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Full tokamak simulation of ITER Scenario 2 using the combined DINA-CH and CRONOS simulator

S.H. Kim[1], J-F. Artaud[2], V. Basiuk[2], V. Dokouka[3], F. Imbeaux[2], R.R. Khayrutdinov[3], J.B. Lister[1], V.E. Lukash[4]

[1]*Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association EURATOM-Confédération Suisse, CH-1015 Lausanne, Switzerland*
[2]*CEA-Cadarache, France*
[3]*TRINITI, Moscow Region, Russia*
[4]*RRC Kurchatov, Moscow, Russia*

1. Introduction Understanding the non-linearly coupled free-boundary physics between the plasma equilibrium evolution and transport is a key challenge to advanced tokamak operation in future devices. The complexity of the physics requires a full tokamak simulation which includes the plasma equilibrium response to the currents flowing in the surrounding conducting systems and poloidal fields coils, advanced plasma transport and source calculations, and the controls of coil currents and plasma profiles. This enables us to study the feasibility of attainable target tokamak operation against the engineering and the physical constraints as well as several control issues such as plasma disturbances and disruptions. In this work, a full tokamak discharge simulator developed by combining a free-boundary evolution code, DINA-CH, and an advanced transport code, CRONOS [1-3], is used for the simulation of ITER operation scenario 2 [4].

2. The combined DINA-CH and CRONOS simulator Coupling of two different codes requires comprehensive considerations not only of the implemented physics in the codes, but also of the technical issues such as consistency, reliability, performance and numerical stability. The objective of combining two codes is to have better consistency by completing the set of related physics. However, the consistency can be easily deteriorated, if there are two different approaches to calculating the same physics. In the combined simulator, the free-boundary equilibrium calculated by DINA-CH is directly used for CRONOS transport and source calculations, and DINA-CH uses the plasma and source profiles provided by CRONOS to calculate a new free-boundary equilibrium and current diffusion. The reliability is enhanced by treating the exchanged data between two codes explicitly in time to minimize the accumulation and propagation of errors. The computational performance is improved by using time-varying source profile update intervals to optimize the time-consuming source profile calculation. The numerical instability caused by non-monotonic initial plasma profiles is reduced by using the SPIDER solver. However, the improvement of numerical stability usually reduces computational performance. An adaptive grid solver is now being tested.

3. Full tokamak simulation of ITER scenario 2 The ITER scenario 2 aims at ELMy H-mode operation with the total plasma current of 15MA for the burn duration of 400sec. A full tokamak simulation of this scenario is presented as a demonstration of the capabilities of the combined DINA-CH and CRONOS simulator, as well as being a design study in itself. The average electron density is assumed to vary with the plasma current and the ion and impurity density profiles are self-consistently calculated with the effective charge profile which is assumed to decrease monotonically as the electron density increases [5]. The KIAUTO transport model [6] controls the energy confinement level and mode transition respecting the confinement time scaling laws. The expansion of the plasma current column and the X-point formation around 29sec are pre-programmed in the reference coil current waveforms. A virtual radial position controller stabilising the plasma shape evolution is switched to a shape controller after X-point formation. The shape controller controls 6 gaps between the plasma boundary and wall until the end of the current ramp-down. The plasma position control weighted at low plasma current (0.4-7.5MA) adequately stabilises the plasma boundary evolution before X-point formation. Appropriate initial eddy currents in the passive structures are determined by trial. To synchronise the sawtooth events between two codes, the effective thermal collapse is triggered in CRONOS when the plasma current was redistributed in DINA-CH. Early neutral beam injection (NBI) is applied at 70sec to avoid the coil current limits by reducing the resistive ohmic flux consumption. During the flat-top, 53MW of additional heating and current drive (H&CD) power (33MW of NBI and 20MW of ICRH) are applied.

4. Simulation results Combined simulation results are shown in Figure 1. The evolution of plasma poloidal beta, internal inductance and safety factor follow the reference scenario. The internal inductance at the start of flat-top (SOF) is slightly higher than the reference scenario. The vertical stability with high internal inductance is addressed later. The evolution of the coil voltages is within limits [7], since they are imposed in the control system as saturation limits. The coil current evolutions are shown in Figure 2. Although the early application of NBI made the CS1 coil current avoid its limit, the PF2 coil current briefly violates its limit at end of flat-top. This violation seems avoidable by either changing the plasma shape evolution or increasing the coil current limit itself, as in the recent ITER design review [8]. The poloidal flux at the plasma boundary is well above the reference scenario, Figure 3. Either the total H&CD power can be reduced or the burn duration can be extended with 53MW of H&CD power. The imbalance current flowing in the Vertical Stabilization Converter (VSC) and the total active power of the power supply system were within the operational limits. Though the plasma shape evolution was well controlled during the whole simulation, the radial dynamic response of the plasma was underestimated during L-H and H-L mode transitions. The 2D current profile used for the free-boundary equilibrium calculation had a fixed shape and was re-scaled to the total plasma current. A correction is underway.

5. Lowering l_i by applying LH Lower Hybrid Heating and Current Drive (LHH&CD) has been applied to reduce the internal inductance which is closely related to the vertical stability through the poloidal field coil currents. The early application of 20MW LHH&CD to the ITER reference scenario 2 [9] was effective to reduce the internal inductance down to 0.71 from 1.05 as shown in Figure 4. The flux consumption during the plasma current ramp-up was reduced to -81Wb from -124Wb. The saved flux is equivalent to about 500sec of additional burn duration. However, the early application of H&CD produces a large change of the plasma profiles which make the shape evolution deviate from the reference scenario. Modification of the coil current evolution, using elongation control, was used to achieve the desired shape evolution.

6. Conclusions The ITER scenario 2 has been successfully simulated by the combined DINA-CH and CRONOS simulator, which is a mature platform for a full tokamak discharge simulation. The feasibility of ITER reference scenarios was studied for the whole operation phases and the early application of H&CD was used to avoid the coil current limits. The LHH&CD was effective to reduce the internal inductance and to save the flux consumption.

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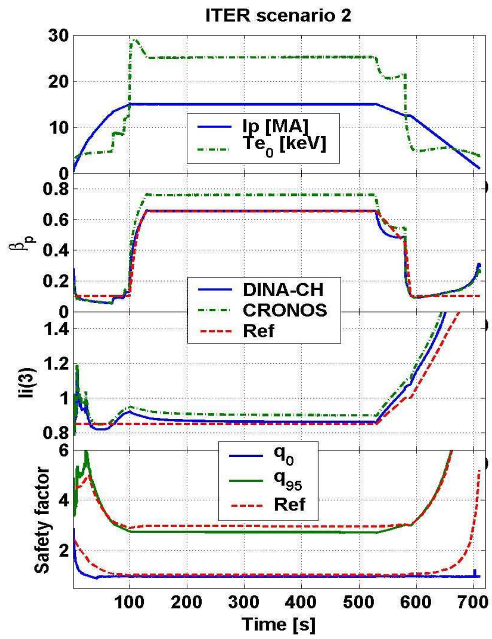

Figure 1 Time trace of plasma parameters, plasma current, central electron temperature, poloidal beta, internal inductance and safety factors (q_0 and q_{95}) (dashed red lines: ITER reference scenario 2)

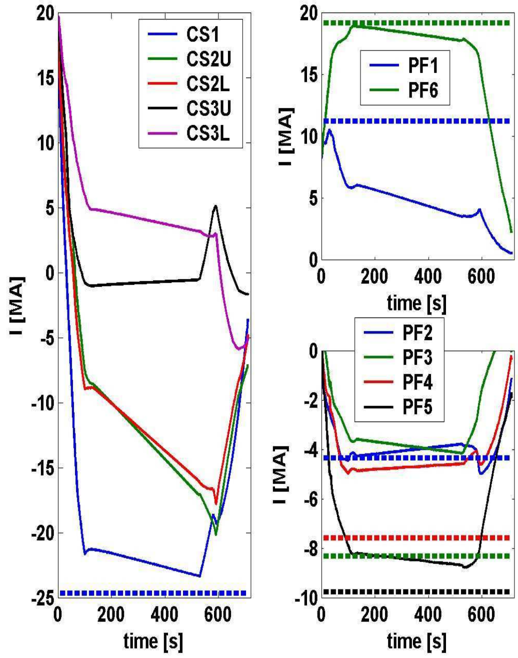

Figure 2 Time trace of coil currents (dashed thick lines: coil current limits)

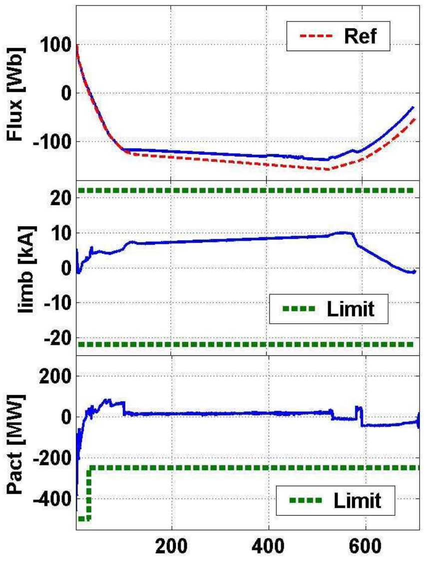

Figure 3 Time trace of poloidal flux at the plasma boundary, imbalance current flowing in the Vertical Stabilization Converter and total active power of the power supply

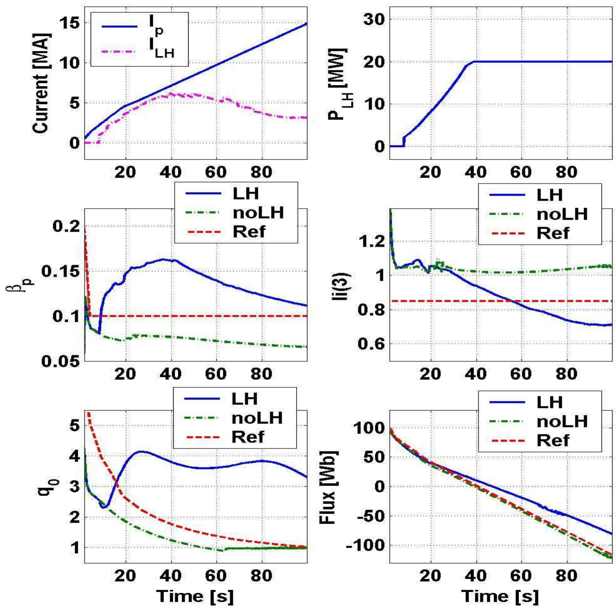

Figure 4 Time trace of plasma parameters, plasma current, poloidal beta, safety factors at the center, LH power, internal inductance and poloidal flux at the plasma boundary (dashed red lines: ITER reference scenario 2)