27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol. **24B** (2000) 1469 -1472

Comparative Analysis of a Low Pressure Microwave Gas Discharges Sustained by Cyclotron Surface Waves

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Introduction

A study of microwave gas discharges produced and sustained by traveling electromagnetic surface waves is of a great interest because of their numerous practical applications see e.g. [1,2]. Here we study a theoretical model of a stationary low-pressure gas discharge sustained by electron cyclotron surface modes (CSM) in discharge chamber that consists of two planar metal electrodes with a dielectric coating. There are two types of CSM that can be utilized for sustaining the microwave gas discharges in such chamber. First of them is the surface type X-mode (STXM) [3]. The second type of the CSM that can be used for sustaining the microwave gas discharge is named as surface cyclotron TM-modes. These waves can be utilized at magnetron type discharge devices for plasma deposition of special coatings and etchings of solids and so on see e.g. [4,5]. Possibility of the TM-modes application for sustaining a microwave gas discharge has been examined in [6].

Basic assumptions and applied equations

The problem is studied using the kinetic description for plasma particles motion taking into account their reflection from the dielectric interface. Distribution function of plasma electrons is assumed to be the sum $f_0 + f_1$, and inequality $f_0 >> f_1$ is assumed to be valid (two-term approximation [7]), f_0 and f_1 are isotropic and anisotropic components of the electron distribution function, respectively. The f_0 is supposed to be of Boltzmann type. Kinetic equation is solved by the method of trajectories. Its solution allows to calculate the Fourier coefficients of the electric current density as function of Fourier coefficients of electric field: $j_i(q) = \sigma_{ij}(q)E_j(q)$, where σ_{ij} is the tensor of magnetoactive plasma conductivity in kinetic approach. This tensor has both hermitian and antihermitian parts, the last one is caused by electrons reflection from plasma interface. Just existence of antihermitian part in σ_{ij} tensor is the cause of collisionless plasma heating that takes place during propagation of surface waves along plasma interface. We consider the case of dense plasma so that Langmuir frequency is much greater than electron cyclotron one. This case is of more importance for plasma technologies. And approach of weak spatial dispersion is also applied.

The CSM fields are described by Maxwell equations. Using method of Fourier transform one can find the CSM fields and electric current taking into account both hermitian and antihermitian parts of the plasma permeability tensor. Penetration depth of the STXM fields into the plasma region is approximately equal to their wave length [3,8]. The dispersion of STXM have been studied analytically for the range of long wavelengths (product of wave number and Larmor radius of electrons is much less than unit). It is found that their frequencies exceed the even magnitudes of electron cyclotron harmonics and their value weakly depends on the produced plasma density and parameters of discharge chamber. The TM- modes penetration depth is greater than the wave length especially in the range of short wave lengths [9]. In order to compare parameters of these both microwave gas discharges we shall consider only the case of long wave lengths. Moreover size of solids interface that could be processed by these discharges is greater just in the range of long wavelengths. Dispersion of the TM-modes differs from that of the STXM: eigenfrequencies of the TM- modes decrease with increasing of the wave number.

To describe stationary process of the CSM energy transfer into plasma we use the equation of energy balance, which describes the decreasing of the wave power flow caused by absorption of their energy by plasma particles Q. Value of parameter Q is determined by two mechanisms of CSM energy transfer into plasma, namely Ohmic heating and kinetic collisionless damping caused by resonant interaction between the wave fields and plasma electrons. Polarization of the TM-modes differs from that of STXM, they have electric field components both parallel and perpendicular to external magnetic field. That is why plasma electrons are situated in the region of maximum value of TM-modes field during much longer time than it happens in the case of STXM. Therefore the discharges that can be sustained by these two CSM will be characterized by different properties and different intrinsic efficiency Θ, which determines the quantity of electromagnetic power that is needed for sustaining of one ion-electron pair in discharge volume [9].

Discussion

The square of interface that can be processed by this discharge and the produced plasma volume are the most important parameters of gas discharge. The plasma volume sustained by surface waves is determined by two parameters, namely, penetration depth of the CSM field $\lambda_{\perp}$ into the plasma and discharge length $\tilde{L}$. Parameter $\tilde{L}$ is determined as length along direction of the corresponding CSM propagation where plasma density n_p decreases by exp times. If discharge is sustained by the STXM then discharge length $\tilde{L}$ are determined by the following formulae:

$$\tilde{L} \approx \frac{\xi\sqrt{\pi}}{k_2^2 \rho_e}, \quad \text{or} \quad \tilde{L} \approx \frac{\zeta\omega}{\nu_e |k_2|}, \tag{3}$$

for the regimes of collisional and collisionless damping, respectively. Here k_2 is longitudinal wave number of these CSM, ρ_e is Larmor radius, $\xi = 0{,}08$ in the case of thick layer of defensive dielectric coating (the inequality $\varepsilon_d \mathrm{cth}|ak_2| << |\varepsilon_1|$ is valid), and $\xi = 0{,}64$ in the case of $\varepsilon_d \mathrm{cth}|ak_2| >> |\varepsilon_1|$, a is the thickness of dielectric coating, $\zeta \approx 0.4$ in the case of thin dielectric coating, and $\zeta \approx 0.1$ in the case of thick dielectric coating.

Under the regime of the STXM collisionless damping, that can be realized for the operating gas pressure $p \le 10\mathrm{mTorr}$ [1,9], one can obtain the following expression for Θ:

$$\Theta_{res} \approx \frac{\varsigma \Omega_e^2 k_2 \rho_e E_0^2}{\pi^{5/2} \omega_e n_p}, \tag{6}$$

where $\varsigma = 0.2$ for the case of thick dielectric coating ($ak_2 >> 1$) and $\varsigma = 0.007\varepsilon_d^2 \mathrm{cth}^2(ak_2)$ for the case of thin dielectric coating ($ak_2 << 1$). One has to keep in mind that formulas (5) and (6) have been found for the range of long wave lengths $k_2 \rho_e << 1$.

Length of the discharge sustained by TM-modes is determined by the following relation under the regime of collisional damping:

$$\tilde{L} \approx \frac{\omega - s\omega_{ce}}{\nu_e k_1} \ , \qquad (7)$$

where k_1 is longitudinal wave number of TM-modes. Because of the TM-modes dispersion properties parameter $\tilde{L}$ decreases with increasing of the utilized wave length and number of cyclotron harmonic. But if collisionless mechanism of the TM-modes energy transfer into the produced plasma is realized (just this regime is usually can be realized [6]), then discharge length is of ρ_e order. The operating square of discharge sustained by TM-modes is much less than that in the case of STXM.

For discharges sustained by TM-modes parameter Θ under the regime of collisionlles damping is determined by the following expression:

$$\Theta_{res} \approx \frac{\omega\Omega_e^2 E_0^2 (s^2 - 1)^2 (k_1^2 \rho_e^2)^{2s-3} n_p^{-1}}{4\pi^2 \omega_e^2 \exp\left[-(\omega - s\omega_e)^2 \lambda_\perp^2 \rho_e^{-2} \omega_e^{-2}\right] 16^s s!^2} . \qquad (9)$$

Conclusions

Orientation of the external steady magnetic field sufficiently affects on the type and properties of eigen surface mode of the considered discharge chamber. Collisionless damping of the TM-modes is proved to be much greater [9] than for the case of the STXM propagation (magnetic field is parallel to the plasma interface [14]). Magnitude of the collisionless electron heating for the case of the TM-modes propagation sufficiently exceeds the resonantly absorbed wave power in the case of the STXM propagation. That is why the distance wherein the TM-modes power can be resonantly absorbed by plasma electrons is much less than that in the case of the gas discharge sustained by STXM. Thus one can chose both value of an external magnetic field and its orientation in order to effectively utilize microwave gas discharge sustained by various surface modes. And sphere of their utilization can be

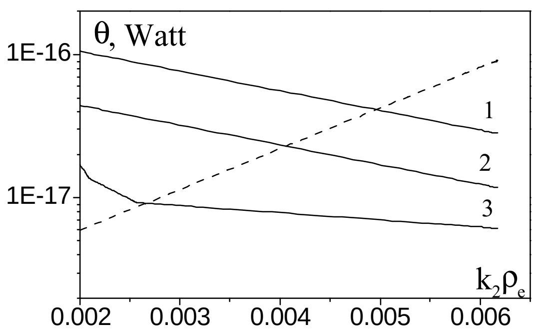

Fig.1. Θ of microwave gas discharge sustained by STXM as a function of $k_2\rho_e$. Thickness of dielectrical coating is 1 cm. Curves marked by 1, 2 and 3 have been drawn for operating gas pressure 50 mTorr, 20 mTorr and 10 mTorr, respectively. Solid and dashed lines relate to the regimes of collisional and collisionless damping, respectively.

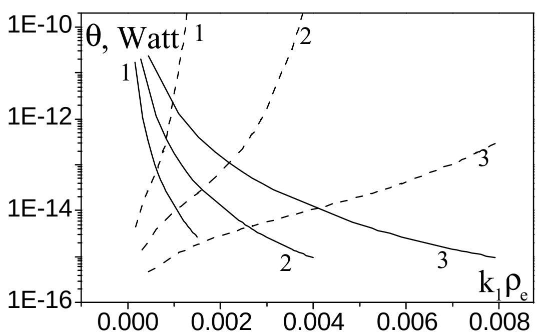

Fig.2. Θ of the discharge sustained by TM-modes as a function of Curvatures 1, 2 and 3 have been drawn for the cases when thickness of dielectric coating is 2 cm, 1 cm and 0,5 cm, respectively. $k_1\rho_e$. Discharge parameters and application of the lines are the same as at fig.1.

also different. It is found that under the condition of low-pressure gas discharge collisionless transfer of the CSM energy into plasma particles is more effective mechanism as compared with collisional one. These peculiarities of the examined CSM make their propagation interesting for application in the microwave gas discharge technologies.

Acknowledgment

The work was partially supported by Science and Technology Centre in Ukraine, Project #1112.

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