Pedestal Optimization for Confinement and ELM Control

Moyer, Evans, Groebner, Reimerdes, Snyder,

1. Open Issues:

Successful operation of ITER and the devices to follow will require optimization of the H-mode pedestal. This optimization has several considerations:

- Confinement: Due to profile stiffness associated with marginal stability in the core, the pedestal height should be as large as possible to maximum performance (e.g., achieve high Q_{fus} in ITER)
- ELM Control: Type I ELMs, generally associated with high pedestal pressure, must be avoided (or mitigated significantly) due to their impulsive power loading to the divertor plasma facing components.
- Particle and Impurity Control: Sufficient transport of density (both main ions and impurities) must be regulated across the transport barrier that forms the pedestal for optimal plasma performance (e.g., high plasma density with minimal impurity dilution).

Integral to this optimization will be the development of an improved physics basis for the processes governing the stability and transport in the pedestal region. While a physics understanding of the controlling mechanisms for the ELM instability has emerged from careful experiment-theory comparisons in recent years, the transport processes that control the spatial structure of the edge profiles are still not well understood. Experiments are urgently needed to close this knowledge gap in order to improve our ability to optimize the pedestal in future devices.

One robust approach to achieving this optimization is to utilize a combination of higher-order 2D shaping and 3D magnetic fields. This approach relies on well established technologies for magnetic coil design, something the fusion program “knows how to do.” These 2D shaping and 3D magnetic field coils provide a mechanism to optimize the pedestal by manipulating the plasma parameters which control the pedestal structure and ELM behavior. Optimizing the pedestal structure and ELM behavior will also require measurement of key pedestal parameters with high spatial and temporal resolution, including the pedestal current, main ion rotation, and pressure profiles, and the magnetic field structure in the pedestal. This optimization will further our understanding of the physical processes involved, and provide the database needed to develop and validate predictive pedestal models for extrapolating the results to the conditions anticipated in next-step devices.

2. Requirements:

Optimizing the H-mode pedestal for confinement and ELM control requires a method for controlling the Type-I ELM-induced heat loads to the divertor that is compatible with the large pedestal height needed for a high level of core plasma performance and Q_{fus}.

The most promising approaches to date use magnetic coils for either higher order 2D shaping or 3D edge resonant magnetic perturbations (RMPs) to suppress Type I ELMs entirely, or to mitigate the size of the ELM-induced divertor heat impulses. ELM-free operation has also been demonstrated in plasma conditions in which an edge instability provides a local source of 3-D magnetic perturbations in the edge (e.g., EDA regime, QH-mode). An improved understanding of the physics mechanisms that lead to ELM suppression (or mitigation) in these regimes is required before these control techniques can be confidently extrapolated to future devices. In addition, for each of these operating scenarios, we will need to develop plasma fueling scenarios (pellet size, speed, and injection location; RMP spectrum and amplitude) that provide core fueling without triggering intolerable ELMs. We will also need to be able to control the H-mode pedestal density and impurity levels in a low collisionality H-mode pedestal while maintaining a high collisionality radiative divertor and scrape-off layer.

Existing devices cannot produce simultaneously all the H-mode pedestal conditions anticipated in ITER. Consequently, it is necessary to develop a predictive model for the pedestal that self-consistently treats equilibrium (including 3D effects), stability, and transport in the kinetic regimes associated with high performance H-modes. This model must be validated against existing experimental results from a variety of devices. In order to develop this predictive pedestal model, we will need to improve our understanding of the interplay between transport and stability in H-mode pedestals. In addition, the plasma response to magnetic perturbations from coils, or from internal modes such as the Edge Harmonic Oscillation in QH-mode, must be understood in order to limit the magnetic field and plasma transport changes to only that region of the pedestal where it is needed to stabilize the peeling-ballooning modes associated with Type I ELMs.

3. Initiatives:

In order to address these needs, the US fusion program should implement the magnetic coils, power supplies, and controls needed to provide detailed, axisymmetric (2D) shaping and 3D edge magnetic field modification (stochastic or not) on at least one device capable of operating with robust Type I ELMs. These systems should have sufficient coil spectrum (amplitudes and phasing) and power supply capability to allow the widest possible flexibility in the 2D shaping and 3D field configurations to ensure a broad operating space for optimization. In addition to this hardware capability, it will be critically important to diagnose better the plasma conditions in the pedestal that govern the equilibrium, transport and stability as the optimization proceeds. This includes high spatial and temporal measurements of the pedestal plasma (electron and ion densities and temperatures), main ion rotation, and of the edge current profile. In addition, because the plasma response to externally applied fields is predicted to significantly screen (at high rotation) or even amplify (near marginal stability, a condition satisfied in the H-mode pedestal) the applied fields, it is critical to measure the structure of the resulting magnetic field inside the plasma pedestal directly. These measurements, in addition to guiding the optimization of the pedestal and ELM behavior, will validate existing models of pedestal transport and stability, while providing the insight needed to guide the development of a predictive, self-consistent pedestal model.

We propose the following initiatives to provide the capabilities required to optimize the H-mode pedestal and ELM behaviour:

- Install set of internal coils (on both low and high field sides) capable of producing a broad range of RMP mode spectra and phases
- Install set of poloidal field coils on low field sides to provide higher order shaping of the plasma equilibrium

We propose the following pedestal diagnostic initiatives to guide optimization:

- Measure the pedestal current profile that plays a crucial role in the MHD stability of the pedestal. The effects of error fields, and RMPs on both the pedestal structure and on ELM stability may also depend on the impact of these 3D magnetic fields on the otherwise axisymmetric bootstrap current profile.

- Measure the pedestal structure with high spatial resolution, 3-color SXR cameras (to provide high spatial and temporal resolution density and temperature profiles).

- Measure the magnetic field inside the plasma pedestal to validate plasma response models for error fields, RMPs, and EHOs.

- Validate simulations of the magnetic field structure with high temporal and spatial resolution visible/EUV imaging in conjunction with local gas injection to enhance contrast ("phase contrast imaging").

Similarities in the plasma behavior between QH mode and RMP ELM-suppressed H-modes suggest that at least some of the physics of the ELM suppression may be common to both operating regimes. The role of RMPs, for example, may be provided by the Edge Harmonic Oscillation. Because of this possible link between ELM suppression in these two regimes, we further propose an initiative to:

- Develop co-injected QH mode for ITER-similar conditions, especially torque input.

Together, the higher order 2D shaping and 3D magnetic field configurations in conjunction with improved pedestal will provide the necessary physical insight and experimental database for developing and validating a predictive pedestal model that self-consistently treats equilibrium (including 3D), stability, and transport for the kinetic regime consistent with high performance H-mode plasmas.