Investigation of oscillatory phenomena in the near electrode plasma of vacuum spark

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Abstract. A research of the vacuum spark plasma properties in the near-electrode area is considered. Results of the observations of the high-frequency electrical oscillatory discharges in the 1-110 MHz range are presented. Plasma element composition and temperature have been analyzed with a spectrometer. It contains the study of the microrelief of the electrode surface. Also observations of the 80-350 nm cellular structure formation are represented. Finally, it describes a proposed possible mechanism of the surface formations occurrence.

Introduction
Vacuum spark, as well as the plasma focus, is used for studying the formation of the dense plasma. One of the directions is studying the formation of plasma points, or micropinches [1-6]. The discharge radiates light intensively in the ultraviolet and the soft X-ray spectrums. All considered, the plasma processes in the discharge lead to high-frequency oscillations [7, 8]. It is very important to study the oscillatory and the wave processes in the vacuum spark to ensure plasma stability. At the same time strong currents strongly influence the surface of electrodes in this installation. Studies of the electrode microstructure have been conducted previously.

Experimental setup
The experiments were conducted on the installation shown in figure 1. The system was powered by the 20 μF storage capacitor at charge voltage 5-20 kV. The discharge was ignited by trigger ignition. Electrodes contained a tapered anode (1) (diameter 3-4 mm) and a cylindrical cathode (2) (diameter 15-20 mm) with a 1.5-2 mm central opening. Electrodes made of steel or copper were used for the experiments. The distance between the electrodes was 4-5 mm. Chamber pressure was in the range 10⁻⁴-10⁻⁵ Tor. The discharge current was in the range 100-150 kA, with the discharge period 6.0 μs.

Strong current causes intensive evaporation of the anode and the central part of the cathode. Gradually a compressed pinch (4) starts to form on the discharge axis, with a shell (5) around it (figure 1). After the formation of a pinch discharge micron-sized objects start to form near the anode, with X-ray range emission; these are plasma points, or micropinches (6) [6]. Photographs of the pinch area in the X-ray range of the electromagnetic spectrum (E>3 keV) are shown in figure 2.

Research of electrical oscillations
The current pulses were studied using the Rogowski coil and Tektronix TDS 2024B oscilloscope. Figure 3a shows the first half-cycle of a typical current oscillogram with a 6.0 μs cycle. Near the
maximum current, the discharged is pinched and the current is constricted, which is connected to the X-ray emissions (energy of quanta: \( E > 1 \text{ keV} \)). In this moment \( (t \approx 2.7 \mu s) \) intensive high-frequency oscillations across the broad spectrum range take place. These high-frequency signals were emitted with the low-induction magnetic probes, which were located on different distances from the discharge. Coils were used for magnetic probes (3-4 mm diameter, 80-120 loops) made of copper wire, diameter 0.1 mm. For recording the signals in close proximity to the pinch the probes (7) were located in the chamber, in a protective dielectric casing (figure 1). To obtain the spectrum of high-frequency oscillations, we used the Origin software. The main frequencies of such oscillations are: 4.1±0.1 MHz, 8.3±0.2 MHz, 45±1 MHz, 92±2 MHz. Alongside the main frequencies a number of less intensive frequencies is also present in the spectrum: 18.2±0.4 MHz, 35±1 MHz, 67±1 MHz, 81±2 MHz. The spectrum of the high-frequency oscillations of the discharge current is given in figure 4.

Let us evaluate the characteristic frequencies of the processes of plasma in the vacuum spark. With the following plasma parameters in the pinch: concentration \( n_e = 1.2 \cdot 10^{19} \text{ cm}^{-3} \), temperature \( T = 2.5 \cdot 10^5 \) K the plasma frequencies are: \( \omega_{pe} = (4\pi n_e e^2/m_e)^{1/2} = 1.9 \cdot 10^{14} \text{ s}^{-1} \) and \( \omega_{pi} = (4\pi n_e e^2/m_p)^{1/2} = 4.5 \cdot 10^{12} \text{ s}^{-1} \). These frequencies are much higher than the frequencies recorded during the experiments. With the characteristic currents running through the pinch plasma \( I = 100-110 \text{ kA} \), for the magnetic field strength \( B \approx 3 \cdot 10^4 \text{ Gs} \) the ion cyclotron frequency is equal to: \( \omega_{ci} = eB/m_p = 2 \cdot 10^8 \text{ s}^{-1} \), and the electron cyclotron frequency, correspondingly, is: \( \omega_{ce} = eB/m_e = 3.6 \cdot 10^{11} \text{ s}^{-1} \). So the oscillations frequencies observed in the experiments \( \nu = 1-110 \text{ MHz} \) would be located in the range of the low frequency waves of the plasma waves. For the plasma waves distribution along the magnetic field, for the electron cyclotron and the ion cyclotron waves the dispersion equation is represented by the following form [9]: \( k^2 = \omega^2/c^2[1 - (\omega_{ce}^2 + \omega_{ci}^2)/(\omega - \omega_{ci})(\omega + \omega_{ci})] \). When we used this equation at the frequency \( \nu = 92 \text{ MHz} \) we will get the

\[\text{Figure 1. Experimental setup: 1 – anode, 2 – cathode, 3 – trigger discharger, 4 – pinch, 5 – discharge shell, 6 – plasma point, 7 – magnetic probe.}\]

\[\text{Figure 2. Images of the vacuum spark plasma in the X-ray range a) plasma in the discharge gap, b) plasma point near the anode surface.}\]
following values of the wavelength and the velocity of the electron cyclotron wave: \( \lambda = 3.1 \cdot 10^{-2} \) cm and \( v = 2.4 \cdot 10^6 \) cm/s.

![Figure 3](image)

**Figure 3.** Discharge current and X-ray emission pulse oscillograms a) typical pulse view, b) intensive high-frequency oscillations.

\[ r_d = \left( \frac{kT}{4\pi\varepsilon_n e^2} \right)^{1/2} = 1.1 \cdot 10^{-6} \text{ cm} \]

The Debye length calculation gives the following result: \( r_d = 1.1 \cdot 10^{-6} \) cm less than the size of the plasma points \( r_p \approx 10^{-4} \) cm. If the plasma points are formed near the anode at 0.5-1.0 mm, it is normal to observe strong oscillations across the broad range of spectrum.

**Spectral researches**

To research the peripheral plasma we used the Ava Spec 2048 spectrometer (spectral range 200-1100 nm, resolution 0.3 nm), MUM monochromator (spectral range, 200-800 nm, resolution 1.5 nm) and a photoelectronic multiplier FEU-85. The emission was registered from the plasma shell, 9-12 mm in diameter. With the steel cathode and anode the following spectrum was recorded. The most intense lines of the elements in the electrodes are iron lines: Fe I 298 nm, 382 nm; iron ions: Fe II 270 nm, 361 nm, 523 nm; silicon ions: Si II 305 nm; carbon atoms C I 601 nm. Atomic nitrogen lines are the lines of the elements produced by the residual as ionization: N I 415 nm, 493 nm, and the oxygen and nitrogen ions: O II 253 nm, N II 464 nm. Parallel to this, the hydrogen lines H\( \alpha \) 656 nm and H\( \gamma \) 434 nm are recorded. There is also a strong continuous spectrum in the radiation. Oscillation processes at frequencies 3.2\( \pm \)0.1 MHz and 10.5\( \pm \)0.2 MHz close to the current measurements results, were observed in all time-line intensity dependencies.
Due to the presence of a rather strong continuous spectrum, an assumption was made that the local thermal equilibrium model is applied to the plasma of the shell [10]. Thus, it is possible to use the method of the relative intensity of the spectral lines. Using the hydrogen lines H_γ and H_α we have calculated the plasma temperature values for various discharge modes. For a discharge at the charge voltage $U_z=16$ kV the resulting temperature values was $T=9200\pm300$ K. This temperature value is more than an order of magnitude lower than the temperatures in the pinch area.

Spectral lines of atomic hydrogen H_γ and H_α (figure 5) have a considerable widening in the range 2.0-10.0 nm. The contours of these lines are dispersive. In the assumption about the presence of micro fields in the plasma we calculated the plasma concentration judging by the Stark broadening, and it was $n_e=(3.4\pm0.3)\cdot10^{16}$ cm$^{-3}$ (charge voltage $U_z=16$ kV). This concentration value is about two orders of magnitude lower than the values in the pinch area.

![Figure 5. Spectral measurements of the vacuum spark: a) discharge emission spectrum, b) temporary dependence of the hydrogen line emission H_α 656 nm.](image)

The continuous part of the spectrum was registered along the whole recording range of the spectrometer (200-1100 nm). Rather intensive lines overlay this dependence in the ultraviolet range (240-310 nm) and (350-400 nm) and in the visible range (400-470 nm) and (480-540 nm). Continuous spectrum has a notable decrease in the 320-360 nm area. Due to the complexity of this dependence, the continuous spectrum may only be approximated using the Planck distribution at temperature $T\approx9400$ K. This temperature value is in the temperature range obtained for the vacuum spark by method of relative intensities, based on the hydrogen lines.

**Investigation of the electrode surface**

According to the studies of the discharge data the main current in the range 100-150 kA runs through the pinch area [5, 6]. The lesser part of the current runs through the peripheral layer of the plasma. The tapered end of anode and the cathode surface near the central opening are subjected to the current effects most of all. Previously concentric circle parameters had been registered on the cathode surface near the central opening [8]. Distance between the two adjacent circles was within the 150-250 μm range. The height of the circles is in the 10-60 μm range. In turn, the circles on the cathode may consist of separate nodules, knobs of 100-150 μm. The circular structure is, apparently, connected with the effect from the plasma waves to the material surface.

Let us see the result of the plasma interaction with the anode surface (figure 1). This electrode is usually made of steel (St.45) and its diameter is 3-4 mm, and the tapered part curvature radius is 1-1.5 mm. During the first half-cycle this electrode is energized with the positive potential, and according to
the data from the electro technical and the X-ray measurements the surface is subjected to strong electron stream with energy density 30-50 J/mm². The microstructure of the electrode surface was examined using electron microscopes Hitachi TM1000 and VEGA 3 SEM. The examination result was that the general relief of the surface consists of “nodules” or “elevations” of irregular shape, sized 10-200 μm (figure 6a). The revealed height of the formations is 10-50 μm. The tops of the most of the flat “elevations” contain 1-10 μm insertions of carbon.

The space between the “elevations” was also examined. The “depressions” had smoother surface divided by dark 0.1-1 μm carbon stripes. The space between the dark stripes consisted of 80-350 nm oval cells (figure 6b). Due to the empty spaces between the cells it can be assumed that the cells height exceeds their width, or exceeds 100-200 nm. The regions 80-150 nm are alternated with the larger ranges 200-350 nm cells.

![Figure 6. Anode surface: a) surface relief, b) cellular structure of the surface.](image)

The anode surface is exposed to strong currents that run through the discharge plasma. It leads to heating and melting of the outer surface of metal during the first current half-cycle \( t \approx 3 \) μs. Anode surface relief may show characteristic dimensions of the current inconsistencies, or the current breaking into smaller currents with the dimensions 10-50 μm. Total duration of the current is usually 3-4 half-cycles or 9-12 μs. After the outer 50-100 μm layer is melted the current shutdown may lead to quick metal crystallization. In many iron containing alloys this also leads to granulation [11].

**Conclusion**

We have researched the parameters of the peripheral vacuum spark plasma. High-frequency oscillations in plasma have been fixed and spectrum of these oscillations in the 1-110 MHz has been plotted. A number of characteristic intensive frequencies are distinguished within the spectrum. We have analyzed the possibility of the presence of various wave types in the plasma shell of the vacuum spark. The recorded high-frequency oscillations are connected to the formation of the electron cyclotron and the ion cyclotron waves in the vacuum spark plasma. We have studied the properties of the peripheral vacuum spark. The spectral analyses have allowed us to determine the plasma shell temperature \( T = 9200 \pm 300 \) K and concentration \( n_e = (3.4 \pm 0.3) \cdot 10^{16} \) cm⁻³.

We have examined the microstructure of the electrodes in the vacuum spark installation. The steel anode surface has showed characteristic relief caused by intense currents. We have discussed the current microstructure that leads to the formation of the microroughness on the surface (“elevations”), sized 10-200 μm. We have also considered a possible model for the 80-350 nm cellular structure formation.

**References**

[1] Cilliers W A, Datla R U and Griem H R 1975 *Phys. Rev. A* 12 1408
[2] Koshelev K N and Pereira N R 1991 *J. Appl. Phys.* 69 21
[3] Stutmany D and Finkenthalz M 1997 J. Phys. B 30 951
[4] Artamonov M F, Krasov V I and Papernyi V L 2001 Tech. Phys. Lett. 27 1018
[5] Rousskih A G, Baksht R B, Zhigalin A S, Oreshkin V I, Chaikovsky S A and Labetskaya N A 2012 Plasma physics reports 38 595
[6] Bashutin O A and Savjolov A S 2016 Plasma Physics Reports 42 347
[7] Kirko D L, Savjolov A S and Sarancev S A 2011 Vestnik kazanskogo technologicheskogo universiteta 14 82 (in Russian)
[8] Kirko D L, Savjolov A S and Vizgalov I V 2013 Russian Phys. J. 55 1243
[9] Kroll N A and Trivelpiece A W 1973 Principles of plasma physics (New York: McGrawHill)
[10] Huddlstone R and Leonard S 1965 Plasma diagnostic techniques (New York: Academic Press)
[11] Glezer A M and Permjakova I E 2012 Nanokristallu, zakalennue iz rasplava (Moscow: Fizmatlit) (in Russian)