Abstract

Electron cyclotron (EC) absorption of electromagnetic (EM) waves is a standard way of generating and heating plasmas. Applications include radio frequency (RF) induced preionization and start up, RF heating and current drive in fusion devices, generation of industrial plasma such as those for etching of surfaces and development of ion sources for a variety of purposes. Wave particle interaction is a common factor in all these applications, but the details of wave propagation and absorption exhibits a great variation from one application to another. For example, mode conversion and parametric decay may or may not be observed in all the applications. This thesis primarily aims to understand mode conversion and parametric decay in terms of wave propagation and absorption. In addition to this, the issues of breakdown and generation of non-thermal electrons are also to be addressed.

Electron cyclotron resonance (ECR) plasma can be produced using various wave launch configurations. For example, whistler mode has been used for parallel launch ($\vec{k} \parallel \vec{B}_0$), whereas X-mode and O-mode have been used for perpendicular launch ($\vec{k} \perp \vec{B}_0$). The difference between X-mode and O-mode lies in the polarization of the launched wave. In the present study, X-mode launch has been used. The X-mode wavelength becomes very short and the amplitude of wave electric field becomes very large near the upper hybrid resonance (UHR) layer. This results in high power density at that location which gives rise to non-linear parametric excitation. In this process, the incoming EM wave breaks up into two electrostatic parts - the electron Bernstein wave (EBW), through X-B mode conversion and the lower hybrid wave (LHW).

Experiments have been carried out in a SS304 cylindrical vacuum vessel of length 10 cm and radius 6.4 cm. Two identical coils produce the required axial magnetic field of 875 G. A 870 W CW magnetron at 2.45 GHz frequency is used as the microwave power source. Microwave is guided to the vessel through a waveguide directional coupler and a circulator in TE_{10} mode. A toughen glass sheet is used as

the vacuum window. Forward and reflected power is monitored using the microwave diode detectors mounted on the directional coupler. The other diagnostics used are: Langmuir probe for measuring the electron density and temperature, a dipole probe for measuring the wave electric field and a capacitive probe for measuring the potential fluctuations.

ECR breakdown has been studied in terms of τ_{delay}, τ_{rise} and τ_{e-fold}. Here, τ_{delay} is the time between microwave power launch and appearance of detectable plasma density, τ_{rise} is the time in which density reaches 90 % of its maximum and τ_{e-fold} is the time in which the density falls down to 1/e of its maximum value after microwave power is switched off. This is the first attempt to measure these breakdown parameters in a cylindrical geometry. During the experiment, the input microwave power is varied from 160 W to 800 W and the gas operating pressure is varied from 2×10^{-5} mbar to 1×10^{-2} mbar. For breakdown studies four different gases, hydrogen, helium, nitrogen and argon are used. As pressure increases τ_{delay} decreases whereas τ_{rise} and τ_{e-fold} increases. On increasing the pressure, the plasma density increases due to the increase in number of neutrals but the temperature goes down because the electron-neutral collision frequency also increases which thermalizes the plasma. With power τ_{delay}, τ_{rise} and τ_{e-fold} follow similar trend as observed in case of pressure. However, the increase in power increases the plasma density as well as plasma temperature. The experimental results show that breakdown parameters, irrespective of the filling gas, follow the same trend systematically.

The plasma parameters have axial and radial variations due to the wave electric field distribution and magnetic field configuration. The spatial profiles for plasma parameters forms the basis for estimation and identification of different wave cut-offs and resonances in the experimental system. Information on plasma parameters is also necessary to set the initial conditions for any experiment. The radial variation in magnetic field is such that the first two harmonics of ECR reside in the system. The UHR resides at two places, on either side of the central axis, because of the symmetric magnetic field.

Parametric decay experiment has been carried out with an axial magnetic field of 875 G which corresponds to 2.45 GHz cyclotron frequency. Though with power the density increases, the plasma always remain underdensed ($\omega_{ce} > \omega_{pe}$). Hence, the UHR layer position does not change considerably at different input power levels. So, the input power is varied to identify the threshold power necessary for the occurance of parametric decay. Parametric decay spectrum has been observed with a capacitive probe placed near the UHR layer. It contains the harmonics of $f_0 \pm f_1$ on either side of the launched frequency f_0. The frequency $f_0 \pm f_1$ is observed to be high whereas the frequency f_1 is low. This indicates the three-wave non-linear interaction. The parametric decay has an input power threshold to occur as on reducing the input power below 600 W, the decay spectrum disappears. If the wave amplitude is sufficiently high then it can decay into two waves, one of higher frequency and another one of low frequency. It is speculated in the present experimental case that the incident EM wave is decaying into two waves in which one is of high frequency and the other one of low frequency which is LHW. Theoretically, the lower hybrid frequency has been estimated to be $\approx$ 23.4 MHz. In this experiment it is observed to be 33 MHz. Also, the estimated theoretical value of the threshold power, $\approx$ 547 W, is compared with the experimental one ($>$ 500 W) and is found in good agreement.

The EBW, generated at the UHR layer due to X-B mode conversion, propagates perpendicularly to the ambient magnetic field towards the first ECR surface near the central axis and gets absorbed there. An attempt has been made to characterize this EBW. The absorption of EBW at ECR layer leads to the generation of highly energetic electrons. The presence of energetic electrons is also observed in electron energy distribution function (EEDF) obtained from I-V probe characteristics. These high energy electrons when lost to the walls produce soft x-rays. The soft x-ray emission is detected with a vacuum photodiode (VPD) operated in the saturated mode. The experiments revealed that soft x-ray signal is feeble in absence of a metal target but gets enhanced when a metal target is placed at the centre. Soft x-ray signal also varies when the inner system wall is covered with aluminium foil. The soft x-ray emission is high at the lower working pressures and at higher input microwave power.

The thesis is organized in the following manner. In the first chapter, a brief introduction of plasma, its different states and modes of its formation in laboratory are presented alongwith the introduction of the subject of ECR plasma and review of the previous work done. A detailed description of the experimental setup, conceived and designed is presented in the second chapter. In chapter three, the investigation of ECR breakdown parameters in different experimental scenarios is discussed. In fourth chapter, the system characterization by obtaining the plasma parameters at different radial and axial locations are presented. The experimental studies of non-linear processes such as parametric decay occuring in ECR plasma and its consequences are discussed in fifth chapter. Chapter six covers the EBW generation at the UHR layer through X-B mode conversion and detection. In chapter seven, the experiments related with the emission and detection of soft x-rays are presented. Chapter eight contains the complete summary about the cylindrical ECR plasma system and the set of experiments performed with important results and the future scope of work. The main circuits and tables referred in the thesis are given in the appendix separately. The bibliography for the complete research work is placed at the end of the thesis.