1. Fluctuations and flows in confined plasmas

1.1.1 Significance of plasma flows

Generation of plasma flow and its effects on plasma confinement are of general physics interest. In the plasmas occurring in nature, magnetic or electrostatic fluctuations are believed to drive plasma flows and/or vice versa [1, 2, 3]. In the objects such as stars, the inter-dependency of flows and magnetic fluctuations is believed to be significant [3]. In the laboratory plasmas, either magnetic or electrostatic fluctuations can be interrelated with the plasma flows. For example, the poloidal flows are found to be strongly connected to the formation of magnetic islands formed due to external magnetic field perturbations, which degrade confinement in stellarators and tokamaks [1, 2]. Further, the improved plasma confinement in tokamaks is found to be associated with increased toroidal rotation [4]. The investigation of plasma flow has gained further significance in recent times, due to its dynamo action in stars and other astronomical objects. To investigate plasma dynamo in the laboratory, a new experimental facility with the name of ‘Madison Dynamo’ has been constructed at University of Wisconsin, Madison, US [3]. Thus addressing these flows and fluctuations would throw light on all the above mentioned phenomena and hence is of fundamental importance.
1.1.2 Magnetically confined laboratory plasmas

Magnetically confined plasmas in toroidal devices have gained significance decades ago, for their potential to achieve controlled fusion [4, 5]. In spite of the remarkable advance in this field, transport of particles and energy have been found to be anomalous and pose challenges in further improving the plasma confinement. Some of the mechanisms which lead to the above mentioned anomalous transport are the density and temperature gradient driven instabilities in curved magnetic fields [6, 7, 8]. A clear understanding of these processes, therefore, is of paramount importance. The presence of complex magnetic field geometry in fusion devices, sets constraints in carrying out individual studies on instabilities mentioned above. A simple magnetized torus with a pure toroidal field provides an excellent alternate facility to carry out the above mentioned studies in much simplified conditions. Though mean plasma parameters are much limited in their range compared to tokamak edge plasma, the plasma behavior observed is relatively similar. For instance, the results of turbulence simulation codes which are applicable to the fusion edge plasmas, agree well with the experimental results for simple toroidal devices, when used with suitable normalized parameters as applicable to them [9]. Hence much useful studies on instabilities and transport can be conducted in such simple toroidal devices.

Plasmas produced in confinement devices, in general, possess intrinsic gradients in typical plasma parameters such as density, electron or ion temperature and plasma potential. In presence of magnetic field, these gradients commonly lead to gradient-driven instabilities. When the density gradient scale-length exceeds the temperature gradient scale-length above a threshold, then the temperature gradient driven instabilities can have dominant contributions to the fluctuations [6, 7, 8]. Furthermore a gradient in the plasma potential indicates a finite electric field in the plasma, which can drive $E \times B$ flow. Presence of a velocity shear can lead to Kelvin-Helmholtz instability [10]. The above mentioned instabilities and waves can co-exist in typical confinement devices with linear or curved magnetic fields. In toroidal devices, the curved magnetic field can lead to additional class of instabilities due to inherent gradient and curvature in the magnetic field. The radius of curvature in a curved magnetic field is analogous to the gravity; when the
density gradient is opposite to the radius of curvature, Rayleigh-Taylor instabilities can become unstable [11]. In fusion devices such as tokamaks, simultaneous fluctuations in density and potential lead to finite fluctuation induced radial transport, degrading the plasma confinement [12]. The poloidal rotation, by self-consistent electric field or external electric field, has been seen to lead to reduced turbulence and high confinement mode in tokamak [13]. An understanding of the origin of the poloidal rotation is crucial to achieve high confinement mode. Moreover, the low and high confinement modes in tokamaks were found to be associated with opposite directions of intrinsic toroidal flow generation; an inter-machine comparison of tokamaks have shown that the intrinsic toroidal rotation velocity increases with plasma stored energy or pressure [4]. Experimental observations on COMPASS-C tokamak have predicted that a rotating plasma will resist externally induced magnetic tearing until the applied resonant magnetic perturbations exceed a critical threshold [2]. Above this threshold, stationary magnetic islands are induced in the background rotating plasma, degrading the confinement. It is also known that due to nonuniform B-field, plasma confined in toroidal fusion devices can be compressible. This compressibility is believed to play a crucial role. Possibility of experimentally studying the above discussed instabilities in a simple toroidal plasmas is highly desirable not only due to its relevance to tokamaks, but also because these physical processes are of fundamental importance. In the following, the fundamental issues concerning the lack of equilibrium in a simple toroidal plasma are described.

1.2 Simple toroidal plasma

Plasma produced in a pure toroidal magnetic field is subject to single particle drifts given by

$$\mathbf{v_R} + \mathbf{v_{\nabla B}} = \frac{m}{q} \frac{\mathbf{R_c} \times \mathbf{B}}{R_c^2 B^2} \left( v_{\parallel} + \frac{1}{2} v_{\perp}^2 \right),$$

(1.1)

where $v_{\parallel}$ and $v_{\perp}$ are the parallel and perpendicular components of the velocity with respect to the magnetic field, of the particle with charge $q$ and mass $m$. The first and second terms in Eq.(1.1) correspond to curvature and gradient drifts respectively. Both the drifts add up for each charge particle; the combined drift is opposite for oppositely charged species, leading to vertical charge separation.
building-up a vertical electric field \((E_z)\). The enhanced vertical electric field leads to increased \(E_z \times B\) drift directed radially outward; hence stationary equilibrium does not exist in a simple toroidal plasma [14].

The non-existence of plasma equilibrium in a pure toroidal plasma can also be understood from the magneto-hydro dynamic (MHD) equations. The two essential conditions for the existence of plasma in equilibrium are

\[
J \times B = \nabla p, \tag{1.2}
\]

\[
\nabla \cdot J = 0, \tag{1.3}
\]

where \(J\) is the current density in the plasma, \(B\) is the magnetic field and \(p\) is the plasma pressure. For a simple toroidal plasma, the validity of the Eq.(1.2) and (1.3) is verified as follows. Taking cross product with \(B\) on both sides of Eq.(1.2), one arrives at

\[
B^2 J - (B \cdot J) B = B \times \nabla p. \tag{1.4}
\]

Since there is no toroidal plasma current, \(B \cdot J = 0\). Now taking divergence on both sides of Eq.(1.4), and on further simplifying

\[
\nabla \cdot J = \frac{\partial p}{\partial z} B \frac{\partial}{\partial R} \left( \frac{1}{B^2} \right). \tag{1.5}
\]

Hence Eq.(1.3) is not satisfied whenever \(\partial p/\partial z \neq 0\), which is usually the case. This suggests that charge separation would occur.

The restoration of plasma equilibrium in a simple toroidal plasma, using a conducting limiter was suggested by Yoshikawa et al [14]. In this equilibrium, the plasma pressure is constant at the core of the plasma and a sharp pressure gradient exists in the boundary. The vertical charge-separation current flows along the magnetic field lines into the limiter, and the short circuit effect inhibits the \(E_z \times B\) drift. There still remains a certain potential difference between the top and bottom because of the potential drop along the path of the short-circuit current and finite resistivity of the conducting limiter. Physically, the current to the limiter is limited by the ion saturation current. If the charge separation current
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exceeds this limit, stationary equilibrium without any time dependence can no longer be maintained. The vertical potential difference can be calculated assuming a finite width boundary for the plasma. The thickness of the plasma boundary is determined by the rate of diffusion of the plasma across the magnetic field. The confinement time $\tau_c$ in this equilibrium model, can be calculated from the distance between the inner to the outer edge of the limiter ($\sim 2a$) divided by the average velocity $kT_e u_0 / (eaB_0)$, obtained by averaging $E_z/B$ from $R - a$ to $R + a$. Thus $\tau_c$ is given by

$$\tau_c \approx 2ea^2B_0 / kT_e u_0,$$  \hspace{1cm} (1.6)

where $a$ is the minor radius, $R$ is the major radius, $B_0$ is the toroidal magnetic field at the minor axis, $T_e$ is the electron temperature, and $u_0$ is a numerical factor; usually $u_0 \ll 1$ which indicates the existence of a finite potential difference between the top and bottom of the limiter. Using this model, the plasma confinement time estimated for a real limiter will be less than that estimated for an ideal conducting limiter. The restoration of plasma equilibrium, using conducting limiter is schematically shown in Fig. 1.1.

Another model is suggested by Nieuwenhove to explain the restoration of plasma equilibrium in a pure toroidal field which is based on fast poloidal rotation [15]. The vertical charge separation is weakened by charge neutralization due to fast poloidal rotation. This is schematically shown in Fig. 1.2. A stationary solution can be found in which the charge density can be kept sufficiently small by imposing a fast poloidal rotation such that

$$\left| \frac{n_i - n_e}{n} \right| \ll 1,$$  \hspace{1cm} (1.7)

where $n$ is the average plasma density, $n_i$ and $n_e$ are the corresponding densities of ions and electrons respectively. Equation (1.7) imposes a condition on the poloidal rotation velocity $v_\theta$, given by Eq.(1.8)

$$|v_\theta| \gg \frac{T}{\Lambda} v_D,$$  \hspace{1cm} (1.8)

where $r$ is the radius of rotating plasma, $\Lambda = |nkT/d(nkT/dr)|$, in which $T = T_i + T_e$, and $v_D \equiv |\mathbf{v}_R + \mathbf{v}_B|$, given by Eq.(1.1). For a Maxwellian distribution,
$v_D \simeq r_L v_{th}/R$, where $r_L$ is the Larmor radius, $v_{th}$ is the thermal velocity, and $R$ is the radius of curvature. Since $v_{th} = c_s \sqrt{m_i/m_e}$, $v_D$ in Eq.(1.8) can be replaced by $r_L c_s \sqrt{m_i/m_e}/R$. This model, therefore, suggests that even in the absence of magnetic rotational transform, a stationary equilibrium can exist in a simple toroidal plasma if a fast poloidal plasma rotation exists. Whether or not the Eq.(1.8) is satisfied in the present experimental conditions, will be discussed in Chapter 3. A suggested application of this model is that in a tokamak plasma, produced initially with low density and low plasma current, is switched to a rapidly spinning state using neutral beam injection (NBI) power; finally the plasma current can be ramp down to zero, while maintaining the simple toroidal magnetic field, NBI power and gas feed to see whether the plasma can assume a new currentless magneto-electric equilibrium. Following the above necessary theoretical understanding of the simple toroidal plasma and issues in attaining equilibrium, a brief review of the previous experimental and theoretical investigation of simple toroidal plasmas is given below.
1.3 Review of previous works

In the experimental observations in simple toroidal plasmas, neither uniform plasma pressure profiles are seen in the core plasma as predicted by Yoshikawa’s model, nor a fast poloidal rotation of magnitude predicted by Nieuwenhove’s model. As suggested by the above two models, the plasma equilibrium in a simple toroidal plasma, therefore, need not exist. The measured confinement time observed in experiments [16], is however, found to be nearly one order higher than that is predicted theoretically from single particle and $E \times B$ drifts described in Sec.1.2; mean profiles accompanied by large fluctuations are seen in such plasmas. This paradox has not been fully resolved. Several devices such as ACT-I [17], BETA [18], BLAAMANN [19], THORELLO [20], TORPEX [21] and more recently LATE [22] have been constructed leading to several interesting and fundamental findings. For example, in ACT-I at PPPL, USA, different kinds of plasma production such as using hot filament, electron cyclotron waves and lower hybrid waves were demonstrated [17]. The plasmas produced in ACT-I using hot filament and electron cyclotron waves was found to possess poloidal asymmetry. An approximately poloidally symmetric plasma could be produced with lower hybrid waves launched from a poloidally symmetric slow wave structure. In the above mentioned work, experiments demonstrating wave propagation, heating and current generation in plasma were also conducted. Another such device is BETA [18] at Institute for Plasma Research, India, in which large fluctuations in plasma parameters, either in coherent or turbulent condition were observed [23]. The plasma behavior was found to be similar to the plasma in equatorial spread F region of ionosphere [24, 11], where the fluctuations due to R-T instability, generated in the favorable region below the density peak, are also found in the unfavorable region above the density peak. Further in BETA, wave propagation, role of finite parallel wave number and existence of coherent structures were also studied [25, 26, 28]. In another set of experiments in BETA, applying a finite vertical magnetic field in either directions, suppression in the fluctuation levels has been observed [27]. In the context of understanding existence of an average equilibrium in BETA, a theoretical model of flow-fluctuation cycle in the plasma has been suggested wherein an initial “seed” equilibrium achieved by a conducting limiter is believed to be further reinforced by the fluctuation driven flow [29]. It was further suggested that the fluctuations in
turn may get modified by the flow it generates. This model is described in detail in the next section. Experiments on yet another simple toroidal device BLAAMANN at University of Tromso, Norway, where plasma is produced using a hot filament, have shown that classical transport is insufficient to explain the observed cross-field diffusion of charge injected by the filament [19]. The anomalous transport is found to be due to a large, coherent flute-mode type vortex, driven by fluctuating cross-field radial current observed in simulations as well as in BLAAMANN experiments [30, 31]. The coherent structures have been found to possess no inherent propagation velocity, rather they were found to propagate with $\mathbf{E} \times \mathbf{B}$ drift velocity; the lifetimes of the structures were found to be the time of one full azimuthal rotation of the plasma column [32]. In another set of experiments in BLAAMANN, the threshold nature for the excitation of fluctuations is demonstrated, where the plasma is found to be quiescent at low magnetic field and transport occurs along the equipotential surfaces; on increasing the field at the threshold monochromatic drift modes are excited which act as a seed for the flute mode instabilities above the threshold [33]. In the coherent flute type vortex, the simulations further suggest that the radial cross-field current, which determines essential features of the fluctuating plasma equilibrium, is due to a fluctuating ion polarization drift [34]. Similar turbulence characterizing measurements have been conducted on THORELLO [20] at Milano, Italy. Recently, intermittent cross-field particle transport in the form of blobs was observed on TORPEX experiments [21] at CRPP, Switzerland. The generation of blobs from radially elongated interchange modes increasing in amplitude, sheared off by $\mathbf{E} \times \mathbf{B}$ flow has been investigated [35, 36, 38]. Later it was found that, blobs which are 3-D structures, exist in drift-interchange regime too; further it is seen that the existence of $\mathbf{E} \times \mathbf{B}$ flow is not essential for generation of blobs [37]. Varying the blob size by changing the ion mass, the analytical expression for the cross-field velocity of the blob including ion polarization currents, parallel currents to sheath, and ion-neutral collisions is derived and found to be in agreement with the experimental results [39]. In relevance to the experimental observations on TORPEX, recent 3-D fluid simulations seem to suggest that depending on parallel wave number or collisionality, an ideal interchange mode or resistive interchange mode or drift mode may become unstable leading to the turbulence [40]. These authors, however, themselves comment that boundary conditions used in this work are debatable, especially in the presence of shear flow. In
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a recent experiment on LATE, another simple toroidal device at Kyoto University, Japan, the explicit measurements were conducted for current through the device, compensating for the vertical charge separation [22]. Through the above mentioned experimental and theoretical investigations in various devices, several mechanisms of cross-field anomalous transport seem to exist, for effective poloidal transport in a simple toroidal plasma. Understanding the poloidal transport mechanism in a simple toroidal plasma, therefore, is of fundamental importance.

In tokamaks, poloidal $E \times B$ rotation by self-consistent $E$ or external $E$ field has been seen to lead to reduced turbulence and improved confinement [13]. Hence it is understood that turbulence, flow generation and improved confinement are interrelated and need to be understood well for a successful fusion device. As it is well known, sheared flows in tokamak plasmas are believed to be triggered by an external radial electric field or self-consistent turbulent Reynolds stress [41]. In such devices compressibility plays a vital role. However, a clear identification of instability in tokamak plasma, which contributes to Reynolds stress is a difficult experimental problem. Simple toroidal devices could play an important role in improving our understanding of such complex phenomena. For example, in a set of interesting experiments in cylindrical plasma columns, the existence of intrinsically generated azimuthal flow has been observed [42, 43, 44, 45]. It has been also shown in this work that a transfer of energy occurs from collisional drift turbulence fluctuations with high frequency into a linearly stable low frequency azimuthally symmetric radially sheared $E \times B$ flow. The observed shear flow has been found to be non-linearly driven by the turbulent Reynolds stress. The coherent drift waves at low magnetic field are observed to turn into a broadband spectrum with increasing magnetic field close to the shear layer, with reduced coherence. In some of the other observations on linear devices, transition from flute modes to drift mode fluctuations is seen with increase in magnetic field [46]. However, due to the cylindrical geometry, the flow is incompressible through out, i.e. $\nabla \cdot v_{E \times B} \approx 0$.

In spite of the above crucial findings, a clear understanding of what plays the role of a “effective rotational transform”, is still lacking. In the present experimental studies, the role of fluctuations in the transport and hence a possible “effective rotational transform” is investigated. A theoretical model of flow-fluctuation cycle
suggested by R. Singh et al. [29], relevant to the present experimental work is briefly described as follows.

1.4 Flow-fluctuation cycle in a simple toroidal plasma

In the context of understanding the existence of equilibrium in BETA, a flow-fluctuation model has been suggested [29, 47], as mentioned in Sec.1.3. According to this model, initially, the limiter provides the “seed” equilibrium. In this equilibrium, fluctuations which are generally due to Rayleigh-Taylor instability, grow to a significant level. These fluctuations provide an “effective rotational transform” in two ways. First, fluctuations directly drive a radial current and hence a poloidal rotation which improves the limiter equilibrium. Second, the flow back reacts on fluctuations to modify the rms level profile. The mean ponderomotive force due to these fluctuations then opposes the free fall of the plasma and further fortifies the limiter equilibrium. The theoretical arguments of this model are briefly described below.

The first of the two ways of providing an “effective rotational transform”, is that fluctuations drive a poloidal flow. In a simple toroidal plasma this can occur as follows. Simultaneous radial electric field and density fluctuations can result in a $\mathbf{E} \times \mathbf{B}$ drift; depending up on the cross-phase between the $\mathbf{E}$ and $\mathbf{n}$, a finite fluctuation induced flux can occur in a particular poloidal direction. The fluctuation induced flux is a time varying quantity, therefore, is calculated as a time average, on sampling large number of cycles. Such estimation is represented by the following expression:

$$\Gamma_{\text{fluct}} = \frac{1}{B}\langle \mathbf{n} \cdot \mathbf{E} \rangle. \quad (1.9)$$

The second way of providing an “effective rotational transform” can be realized as follows. The basic equations describing the equilibrium are the continuity and momentum equations for electron and ion [47]:

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j \mathbf{V}_j) = 0, \quad (1.10)$$
\[ m_j n_j \frac{dV_j}{dt} = -\nabla p_j + q_j n_j \left( \mathbf{E} + \frac{\mathbf{V}_j \times \mathbf{B}}{c} \right) - m_j n_j \nu_m \mathbf{V}_j, \tag{1.11} \]

where \( j = e, i \) stands for the electron and ion, respectively; \( n, p, m, \mathbf{B}, \mathbf{E}, \) and \( \mathbf{V}_j \) are the density, pressure, mass, toroidal magnetic field, electric field and velocity respectively; \( \nu_m \) corresponds to charge-neutral collision frequency. In the limit \( \nu_{en}/\Omega_e \ll 1, \nu_{in}/\Omega_i < 1, T_i/T_e \ll 1, \) and with negligible flow along the magnetic field (i.e. \( V_{\|} = V_{e\|} \approx 0 \)), the above continuity and momentum equations are used to derive an equation in partial time derivative of \( (n_i - n_e) \) [47]. The Poisson equation, with the dominant electric field in the vertical direction, is given by

\[ \nabla \cdot \mathbf{E} = \frac{dE_z}{dz} = 4\pi e (n_i - n_e). \tag{1.12} \]

Substituting Eq.(1.12) in the above mentioned equation in partial time derivative of \( (n_i - n_e) \), simplifying further and solving, a steady state plasma fall velocity \( V_R \) along the major radius can be expressed as [47]

\[ V_R = \frac{1}{\nu_m} \left[ \frac{c_s^2}{R} - \frac{1}{2} \frac{\partial}{\partial R} |\tilde{v}_R|^2 \right], \tag{1.13} \]

where \( c_s = \sqrt{kT_e/m_i} \). The radial component of mean ponderomotive force due to low frequency fluctuations \( m_i n_i \langle (\mathbf{V}_i \cdot \nabla) \mathbf{V}_i \rangle \) can be approximated as

\[ \sim (1/2)m_i n_i \partial |\tilde{v}_R|^2 / \partial R \tilde{R}, \]

where \( |\tilde{v}_R| \) is the amplitude of velocity oscillations of the fluid in the radial direction. Clearly if \( \partial |\tilde{v}_R|^2 / \partial R > 0 \), then the fluctuation driven ponderomotive force (radial component) opposes the free fall due to the effective gravity. The plasma confinement time \( (\tau_c = a/V_R) \), therefore, is increased. In this way, the flow-fluctuation cycle results in an “effective rotational transform”. In the present work we examine the role of fluctuation driven poloidal flow in a simple toroidal plasma, i.e. estimating \( \langle \tilde{v}_p \rangle \) and calculating other poloidal flows. The role of \( \tilde{v}_R \) in creating an effective ponderomotive force experimentally is not being investigated.

### 1.5 Present work

In spite of the experimental and theoretical work described till now, to our knowledge, the role of fluctuations and flows in the formation of an average equilibrium
has not yet been completely resolved. In this thesis, a detailed experimental investigation on the role of fluctuations and self-consistently generated poloidal flows in sustaining mean profiles has been carried out, for the first time, in a simple toroidal device. The co-existence of fluctuations and flows is demonstrated experimentally; the onset of fluctuations and flows is found to be accompanied by enhanced plasma filling on the high field side, which otherwise has lower densities. The fluctuation induced particle flux is found to contribute significantly to the total poloidal flow. The measured toroidal plasma flows are found to be small, and within the measurement resolution of the flow probe. Though the fluctuations are large, the relative phase and coherence between density and potential are found to play important role in generating finite flux. Furthermore, to see the effect of fluctuations on the poloidal transport and mean plasma profiles, experimental investigation with varying toroidal magnetic field strength and ion mass are undertaken. On changing the toroidal magnetic field, a transition occurs in the nature of fluctuations, from highly coherent at low magnetic field to turbulent at high magnetic field. With the change in the nature of fluctuations, the associated poloidal flows and mean plasma profiles are determined experimentally. To see the role of ion mass in the fluctuation-flow generation, plasma is produced using other inert gases such as krypton and xenon, keeping all other operating conditions similar. The nature of fluctuations change from coherent to turbulent with increase in ion mass; the associated poloidal flows and mean plasma profiles are determined experimentally. The results presented in this thesis, indicate that the poloidal flow velocities change systematically with the change in the nature of turbulence; moreover, the fluctuations and flows play a crucial role in sustaining the mean profiles in all the cases. In the following, the lay-out of the thesis is presented; the major topics are organized in chapters, each chapter elucidating a comprehensive summary of motivation behind the measurements, major findings followed by appropriate discussions.

1.6 Thesis outline

Rest of the thesis is organized as follows. In Chapter 2, the Experimental apparatus-BETA, a simple toroidal device in which all the present experimental
investigations are carried out, is described in detail. Various diagnostic techniques developed for measurements on this device are described, which are based on measuring charge flux incident on electrodes. Appropriate theoretical models for the interpretation of the measurements are explained. The details of diagnostic probes, including construction of probes, method of operation and estimation of parameters from the measurements are discussed.

The role of fluctuations and poloidal flows in sustaining the mean profiles is investigated, and the results are presented in Chapter 3. Significant poloidal flows are found to be driven by mean and fluctuating radial electric fields. The charge injected by the filament form a vertically extended source region, toroidally spread in the neighborhood of the magnetic field lines intercepting the filament. This region is found to coincide with the bottom of the observed potential well in the plasma. The experimental determination of the radial spread of primary energetic electrons is important for two reasons. First, it indicates the typical radial width upto which the excess negative charge injected by the filament is confined; the excess negative charge plays an important role in the formation of a potential well and mean electric field driven poloidal flow. Second, it indicates the region in which a significant population of non-thermal electrons is present, potentially affecting the Langmuir probe measurements. The experimental detection of the fast electrons is carried out using a Retarding Field Energy Analyzer (RFEA) [48, 49]. Using RFEA, a suitable sequence of potential barriers is applied to collect the fast electrons; typical fast electron densities are estimated. These measurements using RFEA are described in the Appendix A. The limitations and important in issues using RFEA [50, 51], are also discussed. The observed radial spread of fast electrons is used to identify the possible regions for erroneous estimation of electron temperature due to non-thermal electrons, in the subsequent experimental investigations. In continuation to the above work, the radial profiles of mean plasma parameters are obtained. From simultaneous probe measurements at different locations, the co-existence of fluctuations and enhanced filling of plasma on high field side is observed. Significant poloidal flows and well-spread radial profiles are found to sustain when large fluctuations are present. To understand the role of fluctuations in poloidal flow more quantitatively, poloidal flow measurements are carried out [52, 53]. The fluctuation induced poloidal flow [54, 55, 56] is found to account for
the significant portion of the total poloidal flow, in addition to the mean electric field driven flow. The present experimental findings are in partial support of the theoretical model suggesting the fluctuation-flow cycle as an “effective rotational transform”, in a current less toroidal device [29, 47, 11].

The experimental studies described in Chapter 3 demonstrate that fluctuation induced flux plays an important role in generating flows and sustaining radially well spread plasma profiles. Nature of fluctuations is, therefore, important in determining the mean plasma profiles. Magnetic field is found to be an important control parameter to obtain transitions in fluctuation regimes in a simple toroidal device [20]. In continuation to the above experimental studies, varying the strength of the magnetic field, a change in the nature of fluctuations, poloidal flow generation and attaining mean profiles are investigated. The results are presented in Chapter 4. A transition occurs in the nature of fluctuations from highly coherent at low magnetic field to turbulent at high magnetic field. The transition from coherence to turbulence is found to be accompanied by enhanced flow and density on high field side. The dispersion relation [57] and nonlinear coupling of the fluctuations [58, 59] in each case are estimated. The dominant mechanisms of instabilities are identified [20, 56, 60, 10, 61].

Through the above experimental studies, it is understood that change in the nature of fluctuations with increasing magnetic field is associated with enhanced flow and confinement. Plasma flow is intrinsically associated with ion mass, thus making it another important parameter through which the mean plasma profiles and transport in plasma in a simple toroidal device can vary [62]. In general, the experimental investigation of confinement with mass scaling in tokamak have indicated that the confinement increases with increase in ion mass, which is opposite of the theoretical prediction [63]. In the next set of experiments, fluctuations and flows in plasmas are investigated with different gases, viz. argon, krypton and xenon. The results are presented in Chapter 5. The net poloidal flow and the fundamental frequency of fluctuations, which is seen to be approximately the rotation frequency of the plasma [64], are found to increase with decrease in ion mass. Highly coherent fluctuations which occur in the case of argon, become turbulent at higher ion mass. The dominant fluctuations are, however, found to be flute-like for all ion
masses. In the experimental findings described till now, the estimated fluctuation induced flux is used to calculate an average fluctuation driven flow. A better understanding of the nature of the fluctuation induced flux is possible with statistical analysis [12, 65]. From the time series of fluctuation induced flux, probability distribution function (PDF) can be calculated which will be useful in quantifying the sporadic, large transport bursts. The results of this analysis are presented in Chapter 6. The local PDF can reveal non-Gaussian nature of fluctuations [66]; the non-Gaussian nature of the fluctuations indicate a coupling between the density and electric field fluctuations which can result in finite fluctuation inducing flux. It has been observed in other similar devices that the coherent structures do not contribute to the anomalous transport; rather transport occurs around the vortical coherent structures where dissipative processes takes place [60]. Consequently, the fluctuation induced flux can be sporadic or bursty in nature, which can be established from statistical analysis mentioned above.

In Chapter 7, the conclusions of the experimental investigations and results of various analysis techniques are presented. This thesis work provides the first clear experimental evidence for generation of intrinsic poloidal flow from fluctuations and hence may be regarded as partial support to the model of flow-fluctuation cycle as a mechanism of producing an “effective rotational transform”, in a simple toroidal device.

In the next chapter, the experimental setup and diagnostic methods are described. The construction of the probes, method of operation and interpreting parameters from measurements are discussed.