Low-pressure inductively coupled discharges operating with electronegative gases are increasingly used for industrial materials processes such as etching and deposition. Previously, instabilities have been studied in dc glows\textsuperscript{1-3} and capacitive discharges\textsuperscript{4} and more recently in low-pressure inductive discharges\textsuperscript{5,6}. The first reported study of instabilities in an inductive discharge was by Michel Tuszewski\textsuperscript{5} with the cylindrical configuration using O\textsubscript{2} and Ar/SF\textsubscript{6} plasmas. This source was operated with a 12-turn copper coil and the driving frequency was 0.46 MHz with a power range of 200 – 500 W and pressures of 0.25-10 mTorr. The instabilities were observed using a cylindrical Langmuir probe with frequencies in the range of 1-40 kHz. The instabilities are observed to be self-excited modulations of the ion plasma density perhaps similar to those which have been observed in glow discharges and capacitive discharges. More recently, instabilities were observed in O\textsubscript{2} and SF\textsubscript{6} by Lieberman \textit{et al}\textsuperscript{5} using the planar coil configuration. The applied power to the coil at 13.56 MHz was 100-1000 W. In this case instabilities were observed with frequencies in the range 1 Hz – 900 kHz as detected by the optical emission to a photomultiplier tube and the current to an unbiased Langmuir probe. It has been suggested that a possible cause of this instability is due to the switching between capacitive and inductive modes where the relaxation oscillations had sometimes 100 % modulation i.e. the electrons were almost completely expelled during the oscillation.

In this work a low-pressure radio frequency oxygen discharge is investigated. Oxygen plasmas have been used in industrial material processing such as ashing and the production of oxide films. The simplicity of oxygen in comparison to other electronegative gases (e.g. CF\textsubscript{4} and SF\textsubscript{6}) and the availability of a wide database of reaction rates make oxygen discharges a good subject for experimental investigation.

A reproducible instability has been observed in a low-pressure, 13.56 MHz inductively coupled GEC\textsuperscript{7} rf cell operating in oxygen. The antenna is a 5-turn water-cooled copper coil that couples power to the plasma through a quartz window. The grounded lower electrode diameter is 165.1 mm with an electrode-quartz window spacing of approximately 40.5 mm. The coil is powered through a close coupled, rf matching network by a 350 W rf power supply. Oxygen is fed into the chamber through a 0-10 sccm MKS flow meter. The discharge is operated in the pressure range of 1-100 mTorr. As can be seen from Fig. 1, there is a power and pressure regime that can support either a capacitive or an inductive mode discharge, where the mode
present depends on the history of the system\(^6\). Such behaviour is called hysteresis\(^9\). It is within this power and pressure regime that the instabilities are observed to occur.

An uncompensated Langmuir probe and a photodiode with fibresoptic were used to observe the time variation of the instability. Spatial and temporal variation of the optical emission through one oscillation period of the instability was observed with an ICCD. Currently, probe-assisted laser photodetachment measurements are being made. This setup consists of a frequency doubled Nd:YAG laser with a Langmuir probe detecting the detached electrons. A compensated Langmuir probe is used to make electron density measurements.

The instability is observed in the form of periodic modulations in the output of a photodiode and an unbiased Langmuir probe (Fig. 2). The instability occurs at operating powers between 240 and 340 W (at all times reflected power is kept to a minimum i.e. < 13 W) and at gas pressures from 5 to 23 mTorr. The frequency of oscillations increases with increasing gas pressure from 3 to 21 kHz but do not vary significantly with power. The amplitude of the oscillations varies with both gas pressure and power. These results are consistent with Lieberman et al.\(^6\) and Tuszewski\(^5\). No instabilities have been observed with argon gas.

The instability has also been observed as the spatial movement of the plasma emission as detected by an ICCD. The ICCD was gate triggered at the minimum of the Langmuir probe signal and the variation of the optical emission was observed through one oscillation period (Fig. 3). The frequency of this instability is \(~ 10\) kHz. It has previously been suggested that the instability is due to the expulsion of negative ions from the plasma core. This is perhaps an explanation for what we have observed.

The instabilities in inductive discharges are thought to be due to negative ions as there has been no reported studies of instabilities in inductively coupled electropositive plasmas such as argon. Probe-assisted photodetachment\(^10\) is a valuable technique for determination of negative ion

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**Fig. 2.** Time variation of optical emission and probe current at 11 mTorr and 250 W

**Fig. 3.** Spatial variation of emission at 844 nm through one oscillation period
densities. In a plasma, photodetachment produces an increase in the electron density without an immediate increase in the positive ion density. Thus, by simply collecting the extra electrons on a positively biased Langmuir probe after the negative ions have been destroyed by the laser pulse, the negative ion fraction can be obtained.

The technique of probe-assisted photodetachment has been employed at Queens University to determine negative ion density measurements with both an uncompensated and a compensated Langmuir probe at low pressures (<100 mTorr). A typical photodetachment signal is shown in Fig.4. Preliminary experiments have shown the negative ion fraction to be between 4 and 80% in the capacitive mode and between 1 and 25% in the inductive mode. It is found that the negative ion density decreases with increasing rf power in both capacitive and inductive modes. As a function of pressure, the negative ion fraction is at an optimum pressure of ~15 mTorr in both capacitive and inductive. The results are similar to those of Stoffels et al\textsuperscript{11}. Currently, time resolved photodetachment and edf measurements are being performed in the instability region.

![Photodetachment signal at 15 mTorr, 250 W with an uncompensated Langmuir probe](image)

Fig.4 A typical photodetachment pulse in a oxygen discharge

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References