Chapter 5

Parametric decay in ECR plasma

5.1 Introduction

In the previous chapters of this thesis, the design of experimental set-up with auxiliary sub-systems, ECR plasma breakdown and the measurement of plasma parameters are discussed. The spatial profiles of plasma parameters in the axial as well as in the radial directions are measured. With the help of these profiles, various resonance and cutoff locations in the cylindrical plasma system are identified. The results obtained in these experiments reveal that the ECR plasma system performs well within the design limits and can be used for advanced experimental investigations of nonlinear phenomena occurring in ECR produced plasma.

Plasma, by its nature, is a highly nonlinear dielectric medium. In the presence of an external magnetic field ($\vec{B}_0$), plasma can support a large number of different modes of electromagnetic (EM) and electrostatic (ES) wave under proper conditions. These modes are present in the form of either thermal fluctuations, instabilities or turbulence generated by the launched microwaves from outside. Hence, the macroscopic properties of hot plasma depend on collisionless, turbulent processes. These processes try to establish thermodynamic equilibrium and predict the outcome of the nonlinear phenomena.

Different modes of oscillation in the plasma get coupled and grow exponentially in either space or in time under the influence of high frequency EM waves. If the incident EM wave has a long wavelength as compared with the wavelength of the decay
wave then energy transfer to plasma particles is possible through collective effects. This is the process of anomalous absorption of the incident EM wave. Therefore, the parametric instabilities, which require a finite threshold power for excitation, can transfer EM energy efficiently to hot plasma particles.

In this chapter, the basic nonlinear processes that can occur in an ECR produced plasma are studied. The chapter is organized as follows. In section 2, the parametric decay in plasma is described with its significance and special emphasis on ECR produced plasmas. In section 3, the theoretical and experimental works undertaken earlier pertaining to the study of this nonlinear phenomena are discussed with the motivation it provided for this experimental endeavour. In section 4, the experiments performed to observe and study the parametric decay with different filling gases are presented and the results obtained are discussed. In the same section, the input microwave power threshold for the parametric decay to occur is calculated theoretically followed by the estimation of the sustainment of the lower hybrid waves in this ECR plasma system. At the end of the chapter, in the last section, the main conclusions drawn from these experiments are given.

5.2 Parametric instability in plasma

Parametric instability, in general, means the amplification of an oscillation due to a periodic modulation of a parameter that characterizes the oscillation. In plasma, under the influence of an externally applied high frequency EM field, various plasma modes may become coupled and may be driven unstable. Parametric instabilities are non-absolute and convective in nature particularly in decay approximation.

When high energy EM waves passes through a plasma, strong periodic oscillations of the electrons and ions may be excited. The action of EM field on the plasma, which is the non-relativistic case

$$\frac{v_E}{c} << 1 \quad \frac{v_{Te}}{c} << 1$$

is governed by the electric field component, causes the plasma parameters to vary with time. Due to different charge and mass of electrons and ions, there is a relative oscillation of particles in the wave field (ions being practically motionless). Thus, the
electron current density in plasma undergoes oscillations. When the plasma parameter oscillation amplitude is sufficiently large, the fluctuations of its characteristic oscillations may increase (parametric resonance) leading to parametric instability of the plasma. This instability is the result of nonlinear interaction of waves, when there is a regenerative coupling between various types of oscillation resulting in an exponential increase of their amplitude with time and in space, until saturation is reached.

If the wave incident on plasma (pump wave) is weakly damped in the plasma, it can transfer its energy in nonlinear interaction to another wave (e.g. in the decay process) which is more strongly damped and so increase the efficiency of the collective process of energy transfer to charged particles (Landau damping). Such a mechanism bringing about anomalous absorption of an EM wave in a plasma (similar to turbulent heating) is important for the heating of high-temperature plasmas, where the collisional absorption mechanism becomes ineffective. Hence, the transformation of a strong incident (pump) wave into plasma waves is a nonlinear process, governed by collective phenomena in plasma. This is the parametric action of radiation on the plasma which results in the parametric instability or decay observed near the edge of tokamaks.

The parametric excitation describes the nonlinear coupling of a high frequency electric field to low and high-frequency density oscillation modes of the plasma. This nonlinear coupling can transfer energy from the high-frequency electric field to low-frequency modes and, therefore, drives low-frequency instabilities.

In plasmas, the nonlinear phenomena causes the interaction between different modes of oscillations or waves. This interaction can decay a wave into two waves. The wave amplitude, $A$ has spatial and temporal dependence such as

$$A \sim \exp[i(k\cdot r - \omega t)]$$  \hspace{1cm} (5.2)

This decay follows the relations

$$\omega_0 = \omega_1 + \omega_2$$

$$\omega_0 + \omega_1 = \omega_3$$ \hspace{1cm} (5.3)

$$\vec{k}_1 = \vec{k}_2 + \vec{k}_2$$

and is shown in the figure 5.1.
5.2.1 Significance of parametric effects

The parametric effects, such as the instability or decay, in different fields of plasma physics, can be of practical usage. In controlled thermonuclear fusion experiments, this usage lies in plasma heating by high-frequency EM waves. In this heating scheme, parametric effects provide a rapid dissipation mechanism. In the category of collisionless shock waves, a similar mechanism plays a crucial role. The parametric effects has been found to be of great application in the problem of initiation of fusion in super-compressed condensed materials by means of a strong laser emission. The state of ionosphere can also be influenced upto a great extent due to the parametric instabilities exerted with relatively low power radio-transmitters.

5.2.2 Parametric decay in ECR plasma

In ECRH, the launched EM wave, entering in plasma as X-mode reaches the gap between the UHR surface and the ECR surface. Near the UHR layer, due to resonance, X-mode wavelength becomes very small and the amplitude of wave electric field becomes very large due to high power density at that location. This large wave electric field gives rise to the nonlinear phenomena of parametric excitation in which the incoming EM wave breaks up into two electrostatic parts - the electron Bernstein wave (EBW) [119], through X-B mode conversion and lower hybrid wave (LHW) [120]. The EBW propagates towards the plasma centre and gets absorbed...
at the ECR layer contributing significantly in efficient plasma heating [121–123].

The parametric instabilities generate decay waves with frequencies of the incident pump wave, $f_0$ and $f_0 \pm f_{LH}$ and the LHW itself. The appearance of this decay spectrum is an evidence that X-B mode conversion has occurred. The physical mechanism behind the parametric side-band theory can be given as follows. The presence of a large amplitude (traveling) electron plasma (LAEP) wave in plasma generate a spatially periodic potential for the electrons in the wave frame. The trapping of electrons in the wave trough produces a bounce frequency resonance. The coupling of the LAEP wave with the bounce resonance frequency produces upper and lower sidebands about the traveling wave frequency [124].

5.3 Earlier work on parametric effects

The nonlinear phenomena associated with electron-plasma oscillation is studied since long back by frequency mixing at plasma resonance experimentally [125,126] as well as theoretically [127,128]. The general formulation for the parametric excitation of coupled waves is given by Nishikawa [129,130] who studied the parametric instabilities in the presence of damping and calculated the threshold of parametric instability - the incident wave amplitude, above which the instability sets in. In the parametric excitation or the nonlinear coupling of a high-frequency electric field to low and high frequency density oscillation modes of plasma, the transfer of energy can take place [131]. The existence of nonlinear decay of cyclotron harmonic plasma wave is also experimentally verified [132].

In parametric decay, the launched EM wave can break-up into the two components depending upon the incident wave frequency and the plasma conditions. The parametric decay of the launched pump wave into EC harmonic wave and ion acoustic wave is experimentally observed [133]. The decay is also observed with the incident wave in both polarization schemes : O-mode into electron plasma wave and ion acoustic wave and X-mode into upper hybrid (Bernstein) and lower hybrid or ion acoustic waves in Princeton L-3 [134]. Parametric decay effects are observed with incident wave of $\approx 35 \text{ GHz}$ frequency into a lower hybrid and a electron Bernstein mode [135]. Nonlinearly saturated resonant decay of the launched wave into LHW
and slow ion-cyclotron wave is seen in toroidal ACT-1 plasma [136].

Two types of parametric decay instabilities are observed during ICRH [137,138]. In one of the decay, the incident EM wave breaks into two parts - an ion Bernstein wave (IBW) and an ion cyclotron quasimode (IQM) which is observed earlier also with a fast wave ICRF antenna [139] whereas in the other decay the incident wave decays into an IBW and a cold electrostatic ion cyclotron wave (CESICW) or an electron quasimode (EQM) [140].

The large amplitude electrostatic oscillation, generated near a resonance layer, is capable of giving rise to a variety of nonlinear effects including the parametric decay process [141]. The parametric instability generation is also observed due to an EC wave launched by a helical beam antenna immersed in the plasma column [142].

Under the action of a high-power electromagnetic radiation on a plasma, the parametric instabilities developed in the plasma leading to the appearance of a turbulent state with an increased level of fluctuations of the internal field in the plasma. These fluctuations changes the particle distribution particularly their energies which corresponds to the anomalous fast transfer of the energy of the incident radiation field to the plasma particles [143].

### 5.4 Parametric decay in different gases

The experimental observation of nonlinear phenomena of parametric decay is performed with three different gases namely hydrogen, argon and helium in the cylindrical ECR plasma system. The current in the magnetic field coils is set to give a magnetic field (875 G) corresponding to the fundamental resonance on the axis while the second harmonic resonance layer is adjusted near the edge of the vessel at \( R = 5 \) cm. The output frequency spectrum of the microwave source is shown in figure 5.2. As seen in the figure, the spectrum is asymmetric with a peak at 2.47 GHz and has \( \sim 1 \) GHz FWHM (Full Width at Half Maximum). Therefore, the spectra studied during the experiments are broad and the appearance of new frequencies are over this broad launched spectrum.
5.4.1 Parametric decay in hydrogen plasma

ECR plasma is produced in the experimental chamber with hydrogen gas. The radial profiles of the three frequencies, namely electron cyclotron frequency $f_{ce}$, electron plasma frequency $f_{pe}$, and the upper hybrid resonance frequency $f_{uhr}$, are calculated and plotted for the measured hydrogen plasma density and the magnetic field profile as shown in figure 5.3.

Figure 5.3: Radial variation of $f_{ce}$, $f_{pe}$ and $f_{uhr}$ in hydrogen plasma.
As evident from the figure, \( f_{pe} < f_0 \) and hence the plasma is underdense. At \( R = 0 \text{ cm} \) radial position, \( f_{ce} \approx f_0 \) indicating the presence of first ECR surface at that location. Plasma density during the discharge for an input microwave power of 800 \( W \) is such that the UHR layer during the experiment resides at \( R = 2 \text{ cm} \). The \( f_{uhr} \) location with a variation in input microwave power at constant operating pressure of \( 1 \times 10^{-3} \text{ mbar} \) is plotted in figure 5.4.

![Figure 5.4: \( f_{uhr} \) with input microwave power variation in hydrogen plasma.](image)

The figure clearly shows that despite the change in input microwave power, the UHR layer remains near \( R = 2 \text{ cm} \) position due to weak dependence of plasma density. To observe the parametric decay, the capacitive probe is introduced in the experimental system from the radial port opposite to the microwave power source. The capacitive probe is moved radially to scan the region from \( R = 0 \text{ cm} \) (centre) to \( R = 6 \text{ cm} \) (system edge towards the magnetron) with 800 \( W \) of input microwave power. This is the region in which the nonlinear phenomena is expected to occur. The operating gas pressure is kept constant at \( 1 \times 10^{-3} \text{ mbar} \) during the experiment. The parametric decay spectrum at UHR is shown in figure 5.5. The figure clearly shows the emergence of new frequencies on either side of the launched frequency \( f_0 \) (2.47 \( GHz \)) at 2.442 \( GHz \) and 2.407 \( GHz \) on the lower side and at 2.49 \( GHz \) and 2.508 \( GHz \) on the higher side. These frequencies are checked for the lower hybrid frequency.
The lower hybrid frequency is given by

\[ \frac{1}{\omega_{LH}^2} = \frac{1}{\Omega_{pi}^2} + \frac{1}{\Omega_{ci} \omega_{ce}} \]  

(5.4)

where \( \omega_{LH} \) is the lower hybrid frequency, \( \Omega_{pi} \) is the ion plasma frequency and \( \Omega_{ci} \) is the ion cyclotron frequency. \( \omega_{ce} \) is the electron cyclotron frequency.

The LHW frequency at the UHR layer in hydrogen plasma is calculated as

\[ f_{LH} = \frac{1}{2\pi} \left[ \frac{n_e e^2 B^2}{M (B^2 e_0^2 + mn)} \right]^{1/2} \]  

(5.5)

where \( M = 1.67 \times 10^{-27} \text{ kg} \) is mass of the ion which gives \( f_{LH} = 23.4 \text{ MHz} \).

Hence, the peaks with frequency 2.493 GHz on the higher side (\( f_0 + f_{LH} \)) of the incident wave (Blue shifted) and 2.437 GHz and 2.414 GHz on the lower side (\( f_0 - f_{LH} \)) of the incident wave (Red shifted) are estimated to be observed. It is observed that the difference in frequency of the peaks, \( f_{LH} \) matches well with theoretically estimated values.

The LH frequency is observed separately as the residual frequency in the parametric decay by directly feeding the capacitive probe signal to the spectrum analyser which is shown in figure 5.6. The figure shows the presence of LHW which has a frequency of 37.9 MHz. This frequency matches well within experimental error with the difference of the main and the first lower-side peak which is 33 MHz. The difference is within measurement error in separate shots.
The condition for LH wave is given by

\[ f_{\text{ci}} < f_{\text{LH}} < f_{\text{ce}} \]  

(5.6)

due here, \( f_{\text{ci}} \) is the ion-cyclotron frequency, \( f_{\text{ce}} \) is the electron cyclotron frequency and \( f_{\text{LH}} \) is the lower hybrid frequency. \( f_{\text{ci}} \) at the UHR location is 1.17 MHz, \( f_{\text{ce}} \) is 2.15 GHz and \( f_{\text{LH}} \) is 36.74 MHz. Hence, this frequency satisfies the above condition and confirms the existence of LH wave at that location.

The theoretical calculations also support the existence of LH waves in this ECR plasma system. This is highlighted as follows. The cold plasma dispersion relation with ion motion and including the electron convection (\( \nabla n \neq 0 \)) [144] is given by

\[ 1 + \left( \frac{\omega_{\text{pe}}}{\omega_{\text{ce}}} \right)^2 + \frac{\chi_n k_y \omega_{\text{pe}}^2}{k^2 \omega_{\text{ce}}} - \left( \frac{\omega_{\text{pe}}}{\omega} \cos \theta \right)^2 - \frac{\omega_{\text{pi}}^2}{(\omega - k_y V)^2} = 0 \]  

(5.7)

For \( V = 0 \), the above equation reduces to

\[ 1 + \left( \frac{\omega_{\text{pe}}}{\omega_{\text{ce}}} \right)^2 + \frac{\chi_n k_y \omega_{\text{pe}}^2}{k^2 \omega_{\text{ce}}} - \left( \frac{\omega_{\text{pe}}}{\omega} \cos \theta \right)^2 - \frac{\omega_{\text{pi}}^2}{\omega^2} = 0 \]  

(5.8)

The value of \( \cos \theta \) is given by

\[ \cos^2 \theta = \frac{m_e}{m_i} \frac{\omega_{\text{ci}}}{\omega_{\text{ce}}} \]  

(5.9)

Keeping this in equation (5.8), we get

\[ 1 + \left( \frac{\omega_{\text{pe}}}{\omega_{\text{ce}}} \right)^2 + \frac{\chi_n k_y \omega_{\text{pe}}^2}{k^2 \omega_{\text{ce}}} - \frac{\omega_{\text{pe}}^2 \omega_{\text{ci}}}{\omega^2 \omega_{\text{ce}}} - \frac{\omega_{\text{pi}}^2}{\omega^2} = 0 \]  

(5.10)
In this equation, $\chi_n$, the eigen function is given by

$$\chi_n = \frac{k_x}{\pi n}$$  \hspace{1cm} (5.11)

here $n = 0, 1, 2, 3...$ is the eigen values and $k$ is given by

$$k^2 = k_x^2 + k_y^2 + k_z^2$$  \hspace{1cm} (5.12)

Equation (5.10) now becomes

$$1 + \left(\frac{\omega_{pe}}{\omega_{ce}}\right)^2 + \frac{k_x k_y \omega_{pe}^2}{\pi n k^2 \omega_{ce}} - \frac{\omega_{pe}^2 \omega_{ce}}{\omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2} = 0$$  \hspace{1cm} (5.13)

$k_x$ and $k_y$ individually are small in comparison to $k$. For any $n$ except 0, the ratio $(k_x k_y)/(\pi n k^2)$ is always less than 1. The ratio $(\omega_{pe}^2)/(\omega_{ce})$ is 0.26. So, the third term in equation (5.13) is neglected in comparison with 1. The equation then becomes

$$1 + \left(\frac{\omega_{pe}}{\omega_{ce}}\right)^2 - \frac{\omega_{pe}^2 \omega_{ce}}{\omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2} = 0$$  \hspace{1cm} (5.14)

Simplifying this equation algebraically, we get

$$\omega_{pe}^2 \omega_{ce} = \omega^2 \omega_{ce} - \omega_{pi}^2 \omega_{ce}$$  \hspace{1cm} (5.15)

where

$$\omega^2 = \omega_{ce}^2 + \omega_{pe}^2 = \omega_{ce}^2$$  \hspace{1cm} (5.16)

at the UHR surface. Equation (5.15) becomes

$$\omega_{ce} = \frac{1}{\omega_{pe}^2} \left[ \omega^4 - \omega_{pi}^2 \omega_{ce}^2 \right]$$  \hspace{1cm} (5.17)

The terms in bracket on right hand side of equation (5.17) are compared for the experimental parameters at the UHR layer as

$$\omega^4 = 5.6 \times 10^{40}$$

$$\omega_{pe}^2 \omega_{ce}^2 = 1.6 \times 10^{30}$$  \hspace{1cm} (5.18)

here, $f = 2.45 \ GHz$, $B = 769 \times 10^{-4} \ T$, $n_t = 1.7 \times 10^{16} \ m^{-3}$. Now, equation (5.17) becomes

$$\omega_{ce} \omega_{ce} = \frac{\omega^4}{\omega_{pe}^2} = \omega^2 \frac{\omega^2}{\omega_{pe}^2}$$  \hspace{1cm} (5.19)
the ratio \( \frac{\omega^2}{\omega_{pe}^2} \) is estimated to be

\[
\frac{\omega^2}{\omega_{pe}^2} = \left[ \frac{2.37 \times 10^{20}}{5.4 \times 10^{19}} \right] \approx 4.383
\]  

(5.20)

As the ratio comes out to be more than unity, equation (5.19) suggests

\[
\omega_c \omega_{pe} > \omega^2 = \omega_{LH}^2
\]  

(5.21)

which is condition necessary for the sustainment of lower hybrid waves.

The amplitude of the excited wave as a function of input power at the UHR is shown in figure 5.7. The amplitude is normalized with the pump wave at the UHR layer. As evident from the figure, the normalized amplitude of the low-side peak \( f = 2.441 \pm 0.002 \text{ GHz} \) rises with increase in input power from 300 \( W \) to 800 \( W \) indicating the increase in power coupled in the excited mode.

![Figure 5.7: Normalized amplitude of the first lower-side peak in hydrogen plasma.](image)

The capacitive probe is moved in hydrogen plasma from \( R = 0 \text{ cm} \) towards the UHR layer at \( R = 2 \text{ cm} \). The parametric decay spectrum occurrence strongly depends on the input microwave power. Figure 5.8 shows the capacitive probe output at the UHR layer as a function of microwave power that is introduced to the plasma.

As shown in the figure, microwave power is increased gradually from 160 \( W \) to the maximum possible value of 800 \( W \). As the power is increased, the spectrum is broadened on the lower frequency edge. At 500 \( W \), a peak starts appearing at
2.442 GHz. As the power is increased, the peak develops and a maximum level of \(-10\) dBm is seen at 800 W.

Power threshold for excitation of the sideband is measured from the appearance of the LH frequency in the power spectrum during systematic increase of input power. The parametric decay power threshold depends upon the damping of the wave. The threshold is required to overcome the damping (landau, collisional, etc.) to support the excited modes. The peak at 2.442 GHz in hydrogen plasma appears only beyond 500 W of input microwave power. An approximate threshold value for power is calculated as follows.

The kinetic parametric equations for intermediate RF fields \((v_{RF} > v_{th})\), where \(v_{RF}\)
is the RF drift velocity of electrons and $v_{th}$ is the thermal velocity) are considered for estimating the power threshold for parametric decay. Moreover, if the linear damping is also included, so that the resonances are not too sharp, then it is sufficient to consider only the excitation of a low-frequency ES mode with frequency $\omega$ and two high frequency ES modes at the beat frequency $\omega \pm \omega_0$. The general dispersion relation ([128]) is given by

$$\frac{\epsilon_1(\omega, k)}{\chi_1(\omega, k)} = J^2_0(\mu) \frac{\chi_1(\omega + \omega_0, k)}{\epsilon_1(\omega + \omega_0, k)} + J^2_1(\mu) \left( \frac{\chi_1(\omega + \omega_0, k)}{\epsilon_1(\omega + \omega_0, k)} + \frac{\chi_1(\omega - \omega_0, k)}{\epsilon_1(\omega - \omega_0, k)} \right)$$

(5.22)

where

$$\epsilon_j(\omega + n\omega_0, k) = 1 + \chi_j(\omega + n\omega_0, k)$$

(5.23)

$j = i, e$ designates ions and electrons respectively. $J_n(\mu)$ is the ordinary Bessel function of order $n$. Assuming the external electric field of the form

$$\vec{E} = \vec{E}_0 \cos \omega_0 t$$

(5.24)

Equation (5.22) gives

$$\mu = \left( \frac{e}{m_i} \right) \left[ \left( \frac{E_{0z}k_{||} + \vec{E}_{0\perp} \cdot \vec{k}_\perp}{\omega_0^2 - \omega_c^2} \right)^2 + \left( \frac{(\vec{E}_{0\perp} \times \vec{k}_\perp)^2 \omega_c^2}{(\omega_0^2 - \omega_c^2)^2} \right) \right]^{\frac{1}{2}}$$

(5.25)

and

$$\vec{k}(\omega) \mp \vec{k}(\omega \pm \omega_0) = 0$$

(5.26)

here

$$\omega_{ce} = eB/m_e,$$

$$\vec{B} = B\hat{z},$$

$$\vec{E}_{0\perp} = E_{0x}\hat{x} + E_{0y}\hat{y},$$

$$\vec{k}_\perp = k_x\hat{x} + k_y\hat{y},$$

$$k_{||} = k_z$$

(5.27)

The power threshold required for the parametric decay to occur in the system is characterized by a quantity $\mu$ which involves the electric field, frequency and polarization of the incident EM wave. If $\omega_0 \approx \omega_{ce}$, then

$$\mu \approx \left[ \frac{eE_0}{m\omega_0} \right] \left[ \frac{\omega_{ce}}{\omega_0 - \omega_{ce}} \right]$$

(5.28)
where, $E_0$ is the electric field required for the parametric decay and $\omega_0$ is the angular frequency of incident wave. The parametric decay [12] will occur when

$$\mu \geq 0.1$$  \hspace{1cm} (5.29)

For $\epsilon/m = 1.76 \times 10^{11} C/kg$, $\omega_0 = 15.4 \times 10^9 rad/sec$, $\omega_{ce} = 12.3 \times 10^9 rad/sec$, the wave electric field comes out to be

$$E_0 = 6.62 \times 10^5 V/m$$  \hspace{1cm} (5.30)

Now, the quality factor, $Q$ of the resonant cavity is given by

$$Q = \frac{\omega_0 W}{P}$$  \hspace{1cm} (5.31)

here, $P$ is the power coupled in the plasma and $W$ is time average energy stored in the cavity which is given by

$$W = (\epsilon_0/2) \int_0^a \int_0^{2\pi} \int_0^{2d} (E_r^2 + E_\theta^2) r dr d\theta dz$$  \hspace{1cm} (5.32)

which is simplified as

$$W = E_0^2 VC$$  \hspace{1cm} (5.33)

where, $V$ is the volume of the cavity and $C$ [145] is given by

$$C = [\epsilon_0/8(P_{nm}^1)^2][J_0^2(P_{nm}^1) + J_1^2(P_{nm}^1)]$$  \hspace{1cm} (5.34)

The electric field, $(E_0)$ thus becomes

$$E_0 = \left(\frac{QP_1}{\omega VC}\right)^{1/2}$$  \hspace{1cm} (5.35)

The quality factor $Q$ is estimated in chapter 4 as 4200. For $V = 1.29 \times 10^{-3} m^3$, $C = 2.65 \times 10^{-13} F$, $E_0$ comes out to be

$$E_0 = 2.83 \times 10^4 \sqrt{P} V/m$$  \hspace{1cm} (5.36)

Hence, the power threshold comes out to be

$$P \geq 547 W$$  \hspace{1cm} (5.37)

Hence, the theoretically estimated power threshold supports the experimental observation for the parametric decay to occur.
The parametric decay spectrum has high spatial dependence. On keeping the capacitive probe at $R > 2 \, \text{cm}$ and $R < 2 \, \text{cm}$, the decay spectrum peaks disappear. At these positions, only the launched frequency appears as shown in figure 5.9. The spatial dependence is further verified by shifting the UHR layer away from centre by increasing the magnetic field in the system. The decay spectrum follows the UHR layer. The reduction in operating gas pressure leads to the disruption in the parametric decay process.

The launched frequency spectrum (figure 2.25) is broad in comparison with the parametric decay spectrum (figure 5.5) which is narrow. It shows that during the
parametric decay, the power at UHR is redistributed from the broad spectrum to the side peaks observed in the spectrum. The same argument applies when the spectrum with 500 W input microwave power and the spectrum with 800 W input power at UHR layer in hydrogen are compared.

5.4.2 Parametric decay spectrum in argon plasma

The radial profiles of $f_{ce}$, $f_{pe}$ and $f_{uhr}$ for argon plasma is shown in figure 5.10. The profile shows that the UHR surface for argon plasma is towards the lower magnetic field, as compared to hydrogen, at $R = 3$ cm as plasma density is high.

![Figure 5.10: Radial variation of $f_{ce}$, $f_{pe}$ and $f_{uhr}$ in argon.](image)

The parametric decay spectrum in argon plasma is shown in figure 5.11. This figure clearly shows the splitting of the pump wave to LHW whose frequency for argon $f_{LH}$, is $\approx 4.4 \ MHz$. The low-side frequencies of the decay spectrum are observed along with the first high-side frequency with 800 W of input microwave power. Many peaks appear on the lower side. This could be because of the splitting of the peak in the presence of high power. On reducing the power to 600 W, the higher side peak disappears. At input power below 500 W only the launched frequency peak appears. On reducing the pressure also the peaks starts disappearing. At a filling pressure of $1 \times 10^{-4} \ mbar$, no peak is observed.

The spatial dependance of parametric decay spectrum is also observed for argon.
On placing the probe on either side of the position $R = 3\ cm$, the peaks are not observed.

### 5.4.3 Parametric decay spectrum in helium plasma

The radial profiles of $f_{ce}$, $f_{pe}$ and $f_{uhr}$ for helium plasma is shown in figures 5.12. The profile shows that the UHR surface for helium plasma is towards the higher magnetic field as compared to hydrogen and argon at $R = 1\ cm$ because of lower plasma density.

Parametric decay spectrum is also observed with helium as the filling gas as shown in figure 5.13. The plasma density at the centre is $5 \times 10^9\ cm^{-3}$ and the UHR layer lies at $R = 1\ cm$. Only the low-side peak of the decay spectrum are observed with $800\ W$ of input microwave power. The experimentally observed $\omega_{LH}$ for helium is $16\ MHz$ which is close to the theoretically estimated value of $\approx 12\ MHz$.

On reducing the input microwave power to $700\ W$, the lower side peak of the spectrum disappears. Also, on reducing the operating pressure to $5 \times 10^{-4}\ mbar$, the lower side peak vanishes. The lower side peak does not appear at any other position except $R = 1\ cm$ showing the spatial dependance.

The main experimental results performed with all the three gases are summarized in the following table.
Figure 5.12: Radial variation of $f_{ce}$, $f_{pe}$ and $f_{uhr}$ in helium.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Gas</th>
<th>UHR</th>
<th>$n_e$, UHR $cm^{-3}$</th>
<th>$n_e$, ECR $cm^{-3}$</th>
<th>B G</th>
<th>$f_{LH}$ (est.) MHz</th>
<th>$f_{LH}$ (exp.) MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$H_2$</td>
<td>R = 2</td>
<td>$1.64 \times 10^{10}$</td>
<td>$3.1 \times 10^{10}$</td>
<td>769</td>
<td>23.4</td>
<td>33</td>
</tr>
<tr>
<td>2.</td>
<td>He</td>
<td>R = 1</td>
<td>$1.4 \times 10^{10}$</td>
<td>$1.8 \times 10^{10}$</td>
<td>827.3</td>
<td>11.6</td>
<td>16</td>
</tr>
<tr>
<td>3.</td>
<td>Ar</td>
<td>R = 3</td>
<td>$2.7 \times 10^{10}$</td>
<td>$7 \times 10^{10}$</td>
<td>729</td>
<td>4.4</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 5.1: Experimental results.

5.5 Conclusion

Parametric decay of the launched EM wave, entering in plasma in X-mode, is observed at the UHR layer in the ECR plasma system. The decay spectrum is captured with RF electrostatic probes and recorded on a spectrum analyser. Hydrogen plasma with peak plasma density of $3.12 \times 10^{10} cm^{-3}$ and plasma temperature of $\approx 10 eV$, is formed at the centre at a filling pressure of $1 \times 10^{-3} mbar$ with $\approx 800 W$ of incident microwave power.

The parametric decay spectrum contains the LHW frequency harmonics $f_0 \pm f_{LH}$ about the launched frequency, $f_0$, ($2.450.02 GHz$) indicating the three-wave nonlinear interaction. The experimentally observed value of $f_{LH}$ in the spectrum matches well with the theoretically estimated values within experimental error. The
parametric decay spectrum has an input power threshold to occur. On reducing
the input microwave power below 600 W, the harmonics of $f_0 \pm f_{LH}$ disappears.
This is in accordance with the theoretically estimated power for parametric decay
to occur. The exact power levels in the parametric decay spectrum can not be
estimated because of the problem encountered in the calibration of the capacitive
probe in the presence of plasma.

The phenomenon of parametric decay is independent of the filling gas and is also
observed with gases such as argon and helium. In helium, the high-side peak is not
observed because of the limitation on the maximum input microwave power level
of 800 W. The parametric decay spectrum has a strong spatial dependence in the
system with all the gases. The variation in probe position leads to the disappearance
of the peaks. The peaks are observable only at the estimated UHR locations. The
reduction in the operating gas pressure affect drastically the appearance of these
peaks and below the operating pressure range $5 \times 10^{-4}$ mbar, the decay spectrum
disappears.

The appearance of the parametric decay spectrum is a signature of the X-B mode
conversion. This gives the motivation for next experiments involving the detection
and characterization of the EBW.