LOW PRESSURE DISCHARGE INDUCED BY MICROWAVES WITH STOCHASTICALLY JUMPING PHASE

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We study the gas discharge, initiated by microwave radiation with stochastically jumping phase (MWJP) in a coaxial waveguide in the optimal mode of the beam-plasma generator. In this paper we experimentally examine optical characteristics of the discharge plasma in a wide range of air pressure. The conditions of a microwave discharge ignition, its stable maintenance in air by MWJP, and the pressure range at which required power is minimal are found.

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1. INTRODUCTION

RF 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 [1–10] and references therein). The issues widely discussed in literature are connected with additional plasma heating in tokamaks [1–4], the nature of accelerated particles in space plasmas [5, 6], gas discharge physics [7, 8]. 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 [9, 10]). 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 RF radiation with plasma is a barrier of penetration of the radiation into the overdense plasma. To our knowledge, the most part of investigations in this direction are made with help of RF generators of electromagtetic radiation without jumping phase. Thus the new opportunities that microwave radiation with jumping phase provides in this area would be very important.

In this paper, we describe results of the theoretical and experimental investigation of the interaction of plasma with microwave radiation with jumping phase that obtained whith help of the unique beam-plasma generator made in KIPT [11]. This study continues research on behaviour of plasma discharge subjected to microwave radiation with stochastically jumping phase (MWJP) which started in [12–14]. The paper is organized as follows. The first section contains introduction and brief review of previous research. In section 2, we consider experimental parameters obtained from the plasma beam generator. The scheme of measurement of various parameters is given and experimental studies of optical radiation from the plasma discharge initiated by MWJP are presented. In section 3 numerical simulations of optical radiation transport and computational technique used for simulations are briefly discussed. The illustrative simulation results are presen-ted graphically. Concluding remarks follow at the end.

It was shown in [14–16], 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.

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Gas breakdown and maintenance of a discharge in a rarefied gas by a pulsed MWJP were studied theoretically and experimentally in [15–19], 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 MWJP were found. The pressure range in which the power required for discharge ignition and its maintenance has its minimum was determined [17–19]. It was shown that, in the interval of pressures that have a level less than optimal (about 50 Pa for argon), the minimum of MWJP 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 MWJP. 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 MWJP on a plasma, produced in a coaxial waveguide filled with a rarefied gas, is investigated with use of the above mentioned beam-plasma generator (BPG) [11], which was upgraded for the given experimental conditions. The goal of this work is to study optical radiation spectra. For interpretation of the experimental results on the ignition and maintenance of a microwave discharge in air obtained with MWJP BPG, a numerical code has been developed. This code allows simulating the process of gas ionization by electrons heated in the MWJP field and studying the behavior of plasma particles in such a field.

2. EXPERIMENTAL STUDIES OF OPTICAL RADIATION FROM THE PLASMA DISCHARGE INITIATED BY MWJP

Optical characteristics of plasma discharge initiated by MWJP in coaxial waveguide (Fig. 1) are examined in the conditions of BPG operation in the optimal mode in air for a wide pressure range, in which the discharge is ignited and maintained stably. For experimental studies of the integral intensity of the plasma radiation in the visible spectrum, used photoelectron multiplier of type PEM-29 is attached to a high-stabilized rectifier VSV-2.

For spectroscopic studies of the discharge in the visible spectrum a three-prism glass spectrograph ISP-51 is used. With help of the lens, the radiation from the discharge is focused onto the entrance slit (slit width is 0.2 mm) of the spectrograph. By the output gap with width of 0.1 mm the spectrograph is attached to the photoelectron multiplier of type PEM-36. The signal from the photomultiplier FEU-36 was fed to the digital (2 GB/s) oscilloscope Le Croy Wave Jet 324 with a frequency band of 200 MHz. The ISP-51 spectrograph was calibrated using the spectral lines of a PRK-2M mercury lamp and the Balmer hydrogen lines emitted by a Geissler tube. The mercury lamp and the Geissler tube were powered from an OU-1 lighting unit. The dependence of optical radiation from the discharge on air pressure is compared at the conditions when a stable combustion of the gas discharge is held at the MWRSJP power value that match the optimal BPG mode. The optimal operating mode of BPG corresponds to the following parameters: magnetic induction in the interaction range of the beam with slow-wave structures in BPG is B=0.096 T, a high voltage is $U_{opt} = 13.2$ kV, the current electron gun is $I_{b_{opt}} = 3$ A, high-voltage pulse is 160 μs.

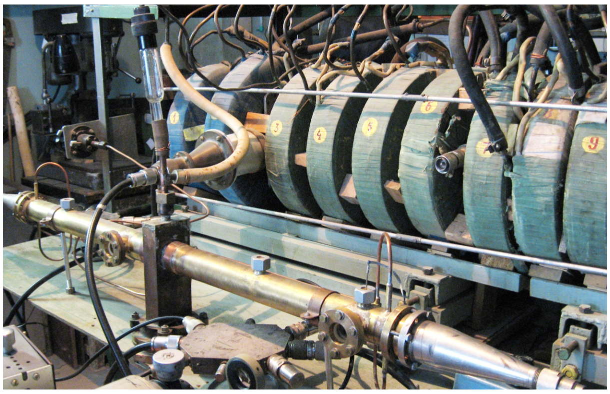
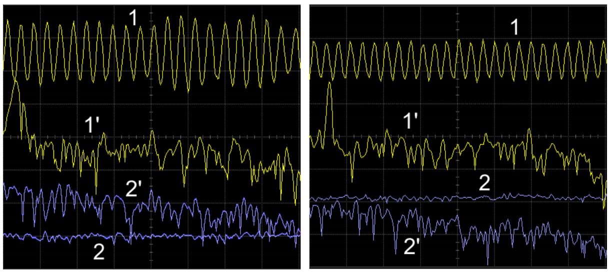


Fig. 1. *General view of the coaxial waveguide*



a b

Fig. 2. *Waveforms of MWRSJP at the input (1) and output (2) of the coaxial waveguide, respectively, and local microwave spectra on a logarithmic scale (10 dB/div) at the input (1') and output (2') of the coaxial waveguide, respectively. The gas pressure in the waveguide is $P = 2.0$ (a) and 30 Pa (b), respectively. The time scale is 5 ns/div, and the voltage scale is 100 (V cm^{-1})/div*

The spectrum of optical radiation from the discharge depends strongly on the pressure of the working gas (air) in a coaxial waveguide. In particular, within the lower range of air pressure, the optical radiation from the discharge is pronouncedly enriched with shorter wavelengths. One can observe that the optical emission starts with a delay relatively to the beginning of current pulse. However, duration of the optical emission exceeds the duration of the high voltage pulse.

Thus, relying on the quantitative indicators of the electric field intensity, frequency MWJP and frequency of phase jumps, etc., the prospect of creating a source of light radiation of low power (100 W) is implemented. It is based on the consideration of a stochastic microwave discharge with high efficience at low pressure of working gas.The discharge ignition and maintenance lead at the waveguide exit to a strong damping of the spectral components, which are corresponded to the maximum range of input signal into the waveguide (Fig. 2).

3. NUMERICAL SIMULATION OF OPTICAL RADIATION TRANSPORT IN A DISCHARGE INITIATED BY MWJP

Numerical code SPECRAY, which uses the approximation of thermodynamic equilibrium and nonscattering medium, computes the spectral power density along the optical rays with a known absorption coefficient. For the illustrative example the mixture of xenon and sodium was choosen. The spectrum of escaping radiation from a uniform layer of the gas mixture Xe, and Na at 0.5 eV (5800 K) was computed. The layer thickness is equal to 18 mm. It was assumed that the gas mixture includes only neutral atomic components, the proportion of Na was 0.1%, the electron density was assumed to be $10^{15}\,\mathrm{cm}^{-3}$, the total pressure of the mixture at a given temperatures was equal to 1 atm. Scattering radiation was assumed to be negligible.

4. CONCLUSIONS

At the stage of discharge in the coaxial waveguide, the discharge becomes nonuniform along its length due to the strong absorption of MWJP. The electric field amplitude decreases by more than one order when approaching to the waveguide exit. If the discharge has a place in the spectrum of the output signal from the coaxial waveguide is not spectral components corresponding to the maximum values in the spectrum of input into the coaxial waveguide. During the maintenance of MWJP discharge in the waveguide, gas ionization leads to almost complete decay of the main spectral components of the input microwave signal. With the distance increasing from the entry of MWJP into the coaxial waveguide, the discharge glow significantly decreases, becoming inhomogeneous, as well as its cross-section decreases. Thus there occurs the discharge contraction. With air pressure decreasing, the optical radiation from the discharge becomes more reach with shorter wavelength. Thus, if at the pressure of 20 Pa, the radiation has red colour, then at pressure of 2 Pa the radiation becomes blue. Microwave oscillations and glow discharge exist in time almost throughout the pulse duration of electron beam current in BPG. When the frequency of MWJP signal and the frequency of phase jumps are those as observed in the conducted investigations, there is enough to have the magnitude of electric field equals to 50 V/cm, for the creation and maintainence of the discharge in air.

The original SPECRAY code has been used to calculate the spectral radiation intensity along the optical rays for the known profile of the absorption coefficient under the assumption that the medium is in thermodynamic equilibrium and does not scatter radiation. Numerically, the spectral power density with a known absorption coefficient along the rays for different gas mixtures was analysed.

Thus, based on the quantitative indicators, such as the electric field intensity, frequencies of MWJP and phase jumps it can be expected the following. The prospective creation of an efficient light radiation source of low power (100 W) in a wide range of air pressure, in which the discharge is ignited and maintained stably, becomes a reality. The main task of future experimental and theoretical research is to optimize the gas mixture for the discharge of quasi-solar optical spectrum.

The results might also be of some use in connection with additional plasma heating in nuclear fusion devices due the fact that, the electron heating by microwave radiation with jumping phase is collisionless. Thus the heating efficiency by MWJP does not decreas when the temperature increases, whereas the usual heating by the regular radiation is to be collisional and becomes less and less efficient. Moreover, instead of pulse working regime of BPG, the constant working regime which is important for tokamak plasma, in principle may be elaborated. The developing of a new type of the high efficiency sources of optical radiation with quasi solar spectrum would make a fundamental breakthrough in lighting technology.

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РАЗРЯД НИЗКОГО ДАВЛЕНИЯ, ИНДУЦИРОВАННЫЙ МИКРОВОЛНАМИ СО СТОХАСТИЧЕСКИ ПРЫГАЮЩЕЙ ФАЗОЙ

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Представлены результаты изучения газового разряда, инициированного микроволновым излучением со стохастически прыгающей фазой (МВИСПФ) в коаксиальном волноводе в оптимальном режиме работы пучково-плазменного генератора. Экспериментально исследованы оптические характеристики плазмы разряда в широком диапазоне давлений воздуха. Найдены условия зажигания и стабильного поддержания разряда в воздухе МВИСПФ, в которых требуемая мощность минимальна.

РОЗРЯД НИЗЬКОГО ТИСКУ, ІНДУКОВАНИЙ МІКРОХВИЛЯМИ ЗІ СТОХАСТИЧНО СТРИБКОВОЮ ФАЗОЮ

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Наведені результати вивчення газового розряду, що ініційований мікрохвильовим випроміненням зі стохастично стрибаючою фазою (МХВССФ) у коаксіальному хвилеводі в оптимальному режимі роботи пучково-плазмового генератора. Експериментально досліджені оптичні характеристики плазми розряду в широкому діапазоні тисків повітря. Знайдено умови запалювання та стабільного підтримання розряду в повітрі МХВССФ, в яких потрібна потужність мінімальна.