Achievement of a high-density, high-confinement, and high beta tokamak plasma regime for ITER and FPP

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Experiments on DIII-D have demonstrated a density-confinement synergy that enables sustainment of high performance in a previously unattained parameter regime of simultaneous very high energy confinement quality (H_{98y2} ≥1.5), very high density Greenwald fraction ($f_{Gr}=\pi a^2<n>/I_P \geq 1.4$), and high toroidal beta (β_T ≥3%). Tokamak operation in this regime is essential for a compact FPP, as well as for Q=10 in ITER at significantly reduced plasma current (desirable for risk mitigation).

High confinement quality, *H*, high plasma density, *n*, and high toroidal beta, β_T, are critical for economical fusion energy: the capital cost of a fusion reactor scales as $1/H^{4.8}$[1], while the fusion power density scales as n^2 and, for ion temperature ~14 keV, as β_T^2. In addition, high f_{Gr} is a powerful knob to ameliorate the wall heat load challenges, both transient and steady state. Thus, high *H* at high f_{Gr} and high β_T can close the core-edge integration gap. A major challenge is how to initiate and sustain such plasma regime. In fact, it is nearly universally observed that attempting to increase the density towards the Greenwald limit results in a loss of confinement quality. This can be attributed to some or all of the following: a deterioration of the H-mode pedestal pressure with strong gas puffing, a reduction of the *ExB* shear turbulence stabilization effect due to lower injected torque per particle at higher density, a reduction of the fast ion fraction due to higher density.

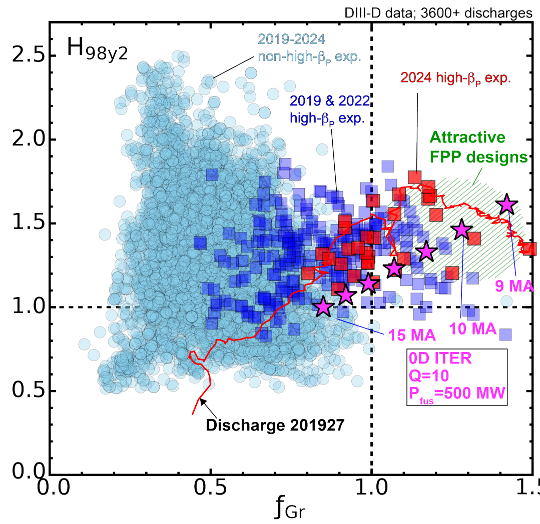

Figure 1: The latest high β_P experiments (red data points and trajectory) extend previous achievements for simultaneously achieved high density and high confinement (blue square data points) [3], and provide a first experimental demonstration of the very high f_{Gr} and H_{98y2} required for ITER Q=10 at I_P<10 MA.

Recent theoretical predictions [2] have shown that, in the high poloidal beta (β_P) regime, impurity and density gradients can enhance the turbulence stabilization effects of high alpha ($\alpha \sim d\beta_P/dr$). These general concepts have been confirmed by gyrokinetic modeling and predictive gyrofluid transport simulations. Experiments on DIII-D [3] have validated the prediction of gyrokinetic theory and simulations, and pointed to practical ways to improve the energy confinement in a fusion reactor. Guided by this understanding, and using an improved plasma shaping, more recent DIII-D experiments have significantly extended the previous results [3] in simultaneous high f_{Gr} and high H_{98y2}, as shown in Fig.1, providing the first experimental demonstration of the f_{Gr} and H_{98y2} values required for ITER Q=10 at I_P<10 MA.

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References

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[2] M. Kotschenreuther *et al*, *Nucl. Fusion* **64** (2024) 076033
[3] S. Ding *et al*, *Nature* **629** (2024) 555