Advanced Tokamak Physics Experiments on DIII–D*

T.S. Taylor and the DIII–D Team, *General Atomics, P.O. Box 85608, San Diego, CA 92138-9784*

Significant reductions in the size and cost of a fusion power plant core can be realized if simultaneous improvements in the energy replacement time, τ_E, and the plasma pressure or beta $\beta_T = 2 \mu_0 < p > / B_T^2$ can be acheived in steady-state conditions with high self driven bootstrap current fraction. In addition, effective power exhaust and impurity and particle control is required. Significant progress has been made both in experimentally achieving regimes having the required performance in all of these aspects and in developing a theoretical understanding of the underlying physics. Recent DIII–D work has advanced the understanding of improved confinement and internal transport barriers in terms of $E\times B$ shear stabilization of micro turbulence. MHD stability has been improved through shape optimization, wall stabilization, and modification of the pressure and current density profiles. Heat flux reduction and improved impurity and particle control have been realized through edge/divertor radiation and understanding and utilization of forced scrape off layer flow and divertor baffling.

Three operational scenarios on DIII–D have demonstrated potential for steady-state high performance, the negative central magnetic shear (NCS) scenario, high internal inductance (high l_i), and radiative improved (RI–) mode. The NCS regime is characterized by an internal transport barrier (ITB) with reduce core transport in both the ion thermal transports and particle transport, and sometimes reduced electron thermal transport. In NCS discharges with an H–mode edge, ion thermal transport approaching the neoclassical prediction is obtained across the entire discharge, and $\beta_N \equiv \beta$ (I/aB) $\geq$ 4%-m-T/MA and $H \equiv \tau_E/\tau_{E\_ITER89P} = \geq 4$ have been simultaneously obtained for short duration.

A wide range of DIII–D data supports the hypothesis that a single physical mechanism, turbulence suppression via $E\times B$ shear flow is playing an essential, though not necessarily unique, role in reducing turbulence and creating a transport barrier in many improved confinement regimes in DIII–D, including NCS, high ℓ_i and RI–mode. In DIII–D the ITB is characterized by suppression of the measured core turbulence, strongly correlated spatially and temporally with the reduced ion transport. In agreement with theoretical predictions, the suppression of turbulence and reduced transport occur when the $E\times B$ shearing rate $\omega_{E\times B}$, exceeds the calculated maximum linear growth rate, γ_{MAX}, of the ion temperature gradient modes. However, electron thermal transport often remains high in discharges with ITBs. The $E\times B$ shearing rate is not sufficient to stabilize shorter wavelength ($k_\theta \gtrsim 10$ cm^{-1}) electron temperature gradient (ETG) modes. Consequently, we conclude these modes may be responsible for the observed electron transport and the increase in the transport observed with direct electron heating.

Stability calculations with wall stabilization, consistent with experimental results show that the stability limit, β_N, increases with increased plasma shaping and broader pressure profiles. Peaked pressure profiles obtained with L–mode NCS discharges are limited by internal resistive interchanges and internal kinks to $\beta_N \sim 2$: $\beta_N > 4$ is obtained with broader pressure profiles with an H–mode edge, and is often limited by edge kink modes. In ELMing H–mode discharges, the duration of high performance ($\beta_N \sim 4$, $H \sim 3$) has been extended to ~ 5 τ_E, and is limited by neoclassical tearing modes. The delay in the onset of the neoclassical tearing modes is a result of maintaining $q_0 \gtrsim 1$, eliminating the sawtooth induced seed islands which can trigger these metastable modes. Wall stabilization is required to realize high beta values in NCS discharges with broad pressure profiles. Theoretical predictions of passive stabilization with a resistive wall and plasma rotation are supported by recent DIII–D experiments where β values up to 1.4 times the no-wall ideal MHD limit have been reached. The no wall limit was exceeded for approximately 30 resistive wall times (200 ms). The mode terminating these discharges when the rotation has slowed showed the characteristics of the theoretically predicted resistive wall mode, with growth rates 2–8 ms and real frequencies, $\omega < \tau_w^{-1}$. Programmed (feed-forward) control of a reproducibly obtained resistive wall mode has stabilized the mode for 30 ms and is very promising for active feedback experiments planned.

To increase the duration of the NCS and other advanced tokamak discharges toward steady state, the DIII–D program is implementing a 110 GHz electron cyclotron current drive (ECCD) system with capability for both axial and off axis current drive. Up to 100 kA of central current has been driven by ECCD as determined from complete equilibrium equilibrium reconstruction using a 35 chord motional Stark effect system to measure the current density profile. Measurements of localized off-axis current drive exceed the predicted values: reduced effect of trapping of a collisional plasma is being explored to explain these results.

Significant reductions in peak heat flux to the divertor have been produced in detached recombining divertor plasmas. The low T_e values required for recombination have been measured and direct spectroscopic line radiation measurement clearly show the strong recombining zone. Near Mach-level flow, measured by probes and spectroscopy, are validated against 2-D computations from UEDGE. With strong gas puffing and pumping, the induced scrape of layer flow leads to increased enrichment of impurities (up to 17 for argon) in the divertor.

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