses is positive. Figs 7 and 8 give the measured velocities of FIWs in air obtained on application of negative and positive 250 kV pulses [14, 26]. These experiments were carried out in a glass tube 0.8 cm in diameter and the coefficient k representing the attenuation of the voltage amplitude, determined from the signals U_1 and U_2 provided by two dividers separated by 70 cm from one another, was $k = 1 - U_1/U_2$. It should be pointed out that in Figs 7 and 8, as well as in Fig. 3, the minimum attenuation coefficient is attained at lower pressures than the maximum values of the velocity of propagation and of the current in FIWs.

The minimum attenuation of the waves in the case of negative polarity pulses is governed almost entirely by the cathode drop of the potential (Fig. 8). For positive voltage pulses the anode drop is much less than the cathode drop. It should be pointed out that in all other investigations there have been no measurements or allowance for the absolute potential at the electrodes. The losses which can determine the minimum attenuation coefficient, apart from the voltage drop which is necessary for the flow of the conduction current, have been investigated by Abramov et al. [23]. The errors in these measurements were reduced by employing a tube 200 cm long with an internal diameter 0.5 cm. Eight capacitor voltage dividers were placed along the tube. The space between the tube and a shield 5.4 cm in diameter was filled with oil. The average velocity of FIWs was determined from the signals provided by the dividers separated by 100 cm. The amplitude of a voltage pulse of negative polarity (-120 kV) was selected to ensure that the velocity of the electromagnetic signal in the coaxial system with a composite (glass–oil) insulator (1.7×10^{10} cm s^{-1}) matched the velocity of free flight of an electron of 120 keV energy. Fig. 9 shows the dependence of the attenuation coefficient (curve *1*) and of the velocity (curve *2*) of FIWs on the air pressure. The attenuation curve is complex near the minimum and the velocity in this range of pressures has a tendency to fall. These features are explained [23] by the excitation of electromagnetic oscillations in the system, as confirmed experimentally. These oscillations appear at a distance of about 50 cm from the cathode and are then

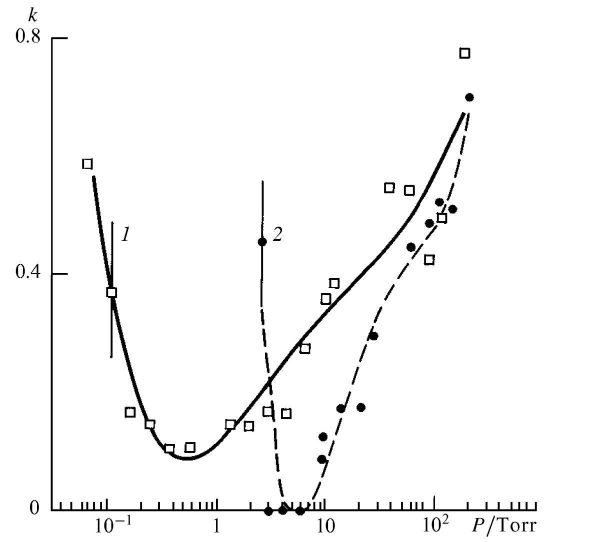

Figure 8. Dependences of the relative attenuation of the voltage amplitude on the air pressure: (*1*) negative polarity of 250 kV voltage pulses; (*2*) positive polarity. Measurement base 70 cm. Oil insulator [14].

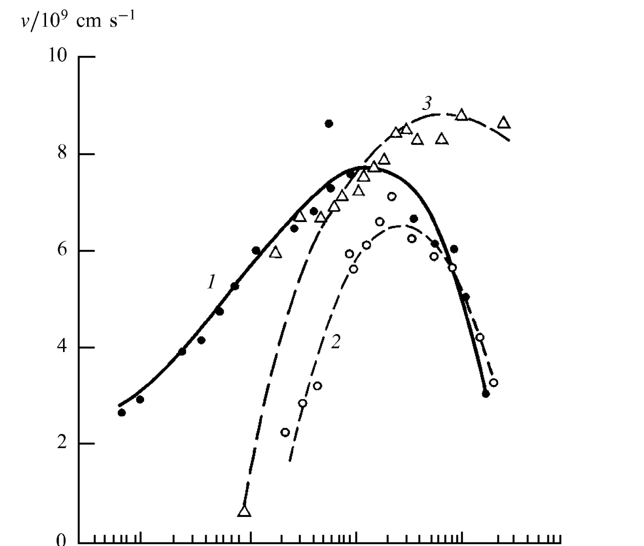

Figure 7. Dependences of the average FIW velocity on the gas pressure: (*1, 2*) air; (*3*) helium; (*1, 3*) negative polarity of 250 kV voltage pulses; (*2*) positive polarity. Measurement base: (*1, 2*) 70 cm; (*3*) 50 cm. Tube diameter 0.8 cm. Oil insulator [14].

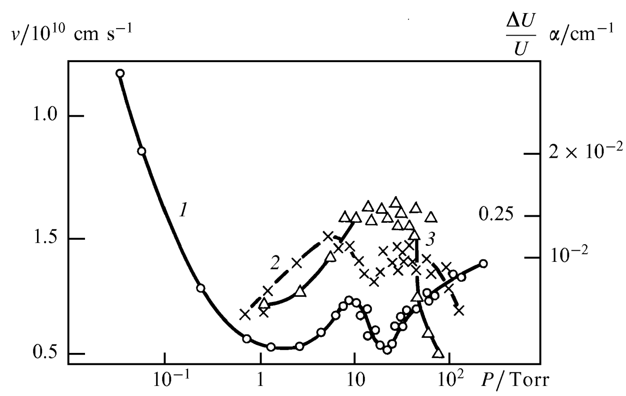

Figure 9. Dependences of the attenuation coefficient (*1*), front velocity (*2*), and relative amplitude of the oscillations (*3*) on the air pressure. Tube 200 cm long and 0.5 cm in diamter. Oil insulator [23].

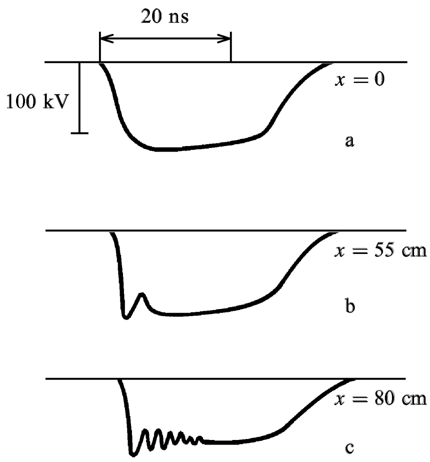

Figure 10. Oscillograms of signals from capacitor dividers located at different distances from the high-voltage electrode: (a) above cathode; (b) 55 cm; (c) 80 cm. Air pressure 12 Torr. Tube 20 cm long and 0.5 cm in diameter. Oil insulator [23].

observed along the whole of the rest of the tube (Fig. 10). Curve *3* in Fig. 9 gives the dependence of the relative amplitude of these oscillations across a capacitor divider located at 80 cm from the cathode. The buildup of the electromagnetic oscillations increases the attenuation coefficient and reduces the wave velocity. Therefore, in the range of the optimal pressures the attenuation during propagation of FIWs may be governed not only by the energy necessary to create a highly conducting plasma column, but also by the buildup of electromagnetic oscillations. The oscillations are evidently related with the existence of a flux of high-energy electrons in the region of the FIW front [14–23] and by the feasibility of an effective exchange of energy between these electrons and the electromagnetic wave when the phase velocity of the wave is close to the electron velocity. The observed oscillations may be the results of excitation of an electromagnetic wave at a frequency close to the frequency of the fundamental mode of the E wave in a circular waveguide because of a resonant interaction of the electromagnetic wave with the high-energy electrons in the coaxial delay structure. The periods 1 and 1.5 ns calculated for a coaxial waveguide filled with oil and water are in good agreement with the experimental values 1.5 and 2.5 ns, respectively [23].

The attenuation of the amplitude of an FIW during its motion should be related, first, to the dynamics of the velocity considered as a function of the distance travelled, because the velocity depends on the voltage amplitude, and second, to the dissipation of energy in the front of the wave and behind it, which is extremely important in practical applications of FIWs.

7. Dynamics of the velocity of fast ionisation waves moving along a discharge gap

The dynamics of FIWs during their motion was studied with the aid of the AGAT-SF3 image-converter streak camera. This camera recorded continuously the radiation emitted by a discharge tube 0.8 cm in diameter and 80 cm long supplied by a line 5.4 cm in diameter filled with water. The pulses causing breakdown were of 150 kV amplitude, 35 ns duration, and rise time of 3.5 ns. The images obtained with the camera were analysed on a computer. The application of a negative-polarity pulse created bright radiation in the cathode region and this was observed at all pressures (0.1–760 Torr). After the appearance of this radiation following certain characteristic delay time t_d a wave started from the high-voltage electrode and travelled along the tube. The delay time t_d decreased when the pressure was increased (Fig. 11) and it could be measured only at pressures below 15 Torr. The replacement of water with transformer oil did not alter qualitatively the launch of the waves. The application of positive-polarity pulses to the high-voltage electrode generated uniform radiation in the electrode region and the intensity of this radiation was the same as the intensity in the plasma column after the passage of the front of the ionisation wave. The velocity of a negative ionisation wave along the tube could be constant, or could increase or decrease (Fig. 12). At high pressures $P > 150$ Torr the slowing down of the front became so significant that even its stopping was observed.

The dynamics of the wave velocity during the initial stage of its motion is shown in Fig. 12a. At practically all the investigated pressures an accelerated motion of the wave was observed from the cathode up to distances of 10 cm and only at pressures close to atmospheric the wave velocity began to decrease practically immediately at the cathode. There was a certain critical pressure above which a strong attenuation was observed in the initial section crossed by the wave.

Fig. 12b shows the dependence of the velocity of FIWs along the whole tube on the gas pressure. A strong reduction in the velocity occurs at pressures above 160 Torr and this pressure is evidently the threshold. On the other hand, in a wide range of pressures an ionisation wave, which has reached in its initial stage the maximum velocity close to the velocity of an electromagnetic signal in the composite glass–water insulator (5.5×10^9 cm s^{-1}), then travels almost uniformly to the anode subject to a slight slowing down.

When the insulator around the discharge tube is altered, for example if water is changed progressively to oil along the length of the tube, the continuous reduction in the

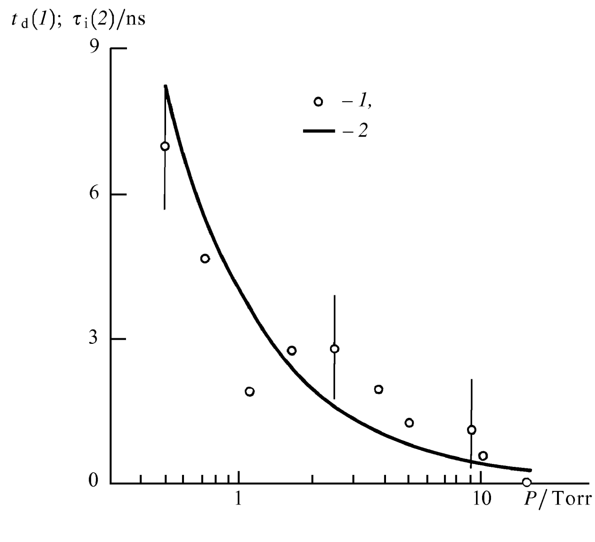

Figure 11. Dependences of the delay of FIWs (*1*) and of the calculated ionisation time (*2*) on the air pressure. $U_0 = 150$ kV. Tube diameter 0.8 cm, shield diameter 5.4 cm. Water insulator [26].

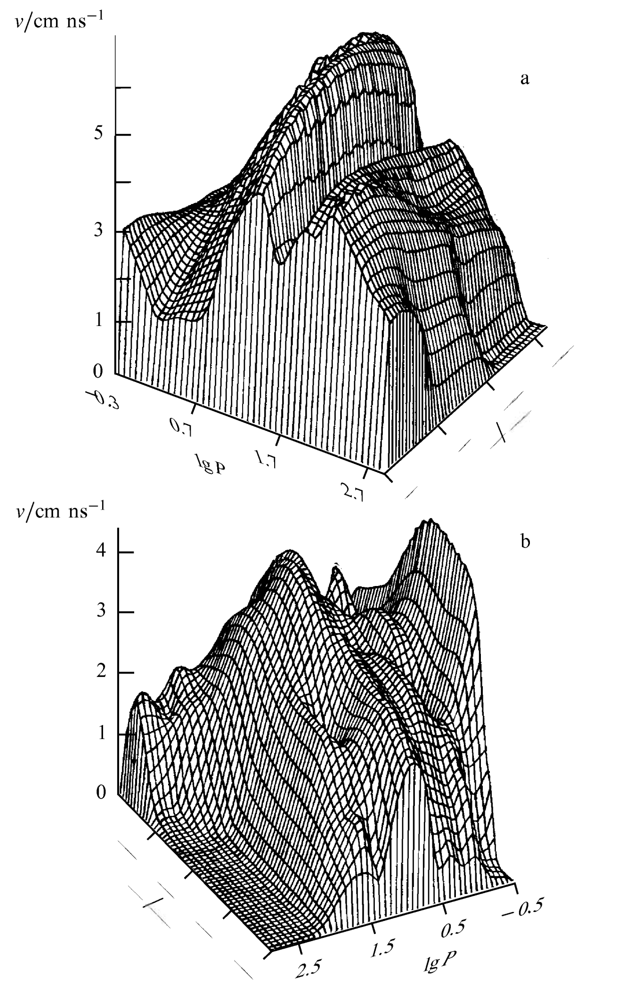

Figure 12. Dependences of the local FIW velocity on the distance travelled and on the air pressure in the initial part of its motion (a) and over the whole length of the tube (b). $U_0 = 150$ kV. Tube diameter 0.8 cm, shield diameter 5.4 cm. Water insulator [26].

known as the peaking of the front. The duration of the front decreases to a certain minimum value in the range of pressures optimal for wave propagation. At low pulsed voltages (5 – 30 kV), this peaking of the FIW front is observed only at a positive polarity. The reduction in the duration of the FIW front to 0.30 ns was recorded by Asinovsky et al. [28] with the aid of a return-current shunt when the amplitude of a positive pulse was 6.2 kV and its rise time was 2 ns. Asinovsky et al. [28] called the observed FIW a 'shock' electrical wave by analogy with shock electromagnetic waves in ferrites. When the pulse amplitude was 25 – 30 kV, the reduction in the front duration was from 5 to 2.5 ns [31]. This peaking of the front depended strongly on the degree of preionisation of the gap. Under negative-polarity pulses an FIW either did not appear or its front began to spread out, leading to the hypothesis that the peaking of the front is possible only when the polarity of the pulses is positive.

However, when the voltage was increased above 100 – 150 kV, the situation changed radically because at these voltages the range of existence of negative-polarity FIWs could be wider than for voltages of positive polarity (Fig. 7). Fig. 13 shows the dependence of the duration of the front of a signal from a capacitor divider, located at a distance of 70 cm from the high-voltage electrode, on the air pressure in a discharge tube 0.8 cm in diameter when the amplitude of the voltage pulses applied to the electrode was 250 kV and the rise time of these pulses was 3.5 ns [14]. There was clearly a range of pressures where peaking of the front occurred both for the positive pulses (the duration of the front was reduced to 0.5 ns) and for negative pulses (the reduction was to 1 ns). When the polarity of the pulses was negative, the FIW front spread out both at low and high pressures to a value greater than the initial duration. Under positive pulses the FIW front did not spread out more than the initial value at low pressures (the FIW simply did not appear), but at high pressures the duration of the FIW front could exceed the initial value. In these investigations the insulator in the transmission line was either oil or water.

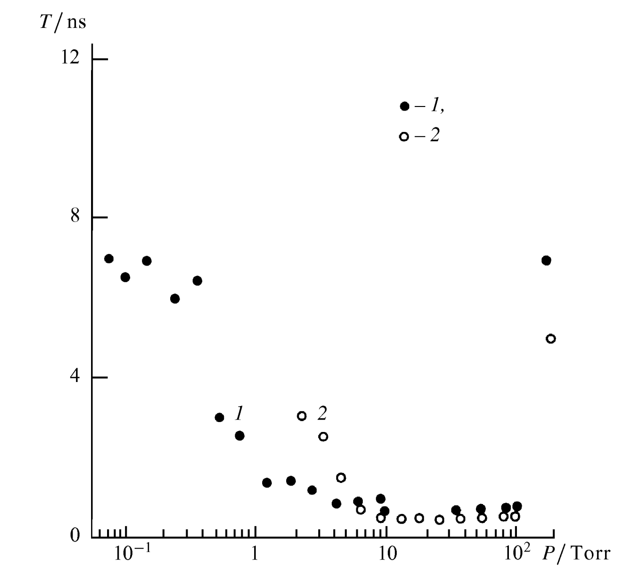

Figure 13. Dependences of the duration of the FIW front at a distance of 75 cm from the high-voltage electrode on the air pressure: (*1*) negative polarity; (*2*) positive polarity. $U_0 = 250$ kV. Tube diameter 1 cm. Oil insulator [14].

permittivity should increase the velocity of the FIW front along the tube, as supported by the relevant experiments [26].

8. The front of a fast ionisation wave

As mentioned in the preceding section, the use of an image-converter streak camera has demonstrated that the formationofanFIWterminatesatsomedistancefromthecathode[26]. The wave becomes detached from the cathode and travels along the discharge gap subject to attenuation of its amplitude and a reduction in its velocity. Since the main ionisation processes occur in the front of the wave, the front also changes in the course of its motion.

The FIW front can be detected and its parameters can be determined using capacitor voltage sensors [14, 16], return-current shunts [28], or the intensity of the radiation emitted by the plasma [31]. A complete agreement between the results obtained in measurements of the front parameters by these three methods cannot be expected because of the complexity and the differences between the processes occurring in the front. However, all these methods yield matching dependences.

One of the unique properties of FIWs is a reduction in the duration of the front as it moves along the discharge gap, The range of pressures in which the front did spread out coincided with the range where the attenuation of the FIW amplitude rose steeply (Fig. 8) and also the velocity fell strongly (Fig. 12). Therefore, in this range of pressures the intensity of the electric field in the FIW front decreased not only because of a strong reduction in the front amplitude, but also because of the spreading of the front. The ionisation frequency in the front depended exponentially on the electric field and, therefore, the ionisation processes slowed down considerably, which increased the resistance of the plasma column and caused a further nonlinear attenuation of the wave which was of near-threshold nature. The reduction in the duration of the FIW front to 1 – 1.5 ns for both the polarities of the pulses was retained also when the rise time of the initial pulse was shortened to 8 – 9 ns and the amplitude of the pulses was increased to 700 kV [14, 32]. This should make it possible to use FIWs for the purpose of peaking in pulse generators.

The minimum duration of the front l_f, estimated from the velocity and the duration of the FIW front $l_f \approx v_f t_f$, has been found to be equal to the diameter of the shield around the tube and is possibly determined by the wavelength of the resultant electromagnetic oscillations representing the fundamental E mode [16].

The profile of the FIW front has not been investigated sufficiently because of the major experimental difficulties, and the main of which are the need for framing photography with an exposure less than 1 ns and insufficient intensity of the plasma radiation. Since FIWs are highly reproducible, at voltages, 25 – 30 kV of these difficulties have been overcome by the superposition in one frame of a few tens or even hundreds of discharges with an exposure of 1.5 ns in each discharge [15, 33]. Such average photographs of the radiation emitted by a discharge tube 5 cm in diameter, subjected to positive pulses at different pressures, are reproduced in Fig. 14 [33]. The profile of the front depends on the initial ionisation of the discharge gap and on the gas pressure in it. At low pressures the front has a peak profile. At higher pressures the FIW velocity rises to its maximum value and the front becomes flat (Fig. 14). A further increase in the pressure reduces the FIW velocity and the discharge is pressed against the side walls of the tube (Fig. 14). In these experiments the FIW velocity was $(2-3)\times10^9$ cm s^{-1}. A model accounting for the profile of the FIW front has not yet been developed. There are insufficient grounds to assume that an increase in the pressure causes the discharge to develop along the walls (sliding discharge). For example, an investigation of the radial distribution of the intensity of the radiation from a nitrogen laser excited by FIWs, recorded at the edge of an earthed electrode with an aperture, showed [34] that at low pressures the laser beam had a ring structure and at high pressures it had a convex profile (Fig. 15). Since the degree of excitation of laser levels should correspond to the profile of the FIW front at high amplitudes of negative pulses (300 kV) the FIW front was pressed against the walls at low pressures and became nearly flat at high pressures.

In the limit the FIW front can be regarded as a moving surface on which the electrical characteristics of the medium change discontinuously. The FIW front acts as a moving mirror for the electromagnetic wave moving along the plasma column. This is a classical problem in relativistic electrodynamics and the solution of this problem demonstrates that a pulse reflected from such a mirror should be longer than the initial pulse by a factor $(1+\beta)/(1-\beta)$ and

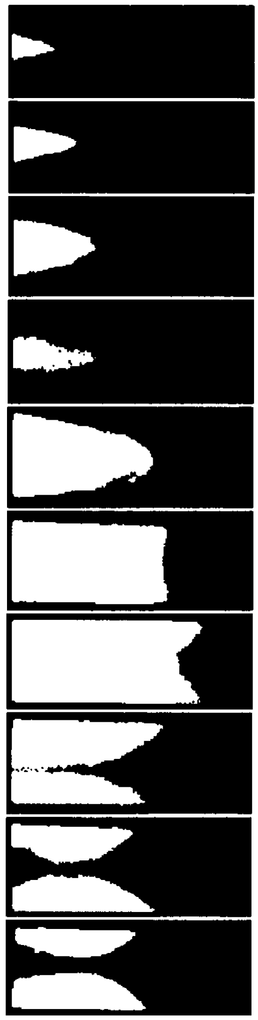

Figure 14. Photographs of the initial stage of formation of a positive-polarity FIW near the high-voltage electrode. Exposure time 1.5 ns. The numbers on the right give the pressure. $U_0 = 30$ kV. Tube diameter 2 cm. Air insulator [33].

its amplitude should be less by the same factor (β is the ratio of the velocity of the front of the wave to the velocity of light). This broadening of the reflected current pulse has indeed been recorded for FIWs at voltage amplitudes of 30 – 40 kV [35].

An increase in the front velocity increases the duration of the reflected pulse and reduces its amplitude. If the velocity of the front is close to that of light, the bulk of the energy of a voltage pulse is dissipated in the plasma and only a small proportion of this energy is reflected back to the voltage generator. It is interesting to note that in this case the length of the plasma column is greater than the product of the duration of the initial voltage pulse and the front velocity [14]. In fact, if the duration of the pulse is determined at the high-voltage electrode, we can see that the leading edge of the voltage pulse reaches the electrode and after a time t_p the trailing edge also reaches the electrode. However, by this time the FIW front has moved along the discharge gap a distance $v_f t_p$. Even if the trailing edge of the pulse then catches up the FIW front at the velocity of propagation of an electromagnetic signal, this happens only after a time $t_p/(1-\beta)$. Therefore, the duration of action of

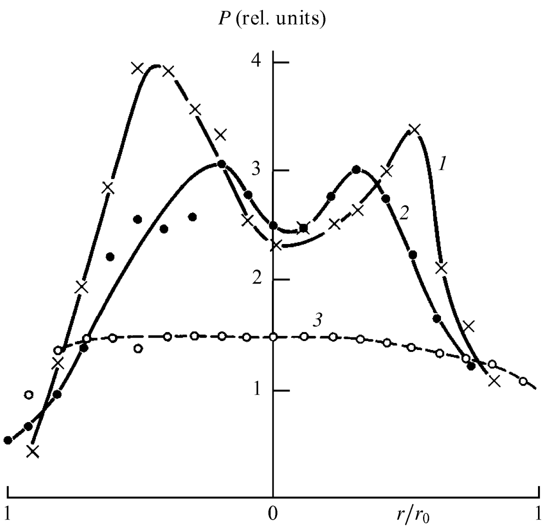

Figure 15. Radial distribution of the peak radiation power from a nitrogen laser: (*1*) air pressure 9 Torr; (*2*) 48 Torr; (*3*) 150 Torr. $U_0 = 250$ kV. Tube 45 cm long and 1 cm in diameter. Water insulator [34].

the electric field on the gas may exceed considerably the duration of the initial pulse. This has indeed been observed [14]: the duration of action of a pulse of 150 kV amplitude was 1.5 times greater than the duration of the initial pulse (35 ns). In other words, a relatively short but powerful pulse can create a channel of considerable length until the trailing edge of the voltage pulse catches up with the wave.

Properties of the FIWs such as peaking of the front, the discontinuities of the electrical parameters of the medium, and the front velocity demonstrate that FIWs have much in common with shock electromagnetic waves, for example with such waves in ferrites.

In addition to peaking of the front and its high velocity, there is a direct analogy between the reduction of the instantaneous value of the shunt resistance of the plasma channel in the front [36], which decreases on increase in the wave current, and the change in the instantaneous resistance during motion of a shock electromagnetic wave in a coaxial line containing a ferrite with a rectangular hysteresis loop [37].

9. High-energy electrons in the front of a fast ionisation wave

At high intensities of the electric field in an ionised gaseous medium an electron may acquire more energy from the field than the energy it loses in collisions. The energy and velocity of such electrons in a plasma subjected to a constant electric field increase with time and, therefore, they are known as the 'runaway' electrons. The published estimates [38] indicate that the critical field intensity $(E/P)_{\text{cr}}$ for a nitrogen plasma is 360 V cm^{-1} Torr^{-1} and 80 V cm^{-1} for a helium plasma.

The presence of the 'runaway' electrons has a significant influence on the development of breakdown [38, 39], including breakdown in nanosecond discharges [39], and this is true right up to the atmospheric pressure. In nanosecond discharges at high electric-field intensities the electron distribution function may be transient and, therefore, the continuous acceleration regime requires that the reduced field intensities should exceed the critical values for a constant field and it is more correct to refer to them as the high-energy electrons. A beam of high-energy electrons has been observed in a sliding-discharge plasma after breakdown of gaps of 1 – 18 cm length by pulses of 170 kV amplitude and 10 ns duration [40].

It is natural to expect the appearance of high-energy electrons in the case of FIWs with amplitudes amounting to tens and hundreds of kilovolts in the front. The field intensity in the front can be estimated from $E \approx U/l_{\text{f}}$, where U is the potential of the front and l_{f} is the spatial length of the front given by the expression $l_{\text{f}} \approx v_{\text{f}} t_{\text{f}}$. In the low attenuation case the voltage drop in the front is close to the amplitude of the high-voltage pulse applied to the electrode. When this amplitude is ≈ 30 kV the velocity of the front at pressures of 1 – 10 Torr is $(1-5)\times 10^9$ cm s^{-1}. For a typical 2 – 7 ns duration of the wave front [31] an estimate of the reduced electric field in the front gives $E/P = 1-10$ kV cm^{-1}. At voltages of 200 – 300 kV it follows from the results plotted in Figs 12 and 13 that if the front velocity is $(5-10)\times 10^9$ cm s^{-1} and the duration of the front is typically ≈ 1 ns, when the pressure is $P \cong 10$ Torr, the reduced field is $E/P \approx 2$ kV cm^{-1} Torr^{-1}. Therefore, in a wide range of pressures the reduced electric field in the FIW front is much higher than the critical value needed for the formation of high-energy electrons.

The presence of high-energy electrons generated by FIWs has been detected at fairly high pulsed voltages of 20 – 40 kV by recording X-ray bremsstrahlung [41, 42], and it has been also detected in the case of high-voltage pulses of 150 – 300 kV with the aid of a Faraday cup placed behind an earthed electrode [14, 16, 43]. Fig. 16 shows the amplitudes of the current due to the high-energy electrons in a Faraday cup (screened from the discharge by a Mylar film transmitting electrons of energy of at least 40 keV and in the absence of such a film), obtained when the pulse amplitude was 250 kV [14, 43]. These measurements were carried out in two gases, air and helium, and the critical values of the field intensity were quite different for these gases: 360 and 80 V cm^{-1} Torr^{-1}. The current due to the high-energy electrons was clearly generated in a wide range of pressures (up to 450 Torr in helium): it could be comparable with the conduction current in the front and could even exceed the latter at low pressures. The curve representing the current of the high-energy electrons in helium was shifted towards higher pressures with the corresponding dependence obtained for air. There was approximately the same shift along the scale for these gases in the case of the dependences of other properties such as the wave velocity, the wave attenuation, and the current transported by the wave (Figs 7 and 8).

The duration of the electron-current signal from an unscreened Faraday cup decreased when the pressure was increased from 30 to 3 ns [14], and at high pressures the duration was close to the rise time of the applied high-voltage pulse. This pressure dependence of the electron-current signal duration differs from the experimental results reported by Abramov et al. [16] in which the duration of the current of the high-energy electrons was found to be about 3 ns and was practically independent of the pressure. The signal from an evacuated cylinder cup, screened by a Mylar film, consisted of short pulses and the total duration of the train of these pulses did not exceed 10 ns. It is evident from Fig. 16 that the signal from the screened cylinder cup had a lower amplitude and disappeared at a lower pressure than the signal from the unscreened cup. The beginning of the electron-current signal coincided with the time of arrival of the FIW front at the electrode behind which the cylinder cup was

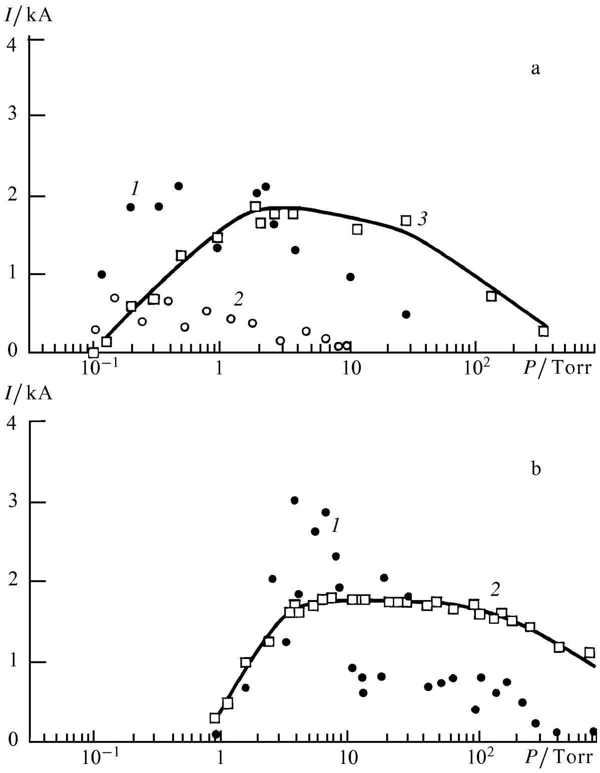

Figure 16. Dependences of the current of high-energy electrons in a nonevacuated Faraday cup (*1*) and in a shielded Faraday cup (*2*), and of the total current in the FIW front (*3*) on the pressure of air (a) and helium (b). $U_0 = -250$ kV. Oil insulator [14].

located. This made it possible to conclude that the high-energy electrons were generated in the region of the FIW front. This confirmed in particular that electric fields of extremely high intensity exist in the region of the FIW front.

The energy distribution of these electrons was not determined directly in the reported experiments and could be judged only qualitatively on the basis of indirect experiments. The different durations and amplitudes of the electron current from the screened and unscreened Faraday cups indicated the presence of a large number of electrons with energies less than 40 keV. At low pressures the electrons with higher energies were the first to reach the Faraday cup and then the electrons with lower energies were recorded for a fairly long time. The appearance of the electron-current signal simultaneously with the FIW front indicated that this front and the region ahead of it contained electrons with high energies which were well in excessof 40 keV.

Since the electrons travel in the same direction as the FIW front, they may experience the electric field in the front for a longer time and may therefore acquire energies higher than the potential of the front. This was the hypothesis put forward by Amirov et al. [42] and illustrated as follows. They assumed that the field in the FIW front is homogeneous and that the velocity of the front is less than $2eU/m$, where U is the potential of the front, and e and m are the charge and mass of an electron. For simplicity, it is assumed that these velocities are equal. In a coordinate system linked to the wave an electron created at the leading edge of the front (Fig. 17) travels at a velocity v_{f} in a retarding electric field. At the trailing edge of the front the electron stops and begins to accelerate in the opposite direction. After crossing the whole front it acquires a velocity $v_{\mathrm{f}} = (2eU_{\mathrm{f}}/m)^{1/2}$ in the coordinate system of the front and then leaves the front. In the laboratory coordinate system we now find that the electron energy exceeds eU_{f} and, depending on the place where the electron is created, it may reach $(2-4)eU_0$. Determination of the X-ray bremsstrahlung spectrum has enabled Amirov et al. [42] to conclude that for a front amplitude of 25 kV the energy of electrons could reach 40 keV.

A study of the distribution of X-ray radiation along the discharge tube showed [42] that it appeared only as a result of the passage of the FIW front. At low pressures the electrons with lower energies were near the walls of the discharge tube, but at high pressures they were found near the tube axis. This distribution of high-energy electrons over the tube cross section was opposite to the distribution of the radiation emitted by the front and shown in Fig. 14.

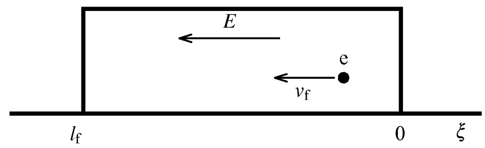

Figure 17. Deceleration and reflection of an electron in a moving coordinate system [42].

10. Influence of high-energy electrons on the formation and motion of fast ionisation waves

The discovery of a flux of high-energy electrons in the region of the FIW front has made it possible to resolve two important problems: the origin of the ‘seed’ electrons and the reason for the wave attenuation at low gas pressures. Moreover, it has become possible to identify the reason for the delay of the formation of FIWs and the difference between these waves in the case of voltage pulses with negative and positive polarities.

The delay of the appearance of FIWs relative to the arrival of a high-voltage pulse at the electrode may be due to a variety of reasons, depending on the experimental conditions. In the case of negative-polarity pulses of relatively low amplitude (~ 30 keV) without preionisation of the gap the flow of the current requires the emission of electrons from the cathode. Under these conditions the delay of the appearance of FIWs is governed by the time of formation of the cathode spot. Sometimes the formation of this spot requires a time exceeding the 100 ns duration of a high-voltage pulse [11] and then the initiation of FIWs requires the use of specially shaped electrodes [11]. The long formation time of FIWs is then explained by the need to ensure high emission currents of 40 – 100 A from the cold electrode, which are required to charge the plasma – shield capacitor which forms during the motion of FIWs.

If preliminary ionisation occurs in the gap, the delay in the appearance of the waves amounting to 5 – 7 ns [13, 41] under voltages of 30 – 40 kV is associated with the polarisation of the plasma which is present. The process of formation of a negative FIW occurs in the following sequence [41]: after the delay associated with the plasma polarisation, the first wave appears and it transports the potential into the gap at a velocity $v_1 = 2\times10^9$ cm s^{-1}. Its motion is accompanied by the ionisation and excitation of the gas. Some time later the cathode spot is formed and a cathode jet appears, which enhances greatly the emission of electrons and increases strongly the current flowing through the electrode and this gives rise to a second FIW at the cathode. Since the conductivity of the plasma in the gap has increased as a result of the passage of the first wave, the velocity of the second wave v_2 is much higher than that of the first, $v_2 \gg v_1$, and is of the order of $v_2 \cong 10^{10}$ cm s^{-1}. The second wave also excites and ionises the gas. Moreover, it increases the potential of the plasma column. Approximately at a distance of 22–24 cm it catches up with the front of the first wave and increases the electric field intensity in this wave. X rays are emitted by the front at this moment and this is evidence of the generation of high-energy electrons in the front. The front of the newly formed wave travels at a velocity 4×10^9 cm s^{-1} and generates high-energy electrons.

The influence of the electrodes on the condition of formation of FIWs has been checked by measuring the FIW velocity for electrodes with different emission and electrophysical properties. In the experiment in question the electrodes were made of distilled water, an aqueous solution of NaOH, and of a metal [44]. In all three cases the dependences of the FIW velocity on pressure of air containing water vapour were the same within the limits of the experimental error for pulses of amplitudes 10–20 kV and this was true of either polarity of the pulses.

An increase in the voltage amplitude increases the FIW current and the role of emission of electrons from the electrode. A study with an image-converter camera carried out by Batenin et al. [26] demonstrated that at voltages in excess of 150 kV a cathode jet appeared simultaneously with the arrival of a high-voltage pulse. However, FIWs appeared only after the delay relative to the jet. The delay time decreased with increase in the air pressure from 8 ns at 0.5 Torr to 0.5 ns at 10–15 Torr [26] (see Fig. 11). The appearance of the cathode radiation was evidently associated with the explosive mechanism of emission from the cathode, which was due to the high values of the electric field intensity. A large electron current from the cathode flowing into the nonionised gas created an uncompensated space charge, which in turn stopped the current and, consequently, stopped FIWs. This process was similar to the stopping of the electron beam injected by a diode into a gas. In the course of motion of FIWs it was necessary to neutralise this space charge, which originated because of the ionisation of the gas by electrons and escape of the newly formed electrons from the region occupied by the space charge to the walls, because the space charge created strong radial fields. The remaining ions created a neutralising background. The characteristic neutralisation time τ_n calculated allowing for the field distribution [26] agreed well with the experimental results (Fig. 11).

After neutralisation of the excess space charge an FIW started from the cathode. During the initial stage of its motion the velocity of the FIW front increased and the duration of the front decreased. The FIW was fully formed after travelling a distance of 5–10 cm, which was approximately equal to two front widths. Obviously the width of the front could not be less than the diameter of the shield because of the resonant excitation of electromagnetic oscillations in the high-energy electrons in the waveguide.

It is quite natural to expect that high-enegy electrons can influence significantly the processes in the front of a moving FIW as well as ahead of the front and behind it [14, 43]. These electrons have the greatest influence on the properties of FIWs at the pressures such that the current is comparable with the conduction current behind the front, which is typical of low gas pressures. At low pressures and high voltages (150 keV) an FIW appears only when the polarity of the voltage pulses is negative and there is an electron emission source.

It therefore follows that at low gas pressures (to the left of the velocity maximum) the characteristics of a wave are governed primarily by the current of high-energy electrons. The processes in the FIW front are similar to those occurring at the 'head' of an electron beam travelling across the gas. It is known that when an electron beam is injected into the gas, an ionisation front appears at the beam 'head' and the velocity of this front may be considerably less than the initial velocity of the electrons [45, 46]. The pressure dependence of the velocity of this ionisation front is qualitatively similar to the analogous dependence of the FIW front velocity, but the maximum velocity at electron energies of 300–1000 keV is reached at lower pressures (0.1–5 Torr) [45] than in the case of the wave breakdown at voltages of 250–300 kV. The pressure dependence of the current (or charge) or energy transported by the beam also has a maximum. The governing process during the motion of the front is neutralisation of the excess charge at the beam 'head' because of impact ionisation by the beam electrons colliding with the gas molecules and, therefore, a reduction in the pressure increases the charge neutralisation time and reduces the front velocity. The reduction in the transport velocity of the beam at high pressures has been attributed [46] to a reduction in the conductivity of the plasma generated in the fields induced in the front, which increases the diffusion time of the potential moving from the anode to the front.

The FIW front is a moving virtual cathode emitting a flux of high-energy electrons. The motion of this virtual cathode requires charge neutralisation of the excess electrons ahead of the front. A reduction in the gas density increases the current of high-energy electrons in the FIW front (Fig. 16) and this makes the FIW motion increasingly similar to the motion of the electron beam. On the other hand, a reduction in the gas density reduces the rate of increase of the electron density and enhances the attenuation of the FIW amplitude, which in turn reduces the velocity of propagation of the front

The difference between the breakdown of a gas by an electron beam and by an ionisation wave is this: in the case of a beam the initial electric field appears because of the penetration of the discharge gap by the beam electrons and formation of a space charge, whereas in the case of a voltage pulse an electric field is first generated in the gap and high-energy electrons are created by the field. In both cases a space charge is set in motion and ionisation occurs in the field of this charge. The potential of the plasma behind the front is equal to the potential of the electrode from which the ionisation front starts. However, the supply of energy to the front proceeds in fundamentally different ways: in the case of an electron beam it is transferred in the form of the kinetic energy of electrons, which have to overcome the whole gap from the anode to the front, whereas a voltage pulse supplies energy to the front in the form of an electromagnetic wave from a coaxial transmission line with the plasma column acting as internal conductor of the line.

At near-optimal and higher pressures the main role of high-energy electrons is the creation of an initial ionisation ahead of the front. We have shown already that the FIW velocity increases with the initial density of electrons ahead of the front. It should be pointed out that the initial electron density may be created both by direct ionisation of the gas with high-energy electrons and by ionisation with X-ray bremsstrahlung, which is generated by collisions of high-energy electrons with the walls of the discharge gap.

The reduction in the FIW velocity with increase in the pressure may be explained by, first, a reduction in the density of electrons present initially ahead of the wave front and created in the course of ionisation of the gas by high-energy electrons, the proportion of which becomes small because of a reduction in the reduced field intensity *E/P* and, second, a reduction in the frequency of ionisation by the plasma electrons in the region of the front, again due to a reduction in the value of *E/P*. At high gas pressures the reduced intensity *E/P* in the front decreases also because of a reduction in the FIW amplitude and an increase in the width of the front, so that the ionisation frequency may lie in the region of its exponential fall in its dependence on *E/P*. All these processes increase the resistance of the column and, consequently, increase the diffusion time of the potential from the electrode along the plasma column to the front, which in turn reduces the amplitude and increases the width of the front, causing a further fall of *E/P* in the front. The result is the onset of an exponential reduction in the ionisation frequency and a corresponding strong reduction in the FIW velocity, which in the range of characteristic times of Fig. 12 is observed as the stoppage of the wave.

Since high-energy electrons in FIWs of negative and positive polarities move in opposite directions relative to the direction of the FIW front, their role is different for waves of different polarity. This is the reason why the properties of FIWs of positive and negative polarities differ so strongly at low gas pressures (Figs 7 and 8). At high pressures the current of high-energy electrons becomes so small that the main processes responsible for the formation of electrons ahead of the front are photoionisation by the radiation from the plasma column and also associative ionisation of photoexcited atoms and molecules, the ionisation frequency of which increases on increase in the pressure. All these processes are independent of the polarities so that at high gas pressures the velocity and attenuation are practically the same for FIWs of both polarities (Figs 7 and 8) [14]. This is supported by the agreement between the experimentally determined velocities of ionisation waves in helium at atmospheric pressure under a voltage of 250 kV [21] and calculations [47] carried out on the assumption that electrons appear ahead of the front because of associate ionisation when collisions take place between excited (He*) and unexcited helium:

$$\mathrm{He}^* + \mathrm{He} \rightarrow \mathrm{He}_2^+ + \mathrm{e}.$$

At low pressures the efficiency of gas preionisation ahead of the front, involving radiation (including X-ray radiation) is insufficient for the propagation of positive-polarity waves. At these pressures a negative-polarity wave appears because of the emission of electrons from the cathode where a cathode voltage drop of 30–40 kV occurs [14].

At low pressures a positive-polarity FIW may be generated as a result of the pure form of the mechanism discussed by Rudenko and Smetanin [48] as one of the possible ways of the development of streamers in strong fields. Since under positive-polarity pulses the runaway electrons propagate from the front into the plasma, their interaction with the plasma may excite longitudinal plasma oscillations. A plasma field may then appear at the cathode end of the plasma during certain half-periods of the oscillations. This field may exceed the external field and be directed opposite to it. Some of the plasma electrons can acquire from the plasma field an energy sufficient to escape outside the plasma where they ionise the gas and cause the streamer to move towards the cathode. This mechanism of the motion of a positive FIW is very probable, but additional investigations are needed to confirm it experimentally.

It therefore follows that the main properties of FIWs observed at low pressures, and particularly in the range of pressures optimal for the wave propagation, are governed by the generation of a large number of high-energy electrons in the region of the front. This circumstance is responsible for the fundamental difference between FIWs and 'slow' ionisation waves that are formed as a result of breakdown of long tubes [48, 49] by relatively low (1–3 kV) voltage pulses with a sufficiently long rise time.

11. Energy deposition in a gas during motion of fast ionisation waves

As pointed out above, the energy dissipation in the discharge has been determined by a method based on the properties of long transmission lines: measurements have been made of the energy of a pulse travelling from a pulse generator to a discharge zone and then the measured energy of a pulse reflected by the discharge gap has been subtracted. This method makes it possible to allow for the energy used in charging the coaxial capacitor formed by the plasma column and the metal shield.

The first experiments [20] carried out under pulse voltages of 6 kV have however shown that the power deposited in the discharge during the motion of an ionisation wave exceeds greatly the power dissipated in the discharge after the establishment of a uniform distribution of the electric field. The measurements in long tubes ($\sim$40 cm, diameter 4.5 cm) carried out using pulses of 40 kV at the electrode [13] have confirmed this conclusion. It was found that under certain conditions the plasma conductivity behind the FIW front was so high that the remaining part of the pulse crossed the discharge zone without a significant reduction in its amplitude. It was also found that 30%–40% of the initial power was dissipated during the motion of an FIW in the discharge, but 40%–50% was stored in the form of an electrostatic energy of the charged plasma–shield capacitor. When the polarity of the pulses was positive, the power dissipated in the discharge was higher than in the case of negative-polarity pulses and it reached 6 MW. The energy deposited in the plasma was 40 mJ.

If the dissipated energy is used mainly in the ionisation of helium, it is possible to estimate the electron density behind the FIW front, which gives $n_e \sim 5 \times 10^{12}$ cm^{-3} [50], in agreement with a similar estimate [11] for an FIW in nitrogen, which is $n_e \sim 10^{12}$ cm^{-3} when the pulse amplitude is 30 kV. These values agree also with n_e found from the current measured behind the FIW front and from the FIW attenuation on the assumption that this attenuation determines the intensity of the electric field behind the front needed for the flow of a current $i = eSn_eV_{dr}$, where S is the cross-sectional area of the discharge and V_{dr} is the drift velocity of electrons behind the front. The value of the electron density $n_e \sim 10^{12}$ cm^{-3} is sufficient for the propagation of an electromagnetic pulse along the plasma column at the velocity of light [11].

An increase in the electron density behind the FIW front requires an increase of the current density, which can be achieved by an increase in the voltage and a reduction in the cross-sectional area of the tube. High current densities are needed in particular in the pumping of lasers. In tackling this task it has been reported that under a voltage of 30 kV the electron density behind the FIW front can be $n_e = 10^{15}$ cm^{-3} in a tube 1.7 mm in diameter [29, 30].

An increase in the voltage to 150 – 200 kV increases the current behind the FIW front to 1 – 10 kA and the electron density, estimated from the current and the attenuation, is $n_e \sim 10^{15} - 10^{16}$ cm^{-3}. The energy deposited in the discharge depends on the gas pressure and is maximal approximately at those pressures when the wave attenuation is minimal [51]. This is not a self-evident observation and it confirms the hypothesis that the bulk of the energy is dissipated in the FIW front where the field intensity is highest. The specific energy deposited in the gas is then quite considerable and reaches 0.1 – 1 J cm^{-3}. These circumstances account, for example, for the observation that the output power of the radiation generated in a nitrogen laser pumped by FIW is highest at the pressures at which the FIW velocity is maximal and its attenuation is minimal [14, 51, 52]. The high specific energy deposited in the gas, together with the high rate of filling of the discharge gap with the plasma, make FIWs very promising for applications in various technical devices.

12. Fast ionisation waves in free space

An important question in the propagation of FIWs is the influence of the discharge-tube walls. Various suggestions have been made: they range from the hypothesis that the walls are needed only to confine the discharge zone and to fill it with the working gas, to the postulate that the wave depends entirely on the presence of the walls and represents a sliding discharge [53] along the wall insulator. In our opinion, the walls do not determine the mechanism of motion of the discharge. This is supported by the data on the appearance of fast waves in long sparks and in lightning, which have been reviewed earlier [9, 10, 12].

The development of the techniques for the generation of high-power laser pulses has made it possible to create and study a special type of electric discharges, which are discharges guided in free space by laser radiation [54, 55]. The most popular and effective system for the initiation of a long electric discharge in space is shown in Fig. 18. Laser radiation of high ($\approx 10^9$ W power), known as a giant pulse, is focused by a lens with a focal length of the order of 1 m. Regions of optical breakdown of the atmosphere appear in that part of a laser beam where the radiation power density exceeds a threshold which amounts to 10^9 W cm^{-2} for air containing aerosol particles and exposed to neodymium laser radiation. Since this breakdown is initiated by aerosol particles, the breakdown regions are distributed at random. A long chain of plasma optical-breakdown regions formed along a laser beam is known as the long laser spark (LLS). For a typical duration of giant laser pulses (50 – 100 ns) the characteristic size of each of the optical-breakdown regions is 0.1 – 1 mm and they do not merge. At the end of a laser pulse the plasma regions continue to expand at a velocity $\approx 10^5$ cm s^{-1} and after 5 – 10 µs their diameter is typically about 1 cm. If the density of the optical-breakdown regions is initially sufficiently high, then on the microsecond scale there is a moment at which the boundaries of these regions coalesce. A continuous quasicylindrical channel with a low gas density may then form in air: its average temperature is 2500 – 3000 K and it is characterised by a high concentration of charged particles which are sufficient to initiate an electrical discharge.

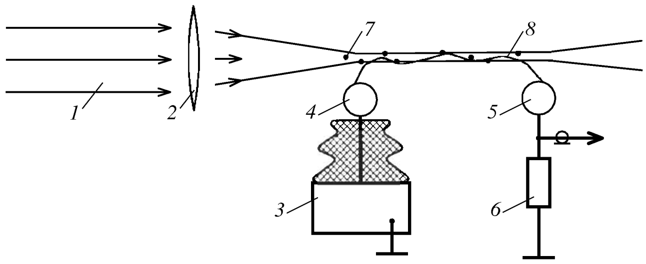

Figure 18. Experimental setup for the formation of laser-guided electrical discharges: (*1*) laser beam; (*2*) long-focus lens; (*3*) generator of high-voltage pulses; (*4*) high-voltage electrode; (*5*) earthed electrode; (*6*) current shunt; (*7*) optical-breakdown region; (*8*) electric discharge channel [54].

A high-voltage electrode is placed in such a way that the LLS channel passes near its surface. A low-voltage electrode is located at some distance from the high-voltage electrode, but in such a way that it is also in contact with the LLS. The application of a high-voltage pulse causes the electric discharge channel to grow along the LLS from the high- to the low-voltage electrode. The length of such a laser-guided electric discharge can range from several centimetres to several metres [56]. The discharge propagation velocity depends on many experimental conditions, primarily on the distance between the optical-breakdown regions in the LLS and on the delay time between the formation of the LLS and the application of a high-voltage pulse. This velocity increases from 10^7 cm s^{-1} [56] when the distance between the optical-breakdown regions is 5 – 10 cm to $10^9 - 10^{10}$ cm s^{-1} [54, 55] if the optical-breakdown regions in the LLS merge to form one channel.

An image-converter study of the development of an electric discharge of length 20 – 50 cm along an LLS, carried out using voltage pulses of 200 – 300 kV amplitude, 35 ns duration, and 4 ns rise time [55] has demonstrated that the discharge began in the form of an FIW starting from the high-voltage electrode at a velocity $(2-3) \times 10^9$ cm s^{-1}. At some distance from the high-voltage electrode the FIW velocity was found to increase abruptly. If an electrical pulse was applied to the LLS 10 – 100 µs after the laser pulse, the guided electrical discharge developed optimally and then the FIW velocity was found to be constant across the whole gap and it amounted to $4 \times 10^9 - 2 \times 10^{10}$ cm s^{-1}.

If the FIW velocity did not exceed 6×10^9 cm s^{-1}, it was found that after the passage of the wave across the whole gap to the earthed electrode a return-stroke wave was also formed and it moved from the earthed electrode to the high-voltage one at a velocity 3 – 5 times higher than the initial FIW. After a long delay (1300 – 1500 µs), when the LLS broke up, the growth of the guided electric discharge occurred in a step-like manner. The FIW starting from the high-voltage electrode slowed down and stopped. Some time after the stoppage of the FIW the motion restarted and its velocity increased severalfold compared with the initial value. The stoppage of a positive-polarity wave occurred much more abruptly than in the case of a negative wave. A theoretical investigation [57] attributed this influence of the polarity to the absence of drift spreading of the shape of the head of the discharge under the influence of an external electric field. The stoppage of the wave due to the spreading of its front in a guided discharge has been observed with the aid of electrical probes [58] and it has been attributed to an abrupt drop of the ionisation frequency because of the fall of the electric field intensity in the front.

Under certain conditions it is possible to observe several FIWs in the gap and they may either follow one another (for example, as in the return-stroke stage mentioned above) or may appear simultaneously. If neither electrode is earthed and a pulse is applied to the electrodes in such a way that one is positive relative to the earth and the other is negative, it is found that FIWs start from both electrodes along an LLS and these waves are directed towards one another meeting inside the gap, which is followed by a steep increase in the brightness of the emitted radiation [55]. It is possible to create simultaneously two guided-discharge channels and to excite two or more FIWs by other methods. For example, if one high-voltage electrode is placed along an LLS between two earthed electrodes, it is found that two FIWs start from the high-voltage electrode in both directions when a high-voltage pulse is applied and these two waves create two guided electrical-discharge channels. One earthed electrode may be placed between two high-voltage electrodes. Then, FIWs start from each high-voltage electrode to the low-voltage one and again two channels are formed.

We can thus see that one or several FIWs can form in free space and they move at different velocities. As in the case of motion of FIWs in long discharge tubes, in this case the FIW velocity increases with increase in the conductivity of the LLS channel, decreases with increase in the gas density in the LLS channel, decreases (right down to the stoppage) on increase in the width of the front. The properties of FIWs in guided discharges have an obvious analogy with the step-like propagation of a leader in lightning and occurrence of a return stroke when this leader reaches an earthed electrode.

13. Theoretical models of fast ionisation waves

In theoretical discussions of FIWs the greatest practical difficulties arise from two problems: the formation of a sufficient number of initiating electrons ahead of the FIW front and explanation of the extremely high propagation velocity, and the existence of a minimum of the coefficient representing the attenuation of the wave amplitude. The early investigations have already established [9, 59] that direct photoionisation, which can explain the motion of streamers, cannot account for the observed front velocities of 10^9-10^{10} cm s^{-1} and, moreover, this photoionisation is ineffective at low gas densities. The most likely mechanism of the formation of free electrons at high gas pressures is the transport of resonant radiation followed by associative ionisation of excited molecules or atoms [47, 59]. In air at atmospheric pressure one further mechanism of the formation of free electrons may be the detachment of electrons from negative ions in strong electric fields [60]. The frequency of electron detachment becomes equal to the attachment frequency when the electric field is of the order of 3 MV m^{-1}. Cosmic rays generate 10 cm^{-3} s^{-1} electron – ion pairs, which give rise to a negative ion concentration of about 10^3 cm^{-3}. Detachment of electrons from these ions can create the same concentration of electrons ahead of the FIW front.

In the majority of theoretical investigations it is assumed that the initial electron density ahead of the front is known and can be specified [61 – 65]. This formulation of the problem corresponds to the conditions of appearance and motion of FIWs in a previously formed plasma; for example, it corresponds to the return stroke stage in lightning or in a long spark [5, 6], to the conversion of a glow discharge into an arc [8], and to the experiments on initiation of FIWs in the plasma of a glow discharge or in a decaying plasma [7, 11 – 13, 27]. The problem is usually considered in the one-dimensional approximation, either by averaging of the discharge characteristics over the cross section of the tube [60, 63, 64] or by introducing additional conditions. For example, a relationship between the longitudinal and transverse vectors representing the intensity of the electric field can be assumed [61, 62] on the basis of a theory of surface waves in plasma waveguides. At wave velocities of the order of 10^9 cm s^{-1} the problem is solved either in the hydrodynamic approximation assuming a potential electric field and a local dependence of the electron temperature on the reduced field intensity E/P, or in the long-wavelength approximation, i.e. when the thickness of the front is assumed to be greater than the diameter of the tube and shield [61 – 64]. An analysis is made of the self-similar solution, i.e. it is assumed that the wave velocity is constant in time. This approach has made it possible to account for the profile of the current pulses [61, 62] reaching an earthed electrode [20] and for the different behaviour of the discharge for different polarities of pulses of 6.4 kV amplitude. The results obtained from this solution are in satisfactory agreement with the measured FIW velocities observed when the amplitude of the voltage pulses is 25 – 30 kV [13].

However, the self-similarity condition postulates constancy of the parameters of the front, which is achieved in the case of zero resistance of the plasma column behind the FIW front, so that it is not possible to predict the attenuation of the wave amplitude and the reduction in the wave velocity. This approach also fails to take account of the important problem of the supply of energy to the front of a wave and the existence of a limiting value of the front velocity.

A more general approach involves an analysis of the system of the Maxwell equations for the solution of an electrodynamic problem, supplemented by the equations of balance of charged particles and by boundary conditions [60, 65]. In the case of the one-dimensional approximation the integral form of the Maxwell equations (for the currents and potential) reduces to a system of what are known as the telegraph equations for long lossy lines:

$$\frac{\partial \varphi}{\partial x} = \frac{\partial L i}{\partial t} - R i \,, \qquad \frac{\partial i}{\partial x} = -\frac{\partial C \varphi}{\partial t} - G \varphi \,, \tag{13.1}$$

where φ is the potential; i is the current; L and C are, respectively, the inductance and capacitance per unit length of the line; R is the instantaneous resistance; G is the line conductance because of insulation imperfections;

the product Ri represents the electric field intensity. The quantity G represents the losses via corona currents. In the case of discharge tubes its value is $G = 0$.

The concepts of the inductance and capacitance can be introduced if the transverse dimensions of the system are much less than the characteristic longitudinal dimension. This is known also as the long-wavelength approximation and is in fact used in all the models of FIWs. It imposes certain restrictions on the FIW parameters and, in particular, the wave velocity v should satisfy the relationship $v \gg r_s/t_f$, where r_s is the shield radius. The system of the telegraph equations has been used earlier [6, 66] to consider the return-stroke stage of long sparks and lightning.

In this analysis the delivery of energy to the front is regarded as the propagation of an electromagnetic pulse in the plasma channel behind the front. The nonlinear coefficients in the telegraph equations, as well as the initial and boundary conditions, are given physical meaning when specific experimental conditions are considered. Models follow from this system and they allow for the influence of the plasma – shield geometry via the instantaneous capacitance of the discharge zone. It has been shown [49] that charging of the plasma – screen capacitance is the dominant process in the motion of slow ionisations waves at velocities of the order of 10^5 cm s^{-1}, which appear because of the breakdown of long gas-discharge tubes by low-amplitude pulses with a low rate of rise of the voltage.

From the point of view of formal electrodynamics the approximations represented by different models reduce to the neglect of some terms in the system of the Maxwell equations. At wave velocities much less than that of light it is usual to ignore the inductance term [59, 60]. The system of equations then transforms to a single equation for nonlinear diffusion of the potential in the plasma column when the role of the diffusion coefficient is played by the electron density:

$$\frac{\partial\varphi}{\partial t} - \frac{1}{R_0 C}\frac{\partial}{\partial x}\left(n_e \frac{\partial\varphi}{\partial x}\right) = 0\,, \qquad (13.2)$$

where $R = R_0/n_e$. Such a diffusion equation for the potential has been derived [63, 64] in the one-dimensional hydrodynamic approximation allowing for the influence of the plasma – shield geometry when the instantaneous capacitance is constant. This model is valid at high initial electron densities $n_{e0} = 10^8$ cm^{-3} and it describes well the dynamics of motion of ionisation waves on transition from a glow discharge to an arc discharge [27].

Modification of these models [62 – 64] by the introduction of inductance terms or by allowance for the electron inertia in the equations for energy and motion has made it possible to describe also higher velocities of propagation of FIWs, for example, the lightning return stroke. In some cases the telegraph equations can be used at velocities much less than that of light by introducing a virtual inductance [29, 30] in order to be able to study the dynamics of waves with an increase in the velocity, as found experimentally.

In the case of subluminal FIW velocities and also for characteristic scales of changes in the quantities in the front, which are comparable with the transverse dimensions of the electrical discharge system, it is necessary to allow for the inductance and for the displacement currents [60, 65, 67] i.e. the equations of balance and charged particles have to be solved simultaneously with the system of the telegraph and total current equations

$$\frac{\partial\varphi}{\partial x} + \frac{\partial Li}{\partial t} + E(x, t) = 0\,,$$
$$\frac{\partial i}{\partial x} + C\frac{\partial\varphi}{\partial t} = 0\,, \qquad (13.3)$$
$$i = \pi r^2\left(\varepsilon_0 \frac{\partial E}{\partial t} + \sigma E\right),$$

where $E(x, t)$ is the longitudinal electric field, r is the tube radius, and σ is the plasma conductivity. The solution of this system together with the equations describing creation and annihilation of charged particles in air at atmospheric pressure under voltage pulses of 1 MV amplitude shows [60] that an FIW front forms where the initial electric field is about 40 MV m^{-1} and the initial velocity is $\approx 10^{10}$ cm s^{-1}. The amplitude and velocity of FIWs decrease during their motion. After 1 m the velocity decreases by an order of magnitude and after a further 20 – 30 cm it falls a further two orders of magnitude. This is equivalent to the stoppage of the wave, since by this moment the electric field in the front falls to the breakdown value of 3 MV m^{-1}.

In an analysis of FIWs for small dimensions of the front it is necessary to allow for the dependences of the capacitance and inductance on the FIW parameters, which is done in the model of Ref. [60], and also to take account of the existence of high electric fields in the front. The calculations and the model approximations [60 – 64] are based on the assumption of a local dependence on the electron temperature on the reduced electric field E/P. It follows from the experimental results that in reality the electric fields at the FIW front are usually so high that the electrons go over to the runaway regime and the influence of such high-energy electrons may be decisive from the point of view of electrodynamics and breakdown processes in the front, as well as in relation to the formation of free electrons ahead of the front. Therefore, the system of electrodynamic equations should be solved together with Boltzmann equation for the electron density distribution function, subject to allowance for the ejection of some of the high-energy electrons to the nonionised gas ahead of the front, as has been done in Ref. [67]. In writing down the expression for the total current the above equation is modified by the introduction of a term which allows for the current in a beam of high-energy electrons j_h:

$$i = \pi r^2\left(\sigma E + \varepsilon_0 \frac{\partial E}{\partial t}\right) + j_h\,. \qquad (13.4)$$

The energy distribution function of high-energy electrons is formed under the action of a pulsed electric field, and of elastic and inelastic collisions with gas molecules; it is both far from steady and spatially inhomogeneous. The boundary separating electrons into 'plasma' (low-energy with chaotic motion) and 'runaway' (high-energy electrons with a preferential direction of motion) may be set at the energy at which the elastic-scattering cross section becomes comparable with the cross section representing the inelastic energy losses. For air and its components this energy is $\cong$ 100 eV. Calculations have been carried out for the experimental conditions in Ref. [21] (Fig. 3), i.e. for a voltage $U = -250$ kV, a pulse rise times of 2.5 ns, a tube radius of 0.2 cm, and a shield radius of 2.7 cm. Calculations indicate that the mechanisms of formation and propagation of FIW as a result of breakdown are neutral [67] and weakly ionised [65] gases have much in common. An additional feature is the generation of 'seed' electrons ahead of the wave by a flux of

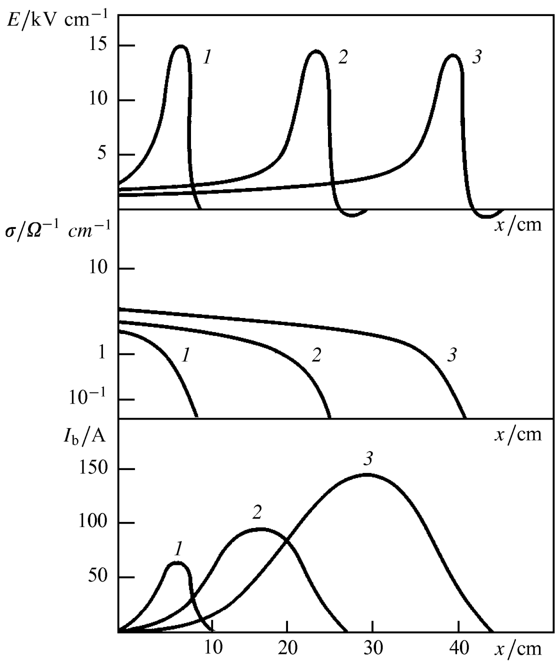

Figure 19. Distributions of the electric field, electrical conductivity, and runaway-electron current at various moments t (ns): (*1*) 2; (*2*) 3; (*3*) 4 [67].

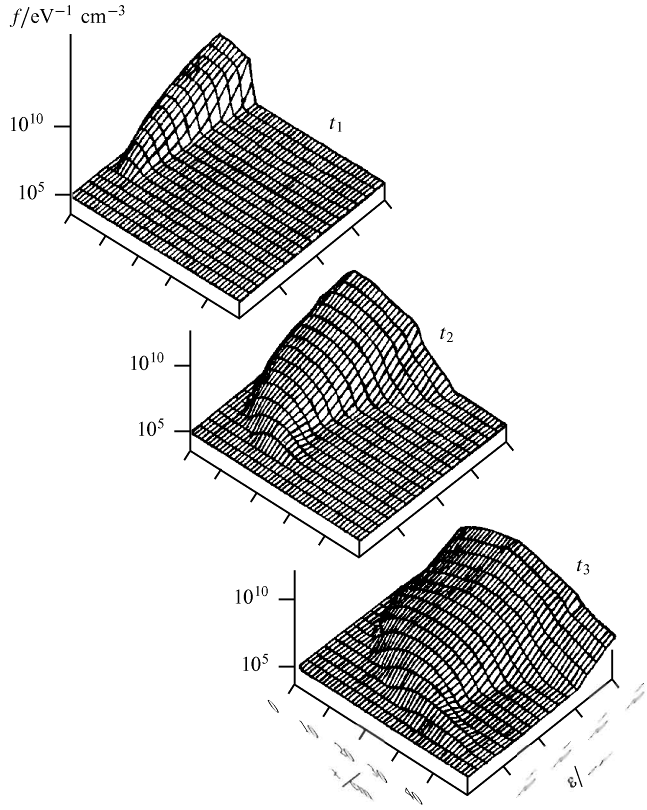

Figure 20. Energy distribution function of the runaway electrons at $t_1 = 2$ ns, $t_2 = 3$ ns, and $t_3 = 4$ ns [67].

runaway electrons. Fig. 19 shows the results of calculations of the spatial distribution of the field, conductivity, and runaway-electron current along the length of a tube at different moments (the gas pressure is assumed to be 10 Torr). We can readily see the formation and motion of a region with a high electric field intensity (front), as well as a near-uniform motion of the conductivity gradient which enters the region of an initially neutral gas.

Fig. 20 shows the electron energy distribution function at the same moments in time. At $t = 2$ ns the energy of the electrons accelerated by the field near the cathode is low and they do not yet make a significant contribution to the ionisation of the gas ahead of the wave front, and the electric field intensity increases as a result of a drop in the conductivity in the cathode region. An increase in the electric field increases the energy of the accelerated electrons and their contribution to the ionisation of the gas ahead of the FIW front, and the region with a high electric field-intensity as well as the runaway electrons are displaced along the channel. At $t = 3$ and 4 ns a beam of fast electrons is formed and a cascade of secondary electrons appears ahead of the wave front. The distribution function at $t = 4$ ns is of the same form as at $t = 3$ ns, but the former is displaced along the tube (in terms of spatial coordinates) because of the motion of the FIW front.

The energy spectrum of the runaway electrons is fairly wide and its upper limit exceeds the value eU_0, as found in earlier experiments [42]. Electrons with energies in excess of eU_0 appear because they are accelerated by the electric field moving at a high velocity. The maximum energy ε_{max} which an electron can acquire can be estimated from the Boltzmann equation in the absence of collisions. This can be done using the self-similar approximation [67] and assuming that $eEl_f/mc^2 < 1$, the result is

$$\beta\left[\left(\frac{\varepsilon_{max}}{mc^2}+1\right)^2-1\right]^{0.5}\frac{\varepsilon_{max}}{mc^2}=\frac{\gamma-1}{\gamma}-\frac{eEl_f}{mc^2}\,, \qquad (13.5)$$

where l_f is the size (thickness) of the front, $\beta = v/c$, $\gamma = (1-\beta)^{-0.5}$.

If the wave velocity is much less than the velocity of light, so that $v/c \ll 1$, and $eEl_f = eU_0$, the maximum energy is $\varepsilon_{max} = 4eU_0$ and the wave moves at the maximum possible velocity $v = v_{max}$, where

$$v_{max}=\left[1-\left(1-\frac{eEl_f}{mc^2}\right)^2\right]^{0.5}. \qquad (13.6)$$

The escape of electrons from the wave front begins from the energy $\varepsilon = mc^2(\gamma-1)$, i.e. the flux of electrons which overtake the front is governed not only by the electric field, but also by the FIW velocity. At high velocities, as demonstrated in Fig. 3 [21], the bulk of electrons cannot overtake the front. The presence of the runaway electrons tends to establish a steady-state velocity of the front because a reduction in the FIW velocity increases the escape of the runway electrons from the front, which in turn increases the FIW velocity. As a result of these processes a steady-state flux of electrons from the front and a steady-state FIW front velocity are established.

It follows from the calculations that the runaway-electron current ahead of the wave front exceeds the plasma and displacement currents, and the field excited by the runaway electrons are similar to the fields excited by injection of an electron beam into a plasma. Fig. 21 shows the distribution of the electric field, and of the plasma and total currents, and of the runaway-electron current in the region of an FIW front when $U_0 = 250$ kV and the results are calculated for $t = 4$ ns. In the region with the opposite direction of the electric field the fast electrons are decelerated and they

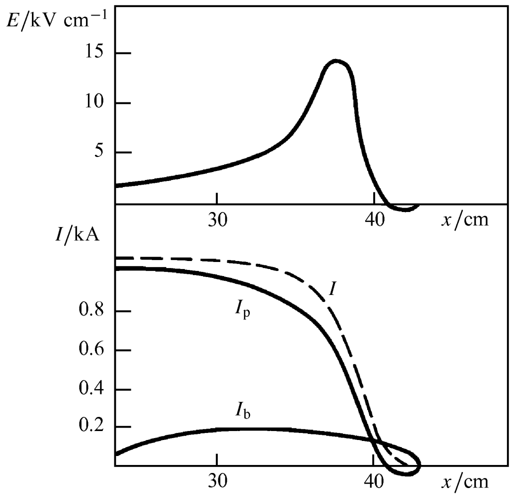

Figure 21. Distributions of electric field and of plasma (I_p) and total (I) currents, and of the runaway-electron current (I_r) at $t = 24$ ns [67].

transfer the energy to the field. The total current rises monotonically over the whole length of an FIW.

A numerical calculation demonstrates a good agreement with the experimental values of the velocity, current, and attenuation considered as functions of the air pressure. The high-energy electron current decreases with increase in the pressure, but it is present throughout the investigated range of experimental parameters, and calculations show that it is ≈ 50 A when the pressure is ≈ 400 Torr. Since an increase in the pressure increases the rate of ionisation of the gas by the high-energy electrons, the influence of these electrons on the initial conductivity of the channel is particularly important throughout the range of pressures under consideration. It should be pointed out that calculation of the FIW motion parameters on the basis of a previously created plasma channel [65] also predicts nonmonotonic dependences of the current, velocity, and attenuation on the gas pressure. It follows, according to Slavin and Sopin [67], that the main processes that govern the properties of FIWs are the ionisation in the front and the diffusion of the potential along the conducting channel.

The model of FIWs in free space when the waves travel along a laser-ionised channel with a uniform and pulse-periodic density of electrons along the channel [57] predicts stoppage and restart of an FIW, and is in agreement with the experiments on guided discharges.

At low gas densities, when the runaway-electron current is comparable with the plasma current, we can expect the appearance of stream plasma instabilities. This may be particularly true when the space between the discharge tube and the shield is filled with a liquid insulator with a high permittivity (for example, water), because the FIW front velocity is then considerably less, so that the runaway-electron current is comparable with the plasma current. It is also particularly interesting to consider a positive-polarity wave in which the flux of the runaway electrons is directed to the plasma column behind the front where the electron density is high. The problems of the resultant oscillations of various types and of the influence of the runaway electrons on the properties of FIWs in the positive-polarity case and of the influence on the velocity of the insulator used as the filler can be solved by further development of the theoretical models mentioned above. Unfortunately, for the majority of the currently available models a comparison with the experimental results is possible only after numerical calculations, so that it is not possible to determine or predict the dependences of the FIW properties on the parameters of the discharge system and of the pulses, or on the properties of the working gas.

The available experimental and theoretical results allow us to summarise briefly the main properties of FIWs as follows.

When a high-voltage pulse is applied to an electrode, the polarisation of the plasma begins near the electrode and screening of the electric field takes place. The leading edge of the pulse should be sufficiently short, so that the excess charge region is not neutralised during the motion of ions or because of the diffusion of the field in the plasma present in the gap and characterised by a low electron density. Intensive ionisation occurs in the strong field of the excess charge and the result is that the potential of the electrode is displaced deeper into the gap and the motion of the waves begins. The stoppage time of FIWs in the case of a preionised gap is governed primarily by the plasma polarisation time.

In the absence of initial ionisation the delay time of the start of FIWs is governed by the processes near the electrodes. When the amplitude of negative pulses is fairly low (3 – 30 kV), the necessary emission can begin only after the formation of the cathode spot which may require tens and hundreds of nanoseconds. When the amplitude is increased to 100 kV or more, the cathode spot appears practically immediately which may be due to, for exmaple, the explosive emission of electrons. The delay of the start of FIWs is in this case associated with the formation of an uncompensated space charge because of the high emission current and insufficient rate of ionisation of the gas by the high-energy electrons, which after a time results in blocking of the electron current. The plasma formation and the displacement of the potential require neutralisation of this space charge by ionisation and escape of secondary electrons. The time needed for neutralisation of this space charge determines the delay time of the start, which is close to zero for the optimal and high gas pressures and which increases on reduction in the pressure.

In the course of propagation of an FIW across the discharge gap the wave velocity is governed by the formation time of the plasma in the front of the wave until it reaches a value sufficient for the polarisation and motion of the potential. It is also governed by the diffusion time of the potential to the region of the front. The plasma formation time in turn is a function of the initial electron density ahead of the front and of the reduced electric field E/P. The range of pressures most favourable for the propagation of FIWs corresponds to the threshold $(E/P)_{cr}$ of generation of the runaway electrons for given values of the amplitudes of the electrical pulses. In this case the newly formed high-energy electrons provide sufficient preionisation of the gas ahead of the FIW front and the rate of accumulation of the plasma in the front is maximal. The time needed for the acquisition by the newly formed electrons of the energy sufficient for ionisation is minimal, because the regime of acquisition of the velocity and energy is close to the regime of free acceleration of an electron in the field. This allows all the electrons to participate actively in the ionisation process during the action of the electric field. The limiting FIW velocity is governed by the rate of supply of the electromagnetic energy to the front along a transmission line with a composite insulator and in the case when $\varepsilon \sim 1$, it is governed by the runaway-electron energy.

A reduction in the pressure increases the value of E/P and the number of high-energy electrons in the front. On the other hand, a reduction in the gas density lowers the ionisation frequency, because the electron velocity changes slightly which in turn reduces the FIW velocity. A further lowering of the gas density first reduces the preionisation ahead of the front and then creates a space charge ahead of the front and blocks the current of the high-energy electrons until charge neutralisation takes place. This reduces the FIW velocity and increases the wave attenuation.

At high pressures there are no high-energy electrons in the front and the initial electron density is created solely by photoprocesses, which (in combination with the reduction in the ionisation rate in weak fields) lowers the FIW velocity.

In the case of voltage pulses of positive polarity the high-energy electrons which appear in the FIW front propagate opposite to the direction of motion of this front, i.e. they propagate through the plasma column and, therefore, they cannot establish the initial ionisation ahead of the front. The initial electrons are created by photoprocesses, so that at high pressures the FIW characteristics are the same for pulses of both polarities. The efficiency of photoprocesses falls steeply when pressure is reduced so that the maximum FIW velocity for positive-polarity pulses is reached at higher pressures than for negative-polarity pulses. This maximum velocity is less because of the lower value of E/P in the region of the front and because of the consequent lower ionisation frequency.

In the range of the optimal pressure the FIW front leaves behind a high-conductivity plasma column, so that the voltage drop behind the front is slight and this enables the FIWs to propagate without a reduction in the velocity. Energy dissipation behind the front is weak compared with that in the front. The FIW front represents a moving mirror for an electromagnetic pulse which catches up with it, so that FIWs may create a plasma column the length of which is greater than the product of the velocity of light and the duration of the pulses.

It follows from the above that FIWs represent a new and powerful pulsed source of nonequilibrium plasmas whose parameters should make it possible to realise a series of very promising scientific and technical applications.

14. Physical and technical applications of fast ionisation waves

The promising applications of FIWs are primarily due to their unique properties, such as the subluminal rate of filling the discharge gap by a highly ionised plasma and the presence in the wave front of strong electric fields and of high-energy electrons, which makes it possible to achieve ionisation and excitation of a gas without heating it significantly, i.e. the bulk of the energy of a voltage pulse can be directed to the channel of inelastic losses. These properties make it possible to consider FIWs as a new powerful source of nonequilibrium plasmas and high-power pulsed radiation. It should be stressed particularly that the presence of a beam of high-energy electrons in the front makes it possible to use this beam in systems where a beam and electrical discharge act simultaneously and also to create a plasma far from equilibrium.

A very promising field of applications of FIWs may be in fabrication of electrophysical devices, such as switches, shapers, and pulse peaking devices. Since at optimal pressures the duration of the FIW front may be considerably less than the rise time of a high-voltage pulse applied to an electrode, the passage of a pulse through a discharge tube can reduce the rise time, i.e. it can cause peaking of the leading edge of the pulse. For example, FIWs have been used to reduce the rise time of voltage pulses (of either polarity) at amplitudes 150 – 700 kV from 8 – 9 to 1 – 1.5 ns and to transmit them to another coaxial line [14, 32]. The rise time of a pulse in the charging line has been longer than the duration of the FIW front, which is evidently due to the reflection of the FIW from the second electrode and due to transient processes resulting from the mismatch of the wave impedance of the charging line and the effective internal resistance of the FIW front. Selection of the gas pressure, of the dimensions of the discharge system, and of the pulse amplitude makes it possible to form a short dome-shaped pulse in the charging line (or in an active resistor), which represents in fact a pulse of the displacement current in the FIW front if the plasma resistance behind the front is sufficiently high and, therefore, the plasma current is low. This principle has been used in the construction of a shaper of short (1.5 ns) pulses with an amplitude of 1.5 kV [33, 68] needed for the shutter plates in an image-converter camera.

After the passage of an FIW through a discharge tube the conductivity of the plasma column may be so high that a high-voltage pulse crosses the tube practically without attenuation, which is important in switches [13, 14, 41]. The high conductivity of the plasma provides an opportunity for using FIWs in fast creation of plasma antennas, as has been done with the aid of laser-guided discharges [69], or this conductivity can be used in pulse-periodic modification or modulation of electrodynamic characteristics of space, and of transmitting or receiving rf systems.

At high FIW amplitudes (100 – 200 kV) and high densities of the current in a tube the concentration of charged particles created behind the FIW front may be so high that a slight heating of the gas after the passage of an FIW can create a nonideal plasma [70], i.e. a plasma in which the Coulomb interaction energy of charged particles is comparable with their thermal energy.

The use of FIWs for the excitation of a gas is most promising in systems with lifetimes in the nanosecond range. The most natural application of this kind is pumping with FIWs of lasers with self-terminating transitions in excimer mixtures. At present these lasers are pumped by a transverse electrical discharge because the pumping efficiency by a longitudinal discharge is considerably lower. This is due to the fact that even when the voltage amplitude is increased to 30 – 100 kV, the average intensity of the electric field in the discharge zone is much lower than in the transverse discharge case, and since the frequencies of ionisation and excitation of a gas depend exponentially on E/P, the pumping is less efffective. On the other hand, in many technical and scientific applications the quality of a laser beam in the case of transverse pumping is unsatisfactory and it is necessary to use longitudinally pumped lasers, in spite of their low output power and lasing efficiency.

Pumping of a nitrogen laser with FIWs when the voltage pulses are of 120 – 300 kV amplitude [17, 23, 34] has made it possible to achieve a peak output power of 450 kW for the same specific output power as in transverse discharges:

$30-40$ kW cm^{-3}. These parameters have been obtained for laser radiation generated in the superradiance regime (without mirrors) and lasing has been found to start after an FIW has travelled $5-10$ cm along a tube. The FIW pumping has been found to be so intense that an FIW has been followed by a laser radiation wave [23] travelling at a phase velocity along the tube equal to the FIW velocity $\approx 5 \times 10^9$ cm s^{-1}. The direction of the laser wave has been found to be the same as that of the primary FIW, travelling from the high-voltage to the earthed electrode, and of the reflected FIW moving in the opposite direction. Laser photons propagate in one direction, namely towards the earthed electrode. Since FIWs excite continuously new portions of the gas, this pumping method makes it possible to generate laser pulses of greater duration than the radiative lifetime of the upper active level of the nitrogen molecule, which is about 40 ns. A laser radiation pulse generated by the excitation of a gas with several FIWs consists of several peaks and the separation between them is governed by the length of the discharge tube and by the FIW velocity. This method can be used to generate several highly stable laser radiation pulses separated by specified time intervals. Such pulses are suitable for diagnostic purposes and for calibration of radiation receivers.

In view of the high stability of the FIW parameters, which has been pointed out in the majority of papers on systems with preionisation [12, 13], such waves can be used as highly stable sources of nanosecond radiation pulses or series of pulses with specific delay times between them.

If a flux of runaway high-energy electrons forms in the FIW front, the provision of windows in the electrical-discharge system, suitable for coupling out of X-ray radiation, makes it possible to construct a source of nanosecond X-ray pulses with specified time intervals between them [71]. Generation of a series of such radiation pulses is based on the motion of the FIW front, which acts as the radiation source, and selection of the radiation from different points along the path traversed by the front.

Since the electrical fields in the front are high, it is possible to use FIWs in high-power radiation sources, including those emitting in the ultraviolet, since this requires the excitation of high atomic or molecular levels. An increase in the repetition frequency of high-voltage pulses can increase also the average power of the radiation source. For example, the excitation of an FIW lamp, filled with a mixture of mercury vapour and a rare gas [72], has made it possible to generate bactericidal ultraviolet ($\lambda = 253.7$ nm) radiation needed in disinfection of water with an average power of the same order as that of high-pressure arc lamps. Further progress will obviously be made in the direction of an increase in the voltage and power of FIWs. Physical applications of FIWs in the very promising field of high-power bactericidal ultraviolet sources and in generation of ozone are at present hindered by the absence of generators of high-voltage nanosecond pulses with ampli-tudes of $20-50$ kV, repetition frequency $1-2$ kHz, average power $1-3$ kW, and a long service life under continuous operating conditions.

The presence of a strong electric field and of high-energy electrons in the FIW front makes it possible to use it as a tool for dissociation of, for example, hydrogen [73], fluorine [70], or nitrogen, in generation of ozone, or in plasma–chemical reactions involving highly excited states, e.g. the reactions producing phosphorus nitrides. These possibilities have been utilised only in the study of fast processes or reactions [70, 73–75]. As is known, the dissociation of fluorine molecules is essential for fast initiation of chemical lasers. Moreover, FIWs provide an ideal means for dissociation, because this can be done in large volumes and the cost of formation of fluorine atoms is low [70].

Use of FIWs in investigations of fast processes and reactions in a plasma can be an alternative method for the excitation of a gas or initiation of chemical reactions by an electron beam, because at higher pressures the beam loses its advantages of monoenergiticity and homogeneous excitation of the gas throughout its volume. In such cases it is possible to use FIWs for the investigation of the processes under conditions approaching the conditions in various devices such as, for example, lasers. This approach has been used to study the effective lifetimes of laser-active levels of the nitrogen molecule and of the quenching of these levels by nitrogen and oxygen molecules [74], and the transfer of excitation and quenching of the 3^1D and 3^1P levels in helium [75]. The applications of FIWs in studies of fast elementary processes in gases and plasma look very promising, particularly bearing in mind the progress made in nanosecond measurements and in generation of high-voltage nanosecond pulses.

Another use of FIWs in research is diagnotics. One of the examples is visualisation of fast-flowing gases or shock waves, or — as suggested in Ref. [76] — the use of FIWs in generating plasma bunches along the path followed by a shock wave.

Even this brief account of possible applications of FIWs provides an idea of the extensive opportunities for the use of these waves in many branches of pulse techniques as a new powerful tool for research, in construction of promising sources of ultraviolet and other radiation, in generation of radicals and ozone, in construction of plasma – chemical reactors, and in tackling topical ecological tasks.

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Note. The spelling of some authors' names varies according to the transliteration scheme used. For example, Asinovsky and Vasiljak would read in our standard transliteration scheme as Asinovskii and Vasilyak.