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Electron cyclotron resonance breakdown studies in a linear plasma system

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Abstract. Electron cyclotron resonance (ECR) plasma breakdown is studied in a small linear cylindrical system with four different gases – hydrogen, helium, argon and nitrogen. Microwave power in the experimental system is delivered by a magnetron at 2.45 ± 0.02 GHz in TE_{10} mode and launched radially to have extra-ordinary (X) wave in plasma. The axial magnetic field required for ECR in the system is such that the fundamental ECR surface ($B = 875.0$ G) resides at the geometrical centre of the plasma system. ECR breakdown parameters such as plasma delay time and plasma decay time from plasma density measurements are carried out at the centre using a Langmuir probe. The operating parameters such as working gas pressure (1×10^{-5}–1×10^{-2} mbar) and input microwave power (160–800 W) are varied and the corresponding effect on the breakdown parameters is studied. The experimental results obtained are presented in this paper.

Keywords. Electron cyclotron resonance breakdown; delay time; e-folding time.

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1. Introduction

Electron cyclotron resonance (ECR) assisted pre-ionization is a common technique used in tokamaks [1–12], stellerators [13,14] and other plasma devices such as tokapole [15] for start-up and to assist plasma formation in the initial stage of the discharge. In ohmic discharge, high loop voltage is required to initiate the discharge when plasma density, temperature and conductivity are low and the line radiation from impurities are the dominating losses. The main attractive feature of the ECR heating (ECRH) start-up lies in the reduction of volt-second consumption. ECRH can also lead to a decrease of the initial runaway electron population in the initial plasma phase. Thus, ECRH-assisted start-up allows the control over the localization of initial breakdown which also reduces the plasma–wall interaction and the losses arising due to low-Z impurity line radiation by the ill-confined plasma of the early stage discharge.

ECR plasma breakdown study is critical for plasma and fusion devices such as tokamaks and stellerators as it helps in achieving reliable and reproducible discharges over a broader parameter space of operation. Hence, plasma breakdown study optimizes the plasma parameters such as plasma density and temperature. The breakdown phase also affects the ultimate plasma parameters in particular relevance with the production of runaway electrons, impurity generation, thermal equilibrium, stability, etc.

Some experiments have been reported on the toroidal plasma systems to study ECR breakdown parameters with microwaves ranging from few GHz to few tens of GHz launched in both O-mode and X-mode from the low-field as well as from the high-field side of the toroidal system. The filling gases used in these experiments are mainly hydrogen, helium and argon. Plasma delay time, τ_{delay}, is observed experimentally in RTP (Rijnhuizen tokamak project) [10] and plasma e-folding time, $\tau_{\text{e-fold}}$ is measured in ISX-B (impurity study experiment) [4]. τ_{delay} gives the parameter space of operation while $\tau_{\text{e-fold}}$ gives the particle confinement. However, due to the presence of stray error fields (B_z) in the plasma volume, prompt breakdown is not achieved with only the ohmic electric field. Further, conservation of volt-sec during the breakdown phase can be optimally carried out with pre-ionization using ECRH.

It is difficult to carry out the basic experiments pertaining with ECR-produced plasmas in large plasma systems such as tokamaks and stellerators because of higher values of plasma parameters such as plasma density and temperature and system parameters such as magnetic fields etc. The dependence on these large machines can be avoided by designing small toroidal systems to carry out basic experiments. The toroidal geometry plasma systems have a basic advantage of better plasma confinement over the cylindrical shaped plasma systems. But this effect of system geometry is not of much significance in ECR-produced plasmas because of higher frequencies (~few GHz) of microwave sources. Hence, a small linear ECR plasma system can also serve the purpose.

In the paper, the time delay measurements carried out with parameters such as power, pressure, etc. are relevant to the tokamaks. The time delay can be reduced either by increasing the input microwave power (oscillating electric field) or by adjusting the operating gas pressure. Hence, the time delay study is very important and necessary for stable and repeatable tokamak discharge. These parameters strongly depend on the initial experimental conditions such as input microwave power and the filling gas pressure. The experiments presented in this paper are intended towards the investigation of these ECR breakdown parameters.

The paper is organized as follows. In §2, the experimental set-up and diagnostics are discussed. Section 3 is dedicated to ECR breakdown parameters. In §4, the experimental results and interpretation is presented. Finally, §5 has the discussion and main conclusions drawn.

2. Experimental set-up

The experimental set-up is described elsewhere [16]. The cylindrical vacuum chamber is 6.41 cm thick and 10 cm long as shown in figure 1 which is evacuated up to

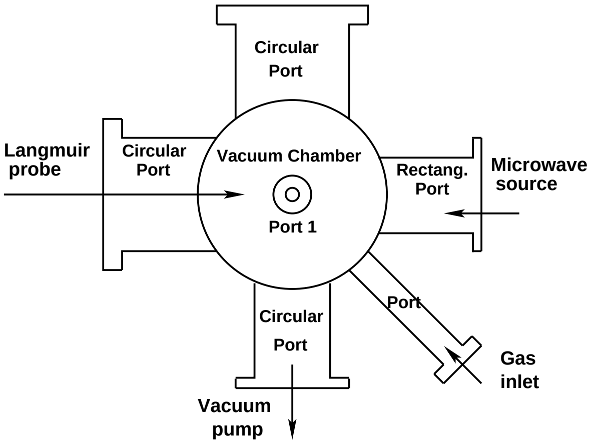

Figure 1. Main chamber (axial view).

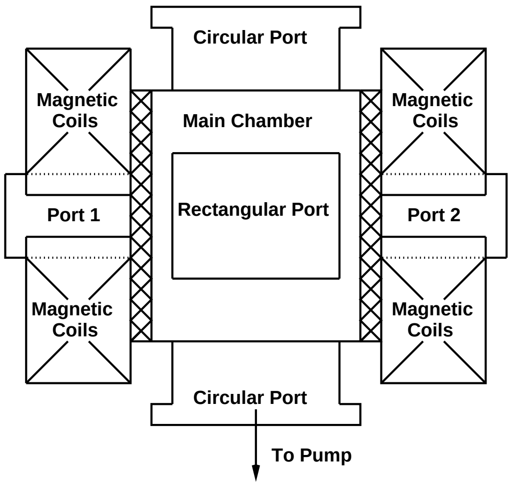

Figure 2. System configuration (radial view).

a base pressure of 6×10^{-6} mbar. The magnetic field in the system is produced by two identical coils placed axially at the two ends of the vacuum chamber as shown in figure 2. Each coil requires 5.3 A direct current to produce 875 G magnetic field at the central axis of the system. The field contours and its axial variation are shown in figures 3 and 4 respectively. This field is kept constant for more than 1 s as shown in figure 5. The microwave source is a 800 W, 2.45 GHz magnetron and the microwave power is measured using a pair of Schottky diode detectors. The schematic is shown in figure 6. To study the ECR breakdown process, high voltage power supply for magnetron is triggered by a tetrode-based fast switch [17]. This fast switching provides a microwave power rise time of ≈ 3 μs. Plasma density, n_e

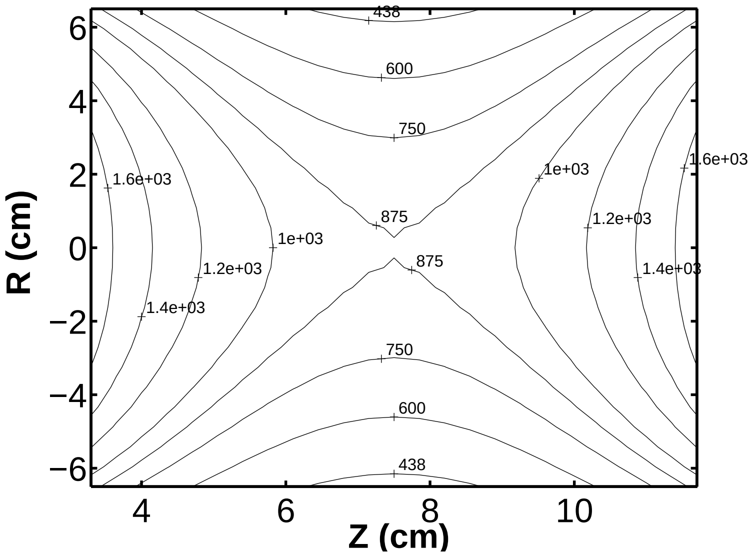

Figure 3. Contour plot of magnetic field in the system.

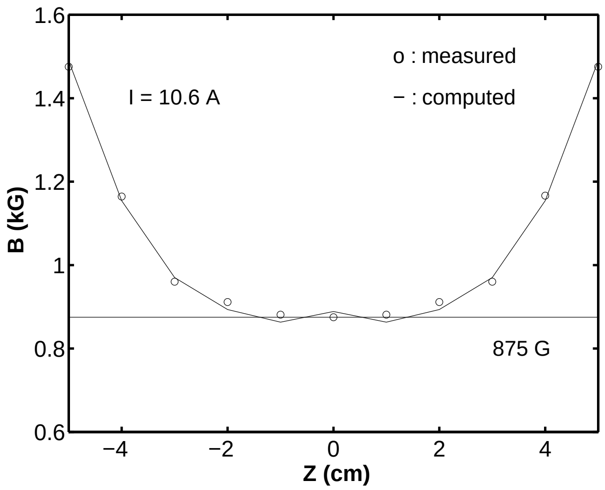

Figure 4. Axial variation of magnetic field in the system.

is measured with a Langmuir probe [18] having tungsten probe tip length ∼5 mm and diameter 0.5 mm. The DC bias voltage applied on Langmuir probe to collect the $I_{\rm sat}$ is −80 V.

Increase in plasma density with launched microwave power is shown in figure 7 in which the top trace is microwave power measured from the forward port of directional coupler and the bottom trace is ion saturation current $I_{\rm sat}$, which gives an estimate of plasma density. For this experimental set-up it is given by [19]

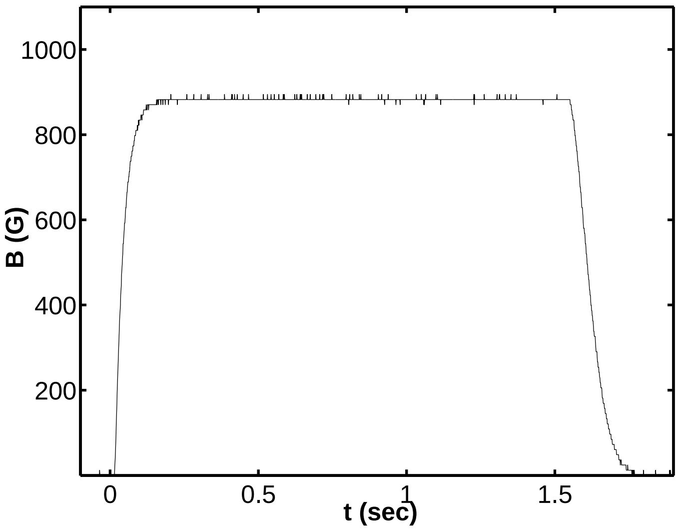

Figure 5. Temporal profile of magnetic field.

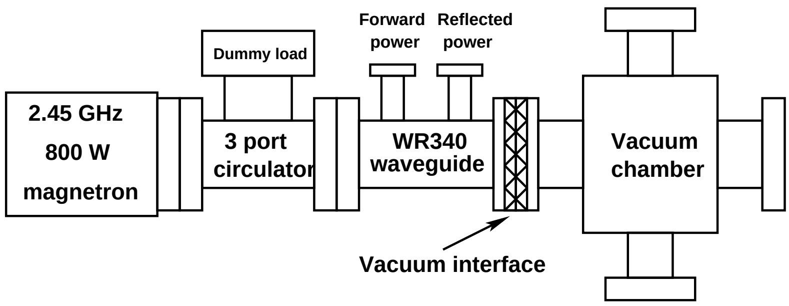

Figure 6. Schematic of the microwave system.

$$n_e(\text{cm}^{-3}) = \frac{8.97 \times 10^8 I_{\text{sat}}(\text{mA})}{\sqrt{KT_e(\text{eV})}}, \tag{1}$$

where T_e is the electron plasma temperature. In the initial phase of ECR breakdown, T_e has a slow time variation. Hence plasma density becomes

$$n_e \propto I_{\text{sat}}. \tag{2}$$

3. ECR breakdown parameters

ECR plasma breakdown parameters are defined as follows. Plasma delay time τ_{delay} is the time interval between the launch of microwave power and the appearance of detectable (∼10%) plasma density as shown in figure 8. Plasma e-folding time

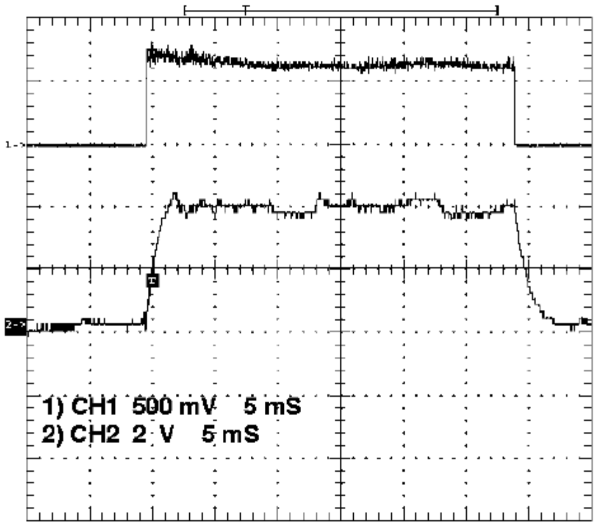

Figure 7. Oscilloscope traces for (1) microwave power and (2) plasma density.

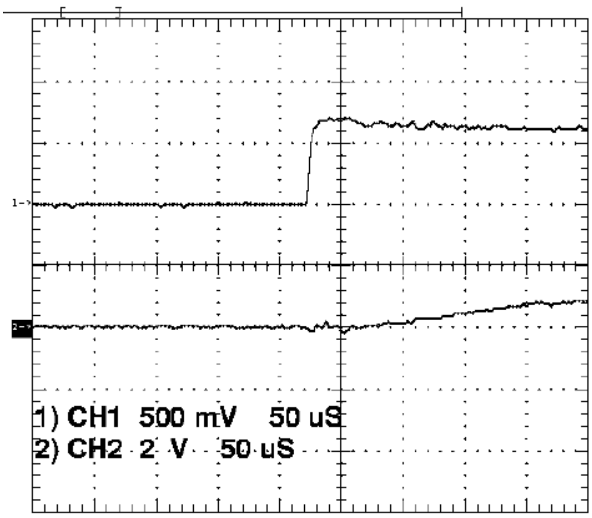

Figure 8. Oscilloscope trace for plasma delay time.

$\tau_{\text{e-fold}}$ is the time after which plasma density decreases to $1/e$ of the maximum value. This measurement is done from the time when microwave power pulse is terminated as shown in figure 9.

In the initial phase of breakdown, electron-neutral collision plays an important role in initiating the discharge. The electron-neutral mean free path λ_{en} [20] is given by

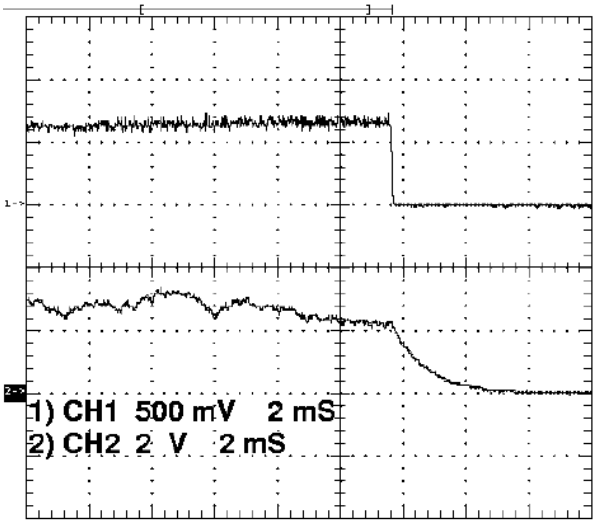

Figure 9. Oscilloscope trace for plasma fall time.

$$\lambda_{\mathrm{en}} = \frac{4}{\pi n_{\mathrm{n}} d^2}, \tag{3}$$

where d is the neutral molecule/atom diameter and n_{n} is the neutral density given by

$$n_{\mathrm{n}} = 244.5 \times p \tag{4}$$

p being the operating pressure in mbar. λ_{e} for various gases at different neutral pressures is given in figure 10 which shows high λ_{e} at lower pressure.

The ionization time τ_{i} [21] is the time at which the breakdown in a neutral gas starts after the application of external electric field. It is expressed as

$$\tau_{\mathrm{i}} = \frac{1}{n_{\mathrm{n}} \sigma v_{\mathrm{e}}}. \tag{5}$$

Here, σ is the electron-impact ionization cross-section and v_{e} is the electron thermal velocity. For ECR breakdown, as in our experiment, we term it as the plasma delay time that is required for plasma formation. Equation (5) shows that τ_{delay} is inversely proportional to n_{n} and on increasing p according to eq. (4), τ_{delay} reduces.

Plasma delay time has a complicated dependence on energy gained E_{in} from the launched microwaves while gyrating in the presence of steady magnetic field. The energy gained in this way is utilized for ionization and to provide kinetic energy to newly generated electrons, given by

$$E_{\mathrm{in}} = eV_{\mathrm{p}} + \frac{1}{2} m_{\mathrm{e}} v_{\mathrm{e}}^2, \tag{6}$$

where V_{p} is the ionization potential for the gas and m_{e} is the mass of the electron. τ_{delay} is now given by

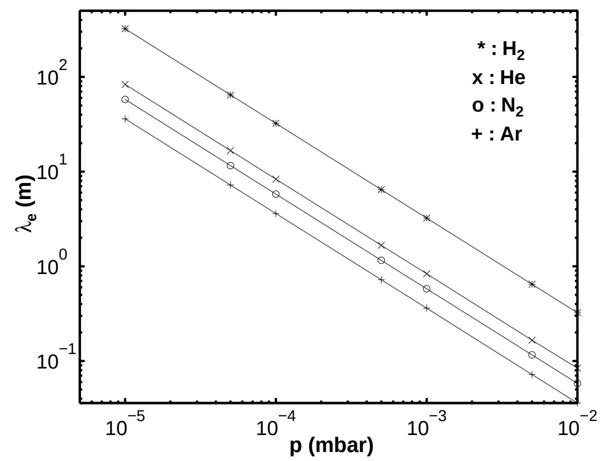

Figure 10. Electron-neutral mean free path at different fill pressures for various gases.

$$\tau_{\rm delay} \propto \frac{1}{\sqrt{2(E_{\rm in} - eV_{\rm p})}}. \tag{7}$$

4. Estimation of losses prior to breakdown

There are two processes taking place simultaneously in an ECR-produced discharge, the ionization of neutral gas by accelerated electrons in the induced electric field of the launched microwave and the loss of electrons to the chamber walls through diffusion or drift and loss by attachment or recombination.

For the experimental conditions prevailing in this plasma system, the attachment and recombination losses are negligible. As the magnetic field is kept constant for all the experiments, the geometrical losses do not change for this plasma set-up.

The diffusion constant of the electrons due to elastic collisions with neutral gas particles perpendicular to the magnetic field lines [19] is given by

$$D_\perp = D_\parallel \left(1 + \frac{\omega_{\rm ce}^2}{\nu_{\rm en}^2}\right)^{-1}, \tag{8}$$

where $\omega_{\rm ce}$ is the electron angular cyclotron frequency, $\nu_{\rm en}$ is the electron-neutral collision rate and $D_\parallel$ is the diffusion coefficient along the magnetic field lines given by

$$D_\parallel = \frac{T_{\rm e}}{m_{\rm e}\nu_{\rm en}}, \tag{9}$$

where $T_{\rm e}$ is the electron temperature ($\approx$1 eV) prior to breakdown in the neutral gas. At a fill pressure of 10^{-3} mbar, $\nu_{\rm en}$ comes out as 1.3×10^5 s^{-1} which gives $D_\parallel$

Table 1. The ionization potential for various gases.

Gas	Z	Ionization potential, $V_{\rm p}$ (eV)	Atomic/ molecular radius (Å)
Hydrogen	1	15.4	1
Helium	2	24.6	1.5
Nitrogen	7	15.58	1.25
Argon	18	15.8	1.9

of 1.17×10^5 cm^2/s in this experiment. The diffusion time $t_{\rm d,\parallel}$ along the magnetic field line can be given as

$$t_{\rm d,\parallel} = \frac{a^2}{D_\parallel}, \tag{10}$$

where $a = 10$ cm is the axial length of the linear system. Hence, $t_{\rm d,\parallel} \approx 1$ ms. Thus, $D_\perp$ turns out to be 3.3×10^{-4} cm^2/s. The diffusion time perpendicular to the magnetic field is given by

$$t_{\rm d,\perp} = \frac{r_{\rm L}^2}{D_\perp}, \tag{11}$$

where $r_{\rm L}$ is the electron Larmor radius which is 2.72×10^{-3} at the geometrical centre of the experimental chamber where the magnetic field is 875 G. $t_{\rm d,\perp}$ finally turns out to be ≈ 22.5 ms.

The drift is not a random process depending upon the presence of other particles. The drift time $\tau_{\rm drift}$ for an electron placed at the central axis of experimental set-up is given by

$$\tau_{\rm drift} = \frac{a}{v_{\rm d}}, \tag{12}$$

where $v_{\rm d}$ is the drift velocity of a free electron. Typically, $\tau_{\rm drift}$ turns out to be few hundreds of μs for this plasma system.

The actual ionization time is ≈ 1 μs which says that to reach the critical plasma density for breakdown which is defined as the breakdown time would lie between 50–100 μs [22]. However, we have measured the formation time which is $\tau_{\rm delay}$ as 10% of the maximum plasma density.

5. Experimental results

The ECR breakdown parameters are studied with variation in experimental parameters such as the operating gas pressure and input microwave power with different gases such as hydrogen, argon, helium and nitrogen. The ionization potential and atomic/molecular radius are given in table 1. During the experiment, ECR breakdown is observed in the pressure range of 1×10^{-5}–1×10^{-2} mbar for a fixed input microwave power of 800 W. For input power variation of 160–800 W, the breakdown

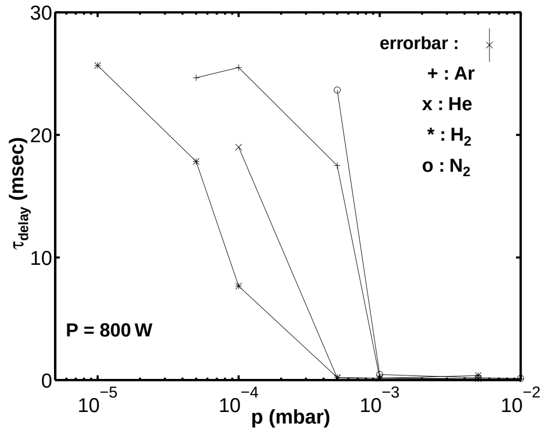

Figure 11. Plasma delay time with fill pressure variation in different gases.

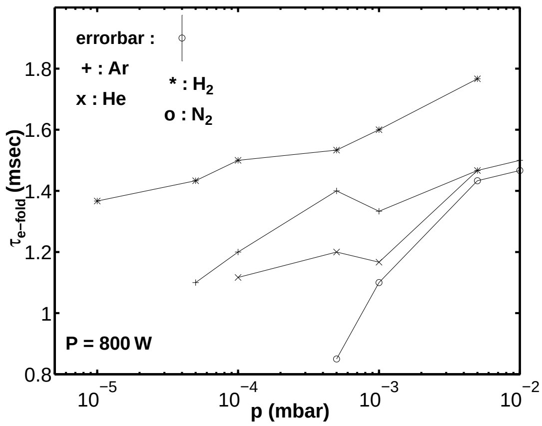

Figure 12. Plasma e-folding time with fill pressure variation in different gases.

is observed at a fixed operating pressure of 1×10^{-3} mbar. All these measurements are carried out on the central axis of the experimental system. During the experiment, magnetic field is adjusted such that the fundamental cyclotron resonance lies on the central axis. Gas is filled intially to a desired pressure during the experiment in the experimental chamber. Prior to the microwave pulse, the magnetic field is switched on. Microwave power is introduced for ∼30 ms during which the ECR breakdown occurs in the system.

A *Breakdown parameters with operating pressure*

During the measurement of ECR breakdown parameters as a function of gas pressure, the input microwave power is held constant at 800 W.

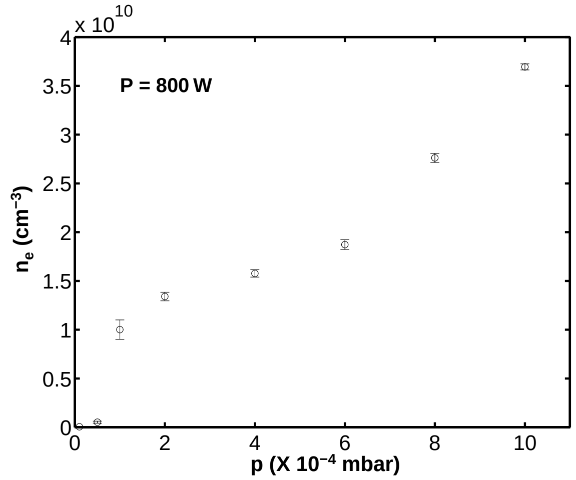

Figure 13. Plasma density variation with gas fill pressure in hydrogen.

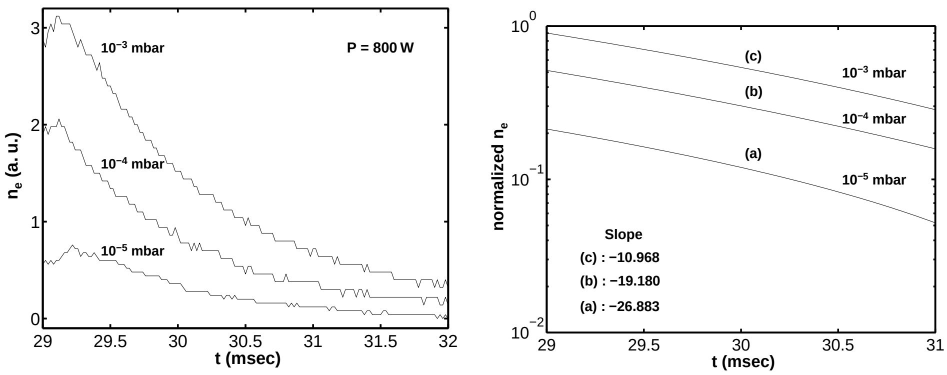

Figure 14. Plasma decay at different gas pressures (left). The corresponding slopes (right).

The time delay, observed with various gases at different pressures, is shown in figure 11. It is clearly seen that at a low gas pressure of 1×10^{-5} mbar, the delay time is larger (in ms range) due to reduced number of electron-neutral collisions compared to higher pressure. As the pressure is increased, λ_{e} decreases (figure 10) and collisions are more frequent. Hence, the delay time reduces and goes into μs range at 5×10^{-3} mbar.

Plasma e-folding time is also measured at variable pressure as shown in figure 12. The e-folding time increases with pressure because of higher plasma density at higher operating pressure as shown in figure 13. In this experiment, ECR discharge is produced at low pressure (10^{-5}–10^{-2} mbar) where the main loss mechanism is diffusion to the chamber walls. The diffusion time increases with plasma density [23]. Plasma diffusion from different density levels due to a variation in pressure is shown in figure 14. The slope of the three curves at different pressures differs which confirms that in the afterglow plasma of a microwave discharge, e-folding time

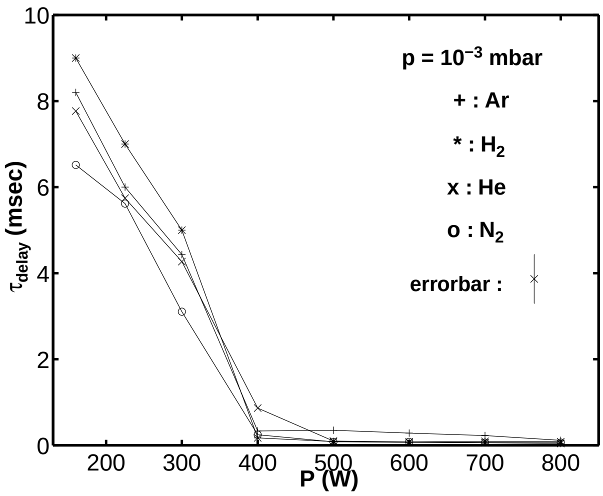

Figure 15. Plasma delay time with microwave power variation in different gases.

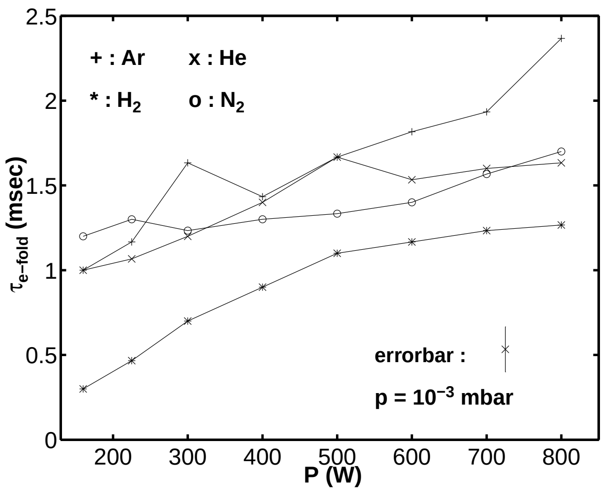

Figure 16. Plasma e-folding time with microwave power variation in different gases.

depends on plasma density level. This result is in contradiction to high pressure discharges in which the main loss mechanism is recombination and the e-folding time reduces with increase in plasma density [23].

$$\tau_{\mathrm{decay}} \propto \frac{1}{\alpha n_{\mathrm{e}}}, \tag{13}$$

where α is the recombination coefficient.

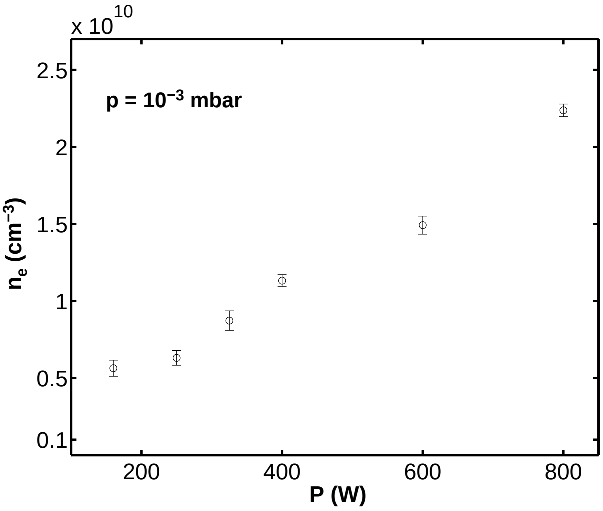

Figure 17. Plasma density variation with input microwave power in hydrogen.

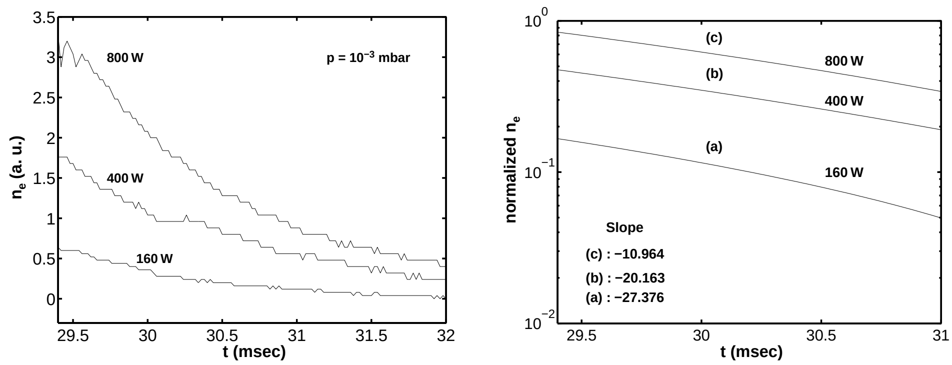

Figure 18. Plasma decay at different microwave power (left). The corresponding slopes (right).

B *Breakdown parameters with input microwave power*

During the measurement of ECR breakdown parameters with input microwave power variation, the operating gas pressure is fixed at 1×10^{-3} mbar.

With different gases, the delay time has a linear relation with input power as shown in figure 15 which shows that at low input power such as 160 W, the electron generation is low and more collisions are required to ionize the neutrals [16]. Hence, the delay time is observed to be a few ms. At higher input power such as 800 W, the delay time decreases in μs range. When the input power is high, electrons gain more energy and each electron does multiple collisions with the neutrals. This increases the rate of ionization and the delay time reduces. This result is in accordance with eq. (7) which shows that on increasing the input power, delay time decreases.

For different gases, plasma e-folding time is measured with variable input power as shown in figure 16. The e-folding time increases with input power because of higher plasma density at higher power as shown in figure 17. This increases the diffusion time for higher plasma densities [23]. Plasma diffusion from different density levels is shown in figure 18. The difference in slopes for the three power levels show that the diffusion depends strongly on plasma density level.

All these experimental results are consistent with similar experiments performed in toroidal machines. The results show that irrespective of the gas species, plasma delay time reduces with operating pressure which is in good agreement with the results obtained in RTP [9] and interchangeable module stellarator (IMS) [14]. The observation in reduction of delay time with input power matches well with results obtained in RTP [10]. Plasma e-folding time increases with pressure as well as with input power for all the gases used.

As no theoretical model is available for ECR breakdown in a linear plasma system, efforts are on to develop a simple model to explain the results obtained in these experiments.

6. Conclusion

ECR plasma has been successfully formed in a cylindrical system. First harmonic breakdown with 2.45 GHz microwave frequency and 875 G magnetic field at the system axis is achieved. ECR breakdown parameters are experimentally measured for hydrogen, helium, nitrogen and argon. The input microwave power is varied for a fixed operating pressure and the breakdown parameters are studied. For the other set of experiments, the operating pressure is changed for a fixed input microwave power.

The parameter space for operating the pulsed experimental system has been identified for different gases. The experimental results show that irrespective of the fill gas, plasma delay time reduces with pressure at constant input power. It also reduces with input power at fixed fill pressure. Plasma decay time increases systematically with fill pressure for fixed input power and for a preset pressure, increases with input power for all the gases used in the experiments. All these results are consistent with similar experiments performed earlier in toroidal machines.

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