# RESULTS FROM THE DIII–D SCIENTIFIC RESEARCH PROGRAM*

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The DIII–D research program is aimed at developing a scientific basis both for advanced modes of operation that can enhance the commercial attractiveness of a fusion power plant, and for the inductively-driven ELMing H–mode on which the ITER design is based. Recent DIII–D work has advanced the understanding of internal transport barriers in terms of E×B shear, as well as the knowledge base and physics understanding of the H–mode edge barrier. MHD stability has been improved through wall stabilization and modification of the pressure and current density profiles. Electron cyclotron current drive, crucial for steady-state operation, has shown promising results in initial experiments. Finally, DIII-D's high and low triangularity pumped divertors have demonstrated effective density control and power handling in support of both conventional and advanced modes of operation.

Recent experiments in DIII–D have shown that E×B shear is crucial to the formation and sustainment of internal transport barriers (ITB). In DIII–D, the ITB is characterized by suppression of the measured core turbulence, strongly correlated spatially and temporally with reduction of ion transport. In agreement with theoretical predictions, suppression of turbulence and reduced transport occurs when the E×B shearing rate, $\omega_{E\times B}$, exceeds the calculated maximum linear growth rate, $\gamma_{max}$, of the ion temperature gradient modes. However, electron thermal transport often remains high in discharges with ITBs. The E×B shearing rate is not sufficient to stabilize shorter wavelength ($k_\theta \gtrsim 10\ \mathrm{cm}^{-1}$) electron temperature gradient (ETG) modes, and these modes may be responsible for the observed electron transport and the increase in the transport observed with direct central electron heating.

To further elucidate both the electron and ion transport, perturbative heating with ECH resonant off axis has been applied, and the resulting temperature response compared against the prediction of a number of transport models. None of the core models tested reproduce the magnitude and phase of both the electron and ion temperature perturbations, presenting a further challenge to transport theories.

In DIII–D, the confinement enhancement factor, H, is well correlated with the pressure at the top of the H–mode pedestal, in general agreement with gyrokinetic and gyrofluid transport models. This correlation highlights the importance of understanding the physics and scaling of the edge pedestal in projecting the performance of future tokamaks, such as ITER. In ELMing discharges, the edge pedestal width, $\delta_{PED}$, scales with the pedestal beta poloidal $\beta_p^{PED}$, $\delta_{PED}/R \propto \left(\beta_p^{PED}\right)^{1/2}$.

Modeling and experiments have shown several approaches to sustaining high performance ITB discharges through avoidance of MHD instabilities driven by large local pressure gradients. The edge pressure gradient has been controlled by discharge shaping, while peaking of the pressure profile can be reduced through expansion of the transport barrier. ELM-free discharges with neoclassical ion transport are limited in duration by low toroidal mode number ($1 \lesssim n \lesssim 5$) ideal MHD instabilities driven by the large edge pressure gradient. This instability and the subsequent large ELMs prevent the sustainment of a strong ITB. However, we have successfully produced ITB discharges with reduced edge pressure gradi-

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ents and reduced sized ELMs by generating plasma shapes (more squareness) in which the edge has no access to the second stable regime for ballooning modes. In L–mode edge discharges with negative central magnetic shear (NCS) and an ITB, modeling indicates that increasing the radius of the ITB and the radius of the minimum in the safety factor q, $\rho_{q_{min}}$, will give a broader pressure profile and a higher stability limit in strongly shaped discharges.

Wall stabilization as an approach to improving the attractiveness of advanced tokamak operational scenarios is supported by recent DIII–D experiments in which $\beta$ values up to 1.4 times the no-wall ideal MHD limit have been reached. The no-wall limit was exceeded for 200 ms, much longer than the resistive wall time $\tau_w$ ~ 3 ms. The mode terminating these discharges has the characteristics of the theoretically predicted resistive wall mode, with growth rates 2–8 ms and real frequencies, $\omega_{rot} \sim \tau_w^{-1}$. Stabilization of the resistive wall mode with external active feedback coils is planned.

In discharges with more conventional, monotonic q profiles, the long-pulse beta limit is often determined by the onset of neoclassical tearing modes. A significant increase in the beta limit has been found by keeping $q_0 > 1$ and eliminating sawtooth-induced seed islands, which can trigger these metastable modes.

DIII–D disruption experiments have focused on understanding and reducing the magnitude of halo currents, and understanding of runaway generation and its amelioration. Killer pellets reduce the vessel force from halo currents by a factor of at least 4, but sometime result in the production of runaway electrons. Externally imposed magnetic perturbations can lead to suppression of the runaways.

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 reconstruction using a 35 chord motional Stark effect system to measure the current density profile. The efficiency of the ECCD exhibits the expected temperature dependence and agrees with theoretical predictions. Measurements of off-axis current drive, needed for sustainment of NCS discharges and stabilization of neoclassical tearing modes, are now under way.

In support of current drive experiments, density control in the range of $0.3 < n_e/n_G < 0.7$, where $n_G$ is the Greenwald density, has been obtained with the recently installed higher triangularity upper divertor baffle and cryopump. The core impurity density in these discharges is primarily from carbon and remains approximately constant as the density is lowered; resulting in $Z_{eff} \sim 2$ at $n_e \sim 4 \times 10^{19}$ m$^{-3}$. Through the use of pellet fueling and divertor pumping, $n_e/n_G \sim 1.5$ has been achieved in other discharges.

Reductions in peak heat flux to the divertor, needed for ITER have been produced in detached recombining divertor plasmas. The low $T_e$ values (1–2 eV) required for recombination have been measured and direct spectroscopic line ratio measurements clearly show the strong recombining zone. Plasma flow in the lower DIII–D divertor region is measured by probes and spectroscopy, and generally indicate a flow away form the plate on field lines near the separatrix and a flow toward the plate on field lines further from the separatrix. These measured flows near the X-point validated against 2-D computations from UEDGE, illustrate the importance of local divertor geometry in entraining impurities to provide a radiative divertor solution consistent with AT operation. With strong gas puffing and pumping, increased enrichment of impurities are obtained in the divertor, enrichments up to 17 for argon, and up to 2.5 for neon.