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ON THE ROLE OF RUNAWAY ELECTRONS IN STIMULATING THE RF BREAKDOWN AND PLASMA FORMATION IN TORSATRONS URAGAN-3M AND URAGAN-2M

We consider a scenario of the initial stage of the RF breakdown of a working gas in torsatrons Uragan-3M and Uragan-2M and the roles of runaway electrons in this process. In our previous works, we studied only the acceleration factor of the breakdown process which occurs, when the intensity of the flow of runaway electrons increases due to the stimulation by an additional ultrahigh-frequency discharge at the front edge of a magnetic field pulse. This work attempts to describe the individual phenomena that accompany the initial stage of plasma formation in the confinement areas of torsatrons Uragan-3M and Uragan-2M in the presence of the flow of runaway electrons.

K e y w o r d s: stellarator, torsatron, runaway electrons, radio frequency heating.

1. Introduction

This work describes individual phenomena that accompany the initial stage of the plasma formation process in the confinement areas of torsatrons Uragan-3M (U-3M) and Uragan-2M (U-2M). The main focus is on the role of high-energy electrons in this process and the effect of a constant antenna potential on the breakdown of a working gas.

The magnetic field in stellarators U-3M and U-2M is applied in the pulse mode. Both of these stellarators are equipped with antennas of the frame type which are not electrically connected to the housing of the facility. Using frame antennas under a floating potential, an identical effect was made on runaway electrons (REs), whose flows are generated at the fronts of the magnetic field pulse [1, 2]. Taking these factors into account, we can consider the processes at the breakdown stage to be similar and use the same model in their description.

Moreover, since the U-2M torsatron has an additional toroidal magnetic field, one should expect a greater efficiency of the RE impact on the working gas both during the breakdown and the holding and heating in the course of the RF pulse. It is worth also noting the constructive difference of these physical facilities. In the U-3M torsatron, with a natural helical divertor, the entire magnetic system is placed in a large vacuum chamber; while, in the U-2M facility, the vacuum chamber is inside the magnetic system and, in the presence of fast particles, is a source of secondary electrons.

First, we would like to provide the data of previous experiments aimed at improving the parameters of the generated plasma, as well as its confinement and heating in the torsatrons U-3M and its predecessor U-3, which had an identical magnetic system.

The presence of hard X-ray radiation was noticed on the torsatron U-3 at the early stage of research. The reason for this was the rapid increase of current in the windings of the helical and compensating fields. The vortex longitudinal electric field generated in this case accelerates background electrons, which are a consequence of background radiation, to the speed necessary to ionize the working gas. Background radiation should be understood as ionizing radiation present in the environment at a particular location which is not due to the intentional injection of radiation sources.

After the working gas ionization, there is the acceleration of electrons and ions of the generated plasma. The acceleration occurs up to the end of the front edge of a magnetic field pulse. At the back edge of the magnetic field pulse, a similar phenomenon also occurs, with regard for the addition of charged particles generated at the front edge of the magnetic field pulse (which move in the th direction opposite to the accelerating field at the back edge of the magnetic field pulse).

Hard X-Rays have negative effect on the human health. A series of experiments on the suppression of this radiation was performed on the facility U-3M. For this, the duration of magnetic field pulses was increased which allowed one to reduce the level of hard X-Rays. However, this solution had to be abandoned due to a sharp deterioration of the gas breakdown and the parameters of the generated plasma.

We mention some difficulties occurred during the operation of the U-3M facility in improving the plasma parameters. They were caused by a strong interaction of the confined plasma with the surface of the antennas of generators Cascade-1 (K1) and Cascade-2 (K2). It was proposed to produce antennas with a surface more resistant to the plasma impact. The surface of the antenna was covered with a layer of titanium nitride [3]. This played a positive role in improving the confined plasma parameters, as the amount of heavy impurities in the plasma decreased significantly. This fact confirms the strong interaction of the plasma with the antenna surface.

The operation and experiments on the torsatron U-3M in 2012 was difficult due to unsatisfactory working gas breakdown conditions. The reasons for this immediately could not be found. However, it turned out later that the difficulties of the working gas breakdown are related to the instability of the front edge of the magnetic field pulse.

In order to improve the working gas breakdown conditions, a mechanism for stimulating it by enhancing the flow of runaway electrons was proposed [4, 5]. The stimulation was an additional ionization of the working gas during the plasma generation at the front edge of the magnetic field pulse. This was performed using a microwave generator, which operated at a frequency of 2.45 GHz. The magnetic field during its operation was about 0.8 kOe. This technique allowed one to improve the breakdown parameters of the working gas and once again confirmed the role of runaway electrons at the initial stage of plasma generation in the U-3M torsatron.

In the experiments on the torsatron U-2M, the presence of a sufficiently large constant potential on the antennas, which were not electrically connected with the housing of the facility, i.e., were under the floating potential, was found. In the initial stage of the RF pulse and before the generation of plasma in the confinement area, the potential value was positive. After the breakdown and generation of plasma in the confinement area, it was negative. In our opinion, the constant potential of the antenna is affected by such plasma characteristics as the density and the distribution of charged particles over velocities. In addition, we assume that the presence of such potential in the peripheral charge area will affect the dynamics of accelerated electrons, their ability to interact with the neutral gas and to ionize it, and thus to improve or worsen the breakdown conditions. We plan to write about this in future works. These results were obtained on U-2M. But since the types of antennas and the RF generators are the same as on U3M, these results can be used to interpret the experiments performed earlier on torsatron U-3M.

The main way to stimulate the breakdown on the U-2M torsatron was to generate preliminarily a low-density plasma with an additional pulsed RF generator. For this purpose, the generator K2 is usually used. The RF pulse of an additional generator ended at the same moment, when the main generator started to operate.

It should be noted that the breakdown of the working gas on the torsatron U-2M did not cause such problems that occurred on the torsatron U-3M.

We also note that the first description of the initial stage of working gas breakdown in the U-3M torsatron was given in [6]. This article uses the concept of idling, which means the time from the beginning of the application of a RF pulse to a sharp decrease in the antenna current, which, in turn, occurs as a result of the appearance of plasma in the confinement volume. The initial stage of breakdown in the U-2M torsatron was described in [7].

2. Experimental Results

We see that, in the RE-stimulated mode, the gas breakdown occurs with a shorter time delay than in the non-stimulated mode. The authors interpret this fact as a result of the effect of the RE on the initial ionization of the working gas [4, 5]. The following information serves as the basis for this conclusion. In stellarators U-2M and U-3M, the generation and heating of plasma are performed by the RF method. Sources of the RF electromagnetic field, by means of which the plasma is generated, are RF generators K1 and K2. These are powerful single-cascade autogenerators built by push-pull circuit, when each arm of the autogenerator works half a period [8]. In this case, when working on the frame grounded antenna, at its middle point, there is no RF voltage (with fully balanced oscillator arms). In practice, due to differences in the parameters of the used active elements (in this case, vacuum triodes), at the middle point, there is a high-frequency voltage. Its amplitude is much less than the main signal. Therefore, any appearance of the DC or RF voltage, different from what was measured when tuning the generator at the middle point of the load-antenna of the RF generator, can be interpreted as an influence on the antenna from the outside. When studying the plasma generation mode using the frame antenna, the voltage at the midpoint of the matching device, which is equipotential midpoint of the potentially isolated frame antenna was monitored [6].

It was found that, when the RF generator works in the mode of generating and/or heating the plasma, the constant potential at $U_{\text{antenna midpoint}}$ during the RF pulse has positive and negative components (Fig. 1).

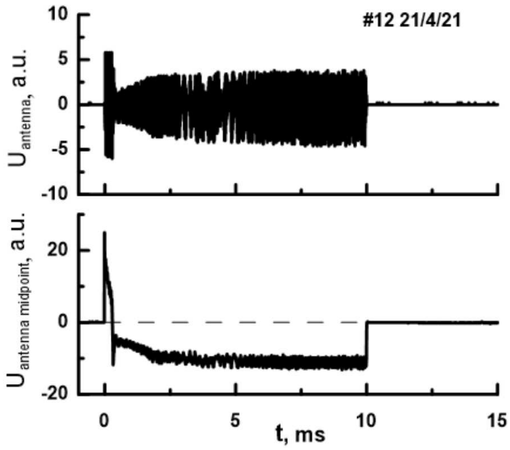

Fig. 1. Time dependences of the RF voltage at the antenna outputs U_{antenna} and voltage at the antenna midpoint $U_{\text{antenna midpoint}}$

Figure 1 shows that the level of the negative voltage at the antenna of generator K-2 on the facility U-2M changes during the pulse, when the load resistance by the plasma into the antenna changes. This can also be judged by a change in the level of RF voltage at the antenna outputs. The conclusion is that the negative potential of the antenna is due to the interaction of the antenna with the plasma. The level of the positive voltage $U_{\text{antenna midpoint}}$ in these experiments was more than 2 kV, and the negative voltage was more than 1 kV.

In works [1, 2, 8], it was shown that, when direct voltage of any polarity with an amplitude above an interval of 50 ... 100 V is applied to the frame antenna in the U-3M and U-2M facilities, the suppression of a RE flow, which is generated at the fronts of the magnetic field pulse, occurs. But since the flow of RE as a result of the acceleration by the vortex field has a high velocity, the interaction only with the antenna field does not allow suppressing it completely. During the RF pulse, it can both decelerate and dissipate (change tin he velocity and direction of motion). At the initial stage of the RF pulse, at a positive potential on the antenna, there is an interaction with the antenna surface. A hard X-ray emission and a secondary electron emission should be observed. Both factors stimulate the breakdown. The dynamics of the constant potential at the frame antenna will be discussed in more details in a forthcoming paper.

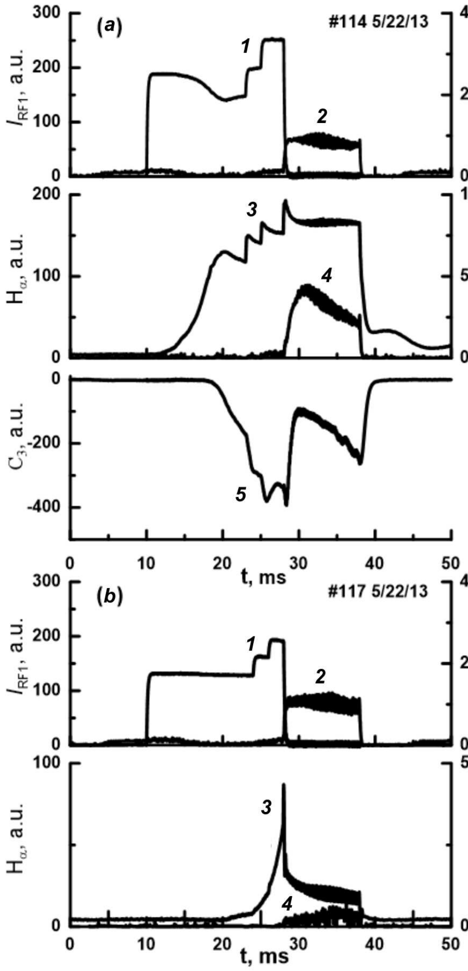

Fig. 2. Temporal behavior of currents fed to the RF antennas of generators – *1* and *2*; glow of the H_α line and X-ray signal – *3* and *4*; glow of the C_3 line – *5*. Case (*a*) – with microwave stimulation at the front edge of the magnetic field pulse and (*b*) – without microwave stimulation

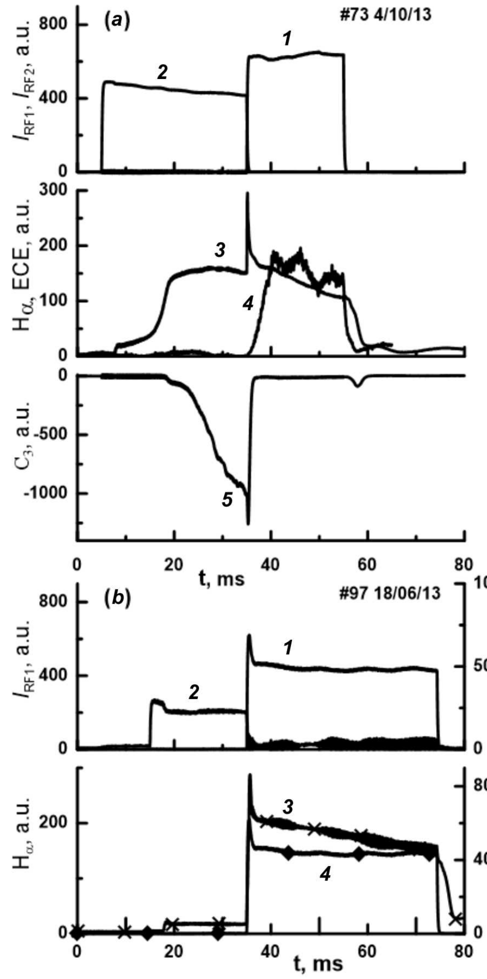

Fig. 3. Temporal behavior of currents fed to the RF antennas – *1* and *2*; glow of the H_α line and the electron cyclotron emission signal – *3* and *4* (*a*); glow of the H_α and H_β lines – *3* and *4* (*b*); glow of the C_3 line – *5* (*a*)

The main attention in this paper is paid to the initial stage of the discharge occurrence in the torsatron U-3M confinement area and to the role of runaway electrons at this stage. Data shown in Figs. from 2 to 7 were obtained on the facility U-3M. All experimental results, which will be presented, are obtained using the microwave stimulation of the discharge at the front edge of a magnetic field pulse, which is the source of the runaway electron flow [4, 5]. The exception is the experimental material shown in Figs. 1, 2, *b*, and 7, *a*.

Figure 2 shows the dynamics of the H_α line glow and the data of the accompanying diagnostic signals. The temporal plots of currents fed to the RF antennas of generators, curves *1* and *2*, illustrate the time intervals of RF generators. The generators were switched on in series, firstly K1 and then K2. Generator K1 was used for the pre-ionization, and generator K2 worked as the main generator to produce and heat the plasma. As a rule, the glow of H_α begins with a significant advance of the breakdown and signals of electron cyclotron emission (ECE) and X-ray radiation (ECE signal is shown in Fig. 3, *a*). At the same time, one can observe the glow of C_3 line, which was also recorded in the antenna area of the generator K1. It should be noted that, in this mode of operation, without stimulating the flow of runaway electrons, the gas breakdown did not occur – Fig. 2, *b*. Voltages at the anodes of RF lamps of generators K1 and K2 were, respectively: $U_{\rm K1} = 3.5$ kV, $U_{\rm K2} = 8$ kV for Fig. 2, *a* and $U_{\rm K1}$=2.5 kV, $U_{\rm K2} = 8$ kV for Fig. 2, *b*. By changing the voltage at the anode of a RF lamp, we changed the RF power which was supplied from the RF generator to the input of the antenna [7].

Figure 3 demonstrates the dynamics of H_α line glow and the data of accompanying diagnostic techniques in the operating modes of generators K1 and K2, when the generator K2 was used for the preionization, and the generator K1 worked as the main one to produce and heat the plasma in the confinement area. The generators were switched on in series, firstly K2 and then K1. The moments of switching-on and -off of the RF generators K1 and K2 can be determined by currents supplied to the antennas and marked as curves *1* and *2*, respectively. During the RF pulse of K2 generator, even before the switch-on of the main generator K1, the line H_α began to glow. The sensor which registered the glow of line H_α was near the antenna of K1 generator and received radiation from both K1 antenna and the confinement area. The sensor which registers the radiation of hydrogen line H_β received radiation only from the confinement area. The hydrogen line H_β glow occurred during the operation in similar modes, but only after the main cascade of Fig. 3, *b* was turned on. These data allow us to follow the dynamics of the plasma appearance from the periphery to the confinement volume. Voltages at the anodes of RF lamps of generators K1 and K2 were, respectively: $U_{\rm K1} = 8.5$ kV, $U_{\rm K2} = 5.5$ kV for Fig. 3, *a* and $U_{\rm K1} = 7$ kV, $U_{\rm K2} = 6$ kV for Fig. 3, *b*.

Figure 4 shows the dependence of the magnitude of a delay of the start of the ECE signal and the glow of the H_α line in the antenna area of the generator K1, as well as the breakdown delay, by the moment of the antenna current sagging from the front edge of the RF pulse, on the duration of the microwave pulse, stimulating the creation of the RE flow.

With increasing the duration of the microwave pulse, there is a reduction in the delay of the breakdown of the working gas in the confinement area, as well as a reduction in the delay of the ECE from the beginning of the H_α line glow. A peculiarity of the microwave generator that was used to stimulate the

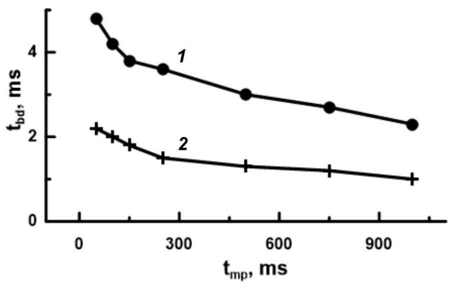

Fig. 4. Delay of the breakdown of the working gas in the confinement area $t_{\rm bd}$ from the duration of the microwave pulse $t_{\rm mp}$, stimulating the RE flow: the delay between the appearance of the ECE signal and the beginning of the H_α line glow – curve *2*; the breakdown delay, by the moment of the antenna current sag, from the front edge of the RF pulse – curve *1*

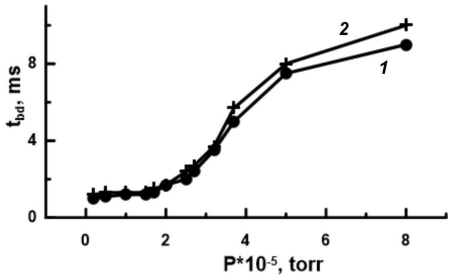

Fig. 5. Dependence of the breakdown delay $t_{\rm bd}$ on the working gas pressure. Delay in ms between the occurrence of the ECE signal and the beginning of the H_α line glow – curve *2*; breakdown delay, by the moment of the antenna current sag, from the front edge of the RF pulse – curve *1*

RE flows should be mentioned. Simultaneously with the growth of a pulse duration, there was a growth of the UHF voltage amplitude at the generator output (peculiarity of the generator).

Figure 5 shows the dependence of the breakdown duration of the working gas in the confinement volume on the working gas pressure. It can be seen that, as the working gas pressure in the chamber increases, the breakdown duration increases as well.

Moreover, with increasing the working gas pressure, the amplitude of ECE and X-ray signals decrease, but the H_α and C_3 signals in the area of the generator antenna K1 increase. It can be assumed that, as the density of the working gas increases, the discharge is suppressed in the confinement area and shifted to the peripheral area. Similar effects were observed at the pulse gas injection in the region of the antenna of generator K1.

Figure 6 shows the dependence and the actual delay of the breakdown time in the presence of pre-

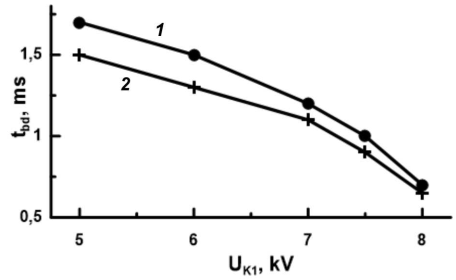

Fig. 6. Dependence of the breakdown delay of the working gas $t_{\rm bd}$ on the antenna voltage of the generator K1. Breakdown delay, by the moment of antenna current sagging, from the front edge of the RF pulse – curve *1*. Delay between the appearance of the ECE signal and the beginning of the H_α line glow – curve *2*

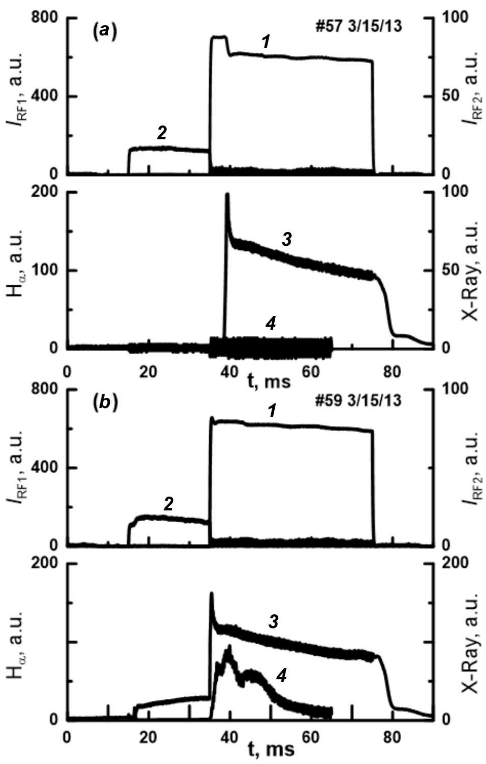

Fig. 7. Dependence of the occurrence of hydrogen line glow H_α in the antenna area of the generator K1, when the generator K2 works as a pre-ionizer, with microwave stimulation of the flow of runaway electrons (b) and without stimulation (a). Temporal behavior of currents fed to the RF antennas of generators – curves *1* and *2*; glow of the H_α line and X-ray signal – curves *3* and *4*

ionization. It was repeatedly confirmed in experiments on the U-3M torsatron that, in the presence of pre-ionization, using the generator K2 or the stimulation of runaway electron flows, with increasing the amplitude of a high-frequency voltage at the antenna of the generator K1, the breakdown conditions of the working gas are improved. This is evidenced by a decrease in the breakdown time in the confinement area and a reduction of the delay time from the start of the glow line H_α in the antenna area of the generator K1 and ECE in the plasma confinement area. In contrast, the experimental results obtained on the U-3M torsatron show the presence of an optimal breakdown voltage at the antenna of generator K1 [6]. This once again shows the necessity of the preliminary ionization for the initial stage of discharge in the torsatron confinement area.

Figure 7 demonstrates the dependence of the occurrence of the hydrogen line H_α glow in the antenna area of the generator K1 on the microwave stimulation of the flow of runaway electrons.

It should be noted that the glow H_α received by the sensor located near the antenna of generator K1 in the vast majority of experiments begins in time before the processes accompanying the generation of plasma in the confinement area. This can be judged by radiation at the electron cyclotron frequency (ECF), X-ray emission, as well as by the disruption of the current of the antenna of generator K1. It should be noted that this sensor also registers the glow of the H_α line, when plasma appears in the containment area. The form of the glow envelope shows the transition from a glow in the antenna area of generator K1 to a glow in the containment area. This transition coincides in time with the beginning of ECE radiation and corresponds to the current disruption in the antenna of generator K1, by which it was judged earlier about the beginning of the plasma formation in the containment area [6]. Such early glow is especially pronounced at low voltages at the antenna of generator K1 on the order of 2.5–3 kV. At the step form of the envelope of the RF pulse, this corresponded to the first stage.

The glow of the H_α line in the antenna area of the generator K1 before its switching-on, when the generator K2 works as a pre-ionizer, can be explained by the generation of plasma in the periphery of the confinement area and even beyond it [9].

3. Conclusions

The above experimental results allow us to draw the following conclusions and assumptions.

1. When a RF voltage is applied, the discharge occurs near the antenna of the generator K1 and can interact with its surface. This can be confirmed by the results of measurements of the glow line C_3, as well as calculations of Z effective throughout the RF pulse [10].

2. The presence of a discharge (plasma) can be the cause for the occurrence and dynamics of the potential on the frame antenna, which is potentially isolated.

3. In turn, the presence of a potential in the peripheral plasma confinement area can affect the RE dynamics.

4. In the pre-ionization mode with the K2 generator, the initial plasma is generated in the peripheral part of the confinement area (minimum-field area) [9].

5. The delay in the breakdown of the working gas in the confinement area decreases, as the amplitude and duration of the microwave voltage pulse stimulating the RE flow increases.

6. As the pressure of the working gas in the chamber increases above 10^{-4} Torr, the duration of the breakdown delay in the confinement area increases. The optimum pressure for the breakdown of the working gas in the interval 10^{-5}–10^{-4} Torr was observed in experiments on the torsatron U-3M, and the rapid growth of the plasma density in the pressure interval $1–2 \cdot 10^{-5}$ Torr [6].

This is confirmed by the results obtained on the U-3M torsatron.

In [6], there is no clear interpretation of this phenomenon.

On the one hand, with an increase of the pressure within these limits, the conditions of discharge should be improved. But, on the other hand, if we assume that the main contribution to the pre-ionization is made by REs, it is necessary to consider the conditions of optimal birth and existence of fast electrons under conditions of the fusion facility U-3M. To optimize this process requires conditions for the generation of plasma at the front of the magnetic field pulse, which requires quite a certain, not small, density. At the same time, the density value must be such that it would not prevent the acceleration of particles to high velocities. In other words, the optimal pressure of the working gas is required to obtain the RE flow in accordance with the proposed scenario.

7. Experiments were performed with and without pre-ionization. When using an additional generator as the source of pre-ionization, the conditions of working gas breakdown are improved with the increase of the RF voltage amplitude at the antenna of the main generator from 3 up to 9 kV on torsatrons U-3M and U-2M. The idle stroke, time between the start of a RF pulse of the main generator and the generation of plasma in the confinement volume, is reduced. The time moment of the breakdown itself becomes stable, repeating from pulse to pulse. The same dependence is observed on torsatron U-3M, if the flow of accelerated electrons stimulated by the microwave generator acts as the source of pre-ionization. It should be noted that experiments on the stimulation of the flow of accelerated electrons by the microwave generator which was started at the front edge of the magnetic field pulse were not performed on torsatron U-2M. These results differ from those obtained on torsatron U-3 and U-3M in the absence of pre-ionization sources. Under these conditions, the idle stroke was decreased with an increase of the voltage at the antenna from 3 up to 7 kV, and with a further increase of the RF voltage at the antenna, the idle stroke stopped decreasing and even slightly increased.

8. When using a pre-ionization source in the initial stage of breakdown on U-3M and U-2M torsatrons, we have got not only positive consequences in the form of the plasma breakdown stability and a small idle time. Thus, when using an additional RF generator for the pre-ionization at the initial stage of discharge, the plasma is generated directly near the antenna. This causes heavy impurities to enter the plasma confinement area [10], which, in turn, leads to additional energy losses from the confinement volume. A similar picture is observed, if the microwave stimulation of the flow of accelerated electrons is used as a pre-ionization. A part of the accelerated electrons interacts with the material of the main RF antenna, causing metal impurities to enter the confinement volume.

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ПРО РОЛЬ ВТІКАЮЧИХ ЕЛЕКТРОНІВ У СТИМУЛЮВАННІ ВЧ ПРОБÓЮ ТА УТВОРЕННЯ ПЛАЗМИ В ТОРСАТРОНАХ УРАГАН-3М, УРАГАН-2М

В роботі розглядається сценарій початкової стадії високочастотного пробою робочого газу в торсатронах Ураган-3М, Ураган-2М та ролі електронів-втікачів у цьому процесі. Раніше в наших роботах розглядався лише фактор прискорення процесу пробою, який мав місце зі збільшенням інтенсивності потоку втікаючих електронів за рахунок стимуляції додатковим надвисокочастотним розрядом на передньому фронті імпульсу магнітного поля. У цій роботі зроблено спробу описати окремі явища, що супроводжують початкову стадію процесу утворення плазми в області утримання торсатронів Ураган-3М і Ураган-2М за наявності в області утримання потоку втікаючих електронів.

Ключові слова: стеларатор, торсатрон, втікаючі електрони, високочастотний нагрів.