Instabilities of electrical properties of He-induced W "fuzz" within the pre-breakdown and breakdown regimes

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Abstract. The investigation of the He-induced W "fuzz" electrical properties was carried out. For the research, an automated experimental setup was designed. The setup was based on a vacuum chamber operated under high vacuum conditions (~10⁻⁷ Pa). The vacuum diode under investigation comprised of a flat W “fuzz” cathode with an area of about 1 cm² and a 2 mm radius cylindrical copper anode with a hemisphere tip. The cathode-anode distance was about 100 µm. The voltage applied was up to 10 kV. A DAC/ADC module controlled an HV power supply and automatically registered currents and voltages in the circuit. The effect of a spontaneous change in the emissive ability of the investigated surface area was observed. These changes can vary significantly in magnitude. Large-scale changes can lead to a permanent increase in the emissive ability of a specific area or to a breakdown of the gap. Small changes, as a rule, are reversible, have a stepped nature, and make it difficult to record and interpret the current-voltage characteristics of the field emitter.

1. Introduction

In thermonuclear fusion assemblies, the development of unipolar arcs between high-temperature plasma and divertors facing the plasma is an extremely undesirable side effect that occurs in magnetic confinement fusion devices [1–5]. The arcing leads to the erosion of the divertors and contamination of the thermonuclear plasma with various impurities (in particular, metal particles). The most suitable material for making divertors is tungsten due to its thermodynamic properties (high melting point, high thermal conductivity, etc.). However, it was shown [6–8] that after exposure to helium fluxes with an incident ion energy of about 20 eV and a fluence of about 10²⁵ m⁻² and a tungsten divertor surface temperature in the range from 1000 K to 2000 K, a thin (about 1 µm) nanostructured layer, the so-called tungsten "fuzz", can form on the surface of the divertor. The layer consists of rod-like nanostructures about 10 nm in diameter. The rods provide a sufficiently high electric field enhancement factor; therefore, the presence of a nanostructured layer of tungsten "fuzz" increases the probability of arcing [8]. Therefore, the study of the electrical properties of such "fuzz" in the pre-breakdown and breakdown modes is an urgent task. In our experimental setup, research was being...
carried out on a vacuum diode with a cathode made of tungsten with a nanostructured surface. Using the automated measuring system, data on the dielectric strength of a diode with a nanostructured tungsten cathode were obtained. The emission properties of the cathode with tungsten "fuzz" were also studied. In the course of the study, some features of the behavior of this type of nanostructured emitters were revealed, which complicate the experiment and the interpretation of the data obtained.

2. Experimental setup
The scheme of the experimental setup for studying the electrical properties of nanostructures on a tungsten cathode is shown in figure 1. The measuring and control unit of the setup was a programmable DAC / ADC module "LCard™ E20-10". This module provided automated control of the high-voltage power supply (HVPS) using the DAC unit, while the ADC unit allowed at the same time to obtain data on the voltage on the vacuum diode under study and the current flowing through it. The HVPS was a DC voltage source with a range of 0-30 kV. The current through the installation was limited by an 11 MΩ resistor $R_b$. The voltage applied to the diode was measured with a resistive divider consisting of resistors $R_1$ and $R_2$ (division ratio of about $10^4$). The current through the diode was measured using an $R_{c1}$-$R_{c2}$ divider, which was used as a current shunt. The total resistance of the shunt was 1 MΩ, the division ratio was 0.3. The maximum current flowing through the setup, determined by the impedance of the measuring system, was about 2 mA.

An image of the electrode system is shown in figure 2. The diode consisted of a flat field-emission cathode and a massive anode. The cathode was a nanostructured surface of a tungsten sample with an
The sample was made from tungsten with a purity of 99.97%. Before the final treatment the sample had a mirror-polished surface. To form a nanostructured layer on the sample surface, it was exposed in the plasma gun QSPA-T and an inductively coupled plasma (ICP) source with low-temperature He plasma. The sample preparation process is described in detail in [9]. The anode was a cylindrical brass rod with a radius of 2 mm with a hemispherical tip. A phosphor screen was installed behind the anode. During the initial manual adjustment of parameters, the current could be monitored by the voltage across the resistive shunt in the cathode circuit and by the glow of the phosphor screen behind the anode. The first type of diagnostics could lead to the failure of the measuring device during the breakdown of the gap and was used only as an auxiliary one. The second type of diagnostics allowed to evaluate the emission intensity with the electrical measuring devices turned off and was quite effective in the range of currents from 100 nA to 10 μA. An examples of the glow of a phosphor screen during the flow of a field emission current are shown in figures 3, 4. The glow is partially obscured by the shadow from the crossbar on which the anode is fixed.

![Figure 3. Screen glow before the breakdown. Gap voltage 10.5 kV, camera shutter 0.3".](image1)

![Figure 4. Screen glow after the breakdown. Gap voltage 9 kV, camera shutter 1/15".](image2)

The cathode and anode assemblies were installed inside the vacuum chamber in such a way as to ensure parallelism between the tungsten sample surface and the plane of the anode phosphor screen. Using a three-axis manipulator with micrometric screws, it was possible to change the position of the anode with an accuracy of no worse than 10 μm. The manipulator made it possible to place the anode near certain areas of the cathode surface and to study the distribution of the electrical properties of W "fuzz" over the sample surface, as well as to change the electrode distance. The used vacuum system provided oil-free high vacuum conditions with a residual pressure of 10⁻⁷ Pa inside the vacuum chamber.

3. Results and discussion

To start field emission, several points were selected on the surface of the tungsten sample, at a distance of at least 1 mm from each other, to exclude the influence of already used points (where a breakdown could occur) on a new measurement. Unfortunately, at this stage of the study, the range of permissible voltages was limited to 11 kV. Therefore, to obtain significant values of the field emission current, it was necessary to use small electrode distances. As a rule, these distances did not exceed 250 μm. When searching for the optimal parameters for measuring the emission characteristics, the voltage across the gap was manually increased gradually with significant pauses between changes. It has been observed that the emission current can spontaneously increase even during such a pause, without increasing the voltage. Often, at currents above 1 μA, such a spontaneous growth led to the breakdown of the gap. This could be observed by a sharp flash of the phosphor, after which the power...
supply was turned off due to overload. In this case, the anode moved to the next planned point. In some cases, spontaneous growth did not lead to a breakdown, but only a significant increase in the intensity of the screen glow. The increase in the emissive ability of the investigated surface area of the cathode was permanent. At the next start of the power supply, the emission current was tens of times higher than the current before the event of spontaneous growth at the same voltage values. The achieved emissive current parameters were multiply reproduced.

Another observation showed that after breakdown, the geometric distribution of the emitters at the cathode can change noticeably. When adjusting the emission parameters at the next point, a picture of the screen glow was obtained, shown in figure 3. After a breakdown occurred, at the setup restart, the emission was already significantly different in spatial distribution and intensity (figure 4). Also, the spatial distribution of the glow and especially its intensity can change noticeably over time, even with a constant voltage across the gap. The current could spontaneously increase or decrease. The duration of these processes, observed by the glow of the screen, could be from fractions of a second to several seconds.

The emission current was measured from the cathode regions where the number and amplitude of current bumps noticeable from the screen glow were minimal. The electrical parameters were selected in such a way as to reduce the probability of breakdown. In addition to the current-voltage characteristic, current waveforms were also taken at a constant voltage (see figure 5).

![Figure 5. Examples of current waveforms obtained at the constant gap voltage 7 kV.](image)

On the waveform of figure 5 (a), oscillations with a frequency of about 20 Hz are noticeable. This frequency is determined by the mechanical vibrations of the anode assembly located on the long rod of the manipulator. When measuring the current, such oscillations are smoothed out well by averaging; they significantly affect the behavior of the gap during a breakdown, as will be shown below. In addition to these harmonic oscillations, significant current drops are visible on both waveforms. These drops are usually stepwise. The current at a constant applied voltage could change several times, both upward and downward. These changes could most likely be determined only by processes on the sample surface (changes in the geometric and field emission parameters of the microstructure – the movement of material on the surface of microprotrusions or microprotrusions as a whole).

The detected spontaneous changes in current also affect the acquisition of the current-voltage characteristic, since a sharp change in the emissive ability can occur during the process of recording the characteristic. Examples of such diagrams in volt-ampere coordinates and Fowler-Nordheim coordinates [10] are shown in figure 6. This data was obtained at decreasing voltage applied to the gap to reduce the probability of breakdown and equipment damage. It is noticeable that before, with a decrease in voltage from 9 to 7.7 kV, the current decreased exponentially. Then, at 7.5 kV, the emissive ability of the investigated area increased sharply and began to decrease further exponentially, but with changed parameters. This is more pronounced in the Fowler-Nordheim coordinates, where periods of stable current decrease are displayed as shifted straight lines with slightly different slope angles. Apparently, some random process led to the activation of an additional emission region on the cathode surface.
The results of the current-voltage curve analysis shown, that typical values of the field enhancement factor were less than 100 and were somewhat lower than the ones presented in the papers of other research groups [11–13]. We incline to believe that this is because of the discarding of the sample surface areas at which a breakdown has occurred, since the larger the field enhancement factor, the larger the probability of breakdown at the short electrode distances used. Therefore, more accurate measurement of the emission parameters requires an upgrade of the experimental setup to use a wider range of voltages and electrode distances.

The gap breakdown voltage was measured at electrode distances of less than 100 μm. The breakdown electric field strength $E_{br}$ increased abruptly right after the very first breakdowns for all nanostructured cathode surface areas investigated. The number of breakdowns being increased, $E_{br}$ changed weakly and become almost constant. For example, the initial value of $E_{br}$ could be about $3.0 \times 10^7$ V/m, and after several breakdowns, $E_{br}$ increased up to $9 \times 10^7$ V/m. This value obtained was close to the $E_{br}$ value for an ordinary tungsten cathode [14]. However, at such short distances, mechanical vibrations of the anode assembly make measurements much more difficult. A situation often arises when mechanical vibrations, which are excited when an increasing voltage is applied to the gap, interfere with further voltage growth and make it difficult to determine the true breakdown voltage value. Figures 7 and 8 show graphs of voltage variation with and without fluctuations. Expanding the allowable voltage range can also reduce the effect of mechanical vibrations in the system on the behavior of the object under study. This will increase the electrode distance and thereby reduce the ratio of the amplitude of these oscillations to the stationary distance between the anode and cathode.
4. Conclusion
In the course of studying the properties of the nanostructured surface of a tungsten cathode, the effect of a spontaneous change in the emissive ability of the investigated surface area was observed. These changes can vary significantly in magnitude. Large-scale changes can lead to a permanent increase in the emissive ability of a specific area or to a breakdown of the gap. Small changes, as a rule, are reversible, have a stepped nature, and make it difficult to record and interpret the current-voltage characteristics of the field emitter. In addition, in installations where one of the electrodes is movable and there is no good vibration protection, mechanical vibrations occur. These fluctuations can stimulate the changes in emissive ability described above, and also make it difficult to measure the breakdown characteristics of the cathode.

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References
[1] Herrmann A, Balden M, Laux M, Krieger K, Müller H W, Pugno R, Rohde V and ASDEX Upgrade team 2009 J. Nucl. Mater. 390–391 747–50
[2] Tokitani M, Kajita S, Masuzaki S, Hirahata Y, Ohno N, Tanabe T and LHD Experiment Group 2011 Nucl. Fusion 51 102001
[3] Rudakov D L, Chrobak C P, Doerner R P, Krasheninnikov S I, Moyer R A, Umstadter K R, Wampler W R and Wong C P C 2013 J. Nucl. Mater. 438 S805–8
[4] Kajita S, Fukumoto M, Tokitani M, Nakano T, Noiri Y, Ohno N, Masuzaki S, Takamura S, Yoshida N and Ueda Y 2013 Nucl. Fusion 53 053013
[5] Savrukhin P V and Shestakov E A 2019 Phys. Plasmas 26 092505
[6] Takamura S, Ohno N, Nishijima D and Kajita S 2006 Plasma and Fusion Research 1 51
[7] Kajita S, Sakaguchi W, Ohno N, Yoshida N and Saeki T 2009 Nucl. Fusion 49 095005
[8] Kajita S, Takamura S and Ohno N 2009 Nucl. Fusion 49 032002
[9] Ogorodnikova O V, Klimov K S, Poskakalov A G, Kaziev A V, Kharkov M M, Efimov V S, Gasparyan Yu M, Volkov N V, Alimov V Kh and Tokitani M 2019 J. Nucl. Mater. 515 150–9
[10] Houston J M 1952 Phys. Rev. 88 349
[11] Sinelnikov D, Bulgadaryan D, Hwangbo D, Kajita S, Kurnaev V and Ohno N 2019 IEEE T. Plasma Sci. 47 5186–90
[12] Sinelnikov D, Bulgadaryan D, Hwangbo D, Kajita S, Kolodko D, Kurnaev V and Ohno N 2016 J. Phys.: Conf. Ser. 748 012012
[13] Hwangbo D, Kajita S, Ohno N and Sinelnikov D 2017 IEEE T. Plasma Sci. 45 2080–6
[14] Alpert D, Lee D A, Lyman E M and Tomaschke H E 1964 J. Vac. Sci. Technol. 1 35–50