On the Generation Mechanism of Supershort Avalanche Electron Beams during a Nanosecond Discharge in High Pressure Gases

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Abstract – The paper analyzes criteria for the electron runaway in gas diodes and optimum conditions for the generation of a supershort avalanche electron beam (SAEB) in high-pressure gases. A mechanism of the SAEB generation is proposed which explains experimental data. According to the proposed mechanism, the highest SAEB amplitudes are attained with a diffuse discharge and electron acceleration between the ionization wave front and the anode.

1. Introduction

The feasibility of electron runaway in discharges in the Earth atmosphere was predicted in [1]. X-rays pulses in an atmospheric-pressure He discharge were recorded for the first time in 1966 [2]. For the generation of X-rays, the authors of [2] used the most promising discharge gap geometry with a cathode of small curvature radius and a planar anode. The generation of X-rays in high-pressure gases owes to the generation of high-energy electrons (runaway electrons). An electron beam downstream of the foil anode of a gas diode in atmospheric pressure air was obtained for the first time in [3]. Runaway electrons and X-rays are generated in various types of laboratory and atmospheric discharges thus affecting the breakdown voltage and the discharge form. Therefore, the generation of runaway electron beams and X-rays in gas discharges is much addressed by researchers [1–33]. Moreover in recent years, interest in this research area has been greatly increased [6–32]. Studies of pulsed discharges show that the generation of runaway electrons in response to electric field amplification near the electrodes and in the gap is an ordinary phenomenon; however, their recording requires special procedures and equipment of high time resolution [8, 15, 16]. The investigation of runaway electron beams becomes particularly difficult with increasing the pressure in the gas diode and the voltage amplitude across the gap, and also with decreasing the voltage rise time. The short current pulse of a runaway electron beam, the inapplicability of part of measuring techniques developed for electron beams in vacuum diodes, the small amplitude of the beam current under nonoptimum conditions, and electromagnetic interferences add complexity to the measurements of the parameters of runaway electron beams and X-rays. Much greater difficulties arise in studying the dynamics of the processes occurring in gas diodes. All the foregoing is responsible for the large discrepancy between the data obtained in various works. By now, there is no consensus on the generation mechanism for runaway electrons and on their possible amplitudes and durations in atmospheric pressure air and other gases [1–31].

The objective of the work is to analyze criteria for the electron runaway in gas diodes and optimum conditions for the generation of a supershort avalanche electron beam (SAEB) in high-pressure gases, and to put forward a mechanism for the generation of runaway electron beams to explain the sequence of the processes responsible for SAEB’s with the highest current amplitudes.

2. Conditions for the generation of runaway electrons in high-pressure gases and criteria for electron runaway

As already noted, the feasibility of runaway electrons in strong electric fields produced by lightning discharges in the Earth atmosphere was first predicted in [1]. The essence of the effect is that in a rather strong electric field, an electron in its free path can gain more energy from the field than it loses in collisions with gas particles. This is because for electrons of energy greater than ~ 100 eV, the energy lost in collisions with gas particles decreases monotonically, and hence the energy of these electrons increases. The criterion for electron runaway was considered in many papers [1, 4, 5, 7, 33]. The electron energy $\varepsilon$ in an electric field of strength $E$, as a rule, is determined by the following balance equation (see, e.g., [33]):

$$\frac{d\varepsilon}{dx} = eE - F(\varepsilon),$$

where $x$ is the distance to the cathode and $F(\varepsilon)$ is the retarding force due to electron collisions with gas atoms. In the nonrelativistic case, the retarding force is often described by the simple expression in the Bethe approximation [33]:

\[ F(\varepsilon) = \frac{2m_e}{e}\sqrt{\varepsilon} \ln \frac{\varepsilon}{m_e} \]

where $m_e$ is the electron mass. The criterion for electron runaway is then written as

\[ \frac{d\varepsilon}{dx} = 0 \]

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\[ F(\varepsilon) = \frac{2\pi e^3 ZN}{\varepsilon} \ln \left( \frac{2e}{I} \right), \]  

(2)

where \( Z \) is the number of electrons in a neutral gas atom or molecule; \( N \) is the density of neutral gas particles; \( I \) is the average energy lost in inelastic collisions. Approximation (2) and more exact calculations of \( F(\varepsilon) \) both give a maximum in the dependence of the retarding force on the electron energy \( F_{\text{max}} = F(\varepsilon_{\text{max}}) \). Expression (2) has a maximum at \( \varepsilon_{\text{max}} = 2 \). For helium, \( I = 44 \text{ eV} \), \( \varepsilon_{\text{max}} = 2.72/2 = 60 \text{ eV} \); more exact calculation gives \( \varepsilon_{\text{max}} = 100 \text{ eV} \). For nitrogen, \( I = 80 \text{ eV} \), \( \varepsilon_{\text{max}} = 2.72/2 = 109 \text{ eV} \); more exact calculation gives \( \varepsilon_{\text{max}} = 103 \text{ eV} \). According to the traditional approach \([4, 33]\), which presumably traces back to \([1]\), the condition for electron runaway (i.e., for a monotone increase in electron energy with increasing \( x \)) in a gas field is the high field strength \( E > E_{\text{crit}} \), where the critical field \( E_{\text{crit}} \) is determined by the maximum retarding force \( E_{\text{crit}} = \frac{F_{\text{max}}}{e} \). For example with expression (2), the critical field \([33], p. 72\):

\[ E_{\text{crit}} = 4\pi e^3 ZN/(2.72I), \]  

(3)

where \( p \) is the gas pressure at 300 °K. For helium, for example, \( E_{\text{crit}}/p = 140 \cdot V/(\text{cm} \cdot \text{torr}) \); for nitrogen, \( E_{\text{crit}}/p = 590 \cdot V/(\text{cm} \cdot \text{torr}) \). This criterion for electron runaway takes no account of electron multiplication and is more appropriate for the initial discharge stage at which the beam current is low and the volume discharge in the gap has no effect on the electric field distribution and on the voltage across the gap.

Avalanche multiplication of fast electrons with an energy of 0.1–10 MeV was considered in [5]. This phenomenon was termed a runaway electron breakdown (REB). In the Earth atmosphere, a REB is initiated at a constant electric field an order of magnitude lower than that for an ordinary breakdown. A necessary condition for the initiation of a REB is the injection of high-energy seed particles, which are absent in laboratory experiments.

A nonlocal criterion for the electron runaway in a homogeneous electric field was obtained S.I. Yakovlenko (see [7] and reference in [7]); the average electron energy \( \varepsilon^* \) was determined with regard to the varying number of electrons. In the simplest form in approximation (1), the law of conservation of energy:

\[ \frac{d(N_e \varepsilon^*)}{dx} = eN \varepsilon - FN \varepsilon, \]  

(4)

where \( N_e(x) \) is the electron density at a point \( x \). Taking into account that \( dN_e/dx = \alpha \varepsilon N_e \), where \( \alpha \) is the Townsend multiplication factor for electrons, expression (4) gives the equation for the average energy \( \varepsilon^* \):

\[ \frac{d\varepsilon^*}{dx} = eE - \alpha \varepsilon^*. \]  

(5a)

Unlike (1), equation (5a) in its right-hand side contains the negative term that describes “smearing” of the electron energy gained \( \alpha \varepsilon^* \) from the field over all electrons, including newborn electrons. Therefore even with complete neglect of deceleration by gas (with \( F(\varepsilon) = 0 \)), the average electron energy is limited. This criterion has the form: \( \alpha(E_{\text{crit}}, p) d = 1 \), where \( \alpha \) is the ionization coefficient, \( p \) is the gas pressure, and \( d \) is the interelectrode gap. At \( E > E_{\text{crit}} \), most of the electrons turn into the runaway mode. At atmospheric pressure, \( E_{\text{crit}}/p \) obtained for helium and nitrogen was \( = 1200 \) and \( = 9000 \cdot V/(\text{cm} \cdot \text{torr}) \), respectively. These values are an order of magnitude greater than \( E_{\text{crit}}/p \) estimated without regard for electron multiplication \([33], p. 72\). However, they are about the same as the ratios obtained in the same work with regard for electron multiplication in the plasma \([33], p. 77\): \( E_{\text{crit}}/p = 550 \cdot V/(\text{cm} \cdot \text{torr}) \) and \( = 4000 \cdot V/(\text{cm} \cdot \text{torr}) \) for helium and nitrogen, respectively.

Analysis of the known criteria for electron runaway allows the following conclusions. For runaway electrons and X-ray to be produced at high pressure, discharges in an inhomogeneous electric field should be used in which the field is amplified at the cathode and dense plasma is generated first at the cathode. Decreasing the ratio \( E_{\text{crit}}/p \) in the region of a high electric field requires initial electrons of high energy; thus, fast electrons in the rest part of the acceleration gap continue their acceleration. Numerical simulation of an atmospheric pressure discharge in nitrogen and helium in an inhomogeneous electric field show that electron runaway begins at \( E/p = 170 \cdot V/(\text{cm} \cdot \text{torr}) \) in nitrogen and at \( E/p = 30 \cdot V/(\text{cm} \cdot \text{torr}) \) in helium \([7], p. 119\). The decrease in \( E/p \) that suffices for the electron runaway is due to the electric field amplification near the cathode and to the presence of high-energy electrons in the plasma. It should also be noted that in electron avalanches, the plasma is polarized. The calculations made in \([7]\) show that with comparatively low average electric fields, runaway electrons can be produced in an inhomogeneous electric field.

Analysis of available data on the electron runaway in high-pressure gases allows the conclusion that this criterion can be determined to high accuracy and in a rather simple form only for discharges in a homogeneous electric field. However, calculation of the generation of runaway electron beams is very difficult.

3. Conditions for the maximum SAEB amplitudes in atmospheric pressure air

As already noted, a runaway electron beam downstream of the foil of a gas diode at atmospheric pressure was first obtained in [3]. In a nanosecond atmospheric pressure discharge, the number of electrons downstream of an Al foil of thickness 8 µm was \( \sim 10^9 \). The lack of high-resolution equipment gave no way to measure the pulse duration of the beam current and hence the amplitude of the beam current. Note that the research team engaged in the above work has not
managed to increase the number of electrons downstream of the foil to over 10^9 [24]. We think that this owes to the nonoptimum design of the gas diode and cathode and to the rather long rise time of the generator voltage.

By now, the highest SAEB amplitudes are attained with the SLEP-150 pulser at the Institute of High Current Electronics of the Siberian Branch of the Russian Academy of Science (IHCE SB RAS). The amplitude of the beam current downstream of the foil of a gas diode filled with atmospheric pressure air is ~ 80 A [25]. This corresponds to ~ 5 · 10^10 electrons at a FWHM of the SAEB pulse of ~ 100 ps. The SLEP-150 pulser (with no transmission line) produces voltage pulses of amplitude ~ 150 kV at a high-resistance load. In the transmission line, the incident wave amplitude is ~ 140 kV. The pulse rise time is thus ~ 250 ps at a level of 0.1–0.9, and the FWHM of the voltage pulse is ~ 1 ns. With the RADAN-120 pulser, the highest amplitude of the bema current in atmospheric pressure air is ~ 50 A, and this corresponds to 2.7 · 10^10 electrons at a SAEB pulse duration of ~ 90 ps [8, 15]. The RADAN-220 pulser produces voltage pulses with a rise time of < 500 ps and amplitude of ~ 270 kV at a high-resistance load. With a matched load, the FWHM is ~ 2 ns. The pulser is connected to the gas diode with minimum inductance. The above results were made possible due to the design of gas diodes and cathodes optimum for the generation of runaway electron beams in high-pressure gases and to the SLEP-150 pulser that produced a voltage pulse with a rise time of ~ 300 ps. The SAEB current amplitude and the number of electrons downstream of the foil were measured with calibrated collectors and fast-response oscilloscope [8, 15, 18, 23, 25–27]. The measuring techniques are described in detail in [8, 15]. The latter papers also report on the pronounced effect of a shock wave on SAEB energy readings of an IMO-2N calorimeter. Note that in our several works performed till 2007, the calibration of the collectors from the results of calorimeter measurements of the energy of a runaway electron beam led to overestimated SAEB amplitudes.

Collectors calibrated from calorimeter measurements of the electron beam energy were used in joint studies of researchers from IHCE SB RAS and from the Institute of Electrophysics (IEP), UrB RAS. The results of the first of these joint studies with RADAN-220, RADAN-303, and SM-NS pulsers are reported in [9–11]. In the studies, a SAEB pulse with a FWHM of ~ 100 ps was obtained for the first time [10]; the frequency for X-rays in the batch mode was 3 kHz [8, 11]. In direct collector measurements, the highest amplitude of the SAEB current on the RADAN-303 and SM-NS pulsers was ~ 5 A (the diameter of the receiving part of the collector was 20 mm). The total current downstream of the foil was about two times greater than the above value and was ~ 10 A. For the both pulsers operated with a gas diode, the voltage rise time was ~ 1 ns. The voltage rise time on the RADAN-220 pulser was shorter than that on the RADAN-303 and SM-NS pulsers and was ~ 0.5 ns; on this pulser with a Ø6-mm tubular stainless steel cathode, the total beam current was ~ 20 A at a generator voltage of ~ 270 kV.

In later works, the researcher from IEP UrB RAS used magnetic field focusing of the electron beam, a modified pulser with a voltage pulse amplitude up to 700 kV, and a gas diode with an insulator, which increased the gas diode dimensions [12, 13, 16]. With a tubular graphite cathode, the beam current downstream of the foil in atmospheric pressure air was 1.5 A, and this corresponded to 10^7 electrons at a FWHM of 120 ps [12]. Replacement of graphite by stainless steel made it possible to increase the amplitude of the beam current to 10–20 A [16]. Under these conditions, the pulse duration was 45 ps and the number of beam electrons downstream of the foil was (3–6) · 10^8. The measurements in [12, 13, 16] were made with a collector. Note that the increase in the amplitude of the beam current with a stainless steel cathode of the gas diode was obtained earlier in [10]. The smaller amplitudes of the beam current obtained at IEP UrB RAS compared to the SAEB amplitudes attained at IHCE SB RAS are due to nonoptimum designs of the gas diode and cathode. In the gas diode, the insulator must shield the side walls of the transmission line. The cathode must have a long sharp edge and provide maximum voltage amplitudes across the gap [23, 25]. Moreover, the voltage amplitude must increase simultaneously over the entire length of the working edge of the cathode [23].

4. Generation mechanism for runaway electrons in high-pressure gases

There are several questions to be answered to determine the generation mechanism for runaway electrons in each specific mode of gas discharge: what processes are responsible for electron emission from the cathode; how the electric field is distributed in the gap and how it varies with time; in what region of the gap the critical field driving the electrons to the runaway mode is reached and how they gain and lose their energy. In other words, it needs to be known how the charged particles are distributed in the gap and how their density and energy vary as the gap is broken down. A complex answer to all these questions can be given only by rather elaborate simulation of the processes occurring in the gas diode. First steps in the simulation of the processes occurring in the gas diode at high voltage pulses were making in papers [4, 7, 17, 19, 28–31].

Below we briefly describe the generation mechanism for runaway electrons in the SAEB mode by which the highest amplitudes of the beam current were obtained downstream of a foil anode at IHCE SB RAS. Our previous studies confirm the SAEB mode; therefore, we omit the figures contained in our previous papers and make only references to them. We think that there are four discharge stages responsible
for a SAEB downstream of the foil. The first stage makes itself evident during the voltage rise at a voltage pulse amplitude of hundreds of kilovolts and corresponds to the onset of the field emission current from the cathode. The electric field is amplified at the cathode, which has a small curvature radius during the generation of a SAEB with maximum amplitudes.

At the second stage, part of the electrons – that are assumed to be fast electrons [8] – turn into the runaway mode due to electric field amplification at micro- and macro-irregularities of the cathode. These electrons ionize the gas and create initial electrons from which electron avalanches develop at the cathode. The density of the initial electrons at the cathode is such that avalanche heads overlap before the avalanches reach the critical size and a streamer develops. Hence, a dense plasma cloud is formed at the cathode in a short time ([27], Fig. 4, c). At this stage, the discharge current and the capacitive current reaches hundreds of amperes at a subnanosecond rise time of the voltage pulse [27] and the field-to-explosive emission transition normally has a chance to occur. As the voltage pulse duration is decreased to 0.1–0.2 ns, a diffuse corona discharge and bright spots can be observed at the cathode [27]. Moreover beginning with the second stage, the radiation from the near-cathode plasma increases the current from the cathode due to photodischarge and bright spots can be observed at the cathode [27]. Note that the electric field at the cathode is additionally amplified by the positive ion charge and this can also give rise to runaway electrons at the cathode, including the region of its side wall. With the collector placed downstream of the grid cathode from the side opposite to the anode, we recorded a positive potential of the ion cloud and an electron beam directed in opposition to the anode [26]. In these experiments, the cathode was at the potential of the gas diode case.

Most of the runaway electrons (the SAEB current) is generated at the third stage and is due to the critical field attained between the dense polarized plasma (ionization wave front) and the anode. In this case, the electrons moving in synchrony with the ionization wave front are affected by both the negative charge of avalanche heads and the amplified electric field in the gap due to its exclusion from the dense plasma. Experiments demonstrate that with the SLEP-150 pulser, the voltage across the gap starts decreasing after 200–500 ps [8, 18]. In this time, the ionization wave front reaches the anode and the ionization becomes stronger throughout the gap. The electron beam downstream of the foil is detected in the vicinity of maximum voltage [8, 18, 23]. Estimates show that under these conditions, the ionization wave velocity reaches ~ 10 cm/ns.

At the fourth stage, the ionization wave front reaches the anode. The electric field distribution in the gap thus becomes more uniform and the generation of the electron beam stops. Moreover, on arrival of the ionization wave front at the anode, the voltage across the gap decreases rapidly, while the discharge current increases.

The FWHM of the SAEB $\tau_{0.5}$ from the entire foil surface is normally 100–200 ps and depends on several factors. First, $\tau_{0.5}$ depends on the time difference between the instant at which the critical field is reached and the instant at which the ionization wave arrives at the anode. Hence, $\tau_{0.5}$ increases with decreasing the maximum voltage across the gap and increasing the pressure of heavy gases. The above tendencies were found in the experiment described in [8]. Second, the ionization wave front and the runaway electrons fail to reach the anode at a time and this also increases $\tau_{0.5}$ [23].

The generation mechanism for runaway electrons with an energy greater than $eU_{\text{max}}$ ($U_{\text{max}}$ is the maximum voltage across the gap) by their self-acceleration at the polarized streamer front near the cathode [4] lacks support from our experiments. With maximum SAEB currents, the fraction of electrons of energy $> eU_{\text{max}}$ is small, and with the discharge streamer, the beam current decreases considerably. Our findings can not be explained by the fact that the runaway electron beam is produced in the plasma of discharge microchannels in which the particle density decreases due to thermal expansion [19]: a diffuse discharge was initiated in the gap. The electron beam was detected within 100–200 ps after the application of a voltage pulse, and the thermal expansion of gas particles in this time is moderate. The generation of the SAEB is also unexplainable by the transient phase of the field emission, which ends on explosions of cathode microedges [13]. The generation of a SAEB was also observed during the formation of cathode spots.

### 5. Conclusion

The foregoing analysis of available data and experimental results obtained at the Laboratory of Optical Radiation of IHCE, SB RAS, confirms the generation mechanism for runaway electron beams proposed in [6] and developed in [8]. A supershort avalanche electron beam of highest amplitudes is generated as the critical field is reached between the ionization wave front and the anode. Attaining the highest currents in the gap requires voltage pulses with a rise time of ~ 0.3 ns and amplitude of hundreds of kilovolts applied to the cathode, a long sharp edge of the cathode, and an insulator of the gas diode shielding the side walls of the transmission line.

The critical field reached between the dense plasma front and the anode allows an increase in gas pressure in the gap at which a SAEB is detected downstream of the gas diode anode. Thus, a SAEB was detected in helium at pressure of 15 atm, and in nitrogen at pressure of 5 atm. The highest average values of $E/p$ for these pressures were $\approx 20$ and $\approx 70 \cdot V/(cm \cdot torr)$, respectively. These values of $E/p$ are comparable with $E/p$ at which electron runaway is...
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found in calculations of the breakdown in an inhomogeneous electric field [7]. The motion of the ionization wave front is also responsible for the production of electrons with an energy $> eU_{\text{max}}$. It is the effect of the ionization wave on the generation of runaway electrons that is the only explanation for SAEB amplitudes of tens of amperes in an atmospheric pressure air at a discharge current greater than 1 kA.

References

[7] Beams of runaway electrons with an energy $> eU_{\text{max}}$. It is the effect of the ionization wave on the generation of runaway electrons that is the only explanation for SAEB amplitudes of tens of amperes in an atmospheric pressure air at a discharge current greater than 1 kA.