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EXPANDING THE PHYSICS BASIS OF THE BASELINE Q=10 SCENRAIO TOWARD ITER CONDITIONS

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Expanding the Physics Basis of the Baseline Q=10 Scenario Toward ITER Conditions PPC

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Much of the physics basis for ITER baseline scenario operation has been obtained in plasmas with significant fueling and applied torque from neutral beam injection (NBI). DIII-D has unique capabilities to extend this physics basis toward ITER conditions by applying neutral beam injection (NBI) with combinations of co- and counter-injection to reduce torque input, applying electron cyclotron heating (ECH) to reduce fueling and torque and to equilibrate the electron and ion temperatures, and exploring the effects of steady-state and transient divertor heat flux reduction with radiative divertor operation. All of these tools have been applied to plasmas with a boundary shape close to that of ITER to minimize systematic effects in projection of the results to ITER.

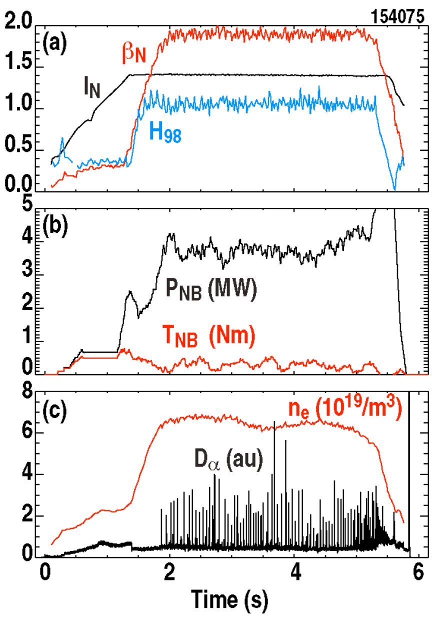

Fig. 1. Time histories of (a) normalized pressure (β_N), current (I_N), confinement (H_{98}), (b) neutral beam power (P_{NB}), torque (T_{NB}), (c) line-averaged density (n_e), and divertor (D_α) light for an ITER baseline scenario demonstration plasma with low applied torque.

Sustained operation with normalized parameters sufficient for Q=10 operation in ITER (β_N=1.9, H_{98}=1.05, I_N=1.41) has been achieved with nearly zero external torque input from NBI (T_{NB}=0.3 Nm) for more than four resistive relaxation times ($4\tau_R$) as shown in Fig. 1. Similar conditions with $P_{EC}>P_{NB}$ and T_{NB}=0.5 Nm have been sustained for $>3\tau_R$. Confinement at low torque is reduced relative to the standard co-NBI (Fig. 2), but there is sufficient confinement margin in DIII-D so that the reduction brings the plasmas to $H_{98}\sim1$. Application of ECH does not reduce the confinement quality of the plasmas relative to those with NBI only as long as plasmas at the same applied torque are compared. DIII-D plasmas at low q_{95} often have a modest amplitude n=2 tearing mode, which also contributes to the transport.

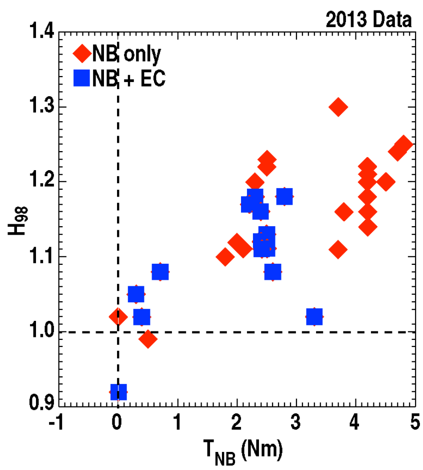

Fig. 2. Normalized confinement (H_{98}) vs applied torque (T_{NB}) for ITER baseline scenario demonstration plasmas.

These results are very positive for ITER; however, operation with near-zero external torque input has proven to be quite challenging in DIII-D. The principal obstacle to sustained operation at low q_{95} is the onset of tearing modes. With co-NBI, the operational boundary is almost always determined by n=1 modes. At reduced or near-zero torque, a greater variety of modes are observed. Many plasmas exhibit instability to the n=1 tearing mode as in the co-NBI plasmas, but at low torque the mode more readily slows the plasma rotation to zero in the lab frame, leading quickly to a disruption. There are also many cases where the n=2 mode grows large enough to slow the plasma rotation to zero. More rarely, the plasma rotation seems to be affected in the absence of a rotating tearing mode precursor. A clear understanding of the phenomenology is not yet in hand, but the leading hypotheses are sensitivity to uncorrected error fields in DIII-D or evolution of the plasma current density to a classically tearing unstable state. Both of these causes would have implications for ITER, either in the design specifications for error field tolerance and correction or in seeking alternative scenarios at higher q_{95} for Q=10 operation where operation at low applied torque appears to be easier.

Radiative divertor operation with neon is successful at reducing both the steady-state and ELM-transient heat flux to the divertor at constant β_N=1.9 under feedback control by NBI. A strong D_2 flow yields reduction in steady-state and transient heat fluxes to the divertor by more than a factor of 2 (Fig. 3). The reduction in the heat flux from the ELMs may be connected with the strong increase in ELM frequency with increasing D_2 flow. Neon is introduced into the private flux region, resulting in further reduction in the heat flux to both the inner and outer divertor. Isolation of the neon to the divertor is achieved in concert with the substantial flow of D_2, with the core neon density actually reduced with increased D_2 flow, even at reduced torque. Use of pellet injection (up to 60 Hz) in place of the gas flow yielded results similar to an equivalent continuous gas flow. The radiation from neon comes predominantly from outside the plasma, consistent with the low core neon density measurements mentioned earlier.

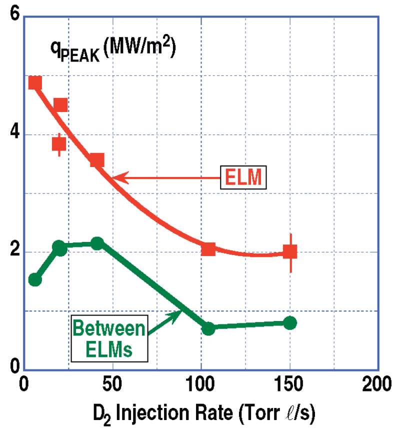

Fig. 3. Peak steady-state (green) and transient (red) heat flux on the outer divertor vs deuterium flow rate for ITER baseline scenario demonstration plasmas.

Experiments without auxiliary heating in DIII-D showed that the optimum current rise for minimizing flux usage is the fastest possible rise while maintaining MHD stability. Optimization of the current rise phase of ITER is important to preserve sufficient flux to satisfy the duration requirement of the first ITER physics objective (>300 s operation). Projection of the DIII-D results to ITER show that the limitations of the ITER poloidal field coil set at low l_i may shift the optimum in ITER to a high l_i startup because more flux is accessible from the poloidal field coil set.

These results obtained recently in DIII-D provide critical information for ITER baseline scenario operation. The existence of stationary plasmas at nearly zero applied torque in DIII-D with sufficient normalized pressure and confinement for Q=10 in ITER at 15 MA is a key validation of the baseline scenario. Radiative divertor operation is successful in DIII-D at low q_{95} and reduced torque without enhanced accumulation of the seed impurity used for radiation. The studies of the flux usage indicate sufficient flux should be available in ITER to meet the >300 s operational requirement. However, the operational difficulties encountered with tearing mode stability at low applied torque suggest that a more diverse set of plasmas should be considered for the Q=10 mission, due to the sensitivity of ITER to disruptions.

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