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The measurements of vacuum arc behaviour at threshold current

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Abstract. The measurements of vacuum arc current parameters at the threshold current were made. The threshold currents for Cu, W, graphite cathodes were measured. It was shown that the current that vacuum arc chops with, has a statistical distribution. The vacuum arc current chopping is accompanied with significant ion current burst. The ion current of W and Cu cathodes contains intensive peaks with 30-50 ns duration. It was shown that the cathode materials that have intense peaks have a significant threshold current.

1. Introduction

Studies of the vacuum arc cathode spot continue for a long time [1]. There are theoretical models that describe the functioning of the cathode spot at the outer parameters: (i) the overall current of the spot area, (ii) the size of the cathode spot [2-4]. Such models describe well the balance of currents and energy flows in the stationary case. In this case, one of the main properties of the cathode spot remains without explanation - the tendency of a cathode spot to split and the existence of a threshold current [5]. The threshold current is a current below which the functioning of the cathode spot is impossible. When the current is exceeded by one cell more than two threshold currents, the cell is split into two parts. Consequently, the existence of a large cathode spot that conducts a large current at a uniform current density in the region of the cathode spot is impossible. One cell of the cathode spot can exist in a limited range of the surface and current value. However, this behavior cannot be explained using one-dimensional stationary models. The nonstationary (explosive) model of the cathode spot describes the cathode spot as an object that exists in a limited region of space and time [6]. This model explains the nature of the cathode spot more comprehensively. The spatial limitation arises from the temporal limitation in the explosive process. However, in this case, the current per spot remains an external parameter. The mechanism governing the process of cathode spot dividing remains unclear. In order to understand what affects the process of the appearance of the cathode spot when the threshold current is exceeded, as well as the division of the cathode spot when the current value is exceeded two values of the threshold current, it is necessary to carry out detailed experiments in the region of low currents. Experimental measurements should contain not only information about the arc current but also about the process of plasma ejection from the cathode spot and its luminescence. This work is devoted to
measuring the arc current, ion current from the region of the cathode spot, and the glow of the cathode spot plasma.

2. Experimental setup
The cathode was a brush-like structure (figure 1). At the cathode holder, three cathode fingers made of copper, tungsten, and graphite were fixed. The discharge was ignited at one of the cathodes using an ignition electrode. The igniting anode was attached to a resistor of 4 kΩ. The limiting resistor set the initial discharge current to 4 A. An ion detector was rigidly fixed to the initiating electrode. The ion detector had a coaxial conical structure. At the top of the cone, there was an aperture 300 µm in diameter. Behind this aperture, an ion collector with a diameter of 100 µm was placed. The distance from the collector to the tip of the ignition electrode was 100 µm. The ion detector was at a potential of −80 V, which made it possible to retard electrons from the plasma. The discharge was fed in the anode circuit with a 40 nF capacitor. In this case, the duration of the discharge was up to 3 μs. As the arc current approached the threshold, the discharge was interrupted; this process made it possible to estimate the threshold currents for three materials of the cathode. The plasma luminescence was measured using a light detector based on a photomultiplier PMT 6.

![Figure 1](image1.png)

**Figure 1.** The waveforms of discharge current, ion current and light emission at a chopping process.

![Figure 2](image2.png)

**Figure 2.** The typical waveform of arc current, ion current and plasma luminescence with the copper cathode at the threshold current.

3. Experimental results
A typical oscillogram of the end of the arc burning when approaching the threshold current is shown in figure 2. The main feature of the time dependence of the arc current and ion current for a copper
cathode is the presence of significant instability in the signal. These bursts are significantly higher than the noise level that can be observed in the last 500 ns on the waveform (figure 2). The ion current consists of a sequence of intense bursts of 30-50 ns duration. The arc current contains sharp drops and bursts. The characteristic burst times coincide with the previously estimated lifetimes of the cathode spot at one location.

An exception is a glowing signal from the plasma of the cathode spot. There are no bursts above the noise level on this signal. The noise signal is superimposed on a smooth dependence. The characteristic oscillation time of the smooth dependence of the glow is about 1 µs. Similar time dependence of the discharge parameters is observed for an arc on a tungsten cathode (figure 3).

In the case of a tungsten cathode, the discharge current is much more stable than in the case of a copper cathode. The waveform of the ion current contains noticeable bursts with a duration of several tens of nanoseconds. A sharp cutoff of the current when approaching the threshold value is accompanied by an intense burst of ion current. A similar surge is observed in the case of a copper cathode. Plasma glow does not have sharp bursts with an amplitude noticeably higher than the noise level.

The nature of the time dependence of the parameters of the arc discharge in the case of a graphite cathode is significantly different. Waveforms of the ion current discharge current and plasma glow are shown in figure 4. In the case of a graphite cathode, sharp bursts are not observed either on the discharge current or on the ion current. The only sharp change is present in the discharge current waveform when the arc is extinguished. In this case, the extinction of the arc occurs at an extremely low current of 120 mA. It is impossible to draw a conclusion about the presence or absence of bursts of ion current from the obtained waveforms. To detect such bursts, another experimental technique is required.

In all measurements, the plasma glow does not reflect the portion structure of plasma generation. Plasma glow is smoothed out. There are no sudden bursts of light that exceed the noise level. Most likely, this behavior of the glow is a consequence of the screening of the plasma core glow in the cathode spot by the peripheral plasma layers.

The presence of sharp surges of the ion current indicates the portion nature of plasma generation in the cathode spot of the vacuum arc. This portioning appears only when discharge current approaching the threshold value when there are only one or two cells of the cathode spot. At higher currents,
portions from single explosions are superimposed, forming a smooth ion current signal. The portion size is a consequence of the limited life of the cathode spot cell. The most likely scenario for the existence of a cathode spot is an explosive process [6].

Figure 4. The typical waveform of arc current, ion current and plasma luminescence with the graphite cathode at the threshold current.

The arc on a graphite cathode is characterized by two features: 1. Very low threshold current. 2. There are no noticeable bursts on the waveform of the ion current.

The explanation can be the size of the explosion area $V_{\text{exp}}$ (figure 5). In the case of a large volume, more current $I_\alpha$ and more time $I_d$ are required for explosion. In this case, the plasma is generated in large portions. A higher threshold current $I_\alpha$ is determined by the need to evaporate a larger volume of material. The process of warming up a larger volume takes a longer time $T_d$, therefore, the plasma emissions are separated by a large time interval $T_d$.

Figure 5. The explosive volume and crater size effect on the discharge parameters. The larger explosion value $V_{\text{exp}}$ requires higher current $I_\alpha$ and longer time interval $T_d$.

4. Conclusions
Measurements of the parameters of the arc discharge at a threshold current show that plasma in the cell of the cathode spot is generated in portions on copper and tungsten cathodes. These portions are noticeable only when approaching the threshold current. The threshold current is a necessary current
for the explosion of a cathode microvolume; the larger the exploded volume, the higher the threshold current and the more noticeable the portion nature of plasma generation.

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