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ON THE INFLUENCE OF VACUUM CONDITIONS ON THE POWER LEVEL OF ELECTROMAGNETIC WAVES GENERATED BY A RELATIVISTIC MAGNETRON

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The high-power microwave radiation, generated in a relativistic high-voltage pulsed magnetron with the range of 8 mm, was experimentally investigated. The factors that negatively affect the generation of microwave radiation were experimentally studied and analyzed. It was determined that the low pressure in the vacuum diode of the magnetron also was associated with the processes reducing the efficiency and duration of the pulse generation. The air components are known to be the major residual gases in the magnetron vacuum diode. During the magnetron operation, a significant increase in the pressure of the residual atmosphere of hydrocarbons, water vapor, and hydrogen is to be observed. A vacuum system was composed to pump them out, thus ensuring the magnetron optimal operation. A cryogenic condensation-adsorption pump was developed and applied for the new vacuum system allowing to increase the evacuation rate of the main residual gases. The peculiarity of the developed pump is that the pumping element with the adsorbent has a double working surface due to the use of a corrugated form of the sorption cartridge. Another feature of the pump is its efficiency, which is achieved due to the use of nitrogen vapors for cooling the space between the walls. Due to the use of the cryogenic means of pumping, it became possible to obtain the pressure at the level of $1\cdot10^{-6}$ Torr, thus achieving an increase in the microwave radiation of the relativistic magnetron by 25 percent.

Keywords: *Relativistic magnetron; Microwave radiation; Vacuum system; Adsorption pump*
PACS: 52.30.q, 50.80.Vp

INTRODUCTION

The use of high-energy microwave radiation is necessary in a variety of applications including plasma physics and many fields of applied research [1]. When operating in the millimeter wavelength range the relativistic magnetron researchers face the problems associated with the efficiency of microwave energy extraction both in the radial direction of the cylindrical structure and in the axial one [2]. Such undesirable effects as an increase of the voltage action duration in the electrodynamic structure (EDS), the pressure at the level of $1\cdot10^{-4}$ Torr resulted in a rapid deterioration of the EMF [3-6]. Therefore, the problem to improve the method of removing high-frequency power from the EMF of the magnetron arose [7-9]. One of the steps that contribute to this result is to obtain the residual gases pressure at the level of $1\cdot10^{-6}$ Torr. The air components are the major residual gases to be known in the magnetron vacuum diode. During operation of the magnetron, a significant increase in the residual atmosphere of hydrocarbons, water vapor, and hydrogen is observed. Before the reconstruction, the vacuum pumping system included a forevacuum pump for obtaining a low vacuum and a magnet discharge pump for obtaining a high vacuum$\cdot$($1\cdot10^{-4}$-$6\cdot10^{-5}$ Torr). This configuration of the vacuum evacuation facilities did not cope well with pumping-out of hydrocarbons, hydrogen and water vapor. This was one of the reasons why the magnetron operation efficiency was low. At the same time, the working surfaces of the magnet discharge pump used to fail, what caused the work stoppages. To generate microwave radiation in the magnetron, it is necessary to maintain a certain pressure in the vacuum system, which should be $1\cdot10^{-6}$ Torr. This is the objective of the work. Achieving the highest vacuum provides the optimal conditions for the formation and stable maintenance of the electron flow, which interacts with the electromagnetic field. This paper presents the results of the microwave radiation increase by 25% due to obtaining the working vacuum at the level of $1\cdot10^{-6}$ Torr.

MAGNETRON VACUUM SYSTEM

The developed vacuum circuit provides optimal conditions for the formation and stable maintenance of the electron flow, which interacts with the electromagnetic field. It is proposed to increase the microwave radiation owing to generation of the pressure in the magnetron vacuum system at the level of $P=1\cdot10^{-6}$ Torr. An increase in the microwave radiation is proposed owing to generation of the pressure in the magnetron vacuum system at the level of $P = 1\cdot10^{-6}$ Torr. The research was carried out on the installation, whose schematic is presented in Fig. 1.

The experiments with the PM-48 magnetron revealed microwave generation at the frequency from 36 to 4 GHz with the magnetic induction magnitude from $B_0 = 0.35$ to 0.8 T and the anode voltage from $U_0 = 190$ kV to 250 kV. The diameters of the anode and cathode were d_a=25 mm and d_c=14 mm, respectively, and the gap between the cathode and

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anode d_{ca} was in the range of 3-5mm. The observed oscillations can be defined as $\pi/2$; π or $(2/3)\pi$ modes. However, the result of the horn-supported axial microwave power feed-out experiments is to be still classified as unsatisfactory one.

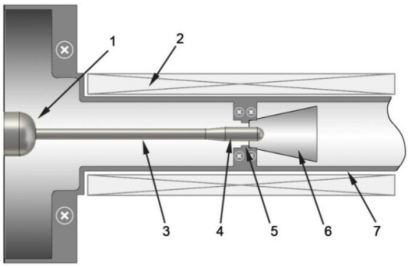


Figure 1. Schematic of a relativistic magnetron
1. Vacuum resonator. 2. Solenoid. 3. Cathode holder. 4. Cathode. 5. Anode. 6. Output horn. 7. Oversized waveguide.

One of the reasons of this problem is the impact of the anode-cathode plasma on the discharge. The worse is the vacuum conditions in the magnetron, the greater is the effect of the anode-cathode plasma on the discharge. If the vacuum level in the magnetron is not properly maintained, several problems can occur:

1. Instability of the electron flow: Insufficient vacuum can cause some fluctuations and instability of the electron flow, thus negatively affecting the generation of microwave radiation.
2. Increased gas pressure: When the gas pressure in the vacuum chamber is increased, some unwanted collisions of electrons with gas molecules can occur, thus reducing the magnetron efficiency.
3. Overheating of the elements: Low vacuum can cause overheating of the magnetron and other system components, which can result in their being damaged or fail.
4. Reduced lifetime: Constant fluctuations in the vacuum level can shorten the lifetime of the magnetron and other system components.
5. Breakdown between the cathode and anode: In the literature, the data are provided that in this case the pressure in the vacuum chamber of the magnetron deteriorates by an order of magnitude [10].

The carried-out studies allow assuming that a pre-breakdown in the anode-cathode gap can occur on a relativistic magnetron. The current that appears in this case is 50-100 μA. Here we see significant destruction of the anode, which has the appearance of hollows. The condition of the anode and cathode surface is shown in Fig. 2.

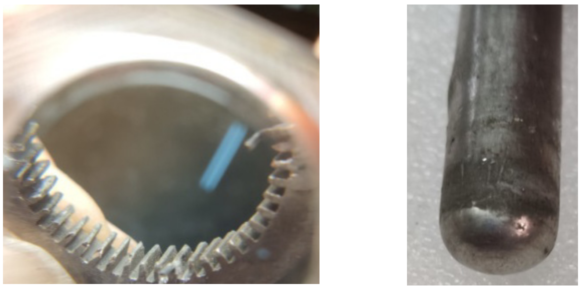


Fig. 2. The condition of the damaged surface of the anode and cathode of the relativistic magnetron

The destruction on the anode indicates the electronic nature of the current. Also, the transfer of metal from the cathode to the anode can be seen. On the anode, in this case, the metal is destroyed and some soot appears. This happens owing to the inability to achieve the required level of vacuum with the existing means of pumping. Therefore, the problem of improving the magnetron vacuum system arose

The new vacuum system was composed basing on the requirements to ensure optimal operation of the relativistic magnetron. The vacuum pumping system includes a pre-vacuum pumping line and a high vacuum pumping line. Fig. 3 shows the schematic diagram of the vacuum pumping system of the relativistic magnetron chamber.

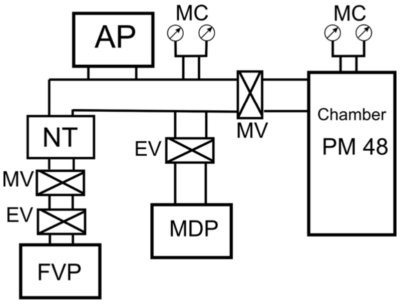


Figure 3. Schematic diagram of the vacuum pumping system of the relativistic magnetron chamber

FVP – forevacuum pump; AP – adsorption pump; MDP – magnet discharge pump; MV – manually operated valves; EAV - electric-actuated valves; Chamber PM48 – magnetron chamber; MC – manometric converters, NT – nitrogen trap, EV - emergency air inlet valve

The vacuum chamber system, presented in Fig. 3, has a forevacuum pumping line, which is designed to pump out Chamber PM48 from the current atmospheric pressure to ~$7{\cdot}10^{-2}$ Torr. The forevacuum pumping is carried out by a forevacuum pump (FVP) through an open electric-actuated valve (EAV) and a nitrogen-filled nitrogen trap NT-LAF-32. The pressure in the line and working chamber is measured by manometric converters (MC). The high vacuum pumping line consists of an adsorption pump (AP) with the manometric converter (MC), connected to the magnetron chamber PM48 through the manually operated valve (MV), and the magnet discharge pump (MDP), which is connected to the relativistic magnetron chamber through the electric-actuated valve (EAV). In addition, the vacuum system includes an emergency air inlet valve (EV), which is activated when the light is turned off.

To obtain the working pressure in the relativistic magnetron at the level of $1{\cdot}10^{-6}$ Torr, it is proposed to use cryogenic means of pumping [11, 12]. For this purpose, a design of a high-vacuum cryogenic condensation-adsorption pump was developed, which works on one refrigerant with efficient use of the outgoing vapors. The use of nitrogen vapors will increase the service life of the pump without increasing the refrigerant consumption. The schematic of the developed cryogenic condensation-adsorption pump is shown in Fig. 4.

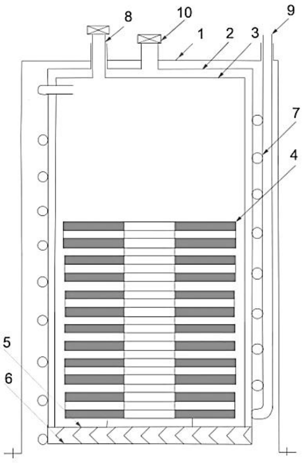


Figure 4. Schematic of the condensation-adsorption pump

The pump consists of an outer casing 1, in which the pumping element is placed, in the form of an inner casing 3 with the refrigerant, and a screen 2. Cassettes with adsorbent 4 (birch activated carbon – BAC) are placed in the lower part of the inner casing 3. The evacuation of the main mass of gas is carried out by condensation on the condensing surface 6 of the inner casing 3. The non-condensed part of the gas, as a consequence of the repeated contact with the surfaces having the temperature of the refrigerant, is absorbed by the adsorbent. Screen 2 with chevron 6 is designed to protect inner casing 3 from external radiation and other thermal flows. Screen 2 is cooled by the vapor flowing through coil 7. The components condensed from the pumped volume are also frozen here. The surfaces of inner housing 3 with the refrigerant and the elements of screen 2 are wrapped in mylar to minimize the heat inflow to them. Screen 2 and inner casing 3 with the refrigerant are suspended in outer housing 2 of the pump on two pipes 8 and 9, so that it would be possible to fill in the refrigerant through pipe 8, and to let the refrigerant vapors out through pipe 9. To reduce the thermal load on the inner casing, the volume between inner casing 3 and screen 2 is pumped out through pipe 10.

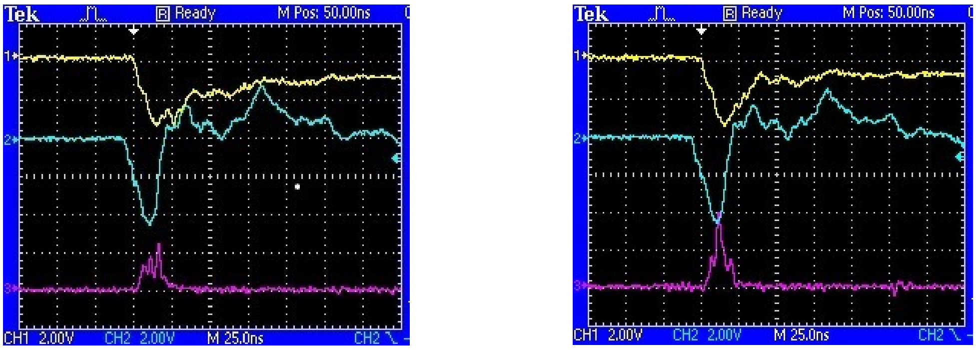
The vacuum system operates in the following way:

1. When MV1, MV2, MV3, EAV valves are open, we pump the accelerator chamber out using the EVP AVZ-20 forevacuum pump through the NT LAF-32 nitrogen trap filled with liquid nitrogen to the pressure of $7{\cdot}10^{-2}$ Torr which is the transitional mode between viscous and molecular gas flow mode. Then we close the MV1 valve and turn off the forevacuum pump.
2. We close the MV3 valve and fill in the adsorption pump (AP) with nitrogen, after starting the AP open MV3 and pump the system up to $3{\cdot}10^{-4}$ Torr.
3. We close the valves EAV and start the magnet discharge pump (MDP) "toward itself". Reaching the pressure of $2{\cdot}10^{-4}$ Tor, we open the pump MDP to the magnetron chamber. This allows obtaining the pressure of $1{\cdot}10^{-6}$ Torr.

The updated vacuum system allows operating the relativistic magnetron in a cyclic mode without failure of the pumping elements.

EXPERIMENTAL PART

After updating the relativistic magnetron vacuum system, the experiments were conducted to obtain the microwave radiation at different pressures of the residual atmosphere in the magnetron vacuum volume. The value of the magnetic induction was $B_0 = 0.75$ T, the anode voltage was $U_0 = 250$ kV. The output microwave radiation of the magnetron passed through a round waveguide with the diameter of 80 mm and the length of 775 mm, and was ejected into free space through a window made of organic glass. The output power of the emitted microwaves was estimated by measuring the magnetron microwave spatial distribution. As a receiving antenna, a pyramidal horn with an open end (4×3.2 cm^2) was used, which was placed in the azimuthal direction at the distance of 1.35 m from the window. The envelope curve of the output microwave signal was obtained using a diode D 404 and recorded by a digital oscilloscope with the bandwidth of 200 MHz. The first experiment was conducted at the pressure in the magnetron vacuum volume $P = 3 \cdot 10^{-4}$ Torr, the second – at the pressure $P = 1 \cdot 10^{-6}$ Torr. The oscillograms of voltage, current and microwave radiation are shown in Fig. 5.



a b

Figure 5. Oscillograms of voltage, current and microwave radiation
a – oscillogram at the pressure in the magnetron vacuum volume $P= 3 \cdot 10^{-4}$ Torr; b – oscillogram at the pressure in the magnetron vacuum volume $P= 1 \cdot 10^{-6}$ Torr

On the oscillograms, the first line is the anode voltage, the second line is the current, and the third line is the microwave radiation.

The calculated microwave radiation power in the first case was 650 kW, in the second – 875 kW. The obtained pressure of the residual gases in the relativistic magnetron at the level of $P = 1 \cdot 10^{-6}$ Torr gives an increase in the microwave radiation power by 25 percent.

CONCLUSIONS

The vacuum system presented in the paper allows obtaining the oil-free vacuum. It provides optimal conditions for the formation and stable maintenance of the electron flow, which interacts with the electromagnetic field. The vacuum pumping system allows to reach the operating pressure of $1 \cdot 10^{-6}$ Torr quickly, maintain the device in a pumped state for a long time, and reduce the time of the vacuum chamber preparation between the pulses. Obtaining the residual gases pressure in the relativistic magnetron at the level of $P = 1 \cdot 10^{-6}$ Torr gives an increase in microwave radiation power by 25 percent.

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ПРО ВПЛИВ ВАКУУМНИХ УМОВ НА РІВЕНЬ ПОТУЖНОСТІ ЕЛЕКТРОМАГНІТНИХ ХВИЛЬ, ЩО ГЕНЕРУЮТЬСЯ РЕЛЯТИВІСТСЬКИМ МАГНЕТРОНОМ

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Експериментально досліджено потужне НВЧ-випромінювання, що генерується в релятивістському високовольтному імпульсному магнетроні діапазону 8 мм. Експериментально досліджено та проведено аналіз факторів, що негативно впливають на генерацію НВЧ випромінювання. Визначено, що до процесів, котрі зменшують ефективність та тривалість імпульсу генерації, відноситься також низький тиск у вакуумному діоді магнетрону. Відомо, що в вакуумному діоді магнетрону головними залишковими газами є компоненти повітря. При роботі магнетрону спостерігається значне збільшення тиску залишкової атмосфери: вуглеводнів, водяної пари і водню. Для їх відкачування була скомпонована вакуумна система, що забезпечує оптимальну роботу магнетрону. Для нової вакуумної системи було розроблено та застосовано кріогенний конденсаційно-адсорбційний насос, якій дозволив збільшити швидкість відкачування основних залишкових газів. Особливість розробленого насосу полягає в тому, що відкачувальний елемент з адсорбентом має збільшену в два рази робочу поверхню-за рахунок використання гофрованової форми сорбційного патрона. Іншою особливістю насосу є його економічність, вона досягнута за рахунок використання парів азоту для охолодження між стінного проміжку. За рахунок використання криогенних засобів відкачування вдалося отримати тиск на рівні $1 \cdot 10^{-6}$ Тор, що призвело до збільшення випромінювання НВЧ релятивістського магнетрону на рівні 25 відсотків.

Ключові слова: *релятивістський магнетрон; мікрохвильове випромінювання; вакуумна система; адсорбційний насос*