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*Lawrence Livermore National Laboratory, Livermore, California.

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# Simulating the ITER Plasma Startup Scenario in the DIII-D Tokamak IT

G.L. Jackson[1], T.A. Casper[2], T.C. Luce[1], D.A. Humphreys[1], J.R. Ferron[1], A.W. Hyatt[1],
T.W. Petrie[1], and W.P. West[1]
e-mail: Jackson@fusion.gat.com

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA.
[2]Lawrence Livermore National Laboratory, Livermore, California 94550, USA.

DIII-D experiments have investigated ITER startup scenarios, including an initial phase where the plasma was limited on low field side (LFS) poloidal bumper limiters. Both the original ITER "small-bore" (constant $q_{95}$) startup and a "large-bore" lower internal inductance ($l_i$) startup that avoids vertical disruption events (VDEs) have been simulated. In addition, $l_i$ feedback control has been tested with the goal of producing discharges at the ITER design value, $l_i$ = 0.85. These discharges have been simulated using the Corsica free boundary equilibrium code. High performance discharges ($\beta_N$ = 2.8, $H_{98y2}$ = 1.4) have been obtained experimentally in an ITER similar shape after the ITER-relevant startup.

ITER startup presents unique challenges due to the low inductive toroidal electric field (0.3 V/m), power supply and poloidal field coil constraints, and plasma current ramp up near the $n$=0 vertical stability limit. Important goals of this work are to test whether the proposed ITER startup scenarios are feasible, to benchmark modeling codes, and to help develop future improvements to these scenarios. Examples of three ITER startup scenarios simulated in the DIII-D tokamak are shown in Fig. 1: the original ITER "small-bore" (constant $q_{95}$) scenario (black), a "large-bore" scenario with an earlier time to divert (red), and the large-bore scenario with internal inductance ($l_i$) feedback (blue). The original ITER startup scenario begins with a small volume plasma [Fig. 1(e)] initially limited on the LFS and increasing at constant $q_{95}$. During the current ramp in these small-bore plasmas (black) the internal inductance, $l_i(3)$,

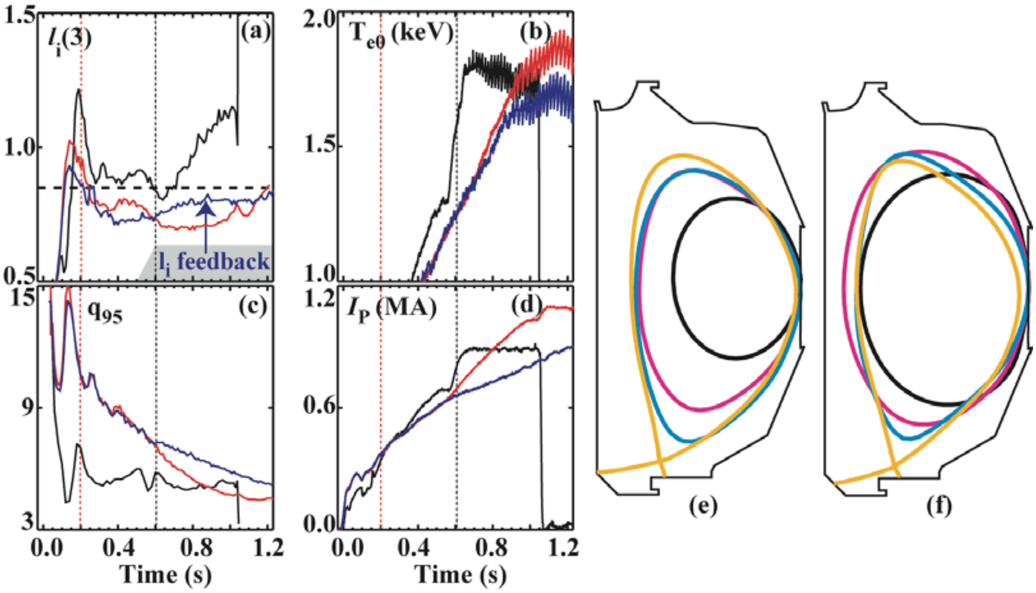

Fig. 1. Three ITER startup scenarios: small-bore constant $q_{95}$ (black), large-bore with early time to divert (red), large-bore with $l_i$ feedback (blue). Plotted is (a) normalized internal inductance, $l_i(3)$, including the ITER design value (dashed line), (b) $T_e(0)$ showing time of sawteeth onset, (c) temporal evolution of $q_{95}$, and (d) $I_p$. Divert time for the small-bore scenario is 0.6 s (black vertical line), while the large-bore scenarios are 0.2 s (red vertical line). Temporal evolution of plasma shape is shown (e) for the small-bore scenario at 0.15 (black), 0.35, 0.55, and 0.75 s, and (f) for the large-bore scenario at 0.05(black), 0.12, 0.19, and 0.25 s.

increased, reaching values of internal inductance much higher than the ITER design value of 0.85 during the current flattop. A second startup scenario, referred to as the "large-bore" startup, was developed that initially had a larger volume and was diverted earlier to minimize heat flux on the outer wall and bumper limiters. The large-bore startup [Fig. 1(f)] exhibited lower $l_i(3)$. The addition of $l_i$ feedback, using the ramp rate of the plasma current as the actuator, allows the flexibility to control $l_i$ in a systematic way to avoid limitations in the ITER poloidal field coil set without prior knowledge of the exact evolution of the current profile.

To simulate ITER startup in DIII-D, the limiter phase of the current ramp was scaled by the LFS radii of both devices, $R_{\mathrm{LFS,ITER}}/R_{\mathrm{LFS,DIII\text{-}D}} \approx 3.5$. The DIII-D toroidal field, $B_T$, was 2.14 T at the major radius $R$ = 1.7 m (compared to 5.3 T at $R$ = 6.2 m in ITER). The scale factor to give the same relative times for the $L_{\mathrm{plasma}}/R_{\mathrm{plasma}}$ time in DIII-D and ITER is about 50 ($L_{\mathrm{plasma}}$ and $R_{\mathrm{plasma}}$ are internal inductance and resistance respectively). For similar $I/aB$, the small-bore 15 MA ITER rampup in 110 s scales to 1.7 MA in 2.2 s for DIII-D. In this initial work, DIII-D flattop current was 1.0 to 1.3 MA.

With higher toroidal inductive electric fields, $E_\phi$ = 0.6 to 1.0 V/m in DIII-D, burnthrough of low Z impurities was not a problem. Electron cyclotron (EC) heating was also evaluated for application in ITER and discharge initiation was more prompt and burnthrough of low Z impurities was faster with the application of EC heating. Future experiments will evaluate the EC heating effectiveness at lower toroidal electric field, $E_\phi$ = 0.3 V/m. After the burnthrough phase, $t_{\mathrm{DIII\text{-}D}} < 0.01$ s, small-bore DIII-D discharges limited on the LFS. Limiter heating was minimal, and no deleterious effects of impurity influx or excessive fueling were observed.

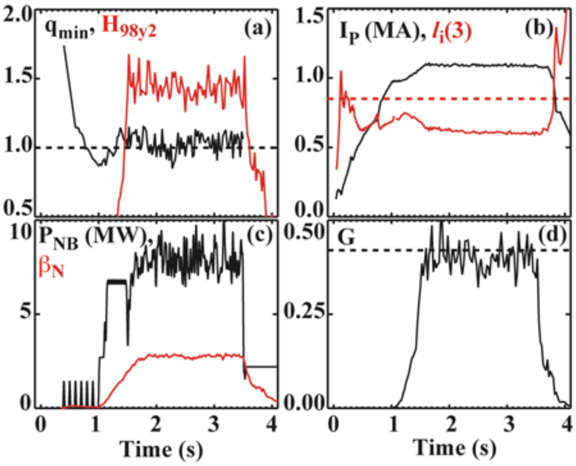

Fig. 2. ITER startup scenario and ITER similarity shape in a high performance discharge: (a) $q_{\mathrm{min}}$ and H factor, $H_{98y2}$, (b) $I_p$ and $l_i(3)$, (c) auxiliary heating power and $\beta_N$, and (d) $G$ factor. ITER design value, $l_i(3)$ = 0.85 is shown as a dashed line in (b) and calculated value of $G$ to produce a fusion gain, $Q$=10 is a dashed line in (d).

High performance discharges, shown in Fig. 2, have also been obtained with the ITER startup scenario. In this case, the large-bore scenario was used, diverting at 0.3 s ($t_{\mathrm{ITER}}$ = 15 s) reaching $q_{95}$ = 4.1 in the flattop phase. A figure of merit, $G = \beta_N \mathrm{x} H_{89P}/q_{95}^2$, of 0.40 was obtained [Fig. 2(d)], approaching the value required in ITER, $G$=0.42, for a fusion gain $Q$=10.

The Corsica free boundary equilibrium code has been used to simulate these DIII-D discharges. Initial modeling predicts the approximate time of sawteeth onset ($q_{\mathrm{min}}$=1) and reproduces the electron temperature evolution during the startup phase.

In summary, experiments in DIII-D have demonstrated an ITER-like scenario that can ramp to plasma current flattop and achieve stable high performance discharges. Feedback control of internal inductance has been demonstrated, allowing additional flexibility in control of the current profile and stable operation further from vertical stability limits. Future work will further evaluate ITER startup scenarios including lower inductive voltage, a detailed comparison of inner and outer wall limiter startup, lower $I/aB$ operation, and benchmarking of predictive codes for ITER.

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