Development, Physics Basis, and Performance Projections for Hybrid Scenario Operation in ITER on DIII-D*

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M.R. Wade,[1] T.C. Luce,[2] R.J. Jayakumar,[3] P.A. Politzer,[2] C.C. Petty,[2] M. Murakami,[1] J.R. Ferron,[2] A.W. Hyatt,[2] and A.C.C. Sips[4]

[1]Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
email: wade@fusion.gat.com
[2]General Atomics, San Diego, California 92186, USA.
[3]Lawrence Livermore National Laboratory, Livermore, California, USA.
[4]IPP-Garching, Garching, Germany.

Experiments in the DIII-D tokamak have demonstrated the ability to sustain ELMing H-mode discharges with high β and good confinement quality under stationary conditions ($\tau_{dur} > 35\tau_E \sim 3\tau_R$). In recent experiments, the range in q_{95} over which this performance could be maintained has been expanded with only small reductions in the sustainable β_N and H_{89P} [Fig. 1(a,b)]. The normalized fusion performance (in terms of $\beta_N H_{89P}/q_{95}^2$) could be maintained at or above the value projected for $Q_{fus} = 10$ in the International Thermonuclear Experimental Reactor (ITER) design [Fig, 1(c)] within the range 3.2 < q_{95} < 4.6. These discharges are stationary on the thermal, resistive, and wall equilibration time scales and involve feedback control only of global quantities. Projections based on these discharges using the standard ITER H-mode scaling laws ndicate that $Q_{fus} = 5$ can be maintained for >1.5 hours in ITER at q_{95} = 4.5, and $Q_{fus} = 40$ for ~2400 s at q_{95} = 3.2. These projected performance levels further validate the ITER design and suggest long-pulse, high neutron fluence operation as well as very high fusion gain operation may be possible in ITER.

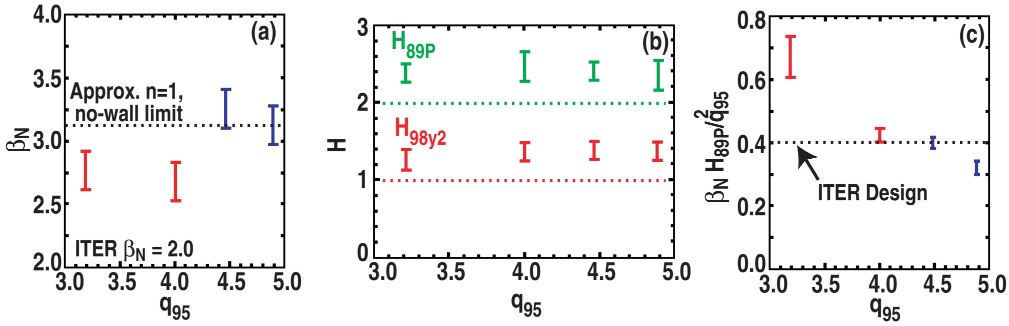

Fig. 1.Variation of (a) β_N, H_{89P} and H_{98y2}, and (c) $\beta_N H/q_{95}^2$ with q_{95}.

Discovered in 2000 [1], this operating regime has been named the "hybrid scenario" by working groups of the International Tokamak Physics Activity (ITPA). In this regime, the current profile is fully penetrated, leading to $q_0 \sim 1$ and bootstrap current fractions of 35%-50%. By contrast, steady-state Advanced Tokamak (AT) regimes on DIII-D are aimed at 100% noninductive current drive with >60% bootstrap current fraction. Akin to the conventional H-mode in many respects, the primary operational element that differentiates this regime is the establishment of high β plasma with low magnetic shear in the core region prior to the onset of sawteeth. The resulting broad current profile has been found empirically to be less susceptible to m=2/n=1 neoclassical tearing modes (allowing higher β operation), and theoretically to have favorable turbulence growth rate characteristics (allowing better confinement). The combination of high β and good confinement quality allows operation at high values of $\beta_N H_{89P}/q_{95}^2$ even with q_{95} = 50% above the ITER baseline design. The reduction in the required plasma current while achieving the same normalized performance would have several beneficial effects in ITER including a significant increase in pulse length, increased spreading of the ELM energy loss, and reduced risk to the device from disruptions.

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Recent studies expanded the operating space over which this regime could be obtained [2]. There are two distinct classes of discharges — $q_{95} < 4$ discharges with sawteeth and $q_{95} > 4$ without sawteeth. As shown in Fig. 1, the performance in terms of β_N and H_{89P} are only moderately affected by the changes in q_{95}. The sustainable β_N is found to be slightly lower in the $q_{95} < 4$, sawtoothing discharges than in the $q_{95} > 4$ cases, but in all cases, is within 10% of the free boundary, n=1 stability limit. Confinement is found to be better than typical H-mode confinement across the entire range of q_{95}.

While this regime shares many characteristics with the conventional H-mode regime, there are some striking differences. The first (and probably the most important) is observed m=1/n=1 behavior. In the conventional H-mode case, sawteeth are ubiquitous, dominate the physics inside the sawtooth inversion radius, and can have deleterious effects on overall plasma performance (e.g., triggering of NTMs). In contrast, sawteeth are either absent or very small in the hybrid regime and play little role in either the transport/stability physics or the overall performance. The lack of sawteeth in the hybrid regime is attributed to two effects. First, the establishment of high β before the onset of sawteeth allows the development of a significant off-axis bootstrap current density, which has the effect of reducing the peaking of the current density profile $J(\rho)$. Second, coincident with the increase in β above a certain threshold, an $n > 1$ (usually m=3/n=2) tearing mode is triggered. Detailed studies of the poloidal flux evolution have shown the existence of a small voltage source (~10 mV) near the q = 1.5 surface. While the exact mechanism for this voltage source is still unknown, its proximity to the q=1.5 surface suggests that the tearing mode is acting as a source of poloidal flux (i.e., as a voltage source). This leads to a broadening of the current density profile and provides a mechanism for $J(\rho)$ to be stationary with $q_0 \gtrsim 1$.

Confinement in this regime is better than the standard H-mode scaling law predictions over a wide range in operation [Fig, 1(b)]. These elevated values of H_{89P} and H_{98y2} are not due to the strong unfavorable beta degradation contained in these confinement scaling relations, a degradation that β scaling experiments in DIII-D and JET failed to reproduce, since the confinement in these discharges is markedly better than the prediction of electrostatic scaling relations [3] as well. Studies using the GLF23 code indicate that low magnetic shear in the core region leads to reduced turbulent growth rates in this region. While the E×B shear and $T_i > T_e$ have a beneficial effect in reducing the turbulent growth rates, the linear growth rates are calculated to be lower than a similar discharge with higher magnetic shear in the core region.

Performance projections based on these discharges are very favorable for ITER (Table 1). Depending on the confinement scaling used, these projections range from Q_{fus} = 3−20 at q_{95} = 4.4 and Q_{fus} = 12−∞ at q_{95} = 3.2. For the standard ITER H-mode scaling, the projection indicates that 530 MW of fusion power could be generated for pulses in excess of 1.5 hours, at q_{95} = 4.4 while ≥700 MW could be realized for >30 minutes at q_{95} = 3.2. Using the pure gyroBohm scaling, ignition is obtained in the q_{95} = 3.2 case even with a 25% reduction from the measured confinement multiplier that is required for energy balance.

Data obtained in 2004 will contribute significantly to the developing physics basis with particular emphasis placed on expansion of the regime to high density and lower T_e/T_i; identifying the phenomena responsible for the stationary current profiles without sawteeth; and long-pulse (~10 s) demonstration with $\beta_N H_{89P}/q_{95}^2$ 50% above the ITER design value.

Table I: Fusion power, auxiliary power requirement, and fusion gain for ITER using various confinement scalings based on DIII-D hybrid discharges

	q_{95} = 4.4 Case				q_{95} = 3.2 Case			
	H	P_{fus}	P_{aux}	Q_{fus}	H	P_{fus}	P_{aux}	Q_{fus}
ITER89P	2.2	550	183.	3.0	2.4	780	60.	12.9
IPB98y2	1.58	530	114.	4.7	1.47	740	18.5	39.
Pure gB	1.61	470	23.	20.	1.25	700	0	∞

[1] M.R. Wade, et al., Phys. Plasmas **8**, 2208 (2001).
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