Space and phase resolved optical emission in mode transitions of radio-frequency inductively coupled plasmas

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Abstract. Inductively coupled radio-frequency plasmas can be operated in two distinct modes. At low power and comparatively low plasma densities the plasma is sustained in capacitive mode (E-mode). As the plasma density increases a transition to inductive mode (H-mode) is observed. This transition region is of particular interest and governed by non-linear dynamics, which under certain conditions results in structure formation with strong spatial gradients in light emission. These modes show pronounced differences in various measurable quantities e.g. electron densities, electron energy distribution functions, ion energy distribution functions, dynamics of optical light emission. Here the transition from E- to H-mode in an oxygen containing inductively coupled plasma (ICP) is investigated using space and phase resolved optical emission spectroscopy (PROES). The emission, measured phase resolved, allows investigation of the electron dynamics within the rf cycle, important for understanding the power coupling and ionization mechanisms in the discharge. The temporal variation of the emission reflects the dynamics of relatively high-energy electrons. It is possible to distinguish between E- and H-mode from the intensity and temporal behaviour of the emission.

1. Introduction
Inductively coupled radio frequency (rf) discharges have proven technological significance, for surface modification, fabrication of modern integrated circuit devices, and thin film deposition [1], [2]. Rf plasmas in oxygen or oxygen containing plasmas have wide applications in material processing such as photo resist etching, chemical vapour deposition, and oxidation. Other technologies include for example thin oxide growth at low temperature for the fabrication of gate oxide of thin film transistors [3].

It is well known that inductively coupled plasmas (ICP) operate in two distinct regimes. At lower powers and plasma densities the discharge operates capacitively in so-called E-mode. When the plasma density increases beyond a critical value the discharge switches to inductive H-mode. This switch is accompanied by sudden changes in several plasma and circuit parameters such as the electron density and electron energy distribution function (EEDF), the coil current and the optical emission signal. [1], [2], [4]. This transition regime between the two modes is a popular parameter space for technological processes, due to improved control over the ion energy and flux onto the substrate. However, it is important to note that this transition is complex and the dominating mechanisms are not fully understood or rather ambiguous. Power dependence of the optical emission intensity, electron density and temperature, ion density, metastable...
density, gas temperature, electrical characteristics and magnetic field, has been reported in the literature through the E to H transition region [5] - [16]. But detailed knowledge, in particular, of the spatial contribution of various plasma formation mechanisms is crucial, to control essential plasma parameters. Different mechanisms responsible for the transition from E-mode to H-mode are discussed in a number of theoretical and experimental studies [17] - [20].

2. Experimental Setup
The optical emission from an inductively coupled plasma operated in oxygen is investigated using both space and phase resolution to identify the transition between E- and H-modes and investigate the important relevant sustaining mechanisms.

2.1. Plasma System - GEC reactor
The plasma system is an ICP GEC reactor driven at a radio-frequency of 13.56 MHz, with a planar antenna coil configuration. The rf power via a matching network is coupled into the plasma through a dielectric quartz window so that the plasma is not in direct contact with the antenna. The oscillating currents in the antenna generate a time dependent magnetic field inducing an electric field in the plasma. However, the antenna can also act as an electrode. Therefore, both inductive and capacitive power coupling mechanisms can coexist in the plasma.

![Figure 1. Experimental setup for phase and space resolved optical emission from the plasma](image)

![Figure 2. Delay generator scheme for phase resolved measurements synchronized with the RF power supply of the plasma](image)
2.2. Diagnostics - Optical Emission Spectroscopy (OES) and Phase Resolved OES

The transition from the capacitive to inductive mode is investigated using optical emission spectroscopy. Time integrated optical emission over the RF cycle is measured using a calibrated spectrograph (300 - 1050 nm, Ocean Optics).

Phase resolved optical emission spectroscopy (PROES) allows investigation of the electron dynamics within the rf cycle, important for understanding the power coupling mechanisms in the discharge. An experimental setup for PROES and the synchronization to the RF power supply are shown in figure 1 and 2, respectively. PROES provides non-invasive access with a spatial resolution of microns [21], in both axial and radial direction, limited in the present case to 5 mm due to integration of the signal of adjacent pixels.

Two emission lines are investigated in the following. 844 nm (O(3\textsuperscript{p3}P\textsubscript{3} → 3s\textsuperscript{3}S)) with a lifetime of 34.7 ns and 777 nm (O(3p\textsuperscript{5}P → 3s\textsuperscript{5}S)) with lifetime of 27.1 ns. This emission is detected using a special fast, gate-able, intensified CCD camera (PicoStar, LaVision). Rather than using a monochromator to select the wavelength, an interference filter is used since it combines relatively high transmission and 2-dimensional spatial resolution although here the second dimension is used to collect more photons. Light is collected from the region below the antenna with the camera synchronised to the rf generator, and measurements are performed with a 2 ns gate width. Phase resolved measurements over the entire rf cycle (74 ns) were obtained using a variable delay between the camera gate and the rf trigger that could be varied in increments of 2 ns (figure 2). For each phase measurement, the emission is integrated over several million rf cycles to obtain an adequate signal to noise ratio. The extremely high repetition rate of the camera accepts sequential rf-cycles for integration allowing high signal-to-noise ratio.

3. Phase resolved emission and excitation

The temporal variations of the optical emission within the RF cycle are caused by temporal changes in the electron energy distribution function (EEDF). Highly excited states in atoms or molecules are excited by electrons in the tail of the EEDF where the modulation is particularly pronounced. Temporal variations can, therefore, be observed in the optical emission from these high electronically excited atoms or molecules.

Electron impact excitation out of the ground state is described by the excitation function \(E_i(t)\). The excitation function \(E_i(t)\) can be determined from the measured number of photons per unit volume and unit time \(n_{Ph,i}(t)\)

\[
E_i(t) = \frac{1}{n_0 A_{ik}} \left( \frac{dn_{Ph,i}(t)}{dt} + A_i n_{Ph,i}(t) \right)
\]

where \(n_{Ph,i}(t) = A_{ik} n_i(t)\) is given by the transition probability \(A_{ik}\) of the observed emission and the population density of the investigated state \(n_i(t)\), \(n_0\) is the ground state density [22]. The effective decay rate \(A_i\) takes into account spontaneous emission, radiation trapping and quenching.

\[
A_i = \sum_k A_{ik} g_{ik} + \sum_q k_q n_q
\]

where \(g_{ik}\) is the so-called escape factor and \(k_q\) the quenching coefficient with the species \(q\) of density \(n_q\). For the 844 nm line the following quenching coefficients were used with \(k_{O_2} = 9.4 \pm 0.5 \times 10^{-10} \text{cm}^3\text{s}^{-1}\) and \(k_{Ar} = 0.14 \pm 0.007 \times 10^{-10} \text{cm}^3\text{s}^{-1}\) [23]. For the 777 nm line quenching with \(O_2\) is \(10.8 \pm 1.8 \times 10^{-10} \text{cm}^3\text{s}^{-1}\) [24].

The time dependence of the excitation function, reflecting the electron dynamics, is strongly dependent on the power coupling mechanisms.
4. Optical emission from RF ICP

Figure 3 shows the optical emission of various emission lines as a function of RF power from an oxygen containing ICP (with an admixture of neon and argon). With increasing power the intensity of the emission lines increases with a jump around 270 W as the discharge transits from capacitive to inductive mode. Different emission lines exhibit different relative percentage changes in the emission intensity. This indicates a complex change in electron density, electron energy distribution function and degree of dissociation in the different modes.

5. Space resolved emission

Figure 4 shows the time integrated space resolved emission of the 777 nm line at 50 W. There is a clear distinct maximum, axially close to the quartz and radially in the center of the discharge. This indicates capacitive coupling where the plasma is sustained through electron acceleration during the expansion of the plasma sheath. At low powers the antenna acts as an electrode and the large voltage at the center of the antenna gives rise to a high potential sheath, causing excitation and ionization.

The time integrated emission of the 777 nm line before the transition regime at 150 W is plotted in figure 5 as a function of space. The radial profile is similar to that at 50 W, while the axial differs slightly, with more excitation further into the bulk plasma. With increasing power the voltage drop across the antenna increases and secondary electrons produced at the quartz surface can be accelerated through this large sheath potential subsequently inducing excitation and ionization. The increased excitation at longer axial distances from the quartz into the plasma is due to very energetic electrons with large penetration depths. These energetic secondary electrons already become obvious in the time integrated images at 150 W.
Figure 4. Time integrated space resolved optical emission at 50 W in capacitive mode

Figure 5. Time integrated space resolved optical emission at 150 W in the mode transition regime

Figure 6 shows the time integrated emission of the 777 nm line at a higher power of 350 W. The radial profile of the plasma emission in inductive mode is quite different to that at lower powers in capacitive mode. In inductive mode the antenna excites a decaying electromagnetic wave in the plasma. The induced electric field in the plasma does not propagate entirely through
the plasma volume, but into the plasma electrons within a small region of the skin depth layer just below the dielectric window. The planar configuration of the antenna geometry deposits the power into the plasma in a ring shaped volume. This arises since the induced electric field is zero on the plasma axis rising to a maximum with increasing antenna radius and decreasing again toward the chamber wall. This ring-shaped structure, illustrating the current path parallel to the plane of the antenna, is clearly observable in the optical emission profile in figure 6.

6. Electron dynamics

As explained above the emission within the rf cycle of the discharge is measured. The temporal variation of the emission, reflects the dynamics of electrons with energies greater than the excitation threshold of 10.73 eV for 777 nm and 10.98 eV for 844 nm. It is possible to distinguish between E- and H- mode from the intensity and temporal behaviour of the emission [25].

Figure 7 shows a plot of the phase resolved excitation for different RF powers over one RF cycle. At low powers in capacitive mode there is one pronounced excitation peak at a phase of 52 ns. This is due to the sheath expansion mechanism as discussed above where electrons are accelerated in the main expansion phase of the sheath. In addition to this there is also a second more minor excitation mechanism at a phase of 26 ns. This can be attributed to heavy particle collisional excitation close to the surface, previously observed in hydrogen [26] and also oxygen [27].

With increasing power at 100 W an additional broad excitation maxima arises at around 2 to 10 ns that even dominates the excitation above 250 W. This corresponds to the energetic electrons, which cause the excitation structure, that penetrates far into the plasma bulk in figure 5.

Increasing the power further the discharge transits into inductive mode, where the dynamics is characterised by two excitation maxima in each rf cycle (approx. 36 ns and 72 ns). In comparison to capacitive mode the two excitation structures are symmetric. These are due to the induced electric currents in the plasma. The induced electric field is opposite in sign during each half of

Figure 6. Time integrated space resolved optical emission at 350 W in inductive mode
the RF cycle, thus resulting in electron acceleration along the ring-shaped trajectory in opposite directions during each half of the RF cycle and correspondingly two excitation maxima.

The dynamics of electrons and corresponding excitation and ionization mechanisms in the different modes are very different and the transition from capacitive to inductive mode is a multi-step process. Energetic electrons, produced during the transition regime, provide additional excitation and ionization and thus the critical increase in electron density required for the induced currents in inductive mode to be sustained in the plasma.

![Graph](image)

**Figure 7.** Phase resolved optical emission for various powers

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8. References
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