Advanced ITER scenarios with the DINA-CH&CRONOS Simulator

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Introduction Advanced scenarios are of particular interest for ITER because they achieve high neutron yield by taking advantage of the specific capabilities of each external power source and their interaction with the plasma. Hybrid scenarios and steady-state scenarios are two sub-classes of advanced scenarios. A hybrid scenario consists of a plasma pulse during which medium-to-high fusion gain is achieved for a medium-duration discharge. A steady-state scenario is a pulse during which the loop voltage is zero for a significant time, thus allowing long discharges with medium-to-low fusion gain.

Performing a hybrid and a steady-state scenario on ITER will exploit some of the tokamak's capabilities to their limit and it is not *a priori* clear that these scenarios are achievable within the present ITER design. Simulating such scenarios is therefore required in order to assess their feasibility within ITER heating capabilities, PF coil power supplies capabilities, and the limits on fields, forces, and currents allowed for the PF coils.

In this paper, we report on the self-consistent free-boundary simulations of the hybrid and steady-state scenarios for ITER, performed with the DINA-CH&CRONOS [1] full tokamak simulator and we discuss the main lessons learned during this work.

Method and assumptions The first step of our approach consisted of defining one specific hybrid scenario and one specific steady-state scenario. This consisted of developing appropriate heating source power waveforms, source configurations, and a plasma equilibrium evolution for both the hybrid scenario and the steady-state scenario. This was achieved using the prescribed-boundary CRONOS suite of codes, which has advanced transport and source calculations.

The second step consisted of simulating the free-boundary equilibrium evolution of both scenarios using DINA-CH in a mode in which the kinetic profiles from CRONOS are imposed rather than calculated. This phase enabled us to simulate the free-boundary evolution of the plasma in a fast and efficient manner, enabling the development of an appropriate plasma shape waveform, plasma current waveform, and PF coil currents waveforms with respect to ITER capabilities. This phase also allowed us to develop and test our plasma control strategy for both the hybrid and steady-state pulses.

The third and final step consisted of performing a hybrid scenario simulation and a steady-state scenario simulation using the full tokamak simulator DINA-CH&CRONOS. The simulations performed using DINA-CH&CRONOS are self-consistent in the sense that both the kinetic and the electromagnetic evolution are evaluated every time step (5ms). Source power deposition is evaluated on demand, typically once every second of simulation, due to the expensive nature of the source power deposition calculations.

For the hybrid scenario: H_{98} = 1.3 is assumed and the ITER baseline heating mix is used at full power during the burn phase (33MW NBI, 20MW ICRH, 20MW ECCD). For the steady-state scenario: H_{98} = 1.4 is assumed, the ITER baseline heating mix is used at full power during the burn phase (33MW NBI, 20MW ICRH, 20MW ECCD) with the addition of 15MW LHCD.

Hybrid scenario results *Start-up:* The simulation was started at a plasma current of I_p = 0.4MA with a small-bore, inboard limited plasma, initialised PF&CS currents and vessel currents. During the first 8s of the simulated pulse, it was assumed that the Switching Network Unit (SNU) could provide the demand PF coil voltages and no saturation of the PF coil power supplies was modelled during this time. After this 8s period, the PF coil power supply limits were simulated throughout the pulse, including a realistic current saturation avoidance above 95% of each supply current limit. The start-up control scheme consisted of four PID controllers for the controlled variables $R \cdot I_p$, $Z \cdot I_p$, I_p, and the 11 PF coil currents. All these controllers used the PF coil voltages as actuators. On top of these, we used VS1 for vertical stabilisation throughout the pulse (as well as VS3, but only marginally) with a D controller. 8MW of ECRH power is deposited within the plasma before the X-point formation (XPF) in order to reduce the ramp-up volt-second consumption and help shape the q-profile and maintain q_{min} at a relatively high value.

X-point formation: The X-point is formed at I_p = 3.6MA, which is early enough to avoid damage to the inner wall. After the X-point formation, the R and Z controllers are switched off and a simple gap controller is switched on over a 6s time interval.

L-H transition: Anticipating a likely L-H transition, we changed the control scheme about 10s before the transition and introduced a full gaps$\cdot I_p$, I_p, and PF coil currents controller, in place of the plasma current controller, the PF coil currents controller, and the simple gap controller. At I_p = 9.3MA, the ECRH power demand was abruptly raised to 20MW, the ICRH power demand was raised to 16MW, and the on-axis NBI power demand was set to 16.5MW. The L-

H transition is imposed to occur 1s after this abrupt increase of externally applied power. Thanks to the self-consistent nature of the DINA-CH&CRONOS simulator, the L-H transition is unsmoothed and the expected strain of the control systems was observed. Our control scheme was sufficient to prevent the plasma from being limited outboard during the transition transient.

End of ramp-up and flat-top: 5s after the L-H transition, the ICRH demand power was raised to 20MW. The plasma current flat-top was reached at I_p = 12.2MA about 15s after the L-H transition. 30s after the L-H transition, 16.5MW of off-axis NBI power was added to the heating mix, mainly to prevent the q-profile to crossing the q=1 threshold too early. The flat-top lasted for about 1135s, and the q-profile was maintained above the q=1 threshold for about 1000s, thus preventing the occurrence of sawteeth during that period.

Ramp-down: The ramp-down was initiated 1200s after the plasma start-up. The on-axis NBI was switched off about 5s before the beginning of the plasma current ramp-down. The ICRH, the on-axis NBI, and off-axis NBI were abruptly switched off half a second after the ramp-down was initiated. The ECRH power was decreased to 13MW over a range of 150s. The control scheme during the ramp-down was similar to the one used during flat-top, with the addition of a controller to prevent the PF coils from creating current dipoles. The H-L transition was set to occur 100s after the beginning of the ramp-down, and the expected strain on the control system was observed but handled by the control system. The plasma terminated outboard at 1371s and I_p = 0.94MA, which is low enough to avoid damage on the wall.

The hybrid simulation required the calculation of about 275’000 time steps and about 9 days of computer time for completion.

Steady-state scenario results *Start-up, X-point formation, and L-H transition:* These phases were identical to those of the hybrid scenario already presented.

End of ramp-up and flat-top: 5s after the L-H transition, the ICRH demand power was raised to 20MW. The plasma current flat-top was reached for I_p = 10MA about 5s after the L-H transition. 25s after the L-H transition, 16.5MW of off-axis NBI power was added to the heating mix. 150s after the L-H transition, 15MW of LHCD was added to the heating mix.

During the first 1500s of flat-top, the operation was almost steady-state with a slight negative loop voltage, thus recharging the transformer. A single simple correction to the heating mix at that time set the loop voltage to -1mV for about 1200s.

Ramp-down: The ramp-down was initiated 2750s after the pulse initiation. The ICRH and the LHCD power demand were abruptly set to zero at that time. A PF dipole controller was introduced as in the hybrid scenario simulation. The H-L transition occurred at 2850s after the plasma initiation, and the plasma terminated inboard at 2960s and I_p = 0.6MA.

The steady-state scenario simulation required the calculation of about 600’000 time steps and about 20 days of computer time for completion.

Lessons learned The main outcome of this work is the demonstration that both a hybrid scenario and a steady-state scenario are feasible within the ITER design limits on heating capabilities, PF coil power supply capabilities, and the engineering constraints on the fields, currents, and forces allowed for PF coils. This statement has to be qualified by the assumed validity of the physics assumptions inherent to the DINA-CH&CRONOS tokamak modelling. The most challenging transient is the H-L transition which can lead to transient inboard wall contact.

Hybrid scenario: During this work, it appeared clear that the most outstanding issue consisted of constraining the q-profile evolution. Our approach was a ‘fire and forget’ method, in the sense that there was no feedback on the q-profile and that the heating mix prepared before the pulse was not updated during the discharge. This method was successful, but it required considerable effort and several iterations, since the DINA-CH&CRONOS self-consistent simulation of the hybrid scenario unveiled the recurring appearance of a current hole at the centre of the plasma. This phenomenon required multiple modifications to the nominal heating scheme developed using CRONOS. This current hole creation is attributed to the small discrepancies in equilibria between the DINA-CH&CRONOS self-consistent simulation and the CRONOS fixed-boundary simulation, which integrate over a long duration thus leading to significant effects.

Steady-state scenario: The steady-state case had a similar core q-profile problem and could not be achieved using a ‘fire and forget’ approach. Steady-state operation was reached by a single simple modification of the heating mix, namely slightly decreasing by hand the LHCD and the ECRH power demand. As in the hybrid scenario simulation, the evolution of the q-profile appeared to be the most sensitive parameter, although we did not observe the apparition of a current hole as opposed to the hybrid scenario simulation.

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