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Ion contribution in the instability of high power microwave-produced plasmas

B. Shokri, M. Ghorbanalilu

Physics Department and Laser Research Institute of Shahid Beheshti University, Tehran, Iran

Abstract

The gas breakdown produced by high-power pulsed linearly and circularly polarized microwave fields which are much weaker than the atomic fields is investigated in the non-relativistic limit. It is shown that the resulting electron distribution function is non-equilibrium and anisotropic. Furthermore, the general dispersion equation is derived and analyzed to study low-frequency ion oscillations. It will be shown that for linearly polarized microwave fields an instability may always develop but for the circular polarization fields an instability grows only when ion density is higher than a critical density.

I. INTRODUCTION

A gas discharge in a microwave (MW) field is a rather complicated phenomenon that exhibits a variety of features. Interest in such a discharge is related not only to its potential in technological applications, but also to general problems related to the discharge physics. In a strong microwave wave field the electron oscillatory energy ϵ_i is much higher than the ionization energy I_i of the gas atoms

$$\epsilon_i = \frac{e^2 E_0^2}{2m\omega_0^2} \gg I_i, \tag{1}$$

where ω_0 is the radiation frequency, m is the electron mass, and E_0 is the electric field strength. When the field amplitude is comparable to the atomic field strength $E_a \approx 5.1 \times 10^9\ V/cm$ the tunneling ionization becomes an important mechanism for direct ionization of the gas atoms.

In the present paper, considering the interaction of linearly and circularly polarized MW pulsed fields with frequencies around $\omega_0 \simeq 2\times10^{10} - 2\times10^{11}s^{-1}$ with a neutral gas in the non-relativistic regime, we will study the low frequency ion oscillations and their instabilities. We will consider a pulsed radiation source which is capable of generating radiation with an intensity of about $10^8 W/cm^2$, whose electric field $E_0 \leq 10^6 V/cm$ is much weaker than the atomic field E_a. In this case, we study the electron distribution function (EDF) and the stability of the discharge plasma in the aforementioned frequency range at non-relativistic regime.

II. DISTRIBUTION FUNCTION

Under condition (1) the thermal velocity of the electrons in a discharge plasma can be neglected in comparison to the electron oscillation velocity in the MW radiation field. Ignoring the collisional randomization of the forced electron oscillation, if the plasma density $n_e(t)$ produced by the field during gas breakdown is less than the critical density (i.e., $\omega_0^2 > \omega_{pe}^2 = 4\pi ne^2/m$), we can neglect the effect of the polarization field. Moreover, the plasma density is assumed to be much less than the neutral gas density n_0. We also suppose that the field is adiabatically switched on in the infinite past and the MW radiation electric field E_0 is constant during a single field period. Therefore, by solving the Vlasov equation under the following condition

$$\omega_0 \gg \gamma(E_0), \omega_i, \tag{2}$$

where $\gamma(E_0)$ is the avalanche ionization constant, one can find the EDF.[1] Condition (2) depends strongly on the neutral gas density and is well satisfied at gas pressures of $P_0 \simeq 10-100$ torr. In this approximation, to calculate the EDF, for linear polarization

$$E_x = E_0 \sin\omega_0 t, \qquad E_y = 0, \qquad E_z = 0, \tag{3}$$

where the electric field amplitude E_0 describes a slowly varying (over the field period) MW pulsed envelope, by averaging the distribution function over the field phase φ we find[2]

$$< \tilde{f}_0(\mathbf{v}) >= \frac{\delta(\mathbf{v}_\perp)}{\pi\sqrt{v_E^2 - (v_\parallel - v_E \sin\omega_0 t)^2}}. \tag{4}$$

Here, $f_0(\mathbf{v}, t) = n_e(t)\tilde{f}_0(\mathbf{v})$ and $v_E = eE_0/m\omega_0$; $v_\parallel$ and $v_\perp$ are parallel and transverse components of electron velocity with respect to the electric field, and $\int d\mathbf{v}\tilde{f}_0(\mathbf{v}) = 1$.

Similar to the linear polarization case, for the circularly polarized field

$$E_x = E_0 \sin\omega_0 t, \qquad E_y = E_0 \cos\omega_0 t, \qquad E_z = 0, \tag{5}$$

we find[2]

$$\left\langle \tilde{f}_0(v_\perp, v_z) \right\rangle = \frac{\delta(v_z)}{2\pi^2 v_\perp \sqrt{4v_E^2 - v_\perp^2}}, \tag{6}$$

where v_z is the perpendicular component of electron velocity with respect to electric field and $v_\perp$ is the component of velocity in the plan of the electric field.

III. DISPERSION EQUATION. III. a. Linear polarization.

Since we will study the instabilities whose growth rate are higher than the ionization rate we can assume electron density to be constant. In addition, the ion velocity distribution function can be regarded as Maxwellian and the EDF is given by Eq. (4). Linearizing the Vlasov equation of the electrons and the ions after tedious calculation we find the following dispersion equation

$$1+\delta\varepsilon_e(\omega,\mathbf{k})+\delta\varepsilon_i(\omega,\mathbf{k})+\delta\varepsilon_e(\omega,\mathbf{k})\ \delta\varepsilon_i(\omega,\mathbf{k})\left[1-J_0^2(\frac{\mathbf{k}_\parallel.\mathbf{v_E}}{\omega_0})\right]=0, \qquad (7)$$

where $\delta\varepsilon_e(\omega,\ \mathbf{k})$ and $\delta\varepsilon_i(\omega,\ \mathbf{k})$ are the partial contribution of the electrons and ions to the longitudinal dielectric permittivity; $\mathbf{k}_\parallel$ is the parallel component of $\mathbf{k}$ with respect to the electric field and J_0 is the zeroth order Bessel function.

III. b. Circular polarization.

By using the same method we find the following dispersion equation for the circular case:

$$1+\delta\varepsilon_e(\omega,\mathbf{k})+\delta\varepsilon_i(\omega,\mathbf{k})+\delta\varepsilon_e(\omega,\mathbf{k})\ \delta\varepsilon_i(\omega,\mathbf{k})\left[1-J_0^2(k_x r_E)\ J_0^2(k_y r_E)\right]=0, \qquad (8)$$

where k_x and k_y are the component of the wave vector $\mathbf{k}$.

IV. THE STABILITY OF THE PRODUCED PLASMA.

The instability analyzed in this section occurs in the range $\omega_0 \gg kv_E \approx \omega_{pe}$. It occurs for a positive (non-equilibrium) slope of the EDF (4) and (6). It should be noted that, the instability studied here never occurs for an equilibrium (Maxwelline) EDF, in the aforementioned frequency range.

IV. a. Linear polarization.

Taking into account the EDF (4), by calculating the the partial longitudinal dielectric function $\delta\epsilon_{e,i}(\omega,\ \mathbf{k})$ of the electrons and the ions and substituting into the dispersion equation (7) we find the following dispersion relation

$$\begin{cases} \omega^2=\omega_{pi}^2\left[1+i\ \frac{\omega_{pe}^2\omega_{Li}}{|k_\parallel v_E|^3}J_0^2(\frac{k_\parallel v_E}{\omega_0})\right] & \text{for} \quad k_\parallel^2 v_E^2 \gg \omega_{pe}^2\ , \\ \omega=|k_\parallel v_E|(\frac{m}{M})^{\frac{1}{3}}\ \frac{\sqrt{3}+i}{2} & \text{for} \quad k_\parallel^2 v_E^2 \ll \omega_{pe}^2, \end{cases} \qquad (9)$$

corresponding to unstable low frequency ion oscillations. Of course, this instability can only grow at the rate which is faster than that at which the plasma density increases.

IV. a. Circular polarization.

Taking into account the EDF (6), analogously to the pervious subsection we find

$$\begin{cases} \omega^2 = \omega_{pi}^2 \left[1 + i(\frac{\omega_{pe}^2 \omega_{pi}}{|2k_\perp v_E|^3} - \frac{\omega_{pe}^2 k_\perp^2}{\omega_{pi}|2k_\perp v_E|k^2}) J_0^2(\frac{k_\perp v_E}{\omega_0}) \right] & 4k_\perp^2 v_E^2 \gg \omega_{pe}^2 \ , \\ \omega = \frac{|2k_\perp v_E|k_\perp}{k} \left[1 - \frac{i}{2}(\frac{|2k_\perp v_E|^2 k}{\omega_{pe}^2 k_\perp} - \frac{\omega_{pi}^2 k^3}{\omega_{pe}^2 k_\perp^3}) \right] & 4k_\perp^2 v_E^2 \ll \omega_{pe}^2, \end{cases} \tag{10}$$

corresponding to unstable low frequency ion oscillations. Dispersion relation (10) shows that in the case of circularly polarized MW field the Cherenkov excitation of the low frequency oscillation takes place only for the perturbations satisfying the following condition

$$\frac{\omega_{pi}^2}{|2k_\perp v_E|^2} \geq \frac{k_\perp^2}{k^2}. \tag{11}$$

Perturbations that do not satisfy condition (11) are not unstable and can not grow in the plasma.

V. CONCLUSION

Studying the interaction of the high frequency linearly and circularly polarized MW field with a neutral gas, we obtained the general dispersion relation of the produced plasma. Analyzing the latter relation we found out that low frequency ion oscillations are unstable. The resultant instability always grows up in the plasma for the linear polarization case. However, for the circular polarization case, it grows up in the plasma only if ion density exceeds a critical density, i.e., $n_i \geq M k_\perp^4 E_0^2/\pi m^2 k^2 \omega_0^2$. For both cases this is described by this fact that the electrons transfer the electric field energy to the ions and the stimulated Cherenkov excitation of the low frequency ion oscillations takes place. This effect is governed by the positive slope of the EDF. Furthermore, in both cases the instability can propagate when the growth rate increases faster than the plasma density does, i.e., the growth rate must exceed the avalanche ionization rate $\gamma(E_0)$.

REFERENCES

[1] M.V. Kuzelev, and A.A. Rukhadze, Sov. J. Plasma Phys., **27**, No. 2, 153, (2001).

[2] B. Shokri, M. Ghorbanalilu, Phys. of Plasmas, **11**, 2989, (2004).