LOW PRESSURE DISCHARGE INITIATED BY MICROWAVE RADIATION WITH STOCHASTICALLY JUMPING PHASE

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Present results continue the line of the previous research. In this paper the conditions of a microwave discharge ignition, its stable maintenance in air by MWRSJP, and the pressure range at which required power is minimal are found. We experimentally examine also optical characteristics of the discharge plasma in a wide range of air pressure. In general the research aims to develop a new type of sources of optical radiation.

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INTRODUCTION

High-frequency (HF) heating is very important field in connection with fundamental questions of plasma physics and applications. 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 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 [4–6], 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 [5-9], as well as propagation of this radiation within the plasma produced in such a way. 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.

1. EXPERIMENTAL STUDIES

1.1. MWRSJP PARAMETERS OBTAINED FROM THE BPG, AND THE SCHEME OF MEASUREMENT OF VARIOUS PARAMETERS

We study MWRSJP parameters and optical radiation characteristics from the plasma discharge of induced by MWRSJP in a gas (air for the present case), taken at low pressure. To conduct experiments, a coaxial waveguide with axial vacuum pumping is connected to the BPG. Coaxial waveguide filled with gas with impedance of about 75 ohms and a length of 1000 mm is made of brass pipes with inner diameter of 45 mm and external diameter of 50 mm. The central conductor is a brass rod diameter of 12 mm. For operating in the regime of narrow-band signal generation the input of the BPG slow-wave structure was attached to a shorting plug. The temporal realizations and spectral characteristics of MWRSJP at the input and output of the coaxial waveguide were studied using an HP Agilent Infinium four-channel broadband (2.25 GHz) oscilloscope. A PEM-29 photomultiplier powered from a VSV-2 high-voltage stabilized rectifier was used to measure the integral intensity of optical radiation from the plasma.

Ignition of the discharge does not affect the penetration into dense plasma of MWRSJP what is evidenced by nearly constant amplitude at the entrance to the waveguide. Because of expenditures of radiation energy on air ionization for the discharge maintenance the MWRSJP amplitude at the output of the coaxial waveguide is essential diminished. It is also important that the MWRSJP local spectrum on the output waveguide significantly changed, a peak associated with the main spectral component of MWRSJP is absent. It should be noted that in the pressure range from P=30 Pa to P=2 Pa at a MWRSJP power that conforming to the optimal operating mode of BPG a similar situation is observed. The optimal operating mode of BPG corresponds to the following parameters: magnetic induction in the interaction range of the beam with slow-wave structure 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…5 A, high-voltage pulse is 160 μs, MWRSJP power is W=36 kW, the pulse repetition frequency is 5 Hz.

The gas breakdown takes place only after the electric field amplitude of MWRSJP reaches a certain critical value, which depends on the gas pressure. The instant of discharge ignition can be easily determined from the abrupt decrease in the amplitude of the microwave signal at the output of the coaxial waveguide to almost zero. It can also be seen that the electric field amplitude required to maintain a steady-state discharge is one order of magnitude lower than that required for breakdown.

Let us now consider the conditions for breakdown in air by microwave radiation from the BPG described in [6]. In optimal regime at narrowband signal of this generator the working frequency is 500 MHz, the mean rate of the phase jumps being ν_{jp}=2·10^{8} s^{-1}. It is important to keep in mind that, when the electron energy increases from zero to the ionization energy I_{air}, the cross section for elastic collisions of electrons with air atoms and molecules varies greatly (by a factor of about 30), being at its maximum several times larger than the ionization cross section corresponding to electron energies of 15…20 eV. This makes it possible to initiate discharges in air by microwaves with a stochastically jumping phase at pressures as low as 4 Pa. In this case, the mean rate of phase jumps is equal to the maximum inelastic collision frequency, which corresponds to electron energies close to the ionization energy. Operation under such conditions is advantageous in that, first, no energy is lost in elastic collisions, and, second, due to the jumps in the phase, the electron diffusion remains insignificant and the electromagnetic energy is efficiently transferred to electrons.

To determine the dependence of the threshold power, required for ignition of the discharge in a coaxial waveguide, on the pressure of working gas, BPG has worked in the mode of generating the maximum output power level of narrow-band signal in which the generation of microwave radiation with a maximum frequency of phase jumps occurs. In this case part of the power with the help of a broadband directional coupler with variable coupling was supplied to analyzed gas-filled coaxial waveguide. The rest of the power assigned to the matched load. Such a method of regulating the power delivered to the coaxial waveguide for ignition of the discharge allows conserving the permanent parameters of microwave radiation. In particular, this concerns the mean rate of the phase jumps and the energy spectrum density of MWRSJP, because in this situation BPG works in the same mode.

While conducting experiments, to determine the dependence of the threshold power on the gas pressure, the left center coax transition coupler was connected to BPG, the lower left coax transition joined the coaxial waveguide, the right central and the lower coaxial transitions were connected to the load. By changing the bond between the central and the lower shoulders of the coupler through the use of different linked curved shoulders, we adjusted the power coming into the coaxial waveguide from 6 to 28 kW. Fig. 1 shows the dependence of power required for the discharge ignition in the air that filled coaxial waveguide on its pressure.

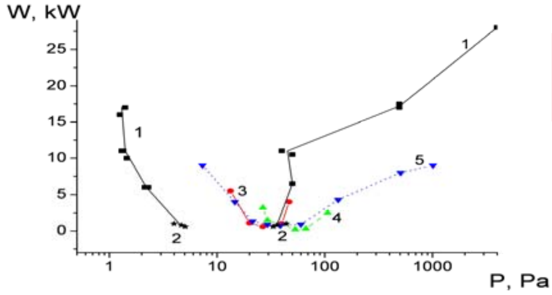

*Fig. 1. Dependences for breakdown power of a microwave signals with a stochastically jumping phase versus a pressure for air in the optimal BPG mode (curves 1 – ■, 2 – *), in the non-optimal BPG mode: for air (curve 3 – •), argon (curve 4 – ▲), helium (curve 5 – ▼), respectively, at narrowband signal*

From Fig. 1 (curves 1, 2) it can be seen that, the power levels from 6 kW to 28 kW MWRSJP discharge is ignited stably at a pressure of gas (air) ranging from 1.5 to 3990 Pa. This result clearly demonstrates the advantages of the discharge, supported by microwave with stochastic jumps in the phase compared with the microwave discharge in the fields of regular waves.

Thus we have the opportunity to create a discharge at a pressure of almost two orders of magnitude lower than the pressure that is necessary for the fulfillment of the condition of minimum capacity of the discharge ignition by regular microwave radiation. Namely, (see [10]) for $\nu_{col} \approx \omega$ (where ν_{col} is the frequency of binary collisions, as well ω is the frequency of microwave radiation), effectiveness of such a discharge is much higher because of the small contribution of energy loss on unnecessary elastic and inelastic collisions when working at low pressures. For comparison, dependence of microwave radiation power required for the discharge ignition in air (curve 3), argon (curve 4) and helium (curve 4), which are filled the coaxial waveguide, on its pressure, obtained while working in the non-optimal BPG mode is given. It is seen that the pressure range in which it is possible the ignition of the discharge is much narrower than under the optimal BPG mode functioning. This is due to a significant difference in mean rates of the phase jumps in these modes of BPG.

Using the delay device, the time for start of the oscilloscope can be modified within the length of high-voltage pulse. This circumstance allows us to observe the shape of the generated signal at a different time moments starting from the very begin of the electron beam current pulse. Features MWRSJP at the inlet and outlet of the coaxial waveguide are studied using the four-channel broadband (2.25 GHz) oscilloscope HP Agilent Infinium Oscilloscope.

1.2. EXPERIMENTAL STUDIES OF OPTICAL RADIATION FROM THE PLASMA DISCHARGE INITIATED BY MWRSJP

Preliminary results of an optical characteristic studies presented in [11]. Optical characteristics of plasma discharge initiated by MWRSJP in coaxial waveguide 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 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 0.01 mm) of the spectrograph. By the output gap with width of 0.015 mm the spectrograph is attached to the photoelectron multiplier of type PEM-106. The photomultiplier PEM-106 has high sensitivity in the wavelength range from 350 to 550 nm. Within zone from 550 nm to 1000 nm the sensitivity is less that will lead to distortion of the discharge optical spectra which are observed on oscilloscope. This fact should be taken into account when the wave forms of the emission spectra are analyzed. The signal from the photomultiplier PEM-106 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 MWRSJP power was input via the conical coaxial junction in the waveguide pumped out to a pressure of 1.33 Pa. In certain ranges of the gas pressure, gas composition, and microwave power, a discharge was ignited in the coaxial waveguide.

In Fig. 2, 3 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 that correspond the optimal BPG mode.

Fig. 2. The emission spectra of discharges in air at a pressure P = 28 Pa

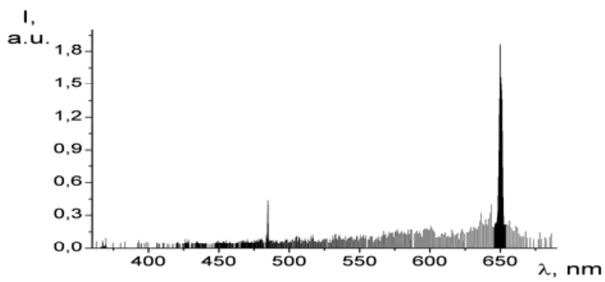

Fig. 3. The emission spectra of discharges in air at a pressure P = 4.8 Pa

Figs. 2, 3 demonstrate that 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. In this way, if value of pressure is P_1=28 Pa then spectrum is depleted at the wavelengths shorter than 550 nm, i.e. red radiation prevails. At the same time, when the pressure is reduced nearly an order of magnitude, see Fig. 3 a spectrum becomes significantly enriched with short wavelengths, i.e. blue light prevails. Further Fig. 4 representes the experimental studies of the temporal characteristics of optical radiation for two specific wavelengths within the duration of the single high-voltage pulse (160 μs).

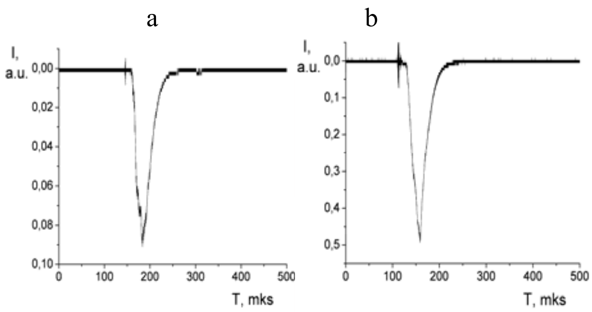

Fig. 4. Dependence of the optical radiation intensity on time for the wavelength 485 nm within a duration of one high-voltage pulse for gas pressures of P = 28 (a) and 4.8 Pa (b)

One can observe that the optical emission starts with a delay relatively to the beginning of current pulse (current pulse is marked on Fig. 4 by vertical risk). However, duration of the optical emission exceeds the duration of the high voltage pulse.

CONCLUSIONS

At the stage of discharge in the coaxial waveguide, the discharge becomes nonuniform along its length due to the strong absorption of MWRSJP. The electric field amplitude decreases by more than one order when approaching to the waveguide exit.

During the maintenance of MWRSJP discharge in the waveguide, gas ionization leads to almost complete decay in the spectrum of the output signal from the coaxial waveguide of the main spectral components of the input microwave signal.

With the distance increasing from the input of MWRSJP into the coaxial waveguide, the discharge optical radiation intensity decreases significantly, becoming inhomogeneous, as well as its cross-section decreases.

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.

MWRSJP and discharge optical radiation are observed in time almost throughout the pulse duration of electron beam current in BPG.

When the frequency of MWRSJP 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.

Thus, based on the quantitative indicators, such as the electric field intensity, frequencies of MWRSJP 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 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 MWRSJP 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 at increasing temperature.

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РАЗРЯД НИЗКОГО ДАВЛЕНИЯ, ИНИЦИИРОВАННЫЙ МИКРОВОЛНОВЫМ ИЗЛУЧЕНИЕМ СО СТОХАСТИЧЕСКИ ПРЫГАЮЩЕЙ ФАЗОЙ

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Настоящие результаты продолжают линию предыдущих исследований. В этой статье найдены условия поджига и стабильного поддержания МВИСПФ микроволнового разряда в воздухе и диапазон давлений, в котором требуемая мощность минимальна. Мы экспериментально изучили также оптические характеристики плазмы разряда в широком диапазоне давлений воздуха. В общем цель исследований – развить новый тип источников оптического излучения.

РОЗРЯД НИЗЬКОГО ТИСКУ, ІНІЦІЙОВАНИЙ МІКРОХВИЛЬОВИМ ВИПРОМІНЮВАННЯМ ЗІ СТОХАСТИЧНО СТРИБКОВОЮ ФАЗОЮ

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Наведені результати продовжують лінію попередніх досліджень. В цій статті знайдені умови підпалу та стабільного підтримання МХВССФ мікрохвильового розряду в повітрі та діапазон тисків, у якому потрібна потужність мінімальна. Ми експериментально вивчили також оптичні характеристики плазми розряду в широкому діапазоні тиску повітря. Взагалі мета – дослідити новий тип джерел оптичного випромінювання.