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DIII-D OVERVIEW – RESEARCH TOWARD RESOLVING KEY ISSUES FOR ITER AND STEADY-STATE TOKAMAKS

by

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DIII-D Overview: Research Toward Resolving Key Issues for ITER and Steady-State Tokamaks

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The DIII-D Research Program has made significant advances in the physics understanding of key ITER issues and the development and characterization of operating regimes important for ITER and future steady-state fusion tokamaks. New results include a significantly improved physics basis for edge localized mode (ELM) control and runaway control and mitigation (Fig. 1), evaluation of operating scenarios at ITER-like neutral beam injection (NBI) torque (Fig. 2), and utilization of off-axis NBI to expand the available operating envelope of advanced tokamak scenarios (Fig. 3). These results are both motivated and supported by a strong emphasis on developing validated physics-based models for use in operating and predicting performance in ITER and future devices.

Developing the Physics Basis for Controlling ELMs and Disruptions is important for obtaining reliable operation of ITER, and experiments in DIII-D have made significant progress in both areas. ELM suppression with resonant magnetic perturbations (RMP) has been demonstrated in the ITER baseline scenario with q_{95}=3.1 at the ITER pedestal collisionality utilizing an n=3 RMP produced by a single row of internal coils. ELM suppression has also been achieved with n=2 RMPs. More importantly, improved physics understanding is emerging: Temporal modulation of the n=2 and n=3 RMP toroidal phase reveals a complex plasma response that includes a kink-like helical displacement at the edge combined with an island-like modulation in T_e and a reduction in the density gradient near the 10/3 rational surface. The data are consistent with recent theory that predicts such island formation can inhibit the pedestal expansion to below the peeling-ballooning stability limit.

Potentially attractive alternatives to RMP ELM control exist for ITER, and DIII-D experiments have focused on two of the leading candidates. Long-duration ELM-free QH-mode discharges were produced with co-current neutral beam injection (NBI) (providing 3-4 times the scaled torque from ITER beams) by using n=3 coils to generate sufficient counter-I_p torque via neoclassical toroidal viscosity to obtain high velocity shear in the pedestal region; in this regime, global energy confinement improves with decreasing rotation. Pellet pacing experiments have utilized new 60 Hz pellet launch capability with injection geometry similar to that planned for ITER to produce a ten-fold increase in the ELM frequency and approximately a factor of 10 reduction in ELM divertor energy deposition.

Routine generation of high-energy runaway electron (RE) beams has been achieved in disruptions triggered by Ar pellet injection, making possible reproducible experiments to study RE generation (Fig. 1) and safely develop techniques for controlling and dissipating beams that reach currents as large as 300 kA with 300 ms lifetimes. Measured RE dissipation rates under these conditions are much faster than expected from electron-electron collisional drag, suggesting that other effects may be important.

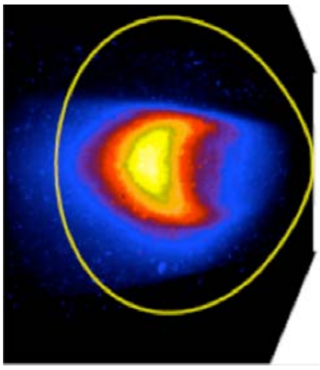

Fig. 1. Image of runaway electron synchrotron emission during runaway plateau.

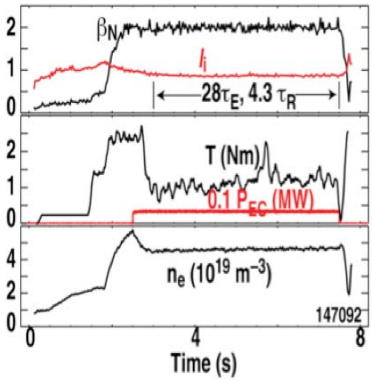

Fig. 2. A stationary ITER baseline scenario discharge with ITER-scaled torque and ECCD for NTM control.

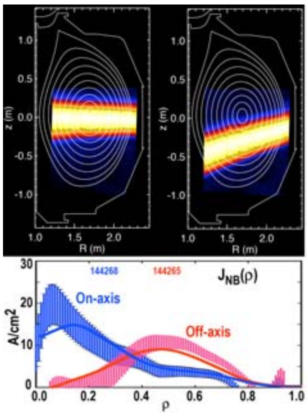

Fig. 3. Off axis NBI deposition and resulting current profiles.

Evaluating Planned ITER Operating Scenarios provides an important test of the underlying physics, informs design choices during construction, and guides operational planning. Recent ITER baseline scenario experiments with β_N=2 and scaled ITER-equivalent NBI torque have revealed the importance of broad electron cyclotron heating (ECH) deposition near the q=3/2 surface to avoid tearing modes. With ECH, ITER baseline discharges at β_N=2 and scaled NBI torque have been maintained in stationary conditions for more than 4 resistive times (Fig. 2). Separate experiments have shown the ability to achieve β_N~3, H_{98}~1 ITER Q=10 equivalent fusion gain with ITER-like NBI torque applied for the entirety of the discharge evolution.

Performance predictions for ITER rely on predictive understanding of transport across the entire profile from the core to the edge. Profile stiffness experiments in DIII-D for the ion and electron channels show that core T_e and T_i profile shapes vary weakly with a 3x increase in NBI power, in agreement with TGLF simulations that predict comparable core stiffness for ITER. Off-axis NBI and new diagnostics have provided valuable data for comparison with numerical simulation to improve understanding of how field errors, instabilities, and microturbulence affect fast-ion transport. Related research sought to test theoretical models of the edge pedestal, finding that the EPED model predictions for pedestal height agreed with data from C-Mod and DIII-D; additional measurements show the evolution of pedestal gradient to be consistent with expectations based on kinetic ballooning modes.

Seed islands from sawteeth and ELMs can trigger disruptive tearing modes if large enough. Experiments using electron cyclotron current drive (ECCD) to increase the magnetic shear near the q=1 surface have demonstrated control of the fast-ion stabilized sawtooth size, allowing operation without large 2/1 tearing modes. In a related experiment, internal magnetic coils were used to align the O-point of a locked neoclassical tearing mode (NTM) with ECCD deposition to stabilize the mode and avoid disruption.

Error field correction (EFC) experiments utilizing large proxy error fields from external coils and the test blanket module (TBM) mockup coil indicate that simple EFC leaves strong residual error field effects, suggesting that optimal EFC may require multiple poloidal harmonics. TBM experiments utilizing improved n=1 EFC recover only ~50% of the rotation reduction previously observed with uncompensated n=1 error fields due to the TBM.

Divertor heat flux profile measurements have revealed an inverse relationship to plasma current with little dependence on toroidal field, plasma current, and heating power. Looking forward to very high power density tokamaks such as FNSF or DEMO, preliminary experiments varied the divertor geometry (strike point radius, connection length, and poloidal flux expansion) to compare against a range of scrape-off layer model predictions.

Off-axis NBI (OANBI) for Advanced Tokamak Research has been enabled by the successful modification of a neutral beam line, providing 5 MW of adjustable OANBI out of 20 MW total NBI power (Fig. 3). Initial experiments verified that the deposition profile, fast ion lifetime, and current drive capability (including dependence on magnetic field direction) agrees with theory. Subsequent experiments utilized this capability to sustain β_N~3 operation with minimum safety factors q_{min} well above 2 accompanied by broader current and pressure profiles than previously obtainable. With q_{min} above 1.5, stationary discharges with β_N=3.5 have been extended to $2\tau_R$, limited by available beam energy (power and pulse length).

The ability to vary the fast-ion pressure population using OANBI has been utilized to explore Alfvèn eigenmode (AE) and resistive wall mode (RWM) stability. Reversed shear AEs localized near the mid-radius are observed to be stable/unstable with OANBI/on-axis NBI while far off-axis TAEs are unaffected, consistent with changes in the fast ion pressure gradient. RWM stability is improved by off-axis NBI, contrary to expectations.

Progress in the study of advanced regimes with dominant electron heating continues with installation of a new 1.2 MW long-pulse gyrotron and an additional real-time steerable launcher. The fast wave heating system has coupled 2.4 MW to advanced inductive discharges, showing low edge losses and core electron heating comparable to ECH, providing a significant increase in electron heating power. Modifications of the existing neutral beam sources is underway to allow much longer pulse length by reducing heating of ancillary components. Future plans for AT and burning plasma scenario research include additional ECH power and realignment of a second beamline for off-axis NBI.

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