BREAKDOWN AND DISCHARGE IN LOW PRESSURE GAS CREATED BY A MICROWAVE RADIATION UNDERGOING STOCHASTIC PHASE JUMPS (II)

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The objective of the paper is to discuss the results of theoretical and experimental studies and numerical simulations of following phenomena: the anomalous character of the breakdown conditions, the anomalous behavior of microwave gas discharges, and the anomalous nature of collisionless electron heating that are attributed to stochastic jumps in the phase of microwave radiation.
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1. Fainberg *et al.*[1] showed that stochastic electric fields with a finite phase correlation time can efficiently heat particles in a collisionless plasma, so physically the inverse correlation time in the interaction between a particle and an electromagnetic wave has in fact the meaning of an effective collision frequency [1]. Earlier we shown with help of the theoretical and experimental investigations and numerical simulation that: (1) a monochromatic wave is reflected from the dense plasma almost totally (except for its front); (2) the microwave with stochastic jumping phase (MWSJP) is reflected to a lesser extent due mainly to the penetration of the wave pulses associated with stochastic jumps in the wave phase; (3) the transmission coefficient for a broad band regular wave with the such spectral enegy density (BBWSSED) as that of MWSJP is one order of magnitude less because, in this case, the plasma slab simply acts as a filter that transmits waves with the frequencies $\omega > \omega_p$ (ω_p is electron longmuir frequency) and reflects others. In particular, the electromagnetic wave incident on the plasma has a strong impact on the electron dynamics, especially at large angles of incidence. The longitudinal electric fields in the plasma are close in strength to the transverse fields. The longitudinal energy of the electrons and their temperature increase severalfold. The electron distribution function becomes non-Maxwellian: it has a tail of accelerated electrons. The energy of the incident transverse MWSJP is partially converted into the energy of the longitudinal wave and partially into the electron energy [2].

In order to illustrate the practical importance of the situation under examination, we present characteristic waveforms of stochastic signals in new types of beam–plasma devices generating intense stochastic microwave radiation in the interaction of electron beams with hybrid plasma waveguides that were developed and put into operation at the National Science Center Kharkov Institute of Physics and Technology (Ukraine) (see [2]).

Our experimental investigations of the excitation of regular and stochastic electromagnetic waves in plasmas of different densities and their passage through a cavity allow us to draw the following conclusions:

- A regular wave excites a cavity less efficiently than does a wave with a stochastically jumping phase (in order for the transmitted signals from an incident regular wave and from an incident wave with a stochastically jumping phase to have the same amplitude, the amplitude of the former should be one to two orders of magnitude larger than that of the latter).
- As a regular monochromatic signal excites a cavity and passes through it, selectivity between eigenmodes and unnatural waves is lacking.

The results of our experimental investigations are in satisfactory qualitative agreement with the theoretical predictions.

2. In 1992 specialists from the Fusion System Corporation (Maryland) designed a highly efficient light source operating in the quasi-solar spectral region and based on an electrodeless microwave gas discharge in a sulfur-containing tube [3]. The continuous (molecular) spectrum of high-power optical radiation from a sulfur-containing lamp resembles that of the Sun, but with depressed levels of IR and UV radiation.

The main problems associated with microwave pumping are as follows (see, e.g., [4]):

- To choose the power of a microwave signal and its shape (continuous or amplitude-modulated).
- To design a microwave transmission line from a microwave source (generator) to a load (electrodeless lamp), to construct a transmitter (whose operating regime should depend on the mode of microwave radiation), and to provide an appropriate topography of the microwave field in the region where it interacts with the working substance of the lamp (just after the generator is switched on and in the plasma operating mode).
- To maintain the stable operation of the microwave generator loaded by the lamp, whose parameters change substantially during the development of a microwave discharge (from the switching on of the generator up to the beginning of the steady-state plasma operating mode).

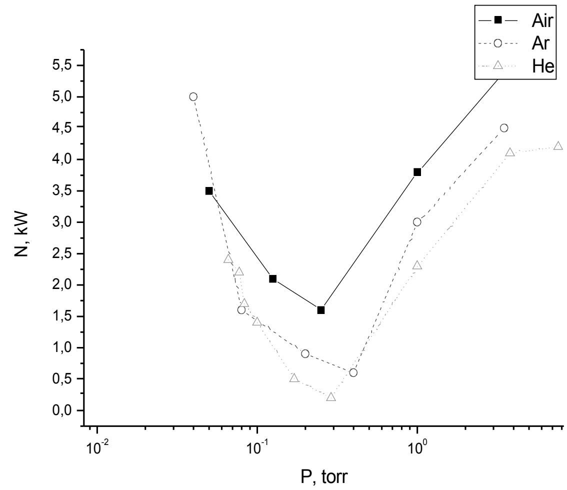
The underlying problem is that of choosing the microwave field frequency so as to satisfy the requirement that the input microwave power be minimum. In order to determine the working microwave frequency, it is necessary to compare three parameters: the diameter of the shell Λ (Λ≈1…2 cm), the electron mean free path *l*, and the electron oscillation amplitude *A*. Discharges in argon that evaporate sulfur (which is an electronegative element) can be initiated only when the electrons oscillate within a quartz shell, i.e., when $A < \Lambda/2$. The capture of electrons by sulfur molecules can only be balanced by intense ionization. It is known (see, e.g., [5]) that, for all gases, the dependence of the threshold field for gas breakdown on the pressure has a minimum that separates two branches.

For regular microwave radiation, the threshold field just obtained is directly proportional to the frequency and is inversely proportional to the gas density (pressure) and the size of the discharge region, in complete agreement with the known experimental data (see, e.g., [5]). An important task is to determine the power of a microwave generator that is required to initiate a discharge in a buffer gas and then to maintain it in a plasma after the evaporation and ionization of sulfur. Recall that, for microwave discharges in regular electromagnetic fields, the threshold field is minimum when the collision frequency is equal to the electromagnetic field frequency (see, e.g., [5]). Thus, at a frequency of $f \approx 3.0$ GHz, the minimum threshold field for breakdown of Ar at a pressure of about 650 Pa is 500 V/cm. Such field strengths can be achieved in a cavity in which one of the walls is transparent to light.

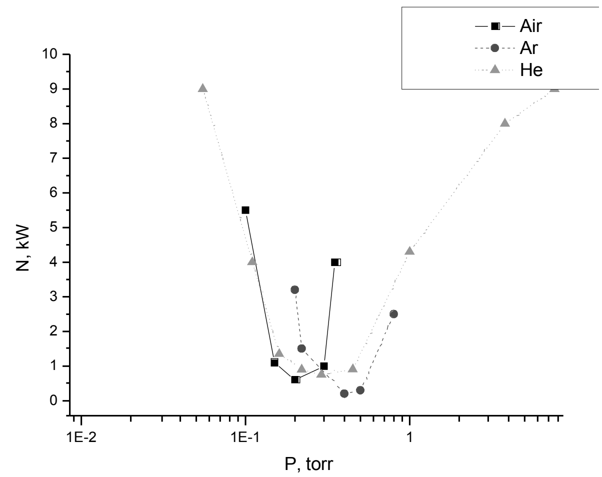
In the present paper, we propose to initiate microwave discharges in argon containing sulfur vapor by MWSJP. The advantages of this method are as follows: (1) such microwaves are capable of initiating discharges at lower gas pressures because the jumping phase slows electron diffusion; (2) the jumps in the phase ensure that the collisionless electron heating is not accompanied by energy losses in elastic and inelastic collisions; (3) a uniform microwave discharge is easy to initiate because microwaves with a stochastically jumping phase can deeper penetrate into an overcritical plasma.

Let us now consider the conditions for breakdown in argon by microwave radiation from the generator described in [6]. The working frequency of this generator is 450 MHz, the mean rate of the phase jumps being $\nu_{jp} = 2 \cdot 10^8$ s^{-1}. It is important to keep in mind that, when the electron energy increases from zero to the ionization energy I_{Ar}, the cross section for elastic collisions of electrons with argon atoms 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 argon 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.

Our numerical simulations and preliminary experiments show (see Figure) that, in order to initiate a microwave discharge at a frequency of 450 MHz in argon at a pressure of 4 Pa, the microwave electric field strength should be about 50 V/cm, whereas sulfur vapor can be excited by an electric field of 25 V/cm, which can easily be microwave cavities.



a



b

Dependences for breakdown power of a micro-wave signals with a stochastically jumping phase vs a pressure for air (curves), argon (curves), helium (curves) a) at broadband signal, b) at narrowband signal

With the use of such chambers, it is possible to substantially reduce the generator power. The working microwave frequency of this system, 450 ± 50 MHz, is consistent with standards adopted for industrial, scientific, and medical applications. With the version of the light system proposed by the company, it becomes possible to design compact low-power SLSs, in addition to the already existing traditional SLSs with output powers in the kilowatts range [3,4,6], which are usually based on 2450 ±50 MHz magnetrons.

CONCLUSIONS

The main results of our investigations are the necessary conditions for gas breakdown and for the maintenance of a microwave discharge in stochastic fields in a light source have been determined. The anomalously large transmission coefficient for microwaves, the anomalous character of the breakdown conditions, the anomalous behavior of microwave gas discharges, and the anomalous nature of collisionless electron heating have been attributed to stochastic jumps in the phase of microwave radiation.

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ПРОБОЙ И РАЗРЯД В ГАЗЕ НИЗКОГО ДАВЛЕНИЯ, СОЗДАВАЕМЫЙ МИКРОВОЛНОВЫМ ИЗЛУЧЕНИЕМ СО СТОХАСТИЧЕСКИ ПРЫГАЮЩЕЙ ФАЗОЙ (II)

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Предметом обсуждения являются результаты теоретических и экспериментальных исследований и численного моделирования следующих явлений: аномального характера условий пробоя, аномального поведения микроволнового газового разряда, аномальной природы бесстолкновительного нагрева электронов, являющихся атрибутом микроволнового излучения со стохастически прыгающей фазой.

ПРОБІЙ ТА РОЗРЯД У ГАЗІ НИЗЬКОГО ТИСКУ, СТВОРЕНИЙ МІКРОХВИЛЬОВИМ ВИПРОМІНЮВАННЯМ ЗІ СТОХАСТИЧНО СТРИБАЮЧОЮ ФАЗОЮ (II)

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Обговорюються результати теоретичних і експериментальних досліджень та чисельного моделювання таких явищ: аномального характеру умов пробою, аномальної поведінки мікрохвильового газового розряду, аномальної природи беззіштовхувального нагріву електронів, які є атрибутом мікрохвильового випромінювання зі стохастично стрибаючою фазою.