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DIII-D CONTRIBUTIONS TOWARD THE SCIENTIFIC BASIS FOR SUSTAINED BURNING PLASMAS

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GENERAL ATOMICS

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Recent DIII-D research has made significant contributions to development of a scientific basis for burning plasma operation in ITER and future devices. These include demonstration of increasingly reactor relevant operating scenarios at low rotation and $T_e \approx T_i$; improved understanding of key issues for projecting performance such as turbulence-driven transport, rotation, and the H-mode pedestal; development and characterization of methods for handling heat and particle efflux including transients [disruptions and edge localized modes (ELMs)], and assessment of specific issues related to the development of the ITER Research Plan (H/He operation, test blanket modules). These activities are supported by a vigorous research program that focuses on testing and validating physics based models that can then be used in predicting performance in ITER and future devices.

Scenario Development, Characterization, and Access. Extending previous demonstrations of four main ITER operating scenarios (baseline, steady-state, hybrid, advanced inductive), recent experiments have improved the fidelity of these simulations through operation at low rotation and $T_e \approx T_i$. In these conditions, confinement in the baseline scenario is reduced ~15%, but projections still imply Q=10 in ITER. These discharges also for the first time demonstrated preemptive neoclassical tearing mode suppression in this scenario. Transport analysis of joint DIII-D/JET ρ* experiments in the hybrid regime indicate energy confinement scaling close to Bohm-like ($B\tau_E \sim \rho^{*-2}$); 1-D transport studies are in progress.

Recent studies aimed at steady-state tokamak optimization have evaluated the optimum q profile for steady-state high performance. A scan of q_{min} and q_{95} at high noninductive fraction and β_N revealed that the temperature and density profiles broaden as q_{min} or β_N increase, so that the bootstrap fraction f_{BS} does not continue to increase when q_{min}>1.5. These results underscore the value of profile control flexibility for scenario optimization. Further profile evaluation and optimization are enabled by the planned addition of off-axis neutral beam injection and additional ECCD.

Access to advanced scenarios requires control over the early current profile, which has been achieved via feedback control of the ramp rate and geometry. CORSICA simulations reproduce many of the observations. A safe and controlled termination is equally crucial. Controlled variation of I_P and elongation during the rampdown have demonstrated reliable operation until I_P falls below 0.14 MA. ITER scenario discharges have been successfully produced in DIII-D with such optimized startup and shutdown phases (Fig. 1).

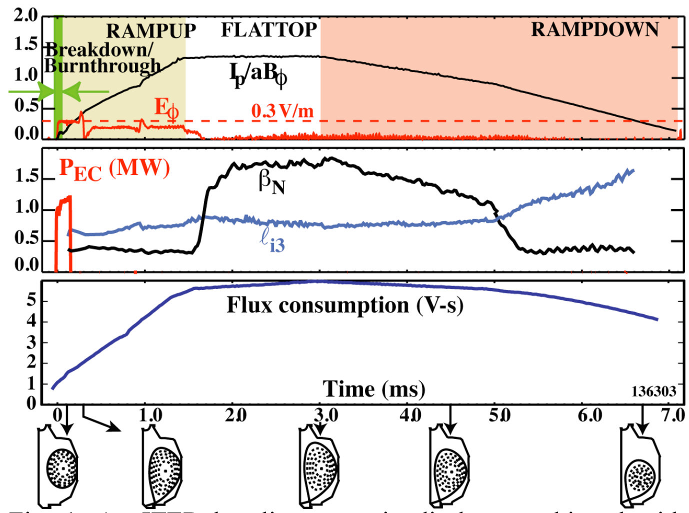

Fig. 1. An ITER baseline scenario discharge achieved with startup, rampup, and rampdown scenarios optimized for the restrictions anticipated in future devices.

Improved Physics Basis for Performance Projections. Exploiting flexible heating and current drive systems and a comprehensive diagnostic set, DIII-D research provides key tests of theory based models of plasma behavior. Transport studies utilize precise measurements of density $\tilde{n}_e$ (over a wide range of scale lengths) and temperature $\tilde{T}_e$ fluctuations while modulating the local temperature or its gradient with localized electron cyclotron heating (ECH). With ECH alternating between two closely spaced locations to modulate the turbulence drive term a/L_{Te}, low-k (long spatial scale) turbulence is observed to increase with a/L_{Te}. At high EC power, intermediate- and high-k turbulence can *decrease* with a/L_{Te}. In another study, $T_e(\rho)$ is varied in a pair of otherwise similar plasmas while the cross phase α_{nT} between $\tilde{n}_e$ and $\tilde{T}_e$ is measured. As predicted by theory, α_{nT} decreases with increasing T_e. Synthetic diagnostics for interpretation of GYRO have been developed and are being applied to such tests over a wide range of conditions.

DIII-D research is also working to clarify the physics of rotation. The measured edge intrinsic rotation is linearly proportional to the edge pressure gradient. Core intrinsic rotation does not scale similarly, but in many cases a momentum pinch brings rotation from the edge. DIII-D has verified theoretical predictions that static non-resonant magnetic fields (NRMF) can drag rotation toward a non-zero counter-I_P offset velocity. A predicted peak in the NRMF torque in the 1/ν collisionality regime has been confirmed in plasmas with low rotation (Fig. 2).

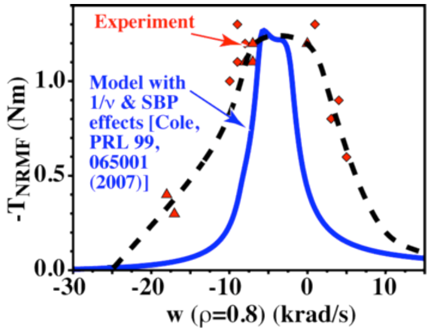

Fig. 2. Recent observations on DIII-D (red symbols) confirm the theoretically predicted (blue curve) large torque in the 1/ν regime, which can be accessed at moderate collisionality and low rotation.

Theory-based prediction of many features of the H-mode pedestal is at hand, but remains uncertain for pedestal width. Joint DIII-D/JET experiments indicate a weak, inverse dependence of the width on ρ*, a favorable result for ITER.

Heat & Particle Flux Control Methods. DIII-D pioneered resonant magnetic perturbations (RMP) as a tool to suppress ELMs with in-vessel coils. At ITER-like collisionality and shape, T_e (but not n_e) near the edge exhibits a strong q_{95} resonance similar to that seen for ELM suppression. In separate experiments, RMP ELM suppression has been combined with a radiative divertor. QH-mode operation has been extended to conditions with both toroidal rotation and neutral beam injected torque near 0 via the application of NRMF, indicating the possible applicability of this ELM-free scenario in future devices with low torque input. A planned new set of high-field side internal coils will provide further insight on the impact of 3D fields on ELM and rotation control.

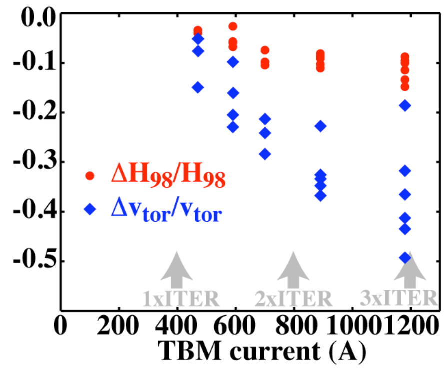

Fig. 3. Relative reductions of confinement factor H_{98} and toroidal velocity as a function of mock-up racetrack coil current. Each 400A is approximately equivalent to one ITER TBM pair as indicated. Below the ITER level, the mock-up's effect on confinement was too small to measure.

Operating at high performance benefits from closely approaching stability limits, advanced control techniques that curtail transients are expected to minimize the threat of disruption. Shutdown via rapid delivery of particles to the core is being developed as a last-resort measure. Studies indicate that particle assimilation is only effective during the thermal quench for massive gas injection (MGI). Shattered D_2 pellets have improved the delivery of neutrals to the plasma core during the thermal quench with record electron densities of 9×10^{21} m^{-3} locally. RMP fields applied during MGI have been shown to deconfine runaway electrons, potentially limiting the particle delivery requirements.

Carbon is an appealing plasma facing material due to its tolerance of heat loads. However, tritium retention in carbon is a serious issue. Particle balance measurements in DIII-D's carbon wall indicate that hydrogenic uptake is virtually eliminated during H-mode. Preparations are underway to test removal of hydrogen bearing codeposits using an oxygen bake.

Specific Issues for ITER Research Plan Development. Improved prediction of the L-H threshold power P_{LH} is needed to support early ITER experiments using H and/or He. Experiments in DIII-D indicate that P_{LH} increases from D to He (30%-50%) to H (×2 above D). The previously reported decrease in P_{LH} with rotation is observed in all three cases.

ITER will include 3 sets of toroidally localized test blanket modules (TBM), encased in ferromagnetic steel. Theory to predict their impact on performance is lacking, so DIII-D undertook to simulate the effect with a mockup of one TBM pair in which coils drive fields up to 3× the relative amplitude of those in ITER. Experiments were carried out to measure the TBM's impact on parameters including L-H threshold, confinement, rotation, and energetic particles. Preliminary analysis does not reveal any serious effects arising from TBMs in ITER (Fig. 3). Detailed analysis will aid in validating physics models for 3D field effects.

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