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Plasma Current Ramp-up Phase Simulation of ITER

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1. Introduction The ITER reference scenarios are proposed considering plasma physics and engineering limitations. They still have uncertainties, mainly from the plasma transport and boundary evolution during plasma current ramp-up and ramp-down phases. The plasma current ramp-up phase is especially emphasized by the fact that the desired flat-top tokamak operation conditions are obtained by tailoring the current ramp-up phase. Therefore, a more detailed assessment of the current ramp-up phase, taking into account related physics and limitations, is necessary for the validation of the proposed ITER scenarios. The complexity of physics requires a full tokamak discharge simulator, such as the combined DINA-CH and CRONOS simulator [1], which can calculate self-consistent plasma shape and profile evolutions with response to the current changes in the surrounding conducting structures. As a first attempt, the plasma current ramp-up phase of the ITER reference scenario 2 [2] has been simulated, focusing on the feasibility of the scenario itself.

2. Current ramp-up simulation The ITER reference scenario 2 aims at ELMy H-mode operation with a purely inductive plasma current ramp-up up to 15MA. In this ramp-up scenario, the plasma is initially limited on the outboard side, expands with the plasma current and density ramp-up, until it reaches its fully diverted shape. In this way, the plasma inductance and the safety factor at the plasma edge are expected to reach their target values. In the simulations, the plasma density is assumed to increase linearly and the effective charge decreases monotonically as the density increases [3]. Heat transport is assumed to follow an ohmic energy confinement time scaling law [4] which is implemented by a transport model in CRONOS. The evolution of the plasma current, position and shape is self-consistently calculated with the electro-magnetic response to the surrounding conducting tokamak systems. In the early phase of the current ramp-up with a small limited plasma starting at 0.4 MA, as well as the vertical position and plasma current controllers, a virtual radial position controller is applied to stabilize the plasma boundary evolution, instead of pre-programming a vertical magnetic field ramp-up in parallel with the plasma current ramp-up. After the formation of the X-point, the virtual radial position controller is turned off and a shape controller is turned on gradually allowing a smooth transition between them. The second controller controls 6 gaps between the plasma boundary and surrounding tokamak structures. The control of the plasma position is more highly weighted than the plasma current control when the plasma current is lower than 7.5MA, because the plasma boundary evolution is critical to sustain the plasma. Feedforward coil voltages are important for the plasma current ramp-up in this early phase. Sawtooth events in the combined simulation are synchronized by detecting the sawtooth event and inversion radius from the safety factor profile and applying high enough heat conductivities inside the inversion radius to produce an effective sawtooth.

Before carrying out this combined DINA-CH and CRONOS simulation, independent simulations using each code separately were performed. First, this was to see if the codes could work for the current ramp-up phases with very small initial current and shape. Secondly, this was to improve our understanding by comparing the results between them. In the DINA-CH simulation, the plasma boundary evolution was studied by testing the virtual radial position controller, its transition to the shape controller after the X-point formation and the effect of voltage saturation on the CS and PF coils. In the CRONOS simulation, the ohmic energy confinement time scaling law and plasma profile evolution were examined with a prescribed plasma boundary evolution. In this way, the difficulties arising from the combined DINA-CH and CRONOS simulation are partly resolved saving significant time and effort. In the combined simulation, the time-step of data exchange between two codes is reduced to 1ms to guarantee the stability of the simulation which experiences very rapid changes of the plasma boundary shape and transport when the plasma is small or when the X-point is formed.

3. Simulation results Combined simulation results of the plasma current ramp-up phase are shown in Figure 1. Plasma current and both vertical and radial plasma positions are well controlled by the feedback. The Zeff profile, which is assumed to be flat, is self-consistently calculated with ion and impurity density profiles. In this combined simulation, DINA-CH uses the plasma conductivity profile from CRONOS, instead of using the Zeff profile. The plasma poloidal beta, internal inductance and edge safety factor deviate to some extent from their reference values according to the plasma kinetic profile evolution. The central safety factor evolution shows a fast plasma current peaking at the center and sawtooth events. X-point formation and the resulting shape transition are shown with spikes around 24 sec when the plasma current is about 6.3 MA. This transition is earlier than in the reference scenario. The X-point formation is also shown as perturbations in the plasma profiles in Figure 2 and sudden variations of the gaps in Figure 3. The gap controller is set to turn on after the transition is stabilized around 29 sec. The gap control is successful and fast enough. For more efficient switching of controllers, automatic detection of X-point formation will be developed.

The time traces of the CS and PF coil currents and voltages are shown in Figure 4. At the beginning of the simulation, the coil voltages are allowed to have higher values than the saturation voltage limited by the main power supplies due to the existence of switching network units (SNUs) for CSs, PF1 and PF6, and booster power supplies for PF2-5. The simulated voltages are comparable with the reference voltage waveforms. Some of the PF coil current and voltage evolutions deviate from the reference at the end of the current ramp-up phase. In order to keep the coil currents within the current limits, it is necessary either to increase the plasma temperature and thereby reduce the resistive ohmic flux consumption or to modify the reference coil current waveforms. Simulation results stopping the density ramp-up from 50 sec show a slight improvement which is limited by the degradation of the energy confinement. Application of NBI power before the end of the current ramp-up phase, which is similar to the ITER reference scenario 1, effectively reduces the resistive ohmic flux consumption. Simulations with modified reference coil current waveforms are not yet successful enough to avoid the current limits, because the control of the plasma current is much stronger than the control of the coil currents during the current ramp-up.

4. Conclusions The feasibility of the plasma current ramp-up phase of the ITER reference scenario 2 is studied using the DINA-CH and CRONOS tokamak discharge simulator which fulfils all requirements for this assessment work. Application of additional heating power seems to be a good choice to reduce the resistive loss of ohmic flux and to prevent the coil currents from crossing the current limits.

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