DEVELOPMENT SPECIAL FEATURES OF LOW PRESSURE DISCHARGE INITIATED BY MICROWAVE RADIATION WITH STOCHASTIC JUMPING PHASE

V.I. Karas`, A.M. Yegorov, I.V. Karas`, A.G. Zagorodny, V.I. Zasenko, I.A. Zagrebelny, L.A. Nazarenko, I.F. Potapenko

E-mail:karas@kipt.kharkov.ua

Abstract. We study the low pressure (LP) discharge plasma (DP), initiated by microwave radiation with stochastically jumping phase (MWRSJP) in a coaxial waveguide (CW) at the optimal operating mode (OOM) of the beam-plasma generator (BPG). Present results continue the line of the previous research. In this paper the conditions of a microwave (MW) gas discharge (GD) 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 DP in a wide range of air pressure.

1. Introduction

High-frequency (HF) plasma heating (PH) 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, 2] and references therein). The issues widely discussed in literature are connected with additional PH in tokamaks [1], the nature of accelerated particles in space plasmas [2], GD physics. Among the problems that attract attention of scientific community is development of sources with solar spectrum [3]. It is worth mentioning that one of the difficulties associated with additional PH 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 PH. Another important challenge in interaction of HF radiation with plasma is a barrier of the radiation penetration into the overdense plasma [3].

In this paper, we describe results of the experimental investigation of the plasma interaction with MWRSJP that obtained with help of the unique BPG made in KIPT [4]. This study continues research on behaviour of DP subjected to MWRSJP which started in [5-7]. It was shown in [5-7], both theoretically and experimentally, that the phenomenon of anomalous penetration of MWRSJP into plasma, conditions for gas breakdown and maintenance of a MW GD, and collisionless electron heating in a MW field are related to jumps of the phase of MWR. In this case, in spite of the absence of pair collisions or synchronism between plasma particles and the propagating electromagnetic field, stochastic MW fields exchange their energy with charged particles. In the present work, the effect of high power pulsed decimeter MWRSJP action on a plasma, produced in a CW filled with a rarefied gas, is investigated with use of the above mentioned BPG [4], which was upgraded for the given experimental conditions. The goal of this work is to study the special features of LPGD initiated by MWRSJP and also optical radiation (OR) spectra. For interpretation of the experimental results on the ignition and maintenance of a MW GD obtained with MWRSJP BPG, a numerical code has been developed [6].

2. Experimental studies

We study MWRSJP parameters and OR characteristics from the DP of induced by MWRSJP in a gas, taken at LP. To conduct experiments, a CW with axial vacuum pumping is connected to the BPG. CW 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. A detector head and D2-13 variable resistive–capacitive attenuator connected to the secondary line of the coupler were used to measure the envelope of MW oscillations and the waveforms of the electron beam pulse. The temporal realizations and spectral characteristics of MWRSJP at the input and output of the CW were studied using an HP Agilent Infinium four-channel broadband (2.25 GHz) oscilloscope. An ISP-51 three-prism glass spectrograph, monochromator MDR-1 and PMT PEM-106 were used for optical spectroscopy of the discharge in the CW. 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 CW. Because of expenditures of radiation energy on air ionization for the discharge maintenance the MWRSJP amplitude at the output of the CW is essential (more than an order of magnitude) diminished. It is also important that the MWRSJP local spectrum on the output CW 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 (OOM) of BPG a similar situation is observed. OOM of BPG corresponds to the following parameters: magnetic induction in the interaction range of the beam with slow-wave structure in BPG is B =0.096T, a high voltage is U_{opt} = 13.2 kV, the current electron gun is $I_{b_{opt}}$ = 5 A, high-voltage pulse is 160 μs, peak MWRSJP power is W = 36 kW, the pulse repetition frequency is 5 Hz. However, in order for the pressure range in which breakdown occurs and a steady-state discharge exists to be sufficiently broad, it is necessary that the phase jump frequency be sufficiently high. Let us now consider the conditions for breakdown in air by MWRSJP from the BPG described in [4]. In OOM 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 MWRSJP 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 breakdown electric field intensity (BEFI), required for ignition of the discharge in a CW, on the pressure of working gas (see fig. 1), BPG has worked in the OOM of generating the maximum output power level of narrow-band signal in which the generation of MW 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 CW. The rest of the power assigned to the matched load. Such a method of regulating the power delivered to the CW for ignition of the discharge allows conserving the permanent parameters of MWRSJP. 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.

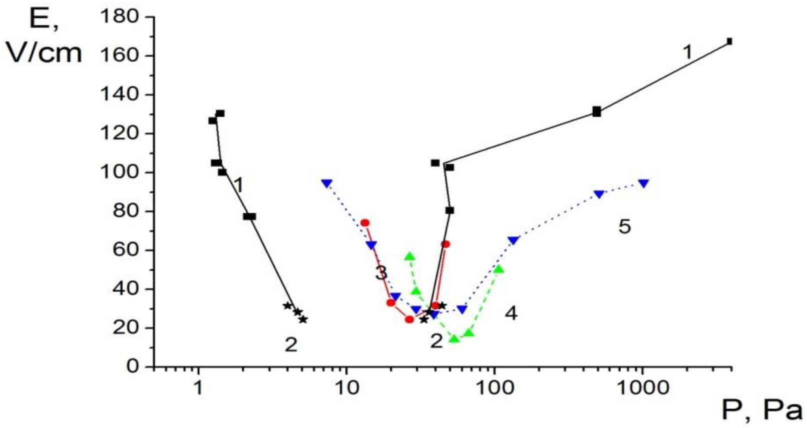

Fig.1. Dependences for BEFI of a MWRSJP versus a pressure for air in the optimal BPG mode (curves 1 – ■, 2 - *), in the non-optimal BPG mode: for air (curves 3 - •), argon (curve 4 – ▲), helium (curves 5 – ▼), respectively, at narrowband signal.

From figure 1 (curves 1, 2) it can be seen that, the peak BEFI levels from 20 V/cm to 160 V/cm MWRSJP discharge is ignited stably at a pressure of gas (air) ranging from 1.5 Pa to 3990 Pa. This result clearly demonstrates the advantages of the discharge, supported by MWRSJP compared with the MW GP 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 MW radiation. Namely, for $\nu_{col} \approx \omega$ (where ν_{col} is the frequency of binary collisions, as well ω is the frequency of MWR), 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 LP. For comparison, dependence of MW radiation power required for the discharge ignition in air (curve 3), argon (curve 4) and helium (curve 5), which are filled the CW, 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.

Optical characteristics of DP initiated by MWRSJP in CW are examined in the conditions OOM of BPG in air for a wide pressure range, in which the discharge is ignited and maintained stably. Preliminary results of an optical characteristic studies is presented in [7]. For spectroscopic studies of the discharge in the visible spectrum a three-prism glass spectrograph ISP-51 and monochromator MDR-1 are used. The PMT PEM-106 has high sensitivity in the wavelength range from 350 nm 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 PMT PEM-106 was fed to the digital (2 GB/s) oscilloscope (11) Le Croy Wave Jet 324 with a frequency band of 200 MHz.

It is observed that the discharge OR intensity decreases along the waveguide. It should be noted that the discharge color depends on the working gas pressure and the microwave power input in the waveguide. It is shown that the spectrum of OR from the discharge depends strongly on the pressure of the working gas (air) in CW. In particular, within the lower range of air pressure, the OR from the discharge is pronouncedly enriched with shorter wavelengths. In this way, if value of pressure is P = 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 a spectrum becomes significantly enriched with short wavelengths, i.e. blue light prevails. One can observe that the OR starts with a delay relatively to the beginning of current pulse and duration of the OR is close on the duration of the high voltage pulse.

Thus, relying on the quantitative indicators of the EFA, frequency MWRSJP and frequency of phase jumps, etc., the prospect of creating a source of OR of low power (100 W) is implemented.

3. Conclusions

At the stage of GP in the CW, 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 CW of the main spectral components of the input microwave signal.

With air pressure decreasing, the OR from the discharge becomes more rich with shorter wavelength. Thus, if at the pressure of 28 Pa, the OR has red color, then at pressure of 4 Pa the OR becomes blue. MWRSJP and discharge OR 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 50V/cm, for the creation and maintenance of the discharge in air. Thus, based on the quantitative indicators, such as BEFI, 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 PH in nuclear fusion devices due the fact that, the electron heating by MWRSJP is collisionless. Thus the PH efficiency by MWRSJP does not decrease when the temperature increases, whereas the usual PH by the regular radiation is to be collisional and becomes less and less efficient at increasing temperature.

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References

[1] S.Shiraiwa et al. // Phys. Plas. 2011, v. 18, 080705-1-16.

[2] Kh.V.Malova, L.M.Zelenyi, O.V.Mingalev et al. // Plas. Phys. Rep. 2010, v. 36, p. 841.

[3] V.I.Karas', V.D.Levchenko. // Probl. of Atom. Sci. and Techn. Ser. Plas. Electronics and New Accel. Methods. 2003, v. 4(3), p. 133.

[4] A.K.Berezin et al. // Plas. Phys. Rep. 1994, v. 20, p. 703.

[5] V.I.Karas` et al. // Plas. Phys. Rep. 2005, v. 31, p. 748.

[6] V.I.Karas` et al. // Plas. Phys. Rep. 2010, v. 36(8), p. 736.

[7]V.I.Karas` et al. // IEEE Trans. on Plas. Sci. 2013, v. 41(9), p. 2458.