STUDIES OF MICROWAVE CHARACTERISTICS AND PLASMA PARAMETERS IN LOW PRESSURE DISCHARGE INITIATED IN COAXIAL WAVEGUIDE BY STOCHASTIC RADIATION

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The research methods are described and the principal characteristics of the generated oscillations are studied. We study the plasma discharge, initiated by microwave radiation with stochastically jumping phase (MWRSJP) in a coaxial waveguide at the optimal mode of the beam-plasma generator. Present results continue the line of the previous research. In this paper the plasma parameters of a microwave discharge at its stable maintenance in air by MWRSJP, and the pressure range at which required power is minimal are measured. We experimentally examine also optical characteristics of the discharge plasma in a wide range of air pressure.

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INTRODUCTION

High-frequency (HF) heating is very important field in connection with fundamental questions of plasma physics and applications. This area of physics is intensively investigated as theoretically and experimentally (for example, see [1 - 3] and references therein). The issues widely discussed in literature are connected with additional plasma heating in tokamaks [1], the nature of accelerated particles in space plasmas [2], gas discharge physics [3]. Among the problems that attract attention of scientific community is development of sources with solar spectrum. This is utmost important problem from the point of fundamental, as well as practical application, and in this direction interesting achievements is obtained (see, for example [4]). It is worth mentioning that one of the difficulties associated with additional plasma heating in tokamaks is a well-known dependence of the Rutherford cross-section on velocity. As a consequence, the probability of collisions decreases with plasma temperature rising, thus creating obstacles for further plasma heating. Another important challenge in interaction of HF radiation with plasma is a barrier of the radiation penetration into the overdense plasma. To our knowledge, the most part of investigations in this direction are made with help of HF generators of electromagnetic radiation with regular phase. Thus the new opportunities that microwave radiation with jumping phase provides in this area would be very important.

In this paper, we describe the results of the theoretical and experimental investigation of the plasma interaction with microwave radiation with jumping phase that obtained with help of the unique beam-plasma generator (BPG) made in KIPT [5]. This study continues research on behaviour of plasma discharge subjected to microwave radiation with stochastically jumping phase (MWRSJP) which started in [6 - 8].

It was shown in [6 - 8], both theoretically and experimentally, that the phenomenon of anomalous penetration of microwave radiation into plasma, conditions for gas breakdown and maintenance of a microwave gas discharge, and collisionless electron heating in a microwave field are related to jumps of the phase of microwave radiation. In this case, in spite of the absence of pair collisions or synchronism between plasma particles and the propagating electromagnetic field, stochastic microwave fields exchange their energy with charged particles. In such fields, random phase jumps of microwave oscillations play the role of collisions and the average energy acquired by a particle over the field period is proportional to the frequency of phase jumps.

Gas breakdown and maintenance of a discharge in a rarefied gas by a pulsed MWRSJP were studied theoretically and experimentally in [10 - 18], as well as propagation of this radiation within the plasma produced in such a way. The conditions for ignition and maintenance of a microwave discharge in air by MWRSJP were found. The pressure range in which the power required for discharge ignition and its maintenance has its minimum was determined [16 - 18]. It was shown that, in the interval of pressures that have a level less than optimal (about 50 Pa for argon), the minimum of MWRSJP breakdown power depends weakly on the working gas pressure owing to several reasons. These reasons are efficient collisionless electron heating, weakening of diffusion and, finally, decrease of elastic and inelastic collisional losses. This allows one to extend the domain of discharge existence toward lower pressures. The intensity of collisionless electron heating increases with increasing rate of phase jumps in MWRSJP. There is an optimal phase jump rate at which the rate of gas ionization and, accordingly, the growth rate of the electron and ion densities reach their maximum. The optimal phase jump rate is equal to the ionization frequency at electron energies close to the ionization energy of the working gas.

In the present work, the effect of high power pulsed decimeter MWRSJP action on a plasma, produced in a coaxial waveguide filled with a rarefied gas, is investigated with use of the above mentioned BPG [5], which was upgraded for the given experimental conditions. The goal of this work is to study the special features of low pressure discharge initiated by MWRSJP und also optical radiation spectra. For interpretation of the experimental results on the ignition and maintenance of a microwave discharge in air obtained with MWRSJP BPG, a numerical code has been developed. This code allows simulating the process of gas ionization by electrons heated in the MWRSJP field and studying the behaviour of plasma particles in such a field.

MEASUREMENT OF PLASMA PARAMETERS IN A MICROWAVE DISCHARGE

If there are microwave plasma electric field, in this case, to determine its density are used double Langmuir probes. This probe consists of two single probes, between which a voltage is applied and measured current flowing there between. Because the plasma in this case produces a stochastic microwave radiation which propagates in the coaxial waveguide with a vacuum suction, the area in which it have place, is under high microwave capacity relative to the housing of the coaxial waveguide. In connection with this, probes lying in the region of plasma must be insulated from the coaxial waveguide circuits and power measurement. Because the generator is operating in a pulsed mode, and the plasma is only during the microwave pulse, the pulse is provided a method for measuring the plasma density, flow chart to explain its operation is shown in Fig. 1.

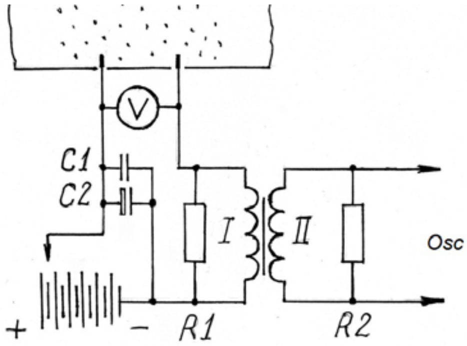

Fig. 1. Block-diagram of the pulse method for measuring the plasma density

Here R1, R2 = 15 Ohm; C1 = 0.5 μF × 100 V; C2 = 100 μF × 100 V. When the plasma is not a resistance in the probe circuit is infinite and no current. In the event of a coaxial waveguide of the plasma, its lifetime is about 160 μs, there is a current and in the resistor R1 voltage pulse arises, which is repeated across the resistor R2, so that the number of turns of the windings and the resistors are equal. To this was designed and manufactured by a pulsed transformer with a transformation ratio equal to one, each of the windings is terminated with an active impedance resistor with denomination 15 Ohm. Wherein each of the inductive reactance of the transformer windings greatly exceeds the resistance connected in parallel with it. The current flowing through the probe is measured by indirect method. For stand-alone power supply circuit that supplies a constant voltage to the probe connected low-resistance resistor specific denomination, knowing where the voltage drop was calculated pulse current. By changing the voltage between the probes recorded the current flowing through them. Previous so the current-voltage characteristic allows us to calculate the density of the plasma near the existing probes.

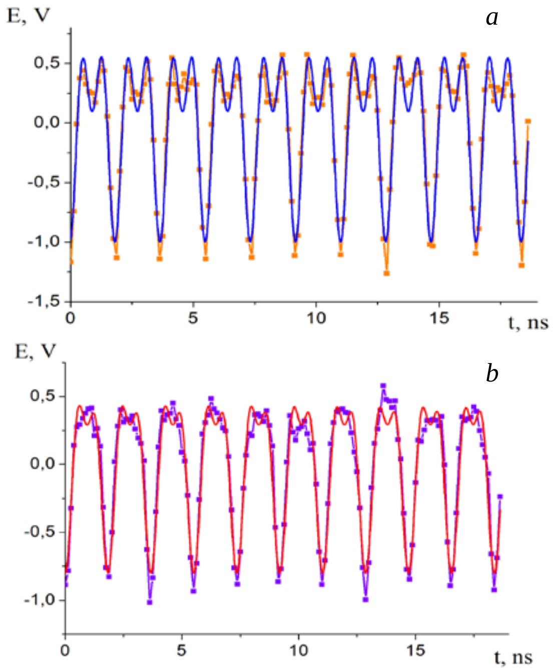

Fig. 2. A microwave signal from the first probe (the low-frequency displacement of voltage concerning zero is $u_3 = 9.1{\cdot}10^{-3}$ V) (a), the microwave signal from the second probe (the low-frequency displacement of voltage concerning zero is $u_3 = 2.4{\cdot}10^{-3}$ V) (b) with external voltage 0 V shifts the low frequency voltage difference with respect to zero between the two probes and the average his shift with respect to zero is respectively: $u_3 = 6.7{\cdot}10^{-3}$, $5.75{\cdot}10^{-3}$ V

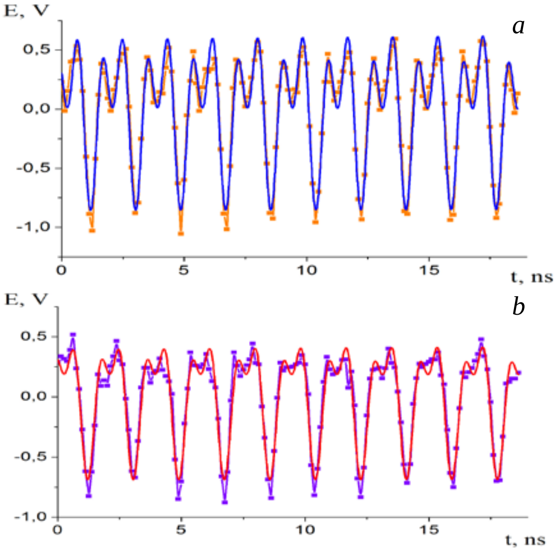

Fig. 3. A microwave signal from the first probe (the low-frequency displacement of voltage concerning zero is $u_3 = 19.0{\cdot}10^{-3}$ V) (a), the microwave signal from the second probe (the low-frequency displacement of voltage concerning zero is $u_3 = 4.9{\cdot}10^{-3}$ V) (b) with external voltage 63 V shifts the low frequency voltage difference with respect to zero between the two probes and the average his shift with respect to zero is respectively: $u_3 = 14.1{\cdot}10^{-3}$, $11.95{\cdot}10^{-3}$ V

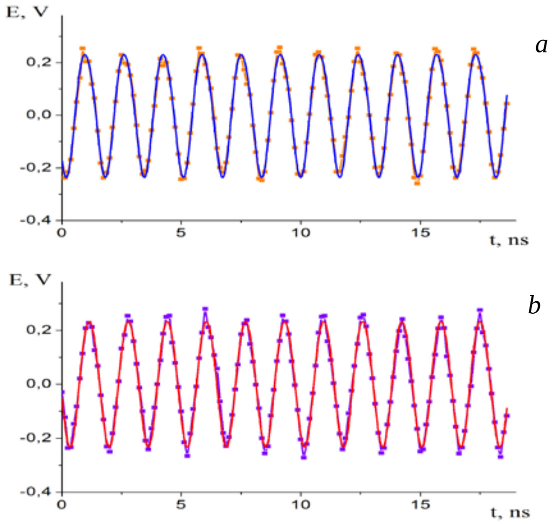

Fig. 4. A microwave signal from the first probe (the low-frequency displacement of voltage concerning zero is $u_3 = 11.6{\cdot}10^{-3}$ V) (a), the microwave signal from the second probe (the low-frequency displacement of voltage concerning zero is $u_3 = 7.7{\cdot}10^{-3}$ V) (b) with external voltage 0 V shifts the low frequency voltage difference with respect to zero between the two probes and the average his shift with respect to zero is respectively: $u_3 = 3.9{\cdot}10^{-3}$, $9.65{\cdot}10^{-3}$ V

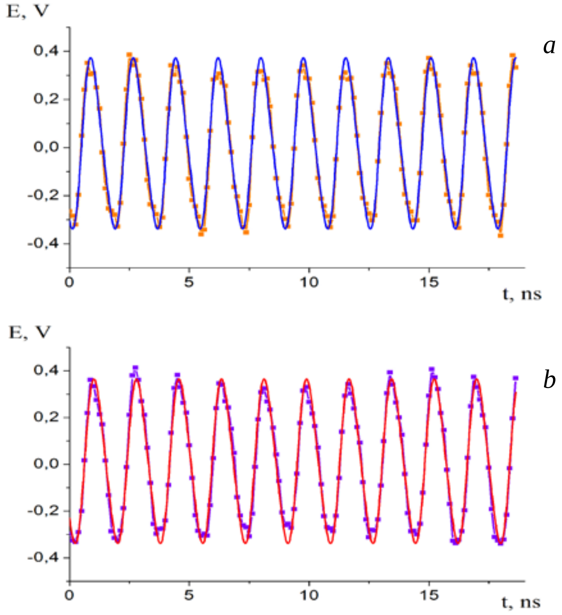

Fig. 5. A microwave signal from the first probe (the low-frequency displacement of voltage concerning zero is $u_3 = 10.4{\cdot}10^{-3}$ V) (a), the microwave signal from the second probe (the low-frequency displacement of voltage concerning zero is $u_3 = 9.1{\cdot}10^{-3}$ V) (b) with external voltage 37.6 V shifts the low frequency voltage difference with respect to zero between the two probes and the average his shift with respect to zero is respectively: $u_3 = 1.3{\cdot}10^{-3}$, $9.75{\cdot}10^{-3}$ V

The measurements were made using a four-channel wideband (2.25 GHz) oscilloscope HP Agilent Infinium. Figs. 2-5 show the results of processing the solid lines by least squares method a signal from first probe (upper figures) and filled squares point shot digital oscilloscope HP Agilent Infinium, the lower figures show the solid lines and filled squares, the results corresponding to the signal from the second probe.

The experimental data are approximated with help the least squares method. Approximating function for the signals shown in Figs. 2, 3 was chosen as:

$$E = u_0 \sin\left(u_1 t + u_2\right) + u_3 + u_4 \sin\left(u_5 u_1 t + u_6\right). \tag{1}$$

Approximating function for the signals shown in Figs. 4, 5 was chosen as:

$$E = u_0 \sin\left(u_1 t + u_2\right) + u_3. \tag{2}$$

Our calculations give plasma density values from $1{\cdot}10^9$ to $3{\cdot}10^9$ cm^{-3}. It should be noted that there are a current at zero voltage on the probe due to movement of electrons in the weakly inhomogeneous high-frequency fields by the force of high pressure (analogue behavior of the pendulum suspension oscillating, Kapitsa first investigated in 1951).

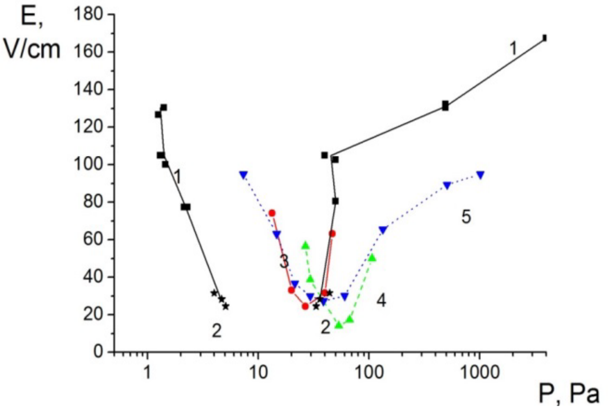

*Fig. 6. Dependence of breakdown electric field intensity for a microwave signals with a stochastically jumping phase versus a pressure for air in the optimal BPG mode (curves 1 – ■, 2 – *) in the non-optimal BPG mode: air (curve 3 – •), argon (curve 4 – ▲), helium (curve 5 – ▼), respectively, for the narrowband signals*

From Fig. 6 (curves 1 and 2) we can see that the levels of the electric field of 20 to 160 V/cm MWRSJP responsible for igniting the discharge is stable at pressures of gas (air) in the range from 1.5 to 3990 Pa. This result clearly demonstrates the benefits of discharge supported by microwave radiation with stochastic phase jumps compared to the microwave discharge on the basis of regular waves. Thus we have the ability to create the discharge at a pressure of about two orders of magnitude lower than the pressure that is necessary to fulfill the conditions of the minimum ignition power discharge initiates a regular microwave. Namely, but because (see [9]), the effectiveness of such a discharge is much higher due to the small contribution to the energy losses on unnecessary elastic and inelastic collisions when working at low pressures. For comparison, the dependence of the electric field of microwaves required to ignite the discharge in the air (curve 3), argon (curve 4) and helium (curve 5), which has been filled with coaxial waveguide on its pressure obtained during non-optimal mode of BPG operation. It can be seen that the pressure range in which the possible discharge ignition is much narrower than at the optimum operation of BPG. This is largely due to the difference in the average frequency of the jump phase in these BPG modes.

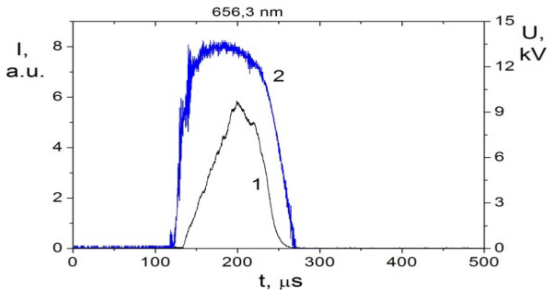

Fig. 7. Dependents of the optical emission intensity of the line 656.3 (curve 1, left scale) and high voltage (curve 2, right-hand scale) versus a time for air pressure 2.8 Pa at a power of 6 kW for optimal regime of the BPG operation

Fig. 7 shows that the pulse of optical radiation lasts almost as much as the last high voltage pulse. Microwave power varies during the pulse 10 times. This suggests that to maintain sufficient discharge of the electric field is much smaller than for the ignition.

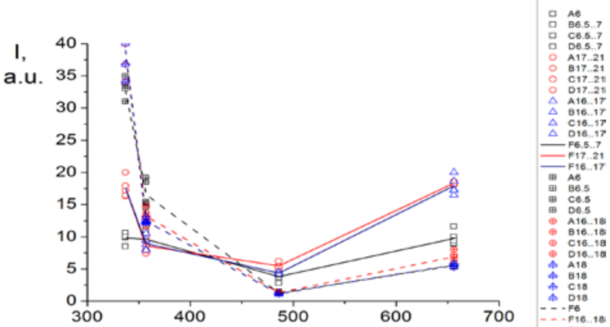

Fig. 8. Dependence of the intensity of optical radiation on the main lines of the wavelength for the two values of air pressure in the waveguide: 4.6 (solid lines) and 28 Pa (dashed lines) and at various powers (the power (in kW) indicated after letter for the optimal operation of the BPG

As can be seen from Fig. 8 spectrum of optical radiation from the discharge varies with different air pressures in the waveguide. Comparison of the intensities of the brightest lines (line of atomic hydrogen and line of the first positive system of nitrogen), are in the visible spectrum, showing that at a pressure P = 4.6 Pa ratio $I_{656} / I_{486} = 4.2$, and at a pressure P = 28 Pa ratio $I_{656} / I_{486} = 11.6$. This means that at a low pressure line 486.1, which lies in a range of blue color appears much better than the same line at a high pressure. Consequently, the observed color of the low pressure discharge more blue, and a high pressure redder, it can be seen with the naked eye in the experiment.

CONCLUSIONS

For the first time measured the plasma density in the low pressure discharge of initiated MWRSJP by the authors of the article developed the original technique of using double Langmuir probes, separate DC power supply, high-frequency transformers, digital oscilloscope and signal processing MWRSJP least squares method using a special form of basic functions. As a result of the experimental data (see Figs. 2-5) we fo-und that plasma density is $1{\cdot}10^9$ to $3{\cdot}10^9$ cm^{-3} at 6 kW.

It should be noted that there are of current and zero voltage on the probe due to movement of electrons in the weakly inhomogeneous high-frequency fields by the force of high pressure (analogue behavior of the pendulum suspension oscillating, P.L. Kapitsa first investigated in 1951).

Some of the results may also be used in connection with the additional plasma heating in fusion devices, because the heating by microwave radiation of charged particles with irregular phase collision less. Due to this, the efficiency of heating by MWRSJP not decrease with increasing temperature of the plasma, while generally regular microwave heating possible without collisions and becomes less and less efficient at higher temperatures. Also, instead of a pulsed mode BCP, you can create a generator of continuous operating mode, which is very important for plasma heating in tokamaks and stellarators.

With the help of a monochromator MDR-12 with a much better spectral resolution than the spectrometer ICP-51 confirmed and refined previously obtained preliminary results.

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ИССЛЕДОВАНИЯ МИКРОВОЛНОВЫХ ХАРАКТЕРИСТИК И ПАРАМЕТРОВ ПЛАЗМЫ РАЗРЯДА НИЗКОГО ДАВЛЕНИЯ, ИНИЦИИРОВАННОГО В КОАКСИАЛЬНОМ ВОЛНОВОДЕ СТОХАСТИЧЕСКИМ ИЗЛУЧЕНИЕМ

В.И. Карась, А.Ф. Алисов, В.И. Голота, А.М. Егоров, И.В. Карась, С.В. Карелин, И.А. Загребельный

Описаны методы исследования и изучены основные характеристики генерируемых колебаний. Изучена плазма разряда, инициированного микроволновым излучением со стохастическими скачками фазы (МВИССФ) в коаксиальном волноводе в оптимальном режиме работы пучково-плазменного генератора. Найдены параметры плазмы микроволнового разряда при его стабильном поддержании в воздухе МВИССФ и диапазон давлений, при котором потребляемая мощность минимальна. Экспериментально исследованы также оптические характеристики плазмы разряда в широком диапазоне давлений воздуха.

ДОСЛІДЖЕННЯ МІКРОХВИЛЬОВИХ ХАРАКТЕРИСТИК І ПАРАМЕТРІВ ПЛАЗМИ РОЗРЯДУ НИЗЬКОГО ТИСКУ, ІНІЦІЙОВАНОГО В КОАКСІАЛЬНОМУ ХВИЛЕВОДІ СТОХАСТИЧНИМ ВИПРОМІНЮВАННЯМ

В.І. Карась, А.Ф. Алісов, В.І. Голота, О.М. Єгоров, І.В. Карась, С.В. Карелін, І.А. Загребельний

Описано методи дослідження і вивчені основні характеристики генерованих коливань. Вивчєно плазму розряду, ініційованого мікрохвильовим випромінюванням зі стохастичними стрибками фази (МХВССФ) у коаксіальному хвилеводі в оптимальному режимі роботи пучково-плазмового генератора. Знайдено параметри плазми мікрохвильового розряду при його стабільному підтриманні в повітрі МХВССФ та діапазон тисків, при якому споживана потужність мінімальна. Експериментально досліджено також оптичні характеристики плазми розряду в широкому діапазоні тисків повітря.