The generation of a supershort avalanche electron beam at nanosecond discharge in dense gases

E.Kh. Baksht, A.G. Burachenko, I.D. Kostyrya, M.I. Lomaev, D.V. Rybka, and V.F. Tarasenko

High-Current Electronics Institute, Siberian Branch of the Russian Academy of Sciences, Tomsk

Received May 16, 2008

The properties of supershort avalanche electron beams (SAEB) generated in inhomogeneous electric field at high pressure of different gases and high temporal resolution (up to ~ 80 ps) are investigated. SAEB was obtained in helium at a pressure of about 12 atm, in nitrogen at a pressure of about 5 atm, in xenon and sulfur hexafluoride at a pressure of about 2 atm. It was revealed that at SAEB generation the scattering angle of SAEB flow exceeds 2π sr. The modes of SAEB generation, at which SAEB current pulse has two maxima were revealed. It was shown that in order to generate electrons with "anomalous" energy, the cathodes with big radius of curvature should be used. It was revealed that the mode of SAEB generation in the inhomogeneous electric field is realized at lower voltages across a gap as compared to the homogeneous one.

Introduction

A beam of runaway electrons behind the foil was first reported in Ref. 1. However, the current amplitude was quite low (10^9 electrons were detected behind a 8 μm foil); and until 2002 the conditions for high current generation were not found.[2] Recently, the study of runaway beams and X-ray, which are generated in gas diodes, when applying high voltage nanosecond pulses to the gap with a cathode of a small radius of curvature, became urgent again.[3–11]

Beams of runaway electrons with maximal amplitude detected behind the foil are of particular importance for applications. However, the obtaining and measuring of runaway electron beams generated in gas diodes at elevated pressures is a difficult task because of their short length. In order to obtain maximal amplitude of supershort avalanche electron beam (SAEB) behind the foil, the pulse generators with a voltage of hundreds of kilovolts at a length of the pulse leading edge less than 1 ns, as well as gas diodes of optimal construction are required.

To record temporal and amplitude characteristics of current and voltage, the detectors, reducers, cables and oscilloscopes with high temporal resolution (~0.1 ns or more) are needed. Besides, a theoretical model, properly explaining the succession of physical processes occurring in gas diode is necessary. The knowledge of the main physical processes, their succession and interrelation would significantly facilitate the choice of voltage pulse optimal parameters and gas diode construction. However, in available papers the data on runaway electron beam parameters and proposed mechanisms of runaway electron generation in gas diodes significantly differ.[1–11]

The influence of various parameters on generation of a supershort electron beam is discussed in this paper. The conditions for maximal SAEB amplitude obtaining are determined. The mechanisms of SAEB generation in gas diodes at high pressures are improved on the basis of the received data.

Experimental setup

The experiment was conducted with the use of different generators of nanosecond pulses and gas diodes, one of which is shown in Fig. 1.

We used a tube of ~6 mm in diameter made of 100 μm steel foil, or a steel ball of 9.5 mm in diameter, or a steel needle as a cathode in the gas diode. The beam was output through a 10–500 μm steel foil or through a ~50 μm aluminum-beryllium foil. The distance between the anode and cathode of the main gap varied from 0 to 30 mm. The diode can be filled with different gases (air, helium, hydrogen, neon, nitrogen, methane, argon, krypton, xenon, sulfur hexafluoride), the pressure of which varied from 0.1 to 11 400 Torr. The main measurements were mainly conducted with air at atmospheric pressure.

RADAN-220 generators[12] (two installations, generators Nos. 1 and 2) had a wave resistance of ~20 Ω and formed a voltage pulse of ~270 kV amplitude on the discharge gap in the idle mode with a ~2 ns length at the half-height at a matched load and a ~0.5 ns leading edge. Generator No. 1 was connected to the gas diode with minimal inductance (lower than that of generator No. 2) and formed a voltage pulse with a shorter leading edge. This allowed the increasing of beam current (the number of electrons) behind the foul with the help of generator No. 1.

0235-6880/08/08 632-05 $02.00

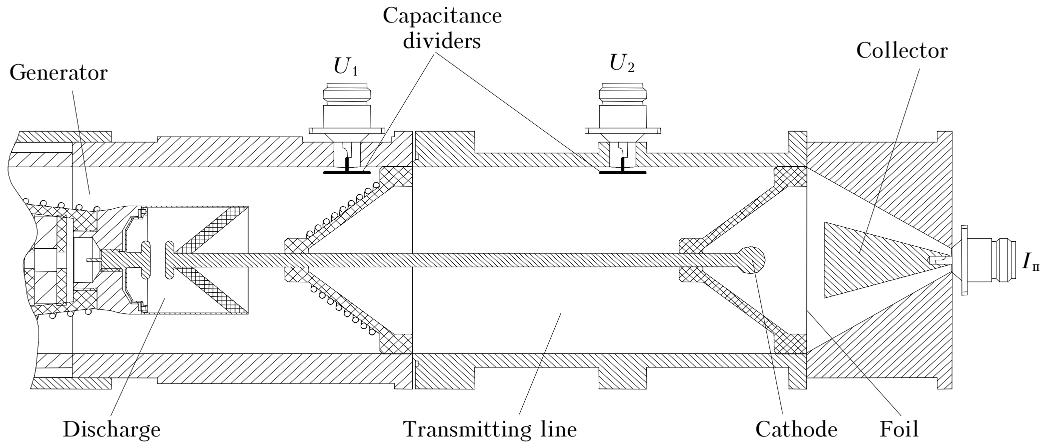

Fig. 1. Schematic view of SAEB-150 generator with gas diode and recording system.

The SAEB-150 generator (generator No. 3) formed voltage pulses in line with wave resistance of 100 Ω with an amplitude of ~130 kV in the incident wave, and a ~1 ns length at the half-height at a matched load and a leading edge of ~0.3 ns. Peak discharger and transmitting line with capacitance dividers are shown in Fig. 1. The use of different generators and their different installations allowed variation of the leading edge length and voltage pulse amplitude in the gap.

The pulse current was measured using collectors with a 50–100 ps temporal resolution.[13,14] The TDS-6604 (6 GHz and 20 sample/ns) or DPO70604 (6 GHz and 25 sample/ns) oscilloscopes were used for recording signals from the capacitance divider, collectors, and shunts. An integral pattern of the discharge glow was photographed with a digital camera. The exposure of the X-ray dose was determined with the Arrow-Tech, Inc. (Model 138) and VICTOREEN 541R dosimeters sensible to the radiation with quantum energy of 16 and 60 keV, respectively. The dosimeters were located at a distance of 0.1–2 cm from the foil plane, perpendicular to the cathode axis. Temporal pulse shape of X-ray radiation was recorded with the SPPD11-04 semi-conductor detector with a ~2 ns temporal resolution. The detector was designed for the recording of X-ray quanta with energy from 0.4 to 40 keV. Measurements have shown the detector to be more sensitive to beam electrons than to X-ray radiation quanta.

Measurement results

Typical oscillograms of discharge current pulses, diode voltage, and beam current pulse are shown in Fig. 2.

Under optimal conditions for reaching the beam current maximal amplitude, the SAEB generation occurs at the maximal voltage. During this process a diffusive discharge with bright cathode spots is formed in the gap. Based on measurements of discharge current pulses, gas diode voltage, and electron beam current under different conditions; as well as measurements of X-ray radiation from gas diode and observations of the discharge shape in the gap, the following conclusions were made.

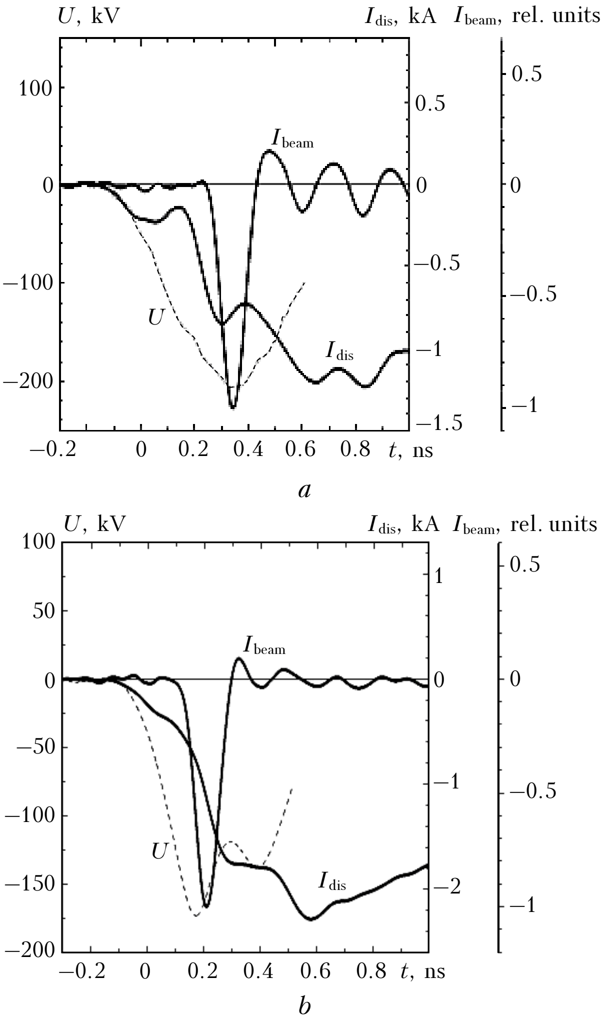

Fig. 2. Oscillograms of discharge current pulses I_{dis}, voltage U in the gap, and electron beam current I_{beam} behind the foil in air at a pressure of 1 atm. Generator No. 3, ball – cathode (*a*), tube (*b*).

The SAEB pulse length recorded behind the foil depends on the cathode construction, interelectrode space, generator parameters, as well as pressure and type of the gas in the gap. The lowest length for the air at the atmospheric pressure in the gas diode (less than 80 ps) was recorded at a gap voltage of hundreds of kilovolts, interelectrode gap of ~10 mm, with the use of collectors with a small receiving area (3 mm in diameter). In these conditions the SAEB pulse length is usually restricted by the oscilloscope resolution, that is proved by the positive peak on the beam current oscillogram. However, SAEB pulse length generated from gas diode exceeds 80 ps along the whole area of foil. Thus, the pulse length at half-height increases with the increase of collector receiving area, as well as when collecting electrons flying at large angles to gas diode central axis or at the increase of length of the voltage pulse leading edge. Besides, the SAEB pulse length can exceed 100 ps at some modes. Lengths of ~200 ps were obtained in helium, sulfur hexafluoride, nitrogen, and air at a generator voltage of 25 kV and pressures of dozens and hundreds of Torr. At a ~250 kV voltage in the gap, the increase of sulfur hexafluoride pressure in the gas diode up to 1.5–2 atm has also led to the increase of a SAEB pulse length up to ~150 ps. An interesting form of the beam current pulse was observed for the first time during the experiments with small gaps in the gas diode (< 8 mm). A share of SAEB pulses had two maxima.

The scattering angle of runaway electrons, as it was stated by us, even at small gaps between the anode and cathode does not correspond to the direction of force lines in gas diode in the absence of plasma. We also found that when generating SAEB, runaway electrons are recorded not only in the foil direction, but also in the direction of gas diode side walls (to an angle more than 2π sr). The runaway electrons were recorded through the window in gas diode side wall at an interelectrode gap several times smaller than the distance from the cathode-holder to gas diode side wall. It follows from the experiment that only a part of SAEB flow is recorded behind the foil.

Maximal amplitudes of the SAEB current are realized in light gases and at formation of diffusive (volume) discharge in the gas diode. Gas pressure in this case should be minimal, but sufficient to support the SAEB generation mode. As compared to vacuum diode mode, the SAEB generation mode is characterized by a wider scattering angle of the runaway electrons and a shorter length of the beam current pulse (to ~100 ps). Apparently, the discharge contraction after SAEB generation does not have a significant influence on its parameters. At the atmospheric pressure of various gases the greatest beam current amplitudes are realized in helium. However, the gap optimal geometry and the cathode construction can differ for different gases. The maximal SAEB current amplitude in air at the atmospheric pressure was obtained with the use of generator No. 1. It was recorded $2.7 \cdot 10^{10}$ electrons behind a 10 μm aluminum foil, that corresponds to 50 A at a pulse length at a half-height of 90 ps.

Electron energy distribution was determined with the help of weakening curves and the method of spectrum retrieval described in Ref. 5. As *a priori* information on spectrum shape, we assumed that one of the maxima on electron energy distribution curve should correspond to the gap voltage during the SAEB generation. Besides, the obtained spectra were compared to the data of time-of-flight spectrometer. It was found that there are three groups of electrons in the beam and that the share of electrons with "anomalous"[1,2,5] energy increases at the increase of the cathode curvature radius. At maximal amplitudes of the pulse current behind the foil the major maximum in the electron energy distribution approximately corresponded to gap voltage during the SAEB generation.

X-ray radiation at a negative polarity of the cathode, which had a small curvature radius and concentrated the electric field, was recorded both from the gap and the anode. With a dosimeter behind the anode, maximal doses were recorded in case when the anode was made of heavy metals. Thus, an exposure dose behind a 20 μm copper foil with generator No. 1 was of ~1.5 mR and ~0.6 mR with generator No. 3. Typical X-ray radiation is usually recorded both from gap and anode in case of small curvature radius of the anode. The generation of runaway electrons and slowing-down X-ray radiation were recorded both at potential cathode and at the earthed one. It is important that the cathode was of smaller size as compared to the anode and voltage pulse parameters corresponded to conditions of the SAEB generation.

The X-ray radiation pulse length at a half-height of ~2 ns was stipulated by temporal resolution of the SPPD11-04 semi-conductor detector. At small gaps X-ray radiation was recorded even at the potential anode, which had a form of a wolfram rod. However, the X-ray quanta energy and the exposure dose were much lower in these conditions.

The mechanism of runaway electron generation in gas diode

The obtained data show that the generation mechanism of runaway electrons and increase of their energy in the gas diode during their movement to anode, significantly differ from generation of electrons and their acceleration in the vacuum diode. First, at short voltage pulses (< 1 ns), ball-form cathode, and equal voltages in the gap, electron beam generation is observed only in case that the diode is filled with gas, and is absent in vacuum. Second, the scattering angle of runaway electrons in SAEB mode exceeds 2π sr. Third, at certain conditions the type of gas and its pressure influence the SAEB pulse length.

Let us separate the main processes, which favor the generation of runaway electron beam recorded behind the foil of gas diode with maximal amplitude or maximal electron energy.

The process of electron emission from cathode

Electrons from cathode in gas diodes appear due to the self-emission. High electric field is achieved due to field gain on micro- and macro-inhomogeneities of the cathode and cathode-holder on the pulse voltage leading edge.

Fast electrons

The emitted electrons can acquire enough energy for runaway (fast electrons) due to field concentration at cathode. When running away from micropeaks on cathode and cathode leading edge, the electric field intensity decreases and fast electrons lose their energy spending it on the ionization of particles in the near-cathode region. Non-local criterion for appearance of a significant number of electrons leaving the volume without reproduction (runaway electron mode) is described in Ref. 4 for homogeneous electric field. However, there should be another criterion in our case with inhomogeneous electric field, which takes into account the inhomogeneous distribution of the electric field in the range of runaway electrons. It should be also taken into account that the electric field, sufficient for electron runaway mode, decreases at the increase of initial electron energy.[15]

Formation of diffusive discharge

Thus, pre-ionization of gas in the cathode vicinity occurs due to the generation of fast electrons. The electrons appeared near the cathode initiate the development of electron avalanches in the electric field which increases due to the increase of gap voltage. The concentration of initial electrons is so high that the avalanche heads overlap, forming a streamer; a relatively dense plasma of diffusive discharge is formed on the cathode, the edge of which moves from cathode to anode. There occurs an excessive negative charge on the edge of dense plasma. When reaching critical field between the dense plasma edge and the anode, a share of electrons with maximal energy from the region of the excessive negative charge passes to the runaway mode as well. The criterion of electron runaway for this situation should also be defined with accounting for both the inhomogeneity of electric field distribution over the gap and the influence of the excessive negative charge. Diffusive discharge is formed throughout discharge gap due to the runaway electrons generated and accelerated in the region between the plasma edge and the anode.

SAEB generation

Generation of runaway electron beam (SAEB) recorded with maximal amplitudes behind the foil of gas diode is a very complicated process determined by the following factors:

– first, the field gain near the cathode and appearance of self-emission of electrons, a part of which (fast electrons) transfer to the runaway mode, actualizes the pre-ionization of the near-cathode region, and favors the formation of plasma near the cathode;

– second, gain of critical field between the edge of diffusive discharge polarized plasma and the anode (the foil and side walls of gas diode). As is seen from data received with pinhole camera in the air at the atmospheric pressure and optimal inter-electrode gap, electrons in the near-cathode region begin to accelerate within the solid angle exceeding 2π sr. The critical field for realization of the electron runaway mode in the inhomogeneous electric field and at plasma edge polarization significantly differs from the critical field in the homogeneous electric field and in the absence of electrons with the extra energy;

– third, the influence of ionization wave, propagated from cathode to anode, on the acceleration of electrons in the gap. The generation of a significant share of electrons with "anomalous" energy at ball-shaped cathode can be explained only by the movement of diffusive discharge ionization wave leading edge. The determination of an accurate interrelation of all these processes requires further modeling, accounting for the actual geometry of the gas gap and the distribution of electric field in it.

To realize the SAEB mode, the dense plasma should be created near cathode in the moment, when voltage amplitude in the gap is maximal.

Conclusion

Generation of runaway electrons due to electric field gain on electrodes and in the gap is a typical phenomenon accompanied pulse discharges in inhomogeneous electric field. However, special methods should be used for their recording. Runaway electrons have a significant influence on the delay time of breakdown in gaps and on spatial shapes of nanosecond discharges.

Acknowledgements

The authors are grateful to V.G. Shpak for granting RADAN-220 and D.V. Shitz for his help in constructing the SAEB-150 generator.

References

1. L.V. Tarasova, L.N. Khudyakova, T.V. Loiko, and V.A. Tsukerman, J. Techn. Phys. **44**, Is. 3, 564–568 (1974).
2. L.P. Babich, *High-Energy Phenomena in Electric Discharges in Dense Gases: Theory, Experiment, and Natural Phenomena*, ISTC Science and Technology Series, V. 2. Futurepast (Arlington, VA, 2003), 358 pp.
3. V.F. Tarasenko, V.G. Shpak, S.A. Shunailov, and I.D. Kostyrya, Laser and Particle Beams **23**, No. 4, 545–551 (2005).
4. V.F. Tarasenko and S.I. Yakovlenko, Plasma Devices and Operations **13**, No. 4, 231–279 (2005).
5. V.F. Tarasenko, I.D. Kostyrya, V.K. Petin, and S.V. Shljakhtun, J. Techn. Phys. **76**, Is. 12, 37–46 (2006).

6. G.A. Mesyats, S.D. Korovin, K.A. Sharypov, V.G. Shpak, S.A. Shunailov, and M.A. Yalandin, Techn. Phys. Lett. **32**, Is. 1, 35–44 (2006).
7. I.D. Kostyrya, V.F. Tarasenko, A.N. Tkachev, and S.I. Yakovlenko, Techn. Phys. Lett. **33**, Is. 7, 79–86 (2007).
8. E.Kh. Baksht, D.V. Rybka, M.I. Lomaev, and V.F. Tarasenko, Techn. Phys. Lett. **33**, Is. 9, 29–36 (2007).
9. I.D. Kostyrya, M.I. Lomaev, V.F. Tarasenko, D.V. Rybka, and E.Kh. Baksht, Izv. TPU **312**, No. 2, 131–135 (2008).
10. E.Kh. Baksht, M.V. Erofeev, M.I. Lomaev, D.V. Rybka, D.A. Sorokin, and V.F. Tarasenko, Izv. TPU **312**, No. 2, 136–138 (2008).
11. E.Kh. Baksht, A.G. Burachenko, M.V. Erofeev, I.D. Kostyrya, M.I. Lomaev, D.V. Rybka, and V.F. Tarasenko, J. Techn. Phys. **78**, Is. 6, 143–145 (2008).
12. M.I. Yalandin and V.G. Shpak, Prib. i Tekhn. Eksperim., No. 3, 5–31 (2001).
13. E.Kh. Baksht, E.V. Balzovskii, A.I. Klimov, I.K. Kurkan, M.I. Lomaev, D.V. Rybka, and V.F. Tarasenko, Prib. i Tekhn. Eksperim., No. 6, 100–103 (2007).
14. V.F. Tarasenko, D.V. Rybka, E.Kh. Baksht, I.D. Kostyrya, and M.I. Lomaev, Prib. i Tekhn. Eksperim., No. 2, 62–68 (2008).
15. A.V. Gurevich and K.P. Zybin, Phys.-Uspekhi **171**, No. 11, 1177–1199 (2001).