Subnanosecond breakdown of air-insulated coaxial line initiated by runaway electrons in the presence of a strong axial magnetic field

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Abstract. Flow of runaway electrons (RAEs) propagating in a radial, air-filled gap of coaxial line (CL) changes the dynamics of breakdown in the field of traveling voltage pulse. However, despite the effect of RAEs, breakdown does not occur if subnanosecond pulse is less in duration and amplitude than some values. In this work, we study the influence of an external axial magnetic field ($B_z$) on the breakdown development. We demonstrate the transformation of the voltage pulse reflection from the ionized (breakdown) zone with changing $B_z$. Due to gyration of fast electrons in an applied magnetic field, the gas region ionized by RAEs does not reach the anode. The ionized bridge between the cathode and anode is gradually replaced by a near-cathode plasma layer representing a discrete, reflecting/absorbing inhomogeneity in the CL.

1. Introduction
In the work, we study the effects preceding the picosecond breakdown of an air gap in the coaxial line (CL) in the field of TEM voltage wave and associated with the emission of runaway electrons (RAEs) from a localized zone at the cathode electrode (see figure 1 (a)). The relevance of such research, developing studies of scenarios of continuous electron acceleration (runaway) in a gas [1-7], is caused, in particular, by the need for an increase of the electric strength of feeder ducts.

In the CL runaway electrons propagate from the region of electric field ($E$) enhancement at the cathode inhomogeneity mainly in the radial direction [8-10]. This can be seen from the simulation of particle trajectories in the vacuum approximation [11] presented in figure 1 (b). If the duration of the voltage pulse after RAE emission onset ($\tau_u$) significantly exceeds the time of their acceleration to the anode $\tau_{ca}$, the impact gas ionization cascades create a conducting trace in the entire radial gap. In this case, the time before subsequent switching is sharply reduced, and a large discharge current is achieved [9]. When $\tau_u \leq \tau_{ca}$, one can observe the fraction of the RAE flow at the anode that has passed the near-anode part of the gap “by inertia”. However, the switching current in this case does not have time to develop, and a short voltage pulse passes a weakly ionized region with almost no loss of the amplitude [10].

In this work, we consider the influence of a strong external axial magnetic field $B_z$ on the breakdown development. The presence of adjustable magnetic field allows one to control the time $\tau_{ca}$.
The inequality $\tau_u \leq \tau_{ca}$ is realized either from an increase in $\tau_{ca}$ due to the bending of the RAE trajectories in a magnetic field as shown in figure 1 (c), or automatically, since electrons do not reach the anode at a sufficiently large $B_z \ (\tau_{ca} \rightarrow \infty$, figure 1 (d)). The field $B_z$ with induction in the enhancement region of up to 2.4 T was created in the experiment by a pulsed solenoid. In the radial gap between $E$-field enhancer and the anode $B_z(r)$ varied within less than 10%. It should be noted that, due to the mirror configuration of the magnetic field, with a sufficiently long motion in the “crossed” fields $E$ and $B$, reflections of fast electrons are possible in principle (figure 1 (c)) from magnetic mirrors in the region of the solenoid coils location [12].

Figure 1. (a) Geometry of CL section including $E$-field enhancer. Trajectories of electrons simulated in vacuum approximation [11] for a constant cathode potential $-100$ kV at $B_z = 0$ where equipotentials are shown (b), at $B_z \approx 0.15$ T when “the fastest” electron trajectory touches the anode (c), and at $B_z \approx 0.6$ T (d). In (b), a minimal time of the electron acceleration to the anode is 87 ps. In (c) and (d), the time of particles motion is not limited.

2. Experiment layout and diagnostics
In the experiment, the RAE flow was injected into the radial air gap from the boundary of the plasma arising in the air due to impact gas ionization by field-emission (FE) electrons emitted by the metal of electric field enhancer. The latter represents a disk insertion into the CL central electrode (figure 1 (a)). Voltage pulses with adjustable amplitude (modulo) of up to $U_{in}^\text{max}=150$ kV (figure 2 (a)) were produced by a setup combining pulsed power devices and components described in [13-15]. Below we consider the passage of high-voltage subnanosecond pulses in the CL, which, at an amplitude value, provide an electric field strength on the central electrode of a uniform line that exceeds the static breakdown strength of atmospheric air (30 kV/cm) by 5 times. In spite of this, no breakdowns of the uniform line were observed at a pulse full width at half maximum (FWHM) of up to 280 ps. This is evidenced by the amplitude $U_{ref2}^\text{max}$ and the stability of a series of reflections from the closed end of CL, obtained both with and without magnetic field (figure 2 (a)). A feature of the use of short pulses was a decrease in the amplitudes $U_{ref2}^\text{max}$ in comparison with $U_{in}^\text{max}$ due to excitation in the CL of the waves of dispersive type along with TEM wave. In figure 2 (b), one can see that the shorter the duration (and amplitude, modulo) of $U_{in}$, the greater the falloff of $U_{ref2}$. 
With aforementioned $U_{in}^{\text{max}} = 150$ kV, and for the enhancer protruding above the cathode surface to the distance $h = 2.5$ mm, maximal $E$-field at the top point of the enhancer half-torus edge ($R = 0.15$ mm) achieved 900 kV/cm. This value exceeds $E$-field in the homogeneous CL section by $\approx 6$ times. This means that both FE and RAEs emission occur earlier than the top (modulo) of $U_{in}(t)$ is attained, i.e., at the pulse leading edge when the conditions for RAE emission and their further propagation [16, 17] are fulfilled. The runaway electron flow was recorded behind a foil window 3 mm in diameter at the anode electrode (Al, 15 µm; electron cutoff energy 40 keV [18]). A collector-type electron current probe was used, the capabilities of which are described in [19].

To register the incident pulses and their reflections from ionization region or the closed end CL, a capacitive voltage probe installed in an oil-insulated transmission line was used. The oil and gas lines were connected through a specially profiled bushing insulator, so that the uniformity of the wave impedance of entire path was no worse than $\pm 0.5$ Ohm. Under these conditions, reflections from the breakdown region could be extracted without distortion by the method of dynamic reflectometry [20]. However, due to short pulse duration ($\approx 0.5$ ns, FWHM) and significant time distance between the probe and reflection region ($\approx 2 \times 2$ ns), the noise signal accompanying the pulse $U_{in}$ dropped significantly. Therefore, ordinary reflectometry could be used to determine the discharge parameters in the region of the field enhancer.

Note that pre-breakdown processes in the $E$-field enhancer region are delayed with respect to the reference reflection from a special metal diaphragm installed in this cross-section. This reflection $U_{\text{ref1}}^0$ imitating “instantaneous commutation” is shown in figure 2 (a) only for the pulse $U_{in}$ of maximum (modulo) amplitude. It will be reproduced later without comment as a half-tone reference signal in the window II, where appropriate. Also, as necessary, the reflection $U_{\text{ref2}}^0$ from the closed end of the line, recorded in the absence of breakdown phenomena in a uniform CL, will be shown in the window III.

Figure 2. (a) Adjustable incident voltage pulses $U_{in}$ and associated variations in the reflections $U_{\text{ref2}}$ from a remote closed end of an air-isolated homogeneous CL. For the pulse $U_{in}^{\text{max}} = 150$ kV (modulo), a set of ten pulses $U_{\text{ref2}}$ is stored (overlapped) at $B_z = 0$ and 0.5 T. Also, reflection $U_{\text{ref1}}^0$ from the metal diaphragm in a cross-section of $E$-field enhancer is shown for $U_{in}^{\text{max}}$. (b) Data on the amplitudes for incident, reflected pulses and their ratio $U_{\text{ref2}}/U_{in}$.

3. Experimental results and discussion

3.1. Effect of magnetic field on the pulse propagation in the CL with a slightly distorted $E$-field

When the used $E$-field enhancer ($h = 1$ mm; $R = 0.4$ mm) relatively weakly distorts the electric field, at a pulse amplitude of $150$ kV the maximum field strength at the enhancer edge is $\approx 380$ kV / cm. This is somewhat less than the critical value (see [16, 17] and references therein) for appearance of RAEs in air at atmospheric pressure. Nevertheless, the FE from the metal of enhancer generates avalanches of thermal electrons, and the plasma arising due to the impact ionization of molecules within a nanosecond exposure time of the field would lead to commutation of the radial gap [8]. For a
subnanosecond pulse duration \( U_{in} \), the plasma remains near enhancer. This is confirmed by the data in figure 3, according to which there are no reflections from the region of the enhancer localization: the reflectogram trace in the window II repeats the case of CL vacuum isolation when there is no plasma in the gap. However, the reflection \( U_{ref2} \) passes through the enhancer region with a delay of \( \approx 2 \) ns. The expansion of the area occupied by plasma during this time (in the absence of \( E \)-field) leads to the distortion of \( U_{ref2} \) (window III in figure 3 (a)). The reason may be both repeated reflection from the ionized region in the enhancer localization zone (see \( U_{ref3} \) in figure 1 (a)), and the absorption of the pulse energy \( U_{ref2} \) by the plasma.

Turning on the longitudinal magnetic field \( B_z = 0.75 \) T significantly increases the amplitude of the reflection \( U_{ref2} \) transmitted through the ionized region, as it is follows from figure 3 (b) (window III). Since free electrons are magnetized, the plasma occupies only a thin layer near the enhancer surface. That is, we can assume that there has been a slight increase in the curvature radius of its edge. The repeated reflection \( U_{ref3} \) in this case is small, since the geometry of the discrete inhomogeneity in CL practically does not differ from the case of the plasma absence. However, a partial absorption of the pulse energy by the plasma layer is possible. Because of this, the amplitude \( U_{ref2} \) in figure 3 (b) turns out to be somewhat less than \( U_{ref2} \) for a homogeneous CL with gas or vacuum (see also maximal \( U_{ref2} \) in figure 2 (a)).

![Figure 3](image.png)

Figure 3. Variations in the amplitudes of reflections \( U_{ref2} \) from a remote closed end of an air-filled CL with a smooth \( E \)-field enhancer \((h=1 \) mm; \( R = 0.4 \) mm) for the cases of \( B_z = 0 \) (a) and \( B_z = 0.75 \) T (b).

3.2. Effects in the CL radial gap with the RAE flow emission and magnetization

As noted in Section 2, at a small curvature radius of the \( E \)-field enhancer edge \((R = 0.15 \) mm), already at a rising (modulo) leading edge of the pulse \( U_{in} \) with an amplitude more than a certain value in the distortion region, electric fields reached the magnitude which is sufficient for RAEs emission and their runaway to the anode. By varying parameters of \( U_{in} \), it was determined that runaway electrons were not recorded at the anode even in the absence of a magnetic field at a pulse amplitude up to \(-90 \) kV and its duration of \( \approx 160 \) ps (FWHM). At \( U_{in} = -95 \) kV (\( \approx 170 \) ps, FWHM), RAEs appeared at \( B_z = 0 \), but already at \( B_z = 0.15 \) T they did not reach collector, similarly to that shown in figure 1 (b) and 1 (c), respectively. With an increase in the amplitude (modulo) up to \( U_{in} = 100 \) kV, in a magnetic field \( B_z > 1.2 \) T, when the RAEs are magnetized and do not reach the anode and the current probe, the range of the ratio \( U_{ref2}/U_{in} \) varied from the window of possible breakdown (in the window II) were observed. Thus, for the pulses \( U_{in} \) with an amplitude (modulo) of 100 kV, that is, greater than in [10], a regime was obtained that resembles “magnetic isolation” of a gas-discharge gap.
Figure 4. Variations in the amplitudes of reflection $U_{\text{ref1}}$ from a zone of RAE emission (II) and reflection $U_{\text{ref2}}$ from a remote closed end of an air filled CL (III) recorded for incident pulse amplitudes $-150$ kV (a) and $-125$ kV (b), and with a change of $B_z$ field: 1 – 0 T; 2 – 0.5 T; 3 – 2.4 T. Peaks of RAE current $I_{\text{rae}}$ corresponding to $B_z = 0$ are shifted identically by the time axis in (a) and (b) with respect to the emission onset occurring just before $U_{\text{ref1}}$.

With an increase in the amplitude $U_{\text{in}}$ (modulo) to 125–150 kV as in figure 4, a flow of fast electrons with duration of $\leq 40$ ps (FWHM) was recorded at the anode. It was observed in the fields $B_z = (0–0.15)$ T, but disappeared at $B_z > 0.2$ T, that is, during the implementation of a scenario similar to the transition from figure 1 (c) to figure 1 (d). At the voltage of $-150$ kV, reflections $U_{\text{ref1}}$ from the discharge gap region dominate (window II, figure 4 (a)). With an increase in $B_z$ up to 2.4 T, the $U_{\text{ref1}}$ amplitude decreases (1→2→3), but not to zero. Figure 5 (a) demonstrates the calculation of the discharge current in the gap performed according to the method [8]. The physical meaning for the cases 1 – 4 shown in the figure is different. Curve 1 corresponds to the short-circuit current as a result of closing the gap with a metal diaphragm. Curve 2 corresponds to the discharge conduction current that develops after the RAEs passage to the anode at $B_z < 0.15$ T. With an increase in $B_z$, the incident pulse is reflected from the “near-cathode” plasma formation, which no longer completely closes the radial gap. Then the currents corresponding to curves 3 and 4 in figure 5 (a) can be interpreted as incomplete discharge currents.

Figure 5. (a) Currents in the CL radial gap calculated basing on comparison of the envelopes and time references of the pulses $U_{\text{in}}$, $U_{\text{in}}^{\text{max}} = 150$ kV, $U_{\text{ref1}}$, and $U_{\text{ref1}}$: 1 – CL discharge gap is closed by the radial diaphragm; 2 – $B_z = 0$; 3 – $B_z \approx 0.5$ T; 4 – $B_z \approx 1.0$ T; (b) Detailed envelopes for the pulses $U_{\text{in}}$ of different amplitudes.
Note that sufficiently large amplitude of reflections $U_{\text{refl}}$ in a strong magnetic field requires special consideration, since it cannot be provided by a thin plasma layer created by highly magnetized RAEs, as shown in the “vacuum” interpretation in figure 1 (d). It can be assumed that, in contrast to the vacuum regime, the orbits of magnetized electrons will be increased in a gas due to a higher rate of energy gain at the front of the ionization wave pushing out the electric field from the enhancer to the anode [10, 21, 22]. In addition, due to elastic collisions with gas molecules of a sufficiently high density, a drift effect can be assumed for RAEs.

Let us make rough estimates of the drift velocity of fast electrons towards the anode across the magnetic field lines under conditions of a constant cathode potential. In the vacuum approximation, an electron starting from the cathode across the magnetic field can return to it under the action of the magnetic force. In a gas, where fast electrons will lose energy in inelastic collisions with molecules, they can no longer return to the cathode, moving against the electric force. This will lead to their drift towards the anode with a velocity $V$, estimated as

$$V \approx -\frac{1}{eE} \frac{dW}{dt} \approx -\frac{u}{eE} \frac{dW}{ds} = \frac{u}{eE} F_e.$$  \hspace{1cm} (1)

Here $e$ is the elementary charge, $E$ is the absolute value of the electric field strength, $W$ is the total energy of electron ($dW/dt$ is the energy loss per unit time), $s$ is the electron path length ($dW/ds$ is the energy loss per unit length), $u$ is the average velocity of the electron, and $F_e$ is the friction force acting on the electron in the gas. For a nonrelativistic electron, we can use the Bethe formula [16, 17].

$$F_e(e) = \frac{2\pi Z e^2}{m} \ln \left( \frac{2e}{J} \right),$$  \hspace{1cm} (2)

where $e$ is the electron kinetic energy (it is related to the velocity $u$ as $e = mu^2/2$; $m$ is the electron mass), $J$ is the average inelastic loss energy, $Z$ is the number of electrons in a neutral molecule of the gas, and $n$ is the molecular density of the gas. Calculations by the method [11] for the electron motion in the vacuum approximation for the cathode potential of $-100$ kV at $B_z = 0.5$ T give the average kinetic energy of magnetized electrons $e \approx 10$ keV. For air (and nitrogen), we can take $Z = 14$ and $J = 80$ eV [16, 17]; $n \approx 2.7 \times 10^{19}$ cm$^{-3}$ under normal conditions. The average field $E$ is 100 kV/cm for the radial gap width of 1 cm (taking into account the presence of the cathode protrusion with a height of 2.5 mm). Then for the drift velocity we find $V \approx 1.6 \times 10^6$ cm/s. If we take $\tau_\perp \approx 200$ ps then, during the pulse, fast electrons will travel the distance $V\tau_\perp \approx 3.2$ mm towards the anode, which, together with the height of the protrusion (2.5 mm), gives almost half (5.7 mm) of the interelectrode distance (12.5 mm) of the homogeneous CL (see figure 1). Taking into account the ionization of the gas by fast electrons, the plasma boundary will already noticeably approach the anode, thereby providing a partial reflection of the pulse from the zone of RAE emission (figure 4 (a)). Note that another factor leading to the expansion of the plasma region may be the scattering of fast electrons due to the elastic collisions with gas molecules, similar to the diffusion of the plasma electron component across the confining magnetic field of the mirror configuration (before “turning on” ambipolar diffusion).

This scenario is supported by the transformation of reflections shown in figure 4 (b), where $U_{\text{in}} = -125$ kV. Here the reflection $U_{\text{refl}}$ is small (as it is shown by the arrow in window II, figure 4 (b)) even when the RAEs reach the anode with a weak or no magnetic field, and their current $I_{\text{refl}}$ is comparable to the case in figure 4 (a). Note that the transformation of reflections in figures 4 (a) and 4 (b) is determined not so much by the variation in the amplitudes of the incident pulses ($-150$ kV and $-125$ kV), but by the difference in their durations. Indeed, the incident pulse (TEM wave) travels along the gas line at the speed of light and, therefore, a shorter pulse ($\approx 220$ ps, FWHM; $-125$ kV) leaves the discharge gap much earlier than a longer high-voltage pulse ($\approx 280$ ps, FWHM; $-150$ kV): see figure 5 (b). For clarification, the horizontal dashed line here shows the voltage level $\approx -90$ kV of the of runaway electrons emission. One can see that parts of pulses with a voltage higher (modulo) than this level differ in duration by more than 1.5 times. Under these conditions, for effective diffusion...
of the fast electron component across the magnetic field during the passage of a short pulse, the time may be insufficient. Then the ionization region will be localized closer to the enhancer and its volume decreases with increasing magnetic field. In this case, the reflection \( U_{\text{ref1}} \) disappears (see window II in figure 4 (b)), and the recorded pulse \( U_{\text{ref2}} \) increases (see transition 1\( \rightarrow \)3 in window III, figure 4 (b)) due to a decrease in the reflection \( U_{\text{ref1}} \) (figure 1 (a)). It is clear that the appearance of the reflection \( U_{\text{ref1}} \) requires the onset of plasma in the gap during the passage of the secondary pulse \( U_{\text{ref2}} \). The absence of \( U_{\text{ref1}} \) indicates that sufficiently dense plasma has not yet formed during the passage of the primary pulse \( U_{\text{in}} \). The factor providing the appearance of free electrons in an air-filled gap may be the photoionization of the gas due to the emission of photons by the excited molecules near the cathode. The lifetime of excited states \( \tau_e \) is usually \( 10^4-10^8 \) s and, as a consequence, photoionization processes are insignificant when exposed to single pulses of subnanosecond duration. However, in our case, the primary \( (U_{\text{in}}) \) and the secondary \( (U_{\text{ref2}}) \) pulses pass through the field enhancer region with a sufficiently large (comparable to \( \tau_e \)) interval of \( \approx 2 \) ns. This can make photoionization an already significant factor leading to the presence of plasma during the passage of the reflection \( U_{\text{ref2}} \). To quantify the role of these processes, additional experiments with pure gases are required.

4. Conclusion
In a sufficiently strong axial magnetic field, RAEs, starting from the selected region at the cathode during the passage of a short high-voltage pulse, do not reach the anode due to the rotational motion. That is, in the crossed fields \( \mathbf{E} \) and \( \mathbf{B} \), there is a separation of the impact gas ionization region from the external electrode of CL (anode). The resulting plasma is concentrated near the cathode in the form of a layer slowly expanding along \( z \) and \( r \). The larger the \( B_z \) field, the smaller the radial size of the layer. The intensity of ionization increases with increasing \( B_z \), since with a decrease in the radial span of cyclotron oscillations, electrons acquire a lower energy, and the impact ionization cross sections increase. With such a magnetization of RAEs and a subnanosecond exposure of the \( E \)-field, there is no commutating conduction current in the radial gap. Plasma expansion as a result of the drift of fast electrons across magnetic field and photoionization of the gas can lead to the closure of the CL gap, but these processes are too slow for the subnanosecond scale of the voltage pulse duration and can only affect the passage of pulse trains following with a small interval, or their reflections (i.e., \( U_{\text{ref2}} \) in our case).

The observed transformation of the amplitudes of reflections from RAEs emission region and the closed end of CL is explained by changes in the volume of the ionized region (including its expansion due to the possible radial drift of fast electrons to the anode across the magnetic field), by repeated reflections from it, as well as the dissipation of TEM voltage wave energy in the plasma of “incomplete discharge”. Thus, the dynamics of gas ionization by magnetized RAEs, drift and photoionization processes in the plasma generated by them limit the possibility of low-losses transmission in CL the voltage pulses with amplitudes and durations above certain threshold values.

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