Optimization of plasma current ramp-up in DINA simulations of 15 MA ITER scenario with JINTRAC plasma transport modelling

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1. Introduction

Developed in 2014, a new version of the DINA code (DINA with prescribed kinetic profiles) [1] allows validation of the capability of ITER PF system to support scenarios obtained with other codes. These other codes may have more sophisticated plasma transport models, but do not have the capability of: 1) detailed simulation of plasma magnetic control, 2) correct calculation of the magnetic flux linked with the plasma from plasma initiation and 3) detailed integration of all engineering limitations. The simulation of ITER 15 MA $Q \approx 10$ scenario described in [1] was performed using the JINTRAC code suite to model plasma transport [2] for the fastest plasma current ramp-up (lasting 50 s) in ITER, which is limited by the voltage produced by the power supply of the Central Solenoid central modules (CS1U, CS1L) connected in series. The results of the JINTRAC modelling were then incorporated into a DINA simulation which showed that, in this scenario, due to the low value of the plasma internal inductance, l_i, at the start of current flattop (SOF), the maximum value of the magnetic field on the PF6 coil conductor, $max(B_{PF6})$, during the burn is significantly higher than the design limit (7.3 T vs. 6.4 T). It should be noted that for a given separatrix shape the maximum current in the PF6 coil (and the magnetic field on the coil conductor) in the flat top phase decreases with: 1) the increase of l_i and 2) the increase of the current in the CS1U-L coils flowing opposite to the plasma current (i.e. with the increase of the poloidal magnetic flux consumption during plasma current ramp-up). Therefore the peak value of the magnetic field on the PF6 conductor can be reduced by increasing the plasma current ramp-up time, t_{ramp}, leading to the increase of the resistive and inductive magnetic flux consumptions in this phase. The corresponding increase of l_i during the current flattop and the increase of negative current in the CS1U-L coils at the SOF lead to a reduction in the PF6 current and magnetic field on the PF6 conductor.

This paper presents the results of an optimization study for the duration of the plasma current ramp-up in the ITER 15 MA Q ≈ 10 scenario simulated with the DINA code using the JINTRAC plasma transport model. The purpose of the optimization was the reduction of the maximum magnetic field on the PF6 conductor to values lower than the design limit while maintaining an appropriate burn length as required for ITER (> 300 s). The simulations were performed for two values of the plasma current ramp-up time of 70 s and 80 s and include the modelling of plasma current, position and shape control taking into account: 1) engineering limits imposed on coils and on their power supplies (including the switching network units and converters), 2) eddy currents induced in the vacuum vessel and 3) allowable values of the plasma-wall gaps and positions of the separatrix strike points on the inner and outer divertor target plates. The simulations were carried out from the start of CS discharge (plasma initiation) to the end of burn (EOB), defined as the state when current in the CS1U-L coils approaches the engineering limit ($I_{CS1U\text{-}L}$(EOB) = -44.2 kA for an engineering limit of 45 kA).

2. Simulation model

The DINA simulations combined a 2-D free-boundary equilibrium evolution solver and 1-D calculation of the poloidal magnetic flux diffusion together with the JINTRAC plasma transport modelling for these plasma conditions.

JINTRAC plasma transport model

JINTRAC is a system of codes for integrated simulations of tokamak scenarios [2]. It includes the 1.5D core transport code JETTO+SANCO and the multi-fluid SOL-divertor code EDGE2D-EIRENE. In JETTO+SANCO, the transport equations are solved for plasma current, pressures, main ion and impurity densities and toroidal momentum. In the ITER baseline scenario simulations for DINA, anomalous transport coefficients in the core are determined by GLF23 in H-mode and by the Bohm/gyroBohm model in L-mode. If the net heat flux, P_{net}, at the separatrix exceeds the L-H transition power threshold, $P_{L\text{-}H}$, anomalous transport within the ETB is gradually suppressed as a function of $exp(-(P_{net} - P_{L\text{-}H})/P_{L\text{-}H})$. The pedestal pressure, ETB width and boundary conditions at the separatrix are derived from EPED1-SOLPS calculations [3].

Steps in scenario simulations

Plasma initiation and early current ramp-up to 1.6 MA (3.5 s after the start of CS discharge) were simulated using the standard version of the DINA code with a 0-D plasma transport model similar to that described in [4]. The plasma current of the first free-boundary plasma equilibrium is 0.1 MA (t = 1.2 s) [1]. When plasma current exceeds 1.6 MA

($t > 3.5$ s), the simulation is performed with the newly developed DINA version using the kinetic profiles obtained in the corresponding JINTRAC simulations. The simulations of scenarios were performed in three steps:

- At the *first* step, the time sequence of the sets of (R, Z) coordinates of a number of points located on the plasma boundary and the waveform of the plasma current, used as input data in the JINTRAC code, were calculated by standard version of the DINA code utilizing the following approach: before the X-point formation (at 11.4 s and with $I_p = 3.4$ MA) the rate of plasma current ramp-up was kept the same as it was in the simulation with the 50 s plasma current ramp-up [1], after the X-point formation the rate of plasma current ramp-up was decreased to achieve the SOF at $t = 70$ s or at $t = 80$ s.
- At the *second* step, the sets of plasma boundaries and the waveform of plasma current obtained in the DINA simulation at step 1 were used in the JINTRAC simulation with prescribed evolution of the plasma current and boundary using a more sophisticated plasma transport model than that in the standard version of the DINA code [5]. Results of the JINTRAC simulations provide, among others, the time evolutions of the following profiles of plasma kinetic parameters: 1) the plasma electric conductivity, 2) the density of non-inductively driven current, 3) the total pressure (produced by the thermal and non-thermal plasma particles), 4) the plasma density (electron and ion) and 5) the plasma temperature (electron and ion). The JINTRAC simulations were carried out up to $t = 200$ s. i.e. beyond the time for which stationary burning plasma conditions are achieved.
- At the *third* step, the JINTRAC produced profiles (with a time step of 1 s and applying linear interpolation between the steps) were used to carry out the scenario simulations using the newly developed DINA code version with prescribed time evolution of the kinetic profiles. The plasma profiles for $t > 200$ s were assumed remain unchanged to the EOB consistent with the JINTRAC modelling findings. The final DINA simulation thus combines the benefits of the DINA plasma magnetic control simulation with accurate calculation of the poloidal magnetic flux and the JINTRAC detailed plasma transport modelling.

3. Results

Fig. 1 shows the waveforms of the plasma current and l_i during the first 100 s of the scenario in the simulations with plasma current ramp-ups of 50 s, 70 s and 80 s. The corresponding waveforms of the maximum magnetic field on the PF6 conductor ($max(B_{PF6})$) are shown in Fig. 2. The increase of the current ramp-up duration from 50 s to 70 s is sufficient to reduce $max(B_{PF6})$ from 7.3 T to its design limit of 6.4 T. The increase of the current ramp-up duration to 80 s decreases $max(B_{PF6})$ further down to 6.1 T.

Figs. 3 and 4 show the evolution of the plasma parameters from plasma initiation to the EOB (t = 742 s) in the scenario with 70 s plasma current ramp-up. The duration of burn in this case is about 650 s. The increase of the duration of the plasma current ramp-up to 80 s results in the reduction of the burn duration to about 500 s. It should be noted that the burn duration values depend on the assumptions regarding Z_{eff} during the burn, which in these simulations is $Z_{eff} \approx 1.2$ consistent with high density operation with Be/W plasma facing components at JET. Seeding of extrinsic impurities for the control of power loads to the divertor during the burn could increase the value of Z_{eff} beyond 1.2 (but still lower than ≈ 1.8 to allow the achievement of $Q \approx 10$ [3]) and correspondingly reduce the burn length inversely proportional to the Z_{eff} value. The reduced burn lengths would still be larger than the minimum of 300 s required for ITER even for the current ramp-up duration of 80 s. In addition, these simulations with 70 and 80 s ramp-up times have all engineering parameters within the design limits.

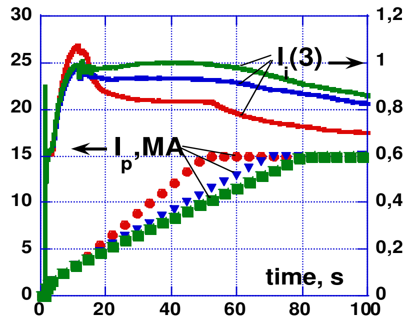

Fig. 1: Time traces of I_p and l_i in scenarios with plasma current ramp-up duration of 50, 70 and 80 s.

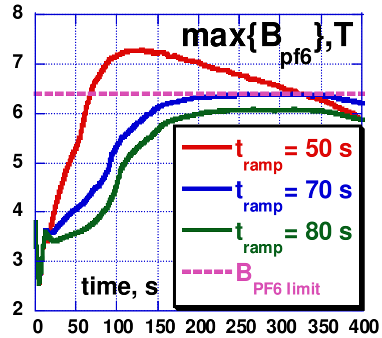

Fig. 2: Time traces of the magnetic field maximum on the PF6 conductor at the various rates of the plasma current ramp-up in Fig. 1.

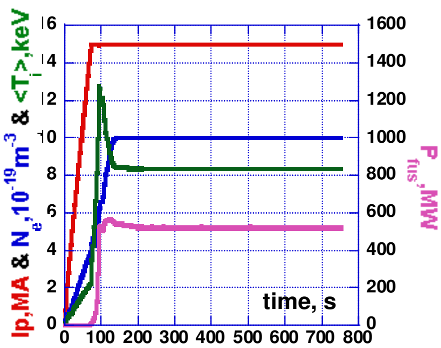

Fig. 3: I_p, electron density, ion temperature and fusion power in scenario with the plasma current ramp-up duration of 70 s.

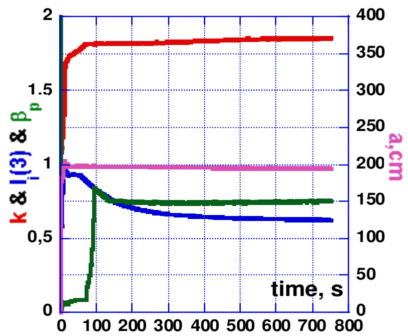

Fig. 4: Plasma elongation, l_i, β_p and minor radius in scenario with the plasma current ramp-up duration of 70 s.

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