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Recent Progress in High Poloidal Beta Scenario Development on DIII-D

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The high poloidal beta (β_P) scenario has many features that make it a promising candidate scenario for a future steady-state fusion reactor, including: high confinement at low plasma rotation, low disruption risk, compatibility of high core performance with divertor detachment, low transient heat loads on divertor, low inductive current fraction, and high minimum safety factor, leading to no sawteeth and no 2/1 mode.

Conceptually, the high β_P approach to a steady-state tokamak reactor was first proposed by Kikuchi in 1990 [1]. Experimentally, high β_P plasmas with density Greenwald fraction (f_{Gw}) up to ~1.0 and H_{98y2}>1.0 were first obtained in JT-60U. These experiments also had low momentum input, albeit transiently and usually operated at low absolute density [2]. Since 2013, joint research activities by the EAST and DIII-D teams have explored this scenario in both tokamaks, and extended it to key reactor relevant conditions, such as: low toroidal rotation of ~20 krad/s at mid-radius (e.g. ρ~0.5), f_{Gw} up to 1.4 at electron density above 8×10^{19} m^{-3} and sustained β_N>4, all the while making significant progress in the fundamental physics understanding [3-6]. Keys to the success of developing this scenario on DIII-D include high q_{min} (>2.0) and high density operation at relatively low plasma current (q_{95}>6.0, f_{Gw}~1.0) but high normalized beta (β_N>2.5).

A typical feature of high β_P plasmas is an internal transport barrier (ITB) at large radius, e.g. ρ~0.7, usually in both temperature and density profiles and for both electron and ion species. This ITB has some crucial differences compared to ITBs in many previous studies where toroidal rotation played a key role (e.g. Ref [7]). For example, DIII-D high β_P experiments have demonstrated almost identical electron temperature ITBs with significantly different neutral beam injected torque and rotation shear profiles, as shown in figure 1. More recently, DIII-D experiments have shown a synergy between ITB strength and edge pedestal mitigation, leading to excellent energy confinement quality sustained with complete divertor detachment. Here, strong α-stabilization and low magnetic shear are the key physics ingredients, as shown in Fig.2.

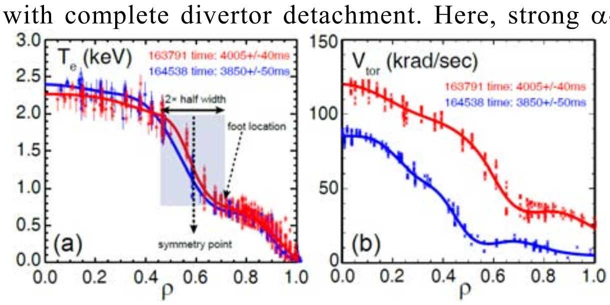

Figure 1. (a) Electron temperature profiles; (b) toroidal rotation profiles. Experimental data points and their error bars are shown in the same color as the fitted profiles.

The latest DIII-D experiments have extended the high β_P scenario to higher performance, meeting the required normalized fusion parameters for ITER Q=5 steady state operation. Plasmas with $H_{98y2}\geq1.5$ and $\beta_N\geq4$ have been achieved at $q_{min}\geq2$ and $\beta_T\geq3\%$ and sustained for a current diffusion time before evolving to an MHD-unstable state. The normalized fusion performance $G_{98}=H_{98y2}\beta_N/q_{95}^2$ in these experiments reaches the value predicted in ITER high β_P Q=5 modeling [8]. Strong internal transport barriers lead to a high confinement core with bootstrap current fraction ≥80% and line-averaged density at the Greenwald limit. These results confirm the high β_P scenario as a highly promising candidate scenario for future fusion reactors.

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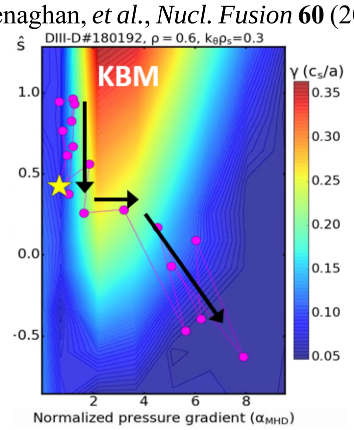

Figure 2. Growth rate of the leading micro-instability (kinetic ballooning mode, KBM) identified by CGYRO, vs. magnetic shear and pressure gradient at ρ=0.6 of experimental equilibrium at 2.75 s marked by yellow star. Discharge evolution (purple dots, from 2.4 s on the top left to 4.0 s on the bottom right) shows decreasing shear, from detachment driven pedestal deterioration, leads to stronger pressure gradient around the KBM instability mountain.