Generation of direct and reverse runaway electron beams in atmospheric air using anodes made of different metals

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Abstract. This study presents results on the generation of runaway electron beams propagating from the cathode in both directions: towards the anode and in the opposite direction. The investigations were carried out in atmospheric air excited by nanosecond voltage pulses of both polarities. In the experiments, anodes made of aluminum, brass, and tantalum were used. It was shown that the amplitude of the current pulse of an electron beam generated in the direction opposite to the anode depends on the atomic number of the metal from which the anode is made. At the same time, it is important to note that for a beam generated in the direction of the anode, such dependence was not observed.

1. Introduction

Currently, pulsed and continuous electron beams generated in vacuum diodes and then extracted through thin foils into a gaseous medium are widely used for pumping gas lasers, exciting cathodoluminescence, and in other applications [1–8]. As a rule, such beams consist of electrons with an energy of hundreds of kiloelectronvolts (keV), and their current density can vary from a few milliamperes to hundreds of amperes.

To extract an electron beam from a vacuum diode, foils made of different metal foils [1–4, 7] or ceramics (in miniature accelerators with electron energy of tens of keV) [8] are used. The current losses of the extracted electron beam depend on the material and thickness of the anode foil. Therefore, foils made of metal with a small atomic weight, e.g., beryllium (Be), aluminum (Al), AlBe, titanium (Ti) are commonly used as an anode in accelerators [1–3, 7].

It is also known about the use of iron foils in repetitively pulsed accelerators, which are used to excite KrF-lasers [4]. In this case, the choice of material with a relatively large atomic number is explained as follows. As a result of contact with fluorine, a protective layer is formed on such a foil, which significantly increases the service life of the anode.

For a number of applications, e.g., in studying the mechanisms of cathodoluminescence in crystals or preionization in lasers, electron beams with a short (~ 100 ps or less) current pulse duration are used. Therefore, as shown in [9–11], in some cases accelerators based on gas diodes are most appropriate for these purposes. Also nowadays, there are more and more directions of practical use of diffuse discharges initiated by runaway electrons in gaps with non-uniform distribution of the electric field strength [12–14]. Runaway electron beams (RAEBs) generated in diodes filled with atmospheric
air and other gases have been investigated for quite a long time (see, e.g., papers and monographs [15–20]). Such beams we call supershort avalanche electron beams (SAEBs) [21]. According to different papers, the SAEB parameters depend on the material from which a cathode and an anode are made [15–23].

The most comprehensive study of the effect of the cathode material on the amplitude of a SAEB current pulse are presented in [22, 23], where diodes filled with atmospheric air were used. In [22], high-voltage pulses with different rise times (0.3, 1 and 15 ns) were applied to the gap formed by a plane anode and a tubular cathode made of different metals (stainless steel, Cu, Al, Ti, niobium (Ni), permalloy and brass). It was shown that with the rise time of 0.3 or 1 ns, the voltage across the discharge gap depended on the material of the tubular cathode. Its magnitude was greatest when using a stainless steel cathode. In this case, the corresponding maximum SAEB current was registered. It was concluded that the difference in the magnitude of the voltage across the gap is due to the difference in the electron emission threshold for different metals [22]. Consequently, when a voltage pulse with the rise time of no more than 1 ns is applied to the interelectrode gap, the SAEB current pulse amplitude can be increased by using a cathode made of a metal with a small work function. In [23], the SAEB current pulse characteristics were also investigated using cone-shaped cathodes made of different metals. It was found that due to the hindered electron emission the largest amplitude of a SAEB current pulse is recorded when using the stainless steel cathode.

However, in [22], it was found that with an increase in the rise time of the applied voltage pulse and a distance between the electrodes to 15 ns and 8 cm, respectively, the cathode material had almost no effect on the voltage across the gap. The X-ray radiation power density measured with a photomultiplier tube equipped with a NaI scintillator was also independent of the cathode materials. As expected, under the same conditions, an efficiency of X-rays initiated by SAEB depends on the anode material [24], and the radiation power increases with increasing atomic number of the metal from which the anode is made.

As in vacuum diodes, in nanosecond pulsed discharges the SAEB current pulse amplitude is affected by the anode material. The current losses of an electron beam extracted from a gas diode depend on the material and thickness of the anode. Accordingly, the SAEB current pulse amplitude increases with decreasing foil thickness, as well as with the use of a metal with a small atomic weight.

On the other hand, it is known [25, 26] that in atmospheric air the anode material has a significant effect on the amplitude and duration (full-width at half maximum, FWHM) of a beam current pulse in the case when runaway electrons are generated in the direction opposite to the anode – reverse runaway electron beam (RRAEB). This is confirmed by the fact that the number of electrons generated in the opposite direction with a tantalum anode is four times more than with aluminum one. It should be noted that in [25, 26] electron beams were generated in both directions from the grounded grid cathode: towards the plane high-voltage anode (direct RAEB – SAEB), and in the opposite direction (reverse RAEB – RRAEB). The first of them, generated in diodes with a high-voltage anode, is identified by bremsstrahlung X-rays arising. The RRAEB current was registered using a collector installed behind an additional grounded Al foil reinforced with a grid. Nevertheless, studies of the effect of the anode material on the parameters of the electron beam propagating in the direction of the anode have not been previously carried out. Also, the parameters of SAEB and RRAEB were not previously compared using the same voltage pulse generator.

The objective of this study was to reveal and investigate the effect of the anode material on the generation of SAEB and RRAEB in a nanosecond pulsed discharge in atmospheric-pressure air. Since the effect of the material and thickness of the anode foil on the energy losses in the beam is quite predictable, large-thickness anodes, completely absorbing electrons, were used in the experiments. However, to extract SAEB under these conditions, a small-diameter aperture was made in the middle of each anode.
2. Experimental setups

In the experiments, two setups were used. A SLEP-150 voltage pulse generator was the basis of both setups. Part of the experimental setup no. 1 with a high-voltage electrode of positive polarity (high-voltage anode) is schematically presented in figure 1.

The same design of a high-voltage output was used in [25, 26]. The anode (4) of the gas diode was a disk with rounded edges. Its thickness and diameter were 3 and 36 mm, respectively. The anode surface facing the cathode (7) was made of Al or Ta. The cathode (7) was made of several steel wires strunged parallel to each other across the 3-mm-thickness metal ring (5). The diameter of each wire and the step between them were 0.2 and 4 mm, respectively. The inner diameter of the ring (5) was 62 mm. An aluminum foil (8) reinforced with a grid with a transparency of 90% was located on the other side of the ring. Collectors (9) with a different diameter of a receiving part were used to measure the runaway electron beam current. A collector was mounted directly behind the 10-µm-thickness Al foil (8). The connection of all the above elements to each other was carried out using appropriate flanges. The distance \( l \) between the grid cathode (7) and the cathode foil (8) was 3 mm.

The total number of electrons was measured with a collector with a 56-mm-diameter receiving part (collector #1; see figure 1). Using diaphragms, the RRAEB current pulse duration was measured with subnano- and picosecond resolution. In the first case (temporal resolution is \(~ 80\) ps), electron beam current pulses were registered behind a diaphragm with a 20-mm-diameter aperture using a collector with the diameter of the receiving part of 20 mm. In the second case, the diameter of the aperture in the diaphragm, the diameter of the collector receiving part, and the temporal resolution were 1 mm, 3 mm, and \(~ 20\) ps, respectively. When registering the direct runaway electron beam, the polarity of the generator was inverted.

Figure 2 shows the design of the high-voltage output of the SLEP-150 pulse generator (see [17] and Chapter 1 in [20]), a gas diode, and a collector (#2) with a 3-mm-diameter receiving part (setup no. 2).

One of the electrodes of a high-voltage line (1) of the generator is a body of a peaking spark gap (2). This made it possible to reduce the length of the line. Finally, a voltage pulse of negative polarity with the amplitude of \(~ 150\) kV and FWHM of \(~ 1\) ns (on matched load) was applied to the gap with a width \( d \). The voltage pulse rise time was determined by the peaking spark gap (2). When the latter operated optimally, the voltage pulse rise time (at the level of 0.1–0.9) was \(~ 250\) ps. A short transmission line (3) with a wave impedance of \(~ 100\) \( \Omega \) was inserted between the gas diode (5) and the high-voltage line (1). The amplitude of the voltage pulse propagating through the transmission line depended on the breakdown voltage of the peaking spark gap. In the idling mode, the amplitude of the voltage pulse arriving the discharge gap was doubled.

Because the generator produced voltage pulses with negative polarity, the high-voltage electrode was a cathode. The cathode was a 6-mm-diameter tube made of a 100-µm-thickness stainless steel foil. Thick Al, Ta and brass foils were used as an anode (8). In the middle, each foil had an aperture with the diameter of 1 mm. On the collector side, the anode foil was reinforced with a 5-mm-thickness metal plate (9). There was a collimating aperture with the diameter of 1 mm in the centre of the plate. The gap width \( d \) was 12 mm.

The SAEB current was measured using the collector #2. A capacitive voltage divider (4) was mounted at the end of the transmission line filled with transformer oil. The distance between the divider and the plane grounded electrode was 22 mm.

The diodes were filled with air at a pressure of 100 kPa. Electrical signals from the capacitive voltage divider, a current shunt, and the collectors were recorded using a LeCroy WaveMaster 830 Zi-A digital oscilloscope (bandwidth is 30 GHz, sampling rate is 12.5 ps). The signals were delivered to the oscilloscope via 1-m-length RG58-A/U (Radiolab) high-frequency cables with Suhner 11 N-50-3-28/133 NE and SMA (Radiall R125.075.000) connectors. To attenuate signals, 142-NM (Barth Electronics) high-frequency attenuators with a transmission band of up to 30 GHz were used. The oscilloscopes were triggered by a signal from the capacitive voltage divider. The voltage and RRAEB/SAEB beam current pulses were recorded simultaneously. In addition, the X-ray dose was measured with an Arrow-Tech dosimeter (Model 138).
It should be noted that the rise time and the amplitude of voltage pulses on setups no. 1 and no. 2 was slightly different. It is explained by the differences in the voltage pulse polarity and gas diode design.

**Figure 1.** Design of the gas diode in the experimental setup no. 1: 1 – coaxial line; 2 – insulator; 3 – capacitive voltage divider; 4 – anode; 5 – steel ring; 6 – collector body; 7 – grid cathode composed of wires; 8 – cathode foil; 9 – collector receiving part.

**Figure 2.** Schematic image of the high-voltage output unit of a SLEP-150 generator, gas diode, and collector with the 3-mm-diameter receiving part (setup no. 2): 1 – high-voltage line; 2 – peaking spark gap; 3 – transmission line; 4 – capacitive voltage divider; 5 – gas diode; 6 – tubular cathode; 7 – collector receiving part; 8 – foils from different metals with a 1-mm-diameter aperture; 9 – 5-mm-thickness metal plate with a 1-mm-diameter aperture (collimator); 10 – collector body; 11 – insulator. On the left, several turns (12) of the high-voltage coil of the pulsed transformer are shown. On the right, the inductance coil (13) connecting the inner electrode of the transmission line (3) to the generator housing is shown on the insulator (11).

3. Experimental results

3.1. Effect of the anode material. Setup no. 1
Using the setup no. 1, investigations of the effect of the anode foil material on the RRAEB parameters were performed. All things being equal, RRAEB current pulses were registered behind the additional Al foil (8 in figure 1). Figure 3 demonstrates the dependencies of the number of electrons in RRAEB on the gap width $d$ between the grid cathode and the disk-shaped anode for two anode materials.

When using the tantalum anode, the number of electrons in the reverse beam measured from the entire foil surface increased by $\sim 4$ times ($\sim 7 \times 10^9$ electrons) compared with what observed when using the Al anode ($\sim 2 \times 10^9$ electrons). A significant increase in the number of fast electrons behind the additional cathode foil was unexpected. These data confirm the result obtained earlier [25, 26]. When measuring the X-ray dose behind the cathode, a fourfold superiority was also observed for the Ta anode. When using the tantalum anode, with the same SAEB current and the simultaneous generation of RRAEB, the measured X-ray dose was 2 mR.
Figure 3. Dependencies of the RRAEB current pulse amplitude on the gap width $d$ between the grid cathode and the disk-shaped anode for (1) Ta and (2) Al anodes.

Figure 4 demonstrates waveforms of the RRAEB current for the Al and Ta anodes recorded with picosecond temporal resolution. In these experiments, the beam current was recorded behind a diaphragm made of a 250-µm-thickness Cu foil with a 1-mm-diameter aperture. The centre of the aperture was located on the longitudinal axis of the gas diode. The amplitudes of RRAEB current pulses for the Ta anode were much higher ($\sim 5$ times) than those for the Al anode. However, the typical FWHM of the RRAEB current pulse was shorter with the use of the Ta anode. An increase ($\sim 4$ times) in the number of electrons in the reverse beam through the 1-mm-diameter aperture with the Ta anode corresponds to an increase in the number of electrons behind the entire surface of the foil (figure 3) and the beam current from entire area of the 20-mm-diameter aperture (figure 5). When increasing the aperture in the diaphragm to 20 mm, the FWHM of the RRAEB current pulse increased to $\sim 100$ ps for both Ta and Al anodes. However, in the both cases the RRAEB current pulse duration was higher for the Al anode.

Figure 4. Waveforms of the voltage across the gap and the RRAEB current behind the diaphragm made of a 250-µm-thickness Cu foil with a 1-mm-diameter aperture for the (a) Al and (b) Ta anodes. Positive polarity of a voltage pulse.
Figure 5. Waveforms of the voltage across the gap and the RRAEB current behind the diaphragm made of a 250-µm-thickness Cu foil with a 20-mm-diameter aperture for the (a) Al and (b) Ta anodes. Positive polarity of a voltage pulse.

From the experiment performed, it follows that the effect of the anode material on the total current of the reverse runaway electron beam is manifested in measurements through both a small (small portion of a beam) and a large (significant proportion of a beam) aperture in the diaphragm.

3.2. Effect of the anode material. Setup no. 2
When using this setup, SAEB was extracted from the gas diode through an 1-mm-diameter aperture in the middle of a foil anode made of Al, brass or Ta mounted before the collimator made of a 5-mm-thickness brass plate (see figure 2). This approach (collimation of the beam passing through the aperture) allowed us to register the SAEB current with picosecond temporal resolution. The foil absorbed electrons that did not enter the aperture. However, as in [25, 26], the anode material could affect the beam formation process.

Since, the collector receiving part was not shielded with a foil, it was necessary to assess the effect of a dynamic displacement current (DDC) [27, 28] on the signal recorded with the collector. DDC we call the current flowing in the plasma-free space between an ionization wave front and the plane electrode, when the ionization wave (a streamer) propagates from a high-voltage electrode with a small radius of curvature [28]. It was found, that using the 5-mm-thickness anode with the 1-mm-diameter aperture the SAEB current pulse amplitude was several orders of the magnitude higher than that of DDC. Therefore, under these conditions, DDC did not affect the SAEB current measurements. There are waveforms of the voltage across the gap and the runaway electron beam current for different anode materials in figures 6a–c. Due to registration through the aperture, the anode material influenced the SAEB generation, but did not affect the SAEB extracted from the gas diode.

As mentioned in the previous section, when using a similar setup with the plane high-voltage anode and the grounded grid cathode, a change in the anode material significantly affected the amplitude of the RRAEB current pulse. Each of the SAEB current pulses shown in figure 6 is a pulse with the highest amplitude in a series of 20 pulses. This figure shows that the SAEB current pulse amplitude does not significantly depend on the anode material. In addition, a slight (~ 10%) decrease in the SAEB current pulse duration with increasing material atomic number is observed. The picosecond duration of the pulses is because only a small fraction of the electron beam passing through the 1-mm-diameter aperture is registered with the collector. As it was shown in [29], the SAEB current pulse duration depends on the aperture diameter. When registering SAEB current pulses behind the 10-µm-thickness Al foil reinforced with a grid with a collector (#3) equipped with a 20-mm-diameter receiving part, their FWHM increased (figure 6d). In the case of using Ta and brass foils with the aperture of 20 mm in diameter, beam current pulses were not measured with this collector. As is known, at the
same foil thickness, the electron beam energy losses depend on the atomic number of the metal from which the foil is made. Therefore, when carrying out research on setup no. 2, it was not possible to compare amplitudes of the electron beam current measured through the 20-mm-diameter aperture in foils made of different metals. However, experiments on setup no. 1 showed that when measuring the beam current through diaphragms with apertures of different diameters, a change in the anode material gives similar results (see figures 4 and 5).

![Waveforms](image)

**Figure 6.** Waveforms of the voltage across the gap and the SAEB current through a 1-mm-diameter aperture in the center of the (a) aluminum, (b) brass and (c) tantalum anodes. The receiving part of the collector had the diameter of 3 mm. (d) Waveforms of the voltage and SAEB current registered behind a 10-µm-thickness Al-foil reinforced with a grid. The receiving part of the collector was 20 mm.

4. Theoretical simulation

The numerical simulation of the discharge formation and development was conducted in terms of two-dimensional drift-diffusion so-called “two-moment” macroscopic discharge plasma model [30] implemented in COMSOL Multiphysics 5.2a with Plasma module. It represents number of electron and ion continuity equations coupled to Poisson’s equation accounting the electrostatic field self-consistently. Since we consider a sub-nanosecond atmospheric pressure discharge only impact ionization (e + N₂ → 2e + N₂⁺) and dissociation (e + N₂ → e + 2N) reactions have to be included into set of plasma-chemical reactions of the model. This reduces total number of equations in the model. The corresponding reactions rates are given elsewhere [31].

The photo-ionization process also gives one of the significant contribution into gas ionization. In this study, we simulate the discharge in atmospheric pressure nitrogen that contains less than 2% of free oxygen admixture. Such an addition of oxygen does not affect the drift-diffusion characteristics noticeably, but the changes of the photoelectron production rate are becoming significant as the characteristic absorption length of ionizing radiation increases considerably. We implement photo-ionization according to the “differential” approach given in [32]. It uses a number of linear wave Helmholtz equations defining additively source terms of photo-ionization rate reaction in right-hand side of continuity equations.
The calculations also take into account the contribution of field emission from electrodes surfaces due to the electrostatic field strength increase around emission centres formed by the natural roughness of metallic surface. The corresponding flux density of field-emission electrons in the Fowler-Nordheim form is used from the original paper [33]. In addition, generalized boundary conditions for the particle fluxes and the electron energy density on solid electrodes walls have been applied in order to satisfy secondary electron emission conditions. The uniform initial plasma number density on the level of \(10^3\) cm\(^{-3}\) was used [34].

The relative accuracy of the time-dependent solution was 0.0001 at the triangular-shaped finite element grid. The maximum mesh size was set to 0.02 mm, while the minimum size was 0.0075 mm in the entire model. Nearly 52000 elements were employed and the number of degrees of freedom (DOF) was about 186 thousands. These calculations represent a significant refinement of simulations of the nanosecond diode with a plane-grid cathode system earlier performed in papers [35, 36].

Figures 7 and 8 show some results of theoretical simulation of the discharge in the gap. Figure 7 shows the time profiles of the voltage and discharge current. The gap voltage profile (curve 1) shows that the discharge goes into a high-current stage by the time instant of 0.36 ns. At this point, the front of the high ionization region reaches the anode. Figure 8 shows the spatial distribution of the plasma number density at different point in time (the dark circle in the center is a wire with a diameter of 0.2 mm at the cathode potential) and plots of the longitudinal field strength (\(E_y\)) in the plane of symmetry of the diode at different time points.

![Figure 7](image_url)

**Figure 7.** Calculated time profiles of the power supply voltage (dashed line), the voltage across the gap (curve 1), and the discharge current (curve 2).

![Figure 8](image_url)

**Figure 8.** The plots of the field strength distribution (a) at different points in time, combined with 3 images of plasma number density near the wire (b).
5. Discussion

Determination of the SAEB parameters is a complex task due to the short rise time and the duration of a beam current pulse [20]. Attempts to solve this problem were made in many papers [16–20]. In these studies, an electron beam was generated both in atmospheric air and in other gases at various pressures. An analysis of the results of studies carried out before 2003 is presented in the monograph [16]. The reviews [17, 19] and the collective monograph [20] present an analysis of the results in this field of research obtained in recent years by different scientific groups (also see [18]).

If we analyze the effect of the material and the thickness of the anode foil on the SAEB parameters, the results obtained are quite predictable. In general, at the same thickness of the anode foil, the amplitude of the SAEB current pulse decreases with increasing atomic number of the metal from which the anode is made. In addition, when increasing thickness of the anode foil, the SAEB current pulse amplitude decreases. This observed in our experiments and in experiments of other scientific teams, including research with vacuum diode based accelerators [1–4, 7, 8, 15–21, 37]. In this study, the following feature was identified.

Replacement of an aluminum anode with a tantalum one lead to a slight decrease in the breakdown voltage (~ 10%), however, the SAEB current pulse amplitude did not noticeably change. A decrease in the breakdown voltage can be explained by the influence of bremsstrahlung X-rays from the anode. The intensity of this radiation increases with the use of anodes from metals with a large atomic number [25, 26]. Unchangeable SAEB current pulse is due to the fact that the process of generation of run-away electrons starts during the rise time of the voltage pulse, and the maximum SAEB current is registered by a collector until the voltage across the gap reaches its maximum value (see figure 6).

However, in the case of reverse runaway electron beam, results differ. They can be explained as follows. The electric potential of the anode falls into the space between the grid cathode and the cathode foil (see figure 1). As a result, a high electric field strength directed towards the cathode foil appears on the surface of the grid wires. Initial electrons appear around every wire, of which the grid cathode consists. Then, they multiply in the high electric field and accelerate both towards the anode and in the opposite direction – in the direction of the cathode foil. This mechanism is well confirmed by the results of theoretical modeling, shown in figure 8a. As can be seen, at the early stage of plasma generation near the wire surface, the electric field strength is high both on the anode side and on the cathode side of wire. During the operating time, the plasma ionization front rapidly moves to the anode and the electric field between the wire and the cathode foil is reduced in magnitude. For this reason, there is a finite probability that runaway electrons generated on the cathode-directed side of the wire can reach the cathode.

A growing number of positive ions affect their acceleration. When braking accelerated electrons in the body of the anode, X-rays are generated. It contributes to an increase in the number of initial electrons in the discharge volume, including regions near the grid cathode. When using the Ta anode, the number of initial electrons, which, other things being equal, is proportional to the intensity of X-ray radiation, is greater than for the Al one. Therefore, the collector signal on setup no. 1 was always greater with the tantalum anode. When SAEB is generated, the number of initial electrons is determined, first of all, by runaway electrons near the cathode. At the same time, a role of X-rays from the anode is negligible and manifests itself only in a slight decrease in the breakdown voltage in the case of using a tantalum anode. As already noted, a similar result was obtained with the second setup.

It should be noted that RRAEB is most easily generated at low pressures of light gases. At voltage of several kilovolts Bokhan et al and Sorokin et al demonstrated that in neon and helium at low pressures (38 and 90 Torr, respectively) and a grid cathode one can observe generation of runaway electron beams in the direction opposite to the anode [38]. However, in the air, the reverse beam was not obtained even at lower pressures. Studies at high voltages (~ 100 kV) in [38] were not carried out.
6. Conclusion
The effect of the anode material on the parameters of current pulses of direct (SAEB) and reverse (RRAEB) runaway electron beams generated in atmospheric air was studied. The investigations were carried out with two gas diodes fed by nanosecond voltage pulses from the SLEP-150 generator.

A voltage pulse of negative polarity with the amplitude of \(~ 150 \text{ kV}\), the rise time of 0.3 ns and the FWHM of 2 ns were used in the experiments with the second diode. The SAEB current was measured through the 1-mm-diameter aperture in the plane anode. It was found that the anode material does not affect significantly the beam current pulse amplitude. These data differ from those for RRAEB obtained at positive polarity of the SLEP-150 generator. The differences can be explained as follows. X-ray radiation arises at the anode under the action of run-away electrons. It significantly affects the plasma formation process and the process of generation of runaway electrons from the grid cathode in the direction opposite the anode.

In addition, a slight decrease (~ 10%) in the voltage across the gap was observed when replacing an aluminum foil by a tantalum one. It could be supposed that the mentioned X-ray radiation, caused by SAEB, affects the breakdown voltage.

These results can be applied, e.g., when creating accelerators based on gas-filled diodes or sources of dense low-temperature plasma formed in diffuse discharges initiated by run-away electrons for surface modification of various materials. In addition, the results can be useful in developing methods for diagnosing of run-away electrons in tokamaks. The problem of the influence of runaway electrons on plasma heating and the destruction of the walls of working chambers \([39–41]\) requires detailed studies of the generation of runaway electrons, including that in the opposite direction.

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