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Since its inception in 2002, the International Tokamak Physics Activity topical group on Integrated Operational Scenarios (IOS) has coordinated experimental and modeling activity on the development of advanced inductive scenarios for applications in the ITER tokamak. This report documents the present status of the physics basis and the prospects for applications in ITER. The key findings of this research activity are: 1) inductive scenarios capable of higher normalized pressure ($\beta_N \geq 2.5$) than the ITER baseline scenario (β_N=1.8) with normalized confinement at or above the standard H-mode scaling have been established under stationary conditions on the four largest diverted tokamaks (AUG, DIII-D, JET, JT-60U); 2) the parameter range where high performance is achieved is broad in q_{95} and density (normalized to the empirical density limit) and is common to all four tokamaks; 3) MHD modes can play a key role in reaching stationary high performance, but also define the stability and confinement limits; 4) results from individual machines with unique capabilities for varying rotation, current drive, and heating sources facilitate more realistic projections for ITER performance; 5) coordinated experiments have yielded clearer measurements of the normalized gyroradius scaling that dominates the projection to ITER; and 6) coordinated modeling activity supports the present research by clarifying the most significant uncertainties in the projections to ITER. Studies extending previous work on pedestal characterization, radiative divertor operation, and edge localized mode (ELM) suppression to advanced inductive scenarios have also been coordinated through the IOS group.

The original mission of the advanced inductive scenarios for ITER was to provide long-pulse operation (>1000 s) at sufficient fusion power for testing of tritium breeding modules. This was called the “hybrid” mission because the increase in duration over the baseline scenario comes from reduced plasma current operation to increase the inductive flux available for flattop while using the current drive capabilities of the auxiliary systems (and additional bootstrap current if q_{95} β_N increases) to reduce the flattop flux consumption. The observation of enhanced performance of stationary discharges introduced the possibility of achieving one of the primary physics objectives, fusion gain Q=10, at lower current and hence lower risk to ITER in the event of disruption. This requires both higher β_N and good confinement. Extension of this improved performance in all four tokamaks to low q_{95} indicates this scenario would be a candidate for the controlled ignition (Q>20) objective and an alternative to 17 MA operation as margin for achieving the Q=10 objective. These are the roles where research is now focused for the development of the physics basis and projections.

Stable operation at $\beta_N \geq 2.5$ for >3 resistive relaxation times (τ_R) has been demonstrated on all four diverted tokamaks, a critical step to establishing these scenarios as candidates for stationary fusion power applications. The longest duration (in real time and τ_R) was achieved in the JT-60U tokamak (Fig. 1). High performance has been obtained over a range of q_{95} (2.2-6) and density normalized to the empirical density limit (0.3-1.1), with common operational parameters among the four tokamaks.

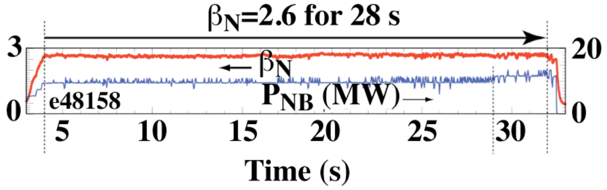

Fig. 1. Long-pulse advanced inductive scenario from the JT-60U tokamak. Duration is >15 τ_R.

The role of MHD in establishing the stationary conditions has been demonstrated by a combination of experiments and modeling. Modeling for AUG and DIII-D showed that $q(0)$ <1 should be obtained for q_{95}>4 operation, contrary to the measured profiles, if the neoclassical Ohm’s law and the standard model for neutral beam current drive applied. In cases with an m=3/n=2 tearing mode, stabilization of the mode by electron cyclotron current drive in DIII-D resulted in the return of sawteeth. Fishbones can play a similar role in keeping $q_{\min}$>1.

Measurements of the fast-ion density in DIII-D indicated that transport of the fast ions could not explain the deviation from neoclassical flux diffusion. Some type of MHD (either small tearing modes or fishbones) is necessary in AUG and DIII-D to explain the stationary current profiles seen for $q_{95}>4$.

The stability and confinement of these operational scenarios are limited by MHD. The limit on β_N is set by the appearance of an $m=2/n=1$ tearing mode in all four tokamaks. The confinement is reduced by the 3/2 mode relative to a fishbone-dominated discharge. A broader current profile results in better confinement, but it is still an open question whether it is the variation of the effects of the MHD or direct influence of the current profile on the underlying turbulence. Stability appears to be enhanced at high density, while confinement is somewhat reduced, consistent with measurements at lower density of the drop in confinement when the electron-ion temperature ratio increases to 1. Higher toroidal rotation also results in better confinement. Both of these effects are important to validate in models used for projection to ITER, since ITER is expected to have equal temperatures and low rotation relative to present experiments.

Dimensionless parameter scaling techniques show the regimes in various tokamaks are, in fact, common and provide a basis for projection of confinement to ITER. The addition of high performance data from JET has established that there is no difficulty in extending these operational scenarios to smaller gyroradius (Fig. 2). Recent results from joint experiments between DIII-D and JET yield very good matches of the temperature and density profiles, indicating the physics leading to high performance is common. Analysis of the global confinement indicates a gyroradius scaling different from standard H-mode database analysis.

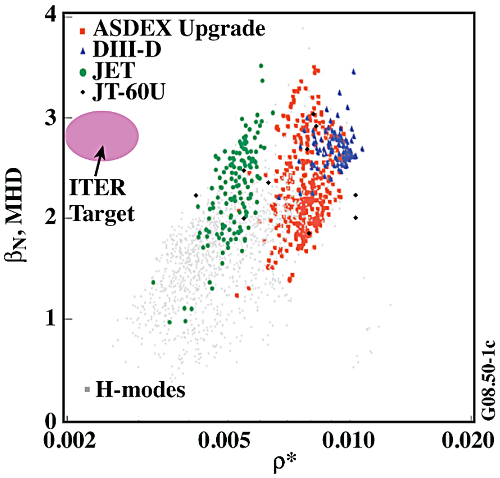

Fig. 2. Existence domain of advanced inductive scenarios vs normalized ρ*.

To project present-day results to ITER applications, 0-D and 1-D modeling are used. The most significant uncertainties are the scaling of the H-mode pedestal and the scaling of the energy transport. Theory-based transport models have been shown to capture some of the important trends observed in experiments, e.g., the variation of confinement with rotation. Modeling of the current profile dependence indicates that increasing the shear in the outer part of the plasma may allow higher gradients in the higher volume region, which may explain the benefits of a broader current profile. The close coordination between the experimental and modeling activities of the IOS group has strengthened significantly the physics basis for the advanced inductive scenarios.

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