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Stability and Dynamics of the Edge Pedestal in the Low Collisionality Regime: Physics Mechanisms for Steady-State ELM-Free Operation*

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Edge localized modes (ELMs) can limit tokamak performance both directly, via large transient heat loads to material surfaces, and indirectly, through constraints placed on the edge pedestal height which strongly impact global confinement. Maximizing the pedestal height (p_{ped}) while maintaining acceptable ELM behavior is a key issue for optimizing tokamak performance, and is of great importance for the success of ITER. Progress in the peeling-ballooning model [1-3] has led to an emerging understanding of the physics of the onset and dynamics of ELMs in the standard moderate to high collisionality pedestal regime.

Recently, highly promising low-collisionality regimes have been discovered, in which a robust, steady H-mode with high pedestal is achieved in the absence of ELMs. These include the quiescent H-mode (QH) regime, observed on DIII-D, ASDEX-U, JT-60U and JET at ITER relevant β and ν_* values, and recently extended to long duration and completely ELM-free operation [4]; as well as low-density ELM-free discharges in which ELMs are suppressed via an externally applied resonant magnetic perturbation (RMP) [5]. The focus of this paper is on understanding the physics of ELM suppression and edge dynamics in these promising low collisionality, ELM-free regimes. We present a theoretical model for the occurrence of QH-mode, in which the observed edge harmonic oscillation (EHO) is proposed to be a saturated low-n kink/peeling mode, which drives particle transport and allows a near steady state quiescent pedestal. In RMP discharges, we find that the imposed magnetic perturbation plays the role of the EHO, similarly allowing steady state quiescent discharges. Analytic theory, massively parallel nonlinear simulations, and extensive successful comparisons with experiment will be presented.

The outer ("pedestal") region of high performance tokamak plasmas is characterized by a sharp pressure gradient and consequent large bootstrap current, which can destabilize peeling, kink and ballooning modes over a wide range of toroidal mode numbers (*n*). The stability boundary be can calculated with efficient MHD codes and characterized as in Fig. 1(a), where the boundary depends strongly on plasma shape and other parameters. In moderate collisionality regimes, the most unstable modes are intermediate *n* (*n*~3-30) coupled peeling-ballooning modes. Calculating the stability boundary provides a quantifiable constraint on thepedestal height, and an onset condition for ELMs, which has been successfully compared

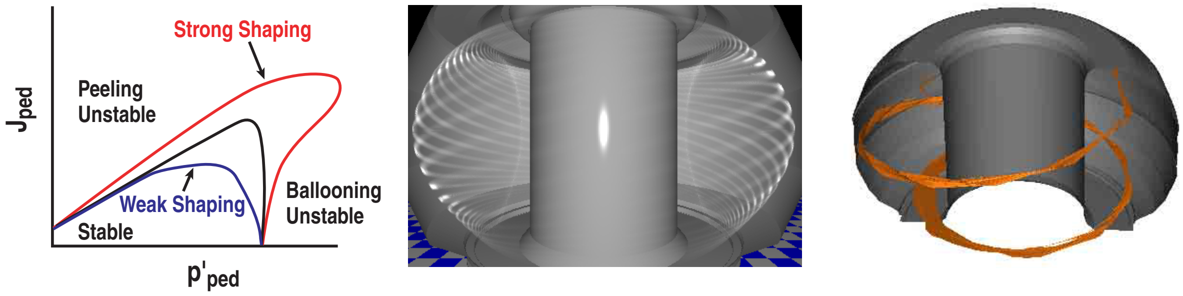

Fig. 1. (a) Schematic diagram of the peeling-ballooning stability limit for different shaped discharges as a function of edge current and pressure gradient. (b) Mode structure of a typical peeling-ballooning mode calculated by ELITE. (c) A filament of plasma from a nonlinear ELM simulation with the BOUT code propagates rapidly outward toward the vessel wall.

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to experiment in numerous studies [2]. The linear mode structure [Fig. 1(b)] provides insight on the impact of the instability. Nonlinear studies, employing massively parallel electromagnetic two-fluid nonlinear simulation [3], find the expected peeling-ballooning structure in the linear phase, followed by an explosive burst of one or many filaments [Fig. 1(c)], which propagate radially and carry heat and particles from the hot core plasma to the material surfaces, leading to a model for the full ELM losses.

In the very low collisionality regime, where the ELM-free QH and RMP regimes are observed, the physics is significantly different. The bootstrap current in the edge is proportional to the pressure gradient, but is suppressed by collisions. Hence the edge plasma traces a path through parameter space [arrows, Fig. 2(a)], and at sufficiently low density (i.e. low collisionality), the trajectory intersects the low-*n* kink/peeling, rather than intermediate-*n* peeling-ballooning, region of the stability boundary. Extensive sets of comparison to experiment confirm that QH operation occurs in the vicinity of this low-*n* kink/peeling stability boundary [4]. Because the limiting modes are low-*n*, they couple more strongly to the conducting wall, leading to a region [open symbols, Fig. 2(a)] of wall stabilization where a slow growing “edge localized resistive wall mode” (ELRWM) is unstable in the absence of rotation. The strong rotation in the QH mode edge can stabilize this ELRWM allowing operation up to approximately the ideal wall kink/peeling boundary.

The strong sheared flow in the edge region strongly stabilizes high-n ballooning modes as shown in Fig. 2(b). However, this stabilization weakens with decreasing n, and for fairly low n ($n \lesssim 10$), rotation shear is generally de-stabilizing. Hence, for the low density, strongly rotating QH-mode edge, the high-*n* modes are strongly stabilized, and the limiting low n (typically n~1-4) modes are actually de-stabilized by rotation.

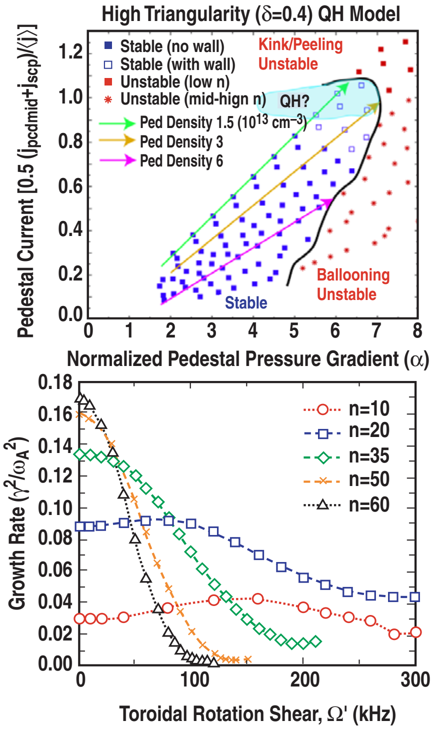

Fig. 2. (a) Calculated stability boundary showing proposed region of QH mode access. (b) Dependence of growth rate on flow shear for a range of mode numbers.

We propose that the EHO, a typically n~1-3 mode observed in most QH plasmas, is a saturated kink/peeling mode, which is de-stabilized by edge current and rotation. As its eigenmode grows to large amplitude, it creates significant magnetic perturbations which allow particle and current transport across the field. In addition, the large amplitude mode couples to the wall, and applies a drag on rotation, allowing the nonlinear mode to damp its drive and saturate at finite amplitude (rather than growing explosively like an ELM). This allows a steady state in all important transport channels and leads to a steady quiescent edge.

Low density RMP discharges operate in a similar regime, but here the role of the EHO is replaced by the applied magnetic perturbation. Because the strength of this perturbation can be varied, it is possible to operate near the edge stability boundary and significantly below it, as confirmed by an extensive set of experimental studies.

We present quantitative predictions of the density and shape parameters required for ELM-free operation and successful comparisons to DIII-D data, notably including access to QH-mode at much higher density in the presence of strong shaping. Planned experiments with balanced beam injection should provide tests of the rotation theory. Detailed calculations for QH access in ITER are presented.

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