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Hysteresis and mode transition in terms of electron energy distribution function for an inductively coupled argon discharge

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The electron energy distribution function (EEDF) with respect to the hysteresis loop of an inductively coupled argon discharge has been studied experimentally. Contrary to *H* mode, knowledge of EEDF in *E* mode is still limited, and an elaborate EEDF measurement with regard to power and pressure for this mode is presented. The Langmuir probe measurements reveal two regions with distinct EEDFs in *E* mode, which might be a critical missing factor in explaining the unresolved hysteresis and mode transition phenomenon of inductive discharges. Furthermore, a Poynting vector representation has been used to explain the power coupling in an inductive discharge, where (azimuthal) $\mathbf{e}_\theta$ component is proposed to be dominant in the “hybrid mode” region. © 2008 American Institute of Physics. [DOI: 10.1063/1.2905213]

I. INTRODUCTION

Inductively coupled radio frequency (rf) discharges are widely used for the plasma processing and lighting industry mainly because they provide high-density plasmas ($\sim 10^{12} \text{ cm}^{-3}$) with large uniformity at low pressure (even below 1 Pa).¹ Many phenomena with regard to power coupling in such discharges along with capacitively coupled rf discharges have been studied during the past years.^{2,3} A distinct feature of inductively coupled rf discharges is the existence of two operational modes which dramatically differ in their electrical and plasma properties.^{1–6} The *E* mode (often referred to as the capacitive mode) excited at low rf powers, exhibiting a fainter light emission, much lower electron density ($\sim 10^9 \text{ cm}^{-3}$), a higher electron mean energy and a high plasma potential. It is thought to be maintained by the electrostatic field developed across the powered end of the coil and the ground. On the other hand, the so-called *H* mode (often referred to as the inductive mode) excited at high rf powers is characterized by bright light emission, low plasma potential, high electron density (exceeding 10^{11} cm^{-3}) and relatively low electron mean energy. It is believed to be maintained by the azimuthal electric field induced by the rf coil current. Abrupt as well as almost smooth transitions between the two modes are reported by several authors (e.g., Refs. 3–6). In addition, hysteresis effects were observed, meaning that the transition from the *E* mode to the *H* mode occurs under different conditions, e.g., electron density, supplied power, and coil current, than the reverse transition from the *H* mode to the *E* mode.

Apart from several experimental studies particularly electrical characterization, theoretical works are proposed to explain these phenomenon including the transformer model, global model and even some electromagnetic (EM) models separately or in combination.^{2,6–10} An elaborate article was

published by Turner and Lieberman² investigating several possibilities, which might induce such phenomenon in an inductive discharge, combining global model and transformer model. El-Fayoumi *et al.*⁹ proposed a combination of electromagnetic theory and electrical circuit analysis. However, the mechanisms behind the mode transition and hysteresis are still not well understood, specifically with regard to the “mixed mode” region, where the two modes are treated separately instead of a realistic *E-H* hybrid description.

The electron energy distribution (EED) translates the electron-field interaction in such plasmas which invokes the electron heating mechanism involved.^{11–13} In literature, several experimental and theoretical study of electron energy distribution function (EEDF) to investigate power coupling in an inductive discharge are present.^{11,12,14–16} In particular, the EEDF evolution with power and pressure has been investigated by several groups for the *H* mode and even for the *E* mode. Moreover, further research is still needed to fully understand the *E* mode and the mode transition region as far as EEDF evolution is concerned. This knowledge will further extend our understanding on the mode transition and hysteresis.

In the present article, a complete overview on the EEDF evolution with respect to the hysteresis cycle is presented to illustrate the heating mechanisms involved in an inductive discharge. Essentially, the new findings of EEDFs in *E* mode presented in this article are an important contribution in the description of the “mixed mode” region. Furthermore, based on the new results and available literature, a Poynting vector representation is introduced to understand better the mixed mode region; where importance of the azimuthal component (of the Poynting vector) is extended as a plausible explanation for the existence of hysteresis and mode jump.

II. EXPERIMENT

The experimental setup is described elsewhere in details.^{16,17} Briefly, the EEDF measurements have been performed by means of a commercial Langmuir probe

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FIG. 1. (Color online) Influence of grounded Faraday shield, placed between the induction coil and the coupling quartz window, on the measured plasma potential using Langmuir probe.

system^{6,16} in a gaseous electronics conference (GEC) reference cell¹⁷ with a five-turn planar induction coil. A grounded Faraday shield was placed between the coil and quartz window in order to reduce the electrostatic coupling. The probe has been positioned at 2 cm below the quartz window on the discharge axis (the reason is documented in detail in Refs. 16 and 18).

The EEDs measured in this work are presented in terms of the electron energy probability function (EPPF, in units of $\text{cm}^{-3} \text{eV}^{-3/2}$) rather than the EEDF.¹⁹ For our purpose, the absence of the $\sqrt{-eU}$ term in the EPPF eases the demonstration of differences in the shape of the distribution function. The probe current was calculated according to the orbital motion limited theory under the assumption that the move-

ment in the space charge layer is collisionless. The Druyvesteyn's method was used for the determination EEPF.²⁰ It is extracted from the second derivative of the Langmuir probe characteristic in the electron retardation regime ($V_s \leq V_p$, where V_s is the probe potential and V_p is the plasma potential) according to

$$f(\varepsilon) = \frac{2m_e}{e^2 A_p} \sqrt{\frac{2e}{m_e}} \frac{d^2 I}{dU^2}, \quad (1)$$

where I and A_p are the probe current and probe tip area, respectively; e and m_e are electron charge and mass, respectively; and $U = V_p - V_s$ is the probe potential referenced to the plasma potential. The zero crossing of the second derivative of the probe current is assumed to be the dc value of the plasma potential, whereas the zero crossing of the current in the characteristic curve is the floating potential of the probe. Measurements in the H mode, as well as in H to E transition region were performed using a $50 \mu\text{m}$ diameter tip. However, due to almost two orders of magnitude low electron density to be probed, the tips were replaced by $100 \mu\text{m}$ thick wires in the E mode, and in E to H transition region. The length of the tip was kept fixed at around 9 mm under all these conditions.

The effect of introduced Faraday shield could be clearly seen in the measured plasma potential utilizing the Langmuir probe, Fig. 1. In contrast to shielded operation, under unshielded conditions the measured potentials were relatively high. Reduced plasma potential indicates low voltages involved in the plasma and, hence, the EEPF measurements were less perturbed by the rf distortions. Essentially important for the measurements in the E mode and in the mixed mode region.

FIG. 2. (Color online) Example of mode transition and hysteresis in terms of n_e (e.g., at 1.3 Pa, where E to H jump occurs at 48 W and H to E jump at 43 W). Insert I: EEPF evolution with pressure in pure H mode; insert II: EEPF immediately before H to E transition point at different pressures.

III. RESULTS AND DISCUSSION

A. Mode transition and hysteresis

The phenomenon of mode transition and hysteresis, and EEPF evolution particularly for H mode is depicted in Fig. 2. Whereas, the novel results of EEPF evolution for the E mode (as mentioned in Fig. 2) will be presented in Figs. 3 and 4.

Mode transition and hysteresis is often illustrated in terms of the electron density (n_e) with respect to the applied rf power to the antenna coil (e.g., Refs. 2–10). At low powers (corresponding to $n_e \approx 10^8$ – 10^9 cm $^{-3}$) the discharge operates in (capacitive) E mode, Fig. 2. Increasing the rf power shifts the discharge from capacitive mode through a capacitive-inductive transition (mixed E - H) regime which finally jumps, at point B, into inductive mode. In inductive H mode, the electron density ($\approx 10^{11}$ cm $^{-3}$) jumps by almost two orders of magnitude which eventually brings the system to point C. With further increase in power, the system stays in H mode, whereas the reverse transition occurs at (relatively low power) point D instead of point C (E to H transition point) passing through the inductive-capacitive transition regime, causing hysteresis. A strong simultaneous mixing of capacitive and inductive heating has been reported for the power region adjacent to both the transition points, e.g., Refs. 8–11. Although this hybrid region cannot discretely be separated, however, due to its dominance in the hysteresis loop ABCD (as shown in Fig. 2), it will be referred as a “mixed mode” regime in this correspondence. Similar to mode transition and hysteresis, the presence of mixed mode has also been reported to be translated in every plasma parameter.^{3,8–12}

B. EEPF evolution in H mode

The EEPF evolution with power and pressure in H mode is elaborately covered in literature;^{12,14–16} however, a brief discussion is presented here in keeping with the goal of this article. These results are summarized together in Fig. 2, insert I and II. The effect of gas pressure on the EEPF evolution in the H mode is depicted in insert I of Fig. 2 (partially taken from Ref. 16). The EEPFs are bi-Maxwellian at low pressures which evolves into a Maxwellian distribution with increase in pressure, for the same power. However, with further increase in pressure EEPF develops into a Druyvesteyn distribution with $\partial f / \partial \varepsilon \rightarrow 0$ as $\varepsilon \rightarrow 0$. This EEPF evolution can be explained on the basis of electron diffusion processes as reported in Refs. 11, 12, and 16. At low pressures (< 1 Pa), the plasma is essentially collisionless; electron-neutral collision is much less than rf frequency, $\nu_{en} \ll \omega_{rf}$, and relatively low electron-electron collisions, ν_{ee} . The electrons are able to interact with the rf field which results in collisionless heating through the skin layer and electrostatic boundary. Hence, the overpopulation in the low-energy part of the EEPF can be explained on the basis of collisionless heating, enhanced Ramsauer minimum¹⁹ in argon and nonlocal electron kinetics.¹⁴ In this pressure range, the inelastic collisions are negligible and the loss of energetic electrons to the wall is the dominant mechanism of the EEPF tail depletion. By increasing the pressure, a nonlinear diffusion regime¹² is reached and collisions start to play a major role in electron

kinetics. Consequently, T_e and, in particular, temperature of the high-energy tail (of EEDF) is reduced. At moderate pressures due to increased elastic collisions the EEPF evolves to a Maxwellian. With further increase in pressure (~ 7 Pa), inelastic collisions start to dominate ($\nu_{en} \gg \omega_{rf}$ and appreciable ν_{ee}) and the EEPF evolves to a Druyvesteyn distribution. In this pressure region, the high-energy tail depletion is dominated by the inelastic collisions. The shape of the normalized EEPF in a pure H mode is independent of increasing power indicating no alterations in the mechanism of power coupling to electrons.^{15,16}

The EEPF evolution with decreasing power particularly in the vicinity of the H to E mode transition (mixed mode) region is noticeable,^{15,16} where the EEPFs have an evident two-temperature structure (measurements for the typical discharge setup¹⁶ are summarized in insert I and II of Fig. 2). The measured bi-Maxwellian distribution (insert II of Fig. 2) can be interpreted in an analogy to two-temperature distribution functions of a parallel plate capacitively coupled rf argon discharge.^{15,21} These EEDFs are the characteristic of a capacitively coupled plasma (CCP) which appears due to the two electron heating mechanisms involved; the stochastic heating adjacent to the sheath and the ohmic heating in the plasma bulk.^{21,22} Close to the H to E transition region due to decreased n_e , sheaths are appreciable; consequently, electrostatic coupling due to the high voltage drop across the sheath starts to appear. Hence, the presence of the overpopulated low-energy electron group is being referred to the stochastic heating in the developed oscillating sheath and by the non-local electron kinetics in the low pressure discharge conditions. The transition from a concave distribution function at lower powers to a Maxwellian or Druyvesteyn distribution (depending on the pressure) at higher powers is due to the shielding of the electrostatic field (by reducing electrostatic stochastic heating) and high $\nu_{ee} (\propto n_e / T_e^2)$, as a result of an increase in n_e with increasing power.^{11,16}

C. EEPF evolution in E mode

In contrast to H mode, investigations in E mode are very limited, until recently only two major works have been devoted to EEDF measurements in this mode.^{23,24} The EEDFs presented in Ref. 23 for pressures 0.67 and 6.7 Pa are reported to be Maxwellian and Druyvesteyn-like, respectively. Authors do not critically comment on the EEDF investigation close to the E to H transition region and do not report any alteration during mode jump. In the other work (Ref. 24), the EEDFs have been measured for several pressures in E mode while keeping the power constant. It has been reported that the EEDF evolves from bi-Maxwellian (at low pressures) to Maxwellian (at moderate pressure) and finally to Druyvesteyn distribution (at high pressures). This evolution has been explained on the basis of similar observations reported by Godyak *et al.*²² for a CCP. However, in this reference, measurement point with respect to the power coupling considering the hysteresis loop has not been mentioned. Note that the E - H mode mixing is high in the transition region and the modification of EEDF is most likely in this power region. Since the width of the hysteresis loop is

FIG. 3. (Color online) EEPF evolution with pressure in pure E mode.

found to be pressure dependent (much smaller in the case of low pressure),^{6,10,23} performing the measurement at one fixed power in E mode will not fairly reflect the similar power coupling conditions. Recently, we have shown that the normalized EEPF immediately before the E to H transition point is identical to the one immediately before the H to E transition point, namely, bi-Maxwellian.¹⁸ We predicted that the field coupling might be identical at these transition points.

Interestingly, EEPF measurements reported here for the E mode reveal two regions with distinct EEDs. As depicted in Fig. 3 the EEPFs evolve from Maxwellian to Druyvesteyn-like at low powers of (the so-called pure) E mode operation, and this is in line with previous report.²⁴ Whereas within the mixed mode (adjacent to E to H transition) region at low pressures, the EEPFs are distinctively concave in nature (see Fig. 4) compared to Maxwellian at very low powers. Furthermore, the EEPFs in this power re-

FIG. 4. (Color online) EEPF evolution, at powers immediately before E to H mode jump, for different pressures.

gime are bi-Maxwellian even at pressure as high as 3 Pa, contrary to the collision dominant almost Druyvesteyn-like in pure H and E mode. Moreover, measurements at high pressures (e.g., at 5 Pa) were difficult with regard to resolution of low-energy electrons in EEPF (a well known problem associated with probes under such conditions²⁵).

This new finding with regard to EEPF evolution contains special information which can be illustrated by dividing the observations into two parts. (i) As depicted by Chung *et al.*,²⁴ a heating mode transition from collisionless heating (stochastic heating) at low pressure to collisional heating at high pressure is also obvious in our observations (Fig. 3).³¹ (ii) With increase in power, in the vicinity of E to H transition point, the observed bi-Maxwellian EEPF could be explained by an increased extra heating process identical in nature to the stochastic heating (Fig. 4).

A noticeable two-temperature structure even at relatively higher pressures clearly indicates alterations in heating mechanism in mode transition region. The E mode is already working under the influence of enhanced capacitive sheath, as predicted in Ref. 24, increased low-energy electron's contribution in Fig. 4 needs further investigation. The possibility of α - γ transition due to a comparatively high voltage drop (near the transition region) across the antenna has been studied and such transitions have been discounted due to low current densities.^{2,6} Furthermore, multistep ionization which might also induce similar effect is essentially negligible at these pressures.^{2,8,18} Hence, the new results could be attributed to the strong alterations close to mode transition region inducing effects similar in nature to stochastic heating.

D. Poynting vector representation for the pure E and H mode

To support the possibility of strong alterations, close to the mode transition region can be easily demonstrated by simple power coupling analysis based on Poynting vector representation. It is established that the Poynting vector ($\mathbf{E} \times \mathbf{B}$) gives the direction and the average energy transfer by the electromagnetic field per unit time, per unit area in an inductive discharge.^{9,26} The typical planar induction coil excites $\{B_r, B_\theta, B_z\}$ and $\{E_r, E_\theta, E_z\}$ (radial, azimuthal, and axial) magnetic and electric field components, respectively.^{9,13,27} These fields are basically complex quantities, and inclusion of the phase relation among them will be quite complicated. Therefore, to make the point by avoiding the complications of heavy mathematics, further discussion will be presented in terms of real field amplitudes only. Under these simplifications, the Poynting vector including all the planar coil field components can be written as

$$\mu_0 \mathbf{S}_T = (\mathbf{E} \times \mathbf{B})_T = \begin{vmatrix} \mathbf{e}_r & \mathbf{e}_\theta & \mathbf{e}_z \\ E_r & E_\theta & E_z \\ B_r & B_\theta & B_z \end{vmatrix} = \mathbf{e}_r(E_\theta B_z - E_z B_\theta) - \mathbf{e}_\theta(E_r B_z - E_z B_r) + \mathbf{e}_z(E_r B_\theta - B_r E_\theta). \quad (2)$$

However, in a pure inductive mode the coil current generates rf magnetic field components $\{B_r, 0, B_z\}$. The magnetic field in vacuum follows the antenna current with the same phase, whereas due to Maxwell's law the azimuthal electric

field is by $\pi/2$ out of phase. In the presence of plasma, the penetrating magnetic field components (due to Faraday's law) induces predominantly an azimuthal electric field component $\{0, E_\theta, 0\}$ and an associated current density $\{0, J_\theta, 0\}$.^{9,13,27} The phase between magnetic fields (B_r and B_z) and electric field (E_θ) will shift depending on the v_{en}/ω_{rf} ratio.^{26,27} The average power delivered from the rf coil (EM wave) to the electrons through inductive coupling is given by integrating the Poynting vector over the volume under the coil. The Poynting vector in H mode reads

$$\mu_0 \mathbf{S}_H = (\mathbf{E} \times \mathbf{B})_H = \mathbf{e}_r(E_\theta B_z) - \mathbf{e}_z(B_r E_\theta). \quad (3)$$

Often, only the dominant fields are chosen for simplicity during the power estimations, e.g., Ref. 27.

The E mode is classically treated as an electrostatic phenomenon similar to the CCP, due to the excitation wavelength much greater than electrode radius ($\lambda_{rf} \gg r_d$), and the plasma skin depth (δ) is much greater than the plasma volume.^{13,21} However, Fayoumi *et al.*²⁷ successfully developed an EM model, where only the dominant Poynting vector component was used to calculate the power coupling for the E mode. The induction effect in E mode is negligible because of low n_e , and in the absence of transformer activity between plasma and the external coil, the non-potential, vortex electric field component E_θ vanishes. Additionally, because of a comparatively high antenna voltage involved; radial, E_r , and axial, E_z , electric fields are induced and the applied voltage is translated through the space charge in the plasma.^{2,27} In an analogy to the current flow in the parallel plate plasma configuration, the dominant E_r and E_z field components generate (due to Maxwell's laws) the B_θ field.^{13,21} The dominant field components believed to carry E mode reads $\{0, B_\theta, 0\}$ and $\{E_r, 0, E_z\}$ and the phase between them will be determined by v_{en}/ω_{rf} . The Poynting vector (average energy flux) in this mode considering the plasma sustained by pure capacitive coupling can be written as

$$\mu_0 \mathbf{S}_E = (\mathbf{E} \times \mathbf{B})_E = -\mathbf{e}_r(E_z B_\theta) + \mathbf{e}_z(E_r B_\theta). \quad (4)$$

E. Poynting vector representation for the mixed mode

It is established that the presence of both modes can to some extent be felt throughout the inductive discharge operation,¹⁻⁶ which is dominant in the mixed mode as demonstrated here with the help of EED evolution. It is quite interesting to revisit this hybrid behavior in terms of field consultations. Magnetic field components B_r and B_z , which are basically supposed to play a major role in H mode heating, are evidently higher in amplitude in E mode operation and they are highest in the mixed mode region of this operational mode.^{9,28} Noticeably, high magnetic field components in E mode are a signature of the inductive heating presence in this mode. As in H mode the more acknowledged electric field (E_r and E_z) components are responsible for electrostatic attribution. Although no direct measurements on these parameters are presented in this work but ample of results are available in literature (e.g., Refs. 2, 10, and 28 and their cross references).

The electric field components E_r and E_z are less evident in pure H mode due to the low voltage sheath and the low antenna voltage. But by lowering power, reaching the transition region (CD, Fig. 2), an increased sheath thickness and voltage drop across it, is translated in measured EED. Alteration in terms of fields will be reflected by an increase in E_r and E_z electric components in the plasma.^{2,19} Also the influence of induction through δ will decrease as a result of increased sheath width and decreased n_e . Hence the influence of H mode sustaining electric field component E_θ will reduce with power.^{2,13,27} Our observations that the antenna current decreases with decreasing power,⁶ consequently reducing B_r and B_z magnetic field components, are consistent with the literature.^{10,28} Obviously in this region the increased E_r and E_z start to play a significant role in the heating mechanism along with pure inductive coupling due to $\{0, E_\theta, 0\}$ and $\{B_r, 0, B_z\}$. By considering the EM phenomenon to play under such circumstances of field configuration, due to Maxwell's law, B_θ will appear as a consequence of time varying E_r and E_z electric field components.^{21,27,28} Furthermore, the E mode is run by relatively (factor of 1.5 to H mode) high antenna current and voltage⁶ which is obviously highest in the mixed mode region (AB, Fig. 2) of the E mode. In this region, increases in B_r and B_z as a consequence of high current have been reported frequently,^{2,10,28} but its influence has always been ignored. In summary B_r , B_z , E_r , and E_z EM field components are dominantly present in the mixed mode region.

So in this peculiar power region, all possible field components generated by a planar antenna coil are present in a considerable strength, and the Poynting vector reads the same as in Eq. (2), instead of Eqs. (3) and (4). A contrasting difference is the appearance of azimuthal, $\mathbf{e}_\theta(E_r B_z - E_z B_r)$ component. This $\mathbf{e}_\theta$ component will act parallel to the planar coil of the typical setup and can be compared to an externally applied (parallel) field to the parallel electrodes of a CCP. The effect of applied parallel field component externally or inherited (Refs. 29 and 30 and their cross references) has been studied for the CCPs and the authors have observed an enhanced extra heating component. Turner *et al.*³⁰ studied the effect of the externally applied parallel magnetic field component on the distribution function and observed alteration due to changed heating mechanism, in a CCP. Recently Chabert *et al.*²⁹ reported the presence of an inductive heating and even a mode transition (identical to the inductive discharges' E to H transition), for parallel plate capacitively coupled discharges operating at very high frequencies. Under the conditions where EM effects are significant, the electric field splits into two components: (i) perpendicular to the electrodes and (ii) parallel to the electrode. They have referred E mode to the traditional capacitive discharges, sustained by the former electric field; however, the H mode is referred to the plasma sustained by the later electric field component. This transition is reported to occur at high applied voltages where the parallel heating component starts to dominate, and the transition is attributed to the extra heating component as a result of the parallel electric field component.

Similarly, the measured extra low-energy electrons (in Fig. 4) even at relatively high pressure in the E mode can be an attribution of the extra induced $\mathbf{e}_\theta$ component. This peculiar feature of mixed mode has been ignored. However, to visualize this region it is essential to include parallel electric and magnetic field components together due to changing phase. The strength of this $\mathbf{e}_\theta$ Poynting vector component in the mixed mode region might give an estimate of the width of the hysteresis loop, as well as a source of extra power input to cause the mode jump.

IV. CONCLUSIONS

A complete picture of the EEPF evolution along the hysteresis loop for different pressures is presented for a modified GEC reference cell. The EEPF evolution in H mode is in line with the available result in the literature. Based on the EEPF evolution observed, the E mode of an inductive discharge can be classified into two operational regions. At low powers, under pure E mode operational conditions, the normalized EEPF evolves from a Maxwellian at low pressure to a Druyvesteyn-like with increasing pressure. However, normalized EEPFs at high powers in E mode (immediately before the E to H mode transition point) are dominantly bi-Maxwellian even at high pressures (as high as 3 Pa). These results clearly classify the mixed mode region (E - H mixing) and pure mode of an E mode. The results are explained on the basis of an heuristic EM approach where the presence of an extra azimuthal component has been proposed. Note that the proposed model is very preliminary and an adequate theoretical treatment is still needed. Inclusion of the azimuthal component in a Poynting vector might provide a complete understanding of an inductive discharge as far as mixed mode is concerned, which might be a key issue in the description of mode transition and hysteresis.

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