Overview of Recent Experimental Results from the DIII–D Advanced Tokamak Program* OV

S.L. Allen and the DIII–D Team

General Atomics, P.O. Box 85608, San Diego, California 92186-5608

The overall research goal of the DIII–D Advanced Tokamak (AT) experiments is to investigate and optimize the upper limits of energy confinement and MHD stability in a tokamak plasma and to simultaneously maximize the fraction of non-inductive current drive. We report recent progress towards this goal in four general areas; these combined results have allowed achievement of $\beta_N H_{ITER\text{-}89P}$ of 9 for over 16 energy confinement times, with 75% of the current driven non-inductively. 1) *Confinement* improvements have been made in H–mode plasmas and Internal Transport Barriers (ITBs) using new control tools, including counter neutral beam injection (NBI), localized electron cyclotron heating (ECH), high-field side pellet injection, and impurity puffing. New fluctuation measurements, including Beam Emission Spectroscopy (BES), continue to support theoretical models of temperature-gradient driven turbulent transport and stabilization of the turbulence by sheared E×B flow. 2) *MHD stability* experiments have demonstrated progress toward stabilization of Resistive Wall Modes (RWM) at high β_N using active feedback control. Experiments also indicate the threshold of neoclassical tearing modes (NTMs), including recently measured mode rotation, is consistent with a new ion polarization model. Experiments that varied the edge stability point to intermediate-n kink/ballooning modes as the likely cause of type 1 ELMs on DIII–D. 3) *Particle and power control* experiments with high-triangularity ($\delta > 0.6$) double null (DN) plasma shapes, new flexible divertor pumping, and both open and closed divertors have produced discharges with good energy confinement from low to high density ($0.3 < n_e/n_{GW} < 1.4$). 4) *Profile control* is carried out primarily with Electron Cyclotron Current Drive (ECCD), and multi-channel high resolution Motional Stark Effect (MSE) measurements of internal current profiles have verified highly localized ECCD, in agreement with theory. Computational modeling indicates that several new gyrotrons, currently being commissioned, will allow us to extend the duration of the high performance modes.

Counter NBI, localized ECH, impurity seeding and pellet injection have provided new techniques to both form and evaluate internal transport barriers. With counter NBI, a higher power threshold for the formation of an ITB (9 MW) and a larger radial extent is observed compared with co-NBI (2 MW). Both observations are consistent with sheared E×B stabilization of micro turbulence, and can be understood by evaluating the components of the shearing rate, $\omega_{E\times B}$. Near the transport barrier, the pressure gradient terms and the plasma rotation terms have opposing signs for co-rotation (co-NBI), and the ITB is limited in radial extent, often confined to the region of negative magnetic shear where the linear growth rate is reduced. For counter-NBI, the pressure gradient terms and the rotation terms are additive and the region where $\omega_{E\times B}$ exceeds the linear growth rate extends to larger radius. Using counter-injected ECCD in negative central shear discharges has resulted in very strong electron transport barriers. Central electron temperatures of > 6 keV were obtained with ~ 0.5 MW of ECCD power and a local reduction in electron transport below the ion neoclassical value was achieved. With neon impurity seeding, a factor of ~2 increase in confinement was observed, and both the increase in confinement and the measured decrease in density fluctuations vary proportionately to the level of impurity injection. ITBs were also obtained with an upgraded pellet injector (inside, top, and outside injection), and very strong localized density gradients and nearly equal ion and electron temperatures were measured. Reduced core transport was observed in the ion thermal, electron thermal, and particle transport channels. In both ITBs and edge transport barriers (H–mode) a reduction in the measured fluctuations accompanies the reduced transport. The reduced turbulence is attributed to both a calculated decrease in the linear growth rate and an increase in the sheared E×B flow leading to stabilization of the low-k turbulence that is characteristic of ITG modes. Two dimensional BES measurements clearly show the magnitude and the radial extent of turbulent eddies decrease significantly at the L–mode to H–mode transition.

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MHD stability experiments have focused on the understanding and active stabilization of RWMs (low toroidal mode number kink modes occurring above the ideal no-wall stability limit); RWMs limit the performance and duration of the DIII-D high performance long pulse discharges. The plasma toroidal rotation decreases as the no-wall beta limit is approached, and this decrease is associated with a RWM. In initial feedback experiments, the slowly growing RWM modes were reduced by a system consisting of six sensor loops located outside the vessel at the midplane and a six-element set of active control coils. Several different feedback schemes have been used to sustain β_N near the no-wall limit (~ 4 ℓ_i). A recently installed set of 24 pickup loops is expected to improve the effectiveness of the RWM control algorithm. We also carried out several experiments for the understanding of NTMs, including the scaling of the NTM threshold beta with collisionality, beta, measured (MSE) current profiles, and the role of island rotation. The NTM threshold, including recently measured island rotation, is consistent with the most recent ion polarization model. In edge stability experiments, the edge pressure profile was varied with impurity puffing and pellet injection, and the ballooning stability limits were varied with plasma shaping, including access to the second stable region. These results indicate that Type 1 ELMs are due to an intermediate-n kink/ballooning mode.

Power and particle control experiments have focused on density control with cryopumping for AT plasmas, plasma shape, impurity control, and radiative divertor operation. A new closed divertor with two cryopumps (RDP-2000) is used to obtain AT target plasmas at $n_{e(core)}/n_{GW}$ ~ 0.3. Plasma shape experiments (with variations from Lower- to Upper- Single-Null (LSN to USN), DN, and several triangularities $\delta < 0.8$) were used to determine the optimum plasma and divertor shape. With respect to up/down heat and particle sharing, magnetically unbalanced DN plasmas behave like SN plasmas except close to magnetic balance. The divertor heat flux profile can be explained by a simple flux mapping from the plasma midplane; the particle profile is broader due to local effects in the divertor. At modest densities $n_{e(core)}/n_{GW} < 0.7$, both core and pedestal performance increase with triangularity. Previously, we have demonstrated strong heat flux reduction with either deuterium puffing and pumping (P&P) or with P&P and impurity injection at $n_{e(core)}/n_{GW}$ ~ 0.5–0.9. Experiments are under way to extend this operating regime to lower core density, consistent with AT operation, using P&P and the added pumping in RDP-2000. We have also obtained high quality H–modes ($H_{ITER-89P}$ ~ 2) at high density ($n_{e(core)}/n_{GW}$ ~ 1.4) by gas puffing and cryopumping. This operation is also favorable because the energy loss of the Type-I ELM (which can induce a large divertor heat flux) is a factor of 5 lower than that predicted by a multi-device lower density scaling. The edge pedestal parameters n_e and T_e do not degrade in these high density discharges, and experiments are underway to determine the exact discharge requirements (e.g. pumping configuration) so that these favorable results can be duplicated in other devices.

In our high performance discharges ($\beta_N H_{ITER-89P}$ of 9 for over 16 energy confinement times) with 75% non-inductive current drive, the remaining inductive current is peaked at approximately the half radius. To increase the duration of these discharges to steady state, we will use ECCD to replace the inductive current at the half radius. A basic theoretical understanding of localized ECCD is necessary to predict the required ECH power for a particular AT scenario. Previous analysis of experiments showed that the EC-driven current was at the radius predicted by theory, but the profile inferred from magnetic reconstructions was broader than the calculated profile. However, recent direct calculations of the multi-channel MSE signals from ECCD theory are in agreement with the raw MSE data, indicating spatial averaging in the current reconstructions and validating the strong spatial localization feature of ECCD. We are currently commissioning several new gyrotrons that will be used in DIII–D experiments (total power ~ 3 MW), along with a steerable launcher for (intershot) variation of the resonance location. Computational models of AT scenarios indicate that by controlling the density with the new pumped divertor, ECCD at these power levels should provide localized current drive and increase the duration of the high performance phase of the discharge. ECH will also be used for heat pulse transport experiments, control of NTMs, and profile control for ITBs.