# Investigation of the E-H transition of an inductively coupled radio frequency oxygen discharge

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This contribution presents the experimental results from the detailed investigation of the mode transition in inductively coupled RF discharges in oxygen (ICP) driven at 13.56 MHz. Depending on the RF power, the discharge can operate in the capacitive (E-) mode or in the inductive (H-) mode [1,2]. During the E-H transition, the electrical and plasma parameter, the electron heating mechanisms and the electronegativity are changed. The mode transition strongly depends on the RF power or coil voltage and can be stepwise or continuously depending on the total gas pressure. For a continuous transition at low gas pressure, a hybrid mode (E/H-mode) with simultaneously existing capacitive and inductive heating occurs.

## 1. Introduction

Inductively coupled RF plasmas (ICP) are relevant for different technologically applications. Therewith, ICPs are used for plasma etching, vapor deposition, surface modification and functionalization, and especially for the sterilization and decontamination of sensitive surfaces. The advantage of this (electrodeless) discharge is the possibility to choose the operation mode which can be strongly different. Further, the inductive discharge arrangement leads to higher densities at lower pressures and reduced plasma sheath potential. The low density capacitive mode (E-mode) occurs at lower RF power. At a critical power value, the heating efficiency of the two modes equalize and the discharge transits into the high density inductive H-mode [1,2]. The mode transition changes the electrical and plasma parameter and the electron heating mechanisms. To investigate the E-H transition, enhanced diagnostic methods were used and are described in the next section.

## 2. Experimental setup

The vacuum apparatus and the used diagnostics are described by Dittmann *et al.* [3] and Küllig *et al.* [4]. The inductive discharge arrangement consists of a planar double spiral antenna (2.75 windings, 115 mm diameter) and a quartz cylinder. The quartz cylinder separates the antenna from the vacuum in the plasma vessel and serves as dielectric barrier. The RF power generator transfers the RF power through a matching unit to the center connection of the antenna. A voltage and current probe are installed directly after the matching unit to measure the coil voltage and current phase resolved.

The RF power was varied in the range from 1 to 600 W which leads to peak-peak values of the coil voltage and coil current in between of 1 and 9 kV and 1 and 50 A, respectively. For some measurements, the RF discharge power was pulsed with a frequency of 10 Hz and a duty cycle of 50 %. The total gas pressure was varied in the range between 5 and 35 Pa.

For a better understanding of the mode transition, the Langmuir probe measurement, the 160 GHz Gaussian beam microwave interferometry, the phase and

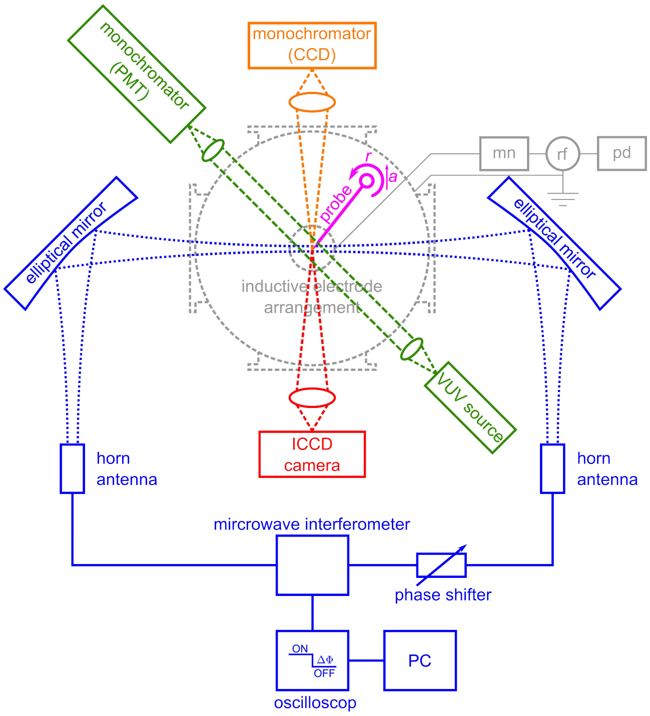


Fig. 1: Schematic top view picture of the experimental setup with the 160 GHz Gaussian beam microwave interferometer, the Langmuir probe diagnostics, emission and absorption spectroscopy. Further, mn is the matching network, RF the RF power supply, pd the pulse delay generator, PP the process pump, TP the turbo pump and BP the booster pump.

space resolved optical emission spectroscopy and the VUV absorption spectroscopy were used. With these methods, the positive ion saturation current, the line integrated electron, ground state and metastables density $O_2\left(a^1\Delta_g\right)$, the electron temperature and rotational temperature from the atmospheric A-band were measured. The last one is a measure for the gas temperature.

## 3. Results

At low RF power, the discharge operates in the E-mode. It is characterized by low positive ion saturation current and line integrated electron density at high electron temperature (6 eV). The gas temperature is comparable to room temperature (300 K). From the space resolved positive ion saturation current, the sheath thickness *s*, which is the axial distance to the maximum current, was determined. This measurement reveals a collision dominated RF sheath with a pressure dependency of the sheath thickness of $s \propto p^{-1/3}$. The phase and space resolved emission spectroscopy reveals two excitation patterns in the E-mode. One pattern appears in the first half of the RF cycle during the RF sheath expansion and the other one in the second half of the RF cycle during the sheath collapse [5]. Beside the sheath heating of electrons, the second excitation pattern is an evidence for high electronegativity. Additionally, an electron density peak in the early afterglow of a pulsed ICP confirms the high electronegativity in the E-mode [6]. The electron release results from the collisional detachment of negative ions by metastable oxygen molecules $O_2\left(a^1\Delta_g\right)$. The density of these metastables is about 2% of the ground state density.

Depending on the total gas pressure, the E-H transition takes place at a critical coil voltage with increasing the RF power. The coil voltage and current decrease during this mode transition. For total gas pressure below 35 Pa, the mode transition is continuously and therewith a hybrid (E/H) mode exists. In the hybrid mode, the ICP operates in the capacitive and the inductive mode simultaneously. For total gas pressure above 35 Pa, the mode transition is stepwise and the heating mechanisms change although stepwise from the capacitive to the inductive heating.

In the pure H-mode, the positive ion saturation current and the line integrated electron density are risen two orders of magnitude. The electron temperature halves while the gas temperature is two times higher. The electron heating is characterized by two heating phases within one RF cycle. Further, the electric field reversal vanishes and the electronegativity is reduced. The line integrated metastables density increases up to 6% of the ground state density.

## 4. Summary

The E-H transition of an inductively coupled radio frequency oxygen plasma was investigated using enhanced diagnostic methods. This mode transition leads to a change of the electric and plasma properties. Additionally, the electronegativity reduces during the transition from the E- to the H-mode. It could be shown, that the transition strongly depends on the total gas pressure. A hybrid mode was found for a continuous E-H transition which is characterized by simultaneous capacitive and inductive heating.

## Acknowledgement

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