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

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It is shown, to create an effective discharge, which initiated by means of radiation with a jumping along phase, expediently to operate only at pressures nearby to the left part of breakdown curve. Because at the increasing of pressure the losses of energy are increased on elastic and non-elastic collisions, that reduces efficiency of discharge. Authors in first measured a plasma density in low pressure discharge initiated by a microwave radiation with the jumps of phase with help developing the original technique of the use the double probes of Langmuir, separate source of direct-current, high-frequency transformers, digital oscilloscope and least-squares method for treatment of signals, using the special type of function of regression.

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INTRODUCTION

It was shown early, 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 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 [1]. This study continues research on behaviour of plasma discharge subjected to microwave radiation with stochastically jumping phase (MWRSJP) which started in [2-4].

It was shown in [2-4], 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 micro-wave field are related to jumps of the phase of micro-wave 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 micro-wave 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 [6 - 13], 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 [12, 13]. 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 [1], 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 coaxialwaveguide 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.

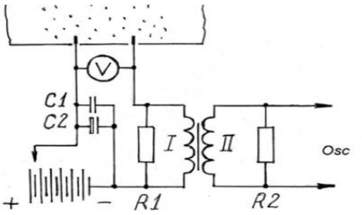

Fig. 1. Block-diagram of the pulse method for measuring the plasma density

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.

The measurements at pressure 4.6 Pa were made under as power 17 kW (Figs. 2, 3) as well power 6.5 kW (Figs. 4, 5) 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. 2-5 was chosen as:

$$E = u_0 \sin(u_1 t + u_2) + u_3 + u_4 \sin(u_5 u_1 t + u_6)\,. \quad (1)$$

Search parameters approximating certain functions carried out an iterative numerical method for solving the problem of finding the least squares using the Levenberg-Marquardt algorithm. The algorithm is designed to optimize the parameters of the nonlinear regression models and different from the Gauss-Newton algorithm that uses the regularization parameter.

Given a sample–a set of m points resulting experiment (E_i, t_i). Given a regression function E (u, t), which depends on the parameters u = (u_0, ..., u_6) and the free variable t. It is required to find such values of the parameters u_i, which would provide at least the sum of squared residuals of the regression:

$$S = \sum_{i=1}^{m} r_i^2\,. \quad (2)$$

where r_i=E_i–$E(u,t_i)$ для i=1,..,m.

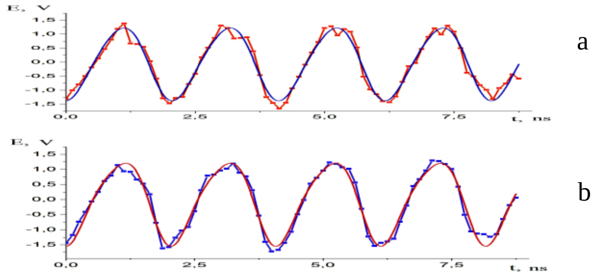

Fig. 2. A microwave signal from the first probe (the low-frequency displacement of voltage concerning zero is u_3 = -29.56·10^{-3} V) (a), the microwave signal from the second probe (the low-frequency displacement of voltage concerning zero is u_3 = -41.32·10^{-3} V) (b) with external voltage 62.3 V; the shifts of both the low frequency voltage difference with respect to zero between the two probes and the plasma density n_p are respectively: u_3 =11.76·10^{-3}V, n_p =8·10^8 cm^{-3}

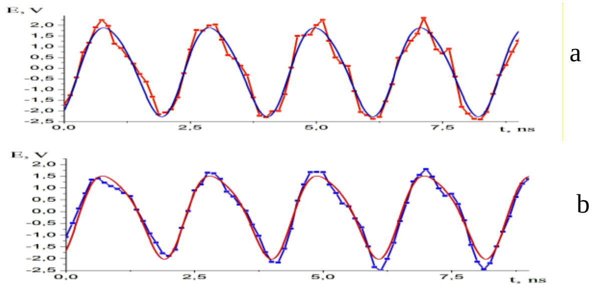

Fig. 3. A microwave signal from the first probe (the low-frequency displacement of voltage concerning zero is u_3 = -36.58·10^{-3} V) (a), the microwave signal from the second probe (the low-frequency displacement of voltage concerning zero is u_3 = -29.36·10^{-3} V) (b) with external voltage -62.3 V; the shifts of both the low frequency voltage difference with respect to zero between the two probes and the plasma density n_p are respectively: u_3 =-7.22·10^{-3} V, n_p =6.1·10^8 cm^{-3}

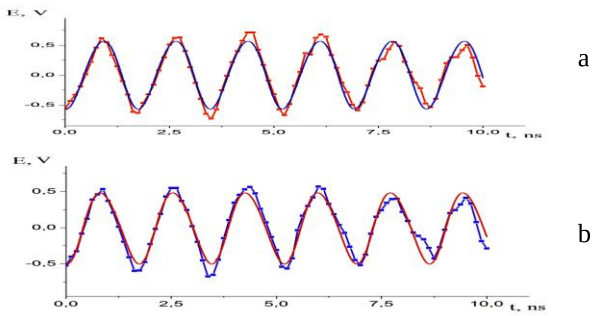

Fig. 4. A microwave signal from the first probe (the low-frequency displacement of voltage concerning zero is u_3 = 20.9·10^{-3} V) (a), the microwave signal from the second probe (the low-frequency displacement of voltage concerning zero is u_3 = 5.6·10^{-3} V) (b) with external voltage 62.3 V; the shifts of both the low frequency voltage difference with respect to zero between the two probes and the plasma density n_p are respectively: u_3 =15.3·10^{-3} V, n_p =1.04·10^{-3} cm^{-3}

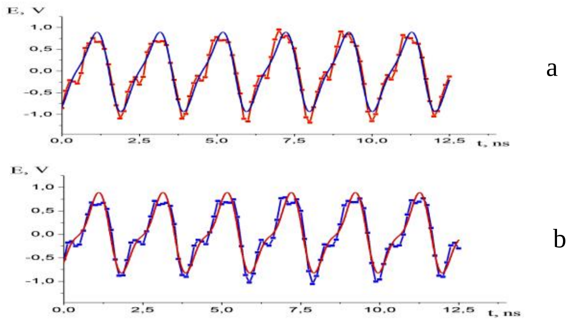

Fig. 5. A microwave signal from the first probe (the low-frequency displacement of voltage concerning zero is $u_3 = 2.75\cdot10^{-3}$ V) (a), the microwave signal from the second probe (the low-frequency displacement of voltage concerning zero is $u_3 = 17.1\cdot10^{-3}$ V) (b) with external voltage -62.3 V; the shifts of both the low frequency voltage difference with respect to zero between the two probes and the plasma density n_p are respectively: $u_3 = -14.35\cdot10^{-3}$ V, $n_p = 0.99\cdot10$ cm^{-3}

To find the minimum of function S, in equate to zero its first partial derivatives of the parameters.

Figs. 2-5 processing shown by the solid lines of least squares signal from the probes, and filled squares points taken with a digital oscilloscope.

Our calculations give plasma density values from $1\cdot10^9$ to $3\cdot10^9\,cm^{-3}$. 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, P.L. Kapitsa first investigated in 1951).

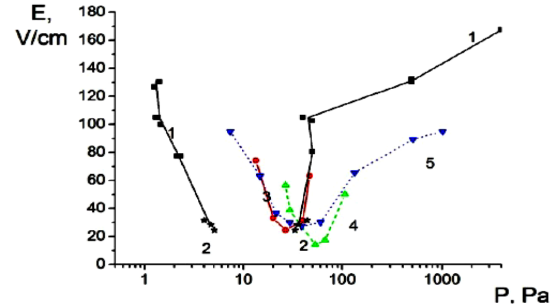

*Fig. 6. Dependence of breakdown electric field intensity for a microwave signals with a stochastically jumping phase versus a pressure for air in the optimal BPG mode (curves 1 – ■, 2 – *) in the non-optimal BPG mode: air (curve 3 – •), argon (curve 4 – ▲), helium (curve 5 – ▼), respectively, for the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

CONCLUSIONS

At presence of jumps of wave phase the curve of breakdown in the area of low pressures. We will remind that at resilient collisions part of energy of radiation is lost. Therefore advantageous is work in area of low pressures (nearby the left edge of curve of breakdown), as a contribution of collisions to the set of energy of electrons is small as compared to a deposit from the jumps of phase. Accordingly, to create an effective discharge initiated by means of radiation with a jumping along phase, as be obvious from abovementioned, expediently only at pressures nearby to the left part of breakdown curve. Because at the increasing of pressure the losses of energy are increased on elastic and non-elastic collisions, that reduces efficiency of discharge.

Characteristic times, for that electrons collect energy corresponding to a maximum of section of ionizing of air, are small as compared to a pulse width, therefore during an impulse there is substantial growth of plasma density to the values of $10^9\,cm^{-3}$.

First measured a plasma closeness in low pressure discharge initiated by a microwave radiation with the jumps of phase authors the articles developing the original technique of the use the double probes of Langmuir, separate source of direct-current, high-frequency transformers, digital oscilloscope and least-squares method, for treatment of signals, using the special type of function of regression. As a result of experimental data we found that a plasma density made from $1\cdot10^9$ to $3\cdot10^9\,cm^{-3}$ at 6 kW.

It should be noted that there is a current and at a zero tension from motion of electrons in the poorly heterogeneous high-frequency fields due to forces of high-frequency pressure (like behavior of pendulum with the quickly hesitating of fixing point, first studied P.L. Kapitsa in 1951).

Some of the got results may be, also to use in connection with the additional plasma heating in thermonuclear devices, because heating of charged particles is collisionless.

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REFERENCES

1. A.K. Berezin, Ya.B. Fainberg, et al. Beam-Plasma Generator of Stochastic Oscillations of Decimeter Wavelength Band // *Plasma Phys. Rep.* 1994, v. 20, p. 703-709.

2. V.I. Karas', V.D. Levchenko. Penetration of a Microwave with a Stochastic Jumping Phase (MSJP) into Overdense Plasmas and Electron Collisionless Heating by it // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Acceleration Methods".* 2003, v. 4, p. 133-136.

3. V.I. Karas`, Ya.B. Fainberg, et al. Interaction of Microwave Radiation Undergoing Stochastic Phase Jumps with Plasmas or Gases // *Plasma Phys. Rep.* 2005, v. 31, № 5, p. 748-760.

4. V.I. Karas`, A.F. Alisov, A.M. Artamoshkin, et al. Low Pressure Discharge Induced by Microwave Radiation with a Stochastically Jumping Phase // *Plasma Phys. Rep.* 2010, v. 36, № 8, p. 736-749.

5. Yu.P. Raiser. *Fundamentals of Modern Gas Discharge Physics.* Moscow: "Nauka", 1980.

6. A.F. Alisov, A.M. Artamoshkin, O.V. Bolotov, V.I. Golota, V.I. Karas`, I.V. Karas`, I.F. Potapenko, A.M. Yegorov, I.A. Zagrebelny. Low pressure discharge induced by microwave with stochastically jumping phase // *Int. Conf. on Plasma Physics EPC ICPP. Stockholm, Sweden.* 2012.

7. V.I. Karas`, V.I. Golota, A.M. Yegorov, I.F. Potapenko, A.G. Zagorodny. Microwave radiation with stochastically jumping phase: generation and application for low pressure discharge initiation // *Applied Radio Electronics. Scientific and Technical Journal*. 2012, v. 11, № 4, p. 463-476.

8. V.I. Karas`, A.F. Alisov, A.M. Artamoshkin, O.V. Bolotov, V.I. Golota, I.V. Karas`, A.M. Yegorov, I.A. Zagre-belny, I.F. Potapenko. Low pressure discharge initiated by microwave radiation with stochastically jumping phase // *Problems of Atomic Science and Technology". Series "Plasma Physics".* 2012, № 6, p. 142-145.

9. V.I. Karas`, A.F. Alisov, A.M. Artamoshkin, O.V. Bolotov, V.I. Golota, I.V. Karas`, A.M. Yegorov, I.A. Zagrebelny, I.F. Potapenko. Optical radiation special features from plasma of low pressure discharge initiated by microwave radiation with stochastic jumping phase // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Acceleration Methods"*. 2013, № 4, p. 183-188.

10. V.I. Karas`, V.I. Golota, A.M. Yegorov, I.F. Potapenko, A.G. Zagorodny. Microwave radiation with stochastically jumping phase: generation and application for low pressure discharge initiation // *Lighting engineering and electric energetics.* 2013, v. 2(34), p. 33-51.

11. V.I. Karas`, A.F. Alisov, A.M. Artamoshkin, O.V. Bolotov, V.I. Golota, I.V. Karas`, A.M. Yegorov, I.A. Zagrebelny, I.F. Potapenko. Special Features of Low-Pressure Discharge Initiated by Microwave Radiation with Stochastic Jumping Phase // *IEEE Transaction on Plasma Science*. 2013, v. 41, № 9, p. 1458-1463.

12. V.I. Karas`, A.F. Alisov, O.V. Bolotov, V.I. Golota, I.V. Karas`, A.M. Yegorov, A.G. Zagorodny, V.I. Zasenko. Special features of interaction between plasmas and microwave radiation with stochastic jumping phase // *Intern. Conference-School on Plasma Physics and Controlled Fusion. Book of ab-stracts.* 2014, Kharkiv, Ukraine, p. 93.

13. V.I. Karas`, A.F. Alisov, V.I. Golota, I.V. Karas`, A.M. Yegorov, S.Yu. Karelin, I.A. Zagrebelny. Studies of microwave characteristics and plasma parameters in low pressure discharge initiated in coaxial by stochastic radiation // *Problems of Atomic Science and Technolo-gy. Series "Plasma Electronics and New Acceleration Methods".* 2015, № 4(98), p. 197-201.

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ИЗУЧЕНИЕ ПАРАМЕТРОВ ПЛАЗМЫ В РАЗРЯДЕ НИЗКОГО ДАВЛЕНИЯ, ИНИЦИИРОВАННОМ В КОАКСИАЛЬНОМ ВОЛНОВОДЕ МИКРОВОЛНОВЫМ СТОХАСТИЧЕСКИМ ИЗЛУЧЕНИЕМ

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

Показано, что для создания эффективного разряда, инициированного с помощью излучения с прыжками фазы, целесообразно работать только при давлениях рядом с левой частью кривой пробоя. Потому что при возрастании давления потери энергии увеличиваются на упругих и неупругих столкновениях, что снижает эффективность разряда. Авторы впервые измерили плотность плазмы в условиях разряда низкого давления, инициированного СВЧ-излучением со скачками фазы, при помощи разработки оригинальной методики использования двойных зондов Ленгмюра, автономного источника постоянного тока, высокочастотных трансформаторов, цифрового осциллографа и метода наименьших квадратов для обработки сигналов, используя специальный тип функции регрессии.

ВИВЧЕННЯ ПАРАМЕТРІВ ПЛАЗМИ В РОЗРЯДІ НИЗЬКОГО ТИСКУ, ІНІЦІЙОВАНОМУ В КОАКСІАЛЬНОМУ ХВИЛЕВОДІ МІКРОХВИЛЬОВИМ СТОХАСТИЧНИМ ВИПРОМІНЕННЯМ

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

Показано, що для створення ефективного розряду, ініційованого за допомогою випромінення зі стрибками фази, доцільно працювати тільки при тисках поряд з лівою ділянкою кривої пробою. Тому що при зростанні тиску втрати енергії збільшуються на пружних та непружних зіткненнях, що знижує ефективність розряду. Автори вперше виміряли густину плазми в умовах розряду низького тиску, ініційованого НВЧ-випроміненням зі стрибками фази, за допомогою розробки оригінальної методики використання подвійних зондів Ленгмюра, автономного джерела постійного струму, високочастотних трансформаторів, цифрового осцилографа та метода найменших квадратів для обробки сигналів, застосовуючи спеціальний тип функції регресії.