Pedestal Structure and Stability in High-Performance Plasmas on Alcator C-Mod

by

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EXECUTIVE SUMMARY

The development of magnetic-confinement fusion into an economical form of power generation is characterized by two overarching and seemingly-contradictory requirements: first, a high level of energy confinement is necessary to reach the desired level of self-heating of the plasma by fusion products, and second, a low level of particle confinement to avoid the deleterious effects of accumulated impurities (both the helium "fusion ash" and eroded plasma-facing wall materials). The latter is particularly important for the high-Z impurities expected from the metal wall materials necessary for reactor-scale devices. A number of operating regimes, collectively termed *H-modes*, have been developed satisfying these requirements in varying degrees. These regimes are characterized by the formation of a *pedestal*, a region of steep gradient in density, temperature, and pressure at the plasma edge that acts as a transport barrier in the plasma. The structure introduces an additional constraint, however – the steep gradients act as a source of free energy for explosive Edge-Localized Modes (ELMs), which on reactor-scale devices drive transient heat loading and erosion damage in excess of material tolerances for plasma-facing surfaces.

As the width and height of the pedestal set a strong constraint on both global performance and stability against ELMs, a firm understanding of the physics governing the pedestal structure is essential for the extrapolation of high-performance regimes to ITER- and

reactor-scale operation. This thesis contributes to the understanding of pedestal physics and high-performance operation in two key areas:

PREDICTIVE ELMY H-MODE PHYSICS

ELMy H-mode is commonly accessible on major tokamak experiments, and is considered the baseline for operation on ITER [1]. However, as large, uncontrolled ELMs are incompatible with ITER or reactor operation, an understanding of the stability space for ELM suppression, mitigation, or avoidance is necessary. This thesis details the testing of the predictive EPED model to operation on Alcator C-Mod. These experiments significantly expanded the parameter range on which EPED has been tested, particularly across a broad range in magnetic fields on C-Mod, and at the highest thermal pressures of any existing tokamak, within a factor of ~ 2 of the target pedestal pressure for ITER. The methods developed in this analysis are subsequently applied to the examination of I-mode pedestals.

I-MODE PEDESTAL STRUCTURE, PERFORMANCE, & STABILITY

I-mode [2] is a novel high-performance regime pioneered on Alcator C-Mod, unique in that it develops an H-mode-like temperature pedestal and good energy confinement, without the accompanying density pedestal or suppression of particle transport. I-mode exhibits three highly attractive properties for a reactor regime:

1. the lack of a particle transport barrier maintains the desired level of impurity flushing from the plasma, naturally allowing stationary operation with low radiative losses
2. Energy confinement in I-mode degrades significantly more weakly with increased heating power compared to H-mode, a highly desirable result for fusion self-heated plasmas
3. I-mode appears to be inherently stable against large, deleterious ELMs, avoiding the need for externally-applied mitigation/suppression techniques

This thesis first details an empirical study of the pedestal structure in I-mode, particularly its response to fueling and heating power, and its impact on global confinement and performance. It then details a computational study of the I-mode pedestal with regards to ELM stability, using the physics techniques developed for ELMy H-modes.

The results in this thesis have been published in a number of peer-reviewed papers, both for the ELMy H-mode results [3] (also featuring in a multi-machine Joint Research Target [4]) and for I-mode [5].