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Temperature peaking at beginning of breakdown in 2.45 GHz pulsed off-resonance electron cyclotron resonance ion source hydrogen plasma

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An experimental study of temperature and density evolution during breakdown in off-resonance ECR hydrogen plasma 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. Evidence of interplay between incoming power and duty cycle giving different kind of plasma parameters evolutions engaged to microwave coupling times is observed. Under relative high power conditions where short microwave coupling times are recorded, high temperature peaks are measured. However, for lower incoming powers and longer coupling times, temperature evolves gradually to a higher final temperature without peaking. On the other hand, the early instant where temperature peaks are observed also suggest a possible connection with preglow processes during breakdown in ECRIS plasmas. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4757113]

I. 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 determined 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.[3–5] In this paper, we present a study of breakdown process on off-resonance ECR hydrogen plasma by means of time-resolved Langmuir probe diagnostics and incoming and reflected microwave power measurements. The main goal of this work is to improve knowledge about evolution of plasma parameters during pulse mode operation that can help ECRIS designers reach better performances.

II. EXPERIMENTAL SETUP AND PROCEDURE

Measurements are made in a plasma reactor driven by a 3 kW adjustable power magnetron of 2.45 GHz operated at 50 Hz in pulsed mode. Figure 1 shows a view of reactor including main subsystems. The plasma chamber is cylindrical with 93 mm length by 90 mm diameter and is made of oxygen-free high-conductivity copper including an external water cooling bath for heat removal. Microwave is injected through one chamber side, while the opposite is used as vacuum pumping and diagnostics ports. From the microwave injection side, a brass piece made with internal steps is used as coupler for adapting impedances of plasma chamber and WR 330 microwave waveguide. A two-stub tuner is used for fine plasma impedance matching and a directional coupler gives readings of incoming and reflected power from magnetron and plasma, respectively. A 10 mm thickness quartz window separates the vacuum enclosure from the microwave driver system. A set of four coaxial coils arranged in two pancakes with independently variable circulating currents of about 10 A can produce different magnetic field profiles by means of a positioning mechanism.

Hydrogen is injected into plasma chamber through a needle valve; flow is measured by a digital flow meter and gas pressure by a gauge connected to the body plasma chamber. Pressure is maintained constant in plasma chamber at 3.8×10^{-3} mbar without necessity of on-flight gas flow adjustments during the experiments. Both sides of plasma chamber are covered by 2 mm thickness boron nitride disks properly machined to fit microwave port, gas inlet, and diagnostic portholes. On the chamber diagnostic side, a lid is mounted including pumping port, a fused silica observation window, and a vacuum feedthrough for probes. Such lid is placed where plasma electrode and extraction system would be placed in case of using this reactor as an ECRIS. On the other hand, diagnostic port design permits taking measures by an electrical probe in the axis of plasma chamber while hydrogen is pumped through the same centered hole. This issue was demonstrated to be important in our experiment for obtaining a symmetrical plasma density distribution with respect to the axis and has to be taken in consideration especially for low gas operating pressures. Clearly, our plasma reactor is an ECRIS reproduction without extraction electrodes.[6] The idea is to have a close reproduction of ISHP (Ion Source for Hydrogen Positive) ion source under development at ESS Bilbao and to use it as a test bench for plasma research and optimization.[7]

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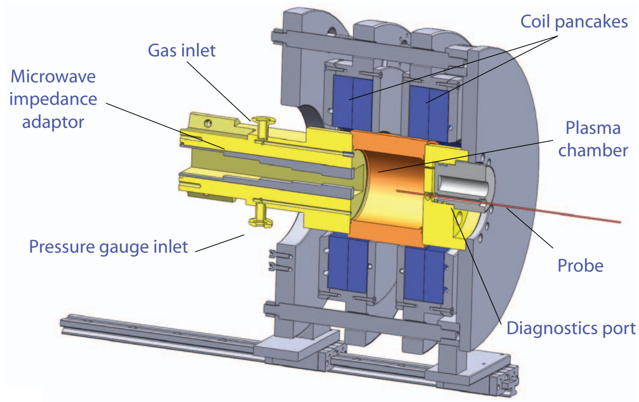

FIG. 1. Cross-sectional view of the plasma reactor: Plasma chamber length: 93 mm. Chamber diameter: 100 mm. Microwave impedance adaptor includes the gas inlet and gas gauge pressure ports. Diagnostic port includes the Langmuir probe holder. Magnetic coil pancakes are provided by mechanical movements for z axis.

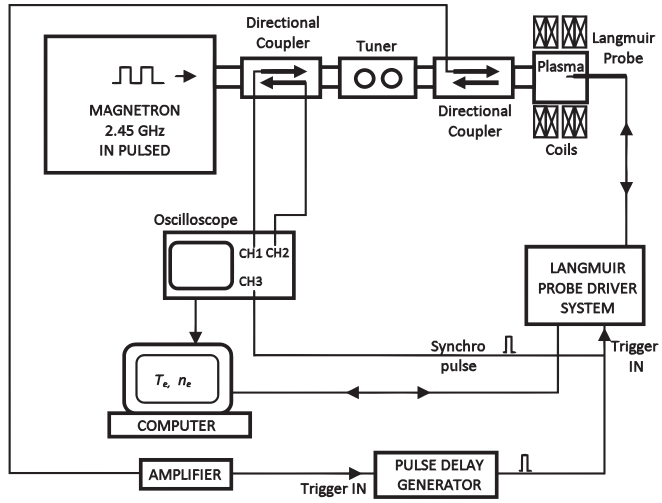

FIG. 2. Experimental arrangement for time resolved density and temperature measurements during breakdown. Resolution is 200 ns.

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 the following one under transistor-transistor logic trigger order (TTL). This process is averaged 20 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. Figure 2 shows the experimental setup.

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 ensure measurement quality. By modifying Langmuir probe trigger delay, it is possible to obtain the time evolution of electron temperature and density. A typical I-V curve obtained during experiments is shown in Fig. 3 where it is clear how the 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.[8,9] 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.[10]

III. RESULTS

A study of breakdown process was conducted taking measurements every 1 μs during breakdown followed by points every 10 and 20 μs on the microwave flat top in order to obtain temporal evolution of electron temperature and density. Figure 4 shows a typical evolution of measured parameters for hydrogen pressure of 3.8×10^{-3} mbar, 1500 W peak microwave 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

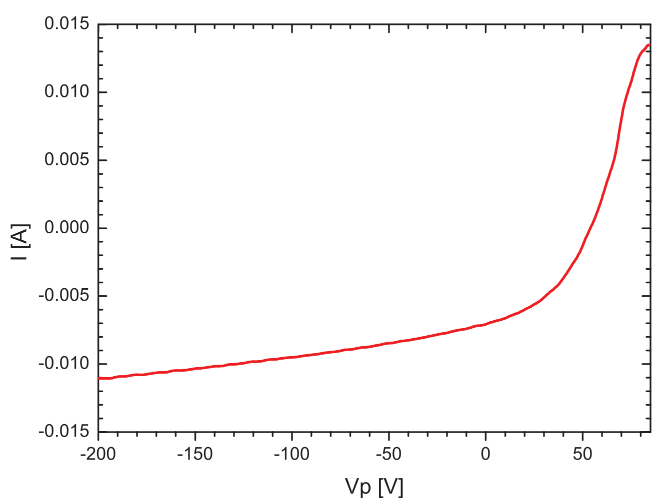

FIG. 3. Typical I-V curve obtained during the experiments.

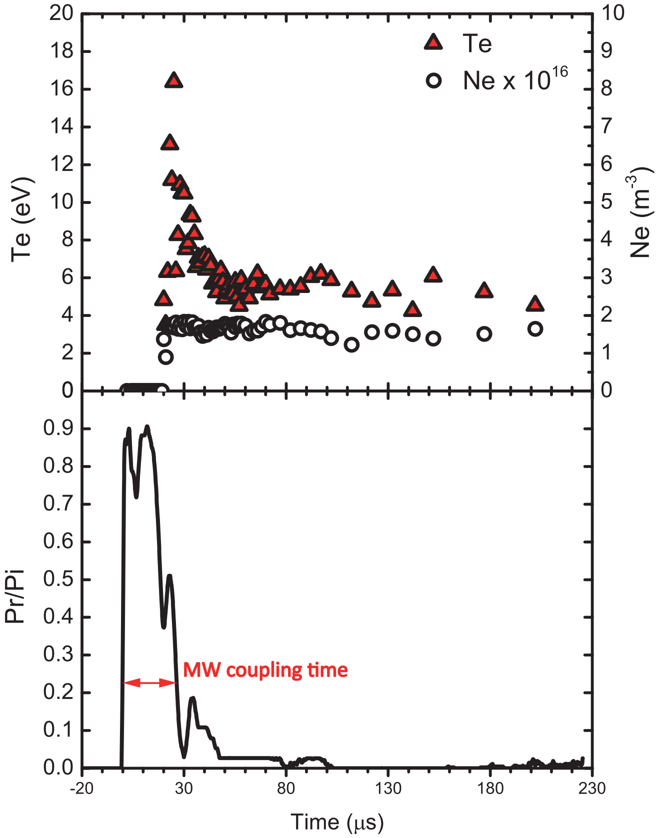

FIG. 4. Upper window: Plasma temperature and density evolution during breakdown. Lower window: ratio of reflected power and incoming power Pr/Pi showing the coupling time definition as the width of pulse drop.

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 1.5×10^{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 below 0.5×10^{16} m^{-3}. Figure 5 shows temperature and density temporal evolution for three cases with hydrogen pressure maintained at 3.8×10^{-3} mbar and the magnetic field at 120 mT as function of duty cycle and incoming power. Figure 5(a) is a duty cycle scan at 1500 W of power, Fig. 5(b) is a duty cycle scan at 900 W of power and Fig. 5(c) is a power scan at 30% of constant duty cycle. In all these cases, the beginning of temperature and density pulses are coincident with Pr/Pi pulse fall as is shown in Fig. 4 where, by measuring the width of the Pr/Pi pulse, the microwave coupling time can be obtained. We consider such coupling time as the time when the pulse drops to 80% of its initial value with an estimated accuracy of 2 μs. Figure 6 represents microwave coupling times obtained by such method as surfaces of linear interpolation between measured points as function of MW incoming power and duty cycles. 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 it 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 dotted lines and they correspond to measurements represented in Figs. 5(a), 5(b), and 5(c), respectively. It is interesting to compare Fig. 5 with Fig. 6 because some connection can be found between microwave coupling time and plasma parameters evolution.

Keeping incoming power constant at 1500 W as indicated in level curve (a) in Fig. 6, practically constant microwave coupling times are observed with values of 35 μs for all range of duty cycles studied. The corresponding plasma parameters evolution in Fig. 5(a) also shows non-relevant difference along all duty cycles studied. All pulses in these cases are characterized by a sharp temperature peak of 16–18 eV and followed by a decay to the final temperature steady state of 5 eV. In this case, short microwave coupling times look related to the occurrence of a sharp temperature peak during the early stage of breakdown. However, interesting changes are observed in the case of constant power at 900 W that is indicated as level curve (b) in Fig. 6. It 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. 5(b) shows that plasma temperature evolves decreasing temperature peak value and increasing final temperature at plasma steady state. In other words, temperature pulse is lower and longer starting at 10 eV and decaying to final temperature values of 7 eV with typical decay times of 100 μs. 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. Finally, keeping duty cycle constant at 30% that is indicated as level curve (c) in Fig. 6, a significant behavior is registered for power ranging between 300 W and 1500 W. Microwave coupling times show tendency to grow when power decreases as can be seen in Fig. 6 and the corresponding plasma parameters evolution of Fig. 5(c) shows how temperature pulse decrease with power and it practically vanishes at low powers. On the other hand, electron density shows a general behavior characterized by a practically no dependence of duty cycle and a slight tendency to grow with incoming power. Higher values reach 2×10^{16} m^{-3} at 1500 W and lower values of 0.8×10^{16} m^{-3} are registered at 300 W.

IV. DISCUSSION

In this work, we report original measurements of temperature and density evolution during breakdown in 2.45 GHz off-resonance ECR plasma. Different plasma parameter

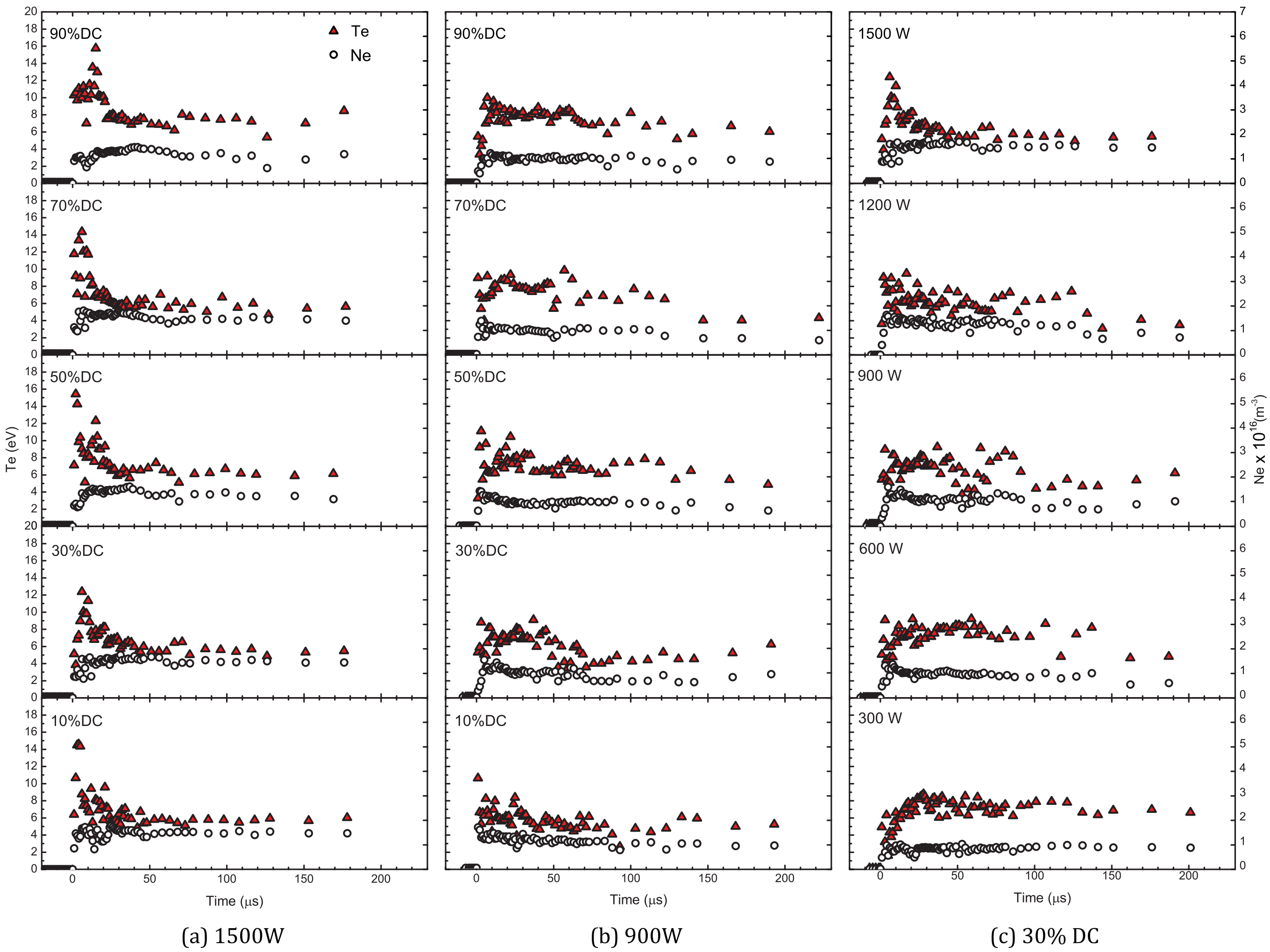

FIG. 5. Temperature and density evolution during breakdown process for a hydrogen pressure of 3.8×10^{-3} mbar and 120 mT Bz magnetic field. (a) Constant power at 1500 W. (b) Constant power at 900 W. (c) Constant duty cycle at 30%.

evolution is observed depending on incoming power and duty cycle in connection to microwave coupling times. Under relative high power conditions where short microwave coupling times are recorded, high temperature peaks are observed during microwave coupling process at very beginning of plasma breakdown. It can support a model of breakdown composed by two stages: microwave coupling, characterized by a fast heating peak followed by a cooling process to final stable temperature and density. However, for lower incoming powers, temperature evolution shows a gradual tendency to reduce the peak values but evolving gradually towards a higher final temperature without peaking. An explanation of such behavior may be found in the influence of seed electrons.[3,11] Immediately after each microwave pulse is extinguished, a residual electron density remains embedded in the neutral gas during enough time to produce effect on the following pulse breakdown. If incoming power is high enough, residual electrons may produce an electron density at beginning of pulses also high enough to guarantee a fast coupling. Under this circumstance, saturation of fast coupling times with respect to duty cycle may be produced as can be seen in the curve (a) of Fig. 6. This effect may be strongly related to the electron temperature peaks reported here and it may be determining for microwave coupling process at early breakdown stage.[12] However, the growth of breakdown times for high duty cycles at lower incoming powers is still contradictory to such explanation. A further research on this point is in the aim of our

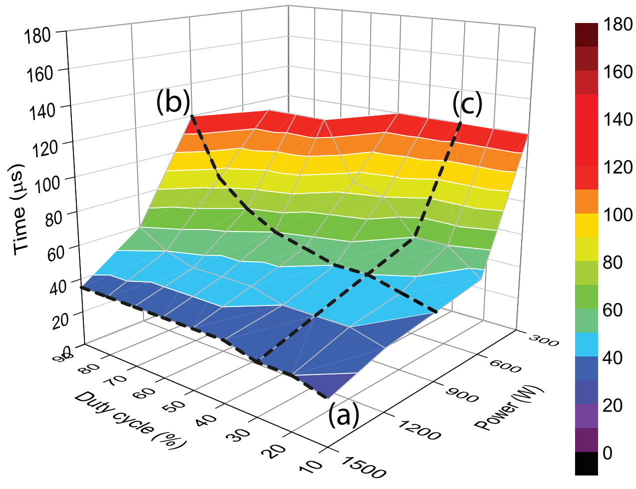

FIG. 6. Microwave coupling time as function of incoming power and duty cycle.

near future work. Finally, the early instant when temperature peaks are observed in our experiment, also suggests a relationship of this observation with preglow processes during breakdown in ECRIS plasmas.[13–15]

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