Supershort avalanche electron beams and x-ray in high-pressure nanosecond discharges

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Abstract. The properties of a supershort avalanche electron beam (SAEB) and X-ray radiation produced using a nanosecond volume discharge are examined. An electron beam of the runaway electrons with amplitude of ~ 50 A has been obtained in air atmospheric pressure. It is reported that SAEB is formed in the angle above $2\pi$ sr. Three groups of the runaway electrons are formed in a gas diode under atmospheric air pressure, when nanosecond voltage pulses with amplitude of hundreds of kilovolts are applied. The electron beam has been generated behind a 45 $\mu$m thick AlBe foil in SF$_6$ and Xe under the pressure of 2 atm, and in He under the pressure of about 12 atm. The paper gives the analysis of a generation mechanism of SAEB.

1. Introduction
For the first time an electron beam behind a foil was generated at a gas-filled gap breakdown at atmospheric pressure in 1974 in [1]. The recorded e-beam duration at a half-height was no more than 1.5 ns. Generation of electron beams was realized by using a nanosecond discharge in a non-uniform electric field. Nanosecond high-voltage pulses (>100 kV) were applied to a gap with a leading edge about 1 ns. In [1] it was supposed about the shorter duration of a beam current of runaway electrons, yet direct measurements of the beam current duration with subnanosecond resolution were not made. In a number of papers (see the review [2] and Refs in [2]) the authors tried to estimate the beam current duration by the duration of light pulses of scintillation plastic materials. Such measurements of the beam current pulse duration gave the value less than 1 ns.

Since 2003, an interest to investigation of e-beams generation in gas-filled diodes with high pressures has been rekindled (see the review [3-5] and papers [6-20], and Refs in [3-20]). In 2005, the advanced recording methods of electron beams and the use of digital oscilloscopes with wide bandwidth provided the measurements of the beam current duration with time resolution of ~ 100 ps. It was established that duration of a SAEB pulse at a half-height at atmospheric pressure of different gases is less than 100 ps (~96 ps in [7]). Such duration approached the limit resolution of the Tektronix TDS6604 oscilloscope used in [7]. The measurements performed in [8] gave the value of the beam current duration of runaway electrons at a half-height of 120-130 ps. It was supposed in [11] that the true value of the beam current pulse duration of runaway electrons should be ~10 ps. However, a question of duration and amplitude of a beam current, as well as of an electron energy distribution is
still open. The authors of [1] reported that the number of electrons behind a foil, generated in atmospheric pressure air is $\sim 10^9$, yet they did not give any value of amplitude there. The following papers by that scientific group did not report about any higher value of the earlier reported number of electrons of $\sim 10^9$, but they specified that most registered electrons have anomalous energies, being greater than the gap voltage (see review [2] and Refs). Our estimation of the beam current amplitude of [1], judged by the number of electrons and duration of the beam current pulse at a half-height of $\sim 100$ ps gives the value of $\sim 1.5$ A. The our papers reported about the SAEB amplitude of tens-hundreds of amperes, and how oscilloscope type and recording methods used in experiments exert influence on amplitude and duration of a recorded signal. The beam current amplitude of 1.5 A with duration of 130 ps at a half-height was obtained in [8] by using the voltage pulses with an amplitude of 270 kV, and duration at a half-height of 250 ps in air under atmospheric pressure.

In order to obtain all above-said results meant for recording (estimation) the number of electrons or beam current amplitude and discharge current, the shunts made of TVO resistors or film resistors, collectors of various design, and a calorimetric method suggested in [21] to determine the nanosecond beam current amplitude were used. At that, the measurement results on peak current of runaway electrons reported by different authors, and by using different methods essentially differed. The electron energy distributions in air gas diodes at atmospheric pressure, obtained by different scientific teams differed as well [2, 7, 10, 20].

In this paper, the recent measurement results on duration and amplitude of e-beams generated at a nanosecond discharge in air at atmospheric pressure and others gases have been summarized.

2. The experimental set-ups and techniques

![Figure 1. Schematic drawing of the gas-filled diode no.1 with collector no. 1: (1) gas-filled diode, (2) flange of the gas-filled diode, (3) collimator or a 250-µm-thick Cu foil with a 1-mm-diameter hole (a 50-µm-thick AlBe foil or a 10-µm thick Al foil is installed between 2 and 3), (4) collector’s body, (5) receiving element of the collector (a 3-mm-diameter cylinder or a cone with a 5-mm-diameter base), and (6) cathode.](image)
The gas diodes demonstrated in Figs. 1 and 2. The design was similar to the one earlier described in [4-7]. The same way as in the most experimental studies devoted to formation of X-ray radiation and runaway electrons in the gas diodes, we used a flat anode and a small-size cathode in order to have an additional gain of electric field in the near-cathode region. The cathode was a stainless steel tube of ~6-mm diameter and 100-μm wall thickness, installed on a metallic rod of ~6 mm in diameter. The flat anode used for e-beam extraction was made of a 45-μm thick AlBe foil or Al-foil of 10-15 μm in thickness. The cathode–anode distance was varied from 6 to 30 mm. The gas diodes shown in Fig. 2 had additional chambers with windows or holes on the sidewalls. That provided recording of an electron beam’s current pulse along (4) and perpendicular (5) to longitudinal diode’s axis; 6, 7 – electron beam’s flows; d – cathode-anode distance.

Figure 2. a - Schematic drawing of the gas-filled diode with the pinhole camera: 1 – diode’s box, 2 – 350-μm-diameter holes; 3 – electrons beam’s and x-ray radiation’s autographs on a film, 4 – tube cathode, 5 – the place of a high-voltage nanosecond pulser connection.

b - Schematic drawing of the gas-filled diode and the registration system of a electron beam’s spatial distribution: 1 – tube cathode; 2 – flat (foil, grid) anode; 3 – grid; 4, 5 – collectors to register an electron beam’s current pulse along (4) and perpendicular (5) to longitudinal diode’s axis; 6, 7 – electron beam’s flows; d – cathode-anode distance.

(when connected to a gas diode with minimum inductance) or ~0.7 ns (when setting a gas diode with an additional chamber, Fig. 2).

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To receive signals from a capacitive divider, collectors and a shunt, the oscilloscopes TDS-6604 with 6 GHz-band with 20 GS/s and DPO70604 with 6 GHz-band with 25 GS/s were used. Note, that in some regimes, the value of the current beam amplitude behind the foil could vary from pulse to pulse. Therefore, the maximum amplitudes of e-beam current are shown for all regimes. Amplitude instability of the gap voltage pulses and gas diode discharge current were low, not exceeding 10%. The discharge glowing was photographed by a digital camera. X-ray radiation was registering by Direct Reading Dosimeters (Arrow-Tech, Inc. Model 138). Such dosimeters made registration of X-ray radiation with quanta energies higher than 16 keV. With the diode geometry shown in Fig. 1, and the pulser RADAN-220 used, the dose was ~1.5 μR/pulse at a 2-mm distance from the anode (20-μm copper foil). Besides that, X-ray radiation and e-beam were registered by RF-2 film placed into a ~100-μm thick black envelope. The envelope was placed either just after the anode (by the edge or side surface of the gas diode covered with grid or (and) Al foil of 10-50 μ thickness, or at a definite distance from the anode made of copper foil of 250 μ thickness, Fig. 2a. In the second case (obscure chamber), the foil had the holes with the diameter of ~350 μm providing formation of images on RF-film. In the experiments with the film placed into a black envelope, images on the film appeared resulting from the e-beam and X-ray radiation influence. The experiments show maximal RF-film blackening due to the effect caused by the e-beam and X-ray radiation appearing at the e-beam deceleration by the envelope and foil. In the experiments with an open film (without the envelope), the discharge plasma image was formed on the film. The film was sensitive to UV and visible spectrum radiation. Time evolution of X-ray radiation pulses was registered using a semiconductor detector SPPD11–04 with the time resolution of ~1.5 ns. The detector makes registration of X-ray quanta with the energies ranging from 0.4 to 40 keV. Nevertheless, the measurements show that the detector had rather higher sensitivity to the beam electrons than to X-ray quanta. Therefore, an additional filter made of lavsan or polyethylene was set ahead of the detector.

3. Results of measurements of SAEB parameters

The main experimental results are presented in Figs.3-8. As it was determined previously [3-6], maximum parameters of SAEB are realized during formation of a volume discharge in a discharge gap. The present investigations confirmed this conclusion. Maximum beam currents behind the foil were recorded if the discharge contraction occurred after SAEB generation. SAEB generation was investigated in most detail in the atmospheric pressure air. Maximum amplitude of the e-beam (number of electrons) was obtained with the pulser no.3 and the gas diode that had the minimum inductance of connection to the pulser. To determine a charge behind the foil, we used a
Figure 4. Waveforms of the voltage across the gap $U$, discharge current $I_d$ and electron beam current $I_b$ behind a foil at the pulser no. 1; spherical (a), and tubular (b) cathode using.

Collector no.1 that had a 5-mm diameter receiving part and moved over the whole surface of the foil, Fig.3. Note, that the beam current behind the foil was recorded over the whole foil surface, even at the periphery, in the places near the sidewall of the gas diode case. The total charge value measured behind a 50-μm thick AlBe foil was of $\sim 3.5 \times 10^{-9}$ coulomb and behind a 10-μm thick Al foil it was of $\sim 4.4 \times 10^{-9}$ coulomb. This charge corresponds to the number of electrons behind a 10 μm thick Al foil that equal to $\sim 2.7 \times 10^{10}$. This value exceeds the number of the electrons obtained behind the 8- μm thick Al foil by more than an order of magnitude in [1]. Electrons with the energy of 10-40 keV being of $\sim 2 \times 10^{10}$ in number were not taken into account in the beam current amplitude. The SAEB amplitude (estimation by the maximum electron charge behind the foil) was of $\sim 50$ A at the beam extraction through a 10-μm thick Al foil. The beam current pulse length at a half-height was set to be equal to $\sim 90$ ps, i.e., corresponded to the duration measured in the given experiments. This amplitude of SAEB is confirmed by the measurements made using a collector no.2 that had a receiving part diameter equal to 20 mm. Increase of the collector receiving part diameter resulted in the proportional rise of the SAEB amplitude, however, the collector time resolution decreased (to 100 ps at the receiving part diameter of 20 mm). The obtained amplitude of SAEB exceeds the beam current of the runaway electrons behind a 15-μm thick Al foil by more than an order of amplitude if a graphite cathode is used in [8].

In the paper [11] it was supposed that the beam current duration of the runaway electrons equals to $\sim 10$ ps. At such duration of the beam current pulse and measurements of the electron charge behind
the foil, the SAEB amplitude will increase in inverse proportion to its duration. E.g., when the pulse WFMH equals to 10 ps and the number of electrons is $\sim 2.7 \times 10^{10}$, the beam current amplitude will be more than 400 $\text{A}$. However, we consider that the real amplitude of SAEB is less and the beam current pulse duration is more than 10 ps. At present time, a design of a collector having a high resolution and a receiving part size enclosing the whole diameter of the foil in the gas diode is unknown. As we noted before, the beam current is recorded over the whole surface of the gas-filled diode foil window that was equal to $\sim 50 \text{ mm}$ in the experiments.

Fig. 4 presents the oscillograms of the voltage pulses at a gap, the discharge current and the beam current behind the foil with a pulser no. 1. To record the oscillograms (Fig.4) with the best time resolution was used. The oscillograms in Fig.4 are synchronized in time with each other. It is seen from the pictures that current through the gap increases practically at once after the voltage supply to the gap and equals to hundreds of amperes at the moment of SAEB generation commencement. The gap voltage for the pulser no. 1 at this moment of time corresponding to SAEB pulse commencement is approximately 200 kV. The beam current amplitude at a fixed duration of the voltage pulse edge grows with the voltage amplitude increase at the moment of SAEB generation. If the voltage pulse amplitude is fixed and the duration of its leading edge is changed, then at the pulse edge duration increase higher than 400 ps the SAEB amplitude usually decreased.

Figure. 5. Attenuation curves of the electron beam current corresponding to cathodes in the form of sphere and tube.

Figure. 6. Energy spectra of the runaway electrons corresponding to cathodes in the form of tube (a) and sphere (b).
Fig. 5 presents the curves of the beam current amplitude attenuation when the aluminum filter thickness is increased and Fig. 6 presents the recovered distributions by energies of the beam current electrons obtained with the pulser no. 1. Two different cathodes were used in these experiments. Three groups of electrons were registered with both cathodes. Recovering electron spectra by the beam attenuation curves in the foils of different thickness, we used a refined technique described in [10]. Improvement of the electron spectra estimation technique owing to more precise definition of electron energy losses at their braking in the foil resulted in displacement of maxima at the distribution towards

Figure 7. Dependence of the electron beam current amplitudes on the voltage amplitude (a); dependences of the electron beam current amplitudes (b) registered along (1) and perpendicular (2) to the longitudinal diode axis on the anode-cathode distance d.
high energies. The shape of the spectrum has not changed essentially in this connection. The first group usually has the electron energy less than 50 keV. The second group of electrons corresponds to the generation of SAEB between the front of the dense plasma and anode. Maximum of electron energy at the electron distribution by energies in SAEB corresponds approximately to the maximum gap voltage. This implies that maximum at a voltage pulse on the gap and maximum of SAEB amplitude occur approximately at the same time. The third group of electrons under existing conditions had the energy essentially exceeding the one achieved by the electrons in vacuum at the maximum voltage on the gap. It was determined that the number of such electrons depends on the cathode design and the voltage pulse leading edge. When a cathode with a small curvature radius was used, e.g., in the form of a tube made of foil, their number was small, less than 10% of the number of electrons in the beam behind the foil. When the voltage pulse leading edge was increased up to 1.5 ns, anomalous energy electrons were not recorded. These measurements as well as the results obtained earlier [7, 10, 20], contradict to the results of [2] reporting about obtaining runaway electrons chiefly with “anomalous” energy in the atmospheric pressure air. We consider that in the paper [2] there was made a mistake in the gap voltage measurements and maximum at the electron distribution by energies corresponds to the maximum gap voltage. This is confirmed indirectly by the electron spectrum obtained in [2] at the air pressure of 0.2 Torr and the cathode design made in the form of a cone in this work.

Essential number of electrons with “anomalous” energy is generated when using a cathode with a large curvature radius. Such spectrum is shown in Fig.6b. Evidently, essential number of electrons with “anomalous” energy was obtained as well in the work [1] where a cathode with a large curvature radius was used.

When conducting the investigations, we discovered a new important feature of SAEB generation. It turned out that electron beam generation occurs not only in the anode direction but also transversely to the gas diode axis in the direction of its side walls (into the angle exceeding $2\pi$ sr). Measurements were made with a gas diode (Fig. 2(b)) for which the breakdown voltage was equal to $\sim 250$ kV at $d = 12$ mm. Time delay $t_d$ of the gap breakdown depended on $d$ as well and was equal to $\sim 700$ ps at $d = 12$ mm. Fig.7 presents the SAEB current amplitude recorded from the gas diode face end versus the value of the interelectrode gap between the cathode and plane anode. The amplitude of SAEB recorded through a lateral window versus the interelectrode gap value is presented here as well. Both dependences were recorded at a simultaneous registration of the beam current from the face end and from one side. Decrease of $d$ resulted in decrease of SAEB current amplitude from one side; however, even at the gap of 8 mm the beam a side collector registered current. The beam current pulse shape from both collectors was similar. The FWHM of the pulses was of $\sim 100$ ps. Both signals came to the oscilloscope practically simultaneously. Pulse duration of the X-ray and the beam current recorded with a detector SPPD11–04 was equal to $\sim 2$ ns. Evidently, a real FWHL of X-ray pulse is essentially shorter but for its measurement it is necessary to have a detector with higher time resolution.

As it appears from the results of the experiments, SAEB is generated both in the main spacing at the gas diode axis and between the cathode (cathode holder) and the gas diode case. Generation of SAEB to the gas diode case occurred even at a small main gap ($d = 8$ mm). This gap was three times less than the distance from the cathode holder to the lateral wall (24 mm). A full solid angle to which SAEB was generated exceeded $2\pi$ sr in the given experiments. Correspondingly, SAEB amplitude at registration of run-away electrons in all directions essentially exceeds the beam current amplitude measured behind the foil installed transversely to a longitudinal axis of the gas diode. This difference will increase slightly at the lengthening of the cathode holder and the gas diode lateral sides. However, at the cathode holder lengthening the beam its length generates current at different time and this will result in the increase of the beam current pulse duration but its amplitude will have no changes.

The absorption curves plotted from the data concerning the beam current attenuation from the face end and one side of the diode turned out to be the same at the equal interelectrode gaps. This testifies to the similarity of the energetic spectrum of the electron beams directed both along and transverse to the diode axis.
Figure 8. Pinhole camera images obtained for conditions depicted on the figure 3. The images were taken with (b, c, d) and without (a) light-proof envelop at using one (a, b) and two (c, d) holes with a diameter of 350 µm in flat Cu anode with a thickness of 250 µm.

Testing of the results obtained at SAEB current measurement by a collector was made at a gas diode that was similar to the gas diode in Fig. 2(a). At the face end and at one side of this gas diode there were windows covered with a thin aluminum foil. Behind the windows there was placed a photographic film in a black paper envelope. This allowed recording the X-ray radiation and the beam current electrons from the face end and from the side of the gas diode by the film blackening. This result also confirms the electron beam generation into a solid angle exceeding $2\pi$ sr. Besides, with the gas diode no.2b there were taken the autographs of the electron beam registered by a photographic
film as well as the photos of the discharge plasma glowing in the visible and UV range. Fig.8 presents the obtained images. At the discharge images in the rays of UV and visible spectrum regions, Fig. 8(a), one can see brighter cathode spots and diffuse jets at the cathode. The obtained pictures coincide with the photographs made by camera in the similar conditions. However, the image obtained at the simultaneous exposure of the electron beam and X-ray radiation to the film placed into an envelope differs essentially from the discharge photograph. Based on the analysis of the images in Fig.8, one can suppose that in these conditions an electron beam is generated from the region with the outer diameter of $\sim 12$ mm. This region has the shape close to the spherical one and occupies approximately a half of the discharge gap. Here, the electron beam generation occurs not only in the anode direction, Fig. 8(b) and Fig.8(c) but also transversely to the gas diode longitudinal axis in the direction of its lateral walls, Fig.8 (d) (to the solid angle exceeding $2\pi$ sr). It should be noted that the electron beam generation region is less than it is registered at the images possibly due to the electron scattering in the air.

Investigation of SAEB generation in other gases at the atmospheric pressure confirmed the well-known data [1-20], that its amplitude is maximal at the gas diode filling with light gases (helium and hydrogen). However, we managed to increase considerably the pressure of various gases at which SAEB was recorded behind the foil. Thus, in the given work with the pulser no.3 the electron beam behind the foil was obtained at the helium pressure of 12 atm. At the gas diode filling with heavy gases, the runaway electron beam amplitude at the atmospheric pressure decreases in comparison with the air. We have managed to increase the pressure for these gases at which SAEB is generated. So, SAEB was obtained in SF6 and xenon at the pressure of 2 atm due to optimization of the gas diode with the pulser no. 3. Besides, increase of SAEB pulse FWHM was revealed for the mixtures with SF6. At the increased pressures (1.6-2 atm) the SAEB pulse duration increased up to $\sim 150$ ps. This result is important for determining a mechanism of the electron beam generation in a gas diode.

4. Interpretation of results

The obtained data can be explained in the following way. When voltage pulses with the amplitude of hundreds of kilovolts are supplied to the gap, then the high electric field strength is achieved due to the current gain at the micro- and macro heterogeneity. This results in the field emission from the cathode at the voltage pulse leading edge. Here, we will testify this conclusion by means of simple estimations. Amplification of the electric field $\beta$ at its surface for a cathode in the form of a blade can be evaluated by the formula [23]: $\beta \sim (r \cdot d)^{-0.5}$, where $\beta = E/U$, $E$ is the field strength near the cathode, V/cm; $U$ is the applied voltage, V; $d$ is the distance between the cathode and anode, cm; $r$ is the radius of the cathode rounding, cm. In the used gas diode $d$ is $\sim 1$ cm, $r=50$ $\mu$m, respectively, $\beta \approx 14$. Micropoints at the cathode provide the field strengthening $10\text{--}100$ times more [24]. Thus, the electric field $E$ near the cathode surface at the voltage pulse edge reaches the values of $\geq 5 \cdot 107$ V/cm [2, 11] that is sufficient for appearance of appreciable field-emission current at the voltage pulse edge. It should be taken into account as well that oxide films at a cathode surface appearing in the presence of air decrease the value of the voltage strength at which the field emission is observed.

Owing to the electric field amplification near the cathode, the emitted electrons can acquire the energy sufficient for their runaway (fast electrons in the near-cathode region of the amplified electric field). When moving away from the micropoints at the cathode and the cathode edge, the electric field strength is decreased and fast electrons lose their energy mainly on particle ionization in the near-cathode region. Simultaneously, secondary and field-emission electrons formed in the electric field that grows owing to the voltage increase at the gap, initiate the development of electron avalanches. Concentration of initial electrons is so great that the heads of avalanches are overlapped up to the streamer formation and relatively dense plasma of a diffusion discharge is formed. The edge of the plasma moves from the cathode to anode. Under these conditions, as it was shown previously [3-6], a
diffusion discharge is formed in the gap at the dense plasma edge formed by the heads of avalanches moving to the cathode resulting in the excess negative charge. When plasma reaches a definite size and, correspondingly, the gap between the plasma edge and anode decreases and the voltage in the spacing increases, a critical field $E_{cr}$ is achieved between the plasma boundary and anode and an electron beam is generated. According to [3-5], the value of $E_{cr}$ at which an essential part of electrons turns into the runaway mode can be determined from the expression $\alpha (E_{cr}, p) d = 1$, where $\alpha$ is the first Townsend coefficient, $p$ is the gas pressure and $d$ is the interelectrode gap. This criterion was obtained for the gaps with the uniform electric field at small (close to zero) initial energies of electrons. It should be noted that increase of the initial energy of electrons results in the critical field decrease and electrons turn into the runaway mode at smaller electric fields [25]. We suppose that under conditions of the given experiment the energy of a part of electrons at the dense plasma edge increases all the time due to their acceleration at the initial part of the voltage pulse edge and excess negative charge in the heads of avalanches and can reach the units of keV [2]. For these electrons, the electrical field in the gap for the conditions of Fig. 8 becomes sufficient for runaway. An excess negative charge of electrons at the dense plasma edge increases the electric field in the gap and the energy preliminary gathered by some part of electrons promotes decrease of the critical field value, as we noted before.

As it was determined in the paper presented, the source of electrons and X-ray radiation is a region that has the form close to the spherical one, Fig. 8. We believe that in this region the dense plasma is formed to the moment of SAEB generation with its front edge moving from the cathode to the anode and lateral walls of the gas diode. Owing to the fact that the dense plasma near the cathode has the form close to the spherical one, SAEB is generated for the electrons at the ionization wave front edge with the highest energy to the solid angle exceeding $2\pi$ sr. Further, the beam electrons continue accelerating at their motion to the anode (gas diode case). The number of runaway electrons can be increased at the expense of ionization cascade electrons. The energy of the electrons is increased both at the expense of the voltage increase at the gap and effect of polarization self-acceleration [26]. Thanks to the polarization self-acceleration, a small part of the beam electrons will have an essential energy. Note, that a part of energy of the runaway electrons is spent on the gas ionization in the gap providing the ionization wave motion [27]. Limitation of SAEB pulse duration is conditioned by the gap bridging with an ionization wave and electric field alignment in it. One can suppose from small lengths of SAEB that it reaches the anode practically simultaneously with the ionization wave front. Increase of SAEB current pulse duration at the increase of SF6 pressure can be explained by decrease of the rate of movement of the ionization wave in a heavy gas and, correspondingly, more late gap bridging by the ionization wave and electrical field alignment in it. Mechanisms of electron beam generation in the gas diodes suggested in [2, 11] have no agreement with the above presented experimental results. However, we do not insist that the suggested mechanism of SAEB generation works absolutely in all experimental conditions. One can suppose that alteration of the experiment conditions can affect the physical processes in the gas diode. We plan to make a comparative analysis of different mechanisms of electron beam generation in the gas diodes in a separate work.

5. Conclusion
This paper reports the properties of supershort avalanche electron beam formed in different gases under atmospheric pressure and analyses the SAEB generation mechanism. It is shown that at a nanosecond discharge in the atmospheric pressure air and SAEB current recording through a small diameter area the pulse duration behind the foil is not larger than 80 ps. In order to record the pulse shape, it is necessary to use a small-size coaxial collector loaded to a high-frequency cable and to read a charge density distribution over the foil surface for determining the SAEB amplitude by means of this collector. The obtained electron distribution over the foil section should be compared with the
distribution obtained per pulse by means of a luminescent screen or a photographic film. An analysis of those data shows that at the beam current duration at a half-height of ~90 ps the beam current amplitude behind the 10-μm thickness Al-foil is ~50 A. It is demonstrated that SAEB is generated into an angle exceeding $2\pi$ sr in the air at the pressure of 1 atm. Decrease of the gap $d$ between the cathode and anode results in the amplitude decrease of the beam current generated to the lateral walls of the gas diode. However, even at small gaps ($d=8 \text{ mm}$) of the interelectrode intervals installed both along and transversely to the gas diode axis. The beam current is generated to the gas diode lateral surface placed at a certain distance from the cathode that exceeds several times the gap in the interelectrode intervals. Generation of the electron beam into the solid angle exceeding $2\pi$ sr is explained by the fact that at SAEB generation the dense plasma near the cathode has the form close to the spherical one. An electron beam was obtained behind AlBe foil of the thickness 45 μm at the pressure of SF6 and xenon in a gas diode up to 2 atm and at the pressure of helium up to 12 atm.

In conclusion we note that Tektronix Company created a unique oscilloscope DPO/DSA72004 (20 GHz-band with 50 GS/s). Researches made by means of this oscilloscope should allow obtaining new data concerning characteristic features of SAEB generation in gas diodes.

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