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Duration of runaway electron current pulses when applying voltage pulses with a subnanosecond rise time

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The conditions for obtaining runaway electron (RE) current pulses with a minimum duration at a subnanosecond breakdown of centimeter gaps filled with air at atmospheric pressure were studied. It is shown that the RE current pulse duration depends on many parameters, such as the cathode form, the magnitude of the interelectrode distance, the diameter of the diaphragm, which is part of the anode, as well as on the size of the receiving part of the collector. It has been established that the use of cathodes with an extended edge having a small radius of curvature, RE current pulses consisting of two peaks of picosecond duration can be recorded.

Keywords: runaway electrons, beam current, picosecond pulse duration, subnanosecond breakdown.

Introduction

At present, much attention is paid to the study of the formation of runaway electrons (RE) under various conditions. Hundreds of papers have been published in recent years alone. The largest number of papers in the last two years have been devoted to studying the effect of RE on plasma heating in units for obtaining controlled thermonuclear fusion, see, for example, [1–3]. In TOKAMAK-type units, the discharges that generate RE, which lead to damage to the walls of the vacuum chamber, are studied in detail. Various atmospheric discharges are being widely studied [4–6], including their modeling in meter discharging gaps [7]. It was established that high-voltage breakdown is accompanied by the generation of high-energy particles [4–7].

Much attention is paid to the study of the parameters of RE beams in laboratory discharges at high pressures of air and other gases, as well as X-ray radiation under the influence of a RE beam (REB) [8–19]. A significant part of these studies is carried out under conditions of breakdown of centimeter-sized gaps with abrupt cathodes filled with air at atmospheric pressure. Both the current parameters of the REB under various conditions and the mechanism of generation of RE are studied. Studies are also carried out by modeling discharges with RE, see, for example, [9–11,15,20–22].

Starting from the first papers on the experimental study of RE generation in air at atmospheric pressure, the duration of the REB pulse behind a foil anode is one of the difficult parameters to measure, since it requires the use of broadband metering devices and attracts the attention of researchers. This issue remains relevant at the present due to the development of measurement technology. It is necessary to establish the effect of various parameters (pressure and type of gas, amplitude and the voltage impulse front duration, length of the discharging gap, design of the cathode and anode) on the duration of the REB pulse. Moreover, such studies should be carried out with a picosecond timing resolution of the metering equipment and sensors used. In addition, there are very few data in the literature on the shape of the REB pulse under conditions of generation of short pulses.

For the first time, direct measurements of the duration and shape of the REB pulse at a discharge in air at atmospheric pressure were performed in [23] using a faraday cup. The duration of the registered pulses did not exceed 1.5 ns at half maximum. According to the authors of the paper, see [23], it was overestimated due to insufficient resolution of the available equipment. Measurements of X-ray pulses duration under the action of REB, performed using a 14ELU10 X-ray electron multiplier tube with a resolution of ~ 1.2 ns along the front, gave a similar result. Note that the beam current pulse measured in [23] had a triangular shape. The studies devoted to the study of the generation of REB under various conditions, carried out in this scientific group, as well as in other scientific groups, were summarized in 2003. It was noted in the monograph [24] that the measured REB duration in air at atmospheric pressure does not exceed 0.5 ns at half maximum. On the other hand, on the basis of estimates, it was assumed that the duration of the current pulse of the runaway electron beam with „anomalous“ energy can be no more than 50 ps. Electrons with anomalous energy include electrons with energy $T_a > eU$, where e — electron charge, U – voltage across the gap. Note that in [25], based on erroneous results at electron spectrum measurement, it was assumed that in air at atmospheric pressure, the REB behind the anode foil is close to monoenergetic and consists of electrons with an energy exceeding eU by ≈ 100 keV, at $U = 150$-210 kV. The presence of a wide spectrum of REB under various conditions, as well as a small number of electrons with anomalous energy, was shown in [26,27], where the number of electrons with anomalous energy did not exceed 10%, and also in [28] (see Fig. 4).

With the use of vacuum diodes, as well as the use of voltage pulses of subnanosecond duration, approximately at this time, beam current pulses with duration at half maximum of $0.12-0.15$ ns [29] were recorded. This was facilitated by the relatively large amplitudes of the beam current, which reached 320 A when using a cathode in the form of a single point. The amplitudes of the beam currents in [29] were several orders of magnitude greater than the amplitudes of the REB obtained in [23–25] with a gas diode filled with air at atmospheric pressure. A disk-shaped collector and an I2-7 oscilloscope were used to record beam current pulses in [29]. To increase the resolution in the oscilloscope, a low-sensitivity tube (3.5 kV/cm) with a coaxial beam-deflection system was used.

The lack of equipment with high sensitivity and resolution, as well as the small amplitudes of the REB under problematic conditions, did not allow to determine the real duration of the REB pulse in [23,25] and in the papers cited in [24]. Only $8 \cdot 10^8$ electrons were obtained in air at atmospheric pressure behind an anode foil 8 μm thick [23].

The use of the TDS-684B (1 GHz, 5 GS/s) oscilloscope in further studies of the generation of REB in air at atmospheric pressure allowed [30] to register REB pulses with duration at half maximum of 0.3 ns using a collector. Coaxial cables and attenuators 142-NM from Barth Electronics with a bandwidth of 30 GHz were used in this paper. The amplitude of the REB was significantly increased, and it was also shown that with a decrease in the size of the receiving part of the collector, the duration of the REB pulse at half maximum decreases in the paper [30].

Shorter REB were recorded using oscilloscopes with higher timing resolution. So, in [31] an oscilloscope TDS-7405 (4 GHz, 20 Gs/s) was used. With a disk collector with a diameter of 2 cm, the duration of the REB was reduced to 0.2 ns. It was also confirmed in [31] that with a decrease in the size of the receiving part of the collector, REB pulses of shorter duration are recorded. Subsequent analysis of the results obtained in [31] showed that the duration of the REB pulse was overestimated due to insufficient timing resolution of the used collector [8].

The registration of REB pulses with duration at half maximum of ≈ 100 ps was reported for the first time in the paper [32]. The resulting duration corresponded to the limiting timing resolution of the TDS-6604 oscilloscope (6 GHz, 20 Gs/s). In this case, the size of the receiving part of the collector was 4 mm and its timing resolution was no worse than 50 ps. However, as subsequent studies have shown, see, for instance, the review [8], this duration corresponded to the average duration of the REB pulses over the entire surface of the anode foil, recorded in air at atmospheric pressure and centimeter gaps with nanosecond voltage pulses with an amplitude ~ 100 kV.

REB pulses with a duration at half maximum of 45 ps were recorded in [33] using a TDS6514C oscilloscope (15 GHz, 40 Gs/s). The timing resolution of the oscilloscope was ≈ 30 ps. This allowed to record shorter REB pulses as well. We consider that the duration of the beam current pulse was determined under the conditions [33] by the diameter of the receiving part of the collector, which was equal to 10 mm.

Even shorter REB pulses were recorded in [34], see also review [35]. This was achieved not only through the use of broadband oscilloscopes LeCroy WaveMaster 830Zi-A (30 GHz, 80 Gs/s) and Tektronix DSA72504D (25 GHz, 100 Gs/s) and a collector with a small (3 mm) with the diameter of the receiving part, but also due to the installation of a diaphragm with a small diameter hole on the anode. As a result, when the diameter in the diaphragm hole is 0.5 and 1 mm, REB pulses with a duration of $20-25$ ps at half maximum were recorded in air at atmospheric pressure. This duration corresponded to the limiting resolution of the oscilloscopes used. In addition, it was shown in experiments [34,35] that with an increase in the diameter of the diaphragm hole at the anode and the receiving part of the collector, the duration of the REB pulse increases and reaches ≈ 100 ps. It followed that when recording only a part of the beam electrons, the duration of the corresponding pulses is significantly shorter than when recording electrons behind the entire surface of the anode foil. It was also found in [34] that the duration of REB recorded through an anode diaphragm with a diameter of 1ṁm from the axial part of the gap depends on the interelectrode distance and cathode design.

Experiments in which REB of the shortest duration were recorded are described in the paper [28]. Keysight DSAZ594A (59 GHz, 160, Gs/s) and Tektronix DPO73304D (33 GHz; 100 Gs/s) oscilloscopes were used to measure the parameters of the REB and the voltage pulse across the gap. With the amplitude and duration of the front of the pulse at the no-load voltage of 180 kV and 250 ps, respectively, and also when using a cathode in the form of a cone, a REB current pulse with a half maximum duration of ≈ 9 ps was recorded. This value corresponded to the timing resolution of the oscilloscope and the collector. Meanwhile, as in [34,35], only a part of the REB current on the axis of the gas diode was measured by using a diaphragm on the anode with a diameter of 1 mm. Measurements at other diaphragm diameters were not carried out. Correspondingly, runaway electrons were recorded in [28], which passed only through a diaphragm 1 mm in diameter.

Our analysis of known papers shows that the question of the duration of the REB pulse and the influence of various factors on it remains open.

The purpose of this paper — is to study the effect of a number of important parameters (diameter of the anode

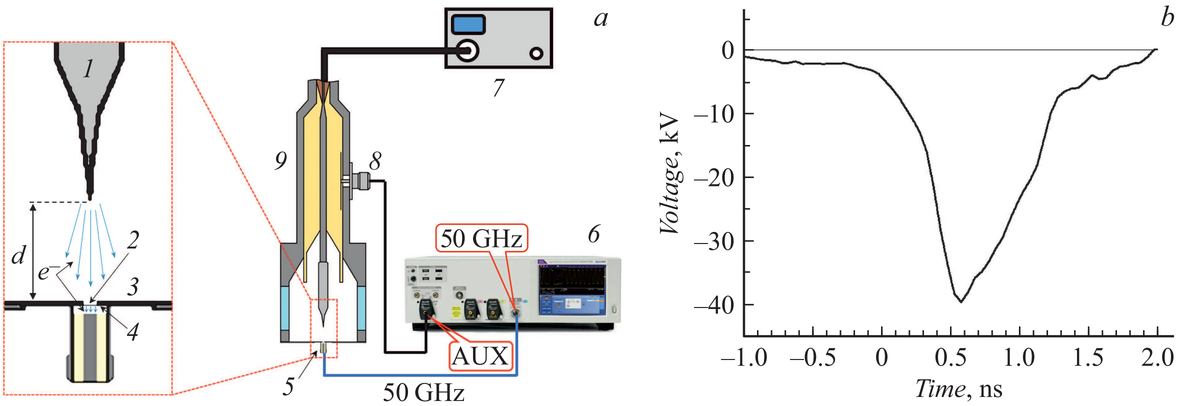

Figure 1. *a* — unit for studying the RE beam parameters with a GIN-55-1 generator: *1* — cathode, *2* — Al-foil, *3* — hole anode, *4* — diaphragm, *5* — collector, *6* — oscilloscope, *7* — high voltage generator, *8* — capacitive divider, *9* — transmitting line 75 Ω; *b* — voltage pulse at the matched load, the amplitude of which doubled at no-load.

diaphragm, cathode design, thickness of the anode foil, size of the interelectrode gap) on the duration and shape of the REB pulse. To implement it, voltage pulse generators with a subnanosecond front duration were chosen, which makes it allows to obtain relatively large amplitudes of the runaway electron beam current.

1. Experimental setup and methods

The studies were carried out on two units with generators making voltage pulses of negative polarity with a rise time shorter than 1 ns. Oscilloscopes with a high timing resolution and collectors with a small diameter of the receiving part, which were installed behind a flat anode with various diaphragms were used in the experiments. The unit with the GIN-55-1 [36] generator is shown in Fig. 1.

Previously, see [13,14,17,19], a similar unit was used to study the formation of a discharge, as well as in studies of a runaway electron beam and dynamic biasing current. The generator formed voltage pulses with an amplitude in the incident wave $U \approx 38$ kV and a front $\tau_{0.1-0.9} \approx 0.7$ ns with a duration $\tau_{0.5} \approx 1$ ns (Fig. 1, *b*), which were fed through a cable and a transmission line *9* with wave resistances 75-Ω to a discharge gap with a space of $d = 6$ mm. Two different abrupt cathodes were used. The first one had the shape of a cone with an apex angle of 90°, as in the paper [28]. The second cathode was made of 5 mm sewing needle trim (stainless steel) with a base diameter 1 mm and a point curve radius 75 μm (Fig. 1, *a*). The flat anode was made of copper foil 0.1 mm thick with a hole in the center 1 mm. It was located on a copper disk 1 mm thick with a hole in the center (coaxial with the hole in the anode) 1 mm in diameter. A copper foil anode with a hole diameter of 0.1 mm was used in some experiments.

The discharge chamber was also equipped with a capacitive voltage divider and a collector. To record the REB, a collector with a diameter of the receiving part ≈ 1 mm, made from an SMA 2.92 mm flange connector was used (Fig. 1, *a*). Aluminum foils 10 and 50 μm thick could be placed between the anode and diaphragm. It was possible to cut off low-energy electrons in the REB with their help. To transmit the signal from the collector to the ATI channel of the Tektronix DPO75002SX (50 GHz, 200 GS/s) oscilloscope, a cable assembly SUCOFLEX 101PEA (HUBER SUHNER) with a length of 1 m was used, designed for signal transmission with low losses up to frequency 50 GHz. No signal attenuators were used in the measurement of short REB pulses.

A unit with a SLEP-150M [8,35] generator, a gas diode, and a collector is shown in Fig. 2, *a*.

The SLEP generator was designed to produce electron beams in gas diodes with the highest amplitudes [8], and the coaxial lines *4* were used to measure the incident and reflected waves and restore the voltage across the gap [35]. The designs of the coaxial line filled with transformer oil and the gas diode were similar to those used in the papers [8,34,35]. The inner conductor with a diameter of 4 cm of a high-voltage coaxial line with a wave impedance of 30 Ω was formed by the housing of the R-43 peaking spark gap. The spark-gap breakdown voltage depended on the specific sample and its service life. In these experiments, the generator usually formed voltage pulses with an amplitude in the incident wave $U \approx 130$ kV and a front $\tau_{0.1-0.9} \approx 0.3$ ns with a duration at half maximum $\tau_{0.5} \approx 1$ ns (Fig. 2, *b*). The cathode was a ≈ 6 mm diameter steel foil tube 100 μm thick or a ball with ≈ 9.5 mm diameter. The electron beam bushing was through the anode, which was made of Al foil 10 μm thick. The distance between the anode and the cathode *d* varied from 6 to 16 mm. To measure electron beams from the paraxial zone of the gas diode, a diaphragm 1 mm in diameter and 5 mm thick was installed behind the Al-foil.

The REB current pulses were recorded with LeCroy WaveMaster 830Zi-A (30 GHz, 80 GS/s) or Tektronix DSA72504D (25 GHz, 100 GS/s) oscilloscopes. High-frequency cable RG58-A/U (Radiolab) 1 m long and SMA

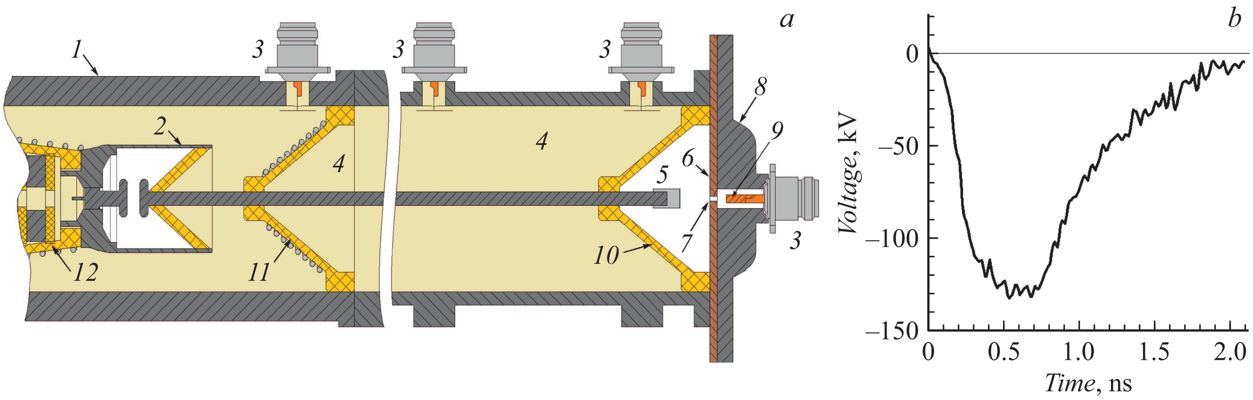

Figure 2. *a* — unit with generator SLEP-150M: *1* — generator housing, *2* — R-43 high pressure arrester, *3* — mount holes for connecting broadband cables, *4* — coaxial lines with a wave impedance of 100 Ω, *5* — tubular cathode, *6* — Al-foil anode, *7* — hole in the diaphragm, *8* — collector housing, *9* — receiving part of the collector with a diameter of 3 mm, *10* — insulator, *11* — insulator with inductance for grounding the center conductor of the coaxial line, *12* — pulse transformer; *b* — voltage pulse at the matched load, the amplitude of which doubled at no-load.

connectors were used. The measurements were carried out at a pulse repetition frequency of no more than 1 Hz.

2. Parameters influencing the REB pulse duration

As already noted, the purpose of the paper — is to study the effect of various parameters on the duration of the REB current pulse behind a flat anode with a diaphragm using oscilloscopes and collectors with high timing resolution. Previously, it was shown in [34,35] that with an increase in the diameter of the diaphragm and an increase in the size of the receiving part of the collector, the duration of the recorded REB current pulses increases. Preliminary studies confirmed these results. Therefore, in the present experiments, the holes in the anode were 1 and 0.1 mm, while the diameter of the receiving part of the collector was 1 mm. Accordingly, the influence of various factors on the parameters of the central part of the electron beam, which was formed on the axis of the gas diode, was studied.

The minimum durations of the REB current pulses in this paper were recorded using a Tektronix DPO75002SX oscilloscope. The durations at half maximum of the REB current pulses were compared to two different diameters of holes in the anode 1 and 0.1 mm. In experiments carried out earlier [35], it was shown that when the hole diameter exceeds 1 mm, the pulse duration increases and amounts to ~ 100 ps in air at atmospheric pressure over the entire surface of the foil. However, when the hole diameter in the anode is less than 0.5 mm, the experiments were not carried out. Figure 3 shows the durations of the REB current pulses at half maximum, obtained for different diameters of holes in the anode, as well as characteristic oscilloscope displays.

With a decrease in the hole diameter in the anode, the spread in the duration of the REB pulses increased, and the current amplitude decreased. Figure 3, *a* shows the results of two series of measurements, in which the measurements of duration $\tau_{0.5}$ at half maximum were recorded at anode hole diameters 0.1 and 1 mm. Figure 3, *b* shows examples of REB beam current oscilloscope displays with minimum and maximum durations for a hole diameter in the anode of 0.1 mm. These oscilloscope displays demonstrate the adjustment in the REB from implementation to implementation, despite the fact that the beginning of generation coincides in some cases. The amplitude of the beam current decreased with a decrease in the diameter of the hole in the anode due to the absorption of most of the beam in the anode. An increase in the spread of the amplitude and duration of the beam current is associated, as we assume, with microinhomogeneities in the spread of the beam current density over the anode surface. With an increase in the hole diameter, the effect of microinhomogeneities decreases. As a result, with a larger diameter hole, the stability of the duration and amplitude of the beam current pulses improves.

A standard oscilloscope display of the REB current with an anode hole diameter of 1 mm is shown in Fig. 3, *c*. The spread $\tau_{0.5}$ for hole diameters 1 mm was estimably smaller than for 0.1 mm. The REB pulse form is close to a non-isosceles triangle (REB pulses will also be shown in Fig. 4–6). Under these conditions, the REB pulse form and $\tau_{0.5}$ were determined only by electrons generated on the axis of the gas diode. The minimum REB duration in these experiments was recorded at a hole diameter of 0.1 mm and amounted to ≈ 16 ps.

The results on the influence of the cathode design on the duration of the REB pulse are shown in Fig. 4.

The experiments were carried out with a hole in the anode 1 mm, since under these conditions the amplitude and duration of the REB were more stable. Figure 4, *c* shows the data for a cathode in the form of a cone (circle), which were obtained in the second series of experiments and were not used in Fig. 3, *a*. It was found that the transition from the cathode from the sewing needle to the cathode, which

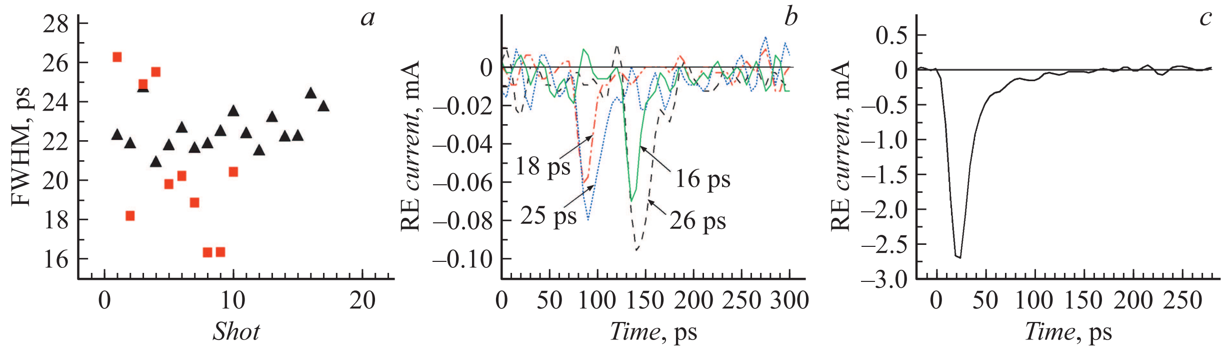

Figure 3. *a* — the duration of the REB current pulses at half maximum in different pulses for anode hole diameter *1* (triangles) and 0.1 mm (squares); *b* — oscilloscope displays of two pairs of REB current pulses with a hole diameter in the anode 0.1 mm, demonstrating the change in the REB from implementation to implementation; *c* — a typical oscilloscope display of the REB current pulse with an anode hole diameter of 1 mm. Generator GIN-55-1. Air pressure $p \approx 100$ kPa. Cathode — needle.

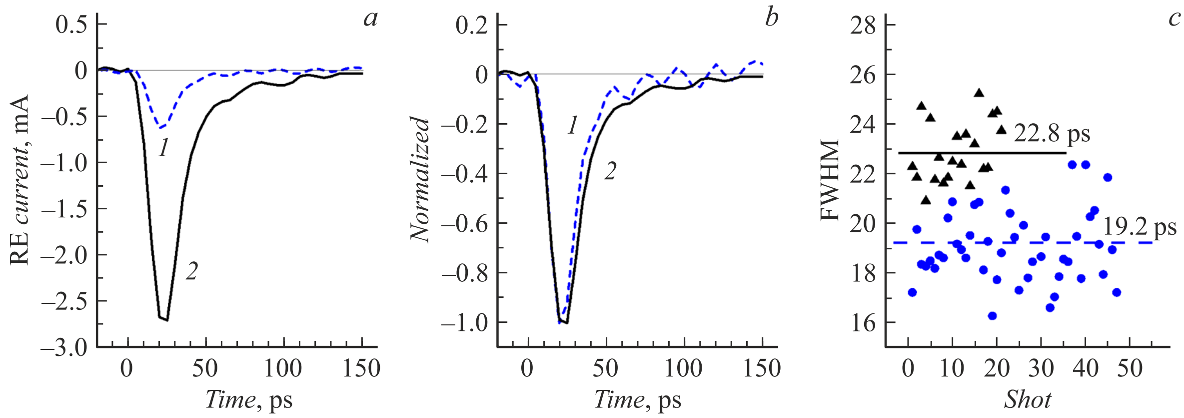

Figure 4. *a, b* — oscilloscope displays of REB current pulses of medium amplitude through a hole in the anode with a diameter of 1 mm with cathodes in the form of a cone *1* and from a sewing needle *2* in absolute and relative units, respectively; *c* — REB current duration at half maximum from pulse to pulse (triangles — cathode in the form of a needle, circles — cathode in the form of a cone). Generator GIN-55-1; $p \approx 100$ kPa.

is in the form of a cone, the duration of the REB current pulse decreased. With a cone cathode with a larger hole diameter in the anode (1 mm), $\tau_{0.5} \approx 16$ ps was recorded in individual pulses. This duration is twice as long as in [28], where the REB current from the paraxial zone of the gas diode was also measured. Note that the amplitude of the voltage pulse in [28] was twice as large, and its rise time was three times shorter than that of the GIN-55-1 generator. This could lead to a decrease in the duration of the REB on the axis of the gas diode.

With both cathodes in air at atmospheric pressure, one cathode spot was usually formed on their points. The duration of the REB pulse with the cathode needle, apparently, increased due to the emission of electrons from the side surface of the needle, the curve radius of which is significantly less than that of the side surface of the cone electrode. The electric field near the cathode from the needle, due to its smaller curve radius and small diameter, is higher than near the top of the cone cathode.

When runaway electrons pass through the foil, the duration of the REB pulse at half maximum did not adjust significantly. This follows from Fig. 5, where the electron beam was also recorded through a hole in the anode with a diameter of 1ṁm.

At the lack of Al-foil, the average duration of the beam current pulse at half maximum over 50 of switching on the accelerator was 23 ps. As is seen from Fig. 5 the pulse duration at half maximum did not practically change with Al-foil with a thickness of 10 and 50 μm. To pass through an Al foil 10 μm thick, the electron energy should exceed 32 keV, and to pass through an Al foil 50 μm thick — 83 keV. Note that the amplitude of the voltage pulse did not exceed 76 kV at no-load with the GIN-55-1 generator.

The duration of the REB pulse at the level of 0.2 when a foil with a thickness of 10 μm was installed on the anode decreased from 38 (without foil) to 33 ps with a foil of 10 μm, and with a foil of 50 , μm to 29 ps. From this, it may be assumed that a part of low-energy electrons under these conditions is generated near the anode. When generating electrons with an initial energy of 30 keV at the cathode, the time for them to pass through the gap of 6 mm will be ≈ 60 ps.

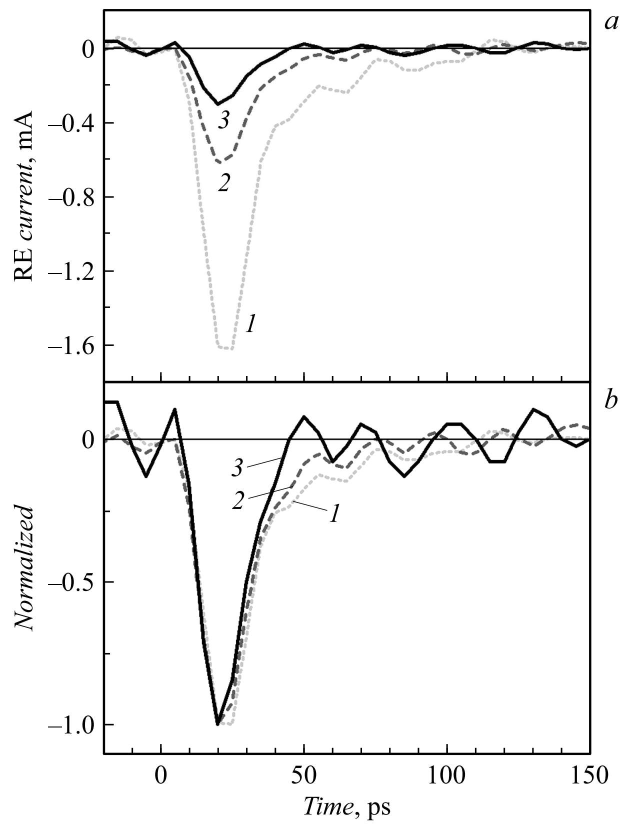

Figure 5. Oscilloscope displays of the REB current pulses with a cone cathode in absolute (a) and relative units (b): *1* — without Al-foil, *2* — Al-foil 10 μm, *3* — Al-foil 50 μm. Generator GIN-55-1. $p \approx 100$ kPa.

Figure 6 shows the oscilloscope displays of the REB current pulses during a discharge in air in gaps of various lengths when voltage pulses are applied from the SLEP-150M generator.

The duration of the REB pulse at half maximum with a tubular cathode increased from 37 ps at a gap of 8 mm to 46 ps at a gap of 16 mm. This tendency coincides with that obtained earlier in the paper [34]. The increase in the pulse duration can be explained by the disruption of electrons as they move towards the anode, as well as by the different initial speed at the cathode. It is known that runaway electrons in a beam have different energies [8], in which 2–3 groups with different energies can be specified.

Fig. 6, b demonstrates the influence of the cathode design and generator voltage. Replacing the ball cathode with a tubular cathode with an extended edge with a small curve radius, on which several bright spots were formed, led to an increase in the duration of the REB pulse from 26 to 34 ps. This increase in the duration of the beam current can be explained by non-simultaneous emission from different parts of the tubular cathode.

The duration of the *4* pulse with the cathode ball was somewhat reduced by increasing the voltage in the incident wave of the SLEP generator to 200 keV. Thus, an increase in the amplitude of the voltage pulse, other things being equal, leads to a decrease in the duration of the REB generated and measured on the axis of the gas diode.

Note an important feature of the REB pulse form recorded using a tubular cathode, which had an extended edge with a small curve radius. When recording dozens of beam current pulses, oscilloscope displays were obtained with two peaks, the amplitude of which varied. In addition, these experiments recorded not only an adjustment in the amplitude of these peaks, but also an adjustment in the delay between their maxima. Figure 7 shows the oscilloscope displays selected from a series of 50 discharge implementations.

The oscilloscope display *1* shows a REB pulse consisting of two peaks with approximately equal amplitude. Duration at half maximum was ≈ 84 ps. The REB *2* current pulse also consists of two peaks. Its duration coincides with the duration of the REB *1* current pulse, but the amplitude of the first peak was greater than that of the second, and the number of electrons in the beam also increased. The delay between peak maxima in *1* and *2* has not changed. However, the REB *3* current pulse had a different delay

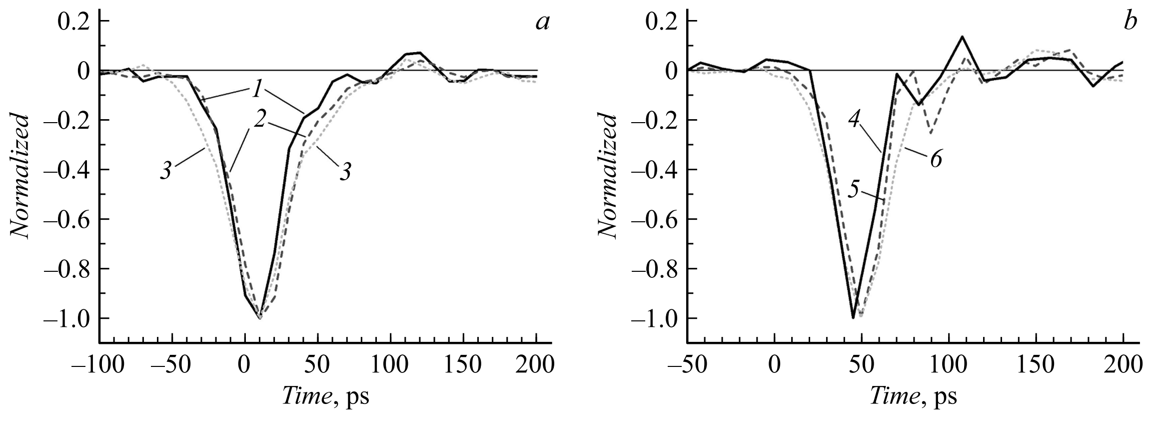

Figure 6. a — oscilloscope displays of the REB current pulses with a tubular cathode at different interelectrode distances $d = 8$ (*1*), 12 (*2*) and 16 mm (*3*). Generator SLEP-150M; b — oscilloscope displays of REB current pulses with cathodes ball (*4, 5*) and tube (*6*) at voltages in the incident wave 200 (*4*) and 130 kV (*6*) and front 300 ps.

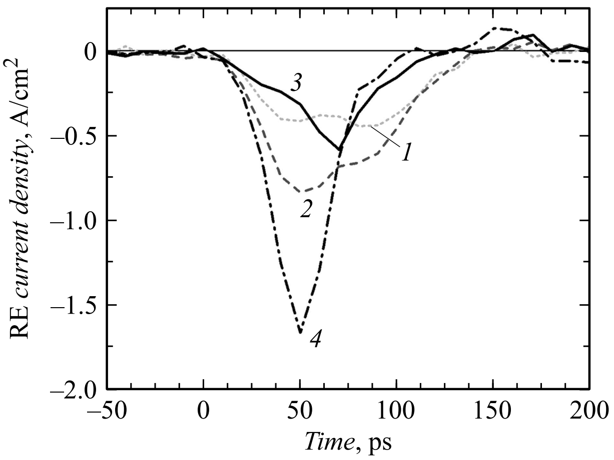

Figure 7. Oscilloscope displays of the current pulses of the REB with a tubular cathode in various modes of emission from a tubular cathode. Generator SLEP-150M. $d = 8$ mm. Diaphragm 0.5 mm.

between the peaks. Such an adjustment in the REB pulse form confirms the non-simultaneous emission of electrons along the length of the sharp edge of the cathode. The highest REB amplitudes are achieved with the simultaneous emission of electrons from the cathode. Meanwhile, the pulse duration decreases, and the amplitude increases. The oscilloscope display *4* corresponds to the optimum mode of runaway electron generation, in which the number of electrons in the beam is maximum. The amplitudes of the REB current pulses in this mode are the largest, and the pulse duration at half maximum is the smallest (37 ps with a tubular cathode). This situation is the most favorable for the implementation of the Askaryan effect [37], in which some of the runaway electrons have „anomalous" energy [8,26,27]. Above it was noted that in the present experiments as well the electron beam was recorded behind an Al-foil with a thickness of 50 μm at an no-load voltage of the generator of 76 kV.

3. Discussion of results

It follows from the results obtained in our previous studies [13,14,17,19,38] and in the present paper that, under the conditions of REB generation, the gap breakdown with the cathode needle occurs due to a wide spherical streamer. With cathodes in the form of a cone and a ball, by selecting their sizes, the angle at the apex of the cone, and the length of the gap, single wide streamers can be formed, as with a cathode in the form of a needle.

With a cathode with a long edge having a small curve radius, for example, from a thin-walled tube, several cylindrical or conical streamers are formed. In this case the streamers move in parallel and cover the gap at approximately the same time. The average streamer speed (ionization wave) increases with increasing voltage across the gap at a constant pressure of air and other gases [21]. The streamer speed reaches its highest values near the electrodes [38]. The generation of runaway electrons begins at the cathode at the very beginning of ionization processes at the maximum voltage across the gap. Due to the high electric field intensity, a streamer is formed from avalanches in an extremely short time (tens of picoseconds). Its appearance and allocation along the gap can be monitored with high (tens of picoseconds) accuracy by measuring the biasing current due to the redistribution of the electric field at the formation of the streamer [14,38]. An important property of RE generated at the cathode is the wide solid angle into which they are directed. RE generations occur not only in the direction of the anode, but also towards the side wall of the discharge chamber [39]. Moreover, RE fall on the side wall not only during the formation of wide streamers [38], but also cylindrical ones, formed when using cathodes with an extended edge, for example, in the form of a tube [39].

The duration of the REB current pulses on the axis of the gas diode (part of the total beam current), which can be separated using a small-diameter diaphragm at the anode, is determined mainly by processes near the cathode. According to the numerical simulation in [28], the generation and termination of the generation of RE is determined by the gas impact ionization the cathode. First, a critical (sufficient for electron runaway) electric field is reached at the boundary of the expanding cathode plasma, and then it becomes below the threshold. The characteristic time, which is determined by the ionization rate in the critical field and which ensures the runaway of electrons, was estimated at 2−3 ps. Experimentally in [28] during a discharge in air at atmospheric pressure, a REB current pulse was recorded on the diode axis with a duration of 9 ps. However, in real conditions (without the use of a diaphragm), the duration of the REB current pulse over the entire surface of a flat anode is an order of magnitude greater [8,34,35,38].

The duration of the REB on the axis of the gas diode when a diaphragm is installed on the anode depends on many factors. At constant pressure and type of gas, as well as the diameter of the diaphragm, the duration of the REB is affected by the length of the interelectrode gap, the design of the cathode, the amplitude of the generator voltage pulse and its front. Further studies of the REB generation conditions with picosecond and sub-picosecond timing resolution may lead to the discovery of other factors affecting the REB pulse duration and form.

The RE generation mode should also be taken into account. As shown in [13,19], the largest REB current amplitudes are recorded when an electron beam and an ionization wave front arrive at the anode simultaneously. In this mode, the contribution to the duration of the beam current pulse is made not only by electrons that are generated near the cathode during streamer formation, but also by electrons accelerated at the front of the ionization wave (streamer) in the gap and near the anode. At REB generation, modes are implemented in which two beam current pulses are recorded, see [14,17]. A detailed analysis of known papers in which the durations of REB were measured is given in the introduction to this paper.

In addition, it should be taken into account that not all runaway electrons spread in the direction of the anode. Some of them, starting in the cathode region, spread perpendicular to the discharge axis [39]. To increase the fraction of runaway electrons directed towards the anode, cone insulators (Fig. 2, *a*), which cover the side wall of the gas diode, were used. The surface of the insulator was negatively charged during the generation of the REB, which led to an increase in the number of electrons behind the anode, as well as in the duration of the REB current pulse. Note that in [16] the number of RE incident on the anode increased due to the magnetic field from the solenoids.

Conclusion

The studies carried out confirmed that runaway electron current pulses of minimum duration are recorded only when using a diaphragm with a diameter of 1mm or less, through which a part of the entire runaway electron flow is released. It has been established that, at small diaphragms and a cathode from a tube with an extended edge of a small curve radius, RE current pulses consisting of two peaks are recorded. This can be explained by the non-simultaneous emission of electrons along the length of the cathode edge. It is shown that for a voltage pulse front duration of 0.3 and 0.7 ns, the shortest durations of the RE current pulse are observed when cathodes in the form of a cone or ball of small radius are used and one emission center is triggered in the region of the maximum electric field.

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Conflict of interest

The authors declare that they have no conflict of interest.

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