Runaway of electrons and initiation of explosive electron emission during pulse breakdown of high-pressure gases

G A Mesyats¹ and N M Zubarev¹,²
¹Lebedev Physical Institute, RAS, 119991, Moscow, Russia
²Institute of Electrophysics, UB, RAS, 620016, Ekaterinburg, Russia

E-mail: nick@iep.uran.ru

Abstract. We propose a scenario of the initiation of explosive electron emission on the boundary of the electrode and a high-pressure gas. According to this scenario, positive ions are formed due to the gas ionization by field-emission electrons and accumulated in the vicinity of protrusions of micron size at the cathode. The distance between the ion cloud and the emitting surface decreases with increasing pressure which results in a growth of the local field. As a consequence, an explosive growth of the emission current density occurs for a dense gas (the gas with the pressure of tens of atm). As a result, explosive-emission centers can be formed in dozens of ps. These centers give a start to plasma channels expanding towards the anode. Runaway electron flow generated near the channel heads ionizes the gas gap, causing its subnanosecond breakdown.

1. Introduction
Runaway electrons (RAEs), as is known [1–4], play an important part in the pulsed breakdown of gases. They are continuously accelerated in a plasma or gas if the applied electric field is strong enough [5, 6]. According, for instance, to [7, 8], RAEs ionize the gas, leading to the ignition of a volume discharge. Recently, significant progress was achieved in understanding the mechanisms of a number of phenomena related to RAEs. Runaway condition has been derived for a sharply nonuniform electric field [9]; mechanisms of the formation of consecutive RAE current bursts have been proposed [10–12]; compression of the RAE flow in a gas gap in an inhomogeneous magnetic field has been reported [13]; the mechanism of interruption for the RAE generation ensuring picosecond duration of the RAE flow has been revealed [14–16]. Nevertheless, no satisfactory explanation has yet been given for the reasons of appearance of RAEs in gases of high (tens of atm) pressure (p) under conditions of quasi-uniform electric field (E₀), when the reduced field E₀/p is relatively low (essentially less than required for electron runaway).

In paper [17], a subnanosecond breakdown of a gas gap has been studied for a quasi-uniform electric field (nitrogen; p > 1 atm; the gap of 1.65 mm width). The amplitude value of the voltage applied to the interelectrode gap was approximately 200 kV. The full width at half-height of the voltage pulse (T) was ~ 450 ps. The breakdown occurred only for pressures of 1–40 atm; for p > 40 atm, the breakdown was not observed. The breakdown voltage for a boundary pressure of 40 atm was approximately 185 kV. The corresponding value of the electric field equals 1.1 MV/cm. The reduced electric field for p = 40 atm is minimum; it equals approximately 40 V/(cm × Torr).
In [17], RAEs were registered for any pressures at which the breakdown occurred. The boundary value 40 V/(cm×Torr) of the reduced field is ~ 10 times less than its critical value required for runaway of free electrons. It is known [18] that the energy loss function for nitrogen has a maximum, $L_{\text{max}} \approx 10^{-14}$ cm$^2$ eV, corresponding to the electron energy of $\nu_0 \approx 110$ eV. The critical runaway field can be estimated as $E_{\text{cr}} = nL_{\text{max}}/e$ (here $n$ is the gas concentration, $e$ is the elementary charge). If the condition $E_0 > E_{\text{cr}}$ is fulfilled, an electron will continuously accelerate (i.e., run away). Under normal conditions ($n_0 \approx 2.7 \times 10^{19}$ cm$^{-3}$), this estimate gives for nitrogen $E_{\text{cr}} \approx 270$ kV/cm that corresponds to the reduced field of ~ 350 V/(cm×Torr) [2, 4]. If $p = 40$ atm, the threshold runaway field $E_{\text{cr}}$ is ~ 11 MV/cm, that is, it exceeds the average field $E_0 \approx 1.1$ MV/cm in the gap in 10 times. In this situation, the appearance of RAEs cannot be explained without considering the redistribution of the initially homogeneous field over the interelectrode gap due to the formation of the space charge of positive ions and free electrons.

In the present paper, we propose a scenario of RAE generation, in which the role of the “enhancer” of the field is played by plasma protrusions at the cathode that develop due to explosive electron emission (EEE) [19]. These protrusions provide local increase in the electric field. If its strength exceeds $E_{\text{cr}}$, then a part of thermal electrons will go into the runaway regime at their heads. According to [9], the electrons will run away not only in the vicinity of protrusion heads, where the electric field is essentially enhanced in comparison with the unperturbed one, but also in the whole interelectrode space (see also our recent work [20]). It is important that the proposed mechanism for the breakdown development can be realized under conditions of relatively low reduced field, when the characteristic time of multiplication of thermal electrons exceeds the pulse duration $T$.

2. Preliminary analysis

Under the considered conditions, free electrons appear in the interelectrode gap due to (i) impact ionization of neutrals and (ii) emission from the electrode surface. At $p = 1$ atm, the emission of even a single electron can lead, as a result of its ionization multiplication, to the development of a critical avalanche, whose electric field becomes comparable with the applied field. Such an avalanche can transform to a streamer, resulting in the gap breakdown [1, 21, 22]. If the pressure grows, the breakdown happens at lower reduced electric fields, but at higher fields [23, 24]. This leads to the intensification of field electron emission (FEE) processes and also to a slowdown of impact ionization processes. All this determines the specifics of a gas breakdown at high pressures.

Let us consider in detail the boundary case of $E_0 \approx 1.1$ MV/cm and $p = 40$ atm. The primary electrons are emitted from microprotrusions at the electrode surface. The electric field strength at the top of such natural defects is $\beta_0$ times greater than the external one, i.e., the local field is $E_{\text{loc}} = \beta_0 E_0$ ($\beta_0$ is the geometric field amplification factor). The field emission current density can be found from the Fowler–Nordheim law [19],

$$j_{\text{FEE}} [A/cm^2] = F(\varphi)E_{\text{loc}}^2 \exp\left(-\frac{G(\varphi)}{E_{\text{loc}} [V/cm]}\right),$$

where

$$F(\varphi) \approx \frac{1.55 \times 10^{-6}}{\varphi} \exp\left(\frac{9.25}{\varphi^{1/2}}\right),$$

$$G(\varphi) \approx 6.51 \times 10^7 \varphi^{-3/2},$$

and $\varphi \approx 4.5$ eV is the work function. The FEE frequency can be estimated from the formula $\nu_{\text{FEE}} = s j_{\text{FEE}}/e$, where $s$ is the emitting area on the microprotrusion. We get $\nu_{\text{FEE}} \approx 2 \times 10^{13}$ s$^{-1}$ if we take $s = 10^{-12}$ cm$^2$ and $\beta_0 = 55$ (see our analysis in section 4).
The ionization frequency is given by \( \nu_i = \alpha V_d \), where \( V_d \) is the electron drift velocity in a gas, \( \alpha \) is the impact ionization coefficient. For nitrogen, the dependence of \( \alpha \) on \( E \) and \( p \) can be approximated [19] by

\[
\alpha [1/\text{cm}] \approx 8.8 p \exp \left( \frac{-275 p [\text{Torr}]}{E [\text{V/cm}]} \right).
\]

For \( V_d [\text{cm/s}] \), we will use linear approximation \( V_d \approx \mu E \), where \( \mu \) is the electron mobility which can be calculated as \( K/p \) with \( K \approx 3.3 \times 10^7 \text{ cm}^2 \text{ Torr/s} \times \text{V} \) for nitrogen [19]. Then we obtain \( \nu_i \approx 2 \times 10^9 \text{s}^{-1} \) that is \( 10^4 \) times less than \( \nu_{\text{FEE}} \). This means the dominance of FEE over ionization processes. It should be noted that, as a rule, the opposite inequality \( \nu_{\text{FEE}} << \nu_i \) is valid for a subnanosecond breakdown at \( p = 1 \text{ atm} \).

It should be noted that, in [17], the breakdown for \( p = 40 \text{ atm} \) happens at the maximum value of the voltage during the pulse. Then we can consider that the electric field \( (E_0 = 1.1 \text{ MV/cm}) \) is not changed essentially during \( \sim 150 \text{ ps} \). Due to the high sensitivity of the frequencies \( \nu_{\text{FEE}} \) and \( \nu_i \) to the field, all the main prebreakdown processes occur near the pulse extremum during this interval of time. We will take the duration of this interval as the estimation of the breakdown formation time \( (t_{\text{f orm}}) \). Then at least \( t_{\text{f orm}} \nu_{\text{FEE}} \approx 3 \times 10^3 \) electrons are emitted from a microprotrusion per the formation time (here the space charge of ions is not taken into account). The characteristic interval between ionization events equals \( \nu_i^{-1} \approx 0.5 \text{ ps} \) that exceeds \( T \) and \( t_{\text{f orm}} \). We can conclude that, if the electric field is homogeneous, thermal electrons practically do not participate in impact ionization processes.

For the conditions of [17], the gas gap can be ionized by the observed RAEs. We believe that the RAE appearance is due to the development of plasma channels starting from the cathode surface. These channels ensure the electric field enhancement near their heads and thereby the runaway conditions. Basing on the comparison of \( \nu_{\text{FEE}} \) and \( \nu_i \), one can conclude that the formation of plasma channels is induced by FEE. According to our notions, the only process which can be responsible for the current flow through the metal-gas interface is EEE. Unser conditions of a radical slowing down of the ionization processes in a high-pressure gas, EEE ensures the flow of free electrons into the gas which lead to the formation of plasma protrusions on the cathode surface (these protrusions can be considered as virtual cathode).

Let us discuss what time \( (t_{\text{EEE}}) \) is sufficient for the EEE initiation in the vacuum approximation, i.e., without considering the influence of the electric space charge. The simplest criterion for the initiation of EEE is based on determining the time during which energy necessary for the metal-plasma transition is accumulated in the protrusion [19]:

\[
\int_0^{t_{\text{EEE}}} \mathcal{E}_{\text{EE}}^2 dt = h.
\]

Here \( h \) is the specific action, which for metals equals approximately \( 2 \times 10^9 \text{ sA}^2 \text{cm}^{-4} \) [19]. Let us take \( t_{\text{EEE}} = 50 \text{ ps} \) for estimates. Then we obtain that the condition (2) is satisfied at a rather high coefficient \( \beta_g \) value of \( \sim 125 \). According to [25], for the average roughness of the cathode surface, the surface density of microtips with \( \beta_g > 100 \) is \( \sim 10 \) per square centimeter. For [17], the area the cathode active surface (\( \mathcal{S} \)) can be estimated as \( \sim 0.03 \text{ cm}^2 \) (its radius was \( \sim 0.1 \text{ cm} \)). Then the probability to meet a surface defect with \( \beta_g = 125 \) is less than unity (it is estimated as \( \sim 0.4 \); see section 4). In this case, only a few explosive-emission centers (EECs) can appear in dozens of ps.

We should take into account that we are dealing with a high-pressure gas, not vacuum. In such a situation, the ion space charge can accumulate due to ionization processes. If the ion cloud is situated in the vicinity of the cathode, its charge will amplify the local field \( E_{\text{loc}} \) and thereby the FEE processes. In [19], a mechanism has been proposed for the transition from field to explosive electron emission due to the influence of the positive space charge of ions moving towards the electrode. According to it, the EEE initiation time can be roughly estimated as \( (\alpha V_d)^{-1} \), where \( V_d \) is the drift velocity of positive
ions. For the considered case ($E_0 = 1.1$ MV/cm; nitrogen with $p = 40$ atm), a similar quantity for electrons $(V_\alpha)$ was estimated. It equals approximately 0.5 ns. The velocity of ions $V_\alpha$ is significantly less than $V_\gamma$. Then the time $(V_\alpha)^{-1}$ falls into a time scale that does not make sense in the context of the present study. However, under conditions of a high-pressure gas, a fundamentally different scenario can be proposed for the appearance of an ion cloud near the emitter. According to this scenario, FEE transforms into EEE in dozens of ps at microprotrusions having relatively low amplification factors ($\beta_5 = 50–60$). This scenario will be considered in the next section.

### 3. Scenario of the EEE initiation

Let us consider the electric field $E_\gamma$ of the cloud of positive ions. This field can be estimated from the formula

$$E_\gamma(t) = \frac{eN_\gamma(t)}{4\pi\varepsilon_0 r^2},$$

where $N_\gamma$ is the number of ions, $\varepsilon_0$ is the electric constant, and $r$ is the characteristic distance to the ions. The total electric field on the emitting cathode surface is the sum of the unperturbed local field on the top of the emitter $\beta_6 E_0$ and of the ion field $E_{\text{loc}}$:

$$E_{\text{loc}}(t) = \beta_6 E_0 + E_\gamma(t). \quad (3)$$

Ion cloud appears due to the ionization of gas by primary electrons. These electrons fall into the amplified electric field in the in the immediate vicinity of the emitting microprotrusion. Initially (when $N_\gamma \approx 0$), the field is $\beta_6 E_0$ that for $\beta_6$ values of 50–60 units gives ~ 60 MV/cm. This is 5.5 times larger than the runaway threshold. Then motion of field-emission electrons can be considered as collisionless. The paper [26] presents the shot of the cathode surface from [17]. One can see numerous protrusions of the micron scale. Then it is reasonable to set for the probable height of protrusions $r_p = 1$ µm. An electron gains in the region of the amplified electric field the energy estimated as $w_p \approx e r_p E_0 \approx 110$ eV, which is very close to $w_0$. The collisionless scale approximately equals $r_\gamma \approx r_p/\beta_6 \approx 0.02$ µm. Beyond the collisionless area the electron falls into the zone with low electric field. Here the behavior of the electron is governed by the braking force $\sim nL_{\text{max}}$. The particle loses its initial energy $w_p$ on the path $w_p/\langle nL_{\text{max}} \rangle \approx 0.1$ µm and turns into a thermal one. It spends a part of the energy on ionizing the gas, having performed several ionization events (the ionization energy for nitrogen $eU_i = 15.6$ eV is seven times less than $w_0$). We can consider only the first ionization event due to the rapid (as $r^{-2}$) decay of the Coulomb field with distance. The average path of electron before this event is $r_i \approx (\sigma n)^{-1} \approx 0.03$ µm. Here $\sigma$ denotes the ionization cross-section; for calculations, we used its maximum value of $\sim 3 \times 10^{-16}$ cm$^2$ [18].

The distance $r$ between the ion cloud and the cathode protrusion is the sum of the sizes $r_\gamma$ and $r_i$ that gives the estimate of ~ 0.05 µm. This scale turns out to be small enough to ensure an essential influence of ion charge on the local electric field $E_{\text{loc}}$. It is of critical importance that we deal with a dense gas. If the gas pressure $p$ drops from 40 to 1 atm, the length $r_i$ becomes forty times greater. Then the field of positive ions on the cathode becomes negligible, and thereby the considered mechanism ceases to work.

It is possible to estimate the number $N_\gamma$ as

$$N_\gamma = \frac{1}{e} \int_0^t j_{\text{EE}} \, dt.$$

Then it follows from (3) that the local electric field is
\[ E_{\text{loc}}(t) = \beta_E E_0 + \frac{s}{4\pi e_0 r^2} \int_0^t j_{\text{FEE}}(t) \, dt. \]

Differentiating this expression over time variable, we get the equation
\[ \frac{dE_{\text{loc}}}{dt} = \frac{s}{4\pi e_0 r^2} j_{\text{FEE}}. \]

Then, using (1), one can find after simple transformations the following ordinary differential equation together with the initial condition:
\[ \frac{d}{dt} \left( -\frac{1}{E_{\text{loc}}} \right) = \frac{sF}{4\pi e_0 r^2} \exp \left( -\frac{G}{E_{\text{loc}}} \right), \quad E_{\text{loc}}(0) = \beta_E E_0. \]

It becomes trivial if we introduce the auxiliary function \( A(t) = -G/E_{\text{loc}} \):
\[ \frac{dA}{dt} = C \exp A, \quad C \equiv \frac{sGF}{4\pi e_0 r^2} = \text{const}. \]

Integrating this equation, we easily find
\[ A(t) = -\ln \left( -Ct + \exp \left( -A(0) \right) \right). \]

Returning to the original function \( E_{\text{loc}}(t) \), we finally get
\[ E_{\text{loc}} = G \ln \left( 1 + \exp \frac{G}{\beta_E E_0} \right). \tag{4} \]

According to (4), the local field will explosively (faster than exponentially) grow with time due to the accumulation of ions near the cathode. It becomes infinite at the moment
\[ t_0 \approx \frac{4\pi e_0 r^2}{sGF} \frac{1}{1 + \exp \frac{G}{\beta_E E_0}}. \tag{5} \]

The singularity is due to the fact that a growth of \( E_{\text{loc}} \) causes an increase in \( j_{\text{FEE}} \). Then the ion generation rate will also grow. In turn, this results in a further growth of \( E_{\text{loc}} \) (i.e., the positive feedback is realized).

It is important that the condition (2) for the EEE initiation is satisfied automatically due to the explosive growth of \( E_{\text{loc}} \). The thing is that the singularity in (4) provides the divergence of the action integral. Expansion of (4) around the moment \( t_0 \) gives in the leading order:
\[ E_{\text{loc}}(t) \approx \frac{4\pi e_0 r^2}{sF} \frac{1}{t_0 - t}. \]

Then we get for the current density:
\[ j_{\text{FEE}}(t) \approx 16\pi^2 e_0^2 r^4 \frac{1}{s^3 F} \frac{1}{(t_0 - t)^2}. \]

In turn, the action integral near the singularity is given by
\[ \int j_{\text{FEE}}^2(t) \, dt \propto \frac{1}{(t_0 - t)^3}. \]

Thus it diverges at \( t \rightarrow t_0 \), ensuring the inequality (compare with (2))
The singularity formation moment $t_0$ can be associated with the EEE delay one $t_{\text{EEE}}$, so that we can take $t_{\text{EEE}} \approx t_0$.

Let us now discuss the dependence of the blow-up time $t_0$ on the gas pressure at a fixed field $E_0$. For this, it is necessary to take into account the relationship between the distance $r$ and the gas concentration $n$:

$$r = r_c + r_i = \frac{r_c}{\beta_g} + \frac{1}{\sigma} n,$$

Substituting this expression into (5), we finally get

$$t_0 \approx \frac{4\pi e_0}{sG} \left( \frac{r_c}{\beta_g} + \frac{1}{\sigma} n \right)^2 \left( 1 + \exp \frac{G}{\beta G E_0} \right)^{-1}.$$

(6)

According to (6), $t_0$ decreases monotonically with increasing $n$ (with increasing pressure, the distance from the cathode to the ion cloud decreases). Formally, at $n \to \infty$, the time $t_0$ reaches its minimum value, which is

$$t_{\text{min}} \approx \frac{4\pi e_0 r_c^2}{sG \beta_g^2} \left( 1 + \exp \frac{G}{\beta G E_0} \right)^{-1}.$$

(7)

However, it should be noted here that the above estimates, which led to formula (6), correspond to the specific case of $E_0 \approx 1.1$ MV/cm and $p = 40$ atm, and therefore are applicable only in a certain limited vicinity of this point. If the pressure significantly exceeds the value of 40 atm, the expressions (6) and, as a consequence, (7) will no longer be applicable. This is due to the fact that, with an increase in the gas concentration, the threshold runaway field of electrons grows and, as a consequence, the size of collisionless area near the microplotrusion $r_c$ will decrease, which was not taken into account in the derivation of (6). Indeed, it is clear from general considerations that, with a significant increase in $n$, the length $r_c$ will begin to decrease and, as a result, reach values for which the field-emission electron will no longer gain energy sufficient to ionize the gas. In this case, there will be no positive space charge of the ions, and the effect considered in the present work will disappear. It can be concluded that there is an optimal pressure value, calculated in tens of atm, for which effect of the ion cloud will be maximum and the blow-up time $t_0$ (and, as a consequence, the EEE delay time $t_{\text{EEE}}$) will be minimum.

4. Number of explosive-emission centers

Let us determine the time $t_{\text{EEE}}$ using the formula (5). For the average surface roughness, $\beta_g = 50–60$ (see [25]), the EEE initiation time falls into the range 15–115 ps, i.e., becomes essentially less than the breakdown formation time. In particular, it is enough to have $\beta_g = 55$ for the above used value $t_{\text{EEE}} = 50$ ps. It is clear that the probability to meet defects having $\beta_g = 55$ is essentially higher than for $\beta_g = 125$ (the value required for the EEE initiation in the vacuum approximation). This leads to the appearance of many EECs on the cathode. Indeed, one can use the following distribution function for the factor $\beta_g$ within the framework of the statistical description of the cathode surface relief [25]:

$$f(\beta_g) = k^{-1} \exp(-\beta_g / k).$$

It specifies the probability that the surface element has the enhancement factor in the range from $\beta_g$ to $\beta_g + d\beta_g$. The parameter $k$ characterizes the surface roughness degree. For such a distribution, the main contribution into the FEE current is provided by surface elements with
\[ \beta_g \approx \sqrt{G(\varphi) / kE_0}. \]

We get \( \beta_g = 55 \) at \( E_0 = 1.1 \text{ MV/cm} \) if we choose \( k \approx 5 \), which corresponds to the average roughness of the cathode. For such \( k \), the probability of encountering a surface element with the enhancement factor of 125, which ensures the transition from field electron emission to the explosion one without the influence of ion space charge (see section 2), will be six orders of magnitude less than that with \( \beta_g = 55 \). The probability that the microprotrusion has the enhancement factor greater than or equal to \( \beta_g \) is \( \exp(-\beta_g/k) \), which gives \( \sim 1.4 \times 10^{-11} \) for \( \beta_g = 125 \). Above, we take \( s = 10^{-12} \text{ cm}^2 \) for the area of the emitting surface at the top of the microtip. For an active cathode surface of the area \( S \approx 0.03 \text{ cm}^2 \), only single protrusions with the enhancement factor of 125 can exist on the surface: their number is estimated as \( (S/s) \exp(-\beta_g/k) \approx 0.4 \). In this case, the number of defects having \( \beta_g = 55 \) will be orders of magnitude larger, which will ensure (already taking into account the Coulomb field of positive ions) the formation of a significant number of EEEc in dozens of picoseconds.

As a result of the electrical explosion of the microprotrusion, a cathode torch develops: a hemispherical region of dense plasma that expands with the velocity \((1-2) \times 10^8 \text{ cm/s}\) emitting an electron flow limited only by its space charge [19]. The EEE initiation leads to the formation of the plasma channel, growing from the EEC towards the anode. Indeed, at a hemispherically perfectly conducting protrusion on the flat electrode subjected to the external homogeneous field, there is a threefold increase in its strength [27]. Our estimates [20] show that this amplification is sufficient to “turn on” the ionization processes. The evolution of the channel can be described, for instance, by the model proposed in [21]. Its application demonstrates the development of plasma protrusions of a size sufficient for generation of RAEs in their vicinity.

5. Conclusion

The scenario of the initiation of EEE at the boundary of the cathode and a dense gas proposed in the present paper provides the formation of multiple plasma channels generating RAEs. Within its framework, the key role is played by the field of positive ions accumulated near microprotrusions with moderate field amplification factors of 50–60. In the absence of this mechanism, the probability of developing plasma channels becomes low. They can start only from rather rare microprotrusions with high amplification factors \( \beta_g > 125 \). RAEs cross the gap in \( \sim 13 \text{ ps} \) (this value corresponds to the vacuum approximation) and ionize it. Then we will get uniform ionization of the interelectrode gap and accompanying diffuse glow in \( \sim 100 \text{ ps} \), which is in good agreement with observations [24] of the glow during the high-pressure nitrogen pulsed breakdown. Further development of the mechanism proposed by us for the initiation of EEE and the subsequent generation of the RAE flow requires detailed numerical calculations of the kinetics of electrons in the vicinity of microtips.

Acknowledgments

The work of G A Mesyats (sections 1, 2) was supported in part by the RSF (project 19-79-30086). The work of N M Zubarev (sections 3, 4, and 5) was supported in part by the RFBR (project 20-08-00172).

References

[1] Mesyats G A, Bychkov Y I and Kremnev V V 1972 Sov. Phys.—Usp. 15 282–7
[2] Babich L P, Loiko T V and Tsukerman V A 1990 Sov. Phys.—Usp. 33 521–40
[3] Stankevich Yu L and Kalinin V G 1967 Dokl. Akad. Nauk SSSR [in Russian] 177 72–3
[4] Babich L P 2003 High-Energy Phenomena in Electric Discharges in Dense Gases: Theory, Experiment, and Natural Phenomena (Virginia: Futurepast)
[5] Gurevich A V 1961 Sov. Phys. JETP 12 904–12
[6] Dreicer H 1960 Phys. Rev. 117 329–42
[7] Mesyats G A and Yalandin M I 2019 Phys.—Usp. 62 699–703
[8] Tarasenko V 2020 Plasma Sources Sci. T. 29 034001
[9] Zubarev N M, Mesyats G A and Yalandin M I 2017 JETP Lett. 105 537
[10] Gurevich A V et al 2012 Phys. Rev. Lett. 109 085002
[11] Yalandin M I et al 2020 Phys. Plasmas 27 103505
[12] Beloplotov D V, Tarasenko V F, Sorokin D A and Shklyaev V A 2021 Tech. Phys. 66 571–82
[13] Gashkov M A et al 2021 JETP Lett. 113 370–7
[14] Levko D, Yatom S, Vekselman V, Gleizer J Z, Gurovich V T and Krasik Y E 2012 J. Appl. Phys. 111 013303
[15] Belomyttsev S Y, Romanchenko I V, Ryzhov V V and Shklyaev V A 2008 Phys. Lett. 34 367–9
[16] Mesyats G A et al 2020 Appl. Phys. Lett. 116 063501
[17] Ivanov S N 2013 J. Phys. D: Appl. Phys. 46 285201
[18] Peterson L R and Green A E S 1968 J. Phys. B: At. Mol. Opt. 1 1131–40
[19] Korolev Yu D and Mesyats G A 1982 Field Emission and Explosive Processes in a Gas Discharge (Novosibirsk: Nauka)
[20] Zubarev N M and Mesyats G A 2021 JETP Lett. 113 259–64
[21] Lozanskii E D and Firsov O B 1964 Spark Theory (Moscow: Atomizdat)
[22] Bazelyan E M and Raizer Yu P 1998 Spark Discharge (Boca Raton: CRC Press)
[23] Korolev Yu D and Bykov N M 2012 IEEE T. Plasma Sci. 40 2443–8
[24] Ivanov S N and Lisenkov V V 2019 J. Appl. Phys. 124 103304
[25] Kozyrev A V, Korolev Yu D and Mesyats G A 1987 Sov. Phys. Tech. Phys. 32 34–8
[26] Lisenkov V V, Ivanov S N, Mamontov Yu I and Tikhonov I N 2018 Izv. VUZ. Fiz. [in Russian] 61 180–4
[27] Landau L D and Lifshitz E M 1984 Course of Theoretical Physics (Electrodynamics of Continuous Media vol 8) (New York: Pergamon Press)