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PROBE DIAGNOSTICS OF HIGH-FREQUENCY GAS DISCHARGES SUSTAINED IN WAVE FIELDS OF TRIVELPIECE-GOULD MODES

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Abstract. Results for plasma parameters, including their radial distributions, from probe diagnostics of diffusion-controlled gas discharges sustained in the wave fields of azimuthally-symmetric Trivelpiece-Gould modes are presented. The study stresses on the probe theory chosen and on the procedure developed for processing the measured probe characteristics.

1. Introduction

Recent studies [1–7], both theoretical and experimental, on high-frequency discharge production in an external magnetic field by travelling Trivelpiece-Gould modes have demonstrated the high-efficiency of maintenance of these discharges, which makes them certainly very attractive for use in the gas-discharge applications [8]. This motivates the interest in their diagnostics by probe diagnostics techniques [7], aiming at obtaining local data for the plasma parameters. However, as it is well known [9–11], using probes for diagnostics of high-frequency discharges and discharges with magnetized plasma production requires special care for avoiding or accounting for the influence on the probe characteristics of the high-frequency field producing the discharge and of the external magnetic field.

The study is an extension of recent experiments [7] on probe diagnostics of 27 MHz argon gas discharges with magnetized plasma production in a diffusion controlled regime by the wave fields of azimuthally-symmetric Trivelpiece-Gould modes. Choosing the probe theory [12,13] of thick sheaths around the probe, a procedure for processing the probe characteristics and results – radial profiles of plasma density and electron temperature – from the diagnostics of the discharges are presented.

2. Experimental arrangements and conditions

The experimental set-up (Figure 1) is the same as it is described in [7]. Argon 27 MHz discharges of magnetized plasmas are produced in a gas-discharge tube (radius $R = 3\,\mathrm{cm}$ and length $L = 1.5\,\mathrm{m}$) by the wave fields of Trivelpiece-Gould modes launched by applying of power $P < 3\,\mathrm{W}$ to a double-ring coupler. The gas pressure p and the external magnetic field B are varied in the experiments: $p = (0.01 - 0.1)$ Torr, $B < 810\,\mathrm{G}$. A passive compensation method is applied for avoiding distortion of the probe characteristics due to effects of the high-frequency field. The measurements of the plasma parameters are performed by using a cylindrical radially-movable probe. The radial profiles of plasma parameters shown in Section 4 are at a fixed position (50 cm) from the discharge end which is achieved by changing the applied power.

Under gas-discharges conditions, as given above, the

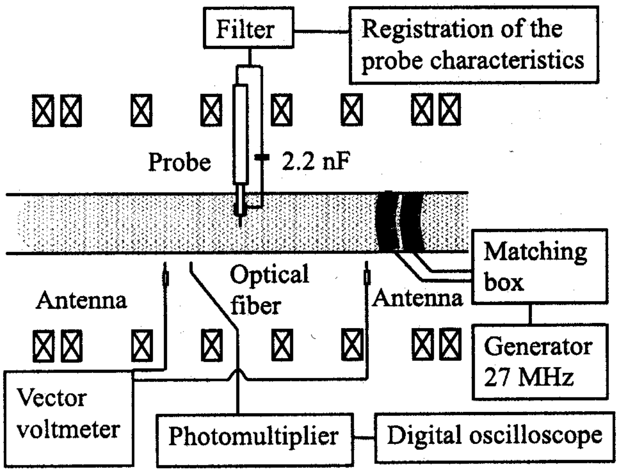

Figure 1. Experimental set-up

plasma is strongly magnetized ($\Omega_e \gg \nu_{e-a}, \omega$ where Ω_e is the electron gyro-frequency, ω is the wave frequency, and ν_{e-a} is the electron-atom collision frequency) and the external magnetic field has a strong impact on the transverse ambipolar diffusion coefficient $D_{A\perp}$: in $D_{A\perp} = D_{A\parallel}[1+2(\Omega_e\Omega_i/\nu_{e-a}\nu_{i-a}]^{-1}$, one has $\Omega_e\Omega_i/\nu_{e-a}\nu_{i-a} > 1$; here $D_{A\parallel}$ is the coefficient of longitudinal diffusion, Ω_i is the ion giro-frequency and ν_{e-i} is the ion-atom collision frequency.

The problem for probe diagnostics of magnetized plasmas is solved here by choosing a probe radius r_p small enough in order to have the unequalities $r_{Le}, r_{Li} > r_p$ fulfilled; here r_{Le} and r_{Li} are the electron- and ion-giroradii. As it is known, validity of these unequalities permits application of a probe theory for unmagnetized plasmas. With the highest value of $B = 810\,\mathrm{G}$ chosen, a probe with a radius $r_p = 0.05\,\mathrm{mm}$, as it is taken in the experiment, meets this requirement. However, the small radius of the probe introduces also complications, since with $r_p < \lambda_D$ (where λ_D is the Debye length) in the experiments, the sheath around the probe is thick and the standard method [14] for determination of the plasma parameters from the probe characteristics is not applicable.

3. Theoretical basis of the procedure of the probe diagnostics

The procedure, developed here for diagnostics with a cylindrical probe, is based on the Allen-Boyd-Reynolds (ABR) theory [12] of radial motion of cold ions to a spherical probe under conditions of a thick sheath around the probe. Thus, the electron temperature is obtained from the electron part of the probe characteristics in the standard manner:

$$T_e = \frac{e}{\kappa}\left[\frac{\Delta \ln I_e}{\Delta V}\right]^{-1} \tag{1}$$

where e and κ are the electron charge and the Boltzmann constant, respectively, and I_e and V, the electron current and the voltage, are taken from the probe characteristics.

The numerical procedure given below concerns the determination of the plasma density from the ion saturation current of the current-voltage probe characteristics.

As it is known, in the ABR-theory the distribution of the potential in the vicinity of the probe is described by the Poisson equation, in our case, in a cylindrical geometry:

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dV}{dr}\right) = -\frac{e}{\varepsilon_0}(n_i - n_e). \tag{2}$$

A Boltzmann distribution

$$n_e = n_{e0}\exp\left(\frac{eV}{\kappa T_e}\right) \tag{3}$$

for the electron concentration is assumed and the ion concentration is expressed through the ion saturation current I_i:

$$n_i = I_i\left[2\pi r l e\left(\frac{2e|V|}{m_i}\right)^{1/2}\right]^{-1}; \tag{4}$$

ε_0 is the vacuum permittivity, l is the probe length, and m_i is the ion mass.

In normalized quantities ($\xi = r/\lambda_D$, $\eta = -eV/\kappa T_e$, $J = I_i(\kappa T_e l 2\pi)^{-1}\sqrt{m_i/2\varepsilon_0 n_{e0}}$) equation (2) reads:

$$\xi\frac{d^2\eta}{d\xi^2} + \frac{d\eta}{d\xi} - J\eta^{-1/2} + \xi e^{-\eta} = 0. \tag{5}$$

The boundary conditions applied at $r \to \infty$ [$r > (50-100)\lambda_D$ in the numerical calculations] are for the potential and its first derivative. The former, reduced to a requirement for a quasi-neutrality ($n_{e0} = n_{i0} = n$), leads to

$$\xi \eta^{1/2} e^{-\eta} = J \tag{6}$$

and the latter, obtained from (6), is in the form:

$$\frac{d\eta}{d\xi} = \left[J e^{\eta} \eta^{-1/2} - \frac{1}{2} J e^{\eta} \eta^{-3/2} \right]^{-1}. \tag{7}$$

A family of numerical solutions of eq. (5) is shown in Figure 2. The values ξ_p and η_p of the quantities ξ and η are for $r = r_p$. In fact, the results in Figure 2 represent – in normalized quantities – ion-saturation parts of probe characteristics. The validity of the boundary conditions used and of the solutions obtained is checked by a comparison of the results for $\xi_p = 1$ with a corresponding solution graphically shown in [11].

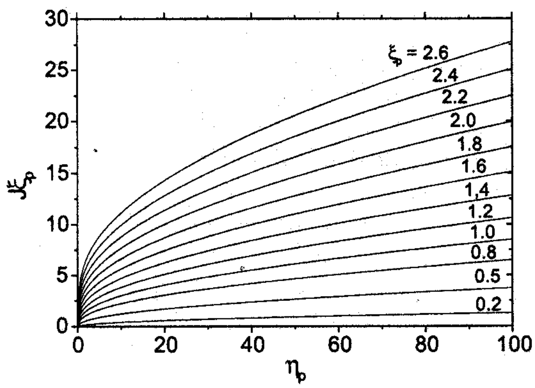

Figure 2. Theoretical results – in normalized quantities – for ion-saturation parts of the probe characteristics

Since the Debye length $\lambda_D = (\varepsilon_0 \kappa T_e / e^2 n)^{1/2}$ stays as a parameter in the solutions (Figure 2), the value of the plasma density n comes out from the fit of the ion-saturation part of a probe characteristic measured with a theoretical result for a given ξ_p value (obtained as described here and shown in Figure 2).

4. Results and discussions

The results from the probe diagnostics of the discharge are for the radial profiles of the electron temperature (Figure 3) and of the plasma density (Figures 4 and 5) measured for different values of the gas pressure p and of the external magnetic field B.

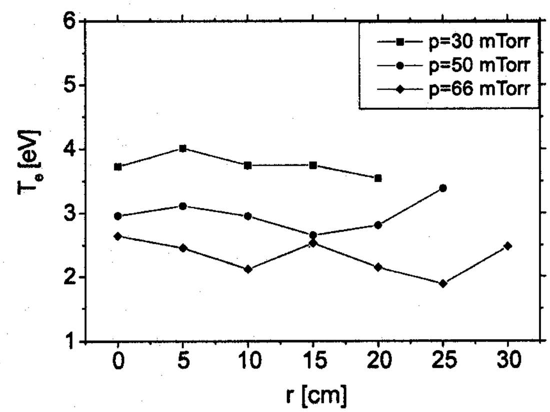

Figure 3. Radial profiles of the electron temperature at different gas-pressure (p) values and $B = 650\,$G

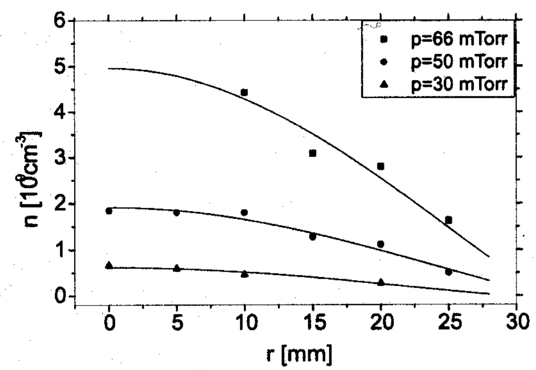

Figure 4. Radial profiles of the plasma density for $B = 650\,$G and different gas-pressure (p) values. Experimental results by symbols; fit by a J_0-Bessel function in solid curves

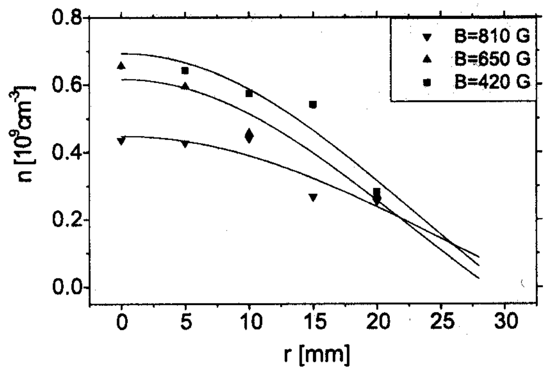

Figure 5. The same as in Figure 4 but for $p = 3 \times 10^{-2}$ Torr and different values of the external magnetic field B

The obtained almost constant values of T_e across the plasma radius is attended by local electron heating in the wave field. As it should be expected for a diffusion controlled regime, the measured radial profiles of the plasma density could be approximated by a $J_0(\mu r/R)$-Bessel function, with a given value μ of the parameter of radial plasma-density inhomogeneity. With the p-increase, the electron temperature decreases and the plasma density increases. Increasing B leads to flattening of the density profiles in the central region of the plasma column.

Stressing here the procedure for processing the probe characteristics we should mentioned that the theoretical results for the saturation current graphically presented in [11] may be also used. However, the applicability of these results is limited by the set of ξ_p-values chosen. Although in diagnostics of comparatively higher-density plasmas the error would not be big (e.g., error of 5% for $n = 5 \times 10^9$ cm^{-3}), in diagnostics of lower-density plasmas the error increases (e.g., error of 50% for $n = 5 \times 10^8$ cm^{-3}). This calls for necessity for including numerics, as it is done here, in the experimental procedure of the probe diagnostics under conditions of thick sheaths around the probe. Having theoretical results for the ion saturation current available for arbitrary ξ_p improves the accuracy in the determination of the plasma density.

5. Conclusion

Results from probe diagnostics of plasmas produced in the wave field of Trivelpiece-Gould modes are presented in the study. By choosing a proper radius of the probe and developing a procedure for data processing within the radial motion theory of thick sheaths around the probe, magnetized plasmas are diagnosed by a method of probe diagnostics of unmagnetized plasmas. It is shown that including numerics, which provide theoretical results for the ion saturation parts of the probe characteristics, improves the accuracy of the determination of the plasma density.

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