Overview of Recent Experimental Results From the DIII-D Advanced Tokamak Program*

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Introduction The DIII–D research program is developing the scientific basis for advanced modes of operation in order to enhance the attractiveness of the tokamak as an energy producing system. This requires high power density (which demands high beta), high ignition margin (high energy confinement time), and steady state operation with low recirculating power (high bootstrap fraction), as well as adequate divertor heat removal, particle and impurity control. These requirements demand an integrated approach, optimizing the plasma from the core, through the edge and into the divertor. To utilize advanced tokamak physics in future devices, we are developing predictive understanding validated in integrated physics demonstrations.

AT Program In the 2001 campaign, advanced tokamak (AT) discharges with $q_{min} \geq 1.5$ and $\beta_N H_{ITER89P} \geq 10$ were sustained for 600 ms or about 4 τ_E. In terms of absolute parameters, these plasmas simultaneously achieve fusion power density β_T = 4.2%, fusion gain $\beta_T \tau_E$ = 0.66% s, $\beta_P \cong 2$, bootstrap current fraction $f_{BS} \cong 0.65$ and total non-inductive current fraction $f_{NI} \cong 0.85$. The shape of these discharges has been altered somewhat relative to those run in the 1999 campaign owing to the presence of the upper cryopump, which is employed to regulate plasma density, for example, for experiments on electron cyclotron current drive (ECCD) under AT conditions. The duration of the high performance phase of previous AT discharges was limited by resistive wall modes (RWM); however, improved error field correction in the present discharges allows rotational stabilization of the RWM. This stabilization has allowed up to a 50% increase in the achievable β_N in these shots. Duration of the high performance phase of the AT discharges is now limited by m=2/n=1 neoclassical tearing modes (NTM) which turn on when q_{min} approaches 1.5. Transport modelling based on transport coefficients determined from AT plasmas indicates that 3.5 MW ECCD should allow us to maintain q_{min} above this value for the duration of the ECCD pulse.

Resistive Wall Modes A key part of the AT program is increasing tokamak beta limits. Experiments on RWM stabilization have demonstrated operation at twice the calculated ideal MHD n=1 free boundary β_T limit utilizing rotational stabilization. With sustained rotation, β_T values have reached values predicted assuming a perfectly conducting wall at the location of the DIII–D wall. When rotation is small, the measured β_T limit is in excellent agreement with the calculated no-wall limit. Achieving rotational stabilization requires minimizing the drag on the plasma rotation caused by small toroidal asymmetries in the magnetic field coil sets. Theory suggests and the present experiments confirm that the RWM itself can amplify the effect of these asymmetries and increase the drag even when the rotation is rapid enough that the RWM is linearly stable. Reducing the initial asymmetry reduces the resonant plasma response; the enhanced rotation maintains the RWM linearly stable even as β_T approaches the "ideal wall" limit. Error field reduction utilized the new internal B_θ sensor loops to measure the increase in the resonant plasma response with increasing β_T and to provide a feedback signal to a set of correction coils which opposed the mode and nulled out the initial asymmetry. The same rotational stabilization effect was achieved when the correction coils were driven with preprogrammed waveforms which had the same average time history, demonstrating that the details of the feedback are not important in this case. In other cases where the plasma rotation was deliberately minimized, active feedback stabilization of the RWM has also been demonstrated.

Neoclassical Tearing Modes Experiments in the 2001 campaign have also demonstrated a 55% increase in β_T by complete stabilization of large m=3/n=2 NTMs in the presence of sawteeth by precisely located (to ± 1 cm) ECCD. Theory predicts that sufficient ECCD localized on the mode surface will suppress the NTM. Using 2.3 MW of ECH, the experiment shows the local peak EC current density needs to exceed about twice the local bootstrap current density for this suppression to take place. The amount of current required represents only 2% of the plasma current contained within the q=3/2 surface. The DIII–D

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plasma control system was modified to do a real-time search and suppress of the NTM by either shifting the plasma or changing the toroidal field to position the ECCD precisely on the mode. The system used the dB_θ/dt signals from one of the Mirnov loops to determine the effect of the ECCD on the mode. This represents the first use of active feedback control to position the ECCD. After NTM suppression, the increase in β_T was limited by Shafarnov shift-induced motion and the q=3/2 surface away from the ECCD location. We are developing techniques to apply the ECCH at the proper location prior to the mode onset so that the NTM will never occur; these should also allow continuous mode suppression by tracking the q=3/2 surface as β_T increases.

Current Drive Motivated by the importance of ECCD in the AT program, we have carried out an extensive program to verify ECCD theory. We find excellent agreement between experiment and calculations carried out with the CQL-3D Fokker-Planck code. These tests have been done over a wide range of plasma conditions, including AT plasmas at performance levels somewhat below those discussed earlier. A key part of theory is the effect of trapped particles and electron beta on the current drive efficiency. The measured efficiency of the off-axis current drive needed for the AT scenarios increases substantially with electron beta, in agreement with theory.

Confinement Physics The recently discovered quiescent H–mode (QH) and quiescent double barrier (QDB) discharges have provided a new operating regime; QDB discharges have both a core transport barrier and an H–mode edge barrier. They exhibit near steady performance (β_N $H_{ITER89P}$ ~ 7 for 10 τ_E) in a plasma with no ELMs, constant density and constant radiated power. For AT physics, they provide a clear demonstration of steady-state core barrier operation; the central barrier persists for over 3.5 s or 25 τ_E, limited only by neutral beam pulse length. The core barrier exhibits low ion thermal transport, comparable to ion neoclassical; however, reflectometry and FIR scattering measurements show incomplete suppression of microturbulence. This microturbulence exhibits short (~ 1 cm) radial correlation lengths, which are factors of 2 to 4 below the L–mode values, consistent with the reduced thermal transport. Gyrokinetic simulations with the UCAN code show similar reductions in radial correlation length. GLF23 simulations show good agreement between measured and calculated ion temperature profiles; the calculated E×B shearing rates and turbulence growth rates from GLF23 are nearly equal, consistent with the measurements showing reduced but not completely suppressed turbulence.

Edge Pedestal Stability and transport of the H–mode edge can significantly affect overall AT performance; the pedestal parameters set the boundary conditions for core transport while ELMs affect both core stability and divertor heat loads. To predict the pedestal parameters, we need to understand what sets the edge gradients and the widths of the steep gradient region. The width of the edge density barrier W_{ne} is consistent with a simplified model which couples the edge neutral and plasma transport; this model includes the effects of both atomic and plasma physics. We have developed a model of ELM stability which includes both current driven (peeling) modes and pressure driven (ballooning) modes. This model can explain both the large Type I ELMs as well as the smaller Type III ELMs. Further validation of this model requires high resolution measurements of the edge current density; we are developing a Zeeman polarimetry system based on lithium beam injection to make this measurement. The quiescent H–mode has given us a new view of the H–mode edge because these shots demonstrate that ELMs are not a necessary feature of a high quality, steady-state H–mode edge. An edge electromagnetic mode, the edge harmonic oscillation, provides adequate edge particle transport to maintain constant core density without significantly degrading edge thermal transport. In addition, because of the relatively high frequency (6 to 12 kHz) of the fundamental of the EHO, pulsed heat load to the divertor is eliminated.

Divertor Physics Divertor transport determines the conditions at the base of the H–mode pedestal as well as determining the partition of heat and particle outflux between the divertor plates and the vessel wall. Consistent with earlier work on Alcator C-MOD, recent detailed observations on DIII–D have shown that intermittent transport events provide about 50% of the $E\times B_T$ radial transport in the scrape off layer. These events occur on and outside the separatrix and have qualitatively similar character in both L–mode and H–mode, although the H–mode amplitudes are significantly lower. The measurements are compatible with the concept of plasma filaments propagating across the scrape off layer due to E×B drift which gradually dissipate owing to reduction of the localized E_θ via parallel current flow.