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Whether abnormal energy electrons are being produced in electric discharges in dense gases?

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Reviewing results of experimental research of picosecond pulses of runaway electrons (REs) generated by discharges in dense gases at multiple overvoltages, including, along with routine measurements of voltage pulses and RE current, direct measurements of RE energy distributions, pressure dependence of RE numbers and experiment with retarding voltage similar to the accelerating voltage, a reality of the effect of "abnormal energy" REs is being substantiated. With this goal we emphasize non-conventional qualitative RE characteristics rather than quantitative.

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I. Introduction. High-energy runaway electrons (REs) produced by discharges in dense gases at high overvoltages relative to the static (direct current) self-breakdown voltage and observed for the first time in the end of 1960s, are being studied further during the next decades in various configurations (cf. for instance [1–8] and citations therein). In the first experiments discharges in air at $P = 1\,\text{atm}$ were discovered to generate REs with the energy ε exceeding a magnitude $eU_{\max}$ corresponding to the maximum value of the voltage pulse $U_{\max}$ [1]; obviously, this is impossible in the framework of the ordinary linear acceleration. Initially the energy ε was estimated using electron attenuation curves measured by wedges technique at the anode outlet. In air at $P = 1\,\text{atm}$ rather frequently the curves were as those typical for monoenergetic electrons: a small initial section with a weak inclination, rather long decreasing linear section and final straggling are inherent for the curves [1–3]. The linear section allows estimating the initial electron energy ε using the extrapolated range $R_{\text{ex}}(\varepsilon)$ [9–11], the energy being somewhat underestimated in the case of wide electron beams, that is the case for REs. One of such curves fitted to ten measured points is illustrated in Fig. 1 [2, 3] along with attenuation curves of monoenergetic electrons by Seliger [11]. The RE energy given by this curve is $\varepsilon \approx 270\,\text{keV} > eU_{\max}$. Note $U_{\max}$ is significantly less than a maximum voltage magnitude U_{idle} in the idle-running mode, which can be doubled relative to amplitude of a self-breakdown voltage U_{self} of a shaping switch in a used generator. Thus, quantitatively ($\varepsilon > eU_{\max}$), but, what it is more important, qualitatively (almost monoenergetic) the REs of "abnormal energy" revealed themselves. However, a reality of this effect is denied [5]. In this paper we review available experimental data arguing in favor of its reality. To prove the effect we emphasize, first of all, qualitative RE characteristics, not quantitative. Such approach allows making the term "abnormal energy" less misleading.

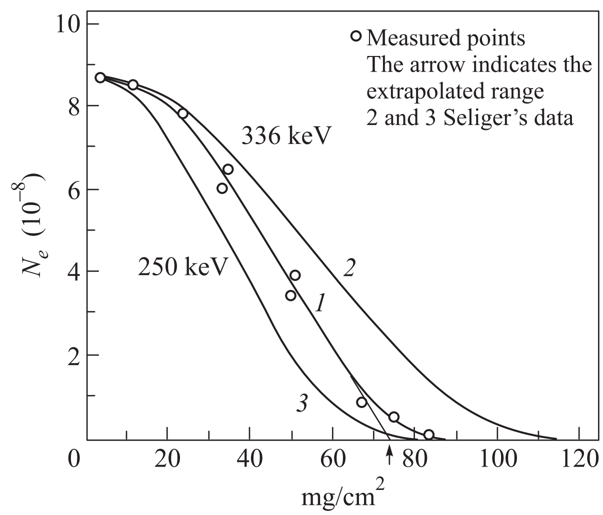

Fig. 1. Attenuation curves (aluminum foils) [2, 3]: *1* – curve of REs generated by the discharge ($U_{\text{idle}} = 270$ kV, air, 1 atm, $d = 15\,\text{mm}$, $r_{\text{cath}} = 6\,\text{mm}$); *2* and *3* – monoenergetic electron curves by Seliger [11]

II. Abnormal energy and voltage pulses. In connection with a negation of the "abnormal energy" REs generation [5], based on that measurements of high-voltage pulses with subnanosecond front are unreliable, it is pertinent to note that voltage pulses were being measured close to the cathode working surface [3]. We

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cannot agree with "that the idle-running mode is a typical regime at the cathode in the pre-breakdown stage in the gap" [5]. The amplitude U_{idle} is achieved during a discharge in sufficiently long gaps, but in gaps with rather small interelectrode spacing d [1–3] (cf., for example, Table) $U_{\max} < U_{\mathrm{idle}}$ or even $\ll U_{\mathrm{idle}}$, because

Dependences on the interelectrode spacing d of the discharge voltage amplitude $U_{\max}$, characteristic energy ε_m, and energy excess $\Delta\varepsilon = \varepsilon_m - eU_{\max}$ of "abnormal energy" REs in air at 1 atm. Amplitude of the voltage pulse in the idle-running mode $U_{\mathrm{idle}} = 270$ kV, $d = 2$ cm, conic cathode with $r_{\mathrm{cath}} = 200\,\mu$m, grid anode

d, cm	3.5	2	1	0.5
$U_{\max}$, kV	210	190	150	130
ε_m, keV	320	290	260	180
$\Delta\varepsilon$, keV	110	100	110	50

the conductivity current in the primary channel in the near-cathode domain, which is closed to the anode by the eddy current in front of the channel along with a current of the secondary avalanches initiated by the RE pulse, increases so fast that the U_{idle} is not achieved.

The term "abnormal energy" has been introduced comparing the RE energy ε, given by $R_{\mathrm{ex}}(\varepsilon)$, to the $U_{\max}$ magnitude, the accuracy of which raises well-founded doubts from the very beginning of the research of discharges with REs. More intriguing and significant are discovered later qualitative characteristics of these REs, which can not be understood in the framework of the ordinary linear acceleration. We must forewarn against interpreting the straggling [9–11] as high-energy "tails" of electron energy distribution. The straggling "tail" appears even in the attenuation curves of initially monoenergetic electrons, such as measured by Seliger [11] (cf. Fig. 1). Obviously electrons with the energy above the initial magnitude can not appear in such experiments. The authors of the paper [8] interpret a long "tail" of attenuation curves, which they observed in the range of the most thick absorber layers, as the "abnormal energy" REs. Most likely, for the "tail" the straggling is responsible.

III. RE energy distribution (magnetic spectrometry). We measured RE energy distributions using the magnetic spectrometry technique with a resolution better than 10 % [2, 3]. The attenuation in substance layers outside the evacuated spectrometer chamber limited measurements from below to the energy of $\varepsilon \approx 50$ keV. In Fig. 2 the RE energy distributions for one of gas-discharge configurations are illustrated. The energy losses reduce the highest electron energy $\varepsilon_{\max}$. With the pressure decrease the $\varepsilon_{\max}$ decreases (cf. upper and middle panels Fig. 2), but then increases (Fig. 2c) according to the $U_{\max}(P)$ variation with the pressure. Above approximately 200 Torr the distributions have expressed maximum, a position of which ε_m increases with the pressure rise. Under conditions of the experiment upper panel in Fig. 2 at $P = 1$ atm. $\varepsilon_m \approx 270$ keV. Under the same conditions the attenuation curve gives $\varepsilon \approx 300$ keV. The measured RE distribution width is of $2\Delta\varepsilon_{\mathrm{meas}} \approx 60$ keV (upper panel in Fig. 2). The intrinsic width of the distribution $2\Delta\varepsilon_{\mathrm{intr}}$ in each separate discharge is much narrower because of the widening due to the scatter of the self-breakdown voltage of the shaping switch U_{self} and the voltage $U_{\max}$ at the studied gap, electron scattering in the spectrometer window and due to non-ideal collimation. Both $\varepsilon_m > eU_{\max}$ and extremely narrow energy spectrum ($2\Delta\varepsilon_{\mathrm{intr}} \ll \varepsilon_m$) agree with the attenuation curves (Fig. 1). With the discharges in sufficiently long gaps ($d \geq 1$ cm, volumetric glow) the excess of the RE energy $\Delta\varepsilon$ above the "allowed" magnitude $eU_{\max}$ is of $\Delta\varepsilon \approx 100-110$ keV; at $d < 1$ cm (contracted channel) the $\Delta\varepsilon$ is much less (cf. Table).

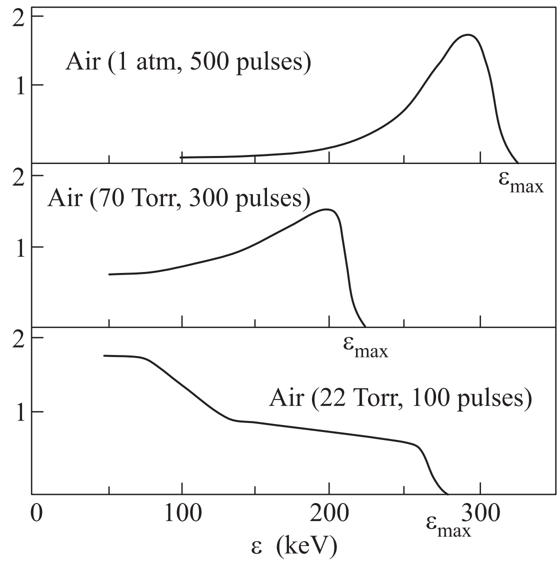

Fig. 2. RE energy distributions (arbitrary units) [2, 3]: $U_{\mathrm{idle}} = 270$ kV, air, 1 atm, $d = 2$ cm, sharp conic cathode with $r_{\mathrm{cath}} = 200\,\mu$m, grid anode

In the experiment in [5] with "the acceleration pulse at the cathode with amplitude of – 570 kV" and using "the cut-off threshold" of the attenuation curve in Fig. 17 [5] the electron energy was estimated to be of $\varepsilon \approx (160-170)$ keV. Estimating ε magnitude by "the cut-off threshold" is not reliable because in the straggling domain fluctuations are comparable to electron numbers themselves and the straggling and, hence, "the cut-off threshold" are dependent on the initial numbers of electrons at the outlet of gas-discharge gap; nevertheless, we estimated approximately the same ε magnitude using the $R_{\mathrm{ex}}(\varepsilon)$ for the curve in Fig. 17 [5]. These estimations do not agree with the data in Figs. 1 and 2, according to which the ε magnitude is much bigger, though voltages were significantly less. Taking into account that a dependence of the RE current on the voltage after approximately 250 kV achieves a plateau of ~ 1 A (Fig. 15 [5]), it is doubtful if the "accelerating" voltage above 250 kV was being achieved with a sharp cathode edge. According to Fig. 15 in [5] the RE current vanished completely at the voltage of ~ 70 kV, whereas in our work [6], in which microsecond voltage pulses 44–66 kV were used, the RE numbers of $N_e \approx 10^7 - 10^8$ per pulse were detected. Note, to the RE current of ~ 1 A with a duration of ~ 50 ps in [5] the RE number of $N_e \approx 3 \cdot 10^8$ per pulse corresponds; this magnitude is not essentially different from $N_e \approx 9 \cdot 10^8$ 1/pulse in Fig. 1.

IV. The RE pulse is generated at the conductivity current front. It is commonly believed that the REs are generated during rise-time of a voltage pulse with extremely steep front. The REs can, though not obligatory, be generated at the voltage front, but, being charge carriers and initiators of secondary electron avalanches, the REs are generated self-consistently with the conductivity current rise, which can sharply grow at the front of the applied voltage pulse, thus limiting amplitude of a really achieved voltage amplitude. To demonstrate this rather obvious statement we detained the ionization development such that the delay time t_{del} of the conductivity current to significantly exceed a duration τ_U of the front of the voltage pulse $U(t)$. This was reached using the barrier discharge. Oscilloscope traces of voltage $U(t)$, total gas-discharge current $I(t)$ and RE current are illustrated in Fig. 3 [2, 3]. The peak in the left part of $I(t)$ in Fig. 3b is the eddy current due to the interelectrode capacity charging. The t_{del} value is of 4 ns. In view of that RE pulse onset coincides with that of $I(t)$ and $\Delta t_e \ll 1$ ns [4, 5], it is allowed asserting that REs are generated during the conductivity current rise.

V. The RE pulse duration. Using a configuration with a cone-like cathode with a top radius of $r_{\mathrm{cath}} \approx 200\,\mu$m a duration of the "abnormal energy" REs pulse $\Delta t_e < 150$ ps was measured [2, 3, 12]. We measured $\Delta t_e < 250$ ps with $r_{\mathrm{cath}} = 3$ mm [12]; this allows claiming that RE pulses, generated by discharges in gaps with smooth cathodes, also are of subnanosecond duration. In order to overcome a limitation of the Δt_e magnitudes imposed by the instrumental resolution, we explored a dependence of the "abnormal energy" RE numbers N_e on the maximum value of the gas-discharge current I_m.

(a)

(b)

(c)

(d)

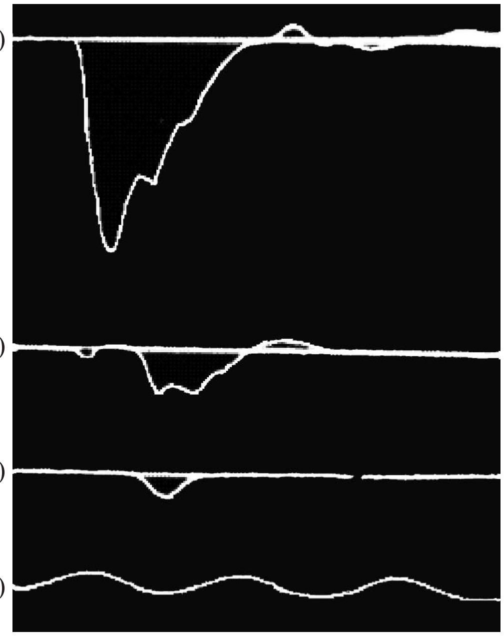

Fig. 3. Barrier discharge. Oscilloscope traces of the discharge voltage $U(t)$ (a), gas-discharge current $I(t)$ (b), RE current (c) [2, 3]; $U_{\mathrm{idle}} = 240$ kV, air, 1 atm, $d = 1$ cm, a hemispherical cathode working surface with $r_{\mathrm{cath}} = 6$ mm, 100 MHz time marker (d)

The N_e appeared to be essentially independent of I_m in the range 0.14–1.4 kA [2, 3]; therefore, allowing for that REs are generated at the current front and using measured current front duration $\tau_I < 0.5$ ns [2, 3], we estimated a duration of the discharge stage responsible for the RE generation, as $(0.14/1.4) \cdot \tau_I < 50$ ps in agreement with the direct Δt_e measurements [4, 5].

VI. Direct demonstration of the effect of "abnormal energy" REs. For the direct demonstration of the effect of "abnormal energy" REs we have executed an experiment [2, 3] using a pulse of the retarding voltage identical to the accelerating pulse. A pulse $U(t)$ of positive polarity was applied at a grid anode positioned in a center of grounded cylindrical gas-discharge chamber. Upon an internal chamber surface a cathode was attached, a conic top of which was located at a distance $h = 2$ cm away from the anode. Opposite to the cathode a cartridge with an x-ray film was located at the same distance 2 cm from the anode upon the internal chamber surface. "Wedges" of aluminum foils were placed ahead of the film with a purpose of measuring the attenuation curve of incident REs. The REs, generated in a gap between the cathode and grid anode, penetrated through the anode into the trans-anode area, where they were to overcome the retarding voltage $U_r(t) \approx -U(t)$. The REs with the energies below $eU_{\max}$ could not get the film because they lose the energy while moving in the retarding field and in interactions with air and the cartridge matter. The energy of electrons capable of overcoming the U_r and penetrating through the substance layers to reach the film was estimated by a magnitude of 90 keV, which is close to the energy excess $\Delta\varepsilon$ in the Table. It is necessary, however, to point out a shortcoming of this experiment, namely, during the time of $\Delta t \sim h/c \approx 70$ ps required for an electron with the speed of light to cross the retarding gap, the voltage could somewhat vary, such that the condition $U_r(t) \approx -U(t)$ is not strictly satisfied.

VII. Origin of seed REs. Two origins of electrons seeding the RE flux are possible: cathode emission and gas ionization. Already results of the first experiments, in which REs have been observed directly, forced one to refuse from the emission source [1–3]. This was done analyzing a dependence of the RE number on the air pressure $N_e(P)$ and the optical thickness of the absorber ρl (ρ is a density and l is a thickness) measured in [1] using a cathode with a vast working surface. The working surface was thoroughly polished to eliminate a deposition of cathode emissions. In the $N_e(P)$ curve at $\rho l = 5\,\mathrm{mg/cm^2}$ in Fig. 4 it is seen that intensive electron runaway is observed below 400 Torr. A decrease in the N_e below 50 Torr is a consequence of the decreasing ionization rate. Below approximately 0.1 Torr, the discharges did not develop at all. Hence, the development of the discharges, self-consistent with the RE generation, is controlled by processes of electron multiplication in the gas. Rather weak dependence of N_e on P at big ρl is an evidence that the RE number in the high-energy section of the energy distribution rather weakly depends on a concentration of atomic particles. As Yalandin et al. demonstrated, even with extremely sharp working edge of a cathode seed REs are produced by ionization in the gas [5].

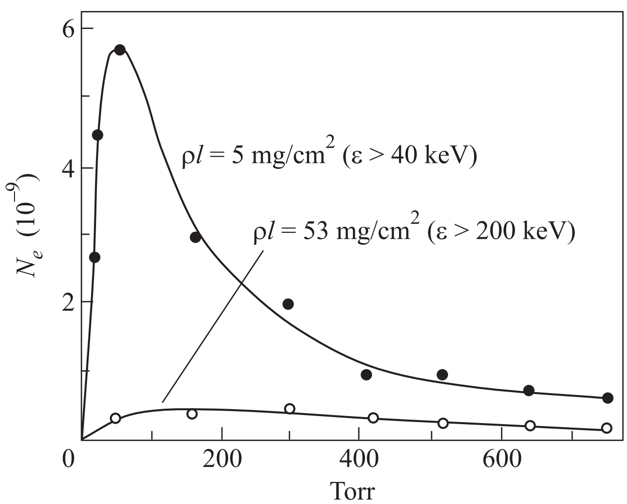

Fig. 4. Dependence of the runaway electron number N_e (e^-/pulse) on the air pressure for two magnitudes of aluminum absorber optical thickness ρl [1–3]; $U_{\mathrm{idle}} = 270$ kV, $d = 1.5$ cm, polished hemispherical cathode with $r_{\mathrm{cath}} = 6$ mm

VIII. Polarization self-acceleration. As measurements of high voltage pulses with picosecond fronts are believed to be untrustworthy [5], the effect of REs with "abnormal energy" ($\varepsilon > eU_{\max}$) really can be called in question [5] if to prove its reality only comparing ε_m and $eU_{\max}$ (Table) and ignoring the RE idiosyncrasies:

- almost monoenergetic energy distribution at rather high gas pressure (Figs. 1 and 2) in spite of extremely high rate of electron–atom interactions in a dense gas,
- REs can be produced during the voltage pulse decay (Fig. 3),
- independence of the RE numbers on the gas-discharge current maximum value,
- extremely weak dependence of high-energy RE numbers (Fig. 4) on the pressure,
- the RE pulse duration Δt_e is much less than that of the voltage pulse Δt_U; in the framework of linear acceleration one can expect that Δt_e is to be close to Δt_U.

As a matter of fact, this is not a problem of the "abnormal energy" ($\varepsilon > eU_{\max}$), but rather a problem of the mechanism capable of accounting for high-energy REs generation in dense gas ($P \sim 1$ atm). Extremely narrow RE spectrum and the lack of electrons in the low-energy range do not fit both the emission mechanism of the RE generation and simple "linear" acceleration.

In low-temperature strongly collisional plasma a mechanism of polarization self-acceleration by Askar'yan [13] seems to be the most adequate, capable of accounting for the generation of electrons with the energy $\varepsilon > eU_{\max}$. The mechanism assumes a self-consistent propagation of the polarizing plasma channel, the domain with amplified electric field at the channel front and accelerating front electrons which produce seed ionization centers ahead of the front supporting the channel propagation. Estimations of the RE numbers, their energy, duration of the acceleration process testify to the consistency of the concept of polarization self-acceleration with experimental data [2, 3, 14, 15]. Within the framework of this mechanism it is clear why "the RE current breaks when the voltage at the electrodes has not fallen yet" [5]: beginning with some moment of time, the field at the front of the polarizing channel is being amplified to such an extent that here a rate of ionization and excitation of air molecules by electron impacts sharply decreases (the "dark space" seen in Fig. 5 is the evidence of this amplification); as a result the link between the accelerating REs and the channel front field supported by the high ionization rate, is being broken off [2, 3, 15].

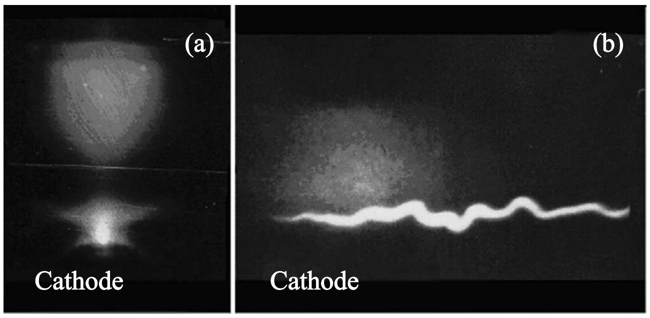

Fig. 5. Photo (a) and photo-chronogram (b) of volumetric diffuse discharge in air at 1 atm; $U_{\mathrm{idle}} \approx 270$ kV, $d = 15$ mm, $r_{\mathrm{cath}} = 3$ mm [2, 3]

At the first sight the polarization self-acceleration seems to be an exotic mechanism met only at multiple overvoltages. But, actually, it is an extrapolation in the range of very strong fields a treatment of the breakdown phenomenology by Raether [16]. The accelerated propagation of streamers [17, 18] also is essentially a polarization self-acceleration, but under conditions that the process is such slow that there is sufficient time for establishing a local equilibrium between the electron average energy and permanently amplifying field at the streamer front. Unlike the Raether model, in which electrons drift in equilibrium with a local field, in the mechanism by Askar'yan the electrons undergo continuous acceleration self-consistent with the motion of the channel front; therefore, they are capable of energizing above the $eU_{\max}$.

IX. Conslusions. The RE pulse with extremely narrow energy distribution with the maximum ε_m vicinity of hundreds keV (Figs. 1 and 2) and duration Δt_e on the order of tens picoseconds is generated by discharges at multiple overvoltages in dense gas during the conductivity current rise-time of $\tau_I < 0.5$ ns (Fig. 3). There are also experimental evidences that ε_m exceeds the magnitude $eU_{\max}$ corresponding to the maximum value of the voltage achieved during the discharge (Table and experiment with retarding voltage). It is impossible to explain such narrow distribution, $\varepsilon_m > eU_{\max}$ and the weak dependence of the high-energy electron number on the pressure (Fig. 4) in the framework of the ordinary linear acceleration, especially in view of extremely high rate of electron-atom interactions, as a rule, leading to strong population of the low-energy domain. The limitation of the RE pulse duration, most likely, is caused by the redistribution of the field intensity as a result of the plasma polarization, evidenced by the "dark space" (Fig. 5), the field in which domain is so strong, that electrons practically do not interact with the gas molecules, as in the dark Hittorf–Crookes layer of the glow discharge [19]. We emphasize that the reality of "abnormal energy" REs is proved by their non-conventional characteristics. The mechanism of RE generation can be discussed and whether the REs always are of "abnormal energies", but, obviously, both the electron acceleration and limitation of their generation are caused by processes in gas-discharge plasmas.

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