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The Anisofrequency Parameter Calculation in the Regions of Langmuir Probe Operation-Application to Argon Plasma

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Abstract: The anisofrequency dimensionless parameter $\Omega(\theta,\phi)$ is calculated for low density argon (Ar) plasma which is studied in his conditions of electrical potential ϕ and ion temperature T_i. However, the varied magnitudes are the potential ϕ which is varied in -10 to 10 V range, ion temperature T_i from 0.1 to 1 eV range and parameter $\theta = T_i/T_e$ from 0 to 0.4. The study is done especially for argon and then relative dielectric function versus parameter $\Omega(\theta,\phi)$ is calculted in different region of Langmuir probe operation. The dispersion relation, medium refractive index and ε_r versus Ω achieved this work.

Key words: Anisofrequency parameter, ion plasma frequency, electron plasma frequency, dielectric function, argon plasma

INTRODUCTION

Low temperature plasmas have wide range of technological applications. Argon (Ar), is among the most used plasmas in experiments and technology applications as ECR plasmas which have been done by Bon-Woong *et al.* (1999), Minayeva and Hopwood (2003) had studied ICP system, Rousseau *et al.* (2002) had made planar microwave reactors, microwave diagnostic results from gaseous electronic conferences rf had been studied by Overzet (1995).

Langmuir Probe (LP) is a tool inserted in plasma in the aim to determine his characteristics. The sheath is formed near the langmuir probe of cylindrical geometry inserted in the plasma, these experiments were made by Laframboise and Rubinstein (1976) and Morales *et al.* (2003 and 2004). An electrical wave is an oscillating periodically field which depended on time and frequency $f = \omega/2\pi$ expressed as $E = E_0\exp(j\omega t)$ and no magnetic field case is studied. In order to compare electron plasma frequency ω_{pe} to ion plasma frequency ω_{pi}, the ratio of ω_{pe} to ω_{pi} is then defined and introduced in this study as called anisofrequency parameter $\Omega(\theta,\phi)$. This last depended on ratio θ and the potential ϕ. The plasma anisofrequency parameter, the relativ dielectric function ε_r are the main magnitudes studied in this research.

MATERIALS AND METHODS

Dielectric function in different frequency regions: Often it is necessary to investigate a plasma that changes in time. Famous are the studies of the variations of electron energy distributions function in ionisations waves which done by Rayment and Twiddy (1969) and Sicha *et al.* (1971) or in a stationnary afterglow studied by Smith and Plumb (1973). Furthermore, Dvoracek *et al.* (1990) took an interest in many studies using probe for exploring plasma in single shot systems, such as tokamak. Also many technolological applications where plasma are generated by tools of alternatif current or radiofrequency power. The approach to problem differs depending on the possibility to make the studied changes of plasma parameters periodic in time with reasonably short period at least several hertz.

Smith and Plumb (1973) used plasma parameters depending on time $t \sim \omega^{-1}$, stationnary afterglow had been studied by Shun'ko (2003), ionisation waves, ac or rf generated plasmas are some examples when the periodicity is realiseable. The frequency regions are compared to free charge carriers, as ions and electrons, plasma frequency ω_{pi} and ω_{pe}.

Five regions of LP operation: There are 5 regions of LP operation as far as the frequency of plasma generation or plasma changes is concerned in the Swift and Schwar (1970) and Winkler *et al.* (1985).

1st region $\omega \ll \omega_{pi}$: Both electrons and ions are in equilibrium with the periodically varying electrical field. The steady ion as well as the electron current increase due to the rectification effect of the nonlinear probe characteristic.

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Time resolved measurement of plasma parameters are possible. This frequency range concerned low frequency plasma oscillations such as ionisation waves, periodically discharge, for example from 100 to 400 KHz.

2nd region $\omega \approx \omega_{pi}$: The electrons are in equilibrium with varying electrical field.

The oscillation period is comparable to the ions transit time through the space charge sheat and therefore a small resonance peak in the incremental increase in the steady ion current is observed. Since the resonance effect is difficult to assess it is not recommended to make probe measurements in this frequency region as remarked by Hippler *et al*. (2000), this frequency range is typical for example plasma generated by a small power signal followed by an amplifier of power.

3rd region $\omega_{pi} < \omega << \omega_{pe}$: Only the electrons are in equilibrium with varying electrical field.

This case is typical for single frequency rf discharges (f = 13.56, 27.12 MHZ) used in the study of Hippler *et al*. (2000).

4th region $\omega \approx \omega_{pe}$: The period of oscillating is comparable to the electrons' transit time through the sheath. It remarked an increase of electron current.

5th region $\omega > \omega_{pe}$: Neither ions nor electrons are able to respond to the oscillating electrical field. This kind of range is available for magneteron generated microwave plasma (f = 2.4 GHz).

Calculation of anisofrequency parameter Ω: Since the langmuir probe technique relies upon the formation of a space charge sheath around the probe, its time resolution cannot be higher than ion plasma frequency ω_{pi}. If the plasma frequency variation as in rf plasma, is higher than ω_{pi}, only measurement of time average values of plasma parameters are possibly obtained by LP. The electron plasma frequency ω_{pe} is a second interesting with ω_{pi}. In plasmas of relatively low density and temperature equal or under 1 and 10 eV for ions and electrons, respectively is well established by Armstrong and Darrow (1994).

This study was conducted at the Plasmas Physics and Conducting Materials and their Applications Laboratory, University of Sciences and Technology (2006). The anisofrequency parameter Ω is defined as the ratio of electron plasma frequency ω_{pe} to ion plasma frequency ω_{pi} which depends directly on the plasma electrical potential ϕ, ion temperature T_i and the anisothermicity parameter θ which is the ratio of ion temperature T_i to electron temperature T_e given by the following expression,

$$\theta = \frac{T_i}{T_e} \tag{1}$$

where $0 \le \theta \le 0.4$ is the range chosen in experiments of Morales *et al*. (2003) and Laframboise *et al*. (1976). The details are shown in following Table 1.

In first, the electron plasma frequency ω_{pe} and ion plasma frequency ω_{pi} are expressed as:

$$\omega_{pe} = \left(\frac{n_e e^2}{m_e \varepsilon_0}\right)^{1/2} \tag{2}$$

$$\omega_{pi} = \left(\frac{n_i e^2}{m_i \varepsilon_0}\right)^{1/2} \tag{3}$$

Where, n_e, n_i are electron and ion density, m_e, m_i are electron and ion mass, respectively. e is the elementary electron charge and ε_0 is the vacuum permittivity, (international system units are used). In our study, the electron and ion density distributions in plasma were maxwellian, respectively (Woong *et al*., 1999). The anisofrequency parameter is then expressed,

$$\Omega(\theta, \phi) = \frac{\omega_{pe}}{\omega_{pi}} \tag{4}$$

Taking into account the density maxwellian distribution the parameter $\Omega(\theta,\phi)$ became:

$$\Omega(\theta, \phi) = \Omega_0 \exp \frac{e\phi(1+\theta)}{k_B T_i} \tag{5}$$

where, the unperturbed parameter Ω_0 in argon plasma is given as follows:

$$\Omega_0 = \sqrt{m_i}\,10^{15} \cong 258 \tag{6}$$

Dielectric function variation: In the $\omega\tau >> 1$ case, the dielectric function ε_r is given as follows:

$$\varepsilon_r(\omega) = 1 - \frac{\omega_p^2}{\omega^2} \tag{7}$$

by introducing the anisofrequency parameter, the Eq. 7 was rewritten:

$$\varepsilon_r(\Omega,\omega) = 1 - \frac{\omega_{pi}^2}{\omega^2}\Omega^2 \quad (8)$$

Using the Eq. 8, in the 1st, 3rd and 5th region, the corresponding frequencies were, respectively then 1E5, 13.56E6 and 2.4E9 Hz. Their corresponding relative dielectric function were noted ε_r^1, ε_r^3 and ε_r^5 (the exposants 1, 3, 5 were, respectively the number of each region), the plasma frequency ω_{pi} and the ion density were kept, respectively to the values 0.66E6 Hz, 1E13 m^{-3} in the expression 8. Therefore, the corresponding graphs were shown in Fig. 6-8 when θ = 0.4. Eq. 8 was then given by the following sets of equations:

$$\varepsilon_r^1(\Omega) \approx 1 - 43.56\Omega^2 \quad (9)$$

$$\varepsilon_r^3(\Omega) \approx 1 - 2.37x10^3\Omega^2 \quad (10)$$

$$\varepsilon_r^5(\Omega) \approx 1 - 7.56x10^{-8}\Omega^2 \quad (11)$$

These sets of equations can be expressed as 2nd degree equation, $y = 1\text{-}\alpha\,^s\Omega^2$, s = 1, 3 or 5.

Ion transit time in sheath in collisionless plasma: In transition regimes, the dimensionless variable $\omega\tau$ is given as follows: In matrix sheath model where ion density n_i is constant and does not depend on sheath distance d, as described in paper of Chen *et al.* (2002) and by Boeuf and Carrigues (2003).

$\tau \approx \omega_{pe}^{-1}$ where n_i = constant

$\tau \approx$ some ω_{pi}^{-1} otherwise,

$\tau \approx$ some 100 ω_{pi}^{-1}

in Child Langmuir CL sheath model which was used Boeuf and Garrigues (2003).

The transit time τ results were given in Table 2 where the term some is taken in average at 10, namely that ion and electron density are kept at the limit of the low density plasma case. Namely, transit time of free charge carriers is linked to its free mean path l and its velocity as $l = v\ \tau$, which was cited in Kittel (1983).

Dispersive relation-refractive index: The dispersion relation, taking in account ion and electron plasma frequency, is given by following expression which were detailed in Golant *et al.* (1980) and in Tran (1989).

$$\omega^2 = k^2c^2 + \omega_{pe}^2 + \omega_{pi}^2 \quad (12)$$

Where, k is a wave vector, c is the light velocity in vacuum (v_i and v_e are the ion and electron velocity in plasma, respectively).

By introducing the parameter Ω, then the dispersion relation is expressed in following:

$$\omega^2 = k^2c^2 + \omega_{pi}^2(1+\Omega^2) \quad (13)$$

The refractive index N is given as follows:

$$N = \sqrt{\varepsilon_r} \quad (14)$$

RESULTS AND DISCUSSION

The $\Omega(\theta,\phi)$ values are plotted in logarithms units. The details were shown in Table 1, 2 and 3 and curves are fitted.

The anisofrequency parameter dependance on plasma physics variables: The parameter $\Omega(\theta,\phi)$ versus the potential ϕ at kept value of T_i = 1 eV with different θ. The Ω shape is illustrated for argon plasma in the Fig. 1 in which the shape could be fitted as two increasing lines which crossed at point of coordinates (0 V, 257.24) for argon plasma. Therefore, $\Omega(\theta,\phi)$ increased to maximum of coordinates (10V, 3E8) for the value θ = 0.4. The slope increased as the parameter θ increased (Fig. 1) so then

Table 1: Values of parameter θ, anisofrequency parameter $\Omega(\theta,\phi)$ and electron temperature T_e

θ	$\Omega(\theta,\phi)$	T_e (eV)
0	$\Omega(0,\phi)$	$>>T_i$
0.1	$\Omega(0.1,\phi)$	10.0
0.2	$\Omega(0.2,\phi)$	5.0
0.3	$\Omega(0.3,\phi)$	3.3
0.4	$\Omega(0.4,\phi)$	2.5

Table 2: Free charge carrier transit time τ for argon when n_i = 1E13, n_e = 1E15 m^{-3}

τ (s)	τ (s)
$\tau \approx \omega_{pe}^{-1}$	5.6E-10
$\omega_{pi}^{-1} < \tau \leq 10\ \omega_{pi}^{-1}$	1.5E-6<$\tau\leq$1.5E-5
$10^2\ \omega_{pi}^{-1} < \tau \leq 10^3\ \omega_{pi}^{-1}$	1.5E-4<$\tau\leq$1.5E-3

Table 3: Different ranges of dimensionless parameter $\omega\tau$ for different frequency regions

ω region	Frequency f (Hz)	$\omega\tau$
1st	f = 1E5-4E5	6.5E5τ-2.5E6τ
2nd	$\omega \approx \omega_{pi}$	$\omega_{pi}\tau$
3rd	f = 13.56 E6	8.5E7τ
	f = 27.12 E6	1.7E8τ
4th	$\omega \approx \omega_{pe}$	$\omega_{pe}\tau$
5th	f = 2.4 E9	1.5E10τ

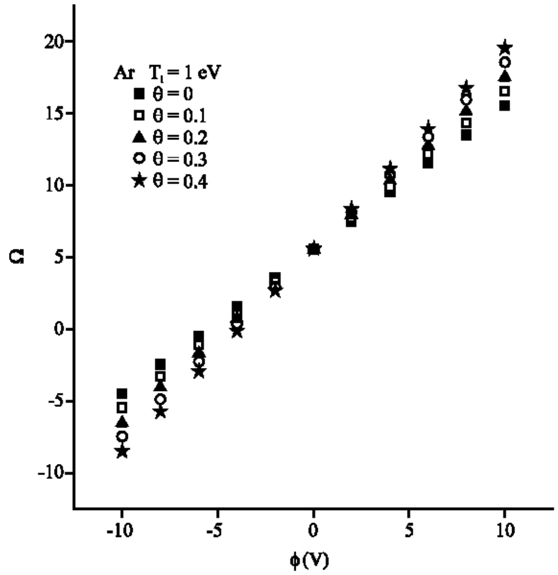

Fig. 1: Anisofrequency parameter $\Omega(\theta,\phi)$ versus electrical potential ϕ of Ar plasma for $0 \le \theta \le 0.4$ and T_i kept at 1 eV

$\Omega(\theta,\phi)$ dependance upon θ is important. By exploiting the result, the maximum value of parameter $\Omega(\theta,\phi)$ led to an electrical potential condition: ϕ >> -16 V, the ϕ range chosen in our study is available with respect to the last condition. $\theta = 0.4$ is the high value of the anisothermicity parameter which corresponded to electron energy of 2.5 eV and to mean electron velocity, $v_e \cong (2k_BT_e/m_e)^{0.5}$, around 10^6 m s^{-1}, it is easy seen that v_e is more less than light velocity c in vacuum. About ion argon, the velocity $v_i \cong (2k_BT_i/m_i)^{0.5}$, which correspond to the fixed ion energy 1 eV, is around 10^3 m s^{-1}, the two velocity values could be compared as follows $v_i/v_e \cong 10^{-3} << 1$.

The parameter $\Omega(\theta,\phi)$ versus the ion temperature T_i whereas the potential is kept at 1 V with different θ values. The Ω shape is illustrated for argon plasma in the Fig. 2. Therefore, the anisofrequency parameter $\Omega(\theta,1)$ followed an exponential decay function of order 1 as shown in figure and fitted in solid line where the fit expression is $y = y_0+A_1\exp(-x/t_1)$, the function y can be the anisofrequency parameter Ω and x the ion temperature, the constants are: y offset $y_0 = 6.82\pm0.13$, amplitude $A_1 = 17.88\pm1.18$ and decay constant $t_1 = 0.14\pm0.01$. The maximum correspond to a point of coordinates (0.1 eV, 3E8) only for $\theta = 0.4$. The maxima are very distinctly located but the minima are disconcerted in an average point of coordinates (1 eV, 1043). The ion energy of 0.1 eV which corresponded to Ω maximum value, the ion velocity is then about 710^2 m s^{-1} with θ equal to 0.4, the electron energy is then deduced 0.25 eV which led to $v_e \cong 10^5$ m s^{-1} and the same ratio, $v_i/v_e \cong 10^{-3} << 1$, was found.

Instead of plasma frequency, the anisofrequency versus ion density is plotted for different electron density in Fig. 3, an important decay is clearly observed mainly for the high electron density which was the top limit value of

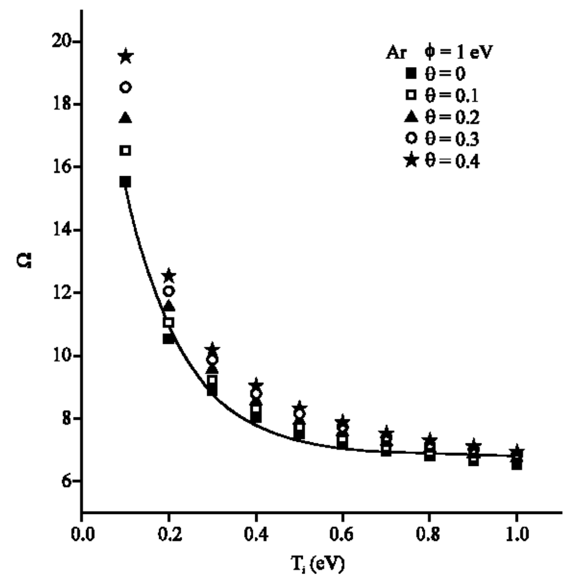

Fig. 2: Anisofrequency parameter $\Omega(\theta,\phi)$ versus ion temperature of Ar plasma for $0 \le \theta \le 0.4$ and ϕ kept at 1 V, exponential decay of order 1 fitted in solid line

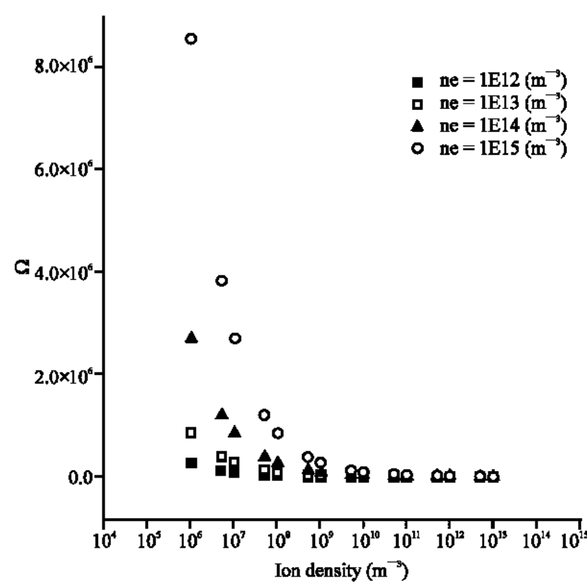

Fig. 3: Anisofrequency parameter versus ion density for several fixed electron density

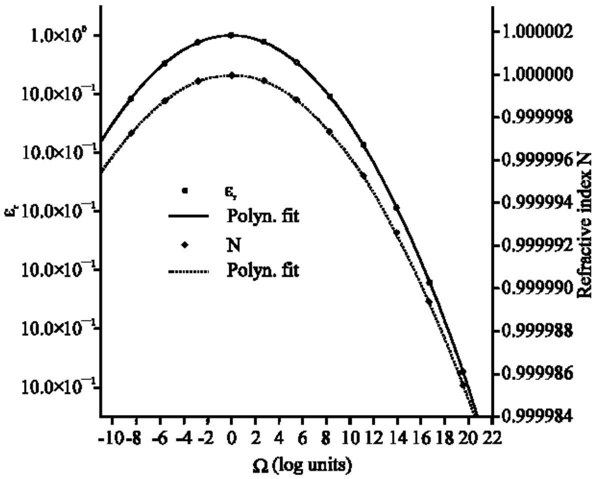

Fig. 4: The dielectric function ε_r (○ left), polynomial fitted curve in solid line and refractive index N (◆ right) polynomial fitted in dash line, versus parameter Ω, for Argon at n_i = 1E13 m^{-3}, θ = 0.4 and T_i = 1 eV

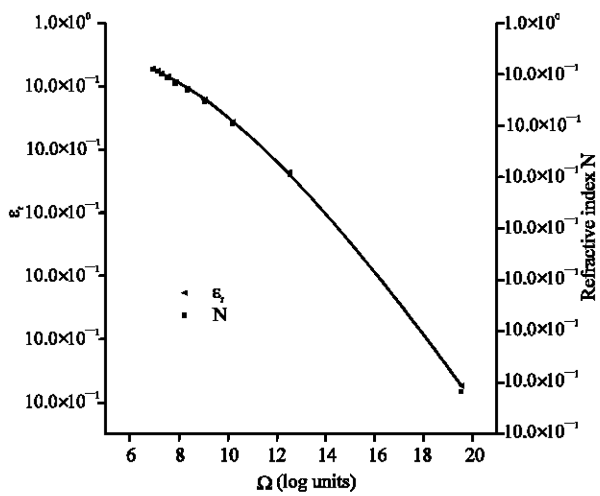

Fig. 5: The dielectric function ε_r (◂ left) and refractive index N (■ right), exponential decay of order 3 fitted curve in solid line versus parameter Ω, for Argon at n_i = 1E13 m^{-3}, when θ = 0.4 and ϕ = 1 V

our low density plasma studied as also shown in Armstrong *et al.* (1994). Whereas the Ω(θ,ϕ) variation is inversely proportional to ion density and became quasi constant when the electron density tends to his low value. The anisofrequency parameter could be constant for the electron density less than 1E12 m^{-3}.

In Fig. 4 where the profile fit equation of ε_r, N are approximatively expressed as $\varepsilon_r \approx 1+(1.35E-18)\,\Omega-(7.50E-8)\,\Omega^2$, $N \approx 1+(3.13E-13)\,\Omega-(3.75E-8)\,\Omega^2$. The profile of both ε_r and N is decreasing as shown in Fig. 5, the exponential decay of order 3 follows the profile expressed as:

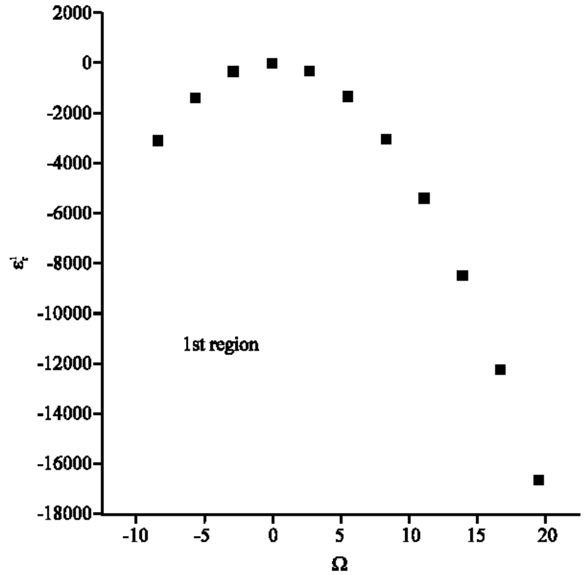

Fig. 6: The dielectric function ε_r versus parameter Ω, solid square ■, for Argon at n_i = 1E13 m^{-3}, when θ = 0.4 (f = 1E5 Hz or 1st region)

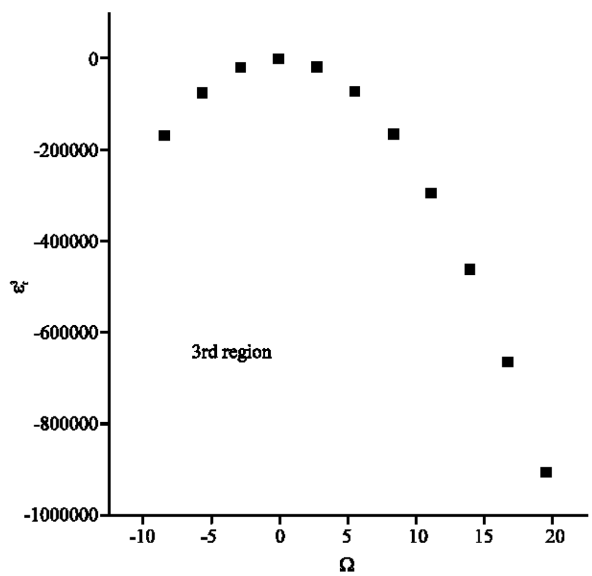

Fig. 7: The dielectric function ε_r versus parameter Ω, solid square ■, for Argon at n_i = 1E13 m^{-3}, when θ = 0.4 (f = 13.56E6 Hz or 3rd region)

$$y = y_0 + A_1\exp(-x/t_1) + A_2\exp(-x/t_2) + A_3\exp(-x/t_3)$$

where y can be ε_r or N. The constants are:

y_0 = 0.99994, A_1 = -5.82242E-5, A_2 = 1.48017E-4, A_3 = -3.15103E-5

t_1 = 12.14939, t_2 = 39.91426, t_3 = -7.183E82

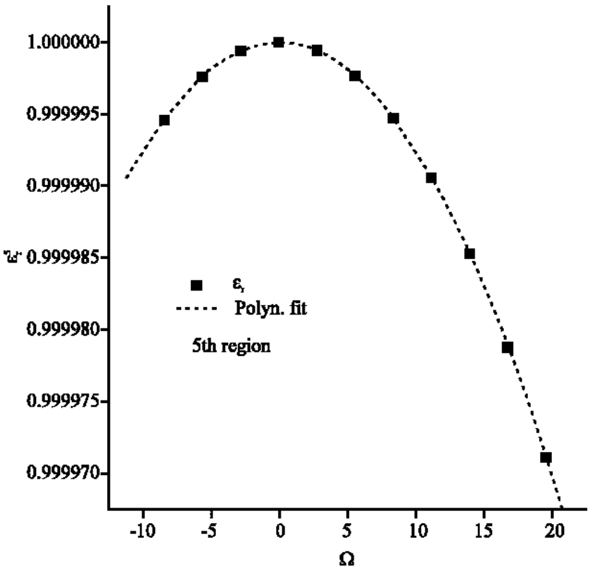

Fig. 8: The dielectric function ε_r versus parameter Ω, solid square ■, for Argon at n_i = 1E13 m^{-3} when θ = 0.4 (f = 2.4E9 Hz or 5th region)

The difference between the Fig. 4 and 5 is the plasma physics variables ϕ and T_i which were kept separately. The comparaison of their corresponding energy $e\phi$ and k_BT_i given more informations for the ion transport in the plasma.

The same shape of dielectric function is observed in 1st, 3rd and 5th region as shown in Fig. 6-8, respectively. The range of Ω when ε_r increased is about -10 to 0 and decreased in the range 0- 20. In 1st, 3rd ε_r is negative and 5th region presented ε_r as positive magnitude. In Fig. 8, the profile is polynomial fitted in dash line and expressed as: $\varepsilon_r \approx 1+(9.94\text{E-}19)\,\Omega-(7.56\text{E-}8)\Omega^2$.

OPEN QUESTIONS

- Do the results change for another plasma for example helium?
- Could the dielectric function ε_r profiles change if the parameters of problems change as potential, ion temperature or even ion density?

CONCLUSIONS

In this study, much magnitudes and parameters have been studied and calculated. The originality of this work is the anisofrequency parameter $\Omega(\theta,\phi)$ calculated for Argon plasma at different values of θ when the variables were the electrical potential $-10 \le \phi \le 10$ V and the ion temperature $0<T_i \le 1$ eV. The optimal case was for θ = 0.4. The originality consists in the parameter $\Omega(\theta,\phi)$ which considered as a tool. This last relies the plasma physics variables as electric potential, ion temperature and density, anisothermicity parameter to measurables magnitudes as dielectric function and refractive index. These last are very used in electromagnetic and optical material applications. Considered the results The relative dielctric function was expressed in several frequency regions. Then the most important frequencies of each region were calculated and discussed as 1E5, 13.56E6 and 2.4E9 Hz. These were the main frequeny examples of each region.

The wave oscillation frequencies identified 3 important regions studied above, 1st, 3rd and 5th region and two boundary regions as known the 2nd and 4th. In which them the plasma frequency of ions and electrons could be compared with wave oscillation frequencies, then the plasma particles will be in equilibrium with superimposed varying electrical field or no. The anisofrequency parameter depended on the density in this study of course, the variation is clearly observed for the high electron density and decreased when the ion density increased.

Transit time is around 1E-10 s in matrix sheath modele and around 1E-3 s in CL sheath modele.

The refractive index N values and the wave velocities in these low density plasma could show that they are anisotropic. The second region $\omega \approx \omega_{pi}$ and the fourth region $\omega \approx \omega_{pe}$ could be considered as boundary region, respectively between 1st and 3rd in one hand and between 3rd and 5th in other hand. The plasma frequency delimitate the border between two domaines, the totally reflection and the transmission of electromagnetic waves in the plasma medium. Any other meduim which is characterized by dielectric function, will have a response which depends on frequency, his refractive index will depend then on electromagnetic wavelength.

The variation of magnitudes as ε_r, N versus anisofrequency parameter Ω with restricted conditions on θ, ϕ, T_i and n_i was distinctly studied and observed in Fig. 4-8.

The knowledge of the ions and electrons behaviour in and near the sheath with an electrical wave depending on time is certainly important to anticipate many plasma variables as the ion current, the conductivity etc.

This study could be expanded to a wide range of charge carriers densities n_i, n_e, the potential range in plasma and ion temperature T_i.

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