Microwave Diagnostics of a Strong Arc Discharge Plasma in SF_6

J. Musil and F. Žáček

Institute of Plasma Physics, Prague

The paper deals with the microwave free-space diagnostics of high collision arc discharge plasmas. It is found that information about the electron density N and the collision frequency ν in such a plasma can be obtained from the energy transmitted through the plasma by an electromagnetic wave. The phase of the electromagnetic wave cannot be used since it is almost the same as that of a wave passing through vacuum. These basic concepts are verified experimentally at a frequency of 37.5 GHz.

It is shown how the time dependence of the electron density in a plasma with constant and with time variable collision frequency may be evaluated.

1. Introduction

The free-space microwave measurement of the electron density N and the collision frequency ν of a plasma is based on the attenuation and the phase shift of the electromagnetic wave after passage through the plasma. The amplitude transmission coefficient of a plane electromagnetic wave penetrating perpendicularly through an infinite slab of a homogeneous dielectric medium with the complex permittivity $\varepsilon_r{}^*$ can be expressed, taking into account the reflections at the boundaries free space — dielectric and dielectric — free space, in the form

$$T_0 = \frac{4\,\gamma_1\,\gamma}{(\gamma_1 + \gamma)^2\, e^{\gamma L} - (\gamma_1 - \gamma)^2\, e^{-\gamma L}} = |T_0|\, e^{-i\varphi} \quad (1)$$

where

where $\quad \gamma = i\,\dfrac{2\,\pi}{\lambda_0}\,\sqrt{\varepsilon_r{}^*} \quad$ and $\quad \gamma_1 = i\,\dfrac{2\,\pi}{\lambda_0}\,\sqrt{\varepsilon_{r_1}{}^*}$.

$\varepsilon_r{}^*$ and $\varepsilon_{r_1}{}^*$ are the relative complex permittivities of the dielectric and the free space, respectively. λ_0 is the free-space wavelength and L the thickness of the slab.

For a plasma studied by means of an ordinary electromagnetic wave ($\boldsymbol{E} \perp \boldsymbol{k}$, $\boldsymbol{E} \parallel \boldsymbol{B}_0$, where $\boldsymbol{E}$ is the electric field, $\boldsymbol{k}$ the wave vector and $\boldsymbol{B}_0$ the external magnetic field) the complex permittivity $\varepsilon_r{}^*$ can be written in the form

$$\varepsilon_r{}^* = \frac{\varepsilon^*}{\varepsilon_0} = 1 - \frac{\omega_0^2}{\omega^2 + \nu^2} - i\,\frac{\omega_0^2}{\omega^2 + \nu^2}\,\frac{\nu}{\omega} \quad (2)$$

where $\omega_0 = (4\,\pi\,e^2\,N/m)^{1/2}$ is the plasma frequency, ω the angular frequency of the probing electro-

magnetic wave and $\nu = \nu_{ei} + \nu_{en}$ the collision frequency of electrons with ions and neutral particles. On substituting Eq. (2) into Eq. (1) a relatively complicated expression for the amplitude coefficient of transmission is obtained. It can be considerably simplified in the following two cases

(i) in an underdense ($\omega_0^2/\omega^2 \ll 1$) collisionless ($\nu/\omega = 0$) or in a low collision ($\nu/\omega \ll 1$) plasma;

(ii) in a high collision ($\nu/\omega \gtrsim 1$) plasma,

when $\gamma \cong \gamma_1$ and reflections on the boundaries are negligible. In both cases Eq. (1) can be written in the form

$$T_0 = |T_0|\, e^{-i\varphi} = \exp\{(2\,\pi/\lambda_0)\,n_i\,L\}$$
$$\exp\{(-2\,\pi\,i/\lambda)\,n_r\,L\} \quad (3)$$

where $\qquad \sqrt{\varepsilon_r{}^*} = n_r - i\,n_i$.

In spite of the fact that in these two extreme cases the transmission coefficient T_0 has the same form, the properties of the electromagnetic waves in low and high collision plasmas differ considerably. In low collision and collisionless plasmas they are well known and widely utilized in microwave plasma diagnostics. Therefore we do not analyse this case. We only remind that in low collision or collisionless plasmas the phase φ of the electromagnetic wave passing through the plasma depends only on the plasma density N, while the attenuation A of the wave ($A \cong 1 - |T_0|^2$) after its passage through the plasma depends on both the electron density N and the collision frequency ν. The situation in a high collision plasma, such as a strong arc discharge plasma in SF_6 [1], is substantially different.

2. Properties of Electromagnetic Waves in High Collision Plasmas and Their Experimental Verification

The basic properties of electromagnetic waves in high collision plasmas can be easily deduced from Equation (3). The main results obtained from the analysis of Eq. (3) are summarized in the graphs given in Figs. 1 and 2. Figure 1 shows the depen-
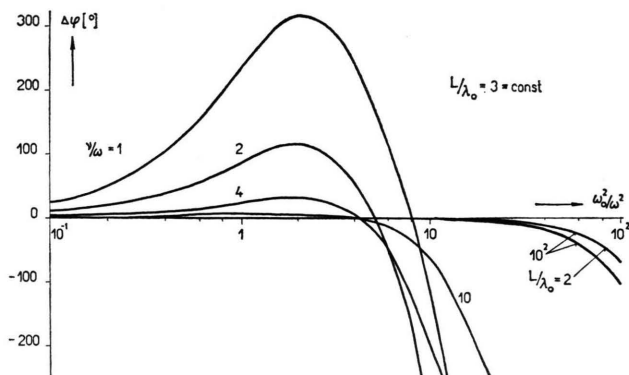

Fig. 1. The dependence of the phase shift of a probing electromagnetic wave passed through a plasma slab of thickness $L = 3\,\lambda_0$ on the plasma density for different values of the collision frequency.
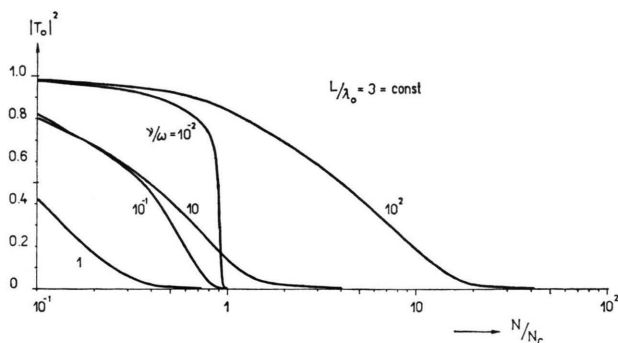

Fig. 2. The dependence of the energy of the probing electromagnetic wave after its passage through a plasma slab of thickness $L = 3\,\lambda_0$ on the plasma density for different values of the collision frequency.

dence of the phase shift of the electromagnetic wave $\Delta\varphi = \varphi_0 - \varphi$ (φ_0 and φ are the phases of the wave after passage of the same path $L = 3\,\lambda_0$ in free space and in a plasma, respectively) on the plasma density for different values of the collision frequency. Figure 2 shows the dependence of the power transmitted through the same plasma slab by the electromagnetic wave on the plasma density, again for different values of the collision frequency.

From Figs. 1 and 2 the following very interesting properties of electromagnetic waves in high collision plasmas can be derived:

(i) At high collision frequencies $\nu/\omega \gtrsim 10$ the phase φ practically does not change, neither with the plasma density nor with the collision frequency, and it approximately equals the phase φ_0 of an electromagnetic wave which passed the same path in vacuo, i. e. $\Delta\varphi = \varphi_0 - \varphi \cong 0$.

(ii) At collision frequencies $1 \lesssim \nu/\omega \lesssim 10$ the phase shift $\Delta\varphi$ increases with decreasing collision frequency ν. Under these conditions the electromagnetic wave behaves qualitatively like an electromagnetic wave in a low collision ($\nu/\omega \ll 1$) or collisionless ($\nu/\omega \cong 0$) plasma, i. e. it propagates as in a medium where it is accelerated ($n < 1$).

(iii) The power transmitted through a collision ($\nu/\omega \gtrsim 1$) plasma with a given density N increases with increasing collision frequency ν.

(iv) Electromagnetic waves can pass through a collision plasma even if the plasma density N is higher than the critical density N_c, i. e. $N > N_c = m\,\omega^2/4\,\pi\,e^2$.

(v) Unlike the collisionless plasma, where the cutoff of the electromagnetic wave accompanied by total reflection of the wave ($n = \sqrt{\varepsilon} = 0$) takes place precisely at the critical density $\omega_0{}^2/\omega^2 = N/N_c = 1$, in the high collision plasma the interruption of electromagnetic wave propagation arises in consequence of the great collision attenuation; moreover, this interruption occurs at densities which can be considerably higher than the critical density, i. e. at $N > N_0$.

These very interesting properties of wave propagation can easily be calculated from approximate formulas. Under the assumptions that $\nu/\omega \gg 1$ and $\nu/\omega > \omega_0{}^2/\omega^2$, it is possible to derive from Eq. (3) the following very simple expressions for the phase shift $\Delta\varphi$ and the power transmission $|T_0|^2$

$$\Delta\varphi = \frac{2\pi}{\lambda_0} L(1 - n_r) = -\frac{\pi}{4}\frac{L}{\lambda_0}\frac{\omega_0{}^4/\omega^4}{\nu^2/\omega^2}, \qquad (4)$$

$$|T_0|^2 = \exp\left\{-4\pi(L/\lambda_0)\,n_i\right\} = \qquad (5)$$

$$= \exp\left\{-2\pi(L/\lambda_0)\frac{\omega_0{}^2/\omega^2}{\nu/\omega}\right\} = \exp\left\{-\omega_0{}^2 L/\nu\,c\right\}$$

where c is the speed of light.

From Eqs. (4) and (5) we obtain further interesting results:

(i) At $\nu/\omega \gg 1$ the phase shift $\Delta\varphi$ is negative, which means that the plasma behaves like a dielectric with a refraction index $n > 1$, i. e. it represents a slow down medium for the electromagnetic wave. In such a plasma the probing electromagnetic wave is, however, strongly attenuated, see Figs. 1 and 2.

(ii) The dependence $|T_0|^2 = f(N)$ does not depend on the wavelength of electromagnetic wave. It only depends on the collision frequency ν and the thickness L of the plasma slab.

From these properties a very important conclusion for the microwave diagnostics of high collision plasmas can be drawn. Since the phase φ of the electromagnetic wave practically does not depend on the plasma density (N) and the collision frequency (ν), information about N and ν can only be obtained from the power transmitted through the plasma.

This conclusion fully endorses the experiment carried out on the model of the switch. Results for a strong arc discharge plasma in SF$_6$ at 4 atm pressure and 20 kA discharge current, obtained by means of electromagnetic waves at 37,5 GHz, are given in Figure 3. The first oscillogram shows the
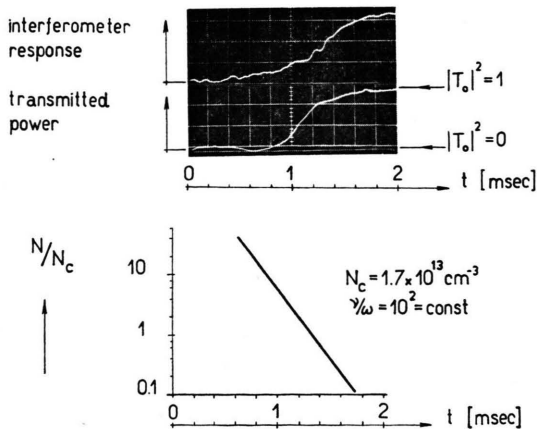

Fig. 3. A comparison of the microwave interferogram and the time dependence of the power of an electromagnetic wave transmitted through a strong arc discharge plasma. The last curve shows the time dependence of the electron density evaluated from the power transmitted under the assumption of constant collision frequency $\nu/\omega = 10^2$.

microwave interferometer response, the second one the time dependence of the power transmitted through the plasma $|T_0|^2 = f(t)$ and the third curve is the time dependence of the electron density evaluated from the measured curve $|T_0|^2 = f(t)$

under the assumption of constant collision frequency $\nu/\omega = 10^2$. The most important result is the finding that the shape of the microwave interferometer response and the time dependence of the power of the microwave signal transmitted through the plasma of the strong arc discharge is practically the same (interferometer response has no interferences). So this experiment clearly shows that, in full agreement with the theory, information about the basic parameters of high collision plasmas can only be obtained from the time dependence of the power transmitted through the plasma.

3. Determination of the Time Dependence of the Electron Density in a High Collision Plasma

In principle there are two cases we can meet with when measuring the time dependence of the plasma density in a high collision plasma:

A) Plasma with Constant Collision Frequency, $\nu/\omega = const$

In this case the time dependence of the tranmitted power directly corresponds to the time dependence of the plasma density $N(t)$. If the collision frequency ν is known, the measured time dependence $|T_0|^2 = f(t)$ can, by means of simple formulas, be transformed into the time dependence $N(t)$. If the collision frequency ν is unknown, the measured curve $|T_0|^2 = f(t)$ shows only the speed of the time development of the plasma density.

B) Plasma with Variable Collision Frequency $\nu/\omega \neq const$

In such a plasma the measured curve $|T_0|^2 = f(t)$ contains both $N(t)$ and $\nu(t)$. In order to separate them it is necessary to supplement the microwave measurement $(\nu/\omega > 1)$ by some other independent measurement, for instance a laser measurement $(\nu/\omega \ll 1)$, which directly yields $N(t)$, or a plasma conductivity measurement $(I = \sigma U, \sigma \sim N/\nu)$.

4. Conclusion

The following conclusion, useful for the microwave diagnostics of strong arc discharge plasmas, e. g. in SF$_6$ at pressures $p \gtrsim 1$ atm, can be drawn:

The time dependence of the electron density $N(t)$ and/or the collision frequency $\nu(t)$ can be

measured without making use of the relatively complicated microwave interferometer. It is sufficient to measure the power of the wave transmitted through the plasma $|T_0|^2 = f(t)$ because it carries the information about both $N(t)$ and $\nu(t)$. Such measurements can be carried out by means of a very simple microwave device. This is a very substantial advantage of the contactless microwave probing of high collision plasmas.

[1] J. Musil and F. Žáček, Res. ÚFP ČSAV No 27/74, prepared under contract no 74/10156/27024/14, Dec. 1974) (in czech, unpublished).