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## Plasma power measurement and hysteresis in the $E-H$ transition of a rf inductively coupled plasma system

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An experimental investigation of the argon plasma behavior near the  $E-H$  transition in an inductively coupled Gaseous Electronics Conference reference cell is reported. Electron density and temperature, ion density, argon metastable density, and optical emission measurements have been made as function of input power and gas pressure. When plotted versus plasma power, applied power corrected for coil and hardware losses, no hysteresis is observed in the measured plasma parameter dependence at the  $E-H$  mode transition. This suggests that hysteresis in the  $E-H$  mode transition is due to ignoring inherent power loss, primarily in the matching system. © 2008 American Institute of Physics. [DOI: 10.1063/1.2844885]

Inductively coupled plasmas (ICPs) are known to support two distinct modes, a low density, electrostatic ( $E$ ) mode and a high density, electromagnetic ( $H$ ) mode. There is a threshold power or coil current below which no inductive discharge can be formed. In addition, the transition between these two modes has been reported to exhibit hysteresis, i.e., when reducing input power starting in  $H$  mode, the transition to  $E$  mode occurs at lower powers than the transition to  $H$  mode when starting in  $E$  mode.<sup>1-8</sup> Hysteresis in the  $E-H$  mode transition has been reported, almost exclusively in argon, in the measured optical emission,<sup>1,3,5-7</sup> electrical characteristics,<sup>2-4</sup> plasma density,<sup>3,4,8</sup> and magnetic field<sup>3,4</sup> dependence on coil current or input power. Most often, the studied ICPs have external<sup>1,5,6,8</sup> or internal cylindrical coils<sup>3</sup> but hysteresis has also been reported in external flat coil ICPs.<sup>2,4,7</sup> The work is predominantly with driving voltages at rf frequencies of 13.56 MHz<sup>1,3,5-8</sup> but hysteresis has also been observed in ICPs driven at 0.56 MHz (Ref. 2) and 500 kHz.<sup>4</sup> The matching conditions are often not explicitly recorded or the matching condition is fixed after matching at one set of input or output parameters.

In this paper, we have explored hysteresis in the  $E-H$  transition in an inductively coupled plasma system operating in argon gas and focusing on a determination of the power deposited in the plasma and using well defined matching conditions. We have measured the power and pressure dependence of the optical emission intensity, electron density and temperature, ion density, and argon metastable densities through the  $E-H$  transition region. Of particular significance is that we observe hysteresis in the  $E-H$  transition at pressures above about 50 mTorr (6.7 Pa) when the applied power is considered but the hysteresis is not present when the applied power is corrected for power loss in the coil and associated hardware.

The argon plasma was produced in an inductively coupled (13.56 MHz) version of the Gaseous Electronics Conference reference cell<sup>9</sup> with a five turn planar coil and no

Faraday shield. The gap between the upper window and the bottom electrode was 40 mm. Measurements of the Ar 750.4, 800.6, and 811.5 nm emission intensities were made with an Oriel 77702 spectrometer. These line-of-sight measurements were made viewing the center of the electrode-window gap. In the same plasma region, the electron density and temperature and the ion density were measured with a compensated Langmuir probe with a platinum tip (0.125 mm diam, 7 mm long) and using Smart Probe data acquisition system. The electron density was also measured using a hairpin probe.<sup>10</sup> In the same plasma region a laser induced fluorescence technique was used to make relative measurements of argon metastable densities in the plasma. For these measurements, the 394.9 nm wavelength was used to pump metastables from  $1s_5$  to  $3p_2$  level and the fluorescence of the  $3p_2$  to  $1s_2$  at 433 nm was recorded using an Andor intensified charge coupled device behind a narrow band filter.

The power from a 450 W ENI ACG-3 XL power supply was coupled to the coil through a characterized matching circuit (Fig. 1). The applied power  $P_a$  was determined, to an accuracy of  $\pm 0.5$  W, from the source forward power minus the reflected power, both measured on the power supply meter. However, to determine the power delivered to the plasma, the plasma power  $P_p$ , it is necessary to determine the effective power loss in the rf coil ( $I^2 R_{\text{eff}}$ ), i.e.,

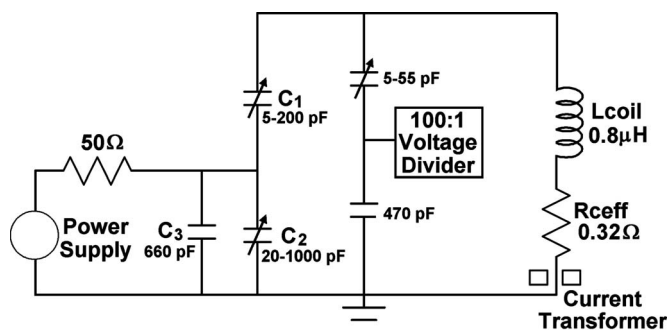


FIG. 1. Schematic diagram of the matching circuit.

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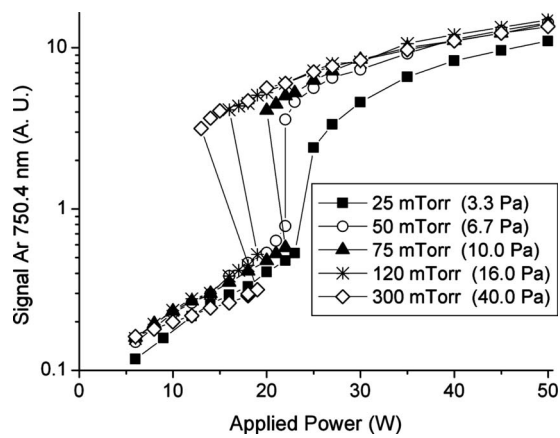


FIG. 2. The dependence of the light emission at 750.4 nm at different gas pressures on applied power (forward power minus reflected power).

$$P_p = P_a - I^2 R_{\text{ceff}}, \quad (1)$$

where  $I$  is the rms current flowing in the circuit and  $R_{\text{ceff}}$  is the effective resistance of the coil and associated hardware.<sup>9</sup>

The matching circuit is an  $L$ -type matcher with a large loading capacitance ( $C_2 + C_3$ ) across the input of the source. The tuning capacitor is  $C_1$ . At all power settings,  $C_1$  was adjusted for resonance by minimizing the reflected power. The effective coil resistance was determined from dissipating a known power in the matching circuit with no plasma present. Based on the power dissipated in the matching circuit and the current, measured using a Pearson current transformer with an error of  $\pm 0.05$  A, the effective coil resistance was measured to be  $0.32 \pm 0.01 \Omega$  during the reported measurements.

The dependence of the light emission at 750.4 nm on the applied power ( $P_a$ ) at different gas pressures is shown in Fig. 2. The stepped increase in emission intensity and the hysteresis effect above about 50 mTorr (6.7 Pa) is typical of previously reported  $E$ - $H$  transitions and hysteresis in ICPs.<sup>5,7,8</sup>

When the plasma power ( $P_p$ ) dependence on the applied power ( $P_a$ ) is explored (not shown), it is found that for small applied powers, the rate of increase of  $P_p$  is much slower than  $P_a$  until about 25 W, where a discontinuity occurs,  $P_p$  jumps, and the rate of further increase in  $P_p$  is similar to that of  $P_a$  with a slope of nearly one. The discontinuity in the graph occurs in the vicinity of the  $E$ - $H$  mode transition and hysteresis seen in the plasma emission measurements (Fig. 2). The measured power transfer efficiency  $P_p/P_a$  rises from a few percent in  $E$  mode to a constant value of around 80% in  $H$  mode, with values changing from  $\sim 15\%$  to 60% at the  $E$ - $H$  mode transition.

Figure 3 shows the dependence of other measured plasma parameters on (a) applied power and (b) plasma power at 120 mTorr (16 Pa), where the hysteresis in Fig. 2 is pronounced. In Fig. 3(a), the dependence on applied power ( $P_a$ ) is shown. The behavior of the ion density follows closely that of the emission at 750.4 nm as the emission intensity at other wavelengths does and the measured electron densities, which are not shown here. All exhibit increases of about an order of magnitude at the  $E$ - $H$  transition. The electron temperature decreases with power but also exhibits hysteresis, again not shown here.

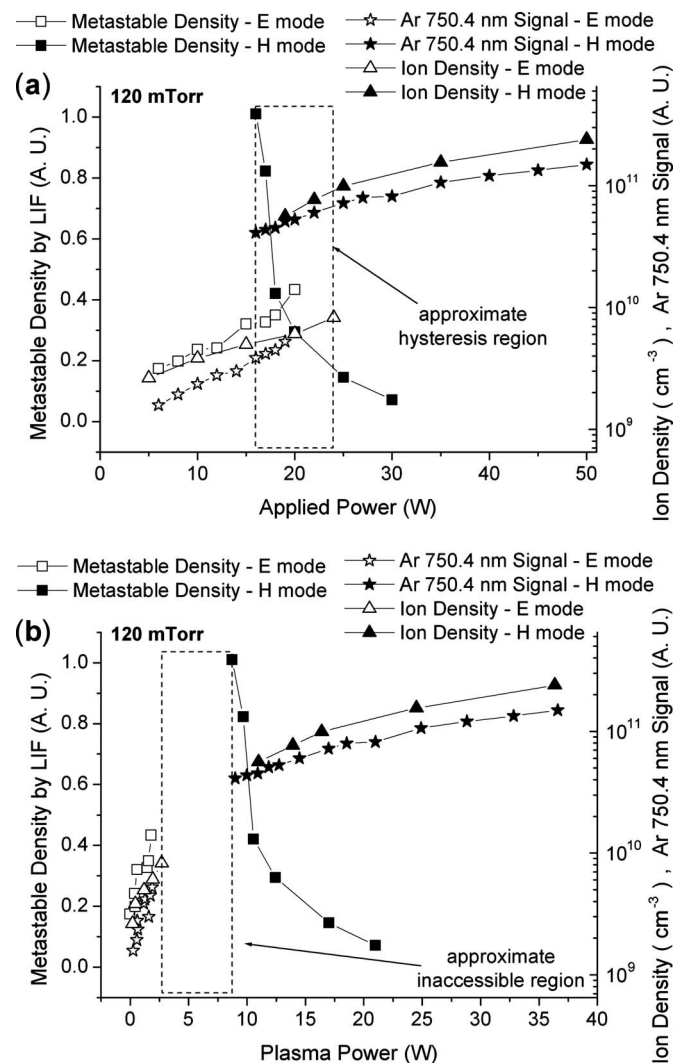


FIG. 3. The dependence of the ion density, plasma emission intensity at 750.4 nm, and relative metastable density on (a) applied power and (b) plasma power at 120 mTorr (16 Pa). The hysteresis and inaccessible regions are indicated in (a) and (b), respectively. Note that the ion density and emission intensity are shown on a log scale while the metastable density is shown on a linear scale.

The relative metastable density behaves somewhat differently, while it also exhibits a hysteresis effect, it increases with power in  $E$  mode but decreases with increasing power in  $H$  mode. The metastable density also increases at the  $E$ - $H$  transition but only by a factor of about 2.5 [Fig 3(a)]. Similar behavior has been previously reported in emission line ratio measurements.<sup>6,7</sup> It is worth noting that at 25 and 50 mTorr (3.3 and 6.7 Pa), the metastable density also increases in  $E$  mode and then decreases in  $H$  mode with increasing power but no increase in metastable density at the  $E$ - $H$  transition is observed [Fig. 3(b)]. The behavior of the metastable density will be discussed in detail in a separate paper.

In Fig. 3(b), the same data are plotted as function of the plasma power ( $P_p = P_a - I^2 R_{\text{ceff}}$ ). The hysteresis is absent, rather the power dependence of light emission and charge particle densities is smooth but the  $E$ - $H$  modes are separated by a range of plasma powers which in the present system cannot be accessed. The result is the same for electron density and temperature and the relative metastable density. The extent of this inaccessible region is well outside of any uncertainties in the plasma power determination arising from

uncertainties in the applied power and effective coil resistance measurements.

Some previous experimental observations of hysteresis in the  $E$ - $H$  transition saw the effect in various measured parameters as a function of coil current but did not take into account the power dissipated in the coil,<sup>1,5,8</sup> which appears to be much more significant in  $E$  mode. Others reported hysteresis as a function of plasma power and in some cases, mentioned the effect of coil losses but actually reported the applied or injected power dependence.<sup>1,7</sup> The present data suggest that the appearance of hysteresis in the  $E$ - $H$  mode transition based on applied power measurements is due to ignoring inherent power loss primarily in the matching system.

Another feature of the present results is that there is an inaccessible region of plasma power over which no stable discharges can be produced, as shown in Fig. 3(b). The actual  $E$ - $H$  transition point depends upon matcher characteristics, as well as the relative amounts of  $E$  and  $H$  mode power depositions at a given gas pressure. At the  $E$ - $H$  transition, there is a rapid change in plasma density and topography and, as a result, the plasma voltage-current characteristic varies rapidly. This makes the system inherently unstable.

Matching drives the system to either the stable  $E$  or  $H$  mode as observed here.

The present results emphasize the need to fully characterize the electrical circuit and power input available to the plasma.

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