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Probe diagnostics of waveguided discharges in an external magnetic field

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Abstract

The study presents results from probe diagnostics of 27 MHz argon-discharges with magnetized plasma production in the field of travelling Trivelpiece–Gould modes. The external magnetic field and the gas pressure are varied in the experiment. Radial profiles of the plasma density and the electron temperature are obtained and discussed in terms of the regimes of the discharge maintenance.

Keywords: Gas discharges; Waveguided discharges; High-frequency discharges; Probe diagnostics

1. Introduction

Magnetized plasma production by guided mode propagation [1–8] is a comparatively new area in the field of the waveguided discharges (gas discharges sustained by travelling waves [9–11]). In the case of waveguided discharges in an external magnetic field, the Trivelpiece–Gould modes [12–16] are the waves which maintain the plasma. Although not yet studied fully, the waveguided discharges with magnetized plasma production are certainly important for discharge applications (e.g., plasma processing technology) because of the high efficiency of the plasma production. For example, the first experiments [7] on discharges in the wave field of Trivelpiece–Gould modes show that plasma columns of density above $10^{10}\,\mathrm{cm}^{-3}$ and 50–90 cm in length (for a radius 1.5 cm of the gas discharge tube) are sustained by applying high-frequency power between 7.5 and 16 W at frequency 390 MHz. In later experiments [8] performed at lower frequency, plasmas in discharge vessels of about 5 l are produced by using even lower high-frequency power (few watts). This should be expected because it is well known [9–11] that, at lower frequency of the wave producing the discharge, the discharge is sustained at lower plasma density. However, for using this high efficiency in the applications, accumulation of results from the discharge diagnostics is needed.

This study presents results from probe diagnostics of gas discharges with magnetized plasmas produced in the field of travelling azimuthally symmetric Trivelpiece–Gould modes. The dis-

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charge is in argon gas, in the pressure range of a diffusion-controlled regime. A power of $P < 3\,\mathrm{W}$ applied in a cw regime at a frequency $f = 27\,\mathrm{MHz}$ maintains a plasma column of radius $R = 3\,\mathrm{cm}$ and length of $L = 1.5\,\mathrm{m}$. The gas pressure and the external magnetic field are varied in the experiment.

Both the experimental arrangements and the procedure for evaluation of the results for the plasma parameters comply with the requirements for probe diagnostics of high-frequency discharges [17,18] and discharges in an external magnetic field [19]. Based on estimations of the plasma parameters, the radial motion theory in the case of thick sheaths is chosen for processing the probe characteristics [19,20] and the procedure outlined in Ref. [21] is applied for obtaining the plasma density from the ion saturation current. The results presented from the diagnostics are for the radial profiles of the electron temperature and the plasma density. The almost constant electron temperature obtained (across the radius of the discharge) calls for a mechanism of a local heating in the field of the wave sustaining the discharge. The experimental results for the plasma density show a Bessel-type of density profile. The values of the parameter μ, which characterizes the radial plasma density profiles, are estimated.

2. Experimental arrangements and procedure for data processing

The experimental set-up is schematically shown in Fig. 1. High-frequency discharges with external magnetic field in argon gas are studied. The power supply (with output power up to 200 W) is at frequency 27 MHz. The magnetic field (homogeneous steady-state field varied in the experiment up to $B_0 = 0.081\,\mathrm{T}$) is produced by a multi-section solenoid of length $l = 1\,\mathrm{m}$. The gas pressure is in the range $p = (1.3-13)\,\mathrm{Pa}$. The discharge tube is of radius $R = 3\,\mathrm{cm}$ and length of $L = 1.5\,\mathrm{m}$.

The discharge is produced in the field of azimuthally symmetric Trivelpiece–Gould modes [12–16]. Owing to the high efficiency of the discharge production (applied cw power P of less then 3 W for creating plasma in the total volume of the vessel), a simple, double-ring coupler [8,22] is used as a wave launcher. The coupler consists of two copper bands which fit tightly over the discharge tube. A resonance circuit is used for matching the output signal of the power supply with the wave launcher. The power absorbed for creating the plasma is measured under the different gas discharge conditions by a power meter combined with a standing-wave meter.

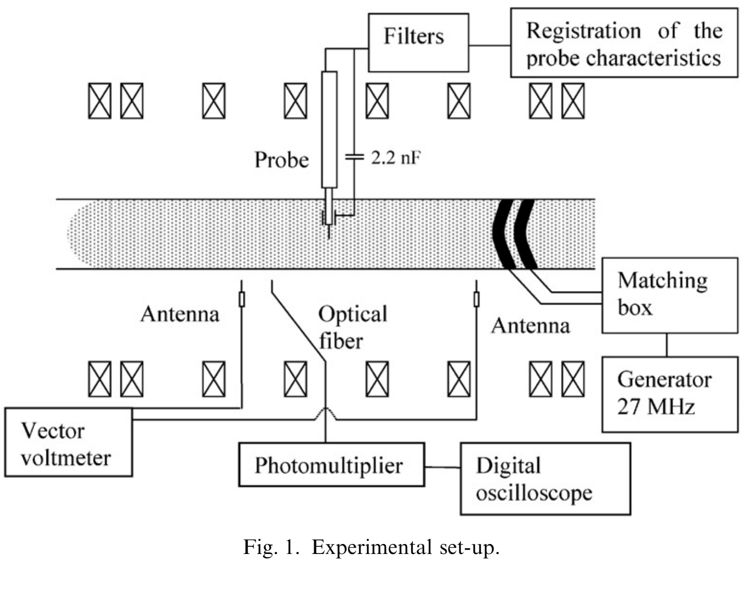

Fig. 1. Experimental set-up.

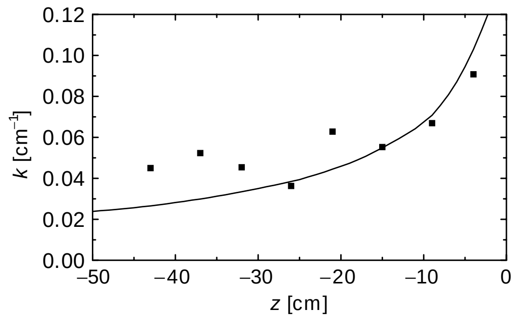

Fig. 2. Measured axial (z) variation (symbols) of the wave-number (k) at $p = 4.0\,\mathrm{Pa}$ and $B_0 = 0.081\,\mathrm{T}$ and comparison with a theoretical result (full curve) taken from the wave phase diagram of the azimuthally symmetric Travelpiece–Gould mode of radially inhomogeneous collisional plasma column.

The type of the discharge (discharge produced by travelling waves) is checked (as has been done before [8]) by measuring the axial variations of the wave number $k(z)$. Two antennae and a vector voltmeter are used. Fig. 2 shows the measured axial variation of the wave number along the discharge length and comparison with a theoretical result extracted from the wave-phase diagram (the $[(\omega/\bar{\omega}_p) - kR]$-dependence where $\omega = 2\pi f$ is the wave frequency and $\bar{\omega}_p$ is the plasma frequency defined with the averaged (over the discharge cross-section) plasma density [15,16]). The total light emission $I(z)$ from the plasma is also measured (by a photomultiplier). The results are similar to those presented in [8]. Giving indication for the plasma density, the $I(z)$-profiles show the typical (for waveguided discharges [9–11]) axial decrease of the plasma density along the discharge length.

The set-up for the probe diagnostics includes a radially movable single Langmuir probe (completed with a floating electrode), three narrow-band rejection filters of frequencies 27, 54 and again 27 MHz (in sequence) for performing a passive compensation at probe diagnostics of high-frequency discharges [17,18,23], arrangements for registration and processing of the probe characteristics and a reference electrode (the metal plate with which the discharge tube ends). The latter has an area large enough as is required for probe diagnostics of high-frequency discharges [17,23]. The floating electrode [24], designed as a metal cylinder is positioned close to the probe tip, above the ceramic tube which isolates the probe rod from the plasma. Its connection to the probe rod is through a 2.2 nF capacitor.

The thin tungsten probe (probe radius $r_p = 0.05\,\mathrm{mm}$) used together with a limitation of the magnetic field up to $B_0 = 0.081\,\mathrm{T}$ permits application of the procedures for probe diagnostics in a weak magnetic field ($r_p < r_{Le}, r_p \ll r_{Li}$ where $r_{Le,i}$ are the electron and ion gyro-radii). Although negligible with respect to the procedure for the probe diagnostics, the external magnetic field (with values of 0.042, 0.065 and 0.081 T as given in the presentation of the results in Section 3) is strong with respect to the plasma magnetization: with the value of $f = 27\,\mathrm{MHz}$, the electrons are strongly magnetized ($\Omega_e \gg \omega \gg \Omega_i$ where $\Omega_{e,i}$ are the electron and ion gyro-frequencies). Moreover, in the pressure range studied [$p = (1.3-13)\,\mathrm{Pa}$], the magnetic field strongly influences the transverse diffusion: in the ambipolar diffusion coefficient $D_{A\perp}$ one has $\Omega_e\Omega_i/\nu_{e-a}\nu_{i-a} > 1$, where $\nu_{e,i-a}$ are the elastic collision frequencies of electrons and ions with neutrals.

With an estimation of the plasma density of the order of $n \cong 10^9\,\mathrm{cm}^{-3}$, the Debye length λ_D is larger than the probe radius ($\lambda_D > r_p$), thus requiring application of the procedure for processing the probe characteristics under conditions of a thick sheath [19–21]. The mean free paths $\lambda_{e,i}$ of the electrons and the ions are larger than the probe radius.

The procedure for obtaining the data for the plasma parameters from the probe characteristics measured is as outlined in detail in Ref. [21]. The electron temperature T_e is obtained in the well-known conventional way from the electron part of the probe characteristics. The plasma density n is obtained from the ion part of the probe characteristics by using the results of the radial motion theory for thick ($\lambda_D > r_p$) collisionless ion sheath around the probe.

The measurements of the radial profiles of T_e and n are performed at different values of p and B_0. However, in all the cases the same distance $L' = 50\,\mathrm{cm}$ of the axial position of the probe from the discharge end is maintained. This is done by changing the power P_0 applied for the discharge production which, as it is well known [9–11], controls the length of the plasma columns in waveguided discharges.

3. Results and discussion

The results for the radial profiles of the electron temperature $T_e(r)$ and plasma density $n(r)$ obtained for a given external magnetic field ($B_0 = 0.065\,\mathrm{T}$) and different values of the gas pressure p are shown in Figs. 3 and 4, respectively.

The electron temperature is almost constant across the discharge radius (Fig. 3) with values which decrease with the gas pressure increase. Since $R > L_\chi$ where $L_\chi = (D_{e\perp}/\nu_*)^{1/2}$ (with $D_{e\perp}$ and ν_*, respectively, the electron diffusion coefficient in the radial direction and the excitation frequency) is the characteristic length of the thermal conductivity, the constant $T_e(r)$-profiles can be related to local heating of the electrons in an almost constant (across the discharge cross-section) field of the wave which sustains the discharge.

The plasma density increases with the gas pressure increase (Fig. 4). The obtained data for $n(r)$ at a given p-value show that the radial profiles of the plasma density are Bessel-type of profiles $n(r) = n(r = 0)J_0(\mu r/R)$ where J_0 is the Bessel function and the parameter μ characterizes the radial plasma-density inhomogeneity. The least-square method is applied in the fitting procedure. In the comparatively narrow range of the p-variation studied, the values of μ are approximately the same ($\mu = 2.00-2.15$ with changes within the experimental error).

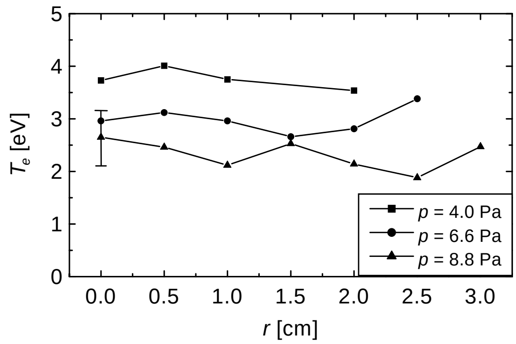

Fig. 3. Radial profiles of the electron temperature (T_e) at $B_0 = 0.065\,\mathrm{T}$ and different values of the gas pressure p.

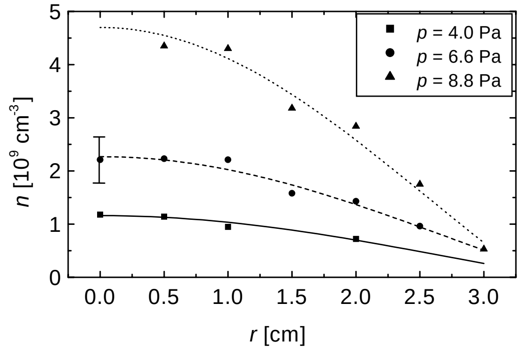

Fig. 4. Radial profiles of the plasma density (n) at $B_0 = 0.065\,\mathrm{T}$ and different values of the gas pressure p. The fits of the experimental data are with Bessel-type of density profiles according to the least-square method.

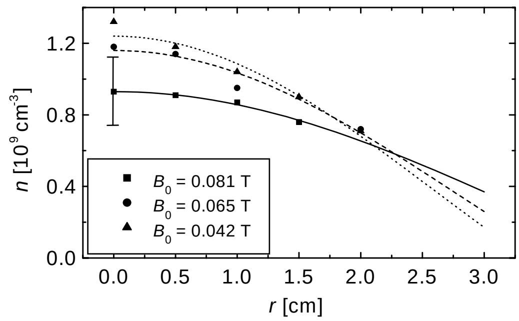

Fig. 5. Radial profiles of the plasma density (n) at $p = 4.0\,\mathrm{Pa}$ and different values of the external magnetic field. The fits of the experimental data are with Bessel-type of density profiles according to the least-square method.

The results for the radial profiles of the plasma density $n(r)$ obtained by varying the external magnetic field are shown in Fig. 5. With the increase of the magnetic field the plasma-density profile is flattened in the central region. Since the experiment is under the conditions of a strong impact of the external magnetic field on the charged particle diffusion (the factor $\Omega_e\Omega_i/\nu_{e-a}\nu_{i-a}$ in the transverse ambipolar diffusion coefficient, taken in its classical form, is larger than unity), the obtained results for $n(r)$ give an indication for a reduced transverse diffusion with the increase in B_0. Again the $n(r)$-profiles can be fitted to Bessel-type of profiles. With the B_0-variation, the μ-values change in the range $\mu = 1.70 - 2.15$.

The estimations of the parameter θ, the power absorbed on average by an electron, for the condition of, e.g., $p = 6.6\,\text{Pa}$ and $B_0 = 0.065\,\text{T}$ and with the measured value (Fig. 4) of the plasma density at the discharge axis, give $\theta \cong 5.10^5\,\text{eV/s}$. The formula [25] for the $(\theta - n)$-dependence obtained from the electron-energy and charged particle balance equations is applied. The magnetization of the plasma is taken into account by using $D_{A\perp}$. The obtained value of θ is in accordance with the results presented in Ref. [3]. With such a value of θ, the power Q absorbed for sustaining the total plasma column is less than 1 W. Simple estimates, based only on the confinement time, confirm this value of the absorbed power (the energy input per electron–ion pair calculated exceeds the ionization potential with a factor of about 20).

4. Conclusion

The study presents results from probe diagnostics of waveguided discharges in an external magnetic field. Special attention is paid to the choice of a proper (for the discharge conditions) procedure for determination of the plasma parameters from the probe characteristics. The radial profiles of the plasma density and the electron temperature and their variation with changing gas pressure and external magnetic field are obtained. The experimental results call for a local heating of the electrons in the wave field and Bessel-type of profiles of the plasma density. Although the work is mainly concerned with the mechanisms of discharge maintenance, the experiment, showing the high efficiency of waveguided discharge production in external magnetic fields, indicates potential possibilities for applications of this type of discharge to plasma processing technology.

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