CORSICA simulations of ITER advanced operation scenarios

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Introduction This paper presents the work on developing advanced plasma operation scenarios for ITER, such as the hybrid and steady-state modes, including relevant physics and engineering constraints. An advanced free-boundary transport simulation code, CORSICA [1-2], has been used to study the feasibility of the proposed operation scenarios and to better optimize them within ITER design parameter ranges. Several realistic source modules for heating and current drive (H&CD), such as the neutral beam (NB) injection, electron and ion cyclotron (EC&IC), and lower hybrid (LH), are either upgraded or newly added to the CORSICA code using the latest source configurations. The integrated discharge modelling capability of the CORSICA code has been continuously improved for ITER scenario study. ITER hybrid mode operation scenarios have been studied focusing on achieving physics goals, such as the fusion power multiplication factor, Q, and plasma burn duration. A study on ITER steady-state mode operation scenarios has been recently started, focusing on operating the plasma with a high non-inductively driven current fraction at a moderate Q and achieving the safety factor (*q*) profile favourable for generating/maintaining internal transport barriers (ITBs).

ITER Hybrid Mode Operation Scenarios The hybrid mode operation observed in several tokamaks [3-5] is characterized by further confinement enhancement over the H-mode plasma operation. This appears to be associated with reduced MHD instabilities with a stationary flat *q* profile in the core region. The ITER hybrid mode is currently aiming at operating the plasma for a long burn duration (>1000s) with a moderate Q of at least 5. We have developed several ITER hybrid mode operation scenarios, including a reference 12.5MA scenario for comparison, by tailoring the 15MA ITER inductive H-mode scenario [2] and expanding the flat-top burn duration up to 1300s, as shown in figure 1. The electron density profile evolution is prescribed with a parabolic shape and the flat-top electron density at the core is assumed to be 85% of the Greenwald density limit. The deuterium and tritium ion density ratio is assumed to be 50:50, taking the neutral beam injected deuterium ions into account. Argon (Ar) and Beryllium (Be) are used as impurity species self-consistently with the evolution of the effective charge number, Z_{eff}, satisfying the quasi-neutrality conditions. The heat transport is computed using the Coppi-

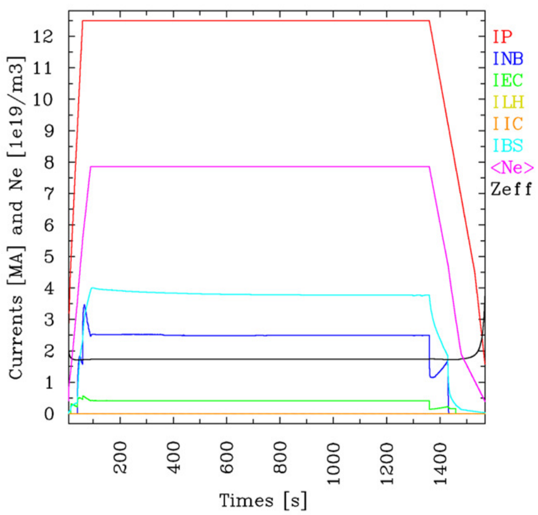

Figure 1. 12.5MA ITER hybrid mode operation scenario (reference case). Time traces of the plasma current, driven currents, bootstrap current, volume averaged electron density and effective charge number.

Tang transport model [6]. The plasma current is ramped up in 60 seconds and an L-H confinement mode transition is assumed at about 2/3 of the current ramp-up. 33MW of NB and 20MW of EC power are applied during the flat-top phase and the plasma is self-heated by fusion-born alpha particles. After the flat-top phase, the plasma current is ramped down in 210 seconds, again assuming an H-L confinement mode transition at about 1/3 of the current ramp-down. In this scenario, the fusion power multiplication factor was above 5 and the alpha particle self-heating power was about 100MW during the plasma burn. The achieved confinement enhancement factor with respect to the H-mode confinement, H_{98}, was 1.2~1.3 and the internal inductance was 0.70~0.75. The safety factor profile initially slightly reversed became flat in the core (ρ_{tor}<0.4) due to the effective sawteeth triggered when q_{min}<0.97. The poloidal field (PF) coil currents were well within their coil current, force and field limits, except the PF2 coil. This violation was caused by a prescribed shape transition to a limited configuration (I_p<3.5MA).

We have then studied accessible operation conditions and achievable range of plasma parameters. ITER operation capability for avoiding the coil current, field and force limits are examined by applying different current ramp rates, and flat-top plasma currents and densities. Modifications to the ramp-down shape evolution and PF coil pre-magnetization [7] were studied to further optimize the evolution of the PF2 and PF6 coil currents within their coil limits. Various combinations of heating and current drive schemes (see figure 2) have been applied to investigate several physics issues, such as the plasma current density profile tailoring, enhancement of the plasma energy confinement, fusion power generation and poloidal flux consumption. At higher auxiliary heating power, larger bootstrap current and alpha particle self-heating power were obtained but at a lower fusion power multiplication factor. When far off-axis LHCD was applied, the internal inductance was effectively reduced and the safety factor profile was maintained over 1.0 until the end of the flat-top phase (see top figure in figure 2). As the non-inductively driven current became higher, the demand on the inductively driven current was reduced for a given flat-top plasma current, and therefore less poloidal flux was consumed (see bottom figure in figure 2).

A parameterized edge pedestal model based on EPED1 [8] was recently added to the CORSICA code and applied to hybrid scenarios (see figure 3). The feedback controlled pedestal top pressure and width were respectively higher and larger than those assumed in the reference case. This implies that the previous simulations

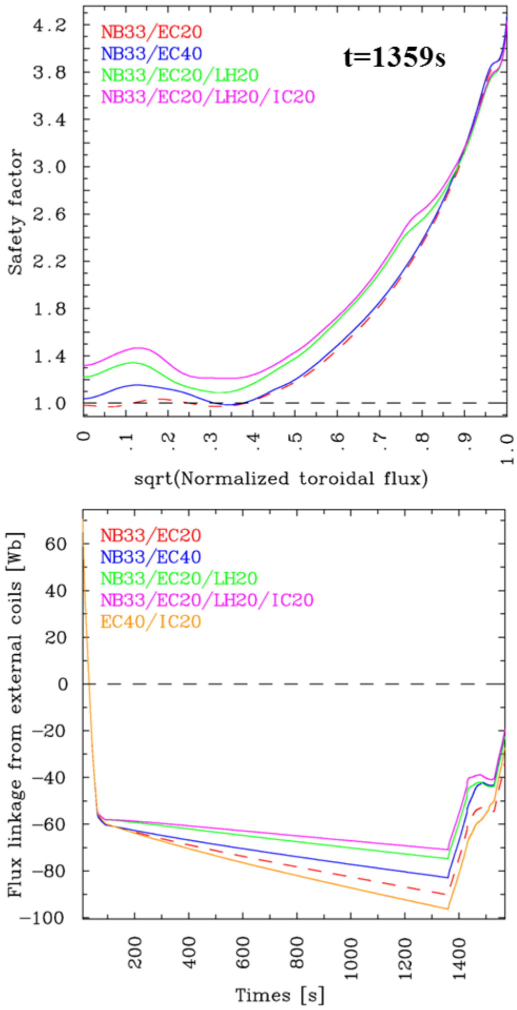

Figure 2. 12.5MA ITER hybrid mode operation scenario (reference case). Safety factor profile at t=1359s (top) and time traces of the flux states (bottom) are compared for various combination of H&CD.

underestimated the stability-based limits for these parameters and better performance can be achieved.

Self-consistent free-boundary transport simulations have been performed to provide information on the PF coil voltage demands and to study the controllability with the ITER controllers, JCT2001 and VS1. In these simulations, the coil currents obtained from the prescribed boundary transport simulations were used as the reference coil currents for the controllers. The PF coil currents were feedback controlled well around the reference coil currents and the shape evolution and plasma parameters were very close to those obtained from the prescribed boundary transport simulations. The plasma stability dynamics studied in the presence of a vertical displacement event triggered by disconnecting the feedback control loop showed that the plasma was vertically stabilized with sufficient control margins [9].

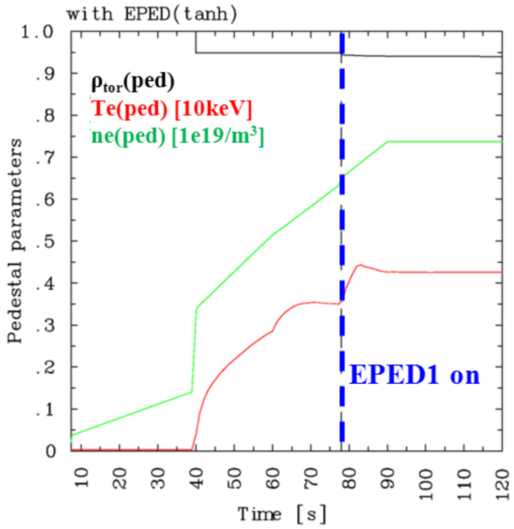

Figure 3. Time traces of the pedestal top location, temperature and density.

ITER Steady-State Operation Scenarios Operating ITER in a steady-state mode appears to be very challenging due to several engineering and burning plasma physics issues. The formation/evolution of ITBs observed with a negative or very low magnetic shear at the core region and strong flow shear [10] is not yet completely understood. The ITER steady-state mode is aiming at operating the plasma with a very high non-inductively driven current fraction and a moderate Q of about 5, for a very long burn duration up to 3000s. This operational capability is studied in ITER for a future reactor application. In this work, we have developed several ITER steady-state mode operation scenarios, including a reference 9MA case, by tailoring the hybrid mode operation scenario and expanding the flat-top burn duration. The electron density profile evolution is again prescribed with a parabolic shape and the flat-top electron density at the core is assumed to be 85% of the Greenwald density limit. The assumptions on the deuterium and tritium ion density ratio, impurity species, evolution of effective charge number are repeated from the hybrid mode simulations. However, the multiplication factors used in the Coppi-Tang transport model are adjusted to generate higher plasma energy confinement enhancement (H_{98} ~1.4-1.6), without necessarily modelling ITBs. 56.5MW of auxiliary H&CD power (16.5MW of NB, 20MW of EC and 20MW of LH) is applied during the flat-top phase. In this scenario, achieving both the target Q (~5) and non-inductively driven current fraction (~100%) was very challenging due to their inverse relationship. It appears that

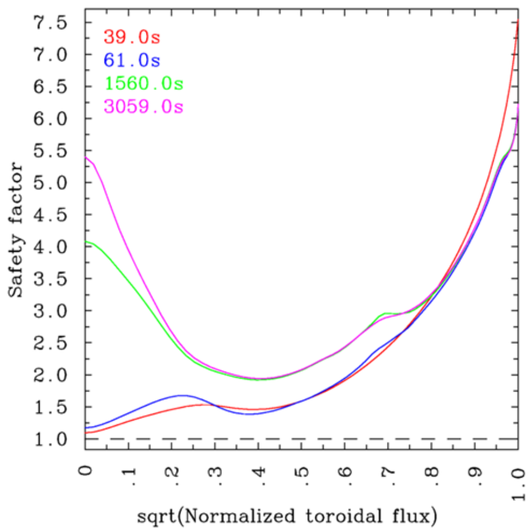

Figure 4. 9MA ITER steady-state mode operation scenario (reference case). Evolution of the safety factor profile.

increasing the flat-top density is one of possible approach, because both the plasma self-heating power and pedestal top pressure will increase as the density increases. The achieved safety factor profile is slightly reversed (q_{min}> 1.5) at the core region and maintained until the end of the flat-top phase (see figure 4). The poloidal field (PF) coil currents were well within their coil current, force and field limits. A fully self-consistent free-boundary transport simulation has also been performed to provide information on the PF coil voltage demands and to study the controllability with the ITER controllers. The PF coil currents were feedback controlled well around the reference coil currents (see figure 5) and the shape evolution and plasma parameters were very close to those obtained from the prescribed boundary transport simulations.

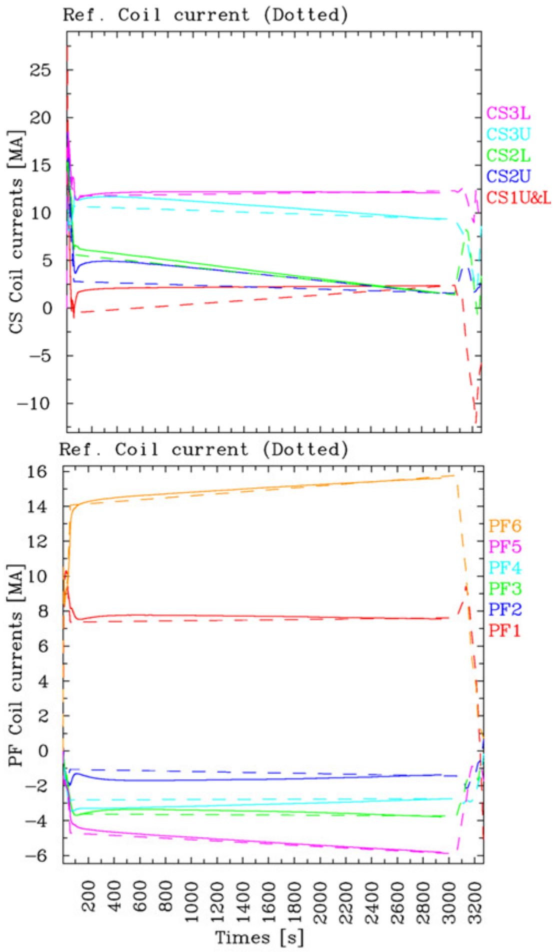

Figure 5. 9MA ITER steady-state mode operation scenario. Time traces of the CS/PF coil currents. (dotted lines represent the reference currents used for controllers)

Summary and future Advanced plasma operation scenarios for ITER, the hybrid and steady-state modes, have been studied using an advanced free-boundary transport simulation code, CORSICA, including relevant physics, engineering constraints and ITER design parameters. This study shows that operating ITER in the advanced operation modes would be possible, if the burning plasma physics and ITB control issues can be resolved. Optimization of the scenarios would require further investigation. The improved tokamak discharge modelling capability achieved in this work will be useful for supporting the ITER Plasma Control System (PCS) and Integrated Modelling (IM) projects recently initiated.

Acknowledgements This work was partly supported by the Principality of Monaco/ITER Postdoctoral Research Fellowship Program. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

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