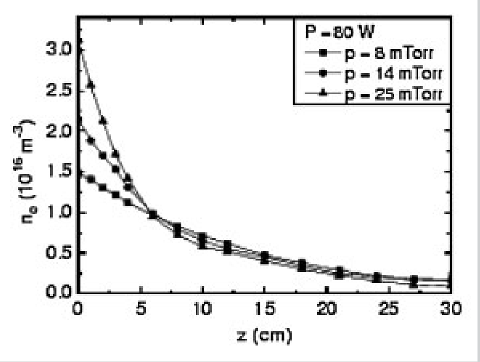
Summary: Results from tandem-type probe diagnostics of a plasma source based on an inductive discharge are presented in this study. The driver region is in the classical form of a cylindrically shaped inductive discharge, with a coil positioned over a gas discharge tube, whereas a bigger metal chamber provides volume for plasma expansion. Low pressure argon discharges were studied. The axial profiles of the plasma parameters were measured in the discharge in the metal chamber. The results obtained show that decreasing electron temperature and plasma density with increasing distance from the driver characterizes the behavior of the expanding plasmas. Moreover, two regions with different rates of variation of the plasma parameters complete the plasma expansion volume: a faster drop close to the driver and slow axial changes away from it. The gas pressure and power applied for the discharge maintenance were the external parameters varied.



Axial profiles of the electron concentration in the plasma expansion region of an inductive discharge.

Probe Diagnostics of Expanding Plasmas at Low Gas Pressure

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Introduction

Inductive discharges, along with capacitive ones, are the plasma sources which are most deeply involved[1–3] in plasma processing technology and industry. The advantage of the inductive discharges is their ability to produce considerable volumes of high density plasma which is the basis for their widespread use. This can be achieved using two discharge configurations: (1) discharges with "pancake" coils; (2) discharges with cylindrically-shaped coils. In the latter case, the construction of the discharge chamber leads to separation of the discharge into two regions. These are a driver region where the discharge is produced and a process chamber, connected to the driver, where the plasma exists due to its expansion from the driver. This type of configuration of the discharge is also known as a tandem-type plasma source. This is also the configuration of inductive discharges in hydrogen studied with a view to their use as sources[4,5] of negative ion beams for additional heating of tokamak plasmas by neutral beam injection. Although the numerous applications of inductive discharges require extended diagnostics of the plasma, in particular in the process chamber, experimental studies to date on the parameters of the expanding plasmas do not meet the needs for such data.

This study provides results from probe diagnostics of low pressure inductive discharges in argon with the construction of a tandem-type plasma source. The experiments, performed by a movable probe (in the axial direction) provide data for the variations of the main plasma parameters along the discharge axis – plasma density and electron temperature. The region of expanding plasmas was studied which, in the use of the discharge for technological purposes is, in fact, the process chamber. The obtained axial profiles showed a decrease in the electron temperature and the plasma density with increasing distance from the driver. Moreover, two regions with a different rate of decrease of plasma parameters could be distinguished – a faster drop close to the

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driver and slow axial changes far away from it. The dependence of the axial variations of the plasma parameters on gas pressure and high frequency power applied for the discharge maintenance was also obtained.

Experimental Part

Experimental Set-up and Data Processing Procedure

The experimental set-up is given schematically in Figure 1. An inductive discharge with a cylindrically-shaped coil was the driver. The coil (a 9 turn water-cooled copper tube) was positioned tightly over a quartz tube with internal and external diameters of $d_1 = 4.5$ cm and $d_2 = 4.9$ cm, respectively, and a length of $l = 30$ cm. The plasma produced in the gas discharge tube expanded and filled the metal chamber, i.e., the second part of the discharge vessel. Made of stainless steel, this chamber was a cylindrical tube with internal and external diameters $D_1 = 22$ cm and $D_2 = 23$ cm, respectively, and a length of $L = 47$ cm.

The measurements were performed in a discharge produced at frequency $f = 27$ MHz using an rf generator (ICOM IC-718) and an ACOM 2000A amplifier with a variable frequency in the range 1.8–29.7 MHz and an output power up to 1.5 kW. In the experiments, the high frequency power applied for the discharge maintenance was varied in the limits $P = (50–200)$W. The coupling to the discharge was through a matching box and the accuracy of the measured values of the incident power was 5%.

Low pressure argon discharges were studied. The variation of the gas pressure was in the range $p = (5–30)$ mTorr.

In the experiments, the axial probe (Figure 1) was used. The biasing voltage applied to the probe by a ramp generator varied from −70 V to +30 V with a repetition frequency of 160 Hz. Resistors of 160 Ω and 1 kΩ were used for measuring, respectively, the total probe characteristic and its ion saturation part. The registration of the probe current-voltage characteristics was by a digital two channel oscilloscope HP54510B and PC.

A cylindrical probe with a radius and tip length of $R_p = 0.25$ mm and $l_p = 4.2$ mm, respectively, was used. The probe was movable, in an axial direction, positioned at the axis of the metal chamber. The compensation,[6] against the influence on the probe characteristics of the high frequency field producing the discharge, was passive, by choke filters (parallel resonance circuits) at frequencies of 27 MHz and 54 MHz connected in series, and a floating electrode connected through a capacitor to the probe.

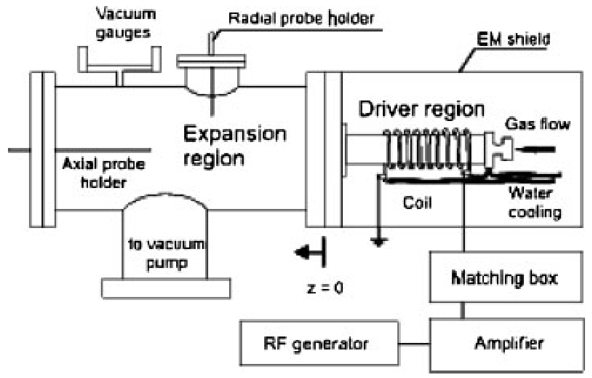

Figure 1. Experimental set-up.

With an assumption for a Maxwellian electron energy distribution, the electron temperature was obtained by the normal procedure[7] according to:

$$T_e = (e/\kappa)(\Delta \ln I_e/\Delta U)^{-1} \quad (1)$$

where e is the electron charge, κ is the Boltzmann constant and I_e and U are, respectively, the electron current of the probe characteristic and the bias voltage. Assuming conditions of a collisionless sheath and cold ions, the plasma density n_e was obtained from the ion saturation current of the probe characteristics according to the ABR theory.[8,9] The procedure for processing the probe characteristics, which is based on numerical solutions of the Poisson equation, has been developed previously.[10]

Results and Discussion

The obtained results were for the axial variations of the electron temperature and concentration in the metal chamber, the region of expanding (from the driver) plasmas. The axial profiles presented here (Figure 2–5) are for three values of the gas pressure ($p = 8$, 14 and 26 mTorr) and three values of the applied power ($P = 80$, 120 and 180 W). The end of the quartz tube (Figure 1) was taken as a zero axial position. The obtained values of T_e and n_e are in

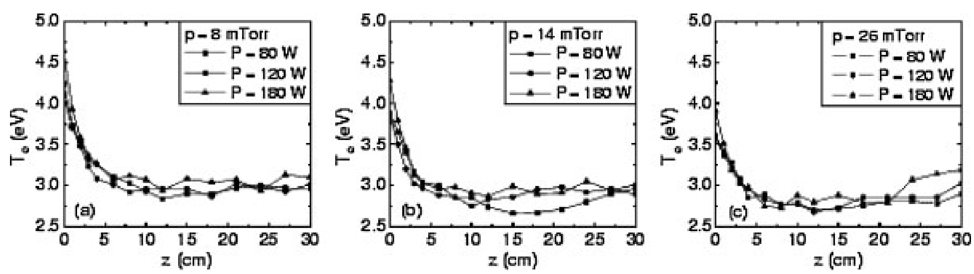

Figure 2. Axial profiles of the electron temperature for the three values of the applied power P and a given gas pressure value: (a) $p = 8$ mTorr; (b) $p = 14$ mTorr; (c) $p = 26$ mTorr.

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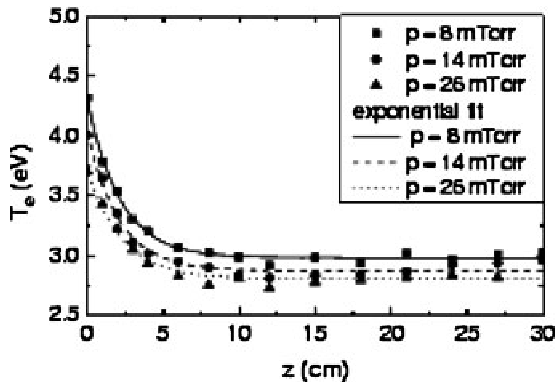

Figure 3. Axial profiles of the electron temperature for different gas pressure values. Fitting with an exponential function is shown to be a good enough approach. The experimental data for each z-position were taken as averaged values of the corresponding results (Figure 2) obtained for the different P values.

conformity with the conditions for applicability of the ABR theory used for processing the probe characteristics. The values of $\xi_p \equiv R_p/\lambda_D = 1-4$ (where λ_D is the Debye length) are within the range $\xi_p \geq 0.25$ discussed[9,11] regarding the ABR theory and the ion mean free path is larger than λ_D.

An axial decrease of both T_e (Figure 2 and 3) and n_e (Figure 4 and 5) with increasing distance from the driver region was the main conclusion drawn from the measurements. Obviously the expansion of the plasma in a larger volume leads to its cooling. Moreover, the results (Figure 2–5) show that two regions (with different rates of change of the plasma parameters) can be distinguished. In the first region, the region close to the driver, both n_e and T_e drop fast. The second region is away from the driver. This is a region where there is a slower decrease in the plasma density accompanied by an almost constant electron temperature. The fast drop of n_e in the first region is better pronounced for higher gas pressure (Figure 4 and 5). The axial position of $z = 6$ cm could be considered as adjoining these two regions.

The obtained experimental results for decreasing T_e and n_e with increasing distance from the driver in the expanding plasma region are in qualitative agreement with the theoretical results from a 2D model[12] of low pressure argon discharges. However, it was developed for capacitively coupled plasmas. Analysis[13] based on a concept for adiabatic expansion of the plasma also predicts an axial decrease of both n_e and T_e.

The dependence of the axial profiles of T_e and n_e on P show (Figure 2 and 4) that the changes in the applied high frequency power lead to an increase of the plasma density without influencing the electron temperature. This should be expected since it is well known that the electron temperature is determined by the charged particle losses in the discharge which depend on the gas pressure and the size of the discharge vessel. With a value of T_e and, respectively, of the power Θ absorbed on average by one electron in the discharge fixed by the gas pressure for a given discharge vessel, increasing the applied high frequency power leads to an increase in the plasma density.

Discussions on changes of the axial profiles of the plasma parameters with varying gas pressure are more complicated since this dependence should be related to the regime of the discharge maintenance. The estimations for the mean free path of the ions show that, whereas in the driver region the discharge maintenance may be attributed to a transition between a free-fall regime and a diffusion-controlled regime, diffusion could be considered as a mechanism of losses in the region of plasma expansion. The obtained higher electron temperature for lower gas pressure p (Figure 2 and 3) is the general behavior of low pressure discharges. Bearing in mind the complications due to the configuration of discharges with expanding plasmas, adiabatic expansion and losses of high energy electrons may be also considered as reasons for the fast drop of T_e in the region close to the driver. However, the exponential fit to the measured axial profile of T_e shown in Figure 3 needs further consideration. Since the electron energy relaxation length[14] ($L_\chi = \lambda_{e(mfp)}\sqrt{\nu_{en}/\nu_*}$, where $\lambda_{e(mfp)}$ is the electron mean free path and ν_{en} and ν_* are, respectively, the electron-neutral elastic collision frequency and the excitation frequency) is of the order of the length of the region away from the driver, electron energy losses through thermal conductivity could be responsible for the almost constant T_e (Figure 2 and 3) in this region. The obtained higher plasma density for higher gas pressure in the region close to the driver (Figure 5) can be associated with decreased diffusion losses which lead to lower T_e and thus lower Θ. The latter

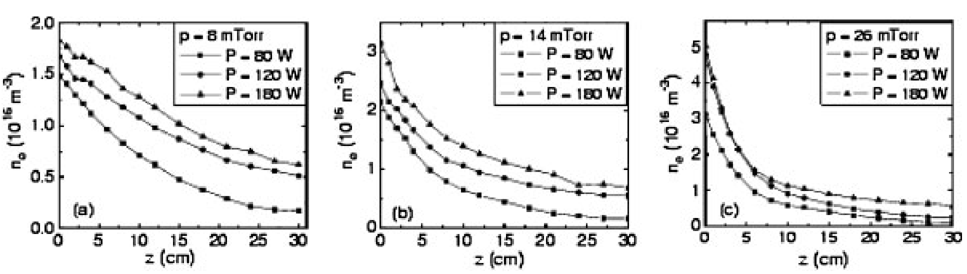

Figure 4. Axial profiles of the plasma density for the three values of the applied power P and a given gas pressure value: (a) $p = 8$ mTorr; (b) $p = 14$ mTorr; (c) $p = 26$ mTorr.

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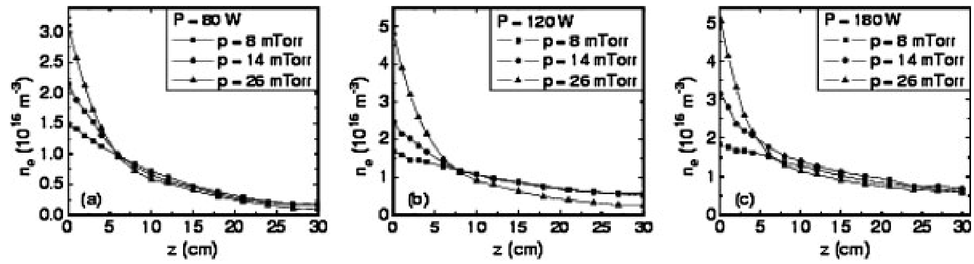

Figure 5. Axial profile of the plasma density for the three values of the gas pressure p and a given value of the applied power: (a) $P = 80$ W; (b) $P = 120$ W; (c) $P = 180$ W.

leads to higher n_e when $P =$ constant. This has been discussed before related to experiments[15] on the radial profiles of the plasma parameters performed with the same experimental set-up. The lower plasma density in the region away from the driver when the gas pressure is higher may also be coupled with diffusion losses.

Conclusion

A probe diagnostic method was applied for measuring the axial variation of the plasma parameters (electron temperature and plasma density) in the region of plasma expansion of an inductively-driven tandem plasma source. Decreasing electron temperature and plasma density with increasing distance from the driver characterized the behavior of the expanding plasmas. The obtained results show that two regions of different rates of variation of the plasma parameters complete the plasma expansion volume. The fast drop of both plasma density and electron temperature close to the driver transforms (with increasing distance from the driver) into a slower decrease of the plasma density and an almost constant electron temperature. Increasing gas pressure leads to an increase of the plasma density drop in the region close to the driver.

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