Core-edge Integrated Scenario with a High-Performance Hybrid Core, Naturally Small ELMs, and a Dissipative Divertor on DIII-D

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Extending hybrid scenario operations on DIII-D to lower torque and higher density led to the discovery of a high performance, naturally small ELM regime. Higher density moved this scenario closer to reactor relevance by increasing the Greenwald fraction up to 85% with peak $\beta_N = 3.8$ and $H_{98y2} = 1.4$. At high density and high gas fueling rates, these hybrid plasmas exhibited high frequency ($f_{ELM} \geq 500$ Hz) ELMs that had oscillations in the stored energy ($\Delta W_{ELM}/\Delta W_{PED}$) of <1%. Adding divertor N_2 seeding to this scenario led to partial detachment with pedestal temperatures of ~1 keV.

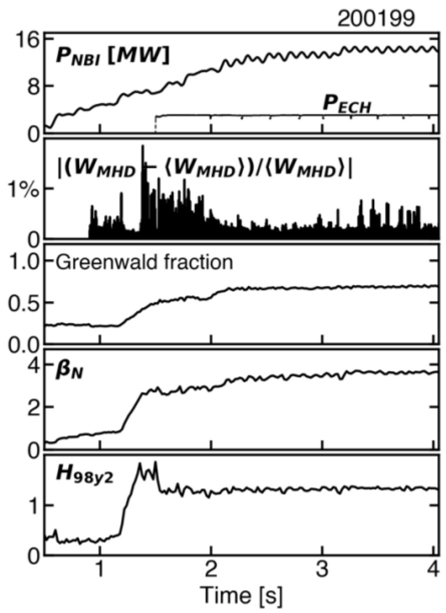

Figure 1:DIII-D hybrid sustains naturally small ELM regime with β_N = 3.6 and H_{98y2} = 1.3 at 70% of the Greenwald density

Hybrid plasmas on DIII-D [1] are characterized as having q_{min} slightly greater than 1 with anomalous diffusion of the current density (j) profile. The anomalous diffusion of j, typically driven by a benign 3/2 neoclassical tearing mode (NTM), inhibits sawteeth by keeping q_{min} above 1. Recent experiments modified the traditional steady-state hybrid scenario [1, 2] by adding additional neutral beam injection (NBI) power in the counter-Ip direction, thereby reducing the injected torque from 9.2 to 6.2 Nm and the core rotation from 240 to 70 km/s. Past attempts at reducing the torque in the hybrid scenario at lower density led to lower β and higher transport because of the reduced ExB shearing rate [3], and a higher propensity for large NTMs that led to a significant drop in confinement. Increasing the plasma density from near 4.0e19 m^{-3} to upwards of 7.5e19 m^{-3} allowed for stable operation without large NTMs. Furthermore, at higher density, neutron rate measurements indicate good confinement of the injected NBI particles and little to no fast ion diffusion.

However, the move to more reactor relevant conditions led to a decrease in the non-inductive current fraction. Hybrid plasmas traditionally inject electron cyclotron (EC) power tangentially into the plasma, with absorption near the magnetic axis, for highly efficient EC current drive (ECCD). The plasmas presented here use O-mode EC injection, with a higher density cut-off than X-mode, for on-axis absorption at higher density; however, O-mode ECCD drives ~90% less current compared to X-mode. Furthermore, counter-Ip NBI reduces the net injected torque, but also decreases the directly driven NBI current. The total bootstrap current is similar between the steady-state hybrid and recent high-density hybrids.

Discharges with a broader pedestal density profile, with approximately twice the typical separatrix density, showed an increase in the ELM frequency and a suppression of type-I ELMs. Stability analysis with BOUT++ indicates that the higher density plasmas are unstable to a local ballooning mode near the separatrix. This mode becomes unstable at higher ratios of separatrix to pedestal density, leading to the high frequency ELMs. These high frequency ELMs prevent the pedestal pressure from reaching the strong peeling-ballooning stability limit where type-I ELMs occur. The ELM behavior in this scenario has some similarities with other small ELM regimes, such as the quasi-continuous exhaust (QCE) mode discovered on ASDEX-Upgrade (AUG) [4]. However, there are some apparent differences between QCE and the small ELM regime in these hybrid plasmas. Higher amplitude fluctuations, from 30 - 150 kHz, are measured in these hybrid plasmas with small ELMs. These fluctuations, measured at the plasma edge by the Beam Emission Spectroscopy (BES) and Charge eXchange Imaging (CXI) diagnostics, peak radially near the separatrix and propagate in the electron diamagnetic drift direction. During periods with type-I ELMs, BES and CXI measure a decrease in the fluctuation amplitude in this frequency range. In addition, the Radial Interferometer Polarimeter (RIP) measures increased magnetic fluctuations at 30 - 150 kHz during times with small ELMs indicating an electromagnetic component to the fluctuations. These broadband fluctuations differ from the discrete frequency fluctuations of the quasi-coherent and high harmonic modes observed in AUG QCE plasmas [5]. In addition, these hybrid plasmas with small ELMs operate at pedestal temperatures ≥ 1 keV and core parameters up to $\beta_N = 3.8$ and $H_{98y2} = 1.4$, which are higher than typical QCE plasmas.

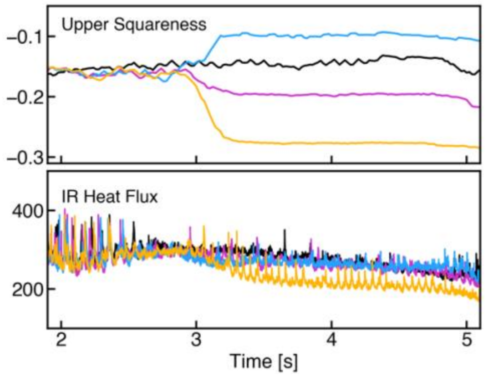

Figure 2: Type-I ELMs return in a plasma shape with lower squareness.

Fueling rates and plasma shape influence access to this small-ELM regime. A transition from type-I ELMs to high-frequency ELMs occurs in these hybrid plasmas as the fueling rate is increased. Type-I ELMs occur at a lower fueling rates (≤ 40 TorrL/s) and a corresponding lower scrape-off layer (SOL) density. Higher fueling rates (≥ 90 TorrL/s) lead to an increase in the SOL density and smaller amplitude ELMs. In addition, type-I ELMs returned at reduced plasma squareness (Fig. 2). Over a series of four discharges, the plasma squareness was scanned while keeping triangularity roughly constant. The IRTV heat flux is similar for the three discharges with the highest squareness; however, at the lowest squareness, the type-I ELMs returned despite similar fueling levels.

Partial divertor detachment at the outer strike point has been achieved in this scenario at pedestal temperatures of 1 keV and pedestal collisionality $\nu^* \leq 0.5$ without a decrease in β_N or pedestal performance (Fig. 3). Core performance is slightly lower in these plasmas, with $\beta_N = 3.1$ and $H_{98y2} = 1.1$, due to lower NBI power and the unavailability of the divertor cryopump during this portion of the experiment. The wider pedestal and high pedestal temperature are beneficial for the core-edge integration of the high-β hybrid core with the naturally small ELMs and divertor detachment.

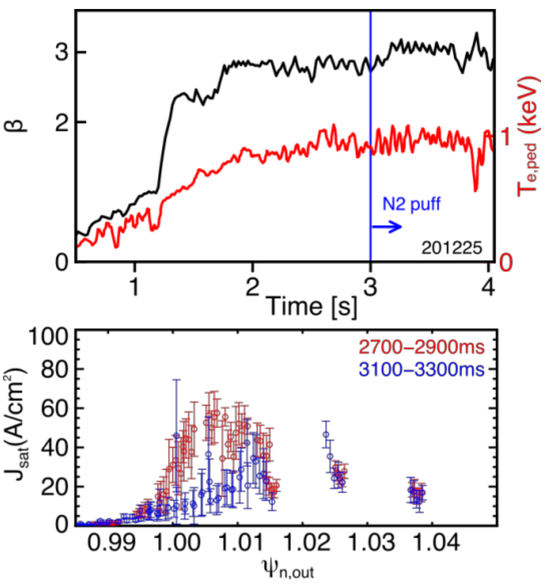

Figure 3: β_N and pedestal temperature are maintained through detachment (top). Divertor ion saturation current, measured by Langmuir probes, decreases after 3100 ms, indicating partial detachment (bottom).

In addition, the high-performance hybrid scenario ($\beta_N = 3.5$, $H_{98y2} = 1.6$) is found to be compatible with a low-collisionality ($\nu^*_{e,ped} = 0.1$–0.4), intrinsically grassy-ELM regime on DIII-D. This new regime, with $\Delta W_{ELM}/\Delta W_{PED} < 2\%$, offers significant power handling advantages, including a ~50% broader heat decay width and a fivefold reduction in peak ELM-induced divertor load. Similar between the high- and low-density scenarios, a large Grad-Shafranov shift and a low pedestal density gradient render the plasma weakly unstable to edge instabilities, which trigger high frequency, small ELMs. This study provides a comprehensive analysis of the compatibility between high-performance hybrid scenarios and small-ELM edges, offering a promising core-edge integration solution for future fusion reactors.

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