Abstract

A detailed study of equilibrium, fluctuations and transport in the context of current-less toroidal devices (CTD) is presented in this thesis. The main issues addressed are the following: (1) The loss of plasma equilibrium in a pure toroidal magnetic field and its restoration by the conducting limiter aperture and poloidal flow, (2) Stability of such an equilibrium to the low frequency fluctuations, (3) Nonlinearly saturated state of Rayleigh Taylor (RT) instability and (4) The role of fluctuation driven ponderomotive force (PF) on the equilibrium and transport in such devices.

A plasma confined by a pure toroidal magnetic field lacks equilibrium. This is because of the fact that the drifts associated with curvature and inhomogeneity of the curved magnetic field lines produce a vertical electric field. The resulting $\vec{E}\times\vec{B}$ drift accelerates the plasma along the major radius, thereby destroying the equilibrium. Firstly, we investigate the effect of a conducting limiter aperture on the toroidal plasma equilibrium. In this case, the plasma pressure is assumed to be constant everywhere except in a small region near the limiter. The electric field is produced only in small region near the limiter which is shorted by current flowing along the magnetic field into the limiter, in the poloidal direction inside the limiter and then again along the magnetic field lines. For a perfectly conducting limiter plasma path, no electric field persists and the only plasma loss is in the time particle takes to drift to the limiter. Our analysis shows that the plasma confinement time in this case is $\sqrt{aR}/2a_s$ times that of a pure toroidal plasma. While taking into account the finite resistivity of the plasma–limiter path, the confinement time is found to be lying in between the two values estimated in the case of pure toroidal plasma and the toroidal plasma surrounded by perfectly conducting limiter. In chapter 2, we also study the effect of fast poloidal rotation on the plasma equilibrium. We show that the plasma equilibrium can be restored if $V_E \gg |V_g r/L_P|$ where V_E is the poloidal flow velocity and V_g is the curvature drift . In this case, the equilibrium is restored by the plasma convection.

Using the above equilibrium provided by the limiter and the poloidal flow, we study various possible low frequency ($\omega < \Omega_i$) fluctuations *e.g.*, Rayleigh Taylor, modified Simon Hoh, Simon Hoh and drift type of instabilities and compare their characteristics with the observed fluctuations in a CTD (*e.g.*, BETA). On the basis of the phase difference between the observed density ($\tilde{n}$) and potential ($\tilde{\varphi}$), we identify the observed fluctuations as flute

modes. In toroidal devices, the curvature of the field lines provides an effective gravity. In the outboard region of such a plasma, the situation is quite similar to that of a heavy fluid supported by a light fluid against gravity. We first investigate the linear properties of the magnetic curvature driven RT instability and the nonlinearly saturated amplitude of fluctuations using the mixing length arguments. Our analysis shows that the experimental observations such as the occurrence of fluctuations both in the inboard and the outboard regions, reduction of the amplitude of the coherent peak with increasing magnetic field and the radial profile of RMS level of fluctuations cannot be explained by the RT mode. Thus, the observed fluctuations cannot be entirely attributed to the magnetic curvature driven RT mode. We explore other possible candidates such as Simon Hoh (SH), modified Simon Hoh (MSH) and drift type of modes in relevance to the current-less toroidal devices. The MSH and the SH modes have been earlier investigated in the intermediate frequency range ($\Omega_i < \omega < \Omega_e$). In this thesis, we investigate these instabilities in the low frequency regime ($\omega < \Omega_i$). Due to large ion Lamror radius, there is a difference in the $\vec{E}\times\vec{B}$ drift of electrons and ions in an inhomogeneous electric field. This relative drift causes the charge separation and enhances the density perturbations only if $\vec{E}\cdot\vec{\nabla}N > 0$. We find that the conditions are favorable for the excitation of MSH instability both in the inboard and the outboard regions of the CTD. In the case of high neutral pressure, we study the SH instability which arises due to the difference of the electron and the ion $\vec{E}\times\vec{B}$ drifts caused by ion–neutral collisions. And a necessary condition for the excitation of the SH mode is $\vec{E}\cdot\vec{\nabla}N > 0$. In the presence of small error/toroidal magnetic field, the toroidal field lines do not close on themselves. This establishes an electrical interaction between the plasma and the conducting limiter aperture. This may either result in the finite $k_{||}$ or the conducting wall effects depending upon the magnitude of the error/vertical magnetic field. In the presence of small error magnetic field, the effect of conducting walls is small. In this case, we study the drift type of mode and the effect of finite $k_{||}$ on the RT and the MSH modes. We show that a new branch of the drift mode arises in a flute regime. The growth rate of this new mode increases with increasing $k_{||}$ and decreases with increasing magnetic field. On further increasing $k_{||}$, this new drift type of mode turns into the usual resistive drift type of mode. We also show that the finite $k_{||}$ has a stabilizing influence on the RT and the MSH modes. In the presence of large error/vertical magnetic field, the conductive wall effects become important. In this case, the parallel current dynamics is governed by the Bohm's sheath criterion. We also study the effect of conducting walls on the RT and the MSH modes and show the stabilization of these modes on negative biasing and destabilization on positive biasing of the limiter. Finally, we study numerically the effect of strong velocity shear on the RT mode using different velocity profiles. We find that for a parabolic velocity profile and a Gaussian density profile, the velocity shear has a stabilizing effect on the RT mode. On the other hand, the role of velocity curvature on the RT mode is governed by the relative sign of the product $\hat{v}_E'\hat{v}_E''$. For the negative sign of the product, the velocity curvature destabilizes while for positive sign, it stabilizes the RT mode.

The linear instability analysis shows that the curvature driven RT mode is one of the prominent candidate in such devices. As nonlinearly saturated fluctuations are observed in experiments, we carry out a numerical study of the nonlinear dynamics of the RT instability using pseudospectral code. The relevant boundary conditions for such an experimental system is conducting boundary conditions in the direction of density gradient and periodic in the other directions. The nonlinear saturation of the RT mode is observed due to the homogenization of the density within the box length. We have carried out a simulation with the doubly periodic boundary conditions. We point out that there are three distinct phases of evolution where it is governed by (i) the linear effects, (ii) the effects arising from the conventional nonlinear terms and (iii) the subtle nonlinear effects arising through the coupling terms. During the third phase of evolution, there is a self generation of shear flow which in turn saturates the RT instability in the case of doubly periodic boundary conditions where, in principle, an infinite amount of gravitational energy can be tapped from the system. Finally, we present a Galerkin approximation to provide to explain our numerical results.

In chapter 5, we provide an explanation of the equilibrium of the plasma in CTD in terms of the flow fluctuation cycle which can be described as follows. In the initial seed equilibrium provided by the limiter, the RT fluctuations grow appreciably. These fluctuations provide an additional source of rotational transform in two ways. First, they directly drive a poloidal flow via Reynolds stress which improves the equilibrium. Second, the flow back–reacts on the fluctuations and modifies the mean rms level of fluctuations in such a way that the mean radial ponderomotive force (PF) due to fluctuations opposes the radial fall of the plasma directly. In order to provide the equilibrium, we identify the constraints on the mean rms profile of fluctuations and ion neutral collisions. We observe that for monotonically increasing rms level of fluctuations, the mean radial PF opposes the free fall of the plasma. A detailed linear theory of the RT instability in the presence of weak shear is presented and criteria for the flow stabilizations are identified. Using the exact eigenfunction of fluctuations, an exact ordinary differential equation for the poloidal flow is derived and solved using an ansatz based on linear theory and experimental observations.

Finally, in order to complement our work on equilibrium, we calculate the particle flux and diffusion coefficient in the presence of ponderomotive force due to background fluctuations (chapter 6). The poloidal variation of equilibrium quantities *i.e.,* density, potential and fluctuation driven mean PF, is taken into account and assumed to be an $\epsilon(= r/R)$ order smaller than the radial variation of the equilibrium quantities. Our analysis shows that the role of fluctuation driven PF on the particle flux or diffusion coefficient critically depends on the characteristics of the background turbulence. For the radially propagating waves *i.e.,* $k_r \neq 0$ with $\nu_{in}/\Omega_i > k_r/k_\theta$, the poloidal component of the mean PF dominates and results in the enhancement of the particle transport. In the other limit of $\nu_{in}/\Omega_i < k_r/k_\theta$, the radial component of PF dominates and results in the reduction of the particle flux *i.e.,* further improving the plasma equilibrium.

In conclusion, we have carried out a detailed study of equilibrium, fluctuations and transport in the context of current-less toroidal devices. The importance of the fluctuations in providing the basic rotational transform in a CTD has been manifested in this thesis.