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Electron energy distribution function close to the mode transition region in an inductively coupled gaseous electronics conference reference cell

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The electron energy distribution function (EEDF) in the E to H mode transition region of an inductively coupled argon discharge has been studied experimentally. The EEDF, which has a Maxwellian- or Druyvesteyn-like shape (depending on pressure) in both "pure" modes, shows a trend to a bi-Maxwellian shape in the vicinity of both the E to H and the H to E mode transitions. Moreover, the normalized electron energy probability functions closely before the E to H and the reverse H to E mode jumps are almost identical, indicating a similar power coupling at both transition points. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2362599]

Inductively coupled radio frequency (rf) discharges are widely used for plasma processing because of their ability to produce high-density plasmas ($10^{16}-10^{18}$ m^{-3}) at low pressure (even below 1 Pa).[1,2] A main characteristic of these discharges is the existence of two operational modes which dramatically differ in their electrical and plasma properties.[3] The so-called H mode (or inductive mode) at high rf power is characterized by bright light emission, high electron density, and relatively low electron mean energy and is believed to be maintained by the electric field induced by the rf coil current. On the other hand, the so-called E mode at low rf power, exhibiting a fainter light emission, a much lower electron density, and a higher electron mean energy, is thought to be maintained by the electrostatic field which develops between the powered end of the rf coil and the grounded surrounding. Abrupt as well as almost smooth transitions between the two modes were reported by several authors (e.g., Ref. 3–5). In addition, hysteresis effects were observed, meaning that the transition from the E mode to the H mode occurs under different conditions of, e.g., electron density, supplied power, and coil current, than the reverse transition from the H mode to the E mode.

Several attempts have been made to explain the mode transition and the hysteresis by combining a transformer model and a global model of the inductively coupled discharge. An elaborate review article was published by Turner and Lieberman.[6] El-Fayoumi *et al.* presented a combination of circuit analysis and electromagnetic theory.[7] Recently, the effect of a change in the ionization mechanisms of the discharge, between direct ionization from the ground state and stepwise ionization through metastable states, on the mode transitions and the accompanying hysteresis was discussed for argon discharges.[8–10]

However, the mechanisms behind the mode transitions are still not well understood, and the established models are not yet sophisticated enough to predict the transition behavior in detail. For example, unknown temporal structures in the transition dynamics were observed recently[11] which show that considerable further research is required to fully understand the discharge operation in the mode transition region.

The electron energy distribution function (EEDF) evolution with power and pressure has been investigated by several groups for the H mode[12,13] and for the E mode.[14–16] In this letter we want to extend these works by the power dependence of the electron energy probability function (EEPF) in argon discharges close to the mode transition at low pressures where the effect of metastables is of minor importance (multistep ionization should contribute typically less than 10% of the total ionization[8]). The measurements have been performed by means of a commercial Langmuir probe system[16,17] in a gaseous electronics conference reference cell with inductive coupling (five-turn planar induction coil). A grounded electrostatic Faraday shield has been placed between the coil and the quartz window in order to reduce capacitive coupling. The probe has been positioned 2 cm below the quartz window on the discharge axis. The normalized EEPF in the H mode does not undergo significant spatial changes (underneath the coil area)[16] but the lack of corresponding data for the E mode prohibits a clear conclusion about spatial variations during the mode transition. Therefore the central position was chosen in order to make sure that discrepancies between the measurements due to different spatial variation of the EEDF in both modes are negligible. The electron distribution functions measured in this work are presented in terms of the electron energy probability function (EEPF, in units of cm^{-3} eV$^{-3/2}$) rather than the EEDF itself. For our purpose, the absence of the $\sqrt{-eU}$ term in the EEPF eases the demonstration of differences in the shape of the distribution function.[18]

Figure 1 shows the evolution of the EEPF with increasing power at 1.33 Pa. At 41 W in the E mode the EEPF is obviously a Maxwellian. At 47 W the low-energy part (below 5 eV) of the EEPF is slightly enhanced and has a steeper slope. This behavior holds until the point directly before (49 W) and even directly after (50 W) the E to H transition.

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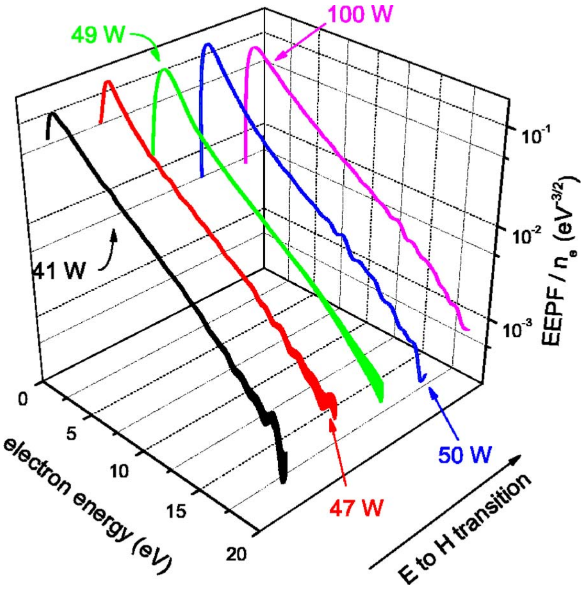

FIG. 1. (Color online) EEPF with increasing input power (*E* to *H* mode transition) at 1.33 Pa in argon.

With further increase in power the EEPF turns back into a Maxwellian.

The system exhibits a very similar evolution in the other direction (Fig. 2). In the *H* mode (at 100 W) the EEPF is clearly a Maxwellian. The probability function turns again into a bi-Maxwellian when the system comes close to the *H* to *E* mode transition (at 44 W) and back into a Maxwellian in the *E* mode. Furthermore, the measurements show that the EEPFs immediately before the *E* to *H* mode transition are almost identical to the ones at the points before the *H* to *E* mode transition. An additional two-dimensional view of four selected EEPFs is given in Fig. 3 to ease the comparison.

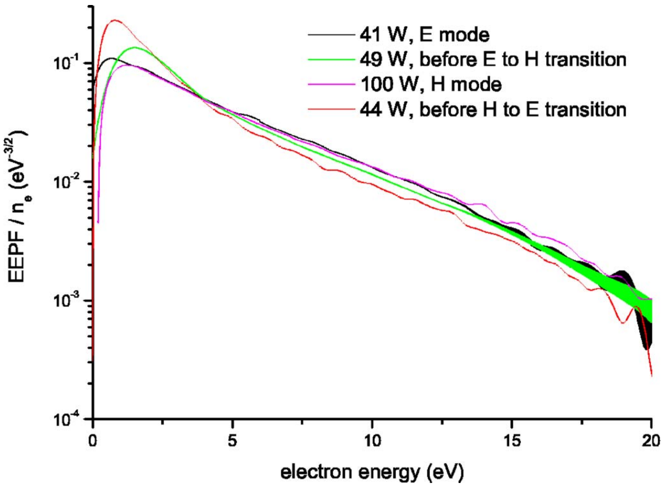

FIG. 3. (Color online) EEPFs in the *E* mode, the *H* mode, and at the transition points at 1.33 Pa in argon.

A bi-Maxwellian EEPF is known to be a characteristic of capacitively coupled low pressure rf discharges,[19] where the two-temperature structure could be attributed to the trapping of low-energy electrons and the Ramsauer effect in argon. It was also reported recently by Lee *et al.*[20] for inductive discharges in the *E* mode, close to the *E* to *H* mode transition, and the same reasons were guessed since the *E* mode is believed to be mainly capacitively coupled and therefore behaves similar to capacitively coupled plasmas. However, these explanations do not cover the fact that the bi-Maxwellian structure of the EEPF appears only when the system is close to the *E* to *H* mode transition.

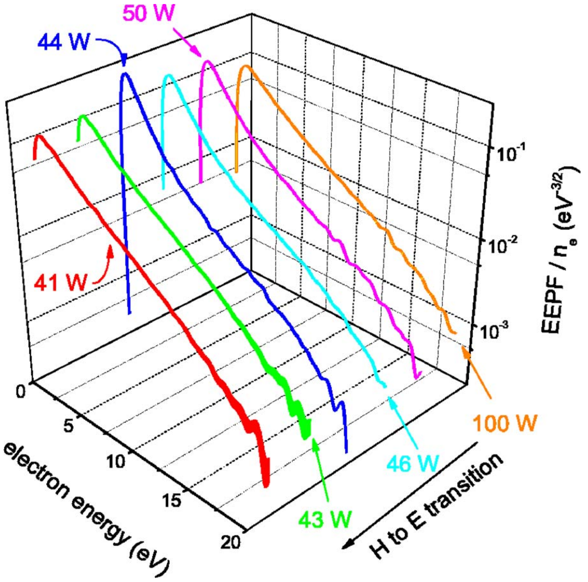

FIG. 2. (Color online) EEPF with decreasing input power (*H* to *E* mode transition) at 1.33 Pa in argon.

The EEPF evolution with power in the *H* mode was reported at several occasions (e.g., Refs. 12, 13, and 21), including the observed two-temperature structure close to the *E* mode which was attributed to the mixing-in of capacitive power coupling.[12]

In analogy to this the bi-Maxwellian EEPF in the *E* mode close to the *E* to *H* mode transition can be explained by the admixture of inductive power coupling which is consistent with the above mentioned fact that the bi-Maxwellian only appears close to the mode transition. In this terminology, the similarity of the normalized EEPFs at both transition points indicates a similar ratio of capacitive to inductive power coupling and supports our assumption that the transition occurs when the domination of one over the other changes.

We conclude that the almost identical shapes of the normalized EEPFs at the mode transition points imply that, although the plasma parameters (electron density and mean energy) differ widely between *E* mode and *H* mode (approximately by two orders of magnitude in the electron density and up to a factor of 3 in the electron mean energy), the mechanisms of power coupling must be very similar when a mode transition in either direction occurs.

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