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SUPER H-MODE: THEORETICAL PREDICTION AND INITIAL OBSERVATIONS OF A NEW HIGH PERFORMANCE REGIME FOR TOKAMAK OPERATION

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Super H-Mode: Theoretical Prediction and Initial Observations of a New High Performance Regime for Tokamak Operation

TH-S

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A new "Super H-mode" regime (Fig. 1) is predicted, which enables pedestal height and predicted fusion performance substantially higher than for H-mode operation. This new regime exists due to a bifurcation of the pedestal pressure, as a function of density, that occurs in strongly shaped plasmas above a critical density. The Super H-mode regime is predicted to be accessible, and to increase fusion performance, for ITER, as well as for DEMO designs with strong shaping. An initial set of experiments on DIII-D has identified the predicted Super H-Mode regime, and finds pedestal height and width, and their variation with density, in good agreement with theoretical predictions.

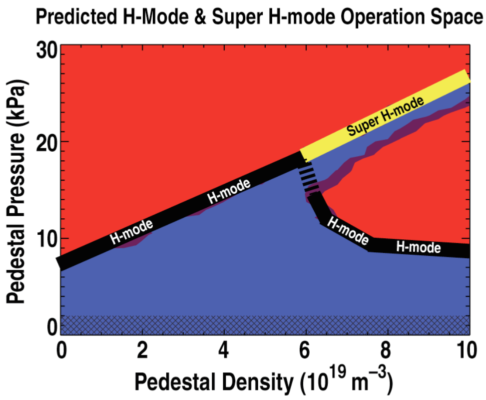

Fig 1. The Super H-mode regime (yellow) is predicted for strongly shaped plasmas above a critical density (for weakly shaped plasmas the black H-mode curve is continuous and more flat). Very high pedestal pressure and fusion performance is predicted in this regime.

The pressure at the top of the edge transport barrier (or "pedestal height") strongly impacts global confinement and fusion performance, with fusion power production expected to scale approximately with the square of the pedestal height. The EPED model [1–3] predicts the H-mode pedestal height and width based upon two fundamental and calculable constraints: 1) onset of non-local peeling-ballooning (P-B) modes at low to intermediate mode number, 2) onset of nearly local kinetic ballooning modes (KBM) at high mode number. Calculation of these two constraints allows a quantitative prediction of both pedestal height and width [Fig. 2(a)]. Both constraints are calculated directly, including important kinetic effects, with no free or fit parameters. The model has been successfully compared to numerous experiments, including detailed parametric studies [e.g. Fig. 2(a)]. A comparison across 288 cases from 5 tokamaks [1–6] finds a ratio of predicted to observed pedestal height of 0.99±0.21, with a correlation of 0.91, consistent with ~10%–15% measurement uncertainty and model accuracy to within ~15%–20% [Fig. 2(b)].

The combination of P-B and KBM physics in the EPED model leads to strong predicted dependence of the pedestal height on poloidal field (B_p), toroidal field (B_t) and plasma shape. These dependencies have been successfully tested in several experiments, for example an experiment on DIII-D in which the plasma current (i.e. B_p) was varied by a factor of three at fixed B_t and plasma shape [Fig. 2(a)]. An important dependence on density derives primarily from the dependence of the bootstrap current on collisionality. At low density, the pedestal is typically limited by current-driven instabilities, and the predicted pedestal height increases with density (because the bootstrap current at a given pressure gradient decreases with collisionality), as shown for example by the black line in Fig. 2(c), at density < 6×10^{19} m^{-3}. At higher density, bootstrap current is suppressed, the pedestal becomes primarily limited by pressure driven modes, and the predicted pedestal height decreases with density (black curve in Fig. 2(c), at density > 6×10^{19} m^{-3}). The collisionality dependence of the bootstrap current is critical, and therefore we employ calculations with the NEO kinetic code [7], which incorporates multiple ion species and the full linearized Fokker-Planck collision operator, both for direct calculations and to assess the accuracy of simpler bootstrap current models.

For weakly shaped plasmas (triangularity ≲0.4), EPED predicts a pedestal height dependence on density which is continuous and relatively mild. However, at strong shaping, the density dependence becomes stronger, and can bifurcate into Super H-Mode and H-mode branches above a critical density (Fig. 1). When this bifurcation occurs, operation at fixed density is still expected to result in a pedestal which rises to the H-mode root and is then limited by peeling-ballooning stability [manifested as Type I edge localized modes (ELMs) or, in Quiescent H-mode, coherent modes]. However, dynamic variation of the density (or collisionality), starting at low values, enables access to the Super H-mode regime and pedestal heights far above the H-mode value.

Recent experiments on DIII-D have tested the predicted density dependence at both high and low density. For example, in Fig 2(c), the green crosshairs show a density ramp in DIII-D shot 153440, finding that the measured pedestal pressure increases with density as predicted. At the highest density value (upper right crosshair), the plasma is found to be deep in the Super H-mode regime. The predicted Super H-mode bifurcation is further confirmed later in the discharge, following a core-tearing mode, as the pedestal drops to the H-mode root [orange crosshair in Fig. 2(c)]. Note that the edge is quiescent at early times (green crosshairs) demonstrating that Super H-mode can be accessed without ELMs.

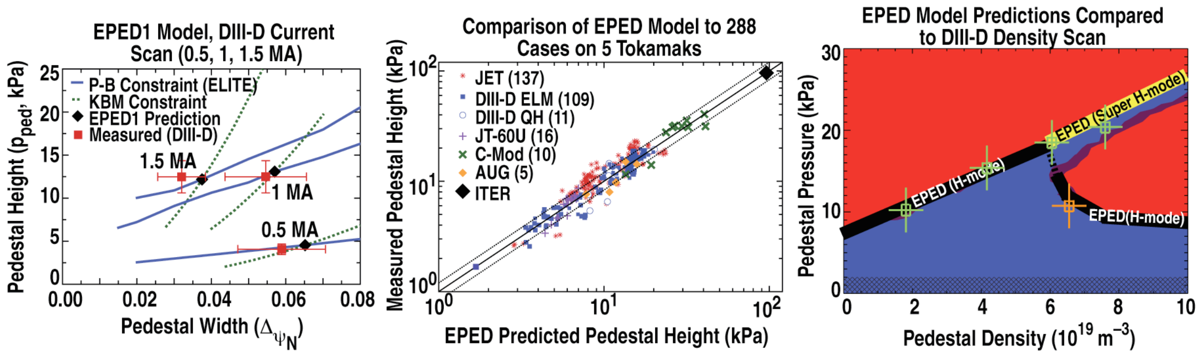

Fig. 2. (a) The EPED model predicts the pedestal height and width (black diamonds) from the intersection of P-B (solid blue line) and KBM (dotted green line) constraints. Predictions for a current scan on DIII-D are found to be in good agreement with observations (red squares). (b) Comparison of EPED predictions to observed pedestal height for 288 cases on 5 tokamaks, with ITER baseline prediction also shown. (c) A density scan on DIII-D (green crosshairs) finds good agreement with the EPED predicted dependence [solid black (H-mode) and yellow (Super H-mode) lines]. At high density (upper right), the Super H-mode regime is accessed, and the bifurcation of the pedestal pressure is apparent in comparison to a later time (orange crosshair).

Super H-mode access is predicted for a wide range of conditions on DIII-D and experiments are planned to further explore this regime. Previous experiments were limited by core instabilities, not pedestal modes, and it is expected that further increases in pedestal pressure and global confinement are possible. Super H-mode access is also predicted for ITER and DEMO, and extensive sets of predictions and optimizations will be presented for ITER at a range of densities and plasma currents. We further note that collisionality is impacted by impurity concentration as well as density, and present scenarios for improving performance of ITER and existing devices by introducing low Z impurities, such as nitrogen.

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