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*University of California-San Diego, La Jolla, California.
†Lawrence Livermore Laboratory, Livermore, California.
‡Oak Ridge National Laboratory, Oak Ridge, Tennessee.

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Simulation of ITER Operational and Startup Scenarios in the DIII-D Tokamak

T.C. Luce[1], E.J. Doyle,[2] J.C. DeBoo,[1] G.L. Jackson,[1] T.A. Casper,[3] J.R. Ferron,[1] P.A. Politzer,[1] M.R. Wade,[1] R.J. Groebner,[1] C.T. Holcomb,[3] D.A. Humphreys,[1] A.W. Hyatt,[1] E.A. Lazarus,[4] J.A. Leuer,[1] M. Murakami,[4] J.-M. Park,[4] T.W. Petrie,[1] C.C. Petty,[1] and W.P. West[1]

[1]*General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA*
[2]*University of California, Los Angeles, California 90095, USA*
[3]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[4]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*

Four operational scenarios designed for use in ITER to achieve its physics and technology goals have been explored in DIII-D using a shape close to that proposed for ITER (Fig. 1). The scenarios studied include the baseline ELMing H mode, a steady-state scenario, and two advanced inductive scenarios. In all cases, performance was obtained at or approaching the level required for ITER to reach the objectives for which each scenario was targeted. While these operational scenario studies focussed on the full-current performance aspects, separate experiments were carried out to explore the current rise and rampdown issues expected in ITER, including investigation of access to advanced scenarios. Large-bore startup was found to be more suitable for ITER due to lower internal inductance (l_i) than the small-bore startup originally envisioned for ITER. Access to the hybrid mode of operation was obtained with the large-bore startup. Demonstration of reliable EC-assisted startup (using second harmonic) at the ITER electric field value was also obtained.

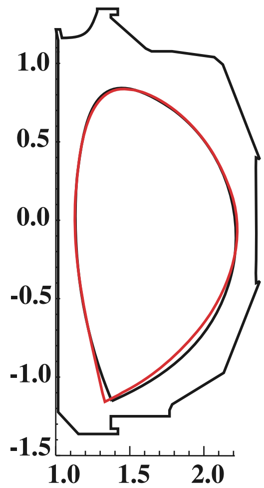

Fig. 1. Comparison of the DIII-D operating shape (red) with the ITER design shape scaled by a factor of 3.7.

Figure 2 compares the time histories of the normalized pressure (β_N), confinement quality (H_{98y2}), and fusion figure of merit ($G \equiv \beta_N H_{89P}/q_{95}^2$) for the four scenarios. These were all operated at the same value of magnetic field (B) in order to facilitate a direct comparison, similar to ITER operation at full B. The baseline H mode scenario [Fig. 2(a)] is targeted at the physics objective of 400 MW fusion power with Q=10 (ITER design values q_{95}=3, β_N=1.8, H_{98y2}=1.0, G=0.42) [1]. The steady-state scenario [Fig. 2(b)] has a physics objective of Q=5 under fully noninductive operation (ITER design values q_{95}=5, G=0.3) [1]. The advanced inductive scenario at q_{95}=3 [Fig. 2(c)] is a candidate for possible operation with Q=30, which the ITER design should not preclude [1]. Finally, the advanced inductive scenario at q_{95}=4 [Fig. 2(d)] is a candidate for "hybrid" operation, which seeks to maximize the nuclear fluence for testing. The performance of this scenario is sufficiently good in present tokamaks to consider it as a possible alternative means to achieve the Q=10 objective [2].

The performance of the baseline scenario is very close to that required for Q=10 at 15 MA in ITER [Fig. 2(a)]. Confinement is slightly reduced by the presence of an m=3/n=2 tearing mode. An increase of β_N by 10% was sufficient to achieve G=0.42 stably. Variations in the q profile at the start of the current flattop might avoid the triggering of this mode.

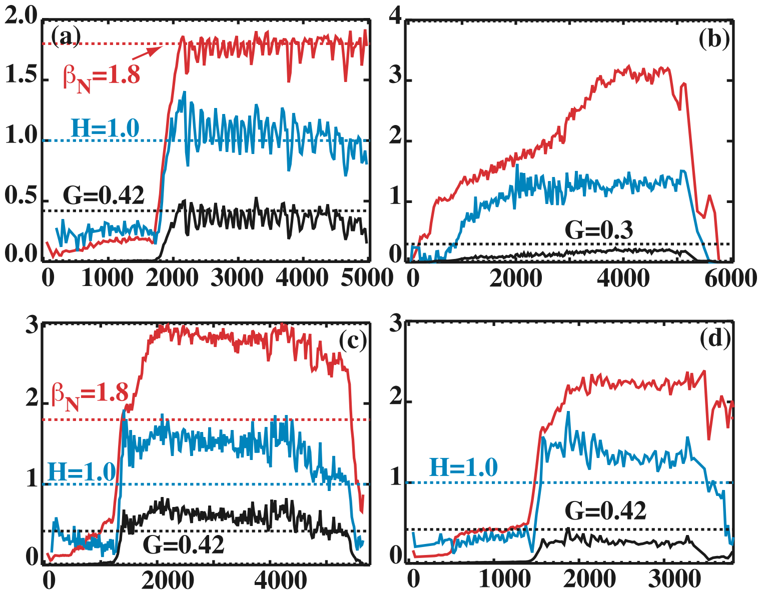

Fig. 2. Time histories of β_N (red), H_{98y2} (cyan), and *G* for the (a) baseline scenario, (b) steady-state scenario, (c) advanced inductive scenario, and (d) hybrid scenario. The dashed lines indicate the ITER design values. *G*=0.42 and *G*=0.3 are sufficient for *Q*=10 and *Q*=5 in ITER, respectively.

Attempts at higher β_N were limited by the appearance of an m=2/n=1 tearing mode. The large excursions in β_N are due to Type I ELMs. The energy loss per ELM is about 10% of the total stored energy and in some cases is more than 30% of the pedestal energy. The pedestal pressure reaches ~50% of the volume-averaged pressure.

A steady-state candidate scenario has been operated stably at β_N>3.0 for 1 s [Fig. 2(b)]. The performance is slightly below that needed in ITER for *Q*=5. Higher β_N (up to β_N=3.3) can be obtained for shorter duration, but β is limited by fast-growing MHD. This may indicate that the shape shown in Fig. 1 does not have a large difference between the no-wall and ideal wall β limits. Further analysis is needed to see how the obtained β compares with MHD stability theory. The large plasma-wall gap on the low-field side may also play a role.

Advanced performance inductive scenarios have been obtained at q_{95} slightly above 3 and 4. At q_{95} near 3 [Fig. 2(c)], quite good performance (β_N=2.8, *G*=0.65) was achieved for about a resistive time, but was eventually terminated by an m=2/n=1 tearing mode. At q_{95} near 4, performance was limited to about β_N=2.4 for the shape shown in Fig. 1. A slightly larger plasma with similar cross-section achieved β_N=2.8 at higher *B*, using the large-bore ITER startup scenario (below). Comparison of these two cases may provide some clues as to the importance of the initial conditions for access to high-performance inductive scenarios.

The original startup scenario envisioned for ITER started from a small outboard-limited plasma [3]. The cross-section was expanded to keep the limiter *q* constant as the current increased, with x-point formation at 7.5 MA. Scaled to DIII-D (Fig. 3), this scenario resulted in rapid current penetration (as designed), but l_i during the limiter phase exceeded the design window for ITER. The design window is set by vertical stability and by the fact that the poloidal coil set must supply more flux to reach flattop when l_i is higher. (The flux stored in the poloidal field is recoverable if l_i drops following the L-H transition, but the issue is reaching the solenoid current limits prior to start of burn due to the higher flux required from the solenoid at high l_i.) Sawteeth appeared during the limiter phase, which would make access to advanced scenarios that require $q > 1$ difficult, if not impossible. These and other issues led to a proposed alternative ITER startup scenario with larger plasma from breakdown and divertor formation as early as 3.5 MA. With this new type of startup, it was possible to reach current flattop without sawteeth in DIII-D for reduced current discharges suitable for steady-state or advanced inductive scenarios for ITER. Hybrid scenario performance approaching that needed for *Q*=10 in ITER was obtained in DIII-D with this startup (Fig. 4), with small sawteeth appearing only at the end of the current rise.

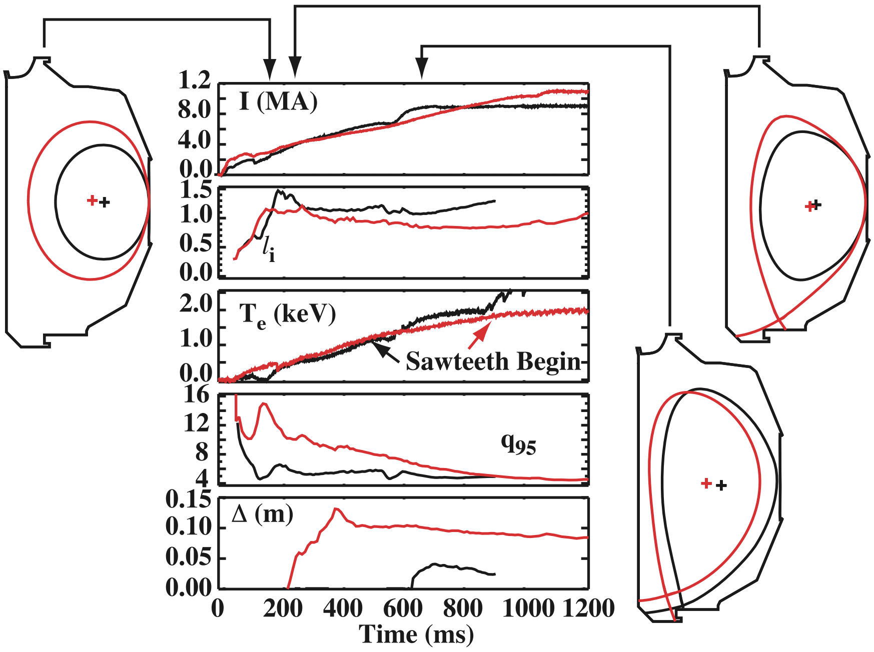

Fig. 3. Comparison of small-bore (black) and large-bore (red) startup on the outer limiter. From top to bottom, time histories of plasma current (MA), l_i, central T_e (keV), q_{95}, and minimum separatrix-limiter distance (m). Insets show the plasma boundaries at the times indicated. Time scaling to ITER is approximately 50X.

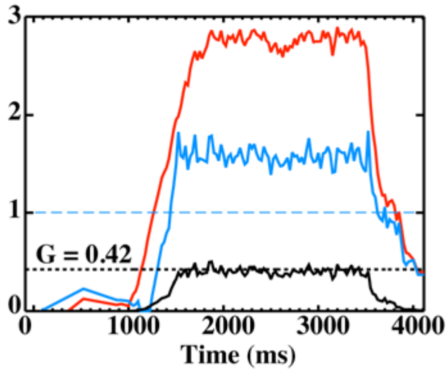

Fig. 4. Time histories of β_N (red), H_{98y2} (cyan), and G for a hybrid scenario plasma generated with the large-bore ITER startup and no auxiliary heating until just prior to current flattop.

Feedback control of l_i was developed in the divertor phase of the current rise of these large-bore startup discharges, using the current ramp rate as the means of changing l_i. Control of l_i in purely inductive current rises [Fig. 5(a)] and with various levels of NBI during the current rise [Fig. 5(b)] was demonstrated successfully. As expected, the inductive cases without heating require higher current rampup rates to achieve lower l_i, while increasing levels of auxiliary heating lead to slower current rampup rates to maintain the same level of l_i. More sophisticated control schemes using density, heating, and current ramp rate are under development [4] for generating a specified q profile, not just a scalar quantity such as l_i or q_{min}.

Work on the operational and startup scenarios has largely been carried out separately; however, a first attempt at a complete simulation discharge of the ITER baseline scenario, including the rampdown, has been made. Figure 6 shows a discharge with a large-bore startup scenario, with current rise up to the equivalent of 15 MA in ITER. The plasma initiation uses the ITER design value of electric field (0.3 V/m) and second harmonic ECH for pre-ionization and burnthrough assist. At current flattop, the stored energy is feedback controlled following the L-H transition to give β_N=1.8, as expected for Q=10 in ITER. The rampdown uses the minimum rate of current decrease to remain in H mode with the feedback system maintaining the specified β_N=1.8. Slower rampdown results in transition back to L mode with a corresponding large increase in l_i. Faster rampdown would give higher l_i and problems with vertical stability. The slowest possible

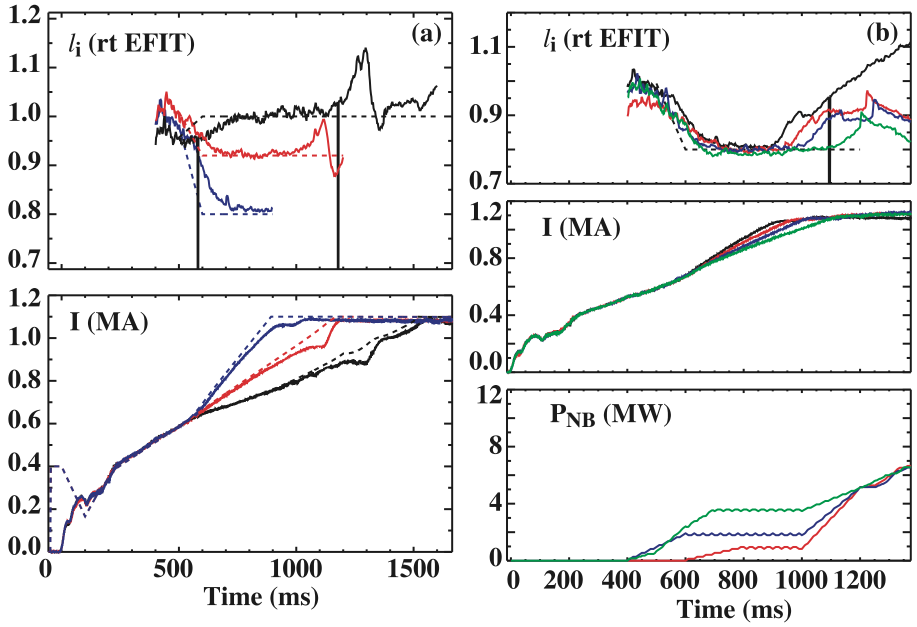

Fig. 5. Demonstration of l_i control to (a) different values without auxiliary heating and (b) the same value with different levels of auxiliary heating. The feedback control ends when the target value of the plasma current is reached.

rampdown with fixed shape still reaches values of l_i corresponding to growth rates for vertical displacements higher than can be stabilized in ITER. To counteract this, the elongation is ramped down to keep the growth rates within the controllable range. When the plasma current is down to the level equivalent to 3.5 MA, the plasma is limited and ramped down to very low current without disruption.

The work reported here is a first attempt to integrate a number of ITER constraints with scenarios developed on DIII-D and other tokamaks. Further optimization and increased fidelity to the ITER design parameters for both the operational scenarios and the startup and rampdown are planned for future experiments.

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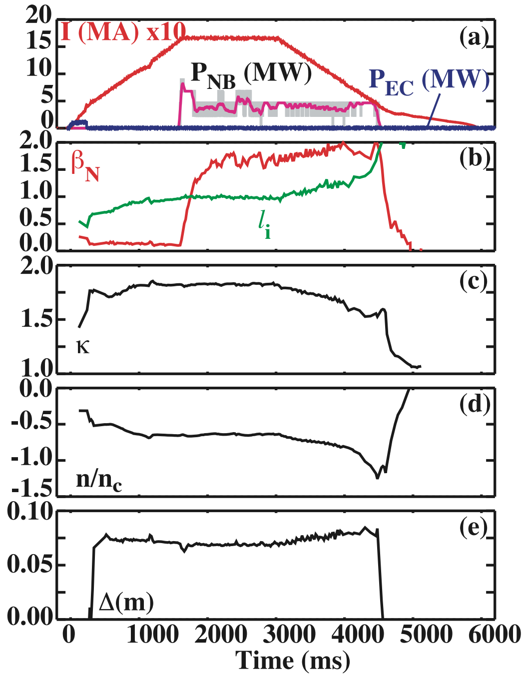

Fig. 6. Prototype of an ITER simulation plasma from startup to baseline scenario operation to safe rampdown. Time histories of (a) plasma current (x10-red) (MA), NB power (instantaneous-gray, smoothed-magenta) (MW), EC power (MW), (b) β_N (red), l_i (green), (c) elongation, (d) critical index for vertical stability, (e) minimum plasma-limiter separation (m).

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