Experimental simulation of ITER discharge rampdown in DIII-D

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Because of the high value of the stored energy in planned ITER plasmas, the controlled rampdown of ITER discharges is an important aspect of ITER operation. In a series of experiments on the DIII-D tokamak, we have simulated the proposed ITER rampdown for the 15 MA baseline operating scenario, as well as for a number of variants of this scenario. These scaled discharges match the reference scenario (including scaled time dependence) with regard to key parameters such as scaled current (I/aB), poloidal beta, elongation and internal inductance. The scaled plasma current is reduced to the equivalent of less than 1 MA, well below the 1.4 MA specified for ITER as the maximum allowable for disruptive termination. The plasma shape and position are controlled during rampdown so that the high heat flux zones near the strike points of the separatrix are held within the equivalent of the armored zones of the ITER divertor; the regulation of the strike point location is an order of magnitude better than required. Scans of the current rampdown rates indicate that a more rapid rampdown than the ITER reference case may be needed to avoid increasing the current in the ITER central solenoid (reducing the available flattop burn duration). Rampdown with a full-size plasma was studied, but was found to be unsuitable for ITER because of transitions to edge localized mode (ELM)-free H-mode with a consequent lack of density control, as well as large excursions in poloidal beta and internal inductance. We find that ELMs play an important role during the H-mode phase of the rampdown, helping to reduce the density as the current is reduced. In several discharges vertical displacement events (VDEs) were triggered during rampdown by freezing the control coil commands. The data obtained on VDE growth rates supports modeling of these events. In addition to experimental simulation of the ITER baseline discharge, we have developed discharges that simulate (from initiation to rampdown) an entirely ohmic ITER plasma, and an enhanced baseline scenario discharge with flattop at the equivalent of 17 MA (q_{95}=2.6)

To scale ITER plasmas to DIII-D all linear dimensions are reduced by a factor of 3.6, to give R = 1.73 m and a = 0.56 m, centering the plasma in the DIII-D limiter aperture. The toroidal plasma current is reduced by a factor of 10, giving the ITER value of I/aB at B = 1.9 T. The time scale is shortened by a factor of 50, according to the magnetic diffusion time which scales as $\tau \propto a^2 T^{3/2}/Z_{\mathrm{eff}}$. Thus the 200 second reference time for ITER rampdown becomes 4 seconds in DIII-D. We began by simulating the reference rampdown for the ITER 15 MA scenario as described in [1]. The ITER prescription for rampdown is to reduce the current to 10 MA in 100 seconds while maintaining H-mode, reducing the external power and the fusion burn rate. The external power is then shut off and an H-L transition ensues. The current is ramped close to zero in another 100 seconds. The DIII-D simulation of this scenario is shown in Fig. 1.

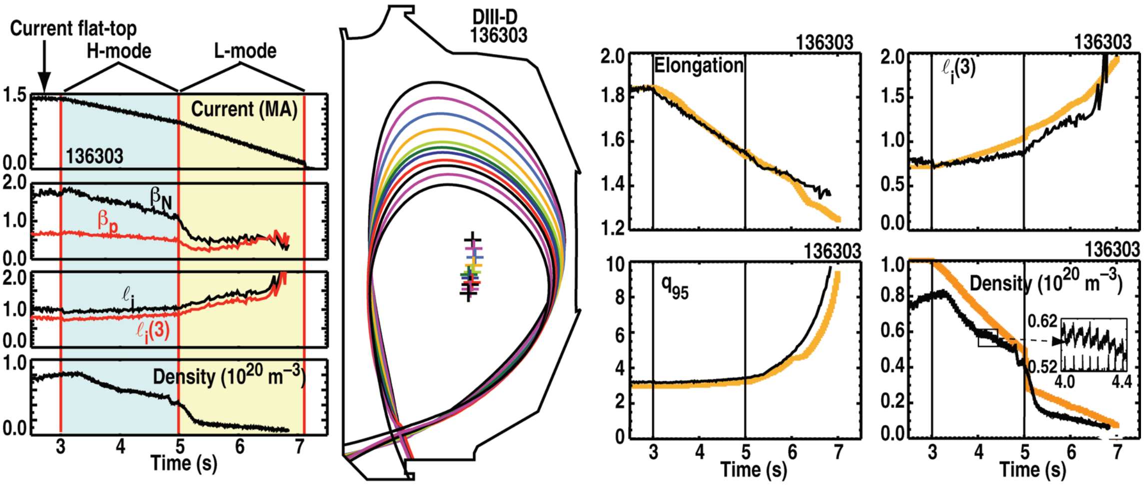

Fig. 1. Parameters of the DIII-D simulation of the ITER reference rampdown scenario. (a) Time history of the current, beta, internal inductance, and density, illustrating the H-mode and L-mode phases. (b) The plasma shape and axis location at 0.4 second intervals during the rampdown. (c) Comparison of the evolution of the internal inductance and density with the DINA numerical simulation (scaled to DIII-D), as well as the programmed quantities elongation and q_{95}.

The rate at which the current is reduced affects two important characteristics of ITER operation. The ITER pulse duration is limited by the available transformer flux; if flux is used during the rampdown then the duration of the flattop burn phase has to be reduced. In addition there are limitations on the allowable current in the ITER central solenoid (CS) that supplies the flux change, due to maximum force constraints on the CS coils. A scan of the rampdown rate in the simulation plasmas, in both the H-mode and L-mode phases indicates that the acceptable range is limited at the slow ramp rate end by limits on the current in the DIII-D equivalent to the ITER CS coils, and at the fast ramp rate end by disruption (Fig. 2). In these experiments there was roughly a factor of 1.5 in *dI*/*dt* between these two limits (in the L-mode phase). The flux consumption constraint was not violated within this range and so appears to be a less important consideration.

One notable feature of successful rampdown in DIII-D is that the vertical position control algorithm was turned off when the plasma current reached ~400 kA, when the magnetic axis is ~0.25 m below the vessel midplane. The algorithm used on DIII-D is designed for a plasma centered in the vessel. With the magnetic axis far off the midplane, the algorithm becomes unstable. Disabling the feedback control was successful because the elongation was also reduced during the rampdown. Thus we were able to bring the current as low as 85 kA before disruption, well below the ITER (equivalent) specification.

There is a broader range of possible ITER operating modes than just the reference 15 MA standard H-mode of scenario 2. We have demonstrated a number of these as part of this experimental simulation work. A simulated discharge at the 17 MA (equivalent) level (q_{95} = 2.6) was produced without difficulty. The rampdown comprised a reduction from 1.7 to 1.5 MA, at constant beta and shape parameters, followed by the standard rampdown from 1.5 MA. We simulated entirely ohmic discharges and discharges in which the heating power was shut off during the current flattop, producing an H-L transition. In these cases the rampdown proceeded successfully with high $l_i(3)$ (~1) and low β_p (~0.05). Attempts to produce a full-bore rampdown (at constant plasma size and shape during rampdown) encountered problems with stability and density control.

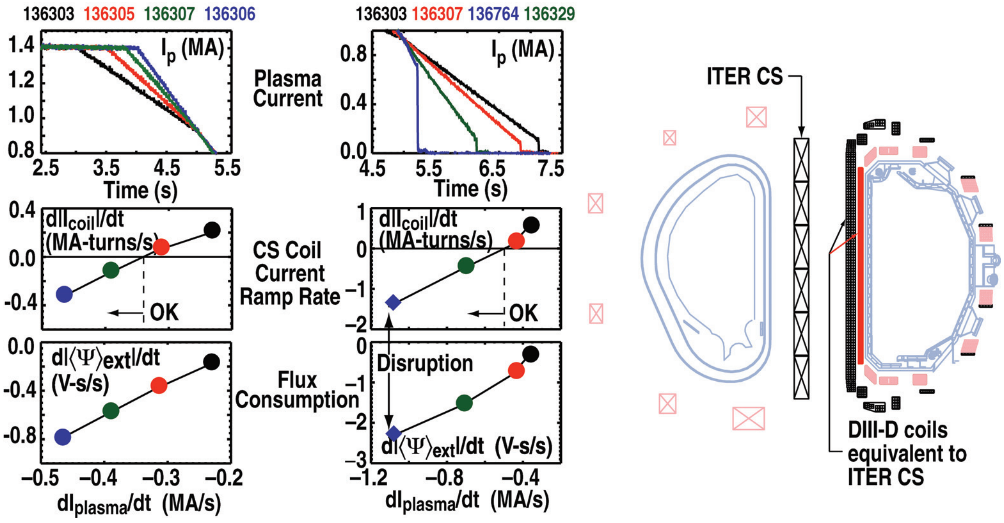

Fig. 2. Scan of current rampdown rates, in the (a) H-mode ($I_p \geq 1$ MA) and (b) L-mode phases. Shown are the dependence of the rates of change of the CS-equivalent current and the flux linked by the plasma vs plasma current ramp rate. (c) The DIII-D coils considered as "equivalent" to the ITER CS.

The ITER rampdown scenario simulated in DIII-D is always terminated by a VDE disruption. Vertical position control is lost before n>1 instability onset, and the thermal quench occurs only after the plasma strikes the wall and q_{edge} drops sufficiently to trigger n>1 MHD. To measure the instability growth rate just prior to the disruption, the DIII-D vertical control system was disabled by freezing all coil commands. This triggers a VDE and allows benchmarking of models for calculation of controllability by fitting the vertical trajectory to the predicted exponential growth. Good agreement was found in three successive discharges in which this was done at different points approaching the closed loop disruption time. This validation enabled reliable calculation of the closed loop control boundary in terms of controllability metrics.

Controllability can be quantified by the maximum vertical displacement metric, ΔZ_{MAX} [2]. This quantity is the vertical distance the plasma can be displaced suddenly and still be controlled. Sudden displacements larger than this value exceed the capability of the vertical control system to restore, and result in a VDE. Previous experiments on DIII-D have shown that ΔZ_{MAX} = 2.5 cm corresponds to marginal control robustness, with a possible VDE under some circumstances; ΔZ_{MAX} = 1.5 cm corresponds to a guaranteed VDE. Figure 3 shows the evolution of (a) the vertical growth rate γZ, (b) controllability metric ΔZ_{MAX} (calculated from the models validated in triggered VDE experiments) and (c) vertical position Z at the end of the current rampdown. As the value of ΔZ_{MAX} falls below 1.5 cm at 6.44 s, an unrecoverable VDE occurs, consistent with the closed loop control limit in DIII-D at that point.

$\Delta Z_{MAX}/a$ represents a machine-independent specification used to guide the design of new in-vessel coils for ITER. The vertical stability control system used in these DIII-D experiments employed only the outboard PF coils, with similar $\Delta Z_{MAX}/a$ to that provided by the ITER in-vessel coils. If the dominant source of noise in ITER scales with minor radius and plasma current (typical of power supply or plasma-sourced noise, but not instrumentation noise), these experiments imply that ITER may also experience such a rampdown-terminating VDE, but well below the ITER current level specified.

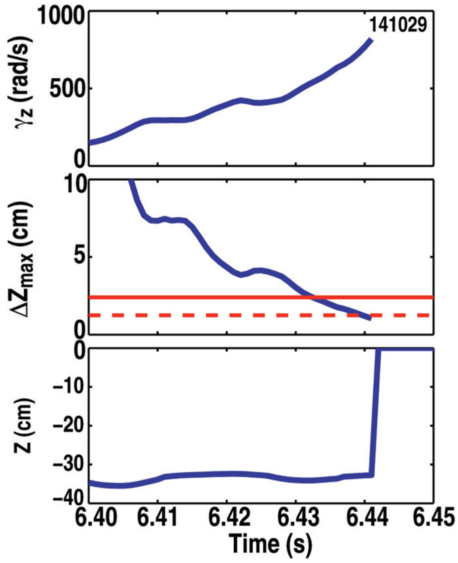

Fig. 3. Evolution of (a) the vertical growth rate γ_Z, (b) controllability metric ΔZ_{MAX}, and (c) vertical position Z at the end of the current rampdown for ITER rampdown simulation experiment (discharge #141029).

The DIII-D program of experimental simulation of ITER discharges has included extensive studies of ITER startup conditions [3]. Recently, use of a fast camera has allowed analysis of the breakdown and plasma formation phase. An Abel inverted image (Fig. 4) shows breakdown within 2 cm of the 2nd harmonic electron cyclotron resonance. After breakdown there is a linear expansion outwards. In addition, the bright region moves inward in discrete steps until it reaches the inside wall. This is currently being investigated. As the magnetic field in ITER may vary but the EC frequency will be fixed, we have examined the effect of the EC resonance location on breakdown and startup. In a scan of the EC resonance location, R=1.29-1.81 m, we have found that startup is robust and reproducible, with P_{EC} = 1.0-1.2 MW and E_f = 0.3 V/m. Startup in He plasmas has also been investigated. With EC assist, startup at the ITER toroidal electric field, $E\phi$ = 0.3 V/m, has been demonstrated. However, the initial dI/dt is smaller than with D. Initial flux consumption is also higher, although flux consumption to reach current flattop is comparable in He and D.

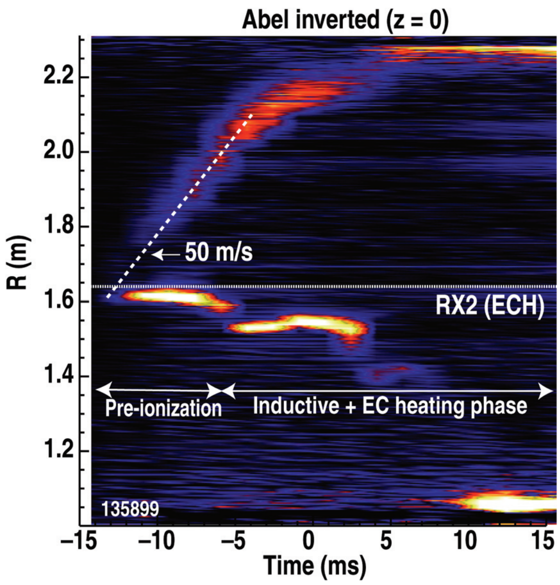

Fig. 4. Inversion of the visible light image to R vs time at Z=0.

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[1] A.A. Kavin, et al., "DINA simulations of 15 MA and 17 MA scenarios", Report ITER_D_2FRCJY, 15 December 2008.
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