Chapter 3 Experimental study of a microwave produced toroidal plasma.

1 Introduction


In this chapter, ECR formed toroidal plasma is investigated. The study is not only directed towards equilibrium properties but also focuses on plasma fluctuations and turbulence. The equilibrium profiles and the characteristics of the low frequency electrostatic fluctuations present in ECR produced hydrogen plasma are investigated.
2 Theoretical background

It is necessary to discuss the theoretical aspects of propagation of microwave power in plasmas before experimental results are discussed. In this section, a short study of waves in a plasma medium is presented with a brief review of basic wave propagation. The purpose is to identify important physical processes that make interpretation of the experimental data possible and the material is not presented with rigorous mathematical details.

Electromagnetic waves in plasmas

The main approach used in analyzing the plasma waves employ use of the dielectric tensor of the plasma and study the dispersion relation. A dielectric tensor for a cold, magnetized plasma may be written as follows:

$$\mathbf{\mathcal{E}} = \varepsilon_0 \sum_\alpha \left[ \begin{array}{ccc} 1 - \frac{i \omega_\alpha^2}{\omega^2 - \omega_\alpha^2} & \frac{i \omega_\alpha^2}{\omega^2 - \omega_\alpha^2} & 0 \\ \frac{i \omega_\alpha^2}{\omega^2 - \omega_\alpha^2} & 1 - \frac{i \omega_\alpha^2}{\omega^2 - \omega_\alpha^2} & 0 \\ 0 & 0 & 1 - \frac{i \omega_\alpha^2}{\omega^2 - \omega_\alpha^2} \end{array} \right]$$

Here $\varepsilon_0$ is the permittivity of the free space, $\omega_\alpha$, $\omega$, and $\omega$ are plasma, cyclotron and wave frequency with $\alpha$ being the suffix standing for ions or electrons as the plasma species. It is well known that a wave traveling in the $z$-direction with frequency $\omega$, is given by the simple form, $E = E_0 \cos (\omega t - kz)$. $E_0$ being the amplitude of the electric field with wave vector $k$, propagating with frequency, $\omega$, in time, $t$. The resulting dispersion relation can be written in vector form as (Stix, 1962):

$$\mathbf{k} \times \mathbf{k} \times \mathbf{E} = \frac{\omega^2}{c^2} \varepsilon \cdot \mathbf{E}$$
This expression is technically only valid when the plasma is infinite in extent, and uniform. However, in the spirit of the ray tracing (discussed later), much of the wave physics can be determined from the behaviour of the local index of refraction. The obtained dispersion relation shows the relation of frequency ($\omega$) with propagation wave number ($k$). All the information about the propagation of a given plasma wave mode is contained in the appropriate dispersion relation. One can easily obtain phase velocity ($v_p = \omega/k$), group velocity ($v_g = d\omega/dk$), propagation region (frequency range where the wave is able to propagate, i.e., not evanescent), reflection points (frequency at which the propagation region is limited by infinite phase velocity, i.e., zero group velocity), resonance points (frequency at which energy can be transferred to plasma particles, i.e., zero phase velocity and infinite group velocity) and wave growth or damping using a dispersion relation.

The way dispersion relation is calculated depends on the adopted plasma theory, which also determines the available wave modes. To begin with, the dispersion relation is obtained for cold magnetized plasma only. It is then straightforward to include the effect of collisions and the addition of mobile ion species. Later, other consideration like collisions between the particles, amplitude of the waves, proper truncation level for the moments of Boltzmann’s equation, inclusion of different types of plasma particles (only electrons, or one or more ions dynamics, or perhaps MHD fluid theory), etc., also play an important role in deriving the dispersion relations. The more complicated the medium is (in terms of species, electric field, etc.), the more wave modes it supports. As a rule, if the studied wave frequency is large (when compared to ion cyclotron frequency), ions contribution can be neglected, as they are much heavier and cannot follow to the wave electric fields readily. Another consideration is whether the external magnetic field is important or not? The presence of magnetic field affects greatly the propagation of some plasma wave modes. Broadly speaking, wave modes, under this category may be classified into four cases.

Case (i), when the magnetic field is absent ($B=0$). Here the wave propagation direction is not important.
Case (ii), when the magnetic field is finite (B>0) and the wave vector ($\vec{k}$) is parallel to B.

Case (iii), when the magnetic field is finite (B>0) and the wave vector ($\vec{k}$) is perpendicular to B and

Case (iv), when the magnetic field is finite (B>0) and the wave vector ($\vec{k}$) is in arbitrary direction to B. We briefly review the propagation of electromagnetic waves for the above four cases to make our discussion complete.

**Case (i) Wave propagation in non-magnetized cold plasma (B=0)**

There are one oscillation mode and one real wave mode in cold isotropic electron plasma. The oscillation mode is generally referred as electron plasma oscillations. They are longitudinal oscillations at electron plasma frequency. Their behaviour shows electrostatic and stationary nature. Though they show no wave propagation, but with warm plasma effect included, the dispersion relation theory reveals the electron plasma waves. Also, inclusion of ions in the cold wave theory changes slightly the oscillation frequency ($\omega^2=\omega_{pe}^2 + \omega_i^2$). The real propagating wave mode is transverse waves, which propagates above the electron plasma frequency, $\omega_{pe}$, which defines the reflection point of the waves. The dispersion relation for this mode is shown in Figure 3-1.

![Figure 3-1 Dispersion relation for the transverse wave in a collisionless isotropic cold electron plasma. The frequency dependence of phase and group velocities is also shown.](image)
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Usually, the dispersion relation is plotted as $\omega$ versus $k$. Another way of representing dispersion relation is shown in Figure 3-1. The $y$-axis represents the velocity and the $x$-axis represents the frequency. Here, it should be noted that for a very high frequencies, both phase and group velocities approach the light velocity, $c$, and we have electromagnetic wave in free space. At this point, even the electrons are unable to respond to the rapidly oscillating electric field. The inclusion of ions into the theory also changes the reflection point frequency.

Case(ii) Parallel wave propagation in magnetized cold plasma (B≠0)
In magnetized plasma, electromagnetic waves parallel to the ambient magnetic field may exist in three different modes, longitudinal electron plasma oscillations, transverse right-hand circularly polarized waves (RCP) and transverse left-hand circularly polarized waves (LCP). Here, the term parallel is used to denote the direction of propagation vector with respect to the ambient magnetic field. The dispersion relation for waves propagating parallel to B, takes the following form

$$k_i^2 c^2 = \omega^2 - \frac{\omega_{pe}^2}{1 \pm \frac{\omega_{pe}}{\omega}}$$

Here, the symbols have their usual meanings. The longitudinal electron plasma oscillations modes are similar to that observed in non-magnetized cold plasma dispersion relation. As expected magnetic field has no influence on these oscillations as they are parallel in direction. The transverse RCP waves are mode that couple to the cyclotron motion of the particles around the magnetic field lines. It is closely tied to the electron motion. The transverse electric field of the wave rotates in the same direction as the electrons about the B field. At electron gyro-frequency, a resonance is created, and energy is transformed from the wave to the electrons. With these waves, plasma electrons can be heated using this method. The dispersion relation for these modes is depicted in Figure 3-2. As obvious from Figure 3-2, these waves propagate in two frequency ranges, i.e., $\omega<\omega_{ce}$ and $\omega>\omega_{ce}$. Usually, RCP waves at lower frequencies than the electron gyro-frequency. $\omega_{ce}$ are commonly known as electron cyclotron waves, whereas at very low frequency region (but well above the $\omega_{ce}$), whistler waves are found. The transverse LCP
waves are also modes that couple to the cyclotron motion of the particles around the magnetic field lines. It is closely tied to the ion motion. As obvious from the Figure 3-2, LCP waves propagate only when \( \omega > \omega_0 \), if ion motion is not taken into account. If ion motion is taken into account, \( \omega < \omega_0 \) branch is created depicting resonance with ions and ion cyclotron waves are found. An important point is that, in the very low frequency limit, the phase velocities of the RCP and LCP waves (if ion motion is included) go to zero.

![Figure 3-2](image)

*Figure 3-2 Frequency dependence of the phase and group velocities for the transverse RCP and LCP waves propagating along magnetic field in a collisionless cold electron plasma.*

This means that in order to get Alfvén waves, one has to use warm plasma theory, where the low frequency phase velocity is, approximately, Alfvén velocity. At low frequency the phase velocity of both the modes tend to Alfvén speed, \( V_A \), given as,
\[ \nu^2 = \frac{c^2}{1 + \frac{\omega_p^2}{\omega_n^2}} \]

The Alfven speed is essentially the propagation speed that results from the fluid motion of the plasma exchanging energy with the magnetic field. These waves are responsible for the “whistling” effect observed in early radio transmissions as these dispersive waves bounced between the earth’s poles along magnetic field lines. In the high-frequency limit, the cyclotron motion does not play much of a role, and the waves appear like plasma oscillations in unmagnetized plasma:

\[ n^2_k = 1 - \frac{\omega_p^2}{\omega_n^2} \]

Here, it should be noted that the RCP wave has found wide usage as the primary wave to work in microwave tubes such as traveling wave tubes.

**Case(iii) Perpendicular wave propagation in magnetized cold plasma (B ≠ 0)**

In magnetized plasma, electromagnetic waves perpendicular to the ambient magnetic field, may be launched in two different ways. Usually they are termed as X - mode launching known as extraordinary mode, and O - mode launching known as ordinary mode. Here, the term perpendicular is used to denote the direction of propagation vector \( \vec{k} \) relative to the undisturbed magnetic field \( \vec{B} \). Thus, for the wave propagation across \( \vec{B} \), the dispersion relation yields two modes. Here, we discuss both the modes, as these modes would exist in our experimental plasma and will form the basis of our experimental studies.

**Ordinary waves or O -modes:**

The ordinary wave is characterized by the alignment of the wave electric field \( E_1 \) purely parallel to the applied magnetic field \( B \). The schematic is shown in Figure 3-3, which shows oscillating electric field \( E_1 \), parallel to the ambient magnetic field. This geometry is approximated by a beam of microwave incident on a plasma column with the narrow dimension of the waveguide in line with ambient magnetic field \( B \).
For purely perpendicular propagation, the dispersion relation for the ordinary mode in cold plasma may be written as:

\[ n_e^2 = 1 - \frac{\omega_{ke}^2}{\omega^2} - \frac{\omega_{pe}^2}{\omega^2}. \]

Here, \( n_e = \frac{k_e^2 c^2}{\omega^2} \) is the perpendicular refractive index, \( c \) represents the speed of light in vacuum, \( k_\perp \) is the perpendicular propagation vector, \( \omega \) is the launched frequency and \( \omega_{pe} \) and \( \omega_{pe} \) is the ion and electron plasma frequency. Notice that above equation does not involve B explicitly. This is consequence of the parallel alignment of wave electric field and the applied magnetic field, which results in no \( E \times B \) motion and no cyclotron motion. As the propagating mode is not affected by the ambient magnetic field, the terminology 'ordinary' is used. These modes are also identical to transverse waves in isotropic plasma, (i.e., B does not affect the propagation). These waves propagate above the electron plasma frequency, \( \omega_{pe} \), and here also the frequency where the reflection point occurs, is affected by ions (the contribution of ions at our frequency may be neglected, as ions may not respond because of large inertia). These modes are also called TEM (Transverse Electric-Magnetic) mode, since both the electric and magnetic fields are transverse to the direction of propagation (linear polarization).
Extra-ordinary waves or X – mode:
The extra-ordinary wave is characterized by the alignment of the wave electric field ($E_i$) purely perpendicular to the applied magnetic field ($B$). The schematic is shown in Figure 3-4, which shows oscillating electric field $E_i$, perpendicular to the ambient magnetic field.

![Schematic of X-mode launching](image)

This geometry is approximated by a beam of microwave incident on a plasma column with the broad dimension of the waveguide in line with ambient magnetic field, $B$. For purely perpendicular propagation, the dispersion relation for the extra-ordinary wave may be written as:

$$n_x^2 = \frac{[(\omega + \omega_{ci})(\omega - \omega_{ce}) - \omega_{pe}^2](\omega - \omega_{ci})(\omega + \omega_{ce}) - \omega_{pe}^2}{(\omega^2 - \omega_{ci}^2)(\omega^2 - \omega_{ce}^2) + (\omega_{pe}^2 + \omega_{pi}^2)(\omega_{ce}^2 - \omega_{ci}^2)}$$

Here $n_x$ ($= \frac{k_{x}^2 c^2}{\omega_{ce}^2}$) is the perpendicular refractive index for X-mode, 'c' represents the speed of light in vacuum, $k_x$ is the perpendicular propagation vector, $\omega$ is the launched frequency, $\omega_{pe}$ is the electron plasma frequency, $\omega_{pi}$ is the ion plasma frequency, $\omega_{ce}$ is the electron gyro-frequency and $\omega_{ci}$ is the ion gyro-frequency. The extraordinary wave, however, is much more complicated because both, the $E \times B$ motion and cyclotron motion, of the particle are involved. These modes are also called TM (Transverse Magnetic) mode, since the magnetic fields are transverse to the direction of propagation.
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The electric field can have a longitudinal component (along k). Hence, these waves are partially longitudinal and partially transverse (elliptically polarized). If ion motion is taken into account, $\omega < \omega_{LH}$ branch is created; this branch relates to the low frequency MHD (Alfven) waves. The resonances of the X-wave are given by,

$$\omega_{res}^2 = \frac{\omega_{pe}^2 + \omega_{ce}^2 + \omega_{pi}^2 + \omega_{ci}^2}{2}$$

$$\pm \sqrt{\left(\frac{\omega_{pe}^2 + \omega_{ce}^2 - \omega_{pi}^2 - \omega_{ci}^2}{2}\right)^2 + \omega_{pe}^2 \omega_{ci}^2}$$

and shows two resonance’s, known as the lower- and upper-hybrid resonance’s. The dispersion relation for this branch is depicted as:

![Figure 3-5 Dispersion relation for perpendicular propagating modes in magnetic plasma](image)

This wave has found wide usage as a means of coupling power to magnetized plasma because it permits propagation across field lines and couples to the thermal motion of the plasma particles. In fact, one can make a plasma source based on this concept.

Case(iv) Arbitrary wave propagation in magnetized cold plasma ($B \neq 0$)

For arbitrary angles, the wave propagation is a mixture of the characteristics of the principle waves discussed above. A phenomenon known as Faraday rotation occurs in the frequency range of RCP and LCP waves, and can be used as a plasma diagnostic tool. We are not going into details here.
Figure 3-6 Wave normal surface which depicts the phase velocity as a function of theta.

Defining the angle \( \tan \theta = \frac{k}{k_{\perp}} \), a wave-normal surface can be found which depicts the phase velocity as a function of \( \Theta \) as shown in Figure 3-6.

Figure 3-7 The CMA diagram for waves in a cold electron gas. The solid lines represent the principal resonance's and the dashed lines the reflection points.

Examination of the dispersion relation shows that the space defined by the plasma density and magnetic field strength \( (\omega_p - \omega_c = \text{space}) \) delineates all the possible modes that can exist.
in cold plasma. The regions in this space are separated by either a cutoff or a resonance from the neighbouring regions. In each region, though there are always two roots to the dispersion relation, there exist one, two or none propagating modes. This representation is often known as the CMA (Clemmow-Mullaly-Allis) diagram (Allis, et. al., 1963, Spitzer, 1962, Stix, 1962). The CMA diagram is a very compact alternative way for presenting solutions of the dispersion relation as shown in Figure 3-7. This diagram is constructed in a two-dimensional parameter space having X-axis representing as \( x = (\omega_p/e\omega)^2 \) and Y-axis as \( y^2 = (e\omega/e\omega)^2 \) and displaying all the resonance and reflection points as a function of both \( x \) and \( y^2 \). As obvious from this diagram, the magnetic field increases in the vertical direction, the plasma electron density increases in the horizontal direction, and the electromagnetic wave frequency decreases in the radial direction (in each case, considering all other parameters fixed). Furthermore, the CMA diagram divides the \( (x, y^2) \) plane into a number of regions such that within each region the characteristic topological forms of the phase velocity surfaces remain unchanged.

**Perpendicular electromagnetic wave launching in toroidal magnetized plasma**

As discussed earlier, there exist a choice to launch electromagnetic waves perpendicularly in toroidal magnetized plasma, either in X-mode or in O-mode. The tunneling of the X-mode through the evanescent region separating a cutoff and the upper hybrid resonance layer can be well understood from the cold plasma theory (Budden, 1961). The Budden-tunneling equation may be written as:

\[
\frac{d^2 E}{d\tau^2} + k_s^2 \left( 1 + \frac{b}{x + i\varepsilon} \right) E = 0
\]

Here, \( \tau = R_1 - R \), where \( R_1 \) is the radial location of the resonance layer, \( E \) is the electric field amplitude and the term \( i\varepsilon \) models a small collisional damping. The parameter \( b \) is the spatial distance between the cutoff and the resonance region, usually refered as evanescent layer. \( k_s \) is the wavenumber far away from the evanescent region and is taken as vacuum wavelength. The tunneling factor which is defined as:
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\[ \eta = \frac{\pi k_s b}{2} \]

turns out to be around 1.6 for our experimental parameter \((k_0=51 \text{ m}^{-1} \text{ and } b=2 \text{ cm})\). If X-mode is launched from low field side, incident on the cutoff layer, Budden analysis of above equation yields the reflection, transmission and absorption coefficient as follows:

\[ R = 1 - e^{-2\eta} \]

\[ T = e^{-\eta} \]

\[ A^2 = 1 - R^2 - T^2 = e^{-2\eta}(1 - e^{-2\eta}) \]

The absorption is independent of the collisional damping rate \(\nu\), and remains finite in the limit \(\nu\) tending to zero. Using above equation, the fraction of transmitted and absorbed power are \(T^2 \approx A^2 \approx 0.04\). The fraction of reflected power is \(R^2 \approx 0.92\), and the reflection is perfect. Hence, the X-mode is generally reflected at the cutoff and only O-mode is transmitted. The O-mode absorption at the ECR is small hence, most of the wave energy in this mode reaches the inner wall and gets reflected. The reflected wave would now have mixed polarization, and the X-mode component will now approach the evanescent layer from the high field side. Here, Buddens theory again yields the same transmission as above, virtually nothing (implying almost perfect reflection or absorption towards the ECR region). Since reflection coefficient is zero (as it encounters UHR), therefore analysis reveals almost complete absorption of the reflected X-mode.

These considerations yield the following qualitative scenario. If we launch mixed modes, then O-mode would directly penetrate the plasma and reach inner wall of the vessel if density limit is not encountered). When X-mode is launched from the low field side, then X-mode would be reflected at the cutoff and may give rise to a standing wave pattern between the cutoff surface and the vessel wall. Since some fraction of X-mode component is converted to the O-mode during reflection at this wall, the injected wave power will eventually leak through the cutoff layer in the form of O-mode waves. These O-mode waves, arriving at the inner wall gets reflected and partly gets converted to X-mode and if these reflected waves reach UHR, they will be completely absorbed. The remaining O-mode is then reflected on the outer wall and returns with mixed polarization, and the cycle repeats itself until all the power is absorbed.
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Due to opening of the toroidal magnetic field lines (as indicated in earlier chapter) and small but finite error in placing the rectangular waveguide exactly perpendicular to the ambient magnetic field lines, it is nearly impossible to launch perfectly, either O - mode or X - mode in toroidal device. It is more likely to launch mixed modes. In our experiment, best of effort has been made to preferably launch X - mode because of following three reasons:

(i) There exist no density limitation, as in the case of O - mode launching.
(ii) Any small component of O - mode, that would be launched, will get converted to X - mode, once they are reflected from the inner wall of the machine and
(iii) Launching of the X - wave would not be greatly affected from the low field sides because vacuum wavelength ($\lambda$≈12cm) is comparable to the minor radius of the machine and it takes $\sim$ 5 -10 times wavelength distance for the wave to completely attenuate.

Theoretical estimate of electron plasma density and temperature

Here, we make an estimate of electron density that would be generated by a microwave produced plasma. Though it is believed that the profile would be governed by the location of the ECR region, however the global electron density would depend on the balance between the plasma production (by the microwave) due to ionization and plasma loss due to transport. We know that under the influence of the electromagnetic field, the electrons oscillate, without gaining any net energy from the field. However, in the presence of elastic electron neutral collisions ($v_{el}$), the electrons have a mean velocity given by:

$$v = \frac{eE}{mv_{el}} - \frac{eE v_{el}}{mv_{el}^2 + \omega^2} \frac{eE v_{el}}{m \omega^2}$$

Here, $E$ is the wave electric field, $m$ is the electron mass, $e$ is the electronic charge and $\omega$ is the wave frequency. In the above equation, it is assumed that the collisions are quite rare compared to the frequency of oscillation of the field ($v_{el} < \omega$). The mean velocity shows that the electron motion in the wave possess an average oscillatory energy $(mv^2/2)$. It can be shown that electron in motion possesses a root mean square (rms) energy, given by:
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\[ \phi_{rms}(eV) = \frac{enP_f}{4\pi^2mc^2} \sim 2 \times 10^{-3} P_f(W) \]

Here, \( \phi_{rms} \) represent the rms energy of the electron and \( \eta \) is free space impedance (~377Ω). Other symbols have their usual meaning. In our experiment, 500 W of rf power at a frequency \( f=\omega/2\pi \) of 2.45 GHz., is coupled to form the plasma. This yields rms energy of 0.01 eV, which is less than the ionization energy (~20 eV). Assuming ions are infinitely massive, there would be no energy transfer from the electrons to the ions. Since the rms energy remains constant, the collisions would convert this rms energy into random energy of electrons resulting in electron heating. For instance, to acquire ~20eV energy, required for ionization, it would take about 2000 collisions. It can also be shown, from fluid model, that the average energy transfer to the electrons becomes:

\[ \frac{d\phi}{dt} = -eE\nu \sim 2v\phi_{rms} \]

Very crudely the equation of power transfer from electron to the neutrals, through inelastic collisions may be written as:

\[ P \sim n_e\nu_i\phi_i \]

Where \( n_e \) is the electron density, \( \nu \) is the total plasma volume, \( \nu_i \) is the inelastic collision frequency and \( \phi_i \) is the ionization energy. The inelastic collision frequency may be expressed in terms of collision cross section as \( \nu_i = n_o\sigma_m\nu \), where \( \sigma_m \) is the inelastic collision cross section and \( n_o \) is the background neutral density. By introducing the ratio \( F (-\sigma_m/\sigma_i) \), where \( \sigma_i \) is the ionization collision cross section and using it in above equation, we may write:

\[ P \sim n_e\nu F\nu_i\phi_i \]

Also, the particle balance equation (electron production \( n_e\nu_i \) is balanced by electron loss, \( n_e\tau_p^{-1} \) ) gives:

\[ n_e n_o < \sigma_i \nu > = \frac{n_e}{\tau_p} \]

or, \( \nu_o = \frac{1}{\tau_p} \)

The above two equations yields,
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\[ P = \frac{n_e V F \phi_i}{\tau_p} \]

or, \[ n_e \sim \frac{P \tau_p}{V F \phi_i} \]

Our estimate (presented in chapter 4) and experimental measurements from filament produced plasma (Bora, et. al., 1986) suggests \( \tau_p \sim 100 \) µsec. For our experimental parameter, we have \( P = 500 \) W, \( V = 0.1 \) m\(^3\), \( \phi_i \sim 20 \) eV and \( F \sim 10 \), which gives \( n_e \sim 3 \times 10^{10} \) cm\(^3\).

![Figure 3-8 Theoretical estimate of electron temperature with different confinement time and fill density.](image)

Electron temperature may be determined using particle balance equation. Under equilibrium, the electron production is balanced by electron loss, which implies,

\[ n_e V_i = \frac{n_e}{\tau_p} \]

or, \[ n_e n_s < \sigma_i V > = \frac{n_e}{\tau_p} \]

or, \[ n_s \tau_p = \frac{1}{< \sigma_i V >} \]

For hydrogen, a good approximation for collision rate constant is given by (Goldston and Rutherford, 1995),
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\[
<\sigma,v> = \frac{2 \times 10^{-13}}{6 + \frac{T_e}{\phi_1}} \left(\frac{T_e}{\phi_1}\right)^{1/2} \exp\left(-\frac{\phi_1}{T_e}\right) \ m^3 \ s^{-1}
\]

Here \( T_e \) is expressed in eV. Using the above two equations, we get.

\[
n_e T_p \sim 1 \times 10^{-13} \left(3 + \frac{T_e}{2\phi_1} \frac{\phi_1}{T_e}\right)^{1/2} \exp\left(\frac{\phi_1}{T_e}\right) \ m^3 \ s^{-1}
\]

The above equation shows the dependence of electron temperature \( T_e \) to neutral density \( n_0 \) and particle confinement time \( T_p \). A typical plot of the above relation is shown in Figure 3-8 for our experimental parameter regime, for various confinement times. For our experimental parameters and confinement time of \( \sim 0.1 \) ms, the above equation yields an electron temperature of \( \sim 3 \) eV.

3 Investigation of equilibrium parameter in \( \pi \)-wave produced toroidal magnetized plasma

![Figure 3-9 Density contour for ECR produced plasma](image-url)
During the experiment toroidal magnetic field is varied from 0.06 T to 0.08 T at the minor axis. Hydrogen plasma is formed using ECR breakdown method. The toroidal magnetic field at the minor axis is varied to tailor the profile of the plasma density. At a magnetic field of 0.08 T at the minor axis, bi-directional density profile is obtained. The density and floating potential at different grid points in the poloidal cross section are measured. Equal density and equal floating potential contours are generated from these measurements. The density and potential are normalized with their maximum values for better representation of the experimental results. A typical plot of density contours at a toroidal magnetic field of 0.08 T is shown in Figure 3-9. The contours exhibit slab nature in the vertical direction within ± 8cm. The extent of slab nature in the vertical direction could not be controlled during these experiments, unlike in the case of filament produced plasma experiments, where the filament length decided the extent of the slab nature in the vertical direction (reported in next chapter).

![Potential contour for ECR produced plasma](Figure 3-10 Contour of potential for ECR produced plasma)

From the ECR condition (Ω = Ωce), breakdown should occur at 0.0875 T. For a toroidal magnetic field of 0.08 T (at the minor axis), the breakdown should occur at r = -4 cm (or
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R = 41 cm, as toroidal magnetic field varies inversely with machine major radius. The contours show that for a toroidal magnetic field of 0.08 T, the plasma is observed over radial locations, defined by -4 cm ≤ r ≤ 9 cm. and experimental observations indicate that no plasma is formed beyond ECR region on high field side. The same behaviour is exhibited by the contours of potential as shown in Figure 3-10. Our results indicate presence of slab equilibrium.

![Figure 3-11 Radial profile of density for a toroidal magnetic field of 0.08 T.](image)

For a toroidal magnetic field of 0.08 T on the minor axis, plasma is formed with a peak density of $3 \times 10^{10}$ cm$^{-3}$. The density peaks at the minor axis. The radial profile of the electron plasma density is shown in Figure 3-11. The figure also shows the radial profile of toroidal magnetic field, when the toroidal magnetic field is 0.08 T at the minor axis. In this case, the magnetic field corresponding to the resonant ECR region is located near radial location of $r \sim -4$ cm of the vessel. From Figure 3-11, it is observed that the plasma is not able to diffuse in the region $r \leq -4$ cm, where the strength of the toroidal field is greater than 0.0875 T.
From the density profile, one can identify three regions. Region I extend from \(-4\,\text{cm} \leq r \leq 0\,\text{cm}\). Here, density gradient is high and is parallel to the effective gravity \(g\), generated due to the curvature in the magnetic field. Density scalelength, \(L_n\) (where \((L_n)^{-1} = 1/n\ \text{dn/dr}\)) for this region is \(\sim 2\,\text{cm}\). Region II extends from \(0\,\text{cm} \leq r \leq 7\,\text{cm}\). Here, density gradient is moderate, with \(L_n \sim 5.2\,\text{cm}\) and is antiparallel to the effective gravity \(g\). Region III extends from \(7\,\text{cm} < r < 9\,\text{cm}\). In this region, the density gradient is antiparallel to the effective gravity \(g\) but density is low and scale-length is very large.

![Radial profile of electron temperature at a toroidal magnetic field of 0.08 T.](image)
obtained from the measured values of floating potential and the electron temperature using the relation (Huddleston and Stanley, 1965),

\[ \phi_s = \phi_f + 3.6 \left( \frac{kT_e}{e} \right) \]

where \( \phi_s \) is space potential, \( \phi_f \) is floating potential, \( k \) is Boltzmann constant, \( T_e \) is electron temperature and \( e \) is electron charge. Taking the derivative of \( \phi_s \) with respect to radial distance, we obtained the radial electric field \( E_r = -\frac{d\phi_s}{dr} \), which is shown in Figure 3-13. From the figure it is seen that \( E_r \) is spatially oscillating in nature. The peak \( E_r \) is about 3 V/cm between 1 cm \( \leq r \leq 3 \) cm, otherwise it is typically around 1 V/cm. It has a positive value over the entire radial profile except at \( 0 \) cm \( \leq r \leq 2 \) cm.

![Figure 3-13 Radial profile of floating potential and electric field at a toroidal magnetic field of 0.08T.](image)

Profiles of electron plasma density, \( n_e \) and electron temperature, \( T_e \) broadens towards the weaker magnetic field region where \( \omega_e < \omega \). The absence of heating where \( \omega_e > \omega \) is well illustrated in Figure 3-12. Similar observations were reported in Culham Levitrons where it was observed that at low power the heating was localized at ECR region but at higher
power levels the profiles broadened towards the weaker magnetic field region up to upper hybrid resonance (UHR) region, where $\omega_{0H}^2 = \omega_p^2 + \omega_c^2$ (Riviere, et. al., 1978). Levitron is a toroidal device with a toroidal current carrying conductor. This produces a strong poloidal component of magnetic field. The externally produced toroidal field is weak and the combined field lines are spiral. The plasma was formed by ECR breakdown in regions between the levitated current ring and outer wall. Now, if we consider a small toroidal section of the levitron and rotate by 90°, it would look as follows: the current ring would be along the major axis with plasma around it. The spiraling field lines would move in the vertical direction. In BETA, the open toroidal field lines behave in a similar fashion with ECR breakdown at different radial locations. The plasma formed would also behave in a similar fashion as in a toroidal section of the levitron, which is equal to the vertical section of BETA. Earlier spiraling of field lines in BETA has been already established. Hence, our observations are expected to be similar to that observed in Levitron.

![Figure 3-14 Radial profile of density for ECR formed plasma at toroidal magnetic field of 0.06 T](image)

It is observed that in the region $R \sim 9$ cm, the condition $\omega_c = \omega_{0H}$ (where $\omega_c$ is the launched frequency) is satisfied, when $B_t = 0.08$ T. The broad absorption profile, we
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observe, could be explained by the plasma resonance, which exists for all \( n_e \) above the UHR, \( \omega_e < \omega \) and \( \omega_p < \omega \). The preferred explanation is that conversion occurs mainly near the UHR and energy is then transported into the plasma by slow electrostatic waves, which propagates freely across the field. In this case there is no restriction on \( (\omega_p/\omega)^2 \) and high density region can be reached. Propagation is not possible for electrostatic modes when \( \omega_e > \omega \), so again an inner boundary to the heating process is formed where \( \omega_e = \omega \) (Riviere et al., 1978).

For a toroidal magnetic field of 0.06 T on the minor axis, the resonance layer lies at the inner most radial position. Plasma is observed over the entire radial location, i.e. between \(-9 \, \text{cm} \leq r \leq 9 \, \text{cm}\) as shown in Figure 3-14. Plasma is formed with a peak density of \( 5 \times 10^9 \, \text{cm}^3 \). Though the minor radius is 15 cm, the limiter of radius 9 cm limits the plasma within \( \pm 9 \, \text{cm} \) about the minor axis.

![Radial profile of plasma potential for a toroidal magnetic field of 0.06 T](image)

In this case bi-directional density profile is not obtained. The radial profile shows two distinct regions. We define them region I, and region III. In region I, the density falls
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from $5 \times 10^9$ cm$^{-3}$ to $2 \times 10^9$ cm$^{-3}$ over a distance of about 10 cm. The density gradient is anti-parallel to effective gravity (due to curvature of the toroidal magnetic field lines). In region III, the density remains nearly constant around $5 \times 10^9$ cm$^{-3}$ with a large density scalelength. The density gradient is parallel to effective gravity. The figure also shows the radial profile of toroidal magnetic field, when the toroidal magnetic field is 0.06 T at the minor axis. Similarly, the floating potential extends across the entire radial location as shown in Figure 3-15.

It is also observed that the plasma density is higher when the toroidal magnetic field is 0.08 T compared to the case when toroidal magnetic field is 0.06 T, almost by an order of magnitude. When the toroidal magnetic field is 0.08 T, the ECR region is well within the vessel volume whereas at 0.06 T the ECR region is almost at the inner edge of the minor radius ($R \sim 31$ cm). Earlier, it has been mentioned (Mattoo and Venkataramani, 1986) that in BETA the toroidal magnetic field lines are open. Therefore, when ECR region is located near the inner edge of the minor radius, the loss of plasma particles is enhanced due to the open field lines. Also, as the magnetic field is reduced, the confinement time and the plasma equilibrium are likely to degrade. This explains why plasma density is more in the former case and less in the latter case. This could be also be the reason why obtained density profile in ECR formed plasma (with resonance layer near the inner wall of the vacuum vessel) is quite different with that obtained in filament-produced plasma, when the filament is placed near the inner wall of the vacuum vessel. In latter case, the density peaked near the inner wall (filament location) of the vacuum vessel and decreased radially outward whereas in former case density is low near the inner wall, increases near the minor axis and remains nearly constant as we go radially outward.

4 Computational analysis using ray tracing code

To strengthen our argument, we made an analysis using a ray tracing code called ECRCYL (a code for electron cyclotron radiation transport) (Chaturvedi and Mills,
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1992). ECRCYL is a code to perform electron cyclotron radiation transport calculations in magnetized plasma. Ray tracing is performed using the cold plasma dispersion relation to determine the ray trajectories. The plasma is assumed to lie in the annular space between two concentric cylinders, which is bounded at both ends. The geometry looks similar to a toroidal device when viewed from top of the toroidal machine. The code takes account of plasma dispersion and collective effects due to finite density. The variation of the absorption coefficient with the angle of propagation, wave frequency and mode type is included. The code also takes into account of spatial variations of wall reflectivity and polarization scrambling due to reflection. The code is valid for low Te (≤ 10 keV) plasmas. Before we present the main results from the code, we give a brief introduction to the code in the next section.

Brief introduction to the code
The ECRCYL code performs ray-tracing calculations in axisymmetric plasma, which lies in the annular space between two concentric cylinders, and is bounded at both ends. Two-dimensional profiles of the magnetic field and electron density and temperature must be specified. Emission and re-absorption calculations take into account the anisotropy of the plasma, and variation of plasma properties in the r-z directions. Before we go into details of the code, let us briefly discuss how ray tracing is obtained.

Ray tracing equations
One of the interesting features of plasma is the fact that the index of refraction can be a function of space. This leads to complex transformations of the waves as they propagate through the non-uniform medium. In linear situations, the frequency is typically constant, set by external conditions, and the wavenumber is a function of position. It is useful to consider wave propagation in the non-uniform medium in terms of rays, which are the trajectories of wavepackets. The trajectories obey a system of Hamilton’s equations

$$\frac{d k^\parallel}{d \tau} = \frac{\partial D}{\partial r}$$
where \( D(\omega, k, r) = 0 \) is the dispersion relation and \( t \) is time. The above equations are also referred as the group velocity equations and Snell’s law equations, respectively. Ray tracing involves the solution of above-mentioned coupled set of differential equations that characterise wave propagation in the plasma medium, with proper initial conditions (Kato, 1983, Stix, 1962, Kritz, 1983). Integration of the ray equations is performed, which yields the ray trajectory, along with the components of the wave vector \( \vec{k} \), at each point on the trajectory. The path is determined by the group velocity, which represents the direction of the energy flow for the wave. At each point ‘r’ on the trajectory, the wave must satisfy the real part of the dispersion relation, \( D(\omega, k, r) = 0 \). To save computational resources, it is more convenient to integrate the equations with respect to path length.

\[
\begin{align*}
\frac{dr}{ds} &= \pm \frac{D_k}{|D_k|} \\
\frac{d\theta}{ds} &= \pm \frac{D_k}{|D_k|} \\
\frac{dy}{ds} &= \pm \frac{D_k}{|D_k|} \\
\frac{dk_z}{ds} &= \pm \frac{(D_r - D_{kr} k_\theta / r)}{|D_k|}
\end{align*}
\]
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\[ \frac{dk_\theta}{ds} = \pm \frac{D_k k_\theta}{|D_k|} \]
\[ \frac{dk_z}{ds} = \pm \frac{D_k}{|D_k|} \]

where, \(|D_k| = \left( D_{k_r}^2 + D_{k_z}^2 + D_{k_\theta}^2 \right)^{1/2}\) and subscripts of D denote partial derivatives with respect to the subscript and \(k_r, k_z\) and \(k_\theta\) are the components of the wave vector in \(r, z\) and \(\theta\)-direction. In the equations, the upper sign is used when \(D(\omega) > 0\), and the negative sign is used otherwise (Kulp, 1978). Hence, six coupled ordinary differential equations are to be solved for six unknowns \((r, z, k_r, k_z\) and \(k_\theta)\). The second part of the problem is to calculate absorption. Following expression is used:

\[ P = P_0 \exp \left( -i \int_0^\infty \alpha ds \right) \]

where \(P\) and \(P_0\) represent the remaining and initial power in the ray respectively. Rays in the vicinity of the upper hybrid resonance (UHR) can undergo mode conversion to electron Bernstein wave. After each step in the integration of the ray equations, the code checks if the conditions for mode conversion are satisfied. Stix has shown that as a cold plasma mode approaches resonance, its character progressively becomes electrostatic. Hence, mode-conversion region can be identified by a rapid increase in the refractive index. Once a ray enters this region, the step size used in integration is reduced and warm plasma effects are included in the dispersion relations. Here, it is ensured that the propagation vector 'k' satisfies the dispersion relation given by Stix.

\[ k_\perp^2 = -2 \frac{\omega_{pe}^2}{\nu_{te}} \sum_{n=1} \exp(-\lambda) \left[ n^2 - \frac{q^2}{n^2 - q} \right] \]

where \(q = \omega/\omega_{ce}, \nu_{te}\) is the electron thermal velocity, \(k_\perp\) is the component of the wave vector perpendicular to toroidal magnetic field, \(B, \lambda = k_\perp^2 \nu_{te}^2/\omega_{ce}^2\) and \(l_n\) is the modified Bessel function of the first kind. The dispersion relation is valid only for weak cyclotron damping and propagation quasi-perpendicular to steady magnetic field. These conditions should normally be satisfied near mode conversion. The absorption coefficient given in (Bornatici, et. al., 1983) is used in the calculations.
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Code results
The propagation and absorption of the extra-ordinary wave in a plasma with plasma parameters as measured in our experiments and for our machine parameter is conducted. In actual experimental scenario, the waveguide launches mixed modes i.e. both O-mode and X-mode. We assume that the rays reach the inner wall of the torus through multiple reflections and then enter the plasma from high field side as X-mode. The analysis is made, using a X-mode ray, entering the plasma from high field side, see Figure 3-16(a).

Figure 3-16 Results of computational analysis carried out for ECR produced plasma in BETA machine.
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The study reveals that when a ray is launched from the inside of the torus, it propagates upto the ECR layer. About 1% of the total energy of the ray is lost to the plasma. The ray further propagates and near UHR \((r \sim 9 \text{ cm})\) it gets mode converted to electrostatic modes and reflects back into the plasma as shown in Figure 3-16(a). After reflection, these electrostatic modes again propagate into the plasma till it encounters ECR region where the absorption coefficient of the wave becomes appreciable and all its energy is deposited in the region near ECR layer. The Figure 3-16(b) shows the plot of radial position with respect to the path length. Also Figure 3-16(c) shows the plot of absorption coefficient in terms of path length. From these figures it is obvious, that the absorption is dominant only when the waves becomes electrostatic, i.e. after mode conversion.

5 Investigation of low frequency fluctuations

Fluctuating component of density and floating potential shows presence of vast information. It is already well known that toroidal plasma supports different low frequency electrostatic coherent modes. The Nyquist sampling limit for our experiment is 25 kHz. But in our experiment, nothing significant is observed beyond 10 kHz. To improve the readability of the data we have plotted the spectrum upto 15 kHz. In tokamak type devices with plasma carrying current, one would expect some activity (Mimov type oscillation) in 50-200 kHz, which is typically a few percent of Alfvén transit frequency, which is about few MHz for our experimental parameters. Here, it is to be noted that BETA is a current-less toroidal device and do not excite these oscillations, which usually occurs during the current ramp up scenarios. To understand the observed fluctuations clearly, we divide the entire radial location into four regions.

Region-A extends from \(-4 \text{ cm} \leq r \leq -1 \text{ cm}\). Here, density gradient is large \((\nabla n \sim 2 \text{ cm})\) and parallel to effective gravity and electric field is moderate \((0 \text{ to } 2 \text{ V/cm})\). The condition \(\nabla n \cdot \nabla B < 0\) is satisfied in this region. Turbulent spectrum is observed. Typical crosspower,
phase and coherence spectra between density and floating potential fluctuations at \( r = -2 \) cm is shown in Figure 3-17.

Region-B extends from \( 1 \text{ cm} \leq r \leq 3 \text{ cm} \). Here, density gradient is moderate (\( L_m \approx 6 \text{ cm} \)) and anti-parallel to effective gravity. Here, the condition \( V_n \cdot V_B > 0 \) is satisfied. Electric field is large (peaks around 3 V/cm) and changes its sign in this region. In this region, we observe coherent spectra. Typical cross-power, phase and coherence spectra between density and floating potential fluctuations at \( r = +2 \) cm are shown in Figure 3-18. In this region, the cross power spectrum exhibits a well-defined peak centered around 2.5 and 5.0 kHz. The second peak shows high degree of coherence (around 0.8). The phase
difference between the density and the floating potential fluctuations at this frequency is between $0^\circ$ and $50^\circ$. It is well known that gradient driven drift instability shows a phase difference close to zero between the density and floating potential fluctuations at the same location (Bora, 1989). Our measurements suggest presence of drift modes in this region.

**Figure 3-18** Crosspower of density and floating potential, phase and coherence spectra of rf produced hydrogen plasma at $B_t = 0.08$ T at $r = +2$ cm.

Region-C extends from $3 \text{ cm} \leq r \leq 6 \text{ cm}$. Here, the condition $\nabla n \cdot \nabla B > 0$ is satisfied. The density gradient is moderate ($L_n \sim 5 \text{ cm}$) and anti-parallel to effective gravity in this
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region. Also, the electric field is moderate and positive (between 0 to 2 V/cm). In this region, the cross power spectrum exhibits a well-defined peak centered around 1.3 kHz, Figure 3-19. The phase difference at this frequency between the density and the floating potential fluctuations is around 100°. As density gradient is antiparallel to the effective gravity 'g', this region is more favourable for the excitation of R-T instability. Also the phase difference observed in this region indicates the presence of a flute mode.

Figure 3-19 Crosspower of density and floating potential, phase and coherence spectra of rf produced hydrogen plasma at B₀ = 0.08 T at r = +6 cm.
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Region-D extends from $7 \text{ cm} \leq r \leq 9 \text{ cm}$. Here, the condition $\nabla n \cdot \nabla B > 0$ is satisfied. The density gradient is low ($L_n \sim 12 \text{ cm}$), electric field is moderate and is positive in sign in this region. In this region, the cross power spectrum exhibits well-defined peaks centered around 2 kHz and 4 kHz, Figure 3-20. The phase difference at this frequency between the density and the floating potential fluctuations is around 40°, showing drift nature of the instability.

![Figure 3-20 Crosspower of density and floating potential, phase and coherence spectra of rf produced hydrogen plasma at $B_r = 0.08 \text{ T at } r = +8 \text{ cm}$.

Figure 3-20 Crosspower of density and floating potential, phase and coherence spectra of rf produced hydrogen plasma at $B_r = 0.08 \text{ T at } r = +8 \text{ cm}$.
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To sum up, turbulent spectra is seen in the region A where $\nabla n \cdot \nabla B < 0$, whereas coherent peaks are observed in the region B, C and D where $\nabla n \cdot \nabla B > 0$ and are highly localized. Our measurements show the presence of both R-T modes and drift modes in ECR formed plasma. We know that heating of the plasma gives rise to region where $\eta = (\nabla \ln T_e / \nabla \ln n_e) < 0$. Fluctuations have been observed in the region where the condition $\nabla \ln T_e / \nabla \ln n_e < 0$ is satisfied in earlier experiments in the Culham Leviton (Riviere, et. al., 1978) and are identified as collisional drift waves. It has been shown (Chen, et. al., 1979, Cordey, et. al., 1979) that in slab approximation the collisional drift wave is stable for all $\eta$. However in toroidal geometry, it has been shown (Register and Hasselberg, 1979) that collisional drift wave is unstable for $\eta < 0$. We have generated a radial plot of $\eta$ for our experimental parameters, shown in Figure 3-21.

![Figure 3-21 The radial profile of $\eta$ for rf produced hydrogen plasma at B, = 0.08T.](image)

It is seen that $\eta < 0$ in the region $-1 \text{cm} \leq r \leq 2 \text{cm}$ and $r \geq 8 \text{cm}$. We observe drift waves only in these locations (see Figure 3-18 and Figure 3-20). Thus, our data suggests that collisional drift modes could be excited when $\eta < 0$ and $\nabla n \cdot \nabla B > 0$, whereas R-T modes could be excited when $\eta > 0$, $\nabla n \cdot \nabla B > 0$ and density gradient is antiparallel to ‘$g$’.
evaluating \( \eta \) we have taken the derivatives of the mean value of \( T_e \) and \( n_e \). It is difficult to estimate errors in the ratio of derivatives of experimentally derived \( n_e \) and \( T_e \) values. However, we have made an attempt to show the behaviour of the derivatives of mean values of the two measured quantities. This perhaps gives us an opportunity to suspect that our plasma is showing similarity with earlier experiments conducted in the Culham Levitron.

6 Conclusion

A theoretical, experimental and computational investigation has clearly revealed the basic features of a toroidal plasma which is produced by launching microwave perpendicular to the toroidal magnetic field in a pure toroidal device, BETA. Theoretical aspects of the propagation of microwave in plasmas are discussed with special reference to microwave power injection perpendicular to the toroidal magnetic field. Both O-mode and X-mode launching is highlighted with qualitative behaviour of these modes when launched in toroidal magnetized plasma. Theoretical estimates of plasma density and electron temperature are made. Electron temperature is estimated by the particle balance equation and is found proportional to the ionization energy. The average plasma density is determined by the power balance and increases with wave power. Equilibrium properties of ECR produced hydrogen plasma suggest that the plasma is formed with a peak density of \( 3 \times 10^{18} \) cm\(^{-3} \). Electron temperature is in the range of 4-7 eV. The measured electron plasma density and electron temperature are consistent with the theoretical estimates based on particle balance and power balance equations supporting the basic physical ideas presented in section 2. Contours of density and floating potential exhibit slab nature of the plasma in the vertical direction of the poloidal cross-section. Our measurements reveal that X-mode wave gets mode converted to electrostatic modes near UHR, which propagates close to ECR region where entire energy of the waves are deposited. Thus, we observe plasma profiles broadened towards the weaker magnetic field region upto the UHR region, with an inner boundary near ECR region. This is further supported by
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numerical calculation. It is observed that significant plasma production occur when ECR layer is located around the minor axis of the machine, indicating that the presence of a wave resonance is essential for efficient wave absorption. However, there is theoretical, experimental as well as computational evidence, which indicates that the wave absorption is mainly related to UHR layer rather than the ECR layer.

Fluctuating component of plasma parameter has also revealed the basic features of the instabilities present in the ECR produced plasma. Turbulent spectra is observed where the condition $\nabla n \cdot \nabla B < 0$. In this region, we also observe large density gradient and moderate electric field. LF coherent fluctuating modes are observed in the region where $\nabla n \cdot \nabla B > 0$. Both RT mode and collisional drift mode are observed in these regions. Drift mode is observed where electric field is large, with moderate density gradient or in the region where electric field is moderate and positive in nature but density gradient is weak. Flute modes are observed in the region where electric field is small and positive. Also, density gradient is moderate and antiparallel to ‘g’. To conclude, our measurements suggest that collisional drift modes could be excited when $\eta < 0$ whereas R-T modes could be excited when $\eta > 0$ and density gradient is antiparallel to ‘g’.