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Effect of cathode materials on the generation of runaway electron beams and X-rays in atmospheric pressure air

CHENG ZHANG,[1,3] VICTOR F. TARASENKO,[2] TAO SHAO,[1,3] EVGENI KH. BAKSHT,[2] ALEXANDER G. BURACHENKO,[2] PING YAN,[1,3] AND IGOR' D. KOSTYRAY[2]

[1]Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China
[2]Institute of High Current Electronics, Russian Academy of Sciences, Tomsk, Russia
[3]Key Laboratory of Power Electronics and Electric Drive, Chinese Academy of Sciences, Beijing, China

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Abstract

In this work, experiments were performed to study the effect of cathode materials on the amplitude of the super-short avalanche electron beam (SAEB) current and X-ray density during discharges in atmospheric-pressure air. In the experiments, discharges were generated by three nanosecond-pulse generators in air gaps between a plane anode and a tubular cathode made of different metals. The output pulse of the three generators had a rise time of 0.3, 1, 15 ns, and a full width at half maximum of 1, 2, 30–40 ns, respectively. For the generators with pulse rise-time of 0.3 and 1 ns, the cathodes used in these experiments were made of stainless steel, permalloy, titanium, niobium, copper, brass, and aluminum. For the generator with pulse rise-time of 15 ns, the cathodes were made of stainless steel, titanium, copper, and aluminum. When the rise time of the applied pulse is 0.3 ns, our experimental results show that the amplitude of the voltage across the gap depends on the cathode material and reaches its maximum value when a stainless steel cathode is used. It is also observed that, under such situation, the maximum amplitudes of the SAEB current occur at maximum voltages across the gap when all other factors are equal. Furthermore, the amplitude of the SAEB current hereof is found to depend not only on the material of the sharp edge of the tubular cathode, but also on the material of the side surface of the tubular cathode. When the rise time of the applied pulse is 1 ns, the experimental results show that the average number of electrons in SAEB is also affected by the cathode materials. In addition, in the case that the rise time of the voltage pulse is 15 ns and the gap spacing is 8 cm, the experimental results show that the cathode material has no effect on the voltage amplitude across the gap and the X-ray density. The increase of the pulse repetition frequency from 250 to 500 Hz under such condition can lead to a three-fold increase in X-ray density in a repetitive pulsed mode.

Keywords: Air diffuse discharge; Cathode material; Nanosecond pulse; Super-short avalanche electron beam; X-ray density

INTRODUCTION

Recently, much attention has been paid to the generation of super-short avalanche electron beams (SAEB) and X-rays in atmospheric pressure air (Levko *et al.*, 2012*b*) and references in it. Scientists have great interests in these high-energy electrons because they have a strong effect on gas breakdowns and diffuse discharges in inhomogeneous electric fields (Babich 2003; Levko *et al.*, 2012*b*; Tarasenko *et al.*, 2003; Tarasenko & Yakovlenko, 2005; Yakovlenko, 2007).

Address correspondence and reprint requests to: Tao Shao, Institute of Electrical Engineering, Chinese Academy of Sciences, P.O. Box 2703, 100190 Beijing, China. E-mail: st@mail.iee.ac.cn

One of the attractive problems to researchers is to create electron accelerators based on diodes filled with atmospheric-pressure gases to provide a beam current as high as possible (Alekseev *et al.*, 2003*a*; Kostyrya *et al.*, 2008; 2009; 2010; 2012; Mesyats *et al.*, 2006; 2008; 2011; Tarasenko, 2011; Tarasenko & Yakovlenko, 2005; Tarasenko & Kostyrya, 2005; Tarasenko *et al.*, 2003; 2004; 2005; 2007; 2008*a*; 2008*b*; 2008*c*; 2011; Tarasova *et al.*, 1974). These accelerators based on gas-filled diodes were used to study luminescence of crystals (Babich *et al.*, 2009; Baksht *et al.*, 2010*b*; Lipatov *et al.*, 2005*a*; 2005*b*); and the runaway electron beams were used for pre-ionization in a CO_2 laser at a mixture pressure of 5 atm (Alekseev *et al.*, 2003*b*; Orlovskii *et al.*, 2011). In the design of electron accelerators for various applications, it is generally required to obtain sufficient large number of electrons with energies of tens and hundreds of kiloelectron-volts downstream of an anode foil or a grid and to know the accurate beam current parameters (pulse duration, amplitude, and electron energy distribution).

The objective of this work is to experimentally study the effect of cathode material on the SAEB and to determine the amplitudes of the voltages across the gap during the generation of the SAEB with tubular cathodes made of different metals. Because the amplitude of the SAEB current depends on many factors, such as cathode and gas diode designs, voltage and its rise time, gas kinds and their pressure, our experiments were performed with the same factors mentioned above. In each series of experiments, the fixed parameters were discharge gap spacing, cathode and gas diode designs, voltage and its rise time. The cathode was a foil tube, whose design was the same as those used in earlier works (Alekseev *et al.*, 2003*a*; Mesyats *et al.*, 2006; Shao *et al.*, 2011*a*, 2011*b*, 2012; Tarasenko *et al.*, 2003). The experiments were conducted on three set-ups at different rise times of the voltage pulses (0.3, 1, and 15 ns). For each rise time, cathodes made of several types of metals with different work functions were investigated. Although the effect of cathode material on the amplitude of the SAEB current was disclosed earlier (Alekseev *et al.*, 2003*a*; Mesyats *et al.*, 2008; Tarasenko *et al.*, 2004; 2005; 2008*c*), systematic research in this effect has not been undertaken so far. Moreover, until now, no available paper has reported on the measurements of the amplitudes of the voltages across the gap during the generation of the SAEB with different cathode materials.

RELEVANT RESEARCHES ON THE MEASUREMENT OF RUNAWAY ELECTRON BEAMS IN ATMOSPHERIC PRESSURE AIR

In general, some relevant parameters are usually used to study the SAEB, such as pulse duration, current amplitude, and electron energy distribution. In this section, relevant researches on these three important parameters would be introduced.

One important parameter for SAEB is the pulse duration. In previous works about the generation of runaway electron beams in atmospheric-pressure air, the pulse duration with sufficient time resolution could not be directly measured due to the time resolution limit of the experimental equipments (Alekseev *et al.*, 2003*a*; Babich, 2003; Tarasenko *et al.*, 2003; 2004; Tarasova *et al.*, 1974). Only since oscilloscopes with required time resolution became available in 2005, a SAEB with a full width at half maximum (FWHM) of about 0.1 ns was detected for the first time (Tarasenko *et al.*, 2005*b*, see also Andreev *et al.* (2006); Mesyats *et al.* (2006); Tarasenko and Kostyrya (2005)). However, in some other works, the SAEB duration was supposed to be much shorter and reached about 10 ps (Mesyats, 2007; Mesyats *et al.*, 2011). Regardless of the accurate value of the SAEB duration, it is certain that the FWHM of the SAEB with a picosecond time resolution at atmospheric pressure could be measured till now.

The measurements with a picosecond time resolution demonstrated that the SAEB duration decreased when it was extracted through diaphragm holes of small diameter (Rybka *et al.*, 2012; Tarasenko *et al.*, 2012). It was also shown that the SAEB duration, in this case, depended on the cathode design and interelectrode gap. According to the results from measurements with an oscilloscope and a collector at a time resolution of up to 20 ps (Rybka *et al.*, 2012; Tarasenko *et al.*, 2012), the minimum SAEB duration extracted through a diaphragm with a thickness of 5 mm and a hole diameter of 1 mm was about 25 ps. The aforementioned studies were conducted at the Institute of High Current Electronics SB RAS (Tomsk, Russia), which demonstrated that at voltages of hundreds of kilovolts, the FWHM of the SAEB from the entire surface of the anode foil was about 0.1 ns (Kostyrya *et al.*, 2010; 2012; Rybka *et al.*, 2012; Tarasenko *et al.*, 2007; 2008*a*; 2008*b*; 2008*c*; 2011; 2012). The experiments also showed that when the voltage pulse amplitude decreased down to 25 kV, the FWHM of the SAEB increased to 200 ps (Baksht *et al.*, 2008). The foregoing data suggested that the studies taken by Mesyats (2007; Mesyats *et al.*, 2011) ignored either actual sizes of gas diodes or SAEB propagation into a solid angle larger than 2π (Tarasenko *et al.*, 2008*a*; 2008*c*).

Another important parameter for SAEB is the amplitude of the SAEB current. The highest amplitude of the SAEB current for gas diodes filled with atmospheric-pressure air was recorded downstream of an aluminum foil anode and was about 100 A with a FWHM of 100 ps (Kostyrya *et al.*, 2012). The amplitude of the SAEB current and the number of electrons downstream of the foil were measured by the use of specially designed collectors with improved measuring techniques (Baksht *et al.*, 2007; Rybka *et al.*, 2012; Tarasenko *et al.*, 2008*b*; 2011; 2012). The above amplitude of the runaway electron beam current was obtained with a compact SLEP-150 generator (Kostyrya *et al.*, 2008; Tarasenko, 2011; Tarasenko *et al.*, 2009; 2011) and a special disk cathode with a stainless steel wire emitter (Kostyrya *et al.*, 2010; 2012). A SAEB current of 100 A with a FWHM of 100 ps corresponded to 6.2×10^{10} runaway electrons downstream of the foil.

The third important parameter for SAEB is the electron energy distribution. Research data on electron spectra will be presented in our future papers. Here it should be pointed out that the electron energy distribution and the possibility of generation of runaway electrons with anomalous energy are still under discussion. Electrons with anomalous energy are electrons with an energy T higher than the energy gained by an electron at maximum voltage across the gap U_m ($T > eU_m$). In some papers (Babich & Loiko, 1985; Babich, 2003), it was stated that in atmospheric-pressure air, the electron energy distribution mainly lied in the range of energies about 100 keV higher than eU_m.

However, in our works (Alekseev *et al.*, 2003*a*; Baksht *et al.*, 2010*a*; Burachenko & Tarasenko, 2010; Tarasenko *et al.*, 2005*b*; 2008*a*; 2007; 2008*b*; 2008*c*; 2011), although certain experimental conditions (a pulse rise time of about 500 ps and shorter, and a cathode with increasing of curvature radius) did allow detecting electrons of energy $T > eU_m$, but their number was small (<10%). Besides, there were some other viewpoints, one of them was as follows: "Therefore, we can reasonably state that the absence of particles of anomalously high energy in the runaway electron beam is a proven fact, at least for air gaps with a highly nonuniform field" (Mesyats *et al.*, 2011). In order to resolve this contradiction, further experimental and theoretical research on the generation of runaway electron beams in pulsed gas discharges is required. We will devote a special paper to our study of runaway electron spectra, covering new experimental and simulation results in the future.

EXPERIMENTAL SETUP AND MEASUREMENT ARRANGEMENT

Experiments were performed on three set-ups with different voltage pulse rise times. The design of set-up 1 is shown in Figure 1. The gas diodes were filled with atmospheric-pressure air. The voltage pulses applied to the gas diode were produced by a SLEP-150M generator (Tarasenko, 2011; Tarasenko *et al.*, 2008*a*; 2008*c*; 2011). In the generator, the energy was stored in a high-voltage line formed by the case of a peaking spark gap switch (P-43) and the generator case made of aluminum tube with an inner diameter of 68 mm. The wave impedance of the high-voltage line was about 30Ω. The amplitude of voltage pulse when the peaking switch operated was about 150 kV. At the generator output, an additional coaxial transmission line of wave impedance 100Ω with a second capacitive voltage divider was installed between the gas diode and the peaking spark gap. The transmission line was filled with transformer oil. On operation of the peaking switch, fluctuations of the voltage amplitude and rise time were observed. Therefore, for data processing, voltage pulses of the same amplitudes in the incident wave

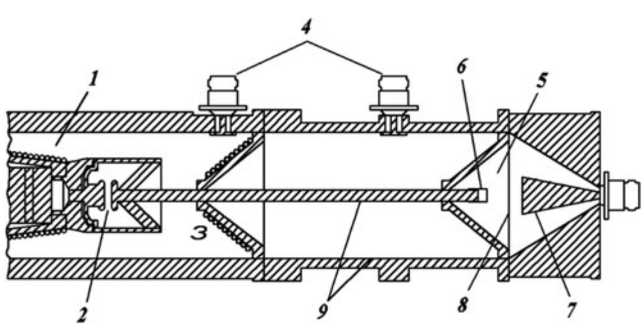

Fig. 1. Design of the output section of the Setup 1 (Generator SLEP-150M) with a gas-filled diode and a collector: (**1**) output section, (**2**) peaking spark gap, (**3**) insulators, (**4**) capacitive dividers, (**5**) gas filled diode, (**6**) cathode, (**7**) receiving part of conical collector, (**8**) foil reinforced with a grid.

(normally about 130 kV) with the same rise time were used. The FWHM of the voltage pulse in the generator transmission line with matched load was about 1 ns and its rise time was about 0.3 ns.

The voltage pulses were measured by two capacitive dividers located at 62 and 155 mm from the anode, making the record of the incident and reflected voltage waves and the determination of the voltage across the gap during the generation of the SAEB being possible. Oscillograms of the voltage pulses with stainless steel cathode recorded by both capacitive dividers in the transmission line are shown in Figure 2a (incident voltage wave) and Figure 2b (incident voltage wave together with reflected voltage wave). The voltage pulses across the gap and the SAEB pulse in the case of stainless steel cathode are presented in Figure 2c, and the voltage pulses across the gap were reconstructed from the oscillograms in Figures 2a and 2b. By using the same method, the voltage pulses across the gap and the SAEB pulse in the case of aluminum cathode were obtained as shown in Figure 2d. The procedure used to synchronize the voltage pulses with the SAEB pulses in Figures 2c and 2d was described elsewhere (Burachenko & Tarasenko, 2010; Tarasenko, 2011).

The electrode of the gas diode was formed by a plane anode and a tubular cathode. The interelectrode gap spacing was varied from 1 to 18 mm. Negative high-voltage pulses were applied to the electrode of the small curvature radius (cathode). The cathode was a metal foil tube. In most experiments, the foil thickness was 100 μm and its diameter was about 6 mm. The cathodes were made of stainless steel, titanium, copper, brass, niobium, and aluminum foil. Among them, the side wall of the stainless steel cathode was coated with copper foil. The edges of the copper foil were 1 mm below the edge of the stainless steel cathode. The beam current was extracted through an aluminum foil with the thickness of 10–15 μm, which was reinforced with a grid of transparency about 60%. The amplitudes of the beam current were mainly measured by a conical collector with a time resolution of up to 80 ps (Fig. 1) (Kostyrya *et al.*, 2010; Tarasenko *et al.*, 2011*b*). The receiving part of the collector was 20 mm in diameter. The amplitudes of the SAEB current were the amplitudes of the beam current measured from the receiving part of the collector downstream of the aluminum foil and the grid. In a series of experiments, the space between the receiving part and the foil was pumped by a forevacuum pump. However, as shown by the measurement results, the pumping added nothing to the collector recordings of the SAEB with a FWHM of about 100 ps and amplitude of about 100 A and less.

The number of electrons downstream of the entire foil surface was measured by a collector whose receiving part was a 70-mm-diameter disk. In these experiments, a 20-mm-diameter tubular cathode was used. The time resolution of the collector was insufficient to determine the FWHM of the beam current pulse, but it was possible to record the total number of electrons downstream of the foil, $N_{e\text{-}b}$. The total number of electrons was determined by the

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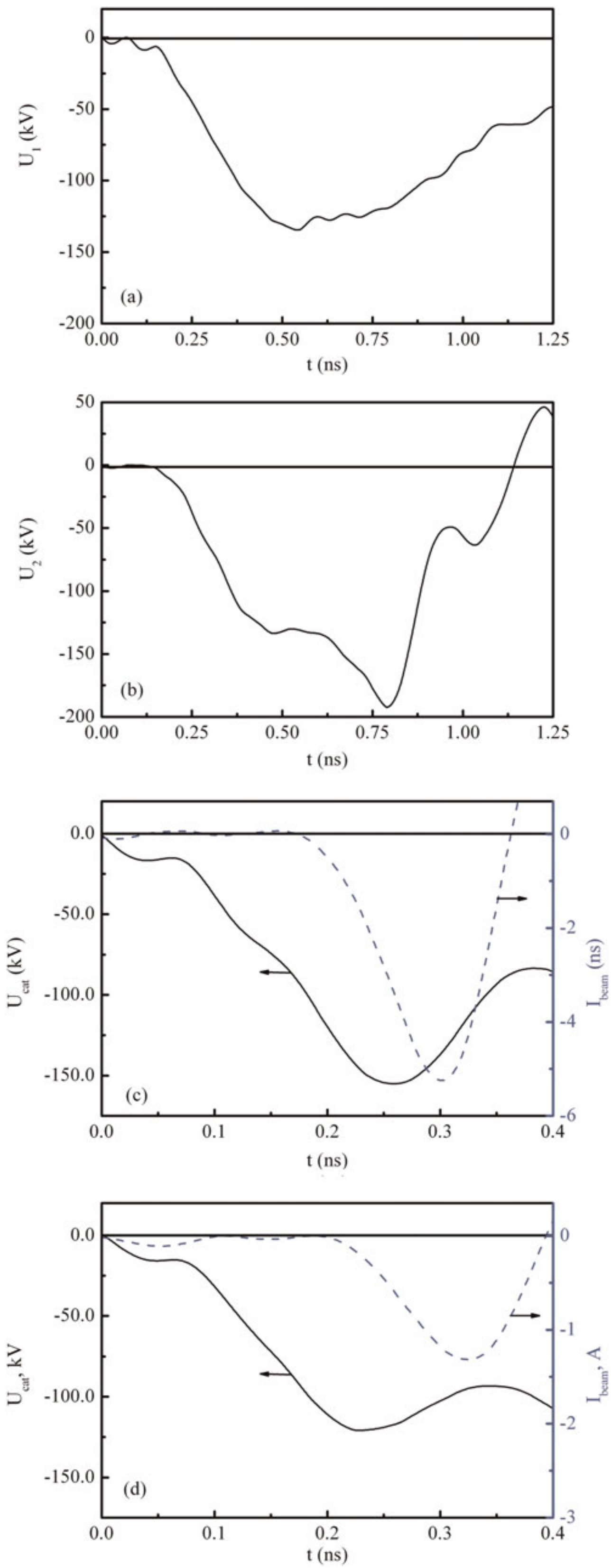

Fig. 2. (Color online) The voltage pulse from left (**a**) and right (**b**) capacitive divides on the Fig. 1, and the voltage pulses across the gap and the electron beam pulses (**c**, **d**) for stainless steel cathodes (a, b, c) and Al (d). Set-up 1 (Generator SLEP-150M). Gap spacing 12 mm.

relation $N_{e\text{-}b} = (I_{e\text{-}b} \times \tau_{0.5})/e$, where e is the electron charge, $I_{e\text{-}b}$ is the measured amplitude of the beam current, and $\tau_{0.5}$ is the FWHM of the beam current.

Electric signals of the collector and the capacitive dividers were recorded by an oscilloscope (Tektronix DPO70604, 6 GHz, 25 GS/s). The sensors were connected to the oscilloscope via wideband coaxial cables. The signals were attenuated by 142-NM attenuators (Barth Electrons).

On set-up 2, a RADAN-220 generator was used (Zagulov *et al.*, 1989). The generator produced voltage pulses of amplitude about 220 kV with a rise time of about 1 ns. The design of the gas diode and the cathode was similar to that shown in Figure 1, and the relevant description could be found in the pervious works (Tarasenko *et al.*, 2004; 2005). With this set-up, the tubular cathodes were made of 50-μm-thick permalloy (Fe-Ni alloy), copper, and aluminum foils, and 100-μm-thick stainless steel foil, respectively. The diameter of all these cathodes was 5.3 mm. The electron beam was measured by a conical collector with a receiving part whose diameter was 20 mm (Fig. 1). Both the applied voltage and the SAEB current were recorded by a digital oscilloscope (Tektronix TDS-3032, 300 MHz, 2.5 GS/s). As shown in our previous work (Tarasenko *et al.*, 2004; Tarasenko & Kostyrya, 2005), the quantity of $\tau_{0.5} \times I_{e\text{-}b}$ varied slightly when recorded by Tektronix oscilloscopes with different time resolutions. As the time resolution of the oscilloscope decreased, the measured beam current amplitude of $I_{e\text{-}b}$ decreased, whereas the FWHM of the pulse $\tau_{0.5}$ increased proportionally. Thus, on set-up 2 with the TDS-3032 oscilloscope, we could measure the number of electrons from the collector, but could not measure the voltage across the gap and the amplitude of the SAEB current.

On set-up 3, a SPG200N generator based on a semiconductor opening switches (Rukin, 1999) was used. The design of set-up 3 is described in detail in previous papers (Shao *et al.*, 2011*a*; 2011*b*; Zhang *et al.*, 2010). The generator produced voltage pulses of amplitude about 200 kV, FWHM 30–40 ns, and rise time about 15 ns. With this set-up, the plate anode was made of copper foil with a thickness of 50 μm. The tubular cathodes were made of 200-μm-thick stainless steel, titanium, copper, and aluminum foils, and the cathode diameter was 12 mm. The discharge gap was 8 cm. With this gap spacing, the highest X-ray count (density) was obtained (Shao *et al.*, 2011*a*). On set-up 3, we measured the applied voltage, the discharge current, and the count of the X-rays produced in the discharge. The voltage probe was a capacitive voltage divider connected to the high-voltage output. The current probe was a current diverter made of a coaxial tubular high-frequency resistor shunt. The above two signals were recorded by a digital oscilloscope (LeCroy WR204Xi, 2 GHz, 10 GS/s). For detecting X-rays count (density), an on-line system consisted of an X-ray detector with a NaI (Tl) scintillator and a photomultiplier tube (PMT), and an integrated multichannel analyzer was used. The X-ray detector was located 12 cm below the air gap. A detailed description of the X-ray measurement

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and calibration could be found elsewhere (Shao *et al*, 2012; Zhang *et al.*, 2010).

EXPERIMENTAL RESULTS ON SET-UPS 1 AND 2

Experimental results on the generation of the SAEB show that when fresh cathodes are used, the minimum amplitude of the beam current is detected within the first few pulses and the amplitude gradually increases with the training of the cathodes. Therefore, each cathode was trained by several tens or hundreds of pulses before measurements in our experiments.

The SAEB measurements taken in this work demonstrated that with thousands of pulses applied to the stainless steel cathode, the amplitude of the beam current within a series varied but slightly. The difference among average amplitude of the beam current in different series of experiments could be attributed to a change in humidity and air temperature under different weather conditions (Kostyrya *et al.*, 2010). In our measurements, we tried to minimize the influence of the above factors on the amplitude of the SAEB current. All comparative experiments (series of experiments) were performed within one day in a time as short as possible, and a series of experiment was conducted within 4 hours.

The comparatively small variation in the amplitude of the SAEB current observed in our experiments during continuous pulses applied on the cathode was inconsistent with the data in some other works (Mesyats *et al.*, 2008). In their works, after "polishing" of the tubular cathode edge in vacuum, the amplitude of the SAEB current decreased at first, and then, the beam current ceased at all. However, during the experiments with tubular stainless steel cathodes on the SLEP-150M and RADAN-220 generators, we had never observed termination of the generation of the SAEB with optimum interelectrode gaps even if more than 100 thousand pulses were applied to the cathode.

On set-up 1, before taking series of experiments to study the effect of copper and stainless steel cathodes on the generation of the SAEB, the dependence of the amplitude of the SAEB current on the inter-electrode gap was investigated. In the case of stainless steel cathode, like in other experiments on the SLEP-150M and SLEP-150 generators (Rybka *et al.*, 2012), the optimum inter-electrode gap was around 12 mm. Figure 3 shows the dependence of the average amplitude of SAEB current on the interelectrode gap for the cathode made of a 200 μm-thick Cu foil. For each point, 20 pulses were applied. The maximum amplitudes were detected at a gap of 10 or 12 mm. Based on the dependence mentioned above, a 12-mm interelectrode gap was chosen to compare the amplitudes of the SAEB current for different cathode materials

Tables 1, 2, and 3, and Figures 2, 4, and 5 present the results of the experiments on the SLEP-150M generator. As mentioned above, recording the incident and reflected voltage waves allowed us to reconstruct the voltage across the gap. The gap voltage amplitudes reconstructed from the incident and reflected voltage waves was consistent with the voltage amplitudes calculated by the program KARAT (Tarasenko *et al.*, 2009). The difference between the voltage amplitude reconstructed and calculated was not greater than 20%.

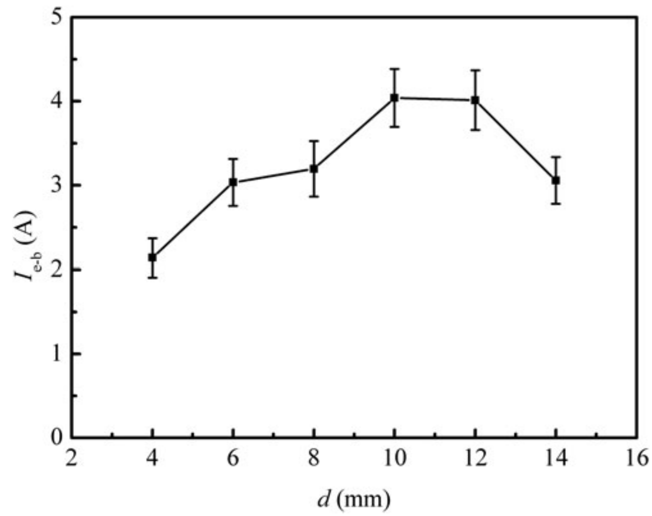

Fig. 3. Dependence of electron beam on gap spacing. Set-up 1 (Generator SLEP-150M). Cu cathode.

Tables 1, 2, and 3, and Figures 2c, 2d, 4, and 5 shows the effect of cathode material on the SAEB current. The amplitude of the SAEB current decreased in the following sequence of the cathode material: stainless steel, titanium, niobium, copper, and aluminum. This experimental result also confirms a previous conclusion on the optimum cathode material for a gas diode (Tarasenko *et al.*, 2004; 2005; 2008*c*). The highest amplitude of the SAEB current was found with a stainless steel cathode (see Tables 1, 2, and 3, and Figs. 2c, 2d, 4, and 5). Tables 1 and 2 present the average amplitudes of the SAEB current $I_{e\text{-}b}$ and the confidence interval of the amplitude $\Delta I_{e\text{-}b}$ obtained in 20 pulses for different cathodes in two series of experiments (Experiments 1 and 2). In both series of experiments, the highest amplitude of the SAEB current was detected with the stainless steel cathode, whereas the lowest amplitude of the SAEB current was detected with the aluminum cathode. The difference between the amplitudes of the SAEB currents for the same cathode materials in these two series taken at an interval of one

Table 1. *Average amplitude of the SAEB current $I_{e\text{-}b}$ from 20 pulses and work function (Michaelson, 1950) with different cathodes. Set-up 1 (Generator SLEP-150M). Gap spacing 12 mm. Diameter of tube cathode 6 mm. Collector 20 mm. Number of experiment 1*

Material of cathode	Stainless steel (Fe-Cr-Ni alloy)	Ti	Nb	Al
$I_{e\text{-}b}$, A	5.3	3.9	2.4	1.3
$\Delta I_{e\text{-}b}$, A	0.37	0.51	0.28	0.09
Work function, eV	4.18–4.84	4.09	3.99	3.74

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Table 2. *Average amplitude of the SAEB current $I_{e\text{-}b}$ from 20 pulses with different cathodes. Set-up 1 (Generator SLEP-150M). Gap spacing 12 mm. Diameter of tube cathode 6 mm. Collector 20 mm. Number of experiment 2*

Material of cathode	Stainless steel	Ti	Nb	Cu	Al
$I_{e\text{-}b}$, A	8.7	5.5	4.4	2.5	1.8
$\Delta I_{e\text{-}b}$, A	1.27	0.47	0.46	0.43	0.21

week, in our opinion, was due to the influence of air humidity.

In the experiments, it was found for the first time that the voltage across the gap changed with different cathode materials (Figs. 2c, 2d, 4, and 5, and Table 3). Figures 4 and 5, and Table 3 illustrate the results of four different series of experiments on the set-up 1. Figure 5 and Table 3 show average values of maximal voltage across the gap for 20 pulses. The maximal gap voltage decreased in the following sequence of the cathode material: stainless steel, titanium, niobium, copper, and aluminum. The highest voltages across the gap were observed with the stainless steel cathode in all series experiments. Note that even with a stainless steel cathode, the gap voltage was much lower than the output voltage without load, which was about 260 kV.

From our research on the effect of cathode material on the SAEB current and the maximal voltage across the gap, it is clear that the SAEB current and the maximal voltage across the gap decrease with the same sequence of the cathode material. Thus, the highest amplitude of the SAEB current with a stainless steel cathode could be explained by the highest voltage across the gap during the SAEB generation under these conditions.

The experiments show that the amplitude of the SAEB current is influenced not only by the material of cathode edge but also by the material of the cathode side wall at the tubular cathode (Table 3). In the case of Experiment 3, for a stainless steel cathode, the gap breakdown voltage considerably decreased and the amplitude of the SAEB current declined when the side wall was coated by copper foil. For a copper cathode, the amplitude of the SAEB current reduced much greater, but the voltage across the gap increased somewhat.

Table 3. *Average amplitude of the SAEB $I_{e\text{-}b}$ from 20 pulses with different cathodes. Setup 1 (Generator SLEP-150M). Gap spacing 12 mm. Diameter of tube cathode 6 mm. Collector 20 mm. Number of experiment 3*

Material of cathode	$I_{e\text{-}b}$, A	U_m, kV
Stainless steel	7.2	130
Stainless steel + back side of tube from Cu	4	99
Cu	3.2	106

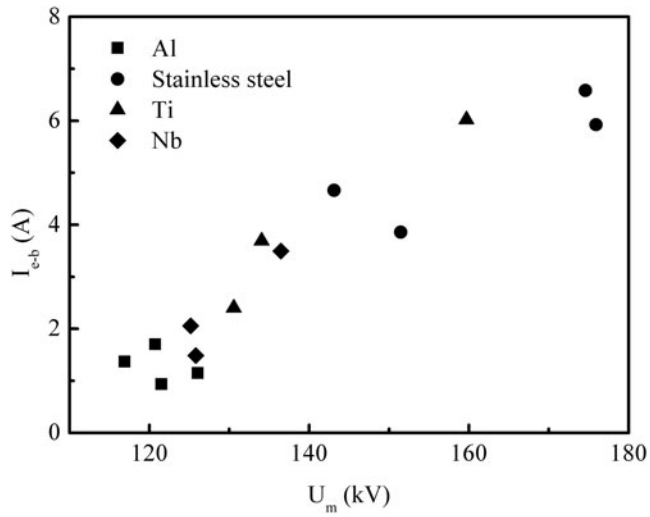

Fig. 4. Dependence of amplitude of SAEB current under maximal voltage on cathode material. Gap spacing 12 mm. Set-up 1 (Generator SLEP-150M).

Additional experiments for different cathode materials under the conditions of the increased cathode diameter were performed on set-up 1 using a SLEP-150 generator. The generator SLEP-150 is the same as SLEP-150M except that the SLEP-150 generator had only one short transmission line with one capacitive divider (Tarasenko *et al.*, 2011). In these experiments, the thickness of the tubular cathode wall was 100 μm. The inter-electrode gap was 8 mm, which was optimum for the cathode of diameter 20 mm. Each point corresponded to the average number of electrons in a series of 10 pulses. As can be seen from Table 4 (Experiment 4), the main tendency was the same and the largest number of electrons downstream of the foil was detected with a stainless steel cathode and the smallest number was found with an aluminum cathode.

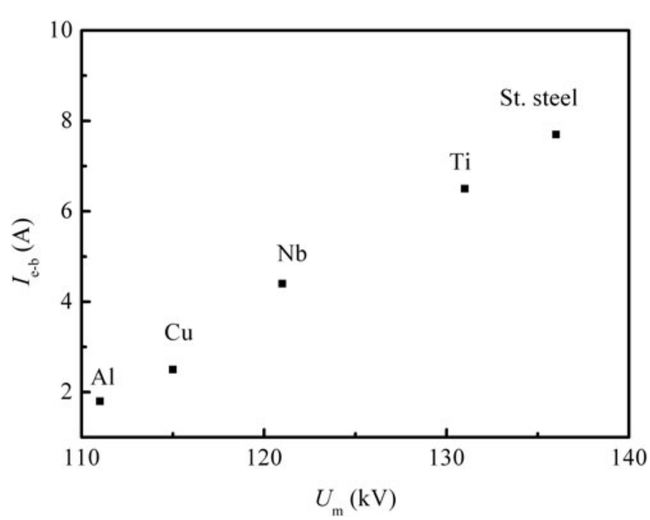

Fig. 5. Dependence of average amplitude of SAEB current under maximal voltage on cathodes material. Gap spacing 12 mm. Set-up 1 (Generator SLEP-150M).

Table 4. *Average number of electrons in SAEB N_e from 20 pulses with different cathodes. Setup 1 (Generator SLEP-150). Disk collector 70 mm. Number of experiment 4*

Material of cathode/diameter of cathode	Stainless steel/Ø28 mm	Stainless steel/Ø20 mm	Cu/Ø20 mm	Brass/Ø20 mm	Al/Ø20 mm
N_e with gap 8 mm, number of electrons	1.2×10^{10}	1.1×10^{10}	6.5×10^{9}	5.9×10^{9}	4.5×10^{9}

Experiments to verify the optimum cathode material were also performed on set-up 2 with a longer voltage pulse rise time (about 1 ns). Two inter-electrode gaps of 12 mm and 16 mm were selected for the experiments. The thickness of the copper and aluminum foils were decreased to 50 μm and the stainless steel cathode was replaced by a permalloy (alloy Fe and Ni) cathode. The experimental results confirmed the same effect of the cathode material on the amplitude of the SAEB current as we obtained on set-up 1. Table 5 presents the average number of electrons from a collector with a 20-mm-diameter receiving part in 10 pulses for the beam extracted through an AlBe foil of thickness 45 μm and a grid of transparency 60%. Note that the number of beam electrons decreased with the increase of the voltage pulse rise time.

EXPERIMENTS RESULTS ON SET-UP 3

The results obtained on set-up 3 are presented in Figures 6, 7, and 8. The experimental data were obtained when the inter-electrode gap was 8 cm with which the highest X-ray count was detected (Shao *et al.*, 2011*a*; 2012), the pulse repetition frequency (PRF) was 500 Hz. In these experiments, four cathodes was using. The diffuse discharges were formed and their integral glow varied little from one cathode material to another (Fig. 6). Note that the pulse shape of the voltage and current through the gap (Fig. 7) and X-rays count (Fig. 8) did not depend on the cathode material. These results differed from those obtained on set-ups 1 and 2, however, it could be given a unified conceptual explanation. The results for set-ups 1, 2, and 3 would be compared in the next section.

Table 5. *Average number of electrons in SAEB N_e from 10 pulses with different cathodes. Setup 2 (Generator RADAN-220). Diameter of tube cathode 5.3 mm. Collector 20 mm*

Material of cathode/ thickness of tube cathode	Stainless steel/ 100 μm	Permalloy (Fe-Ni alloy)/ 50 μm	Cu/ 50 μm	Al/ 50 μm
N_e with gap 12 mm, number of electrons	1.9×10^{9}	1.3×10^{9}	9.3×10^{8}	2.2×10^{8}
N_e with gap 16 mm, number of electrons	1.9×10^{9}	1.3×10^{9}	8×10^{8}	1.6×10^{8}

Measurements of the X-ray count at different pulse repetition frequencies showed that when the PRF increased, the X-ray count disproportionately increased with the number of pulses during the same time period. A two-fold increase in frequency and number of pulses led to a triple increase in X-ray density for all four cathodes (Fig. 8). Thus, the conduction current through the gap increased.

DISCUSSIONS

First, let us analyze which processes are responsible for the effect of the cathode material on the SAEB amplitude under our experimental conditions. The current in the gap arises because electrons emits from the cathode. The highest electric field strength in the gap arises at the cathode is due to its macro-irregularities (sharp edges of the tubular cathodes made of thin foil). Moreover, because of the micro-irregularities on the cathode surface, the electric field strength increases one order of magnitude and more (Mesyats, 2007). During the rise time of the voltage pulse, the electric field concentration at the sharp edge of the cathode produces field emission current. The effect of the cathode material on the number of SAEB electrons and on the voltage amplitude across the gap, in our opinion, is related to the different electron work functions and photoemission electrons from the cathode for different metals. The electron work function depends on the type of metal used as the cathode material and the state of its surface. In order to determine the work function, the cathode surface is normally subjected to special cleaning, and the measurements are taken in pure vacuum. In our experiments, the cathode is in atmospheric-pressure air, so the cathode surface will be eroded and oxidized after beam currents and discharge currents of a few kiloamperes flowing through the gap. These operating conditions could affect the electron work function at the cathode. Therefore, for comparison, we use reference data (Michaelson, 1950), when surface cleaning techniques for determination of the electron work function for different metals were far from perfect. These reference data are the averages of earlier data published from 1924 to 1949, which are presented in Table 1. The respective average electron work function for aluminum, niobium, titanium, and stainless steel (iron, chromium, and nickel in the table) is consistent with the data on the amplitude of the SAEB current and voltage across the gap during the generation of the SAEB in our

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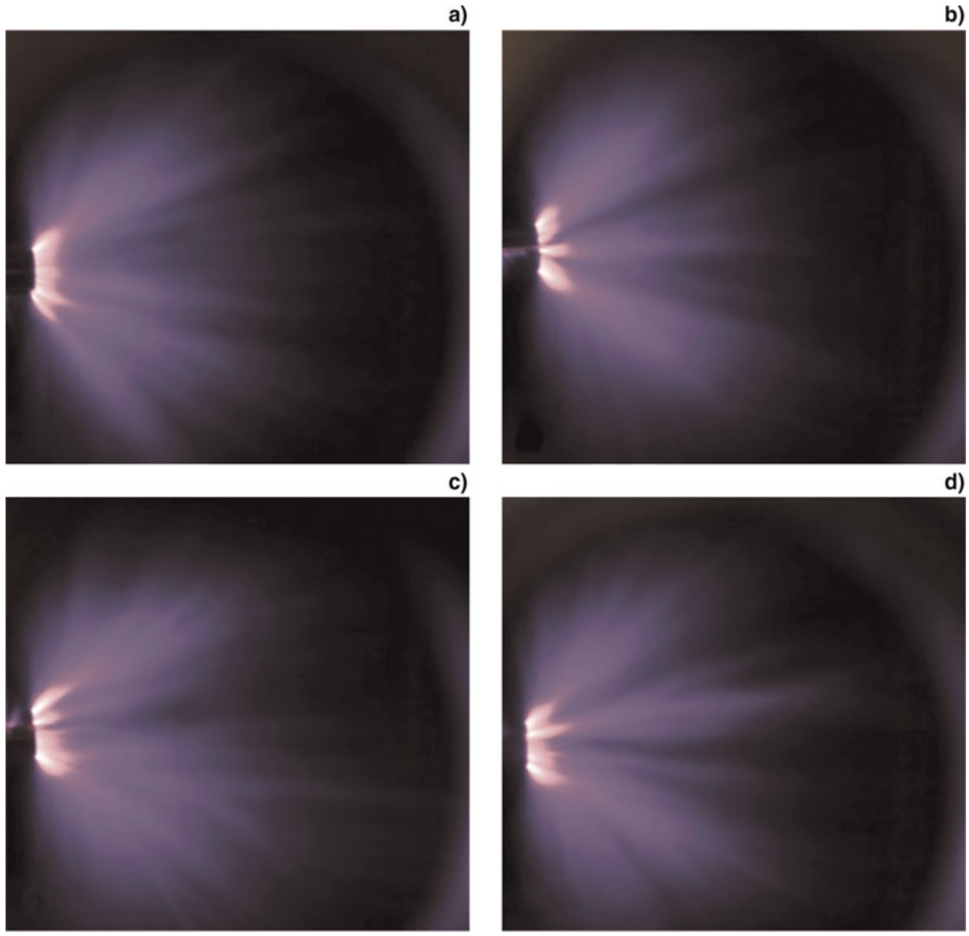

Fig. 6. (Color online) Discharge images taken by a digital-camera under different conditions. (**a**) aluminum cathode, (**b**) titanium cathode, (**c**) stainless steel cathode, (**d**) copper cathode. Set-up 3 (Generator SPG200N). Gap spacing 8 cm. PRF 500 Hz.

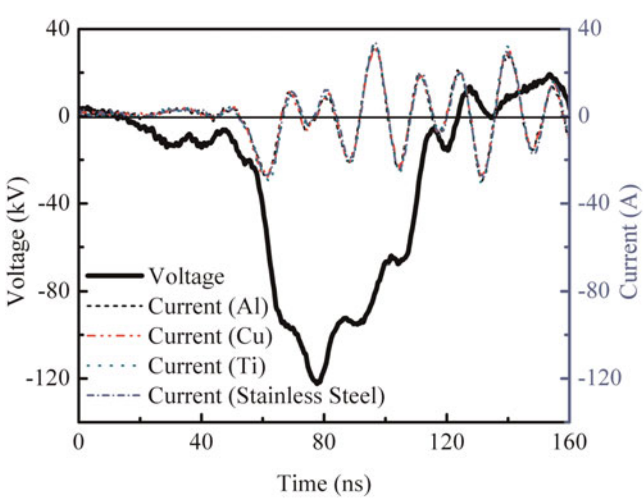

Fig. 7. (Color online) Applied voltage and discharge current waveforms with the cathodes of different materials (aluminum, titanium, stainless steel, copper). Set-up 3 (Generator SPG200N). Gap spacing 8 cm, PRF 500 Hz.

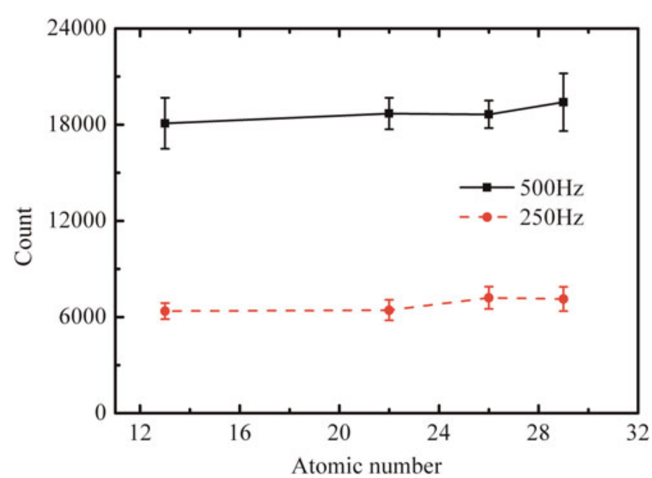

Fig. 8. (Color online) Dependence of X-ray counts under atomic number of cathode material on different pulse repetition frequencies. Set-up 3 (Generator SPG200N). Gap spacing 8 cm.

experiments with set-up 1. We suppose that the decrease of electron work function for aluminum and niobium cathodes makes a current in the gap increase with smaller delays and lower voltages. Therefore, the amplitude of the voltage across the gap decreases, and the number of the SAEB electrons decreases. This supposition is also confirmed by the smaller amplitudes of the SAEB current with fresh cathodes. During the operation with a fixed cathode, the primarily exploding edges are those at which the electric field is dramatically amplified. These edges are formed at the cathode in manufacturing. After several tens of pulses, these edges become blunt. Besides, the cathode surface is partly cleaned from dielectric films. Thus, electron emission from the cathode begins at a higher voltage. The electron work function for a copper cathode (4.47 eV) (Michaelson, 1950) drops out of the observed tendency. Apparently, after cleaning the cathode surface in vacuum, the electron work function for copper increases greatly compared to that of other metals.

Next, let us consider the processes in a gas diode which take place after emission of initial electrons. For field emission, the required electric field is more than 10^7 V/cm (Fursey, 2003), and for the runaway of electrons in atmospheric-pressure air, according to the Yakovlenko's nonlocal runaway criterion, it is more than 10^6 V/cm (Yakovlenko, 2007). If the nonlocal runaway criterion is fulfilled, a considerable number of electrons (fast electrons) will switch to the runaway mode. Consequently, the number of field emission electrons which are bound to switch to the runaway mode is considerable. However, because the electric field rapidly decreases with the distance from micro- and macro-irregularities of the cathode, which part of field emission electrons can switch to the runaway mode under the experimental conditions is still difficult to determine. To solve such difficulties, a complex program that models the discharge development is required as well as the actual geometry of cathode and micro-irregularities and the actual space charge should be taken into account.

Furthermore, the role of fast electrons in the process of discharges would be discussed. When the fast electrons gain energy, they will move from the cathode and ionize the gas. As doing so, the fast electrons mainly release their energy at small distances away from the cathode at the rise time of the applied voltage. When the fast electrons ionize the gas, initial electrons will appear at the cathode, and give rise to electron avalanches. The high concentration of initial electrons and the overlapping of heads of the electron avalanches lead to a diffuse (volume) discharge near the cathode. According to the simulation results (Levko *et al.*, 2012*a*), the highest electron concentrations at the initial discharge stage were detected 0.1 mm away from the cathode. In another experiments with pulse duration of 0.2 ns, brightly glowing plasma was observed in a corona discharge several millimeters away from the cathode (Baksht *et al.*, 2009).

As shown in the previous works (Tarasenko *et al.*, 2008*c*; Baksht *et al.*, 2009), a volume discharge was produced not only at the sharp edge but also at the side surface of a tubular cathode. In our opinion, it is the short-wave radiation from gas at resonant transitions (Bokhan & Zakrevsky, 2010) and/or the characteristic X-ray radiation (Kozyrev *et al.*, 2011) that provide additional electron emission from the cathode and from the side surface of a tubular cathode. Therefore, the total current from the cathode in the gas diode during the generation the SAEB is determined by photoemission from the cathode, and in certain modes, also by explosive electron emission. Photos of the discharges in a gas diode at voltage pulse duration of 0.2 ns had revealed the existence of cathode spots and the appearance of glow plasmas at the cathode side wall (Baksht *et al.*, 2009). The attachment of the plasma to the side wall of the cathode, where the electric field amplification is smaller compared to that at the sharp edge of the cathode, can be explained by photoemission from the cathode. The photoemission increases the discharge current in the gap and decreases the gap voltage. Among the examined cathodes, the longest-wave photoemission boundary and the least work function are found in the case of aluminum cathodes.

Our experiments show that the material of the side surface of the cathode could significantly affect the amplitude of the SAEB current and the voltage on gap. The effect can be explained as follows: the current from the cathode of the gas diode in the initial stage is determined by field emission, and its value is small. The field emission current from one edge was less than 1 A even at short voltage pulses (Ganter *et al.*, 2006). Previous studies on the SLEP-150M generator (Baksht *et al.*, 2009) demonstrated that during the generation of the SAEB, the current through the gap reached hundred of amperes, and the cathode, with a 12-mm inter-electrode gap, revealed no more than 10 cathode spots which arose at the transition from field emission to explosive emission and to photoemission.

During the development of breakdown, part of the current in the gap is due to the conduction current in the dense plasma of an ionization wave whose front moves from the cathode to the anode. The other part of the current is due to the dynamic capacitive current between the dense plasma front and the anode. Therefore, in order to provide the conduction current in the gap during the generation of the SAEB, efficient mechanisms of electron emission from the cathode should make their contribution. As the gap voltage or the pulse width increases, the field emission gives way to explosive emission. With a 12-mm inter-electrode gap and a stainless steel cathode, the explosive emission can provide a current of about 1 kA and more in about 1 ns. This current was obtained when the gas diodes were pumped by a forevacuum pump (Tarasenko *et al.*, 2010). However, the rising rate of the beam current for the vacuum diode within the first 50 ps was lower than that during the generation the for the gas diode filled with nitrogen and helium at low pressures (Tarasenko *et al.*, 2010). Thus, there should be a second mechanism that provides efficient electron emission from the cathode. The second mechanism of generation the SAEB is the photoemission from the cathode.

For the tested metal cathodes (the sharp edge of the cathode and the side surface of the cathode), the most delayed electron emission is found in the case of a stainless steel cathode, causing an increase in voltage amplitude across the gap and hence an increase in the amplitude of the SAEB current.

The above conclusion agrees with the data on amplitudes of the SAEB currents at different gap voltages (Tarasenko, 2007). The data were obtained with different voltage amplitudes and stages of the generation of the SAEB. As to the voltage stages, the SAEB was generated both during the voltage pulse rise time and within the voltage pulse plateau. A notable time delay in the generation of the SAEB was observed with decreasing the amplitude of the voltage pulse of the generator. It was also observed that the stability of the generation of the SAEB was affected by comparatively long duration of voltage pulse (about 2 ns). As the generation delay of the SAEB decreased, the voltage across the gap during the generation of the SAEB greatly decreased and the amplitude of the SAEB current declined. Under these conditions, the highest amplitudes of the SAEB current were detected during its generation within a flat portion of the voltage pulse. The rise time of the voltage pulse was thus increased though the SAEB was generated at the maximum voltage across the gap.

The generation mechanism for most of the SAEB electrons, in our opinion, is associated with the generation of runaway electrons between the dense plasma front and anode. During the rise time of the voltage pulse, comparatively dense diffuse plasma is formed at the cathode. Because of the development of electron avalanches, the plasma formed at the cathode is polarized. When the electrons move to the anode, heavy positive ions almost stay within a fraction of a nanosecond. Parts of the electrons at the ionization wave front are expelled by excess negative charges and are accelerated by the positive potential of the anode. This leads to the generation of most of the runaway electrons.

To increase the amplitude of the SAEB current in the setups with the SLEP-150, SLEP-150M, and RADAN-220 generators, it was required to delay the electron emission from the cathode and to increase the maximum gap voltage during the generation of the SAEB. The gap voltage amplitude increased because the voltage during the generation of the SAEB was lower than the voltage without load. At a rise time of the voltage pulse of about 1 ns and shorter, the amplitude of the SAEB current increased by using cathodes with a large work function; in this paper, with a stainless steel cathode. A considerable increase in the amplitude of the SAEB current could be expected with a platinum cathode, whose work function is 5.29 eV (Michaelson, 1950).

In the repetitive pulse mode when the rise time of the voltage pulse increased to about 15 ns and the interelectrode gap increased to 8 cm were used, the gap breakdown voltage on set-up 3 was not affected by the cathode material. Under these conditions, the X-ray density also was not affected by the cathode material. Note that no matter which cathode material was used, the repetitive pulsed mode of the generator could guarantee the stable voltage of initial discharges with a low conduction current density.

The triple increase in X-rays count with a double increase in PRF can be explained by the effect of the residual particles generated by the previous pulses on the electron emission from the cathode and by the heating of the gas in the gap. As the PRF increases, the amplitude of the voltage pulse remains constant, but the conduction current in the gap and the number of runaway electrons increases. Another explanation is related to the heating of the gas, with trains of pulses applied on the gap, the concentration of molecules of gases in the gap decreases and the number of runaway electrons increases.

CONCLUSION

In this paper, the effect of cathode material on the amplitude of a SAEB current and on the amplitude of the voltage across the gap during the generation of the SAEB was studied. The experiments were performed in atmospheric-pressure air with tubular cathodes made of different metals. The cathode materials in the experiments were stainless steel, permalloy, titanium, niobium, copper, brass, and aluminum. The high-voltage pulses with rise times of 0.3, 1, and 15 ns applied to the tubular cathode-plane anode gap were produced by three generators. It is confirmed that at a voltage pulse rise time of 1 ns and shorter, the SAEB amplitude depends on the cathode material. On the setup with the SLEP-150M generator, it is shown for the first time that the amplitude of the voltage across the gap during the generation of the SAEB depends on the cathode material and reaches the highest value with a stainless steel cathode. When all other factors are equal, the highest maximal amplitudes of the SAEB current are attained with cathodes that ensure the existence of the maximal voltages across the gap. Furthermore, the amplitude of the SAEB current is affected not only by the material of the sharp edge of a tubular cathode, but also by the material of the side surface of a tubular cathode. It is supposed that the increase in gap voltage is due to a decrease in electron emission from the cathode during the discharge initiation.

It is demonstrated that when the rise time of the voltage pulse and the electrode gap are increased, the cathode material will no longer affect the amplitude of the voltage across the gap and X-ray density. In addition, it is found that in the repetitive pulsed mode, increasing the PRF from 250 to 500 Hz could make a triple increase in X-ray density. The obtained result is explained by the effect of the residual particles generated by the previous pulses on the current in the gap and by the heating of the gas in the gap.

We think that the amplitude of a super-short avalanche electron beam (about 100 A) obtained at a FWHM of 100 ps in atmospheric-pressure air (Kostyrya *et al.*, 2012) is not a limit under experimental condition and can be increased by using generators with a voltage pulse amplitude of about 500 kV or higher and by optimizing the rise time of the voltage pulse and the cathode design.

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