ADVANCES IN CORE-EDGE INTEGRATION OF LOW COLLISIONALITY QUIESCENT H-MODE REGIMES RELEVANT TO BURNING PLASMAS

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Among non/small-ELM regimes, Quiescent H-Modes (QH-Modes) and Wide Pedestal QH-Modes (WPQH-Modes) are especially relevant to burning plasmas, featuring turbulence-limited ELM-stable pedestals operating near the peeling instability boundary at low collisionality, low or zero NBI torque, and no degradation with power including with dominant electron heating. On the other hand, these conditions have led to core-edge integration challenges in present machines, namely high divertor temperatures and impurity sputtering. We report significant advances toward resolving these issues for DIII-D QH-Mode regimes to enable future extension to tungsten walls and ITER, including: **(1)** doubling of the divertor heat flux width λ_q by measured electron turbulence [Fig. 1(a,b)], matched by XGC simulations [1], which supports predictions of broadened λ_q for ITER [2]; **(2)** suppression of tungsten accumulation in Wide Pedestal QH-Modes using feedback-controlled nitrogen injection to eliminate large, slow pressure oscillations caused by a tungsten radiative instability; **(3)** reduction of carbon concentrations by a factor of two in hydrogen WPQH-Modes; **(4)** increase of separatrix densities n_e^{sep}/n_e^{ped} by a factor of 5 to attain ITER predicted values of 0.3 to 0.6, creating conditions for divertor detachment and neoclassical pedestal impurity screening [Fig. 1(c,d)]; and **(5)** notable absence of an isotope effect on confinement in WPQH-Modes, when the Z_{eff} profile is matched in hydrogen and deuterium, where pedestal E×B shear is reduced as expected in ITER and high field tokamaks.

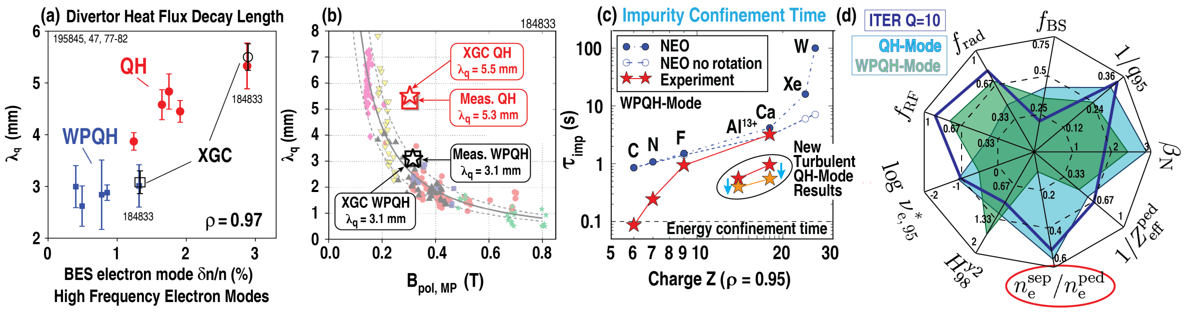

Figure 1: (a) Electron thermal transport from high frequency electron turbulence doubles the divertor heat flux decay width λ_q in turbulence-limited QH-Modes, matched by XGC gyrokinetic particle simulations [1], (b) departing from the Eich empirical multi-machine scaling [3]; (c) Impurity confinement times in Wide Pedestal QH-Mode increase strongly with charge Z, approaching neoclassical values for Z > 10, while new turbulent QH-Modes with strong shaping reduce this high Z impurity influx (blue arrows indicate increased n_e^{sep}/n_e^{ped}); and (d) Attained operating parameters with respect to ITER Q=10 target values for QH/WPQH-Modes. Recent experiments have improved plasma purity, showing these regimes do not require high carbon concentrations. The ratio of separatrix to pedestal density has been increased by a factor of 5 (reaching predicted ITER values of n_e^{sep}/n_e^{ped} ~ 0.3-0.6), creating favorable conditions for divertor detachment and neoclassical impurity screening.

Pedestal E×B shear due to $E_r \sim \nabla p_i / e n_i$ is a likely origin of the isotope effect [3] observed in present machines, but is expected to be much weaker in ITER pedestals. Because the ratio of pedestal E×B shear rate to drift wave turbulence growth rate scales with $\rho_* = \rho_i/a$, pedestal turbulent transport ($\propto \rho_*^{-2}$) could be an order of magnitude larger in ITER, likely strong enough to naturally prevent ELMs [1]. At larger ρ* values in present machines, transport reduction by E×B shear is more important than expected in future machines. Accordingly, the absence of an isotope effect in turbulence-limited Wide Pedestal QH-Mode pedestals, where pedestal E×B shear is greatly reduced relative to Standard QH-Modes and ELMy H-Modes, suggests the absence of an isotope effect in ITER and future high field tokamak pedestals.

While turbulence-limited QH-mode pedestals bring benefits such as turbulence-broadened divertor heat flux widths, new core-edge integration challenges emerge. Prior to this work, divertor detachment in these regimes has been prevented by the low separatrix densities needed to access ITER collisionality in present machines, while steep pedestal density gradients create a strong neoclassical impurity inflow proportional to impurity charge, which is prone to accumulation of metallic impurities. Without ELMs to flush impurities, either the sputtering source must be greatly reduced and/or impurities must be screened by the plasma. Divertor detachment reduces impurity physical sputtering by reducing sheath temperatures and thus sheath potentials and impact energies. Detachment combined with impurity screening in the pedestal, to prevent injected as well as sputtered impurities from contaminating the core, emerge as key requirements for compatibility with tungsten walls. The strongly increased separatrix densities, made possible by the newly increased shaping in DIII-D, bring impurity screening and divertor detachment within reach in QH-Modes.

Impurity confinement times in Wide Pedestal QH-Mode increase strongly with charge Z, approaching neoclassical values for $Z > 10$, as measured using perturbative techniques, as shown in Fig. 1(c). This result shows that we must reduce or reverse the neoclassical inflow velocity for high Z impurities driven by the steep pedestal density gradient, because turbulent impurity transport (evident at low Z where the impurity confinement time is comparable to the energy confinement time) does not appear to compete with the neoclassical convection at high Z. Leveraging a new high-volume, high triangularity ($\delta \sim 0.95$) shape in DIII-D, we have greatly decreased the pedestal density gradient by increasing separatrix densities while retaining low pedestal top collisionality in QH-Modes with $n_e^{sep}/n_e^{ped} \sim 0.5$. Record densities 1.2×10^{20} m^{-3} were reached for QH-Modes without ELMs, with Edge Harmonic Oscillations maintained. Pedestal stability analysis reveals the operating point reaches the entrance of a wide Super H-Mode stable channel, and surprisingly, falls near the ballooning stability boundary. Planned experiments aim to access the Super H-Mode channel to reach even higher densities by increasing the ion temperature, which improves diamagnetic stabilization of ballooning modes. The scenario so far obtained provides a basis for developing QH-Mode compatibility with metal walls via divertor detachment and neoclassical pedestal impurity screening of metals. At lower densities, relatively high pedestal top ion temperatures up to 5.5 keV, promising for impurity screening, are maintained. Analysis of multi-species impurity transport measurements is underway and planned experiments will make further measurements.

Carbon concentrations were reduced by half in WPQH-Mode by operating in hydrogen. Due to its lower mass, hydrogen reduces physical sputtering of carbon by an order of magnitude relative to deuterium. This reduced sputtering source lowered Z_{eff} from 3 to 2, supporting a recently imporoved understanding of WPQH-Mode carbon sourcing and SOL transport [5]. Injecting carbon powder in the hydrogen case to match the reference deuterium Z_{eff} profile resulted in a close match of hydrogen and deuterium T_i, T_e, n_e, and V_{tor} profiles with the same injected power and torque. These results show that QH and WPQH-Modes do not require high carbon concentrations, so that compatibility with metal walls should depend mainly on operational factors. These include attaining sufficiently low collisionality, low torque, sufficient shaping, and avoiding accumulation of metals by cooling the divertor with radiative impurity injection and/or detaching the divertor, and by tailoring pedestal profiles to achieve impurity screening. The recent advances we describe show these requirements can be met.

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REFERENCES

[1] D. R. Ernst, A. Bortolon, C. S. Chang, S. Ku et al., Phys. Rev. Lett. **132**, 235102 (2024).
[2] C. S. Chang et al., Phys. Plasmas **28**, 022501 (2021).
[3] T. Eich et al., Nucl. Fusion **53**, 093031 (2013).
[4] D. R. Ernst et al., Phys. Rev. Lett. **81**, 2454 (1998).
[5] X. Ma et al., Nucl. Fusion **65,** 026017 (2025).

Summary sentence:

Core-Edge integration for burning-plasma relevant Non-ELMing Quiescent H-Mode regimes in DIII-D has been greatly improved for extension to tungsten walls and to ITER, record densities obtained, large tungsten influxes and pressure oscillations eliminated, divertor heat flux widths doubled by turbulence and closely matched by XGC simulations, and carbon concentrations cut in half ($Z_{eff} = 2$) in Wide Pedestal QH-Mode, which shows no isotope effect when Z_{eff} is matched in hydrogen and deuterium, consistent with reduced pedestal ExB shear as expected in ITER.