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DIII-D RESEARCH IN SUPPORT OF ITER

by
E.J. STRAIT and the DIII-D TEAM

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DIII-D research is providing key information for the design and operation of ITER. Recent results have led to improved understanding of several critical issues, including control of instabilities, plasma rotation effects, mitigation of disruptions, and plasma-wall interactions. In addition, DIII-D experiments that simulate the various ITER operating scenarios (e.g., Fig. 1) provide a platform for projections of fusion performance and tests of plasma control.

DIII-D research has made significant progress in understanding the physics of instabilities that may occur in ITER, and in developing strategies to control them. The suppression of edge localized mode (ELM) instabilities by resonant magnetic perturbations, pioneered at DIII-D, offers a promising method to reduce the erosion of ITER's divertor targets. Recent experiments and modeling have provided key information for the assessment of coil options in ITER, including the dependence of ELM suppression on magnetic island overlap at the plasma edge (Fig. 2). Work is in progress to determine the physical mechanism for particle transport that leads to ELM stabilization, including a possible role of E×B convection cells.

Studies with balanced neutral beam injection show that the beta threshold for onset of neoclassical tearing modes (NTMs) decreases as the plasma rotation is reduced to ITER-relevant values, perhaps due to reduced rotational shear. Recent experiments confirm that the electron cyclotron current drive (ECCD) power requirement for NTM stabilization is reduced by synchronous modulation. ECCD is also found to suppress core-localized Alfvén eigenmodes and to reduce the accompanying loss of fast ions.

In high beta plasmas at or above the ideal MHD free-boundary stability limit, such as ITER's Q=5 steady-state scenario, resistive wall modes are stabilized by relatively slow plasma rotation, consistent with theoretical predictions that include kinetic effects. However, rotationally stabilized plasmas are exceedingly sensitive to error fields and to excitation of resistive wall modes by ELMs and other transient events. DIII-D experiments have demonstrated active feedback control both to suppress these transients and to optimize the error field correction. Separate experiments show that even in low beta plasmas, optimum correction of the field errors must take account of their coupling to stable kink modes, not just the vacuum fields.

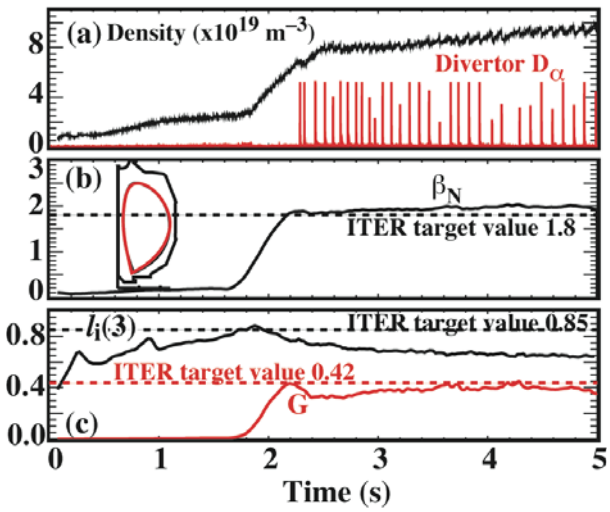

Fig. 1. ITER baseline scenario demonstration discharge at q_{95}≈3 ITER target values are indicated by dashed lines. Inset compares ITER (black) and DIII-D (red) plasma shapes. $G=\beta_N H_{89}/q_{95}^2$.

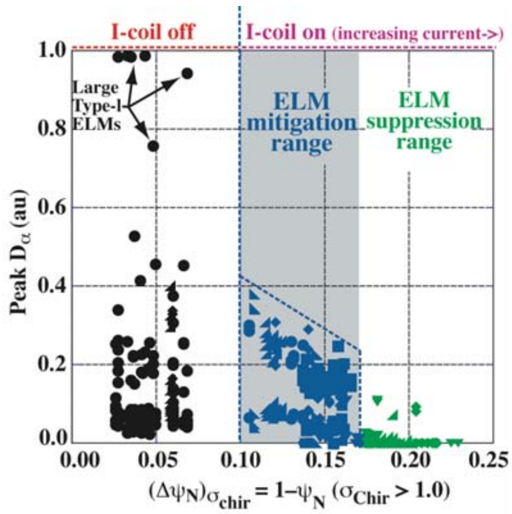

Fig. 2. ELM size vs width of the edge region with island overlap (Chirikov parameter >1). ELMs are strongly reduced when the width exceeds 0.1 in normalized flux, and eliminated as the width exceeds about 0.16.

Disruption mitigation experiments using a new multi-valve system have shown the importance of delivering the gas to the plasma before the thermal quench ends, in order to achieve the high densities needed for suppression of a runaway electron avalanche in ITER. This condition favors light gas species, high throughput, and delivery systems close to the plasma. Experiments and 3D nonlinear modeling show that MHD instabilities are important in mixing the impurity gas into the plasma core.

To ensure reliable operation of high performance plasmas in ITER, control of the internal characteristics of the plasma is being developed in DIII-D using a range of actuators including electron cyclotron heating and current drive, fast wave heating and current drive, and co/counter-injected neutral beams. Recent results include simultaneous feedback control of plasma beta and rotation by independent control of neutral beam power and torque, and feedback control of the minimum safety factor q_{min}.

Using these tools, a more detailed scientific basis for extrapolating key performance measures to ITER is now being developed. The hybrid scenario has been successfully extended to low, ITER-relevant rotation using balanced neutral beam injection. Energy confinement is somewhat reduced at low rotation, but is still consistent with Q=10 operation in ITER. A reduction in confinement, accompanied by a measurable increase in short wavelength turbulence, is also seen as the ratio T_e/T_i is raised toward unity. However, the power threshold for the L-H transition decreases at low rotation, perhaps because of greater poloidal velocity shear — a favorable result for ITER. Experiments will investigate confinement and L-H transition in hydrogen plasmas, the working gas for ITER's startup phase.

DIII-D research is developing approaches to the control of plasma-wall interactions in ITER. Experiments show that co-deposition of carbon and deuterium is reduced on heated surfaces, suggesting a possible means to reduce fuel retention. Laboratory tests have shown that thermal oxidation is effective at removing carbon co-deposits, and additional development is in progress with the goal of an in situ test. Divertor heat flux has been reduced in "hybrid scenario" discharges by radiation from injected argon with little impact on core plasma performance, and resonant magnetic perturbations are found to allow spreading of the divertor heat flux.

Ultimately, DIII-D research is aimed at development of ITER-relevant operating scenarios that integrate high fusion performance, stable operation, and appropriate boundary conditions. Ongoing research will demonstrate integrated scenarios for several possible operating regimes for ITER. Conventional H-mode, advanced inductive, hybrid, and steady state regimes have been developed that achieve the normalized performance goals of ITER with the ITER shape and aspect ratio (as in Fig. 1). A large-bore startup scenario was demonstrated in an ITER-like shape, using feedback control of the internal inductance l_i to maintain good vertical stability during the plasma current ramp, and ongoing experiments are assessing the limits of vertical stability control in ITER-like plasmas. In the baseline scenario demonstration of Fig. 1, the internal inductance $l_i(3)$ is outside ITER's nominal control range; implications for shape control and improvements to the scenario will be investigated. Recent hybrid scenario discharges have begun to integrate core and edge performance, combining moderately high-normalized beta (β_N~2.5) with ELM suppression by resonant magnetic perturbations. Other discharges with almost full (>90%) noninductive current drive and high beta (β_N~3.5) have maintained stationary conditions for 2.5 s, limited only by the neutral beam pulse length (Fig. 3). In the longer term, very high-normalized beta will be explored for the benefit of advanced tokamak devices beyond ITER.

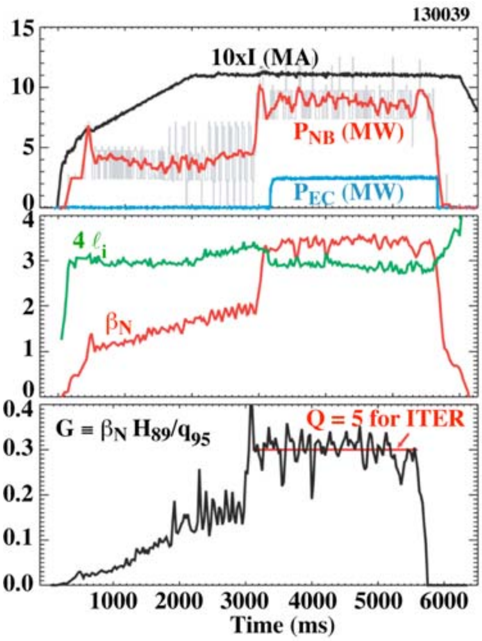

Fig. 3. Stationary performance consistent with Q=5 in ITER, with wall stabilization and nearly full noninductive current drive.

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