# Physics-based prediction of edge pedestal profiles under reactor-like conditions

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The ability of the ITER device to achieve its Q=10 mission depends on having an edge pedestal sufficient to maintain high core confinement. Therefore ITER is required to operate in an H-mode regime, with an expected energy confinement that has been extrapolated from results on existing tokamaks. Uncertainties abound in this extrapolation, however, due to the uniqueness of ITER's operating space, coupled with an incomplete understanding of the physics of edge transport barriers.

In the simplest picture, core confinement is determined largely by the edge boundary condition imposed by the height and radial extent of the edge pedestal, i.e. the pedestal profile structure. Additionally, there is the potential for conditions of core confinement to feed back on the pedestal structure, if for example, pedestal width is sensitive to global parameters such as $\beta_N$. Understanding the transport mechanisms and stability properties that determine pedestal structure should allow confident projection to ITER, along with a prediction for confinement. Such predictability could also provide a means by which the H-mode pedestal may be optimized for improved confinement.

In this document we list areas in which planning for the ITER H-mode baseline scenario, as well as reactors beyond ITER, could benefit from improved understanding of pedestal physics. Also, we propose research efforts and capital expenditures, which should be a part of any research thrust that is intended to address the extension of confinement predictions to burning plasma.

<u>Pedestal structure as limited by ELMs:</u>

Typically when we think of the pedestal, we focus on the gradient-limiting physics inside the edge barrier, with the understanding that the pressure pedestal height will be given by the product of gradient and width: $p_{ped} = \nabla p \times \Delta$. Through development of the theory of peeling-ballooning modes, and their numerical implementation in codes such as ELITE, a fairly robust prediction of edge MHD stability limits is available for existing and projected tokamaks. Recent modeling by Snyder has been quite successful at reproducing the pedestal height in DIII-D and other devices, and has given promising indications for the ITER baseline case. This is work that should be continued and extended to as many devices as possible. Application of the modeling to Alcator C-Mod and to NSTX should help resolve the roles of diamagnetic stabilization and aspect ratio on edge stability.

Projections of height derived from gradient-limiting physics naturally rely on a particular model for the pedestal width. A number of models exist, having varying degrees of

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success in matching experimental measurements. One of the more promising examples (and the one employed by Snyder, above) is the moderate scaling with poloidal beta: $\Delta \propto \beta_p^{1/2}$. However, it is important to test thoroughly this and all other reasonable width models against experimental measurements, and to arrive at conclusions about which width scalings apply under given H-mode conditions. Also, to increase confidence in width models, sound theoretical explanations will be desired, in addition to purely empirical results.

*Thrust components:*

- Expand modeling of the H-mode pedestal, as limited by ELMs, to encompass discharges on all devices, domestic and international.
- Make diagnostic upgrades on tokamaks sufficient to provide full, spatially and temporally resolved, profile information on parameters needed to test models: *e.g.* temperatures and densities of electrons and ions, toroidal and poloidal plasma flows, current density.
- Upgrade facilities as needed to provide increased auxiliary power, with greater stability, for flexibility in obtaining high-beta ELMy regimes.
- Compile data sets containing full profile information, so that analysis of each device's data can be performed in an equivalent manner.
- Carefully validate stability calculations in varied plasma regimes and magnetic configurations, and refine the stability criteria for ELMs.
- Provide a platform for testing pedestal width models.

Transport-determined pedestal structure

An important point to bear in mind is that MHD stability presents only one form of limitation on the obtainable pedestal structure. In between ELMs or in discharges without ELMs, H-mode pedestals possess a finite gradient, which presumably is determined by transport. In some cases, such as the EDA H-mode on C-Mod, approximate constitutive relations for these gradients have been determined. Understanding the transport mechanisms (e.g. marginal stability, heat and particle pinches) that give rise to these relationships is essential for building a general pedestal model.

There is also a practical need for this understanding, since ITER must operate with large ELMs mitigated or suppressed, implying that the edge profile must be held below the threshold for peeling-ballooning instability. For any proposed ELM mitigation or suppression method, it is critical to know the pedestal parameters that can be obtained, and how global confinement will be impacted.

*Thrust components:*

- As above, make needed diagnostic upgrades to capture full profile information. Additional effort is needed to resolve radially the fluctuations in the pedestal region

- Assemble multi-machine data for comparisons of pedestal structure (widths, gradients) prior to ELMs with that in between ELMs or in ELM-free regimes
- Examine relationships between pedestal widths and gradients and local parameters, such as collisionality. Are results consistent with marginal stability? Thermal and/or particle pinches?
- Give high priority to edge simulation, including turbulence-driven edge transport between ELMs. Accelerate progress in simulating the ELM cycle.

<u>Special issues for burning plasma</u>

Several features of ITER will distinguish it from most existing tokamaks in ways that could alter pedestal and confinement scalings. For example, it will operate with an unprecedented opacity to edge fueling, and thus is expected to require pellet fueling in order to achieve its target densities. However, it is not known whether the pedestal can support the densities ($n/n_G$~0.85) required in this regime, or what impact may be had on pedestal by substantial pellet fueling. Next, ITER will have negligible momentum input from neutral beams, meaning that the flow profiles will be predominately generated by the plasma itself. Effects of flow and flow shear on pedestal and ELMs need to be studied carefully for this reason.

*Thrust components:*

- Where possible, study fueling at near ITER opacity, looking for evidence of edge particle pinches.
- Perform facilities upgrades to test pellet fueling with ITER-like tools in ITER-like regimes.
- Experimentally assess impact of flow/torque on pedestal structure through variation in beam-balance, wave-heated plasmas. Useful experiments would include dimensionless matching experiments between C-Mod (RF only) and DIII-D (NBI)
- Examine prospects for flow drive and alternate heating schemes to modify pedestal/ELMs (mode conversion flow drive, ECH, LHRF). Provide substantial resources for source power upgrades to accelerate this line of research.

<u>Marginalities for ITER</u>

The initial phase of ITER operation is intended as a low-activation “break-in” period. In this non-nuclear phase, experience will be gained with control systems, disruption avoidance, ELM mitigation etc. Currently this is envisioned as a helium phase. An outstanding question is the quality of the pedestal and confinement in He discharges, and whether such plasmas will be effective substitutes for the later D-D or D-T phases.

As discussed in a companion paper, the auxiliary power available on ITER, by conservative estimates, will be marginal for triggering H-mode, and one can ask the question (in all phases of operation) how the pedestal and confinement will be affected if, indeed, the ratio of input power to H-mode threshold power is not far above unity.

A third point of consideration is that the magnetic equilibrium on ITER will be rather inflexible, and that its baseline operation will be somewhat close to a balanced double null equilibrium. The lower x-point will be dominant, but the separation between the primary and secondary separatrices will be comparable to the expected pedestal width (a few cm). Recent experimental results suggest that proximity to double null has a measurable influence on pedestal parameters and confinement; these effects should be characterized and understood so that the projection to ITER can be modified accordingly.

*Thrust components:*

- Study isotope dependence of pedestal parameters on single devices and across machines
- Examine pedestal scalings and ELMs as a function of power above threshold
- Examine effect of topology effects on pedestal structure. Should width/gradient modeling be refined?