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 ($H_{98y2} \geq 1.5$), very high line-average density Greenwald fraction ($f_{Gr} = \pi a^2 \langle n \rangle / I_P \geq 1.4$), and high toroidal beta ($\beta_T \geq 3\%$). Tokamak operation in this regime is essential for a compact FPP, as well as for Q=10 in ITER at significantly reduced plasma current.

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.

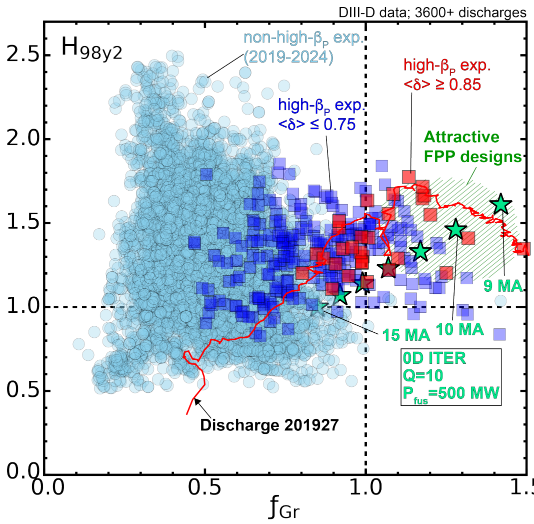

Figure 1: The latest high β_P experiments (red data points and trajectory, having higher average triangularity <δ>) extend previous achievements of simultaneous high normalized density and high confinement quality (blue square data points) [3]. Star symbols indicate the f_{Gr} and H_{98y2} required in ITER for Q=10 with P_{fus}=500 MW, at various levels of plasma current.

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.

The new experiments also extended the previous results [3] in simultaneous beta values, by sustaining f_{Gr} > 1 and H_{98y2} > 1 at very high normalized beta ($\beta_N \geq 4$) and high toroidal beta ($\beta_T > 3\%$), as shown in Fig. 2 by the red and orange timetraces. The slow decay in confinement quality (from its peak at H_{98y2} ~1.8) is correlated with core accumulation of high Z impurities [4]. The figure also highlights the three-fold increase in duration at high performance, compared with the results presented at the previous IAEA meeting (blue timetraces) [5]. In the new experiments, high performance was attained and sustained reproducibly, with the eventual terminations brought about by an MHD mode destabilized as the current profile slowly continued to evolve. A path to stationary fully noninductive operation might include ECH injection to reduce both core impurity accumulation and the electron collisionality, thus increasing the bootstrap current, in addition to external off-axis CD with helicon and/or lower hybrid.

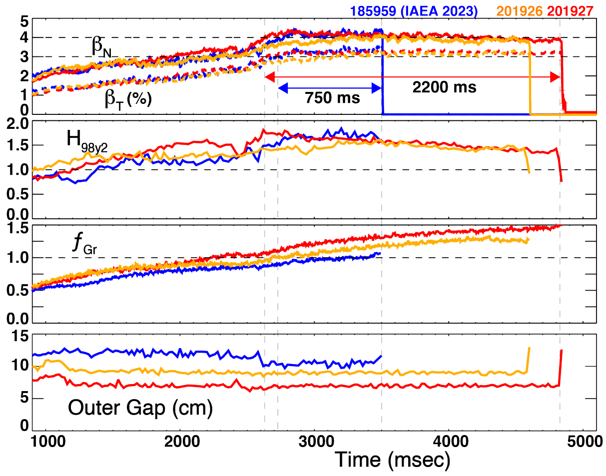

Figure 2: With reduced plasma-wall outer gap to increase the ideal-wall beta limit, recent experiments tripled the duration at $\beta_N \sim 4$ with $\beta_T > 3$ (and $q_{min} \geq 2$), compared with results reported at IAEA-FEC 2023 [4].

These experiments used a smaller plasma-outer wall distance, in order to increase the ideal-wall beta limit, and availed of higher triangularity in the plasma cross section (top/bottom average δ ~0.9), enabled by the recent "shape & volume rise" (SVR) modification to the DIII-D divertor. The stronger shaping may have contributed to higher MHD stability as well, as was predicted. In these experiments, higher triangularity correlates with higher pedestal density (as shown in Fig. 3), which is a probable key reason for the record f_{Gr} values achieved in the SVR shape. Furthermore, pedestal analysis and modeling show that the high poloidal beta with strong Shafranov shift can enable the pedestal density to increase along the peeling boundary even at high collisionality [6].

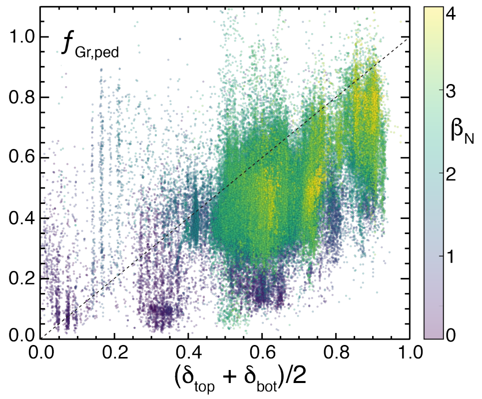

Figure 3: Pedestal density Greenwald fraction measurements versus average triangularity for a database of ~230 DIII-D high β_P discharges.

In summary, high poloidal beta experiments on DIII-D have demonstrated operation in the previously unattained regime of high β_T at very high f_{Gr} and H_{98y2}, necessary for economical fusion energy. Strong Shafranov shift enables access to peeling-limited pedestals even at pedestal density near the Greenwald limit, providing unique references for studies of reactor-relevant cores coupled to reactor-relevant pedestals.

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