Hairpin probe in conjunction with laser photo-detachment technique for negative ion density measurement

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I. Introduction

Electronegative plasmas are being extensively researched as they find important applications in semiconductor industries, in ionosphere, in fusion plasmas for the production of neutral beams for plasma heating, plasma thrusters and in accelerators for increasing the range of particle energy [1-2]. Interaction of electronegative ions with atoms, molecules and light has also been a subject of intensive study. Measurement of negative ion concentration is therefore important for wide range of motivations. Probe assisted laser photo detachment is the most commonly used diagnostic tool for negative ion containing plasmas [3]. Langmuir probe is used to detect the excess electron density during laser photo-detachment. However errors associated with the Langmuir probe is unprecedented because it is sensitive to the changes in surface properties of the probe and presence of external magnetic fields [4]. The Langmuir probe also perturbs the plasma strongly. In this paper we present the hairpin probe technique in conjunction with the photo-detachment of negative ions in an oxygen discharge by a pulsed laser beam for measuring the density of negative ions.

II. Experimental setup and diagnostic method

The experiment was carried out in an inductive rf discharge consisting of a 11 turn of 3 cm in diameter helical antenna in the centre of the cylindrical plasma chamber of 900 mm length and 200 mm in diameter. The antenna is isolated from the discharge by a quartz tube and is driven at 13.56 MHz. Using this configuration dense plasma up to densities of the order of 10^{11} cm^{-3} can obtained at a maximum operating powers up to 1 KW. In this experiment O_2 discharge was produced at a power range between 50 – 500 Watts with background pressure of 30 mTorr.

For measuring negative ion density a pulsed laser beam is injected in the plasma. The energy of the pulse beam is 220 mJ/cm^2, which is sufficient to detach all electrons from negative ions in the path of laser beam. Rise in the number density of electrons created by photo-detachment process is measured by introducing a hairpin probe [5] in the path of laser beam. The difference between the peak electron density and the background gives a direct measure of the negative ions present in the plasma.

III. Experimental results.

The technique for measuring time dependent electron density by hairpin probe can be found in reference [5]. Briefly the hairpin probe has a characteristic resonance frequency f_o in air/vacuum, typically in the range of a 2 – 3 GHz. This sets the probe length, $L = c/4f_o$; where c is the speed of light in vacuum. When the probe is placed in the plasma we observe a shift of resonance frequency f_o to a higher value f_r. The electron density n_e is directly proportional to $(f_r^2 - f_o^2)$.

The background electron density, i.e before the injection of the pulsed laser beam was obtained by scanning the microwave frequency supplied to the hairpin probe over a range of 2 – 5 GHz. The spectrum of the reflected signals from the probe shows a sharp drop at the resonance frequency which corresponds to the background plasma electron density. In order to see the electron density evolution following the photo-detachment process, the microwave frequency is tuned to the resonant frequency of the background plasma and the reflected signal over a period of 5 μs was obtained in synchronization with the pulsed laser waveform obtained using a photo-diode which lasts for a period of 600 ns. By gradually incrementing the applied microwave frequency above the resonance frequency of the background plasma, we observe modulation in the reflected signal characterized by two peaks, because the resonance condition is satisfied at these times, one during the rise and the second during the fall in photo-detached electron density. Figure 1 shows typical wave forms of the reflected signal from the probe. Note that when the probe was tuned to 2.16 GHz, only one peak is obtained because this correspond to the peak

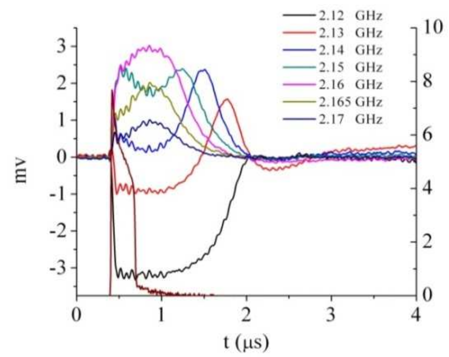

Figure1: Temporal evolution of resonance signal at 100 watt and 30 mtorr with α=0.64. Laser energy density is 212 mJ/cm^2 at 532 nm. Background resonance frequency is 2.12 GHz (before detachment) and corresponding vacuum resonance is 2.056 GHz.

in electron density allowing the maximum electron density to be calculated following the photo-detachment process.

Using this technique electron density and negative ion density is obtained over a range of operating powers 50 – 500 Watts at 30 mTorr as shown in figure-2. As expected both electron and negative ions increase with power, the electron density increase is a result of increased fractional ionization whereas the negative ions increase is a result of dissociative attachments. However the ratio of negative ions to electron density defined as α decrease with the rf power as shown in figure-3. This is due to simultaneous increase in the annihilation of negative ions by electrons which drops the rate of increase.

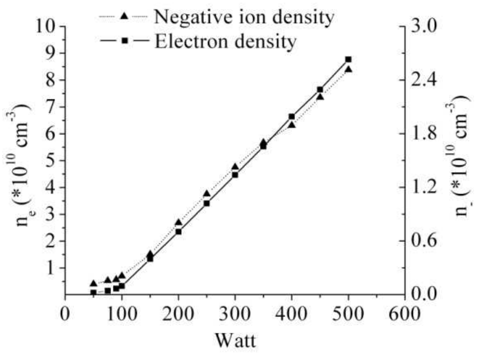

Figure 2: Absolute electron and negative ion densities with rf power at 30mtorr.

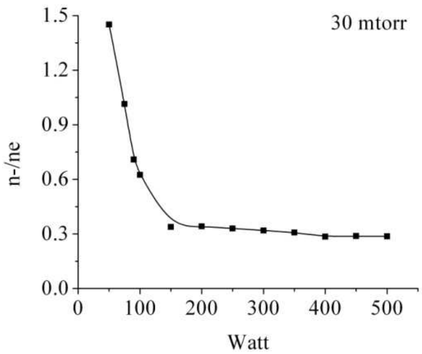

Figure 3: Plot of α= n_-/n_e with rf power.

The hairpin probe can also be used for estimating the temperature of negative ions. In principle when all the negative ions are destroyed by pulsed laser, the central column of beam is left with only electrons and positive ions maintaining the quasi-neutrality. However this equilibrium is short range and it will relax to the equilibrium state as it was prior to the injection of the beam. This will happen at a time which will be governed by negative ions diffusing from the adjacent layer from outside the cylindrical beam column. The refilling time of negative ions is related to thermal speed of negative ions.

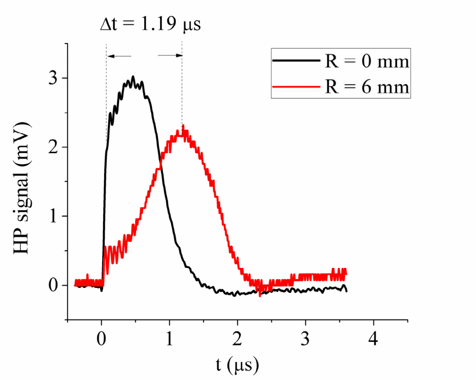

Figure 4: Probes resonance signal corresponding to the peak electron density at the centre of the beam and outside at a radial distance of 6.0 mm from the centre.

When these dynamic changes are happening, negative ions density in the adjacent layer will reduce while electrons from the centre of the beam will move outside in the adjacent layer. This will result in observing a peak in electron density outside the beam volume, but at a later time with respect to the peak electron density at the central column. This is shown in figure-3. The two waveforms, one in the centre of the beam and the other at r = 6.0 mm occurs after a delay of Δt = 1.19 µs. Hence the speed of negative ions is estimated simply by $v_{th}^- = r/\Delta t \sim 5 \times 10^3$ m/s. This amounts to a negative ion temperature one order in magnitude higher than that of background neutrals. The negative ions are created at an excited state by dissociation of O_2 into O and O*(excited atom) by electron impact which follows by electron attachment to form negative ions.

IV. Summary and Conclusion

In this paper we demonstrated the application of resonance hairpin probe for measuring a time-dependent electron density dynamics in conjunction with the pulsed laser photo-detachment for measuring negative oxygen density in 13.56 MHz inductive rf discharge. The negative ions fraction are estimated to be higher at low operating powers with $\alpha > 1$ while the absolute density of negative ions linearly increase with applied rf power. Using the temporal delay of the electron density peak at a fixed radial position from the centre of the beam, we estimated the negative ions speed. The estimates show that the negative ions have significant large temperature as compared with the background neutrals.

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