Overview of DIII-D research towards ITER and future Fusion Power Plants

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The DIII-D tokamak research program advances physics understanding for ITER and future Fusion Power Plants (FPPs), exploring a range of scenarios demonstrating high performance cores coupled with dissipative edges, developing and demonstrating reactor-relevant technologies, and preparing for ITER operations.

Core-Edge Integration: The new upper divertor geometry of the Shape and Volume Rise (SVR) (shown in Fig. 1 inset) enabled plasma regimes with access to reactor-relevant conditions of simultaneous high pressure and density. Of three scenarios run in the SVR divertor, the ELMy H-mode scenario (Fig 1.) achieves the highest absolute parameters (β_N^{ped}>1.3, T_e^{ped}>2 keV, T_i^{ped}>3 keV), with a peeling-limited pedestal with p_e^{ped} approximately double the value of the ballooning-limited pedestal, consistent with model predictions and among the highest pedestal pressures measured at DIII-D.

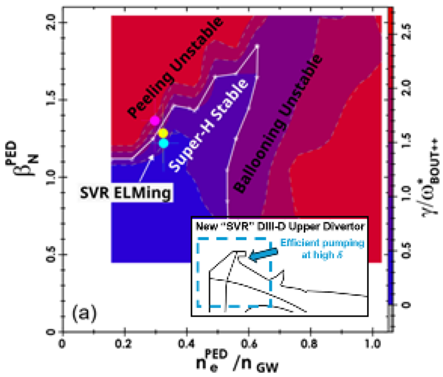

Figure 1. ELITE-EPED analysis for the ELMy scenario in the new SVR divertor, shown at inset. Colored points are 3 distinct ELMing cases. Contours are normalized growth rate, which determines instability threshold.

High-β_P experiments achieved the first tokamak demonstration of density Greenwald fraction f_{Gr}>1 with H_{98y2}>1 (Fig. 2), as required for both steady state FPPs and ITER Q=10 at reduced I_p. Analysis shows that at high β_P a synergy emerges between alpha stabilization of turbulence and density gradients. In recent experiments, this enabled the formation and sustainment of large radius internal transport barriers (ITBs) at f_{Gr}≈1.45 with H_{98y2}≈1.4 and β>3%.

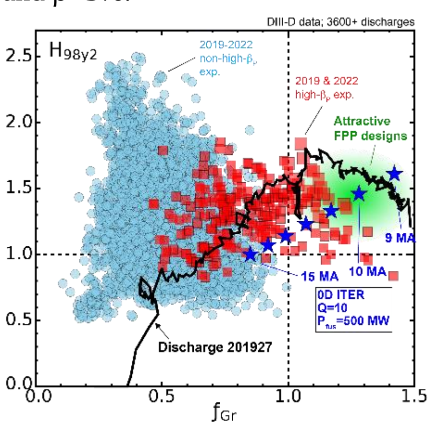

Figure 2. First demonstration of very high f_{Gr} and H_{98y2} required for ITER Q=10 at Ip<10 MA.

Small ELMing scenarios have advanced along two paths towards reactor relevance: (1) low ITER-like collisionality at high performance conditions and (2) high-density, high-collisionality with divertor dissipation. A low-density grassy ELM regime featuring small ELMs (size <1%) is compatible with a high-performance hybrid core at ITER-similar collisionality (ν_e*~0.1) and shape, aligning closely with projected future reactor operational conditions along the peeling boundary. The high-density, small-ELM regime pushed performance metrics to β_N=3.8, H_{98y2}=1.4, and demonstrated coupling to a detached divertor at β_N=3.1, H_{98y2}=1.1. Both small-ELM regimes demonstrate compatibility with high-performance hybrid cores and highlight underlying physics of small-ELM operation: the critical role of a flat density gradient and strong pedestal turbulence in facilitating small ELMs.

Divertor/SOL characterization experiments in Negative Triangularity (NT) show that the scaling of NT SOL heat flux widths (λ_q) is intermediate between L- and H-mode, with BOUT++ two-fluid turbulence non-linear simulations quantitatively reproducing λ_q values. Interpretive fluid modeling with kinetic neutrals (UEDGE, SOLPS-ITER), with cross-field drifts included, show that the high density required for dissipative NT divertors are due to the short divertor leg length and the reduction in λ_q in NT plasmas.

Plasma interacting technology: Instrumented sacrificial limiter structures enable first quantitative studies of runaway electron (RE) wall damage. Wall-impacting RE kinetic energy (K ≈4 MeV) and pitch angle striking the wall (θ≈0.4) are measured to be similar to those measured in the plasma, to within a factor of 2. Graphite damage transitions from negligible at RE heat fluences below 100 J/cm^2, to surface phase transition damage at ≈100 J/cm^2, then explosive dust formation at ≈1000 J/cm^2. These data are being used to provide first validation of PMI damage models to help minimize RE wall damage in ITER and FPP.

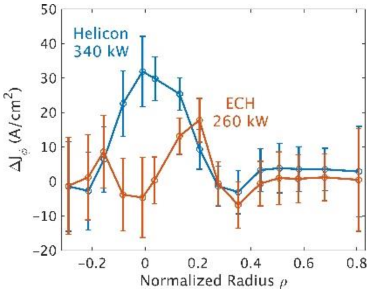

Figure 3. Current density measurements demonstrating helicon current drive in L-mode plasmas.

DIII-D is pioneering a novel current drive system, with recent experiments providing the first conclusive evidence of helicon wave heating and current drive on any device. Clear heating in the core of both L- and H-mode plasmas is seen in these discharges, consistent with GENRAY modeling predictions. Figure 3 shows changes in the current density profile, relative to reference cases without helicon injection. In shots with helicon power, reproducible increases in the current density are observed near the axis.

Significant boron (B) deposition is observed on the divertor and midplane collector probes following solid boron injection via an impurity powder dropper. Modeling attributes the toroidally relatively uniform B distribution on plasma-facing components post-injection to kinetic transport effects and recycling dynamics. To understand this behavior, a comprehensive, integrated modeling workflow has been employed, incorporating particle ablation, kinetic impurity transport, and mixed-material erosion and deposition dynamics. Understanding the distribution and longevity of B-rich surface layers in real-time wall conditioning provides a potential solution for ensuring machine safety and optimizing the fuel cycle.

Preparing for ITER operations: FPP-relevant pedestals with significant neoclassical T_i-screening are produced in a low-collisionality, grassy ELM hybrid scenario (q_{95}≈5.2, β_N≈2.6, H_{98}≈1.3), supporting the idea of dominant T_i screening in ITER pedestals. Neoclassical modeling indicates a T_i screening of the same magnitude as inward density pinch, resulting in a near-zero inward pedestal convection. Pedestal transport coefficients inferred from multi-ion Argon density measurement are in close agreement with the NEO model, as shown in Fig. 4. The unexpectedly high role of T_i screening in this DIII-D scenario is due to a nearly flat electron density pedestal ($n_{e,ped}/n_{e,sep}$≈2.2) and relatively high pedestal top T_i≈2.3 keV.

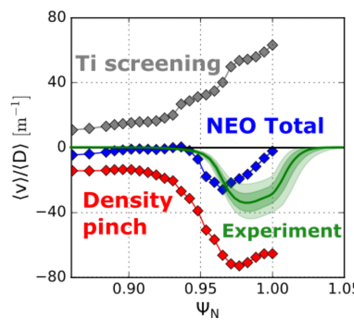

Figure 4. Neoclassical transport coefficients for Ar calculated in pedestal of grassy ELMs hybrid discharge.

Low-k turbulence can significantly decrease in response to Alfvén eigenmode (AE) activity in neutral-beam-heated discharges. Experimental data show local trapped electron mode turbulence is reduced by ≈50% in cases with a single toroidal AE; the ITG is completely suppressed in plasmas with multiple AEs sharing identical toroidal mode numbers. The full suppression of ITG persists for five energy confinement times and is accompanied by a transient improvement in plasma confinement, including a ≈30% increase in electron and ion temperatures at constant heating power.

A recent study in low density ohmic plasmas, a regime planned for ITER during its initial operating phase, provides the first time-dependent measurement of startup RE quantity and energy evolution in a tokamak. Maximum energy measured is >30 MeV, substantially larger than previously observed in other devices. REs with energy ≈0.5 MeV are detected immediately after the burn-through phase over a wide range of startup parameters, consistent with a recent hypothesis that startup REs of varying quantities emerge in all tokamak plasmas.

Disruption mitigation experiments show that adding small amounts of Ne to SPI results in an increased assimilation and consistent shutdown timeframes. Pure deuterium SPI results in erratic, almost unpredictable, increases in electron density and may or may not induce a thermal quench compared to slightly doped SPI. These experiments demonstrate essential features of ITER's proposed two-stage mitigation scheme.

Heating and current drive upgrades coupled with a new tungsten wall and a new innovative divertor geometry with upstream pumping are transforming DIII-D to close additional remaining gaps in the coming years.

This work was supported in part by the US Department of Energy under DE-FC02-04ER54698.