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High-current discharge initiation in a vacuum diode

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Abstract. The research results of forming a low-resistance high-current discharge in the vacuum gap by means of forced initiation of the cathode spot by auxiliary discharge are presented. The discharge with current of more than 30 kA at the current rise time of ~100 ns is formed in a gap of 2.5 cm. In a next phase of the current interruption the energy of 180 J is dissipated in the diode gap.

1. Introduction

One way to generate an electron beam is to use the effect of current interruption in the high-current vacuum discharge. For the discharge ignition at voltage below the breakdown voltage and at the residual gas pressure ~10^{-5} torr in the gaps of 1–10 cm it is necessary to originate the cathode spots and to fill the discharge gap with plasma. Surface breakdown [1, 2], auxiliary discharge with pulsed gas puffing [3], laser ablation [4, 5] are used for plasma generation and high-current discharge ignition in the vacuum diodes.

The high-current discharge in a vacuum can also provide metal vapor flow from the cathode spot of the auxiliary discharge [6, 7]. In [7] vacuum low-resistance discharge and subsequent current cutoff were done in the gap of 12 cm. Current amplitude was about 8 kA at the current rise time of ~1 μs.

In the present paper the cathode flare of auxiliary vacuum discharge is tested as a plasma source for e-beam diode. In addition to the implementation of a low-resistance discharge phase with current of more than 30 kA in the diode, the task was effective transfer energy to electron beam in the phase of the current interruption.

2. Experimental arrangement

Electrical scheme and schematic design of the discharge system are shown in Figure 1. Electrical scheme consists of two discharge circuits based on capacitive storages C_1 and C_2, triggered with time delay t_d.

The first circuit supplies the auxiliary discharge. The discharge is ignited between the rod-shaped electrode (1) having a diameter of 1.5 mm and the cylindrical electrode (2) with an inner diameter of 12 mm. Electrode (1) material is copper, electrode (2) material is stainless steel. The discharge gap between (1) and (2) is d_1=3 mm. A negative polarity voltage pulse is applied to the electrode (1) through coaxial line (3) from the capacitor C_1=8 nF, switching by spark gap S_1. Capacitor C_1 charge voltage is 80 kV. The circuit damping resistance is R=10 Ω.

The second circuit supplies the main discharge in the diode gap d_2=25 mm. The circuit is based on capacitive storage C_2=80 nF with a charging voltage of 80 kV. Negative polarity pulse is applied to the electrode (2) from C_1, switching by S_2 with a time delay t_d relative to S_1, whereby electrode (2) becomes the cathode relative to the grounded plate electrode (4). Short circuit with a ferromagnetic core (5) is connected in parallel with the gap d_2. Short circuit allows to have a ground potential at the coaxial (3) input. Core (5) limits the current in the short circuit during the C_2 discharge.

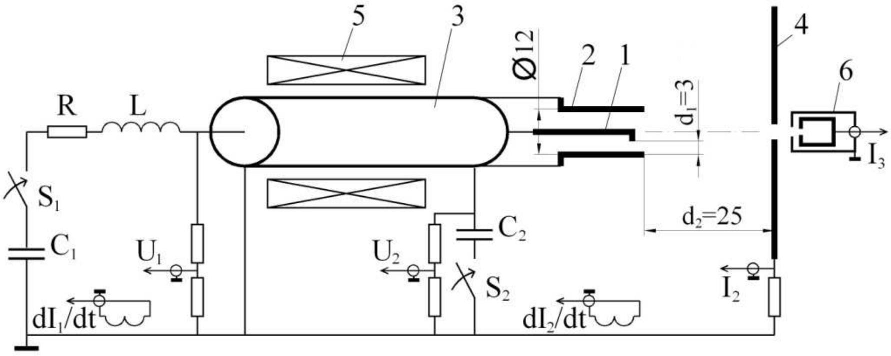

Figure 1. Schematic arrangement: 1– cathode of the auxiliary discharge; 2– anode of the auxiliary discharge and cathode of the main discharge; 3– coaxial line; 4– anode; 5– ferromagnetic core; 6– Faraday cup.

Voltages U_1, U_2 are measured by resistive dividers. The derivative of the auxiliary discharge current dI_1/dt is measured by inductive shunt. The current I_2 in the gap d_2 and its derivative dI_2/dt are measured by resistive shunts and inductive sensor, respectively. In addition, the current I_3 from the auxiliary discharge toward the electrode (4) is recorded by Faraday cup (6). Faraday cup collector is made of graphite. The charged particles flow on the collector is collimated by hole with diameter of 0.6 mm.

The discharge chamber is pumped out by turbomolecular pump to a residual pressure of ~10^{-5} torr.

3. Experimental results

3.1. The auxiliary discharge

Figure 2 shows the waveforms of the total current I_1 and auxiliary discharge voltage across the gap d_1. The voltage is calculated from measured voltage U_1 with taking into account inductive drop on the section between the voltage divider and the end of the electrode (1). The inductance of this section was determined in short-circuit test. The discharge current I_2 is shown in Figure 3. The current density at the anode (4) calculated from Faraday cup current I_3 is shown in Figure 4.

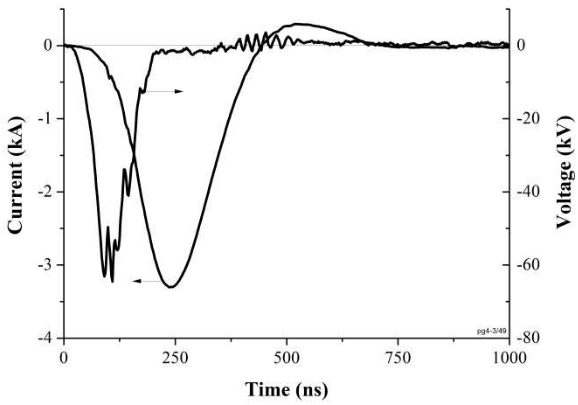

Figure 2. Total current and voltage of the auxiliary discharge.

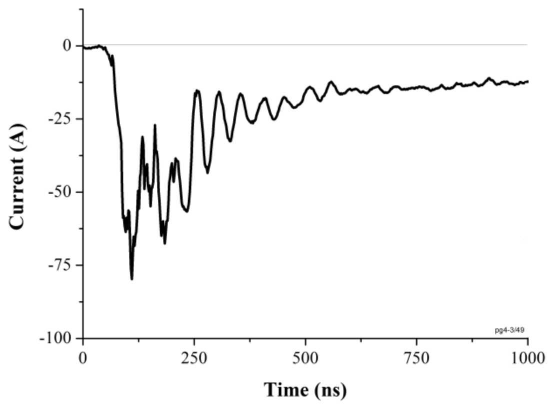

Figure 3. Current to the anode (4).

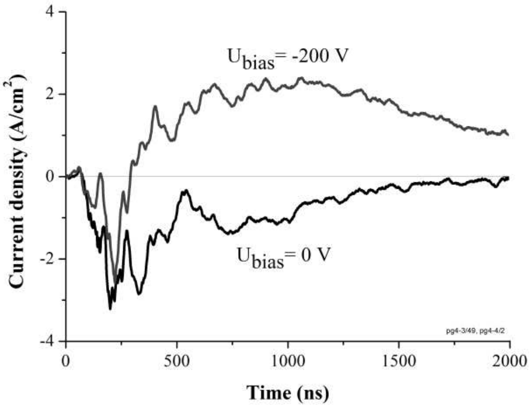

Figure 4. Current density at the electrode (4) from the Faraday cup signal.

The main current of the discharge C_1 flows to the electrode (2). Current amplitude is 3.2 kA, a half period is 400 ns. Part of the current ~50 A also flows to the electrode (4). The current density on the axis measured by Faraday cup at zero bias voltage U_{bias}=0 is above 2 A/cm^2. The current density satisfies the Child-Langmuir law only for a high-voltage discharge phase, when the voltage on the electrode (1) is above 10 kV. Then we have to talk about of ion compensation of the electron current space charge. Faraday cup measurement with a negative bias also suggests the presence of ion flow in the direction of the electrode (4). Negative bias U_{bias}=200 V does not allow cutoff the electronic component of the Faraday cup current in the high-voltage discharge phase and the signal from the Faraday cup is negative. However, signal becomes positive after 250 ns, indicating that the ion flux reaching the electrode (4). Time of appearance of a positive signal corresponds to the ion velocity ~10^7 cm/s. For the copper ions, this velocity corresponds to the energy of more than 1 keV. Ions from the cathode spot toward the anode (4) allow to form a high-current low-resistance discharge in a vacuum gap d_2.

Note, the flow of fast ions from the cathode spot toward the anode is observed in vacuum discharges systematically. The hydrodynamic mechanisms [8] and "potential hump" assumption [7, 9, 10] are invoked for the explanation of the ion acceleration toward the anode.

3.2. Main discharge

Total inductance of the main discharge circuit ~120 nH and circuit wave impedance ~1.2 Ohm were defined in a short-circuit test. In addition, the inductance between voltage divider U_2 and the end of the electrode (2) was defined. This inductance was used to calculate the voltage in the gap d_2 from measured voltage U_2.

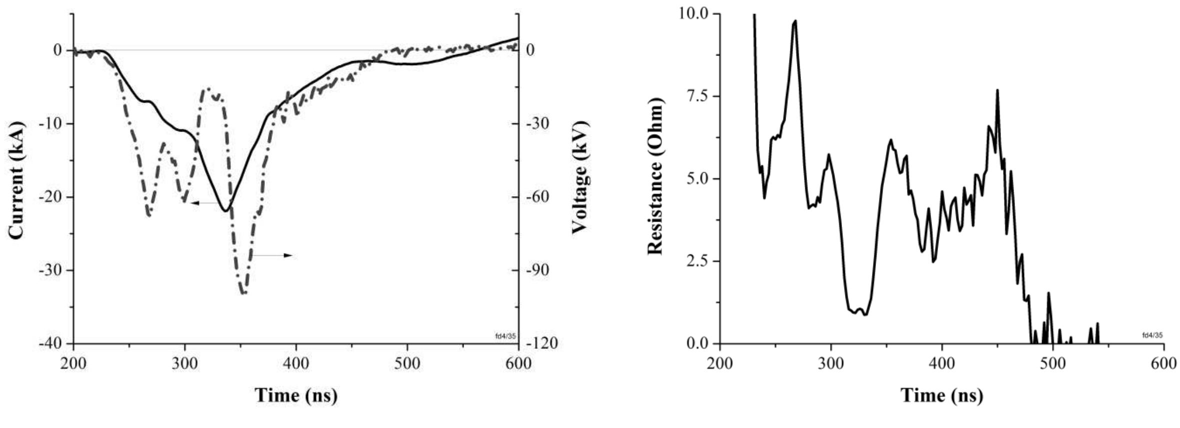

Figure 5. Current, voltage and resistance of the gap d_2 at t_d=200 ns.

The oscillograms of the capacitive storage C_2 discharge at t_d=200 ns and 900 ns are shown in Figures 5 and 6. Time delay t_d=200 ns is not enough to fill the gap d_2 with ions from the auxiliary discharge and to form the low-resistance discharge phase. Discharge is characterized by high resistance of ~5 Ω and a high voltage drop of ~10 kV (Fig. 5). However, the discharge current is noticeably higher than the electron beam limit current in the vacuum. The discharge current amplitude is 20 kA. Several current cutoffs are observed during the pulse. Energy of 80 J is dissipated in the diode gap d_2.

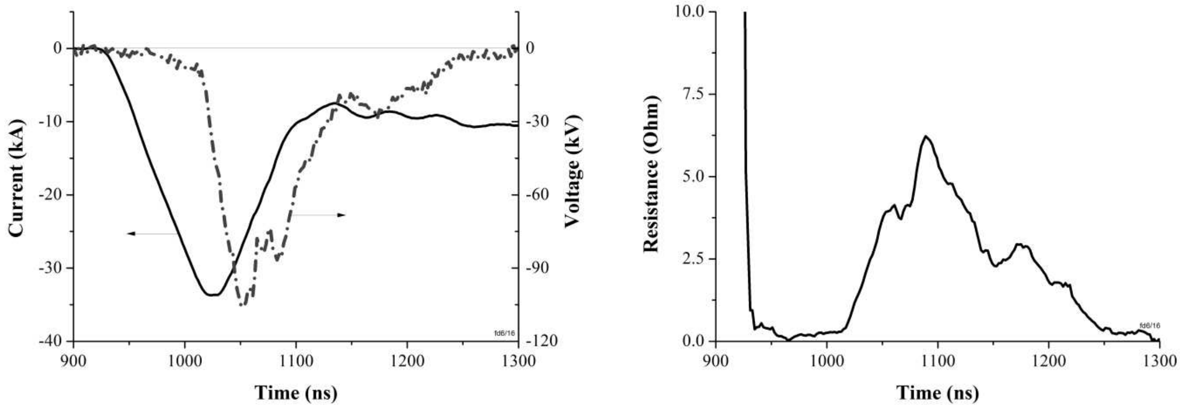

Figure 6. Current, voltage and resistance of the gap d_2 at t_d=900 ns.

Time delay t_d=900 ns is already enough to form discharge with resistance much less than the impedance of the supply circuit and with current amplitude more than 30 kA (Fig. 6). In the current interruption phase the gap resistance increases up to 6 Ω with resistance rise rate of about 0.1 Ω/ns, the voltage pulse and the high-energy electron beam are generated. At stored energy in the capacitor C_2 of 256 J, energy of 180 J is dissipated in the gap d_2 with a peak power of 3 GW.

4. Conclusion

The experimental results confirmed the possibility of forming a low-resistance high-current discharge in the vacuum gap of a few centimeters by means of forced initiation of the cathode spot by auxiliary discharge. The discharge current of more than 30 kA with a rise time of ~100 ns in a gap of 2.5 cm is implemented due to the evaporation of the cathode material. It is used the effect of current interruption in a vacuum discharge for voltage pulse and electron beam generation. Energy of 180 J, which is 70% of stored energy in the primary capacitive storage, is dissipated in the diode gap during current interruption phase.

The absence of dielectric in the ion source allows to avoid life limitation due to evaporation and destruction of the dielectric, as well as to eliminate contamination of the discharge chamber by vaporized dielectric.

Acknowledgments

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