CHAPTER VIII

CONCLUSION AND SCOPE FOR FUTURE WORK

1. Conclusion

2. Scope for future work.
The investigation of radiative phenomena in tokamaks has been presented. The phenomena examined are: the structure and stability of radiative edge equilibria and the radiation dominated plasma evolution during the startup phase. The work in this thesis has following two components: (i) investigation with coronal effects (coronal radiation) and (ii) a quantitative comparison between coronal and non-coronal effects.

In the first, we improve upon the earlier models for coronal radiation and use our models to explain some of the experimentally observed phenomena. In the second, we demonstrate the importance of non-coronal effects and develop a model to include them in the analysis of radiative equilibria, their structure and stability. We also study the evolution in the startup phase with non-coronal effects.

**Coronal effects**

Coronal radiation arises when impurities obey coronal equilibrium, i.e., the ionization and recombination between adjacent charge states balance each other.

Earlier investigations of one-d equilibrium and its stability to marfe perturbations have been carried out with a crude, step-function model for coronal radiation. The analysis of yet another one-d equilibrium called the detached-plasma, also uses a similar model. In this model the radiation is "switched on" below a certain characteristic temperature $T = T_L$. Despite the crudness of the model these
A question, then, can be asked, whether other models of radiation are possible, which not only are more realistic but go beyond the earlier ones in explanation of observed phenomena.

We demonstrate that a novel exponential model \( \text{where radiative power loss behaves as } \exp(-T/T_L) \) is one such useful model. Because it is smoother (in \( T \)), it is a better approximation to exact coronal radiation which decreases with \( T \).

Using such a model, a slab equilibrium and its stability to \text{marfe} (long wavelength) perturbations are exactly carried out. Consistent with previous study we find that: (i) equilibrium exists only for radiation loss \( (L) \) below \( L_c \) (critical value of \( L \)), (ii) the equilibrium is stable to \( m = 0 \) perturbations, (iii) onset of poloidally asymmetric instability somewhat below the density limit, and (iv) \text{marfe} threshold even in the absence of parallel thermal conduction.

Equilibrium radiation profile is like \( \text{sech}^2(x) \) (in contrast to the previous study with step-function) showing that a much broader class of equilibria can be unstable to \text{marfe} instability. This result, in a sense, also improves our confidence in the step-function models.

In a two-d radiative equilibrium, believed to be the nonlinear saturated state of the \text{marfe} instability, the radiation model above, offers a striking result. Exact two-d equilibrias with observed features of \text{marfe} can be
Furthermore, the experimentally observed marfe-detached-plasma (DP) transition can be explained, for the first time, analytically. This is seen by the gradual poloidal symmetrization of radiation as radiated power is increased so as to equal input power. This fact agrees completely with experiments.

The detached plasma equilibrium has also been studied with exponential model for coronal radiation. The scaling law of its radius with plasma current and density is obtained. Incorporating a linearly increasing (with r) impurity density the scaling law as observed in TFTR experiments can be almost exactly obtained. The better agreement, compared to the previous theories is a new feature of this work.

Non-coronal effects

Non-coronal effects are said to arise when impurity charge state densities differ from those given by a balance of ionization and recombination. Diffusion of impurities in the edge plasma, or, rapid time variations, either in the startup phase or during fluctuations, can keep impurities away from the coronal equilibrium.

Even though the importance of non-coronal effects was realized earlier, its treatment could only be numerical. This was because, the non-coronal impurity densities involved solution of several equations (Z+1 diffusion equations for example). Moreover, very often the spatial and/or temporal behaviour of the plasma had to assumed as given. Finally, due
to several parameters and processes involved, the role of non-coronal effects was not clear.

We have made a definite progress in this direction in the present work. For the first time, we give a quantitative and a qualitative demonstration of the impact of non-coronal effects (diffusion and time variations) on both, the structure and stability of radiative thermal equilibria, analytically. The progress comes, fundamentally, from a simple model developed here for impurity radiation – the Two-Ion-model. The important features of this model are: it has fewer parameter, allows analytic progress, and, makes a quantitative comparison possible between non-coronal and coronal effects.

Study of non-coronal effects on the spatial structure of radiative equilibrium involves the coupled heat-diffusion and the impurity-diffusion equations. The coupling arises due to radiative loss of energy from impurities. In the one-d equilibria, diffusion of impurities across the magnetic field (radial) causes two principal effects: smoothening of the radiation profile, and enhanced radiation close to edge, from where the (low-ionized) impurities diffuse into the plasma. The 'smoothening' and 'enhancement' are seen when the results are compared with an appropriate coronal calculation. In the two-d equilibrium, the edge-radiation arises from a region, somewhere near the poloidal angle $\theta - \pi$ (small major radius side of the plasma torus). Both, parallel and perpendicular diffusion of impurities cause alterations in the structure in this case. Parallel diffusion tends to remove radiative ions

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from local region considered here and hence weakens the radiative loss, thereby increasing the local temperature. The perpendicular diffusion, however, brings the impurity ions into the radiative region, as in the one-d case. As a result, radiation near the edge increases, with a concomittant decrease in temperature. The effect of parallel diffusion dominates over that of perpendicular diffusion. A qualitative as well as quantitative change in the structure of radiative equilibrium is then demonstrated.

Study of radiative-condensation instability with non-coronal effects leads to following conclusions. The long wavelength mode-marfe is weakened with enhanced threshold. The reason is the reduction in \( \partial L/\partial T \) drive of this instability. The reduction arises due to two reasons: (i) smoothening of equilibrium L profile where ionization (or coronal-L) varies sharply and the resulting reduction in absolute value of L, and (ii) rapid time variations. The first effect is due to diffusion of impurities, which, although small in the limit considered here (diffusion time over the radiative layer \( \gg \) ionization or recombination time), produces a large enough change in the growth rate. The crucial point here is that stability analysis introduces a new and much smaller scale (scale on which L varies or \( \partial L/\partial T \) is significant) here, on which, diffusion time may be smaller than the ionization time. We then consider a different scenario. In the one-d non-coronal equilibria, we had shown that radiation near the edge can be larger than coronal, due to diffusive influx of impurities. This is a limit where
diffusion is larger than what has been considered above. In a region where radiation is larger than coronal, we show that the short scale, helical, radiative condensation instability has higher growth rate compared to coronal. The instability scale considered is short enough, so that only the local excess of radiation is significant rather than its profile. In essence, the radiative condensation instability is affected significantly by non-coronal effects, e.g. impurity diffusion in equilibrium and rapid time variations in perturbations.

In the startup phase, the impurities radiate a great fraction of input power and therefore modify the time evolution of the tokamak discharge. The instability of impurities to attain coronal equilibrium due to non-stationary plasma and finite confinement time is known. However, the quantitative comparison in the zero-d evolution, with coronal and non-coronal radiation was not known. We present such a comparison. Due to comparatively larger radiation loss, the noncoronal (i.e. the realistic) evaluation leads to lesser values of plasma temperature and current, at the end of the startup phase. The \(<z>\) is also less compared to coronal, with low-ionized charge states of oxygen (considered as a model impurity) surviving up to much higher temperatures.

Our conclusion is that coronal radiation grossly underestimates radiative losses. Since overcoming the radiation barrier requires energy, even the energy input must be comparatively more, to attain certain values of current.
and temperatures at the end of the startup phase. For medium sized tokamaks with ohmic input power, the above consideration imply higher starting voltage. Since total number of volt-seconds are fixed, this could result in lesser discharge duration. Another, conclusion is that line radiation from low-ionized states of oxygen (for example) can survive up to higher (than coronal prediction) temperatures. Thus, while modelling time evolution of emission lines for diagnostic applications, one must account for such effects.

To summarize, the impact of non-coronal effects like impurity diffusion and rapid time variations is demonstrated in the present day tokamaks. Structure and stability of radiative equilibria can be investigated analytically, to examine the influence of these effects. In the startup phase a comparative study of these effects shows enhanced radiation which affects the discharge evolution significantly.

2. **Scope of Future Work**

Several points arise from this work, which suggest extension of the present analysis as follows.

First point concerns, radiative equilibria. We considered simple functional forms for impurity ionization, recombination as well as simplistic boundary conditions. This was done primarily to isolate and elucidate the physics of non-coronal effects, their impact on profiles etc. However, temperature, density and radiation profiles in the edge play a crucial role on the overall plasma behaviour. The H-mode, the improved-ohmic-confinement (IOC) and the supershots in
TFTR are some of the known examples of improved tokamak performance, where edge conditions play a crucial role. Also, the application of divertors to isolate conveniently the plasma-metal interaction zone (to pump out impurity and excess plasma particles) introduces an entirely new set of boundary conditions involving plasma flow. We believe that all these situations above will be affected strongly by non-coronal effects. Therefore, there is a need to examine the various edge equilibria (one-d, two-d etc.) to understand control of edge conditions in a better way.

The second point concerns fluctuations in the edge. We have investigated radiative instabilities alone. It is unlikely that edge fluctuations are solely caused by a particular instability. Several other instabilities like drift-dissipative, rippling instability, which are thought to be the cause of edge fluctuations, must also be examined.

Role of radiation in driving rippling instability [see for example Hahm et al., in Physics Fluids 30, 1452 (1987)] and drift instability [Zhang & Mahajan, Phys. Fluids B4, 207 (1992)] has been realized lately. There is therefore, a need for re-examination of all such edge-fluctuation candidates with non-coronal effects. Radiative instabilities, too, need a re-examination by including perturbations of impurity flow, for example. The nonlinear state of such instability, which is known to saturate at large amplitudes (see references in chapter VI) is going to be affected by non-coronal effects, and hence, needs re-examination.

In a one-d heat transport modelling one necessarily