Voltage, current and electron density measurements in an air radio-frequency plasma.

M. Sorokine, D. Hayashi, W.W. Stoffels, G.M.W. Kroesen
Department of Physics, Eindhoven University of Technology, P.O. Box, 5600 MB Eindhoven, The Netherlands

A study of a low-pressure (50-800 mTorr) air discharge is presented. Measurements of the electron densities in a 13.56 MHz capacitively coupled plasma are performed by means of a microwave resonance technique. Besides, some power input characteristics were determined by means of Plasma Impedance Monitor device (PIM).

I. INTRODUCTION
Various RF discharges are widely used in different kinds of production technologies. Still, questions of quality improvement often arise. That leads companies to look for a way of improving and optimising production processes. This cannot be done without appropriate diagnostic techniques.

Power input control is really alluring because of its simplicity in implementation. In most experiments the main characteristic for the RF discharge is its consumed power. Nevertheless, in most theoretical works, the rf voltage is taken to be constant, which makes comparisons between experimental and theoretical difficult. Using the technique mentioned above it is possible to get the desired results.

Microwave methods to measure electron density are advantageous due to its time resolution possibilities. Moreover, it is also a non-intrusive in situ measurement technique.

In this work a low-pressure radio-frequency (RF) air discharge is treated. Both methods are used for plasma diagnostics, and the most interesting results are presented.

II. EXPERIMENT
The experiment has been carried out with a 13.56 MHz capacitively coupled air plasma, confined in an aluminium cylinder cavity with two symmetrical slits. A schematic drawing of the plasma chamber is shown on Fig. 1. The dimensions are: diameter – 120mm, height – 37mm, slit width – 10mm, distance between antennas – 90mm, the lower power electrode diameter – 107mm.

Fig. 1 Cylindrical microwave cavity Fig. 2 Experimental setup
Power for the discharge is supplied by an RF generator, followed by an amplifier and matching network to optimise the power dissipation in the plasma. Feed gas is air. The pressure in the chamber is measured by Balzers pressure meter.

III. DIAGNOSTICS
A schematic drawing of the measurements is shown on Fig. 2.

As a rule, the most common and at the same time the easiest way to control RF plasma lies through monitoring of its power consumption. Using a Plasma Impedance Monitor (PIM) device by Scientific Systems we obtain information on the amplitudes of voltage and current for the driving frequency and first four harmonics, as well as on the value of phase shift between them. Along with that, power and impedance are calculated.

The IV sensor was designed to overcome some of the problems associated with conventional methods of sensing the RF current and voltage; it contains a unique current sensing loop and a conventional voltage pickup sensor. The design of PIM IV sensor and the sensor location are shown on Fig. 3 and Fig. 4 [1].

![Schematic of PIM IV Sensor](reproduced from [1])

![RF Power Conductor and Sensor PCB Location](reproduced from [1])

Although PIM provides us with real time measurements, all of the PIM data are being saved on the computer and can be recalled anytime.

In order to measure electron density, a microwave resonance method has been used in which rf electrodes, generating the plasma, simultaneously serve as a microwave-cavity. For this purpose a low power microwave signal is coupled into the plasma cavity by means of an antenna, exiting numerous modes. For our needs we use TM_{110} and TM_{210} modes, with frequencies ~3GHz and ~4GHz respectively. The transmission of the cavity is picked up by another antenna and its value is being monitored with a digital voltmeter. The resonance frequency of the cavity, which depends on the number of free electrons within, is determined by tuning the microwave generator to maximum transmission. From the shift \( \Delta f = f - f_0 \) of the resonant frequency \( f \) with respect to its value in vacuum \( (f_0) \) the microwave field averaged electron density \( (n_{e0}) \) is deduced [2]:

\[
n_{e0} = \frac{2\Delta f m_e e_0 (2\pi f)^2}{f_0 e^2}
\]  

(1)
with \( \varepsilon_0 \) the vacuum electric permittivity, and \( m_e \) and \( e \), respectively, the electronic mass and charge. This method does not provide any spatial resolution as \( n_{e0} \) is merely a space averaged density weight with the square of the field strength \( (E^2) \),

\[
n_{e0} = \frac{\int_{\text{cavity}} n_e(x)E(x)^2 \, dx}{\int_{\text{cavity}} E(x)^2 \, dx}
\]  

(2)

It is not always obvious which frequency to take for the measurements. Several spectrum peaks were examined during preliminary experiments. Fig. 5 shows results for 4 of total 7 observed modes. Those that are not presented showed no change in frequency within the error of the measurements.

Frequencies of the cavity modes were calculated beforehand. As it was expected, the two series (3036900 kHz and 3924600 kHz – the two upper lines), that were believed to correspond to TM110 and TM210 modes, showed the best agreement between each other. They were also the best distinguishable in the cavity spectrum observed and had the most appropriate frequency for the calculated modes. So, these two modes were chosen for the experiments, presented in this work.

IV. RESULTS AND DISCUSSION

Two measurements series have been carried out: the 1\textsuperscript{st} - Power variation, with keeping the pressure constant \((0.10 \pm 0.005 \text{ Torr})\), and the 2\textsuperscript{nd} - Pressure variation with constant amplitude of fundamental voltage harmonic \((100 \text{ Volts})\).

For every microwave measurement a double PIM measurement has been performed – directly before and right after it. A half of the difference between values showed by PIM at the beginning and at the end was taken as the measurement error. As an error of the pressure measurements a systematic error was taken. During preliminary measurements it was made sure that the presence of the microwave field had no measurable influence on the PIM performance.

As a result, the following graphs can be presented. In Fig. 6 and 7 calculated electrons density values with error bars are presented. Error in each case was estimated based on the accuracy of determination of the mode frequency. The vacuum frequency for TM110 mode was taken so, that at the first point in Fig. 6 both modes gave us one and the same value, given by the TM210 mode, that is about \(10^{13} \text{ m}^{-3}\).
Fig. 6 Electron Density in air discharge. Fixed pressure O.10 Torr.

Fig. 7 Electron Density in air discharge. Fixed Voltage (100 Volts)

It was noticed that by changing the discharge pressure from 0.6 to 0.8 Torr the discharged seemed to come to another state.

Also, it was clearly seen from the graphs for the phase difference between harmonics of current and voltage (not presented in the abstract), that in mentioned above pressure range the value for the first and, especially, for the third harmonics experiences dramatic changes. The idea of monitoring certain processes through the study of the phase behaviour is not a new one [1] and can be very promising in commercial production environment.

On the poster the other data will also be available.

V. CONCLUSION

The electron densities in a low-pressure (50 – 800 mTorr) air RF discharge have been measured. The electron density is in the range of $10^{13} - 4 \times 10^{15}$ m$^{-3}$. Various plasma parameter dependences for different conditions of experiment have been presented. It has been noticed that the behaviour of the first harmonics of current, voltage, and power is pretty much the same as the behaviour of the electron density.

VI. ACKNOWLEDGEMENT

This work is supported by the European Commission under contract No. NNE5-1999-0004 H-alpha solar. The research of W.W. Stoffels has been made possible by a fellowship from the Royal Netherlands Academy of Arts and Sciences (KNAW).
