EXPERIMENTAL STUDY OF TEMPERATURE AND DENSITY EVOLUTION DURING BREAKDOWN IN A 2.45 GHz ECR PLASMA

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Abstract

An experimental study of temperature and density evolution during breakdown in off-resonance ECR hydrogen plasma by time resolved Langmuir probe diagnostic is presented. Under square 2.45 GHz microwave excitation pulses with a frequency of 50 Hz and relative high microwave power, unexpected transient temperature peaks that reach 18 eV during 20 μs are reported at very beginning of plasma breakdown. Decays of such peaks reach final stable temperatures of 5 eV at flat top microwave excitation pulse. Microwave coupling times are also measured in connection with plasma parameters evolution as function of duty cycles and incoming microwave power for two hydrogen working pressures.

INTRODUCTION

Understanding plasma physics processes during breakdown and decay in pulsed plasma sources is of special interest for many application fields as particle accelerator science, nuclear fusion reactors and plasma processing industry [1, 2]. An extensive research on this subject was conducted by different researchers with electrical probes, spectroscopy and radiation diagnostics under a wide range of parameters for different plasmas. Processes involved during breakdown should be determining for monocharged beam current optimization as well as the improvement of multiple charged ion production efficiency, both cases of great interest and under deep study in the ECRIS community [3, 4, 5]. In this work we present a study of breakdown process in off-resonance ECR hydrogen plasma by means of time-resolved Langmuir probe diagnostics and incoming and reflected microwave power measurements. The main goal is to improve our knowledge about evolution of plasma parameters during pulse mode operation helping to the design of ion sources at ESS Bilbao.

EXPERIMENTAL SETUP AND PROCEDURE

Measurements are made in a plasma reactor driven by a 3 kW adjustable output power magnetron of 2.45 GHz that is operated at 50 Hz in pulsed mode. Four coaxial coils with typical circulating currents of 10 amps produce an axial 120 mT off-resonance magnetic field. Such coils have a positioning mechanism to adjust the magnetic field distribution. On chamber diagnostic side a lid including pumping port, a fused silica observation window and a vacuum feed-through for probes are mounted. Such lid is placed where plasma electrode and extraction system would be placed in case of using this reactor as an ECRIS. Clearly our plasma reactor is an ECRIS reproduction without extraction electrodes. Fig. 1 shows a view of the experiment where the magnetic field system and diagnostic port side can be appreciated in first plane. The idea is to have a closed reproduction of ISHP ion source under development at ESS Bilbao [6] to use it as test bench for plasma research and optimization.

As is well-known in plasma community, Langmuir probes are used immersed in plasmas for acquiring characteristic I-V curves which permit to estimate plasma electron temperature and density. Time needed to make voltage sweep with acquisition of current values is always a limitation for time resolved measurements. However, several instrumentation companies have developed Langmuir probe systems that permit making transient studies of repetitive pulsed plasmas with some tens of ns resolution. These systems take first I-V point at one pulse; second one at following and so on, completing the voltage sweep in a predetermined number of pulses. In other words, each point at I-V curve belongs to different consecutive plasma pulses. When synchronization is carefully made checking during process if jitter is low enough, it is possible to have a good estimation of electron density and temperature at a precise predefined instant. In our case the system acquires an I-V point during 62.5 ns and after approximately 14.6 μs (time necessary for digitalizing and storing data) is ready to take

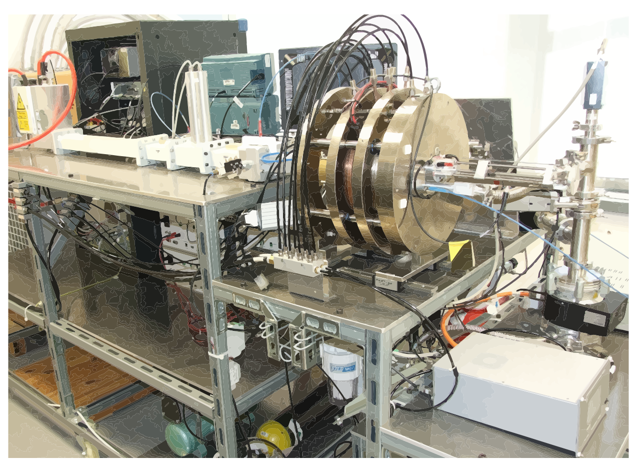

Figure 1: View of the experiment where the plasma reactor, magnetic coils and diagnostic port are shown in first plane.

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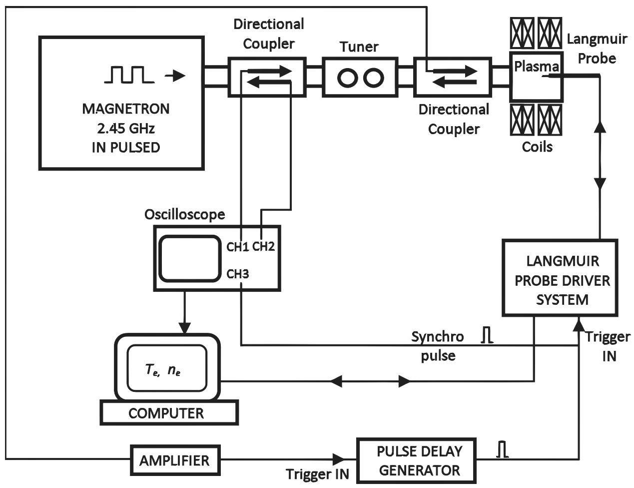

Figure 2: Experimental arrangement for time resolved density and temperature measurements during breakdown with a resolution of 200 ns.

the following one under TTL trigger order. This process is averaged twenty times before moving to the next I-V point. Applying this method, time resolved I-V curves can be obtained by synchronizing Langmuir probe trigger driver and magnetron via a delay generator. Fig. 2 shows the experimental set-up. A Langmuir probe made of tungsten wire 6 mm long and 0.5 mm diameter is placed in the middle of plasma chamber (r = 0 and z = 46 mm). The Langmuir probe driver consists in ESPION system made by Hiden Analytical LTD. Jitter is carefully checked obtaining a value lower than 200 ns in order to obtain an acceptable measurement time resolution. By modifying Langmuir probe trigger delay, it is possible to obtain the time evolution of electron temperature and density during the breakdown. Typical I-V curve obtained during experiments show that ion saturation current increases following negative voltage. For low plasma densities and small probes the sheath expansion produces an increase in the collected current because effective area for particle collection is the sheath area and not the geometric probe area [7, 8]. Such situation is reflected by ion currents that do not show clear saturation values increasing gradually with increasing negative voltage. The slope in the I-V curve ion current branch is an unequivocal sign of low density plasma always with values under critical density. Considering such fact, density calculations were carried out by modeling the left branch or I-V curve using the numerical results of Laframboise [9].

RESULTS

The study of plasma parameters evolution during breakdown was conducted for two hydrogen working pressures taking measurements every 1 μs followed by points every 10 and 20 μs on the microwave pulse flat top. Fig. 3 shows a typical evolution of measured parameters for hydrogen pressure of 3.8 x 10^{-3} mb, 1500 W peak mi-

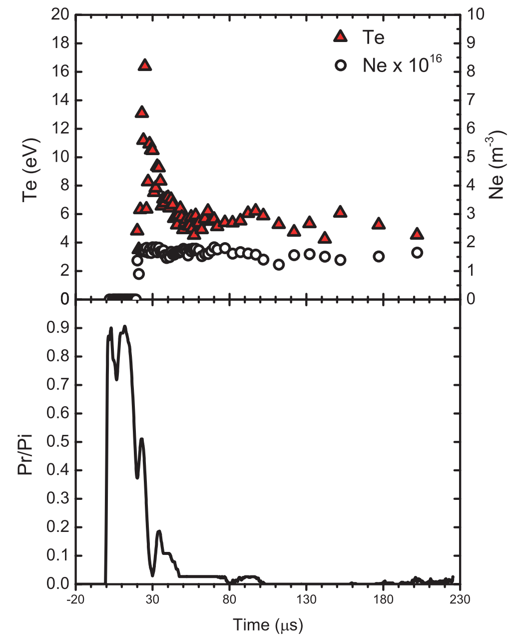

Figure 3: Upper window: Plasma temperature and density evolution during breakdown. Lower window: ratio of reflected power and incoming power *Pr/Pi*.

crowave incoming power and 90% duty cycle. Upper window shows evolution of electron temperature and density during the breakdown process until reaching flat top microwave excitation pulse. Lower window shows evolution of reflected/incoming power ratio *Pr/Pi* on same time-base. It shows that at the very beginning of the pulse the electric field inside the chamber is much higher than later during steady-state when plasma damps microwave and electric field drops. Such behavior reflects the interplay between the electric field strength and plasma load of the cavity during the ignition transient[5] showing microwave coupling time as directly the width of the *Pr/Pi* pulse. Note in the upper window that a temperature peak reaching almost 20 eV is observed in coincidence with a drastic reduction of reflected power during microwave coupling process. Such peak is followed by a decreasing behavior that reaches about 5 eV as final steady state temperature, remaining practically constant during flat top microwave pulse. Electron density reaches stable values about 1.5 x $10^{16} m^{-3}$ at the time when temperature peak is produced, fact that suggests this process as deeply associated to plasma evolution during breakdown. The error bar in temperature measurement is estimated below 5% , reaching 1 eV at high values during peak and 0.25 eV during steady state. Accuracy in electron density is estimated lower than 0.5 x 10^{16} m^{-3}.

Low Pressure Regime (3.8 x 10^{-3} mb)

Fig. 4 shows temperature and density temporal evolution for three cases with hydrogen pressure maintained at 3.8 x 10^{-3} mb and the magnetic field at 120 mT as function of duty cycle and incoming power. Fig. 4(a) is a duty cycle

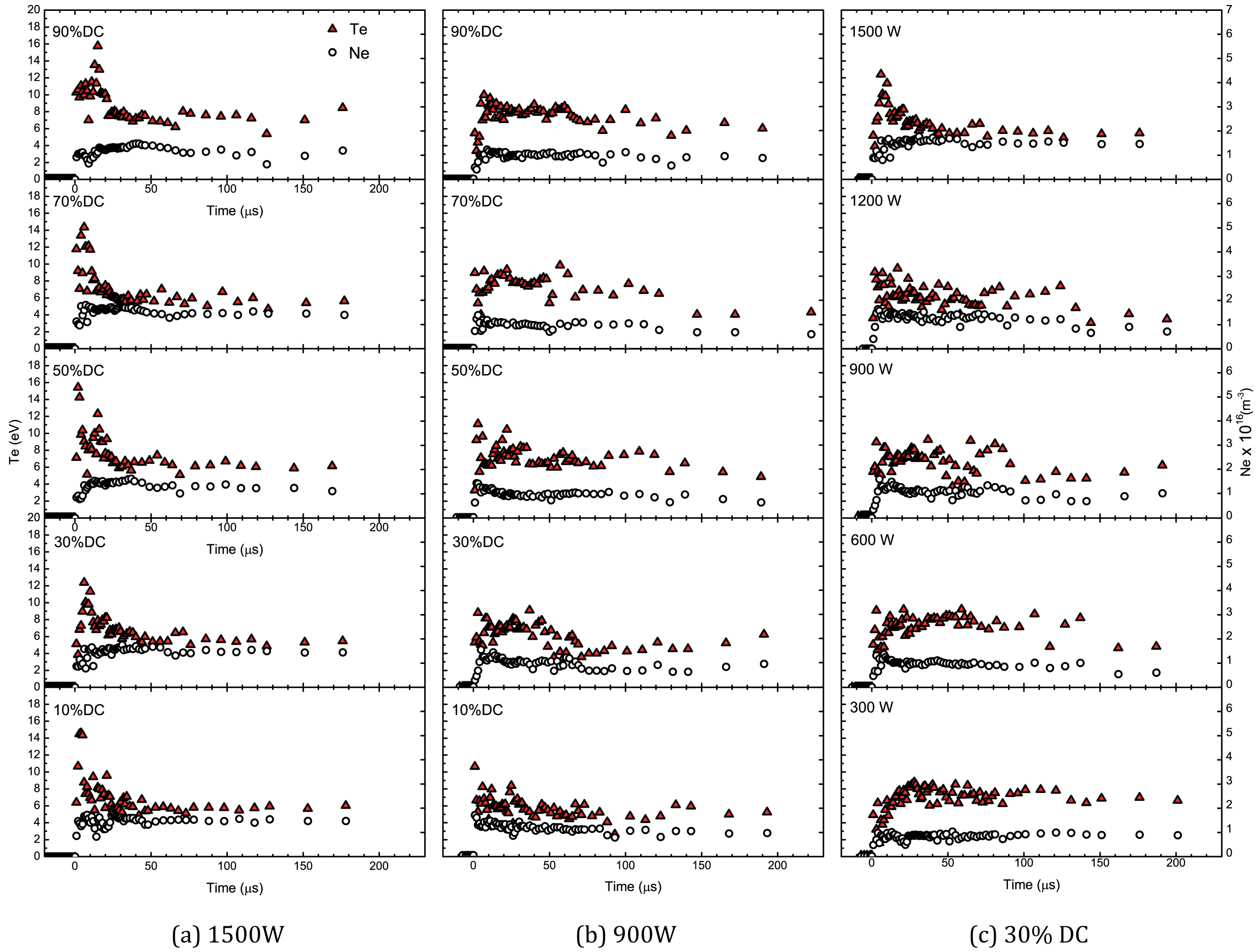

Figure 4: Temperature and Density evolution during breakdown process for a hydrogen pressure of 3.8 x 10^{-3} mb and 120 mT Bz magnetic field. (a) Constant power at 1500 W. (b) Constant power at 900 W. (c) Constant duty cycle at 30%.

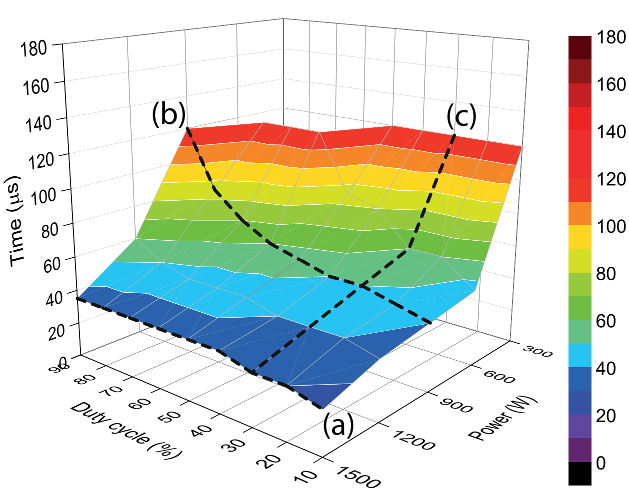

Figure 5: Microwave Coupling time as function of incoming power and duty cycle for low pressure regime (3.8 x 10^{-3} mb).

scan at 1500 W of power, Fig. 4(b) is a duty cycle scan at 900 W of power and Fig. 4(c) is a power scan at 30 % of constant duty cycle.

In all theses cases the beginning of temperature and density pulses are coincident with *Pr/Pi* pulse fall as is shown in Fig. 3. On the other hand, the microwave coupling time can be estimated by measuring the width of such *Pr/Pi* pulse. Theses measurements are represented as a surface obtained by linear interpolation between measured points as function of MW incoming power and duty cycles in Fig. 5. Note that this figure shows an empty area in the corner of low powers and high duty cycles corresponding to a high jitter measurement zone where is not possible to take data. As can be seen in this surface, the level curves of 1500 W (a), 900 W (b) and 30 % of duty cycle (c) are marked as doted lines and they correspond to measurements represented in Fig. 4(a), Fig. 4(b) and Fig. 4(c) respectively. It is interesting to compare Fig. 4 with Fig. 5 because some connection can be found between microwave coupling time and plasma parameters evolution. For example,

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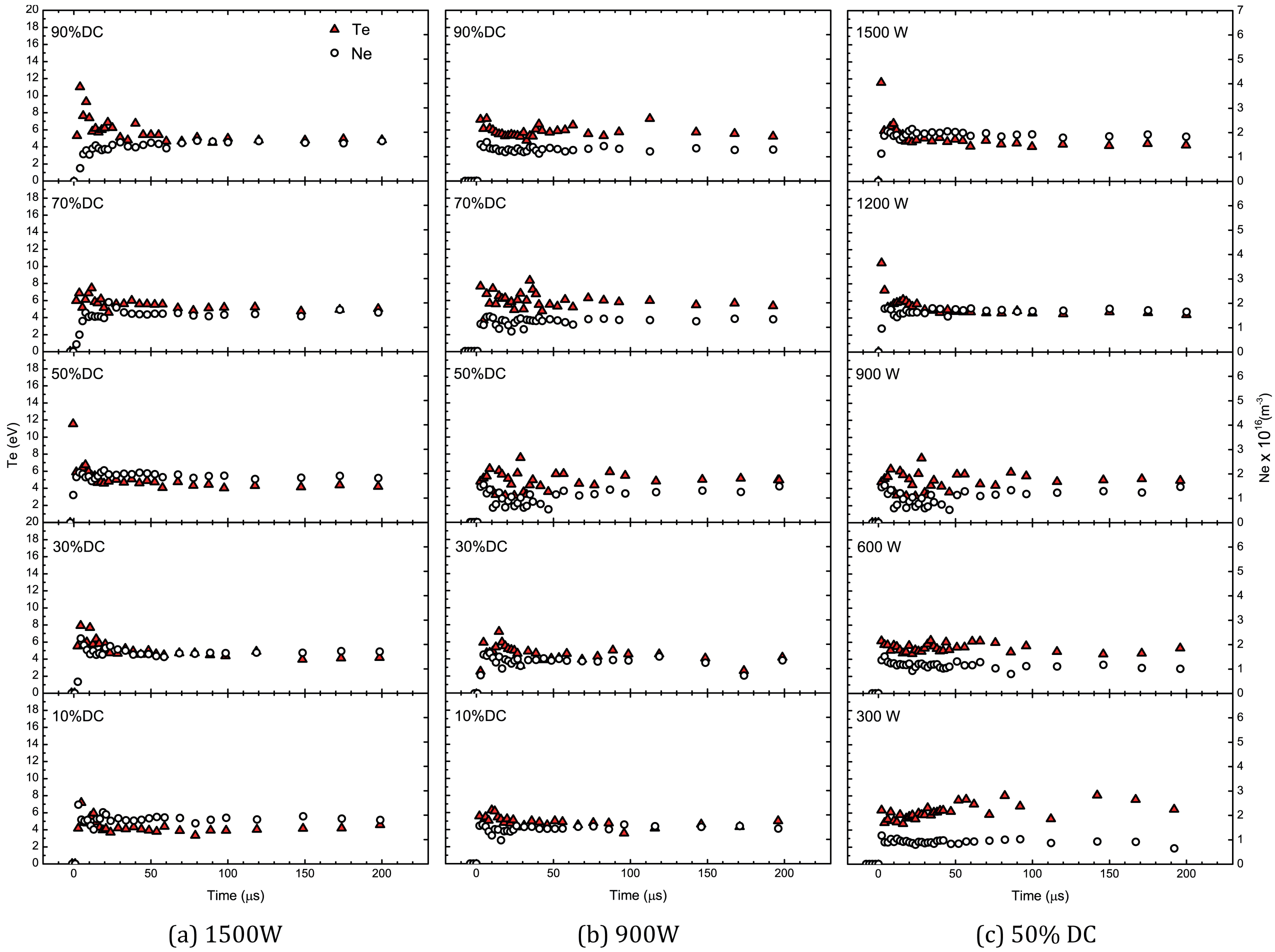

Figure 6: Temperature and Density evolution during breakdown process for a hydrogen pressure of 6.2 x 10^{-3} mb and 120 mT Bz magnetic field. (a) Constant power at 1500 W. (b) Constant power at 900 W. (c) Constant duty cycle at 50%.

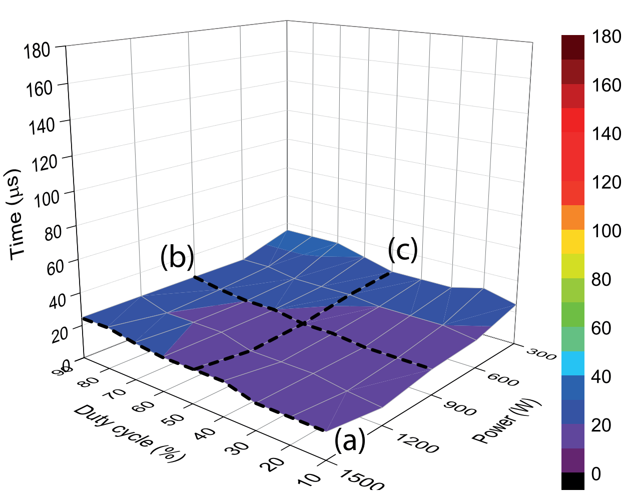

Figure 7: Microwave Coupling time as function of incoming power and duty cycle for high pressure regime (6.2 x 10^{-3} mb).

keeping incoming power constant at 1500 W as indicated in level curve (a) in Fig. 5, practically constant microwave coupling times are observed with values around of 35 μs for all range of duty cycles studied. The corresponding plasma parameters evolution in Fig. 4(a) also shows non relevant differences along all the studied range. Temperature and density evolution suggest that this case is characterized by sharp temperature peaks of 16-18 eV followed by decays to final temperature steady state around 5 eV. However, the case of constant power at 900 W that is indicated as level curve (b) in Fig. 5 shows a remarkable coupling time tendency to increase when duty cycle is also increased, starting at values of 40 μs at 10 % of duty cycle and reaching 120 μs at 90 %. The corresponding plasma parameters evolution in Fig. 4(b) shows that plasma temperature evolves by decreasing temperature peaks values and increasing final temperatures at plasma steady state. In this case the relationship between microwave coupling times and temperature evolution indicates that for longer coupling times, longer and lower temperature pulses are observed with slight higher final temperatures. The last case where duty cycle is kept constant at 30 % is indi-

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cated as level curve (c) in Fig. 5 for power ranging between 300W and 1500W. Microwave coupling times show the tendency to grow when power decreases and the corresponding plasma parameters evolution in Fig. 4(c) shows how temperature pulse decrease with power and it practically vanishes at low powers. On the other hand, electron density show a general behavior characterized by a practically no dependence of duty cycle and a slightly tendency to grow with incoming power. Higher values reach 2 x $10^{16} m^{-3}$ at 1500 W and lower values of 0.8 x $10^{16} m^{-3}$ are registered at 300 W.

High Pressure Regime (6.2 x 10^{-3} mb)

The same scheme of previous section is conducted for a relative higher hydrogen working pressure. Fig. 6 shows three cases of temperature and density evolutions for different values of incoming power and duty cycles maintaining hydrogen pressure at 6.2 x 10^{-3} mb and magnetic field at 120 mT. Fig. 7 shows the microwave coupling times obtained for such experimental condition keeping the same representation scale of Fig. 5 in order to facilitate comparisons. Note that measured times are shorter and practically constant during the studied interval with values between 20 and 35 μs showing a slight tendency to grow for lower power inputs and high duty cycles. Cases shown in Fig. 6 are represented on the surface as level curves (a), (b) and (c) for 1500 W, 900 W and 50 % of duty cycle respectively. Such data show that temperature peaks reach lower values respect to the previous low pressure regime suggesting that incoming power is the predominant factor for its increment. Specially interesting is the the case of Fig. 6(a) where the influence of duty cycle is remarkable for our maximum power input value under study. On the other hand, electronic densities show higher values reaching 2 x $10^{-16} m^{-3}$ following the relative increment for this pressure regime.

REMARKS

Evolution of plasma parameters for a 50 Hz pulsed off-resonance 2.45 GHz ECR plasma at two hydrogen working pressures (3.8 and 6.2 x 10^{-3} mb) during breakdown is reported . For low pressure regime, different plasma parameter evolution is observed depending of incoming power and duty cycle in connection to microwave coupling times. Under relative highly power conditions where short microwave coupling times are recorded, high temperature peaks are observed during microwave coupling process at very beginning of plasma breakdown. However, for lower incoming powers, temperature evolution shows a slow tendency to reduce the peak values by evolving gradually towards a higher final temperature without peaking. On the other hand, when pressure is increased to the high regime the peaking behavior turns less notorious keeping the dependence with incoming power and duty cycles while electron densities reach higher values of typically 2 x 10^{16} m^{-3}. In general terms, the temperature peaks duration seems to be related to microwave coupling quality in terms of the time needed to establish a good power transfer to plasma. For the high pressure regime, where microwave coupling times are short and practically uniform over all our studied range, temperature evolutions show lower peak values and shorter duration. However, for the low pressure regime where microwave coupling times show a strong dependence of power and duty cycle, a significant evolution of peaking behavior is observed. This effect suggest that the temperature peaking could be strongly related to plasma formation process and how the microwave interaction with neutral gas and a very low dense plasma evolves during the early breakdown stage. The influence of seed electrons remaining in the neutral gas between pulses[10], could be a factor to have into account to explain the dependence observed with duty cycle at relative high power. Finally, the early instant when temperature peaks are observed in our experiment suggests that may be interesting to conduct this diagnostic on others ECR plasmas of higher frequencies in order to see possible connections with the ECRIS preglow [11, 12].

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