# Simulation of ITER plasma scenarios starting from initial discharge of central solenoid

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## 1. INTRODUCTION

Till recently self-consistent simulations of plasma scenarios in ITER were divided in two stages. The first stage is simulation of the plasma initiation. It includes the start of discharge of the Central Solenoid (CS), the breakdown and the plasma current ramp-up till about 0.5 MA. At this stage simulation is performed with 0D plasma transport model without self-consistent calculation of plasma equilibrium [1, 2]. The second stage comprises simulation of the rest parts of plasma scenario. A 1D plasma transport model and self-consistent simulation of 2D plasma equilibrium are used at this phase. Such simulation starts from plasma current $1 \div 2$ MA, assuming zero current in the vacuum vessel [3]. So far simulation of these two stages of plasma scenario was not linked self-consistently. Recent development of the DINA code [4] allows the continuous self-consistent simulation of plasma scenario starting from initial discharge of the CS. This paper presents description of this development and results of self-consistent simulations of plasma current ramp-up with different assumptions on the plasma transport models.

The simulations were performed with feedback control of plasma current, position and shape taking into account the coils, the engineering limits imposed on their operation, the coil power supplies (the switching network units and converters), the vacuum vessel and other input data as they are in the present ITER design.

## 2. SIMULATION OF EARLY PHASE OF PLASMA CURRENT RAMP-UP

DINA simulation of early phase of ITER plasma current ramp-up is described in [5]. The simulations reported in this paper start from discharge of the CS producing at the beginning ($t = 0$) about 118 Wb of the magnetic flux. Resistances of the switching network units and waveforms of the feedforward (pre-programmed) voltages in all CS and PF coils from 0 to 1.5 s are taken from the corresponding TRANSMAK simulation. The gas breakdown is assumed at $t = 1.1$ s, when about 2 MW of ECRF heating is applied, the PF system produces 0.3 $\mathrm{Vm^{-1}}$ of the toroidal electrical field in the centre of breakdown region ($R = 5.65$ m, $a \approx 1.6$ m, $Z = 0$) and the stray magnetic field in this region is less than about

2 mT. It is assumed, that after the breakdown the plasma current increases until $I_p$ = 0.1 MA at $t$ =1.2 s, when the first free boundary plasma equilibrium is calculated with the DINA code, taking into account about 1.6 MA of eddy currents induced in the conducting structures during the CS discharge. At this time the plasma with minor radius $a \approx 1.6$ m (see Fig. 1) and safety factor on the boundary $q_b \approx 150$ touches the inboard side of the first wall. After $t$ = 1.5 s ($I_p \approx 0.4$ MA) the feedforward voltages were corrected by feedback voltages produced by the system controlling the plasma vertical and radial positions. The necessity of feedback control of plasma position can be explained by the low value of the plasma current relative to the currents in the coils (≈100 MA∗turns in the CS) and in the vacuum vessel (≈1.6 MA), and by fast variations of $l_i$ and $\beta_p$ at the beginning of plasma initiation (evolution of these parameters is calculated with the DINA code). The inputs of the controller are the errors between the plasma vertical and radial positions and the prescribed values of these parameters. The outputs of the controller are the CS, PF coil feedback voltages.

Evolution of the profile of plasma current is calculated self-consistently after $t$ = 1.2 s ($I_p \approx 0.1$ MA). Before $t$ = 3.5 s (1.5 MA) 0D plasma transport model, described in [5], is used in DINA simulations. It assumes parabolic profiles of the electron and ion temperatures. Then the standard 1D plasma transport models [6] are used. The waveforms of the plasma density, $Z_{eff}$ and the power of additional heating are prescribed. Evolution of plasma current $I_p$, electron temperature $T_e$, $Z_{eff}$ and $l_i(3)$ during first 5 s after breakdown is shown in Fig. 2.

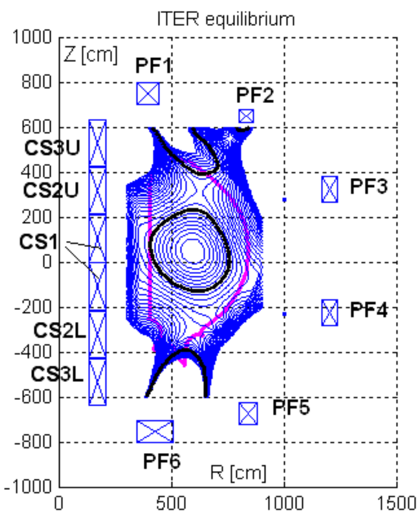


FIG 1. Fist plasma equilibrium simulated with the DINA code (0.1MA).

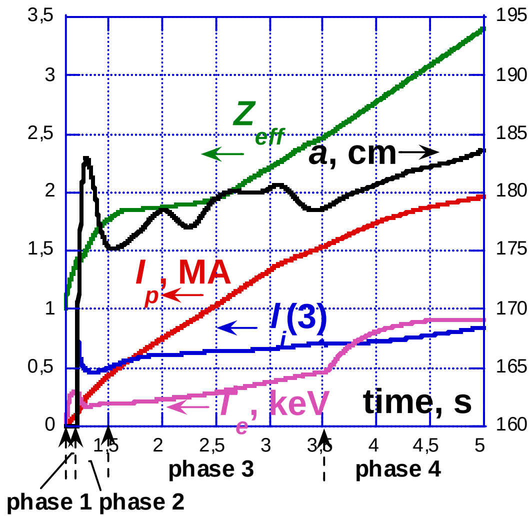


FIG. 2 Plasma current $I_p$, average electron temperature $T_e$, $Z_{eff}$ and $l_i(3)$ during first 5 s after breakdown.

Examples of several ITER plasma current ramp-up simulations performed with the modified DINA code are given in the next section.

## 3. EXAMPLES OF SIMULATIONS OF PLASMA CURRENT RAMP-UP IN 15 MA SCENARIO

Here we present results of simulations of plasma current ramp-up in 15 MA scenario performed with different plasma transport models. These are Coppi-Tang L-mode model [7] ("CT" model), Bohm-gyroBohm L-mode model [8] ("BGB" model) and two models with ITER L-mode scaling [9]. Different assumptions on the radial profiles of plasma thermal conductivity, $\chi(\rho)$, were used for the last two models. For getting high values of $l_i(3)$ with this scaling, it was assumed $\chi(\rho) \sim (0.3+\rho^2)$ ("ITER high $l_i$" model). For getting low values of $l_i(3)$, the assumption was $\chi(\rho) \sim (0.3+\rho^{0.6})$ ("ITER low $l_i$" model). In L-mode, the boundary conditions for the ion and electron temperatures are assumed: $T_{e,i}$ = 25 eV in the limiter phase and $T_{e,i}$ = 100 eV in the divertor phase. In H-mode, $T_{e,i}$ = 190 eV.

In the simulations we consider the case of the fastest plasma current ramp-up (during 50 s, limited by the converter voltages) with early X-point formation (at 3.5 MA). 4 MW of ECRH were applied soon after the X-point formation (at 3.56 MA). Evolution of the plasma current, minor radius, elongation, volume averaged electron density, $Z_{eff}$ and $q_{95}$ is shown in Figs. 3a and 3b. Plasma internal inductance and the volume averaged electron temperature for the plasma transport models considered are shown in Figs. 3c and 3d, respectively. Fig. 3e shows averaged over the plasma cross section poloidal magnetic flux produced by the currents flowing in the CS and PF coils and the currents in passive structures: $\Psi_{ext} = \int \Psi_{coils+passtr} j_p dS_p \Big/ \int j_p dS_p$ .

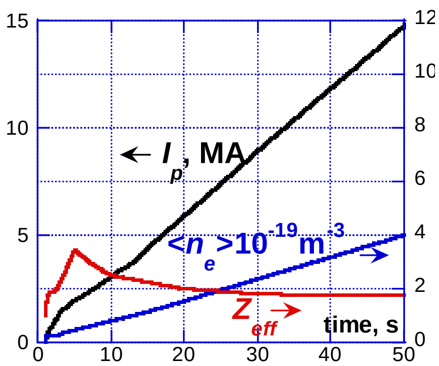


FIG 3a. Plasma current, averaged density and $Z_{eff}$.

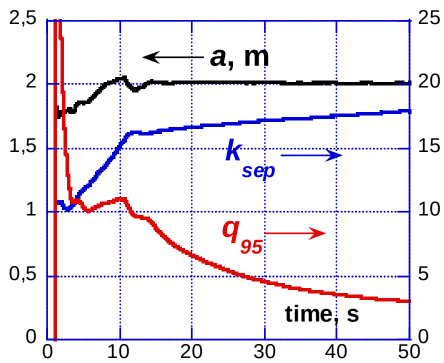


FIG 3b. Plasma minor radius, elongation and $q_{95}$.

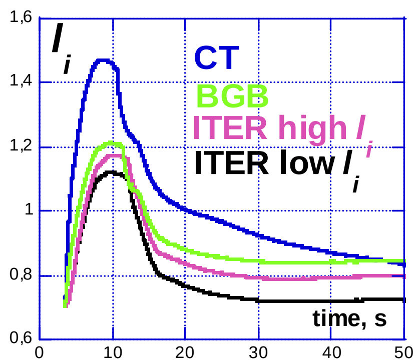


FIG 3c. Plasma internal inductance, $l_i(3)$ for different transport models.

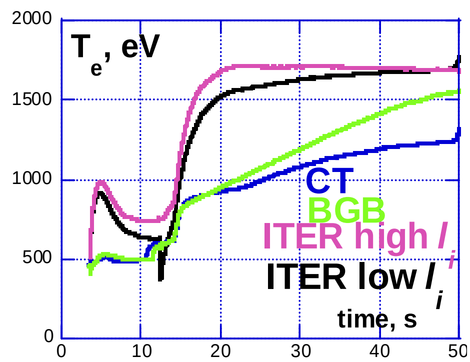


FIG 3d. Average electron temperature for different transport models.

Fig. 3e shows current in the central sections of the CS (CS1 coils).

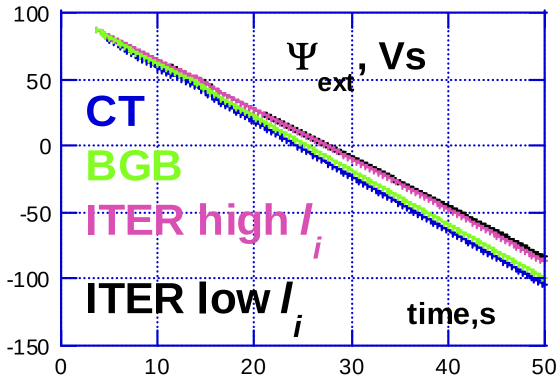


FIG 3e. Poloidal magnetic flux produced by the coil currents and the currents in passive structure linked with the plasma for different transport models.

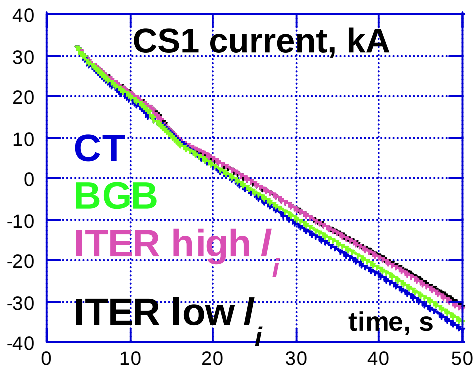


FIG 3f. Current in the central sections of the CS for different transport models.

## 4. CONCLUSION

Upgraded version of the DINA code has been developed with the goal of simulation of the whole scenario of PF system operation (from the start of CS discharge till the end of plasma current ramp-down).

The simulations of plasma current ramp-up in 15 MA scenario performed with four plasma transport models have shown that at the Coppi-Tang model is the most pessimistic from the point of view of the magnetic flux consumption during the plasma current ramp-up. At the start of current flattop it requires the highest values of the magnetic flux. The corresponding value of current in the CS1 coils is 37.5 kA, which is by 7.5 kA lower than the engineering limit.

*The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.*

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