LETTERS TO THE EDITORS

PACS numbers: 41.75.Fr, **51.50.** + v, 52.80.Dy

On the electron runaway effect and the generation of high-power subnanosecond beams in dense gases

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DOI: 10.1070/PU2006v049n07ABEH006019

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Abstract. **Fundamental errors are revealed in the critical paper by L P Babich [*Physics – Uspekhi* 48 1015 (2005)], which completely rejects the results of the present authors' review in *Physics – Uspekhi* 47 887 (2004).**

1. Introduction

During recent years extensive research, both theoretical and experimental, has been in progress in the field of the pulsed breakdown of dense gases and the formation of high-power electron beams in dense gases (see Refs [1 – 3] and the reviews [4 – 7]). The results of this research [1 – 7] constitute an entirely new step compared to a series of works done by a group of scientists at the All-Russia Research Institute of Experimental Physics (VNIIEF) [8]. The conditions needed for the generation of subnanosecond electron beams with an amplitude of several hundred amperes have been revealed, implemented, and explained in Refs [1 – 7] and in other publications of the groups of scientists at the High-Current Electronics Institute of the Siberian Branch of the Russian Academy of Sciences (RAS) and the A M Prokhorov General Physics Institute, RAS. However, the entire concept of Refs [1 – 7] has been questioned in Ref. [9]: it is stated that the theory suggested is wrong in all its aspects and that the experiments are questionable, since similar results could not be obtained earlier by this group at VNIIEF. Since the number of erroneous, inaccurate, and tendentious statements in Ref. [9] are large, it is impossible to analyze them all in this space. Below we point out only the key mistakes made by the author of Ref. [9].

2. On the applicability of the notion of the Townsend coefficient in strong fields

The key statement [9, p. 1023] in the criticism of the theory is that the notion of the Townsend coefficient α_i as a function of E/p, where E is the electric field strength, and p is the gas pressure, is 'physically meaningless' at large E/p. According to the author of Ref. [9], even if the electric field is uniform, the electron distribution function and (with it) the Townsend coefficient should exhibit explicit dependence on the coordinate. A direct numerical simulation of the distribution function in a strong field and a simple analytic study show that this statement by the author of Ref. [9] is false (see Fig. 1).

3. On the restriction of the mean electron energy set by electron multiplication

In Ref. [9, p. 1017] it is stated that there is no need to take into account the restriction on the mean electron energy set by electron multiplication because the friction force calculated by the Bethe formula contains the energy transferred to a second electron. Therefore, it is stated that the mean electron energy in a strong field increases with the coordinate x without bound.

The fact that the Bethe friction force contains the energy of the secondary electron is well known, and there was no need for a long proof of this conclusion [9, pp. 1017 – 1020]. However, the drag by itself does not describe the variation in the mean energy per electron, a variation caused by a change in the number of electrons. The corresponding terms in the heat balance equation are always taken into account when

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Received 21 December 2005, revised 20 February 2006
Uspekhi Fizicheskikh Nauk **176** (7) 793 – 796 (2006)
Translated by E Yankovsky; edited by A Radzig

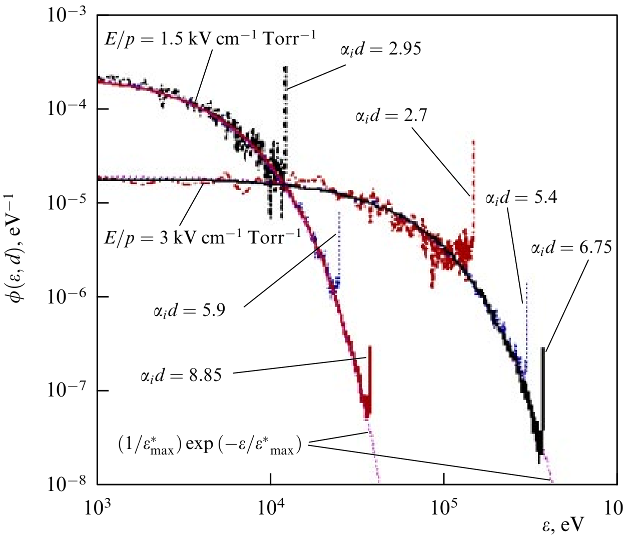

Figure 1. Energy distributions (normalized to unity) of electrons that have crossed a plane with $x = d$, for different electrode separations d. Helium number density $N = 5.15 \times 10^{17}$ cm^{-3} ($p = 16$ Torr). For $E = 24$ kV cm^{-1} ($E/p = 1.5$ kV cm^{-1} Torr^{-1}), $d = 5$, 10, and 15 mm. The sharp peaks correspond to the maximum values of the electron energy (runaway electrons): $eEd = 1.2 \times 10^4$ eV, 2.4×10^4 eV, and 3.6×10^4 eV. For $E = 48$ kV cm^{-1} ($E/p = 3$ kV cm^{-1} Torr^{-1}), $d = 30$, 60, and 75 mm, and we have $eEd = 1.44 \times 10^5$ eV, 2.88×10^5 eV, and 3.6×10^5 eV, respectively. In the analytical expression for the distribution function, $\varepsilon^*_{\max} = eE/\alpha_i$ is the energy that the electrons acquire at large x's, i.e., the maximum mean electron energy.

processes with a varying number of particles are considered (e.g., see Ref. [10], p. 72).

Note that the restriction on the mean electron energy can also be derived from the momentum conservation law

$$m_e N_e u \frac{du}{dx} = eN_e E - FN_e - \frac{dp_e}{dx} ,$$

where u and N_e are the mean velocity and the number density of electrons, F is the drag, and p_e is the pressure of the electron gas. For $E \gg F/e$ and $du/dx = 0$, estimating the pressure by the formula $p_e \sim N_e \varepsilon^*_{\max}$, we again arrive at $\varepsilon^*_{\max} \sim eE/\alpha_i$ (cf. Fig. 1 and Refs [4–7]).

Finally, equation (5) in Ref. [4], criticized in Ref. [9], serves only as a qualitative illustration and is not utilized in specific calculations. The fact that the mean energy and velocity of the electrons are restricted was demonstrated directly by employing a numerical simulation method which does not rely on the Bethe friction force. The mean electron energy ceases to depend on the coordinate x directed along the field for all its intensities if $x > 3\alpha_i^{-1}$ (see Fig. 1 and Refs [4–7]).

4. On the nonlocal criterion of electron runaway

In the research summarized in the reviews [4–7] we introduced a criterion that determines the boundary value E_{cr} of the electric field strength: $\alpha_i(E_{cr}, p)d = 1$. This criterion can be written down in a more rigorous form

$$\int_0^d \alpha_i(E_{cr}, p, x)\, dx = 1 .$$

However, there is no real need for such a complication.

The runaway criterion of a significant fraction of electrons from the gap between flat electrodes was rewritten in Refs [4–7] in the form

$$pd\,\xi\left(\frac{U_{cr}}{pd}\right) = 1 ,$$

where $\xi(E/p) = \alpha_i(E, p)/p$, $U = Ed$, and $U_{cr} = E_{cr}d$. The above formula expresses the implicit dependence of the critical voltage U_{cr} on pd, i.e., the escape curve $U_{cr}(pd)$. This curve separates in the (U_{cr}, pd) plane the region where electrons breed from the region where electrons leave the discharge gap without having enough time to breed to significant numbers. It is two-valued since the function $\xi(E/p)$ is nonmonotonic.

The author of Ref. [9] states that the upper branch of the escape curve $U_{cr}(pd)$ (called in Refs [4–7] the runaway curve), corresponding to the formation of a large fraction of runaway electrons, does not exist ([9], p. 1015) and invites us to reconsider the runaway criterion ([9], p. 1036).

However, the existence of a transition region in which effective multiplication transforms into a mode in which electrons that have been accelerated to the energy $\approx eU$ dominate is obvious from the general consideration related to the drop in all scattering cross sections at high energies. Moreover, we have verified this fact directly by numerical calculations, and the results were represented by curves of equal effectiveness of formation of runaway electrons as functions of pd.

Contrary to what we have written on p. 893 of Ref. [4], the author of Ref. [9] on p. 1031 suggests that we have obtained the curves of equal effectiveness from runaway curves by using some sort of a linkage. Certainly not: they have been obtained through direct numerical simulation, and the very fact that they coincide with runaway curves only proves the expediency of the runaway criterion we introduced.

5. On the energy distribution of electrons and X-ray quanta

Measurements of the energy distribution of electrons, taken with the foil method [11–14], have shown that the beam carries at least three groups of electrons (Fig 2a) and have corroborated the statement (see Refs [4–7]) that the number of electrons with anomalously high energies ($\varepsilon > eU$) is small. A fraction of the electrons from the first group ($\varepsilon < 60$ keV) is generated before the emergence of a peak in the current of the beam of runaway electrons [14]. When grids and thin foils are used as the anode, the current oscillogram exhibits a precursor pulse coming earlier than the main peak, whose half-height duration is about 100 ps [12], by 100–500 ps [13, 14]. The current oscillogram of the second group of electrons exhibits a maximum corresponding to 100–150 keV in the electron energy distribution. The electron energy at this peak is lower than the voltage across the gap. There may more than one maximum in this group of electrons (see Fig. 2a and the results of the calculations done by Jiang et al. [15]). The third group (anomalous electrons) contributes little to the beam current (less than 5%).

In addition to all this, we used the RADAN-303 accelerator and measured, in the same conditions, the exposure doses of X-ray radiation as functions of a filter thickness and calculated the energy distribution of the X-ray quanta (Fig. 2b) [13]. Figure 2 shows that there is good agreement between the two distributions (cf. Figs 2a and 2b).

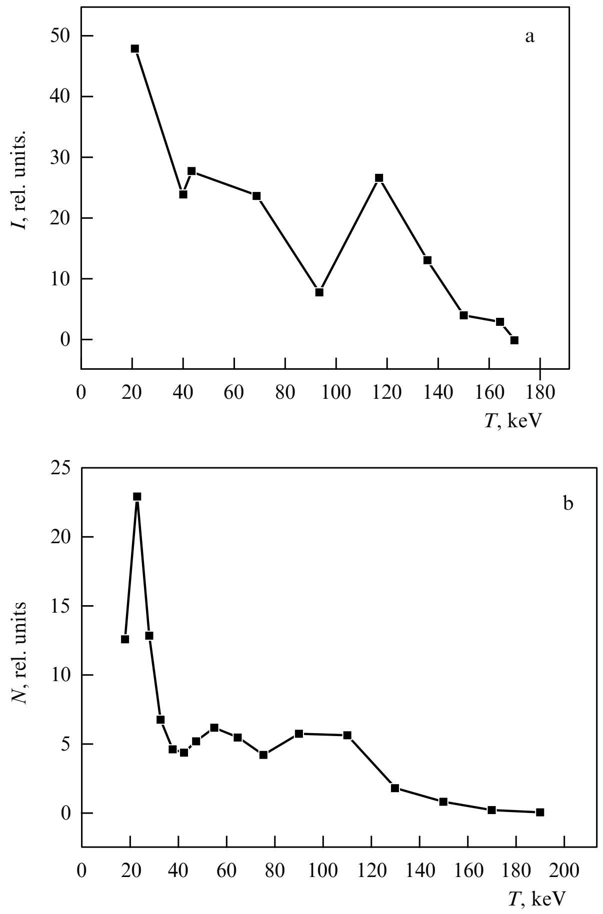

Figure 2. Energy distributions of electrons (a) and X-ray quanta (b). Measurements were made with a RADAN-303 generator; maximum voltage across the gap was $\sim$ 150 kV.

However, in his 2005 publication [9], Babich persists to assert that an electron beam emerging from a gas diode filled with air at atmospheric pressure consists mainly of electrons with anomalously high energies, which are produced at the cathode on the streamer head because of polarization self-acceleration. New experimental data are absent from Ref. [9], while the results of many works (e.g., see Ref. [16]), which prove that applying voltages of several hundred kilovolts beams were generated in which electron energies were found to be lower than the voltage across the gap, are ignored. Furthermore, Babich also ignores the results of his own calculations of the parameters of an electron beam in helium at atmospheric pressure [17]. There, the calculated beam current was reported to amount to 1 kA, while no anomalous electrons were taken into account by the calculations.

6. On the amplitude and shape of the beam current

Measurements of the amplitude of the beam current are extremely difficult for subnanosecond durations of the pulse and differ significantly when utilizing different shunts and collectors [13]. A collector put under load to a coaxial cable that has a wave resistance of 50 Ω and is matched to it possesses a good time resolution but lowers the beam current amplitude appreciably.

The calorimetric method is best suited for measurements of the beam current amplitude. Earlier, Shpak [18] studied this method as applied to beams of nanosecond duration and recommended using it. To determine the amplitude of the beam current, one must measure the total beam energy. What is more, the energy distribution of the electrons and the beam current half-height duration must also be known. Using these data, one can calculate (estimate) the amplitude of the current of the electron beam. Our measurements of the amplitude of the beam current by the calorimetric method yielded a value of $\sim$ 100 A or even higher when the air was at atmospheric pressure. The maximum amplitude of the beam current, $\sim$ 400 A, was produced with a RADAN-220 generator behind aluminum foil about 10-μm thick, with the gas diode having the smallest possible dimensions and inductance [12]. A steel ball 9.5 mm in diameter served as the cathode in these experiments.

What is also important is that for a given interelectrode separation and length of the voltage pulse front, there exists an optimum value of the voltage pulse amplitude [4–7]. The maximum currents of the electron beam are recorded behind the foil as the electron beam forms at the point in time when the maximum of the voltage across the gap is attained.

The statement made in Ref. [9] about the small amplitudes of the currents of runaway-electron beams, which were actually recorded in Refs [1–7], is erroneous. The fact that the optimum was never reached in the experiments described in Ref. [8] is due primarily to the nonoptimal design of the gas diode.

7. Conclusion

Studies that continue the research summarized in the reviews [4–7] go on, and new results pertaining to the formation of electron beams in various gases at elevated pressures and to the formation of volume discharges without preionization have already emerged [12–14, 19–21]. We believe that high-power ultrashort avalanche electron beams and discharges that form without sources of additional ionization will find wide application in science and technology.

At present in Russia there is a large number of X-ray devices such as MIRA, NORA, and ARINA, manufactured commercially, along with generators and accelerators such as RADAN, SINUS, and SM-3NS, developed at the High-Current Electronics Institute of the Siberian Branch of the RAS and the Electrophysics Institute of the Ural Branch of the RAS. Information about the MIRA, NORA, ARINA, RADAN, SINUS, and SM-3NS generators can be found in monograph [22]. The design of gas diodes is fairly simple, especially when they are filled with air at atmospheric pressure. Our research has shown that for the insulator of the gas diode it is best to use the insulators from standard IMA-350D X-ray tubes. With any one generator listed above, it is fairly easy to build in the laboratory a simple, compact accelerator that will form a high-power electron beam with a half-height pulse duration reaching $\sim$ 0.1 ns.

We invite all specialists to participate in this research.

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