Chapter 1 Introduction

Since the early investigations in plasma physics (D'Angelo, et. al., 1963, Chen, 1965, Hendel, et. al., 1968, Kent, et. al., 1989, Perkins, et. al., 1971) many studies have been devoted to plasma instability in laboratory plasmas. In the case of magnetized plasmas, the plasma instabilities research topics are related to the problems of anomalous transport in magnetically confined fusion plasmas (Horton, 1999 and Garbet, 2001). It is generally recognized that low frequency fluctuations ($\omega < \omega_i$), excited in the scrape of layer (SOL) region of confined plasmas by the release of free energy, may very well be contributing to anomalous plasma transport across magnetic field lines. Here, $\omega$ is the excited frequency of the instability and $\omega_i$ is the ion-gyro frequency. Also, plasmas found in space (natural laboratory), which are weakly ionized and have low density and low temperature, exhibit variety of coherent and turbulent low frequency wave phenomena. Further, the study of low temperature plasmas such as those produced in laboratory is still a topic of research due to the fact that some of the characteristics of low frequency instabilities have not yet been explored in detail. They, in some sense, resemble the edge plasmas and under some conditions also simulate some of the ionospheric processes. The advantage in such plasmas is that the study of instabilities can be done in a controlled way. Hence, understanding of the low frequency instabilities in such plasmas is essential. Different kind of instabilities associated with low frequency fluctuations has been recognized in laboratory plasma and are reviewed in next section. Motivation, which leads to this thesis, is presented in section 1.2, followed by thesis structure in section 1.3.
1 Review of earlier works.

The first experimental observation of drift waves came from Q-machine, using low temperature, low β-plasma. The Q-devices (Motley, et. al., 1975) have alkali metal plasmas confined by straight uniform magnetic field. The only source of free energy being the density gradient (\nabla n). The collisional drift waves and the turbulence generated in the Q-machine were extensively studied (D’Angelo, et. al., 1963, D’Angelo and Motley, 1963, Hendel, et. al., 1968, Pecseli, et. al., 1983). The Rayleigh-Taylor (RT) instability has been studied in mirror devices and 0-pinches by several workers (Kolb, et. al., 1965, Hintz, et. al., 1965). R-T instability has been observed in linear curved system (Komori, et. al., 1978). It was observed that, depending on the system parameters, one could excite curvature-induced RT instability in the bad curvature region. The Kelvin-Helmholtz, instability has also been excited (Sugai, et. al., 1975).

In order to get deep insight into the plasma behaviour, different experimental devices evolved, for example, mirror machine (Fowler, et. al., 1981, Post, et. al., 1983), linear machines (Motley, et. al., 1975), curved linear machine (Komori, et. al., 1978), etc. As experiments progressed, experimental set-ups also changed its shape. In early eighties, it was realized that plasma confined by a pure toroidal magnetic field has an immense potential to carry out basic plasma physics experiments, due to their obvious advantages over the linear and curved machines. Most of the shortcomings of the linear and curved systems such as low electron and ion temperatures, domination of the parallel transport, effect of sheath, etc., have been automatically overcome as the plasma is of infinite extent in the direction of the ambient magnetic field. This makes the study of the propagation of large number of waves, for e.g., cold electron waves, ion Bernstein waves, lower hybrid waves, etc., possible in such devices (Wong, et. al., 1982). Thus toroidal devices evolved and became much popular as they provided an opportunity to study basic plasma phenomenon, with improved plasma parameters (compared to linear devices), in a much-controlled manner unlike tokamak and stellaraters. The striking features of some of the toroidal machines are shown in Table 1-1.
Different problems have been studied experimentally in these systems. ACT-I was the first machine where non-inductive current drive experiments in toroidal geometry, ion Bernstein wave launching and other radio-frequency wave related experiments were conducted (Wong, et. al., 1982). The THORELLO toroidal device (Riccardi, et. al., 1994) has also concentrated on wave launching experiments. The BLAAMANN toroidal device in Norway is engaged in transport, equilibrium and instability studies (Rypdal, et. al., 1994, Oyens, et. al., 1995). TOMAS is engaged in the investigation of wall conditioning methods by microwave induced methods (Stork, et. al., 2001). Recently TORPEX has come up in Switzerland, which aims at basic transport studies (Podesta, et. al., 2003).

Plasma in a toroidal geometry is very interesting due to natural occurrence of various waves and instabilities arising in it. It is well known that the plasma embedded in a
toroidal magnetic field is subjected to an additional class of instabilities compared with linear systems. Besides the types of drift instabilities that occur in a linear device, flute instabilities due to the curvature of the system could also be excited. This is because the curvature of the magnetic field lines gives rise to an effective gravity and the density gradient is anti-parallel to this effective gravity. BETA (Basic Experiment in Toroidal Assembly) is the basic experimental device in our laboratory and has been in operation for over a decade (Bora, 1989). The emphasis of the studies conducted in this machine has been primarily to study low-frequency (LF) (\(\omega \ll \Omega \)) magnetohydrodynamic (MHD) fluctuations.

Although initially studied in the context of hydrodynamic theory (Land, 1960), this type of instability has been shown to exist in magnetized plasma. One such mode, namely Rayleigh-Taylor (R-T) instability has become an important area of research in the plasma physics community and a considerable amount of work (theoretical, experimental, and computational) have been done over the past few decades. The bulk of the research has been motivated by the fusion research program, especially in regard to the stability of the magnetized plasma (Longmire, et. al., 1957), imploding laser target pellets (Bora, 1974) and also in space plasmas (Siscoe, 1983).

The drift wave and RT instability were also reported by Bora, 1989, in pure toroidal plasma. Later experiments (Prasad, et al., 1992, Prasad, et al., 1998) reported the detailed spectrum of the instability in the same device. The above studies of low frequency instabilities in toroidal plasma have established that magnetized low-\(\beta\) plasma embedded in a pure toroidal magnetic field is also subjected to R-T instability arising from an unfavourable curvature in the toroidal magnetic field (simulating effective gravity 'g') with density gradient (\(\nabla n\)) antiparallel to it. Here \(\beta\) is the ratio between kinetic and magnetic pressure and its value is typically \(\approx 10^-1\) in our device. This device also provided scope for the study of moving coherent structures (Singh, 1992), electrode bias experiments (Jain, 1993), role of shear and flow curvature in the suppression of LF fluctuations (Sen, et al., 1998), modification of LF instabilities with high frequency
pump waves (Sharma and Bora, 1998) and suppression of R-T type fluctuations by velocity shear (Sen, et. al., 1997).

2 Motivation

In all the experiments reported above, the plasma production scheme was similar. Plasma was primarily produced using the hot cathode discharge method. An incandescent filament, placed in the toroidal vacuum vessel is biased with respect to the vessel, thus initiating a hot cathode discharge. However, the source within the plasma volume may perturb the plasma. Furthermore, the filament is biased with respect to the vacuum vessel. This imposes an external electric field between the filament and the grounded vessel, which has components in all directions. This could affect the plasma properties and hence the observed low frequency fluctuations. In order to eliminate this, we need a plasma source other than filament. Injection of electron for discharge build-up will be influenced by external magnetic field. Thus electron source gets affected by magnetic field, hence it is undesirable. Electromagnetic field produced plasma could be used. The best source would be electron cyclotron resonance (ECR) produced plasma, which would also simulate filament characteristics like local ionization. ECR being a magnetic resonance phenomenon depends on the strength of the toroidal magnetic field. The plasma would be formed at location, where the wave frequency, \( f_c \), matches with the electron gyro-frequency, \( f_{ce} \). Since the electron gyro-frequency depends on the strength of the toroidal magnetic field, therefore the electromagnetic resonance can be generated at different radial locations in toroidal plasma.

An ECR produced magnetized plasma offers a number of desirable characteristics, including high plasma density, wide range of pressure operation and uniform plasma with a high degree of ionization. Further, the plasma is formed without any electrodes within the plasma volume and hence sheath effects are minimized. Plasma source based on ECR are widely used in plasma processing applications like etching, deposition and ion implantation (Chapman, 1980, Lieberman, et. al., 1994) and lot of work has been carried
out in magnetized ECR plasma in linear machine (Yoshinuma, et. al., 1999). However, very little work has been done in magnetized ECR produced toroidal plasma. It is not very clear about the nature of low frequency electrostatic fluctuations in ECR produced toroidal plasma. Will it be similar to that observed in filament produced toroidal plasma or will it be quite different? Thus ECR formed toroidal magnetized plasma is studied and it forms a first step toward our studies.

In toroidal device, the toroidal magnetic field varies inversely with major radius, in the radial direction and decides the location of the resonance layer for ECR formed toroidal plasma. However if we move up or down in the poloidal cross-section of the machine at a fixed radial location, the magnitude of the toroidal magnetic field remains constant. Thus in ECR formed plasma, the resonance layer acts as a line source (where the source frequency matches with the cyclotron frequency) and one may expect equilibrium different than observed in filament-produced plasma (Rypdal, et. al., 1994). It is highly probable to get a slab like equilibrium or elongated equilibrium in this type of plasma production scheme. In earlier work, the slab nature of the plasma was assumed in filament-produced plasma, however, it was not established experimentally. While investigating the vortex structures in toroidal plasma (Singh, 1992), the instantaneous values of potential was measured and their contours were generated using conditional averaging method, but the study did not address the issue of equilibrium in toroidal plasma. However, in some experiments, equilibrium study for toroidal plasma shows that equilibrium plasma exhibits circular density and potential contours in a filament discharge (Rypdal, et. al., 1994). It has been argued that plasma in pure toroidal magnetic field with circular contours do not exhibit equilibrium since

\[
\nabla \cdot \vec{J} \propto \frac{\partial p}{\partial z} \neq 0
\]

However, if slab equilibrium, as argued above, exists then \( \nabla \cdot \vec{J} = 0 \), as plasma density contours will have weak dependence on vertical location (z-direction). Thus, in slab or elongated equilibrium, we may get \( \nabla \cdot \vec{J} = 0 \) over the extended region and may establish the plasma equilibrium state. Now, if \( \nabla \cdot \vec{J} = 0 \), then we can write,
Chapter 1 Introduction

\[ \vec{k}_1 \cdot \vec{J}_1 + k_n \cdot \vec{J}_n = 0 \]

The four parameters \((k_1, k_n, J_1, J_n)\), satisfying the above equation would establish the existence of elongated or slab like equilibrium. Hence, one would like to obtain the above parameter experimentally and see if it satisfies the above equation.

Suppose we assume that elongated or slab equilibrium exists. Then, we should show that the ratio \(\frac{|J_n|}{|J_1|} \) should be equal to the ratio \(\frac{k_n}{k_1}\), i.e.,

\[ \frac{|J_n|}{|J_1|} = \frac{k_n}{k_1} \]

\(\vec{J}_n\) and \(\vec{J}_1\) contribute to discharge current and can be estimated from the measurement of discharge current. Now, the task reduces to experimentally measure the ratio of perpendicular and parallel wave-number by an independent method and compare the two results. If both, the right hand side and left hand side of the above equations are equal, then, one can conclude that the elongated or slab like equilibrium exists.

However, measurement of discharge current in ECR produced plasma is difficult and not trivial, as the vessel is not biased. Thus, to establish elongated or slab like equilibrium, experiment is conducted with hot cathode discharge produced plasma, with elongated filament source. The plasma in toroidal devices is produced with the help of a vertically extended (along the z-axis) hot-cathode filament source placed at different radial positions. Here, also two important prerequisite conditions need to be satisfied to make this study possible. First, to establish slab nature of the contours in filament-produced plasma and second, introduction of finite \(k_n\) into the system (as measurement of \(k_n\) is trivial). In our work, we have found a novel way to introduce and estimate \(k_n\) by using a weak vertical magnetic field. Hence, experimental study of toroidal plasma in the presence of weak vertical magnetic field is conducted. The experiment with weak vertical
magnetic field also provides an opportunity to study the effect of $k_y$ on flute type of instabilities, identified in the toroidal system earlier. In literature, no mention is made where the above study is conducted using the above-mentioned novel technique. This part of the experiment forms the next step towards our thesis study.

3 Thesis structure

The thesis starts with an introduction chapter where earlier works in the field of low frequency fluctuations in different plasmas are reviewed. The motivation for the present work is highlighted followed by thesis structure. The experimental set-up, diagnostics and data analysis is presented in chapter 2. It briefly describes the experimental device along with its sub-systems. Plasma production schemes using microwave and filament methods are discussed. Diagnostics and signal processing electronics employed in this experimental campaign is reported. Microwave instruments used and measurements made using it are also discussed in this chapter. Modeling of microwave components using high frequency structure simulator (HFSS) code have been made and is briefly discussed in this chapter. Finally, the data analysis techniques employed for analysis of our data is outlined. The study of ECR produced toroidal plasma is reported in chapter 3. The chapter introduces some theoretical background of microwaves in plasmas. Experimental results are reported and compared with theoretical estimates and computational analysis. The computational analysis is based on ray-tracing code and is briefly discussed in this chapter. Investigations of low frequency fluctuations are discussed. Experimental study of toroidal plasma in the presence of a weak vertical magnetic field is described in chapter 4. In this part of the work, the plasma in the device is produced with the help of a vertically extended (along the z-axis) hot-cathode filament source placed at the minor axis. The experiment has been conducted to investigate (i) the transverse (in the r-z plane) density and floating potential profiles and (ii) the effect of finite $k_y$, due to the error field, on the LF fluctuations along with an estimate of $k_y$ in plasma. Equilibrium
studies are made with and without weak vertical magnetic field. Effect of weak vertical magnetic field and concept of parallel wavenumber is introduced. Low frequency fluctuations are studied in filament produced toroidal plasma with small but finite parallel wavenumber. Equilibrium in BETA is discussed and slab equilibrium is argued based on experimental observations. Chapter 5 concludes the thesis and highlights the scope for future work. It compares the microwave-produced plasma with filament-produced plasmas. The behaviour of low frequency fluctuations in both the cases are discussed and compared.