Different modes of runaway electron beams generated in high-pressure gases

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Abstract. This article presents the results of experimental studies of different modes of a runaway electron beam (RAEB) generation in high-pressure gases as well as X-rays caused by it. In particular, the mode with the greatest beam current amplitude, the one with two current pulses, that with the X-ray pulse duration of 100s ns, the mode in which a RAEB propagates in the direction opposite from an anode, and some others are described. The effect of the cathode design and material on the RAEB current amplitude and duration in atmospheric-pressure air is shown. When analyzing the most common modes, the features of the gap breakdown are used.

1. Introduction
Runaway electrons (RAEs) in high-pressure gases are a fundamental physical phenomenon that began to be investigated in the last century [1, 2]. Runaway electron beams (RAEBs) are actively studied in this century as well (see, e.g., reviews [3, 4]). In order to reliably register runaway electrons behind an anode foil at atmospheric pressure and higher, it is necessary to feed cathodes with a small radius of curvature with voltage pulses having a subnanosecond rise time and an amplitude of about 100 kV and higher. Due to RAEBs, a diffuse discharge is formed in various gases without a source of additional preionization [5]. Diffuse discharge plasma is used in various fields [6–9], including lasers [10] and excilamps [11].

Since 2005, thanks to progress in pulsed technologies, as well as in experimental and modeling techniques, interest in the study of fast physical processes in high-pressure laboratory discharges initiated by RAEBs and X-rays, has significantly increased [12–24]. Although, many new facts have been obtained over the past decade, the influence of various factors on the characteristics and generation mechanism of a RAEB during HV nanosecond discharges in gas-filled gaps under high overvoltage, are still being intensively studied by research teams from different countries. So, in recent studies in atmospheric-pressure air [22, 23], the dynamic displacement current (DDC) evolution reflecting the discharge formation stage was correctly recorded and analyzed. Based on these data the moment of RAEB generation regarding to the beginning of the development of a wide streamer (an ionization wave, IW) was determined [24].

Note that the above-mentioned papers deal with a relatively narrow range of conditions under which runaway electrons are generated. Various modes of RAEB generation and how this is affected by the propagation speed of an ionization wave are not considered.
The main objective of the study is generalization of the main RAEB generation modes and their explanation taking into account the peculiarities of the development of ionization processes in an interelectrode space. The paper continues the research published in [22–25].

2. Experimental setup and techniques

In the experiments five voltage pulse generators were used: three industrially produced (MIRA-2D [26], NPG-18/3500N [27], GIN-55-1 [28]) and two homemade (SLEP-150 [20], GIN-1-200 [29]). The generators SLEP-150, MIRA-2D, NPG-18/3500N and GIN-55-1 produced negative voltage pulses with amplitudes and rise times in the ranges 10–200 kV and 0.3–3 ns, respectively. A voltage pulse produced by the GIN-1-200 had following parameters: the amplitude and rise time are up to 200 kV and about 1.5 µs, respectively. A gas-filled diode consisted of a HV pointed electrode and a flat grounded one and was fed by voltage pulses from the indicated above generators.

Pointed HV cathodes of various shapes (tube, needle, ball, cone and grid) were made of stainless steel. A grounded anode was made of a metal foil or mesh with varying transparency degree. To measure the RAEB a current collector was mounted behind the grounded anode. There were several collectors with different diameters (3, 7, 20 and 30 mm) of a current-collecting part in the experiments. This allowed us to record simultaneously both a RAEB and the DDC. With this approach, there is a high temporal resolution (dozens of picoseconds). Note that the DDC evolution completely determines that of a streamer ensuring the gap breakdown [22–25]. A more detailed description of the experimental setup will be given in the following sections.

To measure the voltage across the gap and discharge current we used, correspondingly, a capacitive voltage divider and a chip-resistor based current shunt. They were recorded with digital oscilloscopes Keysight MSOS804A (6 GHz, 20 GSa/s) or LeCroy WaveMaster 830Zi-A (30 GHz, 80 GSa/s). A RAEB energy spectrum was determined with filtration method. To do it, we used a set of Al foils of arious thickness, as well as a Kimfol film (thickness is 2 µm) coated with an Al layer (thickness is 0.2 µm). These filters in different combinations served as the grounded anode. Using Al or Cu foils of various thickness, we could to determine the energy of X-rays.

The evolution of plasma glow at the breakdown stage was recorded with the high-speed image capturing techniques. To solve this task, we used a four-channel ICCD camera HSFC-PRO and an ultra-speed streak camera Hamamatsu C10910-05. Integral images of the discharge plasma glow were captured with a digital camera SONY A100.

3. Streamer breakdown of a high-pressured “needle-plane” gap

A schematic of experimental setups are shown in figure 1. One was used in studies of the streamer formation and the other was used to register the dynamic displacement current.

A HV electrode (4) with a length of 5 mm was made of a pointed part of a sewing needle. Its base diameter and radius of curvature at the end were 1 mm and 75 µm, respectively. This part was fixed on an apex of a cone that was gradually transformed into a 6-mm-diameter cylinder. An anode was a mesh. A width of the “needle-plane” gap was 8.5 mm.

During one discharge implementation, the ICCD camera captures four consecutive images. The delay of frames relative to each other is known to us. Although the minimum gate of the camera is 3 ns, due to the nuances in its operation (there are jitters between the channels when they are simultaneously switched on), the temporal resolution can reach hundreds of picoseconds. In the experiments, three camera channels (C1–C3) had an exposure time of 3 ns. The exposure time for the fourth one (C4) was 20 ns. This corresponded to the total voltage pulse duration. All channels were switched on simultaneously. This occurred 2–3 ns before the arrival of a voltage pulse to the gap. However, and this was found empirically, due to imperfections in the camera operation, the channel C2 is triggered 0.1 ns later relative to C1, and the channel C3 is triggered 0.7 ns later than C1. So, it was possible to register processes developing at the subnanosecond time scale at the breakdown stage [23].
Figure 1. Sketches of experimental setups: for the streamer formation research (a) and for DDC recording (b). 1 – pulse generator (GIN-50-1 or NPG-18/3500N); 2 – triggering generator; 3 – capacitive voltage divider; 4 – pointed HV electrode; 5 – grounded flat electrode; 6 – quartz window, 7 – chip-resistors of the current shunt; 8 – streak camera; 9 – four-channel ICCD camera HSFC-PRO; 10 – delay line; 11 – digital oscilloscope; 12 – PC; 13 – current collector (a differential voltage divider). See [22] as well.

Figure 2. Sequence of images from the ICCD camera (a) and a streak camera image (b) of the diffuse discharge plasma glow at the breakdown stage. Air pressure is 100 kPa. “Needle-plane” geometry. Gap width is 8.5 mm. Applied voltage pulse amplitude is 18 kV. See [25] as well.

Thus, the C1–C3 channels made it possible to study the dynamics of the discharge formation. The C4 channel captured an integral image of the discharge. The oscilloscopes recorded signals from the divider and collector. A sync signal from the C1 channel of the ICCD camera was also recorded. The latter allowed us to synchronize ICCD images and waveforms of the voltage, DDC and RAEB current [22, 23].

Figure 2 demonstrate the streamer evolution in a “needle-plane” gap filled with atmospheric-pressure air. The gap was fed by voltage pulses with the amplitude of 18 kV and the rise time of 4 ns (NPG-18/3500N generator). At the pressure of ~1 atm and higher, the glow arises at the tip of the needle cathode. In this case, a spherical-shaped streamer is formed (see 1 and 2 in figure 2a). The
streamer bridges the gap in a short time (from dozens of ps to several ns). It depends on the $E/N$ parameter (or $E/p$ under normal conditions; $E = U/d$ – electric field strength, $N$ – gas concentration, $p$ – gas pressure) and not only that. The streamer velocity reaches its highest values near the electrodes. The average ones increases nonlinearly with an increase in $E/N$ [25, 30]. The RAEB current pulse reaches its maximum value both before and after the arrival of the IW at the anode (figures 3–6). Thus, there are three main modes of RAEB generation upon ignition the high-voltage nanosecond discharge. Additionally, two more modes are presented.

4. Mode 1: RAEB generation before an ionization wave bridges a gap
This mode takes place in two cases: a completed HV nanosecond discharge (diffuse discharge) [15, 30] and a pulsed corona [31]. In both cases, while a RAEB passes through the anode, ionization processes occupy the interelectrode space only partially. They mainly take place near the pointed cathode. Synchronized with each other waveforms of the voltage across the gap, discharge current, RAEB current and DDC are shown in figure 3. When timing the RAEB current pulse to the voltage one (point $s$), the transit time ($\approx 75$ ps) of electrons from the cathode to the collector was taken into account. When the streamer reaches the anode, the DDC behavior (point $f$) significantly changes and a drop in voltage is observed again (figure 3).

It is seen that the RAEB generation starts at the time moment corresponding to the maximum voltage across the gap. The RAEB current pulse is registered with the collector even before touching the anode by an IW front. At the HV nanosecond discharge in atmospheric-pressure air, a FWHM (full width at half-maximum) of the RAEB current pulse measured behind an anode foil usually does not exceed 100 ps. We call such electron beam a supershort avalanche electron beam (SAEB; see, e.g. [12]).

Similar mode is also implemented in the corona discharge [31]. In this case, ionization processes occupy mainly only the region near a pointed cathode. However, to register SAEB with a collector located behind a grounded anode, high-voltage pulses with a subnanosecond rise time should be applied to a discharge gap. Figure 4a demonstrates the design of a cylindrical-shaped gas diode with a 16-cm-diameter and 25-cm-length transmission line filled with atmospheric air. The discharge gap was fed by voltage pulses from the MIRA-2D generator. The interelectrode distance was 5 cm. The discharge plasma glow image is embedded in figure as well. The SAEB current pulses were recorded with the collector 5. This was carried out both from the end, i.e. downstream a foil anode 4 and from the side, i.e. behind a rectangular (25 cm × 5 cm) window 8. The window was covered with a 15 µm thick Al foil. The 7-mm-diameter tubular cathode 3 was made of foil. An inner 7-mm-diameter
cylindrical conductor 2 held it. Due to the short voltage pulse front (\(\sim 0.5\) ns), the threshold \(E/N\) reached during the corona discharge. This leads to a noticeable fraction of electrons going into the runaway mode.

![Image](2021) 012001

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Figure 4. (a) Discharge chamber equipped with collectors and an integral image of a plasma glow (diffuse discharge at the chamber's end and corona discharge at the central conductor). 1 – chamber housing; 2 – central conductor; 3 – tubular HV cathode; 4 – flat anode; 5 – current collector; 6 – diffuse discharge plasma; 7 – corona discharge plasma; 8 – side foil window. (b) Waveforms of SAEB beam current pulses recorded at the chamber's end (front RAEB) and side foil window (side RAEB). See [16, 25] as well.

Waveforms of the SAEB current behind the side window and anode are shown in figure 4b. The SAEB beam current behind the anode was approximately two orders of magnitude higher than the side one. Nevertheless, side SAEB was registered along the entire window length. This RAEB (SAEB) generation mode is observed at \(E/N \sim 1.5 \times 10^{-15}\) V/cm\(^2\) (= 150 Td) and less. It is known that the voltage pulse rise time affects a gap breakdown voltage. Therefore, this mode is manifested at the diffuse discharge in long gaps filled with dense gas and fed by voltage pulses with the rise time of \(\geq 1\) ns. \(E/N\) reaches its threshold value for the SAEB generation near the pointed cathode. The electrons generated near the cathode then move along the gap. The electric field in which they travel is relatively weak. It is important to note that in this mode, the effect of an increase in the electric field strength \(E\) at the IW front on the formation of runaway electrons occurs only in the cathode region. The SAEB current pulse amplitude and FWHM measured behind the anode are relatively small in this mode.

5. Mode 2: the highest amplitudes of RAEB current pulses

In this mode, an ionization wave front first touches a grounded anode, and then the RAEB generation occurs. This is typical for different gases both at atmospheric pressure [32] and for lower ones. The highest SAEB current amplitudes are registered in this case. The RAEB current can be as large as several hundreds of amperes [33]. In this case, the SAEB current pulse amplitude is reached a little bit later of the DDC drop. This drop on a DDC waveform corresponds to the arrival of the streamer at the anode. This mode is implemented at \(E/N \sim 6 \times 10^{-15}\) V/cm\(^2\) (= 600 Td) and higher. Most easily, this can be achieved by decreasing the gas density \(N\). An increase in \(U\) leads to an increase in the IW front velocity. With decreasing the rise time of a voltage pulse, the IW front begins to lead maximum of SAEB. So, the gas gap breakdown occurs at higher \(U\) and \(E/N\).

Figure 5a shows waveforms of the voltage across the gap, as well as discharge and SAEB current at the atmospheric-pressure HV nanosecond discharge in air formed by pulses from the SLEP-150 generator (rise time of the voltage pulse is 0.3 ns).
The maximum of the SAEB current pulse corresponds to that of the voltage across the gap. The maximum discharge current is about 3500 A. The beam current pulse amplitude in this mode depends on the number of streamers starting and propagating from a cathode with a small radius of curvature to a grounded anode. This amplitude increases with an increase in the length of sharp edge of the cathode [32]. In this case, when using a voltage pulse with the same amplitude the optimal gap width decreases. Another extremely important factor in the case of a subnanosecond voltage pulse front is the influence of the travelling thin streamers with the voltage across the gap (waveform 3 in figure 5a). When registering only a fraction of a SAEB (e.g., only its central part is separated for registration), the duration of its current pulse are significantly shortened [35] (waveform 5 in figure 5a).

The highest SAEB current pulse amplitudes take place in this mode due to the Askaryan effect [36]. This effect consists in gaining additional acceleration by electrons due to their synchronous travelling with an IW front, i.e., in an enhanced electric field. Thorough theoretical consideration of the influence of the IW front velocity on SAEB generation process was realized in [37]. The energy spectrum of electrons in this mode usually has a complex structure consisting of three parts [38]: the maximum of the main part of the distribution is less than $eU_m$ ($e$ – electron charge, $U_m$ – maximum voltage across the gap); a group of electrons with low energies; a fraction (less than 10%) of electrons with the energy greater than $eU_m$ [38].

Note that at $E/N \geq 6 \cdot 10^{15}$ V/cm² and high gas pressure, it is hard to discern the moment of contact of the anode by an IW front and a SAEB (3 and 4 in figure 5a). So, to unambiguously identify this mode, there are time-synchronized waveforms of the idle and breakdown voltage, as well as the

Figure 5. (a) Waveforms of the voltage across the gap (1), the discharge current (2), the SAEB current recorded with collectors with the temporal resolution of $\sim$ 80 (3, 4) and $\sim$ 20 ps (5). SLEP-150 generator ($U_m = 170$ kV, $t_{0.1-0.9} = 0.3$ ns); tubular (diameter is 6 mm) cathode made of 100-μm-thickness stainless steel foil; mesh or foil anodes; $d = 12$ mm; atmospheric-pressure air. (b) Waveforms of the voltage across the gap (idle and breakdown modes), discharge current, SAEB current and DDC. NPG-18/3500N generator ($U_m = 18$ kV, $t_{0.1-0.9} = 4$ ns); needle cathode; plane anode; air, $p = 6$ kPa. See [25] as well.
corresponding ones of the discharge, SAEB and dynamic displacement currents at the air pressure of 6 kPa in figure 5b. It is seen that the IW front touches the anode before the RE beam current maximum is reached. Upon these conditions \((E/N \approx 2.6 \times 10^{-14} \text{ V/cm}^2 = 2600 \text{ Td})\), the SAEB current pulse amplitude and FWHM increased substantially. Additionally, the electron beam current continues after its first peak.

6. Mode 3: two RAEB current pulses
Whether this mode is implemented or not, depends on whether an explosive emission occurs and how soon it happens. Typical waveforms of the gap voltage, discharge current, RAEB current and DDC are shown in figure 6.

As in the case in figure 3, the first pulse on the RAEB waveform (a SAEB) reaches the anode earlier than the IW front. This is in good agreement with the DDC evolution (figure 6, bottom panel). However, after the first beam current pulse, the second one is recorded with the collector. When conditions are optimal, it has the larger current pulse amplitude and FWHM. Electrons corresponding to the second pulse have a lower energy than SAEB electrons.

Simultaneous registration of the plasma glow and RAEB current demonstrated that a cathode spot is absent during generation of the second pulse. If the cathode spot (frame 2, figure 2a) is formed during the generation of the first RAEB or immediately after it, the second one is not recorded [23]. The reason for the generation of the second RAEB is an increase in \(E\) at the cathode. The latter is explained by the positive ions concentrating there. In addition, an increase in \(E\) takes place at the front of the backward ionization wave (starts from the anode). To obtain the second RAEB current pulse at the gap breakdown stage, it is necessary to ensure high enough values of \(E/N \sim 6 \times 10^{15} \text{ V/cm}^2\).

7. Mode 4: generation of 100s-ns-duration X-ray pulses
In the experiments a source generating negative voltage pulses with the amplitude of up to 200 kV and the rise time of 1.5 \(\mu\)s was used. A waveform of the voltage pulse in the idle mode is presented in figure 7a.

The gas diode was filled with air, nitrogen, argon, or helium at pressures in the range 1–100 kPa. X-ray radiation arises when REs with the corresponding pulse duration are decelerated at the anode. More detailed data on this mode are given in [29, 39, 40]. Note that in this mode it is difficult to register long-duration runaway electron beam current pulses behind the foil because of their low energy. With an increase in the voltage pulse front duration, the breakdown voltage decreases. This is most true when using a pointed cathode. Accordingly, the energy of REs decreases. Therefore, in the number of studies spherical cathodes with a tip were used to increase the breakdown voltage [29, 39–
In this case, a SAEB was recorded during the gap and its FWHM was from fractions to several nanoseconds.

Due to the lower absorption of X-ray radiation, for a long time its registration served as an indicator of the generation of RAEBs with a long pulse duration. The longest X-ray pulse durations have so far been recorded in [29, 40]. The setup consisted of a GIN-1-200 generator, a gas-discharge chamber with a pumping system, and recording equipment. To register a RAEB, a collector with a 30-mm-diameter receiving part or a scintillator were mounted behind an anode foil. The design of the discharge chamber is shown in figure 7b.

**Figure 7.** (a) Waveform of the idling voltage pulse. (b) Discharge chamber schematic. 1 – quartz window; 2 – current shunt; 3 – scintillator made of a film; 4 – metallic foil; 5 – anode mesh; 6 – cathode; 7 – flange for mounting the anode mesh and current shunt; 8 – insulator of the discharge chamber; 9 – HV electrode; 10 – camera housing and external cylinder of the coaxial line; 11 – shunt insulator. (c, d) Waveforms of the voltage across the gap and X-rays intensity. X-ray radiation was recorded with the PMT by the luminescence of scintillator behind a 15-μm-thickness aluminum foil. Nitrogen at the pressure of 100 (c) and 6 kPa (d). See [29, 40] as well.

X-ray radiation pulses were recorded with a photomultiplier tube (PMT) FEU-100 via a 150-μm-thickness film scintillator luminescence. The rise time and fall time of the PMT impulse response were, correspondingly, ~ 3 ns and ~ 30 ns. When registering X-rays, a current collector was replaced with a 120-mm-diameter quartz window 1 (figure 6a). From one to several aluminum or copper foils of different thickness (Al: 15, 30, and 55 μm or Cu: 25 and 40 μm) were installed closely behind the
mesh anode. Their edges were tightly attached to the flange 7 and covered by black paper. This helped to prevent the discharge plasma radiation reaching the PMT. The PMT operation in an approximately linear mode was ensured by placing it at a distance of 35 cm from the scintillator located behind the foil, as well as by installing additional mesh attenuators.

In the experiment at high nitrogen and air pressures (mainly atmospheric one), various voltage waveforms were recorded. As far as an electron beam is concerned, the collector only at low pressures of the indicated gases reliably recorded it. In this case, the FWHM of its current pulse did not exceed a few nanoseconds.

Figure 7c demonstrates a discharge mode in which breakdown developed from the tapered ledge do not lead to an essential voltage drop. In this case, the diffuse discharge is implemented in the gap, lasting several hundred nanoseconds. Note that X-ray radiation was also detected with a 55-μm-thickness aluminium foil, as well as 25-μm-thickness copper one.

When decreasing pressure of nitrogen and air, both a decrease in the breakdown voltage and a decrease in the voltage fall time were found. At the nitrogen pressure of 6 kPa the gap voltage is dropped quickly to almost zero level (figure 7d). “Tails” of X-ray radiation pulses recorded with the PMT and having the small amplitude and duration of several tens nanoseconds. These “tails” can not be attributed to film luminescence caused by X-rays. With low pressure of gas, the gap voltage is small. We suppose that they can be explained by the imperfections in the recording system.

The voltage drop rate and a magnitude of the residual voltage across the gap depend on the gas kind and pressure, as well as on the discharge morphology. The voltage waveforms for air and nitrogen were similar. In contrast, in argon and helium, a significant rapid voltage drop occurred even at 100 kPa. The rapid spark formation in air and nitrogen, including at atmospheric pressure, led to a decrease in the gap voltage to low values in a time of ~10 ns. In this case, X-ray radiation pulses don’t have a long duration.

8. Mode 5: generation of RAEBs in the direction opposite to the anode

One more experimentally found mode is in generation of an RAEB in the direction opposite to the anode. This mode is implemented when an interelectrode assembly consisted of a HV flat anode and a grounded cathode made of a grid is used. The design of a gas diode for generation of RAEBs in the direction opposite to the anode is shown in figure 8a (see also [42]).

![Figure 8](image-url)

**Figure 8.** (a) Design of a gas diode for generating a RAEB in the direction opposite to the anode. 1 – HV line; 2 – insulator; 3 – capacitive voltage divider; 4 – HV flat Ta anode; 5 – metal ring; 6 – collector housing; 7 – grounded cathode made of a grid; 8 – Al foil; 9 – collector receiving part. (b) Waveforms of the gap voltage (1) and RAEB current in the direction opposite to the anode recorded with collectors having the diameter of the receiving part of 20 (2) and 3 mm (3). SLEP-150 (positive polarity). d = 4 mm; l = 3 mm.
In this mode, the main part of the current from the grid cathode flows to the flat anode, causing bremsstrahlung X-ray radiation. However, the beam current in the direction opposite to the anode, which in its characteristics corresponds to a SAEB and is recorded behind an Al foil, reached several amperes (2 in figure 8b). The collector having a 30-mm-diameter receiving part was used. When only a fraction of the RAEB current is measured with a collector with the small receiving part diameter (3 mm), its FWHM duration decreases (3 in figure 8b).

An important feature of this mode is the effect of the anode material on the beam current. When using a Ta anode, the beam current was four times higher than that when using an aluminum one, and the exposure dose of X-ray radiation during a discharge in atmospheric-pressure air was 3.5 mR. Apparently, X-ray radiation affects the formation and movement of an IW in the direction opposite to the anode. With an increase in the X-ray radiation intensity with the Ta anode, the beam current in the direction opposite to the anode increases.

9. Conclusion
In studies performed with the ICCD and streak cameras it was shown that all the RAEB generation modes described mentioned above could take place under conditions of the breakdown of a gas-filled gap occurring in accordance with the streamer mechanism. Using the measurement data from collectors and cameras, the ionization wave front (streamer front) velocity was determined with high accuracy. In addition, we could identify the conditions under which an IW front propagates faster than an electron beam. It was established that during the synchronous motion of an IW front and a RAEB the largest beam current pulse amplitudes take place. It should be emphasized that an ionization wave front in this mode propagates ahead of a RAEB.

Depending the HV cathode design and voltage pulse parameters, different number of streamers are formed near it. In the case of a pointed cathode, a single streamer with a large transverse dimensions usually starts from the HV electrode. At the initial stage of the breakdown, such streamer is ball-shaped. With an extended sharp edge cathode, there are several streamers, which have smaller diameter propagating in parallel. Together they form what is commonly called an ionization wave. Recording the dynamic displacement current allowed us to determine with high accuracy time points when a streamer (an ionization wave) starts from the cathode and when it arrives at the anode. as well. The time moment corresponding to the beginning of the formation of a RAEB at the cathode was established as well.

Upon simultaneous recording the discharge plasma glow and the runaway electron beam current, it was found that, a second pulse of RAEB is generated. This occurs when no a cathode spot is formed.

At the microsecond rise time of a voltage pulse, the number of runaway electrons and X-ray quanta is sufficient to ensure formation of the diffuse discharges in high-pressure gases. The diffuse stage duration, which can transform into a spark, strongly depends on the cathode shape and interelectrode distance, all other things being equal.

A mode that was found in experiments [42] is generation of an RAEB in the direction opposite to the anode. This mode was implemented in air at atmospheric pressure.

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References
[1] Wilson C T R 1924 P. Phys. Soc. Lond. 37 32D
[2] Tarasova L V, Khudyakova L N, Loiko T V and Tsukerman V A 1974 Sov. Phys.-Tech. Phys. 19 351
[3] Babich L P, Loiko T V and Tsukerman V A 1990 Sov. Phys. Uspekhi 33(7) 521
[4] Tarasenko V F and Yakovlenko S I 2004 Phys.-Usp. 47 887
[5] Tarasenko V F, Panchenko A N and Beloplotov D V 2020 Plasma Phys. Rep. 46(8) 850
[6] Yu Q S et al 2006 Appl. Phys. Lett. 88 013903
[7] Shao T, Wang R, Zhang C and Yan P 2018 High Voltage 3(1) 14
[8] Dong S et al 2018 Ind. Crop. Prod. 115 124
[9] Korotaev A G et al 2020 Surf. Coat. Tech. 387 125527
[10] Panchenko A N, Sorokin D A and Tarasenko V F 2021 Prog. Quant. Electron. 76 100314
[11] Erofeev M V and Tarasenko V F 2006 J. Phys. D Appl. Phys. 39(16) 3609
[12] Tarasenko V F, Shunailov S A, Shpak V G and Kostyrya I D 2005 Laser Part. Beams 23 545
[13] Rep’ev A G and Repin P B 2008 Tech. Phys. 53 73
[14] Chaparro J. E. et al 2008 IEEE T. Plasma Sci. 36 2505
[15] Tarasenko V F et al 2008 Plasma Devices Oper. 16 267
[16] Zhang C et al 2010 Rev. Sci. Instrum. 81 123501
[17] Levko D et al 2012 J. Appl. Phys. 111 013303
[18] Mesyats G A et al 2018 Appl. Phys. Lett. 112(16) 163501
[19] Zubarev N M et al 2020 Plasma Sources Sci. T. 29(12) 125008
[20] Tarasenko V 2020 Plasma Sources Sci. T. 29 034001
[21] Mesyats G A et al 2020 J. Appl. Phys. 116 063501
[22] Beloplotov D V, Lomaev M I, Tarasenko V F and Sorokin D A 2018 JETP Lett. 107 606
[23] Beloplotov D V, Tarasenko V F, Shklyaev V A and Sorokin D A 2021 JETP Lett. 113 129
[24] Tarasenko V F et al 2020 Plasma Phys. Rep. 46 320
[25] Sorokin D A, Beloplotov D V, Tarasenko V F and Baksht E K 2021 Appl. Phys. Lett. 118(22) 224101
[26] Mesyats G A 2007 Pulsed Power (New York: Springer Science & Business Media)
[27] Lyublinsky A G, Korotkov S V, Aristov Y V and Korotkov D A 2013 IEEE T. Plasma Sci. 41 2625
[28] Efanov V M et al 2010 Ultra-Wideband, Short Pulse Electromagnetics 9 part 5 (New York: Springer-Verlag)
[29] Tarasenko V, Beloplotov D, Burachenko A and Baksht E 2020 J. Atmos. Sci. Res. 03(1) 28
[30] Sorokin D A, Tarasenko V F, Beloplotov D V and Lomaev M I 2019 J. Appl. Phys. 125 143301
[31] Shao T et al 2011 New J. Phys. 13(11) 113035
[32] Kostyrya I D, Rybka D V and Tarasenko V F 2012 Instrum. Exp. Tech. 55 72
[33] Tarasenko V F et al 2010 IEEE T. Plasma Sci. 38 2583
[34] Zhang C et al 2013 Laser Part. Beams 31 353
[35] Tarasenko V F et al 2012 Rev. Sci. Instrum. 83, 086106
[36] Askar’y an G A 1965 JETP Lett. 1 97
[37] Kozyrev A, Kozhevnikov V and Semeniuk N 2018 EPJ Web Conf. 167 01005
[38] Baksht E H et al 2010 J. Phys. D Appl. Phys. 43 305201
[39] Sorokin D A et al 2018 Laser Part. Beams 36 186
[40] Burachenko A, Tarasenko V and Baksht E 2020 Proc. 7th International Congress on Energy Fluxes and Radiation Effects (Tomsk: IEEE)
[41] Babich L P and Loiko T V 2009 Dokl. Phys. 54 479
[42] Tarasenko V F, Kostyrya I D and Beloplotov D V 2016 Laser Part. Beams 34 23