Chapter 10

Summary, Conclusion and Future

Dreams

Turbulence driven transport has been found to play an important role in plasma confinement in the edge and SOL regions of tokamak. Therefore, understanding the underlying physics of turbulent transport in tokamak plasma is one of the key issues in magnetic confinement research. This work has been strongly motivated by some of these outstanding problems of the edge and SOL turbulence. Various instabilities cause the plasma turbulence. These instabilities are almost inevitable as there is no method (not discovered yet) that can suppress the instabilities completely. Therefore, fusion scientists must live with these instabilities. But there are several methods that can control some types of instabilities quite efficiently. For this purpose, detailed knowledge of these instabilities is necessary.

This thesis contains mainly three major parts. First part describes SOL instabilities (Chapters 4, 5, and 6). The second part deals with combined edge and SOL turbulence studies (Chapters 7 and 8). These two parts describe instabilities in collisional plasma. The final or third part contains collisionless instabilities (Chapter 9) that are relevant to high temperature and mainly for fusion grade tokamak plasma. We shall now sum-
In this thesis, SOL instabilities using three different models (2F, 3F and 4F) have been studied. The 2F model is a very rough model; it uses dynamics of density and potential. The 3F is an improved model as it includes electron temperature that is more realistic than the 2F model. Still, 3F model uses cold ion approximation that is not a good approximation for tokamak plasma. Therefore, 4F model has been used to include ion temperature dynamics in the SOL. This indicates that if we compare these three models, we can get a clear picture of the SOL turbulence and roles of electron and ion temperatures can be possible to identify. A comparative discussion among these three models is given in the following.

**A comparative study of 2F, 3F and 4F results**

A comparison of linear growth rates among 2F, 3F and 4F results is shown in Fig. 10.1 when all scale lengths ($L_n, L_{Te}, L_{Ti}$) are equal to 20.0. Figure indicates that for $0.02 \leq k_y \leq 0.18$ the growth rate obtained from 3F model is higher than 2F and 4F models. For very low $k_y \leq 0.02$ the growth rates obtained from the 3F and 4F models are slightly negative mainly because of sheath stabilization that is most dominant by the electron temperature. For $0.18 \leq k_y \leq 0.3$ maximum growth rate obtained from 4F results is the highest and growth rate obtained from 3F model is higher than 2F model. In Chapters- 5 and 6, it is shown that effect of electron temperature gradient is not monotonic. The growth rate obtained from 3F model is maximum at $L_{Te} \sim 13.0$ (Fig 5.3) and growth decreases for higher as well as lower values of $k_y$. It decreases more sharply towards lower values of $k_y$. This indicates that the lower values of $L_{Te}$ kill normal effects of density and ion temperature gradients. This is most unlike to Berk mode where it is stated that low $L_{Te}$ always destabilizes the mode. Detailed cause of it has been identified in Chapter- 5. Electron temperature shifts turbulence along the lower $k_y$s. It is also found that when ion temperature is added with the electron tem-
Figure 10.1: A comparison of linear growth rates obtained from three models.

Temperature dynamics then the turbulence again shifts back to higher $k_y$ (that is similar to 2F model). Numerical results during initial phase of turbulence also support the above observation.

During fully saturated phase of turbulence, we have analyzed the $k_y$ spectrum on the density, potential, electron and ion temperatures field quantities. Amplitudes of Fourier transformation of the radial and time averages of these field quantities have been done for this purpose in Chapter- 4, 5, and 6. Figure 10.2 summarizes these. In 3F and 4F models, the Fourier amplitudes of the field quantities are maximum at $k_y = 0.1$ and $k_y = 0.15$, respectively. In the 2F model, the quantities have a broad maximum at $k_y = 0.2$. When these are compared with the linear theory it is found that all models show inverse cascades that are typical for turbulence of tokamak.

A comparison of time and poloidal averages of density profiles has been shown in Fig. 10.3. The profiles have been renormalized to unity at $x = 0$ to get a quantitative comparison. The e-folding density profile is the lowest in 4F model; it is about 35 ions Larmor radius (one ion Larmor radius is equal to about $6 \times 10^{-4}$ m). The 3F and 2F
Figure 10.2: Fourier amplitudes of time and radial averages of a field quantity have been plotted as a function of $k_y$.

Figure 10.3: Comparison of density profiles obtained from 2F, 3F, and 4F models
Figure 10.4: Comparison of temperature profiles obtained from 3F and 4F models.

models show 45 and 60 ions Larmor radius respectively. Aditya tokamak measurements show that e-density profile is about 1.5 cm; therefore, the 4F model yields (2.1 cm) good agreement with the experimental result. The e-folding density in 3F and 4F models is lower than 2F model mainly because of existent of radial electric field by the electron temperature dynamics. Strong shear of radial electric field stabilizes the interchange instability that is why the e-folding length is lower. We have also compared e-folding density scale lengths obtained from 3F and 4F models. In 4F model, the length is lower than the 3F model (even shear of radial electric field is similar to 3F model) mainly because of an influence of extra sheath current induced by ion temperature (ion sound speed increases by the effect of $T_i$). The electron temperature profiles obtained from 3F and 4F models have been plotted in Fig. 10.4. The e-folding length of $T_e$ profile in the 4F model is lower than the 3F model that is mainly because of extra sheath current.

A comparison of radial electric fields obtained from three models has been done in Fig. 10.5. The 2F model shows the lowest value of radial electric field that is about 10-20 times lower than the 3F and 4F models. The 3F model shows the highest value of radial electric field. This is mainly because of electron temperature dynamics. The
electron temperature charges different magnetic field lines at different potentials [floating potential $\phi_f(x) = \Lambda T_e(x)$]. This causes the existent of radial electric field. In the 4F model, mechanism of radial electric field is same as in the case of 3F model, but in 4F model ion temperature reduces the field mainly because of extra ion loss through the sheath. The extra ion loss reduces the floating potential; therefore radial electric field reduces. As far as radial electric field is concerned, both 3F and 4F results are close to the Aditya tokamak measurements. As radial electric field induces zonal flows, these flows are maximum in the 3F model. But difference between 3F and 4F models as far as zonal flows are concern is not substantial.

Particle transport obtained from 2F, 3F, and 4F models has been compared. The transport is the highest in 2F model and is the lowest in 4F model. Particle and energy fluxes in three different locations $(x, y) = (25, 0), (30, 0), (35, 0)$ are given in Table 6.1 in Chapter-6. Particle flux at these locations in 2F model is $3.8 \times 10^{-3}$, $2.9 \times 10^{-3}$, and $2.6 \times 10^{-3}$. The linear growth rate in the 2F model is the lowest still transport is highest mainly because of the absence of shear stabilization of radial electric field. In the 4F model, the shear is almost same with the 3F model and linear growth rate is higher than the 3F model. Therefore, one can expect higher transport than the 3F model. But
still the 4F model shows lower transport mainly because of dominance of turbulence at higher $k_y$s (small scale turbulence). The electron energy transport in the 3F and 4F models shows the same behavior. Similar to particle transport, the energy transport in 4F model is lower than the 3F model. It is to be noted that the ion energy transport has not been measured in tokamak experiment. Therefore, we cannot compare results with actual experiment.

Plasma blob formation in 2F, 3F, and 4F models is presented. The blob structure in the 3F model shows internal electron temperature and 4F model shows internal electron and ion temperatures. All blobs decay in time. Density decay in 2F model is exponential. But presence of electron temperature in 3F and 4F models indicates that the decay is non-exponential. Blob density decay in 2F is the fastest and in 3F it is the slowest. Blob decay in 4F lies between decays obtained from 3F and 2F models. It is found that ion temperature introduces extra density loss in 4F model. That is why, density decay in 4F model is faster than 3F model. These are shown in Fig. 10.6(a). Internal electron temperature decay in 3F and 4F models is faster than the density decays. This is mainly because of higher sheath energy transmission factor $\zeta = 4$ than current transmission. It is also found that temperature decay in 4F model is slightly higher than the 3F model. This is again mainly because of extra loss term in 4F model due to higher ion sound velocity. Electron energy decays obtained from 3F and 4F models are shown in Fig. 10.6(b).

It is to be noted that we have submitted summary and comparison of results obtained from 2F, 3F and 4F models for journal publication.

Plasma turbulence in the presence of electron, and ion temperatures is studied and many important experimental facts have been explained so far. Instead of these successes, the 2F, 3F and 4F models do not include many physics. These are described in the following.
Figure 10.6: Plot(a) shows comparison of decay of blob density among 2F, 3F and 4F models. Plot(b) shows comparison of electron temperature decay between 3F and 4F models. The data are generated from algebraic fitting as are discussed in Chapters-4, 5, and 6.

1. **Blob Formation Mechanism:** Blob formation, its rotation and decay have been studied in the SOL region. But blob formation mechanism has not been identified. Blob formation mechanism that has been studied in Chapter-8 cannot be applicable in this region as the blob forms deep into the SOL region where the zonal flow is very small. It is believed that blob formation mechanism in this region will be slightly different from the edge region. Local zonal flows triggered by Kelvin-Helmholtz instability may play a substantial role in this region. We shall be looking this problem in future.

2. **Role of Limiter Biasing:** In this thesis, we have studied the turbulence when the limiter/divertor is floating. If the limiter/divertor is biased then many important phenomena can happen. This is mainly because of the fact that limiter/divertor biasing will carry substantial amount of equilibrium sheath current. This current has a substantial stabilizing effect on the turbulence.
3. **Role of Electrode Biasing:** Many tokamak experiments include electrode biasing where some extra electrodes are placed in the SOL region. These draw current depending on the polarity of the biasing [30]. Therefore, effect of the biasing is somewhat similar to the limiter biasing; only difference is that it can introduce additional shear of radial electric field, which is closer to LCFS than the shear obtained from limiter/divertor biasing.

4. **Role of Neutral Gas:** It is generally found that neutral density in the edge and SOL regions is very high. These are easily ionized by plasma and alter turbulence in this region by ionization instability. Recycling of neutral from the limiter/divertor and tokamak walls also plays a substantial role on the turbulence.

5. **Role of Impurities:** Plasma impurities may play a substantial role for plasma turbulence. Normally, tokamak wall material and limiter/divertor plate release lots of impurities into the plasma. These impurities normally radiate (by excitation processes) and hence plasma becomes cold in this region. These impurities are sometimes trapped inside plasma holes (plasma ‘hole’ has been discussed in Chapter-8) and are transported inside the tokamak by the turbulence. Therefore, it may cool down the core temperature of the plasma.

In future, the effect of limiter biasing, neutral gas, and impurities will be included into a model and role of each will be identified. Already a significant amount of work has been done separately by many authors. Integrated work (including all these effects) is necessary for better understanding of the problem.

A simple but an important effort has been done to integrate edge and SOL turbulence studies in Chapters-7 and 8. Edge and SOL turbulence has been studied jointly by connecting edge and SOL conductivities that brings influence of edge turbulence on the SOL. We have ignored electron and ion temperature effects for simplicity of the problem. These work successfully have demonstrated the mechanism of density blob formation for the first time. Transport in the edge and SOL has been successfully compared with
the experiment. Extensive work is also necessary to include the following effects.

1. **Effect of Electron and Ion Temperatures**: Electron temperature in the edge region may play a substantial role as it adds an additional instability into the turbulence. Electron temperature instability has a specialty that it can occur even in the HFS of the tokamak where the interchange instability is stable. For stiff electron temperature gradient its effect may be important. (Some of these have been demonstrated in the Chapters 5, 6 for the SOL turbulence.) Therefore, it is necessary that the effect of electron temperature should be included in the joint edge and SOL turbulence studies.

2. **Parallel Dynamics**: Tokamak plasma dynamics in the edge region is mainly 3D in nature as the parallel dynamics plays a substantial role on the plasma turbulence. Therefore, 2D nature of turbulence that is discussed in this thesis by approximating parallel dynamics is not enough for the edge instability.

3. **Effect of core turbulence**: The flux that drives instability in the edge region (flux driven source) is mainly obtained from core region of tokamak. It demands that it will be better if the flux driven source obtained from the core turbulence will be connected directly with this edge turbulence. Origin of core and edge turbulence is quite different. Therefore, two completely different instabilities are needed to study by a single code. In this case, it is not necessary to assume the driving flux. It will be obtained self consistently from the core turbulence.

Therefore, in future we shall be studying the edge turbulence using 3D code that will include effects of electron temperature and core turbulence. An extensive work is necessary in this direction.

In fusion grade tokamak, plasma is normally collisionless. Therefore, collisional edge instability cannot be applicable in this condition. It is found that tokamak plasma even in the collisionless condition is also unstable. In this work, tokamak edge instability
has been studied in the collisionless and $\beta < \beta_{\text{crit}}$ conditions in the presence of trapped electrons using simple drift ballooning type of mode. Electron inertia mainly drives instability both in the electrostatic and electromagnetic perturbations. Many important results have been discussed in Chapter 9 without using sophisticated kinetic theory. We have identified two areas where this work can be extended. These are given in the following.

1. This work yields real frequency that is slightly higher than the parallel electron transit frequency. Therefore, wave particle interaction is important in this condition. In future, we want to include this effect by using gyrokinetic theory so that the above problem will be removed.

2. This work indicates that trapped particles destabilize the instability as the particles are trapped inside the magnetic mirror and hence do not move to cancel the space charge separation resulting from the drift ballooning modes. Therefore, this result indicates that collisionless tokamak plasma will be more stable if we do something so that more particles will be detrapped from the magnetic mirror. Radio frequency (RF) wave can be used carefully so that only trapped particles will absorb energy from the RF wave and will come out from the magnetic mirror. We shall be looking into this problem in future.